Prospectus

KUPARUK RIVER WATERSHED, PROPOSED LONG TERM HYDROLOGIC OBSERVATORY, NORTH SLOPE, ALASKA

Air/Land/Sea Interactions

High latitude regions of the world are important in Earth's climate engine. Excess energy absorbed from solar radiation at the lower latitudes is transferred laterally by oceanic and atmospheric circulation poleward as both latent and sensible heat. This energy is ultimately expelled from earth by long wave radiation at high latitudes. The hydrologic cycle of the Arctic is a prominent mechanism in this process. Snow, ice and frozen ground (permafrost and seasonal frost) are significant characteristics of the northern catchments. The hydrologic cycle can only be understood through a comprehensive understanding of both energy and mass fluxes and reservoirs. Hydrological processes important in most northern basins include formation and decay of lake and river ice, freezing and thawing of surficial soils, redistribution and sublimation of snow, evapotranspiration from surface water, melting snowpack, vegetation and highly organic soils. . However, arctic basins also include many unique processes elevate their importance in hydrological science. Watersheds in the Arctic are currently demonstrating physical, biological and ecological changes in response to a changing climate. These changes often include dramatic, threshold changes as frozen ground thaws or vegetation changes from forbs and mosses to being more dominated by shrubs. Runoff from some basins is markedly increasing freshwater discharge into the Arctic Ocean, potentially impacting the globe's oceanic conveyor belt. More than any other region, near-term changes in arctic hydrology will affect the climate and society in the more temperate latitudes.

The impact of freshwater discharge into the Arctic Ocean on climate cannot be ignored. The ice-covered (high albedo) Arctic Ocean plays a significant climatic role in the cooling of Earth. Unlike all other oceans, the Arctic Ocean is rather shallow and therefore freshwater discharge from the north draining basins of Europe, Asia and North America can influence both the thermohaline structure and sea ice regime of marginal seas. Since sea ice extent measurements have started, summer sea ice extent is at a minimum (there is also an overall thinning of the icepack). The delivery of freshwater from the continental land mass is of special importance to the Arctic Ocean since it contains only 1% of the world's ocean water, yet receives 11% of world river runoff (Shiklomanov et al. 2000). The Arctic Ocean is the most river-influenced and landlocked of all oceans and is the only ocean with a contributing land area greater than its surface area (Ivanov 1976; Vörösmarty et al. 2000).

There now exists substantial evidence that the hydrological regime of the Arctic is demonstrating distinct changes in response to a changing climate (SEARCH, 2001; Vörösmarty et al., 2001); however, at present most of this evidence is observational or anecdotal with no real synthesis of information from identification of changes through projection of impacts. Hydrological processes are the primary driver of ecosystem and climate dynamics, particularly in high latitudes where then entire system progresses through dramatic changes as the available water freezes and thaws each year. Arctic hydrology differs substantially from the hydrology of temperate zones, largely due to the interactions of extremes in climate and the land surface characteristics. That is, the presence of permafrost strongly affects hydrologic processes and the fact that its distribution is currently undergoing warming and in some places thermal degradation. Permafrost underlies 13-18% (Zhang et al., 2001) of the terrestrial surface of the northern hemisphere.

Even though the principles governing groundwater movement in arctic regions are the same as those in more temperate regions, groundwater in the far North is affected by the presence of relatively impermeable permafrost that can be viewed as an aquitard. Above the permafrost is the active layer, a zone that freezes in winter and thaws in summer. This seasonally thawed zone supplies the summer moisture to plants and for evaporative flux. Water flowing in the thawed substrate of rivers (above the permafrost) is a source of freshwater for some villages near the Arctic Ocean; but for most villages, water is pumped from freshwater lakes in summer and stored in heated tanks for winter use.

Subpermafrost aquifers are those consisting of permeable material below the permafrost. Permafrost affects groundwater recharge, movement, and discharge. Ice-rich permafrost prevents infiltration of rainfall or snowmelt water, often maintaining a moist to saturated active layer where the permafrost table is shallow. Permafrost also blocks the lateral movement of groundwater, and acts as a confining unit for water in sub- or intra-permafrost aquifers. Discharge of water confined beneath the permafrost is possible only through unfrozen zones (taliks), or higher permeable zones such as faults or springs that may perforate the permafrost layer. Although a huge quantity of water is stored in or below the permafrost, this water has historically not been an important component of the hydrologic cycle. However, as permafrost degrades, profound changes in interactions between groundwater and surface water may occur that affect the volume of runoff reaching the Arctic Ocean, potentially impacting oceanic circulation and global climate. A detailed understanding of the processes responsible for these storage phenomena is lacking.

Large-scale atmospheric circulation is a primary driver of arctic hydrologic variability for a wide range of time scales, including synoptic, seasonal, inter-annual, decadal and longer (Walsh, 2000). Precipitation generally decreases with increasing latitude and many high latitude areas would be classified as arid or semi-arid. However, this is deceiving as many of these areas are fully vegetated with shrubs, grasses, etc. Permafrost in many cases is responsible for trapping moisture near the ground surface where it is available for plants. Cool temperatures and short warm seasons are mostly responsible for reducing evapotranspiration fluxes back to the atmosphere. While snow accumulates from eight to ten months and produces a significant runoff event each year, rainfall is the dominant form of precipitation and can occasionally produce significant floods (Kane et al., 2003).

Site Characteristics

We propose that the Kuparuk River (8140 km^2) and some surrounding nested drainages on the North Slope of Alaska be considered as a Long-Term Hydrologic Observatory (LTHO). The Kuparuk River is a north-draining river that drains into the Arctic Ocean. It originates in the northern foothills of the Brooks Range (Rocky Mountains) and flows out of the foothills onto the coastal plain before emptying into the ocean. The foothills represent 56 % of the basin and the coastal plain the remainder. The elevation range is from 0 to 1464 m. There are some scattered pockets of lakes in the foothills; on the coastal plain, lakes, ponds and wetlands dominate. The watershed is treeless (except for some riparian areas) and underlain by continuous permafrost from ~300 to 600 m in thickness. The area is relatively undeveloped or in a natural state except at Prudhoe Bay on the Arctic Ocean. The Dalton Highway and the Trans-Alaska oil pipeline run north/south along and across the Kuparuk River basin.

Describing the environment of this watershed as extreme is justified. Winter minimum temperatures drop below –40 ºC, while maximum summer temperatures have exceeded +30 ºC. Freezing temperatures and snow are possible during any month. Mean annual temperatures are approximately –5 to –10 ºC ; these low temperatures sustain the deep permafrost that exists continuously throughout the proposed LTHO watershed.

Hydrologic studies in the Alaskan Arctic have been, relatively speaking, of short duration (Kane et al., 2000): Imnavait Creek, which is a headwater stream within the Kuparuk River drainage is an anomaly, has been monitored since 1985, but it is only 2.2 km^2. Both the Upper Kuparuk catchment (146 km^2) and the Kuparuk River basin have been studied since 1993, but not as intensively as Imnavait Creek. The discharge from the Kuparuk, Putuligayuk (456 km^2, completely on the Arctic Coastal Plain) and the upper Sagavanirktok Rivers (4840 km^2, adjacent on the east side of the Kuparuk River, drains Brooks Range and foothills) have been gauged by the USGS since 1970, but have not received intensive scientific study.

Extensive research has been directed at characterizing hydrologic and thermal processes occurring in three nested watersheds (Kuparuk, Upper Kuparuk and Imnavait) on the North Slope of Alaska and developing the tools to accurately simulate these processes (Zhang et al, 2000; Hinzman et al., 1998) and their interactions with other components of the ecosystem. Concurrently, a multitude of ecological and climatological research projects have been conducted in these watersheds including those funded under large programs supported by the NSF Long Term Ecological Research Program, the Arctic System Science Program and the Department of Energy's R4D and ARM programs. From the inception of hydrologic research in the Kuparuk and Imnavait basins, all hydrological and meteorological data have been freely shared with anyone to ensure the greatest scientific benefit for all. These data are shared through public webpages at http://www.uaf.edu/water/projects/NorthSlope/introduction.html .

In expanding this research program as a Long Term Hydrological Observatory, we intend to focus upon facets of arctic hydrology that interplay strongly with ecosystem dynamics, climate change, geophysics, nearshore estuarine processes, energy dynamics and geomorphology. The climate is currently undergoing significant, broad scale change in the Arctic. The hydrological cycle is an integral component of the climate system, both moderating and driving changes in meteorology, coastal processes, and terrestrial and aquatic ecology. Warming of permafrost, a decrease in sea ice extent, thinning of the sea ice, later freezeup and earlier breakup of lakes, reduction of snowcover extent in northern hemisphere and shorter season of snow on the ground are a few indications of warming in the Arctic and targets of important hydrological research.

Existing Data Infrastructure

Presently, there are four watersheds (entire Kuparuk River, Imnavait Creek, Upper Kuparuk River and PutuligayukRiver) gauged in or adjacent to the Kuparuk River basin; complemented by seven major meteorological stations and five minor ones. Variables measured at each major station are temperature, relative humidity and wind speed profiles to an elevation of 10 m; other measurements include barometric pressure, rainfall precipitation, wind direction, soil temperatures and moisture content, snow depth, incoming and emitted long wave radiation and incoming and outgoing short wave radiation. The five minor stations record precipitation and air temperature and wind speed at just one elevation. These stations are all located in the Upper Kuparuk River catchment where there is considerable elevation difference over relatively short distances. Generally readings are taken every minute and recorded every hour; however some like precipitation are recorded every minute so that rainfall intensities for time durations from 5 minutes to several days can be determined. The USGS presently gauges the Kuparuk River near the coast and two drainages (Oksrukuyik Creek (a.k.a. Sagavanirktok tributary) and Sagavanirktok River) that border on the east side of the Kuparuk basin. These two basins are not supported by other climatological and hydrological data. It is proposed that the Kuparuk River study be expanded to include both of these basins, this would add a component of mountain hydrology (with small glaciers) that is presently lacking.

Data from the remote sites is transferred in near real time by a variety of telemetric pathways. Using radio transmission, data is transferred from meteorological and hydrological stations either directly, through a repeater or through other stations acting as repeaters to a radio base station. This is done hourly, the limitations being the power required. Sites are powered with 12 volt batteries recharged using solar panels. From the radio base station, data is put on the internet and transferred to the University of Alaska Fairbanks through a geostationary satellite. This system allows us to monitor the continuous operation of these remotely situated stations as some are only visited twice per year. Power loss, mechanical problems, wildlife and occasionally humans (sites along the Dalton Highway) result in failures at sites; the use of the data transmission scheme allows us to identify rather quickly when there are problems at a site. Twenty years of experience has lead to reliable station designs that can operate under extreme conditions in remote regions without operator assistance or power from a standard electrical grid.

Additional data that exist to support hydrologic research include high quality digital elevation data sets and vegetation maps. The digital elevation data were obtained recently through funding from NASA and NSF. An aircraft using x-band radar produced 2.5 x 2.5 m raw gridded elevation data over the watershed, this was used to generate 5 by 5 m gridded data (the absolute error could be 2 to 3 m, but the relative error is a few cm). One data set that we are lacking is a map of soil distribution.

SCIENCE QUESTIONS

The importance of the high latitudes in the global climate must be emphasized. It is apparent that climate driven changes are presently ongoing. This is impacting the hydrologic cycle, not only through the land/atmosphere interactions, but also the physical structure of the basin. The development of thermokarst, deeper active layer and an increase in shrubs (vegetative shift) are changes that will be reflected in the hydrologic response of these catchments.

Because permafrost limits storage in subsurface reservoirs, runoff ratios are significantly higher than the world average of 0.36. Annual runoff ratios of 0.50 are typical for arctic catchments; so even though the annual precipitation would be classified as semi-arid, substantial runoff is delivered to the Arctic Ocean. The fact that the Arctic Ocean is shallow, surrounded by land masses and ice-covered means that the freshwater discharge can impact the sea ice extent and thermohaline stratification.

We hypothesize that:

1) The Kuparuk watershed will display threshold changes in many interrelated processes (such as nutrient cycling and transport, sediment transport, surface energy balance, fire frequency, soil gas flux among others) as the permafrost continues to warm and the active layer becomes thicker.

2) The rudimentary drainage patterns common in arctic drainages will evolve into more complex dendritic drainage pattern as the permafrost thaws and erosional processes increase.

3) Over time, this nearly pristine watershed will experience introduction of atmospheric borne contaminants as the industrial development continues throughout the world. The introduction of air borne contaminants will be first apparent in the quick growing shrubs, later becoming apparent in soils and stream sediment..

4) The availability of freshwater for domestic and industrial uses is severely limited during the long winter months due to lack of subsurface water because of permafrost, most water in the predominantly shallow lakes is frozen (~2 m) and baseflow is nonexistent in streams, except the larger ones.

The primary justification for including the Kuparuk Watershed as an LTHO is that climatic warming is occurring in the Alaskan Arctic. This is well demonstrated by the observations of warming permafrost, the unequivocal mass loss of glaciers in the Brooks Range and the increase in the rate of this loss in the late 70's (Rabus et al., 1995). Over the Alaskan Arctic, this will result in a thicker active layer (the layer of soil near the surface that undergoes freeze and thaw each year) with more shrubs that will eventually alter the present hydrology. Shading by shrubs will result in less heat transfer to the surface, but increased ET will result in drier soils. These changes may be most pronounced in riparian zones, which are dominant regions of physical and biological activity in watersheds. Such changes in surface characteristics will affect the surface energy balance, ultimately leading to responses in the more temperate regions as the warmer Arctic is no long capable of accepting the same levels of excess energy absorbed in lower latitudes.

Within the broad thematic construct of an Arctic LTHO, with open collaboration among many qualified investigators, we would like to explore the following issues:

1. Continue to monitor the existing hydrological and meteorological stations in the Kuparuk River basin to examine inter-annular variation in hydrologic processes at the basin scale. Both the Upper Kuparuk and the Kuparuk Rivers have been monitored since 1993; stream flow measurements have been made since the early 1970s on the Kuparuk River, but no complementary measurements of rainfall or snow water equivalent (or any other hydrologic measurements) were made at that time.
2. Examine potential changes in the drainage network of arctic watersheds in response to climatic warming. We have hypothesized that the shallow nature of the active layer has resulted in an immature drainage network; however, a mature network could replace the present water track/linear stream network if a deeper active layer prevails.
3. Explore how changes in the climate dynamics and watershed drainage network will affect soil moisture. There exist strong correlations among vegetation/snow distribution/soil moisture/topography in arctic watersheds. This may alter vegetation distribution and subsequently snow distribution with long-term consequences for the arctic surface energy balance.
4. Develop methods to determine spatial soil moisture distribution by remotely sensed methods. Hydrologic studies, CO_2 and CH_4 flux estimates, and surface energy balance estimates all require soil moisture distribution at the watershed scale. Arctic regions are particularly suited to this application where canopy interference is minimal.
5. Develop and apply process based, spatially distributed hydrologic models to the entire Kuparuk, Putuligayuk, Imnavait and the Upper Kuparuk basins. These models will be used in concert with ecosystem studies to quantify nutrient cycling and transport. They will also be applied to quantify changes in watershed geomorphology.

BACKGROUND

For the past 20 years, we have been conducting hydrologic studies in the area of the Kuparuk basin. Additional field sites have been added to this network as resources became available, such as the five micro-meteorological sites added in 1996 to better define rainfall, air temperature and wind speed in the rugged headwater catchments of the Kuparuk basin. Hydrologic processes monitored included: runoff at four scales, snowmelt, snow distribution just prior to snowmelt, measurement of soil moisture at selected sites in foothills and coastal plain, rainfall at seven to twelve sites (depending upon year), pan evaporation at each end of the Kuparuk basin, stream nutrient chemistry at selected points and meteorological variables. Many of these data stations are now connected via near-real time telemetry (http://www.uaf.edu/water/projects/NorthSlope/currentconditions.html) so investigators are able to monitor field conditions and better plan event dependent studies.

McNamara et al. (1997d) suggested that channel networks in the Kuparuk River basin are under-developed due to permafrost. Hillslopes are not dissected into channeled valleys, but contain numerous water tracks to transmit water. The presence of water tracks has important consequences to many aspects of the arctic system including vegetation distribution, snow retention, soil moisture, and nutrient dynamics. Thus, an understanding of the physical controls on drainage pathways would contribute greatly to understanding several other components of an arctic drainage basin. A basic question is this: are water tracks erosional features that form under the same controls as fluvial channels? It is plausible that both thermal (conductive and advective) and mechanical (erosive and sedimentary) processes are responsible for changes in the channel network. Water tracks are essentially zones of enhanced soil moisture that drain directly downslope. They rarely contain incised channels, but function as integral components of water removal from the hillslopes. Water tracks typically do not converge, but flow parallel to one another directly downslope from near the drainage divides directly to the valley bottoms. If water tracks are considered part of the channel networks, the channel networks have an immature feathered pattern with numerous first order drainages (water tracks) contributing to a valley bottom streams. Water tracks in the Imnavait Creek basin originate on hillslopes where erosional channels should begin, but their arrangement does not possess certain characteristics common to mature fluvial networks (McNamara et al., 1997d). A possible explanation is that permafrost is restricting the erosional development of a rudimentary network that was laid down soon after deglaciation. The early network remained in place and water tracks formed in the poorly developed channels. If permafrost has restricted the development of fluvial channels, then drastic changes will occur in the structure of arctic watersheds in the advent of climate warming. This initial study was limited in scope, and restricted to one basin in the northern foothills of the Brooks Range. Thus, similar studies are needed in other regions of the Arctic to determine if these findings are robust and to elucidate the impacts of network evolution.

The ecology of arctic watersheds is primarily confined to the shallow active layer, therefore it is necessary to understand how this layer functions physically in terms of heat and mass transfer processes. It is this shallow active layer that will be impacted most following an intensive disturbance such as road construction or a more subtle disturbance such as changing climate or imposition of dust. We have recently conducted extensive research on arctic hydrologic and thermal processes (Kane et al., 1997; Hinzman et al., 1997a) but we still lack critical information regarding the interaction of atmospheric, terrestrial and aquatic processes. In particular, efforts to model the thermal response of the active layer to climatic warming were limited by our inability to model the energy transferred via moving water (rainfall and surface and subsurface runoff) (Hinzman et al., 1991b). Efforts to simulate the hydrologic response to climatic warming were limited primarily because it was not possible to dynamically couple thermal and hydrologic processes (Hinzman and Kane, 1992) and also due to the uncertainty of the magnitude of climatic change. In order to adequately simulate the present or future ecosystem dynamics, we must understand how changing drainage paths impact the soil moisture levels in the surrounding areas.

In addition to changes in the drainage network, the formation of thermokarst in the ice-rich tundra soils in a warmer climate is already occurring. Developing a quantitative understanding of the complex nature of thermokarst formation is no easy task (Rawlinson, 1983). Thermokarst topography forms whenever ice-rich permafrost thaws, either naturally or anthropogenically, and the ground surface subsides into the resulting depression (Hinzman et al., 1997). The important and dynamic processes involved in thermokarsting include thaw, ponding, drainage, surface subsidence and related erosion. A significant disturbance of the tundra may result in an increase in surface temperature leading to an increase in active layer depth. Occasionally this may result in a slight depression on the surface where water will accumulate causing an even greater absorption of shortwave radiation and further increasing the average annual temperature. As the depression grows, water may begin to flow laterally into the newly formed pond transferring even more heat causing more thawing of the permafrost and further subsidence of the ground surface. If the depth of water in the pond is sufficient (>1.5 - 2.0 m), it will not completely freeze during the winter leaving an unfrozen zone or talik below the pond. The pond will either drain and the tundra will recover, completing the thaw lake cycle or a deep thaw bulb will develop leading to formation of a deep lake (Billings and Peterson, 1980). As the extent of thermokarst increases, the thawing ice wedges of a polygon network more typically join into a spider web of drainage channels, potentially impacting large wetlands. For example, extensive thermokarsts have developed on the Coastal Plain along roads constructed to support the oil industry. In some of those areas, ice wedges have degraded up to one meter, causing a marked lowering of the water table, drying of the surface soils between ice wedges and a shift in vegetative species from wetland plants to dune plants. The time scales involved in recovery are long and variable. Our previous work has shown that the nutrient status of small ponds over thawing ice wedges is enriched compared to larger tundra ponds (Hinzman et al., 1998), which further emphasizes the importance of thermokarst upon the aquatic system.

RESEARCH TASKS

Quantifying inter-annual and regional variability of water and energy budgets: The Arctic LTHO will maintain the Kuparuk River basin hydrologic data collection at four watershed scales: Imnavait Creek (2.2 km^2), Upper Kuparuk River (146 km^2), Putuligayuk (456 km^2) and Kuparuk River (8140 km^2). In addition, we would continue to operate the seven major meteorological sites in the Kuparuk River basin and the five micro-met sites in the Upper Kuparuk River. All of these sites have been automated through VHF transmission and can be accessed via the internet. The rational for doing this is to develop long term hydrologic and meteorological data sets on selected sites to a) enable the determination of climatic influence upon the arctic system. b) create complete and high quality data sets needed to monitor and detect climatic variability and c) obtain the data sets needed to drive hydrologic and thermal models, carbon flux, snow distribution and ecosystem dynamics models.

Regional Water Balance Studies: We will continue monitoring the water balance of four other basins on the North Slope (Imnavait Creek, Upper Kuparuk, Putuligayuk River and the Entire Kuparuk). All of these basins will be monitored for the following reasons: 1) Hydrologic response in the headwaters of the Kuparuk in the Foothills and the Coastal Plain are markedly different, but it is not possible to separate these influences upon the entire Kuparuk (and its consequent contribution to the Arctic Ocean) unless all basins are monitored simultaneously.

The role of Hydrology in Ecosystem Dynamics

The Upper Kuparuk basin and Toolik Lake has been the home of the Arctic Long Term Ecological Research (LTER) program since 1987. The current LTER program is largely based on aquatic research. Most of the original research group (John Hobbie, Bruce Peterson, John O'Brien, Mike Miller and Gaius Shaver) are still active in this research program. A major theme of the Arctic LTER is long-term, whole-ecosystem experiments, along with monitoring of key ecological variables over long time periods. A growing emphasis in the LTER research is the linkages between terrestrial and aquatic ecosystems, which requires scaling-up of knowledge from individual plots, lakes, and streams to larger watersheds and heterogeneous landscapes (e.g. Shaver et al., 1991; Kling, 1995) and will benefit greatly from development of a complementary LTHO. Detailed information on past and proposed Arctic LTER activities is available at http://ecosystems.mbl.edu/ARC/ .

Hydrology is typically an interdisciplinary science forming an integral component of many research projects in arctic regions. In previous years, we have collaborated with many investigators in various fields whenever possible. We have always freely distributed data, interpretation and advice in arctic field studies upon request. Our soil moisture and thermal simulations and measurements of meteorological variables, streamflow discharge, soil moisture and active layer depth were used broadly to complement many other analyses. Knowledge of soil moisture levels, sub-surface thermal profiles and water flux rates are critical parameters in correctly understanding CO_2 and methane flux, vegetation patterns, regional climatic dynamics, and nutrient transformations and transport. Such collaborative efforts enable achievements unattainable through single investigator programs. We will continue these collaborative efforts through focused research topics where complementary analyses will benefit all groups and arctic science.

PROGRAM MANAGEMENT

The Arctic LTHO will be managed by the University of Alaska Water and Environmental Research Center; however, the guiding principals will be established upon the concepts of collaboration and open access to all qualified investigators. Professor Douglas Kane, the program director will strive to ensure maintenance of essential hydrological and meteorological data collection and open data archiving by all participants. He will also be responsible for protection of the watershed from unnecessary destructive sampling or unrestricted development within watershed boundaries

All of the meteorological and hydrological data that we have collected in our investigations on the North Slope of Alaska (including those funded by NSF, DOE and EPA) have been archived in open files at the National Snow and Ice Data Center (NSIDC) in Boulder Colorado (http://www-nsidc.colorado.edu). We have always encouraged any interested scientist to utilize these data and have offered interpretive assistance upon request. All of the data collected in the Arctic LTHO will also be rigorously assessed for quality assurance and then archived for free and access by the scientific community.