An annotated bibliography of research related to the possible long-term impacts of pumping water from tundra ponds for the creation of ice roads

Prepared by

Matt Nolan
Institute of Northern Engineering,
University of Alaska Fairbanks

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Introduction

Overview

The intent of this literature review was to identify published work from the peer-reviewed literature that might be relevant to understanding potential impacts caused by withdrawing water from lakes to build ice roads in the Arctic. I identified about 300 peer-reviewed papers related to this issue. I have written short summaries of about 100 of them that I perceived had the greatest relevance to the issue of water withdrawal impacts and I listed about 100 more related references; abstracts of most of these papers are also contained in this review. I found no peer-reviewed papers that directly addressed the question of long-term impacts on lakes due to pumping, but many relevant background issues are addressed in the literature and these are categorized by topic within the review. Fifteen papers or books are suggested as highly recommended reading by anyone interested in the subject. A list of gray literature reports found as part of this review are also included.

The Need to Understand Impacts from Water Withdrawal

Since at least 2000, individuals representing government agencies, private companies, and nongovernmental organizations have expressed concerns about potential impacts to tundra lake ecosystems resulting from the withdrawal of water for construction of ice roads. Although dramatic evidence of impacts was elusive, concerns that undocumented impacts could be occurring remained. The National Academy of Science's *Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope* (NRC, 2003) summarized the issue with several comments, as follows:

- "A study of the effects of withdrawing water from lakes that do not contain fish should also be conducted to assess the degree to which current water use affects the biota associated with those bodies of water." (page 10)
- "Fish populations in lakes subjected to this maximum allowable withdrawal [typically 15% of minimum winter liquid water volume] appear to be unaffected, but data on consequences are limited, and there has been no research to determine the effects of withdrawals on populations of invertebrates in lakes or on vertebrate food supplies." (page 127)
- "For lakes that do not support wintering fish, there is essentially no current regulation of winter water withdrawal . . . This practice essentially allows withdrawal of all remaining unfrozen water in the lake at the time of withdrawal. The effects of such withdrawals on lake flora and fauna have not been analyzed . . The potential effects of reduced water levels on vegetation and waterfowl nesting or feeding have not been evaluated." (page 127)
- "An initial study of the 15% criterion [i.e., restrictions that prevent withdrawal of more than 15% of minimum winter liquid water volume from fish bearing lakes] should determine the degree to which that criterion prevents harm to fish and

> invertebrates. A study of the effects of withdrawing water from lakes without fish should be conducted to assess the degree to which current water use affects biota associated with these water bodies." (page 153)

In a series of open forums and discussions on the issue of long-term impacts to lakes due to pumping, held at the University of Alaska Fairbanks in 2001 and 2002, public comment was also solicited. Representatives from several non-governmental organizations expressed concerns similar to those above and especially about the issue of whether the lakes are completely recharged with precipitation. One concern that consistently emerged throughout the discussions was that the criteria used during the permitting process were not based on any formal scientific studies but rather on an initial assessment that was considered conservative and would likely result in minimal impact on recharge and long-term disturbance.

Background on the Literature Review

Although it was widely recognized that few studies had directly assessed impacts from water withdrawals, a number of discussions among stakeholders in 2001-02 suggested that a thorough review of technical literature related to water budgets for arctic lakes, thaw lake evolution, and related topics might be valuable. I was therefore contracted to undertake this literature review, working with funds provided by BP. This work coincided with work initiated by Professor Larry Hinzman and his colleagues, also based at the University of Alaska, with funding provided by the U.S. Department of Energy, BP, and ConocoPhillips Alaska (CPA). In addition, BP, CPA, the US Bureau of Land Management and the Alaska Department of Natural Resources undertook various studies in support of specific proposed or active exploration and development projects. Because this literature review occurred concurrently with work by Dr. Hinzman and others, the review does not capture recently completed and ongoing work that bears most directly on water withdrawal impacts. Instead, the review provides the background against which these and future studies of water withdrawal may be compared. This review was circulated for review within the scientific community, the public, and stakeholders in February of 2004; only a few comments were received on it and no new peer-reviewed papers were recommended.

Building Ice Roads

To better set the stage for the review, some background on ice road construction, water usage, and permitting may be helpful. The general reasoning behind ice road construction is that, unlike gravel roads, they leave little or no trace behind and require no mitigation or reclamation activities once they are no longer used. Ice roads of course can only be created and used in winter, when air temperatures are substantially below freezing. One kilometer of ice road on tundra requires about 3.5 (±1.2) x10^6 liters of water from lakes, depending on the local roughness of the terrain (Michael Lilly, pers. comm.). In spring and early summer, ice roads melt, usually lagging behind snowmelt. While this water may not return to the same watershed from which it was withdrawn, no further human activity purposefully determines its destiny and it returns to North Slope tundra, pond, and stream ecosystems.

Permits typically allow water withdrawal from a large number of lakes along a road right-of-way, providing construction contractors with the flexibility to draw from lakes as close to the right-of-way as possible to minimize transportation costs. For lakes without fish, the full liquid volume and the ice can be used for ice road construction. For lakes with fish, water withdrawal is typically limited to 15% of the minimum unfrozen water volume in winter. Typically much more water is permitted than is actually withdrawn. As an example, between 1998 and 2001 annual permits were issued to one company allowing withdrawals of more than 8.3 billion liters of water each year, but less than 0.9 billion liters (~10%) were actually used (NRC, 2003). The need to minimize transportation costs generally limits water withdrawal to only several centimeters of depth in a particular lake. Occasionally, however, much deeper withdrawals are made.

Results

I identified about 300 peer-reviewed papers during the review process, but not one of them directly addressed the issue of long-term impacts due to pumping. It is probably safe to say that none exist, though there were some related gray literature reports. In any case, the review shows that the scientific literature available currently does not reveal a quantitative understanding of the degree and nature of potential impacts from water withdrawal, a reality that many researchers suspected before the review was undertaken. However, there is a wealth of related information, as nearly all processes in the Arctic are interrelated and trying to understand one requires some understanding of the others. Therefore, the literature in the annotated bibliography was organized to highlight those aspects of tundra ponds that would be most important towards 1) generating and testing reasonable hypotheses about the possible long-term impacts of pumping and 2) understanding the long-term natural variability in these lakes. These aspects included their origins, water chemistry, ice cover, water balance, biota, surrounding permafrost, related numerical modeling and measurement techniques, taliks, and induced drainage experiments. Various gray literature, mostly consulting studies funded by the major oil companies that deal more directly with pumping-related issues, were also identified; no doubt more such reports and many state agency studies exist as well that remain unidentified, as these were not the focus of this review.

The main finding of this review is that further work is warranted to specifically assess impacts from water withdrawal (such as those indicated by NRC (2003)), though it does seem clear from the literature that generally speaking typical water-withdrawal volumes will not prevent complete recharge in spring, even considering the fall deficit from evapotransipiration (ET). Because summer ET is typically larger than summer rainfall, the lakes enter winter with a deficit (Mendez et al., 1998). However, it is likely that there is typically more than double the amount of water available each year from spring snow-melt to completely recharge these shallow lakes above the fall deficit (Bowling et al., 2003). Considering that typical losses due to winter water withdrawals are less than summer ET (about 10 to 20 cm per unit area (Mendez et al., 1998)), sufficient water for recharge should be available from typical snow packs, especially considering that only a small fraction of the hydrologically-connected area is pumped. The impact of heavier withdrawals needs further site-specific evaluation, but this conclusion will likely still hold in any lake that is well connected to a larger up-gradient drainage network during the spring floods. Note that no studies were identified in this review that directly addressed the impact of withdrawal on recharge, so these conclusions are not verified directly by peer-reviewed papers.

The primary value of this review, as stated above, is to provide background information that was available before new studies assessing water withdrawal impacts were undertaken. Continued research has been underway for the past several years by the University of Alaska Fairbanks and will soon yield final reports and peer-reviewed publications that will yield more quantitative information on this subject than was available at the time this review was completed.

How to use this bibliography

This bibliography contains three sections and thus different ways to search for information:

- Section One (page 7): References sorted by topic, with my annotations
- Section Two (page 46): References sorted alphabetically
- Section Three (page 59): References sorted alphabetically including abstracts

The first section has papers organized first by scientific topic and then by relevancy to long-term impacts of pumping; many of the papers here also contain notes as to my impressions of the paper and why it may or may not be relevant. The second section lists all papers alphabetically by first author. The third section is the same as the second, but including abstracts and so is significantly longer.

Note that I created all of the annotations and categorizations as to relevancy contained in this bibliography and I take full responsibility for them. Difficult decisions had to be made by allocating each reference to one of three categories: "Highly Relevant", "Relevant", and "Related". All of the 200 or so references in this bibliography were at least skimmed, and about 100 of them read carefully; those labeled "*Possibly* Relevant" (etc.) are those that were skimmed due to lack of time. When making decisions, those labeled "Highly Relevant" were limited to those that, as a group, offered a broad understanding of the most important aspects of tundra pond dynamics, covering basic topics that anyone involved in their use should understand; there are about 15 references in this category. The "Relevant" category (about 80 references) would be essential reading for graduate students or scientific professional interested in advancing the state of knowledge here. The "Related" papers are those deemed either not directly relevant or now out-dated by more recent papers in the other categories, but nonetheless interesting related reading for those in the field. An additional 100 papers or so were skimmed and not included, many dealing with lakes in other geographic regions or formed by other processes. As much as possible, the references were limited to those related to coastal plain lakes created by thermokarst processes, which are described as "tundra ponds" to distinguish them from waterbodies formed by different processes, but in some cases (notably, related to dissolved oxygen depletion) studies from other ice covered lakes were included.

I hope that you will find this review useful, and that it will ultimately lead to an improved understanding and stewardship of these interesting, ubiquitous, and potentially useful features of the Arctic coastal plain.

Acknowledgements

I would like to thank BP for funding this project, as well as Judy, Nora, and Ann from the Geophysical Institute library for their hard work and patience with me. I would also like to thank Larry Hinzman of UAF, Michael Lilly of GW Scientific, and Bill Streever of BP for providing useful guidance and review along the way. The references contained here are organized in an EndNote database (thanks ISI ResearchSoft), which is available from me upon request.

Section One

References sorted by topic, with annotations

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Highly relevant

The references listed here are all of the “Highly Relevant” literature that I found and makes what I believe would be a good introduction to understanding the dynamics of tundra ponds and the possible long-term impacts of pumping water from them.

W. D. Billings and K. M. Peterson (1980). "Vegetational change and ice-wedge polygons through the thaw-lake cycle in Arctic Alaska." Arctic and Alpine Research **12**(4): 413-432.

1. Highly Relevant. Comments: Perhaps the best paper on vegetational succession as it relates to the dynamics of tundra ponds. The paper asks three questions: 1) Are there predictable successional pathways following natural geomorphic or climatic changes? 2) If so, is succession or vegetational change linear, cyclic, or a combination of both? 3) Are man-caused perturbations followed by ecosystemic changes which are similar to those occurring naturally?

L. Bowling, D. Kane, R. Gieck, L. Hinzman and D. Lettenmaier (2003). "The role of surface storage in a low-gradient Arctic watershed." Water Resources Research **39**(4): 1087.

1. Highly Relevant. Comments: Perhaps the best recent paper on remote sensing of water balance in the Arctic. This paper shows that the amount of snow melt available in spring is more than double what is typically necessary to recharge the wetlands (1999-2001), and excess snows do not help this, they just cause widespread flooding.

C. R. Ellis and H. G. Stefan (1989). "Oxygen demand in ice-covered lakes as it pertains to winter aeration." American Water Resources Association **33**(6): 1363-1374.

1. Highly Relevant. Comments: Very interesting paper that describes the physics of oxygen consumption in lakes with an eye towards preventing depletion. Most consumption occurs near the bed, not water column, and when level drops below 3 mg/l, the rate of depletion at bed drops substantially. So by keeping the bottom water still and drawing water from the top of the column, you can reduce the overall consumption within the lake. Perhaps the best overview of dissolved oxygen dynamics in ice covered lakes.

A. Hershey, G. Gettel, M. McDonald, M. Miller, H. Mooers, W. J. O'Brien, J. Pastor, C. Richards and J. Schuldt (1999). "A geomorphic-trophic model for landscape control of Arctic food webs." BioScience **49**: 887-897.

1. Highly Relevant. Comments: An interesting paper that describes a method of predicting fish types and food webs based on landscape characteristics (primarily stream gradients). "Because landscape criteria control the distribution of fishes, and fish control trophic structure, the landscape indirectly controls lake trophic structure." Perhaps the best recent paper on predicting fish distribution in Arctic lakes, though mostly related to the foothills, not the coastal plain.

J. Hobbie (1980). Limnology of tundra ponds. Stroudsberg, PA, Dowden, Hutchinson and Ross.

1. Highly Relevant. Comments: Without doubt the best overview of the physics and chemistry of tundra ponds on the north slope, based on the IBP research in the Barrow Area. Complete chapters on most everything related to modern limnological components and dynamics, though weak in permafrost/water interactions especially in the long-term.

J. Hobbie (1984). Polar Limnology, In: F. Taub (ed.), Lakes and Reservoirs. Elsevier, Amsterdam.In: F. Taub (ed.), Lakes and Reservoirs. Elsevier, Amsterdam.
1. Highly Relevant. Comments: This paper is a great introduction to Arctic lakes, though it also includes Antarctic lakes as well. It includes discussions of both thermal and biological characteristics.

J. R. Mackay (1992). Lake stability in an ice-rich permafrost environment: examples from the Western arctic coast. Environment Canada. N.H.R.I Symposium Series Aquatic Ecosystems in Semi-Arid Regions: Implications for Resource Management;.
1. Highly Relevant. Comments: Possibly the best overview of the natural stability of thaw lakes in the context of climate change of the past 10,000 years. Reviews major geomorphological areas in northern Canada in terms of their lakes, the nature and origin of ice rich permafrost, the thaw lake cycle, drainage mechanisms, and future dynamics in the context of climate change. Also discusses thaw lake creation in two distinct phases (10ka and 5ka), and decreasing liklihood for formation today.

J. Mellor (1987). A statistical analysis and summary of radar-interpreted Arctic lake depths: an addendum to 12 map products. Anchorage, BLM.
1. Highly Relevant. Comments: Describes the use of airborne SAR to measure lake depths in the NPR-A area; later work showed the same could be done with satellite SAR. This work produced many high-quality maps that could be used in practice today, and points the way towards what could be done on the entire north slope.

J. Mendez, L. Hinzman and D. Kane (1998). "Evapotranspiration from a wetland complex on the Arctic coastal plain of Alaska." Nordic Hydrology **29**(4/5): 303-320.
1. Highly Relevant. Comments: Perhaps the most comprehensive review of both evaporation rates and methods for measuring it in arctic tundra and lakes.

S. E. Rawlins (1983). Prudhoe Bay, Alaska: Guidebook to Permafrost and Related Features. Fairbanks, AK, Department of Natural Resources Division of Geological and Geophysical Surveys 140-143.
1. Highly Relevant. Comments: A short but thorough review of oriented lake research, presenting all theories of lake genesis and development to that time, as well as background info on morphology.

P. V. Sellman, J. Brown, R. I. Lewellen, H. McKim and C. Merry (1973). The classification and geomorphic implications of thaw lakes on the Arctic coastal plain, Alaska, Cold Regions Research and Engineering Laboratory 21.
1. Highly Relevant. Comments: Perhaps the most comprehensive survey and classification of physical lake features on the North Slope. They used an early version of Landsat to classify lakes based on percent of cover, size, shape, and orientation. They

also looked at surface slope as a means to predict percent of cover (steeper terrain supports few lakes). They used floating ice extents in spring to identify deep lake basins. They also compared lake distribution to elevation and marine transgressions.

J. Truett and S. Johnson, Eds. (2000). The natural history of an oil field: development and the biota. San Diego, Academic Press.

1. Highly Relevant. Comments: Great introduction to the ecosystem dynamics in the oil fields, covering all of the major mammals, birds, and aquatic life found there. It is very complementary to the Hobbie and NAS books, and gives the reader great insights into the 'users' of arctic lakes and how they may be affected by long-term impacts of water withdrawal.

T. Zhang and M. Jeffries (2000). "Modeling inter-decadal variations of lake-ice thickness and sensitivity to climatic change in northernmost Alaska." Annals of Glaciology **31**: 339-347.

1. Highly Relevant. Comments: An interesting paper that demonstrates the natural variability in lake ice thickness is high, ranging from 1.3 to 2.4 m. This was determined through modeling, as no long-term measurements were found by them or me. This natural variability in ice thickness (~1m, water equivalent) greatly exceeds the amount of water typically withdrawn for ice roads (~0.05m).

J. E. Hobbie, B. J. Peterson, N. Bettez, L. Deegan, W. J. O'Brian, G. W. Kling, G. W. Kipphut, W. B. Bowden and A. E. Hershey (1999). "Impact of global change on the biogeochemistry and ecology of an Arctic freshwater system." Polar Research **18**(2): 207-214.

1a. Possibly Highly Relevant. Comments: I have not read this paper as I found it very late into my search, but in skimming it the focus of the paper is addresses the impact of climate change on Arctic lakes, rather than permafrost in general. The lakes they are considering seem to be foothills lakes (not of the thermokarst variety), but there are some obvious parallels.

Books

There are some really good books that can help us understand the dynamics of tundra ponds, in a form that may be easier to read than individual papers. In most of the cases below, it is not necessary or recommended to read the entire book, but at least several sections of the highly relevant books should be examined. When books were available, I tended not to include the individual papers that they were based on in this bibliography.

J. Hobbie (1980). Limnology of tundra ponds. Stroudsberg, PA, Dowden, Hutchinson and Ross.

1. Highly Relevant. Comments: Without doubt the best overview of the physics and chemistry of tundra ponds on the north slope, based on the IBP research in the Barrow Area. Complete chapters on most everything related to modern limnological components and dynamics, though weak in permafrost/water interactions especially in the long-term.

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J. Truett and S. Johnson, Eds. (2000). The natural history of an oil field: development and the biota. San Diego, Academic Press.

1. Highly Relevant. Comments: Great introduction to the ecosystem dynamics in the oil fields, covering all of the major mammals, birds, and aquatic life found there. It is very complementary to the Hobbie and NAS books, and gives the reader great insights into the 'users' of arctic lakes and how they may be affected by long-term impacts of water withdrawal.

A. Milner and M. Oswood (1997). Freshwaters of Alaska: Ecological synthesis. New York, Springer-Verlag.

2. Relevant. Comments: An interesting book covering many aspects of limnology in Alaska, with unfortunately only a superficial treatment of tundra ponds on the north slope. I only skimmed it, but there were good chapters on Toolik Lake and the Kuparuk River, as well chapters the history of Alaskan limnology and commercial impacts. A must read for Alaskan limnologists.

NRC (2003). Cumulative environmental effects of oil and gas activities on Alaska's North Slope. Washington DC, National Academies Press.

2. Relevant. Comments: Presents a great overview of the long-term industry impacts to many aspects of the natural and social environment. Unfortunately, there is only superficial coverage of impacts to hydrology, including lakes; in fact, this is listed as a research gap. A must read for anyone studying the environment in the oil fields.

J. F. Reynolds (1996). Landscape function and disturbance in Arctic tundra. Berlin, Springer-Verlag.

2. Relevant. Comments: Presents results of US Department of Energy's R4D multidisciplinary research project on disturbance of Arctic ecosystems carried out at Imnavait Creek watershed near Toolik Lake, North Slope, Alaska. Great introduction and overview of Arctic tundra dynamics, but related mostly to foothills region with no direct treatment of coastal lakes. Great overview of tundra dynamics for anyone working on the north slope.

R. Wetzel (2001). Limnology: lake and river ecosystems. San Diego, CA, Academic Press.

2. Relevant. Comments: One of the top text books on limnology, with comprehensive chapters on nearly all aspects of limnology. A must read for anyone becoming a limnologist and a great reference. Unfortunately the treatment of ice covered lakes is minimal, but useful.

G. Ashton, Ed. (1986). River and lake ice engineering. Chelsea, Michigan, Book Crafters, Inc.

3. Related. Comments: Great text for anyone interested in lake ice and how to engineer for it, but has little directly related to the long-term impacts of pumping.

C. Burn (2002). Landforms, Climate, Ice Ages, Permafrost, Mackenzie Delta, Rivers and Lakes. Natural History of the Western Arctic. Inuvik, Western Arctic Handbook Committee**:** 4-10, 11-12, 15-18, 19-23, 24-29, 35-38.

3. Related. Comments: A short book on the major components and dynamics of the Arctic system. A great introduction for those unfamiliar with the Arctic, with great breadth and some depth.

Lake natural history

Understanding the origins of tundra ponds is essential to developing any reasonable hypotheses regarding how pumping may affect their long-term dynamics. Similarly, understanding the long-term natural variability of these ponds is essential to teasing apart the effects of human influences on them.

W. D. Billings and K. M. Peterson (1980). "Vegetational change and ice-wedge polygons through the thaw-lake cycle in Arctic Alaska." Arctic and Alpine Research **12**(4): 413-432.
1. Highly Relevant. Comments: Perhaps the best paper on vegetational succession as it relates to the dynamics of tundra ponds. The paper asks three questions: 1) Are there predictable successional pathways following natural geomorphic or climatic changes? 2) If so, is succession or vegetational change linear, cyclic, or a combination of both? 3) Are man-caused perturbations followed by ecosystemic changes which are similar to those occurring naturally?

J. R. Mackay (1992). Lake stability in an ice-rich permafrost environment: examples from the Western arctic coast. Environment Canada. N.H.R.I Symposium Series Aquatic Ecosystems in Semi-Arid Regions: Implications for Resource Management;.
1. Highly Relevant. Comments: Possibly the best overview of the natural stability of thaw lakes in the context of climate change of the past 10,000 years. Reviews major geomorphological areas in northern Canada in terms of their lakes, the nature and origin of ice rich permafrost, the thaw lake cycle, drainage mechanisms, and future dynamics in the context of climate change. Also discuss thaw lake creation in two distinct phases (10ka and 5ka), and decreasing likelihood for formation today.

S. E. Rawlins (1983). Prudhoe Bay, Alaska: Guidebook to Permafrost and Related Features. Fairbanks, AK, Department of Natural Resources Division of Geological and Geophysical Surveys 140-143.
1. Highly Relevant. Comments: A short but thorough review of oriented lake research, presenting all theories of lake genesis and development to that time, as well as background info on morphology.

J. Truett and S. Johnson, Eds. (2000). The natural history of an oil field: development and the biota. San Diego, Academic Press.
1. Highly Relevant. Comments: Great introduction to the ecosystem dynamics in the oil fields, covering all of the major mammals, birds, and aquatic life found there. It is very complementary to the Hobbie and NAS books, and gives the reader great insights into the 'users' of arctic lakes and how they may be affected by long-term impacts of water withdrawal.

C. Burn (1997). "Cryostratigraphy, paleogeography, and climate change during the early Holocene warm interval, western Arctic Coast Canada." Canadian Journal of Earth Sciences **34**: 912-925.

2. Relevant. Comments: An interesting paper that looks at the combined effects of climate change and ocean shoreline migration on the thermal and botanical dynamics of the western Canadian Arctic. Filled with field data from a variety of sources to reconstruct climate, shorelines, and the resulting effects.

C. Burn and M. W. Smith (1988). Thermokarst lakes at Mayo, Yukon Territory, Canada. Proceedings of the 5th International Conference on Permafrost, Trondheim, Norway.
2. Relevant. Comments: One of the few studies that document thermokarst lake development, though not on the coastal plain. An interesting paper using several methods for documenting lake formation and growth.

C. Burn and M. W. Smith (1990). "Development of thermokarst lakes during the Holocene at Mayo, Yukon Territory." Permafrost and Periglacial Processes **1**: 161-176.
2. Relevant. Comments: An interesting paper that contains some of the only data on the initiation phase of thermokarst lakes. In this case, initiation was likely due to forest fires in the 1800s. Data on lake expansion rates (~1 m/a) and talik formation are presented.

L. D. Carter (1987). Oreinted lakes. Geomorphic system of North America. W. L. Graf. Boulder, CO, Geol. Soc. Am. **Centennial Special Vol. 2:** 615-619.
2. Relevant. Comments: A short, clear overview of the debate on how tundra ponds become oriented perpendicular to the prevailing wind. Suggests different mechanisms based on pond size, with sublittoral shelves playing a dominant role at every level.

L. D. Carter (1987). Loess, syngenetic ice wedges, and deep thermokarst basins on the Alaskan North Slope. 5th International conference on Permafrost, Trondheim, Norway.
2. Relevant. Comments: A very interesting paper about a poorly described phenomenom, namely the formation and degradation of very large ice wedges found in loess deposits on the north slope. Melting of these ice wedges can create lakes much deeper than those typically observed (>20 m deep!), but only in a thin belt of silt that stretches across the state but is widest in ANWR.

M. M. Cote and C. Burns (2002). "The oriented lakes of Tuktoyaktuk Peninsula, Western Canada: A GIS based analysis." Permafrost and Periglacial Processes **13**: 61-70.
2. Relevant. Comments: A very interesting paper that conclusively demonstrates that the orientation of lakes is dependent on wind direction, at least near Tuk. Matches wind to lake direction (determined through GIS stats on over 500 lakes) to within a degree, if winds greater than 30 km/hr are used. Looks at former basins to show that wind regime hasnt changed much since those lakes formed. Perhaps the best recent paper on lake orientation.

D. G. F. Harry, H.M. (1983). The orientation and evolution of thaw lakes, southwest Banks Island, Canadian Arctic. Proceedings of the Fourth International Conference on Permafrost, July 17-22, 1983., Fairbanks, AK, National Academy Press.
2. Relevant. Comments: An interesting paper on thaw lakes in the high arctic, in an ice-rich area. They describe the evolution of lakes here, wind orientation, and some ideas

about their stability. I'm not sure I understood their point that these lakes do not follow the standard thaw lake cycle.

K. Hinkel, W. Eisner, J. Bockheim, F. Nelson, K. M. Peterson and X. Dai (2003). "Spatial extent, age, and carbon stocks in drained thaw lake basins on the Barrow Peninsula, Alaska." Arctic, Antarctic and Alpine Research **35**(3): 291-300.
2. Relevant. Comments: Excellent introduction to the natural setting, history and dynamics of tundra ponds. Here they characterize percent of land cover, basin ages, and correlate basin age with soil organic carbon, with an eye towards climate warming and release of stored carbon to the environment. Note that this paper studies primarily drained basins, not the lakes themselves.

D. Hopkins (1949). "Thaw lakes and thaw sinks in the Imuruk Lake area, Seward Peninsula, Alaska." Journal of Geology **57**: 119-131.
2. Relevant. Comments: Classic original work on tundra ponds. Study sites were on the Seward Peninsula but there are obvious relations to north slope. Looks at relationships to landscape, permafrost, ice wedges, anthropogenic, and climate. Lake migration, talik refreezing, rapid drainage events are also described.

D. M. Hopkins and J. G. Kidd (1988). Thaw lake sediments and sedimentary environments. 5th International Conference on Permafrost, Trondheim, NO, Tapir Publishers.
2. Relevant. Comments: Perhaps the best paper on identifying thaw lakes based on the depositional evidence they leave behind. Has lots of sketches and notes on lake bed stratigraphy and processes. Most of the research was done on the Seward Peninsula, but there are obvious relations to coastal plain.

R. Kaczorowski (1977). The Carolina Bays and their relationship to modern oriented lakes, University of South Carolina.
2. Relevant. Comments: A very interesting thesis that explores similarities between oriented lakes in Alaska, Texas, Chile and mostly the eastern US coastal plain. Contains not only wind data for all four that shows all lakes are oriented perpendicular to wind, but also shows water current measurements for each. He also constructed a physical lab model (real water, sand and wind) which shows that nearly any shaped shallow lake will eventually become oriented perpendicular to the prevailing wind, and presents theory that supports the model outcomes. He discusses the common features of these lakes: unconsolidated sediments, oriented with long axis perp. to wind, a ponding mechanism (eg., permafrost), and shallow water. He determines the requirements to produce a shallow lake are: adequate precipitation along with a ponding mechanism, development in unconsolidated sediments, a wind regime that is either unidirectional or opposing bi-directional, and a land surface with a gentle slope.

D. S. Kaufman, T. A. Ager, N. J. Anderson, P. M. Anderson, P. J. Andrews, P. J. Bartlein and a. others (in press). "Holocene thermal maximum in the western Arctic (0 - 180 degrees W)." Quaternary Science Reviews.
2. Relevant. Comments: This is the best review of climate dynamics in the Alaska/Canada arctic for the past 15,000 years (pun intentional). This period of time is

important because this is when coastal plain thaw lakes formed; this paper does not discuss the thaw lake cycle directly however. Using a variety of proxy evidence from many researchers (most authors), they show that warming began first in Alaska and Northwest Canada between 11 and 9 thousand years ago; further east was delayed 4000 years by slow demise of the ice sheet. The warming is thought to be caused by peak in solar insolation on the precessional cycle. Temperatures were 1.6 C warmer.

R. W. Rex (1960). Hydrodynamic analysis of circulation and orientation of lakes in Northern Alaska. Geology of the Arctic, Proceedings of the First International Symposium on Arctic Geology, Calgary, Alberta, University of Toronto Press.
2. Relevant. Comments: Perhaps the only paper that has attempted to apply hydrodyanamic principles to the evolution of thaw lakes. My impression was that this study needs to be repeated using modern measurement and modeling techniques, as quite a bit more could probably be learned. In any case, he presents some ideas on what's actually going on and presents some math that supports the idea that perpendicular winds lead to elongated lakes.

F. C. Ugolini (1975). "Ice rafted sediments as a cause of some thermokarst lakes in the Noatak River Delta, Alaska." Science **188**: 51-53.
2. Relevant.

H. J. Walker and M. K. Harris (1976). "Perched ponds: an arctic variety." Arctic **29**(4): 223-238.
2. Relevant. Comments: This is the only paper I found that studies lakes in Colville River delta. These lakes are different than thaw ponds, in that they are formed in sand dunes and not through a thermokarst process, but rather just uses permafrost as an aquaclude. Another interesting feature of the paper is their in-depth studies between snow, shrubs, and active layer depth, which may relate to Sturm's modern work.

M. E. Britton (1966). Vegetation of the Arctic tundra. Corvallis, OR, Oergon State University Press.
2a. Possibly Relevant.

J. Brown and P. V. Sellman (1973). Permafrost and coastal plain history of arctic Alaska. Alaskan Arctic Tundra. e. Britton, Arctic Institute of North America. **Technical paper 25:** 31-47.
2a. Possibly Relevant.

R. I. Lewellen (1972). Studies on the fluvial environment Arctic Coastal Plain Province Northern Alaska. Palmer, AK, Lewellen Arctic Research 282.
2a. Possibly Relevant.

R. Black and W. Barksdale (1949). "Oriented lakes of northern Alaska." Journal of Geology **57**: 106?-118.
3. Related. Comments: One of the early papers on tundra ponds, with specific emphasis on their orientation. Perhaps first to measure and document orientation with respect to wind. Also makes comparisons with Carolina Bays.

R. F. Black (1969). "Thaw depressions and thaw lakes: a review." Biuletyn Perylacijalny **19**: 131-150.
3. Related. Comments: An interesting review of tundra ponds at that time. Reviews possible origins, development, and dynamics. Much of the information is now dated.

C. Burn (2002). Landforms, Climate, Ice Ages, Permafrost, Mackenzie Delta, Rivers and Lakes. Natural History of the Western Arctic. Inuvik, Western Arctic Handbook Committee**:** 4-10, 11-12, 15-18, 19-23, 24-29, 35-38.
3. Related. Comments: A short book on the major components and dynamics of the Arctic system. A great introduction for those unfamiliar with the Arctic, with great breadth and some depth.

C. Carson and K. Hussey (1959). The multiple-working hypothesis as applied to Alaska's oriented lakes. Iowa Academy of Sciences Proceedings.
3. Related.

K. V. Kremenetski, A. A. Velichko, O. K. Borisova, G. M. Macdonald, L. C. Smith, K. E. Frey and L. A. Orlova (2003). "Peatlands of the western siberian lowlands: current knowledge on zonation, carbon content, and late Quarternary history." Quaternary Science Reviews **22**: 703-723.
3. Related.

D. A. Livingstone (1954). "On the orientation of lake basins." American Journal of Science **252**: 547-554.
3. Related. Comments: One of the classic original papers on tundra ponds. Several of the ideas here are now outdated, but the general concept of a double circulation cell is still a popular theory, though criticized by Rex. Develops the idea that longshore and rip currents are responsible for the scour and deposition patterns that result in elongated lakes.

D. A. Livingstone, K. Bryan and R. G. Leahy (1958). "Effects of an arctic environment on the origin and development of fresh-water lakes." Limnology and Oceanography **3**(2): 192-214.
3. Related. Comments: Account of investigations carried out during two summers in the Brooks Range and the Arctic Coastal Plain of northern Alaska. Climate, geology and vegetation of the area are sketched. The lakes visited (glacial, thaw, etc.) are described. Their origin and morphometry, physical conditions (temperature, heat balance, color, transparency, permafrost, etc.) chemical conditions and biology are dealt with in turn. Past conditions are reconstructed from analysis of sediments. The extended cold, seasonal distribution of insolation, and low precipitation have little direct effect on the life in far northern lakes, but the environment is a major factor in physical processes affecting origin, sedimentation and drainage. Basically putting Arctic lakes in the context of lakes elsewhere.

J. C. Tedrow (1969). "Thaw lakes, thaw sinks, and soils in northern Alaska." Biuletyn Perylacijalny **20**: 337-344.
3. Related. Comments: An early paper describing lakes near the Colville River and Umiat. Emphasizes the role of lakes not just in erosion, but in filling. Also discusses benches that have formed in lake shores as water level changes, along with grain sizes.

C. W. Cooke (1954). Carolina Bays and the shapes of eddies, USGS.
3a. Possibly Related. Comments: I only skimmed this paper, but it looks very interesting though it has little to directly to do with tundra ponds other than the perspective given by comparing them to other oriented lakes and waterbodies.

T. Czudek and J. Demek (1970). "Thermokarst in Siberia and its influence on the development of lowland relief." Quat. Res. **1**: 103-120.
3a. Possibly Related.

Frohn, W. Eisner, K. Hinkel and Arellana-Neri (2001). Neural net classification of thaw lake basins on the coastal plain of northern Alaska. IEEE Proceedings of the IGRSS2001, Sidney, Australia.
3a. Possibly Related.

J. R. Mackay (1971). "The origin of massive icy beds in permafrost, Western Arctic Coast, Canada." Canadian Journal of Earth Sciences **8**(4): 397-422.
3a. Possibly Related.

J. R. Mackay (1999). "Periglacial features developed on the exposed lake bottoms of seven lakes that drained rapidly after 1950, Tuktoyaktuk Peninsula area, western Arctic coast, Canada." Permafrost and Periglacial Processes **10**(1): 39-63.
3a. Possibly Related.

J. R. Mackay (1999). "Cold-climate shattering (1974 to 1993) of 200 glacial erratics on the exposed bottom of a recently drained arctic lake, Western Arctic coast, Canada." Permafrost and Periglacial Processes **10**(2): 125-136.
3a. Possibly Related.

G. A. Rosenfeld and K. M. Hussey (1958). A consideration of the problem of oriented lakes. Iowa Academy of Science Proceedings.
3a. Possibly Related.

J. R. Williams and Yeend (1979). Deep thaw lake basins of the inner Arctic Coastal Plain, Alaska, USGS 35-37.
3a. Possibly Related.

Water balance

An obvious concern about removing water from a lake is whether long-term lake levels will decline. Papers in this section address all aspects of the water balance in the Arctic, including snow, rain, evapotranspiration and run-off, as well as their temporal and spatial variability. The literature here is larger than I have listed; what is of most interest at this point are recent studies that summarize water balances from across the north slope or studies that looked at large spatial scales.

L. Bowling, D. Kane, R. Gieck, L. Hinzman and D. Lettenmaier (2003). "The role of surface storage in a low-gradient Arctic watershed." Water Resources Research **39**(4): 1087.
1. Highly Relevant. Comments: Perhaps the best recent paper on remote sensing of water balance in the Arctic. This paper shows that the amount of snow melt available in spring is more than double what is typically necessary to recharge the wetlands (1999-2001), and excess snows do not help this, they just cause widespread flooding.

J. Mendez, L. Hinzman and D. Kane (1998). "Evapotranspiration from a wetland complex on the Arctic coastal plain of Alaska." Nordic Hydrology **29**(4/5): 303-320.
1. Highly Relevant. Comments: Perhaps the most comprehensive review of both evaporation rates and methods for measuring it in arctic tundra and lakes.

M. Konig and M. Sturm (1998). "Mapping snow distribution in the Alaskan Arctic using aerial photography and topographic relationships." Water Resources Research **34**(12): 3471-3483.
2. Relevant. Comments: An excellent paper describing an interesting technique to measure snow-depth in the Arctic using computer classification and air photos.

P. Marsh and M. K. Woo (1986). "Water balance of a small pond in the High Arctic." Arctic **30**: 109-117.
2. Relevant. Comments: A short paper describing a simple yet convincing experiment to track storage and evaporation relationships between a small pond and its small watershed.

R. Rovansek, L. Hinzman and D. Kane (1996). "Hydrology of a tundra wetland complex on the Alaskan Arctic coastal plain, USA." Arctic and Alpine Research **28**(3): 311-317.
2. Relevant. Comments: Several ponds in the Prudhoe oil fields were monitored through 1991-1993 for water balance. The major finding is interesting in that the ponds do not have enough precipitation locally to keep them from drying out, that is their continued existence depends on resupply from the headwaters. This is something that should be compared to other papers.

H. J. Walker and M. K. Harris (1976). "Perched ponds: an arctic variety." Arctic **29**(4): 223-238.
2. Relevant. Comments: This is the only paper I found that studies lakes in Colville River delta. These lakes are different than thaw ponds, in that they are formed in sand dunes and not through a thermokarst process, but rather just uses permafrost as an aquaclude.

Another interesting feature of the paper is their in-depth studies between snow, shrubs, and active layer depth, which may relate to Sturm's modern work.

D. Yang, D. Kane, L. Hinzman, R. Gieck and J. McNamara (2000). Hydrologic response of a nest of watersheds to an extreme rainfall event in northern Alaska. Water resources in extreme environments, Anchorage, AK, AWRA.
2. Relevant. Comments: This paper is one of the few on extreme rain flooding events in the Arctic, which are rare but potentially important geomorphic processes. Nothing directly is mentioned about lakes, but there are obvious implications.

L. Hinzman, D. Kane and R. Gieck (1990). Regional snow ablation in the Alaskan Arctic. Northern Hydrology Symposium, Saskatoon, Saskatchewan.
2a. Possibly Relevant.

L. Hinzman, G. Wendler, R. Gieck and D. Kane (1992). Snowmelt at a small Alaskan Arctic watershed, 1. Energy related processes. 9th International Northern Research Basins Symposium, Canada.
2a. Possibly Relevant.

D. Kane, R. Gieck and L. Hinzman (1997). "Snowmelt modeling at small Alaskan Arctic watershed." Journal of Hydrological Engineering **2**(4): 204-210.
2a. Possibly Relevant.

G. Liston and M. Sturm (2002). "Winter precipitation patterns in Arctic Alaska determined from a blowing-snow model and snow-depth observations." Journal of Hydrometeorology **3**: 646-659.
2a. Possibly Relevant.

P. Marsh and C. Bigras (1988). "Evaporation from Mackenzie Delta lakes." Arctic and Alpine Research **20**: 220-229.
2a. Possibly Relevant.

N. T. Roulet and M. K. Woo (1998). "Runoff generation in a low arctic drainage basin." Journal of Hydrology **101**: 213-226.
2a. Possibly Relevant.

B. Bolton, L. Hinzman and K. Yoshikawa (2000). Stream flow studies in a watershed underlain by discontinuous permafrost. Water resources in extreme environments, Anchorage, AK.
3. Related.

J. Brown, S. L. Dingman and R. I. Lewellen (1968). Hydrology of a drainage basin on the Alaskan coastal plain. Hanover, NH, Cold Regions Research and Engineering Laboratory 18.
3. Related. Comments: This paper summarizes water balance data from an interesting period in Barrow's history when the extremes of wetness and dryness occurred. It is worth reading for anyone studying water balances of lakes or lake chemistry.

K. Everett, G. M. Marion and D. Kane (1989). "Seasonal geochemistry of an arctic tundra drainage basin." Holarctic ecology **12**: 279-289.
3. Related. Comments: One of the few papers found that looks at chemistry of snow meltwater and what might be resupplied to lakes.

L. Hinzman, M. Wegner and M. Lilly (2000). "Hydrological investigations of groundwater and surface-water interactions in sub-arctic Alaska." Nordic Hydrology **31**(4/5): 339-356.
3. Related. Comments: An interesting paper on the relationship between river stage and groundwater flux into and out of the river, but having little direct application to pumping tundra ponds.

D. Kane, S. Bredthauer and J. Stein (1981). Subarctic snowmelt runoff generation. Proceedings of The Northern Community: A search for a quality environment, Seattle WA 1981, Seattle, WA, ASCE.
3. Related. Comments: An interesting paper on moisture dynamics within winter snowpacks, but a bit too esoteric for this pumping study. It does indicate, however, that the moisture deficit in fall on the coastal plain might be enhanced by vertical withdrawal of water into the snowpack over winter.

D. Kane, L. Hinzman, H. Yu and D. Goering (1996). "The use of SAR satellite imagery to measure active layer moisture contents in Arctic Alaska." Nordic Hydrology **27**: 25-38.
3. Related. Comments: An interesting paper on the measurement of soil moisture using SAR in Arctic tundra, but more of a technique paper than one with applicable results.

D. Kane and J. Stein "Patterns of subarctic snowmelt infiltration."
3. Related. Comments: The general result of this paper -- that the amount of snow melt runoff is dependent on autumn soil moisture levels -- needs to be understood for a full understanding of lake recharge. This paper presents field studies of snow melt as a function of prior soil moisture conditions, and is one of the few studies of its kind that I found.

J. Knudson and L. Hinzman (2000). Prediction of streamflow in an Alaskan watershed underlain by permafrost. Water resources in extreme environments, Anchorage, AK, AWRA.
3. Related.

J. McNamara, D. Kane and L. Hinzman (1998). "An analysis of streamflow hydrology in the Kuparuk River Basin, Arctic Alaska: a nested watershed approach." Journal of Hydrology **206**: 39-57.
3. Related.

W. R. Roulet and M. K. Woo (1986). "Wetland and lake evaporation in the Low Arctic." Arctic and Alpine Research **18**: 195-200.
3. Related. Comments: A short but interesting paper that compares evaporation over wetland and lake surfaces.

W. R. Rouse, D. W. Carlson and E. J. Weick (1992). "Impacts of summer warming on the energy balance and water balance of wetland tundra." Climatic Change, Vol. 22(305-326).
3. Related. Comments: An interesting paper that explores changes in evapotranspiration in relation to climate change. They took several years of field data which were characterized by differing amounts of air temperature and rainfall and extrapolated these results into a climate change scenarios. The general result was that this was a complicated problem, with many balancing feedbacks, but that generally evapotranspiration is likely to increase, soils likely to get drier and warmer, and permafrost to disappear in a warming climate.

L. Stuart, S. Oberbauer and P. C. Miller (1982). "Evapotranspiration measurements in Eriophorum vaginatum tussock tundra in Alaska." Holarct. Ecol. **5**: 145-149.
3. Related.

W. T. Allen (1977). Freeze-up, break-up, and ice thickness in Canada. Atmospheric Environment, Fisheries, and Environment Canada. Downsview, Ont.
3a. Possibly Related. Comments: Presents many statistics of lake ice dynamics, in a form I did not find easy to interpret.

G. G. E. Bursey, T.W.D.; Frape, S.K. (1991). Water balance and geochemistry studies in a tundra watershed, District of Keewatin, Northwest Territories. NHRI Symposium Northern hydrology : selected perspectives : proceedings of the Northern Hydrology Symposium, 10-12 July 1990, Saskatoon, Saskatchewan, Canada, National Hydrology Research Centre, Environment Canada. National Hydrology Research Institute.
3a. Possibly Related.

J. J. E. Gibson, T. W. D. (2002). "Regional water balance trends and evaporation-transpiration partitioning from a stable isotope survey of lakes in northern Canada." Global Biogeochemical Cycles **16**(2): 14.
3a. Possibly Related.

L. Hinzman, M. Nolan, D. Kane, C. Benson, M. Sturm, G. Liston, J. McNamara, A. Carr and D. Yang (2000). Estimating snowpack distribution over a large arctic watershed. Water resources in extreme environments, Anchorage, AK, AWRA.
3a. Possibly Related.

D. Kane, R. Gieck and L. Hinzman (1990). "Evapotranspiration from a small Alaskan Arctic watershed." Nordic Hydrology **21**: 253-272.
3a. Possibly Related.

D. Kane, L. Hinzman, J. McNamara, Z. Zhang and C. Benson (2000). "An overview of a nested watershed study in Arctic Alaska." Nordic Hydrology **31**(4/5): 245-266.
3a. Possibly Related.

D. Kane and C. Slaughter (1973). Recharge of a central Alaska lake by subpermafrost groundwater. Proceeding of the 2nd International Conference on Permafrost, Yakutsk, Russia.
3a. Possibly Related.

P. M. LaFleur (1990). "Evaporation from sedge-dominated wetland surfaces." Aquatic Botany **37**(341-353).
3a. Possibly Related.

P. M. LaFleur and W. R. Rouse (1988). "The influence of surface cover and climate on energy partitioning and evaporation in a subarctic wetland." Boundary-Layer Meteorology **44**: 327-347.
3a. Possibly Related.

W. R. Roulet and M. K. Woo (1986). "Hydrology of a wetland in the continuous permafrost region." Journal of Hydrology **89**: 73-81.
3a. Possibly Related.

W. R. Rouse and e. al (1977). "Evaporation in high latitudes." Water Resources Research **13**: 909-914.
3a. Possibly Related.

R. B. Stewart and W. R. Rouse (1976). "Simple models for calculating evaporation from dry and wet tundra surfaces." Arctic and Alpine Research **8**: 263-274.
3a. Possibly Related.

D. A. Wessel and W. R. Rouse (1994). "Modeling evaporation from wetland tundra." Boundary-Layer Meteorology **68**: 109-130.
3a. Possibly Related.

M. K. Woo, R. Heron and P. Steer (1981). "Catchment hydrology of a high arctic lake." Cold Regions Science Technology **5**: 29-41.
3a. Possibly Related.

Lake drainage

Catastrophic, unintentional drainage of tundra ponds is a possibility when working around tundra ponds because their shores are contained by permafrost soils that are sensitive to disturbance. Draining them creates more exposed ground with effects on soil temperatures, hydrology, and habitat. Papers in this section relate to both human-induced and random drainages observed and studied in the Arctic.

J. R. Mackay (1992). Lake stability in an ice-rich permafrost environment: examples from the Western arctic coast. Environment Canada. N.H.R.I Symposium Series Aquatic Ecosystems in Semi-Arid Regions: Implications for Resource Management;.
1. Highly Relevant. Comments: Possibly the best overview of the natural stability of thaw lakes in the context of climate change of the past 10,000 years. Reviews major geomorphological areas in northern Canada in terms of their lakes, the nature and origin of ice rich permafrost, the thaw lake cycle, drainage mechanisms, and future dynamics in the context of climate change. Also discuss thaw lake creation in two distinct phases (10ka and 5ka), and decreasing likelihood for formation today.

M. C. Brewer, L. D. Carter, R. Glenn and J. a. o. Brown (1993). Sudden drainage of a thaw lake on the Alaskan Arctic coastal plain. Permafrost Sixth International Conference., Beijing, China, South China University of Technology Press.
2. Relevant. Comments: One of the few papers that describes field observations of a drained lake, this one south of Barrow, near the foothills. Discusses concerns of natural vs anthropogenic causes of drained lakes, without coming to any conclusions. Suggests increased precipitation is more important than higher air temps in causing lake drainages.

J. R. Mackay (1981). An experiment in lake drainage, Richards Island, Northwest Territories: a progress report, Geological Survey of Canada 63-68.
2. Relevant. Comments: This older paper describes the only experimental drainage of a tundra pond that I was able to locate; later papers largely review and update this information, though this one has original photos and more detail on the experimental procedures. Basically they found a lake that was likely to drain anyway, excavated an outlet working from the coast towards the lake, then breached the dam and ran. They have been revisiting the site for the 25 years since then.

J. R. Mackay (1988). Catastrophic Lake Drainage, Tuktoyaktuk Peninsula, District of Mackenzie, Geological Survey of Canada 83-90.
2. Relevant. Comments: Short but classic paper on lake drainage mechanisms and frequency near Tuk. Contains lots of photos and describes principle mechanisms.

J. R. Mackay and C. Burn (2002). "The first 20 years (1978/79 to 1998/99) of ice-wedge growth at the Illisarvik experimental drained lake site, western Arctic coast, Canada." Canadian Journal of Earth Sciences **39**(1): 95-111.
2. Relevant. Comments: An interesting paper following up on the post-drainage phase of the thaw lake cycle for Illisarvik. Perhaps the most interesting finding is that ice wedges

are no longer forming there, strongly suggesting that current climate plays an important role in the 'cycle'. He documents a 20 year record using various home-made instruments for measuring ice wedge dynamics. Perhaps the only paper of its kind.

P. Marsh and N. Nuemann (2001). "Processes controlling the rapid drainage of two ice-rich permafrost-dammed lakes in NW Canada." Hydrological Processes **15**: 3433-3446.
2. Relevant. Comments: An interesting paper that attempts to apply glaciological models to pond drainages, where water temperature and head loss are major variables. Finds that models agree well initially, but that later discrepancies may be due to a change in erosional mechanisms from thermal to mechanical. There is not really enough data to be very conclusive, but points towards future research.

K. Yoshikawa and L. Hinzman (2003). "Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska." Permafrost and Periglacial Processes **14**: 151-160.
2. Relevant. Comments: An interesting paper describing observations of lake drainages through taliks, a mechanism that is not likely to be important in Prudhoe ponds for some time yet. The techniques used for measurement are likely applicable here.

J. R. Mackay and C. Burn (2002). "The first 20 years (1978/79 to 1998/99) of active-layer development, Illisarvik experimental drained lake site, western Arctic coast, Canada." Canadian Journal of Earth Sciences **39**(11): 1657-1674.
3a. Possibly Related.

Lake ice, lake snow, lake water, and lake depth

Because tundra ponds are ice-covered most of the year, it is important to understand how this ice cover affects their dynamics, such as water temperature, chemistry, and circulation. Ice cover can also be used to determine information about ice depth and water chemistry, which are both important to understanding the long-term impacts of water pumping. I could find no systematic measurement of lake bathymetric for the entire north slope, but several studies compiled numerous bathymetries and point towards methods for a comprehensive survey.

J. Mellor (1987). A statistical analysis and summary of radar-interpreted Arctic lake depths: an addendum to 12 map products. Anchorage, BLM.
1. Highly Relevant. Comments: Describes the use of airborne SAR to measure lake depths in the NPR-A area; later work showed the same could be done with satellite SAR. This work produced many high-quality maps that could be used in practice today, and points the way towards what could be done on the entire north slope.

P. V. Sellman, J. Brown, R. I. Lewellen, H. McKim and C. Merry (1973). The classification and geomorphic implications of thaw lakes on the Arctic coastal plain, Alaska, Cold Regions Research and Engineering Laboratory 21.
1. Highly Relevant. Comments: Perhaps the most comprehensive survey and classification of physical lake features on the North Slope. They used an early version of Landsat to classify lakes based on percent of cover, size, shape, and orientation. They also looked at surface slope as a means to predict percent of cover (steeper terrain supports few lakes). They used floating ice extents in spring to identify deep lake basins. They also compared lake distribution to elevation and marine transgressions.

T. Zhang and M. Jeffries (2000). "Modeling inter-decadal variations of lake-ice thickness and sensitivity to climatic change in northernmost Alaska." Annals of Glaciology **31**: 339-347.
1. Highly Relevant. Comments: An interesting paper that demonstrates the natural variability in lake ice thickness is high, ranging from 1.3 to 2.4 m. This was determined through modeling, as no long-term measurements were found by them or me. This natural variability in ice thickness (~1m, water equivalent) greatly exceeds the amount of water typically withdrawn for ice roads (~0.05m).

M. Jeffries, K. Morris and G. Liston (1996). "A method to determine lake depth and water availability on the North Slope of Alaska with spaceborne imaging radar and numerical ice growth modeling." Arctic **49**(4): 367-374.
2. Relevant. Comments: An interesting paper using a neat trick to measure whether tundra ponds in the Barrow area are deeper than lake ice depth. Here it is used to determine percentages of deeper-than-ice lakes, but in a subsequent paper it is used to actually map bathymetry.

M. Jeffries, K. Morris and W. Weeks (1994). "Structural and stratigraphic features and ERS1 synthetic aperture radar backscatter characteristics of ice growing on shallow lakes in

NW Alaska, winter 1991-1992." Journal of Geophysical Research **99**(C11): 22459-22471.
2. Relevant. Comments: An interesting paper that examines time-series of ERS SAR over two winters, exploring the nature of bubble-inclusions within the ice. These bubbles have various things to say about the underlying lake water, so this is both a technique paper and one with potentially useful information about water chemistry evolution through winter that may relate to pumping effects.

N. Kozlenko and M. Jeffries (2000). "Bathymetric mapping of shallow water in thaw lakes on the North Slope of Alaska with spaceborne imagining radar." Arctic **53**(3): 306-316.
2. Relevant. Comments: An interesting paper that describes a technique to measure tundra pond bathymetry using satellite SAR over wide-spatial scales. Unfortunately only a few example bathymetries are given, but this technique could be applied to the entire North Slope to produce a map-series.

G. Liston and D. Hall (1995). "An energy-balance model of lake-ice evolution." Journal of Glaciology **41**: 373-382.
2. Relevant. Comments: This paper describes the physics coded into a very well respected lake ice model, with a few example applications. Highlights the importance of wind in lake ice evolution.

H. E. Welch and M. A. Bergmann (1985). "Water circulation in small arctic lakes in winter." Canadian Journal of Fisheries and Aquatic Science **42**: 506-520.
2. Relevant. Comments: An interesting paper detailing dye-tracer experiments that clearly indicate some type of convection cell beneath the ice. Not terribly relevant to pumping studies, though does have implications for dissolved oxygen and thermal dynamics within the lakes.

R. Gu and H. G. Stefan (1993). "Validation of cold climate lake temperature simulation." Cold Regions Science Technology **22**: 99-104.
2a. Possibly Relevant.

R. Heron and M. Woo (1994). "Decay of a high Arctic lake-ice cover: observations and modelling." Journal of Glaciology **40**: 283-292.
2a. Possibly Relevant.

M. Hondzo and H. G. Stefan (1993). "Lake water temperature simulation model." Journal of Hydraulic Engineering ASCE **119**(11): 147-160.
2a. Possibly Relevant.

G. E. Likens and R. A. Ragotzkie (1965). "Vertical water motions in a small, ice-covered lake." Journal of Geophysical Research **70**: 2333-2344.
2a. Possibly Relevant.

G. Liston and D. Hall (1995). "Sensitivity of lake freeze-up and break-up to climate change: a physically based modeling study." Annals of Glaciology **21**: 387-393.

2a. Possibly Relevant. Comments: Describes the use of a well-respected energy-balance lake ice model to predict ice freeze-up, break-up, and thickness. Here the environmental variables for a particular set of lakes are varied to determine their importance in affecting outputs.

J. Malm, L. Bengtsson, A. Terzhevik, P. Boyarinov, A. Glinsky, N. Palshin and M. Petrov (1998). "Field study on currents in a shallow ice covered lake." Limnology and Oceanography **43**(7): 1669-1679.
3. Related. Comments: An interesting paper on seiches, but without much direct relevance to pumping lakes for ice roads. Presents both thermal and current information. Useful mathematic derivations for calculating seiche frequency.

P. C. Matthews and S. I. Heaney (1987). "Solar heating and its influence on mixing in ice-covered lakes." Freshwater Biology **18**: 135-149.
3. Related. Comments: A very interesting paper which does not have a lot of relevance to pumping, except that it gives some background on water temperature dynamics through the ice that may relate to ice wedge erosion and biota dynamics. This paper develops a model of solar absorption within the water and how this can propogate downwards to warm and mix a cold stratified lake in spring.

J. Mellor (1994). ERS1 SAR use to determine lake depths in Arctic and sub-Arctic regions. Proceedings of the second ERS1 Symposium-- Space at the service of our environment, Hamburg, Germany.
3. Related. Comments: Abstract only, comparing airborne to space-borne radar for measuring lake depth.

M. Nolan, G. Liston, P. Prokein, J. Brigham-Grette, V. Sharpton and R. Huntzinger (2003). "Analysis of lake ice dynamics and morphology on Lake El'gygytgyn, NE Siberia, using synthetic aperture radar (SAR) and Landsat." J. Geophys. Res. **108**(D2): doi:10.1029/2001JD000934.
3. Related. Comments: An absolutely brilliant paper that has profound and far-reaching implications for a variety of topics that have little to do with pumping tundra ponds unfortunately.

C. R. Ellis, J. G. Champlin and H. G. Stefan (1997). "Density current intrusions in an ice-covered urban lake." Limnology and Oceanography **36**(6): 324-335.
3a. Possibly Related.

C. R. Ellis, H. G. Stefan and R. Gu (1991). "Water temperature dynamics and heat transfer beneath the ice cover of a lake." Limnology and Oceanography **36**(2): 324-335.
3a. Possibly Related.

H. E. Hennenman and H. G. Stefan (1999). "Albedo models for snow and ice on a freshwater lake." Cold Regions Science Technology **765**.
3a. Possibly Related.

H. Hill (1967). "A note on temperature and water conditions beneath lake ice in spring." Limnology and Oceanography **12**: 550-552.
3a. Possibly Related.

R. Leconte and P. D. Klassen (1991). "Lake and river ice investigations in northern Manitoba using airborne SAR imagery." Arctic **44**: 153-163.
3a. Possibly Related.

P. V. Sellman, W. F. Weeks and W. J. Campbell (1975). Use of side looking airborne radar to determine lake depth on the Alaskan North Slope. Hanover, NH, Cold Regions Research and Engineering Laboratory.
3a. Possibly Related.

C. T. Swift, W. L. Jones, R. F. Harrigton, J. C. Fedors, R. H. Couch and B. L. Jackson (1980). "Microwave radar and radiometric remote sensing measurements of lake ice." Geophysical Research Letters **7**: 243-246.
3a. Possibly Related.

W. F. Weeks, A. G. Fountain, M. I. Bryan and C. Elachi (1978). "Differences in radar returns from ice-covered North Slope lakes." Journal of Geophysical Research **83**(C8): 4069-4073.
3a. Possibly Related.

W. F. Weeks, A. J. Gow and R. J. Schertler (1981). Ground truth observations of ice-covered North Slope lakes imaged by radar. Hanover, NJ, Cold Regions Research and Engineering Laboratory.
3a. Possibly Related.

W. F. Weeks, P. V. Sellman and W. J. Campbell (1977). "Interesting features of radar imagery of ice-covered North Slope lakes." Journal of Glaciology **18**(78): 129-136.
3a. Possibly Related.

Water chemistry

Water chemistry, including dissolved oxygen and ion content, has a profound influence on primary productivity and habitat quality. Pumping water out of the lake may affect chemical concentration, and it may do so differently at different times of year or by pumping water from different depths within a lake.

C. R. Ellis and H. G. Stefan (1989). "Oxygen demand in ice-covered lakes as it pertains to winter aeration." American Water Resources Association **33**(6): 1363-1374.
1. Highly Relevant. Comments: Very interesting paper that describes the physics of oxygen consumption in lakes with an eye towards preventing depletion. Most consumption occurs near the bed, not water column, and when level drops below 3 mg/l, rate of depletion at bed drops substantially. So by keeping the bottom water still and drawing water from the top of the column, you can reduce the overall consumption within the lake. Perhaps the best overview of dissolved oxygen dynamics in ice covered lakes.

M. B. Jackson and D. C. Lasenby (1982). "A method for predicting winter oxygen profiles in ice-covered Ontario lakes." Canadian Journal of Fisheries and Aquatic Science **39**: 1267-1272.
2. Relevant. Comments: This paper presents some data and simple equations for predicting oxygen content with depth. While in principle this could be repeated in Arctic lakes, it would have to be based on new measurements as the biology of the lakes are quite different.

A. R. Phelps, K. M. Peterson and M. Jeffries (1998). "Methane efflux from high latitude lakes during spring ice melt." J. Geophys. Res. **103**(D22): 29,029 - 29,036.
2. Relevant. Comments: I haven't read this paper, but it looks interesting, making the point that the largest changes in water chemistry occur during break-up. It's not as relevant to long-term impacts as it is to measuring long-term impacts.

K. S. Ruhland, J.P. (1998). "Limnological characteristics of 70 lakes spanning arctic treeline from Coronation Gulf to Great Slave Lake in the central Northwest Territories, Canada." International Review of Hydrobiology **83**(3): 183-203.
2. Relevant. Comments: This paper presents one of the broadest surveys across ecosystems of Arctic lakes that I have found, though concentrated in northern Canada. Thus it provides some context for coastal lakes, within the latitudinal and ecosystem gradients present there. The paper presents many tables with ion concentrations that may be useful to anyone studying lake chemistry.

D. Stefanovic and H. Stefan (2002). "Two-dimensional temperature and dissolved oxygen dynamics in the littoral region on an ice-covered lake." Cold Regions Science and Technology **34**: 159-178.

2. Relevant. Comments: An interesting paper presenting many measurements of temperature and dissolved oxygen on transects with depth. Clearly shows thermal and dissolved oxygen mixing, and presents some theory for calculating mixing velocities.

H. E. Welch and M. A. Bergmann (1985). "Water circulation in small arctic lakes in winter." Canadian Journal of Fisheries and Aquatic Science **42**: 506-520.
2. Relevant. Comments: An interesting paper detailing dye-tracer experiments that clearly indicate some type of convection cell beneath the ice. Not terribly relevant to pumping studies, though does have implications for dissolved oxygen and thermal dynamics within the lakes.

Hinzman, L.D., D.W. Robinson, and D.L. Kane (1998). A Biogeochemical Survey of an Arctic Coastal Wetland. Seventh International Conference on Permafrost. Yellowknife, Canada: 459-464.
2a. Possibly Relevant.

W. S. Brewer, A. R. Abernathy and M. B. Poynter (1977). "Oxygen consumption by freshwater sediments." Water Resources **11**: 471-473.
3. Related. Comments: A simple but effective study demonstrating that the rate of oxygen uptake is determined by the biota living in the sediments.

I. P. Semiletov (1999). "Aquatic sources and sinks for CO2 and CH4 in the polar regions." J. of the Atm. Sci. **56**: 286-306.
3. Related.

S. A. Zimov, Y. V. Voropaev, I. P. Semiletov, S. P. Davidov, S. F. Prosiannikov, F. S. Chapin, M. C. Chapin, S. Trumbore and S. Tyler (1997). "North Siberian Lakes: a methane source-fueled by Pleistocene carbon." Science **277**: 800-802.
3. Related. Comments: An interesting paper that highlights a major difference between Siberian and Alaskan lakes: Siberian lakes give off signficantly more methane from a Pleistocene source, whereas Alaskan lakes overlay a more recent sediment without large methane ebullitions.

Barica, Gibson and Howard (1983). "Feasibility of snow clearing to improve dissolved oxygen conditions in a winterkill lake." Canadian Journal of Fisheries and Aquatic Science **40**: 1526-1531.
3a. Possibly Related.

J. G. Champlin and H. G. Stefan (1996). Field study of the ice cover of a lake: implications for winter water quality monitoring. Minneapolis, MN, University of Minnesota, St Anthony Falls Laboratory.
3a. Possibly Related.

B. T. Hargrave (1969). "Similarity of oxygen uptake by benthic communities." Limnolog. Oceanogr. **14**: 801-805.
3a. Possibly Related.

B. B. Jorgensen and N. P. Revsbech (1985). "Diffusive Boundary Layers and the Oxygen Uptake of Sediments and Detritus." Limnolog. Oceanogr. **30**(1): 111-122.
3a. Possibly Related.

D. S. S. D. Lim, M.S.V.; Smol, J.P.; Lean, D.R.S. (1997). Limnology of high arctic ponds (Bathurst Island, N.W.T., Canada). 27th Arctic Workshop, Department of Geography,University of Ottawa , February 27-March 2, 1997, University of Ottawa.
3a. Possibly Related.

Future Impacts

Because the dynamics of tundra ponds are intimately linked with current climate dynamics, it is important to understand how a changing climate may induce change in these ponds. Conversely, it turns out that climate itself may be affected by changes in these ponds, primarily through changes in gas flux and surface energy balance on large spatial scales.

J. E. Hobbie, B. J. Peterson, N. Bettez, L. Deegan, W. J. O'Brian, G. W. Kling, G. W. Kipphut, W. B. Bowden and A. E. Hershey (1999). "Impact of global change on the biogeochemistry and ecology of an Arctic freshwater system." Polar Research **18**(2): 207-214.
1a. Possibly Highly Relevant. Comments: I have not read this paper as I found it very late into my search, but in skimming it the focus of the paper is addresses the impact of climate change on Arctic lakes, rather than permafrost in general. The lakes they are considering seem to be foothills lakes (not of the thermokarst variety), but there are some obvious parallels.

D. Kane, L. Hinzman, M.-k. Woo and K. Everett (1992). Arctic hydrology and climate change. Ecosystems in a Changing Climate. F. S. Chapin, Academic Press**:** 35-57.
2. Relevant. Comments: A good overview of arctic hydrology, including qualitative and quantitative descriptions of water balance components and interactions, as well as a review of modeling efforts to describe the impact of climate change on this balance.

D. Kane, L. Hinzman and J. Zarling (1991). "Thermal response of the active layer to climatic warming in a permafrost environment." Cold Regions Science and Technology **19**: 111-122.
2. Relevant. Comments: An interesting paper describing a numerical model used to predict soil temperatures under warming climates over a 50 year period. It was found, as expected, that warming air temperatures cause warmer soils, deeper active layers, and longer thaw seasons. A warming of 4.5C in mean annual air temperature was predicted to cause talik formation in the foothills, which would ultimately lead to the demise of permafrost there. Such a warming would have drastic effects also on tundra ponds.

N. T. Roulet (2000). "Peatlands, carbon storage, greenhouse gasses, and the Kyoto Protocol: Prospects and significance for Canada." Wetlands **20**(4): 605-615.
2. Relevant. Comments: An interesting paper in that it discusses a potential long-term impact of water pumping from tundra ponds not on the ponds themselves, but on the atmosphere through an alteration of gas flux. That is, if it were found that water pumping was significantly affecting the amount of areal coverage of lakes or their biogeochemistry, then long term impacts to the environment might result.

W. R. Rouse and a. others (1997). "Effects of climate change on the freshwaters of arctic and subarctic North America." Hydrologic Processes, Vol II: 873-902.
2. Relevant. Comments: Presents a comprehensive and big picture look at the effects of climate change in the Arctic, with substantial emphasis on the impacts on lakes.

Emphasizes that while excellent local-scale research has been conducted, full limnological system studies are insufficient, particularly on the coastal plain. Has many references to many aspects of permafrost dynamics, including biological aspects.

L. Hinzman and D. Kane (1992). "Potential response of an arctic watershed during a period of global warming." Journal of Geophysical Research **97**(D3): 2811-2820.
3. Related. Comments: An interesting paper which uses modeling to confirm suspicions that an increase in mean annual air temperature will lead to warmer soils, deeper active layers, and more evapotranpirations. The response of runoff depends on timing of events and soil dessication from the previous years. Though not treating lakes specifically, the implications are that lakes may get drier due to increased evaporation, ice wedge degradation, and potentially less recharge.

D. Kane (1997). The impact of hydrological perturbations on Arctic ecosystems induced by climate change. Global change and arctic terrestrial ecosystems. W. Oeschel, T. Callaghan, T. Gilmanov, J. Holten, B. Maxwell, U. Molau and B. Sveinbjornsson. New York, Springer-Verlag**:** 63-81.
3a. Possibly Related.

V. J. Lunardini (1996). "Climatic warming and the degradation of warm permafrost." Permafrost and Periglacial Processes **7**: 311-320.
3a. Possibly Related.

W. F. Vincent, I. Laurion and R. Pienitz (1998). "Arctic and Antarctic lakes as optical indicators of global change." Annals of Glaciology **27**: 691-696.
3a. Possibly Related.

Pingos

Pingos are (typically) conically shaped hills often found in drained tundra pond basins, and are therefore a potential long-term outcome of inadvertently draining a pond. They are also unique islands of biological processes as well as a key to understanding the natural history of tundra ponds.

D. Walker, M. Walker, K. Everett and P. Webber (1985). "Pingos of the Prudhoe Bay Region, Alaska." Arctic and Alpine Research **17**(3): 321-336.
2. Relevant. Comments: Classic paper on pingos in the Prudhoe oil fields, describing field work and topographic measurements classifying and understanding the origins and importance of these features.

J. R. Mackay (1979). "Pingos of the Tuktoyaktuk Peninsula Area, Northwest Territories." Geogr. phys. Quat. **33**(1): 3-61.
2a. Possibly Relevant.

K. Yoshikawa (1998). The groundwater hydraulics of open system pingos. 7th International conference on permafrost.
3. Related.

J. R. Mackay (1972). "The world of underground ice." Annals of the Association of American Geographers **62**(1): 1-22.
3a. Possibly Related.

J. R. Mackay (1973). "The growth of pingos, Western Arctic Coast, Canada." Canadian Journal of Earth Sciences **10**: 979-1004.
3a. Possibly Related.

J. R. Mackay (1977). "Pulsating pingos, Tuktoyaktuk Peninsula, NWT." Canadian Journal of Earth Sciences **14**: 209-222.
3a. Possibly Related.

Taliks

Taliks are unfrozen layers of ground that typically form beneath tundra ponds that are deeper than maximum ice depth (about 2 m). Because the frozen and unfrozen ground have quite different thermal, hydrological, biological, and chemical properties, understanding the dynamics of taliks beneath lakes is potentially important to understanding the long-term impacts of changing lake dynamics, especially as related to hydrology and catastrophic drainage.

C. Burn (2002). "Tundra lakes and permafrost, Richards Island, western Arctic coast, Canada." Canadian Journal of Earth Sciences **39**(8): 1281-1298.
2. Relevant. Comments: Studies a large area near Tuk with GIS and modeling to determine talik probability. Looks at Todd lake in detail with bathymetry, water temp, active layer, and permafrost, plus a north-south transect of about 12 lakes for ice thickness, bathymetry and water temperature were measured. Perhaps the best paper dealing with taliks and water temperatures.

F. Ling and T. Zhang (2003). "Numerical simulation of permafrost thermal regime and talik development under shallow thaw lakes on the Alaskan Arctic Coastal Plain." J. Geophys. Res. **108**(D16): doi:10.1029/2002JD003014.
2. Relevant. Comments: The best recent reference on modeling talik formation beneath thermokarst lakes. Curves are given for a range of possible parameters and their temporal and spatial effects on ground temperature. Most rapid thawing occurs in first 500 years, with long term talik depths between 20 and 60 meters, depending on water temperature variations from 1 to 3C respectively.

F. Ling and T. Zhang (2004). "Modeling study of talik freeze-up and permafrost response under drained thaw lakes on the Alaskan Arctic Coastal Plain." J. Geophys. Res. **109**(D01111): doi:10.1029/2003JD003886.
2. Relevant. Comments: The best recent paper I found on the modeling of talik refreezing after lake drainage. It was found that talik are completely refrozed after only 40-150 years, depending on initial conditions, though temperature re-equilibration continued for many hundreds of years.

J. R. Mackay (1997). "A full-scale experiment (1978-1995) on the growth of permafrost by means of lake drainage, western Arctic coast: a discussion on the method and some results." Canadian Journal of Earth Sciences **34**(1): 17-33.
2. Relevant. Comments: An interesting paper on what happens to the exposed lake bottom of a drained lake after drainage, over a period of 20 years; the only study of its kind. Largely focusses on the the rates and mechanisms of permafrost growth, but emphasizes the need to examine whole system in 3D as opposed to 1D simplifications.

K. Yoshikawa and L. Hinzman (2003). "Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska." Permafrost and Periglacial Processes **14**: 151-160.

2. Relevant. Comments: An interesting paper describing observations of lake drainages through taliks, a mechanism that is not likely to be important in Prudhoe ponds for some time yet. The techniques used for measurement are likely applicable here.

M. C. Brewer (1958). "Some results of geothermal investigations of permafrost in northern Alaska." Transactions, American Geophysical Union **39**(1): 19-26.
2a. Possibly Relevant.

Lake biota

Because a variety of mammals, fish, invertebrates, and plants depend on tundra ponds for survival, it is important to understand these linkages in order to hypothesize and test how water withdrawal may affect this habitat. I am not a biologist, and some may find this section noticeably thin. There has been a wealth of lake biota research generated through research in the Brooks Range foothills, primarily in the Toolik Lake region. However, lakes here are typically not of the thermokarst type and have a reduced coastal influence, so I tended to not include them. There is also a lot of literature on lakes south of the Alaska Range, which I also did not include. It seemed to me that the most important biological information required to generate hypotheses related to long-term impacts could be found in one of several books, including those by Hobbie, Truett, and Milner listed in the Book section, as well as the Wetzel textbook found there. Here I've included a few papers that I thought might add to those books. But, not being a biologist, I welcome other perspectives on papers that would improve this section of the bibliography, particularly on tundra ponds subsequent to 1985.

A. Hershey, G. Gettel, M. McDonald, M. Miller, H. Mooers, W. J. O'Brien, J. Pastor, C. Richards and J. Schuldt (1999). "A geomorphic-trophic model for landscape control of Arctic food webs." BioScience **49**: 887-897.
1. Highly Relevant. Comments: An interesting paper that describes a method of predicting fish types and food webs based on landscape characteristics (primarily stream gradients). "Because landscape criteria control the distribution of fishes, and fish control trophic structure, the landscape indirectly controls lake trophic structure." Perhaps the best recent paper on predicting fish distribution in Arctic lakes, though mostly related to the foothills, not the coastal plain.

D. R. Schmidt, W. B. Griffiths and L. R. Martin (1989). "Overwintering biology of anadromous fish in the Sagavanirktok River delta, Alaska." Biol. Pap. Univ. Alaska **24**: 55-74.
2a. Possibly Relevant.

J. Braddock and K. McCarthy (1996). "Hydrologic and microbiological factors affecting persistence and migration of petroleum hydrocarbons spilled in a continuous-permafrost region." Environmental Science and Technology **30**(8): 2626-2633.
3a. Possibly Related.

Permafrost

Because stability of tundra ponds is intimately linked with the thermal state of the permafrost and all that it controls, I created a section for related and relevant papers that did not fall into the other more focused sections. A section labeled "Permafrost" could include hundreds or thousands of papers, so deciding what to include here was a challenge, and largely reflects my prior familiarity. This section therefore does not need to get much larger, but if I have missed any key references on either ice-wedge dynamics or thermokarst dynamics, or very recent papers on permafrost temperatures, they should be added.

L. Hinzman, D. Goering, S. Li and T. Kinnery (1997). Numeric simulation of thermokarst formation during disturbance. <u>Disturbance and recovery in Arctic lands: an ecological perspective</u>. R. Crawford. The Netherlands, Kluwer Academic Publishers.
2. Relevant. Comments: An excellent overview of the successes and difficulties of field and modeling studies of thermokarst formation. An example used here was simulating the effects of scraping the tundra off of the mineral soil and forming a shallow lake.

D. Walker (1985). Vegetation and environmental gradients of the Prudhoe Bay region, Alaska, Cold Regions Research and Engineering Laboratory 240.
2. Relevant.

L. Hinzman, D. Goering and D. Kane (1998). "A distributed thermal model for calculating soil temperature profiles and depth of thaw in permafrost regions." <u>Journal of Geophysical Research</u> **103**(D22): 28975-28991.
3. Related. Comments: This paper describes a numerical model based on surface energy balance and 1D heat conduction to predict active layer depths and soil temperatures in the tundra. It is one of only a few such models, and compares well with measured data. It is not directly related to pumping tundra ponds, except perhaps as a prediction tool for climate change scenarios.

L. Hinzman, D. Kane, R. Gieck and K. Everett (1991). "Hydrological and thermal properties of the active layer in the Alaskan Arctic." <u>Cold Regions Science and Technology</u> **19**: 95-110.
3. Related. Comments: An interesting paper that largely describes the relationship between snowmelt/rainfall and infiltration in tundra. One general conclusion is that runoff largely does not infiltrate the mineral soils beneath the organic mat because these are still frozen at snowmelt, which limits nutrient transport from the mineral soils. Rainfall events later in summer carry more nutrients from deeper soil layers.

M. Jeffries, T. Zhang, K. Frey and N. Kozlenko (1999). "Estimating late-winter heat flow to the atmosphere from the lake-dominated Alaskan North Slope." <u>Journal of Glaciology</u> **45**(150): 315-347.
3. Related. Comments: An interesting paper, but with little directly to do with the long-term effects of pumping, unless widespread changes in lake area begin occurring which would change the heat flux to the atmosphere.

J. McNamara, D. Kane and L. Hinzman (1999). "An analysis of an arctic channel network using a digital elevation model." Geomorphology **29**: 339-353.
3. Related. Comments: An interesting paper on surface water flow, with particular insights into water tracks origin and significance, but having little to do with pumping lakes.

J. L. Morack and J. C. Rogers (1981). "Seismic evidence of shallow permafrost beneath islands in the Beaufort Sea, Alaska." Arctic **34**(2): 169-174.
3. Related.

T. E. Ostercamp and V. E. Romanovsky (1999). "Evidence for warming and thawing of discontinuous permafrost in Alaska." Permafrost and Periglacial Processes **10**: 17-37.
3. Related. Comments: Good recent reference on increased in permafrost temperature, but with no direct treatment of lakes.

T. E. Osterkamp, L. Viereck, Y. Shur, M. T. Jorgenson, C. Racine, A. Doyle and R. D. Boone (2000). "Observations of thermokarst and its impact on boreal forests in Alaska, USA." Arctic and Alpine Res. **32**(3): 303-315.
3. Related. Comments: Interesting recent paper on thermokarsting and thaw lake dynamics within Interior Alaska, but no direct treatment of lakes on the north slope.

L. Price, L. C. Bliss and J. Svoboda (1974). "Origin and significance of wet spots on scraped surfaces in the high Arctic." Arctic **27**(4): 304-306.
3. Related. Comments: One of the few papers I found on the interaction between deliberate bulldozer scraping and its effects on the tundra. General conclusion was that in the high arctic, such effects would equilibrate in several years and not impede runway use. I'm not so sure.

R. Sherman (1973). A groundwater supply for an oil camp near Prudhoe Bay, Arctic Alaska. Second International Permafrost Conference, Yakutsk, USSR, National Academy of Sciences.
3. Related. Comments: A short but interesting paper on the pumping of a groundwater aquifer beneath the Sag River but above the permafrost zone. They tested water quality in lakes, streams and aquifers and publish results. Found that the acquifer, though more difficult to locate, offer the best drinking water with the least maintenance.

J. Braddock and K. McCarthy (1996). "Hydrologic and microbiological factors affecting persistence and migration of petroleum hydrocarbons spilled in a continuous-permafrost region." Environmental Science and Technology **30**(8): 2626-2633.
3a. Possibly Related.

J. Brown (1967). "Tundra soils formed over ice wedges, northern Alaska." Soil science society of America Proceedings **31**(5): 686-691.
3a. Possibly Related.

K. M. Hinkel, J. A. Doolittle, J. G. Bockheim, F. E. Nelson, R. Paetzold, J. M. Kimble and R. Travis (2001). "Detection of subsurface permafrost features with ground penetrating radar, Barrow, Alaska." Permafrost and Periglacial Processes **12**(2): 179-190.
3a. Possibly Related.

K. M. Hinkel, F. E. Nelson, Y. Shur, J. Brown and K. R. Everett (1996). "Temporal changes in moisture content of the active layer and near-surface permafrost at Barrow, Alaska: 1962-1994." Arctic and Alpine Research **28**: 300-310.
3a. Possibly Related.

N. Ishikawa, N. Sato, K. Kawauchi, K. Yoshikawa and L. Hinzman (2001). "Characteristics of the water cycle in the discontinuous permafrost region in interior Alaska." Polar meteorol. glaciol. **15**: 78-90.
3a. Possibly Related.

G. H. Johnston and R. J. Brown (1964). "Some observations on permafrost distribution at a lake in the Mackenzie delta, NWT, Canada." Arctic **17**: 162-175.
3a. Possibly Related.

G. H. Johnston and R. J. Brown (1966). "Occurrence of permafrost at an Arctic lake." Nature **21**(5052): 952-953.
3a. Possibly Related.

J. R. Mackay (1972). "The world of underground ice." Annals of the Association of American Geographers **62**(1): 1-22.
3a. Possibly Related.

J. R. Mackay (1995). "Ice wedges on hillslopes and landform evolution in the late Quaternary, western Arctic coast, Canada." Canadian Journal of Earth Sciences **32**(8): 1093-1105.
3a. Possibly Related.

J. R. Mackay (1995). "Active layer changes (1968-1993) following the forest-tundra fire near Inuvik, NWT, Canada." Arctic and Alpine Research **27**(4): 323-336.
3a. Possibly Related.

L. A. Morrissey, S. L. Durden, G. P. Livingston, J. A. Stearn and L. S. Guild (1996). "Differentiating methane source areas in Arctic environments with multitemporal ERS-1 SAR data." IEEE TGRS **34**(3): 667-673.
3a. Possibly Related.

F. E. Nelson, K. M. Hinkel, N. I. Shiklomanov, G. R. Mueller, L. L. Miller and D. A. Walker (1998). "Active-layer thickness in north-central Alaska: systematic sampling, scale, and spatial autocorrelation." Journal of Geophysical Research-Atmospheres **103**(22): 26963-28973.
3a. Possibly Related.

V. N. Rampton (1973). The influence of ground ice and thermokarst upon the geomorphology of the Mackenzie-Beaufort region. 3rd Guelph Symposium on Geomorphology, Guelph, Guelph, Ontario.
3a. Possibly Related.

M. Smith (1976). Permafrost in the Mackenzie Delta, Northwest Territories, Geological Survey of Canada 34.
3a. Possibly Related.

Gray Literature

Sitting in desk drawers and dusty shelves of many arctic researchers are undoubtedly many reports that would be of use to assess possible long-term impacts of pumping from tundra ponds. Here I have compiled many of those reports that I could find, but I suspect that many more are out there and this section no doubt will grow the largest over time. I have not read any of these, as the priority of this review was on peer-reviewed literature.

B. Streever, S. Bedwald, A. McCusker and B. Shaftel (2001). Winter measurements of water quality and water levels: the effects of water withdrawal for ice road construction on lakes of the NPR-A. Anchorage, AK, BP Exploration Alaska.
1a. Possibly Highly Relevant.

B. Haley and D. Funk (2003). Prudhoe Bay lake surveys July 2002 and April 2003. Anchorage, Alaska, Prepared for BP Exploration, AK, by LGL Alaska Research Associates, Inc 70 pages plus appendices.
2a. Possibly Relevant.

R. I. Lewellen (1972). Studies on the fluvial environment Arctic Coastal Plain Province Northern Alaska. Palmer, AK, Lewellen Arctic Research 282.
2a. Possibly Relevant.

Michael Baker Jr (2002). National Petroleum Reserve Alaska 2002 Lake Monitoring and Recharge Study. Anchorage, AK, Prepared for ConocoPhillips 67 pages, plus appendices.
2a. Possibly Relevant.

Michael Baker Jr (2002). Alpine facility and vicinity, 2002 Lake monitoring and recharge study. Anchorage, Alaska, Prepared for Conoco Phillips by Michael Baker Jr., Inc. 20 pages plus appendices.
2a. Possibly Relevant.

Michael Baker Jr. (2002). Kuparuk 2002 Lake Monitoring and Recharge Study. Anchorage, AK, Prepared for ConocoPhilips by Michael Baker Jr., Inc. 15 pages, plus appendices.
2a. Possibly Relevant.

L. Moulton (1998). Lakes samples for fish in and near the Colville River Delta, Alaska, 1979-1998. Lopez Island, WA, Prepared for ARCO Alaska, Inc., by MJM Research 513 pages.
2a. Possibly Relevant.

L. Moulton (2000). Fish utilization of lakes in eastern NPR-A 1999-2000. Lopez Island, WA, Prepared for Phillips Alaska, Inc., by MJM Research 129 pages.
2a. Possibly Relevant.

L. Moulton (2000). 2000 North Slope fish survey, preliminary summary of eastern NPR-A and Alpine results. Lopez Island, WA, Prepared for Phillips Alaska, Inc., by MJM Research 8 pages plus 1 appendix.
2a. Possibly Relevant.

L. Moulton (2001). Monitoring of water-source lakes in the Alpine Development Project: 2000. Lopez Island, WA, Prepared for Phillips Alaska, Inc., by MJM Research 6 pages plus appendices.
2a. Possibly Relevant.

R. Reanier (2000). Year 2000 lake studies in the Phillips Exploration Area, National Petroleum Reserve - Alaska. Seattle, WA, Prepared for Phillips Alaska, Inc., by Reanier & Associates 8 pages plus 1 appendix.
2a. Possibly Relevant.

URS (2001). 2001 Lake Monitoring Study, National Petroleum Reserve - Alaska. Anchorage, AK, Prepared for Phillips Alaska, Inc., by URS 15 pages plus 4 appendices.
2a. Possibly Relevant.

W. Wilson, E. Buck, G. Player and L. Dreyer (1977). Winter water availability and use conflicts as related to fish and wildlife in Arctic Alaska - synthesis of information, U.S. Fish and Wildlife Service.
2a. Possibly Relevant.

I. Greeneridge Sciences (2000). Vibrator sounds in a frozen arctic lake during a winter seismic survey. Santa Barbara, CA, Prepared for Western Geophysical by Greeneridge Sciences, Inc. 16 pages.
3a. Possibly Related.

M. Jorgensen, E. Pullman, Y. Shur, M. Smith, A. Stickney, J. Aldrich, S. Ray and H. Walker (1996). Geomorphology and hydrology of the Colville River Delta, Alaska, 1995. Fairbanks, AK, Prepared for Arco Alaska, Inc., and Kuukpik Unit Owners by ABR, Inc., Shannon&Wilson, Inc., and Louisiana State University.
3a. Possibly Related.

Michael Baker Jr (2000). Alpine Development Water Supply, 1999 Monitoring and Assessment. Fairbanks, AK, Prepared for ARCO Alaska, Inc., by Michael Baker Jr. Inc. 8 pages plus 1 appendix.
3a. Possibly Related.

L. Moulton (2000). Fish occurrence in lakes of the CD-South Exploration Area. Lopez Island, WA, Prepared for Phillips Alaska, Inc., by MJM Research 60 pages.
3a. Possibly Related.

L. Moulton (2001). Fish occurrence in lakes of the CD-North Exploration Area. Lopez Island, WA, Prepared for Phillips Alaska, Inc., by MJM Research 91 pages.

3a. Possibly Related.

L. Moulton (2002). Evaluation of potential fish habitat in lakes in the Grizzly/Heavenly/Supercub region - 2001. Lopez Island, WA, Prepared for Phillips Alaska, Inc., by MJM Research 98 pages.
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Section Three

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Abstract: Although periodic mechanical snow removal from the surface of an experimental plot on Rock Lake, southern Manitoba, between January and February did not provide an expected increase of dissolved oxygen levels that would reduce the likelihood of fish winterkill in the localized area of the lake, it provided a basis for analyzing the practicality and feasibility of the method, The minimum lake area to be kept clear of snow for prevention of winterkill was calculated to be 15% of the total lake area. Snow clearing should start soon after freeze-up to provide at least 0.3 gm-2d-1g-m dissolved oxygen needed to compensate for bacterial oxygen uptake during the winter months.

Billings, W. D. and K. M. Peterson (1980). Vegetational change and ice-wedge polygons through the thaw-lake cycle in Arctic Alaska. Arctic and Alpine Research. **12** 413-432.
Abstract: Britton's thaw-lake cycle hypothesis is examined and modified in light of new obser-vations on ice-wedges and revegetation follow-ing drainage of lakes in the wet coastal tundra of arctic Alaska. Two thaw-lakes which were artificially drained in 1950 provided base-line data for the ages of basin surfaces. Sizes of clonal colonies of Eriophorum angustifolium and Carex aquatilis were used in an attempt to age older, naturally drained lake basins. The floristic composition of the vegetation through the cycle is predictable. Pioneer species are Dupontia fisheri and Arctophila fulva. Eriophorum angustifoliuTn is characteristic throughout all of the terrestrial part of the cycle. Carex aquatilis enters the vegetation slowly but is the most successful competitor and dominates the vegetation for perhaps 2000 to 3000 yr. It disap-pears locally when thaw-ponds developing from low-center polygons become too deep. Ice-wedges exist longer than the thaw-lakes and persist beneath them. They reassert them-selves after drainage and are important in re-initiating the polygonal, terrestrial part of the cycle. Drained lake basins are very susceptible to thermokarst erosion when vehicles damage the insulating peat which covers the ice-wedges. Vegetational succession through the thaw-lake cycle is closely attuned to geo-morphic changes and therefore is cyclic. It does not fit most recent models of succession because it is not autogenic but, rather, is controlled by the cold physical environment both above and below ground.

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Abstract: Contents: Introduction - Historical perspective - Synopsis of principles - Ice content of permafrost - Thaw depressions - Thaw lakes - Oriented lakes of northern Alaska and Northwest Canada - Vegetation and thaw depressions and thaw lakes - Thermal aspects of thaw lakes - Other limnological aspects of thaw lakes - Suggestions for future study - References

Bolton, B., L. Hinzman and K. Yoshikawa (2000). Stream flow studies in a watershed underlain by discontinuous permafrost. Water resources in extreme environments. D. Kane. Anchorage, AK.
Abstract: ABSTRACT: Permafrost plays an important role in the hydrology of sub-arctic watersheds. Ice-rich conditions at the permafrost table do not allow significant percolation, resulting in decreased response time to precipitation events (including snowmelt), limited subsurface storage, and low base flows between precipitation events. The Caribou-Poker Creeks Research Watershed (CPCRW), located 48 km north of Fairbanks, Alaska, is underlain by discontinuous permafrost along north facing slopes and valley bottoms. Spring snowmelt is usually the major hydrologic event of the year but accurate discharge measurements have been difficult to obtain due to extensive aufeis formation at the stream gauging stations. Although spring snowmelt is usually the dominant hydrologic event of the year, maximum stream discharge was recorded during a major rainfall event in June. Comparison of the specific discharges from the C2, C3, and C4 sub-watersheds which are underlain, respectively, with 3.5, 53.2, and 18.8 permafrost show that the C3 sub-watershed had higher peak specific discharges and a lower specific base flow compared to the C2 and C4 sub-watersheds. However, as the active layer depth (the layer of soil above the permafrost that thaws and freezes seasonally) increased throughout the summer, the C3 sub-watershed displayed decreasing peak specific discharges, the result of increased subsurface storage, during precipitation events. Recession analysis show the contribution of subsurface water during precipitation events from the C3 and C4 sub-watershed increased throughout the summer as the active layer increased in thickness while the contribution from subsurface flow in the low permafrost basin remained nearly constant.

Bowling, L., D. Kane, R. Gieck, L. Hinzman and D. Lettenmaier (2003). The role of surface storage in a low-gradient Arctic watershed. Water Resources Research. **39** 1087.
Abstract: The Arctic land surface water balance plays an important role in regulating the planetary heat balance and global ocean circulation. Lakes and wetlands are common features in the low-gradient Putuligayuk River watershed in northern Alaska, with important implications for the annual water balance. Evapotranspiration exceeds precipitation over the summer, and there is a gradual reduction in wetland extent. Total inundated area derived from RADARSAT ScanSAR synthetic aperture radar images throughout 1999 and 2000 varied from 15 to 67 percent of the 471 km2 watershed. The hydrological system becomes disconnected within 2 weeks of snowmelt, and overland flow largely ceases. End-of-winter snow water equivalent and discharge during the melt

period for 1999, 2000, and 2001 were used to estimate that between 30 and 37 mm (24 42 percent) of snow meltwater serves to recharge the evaporation deficit of the previous summer. The percent of snowmelt entering storage is dependent on the available surface Storage.

Braddock, J. and K. McCarthy (1996). Hydrologic and microbiological factors affecting persistence and migration of petroleum hydrocarbons spilled in a continuous-permafrost region. <u>Environmental Science and Technology</u>. **30** 2626-2633.
Abstract: Fuel spills, totaling about 1300 m3, occurred between 1976 and 1978 adjacent to Imikpuk Lake, a drinking water source near Barrow, AK. Substantial con-tamination of soils and groundwater near the lake persists. We examined the magnitude and direction of groundwater flux and the microbial activity at this site to understand the persistence of contamination and its effect on the lake. We found that ground-water flux is small due to shallow permafrost, which restricts the cross-sectional available for flow, and to the short annual thaw season (ca. 90 days). The small flux and limited depth also constrain contaminant transport and dispersion, resulting in persistent, shallow contamination. The numbers of hydrocarbon-oxidizing microorganisms and their laboratory mineralization potentials for benzene (at 10 °C) were higher in samples from contaminated areas than in reference samples. Benzene mineralization potentials in groundwater samples were comparable to more temperate systems (0.1-0.5 mg of benzene mineralized L~1 day"1) and were stimulated by nutrient additions. Field measurements of dissolved oxygen, nitrate, ferrous iron, and sulfide in groundwater provided evidence that biodegradation of petroleum hydro-carbons is occurring in situ. Despite evidence of an active microbial population, microbial processes, like contaminant transport, are likely limited at this site by the short annual thaw season.

Brewer, M. C. (1958). Some results of geothermal investigations of permafrost in northern Alaska. <u>Transactions, American Geophysical Union</u>. **39** 19-26.
Abstract: Frequent, regular thermal measurements in northern Alaska over a six-year period have provided information on many of the problems related to the temperature and distribution of permafrost in the Arctic. The maximum depth of permafrost near Barrow is 1330 ft. The minimum permafrost temperature recorded, below the depth of measurable (0.01° C) seasonal fluctuation (70 to 100 feet), is -10.6° C. The temperature effect of medium-sized (40 by 100 ft) heated buildings resting on permafrost is measurable to depths well below 50 ft. It is doubtful that frozen ground at shallow depths extends outward more than a few tens of feet from the shore of the Arctic Ocean although it may be present at depths greater than 100 ft. Lakes deeper than about seven feet do not freeze to bottom and may have an un-frozen zone approaching several hundred feet in depth beneath them.

Brewer, M. C., L. D. Carter, R. Glenn and J. a. o. Brown (1993). Sudden drainage of a thaw lake on the Alaskan Arctic coastal plain. <u>Permafrost Sixth International Conference.</u> Beijing, China, South China University of Technology Press 48-53.
Abstract: Drainage of this and other lakes in Prudhoe Bay area, which occurred during summer 1989, is thought to have resulted from processes expected to become more

frequent with changing global climate. However, there is no evidence whether these events in 1989 are beginning of long-term trend or consequence of unusually wet summer

Brewer, W. S., A. R. Abernathy and M. B. Poynter (1977). Oxygen consumption by freshwater sediments. Water Resources. **11** 471-473.
Abstract: The purpose of this study was to measure the oxygen consumption rate of sediments and to determine the amount of oxygen consumption attributable to biological activity. Closed systems were utilized to measure oxygen uptake and phenol or potassium cynanide were introduced to eliminate biological respiration.

Britton, M. (1967). Vegetation of the arctic tundra. 18th Biology Colloquium. Oregon State College, Corvallis, OR 26-61.

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Abstract: No abstract.

Brown, J. (1967). Tundra soils formed over ice wedges, northern Alaska. Soil science society of America Proceedings. **31** 686-691.
Abstract: The physical and chemical properties oftandra soils overlying fee wedges are determined and the role of ice wedge growth in the genesis of these soils is evaluated. Ice wedges form in perennially frozen ground as a result of repetitive winter cracking of the ground and filling in by ice. A thin layer of soi! is isolated over the enlarging wedge in narrow depressions which result in polygonal ground. The soil thaws seasonally from the surface downward and freezes from both the top and bottom. Accompanying moisture migration results In a dehydrated midsection. No significant migration of cations or mineral grains was observed In a 70-cm deep tundra soil. The ice wedges are subjected to melting which creates new soil environments. Evidence of these changes have been traced over a 14,000-year period at Barrow, Alaska.

Brown, J., S. L. Dingman and R. I. Lewellen (1968). Hydrology of a drainage basin on the Alaskan coastal plain. Hanover, NH, Cold Regions Research and Engineering Laboratory 18.
Abstract: Analyzes a 1963-66 summer hydrologic record from a 1.6 km (super 2) drainage basin northeast of Barrow. The watershed is a drained lake bed underlain by permafrost at 0.3 m depth, and is covered by ice-wedge polygons and many small ponds. Snow melt begins in early-mid June, freeze-up in late Aug-early Sept. The four-yr record included extremely high rainfall-runoff in 1963 and extreme drought in 1964. The average depth of thaw was about 30 cm; only 24 cm in the dry summer. Runoff varied greatly from storm to storm and, in the subdued coastal topography, varying areas contributed to runoff from different storms. Runoff occurs primarily through and over the tundra mat and through an intricate system of polygonal troughs and ponds. Lag times are generally 3-10 hr; recession constants are of about 50 hr, at times up to 160 hr. Evaporation for an average thaw season is about 160 mm and evapotranspiration is about 60 mm. Assuming all winter precipitation runs off, about 50% of the measured annual precipitation in this region runs off into the Arctic Ocean.

Brown, J. and P. V. Sellman (1973). Permafrost and coastal plain history of arctic Alaska. Alaskan Arctic Tundra. e. Britton, Arctic Institute of North America. **Technical paper 25** 31-47.

Abstract: Permafrost as a major phenomenon was first discussed by Middendorfin the USSR in 1 848, but not until World War II did its true significance emerge in North America. Construction of the Alaska Highway as well as construction and exploration through-out Alaska, particularly in Naval Petroleum Reserve No. 4 (PET 4), brought the extent and significance of permafrost into prominence. Not until the late 1940's, however, did efforts get underway to investigate permafrost in the Alaskan Arctic. Permafrost and related research have comprised a significant cross section of ter-restrial scientific and engineering investigations during the first 25 years of the Naval Arctic Research Laboratory. Emphasis is placed on related research since, unlike the situation in the USSR, the science of permafrost has not reached a stage of develop-ment in North America, and particularly in the United States, where individuals are identified as permafrost specialists (geocryologists). For this reason, geophysicists, geologists, geomorphologists, pedologists, and engineers have pioneered early perma-frost research in this country. These researchers have been ably assisted by biologists and ecologists. Both academic and federal participants have shared in pioneering arctic permafrost research in the United States. For northern Alaska, the Naval Arctic Research Laboratory, through the Office of Naval Research in Washington and the staff and facilities at Barrow, has provided a focal point through which permafrost science and technology have developed. The book Arctic Laboratory recounts much of this development (Reed and Ronhovde 1971). This discussion of permafrost research will be restricted mostly to the Alaskan Arctic. What has been observed and learned there has its counterparts in other north-ern regions. Permafrost is a circumpolar phenomenon, and the commonality of prin-ciples governing its formation and modification is shared regardless of national boundaries. In addition to permafrost research, a brief account of current under-standing of the late Quaternary history of the Arctic Coastal Plain will be presented. The understanding of the origin of the subsurface sediments and their subsequent modification is important in appreciating and interpreting permafrost terrain.

Burn, C. (1997). Cryostratigraphy, paleogeography, and climate change during the early Holocene warm interval, western Arctic Coast Canada. Canadian Journal of Earth Sciences. **34** 912-925.

Abstract: Botanical and cryostratigraphic records from northwest Canada indicate that the climate of the early Holocene was considerably warmer than today: tree line was over 100 km farther north; and a thaw unconformity, dating from 8000 ^C years BP, formed at the base of an active layer 2.5 times thicker than at present. Numerous thermokarst-lake basins formed in the preceding millennia. Both the botanical and cryostratigraphic indices described are products of summer conditions. Previous reconstructions of early Holocene climate have not assessed the significance of paleocoastal location on the seasonably and extent of apparent climate warming. At present, there is a steep gradient in growing-season conditions between cooler sites on the Beaufort Sea coast and warmer, inland locations. Winter conditions are more uniform because both sea and land are snow-covered. Coastal retreat in the region has been rapid, due to sea level rising over a gently sloping shelf containing readily credible sediments. The coastline has moved about 100 km southward during the Holocene. The increasing proximity to the coast, through time, of points currently within 100 km of the sea may account for between one and two thirds of the cooling in summer climate experienced there since the mid-Holocene.

Burn, C. (2002). Tundra lakes and permafrost, Richards Island, western Arctic coast, Canada. Canadian Journal of Earth Sciences. **39** 1281-1298.
Abstract: Lakes, of average size 33 ha, occupy a quarter of the surface area of Richards Island, Northwest Territories. Most of the lakes have a central pool deeper than the thickness of winter ice, and many have prominent, shallow, littoral terraces. The relatively warm lake bottoms cause considerable disturbance to the surrounding continuous permafrost. Water and lake-bottom temperatures, the configuration of permafrost, and active-layer thickness were measured at a tundra lake between 1992 and 1997. The lake is oval, 1.6 km long, 800 m wide, and as deep as 13 m. Sandy terraces, covered by less than 1 m of water, extend over 100 m from the shore. The terraces are underlain by permafrost, which terminates almost vertically at their edge. The annual mean temperature measured at lake bottom in the central pool ranged between 1.5°C and 4.8°C, depending on depth, and between -0.2°C and -5°C on the terraces, due to differences in snow cover and proximity to the central pool. In consequence, the temperature of permafrost at 7 m depth in the terraces also varied, from -2°C near shore to -5°C in mid-terrace. The active layer in the terraces was uniformly 1.4 m deep. Geothermal modelling of talik configuration indicates that there is no permafrost beneath the central pool of the lake. The modelling indicates that, under equilibrium conditions, about one quarter of the lakes on Richards Island have taliks that penetrate permafrost, and at least 10-15 of the island is underlain by talik. Short-term climatic changes predicted for the region imply a small increase in summer lake-water temperature and an extension of the open-water season, accompanied by thicker snow cover in winter. Following such changes, with longer freeze-up and warmer terrace temperatures in winter, permafrost may not be sustainable in the lake terraces.

Burn, C. (2002). Landforms, Climate, Ice Ages, Permafrost, Mackenzie Delta, Rivers and Lakes. Natural History of the Western Arctic. Inuvik, Western Arctic Handbook Committee 4-10, 11-12, 15-18, 19-23, 24-29, 35-38.
Abstract: No abstract

Burn, C. and M. W. Smith (1988). Thermokarst lakes at Mayo, Yukon Territory, Canada. Proceedings of the 5th International Conference on Permafrost. K. Senneset. Trondheim, Norway 700-705.
Abstract: The evolution of thermokarst lakes in ice-rich glaciolacustrine sediments near Mayo, Yukon Territory, has been documented through examination of aerial photographs, field surveys and analysis of the annual growth rings of submerged trees. In addition, the thermal regime of a typical lake has been studied, and a geothermal simulation analysis of lake development carried out. The tree-ring analysis indicates that the lakes were initiated around 1880. The geothermal simulation analysis of talik development also indicates that the lakes are about 100 years old. It is suggested that the lakes were initiated by forest fire. The growth of three lakes has been relatively constant

since 1949, and shows little correlation with climatic variations. Careful observation of lake development over the next 10 to 20 years could yield information on. growth patterns as a function of climatic changes.

Burn, C. and M. W. Smith (1990). Development of thermokarst lakes during the Holocene at Mayo, Yukon Territory. Permafrost and Periglacial Processes. **1** 161-176.
Abstract: The origin and growth of numerous thermokarst lakes near Mayo, central Yukon, has been examined, using ground surveys, aerial photographs and dendrochronology. Many of the lakes are currently expanding, at rates of axial increment up to 1.2 m/yr. Three lakes, whose axes are currently enlarging at about 1.0 m/yr, were studied in particular detail: tree-ring analysis indicates that these lakes formed by the middle to the late part of the last century. The talik profile was determined beneath one lake, and is consistent with the Stefan solution for thawing of ice-rich soil with such an initiation date and rate of expansion. Organic-rich horizons containing logs, vegetative detritus and fresh-water ostracods have been exposed in two retrogressive thaw slumps near the lakes. These horizons have been interpreted as the bottoms of former thermokarst lakes. Radiocarbon dates of approximately 8500 BP, 3900 BP and 2300 BP have been obtained, indicat-ing several periods of thermokarst activity during the Holocene. The results suggest that thermokarst lake development is not solely associated with changing climatic conditions in this region, since the current lakes and those that formed around 2300 BP do not appear to be directly linked to climatic warming. It is suggested that the most recent initiation of thermokarst activity is related to the effects of forest fires.

Bursey, G. G. E., T.W.D.; Frape, S.K. (1991). Water balance and geochemistry studies in a tundra watershed, District of Keewatin, Northwest Territories. NHRI Symposium Northern hydrology : selected perspectives : proceedings of the Northern Hydrology Symposium, 10-12 July 1990, Saskatoon, Saskatchewan. T. D. O. Prowse, C.S.L. Canada, National Hydrology Research Centre, Environment Canada. National Hydrology Research Institute. **6** 17-32.
Abstract: Results are reported from hydrological field studies in the summers of 1988 and 1989 in a tundra watershed in the eastern Arctic. Investigations of the water cycle in terrain underlain by continuous permafrost are being conducted using isotopic and geochemical data from precipitation, surface water, and active-layer ground water, coupled with hydrogeological and hydrological field observations. Water-balance calculations based primarily on isotopic data (18O/16O and 2H/1H ratios) indicate wide variation in the degree of evaporation from various levels in the drainage system. Evaporation can account for 40% or more of the discharge from shallow tundra ponds, whereas the average annual vapour discharge from the entire watershed is likely about 10%, in spite of the arid low-arctic climate. Evaporative losses are minimized in part by the relative importance of subsurface storage and flow within the active layer. Surface and subsurface waters are characterized by extremely low solute concentrations and are undersaturated with respect to most mineral phases, except the amorphous forms of silica and Fe(OH)3. High iron contents (up to 0.68 mmol/L) in some ground-water samples may stem from complexing with dissolved organic carbon. Other processes such as

cation exchange and freezing influence the chemistry of ground waters within the active layer.

Carson, C. and K. Hussey (1959). The multiple-working hypothesis as applied to Alaska's oriented lakes. Iowa Academy of Sciences Proceedings. **66** 334-349.
Abstract: The problem of the oriented lakes on Alaska's Arctic Coastal Plain provides an excellent opportunity for illustrating the application of the, method of multiple-working hypotheses to a geologic problem. '^Five hypotheses are considered and are deemed to be inconclusive; a composite of these is thought to provide an explanation of the lakes' origin. The hypotheses considered are: (1) that waves, produced by an ancient prevailing wind blowing parallel to the lake elongation, eroded the basins; (2) that the present winds produce wave current systems which preferentially scour the north and south lake shores, thus producing elongation; (3) that the winds produce a preferred distribution of sediment which determines orientation of the lakes by insulating the east and west shores, thus protecting them from erosion; (4) that orientation is developed by thaw produced by maximum insola-tion during the noon-hours; and (5) that the lakes are developed along north-south trending ice-wedges which formed in the north-south components of a right-angle fracture system. The process of consideration and elimination of these hypotheses leads to a composite hypothesis. This proposes that oriented ice-wedges might develop in the fracture system; that maximum insolation would be more effective in melting the north-south trending wedges than the complementary set; that the oriented depressions so oriented would in effect be perpetuated and enlarged by thaw and wind (wave) oriented sediments on the east-west shores.

Carter, L. D. (1987). Oreinted lakes. Geomorphic system of North America. W. L. Graf. Boulder, CO, Geol. Soc. Am. **Centennial Special Vol. 2** 615-619.
Abstract: No abstract.

Carter, L. D. (1987). Loess, syngenetic ice wedges, and deep thermokarst basins on the Alaskan North Slope. 5th International conference on Permafrost. Trondheim, Norway.
Abstract: Silt, locally more than 30 m thick, forms a discontinuous east-west trending belt 5 to 70 km wide across northern Alaska. In the central part of this belt, stratigraphic details and geologic relations indicate that much of the silt was deposited as loess during the last glacial cycle. Syngenetic ice wedges as much as 26 m deep and 3 m wide occur within the loess and in places penetrate the entire deposit. Because ground ice formed as the loess accumulated, ice content does not decrease with depth as it does in sediments that primarily contain epigenetic ice. This ice distribution within the loess has allowed thermokarst basins as deep as 20 m to form during the Holocene, whereas outside the area of loess, thermokarst basins commonly are only a few meters deep. Ice-rich loess may characterize much of the northern Alaska silt belt, which in the east extends across the coastal plain of the Arctic National Wildlife Refuge (ANWR). Research should be undertaken to determine the extent of ice-rich loess in ANWR, because it is a possible future site of oil exploration activity, and such sediments are especially sensitive to modern anthropogenic disturbance of the ground surface.

Champlin, J. G. and H. G. Stefan (1996). Field study of the ice cover of a lake: implications for winter water quality monitoring. Minneapolis, MN, University of Minnesota, St Anthony Falls Laboratory.

Abstract: Never obtained thesis

Cooke, C. W. (1954). Carolina Bays and the shapes of eddies, USGS.

Abstract: All classes of matter have gyrostatic properties following the universal laws of motion. Liquids moving in a curved path react in the same way as solids, though the manifestation ap-pears different because particles of a liquid are able to move independently of one another. So, if the plane of rotation of a liquid is tilted, the circular orbits of the particles are distorted into ellipses because the horizontal components of the cen-trifugal force vary in intensity according to the direction.

An eddy, like a spinning flywheel, resists any couple that tends to alter the direction of the axis of rotation. The application of such a couple causes the axis either to precess or to set its direction parallel to the axis about which it is forced to turn. The rotation of the earth is constantly turning the axis of rotation of an eddy out of its initial direction in space. Conse-quently, the axis of rotation of the eddy either processes about the horizontal east-west diameter of the eddy or the axis becomes parallel to the axis of the earth. In either position the plane of rotation of the eddy is tilted, and the outline of the eddy becomes elliptical.

The ideal shape of a processing eddy is an ellipse whose shorter diameter, 6, divided by its longer diameter, c, equals the cosine of the latitude, <f>. The direction of elongation extends northwestward in the Northern Hemisphere and northeastward in the Southern Hemisphere at such a bearing from the north (a) that cot a= cos <f>. The ideal proportions of a fixed eddy are & : a==sin <f>; the direction of elongation is N. 45° W. in the Northern Hemisphere and N. 45° E. in the Southern.

A sand bar, Halfmoon Island, partly surrounding a tidal eddy in Chesapeake Bay has the proportions and orientation of the ideal processing eddy. Other bars of similar shape are more or less filled with salt marshes like the fresh-water bogs called the Carolina bays. The Carolina bays have the proportions and orientation approximating those of the ideal fixed eddy. They occur at various altitudes within the tidal ranges of several marine terraces. The most symmetrical of the Carolina bays are interpreted as the sites of former tidal eddies.

Cote, M. M. and C. Burns (2002). The oriented lakes of Tuktoyaktuk Peninsula, Western Canada: A GIS based analysis. Permafrost and Periglacial Processes. **13** 61-70.

Abstract: The orientation, size and shape of 578 lakes on Tuktoyaktuk Peninsula were obtained from 1 : 250 000 Canadian National Topographic Survey map sheets, using ArcView geographic information system. These lakes are outside the glacial limits in a tundra plain with <15 in relief. The lakes range from 20 to 1900 ha, and have mean orientation N07 °E, with standard error 1.6". The maps show 145 former lake basins, with lakes inset in 130 of these. The mean orientations of the basins and inset lakes are not statistically different from each other or the general population. Several theories have been proposed for the origin of the oriented lakes, and one theory attributes the orientation to cross winds establishing currents that preferentially erode the ends of the lakes. Data from Tuktoyaktuk and Nicholson for 1970-95 indicate a consistent wind regime within the region, with prevailing winds from the east and west. Using data from Nicholson, a geometric model generates resultant lake orientations ofN if all winds are considered, and N08 °E if winds above 30 km 1-T1 are used. The coincidence of the modelled orientation and lake statistics supports the efficacy of cross wind-induced effects in orienting the lakes. The similar orientation of existing lakes and former basins suggests that these processes have been effective for at least several centuries.

Czudek, T. and J. Demek (1970). Thermokarst in Siberia and its influence on the development of lowland relief. <u>Quat. Res.</u> **1** 103-120.
Abstract: "Thermokarst" as a process is the melting of ground ice and the consequent formation of depressions. Thermokarst landforms depend on the tectonic regime of a region, the ground ice content, and the degree to which the permafrost equilibrium is disturbed. Thermokarst forms are especially prominent in the lowlands of the subnival region with permafrost. The authors distinguish two modes of thermokarst development-permafrost back-wearing and down-wearing-based on their investigations in Siberia. The first mode is characteristic of a more dissected relief. In this case permafrost back-wearing takes place and the process is characterized by development of gullies, thermocirques, and parallel retreat of steep walls with ice veins, resulting in a lower lowland level. The second mode of thermokarst development is due to permafrost melting from above and is typical of a flat undissected relief, mainly that of water-shed regions. Characteristic forms are depressions with steep slopes and flat floors (alases). Thermokarst valleys develop through coalescence of alases. Thermokarst processes destroy the lowland relief of large areas and create characteristic forms resulting in a lower lowland level. Thus thermokarst represents a special type of low-land development in permafrost conditions.

Ellis, C. R., J. G. Champlin and H. G. Stefan (1997). Density current intrusions in an ice-covered urban lake. <u>Limnology and Oceanography</u>. **36** 324-335.
Abstract: Evidence is presented that snowmelt runoff from an urban watershed can produce density current intrusions (under-flows) in a lake. Several episodes of density current intrusions are documented. Water temperatures and salinities measured near the bottom of a 10 m deep Minneapolis lake during the late winter warming periods in 1989, 1990, 1991, and 1995 show significant rapid changes which are correlated with observed higher air tem-peratures and snowmelt runoff. The snowmelt runoff entering this particular lake (Ryan Lake) has increased electrical conductivity, salinity, and density. The source of the salinity is the salt spread on urban streets in the winter. Heating of littoral waters in spring may also contribute to the occurrence of the sinking flows, but is clearly not the only cause.

Ellis, C. R. and H. G. Stefan (1989). Oxygen demand in ice-covered lakes as it pertains to winter aeration. <u>American Water Resources Association</u>. **33** 1363-1374.
Abstract: Winterkill, the death of fish under ice due to oxygen de-ficiency, threatens hundreds of shallow lakes in the upper Midwest of the United States every winter. For decades, attempts have been made to prevent winterkill, usually through aeration, with mixed re-sults. In large part, the failure of strategies to prevent winterkill can be linked to

a lack of understanding of winter limnology and in par-ticular, of oxygen dynamics under ice.
Most winterkill lakes behave as closed systems with regard to oxygen. Consequently, the oxygen content of an ice and snow covered lake is essentially a function of the amount of initial storage and the rate of depletion. Should the stored oxygen be insufficient to prevent near anoxia before melting of the ice cover occurs, winterkill will result.
Most oxygen consumption in ice covered lakes is due to bacterial respiration and chemical oxidation at the sediment/water interface, the remainder occurring in the water column. Oxygen consumption (and thus depletion) is a function of the velocity and oxygen concen-tration of the near sediment water. This is due to the fact that oxygen transport to the sediment is mediated by a diffusive boundary layer adjacent to the sediment surface. Winter oxygen depletion rates de-cease when the oxygen concentration of the overlying water falls be-low about 3 mg/1. Aeration techniques which increase the oxygen concentration and velocity of the near-sediment water also increase the oxygen consumption (depletion) rate.

Ellis, C. R., H. G. Stefan and R. Gu (1991). Water temperature dynamics and heat transfer beneath the ice cover of a lake. Limnology and Oceanography. **36** 324-335.
Abstract: Water temperature profiles were measured every 2 min in a small and shallow urban Minnesota lake from 8 February 1989 until ice-out on 11 April. The temperature record showed two distinct segments. Before 24 March, the temperature profile remained relatively constant, but later (when air temperatures were mostly above freezing) temperatures were dynamic and rose.
During the quiescent period, the upper 3 m of the water column cooled slowly while the lower water remained virtually isothermal. The calculated thermal diffusion coefficient approached molecular thermal diffusivity near the ice cover and was roughly 3 times molecular diffusivity through much of the region of the thermocline (the upper 2 m). The average computed heat flux through the ice (50-55 cm thick) and snow (I0-30 cm deep) cover during this period was 2.8 W m-2.
With the onset of above-freezing air temperatures, temperatures began to change rapidly. Observed intrusions of warm water were most likely the results of advected inflows of warm water from the periphery of the lake.

Everett, K., G. M. Marion and D. Kane (1989). Seasonal geochemistry of an arctic tundra drainage basin. Holarctic ecology. **12** 279-289.
Abstract: The snow melt food at Imnavait Creek takes place sometime between 12 May and 2 June and constitutes the single most important hydrological and geochemical event. Three years of study indicate this event spans 7 to 10 days and that peak discharge can be expected to be between 0.6 and 0.9 cu. mes. Ion concentrations peak during the first 15 of the event while pH is at a minimum. In all cases, ion concentrations in the spring runoff are 4 to 9 times those of the snow pack. Precipitaion, including dryfall. contributes significant amounts of Ca. Mg. K. Na, Cl and SOi. Postassium is present in surface waters only during melt-off and for a short time after. Calcium, Mg, suspended solids and electrical conductivity all reach broad, poorly defined peaks in mid-summer. Only pH shows a significant relationship to discharge. On a seasonal basis a substantial charge imbalance favoring cations occurs. It seems probable that the, as yet, unmeasured

negative charge is associated with organic amons . No seasonal trends were recorded for Mg. K or Mn in subsurface flow in the surrounding slopes. Calcium. Fe and Al showed a late season peak. and the concen-tration of Na and Si decreased as the melt season progressed.

Frohn, W. Eisner, K. Hinkel and Arellana-Neri (2001). Neural net classification of thaw lake basins on the coastal plain of northern Alaska. IEEE Proceedings of the IGRSS2001. Sidney, Australia.
Abstract: Drained thaw lake basins on the North Slope of Alaska are characterized by subtle changes in topography, pattern, texture, and vegetation. These basins become sites for the accumulation of organic carbon as peat deposits. Drained lake basins are distributed along an age continuum as defined by the degree of vegetation succession and geomorphic development since lake drainage. We are using Landsat-7 data to map these basins and classify them into relative age groups. Textural and spectral data transforms were utilized with pattern recognition algorithms to enhance features of the basins associated with age. A neural network classification scheme is being developed based on information from this study to classify basins into one of 4 relative age groups: young (recently drained); medium; old; and ancient. Young basins are characterized by highly productive grasses (Arctophila fulva and Dupontia fisheri} and sedges and exhibit a unique spectral signature. Medium basins are characterized by fewer grasses and more sedges and generally less vigorous vegetation, a slightly coarser texture, and generally drier soils than those of young basins. Old basins are characterized by well-developed polygon networks and dominated by Carex aquatslis^ which has a variable spectral response based on the amount of standing water throughout the basin. Ancient basins are also dominated by Carex aquatilis but have a unique texture and pattern and are characterized by a significant amount of ponding. The relative age and classification of these basins will be tested against surface and core samples to determine more accurately their approximate age.

Gibson, J. J. E., T. W. D. (2002). Regional water balance trends and evaporation-transpiration partitioning from a stable isotope survey of lakes in northern Canada. Global Biogeochemical Cycles. **16** 14.
Abstract: Regional variations in evaporation losses and water budget are interpreted from systematic isotopic patterns in surface waters across a 275,000 km2 region of northern Canada. Differential heavy isotope enrichment in a set of >255 nonheadwater lakes sampled by floatplane during 1993 and 1994 is strongly correlated to varying hvdrochromatic conditions across the region. Calculated catchment-weighted evaporation losses typically range from ~10- 15 in tundra areas draining into the Arctic Ocean to as high as 60% in forested subarctic areas draining to the Mackenzie River via Great Bear or Great Slave Lakes. Because of the diversity in drainage order and the ratio of catchment to surface area lakes in the region may inherit as little as 30% to as much as 99% of their isolopic enrichment signal from upstream water bodies. Open-water evaporation linearly decreases with increasing latitude and accounts for 5-50% of total evapotranspiration. Coupling of meteorological and isotopic data permits a novel assessment of regional evaporation-transpiration flux partitioning in the three major ecoclimatic zones (high-boreal forest, subarctic forest-tundra, and low-arctic shrub tundra), while the differing

frequency distributions of lake water balance in these zones provides a new index of landscape-scale hydroclimatology that may have significant potential for investigating ongoing (or past) changes in response to high-latitude climate change.

Greeneridge Sciences, I. (2000). Vibrator sounds in a frozen arctic lake during a winter seismic survey. Santa Barbara, CA, Prepared for Western Geophysical by Greeneridge Sciences, Inc. 16 pages.

Gu, R. and H. G. Stefan (1993). Validation of cold climate lake temperature simulation. Cold Regions Science Technology. **22** 99-104.
Abstract: A detailed set of water temperature profiles, ice thicknesses, snow depths, and weather parameters collected on an urban Minnesota lake is reported and compared to simulations with a one-dimensional, unsteady heat transfer model.

Haley, B. and D. Funk (2003). Prudhoe Bay lake surveys July 2002 and April 2003. Anchorage, Alaska, Prepared for BP Exploration, AK, by LGL Alaska Research Associates, Inc 70 pages plus appendices.

Hargrave, B. T. (1969). Similarity of oxygen uptake by benthic communities. Limnolog. Oceanogr. **14** 801-805.
Abstract: The rate of consumption of dissolved oxygen from overlying water by undisturbed sediments is a rapid and sensitive index of benthic community metabolism. In sediments covered with well-aerated water, reducing substances in the surface layers are rapidly oxidized; oxygen is also consumed by the organisms within the benthic community. Oxygen consumption by a benthic community is the net result of these two processes. Many studies of benthic oxygen uptake have been carried out with different types of aquatic sedi-ments using a variety of techniques, and the importance of various factors affecting oxygen consumption by undisturbed sedi-ments has been considered (Edwards and Rolley 1965). Although previous workers have noted the importance of temperature to oxygen uptake in individual benthic communities (Edwards and Rolley 1965; Carey 1967; Pamatmat 1968), the wide-spread importance of this factor has not been recognized. Despite the variety of environments considered, the logarithm of sediment oxygen uptake is significantly correlated with the logarithm of tempera-ture (Fig. 1). Only measurements on sedi-ment covered with water in short-term (1-3 hr) experiments are included in the regression calculation.

Harry, D. G. F., H.M. (1983). The orientation and evolution of thaw lakes, southwest Banks Island, Canadian Arctic. Proceedings of the Fourth International Conference on Permafrost, July 17-22, 1983. Fairbanks, AK, National Academy Press 456-461.
Abstract: On southwest Banks Island, the melt-out of ice within unconsolidated permafrost sediments has resulted in the formation of numerous thaw lakes. A majority of basins are oriented perpendicular to prevailing winds and possess a D-shaped outline which is in equilibrium with wind-generated geomorphic processes. In particular, a strong relationship exists between lake morphology and the storm wind regime during the summer period of open water conditions. Thaw lakes in this area cannot be interpreted within the traditional thaw lake cycle and appear to represent quasi-equilibrium

landforms. Shoreline erosion results in asymmetrical expansion rather than a lateral migration of the basin. Lake drainage occurs primarily by catastrophic outflow, following basin capture or truncation by coastal retreat (Author)

Hennenman, H. E. and H. G. Stefan (1999). Albedo models for snow and ice on a freshwater lake. Cold Regions Science Technology. **765**.
Abstract: Snow and ice albedo measurements were taken over a freshwater lake in Minnesota for three months during the winter of 1996-1997 for use in a winter lake water quality model. The mean albedo of new snow was measured as 0.83 + 0.028, while the mean ice albedo was measured as 0.38 ± 0.033. The period from December 17, 1996 to February 17, 1997, was marked as the nonmelt, or high albedo, season when albedo decayed at an average rate of 0.02 per day. The melting, or rapid albedo decay, season began on February 18 and continued until the end of the study on March 21. During the melt season the albedo decay rate varied from 0.10 to 0.20 per day. Two albedo models were developed for the entire winter season; they use separate equations for the nonmelt and melt periods. The input data for both models are climatic data. The first model requires daily incident solar radiation, air temperature, and snowfall data as input, while the second model requires daily air temperature and snowfall data only. The models predict albedo with modeling efficiencies of 0.94 and 0.89 for the entire three month period, respectively. The mean absolute error between values observed on the lake surface and values predicted by the model was 0.023 for the first model and 0.029 for the second model. Albedo predictions made by three albedo models given in the literature were also compared to the observed lake surface data. The two models developed herein predicted albedo better than the three existing surface albedo models because they were calibrated to the observed lake surface data. Albedo predictions from both new models and the three existing models were also compared to 11 years of observed surface albedo data collected over land. (No other lake surface observations were available.) The new models reasonably predicted albedo during those winters when the total snowfall depth was greater than 60 cm. The new model predictions for the land data were as good, if not better, than those by the three existing models.

Heron, R. and M. Woo (1994). Decay of a high Arctic lake-ice cover: observations and modelling. Journal of Glaciology. **40** 283-292.
Abstract: The decay of a lake-ice cover In the Canadian High Arctic was studied for 2 years. Melt at the upper surface accounted for 75 of the decrease in ice thickness, while 25 occurred at the ice-water interface. An energy-balance model, incorporating density reduction due to internal ice melt, was used to simulate the decay of the ice cover. The overall performance of the model was satisfactory despite periods when computed results differed from the observed ice decay. Energy-balance calculations indicated that the absorption of shortwave radiation within the ice provided 52% of the melt energy while 33 and 15% came from the surface-energy balance and heat flux from the water.

Hershey, A., G. Gettel, M. McDonald, M. Miller, H. Mooers, W. J. O'Brien, J. Pastor, C. Richards and J. Schuldt (1999). A geomorphic-trophic model for landscape control of Arctic food webs. BioScience. **49** 887-897.
Abstract: No abstract

Hill, H. (1967). A note on temperature and water conditions beneath lake ice in spring. Limnology and Oceanography. **12** 550-552.
Abstract: No abstract

Hinkel, K., W. Eisner, J. Bockheim, F. Nelson, K. M. Peterson and X. Dai (2003). Spatial extent, age, and carbon stocks in drained thaw lake basins on the Barrow Peninsula, Alaska. Arctic, Antarctic and Alpine Research. **35** 291-300.
Abstract: Thaw lakes and drained thaw lake basins are ubiquitous on the Arctic Coastal Plain of Alaska. Basins are wet depositional environments, ideally suited for the accumulation and preservation of organic material. Much of this soil organic carbon (SOC) is currently sequestered in the near-surface permafrost but, under a warming scenario, could become mobilized. The relative age of 77 basins on the Barrow Peninsula was estimated using the degree of plant community succession and verified by radiocarbon-dating material col-lected from the base of the organic layer in 21 basins. Using Landsat-7+ imagery of the region, a neural network classifying algorithm was developed from basin age-dependent spectra and texture. About 22 of the region is covered by 592 lakes (> 1 ha), and at least 50 of the land surface is covered by 558 drained lake basins. Analysis of cores collected from basins indicates that (1) organic layer thickness and the degree of organic matter decomposition generally increases with basin age, and (2) SOC in the surface organic layer tends to increase with basin age, but the relation for the upper 100 cm of soil becomes obscured due to cryoturbation, organic matter decomposition, and processes leading to ice enrichment in the upper permafrost.

Hinkel, K. M., J. A. Doolittle, J. G. Bockheim, F. E. Nelson, R. Paetzold, J. M. Kimble and R. Travis (2001). Detection of subsurface permafrost features with ground penetrating radar, Barrow, Alaska. Permafrost and Periglacial Processes. **12** 179-190.
Abstract: A ground-penetrating radar (GPR) survey was conducted in May 1999 on the 1 km2 Circumpolar Active Layer Monitoring (CALM) grid 5 km east of Barrow, Alaska. Spatially continuous measurements were collected along established transects while the active layer remained frozen. The primary objectives were to determine the 'long-term' position of the permafrost table, to recognize ice wedges and ice lenses, and to locate the organic-mineral soil interface. GPR signal and core collection were performed in tandem to verify signal interpretation, to calibrate the instrument, and to determine optimal GPR data-collection parameters. Two-way travel times from the antenna to subsurface reflectors were compared with measured depths obtained from soil cores to estimate an average pulse propagation velocity of 0.13 m/ns through the frozen soil. The most conspicuous subsurface reflectors were ice wedges, which gave high-amplitude hyperbolic reflections. Owing to its higher ice content, the approximate long-term position of the permafrost table could be traced laterally across the profile. Radar interpretations were obscured by the effects of cryoturbation, and because some horizons lack sufficient contrast in electrical properties. Highly detailed information can be obtained by collecting radar data at relatively slow speeds of advance, by using faster scanning rates (>32 scans/s), and by employing high-frequency antennas (>400 MHz).

Hinkel, K. M., F. E. Nelson, Y. Shur, J. Brown and K. R. Everett (1996). Temporal changes in moisture content of the active layer and near-surface permafrost at Barrow, Alaska: 1962-1994. Arctic and Alpine Research. **28** 300-310.
Abstract: Cores were extracted from frozen ground along a transect near Barrow, Alaska in spring 1963, and resampled within 0.5 m of the original boreholes in November 1993 and again in May 1994. Cores were cut into 5-cm segments and moisture content determined using standard techniques. The near-surface permafrost appears, on average, to have undergone ice enrichment from 1963 to 1993 since the mean volumetric water increased from about 57 to 62 over this 30-yr period. Comparison of the 1993 and 1994 data sets indicate slight depletion (3) of moisture during winter in the paired samples extracted from the permafrost and the active layer. Although the results indicate winter desiccation and long-term (30-yr) net moisture gain in the upper permafrost, some evidence suggests that these patterns reflect the effects of spatial heterogeneity across short (<0.5 m) lateral distances.

Hinzman, L., D. Goering and D. Kane (1998). A distributed thermal model for calculating soil temperature profiles and depth of thaw in permafrost regions. Journal of Geophysical Research. **103** 28975-28991.
Abstract: A spatially distributed thermal model has been developed that simulates thermal processes at the surface of the tundra, within the active layer, and in the underlying permafrost. This model was developed and applied to simulate processes on the Kuparuk River watershed on the North Slope of Alaska. Gridded meteorological data came from seven stations. Meteorologic data to calculate the surface energy balance at each of the nodes were distributed across the watershed using kriging. The kriged air temperature was also adjusted to account for elevation differences using the dry or wet adiabatic lapse rate as appropriate, and incident shortwave radiation was adjusted to consider slope effects. The equations describing the thermal processes of the surface energy balance were solved simultaneously for the surface temperature. This calculated surface temperature was then used in the subsurface finite element formulation to calculate the temperature profile and depth of thaw in the soil. Thermal properties of the soil were estimated spatially on the basis of measurements collected in typical landform vegetation units and then distributed on the basis of a vegetation map. Performance of the model was judged on the basis of comparison to measurements of soil temperatures and thaw depths. The model performs quite well in areas where subsurface thermal properties are well known. The model explains greater than 80 of variance at the surface when comparing predicted subsurface temperatures versus measured soil temperatures, and it increases in performance at greater depths. The model explains 82 of variance when comparing predicted thaw depths versus thaw depths measured over 1 km2 grids.

Hinzman, L., D. Goering, S. Li and T. Kinnery (1997). Numeric simulation of thermokarst formation during disturbance. Disturbance and recovery in Arctic lands: an ecological perspective. R. Crawford. The Netherlands, Kluwer Academic Publishers.
Abstract: Introduction. Thermokarst topography forms whenever ice-rich permafrost thaws, either naturally or anthropogenically, and the ground surface subsides into the resulting voids. The important and dynamic processes involved in thermokarsting include thawing ponding, drainage, surface subsidence and related erosion. These processes are

capable of rapid and extensive modification of the landscape and preventing or controlling anthropogenic thermokarst is a major challenge for northern development. This chapter presents an investigation of the physical factors which influence thermokarst formation, beginning with a field investigation of environmental factors affecting active layer thermal processes and concluding with numerical simulations of active layer dynamics. This research demonstrates that depth of thaw is greatly influenced by many local factors, especially site hydrology.

Hinzman, L. and D. Kane (1992). Potential response of an arctic watershed during a period of global warming. Journal of Geophysical Research. **97** 2811-2820.
Abstract: Climatic warming presents an imposing problem to scientists everywhere. Its effect in the Arctic is accentuated for several reasons. The temperature increase is expected to be greatest in the higher latitudes and the ramifications of this warming may be more crucial there due to the melting of permafrost. Precipitation changes will likely accompany climatic warming in the Arctic, compounding the effect of a temperature increase. The interaction of changing hydrologic and thermal processes presents a complex problem which would be difficult if not impossible to analyze without the use of detailed computer modeling. To analyze the thermal impact of climatic warming on a permafrost environment, TDHC, a heat conduction model which incorporates phase change, was used. Then the response of the active layer to climatic wanning was incorporated into HBV, a hydrologic model, to elucidate the effects on the hydrologic regime. Several scenarios of climatic warming have been examined to determine the impact on the active layer depth, but only results of 4°C wanning at a typical arctic site will be presented here. In the case of 4°C warming, three scenarios of precipitation were studied: no change, +15, and -15. The most obvious and perhaps significant response to climatic wanning was an increase in active layer depth. Other changes worth noting were warming of the entire soil profile, increased soil moisture storage, increased evaporation, and variable response in runoff, depending upon the scenario. Evaporation now vies with mnoff as the primary loss of moisture from the watershed. If evaporation increases due to a wanner climate, the entire character of arctic hydrology could change, depending on changes in precipitation.

Hinzman, L., D. Kane and R. Gieck (1990). Regional snow ablation in the Alaskan Arctic. Northern Hydrology Symposium. P. a. Ommanney. Saskatoon, Saskatchewan 121-139.
Abstract: The rates of snowpack ablation were monitored at three sites in northern Alaska for four years in a transect from the Brooks Range north to the Arctic Coastal Plain. These data were analysed along with meteorological data collected at each site. The initiation of ablation was site specific being largely controlled hy the complementary addition of energy from radiation and sensihie-heat flux. Although the research sites were only / /5 km apart, the rates and mechanisms of snowmelt varied greatly. Snowmelt begins at the mid-elevations in the foothills and progresses northwards toward the coast and southwards up into the mountains. In the more southerly sites. snowpack ablation progressed much faster when compared to the northerly site. The southerly sites are much more influenced by sensible heat advected from areas south of the Brooks Range. A comparison of the measured energy balances reflected the increasing importance of net radiation in the more northerly site. Many possible reasons exist to explain regional

differences in certain climatic parameters such as long-wave or short-wave radiation. The purpose of this paper is not to fully explain the climatic variability but rather, from a limited data base. to explore trends and examine differences.

Hinzman, L., D. Kane, R. Gieck and K. Everett (1991). Hydrological and thermal properties of the active layer in the Alaskan Arctic. Cold Regions Science and Technology. **19** 95-110.
Abstract: Almost all biological activity in far north regions takes place within a shallow zone above the permafrost called the active layer. The active layer is the surficial layer of the soil system which thaws every summer. In Imnavait watershed, a small headwater watershed north of the Brooks Range on the North Slope of Alaska, the active layer is an extremely variable multilayered system consisting of a mat of mosses and sedges on about 10 cm of organic soil over silt. The layer of organic soil tends to mollify thermal and hydrologic fluctuations below it. The thermal conductivity of the surface organic layer at average moisture contents is about one-third that of the silt and thus functions as a layer of insulation for the permafrost. Before spring melt or after a period of low precipitation, the organic mat is desiccated and will absorb 1.5 cm of water before downslope runoff occurs. The hydraulic conductivity of the organic soils is 10 to 1000 times greater than the silt, thus during a large rainfall event, downslope movement will primarily occur in the organic layer. The subsurface mineral soil tends to remain saturated with little annual variation and shows little response to precipitation events. In comparison, the moisture content of surficial organic soil fluctuates between 10 and 90 by volume. To adequately model physical processes, we need a detailed understanding of the thermal and hydrologic properties because these properties vary so dramatically over short vertical distances.

Hinzman, L., M. Nolan, D. Kane, C. Benson, M. Sturm, G. Liston, J. McNamara, A. Carr and D. Yang (2000). Estimating snowpack distribution over a large arctic watershed. Water resources in extreme environments. D. Kane. Anchorage, AK, AWRA 13-18.
Abstract: Extensive snowpack surveys were conducted throughout the 8140 km2 Kuparuk River basin on the North Slope of Alaska every spring prior to initiation of melt from 1993 through 1999 for the purpose of quantifying the water equivalent of the snowpack and its spatial distribution. The watershed includes a wide variety of terrain types, from mountainous headwaters in the south, to glaciated foothills in the central watershed to coastal plain in the north (McNamara et al., 1998). The vegetation is primarily tussock tundra with smaller proportions of riparian shrubs along drainages. The end-of-winter snowpack distribution is primarily controlled by the dominant wind direction, topography, vegetation and the cumulative precipitation. We numerically characterized generalizations of these processes and incorporated them into a model that generates end-of-winter snow water equivalent distribution maps for the entire Kuparuk watershed for 1994-1997. We present a simple method here for extrapolating a minimal amount of field data to a large area. This method does not require any meteorological data throughout the winter, and so could be applied to any area that has end-of-winter measurements. These measurements and modeling studies reveal interesting characteristics of the Kuparuk Watershed snowpack distribution.

Hinzman, L.D., D.W. Robinson, and D.L. Kane. A Biogeochemical Survey of an Arctic Coastal Wetland. Seventh International Conference on Permafrost. Yellowknife, Canada. June 1998. Pp. 459-464.

Hinzman, L., M. Wegner and M. Lilly (2000). Hydrological investigations of groundwater and surface-water interactions in sub-arctic Alaska. <u>Nordic Hydrology</u>. **31** 339-356.
Abstract: Dynamic interactions between rivers and adjacent aquifers can significantly affect near-bank geochemistry and processes associated with natural attenuation of contaminants by mixing water or introducing oxygen or nutrients. During 1997 and 1998 in a study near Fairbanks, Alaska U.S.A, the hydrologic condi-tions in the Chena River and in the adjacent groundwater were monitored. The river stage, groundwater elevations, and the water chemistry and temperature in both river and groundwater were measured. In the spring of 1997, the ground-water gradient close to the Chena River reversed causing surface water to enter the aquifer. Changes in temperature, specific conductance and alkalinity were used to determine the extent of bank recharge. For approximately one week dur-ing spring snowmelt of 1997, surface-water influx from the Chena River occurred approximately between the depths of 5.33 m and 9.1 m below ground surface. The effects of bank recharge extended at least 6.1 m but not to 30.5 m from the banks of the Chena River into the aquifer. Bank recharge caused 64 to 68 per cent of the groundwater, 6.1 m from the bank at a depth of 6.78 m to be displaced by surface water influx. Peak flows during 1998 were not high enough to cause flow reversals.

Hinzman, L., G. Wendler, R. Gieck and D. Kane (1992). Snowmelt at a small Alaskan Arctic watershed, 1. Energy related processes. <u>9th International Northern Research Basins Symposium</u>. O. Prowse, and Ulmer. Canada 171- 197.
Abstract: Snowmelt has been monitored over a six year period at Imnavait Creek watershed in Northern Alaska. Energy for snowmelt is a combination of sensible and net radiation. Because of a characteristically light snowpack and the fact that the ablation occurs so close to the solstice, the melt period only lasts about 7 to 10 days. West-facing slopes constitute approximately 78 of the drainage area versus 17 for the east-facing slope, the valley bottom making up the remainder. The snowmelt period is annually the most dynamic hydrologic event in this arctic watershed with a rapid transition from a situation of a daily negative energy balance to a positive one. The surface energy budget for this watershed was calculated for the snowmelt periods from 1987-1992. A large change is observed in the albedo, which dropped from the high 70's in early May to less than 20 in June after ablation. This change affects the radiation budget, which becomes strongly positive after ablation. The direct shortwave radiation was adjusted to consider the effect of topography (slope and aspect). One reason for the higher rates of snowmelt on west-facing slopes is shown to be due to the complementary effects of greater radiation on that slope during the hours of warmest temperatures.

Hobbie, J. (1980). Limnology of tundra ponds. Stroudsberg, PA, Dowden, Hutchinson and Ross.
Abstract: This is not the abstract, but a quote pulled from the first chapter which makes a concise overview of Arctic lakes:
1. Arctic lakes and ponds seldom warm above 10°C and almost never stratify.
2. Arctic lakes and ponds shallower than 1.7 to 2.0 m usually freeze completely.

3. Ponds and lakes less than 2 m in depth do not contain fish. One consequence of the lack of predation is that the zooplanktonic crustaceans are almost all large species in ponds and shallow lakes.
4. The ice cover is 1 to 2 m thick and lasts for 8 or 9 months.
5. Arctic lakes and ponds usually contain low amounts of available nutrients and low total dissolved salts. However, as in the temperate regions, the total inorganic ion concentration is dif-ferent for drainage basins in different types of bedrock.
6. Oxygen is usually present in saturation concentrations in open waters but becomes depleted to some extent near the end of the under-ice period. In shallow lakes the exclusion of oxygen during the freezing of the ice may result in super-saturation (200).
7. The biota of shallow freshwater lakes and of ponds are subjected to strong physiological stresses as the ions may be concentrated 30-fold during freeze-up, while the water immediately after the spring melt may resemble distilled water.
8. Only nannoplankton are found in arctic lakes and ponds. These usually bloom beneath the springtime ice of lakes but total primary production is low and lakes and ponds are oligotrophic.
9. With a few exceptions, each species of zooplankton has a dor-mant phase in its life cycle.
10. Fish are very slow-growing, but large fish may live for 40 years.
11. There are no benthic animals that graze on aquatic plants or that shred large organic particles or leaves.
12. The number of animal species is small and some groups-for example, sponges, Notonectidae, Corixidae, Gyrinidae, Dytisci-dae, and Amphibia-are rare or not present.
13. Decomposition rates are slow and large amounts of energy and nutrients are tied up in dead organic matter.

Hobbie, J. (1984). Polar Limnology, In: F. Taub (ed.), Lakes and Reservoirs. Elsevier, Amsterdam.In: F. Taub (ed.), Lakes and Reservoirs. Elsevier, Amsterdam. 63-105.
Abstract: No abstract, this is the Introduction:
The Antarctic region is easily defined as the Antarctic continent and nearby islands. The Arctic region is more difficult to delineate, but can be defined as the northern tundra areas where the mean air temperature of the coldest month is below -3C and that of the warmest month is between 0 and 10 C (Safer, 1969). This region includes north-ern Alaska and Canada, Greenland, the northern Kringe of Scandinavia, Spitsbergen (Svalbard), and orthern U.S.S.R. It excludes the maritime tundra areas of Ireland, Scotland, and the Aleutians, and also the alpine subarctic regions of Scandinavia such as the well-studied Abisko area (68 N).
The inland waters of the polar regions are as diverse as temperate lakes and include very dilute and very salty lakes, hot springs, deep lakes and shallow ponds, rivers, and streams. They have two common features: ice is very important, and there is both continuous light during a part of the summer and continuous darkness during a part of the winter.

Hobbie, J. E., B. J. Peterson, N. Bettez, L. Deegan, W. J. O'Brian, G. W. Kling, G. W. Kipphut, W. B. Bowden and A. E. Hershey (1999). Impact of global change on the

biogeochemistry and ecology of an Arctic freshwater system. Polar Research. **18** 207-214.
Abstract: Lakes and streams in the foothills near Toolik Lake, Alaska, at 68 N have been studied since 1975 to predict physical, chemical and biological impacts of future global change. Experimental manipulations include whole lake and continuous stream fertilization as well as removal and addition of predators (copepods, lake trout, grayling, sculpin). Based on our evidence the following scenario is likely. Warming thaws the upper layers of permafrost and streams and lakes become enriched with phosphorus. Streams respond quickly with higher production of diatoms but animal grazers keep biomass changes to a minimum. Fish productivity also increases. If phosphorus levels are too high, mosses become the dominant primary producer and sequester all of the nutrients. Growth of Arctic grayling under the present conditions only occurs in summers with higher than average stream flow. The present population would be stressed by warmer temperatures. When higher phosphorus levels reach lakes and cause slight eutrophication, the number of trophic levels will increase, especially within the microbial food web. Wanner lake temperatures increase stratification and. combined with eutrophication, could decrease oxygen in the hypolimnion. Oxygen levels will also decrease in winter under the ice cover. Eventually this habitat change will eliminate the lake trout, a top predator. Removal of lake trout results in a striking increase in abundance and productivity of smaller fish, including small lake trout, and the emergence of burbot as an alternate top predator. Large species of zooplankton will become virtually extinct.

Hondzo, M. and H. G. Stefan (1993). Lake water temperature simulation model. Journal of Hydraulic Engineering ASCE. **119** 147-160.
Abstract: Functional relationships to describe surface wind mixing, vertical turbulent diffusion, convective heat transfer, and radiation penetration based on data from lakes in Minnesota have been developed. These relationships have been introduced by regressing model parameters found either by analysis of field data or by calibration (minimizing the difference between measured and predicted tem-peratures) in simulations on individual lakes, against gross lake properties such as surface area or Secchi depth. Results of the deterministic lake water temperature stratification model using the functional relationships are not much different than results using the individual calibrations on a great variety of lake surface areas depths, and transparencies. The model also requires no on-lake weather but uses input from existing off-lake weather stations. First order uncertainty analysis showed moderate sensitivity of simulated lake water temperatures to model coefficients. The numerical model which can be used without calibration has an average 1.1°C root mean square error, and 93 of measured lake water temperatures variability is explained by the numerical simulations, over wide ranges of lake morphometries, trophic levels, and meteorological conditions.

Hopkins, D. (1949). Thaw lakes and thaw sinks in the Imuruk Lake area, Seward Peninsula, Alaska. Journal of Geology. **57** 119-131.
Abstract: Certain lakes and depressions in the Imuruk Lake area, Alaska, are ascribed to subsidence following the thawing of perennially frozen ground. The frozen, silty soils of the region contain large quantities of clear ice, which in volume greatly exceed the

natural porosity of the unfrozen material. Melting of the clear ice results in surface subsidence; water accumulates in the resulting depressions.
Thaw lakes are described, and mechanisms of enlargement and eventual drainage are discussed. The origins of drained thaw lakes and of thaw sinks are compared.
Evidence is presented to show that the present climate in the Imuruk Lake area is sufficiently cold to form a small thickness of perennially frozen ground in previously unfrozen deposits but that the present large thickness of frozen ground probably is unstable under existing climatic conditions.

Hopkins, D. M. and J. G. Kidd (1988). Thaw lake sediments and sedimentary environments. 5th International Conference on Permafrost. Trondheim, NO, Tapir Publishers 790-795.
Abstract: The thaw-lake sediment sequence, seen in cross section, consists of (1) a basal, coarse, time-transgressive sequence consisting largely of sand and organic detritus, often cross-bedded, which accumulates near the migrating basin margin and (2) an overlving sequence of thin- and flat-bedded silt, peaty silt, or detrital peat which accumulates in the quiet water of the central basin. Thick accumulations of detritat peat representing lee-shore accumulations of organic detritus, appear at the margins of some thaw lake sediment sequences. Analyses of organic remains preserved in thaw-lake sediment suites can contribute to reconstruction of ancient vegetation mosaics.

Ishikawa, N., N. Sato, K. Kawauchi, K. Yoshikawa and L. Hinzman (2001). Characteristics of the water cycle in the discontinuous permafrost region in interior Alaska. Polar meteorol. glaciol. **15** 78-90.
Abstract: In order to better understand the water cycle in the discontinuous permafrost area, field observations of soil moisture content, groundwater table, dis-charge and evaporation have been carried out in the Caribou-Poker Creeks Research Watershed since 1997. This investigation aims to characterize the soil moisture and ground water dynamics of interior Alaska. Soil moisture content depends on topo-graphic factors, increasing toward the bottom of a slope. In the flood plain, soil moisture is higher in depressions than on mounds. The depth of the active layer is less than 1 m at the end of summer and unfrozen soil exists below the permafrost, as determined through geophysical exploration and drilling. The groundwater table reaches a maximum height in early October and decreases monotonically to reach a minimum in early April, then starts to increase after snowmelt. The ground water of a shallow well and soil moisture near the ground surface show variations, as influenced by precipitation and evaporation; however, a deeper well on the upper slope does not respond similarly. Evaporation occurs over the whole watershed during summer: however, directly over a stream condensation dominates because of low water temper-ature due to the permafrost underneath.

Jackson, M. B. and D. C. Lasenby (1982). A method for predicting winter oxygen profiles in ice-covered Ontario lakes. Canadian Journal of Fisheries and Aquatic Science. **39** 1267-1272.
Abstract: A simple method is presented for predicting oxygen profiles under ice cover in selected Ontario lakes. The oxygen loss rate within individual lake strata over winter can be predicted from the oxygen concentration in each stratum about 5-15d after freeze-up (at the time of maximum volume-weighted oxygen concentration for the lake). Shield

lakes and limestone transition lakes are described by two distinct relationships: the rate of oxygen loss per unit oxygen concentration is greater in the limestone-transition lakes.

Jeffries, M., K. Morris and G. Liston (1996). A method to determine lake depth and water availability on the North Slope of Alaska with spaceborne imaging radar and numerical ice growth modeling. Arctic. **49** 367-374.
Abstract: Spacebome synthetic aperture radar (SAR) images and numerical ice growth modelling were used to determine maximum water depth and water availability in two areas of the North Slope in northwestern Alaska. SAR images obtained between September 1991 and May 1992 were used to identify when and how many lakes froze completely to the bottom, and how many lakes did not freeze completely to the bottom. At Barrow, on the coast, 60 of the lakes froze completely to the bottom in mid-January alone, and by the end of winter 77 of the lakes were completely frozen. In contrast, 100 km to the south in the 'B' Lakes region, only 23 of the lakes froze completely, and there was no sudden freezing of many lakes as occurred at Barrow. A physically based, numerical model was used to simulate ice growth on the lakes. The simulated maximum ice thickness is 2.2 m. Consequently, any lake where some part of the ice cover does not freeze to the bottom has some water more than 2.2m deep. For those lakes where the ice cover had frozen completely at some time in the winter, the simulated ice growth curve provides the ice thickness at the time each lake had frozen completely to the bottom and thus the lake's maximum water depth. At Barrow, 60 of the lakes are between 1.4 m and 1.5 m deep, and 23 are more than 2.2 m deep. At the 'B' Lakes, 77 of the lakes are more than 2.2 m deep. Thus, there is a considerable contrast in lake depth and water availability between the Barrow and the 'B' Lakes regions. This method is simple to implement, and the relatively inexpensive SAR data have good spatial and temporal coverage. This method could be used to determine lake depth and water availability on the entire North Slope and in other polar and sub-polar areas where shallow lakes are common. Key words: Synthetic Aperture Radar, Alaskan North Slope, lake ice, lake depth, water availability.

Jeffries, M., K. Morris and W. Weeks (1994). Structural and stratigraphic features and ERS1 synthetic aperture radar backscatter characteristics of ice growing on shallow lakes in NW Alaska, winter 1991-1992. Journal of Geophysical Research. **99** 22459-22471.
Abstract: Changes in ERS 1 C band synthetic aperture radar (SAR) backscatter intensity (o°) from ice growing on shallow tundra lakes at three locations in NW Alaska are described. Ice core analysis shows that at all lakes on the coast at Barrow the ice, whether floating or frozen to the bottom, includes an inclusion-free layer overlying a layer of ice with tubular bubbles oriented parallel to the direction of growth. The clear ice may also be overlain by a discontinuous layer of bubbly snow ice. Backscatter is low (-16 to -22 dB) at the time of initial ice formation, probably due to the specular nature of the upper and lower ice surfaces causing the radar pulse to be reflected away from the radar. As the ice thickens during the autumn, backscatter rises steadily. Once the ice freezes to the lake bottom, regardless of the presence of forward scattering tubular bubbles, low backscatter values of-17 to -18 dB are caused by absorption of the radar signal in the lake bed. For ice that remains afloat all winter the ice-water interface and the tubular bubbles combine, presumably via an incoherent double-bounce mechanism, to cause maximum backscatter

values of the order of -6 to -7 dB. The 0° saturates at -6 to -7 dB before maximum ice thickness and tubular bubble content are attained. A simple ice growth model suggests that the layer of ice with tubular bubbles need be only a few centimeters thick midway through the growth season to cause maximum backscatter from floating ice. During the spring thaw a previously unreported backscatter reversal is observed on the floating and grounded portions of the coastal lakes but not on the lakes farther inland. This reversal may be related to the ice surface topography and wetness plus the effects of a longer, cooler melt period by the coast. Time series of backscatter variations from shallow tundra lakes are a record of (l) the development of tubular bubbles in the ice and, by association, changes in the gas content of the underlying water and (2) the freezing of ice to the bottoms of the lakes and therefore lake bathymetry and water availability. SAR is also able to detect the onset of lake ice growth in autumn and the initiation of the spring thaw and thus has potential for monitoring high-latitude lake ice growth and decay processes in relation to climate variability.

Jeffries, M., T. Zhang, K. Frey and N. Kozlenko (1999). Estimating late-winter heat flow to the atmosphere from the lake-dominated Alaskan North Slope. Journal of Glaciology. **45** 315-347.
Abstract: The conductive heat flux through the snow cover (Fa) is used as a proxy to examine the hypothesis that there is a signficant heat flow from the Alaskan North Slope to the atmosphere because of the large number of lakes in the region. Fa is estimated from measurements of snow depth, temperature and density on tundra, grounded ice and floating ice in mid-April 1997 at six lakes near Barrow, northwestern Alaska. The mean Fa values from tundra, grounded ice and floating ice are 1.5, 5.4 and 18.6 Wm-2, respectively. A numerical model of the coupled snow ice water soil system is used to simulate Fa and there is good agreement between the simulated and measured fluxes. The flux from the tundra is low because the soils have a relatvely low thermal conductivity and the active layer cools significantly after freezing completely the previous autumn. The flux from the floating ice is high because the ice has a relatively high thermal conductivity, and a body of relatively warm water remains below the growing ice at the end fof winter. The flux from the grounded ice is intermediate between that from the tunrdra and that from the floating ice, and depends on the timing of the contact betwen the growing ice and the lake sedments, and whether or not those sediment freeze completely. Using the estimated Fa value combined with the areal fractions of tundra, rounded ice and floating ice derived from synthetic aperture radar images, area-weighted Fa values are calculated for six areas, Fa value for the ice vary bewteen 9.3 and 13.8 Wm-2, and those from the ice plus tundra vary bewteen 3.8 and 5.3 Wm-2. The Fa values are similar to those observed in the sea ice covered regions of the south and north polar oceans in winter. The North Slope of Alaska may thus make a signficant contribution to the regional energy budget in winter.

Johnston, G. H. and R. J. Brown (1964). Some observations on permafrost distribution at a lake in the Mackenzie delta, NWT, Canada. Arctic. **17** 162-175.
Abstract: No abstract.

Johnston, G. H. and R. J. Brown (1966). Occurrence of permafrost at an Arctic lake. Nature. **21** 952-953.
Abstract: No abstract

Jorgensen, B. B. and N. P. Revsbech (1985). Diffusive Boundary Layers and the Oxygen Uptake of Sediments and Detritus. Limnolog. Oceanogr. **30** 111-122.
Abstract: The thickness of diffusive boundary layers and their role for the oxygen uptake of sediments and detritus were studied by the use of microelectrodes. Gradients of oxygen were always detectable within the boundary layer, which varied in thickness from 0.2 mm to >1 mm. The thickness depended on the flow velocity of the water and on the roughness of the solid surface. Oxygen diffused through the boundary layer with a mean diffusion time of 1.2-9 min. The diffusive boundary layer constituted a transfer resistance for oxygen flux across the solid-water interface which limited the oxygen flux at high uptake rates. Sediments or detritus exposed to aerated water could therefore be almost anoxic at the surface, provided that they had sufficiently high rates of oxygen uptake. This can explain the occurrence ofmicroaerophilic or anaerobic bacteria on exposed sediments where fully oxic conditions would intuitively have been expected.

Jorgensen, M., E. Pullman, Y. Shur, M. Smith, A. Stickney, J. Aldrich, S. Ray and H. Walker (1996). Geomorphology and hydrology of the Colville River Delta, Alaska, 1995. Fairbanks, AK, Prepared for Arco Alaska, Inc., and Kuukpik Unit Owners by ABR, Inc., Shannon&Wilson, Inc., and Louisiana State University.

Kaczorowski, R. (1977). The Carolina Bays and their relationship to modern oriented lakes, University of South Carolina.
Abstract: The origin of the Carolina Bays has been something of a geo-logical enigma since their existence in the Coastal Plain was first recognized in 1848. Theories that have been proposed for the origin of the "bays" are numerous and diverse. Surprisingly, however, most workers seem to have neglected the concept of uniformitarianism in their studies of these remarkable features; hence, few investigations have been designed to compare or contrast the Carolina Bays with modern analogues in Alaska, Chile, and Texas.

Investigations of oriented lakes and "bays" in these different geographic areas have shown that the processes that initially produced them apparently differ. However, absolutely no evidence has been encountered that would support an extraterrestrial origin. Incipient oriented lakes develop in topographic depressions created by coastal, fluvial. aeolian. solutioning, glacial, peri-glacial, and perhaps some tectonic processes. Infiltration is limited in these low areas by the existence of an impermeable unit whose geologic character varies among the areas investigated. In all cases, however, oriented lake development has occurred in unconsolidated sediments, easily transported by wave action.

Orientation is found to be a function of wind regime and is produced by surficial processes associated with wind activity and wave action. However, these processes are not necessarily related to initial lake formation. Once lakes have initially developed, opposing or uni-directional prevailing winds produce a wave climate that induces lake-shore erosion in zones perpendicular to wind direction where wave approach angles are high. Calculations show that for the average sized oriented lake (2 km x 1.25 km; depth = 2 m), wave energy flux is at a maximum in the lake "ends" (2.43 x 10 ergs/meter sec) and minimum (0.42 x 10 ergs/meter sec) near the nodal point where waves approach the beaches at a low angle (5°). Sediment transport rate calculations also show maximum transport rates in the "ends" and minimum rates near the no point.

Resultant lake morphology is a function of the degree to which the surficial processes remain active and effective throughout the year. Seasonal variations in wind regime, lake water levels, and temperature, along with secondary factors such as sediment character, have produced oriented lakes of a somewhat different character in each of the areas investigated. Observations, field measurements, and a model study sup-port the theory that the processes and geologic agents that were responsible for producing the Carolina Bays are terrestrial in nature and are currently producing or have produced similar features in other parts of the world.

Kane, D. (1997). The impact of hydrological perturbations on Arctic ecosystems induced by climate change. Global change and arctic terrestrial ecosystems. W. Oeschel, T. Callaghan, T. Gilmanov, J. Holten, B. Maxwell, U. Molau and B. Sveinbjornsson. New York, Springer-Verlag 63-81.
Abstract: No abstract

Kane, D., S. Bredthauer and J. Stein (1981). Subarctic snowmelt runoff generation. Proceedings of The Northern Community: A search for a quality environment, Seattle WA 1981. Seattle, WA, ASCE 591-601.
Abstract: Many of the floods of record in cold regions are produced bv snow ablation. Accurate prediction of flood magnitudes, using computer models, hinges on an understanding of the hydrologic role of frozen soils. One objective of this study was to examine how the moisture-content in the soil profile changes over the winter season and how this redistribution of moisture influences the infiltration of snow-melt in the spring. In general, soil moisture migrated towards cne freezing front from the warmer soils. This has the net effect: of increasing the moisture content near the surface of the mineral soil. With high ice contents, the infiltration rate is reduced and greater runoff produced. For the area studied, two extreme soil conditions exist. Ice-rich soils are found in conjunction with permafrost, while relatively well-drained soils exist in nonpermafrost areas. Our field studies indicated that little runoff was generated from nonpermafrosc areas although extensive seasonal frost existed. The measured runoff was therefore generated from permafrost areas of the watershed.

Kane, D., R. Gieck and L. Hinzman (1990). Evapotranspiration from a small Alaskan Arctic watershed. Nordic Hydrology. **21** 253-272.
Abstract: Evapotranspiration (ET) vies with runoff as the primary mechanism for water loss from a watershed underlain by permafrost, yet past attempts to predict ET have proven to be less than completely successful in the Arctic. Imnavait Creek, a small 2.2 km2 watershed underlain by continuous permafrost has been studied for 4 years. Evapotranspiration on a watershed scale has been calcu-lated from water balance studies. These results are compared with point mea-surements of pan evaporation and daily estimates of ET by the energy balance and Priestley-Taylor methods. Since it is difficult

to determine the daily change in soil moisture, the energy balance approach appears to be the best method to determine daily ET. The water balance approach is the best method to determine total ETover the course of the summer because it is possible to delete the soil moisture term due to an insignificant change annually in this watershed. Priestley-Taylor gave adequate estimates of ET with only limited data. After a pan coefficient is determined, the evaporation pan functions well over extended time periods but is less accurate for shorter periods. Evapotranspiration is greatest in early summer, immediately following the spring snowmelt, during the period of maximum incoming radiation but not necessarily maximum air or soil temperatures. The cumulative potential evaporation is greater than the cumulative summer precipitation. The source of moisture for ET in early summer is from snowmelt or moisture stored in the active layer.

Kane, D., R. Gieck and L. Hinzman (1997). Snowmelt modeling at small Alaskan Arctic watershed. Journal of Hydrological Engineering. **2** 204-210.
Abstract: ABSTRACT: The snowpack in the Alaskan Arctic can be described as light with the average annual snowpack varying between 5 cm and 20 cm of water in nonmountainous areas, and exposed to considerable wind redistribution during the winter. Melting of this snowpack occurs over a relatively short period of time (7 to 10 days) from early May to early June. Ablation has been monitored since 1985 in a small headwater drainage of the Kuparuk River. The results of the following three different models to predict snowmelt are presented: energy balance, degree day, and combined degree day-radiation. Performance of all of the models was very good, with the energy balance model predicting ablation the best. The models, particularly the temperature and temperature/ radiation index models, had some difficulty in predicting what happens when cold spells interrupt the melt. There is also some discrepancy at the end of the snowmelt period when large areas become snow-free.

Kane, D., L. Hinzman, J. McNamara, Z. Zhang and C. Benson (2000). An overview of a nested watershed study in Arctic Alaska. Nordic Hydrology. **31** 245-266.
Abstract: The hydrology of a nest of three watersheds has been studied since 1992 on the North Slope of Alaska, with some additional data collected at individual sites previously. Hydrologic studies of nested watersheds are rare in the circumpolar arctic. Presented here is a comparison of the variability of important runoff-re-lated processes from the headwater foothills to the low gradient, wetland domi-nated coastal area. Watersheds studied include Imnavait Creek, Upper Kuparuk River and finally the entire Kuparuk River. Also, runoff data from the low gra-dient Putuligayuk River, measured earlier (1970-1986), is included. Generally, rainfall constitutes 53 to 67 of the annual precipitation. Most runoff is gener-ated from the foothills; runoff is normally only generated from the coastal plain during snowmelt. Surface storage is an important process on the coastal plain where vertical processes (precipitation and evapotranspiration) are dominant during the summer. Continuous permafrost produces high soil moisture levels except where there are relatively steep slopes with gravity-induced drainage. Snowmelt results in a nearly saturated active layer with summer moisture levels closely allied with summer precipitation. High runoff ratios prevail during snowmelt and rainfall, except for the summer rainfall-generated runoff of the low gradient Putuligayuk River.

Kane, D., L. Hinzman, M.-k. Woo and K. Everett (1992). Arctic hydrology and climate change. Ecosystems in a Changing Climate. F. S. Chapin, Academic Press 35-57.
Abstract: No abstract

Kane, D., L. Hinzman, H. Yu and D. Goering (1996). The use of SAR satellite imagery to measure active layer moisture contents in Arctic Alaska. Nordic Hydrology. **27** 25-38.
Abstract: Synthetic aperture radar (SAR) has the potential for measuring near surface soil moisture contents for very large areas. The polar orbiting European Remote Sensing satellite (ERS-1) of the European Space Agency (ESA) has onboard an active C-band SAR sensor. We have analyzed SAR imagery over a small research watershed, Imnavait creek, located in the northern foothills of the Brooks Range in Alaska, U.S.A. This watershed is treeless and completely underlain with permafrost. Alter geometrically and radiometrically correcting each pixel (25 m by 25 m) in the image, corrected pixel values were correlated with corresponding field moisture contents measured along transects in the watershed tor two passes of the satellite. Coefficients of determination, r2, between the corrected pixel value and measured moisture content were 0.49 on June 12, 1993 and 0.53 on August 2, 1993; with the data sets combined the value was 0.50.

Kane, D., L. Hinzman and J. Zarling (1991). Thermal response of the active layer to climatic warming in a permafrost environment. Cold Regions Science and Technology. **19** 111-122.
Abstract: Global warming is occurring, the only question is what will be the magnitude of the temperature change and the temporal and spatial distribution? Existing models predict that the greatest change from present climatic conditions will happen in the polar regions. In the Arctic, continuous permafrost exists and climatic warming could have severe consequences. In this paper the consequences of global warming on the active layer are examined. Soil temperature data were collected over a four-year period at a field site near Toolik Lake, Alaska. A finite-element, two-dimensional, heat conduction model with phase change was used to predict soil temperatures at the site. After verification that the model could be used with confidence to predict the soil thermal regime, various climatic warming scenarios were used as inputs to estimate the thermal response for the next fifty years. The impact of climatic warming on the thickness of the active layer is reported.

Kane, D. and C. Slaughter (1973). Recharge of a central Alaska lake by subpermafrost groundwater. Proceeding of the 2nd International Conference on Permafrost. T. Pewe and R. Mackay. Yakutsk, Russia 458-462.
Abstract: No abstract, this is the Introduction: Information on groundwater flow systems in permafrost-dominated environments is quite sparse. Review of the available literature as summarized by Williams10'11 indicates a dearth of quantitative data on permafrost-groundwater relationships, particularly in Alaska. Brandon1 reports that the lack of subsurface data on permafrost has hindered the understanding of groundwater flow in permafrost environ-ments. Groundwater flow systems may be simply considered as comprising three components: recharge area, transmission zone, and discharge area. Typically, topographic highs con-stitute recharge areas, and low sites are discharge areas. Characteristics of the transmission zone, the area between recharge and discharge points,

are largely determined by topography and geology.In permafrost settings, all three components (recharge. transmission, and discharge zones) can be affected by pres-ence of local or regional areas of frozen ground. Permafrost in the recharge area can act as a barrier to downward water movement, thus restricting aquifer recharge. The presence of permafrost can affect groundwater movement in the transmission zone. For suprapermafrost groundwater, the permafrost forms an impermeable base; for subpermafrost groundwater, the permafrost acts as an overlying confining bed and thus creates a confined aquifer. Wells that penetrate permafrost to the subpermafrost groundwater are com-monly artesian. The presence of permafrost in discharge zones can similarly influence the groundwater movement and yield. Presence of an unfrozen zone beneath small lakes has been reported by a number of workers.2'4'6'7 The presence or absence of a thawed zone linking lakes and subperma-frost aquifers has been only postulated to date.

Kane, D. and J. Stein Patterns of subarctic snowmelt infiltration.

Abstract: The ability to accurately partition a melting snowpack into evaporation, infiltration, and near-surface runoff is critical to the hydrologist involved in f^ood forecasting, reservoir system operating, or estimating possible groundwater recharge. Several small runoff plots were monitored over five years in a subarctic setting to determine the proportions of evaporation, near-surface runoff and infiltration from a melting snowpack. Daily snow surveys were conducted to assess the snowpack status. Surface and near-surface runoff was collected and measured at the base of the 89 square ffieter plots. Evaporation was calculated from measured meteorological variables. Infiltration quantities were estimated by subtracting the daily calculated evaporation and measured runoff from the daily snowmelt volume.

Over the period of study, year-to-year variations occurred in the maximum water content of the snowpack, soil moisture levels at the onset of freezing, and meteorological conditions during melting. For high moisture levels (near or excess of saturation in the upper 15 cm of mineral soil), we observed little variation in the total runoff volume reduced infiltration because of the development of ice tenses and/or ice crystals in soil pores, For intermediate moisture levels, considerable variation occurred among plots in the total runoff volume, but the volume of water infiltrating still represented a major portion of the snowpack. For drier soil conditions (<l2 by volume), infiltration rates exceeded the melt rate and no runoff was produced. In general, we concluded that the volume of runoff is a function of the near-surface moisture conditions in the mineral soil at the outset of seasonal freezing and, as this moisture level increases, infiltration is reduced.

Kaufman, D. S., T. A. Ager, N. J. Anderson, P. M. Anderson, P. J. Andrews, P. J. Bartlein and a. others (in press). Holocene thermal maximum in the western Arctic (0 - 180 degrees W). Quaternary Science Reviews.

Abstract: The spatio-temporal pattern of peak Holocene warmth (Holocene thermal maximum, HTM) is traced over 140 sites across the western hemisphere of the Arctic (0 to 180°W; north of~60°N). Paleoclimate inferences based on a wide variety of proxy indicators provide clear evidence for warmer-than-present conditions at 120 of these sites. At the 16 terrestrial sites where quantitative estimates have been obtained, local

HTM temperatures (primarily summer estimates) were on average 1.6 ± 0.8°C higher than present (approximate average of the 20th century), but the warming was time-transgressive across the western Arctic. As the precession-driven summer insolation anomaly peaked 12-10 ka (thousands of calendar years ago), warming was concentrated in northwest North America, while cool conditions lingered in the northeast. Alaska and northwest Canada experienced the HTM between ca. 11 and 9 ka, about 4000 yr prior to the HTM in northeast Canada. The delayed warming in Quebec and Labrador was linked to the residual Laurentide Ice Sheet, which chilled the region through its impact on surface energy balance and ocean circulation. The lingering ice also attests to the inherent asymmetry of atmospheric and oceanic circulation that predisposes the region to glaciation and modulates the pattern of climatic change. The spatial asymmetry of warming during the HTM resembles the pattern of warming observed in the Arctic over the last several decades. Although the two warmings are described at different temporal scales, and the HTM was additionally affected by the residual Laurentide ice, the similarities suggest there might be a preferred mode of variability in the atmospheric circulation that generates a recurrent pattern of warming under positive radiative forcing. Unlike the HTM, however, future warming will not be counterbalanced by the cooling effect of a residual North American ice sheet.

Knudson, J. and L. Hinzman (2000). Prediction of streamflow in an Alaskan watershed underlain by permafrost. Water resources in extreme environments. D. Kane. Anchorage, AK, AWRA.

Abstract: Prediction ofstreamflow in subarctic regions can be challenging due to the host of unique environmental factors present. Discontinuous permafrost, extensive aufeis, and fluctuating active layers are just several of the factors to be contended with in this region, m addition, reliable historical data is non-existent for much of interior Alaska, potentially limiting the strength ofhydrologic models even in relatively uniform conditions. Our long-term goal is to perform hydrologic forecasting in a variety of basins by compensating for the aforementioned variability and limitations. This particular project serves to confirm the effectiveness of the Swedish HBV-3 model in this endeavor, with the incorporation of additional factors as needed. The HBV model was chosen due to its previously demonstrated success in predicting streamflow in arctic and subarctic conditions, as well as its simplicity and ability to accurately forecast in the event of limited historical data. For our analyses, the model was used to predict streamflow within the Caribou-Poker Creeks Research Watershed (CPCRW), located in interior Alaska, northeast of Fairbanks. The watershed provided an excellent opportunity to test the model under highly variable conditions, including those mentioned above, that are typical of the region. The model proved to adequately simulate streamflow, which will allow us to determine more about the influence of discontinuous permafrost on hydrologic processes, including losses to groundwater and differences in soil moisture reservoirs. This success supports the continued use of the HBV-3 model as a viable tool for hydrologic modeling within the Caribou-Poker Creeks research watershed, as well as strengthening previous evidence for its potential use throughout the subarctic as a viable means of short-term hydrologic forecasting.

Konig, M. and M. Sturm (1998). Mapping snow distribution in the Alaskan Arctic using aerial photography and topographic relationships. Water Resources Research. **34** 3471-3483.
Abstract: A method is presented for mapping the end-of-winter snow distribution in the Arctic using vertical aerial photographs taken during the melt. The photos show a limited number of distinctive snowmelt patterns that arise reliably year after year. Data and results from an energy balance melt model indicate that the patterns are not caused by differential melt but instead represent areas of distinctive end-of-winter snow depth. A map of these snowmelt patterns is thus a map of the end-of-winter snow distribution. Because wind transport of snow is common, the patterns are closely related to the topography. Rules based on this pattern-topography relationship are developed and used to map the snow cover directly from topographic maps for three areas covering -220 km2 of the Kuparuk Basin in northern Alaska. Analysis of the snow maps suggests that about 75 of the area was mapped correctly. Applicability, reliability, and limitations of this mapping approach are discussed.

Kozlenko, N. and M. Jeffries (2000). Bathymetric mapping of shallow water in thaw lakes on the North Slope of Alaska with spaceborne imagining radar. Arctic. **53** 306-316.
Abstract: Few bathymetric maps are available for the thousands of thaw lakes on the North Slope of Alaska. We describe a semiautomated procedure for bathymetric mapping of water up to 2 m deep (i.e., less deep than the maximum ice thickness) in these lakes. A sequence ofERS-1 synthetic aperture radar (SAR) images and a simulated ice growth curve for winter 1991-92 are used to derive a digital elevation model of lake basins. The method is based on discriminating between floating ice and grounded ice in the SAR images to define raw isobaths; assigning an ic-e thickness or water depth to each isobath from the simulated ice-growth curve, and interpolating to create equally spaced (0.25 m) isobaths. There is modest agreement between SAR-derived maps and the few available bathymetric maps. Differences between the SAR maps and the original maps are probably unavoidable because of different production methods and original data formats. The concept of using SAR and a simulated ice-growth curve for bathymetric mapping of thaw lakes would benefit from verification based on a comparison with new maps derived from accurate field measurements at a selection of lakes with different morphological characteristics. Nevertheless, it is concluded that this technique is sound and could be used routinely for inexpensive and accurate bathymetric mapping across the entire North Slope and elsewhere (e.g., in Siberia, where large numbers of thaw lakes also occur). Such mapping would greatly increase the amount and spatial coverage of bathymetric data and would provide an accurate baseline against which to detect changes in the size, shape, bottom topography, and location of lakes.

Kremenetski, K. V., A. A. Velichko, O. K. Borisova, G. M. Macdonald, L. C. Smith, K. E. Frey and L. A. Orlova (2003). Peatlands of the western siberian lowlands: current knowledge on zonation, carbon content, and late Quarternary history. Quaternary Science Reviews. **22** 703-723.
Abstract: The Western Siberian lowlands (WSL) are the world's largest high-latitude wetland, and possess over 900,000 km2 of peatlands. The peatlands of the WSL are of major importance to high-latitude hydrology, carbon storage and environmental history. Analysis of the existing Russian data suggests that the mean depth of peat accumulation

in the WSL is 256cm and the total amount of carbon stored there may exceed 53,836 million metric tons. A synthesis of published and unpublished radiocarbon dates indicates tliat the peatlands first developed at the end of the Last Glacial, with a rapid phase of initiation between 11,000 and 10,000 cal yr BP. Initiation slowed after 8000 cal yr BP and reached a nadir at 4000 cal yr BP. There has been renewed initiation, particularly south of 62°N, following 4000 cal yr BP. The initial development of peatlands in the WSL corresponds with the warming at the close of the Pleistocene. Cooling after 4000 Cal yr BP has likely led to increased permafrost and increased peatland development particularly in central and southern regions. Cold and dry conditions in the far north may have inhibited peatland formation in the late Holocene.

LaFleur, P. M. (1990). Evaporation from sedge-dominated wetland surfaces. Aquatic Botany. **37**.
Abstract: The evapotranspirauon (ET) regimes of two sedge communities in a subarctic coastal wetland were investigated during non-vegetated and vegetated periods. Surface moisture availability strongly controlled ET dunng non-vegetated conditions, bus with less important during the vegetated period. The results suggest that the evaporation efficiency of these sites changed in response to vegetation growth. Vegetation cover reduced the evaporating efficiency of the wet site and slightly increased evaporation efficiency of the dry site. Simple linear regression models based on Penman's open water evaporation formula were found to predict ET accurately at each site under all surface cover conditions. However, model coefficients for the two sites differed substantially. Dividing the data set into non-vegetated and vegetated periods improved the model performance only marginally.

LaFleur, P. M. and W. R. Rouse (1988). The influence of surface cover and climate on energy partitioning and evaporation in a subarctic wetland. Boundary-Layer Meteorology. **44** 327-347.
Abstract: Energy partitioning and evaporation over three wetland surfaces in a subarctic coastal marsh during pre-growing and growing periods. These surfaces included an alder/willow woodland, a sedge marsh, and a raised backshore meadow. A combination model analysis was used to assess the relative importance of surface resistance and meteorological conditions on the magnitude of the Bowen ratio, B, during the growing period.
Overall, the three surface experience important site-to-site and seasonal differences in B and evaporation, Qe. During the non-foliated period, Qe was largest and B was smallest for the open water marsh, while the dry backshore site experienced the smallest Qe and largest B. The non-foliated woodland assumed intermediate values of B and Qe. After the vegetation covers were established, the woodland assumed the smallest B and largest Qe. After the vegetation covers were established, the woodland assumed the smallest B and largest Qe flux. It was also found that B at the marsh site increased with the presence of a vegetation cover.
Wind direction was always an important factor in determining Qe and B at all sites. B was substantially larger and Qe was smaller for onshore winds (i.e., originating from James Bay) than for offshore winds. The combination model analysis showed that canopy resistance at all sites was largest during warm offshore winds, which were associated with large saturation deficits. However, the effect of increased canopy

resistance on B during offshore winds was offset by a large climatological resistance, resulting in small B values and large Qe. When winds originated from James Bay, canopy resistance was smaller than for offshore winds, but the climatological resistance also was much smaller, resulting in larger B and small Qe. The results have important implications for changes in land cover and climate on the regional water balance.

Leconte, R. and P. D. Klassen (1991). Lake and river ice investigations in northern Manitoba using airborne SAR imagery. Arctic. **44** 153-163.
Abstract: ABSTRACT. Multichannel airborne SAR data were collected over northern Manitoba in April 1989 and January 1990. During the week of the SAR flights, several reconnaissance helicopter flights were undertaken, and ground calibration sites were visited to collect ice, snow. and water data. A total of six SAR image passes were flown in April 1989 and seven in January 1990, in order to collect a data set with numerous incidence angle, fre-quency, polarization, and look direction combinations. The data have been qualitatively assessed, with specific emphasis on C-band horizontally polarized imagery - the proposed SAR configuration for Radarsat. Results of the analysis have shown that airborne SAR can be used to identify various freshwater ice features, such as juxtaposition ice, refrozen slush, river ice runs, and lake ice. Open water leads were also successfully identi-fied. A careful interpretation of the airborne SAR imagery in conjunction with the ground truth data has shown that the unusually bright returns characterizing the Bumtwood River and the west portion of Split Lake were caused by a layer of refrozen slush that was generated during the initial for-mation of the ice cover. Although the results reported here focused exclusively on a qualitative analysis of C-HH data, preliminary analysis of the digital data suggests that changes in frequency and polarization produce measurable differences and can be used to develop classification algorithms for freshwater ice.

Lewellen, R. I. (1972). Studies on the fluvial environment Arctic Coastal Plain Province Northern Alaska. Palmer, AK, Lewellen Arctic Research 282.

Likens, G. E. and R. A. Ragotzkie (1965). Vertical water motions in a small, ice-covered lake. Journal of Geophysical Research. **70** 2333-2344.
Abstract: The use of radioactive tracers in previous studies has demonstrated that appreciable water movement can occur in ice-covered lakes. Mathematical evaluation of those results shows that the vertical component of this motion can be calculated and is between one and three orders of magnitude less than the horizontal component. The overall pattern of circulation is consistent with convective motion caused by heating from below. Sources of heat in the sediments are considered and evaluated. Because of the organized nature of the circulation observed beneath the ice cover, the validity of classical terminology such as 'winter stagnation' ;ind 'dimixis' is questioned.

Lim, D. S. S. D., M.S.V.; Smol, J.P.; Lean, D.R.S. (1997). Limnology of high arctic ponds (Bathurst Island, N.W.T., Canada). 27th Arctic Workshop, Department of Geography,University of Ottawa , February 27-March 2, 1997. n. G. L. a. S. V. Kokelj. University of Ottawa 169.

Abstract: A limnological survey of 40 ponds on Bathurst Island, NWT, was conducted during July 1994. Water, algal, zooplankton and sediment samples were obtained from each site in order to characterize their abiotic and biotic characteristics. This project further expands our growing database on shallow arctic ponds and deeper lakes. This presentation reports on the physical, chemical analyses of the water samples. The study ponds ranged in elevation from sea level to 600 m asl. Most ponds were approximately 22-300 m wide but, as is typical for most high arctic sites, few exceeded 1 m in depth. All were clear and oligotrophic, with water temperatures ranging from 3 C to 19.5 C in shallower sites. All were within a restricted alkaline pH range (pH = 8.0-8.6), reflecting the calcareous, limy and dolomitic nature of the drainage basins. Conductivities of the study ponds rarely exceeded 150 micro S/cm with the highest value being 282 micro S/cm from a pond situated closest to the ocean. Major ion concentrations are relatively similar amongst sites, although environmental gradients are apparent, reflecting differences in production (Chla), drainage basins and locale. Ca, Na and Mg are the major cations, while Cl is the major anion. Other monitored environmental variables also reflected alkaline conditions in the ponds. Detrended correspondence analysis (DCA) was used to ordinate the sites and environmental data. The largest amount of variance is accounted for by the first axis of the DCA ordination at 28.6%, while the second axis accounts for 23.7% of the variance. The DCA ordination of the environmental variables shows a transition along axis 1 from trace elements to more common pond constituents such as Ca, Mg, Na and Cl; axis 2 appears to capture a productivity gradient. The DCA ordination for the pond sites indicates similar gradients given their proximity to the sea and their geology. This work provides an environmental framework for the diatom assemblages and other biota which serve as paleolimnological indicators. Until recently, there have been few published limnological studies carried out on a regional scale in the Arctic. However, these data prove invaluable when attempting to attribute specific environmental conditions to diatom assemblages and other biota which serve as paleolimnological indicators as well as biomonitors for arctic regions. This need for baseline data has become increasingly important since high arctic ponds such as these may be especially sensitive monitors of environmental, both past and present, change

Ling, F. and T. Zhang (2003). Numerical simulation of permafrost thermal regime and talik development under shallow thaw lakes on the Alaskan Arctic Coastal Plain. J. Geophys. Res. **108** doi:10.1029/2002JD003014.

Abstract: Thaw lakes are one of the most obvious manifestations of the hydrological system at work in the tundra regions of the Alaskan Arctic Coastal Plain, but the extent of the role of thaw lakes in Arctic land-atmosphere interactions and feedback has yet to be fully understood. This study uses a two-dimensional heat transfer model with phase change under a cylindrical coordinate system to simulate the long-term influence of shallow thaw lakes on the thermal regime of permafrost and talik development on the Alaskan Arctic Coastal Plain. On the basis of previous studies of permafrost and thaw lakes at Barrow, Alaska, a series of simulation cases was conducted using different combinations of long-term mean lake bottom temperature and lake depth. The simulated results indicate that shallow thaw lakes are a significant heat source to permafrost and talik. For a thaw lake with a long-term mean lake bottom temperature of greater than 0.0C a talik forms under the thaw lake. The maximum talik thicknesses (vertical distance from the ground surface to the permafrost surface) are 28.0, 43.0, and 53.2 m 3000 years after the formation of a shallow thaw lake with long-term mean lake bottom temperatures of 1.0, 2.0, and 3.0C, respectively. Talik development rate is very high in the first several years after a thaw lake formation and decreases gradually with time. No talik forms below a thaw lake with a long-term mean lake bottom temperature equal to or lower than 0.0 C, but the temperature of permafrost below the thaw lake increases with time. Three thousand years after the formation of a thaw lake with a long-term mean lake bottom temperature of greater than or equal to 2.0 C, ground temperature increases of more than 0.5C occur as far as 300 m from the lake shore and as deep as about 400 m below the ground surface. It is concluded that variation of long-term mean lake bottom temperature has a significant influence on permafrost thermal regime and talik development. Continued monitoring for thaw lake bottom temperature and ground temperature under shallow thaw lakes is needed to further improve the simulation.

Ling, F. and T. Zhang (2004). Modeling study of talik freeze-up and permafrost response under drained thaw lakes on the Alaskan Arctic Coastal Plain. J. Geophys. Res. **109** doi:10.1029/2003JD003886.
Abstract: Numerical simulations were conducted to investigate the long-term impact of thaw lake drainage on the thermal regime of ground under and around drained thaw lakes on the Alaskan Arctic Coastal Plain. The numerical model used in this study is a two dimensional unsteady finite element model for heat transfer with phase change under a cylindrical coordinate system. The initial conditions are the simulated ground thermal regime and talik thickness data at year 3000 under a thaw lake with long-term mean lake bottom temperatures of 1.0, 2.0, and 3.0_C near Barrow, Alaska. The simulated results indicate that lake drainage leads to a rapid freeze-up of talik and a substantial decrease in permafrost temperatures under the former lake bottom. The initial ground temperature conditions have significant influence not only on the talik freeze-up time, but also on the permafrost temperature decrease processes. After thaw lake drainage, taliks with thicknesses of 28, 43, and 53 m under the lake will freeze-up completely by 40, 106, and 157 years, and the corresponding ratios of upward and downward freeze-up depths for the three simulation cases are 1: 8.0, 1: 7.6, and 1: 6.1, respectively. After completion of talik freeze-up, permafrost temperatures still decreased with time and gradually reached a relatively stable value, depending on the initial ground temperature and the distance to the former lake bottom.

Liston, G. and D. Hall (1995). An energy-balance model of lake-ice evolution. Journal of Glaciology. **41** 373-382.
Abstract: A physically based mathematical model of the coupled lake. lake ice. snow and atmosphere system is developed for studying terrestrial atmospheric interactions in high-elevation and high-latitude regions. The ability to model lake-ice freeze-up, break-up, total ice thickness and ice type oilers the potential to describe the effects of climate change in tliese regions. Model output is validated against lake-ice observations made during tlie winter of 1992 93 in Glacier National Park, Montana, U.S.A. The model is driven with observed daily atmospheric forcing of precipitation, wind speed and air temperature. In addition to simulating complete energy-balance components over the annual cycle, model output includes ice freeze-up and break-up dates, and the end-of-

season clear ice, snow-ice and total ice deptlis (or two nearby lakes in Glacier National Park. each in a different topographic setting. Modeled ice features are found to agree closely witli tlie lake-ice observations. Model simulations illustrate tlie key role lliat tlie wind component of tlie local climatic regime plays on the growth and decay of lake ice. The wind speed affects both tlie surface temperature and the accumulation of snow on the lake-ice surface. Higher snow accumulations on the lake ice depress the ice surface below tlie water line. causing tlie snow to become saturated and leading to tlie formation of snow-ice deposits. In regions having higher wind speeds, significantly less snow accumulates on the lake-ice surface, thus limiting snow-ice formation. The ice produced by these two different mechanisms has distinctly different optical and radiative properties, and affects the monitoring of frozen lakes using remote-sensing techniques.

Liston, G. and D. Hall (1995). Sensitivity of lake freeze-up and break-up to climate change: a physically based modeling study. Annals of Glaciology. **21** 387-393.
Abstract: ABSTRACT. To assess the response of lake freeze-up and break-up dates to changes in atmospheric forcing, a physically based computational model of the coupled lake, lake-ice, snow and atmosphere system has been developed. Model performance is validated using meteorological and lake-ice observarions from Great Slave Lake in northern Canada in 1991/92, and St Mary Lake in Glacier National Park. Montana in 1992/93. Model integrations with modified atmospheric forcing-indicate that air-temperature changes of ±4C can delay or speed up the freeze-up and break-up dates by as much as 4 weeks tor St Mary Lake and 2 weeks for Great Slave Lake. For both lakes, break-up date is more sensitive to air-temperature changes than is freeze-up. Changes of ±3/10 cloud-cover fraction produce a shifting of break-up dates bv 1 week. Changes in wind speeds of ± 3 in s modify the maximum ice depth of the lakes by 5-10cm. For Great Slave Lake, lower wind speeds produced a surface temperature low enough to delay the onset of break-up bv 2 weeks.

Liston, G. and M. Sturm (2002). Winter precipitation patterns in Arctic Alaska determined from a blowing-snow model and snow-depth observations. Journal of Hydrometeorology. **3** 646-659.
Abstract: A blowing-snow model (SnowTran-30) was combined with field measurements of end-of-winter snow depth and density to simulate solid (winter) precipitation, snow transport, and sublimation distributions over a 20 000-km2 arctic Alaska domain. The domain included rolling uplands and a flat coastal plain. Simulations were produced for the winters of 1994/95, 1995/96. and 1996/97. The model, which accounts for spatial and temporal variations in blowing-snow sublimation, as well as saltation and turbulent-suspended transport, was driven with interpolated fields of observed temperature, humidity, and wind speed and direction. Model outputs include local (a few hundreds of meters) to regional (several tens of kilometers) distributions of winter snow-water-equivalent depths and blowing-snow sublimation losses, from which the regional winter precipitation distributions are computed. At regional scales, the end-of-winter snow depth is largely equal to the difference between winter precipitation and moisture loss due to sublimation. While letting SnowTran-3D simulate the blowing-snow sublimation fluxes, the precipitation fields were determined by forcing the regional variation in model-simulated snow depths to match measured values. Averaged over the entire domain and

the three simulation years, the winter precipitation was 17.6 cm, with uplands values averaging 19.0 cm and coastal values averaging 15.3 cm. On average, 21% of the precipitation was returned to the atmosphere by blowing-snow sublimation, while in the windier coastal regions 34% of the winter precipitation sublimated.

Livingstone, D. A. (1954). On the orientation of lake basins. American Journal of Science. **252** 547-554.
Abstract: A theoretical horizontal circulation system is described for a circular lake with a constant wind blowing across it. The shape of many oriented lakes in northern Alaska indicates that their present circulation system approaches the theoretical one, and that it is this system to which they owe their orientation.
Because the Carolina Bays are oriented along the probable direction of the winds which excavated them they are believed to be deflation basins, and not lakes whose shape is due to wave action and water circulation.

Livingstone, D. A., K. Bryan and R. G. Leahy (1958). Effects of an arctic environment on the origin and development of fresh-water lakes. Limnology and Oceanography. **3** 192-214.
Abstract: Thaw lakes beyond the glacial boundary in northern Alaska may be quiescent, with elliptical saucer-shaped basins, or they may be actively expanding, with deeply pocked basins. Glacial lakes of the usual types are found in the glaciated southern part of the region. The lakes freeze to a depth of almost 2 meters in winter and warm without strati-fying to about 13°C in summer. Of the annual heat budget of some 28,000 cal/cm2 only 6,000 cal is wind distributed. Total dissolved solids are known to range from 35 to 159 ppm, and the water is of a calcium bicarbonate type except where sea-spray influence is strong. The silica content is very low. A shore community is poorly-developed or absent, appar-ently because of ice-push, and the standing crop of benthos varies from an indetectable amount to 89.4 kg/ha.' Remains of the midge Dryadotanytarsus are found throughout the sedimentary column of one lake, indicating that this genus, which is known only as a late-Pleistocene fossil, lives there today. The sediments of lakes receiving the products of the widespread processes of arctic weathering are very inorganic, with few and poorly-preserved microfossils. Computations based on a radiocarbon-dated pollen chronology suggest a net community productivity averaging less than 2 mg of organic matter/cmVyr, and Bosmina and tendipedid productivities of less than lO/cm'/yr during the past 6,000 years. Further computations involving the data of other authors suggest that of the solar energy fixed by a temperate or arctic lake about one-quarter is preserved in the sediments, one-half is dissipated by the decomposing organisms and one-quarter is dissipated by all the other plants and animals. The arctic environment appears to influence lakes principally through physiographic processes affecting origin, sedimentation, and drainage.

Lunardini, V. J. (1996). Climatic warming and the degradation of warm permafrost. Permafrost and Periglacial Processes. **7** 311-320.
Abstract: Permafrost - a widespread constituent of the terrestrial environment - by definition is depen-dent upon the ambient temperature for its existence and properties. Thus, it is very sensitive to climatic changes. Simple relations based upon conductive heat transfer, with thawing and geothermal heat flow, are presented to predict the

transient effects of surface temperature increases on the thermal state of permafrost. The results indicate that, based on the usual global warming scenarios, relatively small amounts of permafrost will disappear within 50-100 years. This is specifically shown for the most thermally sensitive cases, that is, warm or relict permafrost.

Mackay, J. R. (1963). The Mackenzie Delta area, NWT, Canadian Dept. Mines and Tech. Surveys, Geog. Br., Mem. 45-65.

Mackay, J. R. (1971). The origin of massive icy beds in permafrost, Western Arctic Coast, Canada. Canadian Journal of Earth Sciences. **8** 397-422.
Abstract: Massive beds of ground ice are shown to exist along the arctic coastal plain east of the Alaska-Yukon boundary for a distance of at least 500 km. The massive ground ice can be seen in both undisturbed and glacially disturbed Pleistocene sediments. An examination of several thousand seismic shot hole logs, from drill holes of 15 to 35 m in depth, also cor-roborates the widespread occurrence of ground ice. The icy beds typically have an ice content, defined in terms of the weight of ice to dry soil, in excess of 200 for sections as much as 35 m thick. A theory is presented which suggests that: the ice is of segregation origin; the source of excess water was from the expulsion of ground water during the freezing of sands; and high pore water pressures, favorable to ice segregation, developed beneath an aggrading impermeable permafrost cover. Permafrost aggradation may have occurred either on an exposed sea floor during a period of sea level lowering which would have accompanied a glacier advance, or following a warm interval in which there had been deep thaw. Similarities in the origin of pingo ice and massive ice are discussed.

Mackay, J. R. (1972). The world of underground ice. Annals of the Association of American Geographers. **62** 1-22.
Abstract: ABSTRACT. Underground ice is restricted to permafrost areas where its distribution is sporadic and often unpredictable. A knowledge of the distribution and abundance of underground ice is essential to northern development, because a variety of man induced disturbances can cause underground ice to thaw, often with serious consequences. The criteria for a classification of the principal types of underground ice are the source of the water prior to freezing and the processes which transfer water to the freezing plane. The origin of massive icy bodies in the Western Arctic of North America is explained by a water expulsion theory. The excess water now found in the icy bodies is attributed to water expelled from coarse textured sediments by the downward growth of permafrost. The suggested mechanism is illustrated by three pingos which have grown since 1950. The role of glaciation in the formation of relic offshore permafrost in relatively shallow Arctic coastal areas is examined. The evidence suggests that offshore permafrost is present in some shallower portions of the Beaufort Sea from northeastern Alaska eastwards to the high Arctic islands of Canada. If offshore permafrost with underground ice is present, then thermal disturbance problems must be taken into consideration in future offshore exploration.

Mackay, J. R. (1973). The growth of pingos, Western Arctic Coast, Canada. Canadian Journal of Earth Sciences. **10** 979-1004.

Abstract: The growth rates of 11 closed system pingos have been measured, by means of precise levelling of perma-nent bench marks anchored well down into permafrost, forthe 1969-1972 period. As pingo growth decreases from the summit to the base, growth of the ice-core decreases from the center out to the periphery. The pingos have grown up in the bottoms of takes which have drained rapidly and thus become exposed to per-mafrost aggradation. The specific site of growth is usually in a small residual pond where permafrost aggra-dation is retarded. The size and shape of a residual pond exercises a strong control upon the size and shape of the pingo which grows within it. The ice-core thickness equals the sum of the pingo height above the lake flat and the depth of the residual pond in which the pingo grew. Pingos tend to grow higher rather than both higher and wider. Pingos are believed to grow more by means of ice segregation than by the freezing of a pool of water. The water source, and the associated positive pore water pressure, result from permafrost aggradation in sands and silts in the lake bottom under a closed system with expulsion of pore water. The fastest growth rate of an ice-core, for the Western Arctic Coast, is estimated at about 1.5 m/yr, for the first one or two years. After that, the growth rate decreases inversely as the square root of time. The largest pingos may continue to grow for more than 1000 yr. Four growth stages are suggested. At least five pingos have commenced growth since 1935. As an estimate, probably 50 or more pingos are now growing along the coast.

Mackay, J. R. (1977). Pulsating pingos, Tuktoyaktuk Peninsula, NWT. Canadian Journal of Earth Sciences. **14** 209-222.
Abstract: Most pingos have grown in residual ponds left behind by rapid lake drainage through erosion of ice-wedge polygon systems. The field studies (1969-78) have involved precise levelling of numerous bench marks, extensive dril-ling, detailed temperature measurements, installation of water pressure transducers below permafrost and water (ice) quality, soil, and many other analyses. Precise surveys have been carried out on 17 pingos for periods ranging from 3 to 9 years. The field results show that perma-frost aggradation in saturated lake bottom sediments creates the high pore water pressures necessary for pingo growth. The subpermafrost water pressures fre-quently approach that of the total lithostatic pressure of permafrost surround-ing a pingo. The water pressure is often great enough to lift a pingo and intrude a sub-pingo water lens beneath it. The basal diameter of a pingo is established in early youth after which time the pingo tends to grow higher, rather than both higher and wider. The shutoff direction of freezing is from periphery to center. When growing pingos have both through going taliks and also permeable sediments at depth, water may be expelled downwards by pore water expulsion from freezing and consolidation from self loading on saturated sediments. Pingos can rupture from bursting of the sub-pingo water lens. Otherwise, pingo failure is at the top and periphery. Hydraulic fracturing is probably important in some pingo failures. Water loss from sub-pingo water lenses causes sub-sidence with the subsidence pattern being the mirror image of the growth pattern; i.e. greatest subsidence at the top. Small peripheral bulges may result from subsidence. Old pingos collapse from exposure of the ice core to melting by overburden rupture, by mass wasting, and by permafrost creep of the sides.

Mackay, J. R. (1979). Pingos of the Tuktoyaktuk Peninsula Area, Northwest Territories. Geogr. phys. Quat. **33** 3-61.

Abstract: Most pingos have grown in residual ponds left behind by rapid lake drainage through erosion of ice-wedge polygon systems. The field studies (1969-78) have involved precise levelling of numerous bench marks, extensive dril-ling, detailed temperature measurements, installation of water pressure transducers below permafrost and water (ice) quality, soil, and many other analyses. Precise surveys have been carried out on 17 pingos for periods ranging from 3 to 9 years. The field results show that perma-frost aggradation in saturated lake bottom sediments creates the high pore water pressures necessary for pingo growth. The subpermafrost water pressures fre-quently approach that of the total litho-static pressure of permafrost surround-ing a pingo. The water pressure is often great enough to lift a pingo and intrude a sub-pingo water lens beneath it. The basal diameter of a pingo is established in early youth after which time the pingo tends to grow higher, rather than both higher and wider. The shutoff direction of freezing is from periphery to center. When growing pingos have both through going taliks and also permeable sedi-ments at depth, water may be expelled downwards by pore water expulsion from freezing and consolidation from self loading on saturated sediments. Pingos can rupture from bursting of the sub-pingo water lens. Otherwise, pingo failure is at the top and periphery. Hydraulic fracturing is probably impor-tant in some pingo failures. Water loss from sub-pingo water lenses causes sub-sidence with the subsidence pattern being the mirror image of the growth pattern; i.e. greatest subsidence at the top. Small peripheral bulges may result from subsidence. Old pingos collapse from exposure of the ice core to melting by overburden rupture, by mass wasting, and by permafrost creep of the sides.

Mackay, J. R. (1981). An experiment in lake drainage, Richards Island, Northwest Territories: a progress report., Geological Survey of Canada 63-68.

Abstract: In the Tuktoyaktuk Peninsula and Richards Island region, Northwest Territories, some thousands of lakes have drained naturally, either in whole or in part, in the past few thousand years. The present drainage rate is about one lake per year. Most lakes have drained by channel erosion of ice-wedge systems. Since the region lies in the zone of continuous permafrost, lake drainage and permafrost growth have produced a complex three dimensional permafrost distribution. In order to understand better the processes associated with permafrost growth in drained lakes, a lake 600 m long, 300 m wide, and up to 5 m deep was artificially drained by channel flow along an ice-wedge system in order to simulate natural drainage.

Following drainage on 13 August 1978, the outlet has widened by thaw of ice-rich permafrost to produce a greatly oversized canyon similar to many natural channels and indicative of catastrophic drainage. Probing of the lake bottom immediately after drainage showed that the permafrost surface dipped steeply lakeward where water depths had exceeded 1.5 m. Temperature measurements show that in nearshore areas, where permafrost was less than 10 m deep, freeze-through from the lake bottom to permafrost at depth was completed from 1978 to 1980 by both downward and upward freezing. Where permafrost was much deeper (e.g. more than 20 m), only 5 to 6 m of the lake bottom froze from 1978 to 1980. Accurate levelling of numerous lake bottom bench marks 2 to

23 m deep has shown that frozen ground has continued to heave after the temperature was below 0°C.

Mackay, J. R. (1988). Catastrophic Lake Drainage, Tuktoyaktuk Peninsula, District of Mackenzie, Geological Survey of Canada 83-90.
Abstract: In the 36 war period from 1950 to 1986 about 65 lakes in the Tuktoyaktuk Peninsula area have undergone at least partial drainage. Data on lake drainage have been obtained from Held studies and a comparison of NTS 1:250 000 maps prepared from 1950 air photographs with 1986Landsal imagery. The majority of the lakes have drained rapidly, if not catastrophically, hy erosion of ice-rich terrain at their outlets. Most erosion has been along ice-wedge systems. One lake probably drained as a result of the disturbance of a bulldozed winter road that crossed the outlet creek.

Mackay, J. R. (1992). Lake stability in an ice-rich permafrost environment: examples from the Western arctic coast. Environment Canada. N.H.R.I Symposium Series Aquatic Ecosystems in Semi-Arid Regions: Implications for Resource Management;. R. D. B. Robarts, M.I. 26.
Abstract: Lake development since Late Wisconsinan glaciation along the western Arctic coast of Canada has resulted primarily from the interplay of three factors: climatic warming (about 13000 to 8000 BP) followed by gradual cooling (about 8000 to 4500 BP), the widespread distribution of ice-rich permafrost:, and ice-wedge growth since about 4500 BP. During thy warm period the thickness of the active layer increased and numerous thaw (thermokarst) lakes grew where enlarging sub-lake thaw bulbs encroached upon ice-rich permafrost. Since about 4500 BP, ice-wedge growth, which had been inactive during the warm period, was renewed. After the cooling trend started, thousands of lakes have drained, often catastrophically, frequently by diversion of snowmelt overflow along easily eroded ice-wedge systems or over ice-rich permafrost terrain. Countless lakes are now in a state of instability where a slight change, whether from climatic warming or a human-induced disturbance, could initiate either lake drainage or thaw lake enlargement. Any climatic warming accompanied by a modest temperature increase and a heavier snowfall would likely lead to a cessation of ice-wedge growth along the co-ast and increased lake drainage.

Mackay, J. R. (1995). Ice wedges on hillslopes and landform evolution in the late Quaternary, western Arctic coast, Canada. Canadian Journal of Earth Sciences. **32** 1093-1105.
Abstract: In rolling to hilly areas of the western Arctic coast of Canada, anti-syngenetic wedges, which by definition are those that grow on denudational slopes, are the most abundant type of ice wedge. Through prolonged slope denudation, hilltop epigenetic wedges can evolve into hillslope anti-syngenetic wedges, and some bottom-slope anti-syngenetic wedges, by means of deposition from upslope, can evolve into bottom-slope syngenetic wedges. The axis of a hillslope wedge is oriented perpendicular to the slope, so the wedge foliation varies according to the trend of the wedge with respect to the slope. Because the tops of hillslope wedges are truncated by slope recession, the mean chronological age of anti-syngenetic wedge ice decreases with time, so the growth record for an old wedge is incomplete. Summer and winter measurements show that a thermally induced net movement of the active layer of hillslope polygons tends to transport material

from their centres towards their troughs independent of the trends of the troughs relative to the slope. Wedge-ice uplift, probably diapiric, has been measured. Some hillslope polygon patterns may predate the development of the present topography. Many Wisconsinan wedges, truncated and buried during the Hypsithermal period, have been reactivated by upward cracking.

Mackay, J. R. (1995). Active layer changes (1968-1993) following the forest-tundra fire near Inuvik, NWT, Canada. Arctic and Alpine Research. **27** 323-336.
Abstract: Active layer changes after the 1968 forest-tundra fire at Inuvik, N.W.T, have been monitored from 1968 to 1993 at three burned and two unburned sites. In addition, a burned site has been used for field experiments on changes to the active layer. The active layer depths have been measured at the same points, marked initially by 58 permanent stakes, nearly every year and the vegetation described in general terms and frequently photographed. The changes to the active layer have been site specific so that broad generalizations for the three burned and the two un-burned sites for the 25-yr period are limited. For brief periods, summer air tem-peratures correlated reasonably well with changes in the depth of the active layer at two sites. For only one summer (1993), active layer depth increases were controlled primarily by the previous winter's temperature and snow conditions. At all sites where the active layer deepened, the underlying ice-rich permafrost thawed to produce thaw settlement. The addition of thaw water to the bottom of the active layer at the more poorly drained sites created moist conditions which favored vegetation growth. In response to the vegetation growth which shielded the ground surface, active layer depths decreased, permafrost aggraded upward, and there was some ground uplift from the growth of aggradational ice. Although there was a pronounced winter warming during the observation period, the effects on ground warming were offset, to an unknown degree, by a decrease in winter snow depths which led to winter ground cooling.

Mackay, J. R. (1997). A full-scale experiment (1978-1995) on the growth of permafrost by means of lake drainage, western Arctic coast: a discussion on the method and some results. Canadian Journal of Earth Sciences. **34** 17-33.
Abstract: On 13 August 1978, a lake on the western Arctic coast was artificially drained, in a multidisciplinary experiment on the growth of permafrost on the unfrozen bottom of the drained lake. A bowl-shaped talik (unfrozen basin) with a maximum depth of about 32 m underlay the lake bottom prior to drainage. In the first winter after drainage, downward freezing started on the exposed lake bottom and upward freezing from permafrost beneath the talik. After drainage, the soft lake-bottom sediments hardened from water loss and freeze-thaw consolidation. Gradual thinning of the active layer at many sites was accompanied by ground uplift and the growth of aggradational ice. Downward and upward freezing has resulted in solute rejection, freezing-point depressions, pore-water expulsion from the freezing of the saturated lake-bottom sands, and convective heat transfer from groundwater flow in an open hydrologic system. The increasingly saline intrapermafrost groundwater, flowing at an increasingly negative temperature because of a freezing-point depression, has accelerated the rate of permafrost growth in the interpermafrost zone in the direction of flow. The experiment has demonstrated that the growth of permafrost at the drained lake site, and at other sites with

groundwater flow, requires a three-dimensional conductive-convective heat transfer approach.

Mackay, J. R. (1999). Periglacial features developed on the exposed lake bottoms of seven lakes that drained rapidly after 1950, Tuktoyaktuk Peninsula area, western Arctic coast, Canada. <u>Permafrost and Periglacial Processes</u>. **10** 39-63.
Abstract: A variety of periglacial features have been studied on the exposed bottoms of seven lakes that drained rapidly after 1950 in the Tuktoyaktuk Peninsula area, western Arctic coast, Canada. Ice-wedge growth commenced as early as the first winter following drainage. In most areas, ice-wedge growth cease within several decades, because of the growth and spread of vegetation which resulted in snow entrapment and increased ground temperatures. At sites where thermokarst lake enlargement had transgressed across terrain with ice-wedge polygons, reactivated polygon patterns developed rapidly in some pre-drainage shallow water areas, with the sites of former troughs becoming ridges. Excavations across the ridges exposed extensive differential frost heave, cryoturbations, and slickensided vertical shear planes. Many collapse pits developed because of differential frost heave between silts and sands, cavity formation beneath the frozen silts, and cavity infilling with adjacent sand in late summer. Other collapse pits developed, either sub-aqueously prior to drainage or subaerially after drainage. Underground flow has been observed, in early summer, where a near-surface layer of ice-rich silts was underlain by desiccated active layer sands at a temperature well below 0 °C. At some sites where there has been underground flow some differential loading and water escape features appear to have developed during the thaw period.

Mackay, J. R. (1999). Cold-climate shattering (1974 to 1993) of 200 glacial erratics on the exposed bottom of a recently drained arctic lake, Western Arctic coast, Canada. <u>Permafrost and Periglacial Processes</u>. **10** 125-136.
Abstract: The shattering of 200 glacial erratics on the exposed bottom of an Arctic lake that drained rapidly, probably in 1955, was studied from 1974 to 1993. Most of the erratics were igneous rocks derived from the Canadian Shield. The erratics, which were unshattered before 1974, had already survived, in varying degrees, at least three prior stages of shattering: first, when many of the rocks were in the thin active layer of the glacial till that covered the area; second, when all of the rocks, after submergence by lake enlargement, underwent annual freeze-thaw cycles under saturated conditions; and third when, after rapid lake drainage, the rocks were exposed to cold sub-aerial climate conditions before being marked for study in 1974. The 200 rocks were checked in 1977, 1978, 1979, 1987, 1988 and 1993. In 1993, the last year of observation, 180 of the original 200 rocks were'relocated. The results showed that at least 10 of the 200 rocks had shattered, these being: at least 2 out of about 136 granites; 1 out of about 6 gneisses; 1 out of 2 sandstones; and 6 out of about 22 dolomites. The impervious granites probably hydrofractured from the freezing of water in closed to semi-closed systems or from thermal shocks. Rocks which facilitated the entry of water, such as those with a foliation, schistosity or porosity, broke the most frequently, many probably from ice segregation. Some of the dolomites probably shattered explosively. In support of the ice segregation theory of shattering for some types of rocks, an example is given of present-day ice segregation in a Cretaceous shale at the mouth of nearby Horton River, NWT.

Mackay, J. R. and C. Burn (2002). The first 20 years (1978/79 to 1998/99) of active-layer development, Illisarvik experimental drained lake site, western Arctic coast, Canada. Canadian Journal of Earth Sciences. **39** 1657-1674.
Abstract: Active-layer thickness, snow depth, minimum soil temperatures, near-surface ground ice, soil heave, and permafrost temperatures have been measured for over 20 years following the 1978 artificial drainage of Lake Illisarvik. Measurements of active-layer thickness and other variables have been made at 25-m intervals along the major and minor axes of the oval-shaped drained-lake bed. Permafrost aggradation commenced in the lake bottom during the first winter following drainage. Before the establishment of vegetation, there was little snow cover, minimum ground temperatures were low, and the active layer was relatively thin. However, both snow depth and minimum ground temperatures have risen where vegetation has grown, the active layer has thickened, and in response, the temperature in permafrost has gradually increased. In the lake bottom, the change in snow depth associated with vegetation growth has been the dominant control on variation in active-layer thickness and not summer weather conditions, which are well correlated with thaw depths along an active-layer course established in the adjacent tundra. Changes in elevation of the surface of the lake bed have been measured with respect to some 40 bench marks anchored in permafrost, and indicate vertical movements of the surface associated with frost heave, thaw subsidence, and the growth of aggradational ice. The ground ice content of near-surface permafrost determined by drilling is in close agreement with the measured uplift of the lake bed. The rate of growth of aggradational ice has been -0.5 cm a~1 over 20 years.

Mackay, J. R. and C. Burn (2002). The first 20 years (1978/79 to 1998/99) of ice-wedge growth at the Illisarvik experimental drained lake site, western Arctic coast, Canada. Canadian Journal of Earth Sciences. **39** 95-111.
Abstract: In August 1978, a large tundra lake was drained to study the aggradation of permafrost into newly exposed lake-bottom sediments. Ice-wedge growth, which started in the first winter following drainage, had ceased in most of the lake bottom within about twelve years. The gradual cessation of thermal contraction cracking can be attributed to rapid vegetation growth, snow entrapment, an increase in winter ground temperatures, and a decrease in the linear coefficient of thermal contraction associated with freeze-thaw consolidation of the initially saturated lake-bottom sediments. The tilt and separation of markers in the active layer revealed gradual convergence towards the troughs even after ice-wedge growth had ceased. For the first few years the ice-wedge growth rate was up to 3 cm/a as determined by excavation, drilling, separation of the bottoms of benchmarks installed into permafrost, and divergence of free-floating inductance coils placed on the sides of ice wedges well below the bottom of the active layer. The vertical extent of most ice wedges was probably about 2 m, as deduced from the depths of ice-wedge cracks and the geometries of the wedge tops. Many thermal contraction cracks propagated upward to the ground surface from the tops of the ice wedges rather than downward from the ground surface. Small, upward facing, horizontal steps and vertical slickensided surfaces in permafrost on both sides of an excavated ice wedge near its top indicated that the adjacent permafrost had moved upward, relative to the wedge, from thermal expansion during the warming period.

Malm, J., L. Bengtsson, A. Terzhevik, P. Boyarinov, A. Glinsky, N. Palshin and M. Petrov (1998). Field study on currents in a shallow ice covered lake. Limnology and Oceanography. **43** 1669-1679.
Abstract: A field study on current structure and circulation characteristics in Lake Vendyurskoe, a small, shallow, ice-covered lake in Karelia, Russia, is presented. The current velocity magnitudes were generally found to be small.
The most pronounced currents had an oscillating character, with velocity amplitudes on the order of millimeters per second. The oscillation period, obtained from spectral density calculations, corresponded to that of a barotropic uninodal seiche. The seichelike nature of the current oscillations was supported by the results from analysis of ice-level fluctuations, giving identical periods and a phase shift of one-fourth the period between the two types of oscillations.
Mean currents measured during the winter were on the order of millimeters per second. Because Lake Vendyur-skoe does not have any significant river inflow or outflow during winter, the most probable cause of these currents is horizontal temperature (pressure) gradients. Scaling analysis indicated that these currents are geostrophic. This was supported by theoretical estimates, based on observed horizontal temperature gradients, being of the same order as the observed currents. The mean current velocities increased considerably after spring convection from <1 to several millimeters per second.

Marsh, P. and C. Bigras (1988). Evaporation from Mackenzie Delta lakes. Arctic and Alpine Research. **20** 220-229.
Abstract: Evaporation is an important component of the water balance of lakes in the Mackenzie Delta, but the amount of summer evaporation in this area is not well known. A microclimato-logic and water balance study conducted over a 5-yr period demonstrated that lake evaporation ranged from 200 to 387 mm per summer. Evaporation was always greater than summer precipitation and in some cases greater than annual precipitation. Measured evaporation varied significantly from lake to lake and was considerably different from that given in standard maps of evaporation over northern Canada.
Since these delta lakes receive little runoff from the surrounding basin, lakes which are not flooded by the Mackenzie River experience gradually decreasing water levels. Given sufficient time between flooding events, these lakes will completely dry up. This has important implications to the effect of flow regulation on the hydrology of lakes in the Mackenzie Delta.

Marsh, P. and N. Nuemann (2001). Processes controlling the rapid drainage of two ice-rich permafrost-dammed lakes in NW Canada. Hydrological Processes. **15** 3433-3446.
Abstract: This paper considers the processes controlling the rapid drainage of ice-rich permafrost-dammed lakes. It is postulated that the primary process controlling lake drainage is the melting of ice-rich permafrost, irt a manner similar to that controlling the drainage of glacier-dammed lakes. Two lakes are considered in the analysis: one that drained naturally over a period of less than 16 h, and Lake lllisarvik, which was experimentally drained in 1978. Preliminary analysis showed that the energy contained in the lake water was sufficient for melting the ice content of the resulting drainage channel for both study lakes. Discharge estimated using a glacier-dammed lake model developed

by Clarke (Journal of Glaciology 1982; 28: 3) compared reasonably well with measured discharge during the period of rapid channel enlargement at lllisarvik, and resulted in the draining of Trail Valley Creek lake within the brief period indicated by a gauging station. These results suggest that melting of the ice-rich permafrost during drainage dominates at least the early stages of drainage. However, further work is required to consider the processes of mechanical erosion, which in some cases may dominate the later stages of drainage, and to consider the appropriateness of certain assumptions in the lake drainage model.

Marsh, P. and M. K. Woo (1986). Water balance of a small pond in the High Arctic. Arctic. **30** 109-117.
Abstract: Tundra ponds are ubiquitous features in the High Arctic. The water balance of one such pond situated on Ellesmere Island was found to be dependent upon the groundwater supplies from the internally-drained basin in which it was located. For the basin as a whole, evaporation constituted an important component of the water balance, accounting for over 90 per cent of the rainfall over a summer period of less than six weeks. Changes occurring in the quantity of water in the pond in response to rainfall were found to depend upon the degree of saturation of the active layer of the underlying permafrost.

Matthews, P. C. and S. I. Heaney (1987). Solar heating and its influence on mixing in ice-covered lakes. Freshwater Biology. **18** 135-149.
Abstract: SUMMARY. 1. The influence of solar heating on the formation of temperature and density profiles of ice-covered lakes is considered.
2. Mathematical models are derived to quantify the effect of solar heating on vertical stability and its dependence on critical parameters.
3. Solar heating is shown to be able to account for the thermal structure and mixing patterns of certain ice-covered lakes.
4. The importance of convective mixing is discussed in relation to the distribution of phyloplankton and nutrients.

McNamara, J., D. Kane and L. Hinzman (1998). An analysis of streamflow hydrology in the Kuparuk River Basin, Arctic Alaska: a nested watershed approach. Journal of Hydrology. **206** 39-57.
Abstract: A hydrologic monitoring program was implemented in a nest of watersheds within the Kuparuk River basin in northern Alaska as part of an interdisciplinary effort to quantify the flux of mass and energy from a large arctic area. Described here are characteristics of annual hydrographs and individual storm hydrographs of four basins draining areas of 0.026 km2, 2.2 km2, 142 km , and 8140 km2; an assessment of the influence that permafrost has on those characteristics; and comparisons to rivers in regions without permafrost. Snowmelt runoff dominated the annual runoff in each basin. A typical storm hydrograph in the Kuparuk River basin had a fast initial response time, long time lags between the hyetograph and hydrograph centroids, an extended recession, and a high runoff/precipitation ratio due to the diminished storage caused by permafrost. The seemingly contradictory results of fast response times and extended recessions can be explained by the presence of a large saturated area occupied by hillslope water tracks.

This saturated area provides a partial-source area for fast runoff generation that bypasses the storage capacity of organic soils and tundra vegetation.

McNamara, J., D. Kane and L. Hinzman (1999). An analysis of an arctic channel network using a digital elevation model. Geomorphology. **29** 339-353.
Abstract: Drainage basins possess spatial patterns of similarity that can be characterized by universal qualities in the fractal dimension and the cumulative area distribution. Features called water tracks often drain hillslopes in basins with permafrost and impose significant control on the hydrologic response of watersheds. We analyzed the arrangement of channel networks and water tracks in Imnavait Creek in Northern Alaska to determine if basins with permafrost possess the same universal characteristics as basins without permafrost. Using digital elevation models (DEMs), we explored the hillslope/channel scaling regimes, the spatial distribution of mass through the cumulative area distribution, and the fractal characteristics of channel networks in the Kuparuk River basin in Northern Alaska. Fractal analysis, slope-area analysis, and field mapping suggest that water tracks are positioned on the hillslopes where channels should occur. Fully-developed channel networks, however, possess certain universal characteristics in aggregation patterns that are manifested in a common cumulative area distribution. Imnavait Creek possesses those universal characteristics only above the scale of the hillslope water track, or when the drainage areas reach the main channels in the valley bottom. Our interpretation is that a rudimentary channel network formed on the hillslopes, but never developed into a mature channel network because permafrost is limiting erosion. Consequently, the undissected hillslopes are extensive. Given the dependence of permafrost on a cold climate, a warming climate and subsequent degradation of permafrost may have significant impacts on the erosional development of channel networks in the Arctic.

Mellor, J. (1987). A statistical analysis and summary of radar-interpreted Arctic lake depths: an addendum to 12 map products. Anchorage, BLM.
Abstract: All resolvable (>10 ha) lakes on 12 U. S. Geological Survey 1:250,000 scale quadrangles covering the National Petroleum Reserve in Alaska have been mapped to depict three depth ranges. The ranges were mapped by delineating the ~1.6m and ~4m radar-interpreted isobaths. After a well-trained individual interpreted depths on all 12 quadrangles, fathometer transects were acquired on 157 field verification lakes for statistical comparison with radar-interpreted lake depths. Lakes depicting the ~1.6m radar-interpreted isobath were verified in 99 percent of the 109 test lakes sounded by fathometer. Mean horizontal displacement of the confirmed ~1.6m radar isobaths from the fathometer-determined 1.6m depth was 62m (predominantly shoreward). Lakes with interpreted depths >-4m were verified in only 63 percent of the 27 test lakes sounded by fathometer. Mean horizontal displacement of the confirmed ~4m radar-interpreted isobaths from the fathometer-determined 4m depth was 147m.

Mellor, J. (1994). ERS1 SAR use to determine lake depths in Arctic and sub-Arctic regions. Proceedings of the second ERS1 Symposium-- Space at the service of our environment. Hamburg, Germany. **Special Publication SP36-361** 1141-1146.

Abstract: Water depth is a major factor in predicting resources associated with United States (U.S.) Alaskan Arctic lakes. Side-Looking Airborne Radar (SLAR) imagery was acquired over the National Petroleum Reserve in Alaska (NPR-A) in 1978, 1979 and 1980. Images over the entire NPR-A were acquired during April of 1980. These images were used to interpret lake depths and test the validity of interpreting these areas of depth from shoreline to 1.6m, 1.6m to 4m, and >4m. Ice thickness and fathometer-determined isobaths on 157 field verification lakes were used to analyze validity of interpretation on 21,000 resolvable lakes (greater than 10 ha) published on 12 U.S. Geological Survey 1:250,000 quadrangles covering NPR-A. Changes in radar return intensity of the lakes are a function of physical and dielectric properties of the snow, ice, water, bottom substrates, and gaseous inclusions in ice cover for these lakes. Sequential Synthetic Aperture Radar (SAR) images from the European Remote-Sensing Satellite (ERS-1) have been compared with the above SLAR data. ERS-1 SAR images were acquired during the winters of 1991-1992 and 1992-1993. Image analysis locations for the winter of 1991-1992 were the Siberian, Canadian and Alaskan Arctic and the Alaskan subarctic. During the winter of 1992-1993 sequential images over the Alaskan Arctic and scenes from the Canadian and U.S. subarctic were analyzed. The primary emphasis was to relate SAR return brightness characteristics to lake depths. Some other brightness characteristics from ice and snow cover were noted. Bright returns from berms of snow trails were visible and some SAR return signatures indicative of depth were noted on large frozen rivers. Preliminary assessments of the ERS-1 Satellite SAR data are favorable, indicating that SAR data interpretation: a) duplicates SLAR depth interpretation capability; b) will provide circumpolar capability in lakes with similar bathymetric characteristics; c) has potential for extending interpretation capability into the subarctic; and d) can provide for future repetitive synoptic SAR images that may provide refined depth interpretation capability, as well as, regional monitoring of the depth of freeze each winter. Radar-interpreted lake depths interpreted from shallow northern lakes may help delineate access points and routes such as safe winter trails and ice landing strips. Resource values, such as potential over wintering fish habitat, waterfowl breeding and feeding habitats and fresh water availability, may be better defined. These data can help us manage, enhance and develop these resources while mitigating impacts from potentially conflicting aquatic resource use. In addition to determining regional aquatic resource information associated with surface water depths, SAR images may be useful in regional monitoring of each winter's depth of freeze. Once ERS-1 SAR is successfully applied to determine depths of remote lakes in the northern hemisphere, a network of selected lakes with extensive shallow shelves may be used to monitor ice thicknesses (a summation of winter freezing) synoptically. This may become useful in monitoring of local, regional and global change.

Mendez, J., L. Hinzman and D. Kane (1998). Evapotranspiration from a wetland complex on the Arctic coastal plain of Alaska. Nordic Hydrology. **29** 303-320.
Abstract: Evapotranspiration (ET) from an arctic coastal wetland near Prudhoe Bay, Alas-ka, was studied during the summers between 1994 and 1996. The purpose of the study was to compare different ET models and to gain a better understanding of evapotranspiration from arctic wetlands. The models used to obtain ET from the watershed were the Bowen ratio energy balance (BREB), Priestley-Taylor (PT), Penman-Monteith (PM), Penman Combination (PC), energy balance (EB), water balance (WB),

and WB based on Time Domain Reflectometry (TDR). For one of the ponds, evaporation determined by the EB, PT, PC, BREB, WB, and the aerodynamic (AD) methods were also compared. ET during the summer snow-free period for the watershed averaged 1.45 mm/day obtained via the BREB model. Evaporation from all ponds after spring snowmelt averaged 3.11 mm/day (obtained via the WB). Evaporation rate from ponds was on average twice that of the tundra as a whole. Latent heat flux was the dominant energy sink in wetlands and ponds, whereas sensible heat flux dominated in the drier upland area. The PT and PM models compared well to the BREB (used as the standard of comparison for ET) for 1994 and 1995, once parameters were properly calibrated using 1996 data. The BREB compared well with independent values of ET from the water balance and eddy correlation methods. For the pond, the EB, BREB, WB, PT, and AD methods gave very similar evaporation results for the summer.

Michael Baker Jr (2000). Alpine Development Water Supply, 1999 Monitoring and Assessment. Fairbanks, AK, Prepared for ARCO Alaska, Inc., by Michael Baker Jr. Inc. 8 pages plus 1 appendix.

Michael Baker Jr (2002). National Petroleum Reserve Alaska 2002 Lake Monitoring and Recharge Study. Anchorage, AK, Prepared for ConocoPhillips 67 pages, plus appendices.

Michael Baker Jr (2002). Alpine facility and vicinity, 2002 Lake monitoring and recharge study. Anchorage, Alaska, Prepared for Conoco Phillips by Michael Baker Jr., Inc. 20 pages plus appendices.

Michael Baker Jr. (2002). Kuparuk 2002 Lake Monitoring and Recharge Study. Anchorage, AK, Prepared for ConocoPhilips by Michael Baker Jr., Inc. 15 pages, plus appendices.

Milner, A. and M. Oswood (1997). Freshwaters of Alaska: Ecological synthesis. Ecological Studies. M. M. Caldwell. New York, Springer-Verlag. **119** 369.
Abstract: No abstract

Morack, J. L. and J. C. Rogers (1981). Seismic evidence of shallow permafrost beneath islands in the Beaufort Sea, Alaska. Arctic. **34** 169-174.
Abstract: Shallow ice-bonded permafrost has been shown by seismic refraction methods to exist beneath several islands in the Beaufort Sea. The marked contrast of seismic velocities in bonded materials (> 2500 m/sec) and unbonded materials (< 2100 m/sec) was used to determine the location of permafrost. In many cases these data were confirmed by shallow probing and drill holes.
Several general conclusions are made about the distribution of shallow bonded permafrost beneath islands in the Beaufort Sea. Shallow permafrost occurs under areas where remnants of tundra stili exist. These conditions exist on the larger islands that have not been eroded away by the ocean. Islands which have been eroded by the ocean, leaving only accumulation of sand and gravel, are generally moving westward and landward and for the most part are not underlain by shallow permafrost. However, the oldest and most persistent parts of these islands are in some cases underlain by shallow

permafrost. This is believed to be a consequence of repeated freezings and thawings causing a reduction of salt brine in the sediments and allowing the materials to freeze.

Morrissey, L. A., S. L. Durden, G. P. Livingston, J. A. Stearn and L. S. Guild (1996). Differentiating methane source areas in Arctic environments with multitemporal ERS-1 SAR data. IEEE TGRS. **34** 667-673.

Abstract: Abstract-An assessment using ERS-1 SAR data to differentiate methane source (wetland) and nonsource (nonwetland) areas was undertaken based on radar backscatter modeling and empirical observations of 24 scenes collected over Barrow, AK, in 1991 and 1992. Differences in backscatter between source and nonsource areas were dependent on surface hydrology and air temperature. Differential freezing of surface materials on daily to seasonal time scales greatly enhanced the separability of wetlands and nonwetlands with ERS-1 SAR. Radar return for nonwetlands decreased dramatically whereas backscatter from wetlands decreased little when freezing air temperatures coincided with the SAR overpass. Maximum separability between wetlands and nonwetlands, as determined from observed and modeled radar backscatter, were the result of changes in the dielectric constant of the plant and surface materials with phase change during freezing. This study has indicated the need to consider air temperature at the time of acquisition in selecting ERS-1 SAR scenes for differentiating methane source and nonsource areas.

Moulton, L. (1998). Lakes samples for fish in and near the Colville River Delta, Alaska, 1979-1998. Lopez Island, WA, Prepared for ARCO Alaska, Inc., by MJM Research 513 pages.

Moulton, L. (2000). Fish utilization of lakes in eastern NPR-A 1999-2000. Lopez Island, WA, Prepared for Phillips Alaska, Inc., by MJM Research 129 pages.

Moulton, L. (2000). Fish occurrence in lakes of the CD-South Exploration Area. Lopez Island, WA, Prepared for Phillips Alaska, Inc., by MJM Research 60 pages.

Moulton, L. (2000). 2000 North Slope fish survey, preliminary summary of eastern NPR-A and Alpine results. Lopez Island, WA, Prepared for Phillips Alaska, Inc., by MJM Research 8 pages plus 1 appendix.

Moulton, L. (2001). Fish occurrence in lakes of the CD-North Exploration Area. Lopez Island, WA, Prepared for Phillips Alaska, Inc., by MJM Research 91 pages.

Moulton, L. (2001). Monitoring of water-source lakes in the Alpine Development Project: 2000. Lopez Island, WA, Prepared for Phillips Alaska, Inc., by MJM Research 6 pages plus appendices.

Moulton, L. (2002). Evaluation of potential fish habitat in lakes in the Grizzly/Heavenly/Supercub region - 2001. Lopez Island, WA, Prepared for Phillips Alaska, Inc., by MJM Research 98 pages.

Nekrasov, I. A. Ice cover on Lake El'gygytgyn.

Ledyanoy pokrov ozera El'gygytkhyn. Zapiski Chukotskogo Krayevedcheskogo Muzeya no.3; p.8-10;   graph, illus.;   4 refs.
Abstract: Reports on the ice conditions of this lake as observed during three months. Freeze-up begins in Sept and breakup ends in Aug. In colder years the ice remains throughout the entire year. Its thickness, hummocks, gas inclusions, temperature and other features are briefly characterized. Formation of cracks and ice behavior through the course of the seasons are briefly noted.

Nelson, F. E., K. M. Hinkel, N. I. Shiklomanov, G. R. Mueller, L. L. Miller and D. A. Walker (1998). Active-layer thickness in north-central Alaska: systematic sampling, scale, and spatial autocorrelation. Journal of Geophysical Research-Atmospheres. **103** 26963-28973.
Abstract: Active-layer thickness was determined in late August 1995 and 1996 at 100 m intervals over seven 1 km2 grids in the Arctic Coastal Plain and Arctic Foothills physiographic provinces of northern Alaska. Collectively, the sampled areas integrate the range of regional terrain, soil, and vegetation characteristics in this region. Spatial autocorrelation analysis indicates that patterns of active-layer thickness are governed closely by topographic detail, acting through near-surface hydrology. On the coastal plain, maximum variability occurs at scales involving hundreds of meters, and patterns were similar in the two years. Substantially less spatial structure and interannual correspondence were found within the foothill sites, where high variability occurs over smaller distances. The divergence in patterns of thaw depth between the two provinces reflects the scale of local terrain features, which predetermines the effectiveness of fixed sampling intervals. Exploratory analysis should be performed to ascertain the scale(s) of maximum variability within representative areas prior to selection of sampling intervals and development of long-term monitoring programs.

Nolan, M., G. Liston, P. Prokein, J. Brigham-Grette, V. Sharpton and R. Huntzinger (2003). Analysis of lake ice dynamics and morphology on Lake El'gygytgyn, NE Siberia, using synthetic aperture radar (SAR) and Landsat. J. Geophys. Res. **108** doi:10.1029/2001JD000934.
Abstract: A time series of more than 450 combined ERS-2, Radarsat-1, and Landsat-7 scenes acquired between 1998 and 2001 was analyzed to develop a fairly complete picture of lake ice dynamics on Lake El'gygytgyn, NE Siberia (67.5°N, 172°E). This 14-km3 lake partially fills a meteorite impact crater formed 3.6 million years ago and is home to a paleoenvironmental coring project. The duration of lake ice cover and the onset of lake ice breakup are important both to interpretations of the archived sediment core record and to future drilling projects that will use the ice as a stable platform. Ice formation, snowmelt, and ice breakup likely occur in late October, mid-May, and early July, respectively. These data were used to validate a one-dimensional energy-balance lake ice model, which can now be used to hindcast paleoclimate based on core proxy information. Synthetic aperture radar (SAR) backscatter from the lake ice also revealed unusual spatial variations in bubble content, which were found to indicate the level of biological productivity in the sediments directly beneath the ice, with the highest productivity located in the shallowest (0-10 m) as well as the deepest (170 -175 m) regions of the lake. Seismic data indicates that the backscatter anomaly above the deepest

water is collocated with the central peak of the impact crater, 500 m below the surface. Several hypotheses are presented to explain this anomaly. Regardless of cause, the fact that large spatial variations in biological productivity exist in the lake has important implications for selecting the locations of future sediment cores.

Nolan, M., G. Liston, P. Prokein, J. Brigham-Grette, V. Sharpton and R. Huntzinger (2003). Analysis of lake ice dynamics and morphology on Lake El'gygytgyn, NE Siberia, using synthetic aperture (SAR) and Landsat. J. Geophys. Res. **108** 8162.

NRC (2003). Cumulative environmental effects of oil and gas activities on Alaska's North Slope. G. Orians. Washington DC, National Academies Press 288.
Abstract: No abstract

Ostercamp, T. E. and V. E. Romanovsky (1999). Evidence for warming and thawing of discontinuous permafrost in Alaska. Permafrost and Periglacial Processes. **10** 17-37.
Abstract: Data show that permafrost temperatures along a north south transect of Alaska from Old Man to Gulkana and at Healy generally warmed in the late 1980s to 1996. This trend was not followed at Eagle, about 330 km east of the transect. Estimates of the magnitude of the warming at the permafrost table ranged from 0.5°C to 1.5°C. Warming rates near the permafrost table were about 0.05 to 0.2°C/a. No reliable trends in the depth of the base of ice-bearing permafrost or in the depth of the 0 °C isotherm could be detected. Thermal offset allowed mean annual temperatures at the permafrost table to remain below 0 °C with ground surface temperatures up to 2.5°C for a period of 8 years. The observed warming has probably caused discontinuous permafrost in marginal areas to begin thawing. Thawing permafrost and thermokarst have been observed at several sites. Thawing rates at the permafrost table at two sites were about 0.1 m/a, indicating time scales of the order of a century to thaw the top 10 metres of ice-rich permafrost. Calculated thawing rates at the permafrost base are an order of magnitude smaller. Calibrated numerical models indicate that the permafrost warmed in the late 1960s and early 1970s in response to changes in air temperatures and snow covers. Additional warming in the late 1970s was caused by an increase in air temperatures beginning in 1977. Permafrost temperatures were nearly stable during the 1980s and then warmed again from the late 1980s to 1996, primarily in response to increased snow depths. This interpretation appears to be valid for all the sites in the region of the transect and at Healy. Copyright € 1999 John Wiley & Sons, Ltd.

Osterkamp, T. E., L. Viereck, Y. Shur, M. T. Jorgenson, C. Racine, A. Doyle and R. D. Boone (2000). Observations of thermokarst and its impact on boreal forests in Alaska, USA. Arctic and Alpine Res. **32** 303-315.
Abstract: Thermokarst is developing in the boreal forests of Alaska where ice-rich discon-tinuous permafrost is thawing. Thawing destroys the physical foundation (ice-rich soil) on which boreal forest ecosystems rest causing dramatic changes in the ecosystem. Impacts on the forest depend primarily on the type and amount of ice present in the permafrost and on drainage conditions. At sites generally underlain by ice-rich permafrost, forest ecosystems can be completely destroyed. In the Mentasta Pass area, wet sedge meadows, bogs, thermokarst ponds, and lakes are replacing forests. An upland

thermokarst site on the University of Alaska Campus consists of polygonal patterns of troughs and pits caused by thawing ice-wedge polygons. Trees are destroyed in corresponding patterns. In the Tanana Flats, ice-rich permafrost supporting birch forests is thawing rapidly and the forests are being converted to minerotrophic floating mat fens. At this site, an estimated 83 of 2.6*105 ha was underlain by permafrost a century or more ago. About 42 of this permafrost has been influenced by thermokarst development within the last 1 to 2 centuries. Thaw subsidence at the above sites is typically 1 to 2 m with some values up to 6 m. Much of the discontinuous permafrost in Alaska is ex-tremely warm, usually within 1 or 2°C of thawing, and highly susceptible to thermal degradation. Additional warming will result in the formation of new ther-mokarst.

Phelps, A. R., K. M. Peterson and M. Jeffries (1998). Methane efflux from high latitude lakes during spring ice melt. J. Geophys. Res. **103** 29,029 - 29,036.
Abstract: Ice cores removed from shallow ice-covered tundra lakes near Barrow, Alaska, and taiga lakes near Anchorage, Alaska, exhibit increasing concentrations of methane with depth. Methane concentrations in the ice cores increased from 0 uM in the top 15 cm sections to a maximum of 23 uM in the lowest 15 cm sections of tundra lake ice and to a maximum of 147 uM in taiga lake ice. Methane concentrations in the water beneath the ice reflect a similar pattern, with values near 5 uM early in the ice-covered season, increasing up to 42 uM in the tundra lakes, and up to 730 uM in the taiga lakes. Methane levels increase in the water beneath the ice during the course of the winter due to decreasing water volume, exclusion from growing ice, and continued methane production in thawed sediments. Since the ice layer prohibits gas exchange with the atmosphere, the methane is not oxidized, as it would be during the summer months, allowing the winter accumulation and storage of methane in the ice and lake waters. Efflux measurements, taken with floating chambers on the taiga lakes, indicated a large pulse of methane released during the period of ice melt and spring turnover. The efflux from one lake ranged from 2.07 g CH4 m-2 in 1995 to 1.49 g CH4 m-2 in 1996 for the 10 day period immediately after ice melt. Estimation of methane efflux using a boundary layer diffusion model and surface water concentrations during the entire ice-free period in 1996 predicted an efflux of 1.79 g CH4 m-2 during the same 10 day period, compared with 2.28 g CH4 m-2 for the remainder of the summer season. This observation suggests that almost as much methane efflux can occur during a brief period immediately after ice melt as occurs during the remainder of the ice-free season. Since measurements of methane efflux from high-latitude-lakes are generally made after this breakup period, the overall contribution to atmospheric methane from high-latitude lakes may be twice that of current estimates.

Price, L., L. C. Bliss and J. Svoboda (1974). Origin and signficance of wet spots on scraped surfaces in the high Arctic. Arctic. **27** 304-306.
Abstract: No abstract

Ramlal, P. S., R. E. Hesslein, R. E. Hecky, E. J. Fee, J. W. Rudd and S. J. Guilford (1994). The organic carbon budget of a shallow, arctic tundra lake on the Tuktoyaktuk Peninsula, NWT, Canada. Biogeochemistry. **24**.

Rampton, V. N. (1973). The influence of ground ice and thermokarst upon the geomorphology of the Mackenzie-Beaufort region. 3rd Guelph Symposium on Geomorphology, Guelph. Guelph, Ontario 43-60.

Abstract: No abstract, this is the Introduction: The Mackenzie-Beaufort region encompasses the Yukon coastal plain and adjacent mountain ranges, the Mackenzie Delta, Richards Island, Tuktoyaktuk Peninsula, and areas southeast and east of the Eskimo Lakes and Liverpool Bay (Figure 1). Most of the area has been glaciated, although not necessarily during late Wisconsin time. The geology of the area varies from areas of bedrock outcrop in the mountains west of the Mackenzie Delta and in the hills south of Inuvik to thick Pleistocene and recent accumulations of fine-grained deltaic sediments in the Mackenzie Delta itself.

The two areas of greatest interest are that part of the Yukon coastal plain where Pleistocene sediments are in excess of 200 ft (70 m) and the Pleistocene Coastlands (Mackay, 1963) east of the Mackenzie Delta where again the Pleistocene sediments are well in excess of 200 ft (70 m) through-out most of the area. A typical stratigraphic sequence along the glaciated Yukon coastal plain might show from top to bottom:

5 ft (1.5 m) ± Peat
20 ft (6.1 m) ± Lacustrine sand, silt, and clay, generally organic
15 ft (4.6 m) ± Till, the upper portion in part reworked
50 ft (15.2 m) ± Preglacial fluvial, lacustrine, estuarine, and marine sediments; generally these sediments are fine-grained but occasionally fluvial gravels and sands may be exposed.

Typical of the Pleistocene Coastlands east of the Mackenzie Delta is an exposure reported in Fyles et al, (1972) which shows from top to bottom:

8 ft (2.4 m) Sand, fine-grained; eolian
0.5 ft (0.15 m) Gravel, sandy (slopewash)
5 ft (1.5 m) Sand, fine-grained; deltaic; unit often in excess of 50 ft
(15.2 m)
35 ft (10.6 m) Sand, medium-grained; glaciofluvial (?)
45 ft (13.7 m) Clay, silty; marine
30 ft (9.1 m) Massive ice In some areas, such as immediately east of Tuktoyaktuk, till at the strati-graphic level of the gravelly slopewash may thicken to more than 20 ft (6.1 m). In other areas, the section appears to have been truncated by glaciofluvial activity and is capped by glaciofluvial sand or gravel. Accumul-ations of lacustrine sediments range up to 20 ft (6.1 m) thick in some basins. The above gives only a very generalized picture of the stratigraphy; for more details the reader is referred to Hughes (1972), Mackay (1959, 1963). Naylorefa/, (1972) and Rampton (1970, 1971a, 1972a, b, c, d).

Topography of the Yukon coastal plain and the Pleistocene Coastlands is for the most part gently rolling to hummocky. Rampton and Mackay (1971) have described the topography of Richards Island and the Tuktoyaktuk Peninsula as follows: "Richards Island and the southern and central parts of the peninsula consist of rolling hills with local relief sometimes attaining 300 ft (91.4 m). The topography of this hilly plain varies from one of closely spaced hills with steep slopes to one of broad hills with more gentle slopes. Depressions separating these broad hills may be more than a mile across. All areas are characterized by an abundance of lakes ..." However low broad areas of outwash such as the northern tip of the Tuktoyaktuk Peninsula are relatively flat - the

only relief being small sand dunes or 5-20 ft (1.5-6.1 m) scarps marking old lake boundaries.
The objective of this paper is to describe the ground ice present in the terrain and sediments described above, its landform expression, and the effect of its melting upon the geomorphology. In addition to observations by myself on permafrost phenomena made during a regional inventory of Quaternary deposits and landforms in the Mackenzie-Beaufort region, the paper includes information from permafrost studies conducted by J.R. Mackay (e.g. Mackay, 1972a) and others (e.g. Kerfoot, 1972).

Rawlins, S. E. (1983). Prudhoe Bay, Alaska: Guidebook to Permafrost and Related Features. Fairbanks, AK, Department of Natural Resources Division of Geological and Geophysical Surveys 140-143.
Abstract: No abstract

Reanier, R. (2000). Year 2000 lake studies in the Phillips Exploration Area, National Petroleum Reserve - Alaska. Seattle, WA, Prepared for Phillips Alaska, Inc., by Reanier & Associates 8 pages plus 1 appendix.

Rex, R. W. (1960). Hydrodynamic analysis of circulation and orientation of lakes in Northern Alaska. Geology of the Arctic, Proceedings of the First International Symposium on Arctic Geology. Raasch. Calgary, Alberta, University of Toronto Press. **2** 1021-1043.
Abstract: A theoretical horizontal circulation system is described for a circular lake with a constant wind blowing across it.
The shape of many oriented lakes in northern Alaska indicates that their present circulation system approaches the theoretical one, and that it is this system to which they owe their orientation.
Because the Carolina Bays are oriented along the probable direction of the winds which excavated them they are believed to be deflation basins, and not lakes whose shape is due to wave action and water circulation.

Reynolds, J. F. (1996). Landscape function and disturbance in Arctic tundra. J. F. T. Reynolds, John D. Berlin, Springer-Verlag 437.
Abstract: No abstract

Rosenfeld, G. A. and K. M. Hussey (1958). A consideration of the problem of oriented lakes. Iowa Academy of Science Proceedings. **65** 279-286.
Abstract: The problem of oriented lakes has been a subject of controversy in North America as well as other parts of the world. Much has been written on why lakes are oriented, but for the most part no suitable theories have been proposed that satisfactorily explain some of the observed facts associated with orientation. The two most famous examples in North America are the Carolina Bays, located on the Atlantic Coastal plain in the Carolina region, and the Oriented Lakes of Northern Alaska. For both of these areas, several widely differing theories on cause of orientation have been proposed. Some workers have attempted to compare the two areas and have proposed the same origin for both. The writers have worked primarily with the Alaskan lakes and necessarily are more familiar with that area. However, the discussion to follow may be applicable to the

Carolina Bays or other areas of oriented lakes. This paper will not offer a final solution to the problem. Its purpose is to point out some discrepancies in proposed causes of orientation, and to present some different hypotheses in light of new information.

Roulet, N. T. (2000). Peatlands, carbon storage, greenhouse gasses, and the Kyoto Protocol: Prospects and significance for Canada. Wetlands. **20** 605-615.
Abstract: The Kyoto Protocol accepts terrestrial sinks for greenhouse gases (GHGs) as offsets for fossil fuel emissions. Only carbon sequestered in living bioinass from re- and afforestation is presently considered. but the Protocol contains a provision for the possible future inclusion of oilier land uses and soils. As a result, the possibility of sequestration of carbon in wetlands, and particularly peatlands, is being discussed. Natural peatlands are presently a relatively small sink for CO2 and a large source of CH4: globally, they store between 400 and 500 Gt C. There arc large variations among peatlands, but when the "global warming potential" of CH4, is factored in, many peallands are neither sinks nor sources of GHGs. Some land-use changes may result in peatlands acting as net sinks for GHGs by reducing CH4, emissions and/or increasing CO2 sequestration (e.g., forest drainage), while other land uses may result in large losses of CO2, CH4,, and N20 (e.g., agriculture on organic soils, flooding for hydroelectric generation). Other land uses, such as peatland creation and restoration, produce no net change if they are replacing or restoring a previous level of GHG exchange. These arc analogous to reforestation of deforested areas. On closer examination, the inclusion of peallands in a national greenhouse gas strategy as sinks, despite their large role in the terrestrial carbon cycle, may not significantly reduce net greenhouse gas emissons. If the sinks are to be considered. it is reasonable that terrestrial sources associated with all land uses on peatlands also should be considered. If peatlands arc not considered explicitly, but soils in forest and agriculture systems are included in the Kyoto Protocol in the future, then those peallands impacted by these land uses will be incorporated implicitly.

Roulet, N. T. and M. K. Woo (1998). Runoff generation in a low arctic drainage basin. Journal of Hydrology. **101** 213-226.
Abstract: The production of runoff from a small drainage basin in the continuous permafrost area of continental Canada was studied for two years. The basin comprises two main land types (dry tundra slopes and valley bottom wetlands) and several lakes. In spring, meltwater from most parts of the basin contributed to total runoff but the magnitude and timing of slope and wetland runoff differed. In summer this difference in runoff production was more marked. In both seasons the base of the slopes initiated runoff, which increased significantly once the wetlands began to discharge. The combined runoff mechanisms of the two land types and linkages between them provide a general framework for an understanding of runoff generation in low Arctic basins.

Roulet, W. R. and M. K. Woo (1986). Wetland and lake evaporation in the Low Arctic. Arctic and Alpine Research. **18** 195-200.
Abstract: Evaporation from wetland and lake surfaces in the continuous permafrost region of the Low Arctic was studied using an energy balance Bowen ratio approach and lysimeter measure-ments respectively. Daily evaporation was also estimated using the Priestley-Taylor model. Over th.e summer, mean evaporation from the wetland and lake

were similar, but day-to-day variation was large at times. Differences of available energy and surface roughness between the lake and wetland surface produce a larger Priestly-Taylor α value for wetland evapora-tion. The approach presented in this paper can be used to estimate evaporation for wetland and lake surfaces in the low arctic region.

Roulet, W. R. and M. K. Woo (1986). Hydrology of a wetland in the continuous permafrost region. Journal of Hydrology. **89** 73-81.
Abstract: This study examines the hydrological system of a northern wetland in the continuous permafrost region. Water balance computation quantifies the relative importance of various hydrological processes including snowmelt, rainfall, inflows, evaporation, surface and subsurface outflows. The existence of this wetland is closely related to a lake upslope which provides the bulk of the water input.
The ability of northern wetlands to absorb water input is limited by the frozen ground and the high specific retention of the peat, rendering the wetland a poor regulator of streamflow. Storage capacity increases in summer as evaporation reduces the moisture content of the peat. Subsurface flow remains insignificant because of the low hydraulic gradient and conductivity. Thus, when the water table lies within the peat layer, there is little wetland contribution to streamflow but when the water table lies above the ground during some intense storms, streamflow is rapidly increased by surface flow on the wetlands.

Rouse, W. R. and e. al (1977). Evaporation in high latitudes. Water Resources Research. **13** 909-914.
Abstract: A simplified form of the equilibrium model of evaporation predicts evaporation from six subarctic and tundra surfaces with an accuracy of 8%. Input data to the model are net radiation, screen air temperature, and an evaporability factor characteristic of the surface. The radiation and energy balances of the six surfaces are compared.

Rouse, W. R., D. W. Carlson and E. J. Weick (1992). Impacts of summer warming on the energy balance and water balance of wetland tundra. Climatic Change, Vol. 22.
Abstract: Measurements, made at a high subarctic, maritime, wetland tundra site, are presented for three different growing seasons. These are divided into hot-dry, normal-dry and normal-wet years and the behaviour of their surface energy and water balances is examined within the framework of a combination model. For periods of comparable energy availability, evapotranspiration during hot-dry conditions can be larger than during cooler and wetter periods. This results from small stomatal resistance in the sparse canopy of well-rooted sedges, and from the ability of peat soils to supply water under conditions of large atmospheric demand. This demand is expressed in terms of the vapour pressure deficit and it counteracts the large surface resistances which develop during dry periods. In many respects, the energy balance of a subarctic wetland tundra is comparable to observations and models for temperate agricultural and forest lands, in spite of the fact that the soils are organic, the vegetation canopy is sparse and there is continuous permafrost. A dry year promotes deeper thaw depths in the permafrost soils, during the growing season, than does a wet one. This is due to larger ground heat fluxes and larger soil thermal diffusivities. We concluded that maritime, wet-land tundra, growing on peat soils, displays feedback mechanisms, which can off-set the effects of moisture stress,

caused by summer climate warming of a similar magnitude to that simulated by General Circulation Models for a 2 x CO2 scenario.

Rouse, W. R. and a. others (1997). Effects of climate change on the freshwaters of arctic and subarctic North America. Hydrologic Processes, Vol II 873-902.
Abstract: Region 2 comprises arctic and subarctic North America and is underlain by continuous or discontinuous permafrost. Its freshwater systems are dominated by a low energy environment and cold region processes. Central northern areas are almost totally influenced by arctic air masses while Pacific air becomes more prominent in the west, Atlantic air in the east and southern air masses at the lower latitudes. Air mass changes will play an important role in precipitation changes associated with climate warming. The snow season in the region is prolonged resulting in long-term storage of water so that the spring flood is often the major hydrological event of the year, even though, annual rainfall usually exceeds annual snowfall. The unique character of ponds and lakes is a result of the long frozen period, which affects nutrient status and gas exchange during the cold season and during thaw. GCM models are in close agreement for this region and predict temperature increases as large as 4°C in summer and 9°C in winter for a 2 x COs scenario. Palaeoclimate indicators support the probability that substantial temperature increases have occurred previously during the Holocene. The historical record indicates a temperature increase of >1°C in parts of the region during the last century. GCM predictions of precipitation change indicate an increase, but there is little agreement amongst the various models on regional disposition or magnitude. Precipitation change is as important as temperature change in determining the water balance. The water balance is critical to every aspect of hydrology and limnology in the far north. Permafrost close to the surface plays a major role in freshwater systems because it often maintains lakes and wetlands above an impermeable frost table, which limits the water storage capabilities of the subsurface. Thawing associated with climate change would, particularly in areas of massive ice, stimulate landscape changes, which can affect every aspect of the environment. The normal spring flooding of ice-jammed north-flowing rivers, such as the Mackenzie, is a major event, which renews the water supply of lakes in delta regions and which determines the availability of habitat for aquatic organisms. Climate warming or river damming and diversion would probably lead to the complete drying of many delta lakes. Climate warming would also change the characteristics of ponds that presently freeze to the bottom and result in fundamental changes in their limnological characteristics. At present, the food chain is rather simple usually culminating in lake trout or arctic char. A lengthening of the growing season and warmer water temperature would affect the chemical, mineral and nutrient status of lakes and most likely have deleterious effects on the food chain. Peatlands are extensive in region 2. They would move northwards at their southern boundaries, and, with sustained drying, many would change form or become inactive. Extensive wetlands and peatlands are an important component of the global carbon budget, and warmer and drier conditions would most likely change them from a sink to a source for atmospheric carbon. There is some evidence that this may be occurring already. Region 2 is very vulnerable to global warming. Its freshwater systems are probably the least studied and most poorly understood in North America. There are clear needs to improve our current knowledge of temperature and precipitation patterns; to model the thermal behaviour of wetlands, lakes

and rivers; to understand better the interrelationships of cold region rivers with their basins; to begin studies on the very large lakes in the region; to obtain a firm grasp of the role of northern peatlands in the global carbon cycle; and to link the terrestrial water balance to the thermal and hydrological regime of the polar sea. Overall, there is a strong need for basic research and long-term monitoring.

Rovansek, R., L. Hinzman and D. Kane (1996). Hydrology of a tundra wetland complex on the Alaskan Arctic coastal plain, USA. Arctic and Alpine Research. **28** 311-317.
Abstract: The hydrology of the Alaskan Arctic Coastal Plain is investigated by studying a complex of small ponds and wetlands near Prudhoe Bay, Alaska. The two summers (1992-93) during which this study took place were both drier than normal in the early part of the season. Summer water balance after snowmelt is dominated by evapotranspiration (ET), which exceeds precipitation in both ponds and wet-lands. Water levels drop through June and July, when ET is greatest, and recover somewhat during August, when precipitation increases and ET decreases. Ponds and wetlands, which experience a net loss of water over the summer, are filled to capacity by snowmelt runoff in spring. Ponds and wetlands serve as storage sites for snowmelt runoff; the net loss of water over the wetland watershed from the previous summer must be replenished by snowmelt waters before runoff can leave the basin. Annual ET from ponds and wetlands exceeds annual precipitation and, as a result, snowmelt runoff from surrounding upland areas is necessary to maintain wetlands and ponds.

Ruhland, K. S., J.P. (1998). Limnological characteristics of 70 lakes spanning arctic treeline from Coronation Gulf to Great Slave Lake in the central Northwest Territories, Canada. International Review of Hydrobiology. **83** 183-203.
Abstract: Latitudinal transects across subpolar ecozones display striking changes in lakewater chemistry reflecting steep gradients in vegetation, climate, and other variables. This paper explores the relationships among chemical and physical lakewater characteristics of 70 lakes spanning arctic treeline in Canada's Central Northwest Territories. Principal components analysis (PCA) was used to examine trends and relationships among environmental variables and these 70 sites. In general, lakes in this dataset were dilute, slightly acidic to slightly alkaline, and nutrient-poor. However, a strong trend toward more concentrated lakewater conditions in densely forested areas was observed relative to tundra regions. Interrelationships among measured limnological variables appear to be strongly influenced by catchment characteristics associated with proximity of sites to treeline.

Schmidt, D. R., W. B. Griffiths and L. R. Martin (1989). Overwinting biology of anadromous fish in the Sagavanirktok River delta, Alaska. Biol. Pap. Univ. Alaska. **24** 55-74.

Sellman, P. V., J. Brown, R. I. Lewellen, H. McKim and C. Merry (1973). The classification and geomorphic implications of thaw lakes on the Arctic coastal plain, Alaska, Cold Regions Research and Engineering Laboratory 21.
Abstract: No abstract

Sellman, P. V., W. F. Weeks and W. J. Campbell (1975). Use of side looking airborne radar to determine lake depth on the Alaskan North Slope. Hanover, NH, Cold Regions Research and Engineering Laboratory.

Abstract: Side-looking airborne radar (SLAR) imagery obtained in April-May 1974 from the North Slope of Alaska between Barrow and Harrison Bay indicates that tundra lakes can be separated into two classes based on the strength of the radar returns. Correlations between the areal patterns of the returns, limited ground observations on lake depths, and information obtained from ERTS imagery strongly suggest that freshwater lakes giving weak returns are frozen completely to the bottom while lakes giving strong returns are not. Brackish lakes also give weak returns even when they are not completely frozen. This is presumably the result of the brine present in the lower portion of the ice cover limiting the penetration of the X-band radiation into the ice. Although the physical cause of the differences in radar backscatter has not been identified, several possibilities are discussed. The ability to rapidly and easily separate the tundra lakes into these two classes via SLAR should be useful in a wide variety of different problems.

Semiletov, I. P. (1999). Aquatic sources and sinks for CO2 and CH4 in the polar regions. J. of the Atm. Sci. **56** 286-306.

Abstract: The highest concentration and greatest seasonal amplitudes of atmospheric CO2 and CH4, occur at 600-700N. outside the 30°-60°N band where the main sources of anthropogenic CO2 and CH4 are located, indicating that the northern environment is a source of these gases. Based on the author's onshore and offshore arctic experimental results and literature data, an attempt was made to identify the main northern sources and sinks for atmospheric CH4 and CO2. The CH4 efflux from limnic environments in the north plays a significant role in the CH4 regional budget, whereas the role of the adjacent arctic adjacent seas in regional CH4 emission is small. This agrees with the aircraft data, which show a 10-15 increase ofCH., over land when aircraft fly southward from the Arctic Basin. Offshore permafrost might add some CH., into the atmosphere, although the preliminary data are not sufficient to estimate the effect. Evolution of the northern lakes might be considered as an important component of the climatic system. All-season data obtained in the delta system of the Lena River and typical northern lakes show that the freshwaters are supersaturated by CO2 with a drastic increase in the CO2 value during wintertime. The arctic and antarctic CO2 data presented here may be used to develop understanding of the processes controlling CO2 flux in the polar seas. It is shown that Arctic seas are a sink for atmospheric CO2, though supersaturation by CO2 is obtained in areas influenced by riverine output and in coastal sites. The pCO2 difference between the surface of the Southern Ocean and atmosphere observed in the austral autumn shows that the area east of 7°W might be considered a source of CO2 into the atmosphere, whereas the area west of 7°W is a net sink of CO2. This is corroborated with literature data that indicate an overestimate of the role of antarctic waters as a sink for atmospheric CO2.

Shannon & Wilson (1996). Flood-frequency analysis for the Colville River, North Slope, Alaska. Fairbanks, AK, Shannon & Wilson, Inc. 11 pages plus appendices.

Sherman, R. (1973). A groundwater supply for an oil camp near Prudhoe Bay, Arctic Alaska. Second International Permafrost Conference. Yakutsk, USSR, National Academy of Sciences 469-472.

Abstract: Attempts to locate supplies of potable water in northern Alaska have met with little success: Aquifers near the sur-face in unconsolidated deposits are perennially frozen to a depth of at least 150 m; ponds and streams are not resup-plied during the long, cold winters; and unfrozen bedrock beneath the frozen layer is generally of low permeability and contains brackish to saline water. Careful planning in locating campsites and in designing sanitary facilities to prevent pollution is required due to the limited water supplies, the susceptibility to contamination, and the expense of piping water in heated water lines to points of use.

In designing an oil camp on the west bank of the Sagavanirktok River 11 km south of Prodhoe Bay, the first step was to locate a year-round supply of potable water. Previous studies at Barrow, Umiat, Cape Lisbume, Antarctica, and Greenland indicate that three potential sources of water should be investigated: ponds, the river, and deep or shallow aquifers. Permafrost thickness of as much as 610 m in the campsite area eliminated consideration of deep aquifers. Potential sources in lakes and in the nearby Sagavanirktok River and in aquifers beneath the lakes and the river were explored.

Skopets, M. (1992). Secrets of Siberia's white lake. Natural History. **11** 2-4.

Abstract: Describes ichthyological expedition to lake El'gygytgyn in Chukotskiy Avtonomnyy Okrug in 1979 and discovery there of new species of char Salvethymus svetovidovi. Lake has ecosystem which has been uninterrupted for three million years and contains several species of invertebrates not found elsewhere

Smith, M. (1976). Permafrost in the Mackenzie Delta, Northwest Territories, Geological Survey of Canada 34.

Abstract: Variations in ground temperature regime and permafrost distribution -were studied between 1969 and 1971 in a small area in the east-central part of the Mackenzie Delta about 50 km north-west of Inuvik, North-west Territories. The Delta is an area of active sedimen-tation and erosion, and about 50 per cent of the study area is covered by -water. A major distributary in the study area is undergoing lateral migration, and the local configuration of permafrost is closely related to the history of river migration. The vegetation shows a successi'ona! sequence related to river migration indicating a complex interaction between vegetation, topography, and microclimate.

The major objectives of the study -were to:

(1) describe the permafrost and ground temperature variations in the study area;

(2) understand how local environmental factors influence the ground temperature field; and

(3) analyze the development of the present ground temperature field in terms of its position in the long-term migration history of a shifting channel.

In order to monitor the ground temperature variations, boreholes -were drilled to various depths up to 30 m. Temperatures -were measured with thermistors, and these measurements were augmented with seismic and resistivity surveys. Lake and river temperatures also were recorded and ground materials were sampled from boreholes. Measurements of ground temperatures, snow depths, and ice cover were made in winter.

Permafrost is discontinuous; calculations indicate that permafrost is absent beneath channels and lakes that are wider than 80 to 100 m. Ground temperatures are warmer close to water bodies, and the permafrost table falls steeply beneath cutbanks. Observations indicate permafrost thicknesses of between 50 to 65 m in stable, spruce-covered areas. Calculations show that the maximum permafrost thickness in the area is about 100m at sites most distant from water bodies. Beneath slip-off slopes, where temperatures are warmer than beneath cutbanfcs, permafrost is only 2. 5 to 9 m thick, thickens away from the river, and disappears towards it. Permafrost is absent in some places where winter snow drifts are deep.
Using simple heat conduction theory a consistent explanation of permafrost distribution in terms of local environmental factors is developed. The heat conduction models are suitable for ground temperature prediction, with agreement typically within ±0. 5°C of observed values for most sites. Calculations of thermal disturbance due to channel shifting are in general agreement with observations, although omission of the latent heat term leads to some errors.

Stefanovic, D. and H. Stefan (2002). Two-dimensional temperature and dissolved oxygen dynamics in the littoral region on an ice-covered lake. Cold Regions Science and Technology. **34** 159-178.
Abstract: Temperature and dissolved oxygen were measured along a transect of Ryan Lake, MN, from February 3 to March 25, 1999 to gain information on water quality dynamics associated with convective exchange processes between littoral and profundal regions of an ice-covered mid-latitude lake. The observations show a difference in the vertical distribution of heat and dissolved oxygen between the shallow and deep regions of a freshwater lake, and imply significant horizontal transport under the ice cover. The new measurements complement the lake database for winter observations, and will be used to improve predictive numerical modeling of lake mixing dynamics and water quality under the ice. Herein, the data and their analysis are presented.

Stewart, R. B. and W. R. Rouse (1976). Simple models for calculating evaporation from dry and wet tundra surfaces. Arctic and Alpine Research. **8** 263-274.
Abstract: Energy-budget calculations and equilibrium evaporation estimates from a well-drained lichen-dominated raised beach ridge and a wet sedge meadow in the Hudson Bay lowlands are presented. Energy-budget calculations reveal that on average 54 and 66% of the daily net radiation are utilized in the evaporative process over a ridge and sedge meadow surface, respectively. For the ridge, half-hourly and daily values of evaporation were approximated closely by equilibrium estimates, while for the sedge meadow close approximation was achieved by the Priestley and Taylor (1972) model where the ratio of actual to equilibrium evaporation equals 1.26. A simple model, expressed in terms of incoming solar radiation and air temperature, is developed for each surface from the comparison of actual and equilibrium evaporation. Tests of the models at different locations indicate that the actual evaporation can be estimated on a daily basis within +/-10%, for dry upland and saturated sedge meadow surfaces,

Streever, B., S. Bedwald, A. McCusker and B. Shaftel (2001). Winter measurements of water quality and water levels: the effects of water withdrawal for ice road construction on lakes of the NPR-A. Anchorage, AK, BP Exploration Alaska.

Stuart, L., S. Oberbauer and P. C. Miller (1982). Evapotranspiration measurements in Eriophorum vaginatum tussock tundra in Alaska. Holarct. Ecol. **5** 145-149.
Abstract: Evapotranspiration was measured periodically from late June through mid-August 1978 in Eriophorum vaginaium tussock tundra near Eagle Creek, Alaska. The average evapotranspiration rates from tussock and intertussock areas were 0.8 m/d and 1.3 mm/d, respectively. Potential evaporation was calculated according to the Penman equation using microclimate data collected at the same time actual evapo-transpiration was measured. Actual evapotranspiration was 0.56 ± 0.06 (X ± SE, N = 10) of the potential evaporation from moss and 0.43 ± 0.08 (X ± SE, N = 10) of the potential evaporation from E. vaginatum tussocks. Seventy three percent of the variability in the ratio of actual evapotranspiraiion to potential evaporation from tussocks was accounted for by linear regression on net radiation. Eighty nine percent of the variability in the same ratio for mosses was explained by linear regression on the vapor pressure deficit of the air and net radiation.

Swift, C. T., W. L. Jones, R. F. Harrigton, J. C. Fedors, R. H. Couch and B. L. Jackson (1980). Microwave radar and radiometric remote sensing measurements of lake ice. Geophysical Research Letters. **7** 243-246.
Abstract: Abstract. Simultaneous microwave radar and spectral radiometric data were collected over Lake Erie during March 1978. A theoretical development is presented which interprets the data collected at nadir in terms of changes in the ice thickness and the electromagnetic attenuation coefficient. The theory also addresses the failure of the spectral radiometer to determine ice thickness through observations of quarter wavelength excursions in the reflec-tivity. Radar data collected off-nadir showed a substantially different behavior compared to that collected near nadir. This difference is attributed to a change in propagation characteristics from quasi-specular return from the ice-water interface to scattering from the rough air-ice interface.

Tedrow, J. C. (1969). Thaw lakes, thaw sinks, and soils in northern Alaska. Biuletyn Perylacijalny. **20** 337-344.
Abstract: Thaw lakes and thaw sinks are present in the aeolian silts just south of Umiat, Alaska. Through headward erosion, thawing of perennially frozen ground and filling, most lakes have undergone partial drainage exposing the lake floors. The lake floors are in step-like fashion, usually with 1 to 5 feet in elevation between the steps. The steps are a result of a complex of downcutting of drainage channels and collapse of underlying ground together with erosion and filling along the lake margins. Two C-14 dates from buried organic matter in the aeolian silts yielded ages of 9320 and 9130 yr. B. P. whereas one date from the 5-foot depth of the exposed lake floor yielded an age of 4590 yr. B. P.
Whereas the original aeolian silts were once virtually organic-free, the sediments of the lake floors have a considerable quantity of organic matter mixed throughout the substrate. This increased organic matter content in the lower positions is reflected in the soil morphology.

Truett, J. and S. Johnson (2000). The natural history of an oil field: development and the biota. San Diego, Academic Press 422.
Abstract: No abstract

Ugolini, F. C. (1975). Ice rafted sediments as a cause of some thermokarst lakes in the Noatak River Delta, Alaska. Science. **188** 51-53.
Abstract: A very interesting, short paper describing a method for thermokarst lake initiation that does not depend on ice wedge depression. Here, on the Noatak River delta, it was observed that spring break-up and storm surges could flood the delta, lifting hunks of lake ice out of their depressions and depositing them elsewhere. These hunks of lake ice have bottom sediments attached to them, which then get deposited on the tundra and change the albedo their and at least in some cases lead to thermokarst depressions which then fill with water and become ponds.

URS (2001). 2001 Lake Monitoring Study, National Petroleum Reserve - Alaska. Anchorage, AK, Prepared for Phillips Alaska, Inc., by URS 15 pages plus 4 appendices.

Vincent, W. F., I. Laurion and R. Pienitz (1998). Arctic and Antarctic lakes as optical indicators of global change. Annals of Glaciology. **27** 691-696.
Abstract: Lakes are a major feature of Arctic and Antarctic landscapes and are likely to be sensitive indicators of climate change. New bio-optical technologies for in situ measurements (e.g. UV-profiling) and remote sensing (e.g. light detection and ranging) now offer a suite of options for long-term monitoring at these sites. Certain properties of high-latitude lakes are highly responsive to changes in climate forcing and could be targeted within a monitoring strategy based on optical properties; these include lake levels, lake-ice dynamics, phytoplankton biomass and chromophoric dissolved organic matter (CDOM). High-latitude lakes are optically sensitive to changes in CDOM export from their surrounding catchments that could result from climate effects on hydrology and vegetation. Using a new model based on biologically weighted transparency, we show that a 20% change in CDOM concentration (as measured by dissolved organic carbon) can have a much greater effect on UV inhibition of phytoplankton than a similar percentage change in stratopheric ozone. Much of this effect is due to UV-A, because the reduced photodamaging effect per unit energy (i.e. low biological weighting) in this waveband is offset by its higher incident flux at the lake surface relative to UV-B and its deeper penetration into the water column. These transparency calculations also show that small changes in CDOM in polar lakes will have a large effect on underwater light availability for photosynthesis. The spectral absorption and fluorescence properties of DCOM lend themselves to a variety of optical monitoring approaches. Future research on the paleo-optics of DCOM will allow the interpretation of current optical trends in high-latitude lakes relative to the scales of natural variability in the past.

Walker, D. (1985). Vegetation and environmental gradients of the Prudhoe Bay region, Alaska, Cold Regions Research and Engineering Laboratory 240.

Walker, D., M. Walker, K. Everett and P. Webber (1985). Pingos of the Prudhoe Bay Region, Alaska. Arctic and Alpine Research. **17** 321-336.
Abstract: Two distinctive types of small dome-shaped hills occur in the Prudhoe Bay region. One type has small basal diameters, steep side slopes, and occurs primarily in drained thaw-lake basins; the other type consists of mounds of larger diameter and commonly occurs outside modern lake basins. The U.S. Army Cold Regions Research and Engineering Laboratory drilled three of the mounds including one broad-based mound and encountered massive ice in all of them. It is thus likely that all of the steep-sided mounds and at least the larger broad-based mounds are pingos. It is clear that the largest of the broad-based mounds are neither dunes, unmodified remnants, nor highly eroded steep-sided pingos of the type common in the region today. Discriminant analysis of topographic-map data indicates that mean slope and length of the longest axis are the clearest discriminators between the two groups of mounds. The broad-based mounds are limited to older surfaces in the region and are thus likely to be quite old (< 12,000 yr). Explanations for the large size of many of the broad-based mounds and their occurrence outside lake basins will have to await detailed drilling studies.

Walker, H. J. and M. K. Harris (1976). Perched ponds: an arctic variety. Arctic. **29** 223-238.
Abstract: Data obtained during several seasons of field research on a small drainage basin in the Colville River delta of northern Alaska were used in a study of permafrost as an aquaclude for the maintenance of a pond above the regional water table. The development of the active layer of permafrost in the basin and the water budget of the pond were monitored. It was shown that the permafrost table enables the general form of the basin's subaerial surface to be maintained throughout the thaw season. The resulting prevention of percolation, when combined with a low evaporation rate, is sufficient to ensure that the pond is perennial.

Weeks, W. F., A. G. Fountain, M. I. Bryan and C. Elachi (1978). Differences in radar returns from ice-covered North Slope lakes. Journal of Geophysical Research. **83** 4069-4073.
Abstract: Comparisons are made between L and C band synthetic aperture radar images of frozen lakes on the North Slope of Alaska and ground truth observations of the nature of their ice covers. It is shown that the differences in radar backscatter observed on different areas of a lake can he correlated with whether or not the lake is frozen completely to the bottom at the site in question. This explanation is reasonable inasmuch as the reflection coefficient associated with ihe high-dielectric contrast ice water interface is signincantly higher than that associated with a low -contrast ice/soil interface. However, the presence of the ice/water interface cannot be the only condition required for the higher backscatter because the ice water interface per se would he specular at .V and L band frequencies, causing the energy returned Iron the interface to he reflected away from the radar receiver. The other principal factor contributing 10 the return of energy from the ice'water interface to the receiver is believed to be the presence in the ice of numerous vertically elongated air bubbles which would act as scatterers.

Weeks, W. F., A. J. Gow and R. J. Schertler (1981). Ground truth observations of ice-covered North Slope lakes imaged by radar. Hanover, NJ, Cold Regions Research and Engineering Laboratory.

Abstract: Field observations support the interpretation that differences in the strength of radar returns from the ice covers of lakes on the North Slope of Alaska can be used to determine where the lake is frozen completely to the bottom. An ice/frozen soil interface is indicated by a weak return and an ice/water interface by a strong return. The immediate value of this result is thatSLAR (side-looking airborne radar) imagery can now be used to prepare maps of large areas of the North Slope showing where the lakes are shallower or deeper than 1.7 m (the approximate draft of the lake ice at the time of the SLAR flights). The bathymetry of these shallow lakes is largely unknown and is not obvious from their sizes or outlines. Such information could be very useful, for example in finding suitable year-round water supplies.

Weeks, W. F., P. V. Sellman and W. J. Campbell (1977). Interesting features of radar imagery of ice-covered North Slope lakes. Journal of Glaciology. **18** 129-136.
Abstract: ABSTRACT. Side-looking airborne radar (SLAR) imagery obtained in April-May 1974 from the North Slope of Alaska between Barrow and Harrison Bay indicates that tundra lakes can be separated into two classes based on the strength of the radar returns. Correlations between the areal patterns of the returns, limited ground observations on lake depths and water compositions, and information obtained from LANDSAT imagery strongly suggest that areas of fresh-water lakes giving weak returns are frozen completely to the bottom while areas giving strong returns are not. This is a reasonable interpretation inasmuch as the reflec-tion coefficient associated with the high-dielectric-contrast ice-water interface would be roughly twelve times that associated with the low-contrast ice-soil interface. Brackish lakes also give weak returns even when they are not completely frozen. This is the result of the brine present in the lower portion of the ice cover limiting the penetration of the X-band radiation into the ice. The ability to separate tundra lakes rapidly and easily into these two classes via SLAR should be useful in understanding a wide variety of problems.

Welch, H. E. and M. A. Bergmann (1985). Water circulation in small arctic lakes in winter. Canadian Journal of Fisheries and Aquatic Science. **42** 506-520.
Abstract: Dye experiments and detailed measurements of conductance and temperature in small lakes at Saqvaqjuac (63d39'N, 90d39'W), showed how water circulated in midwinter. Stored heat returning from the sediments warms adjacent water, which then sinks downslope. Water immediately beneath the ice moves laterally shoreward, picking up cryoconcentrated salts and linking downslope. Displacement of deep waters upward at the lake center is postulated as completing the circulation. Rates of water movement are on the order of 10m/d in 2- to 10-ha lakes. This tvpe or winter circulation is expected to be ubiquitous throughout the arctic.

Wessel, D. A. and W. R. Rouse (1994). Modeling evaporation from wetland tundra. Boundary-Layer Meteorology. **68** 109-130.
Abstract: Evapotranspiration is a major component of both the energy and water balances of wetland tundra environments during the thaw season. Reliable estimates of evapotranspiration are required in the analysis of climatological and hydrological processes occurring within a wetland and in interfacing the surface climate with

atmospheric processes. Where direct measurements are unavailable, models designed to accurately predict evapotranspiration for a particular wetland are used.
This paper evaluates the performance, sensitivity and limitations of three physically-based, one-dimensional models in the simulation of evaporation from a wetland sedge tundra in the Hudson Bay Lowland near Churchill, Manitoba. The surface of the study site consists of near-saturated peat soil with a sparse sedge canopy and a constantly varying coverage of standing water. Measured evaporation used the Bowen ratio energy balance approach, to which the model results were compared. The comparisons were conducted with hourly and daily simulations.
The three models are the Penman-Monteith model, the Shuttleworth-Wallace sparse canopy model and a modified Penman-Monteith model which is weighted for surface area of the evaporation sources.
Results from the study suggest that the weighted Penman-Monteith model has the highest potential for use as a predictive tool. In all three cases, the importance of accurately measuring the surface area of each evaporation source is recognized. The difficulty in determining a representative surface resistance for each source and the associated problems in modelling without it are discussed.

Wetzel, R. (2001). Limnology: lake and river ecosystems. San Diego, CA, Academic Press 1006.
Abstract: No Abstract

Williams, J. R. and Yeend (1979). Deep thaw lake basins of the inner Arctic Coastal Plain, Alaska, USGS 35-37.

Wilson, W., E. Buck, G. Player and L. Dreyer (1977). Winter water availability and use conflicts as related to fish and wildlife in Arctic Alaska - synthesis of information, U.S. Fish and Wildlife Service.

Woo, M. K., R. Heron and P. Steer (1981). Catchment hydrology of a high arctic lake. Cold Regions Science Technology. **5** 29-41.
Abstract: In small lake catchments of the High Arctic, hydrologic processes are highly variable both spatial-ly and temporally, so that single site measurements of hydrologic phenomena are seldom representative of catchment averages. Throughout spring and summer, snow and ice melts often occur alongside evaporation and runoff from bare ground. The evaluation of various hydrologic quantities there-fore is prerequisite upon an incorporation of the changing spatial patterns of the major hydrologic processes. Through budgeting the water inputs and losses of a typical lake and its catchment, this study demonstrates the dependence of small High Arctic lakes upon their catchments for water supplies. In turn, the lakes modify storage and thus alter the outflow regime of their catchments.

Yang, D., D. Kane, L. Hinzman, R. Gieck and J. McNamara (2000). Hydrologic response of a nest of watersheds to an extreme rainfall event in northern Alaska. Water resources in extreme environments. D. Kane. Anchorage, AK, AWRA 25-30.
Abstract: ABSTRACT: Most annual floods in the Arctic occur in the spring season due to melting of the winter snowpack. However, since the potential daily rainfall rates can far

exceed daily snowmelt, the highest floods of record will almost always be associated with heavy rainfall in summer. In July 1999, an intensive storm dumped about 100mm rain in 48hrs in the upper Kuparuk watershed in northern Alaska that resulted in a widespread flooding in the upper river basin. This flood was approximately two-times greater than the previously recorded snowmelt-generated peak. It seriously changed sections of river channels through bank erosion, bed scouring and deposition. Hourly rainfall data for this extreme event were collected by our monitoring network and discharge data were also obtained at gauging stations along the river. Based on these data, we report on the variability ofhydrologic response of a nest of arctic watersheds to an extreme rainfall event, with particular emphasis on (1) characteristics of the extreme rainfall event; (2) features of the extreme flood, and (3) hydrologic responses of watershed to this heavy storm. These results will improve our understanding ofhydrologic processes in the arctic regions.

Yoshikawa, K. (1998). The groundwater hydraulics of open system pingos. 7th International conference on permafrost 1177-1184.
Abstract: The characteristics of spring water from open-system pingos in interior Alaska and Svalbard were examined to elucidate the relationship between groundwater and open system pingos. Water from springs under pingos creates a variety of icing blister formations in the winter. It was concluded that pingo formation pressure varied from pingo to pingo/ with artesian pressures sometimes less than 20 kPa. The pressure from ice crystallization is one of the important factors for pingo growth when artesian pressure was low. Springs warmer than 3°C or with discharge rates greater than 3 liters per second did not have pingos associated with them. Experimental evidence indicates that in order for pingo growth to occur, heat transferred to the pingo through groundwater discharge must be less than 37 kW.

Yoshikawa, K. and L. Hinzman (2003). Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska. Permafrost and Periglacial Processes. **14** 151-160.
Abstract: The purpose of this study was to characterize the geomorphological processes controlling the dynamics of ponds and to identify and characterize groundwater infiltration and surface water dynamics for a tundra terrain located in discontinuous permafrost near Council, Alaska. Thermokarst processes and permafrost degradation were studied, focusing upon the interaction between surface and groundwater systems via an open talik. Synthetic aperture radar (SAR) data were used for classification of terrain units and surface water properties, while historical aerial photographs and satellite images (IKONOS) were used for assessment of pond shrinking and recent thermokarst progression. Geophysical surveys (ground penetrating radar and DC resistivity) were conducted to detect permafrost thickness and talik formations. Temperature boreholes and hydrological observation wells were monitored throughout the year and provided ground truth for validation of remotely-sensed data and geophysical surveys. Field and laboratory analyses enabled quantitative determination of subsurface hydrologic and thermal properties. We found many areas where alluvium deposits and ice-wedge polygonal terrain had developed thermokarst features within the last 20 years. Thermokarst ponds located over ice-wedge terrain have decreased in surface area since at

least the early 20th Century. Small thermokarst features initially developed into tundra ponds perched over permafrost in response to some local disturbance to the surface. These thermokarst ponds grew larger and initiated large taliks that completely penetrated the permafrost. These taliks allowed internal drainage throughout the year causing the ponds to shrink under recent climatic conditions. Shrinking pond surface areas may become a common feature in the discontinuous permafrost regions as a consequence of warming climate and thawing permafrost.

Zhang, T. and M. Jeffries (2000). Modeling inter-decadal variations of lake-ice thickness and sensitivity to climatic change in northernmost Alaska. Annals of Glaciology. **31** 339-347.
Abstract: A physically based finite-element heat-transfer model with phase change is used to simulate ice growth and thickness variahility on shallow, thaw lakes on the North Slope of Alaska during the period 1947-97. The basic inputs to the model are air temperature and snow depth as recorded at. the U.S. National Weather Service station, Barrow, Alaska. Simulated long-term mean maximum ice thickness was 1.91 +/- 0.21m with a range from 1.33m (1962) to 2.47m (1976). Variations in the seasonal snow cover played a much greater role than air temperatures in controlling ice-thickness variability during the 50 year simulation period. The sensitivity of lake-ice growth to extremes of snow depth, air temperature and snow bulk thermal conductivity is investigated. This study shows that lake-ice thickness has varied significantly from year to year in northern Alaska. Continued variability combined with potential climate change could affect the area of ice that freezes completely to the bottom of lakes each winter, resulting in changes in water storage and availability, permafrost thermal regime and talik dynamics beneath lakes, and methane efflux and energy fluxes to the atmosphere. It is concluded that quantification and a full understanding of these potential effects will require systematic and continuous field measurements that will provide better forcing and validation fields tor improved models.

Zimov, S. A., Y. V. Voropaev, I. P. Semiletov, S. P. Davidov, S. F. Prosiannikov, F. S. Chapin, M. C. Chapin, S. Trumbore and S. Tyler (1997). North Siberian Lakes: a methane source-fueled by Pleistocene carbon. Science. **277** 800-802.
Abstract: The sizes of major sources and sinks of atmospheric methane (CH4), an important greenhouse gas, are poorly known. CH4 from north Siberian lakes contributes ~1.5 teragrams CH4 /year to observed winter increases in atmospheric CH4 concentration at high northern latitudes. CH4 emitted from these lakes in winter had a radiocarbon age of 27,200 years and was derived largely from Pleistocene-aged carbon.