1 Results from prior NSF support

Key Connections in Arctic Aquatic Landscapes (NSF OPP-9615949, 1996-1999, $1,962,905, PIs are J. Hobbie, A. Giblin, L. Deegan, and B. Peterson at the Ecosystems Center, Woods Hole):

The goal of this study is to understand the important connections that occur among different parts of the arctic aquatic ecosystem including those from uplands to the riparian zone, from the riparian zone to the surface waters, from the streams to lakes, and from the lakes to their outlets. As a subcontractor on this project Stieglitz ($75,000) is responsible for: (1) producing a computationally efficient, physically based hydrology model that is effective in arctic environments and is capable of simulating the flow of water from the hillslope to the river network; (2) incorporating biological processes into the model framework so as to predict the fluxes of CO_2 and CH_4 between the terrestrial landscape and the atmosphere, and the transport of dissolved organic carbon (DOC) and nutrients to the rivers; and (3) scaling the model results to large basins. Research has focused on simulating the hydrology, growth and ablation of the snowpack, and the evolution of the soil active layer at the Imnavait Creek watershed (2.2 km^2), located in the Upper Kuparuk Basin of northern Alaska. To date one paper has been accepted to Journal of Gepophysical Reviews [*Stieglitz et al.*, 1999b] one paper is in revision at Global Biogeochemical Cycles [*Stieglitz et al.*, in review], one paper is in preparation [*Stieglitz et al.*, in preparation], and three presentationshave been given at AGU [*Stieglitz and Giblin*, 1997; *Stieglitz et al.*, 1998; *Stieglitz et al.*, 1999a] on topics ranging from simple hydrologic validations at the watershed scale, to exploration of the feedbacks between soil moisture evolution and the microbial decomposition of soil organic matter, to climate change experiments.

Validation of Land Surface Hydrology Parameterizations for Climate Models (NSF 9318896, EF Wood, PI):

This work is relevant to the proposed research in that the goals of the former award was to determine the relative performance of land surface hydrology representations (models) appropriate for macroscale hydrologic modeling. The performance was assessed in terms of their ability, to characterize 1) energy fluxes at the land surface, including latent and sensible heat, outgoing short- and long-wave radiation, and ground heat, and 2) the surface water budget, including soil moisture, infiltration, and runoff production. The comparisons were carried out within the context of the Project for Intercomparison of Landsurface Parameterization Schemes (PILPS). PILPS is sponsored by the WMO Committee on Atmospheric Sciences Working Group on Numerical Experimentation and the Science Panel of the GEWEX Continental-scale International Project.

The first phase of the project was to evaluate the VIC-2L land-surface hydrological model within the PILPS experiments. This evaluation and intercomparison within PILPS allowed for systematic testing of the model [*Chen et al.*, 1997; *Liang et al.*, 1996a; *Pitman et al.*, 1999] and indicated areas for improved parameterizations of specific hydrological processes [*Liang et al.*, 1996b; *Liang et al.*, 1998; *Peters-Lidard et al.*, 1998].

During the second phase of the project, a PILPS intercomparison experiment was conducted [*Wood et al.*, 1998] based on 10 years of hourly data for 61 1x1 degree simulation grids representing the Red-Arkansas River basins in the southern great plains region of the United States. This experiment was the first PILPS intercomparison experiment using multiple years of observed meteorological data. Sixteen land surface hydrological models participated and detailed intercomparisons were carried out to evaluate the ability of the models to predict land-surface fluxes of water and energy at the scale of global atmospheric models [*Liang et al.*, 1998; *Lohmann et al.*, 1998a; *Wood et al.*, 1998].

2 Relevant Arctic Programs

2.1 ARCSS, LAII, Flux Study

The goal of the U.S. Arctic System Science (ARCSS) Program is two-fold: (1) to understand the physical, biological, and social processes of the arctic system that interact with the total Earth system and thus contribute to or are influenced by global change, in order to (2) advance the scientific basis for predicting environmental change on a decades-to-centuries time scale and for formulating policy options in response to the anticipated impact of changing climate on humans and social systems. One of the three components of the ARCSS was Land/Atmosphere/Ice/Interactions or LAII. Within LAII, four research areas were chosen for initial emphasis: (1) arctic feedback processes that may amplify global climate change; (2) changes in arctic hydrological and biogeochemical systems; (3) changes in biotic communities; and (4) regional and global effects of all these changes (the ARCC and LAII goals are summarized from [*ARCUS*, 1993].

The LAII Flux Study addressed some of these research areas. Its primary components were: (1) measurements of fluxes of trace gases, water and energy between the arctic terrestrial ecosystem and the atmosphere, and of the transport of water and materials to the ocean, (2) determination of the primary controls on the fluxes, and (3) scaling and synthesis to the regional scale [*LAII-SMO*, 1994]. Twelve individual projects made up the flux study and were focused on the Kuparuk River basin as the study site. The long-term goals were to make predictions of fluxes for the entire Arctic, based upon measurement techniques and models developed. The goals of "Key Connections in Arctic Aquatic Landscapes" are entirely complimentary with the Flux Study.

2.2 Scaling up from small watersheds: ATLAS

A recently funded LAII program is “Arctic Transitions in the Land-Atmosphere System” (ATLAS). The overall goal of this program is “to determine the geographical patterns and controls over climate-land surface exchange (mass and energy) and to develop reasonable scenarios for future climate change.”(ATLAS web site) Currently over a dozen projects are being funded, encompassing both field research and modeling studies. The initial focus will concentrate on the North Slope Western Transect that includes Barrow, Atquasuk, Oumalik, and Ivotuk. Data collected by the various groups will include water, energy, and trace gas fluxes between the terrestrial landscape and the atmosphere, hydro-meteorological measurements, ground temperatures and soil moisture status, soil respiration, etc. The modeling studies, which will make use of data collected in the field projects, include permafrost models, the ARCSyM regional climate model [*Lynch et al.*, 1995], and a suite of ecosystem models such as GEM [*Rastetter et al.*, 1991], TEM [*Raich et al.*, 1991], CENTURY [*Parton et al.*, 1987], and SPA [*Williams et al.*, 1996]. However, a major gap in this program that is specifically identified is hydrology. As stated in the ATLAS implementation document [*ATLAS*, 1998], “Many of the relevant parameters are to be measured at the major tower sites. However, there is currently no basis for estimating these parameters in a spatially distributed fashion or in projecting these parameters into the future based on reasonable scenarios of climatic change. We need a project in meteorology and hydrology that focuses on spatial and temporal patterns of climate and soil moisture, and considers the relationship between these parameters and energy exchange and runoff". The planning document goes on to “… recommend that another project be added to focus on scaling of hydrology to the regional scale. This would make use of all the meteorology and soil moisture information from the field research but would aggregate this information to produce sub-grid scale fluxes and lateral transport at scales necessary for climate prediction.” A field study specifically aimed at determining the spatial distribution of soil moisture is currently funded (Hinzman, Goering, Kane).

We propose here to fill this modeling gap in hydrology by making use of this hydro-meterological data being collected in the field. We will use, as our starting point the catchment based LSM that is currently being developed by the NASA NSIPP group. Ultimately, this will lead to an improved seasonal and inter-annual variability in climate simulations through a better representation of sub-grid scale land-atmosphere water and energy fluxes. The approach is computationally efficient, physically based, and can be scaled to large watersheds. As a member of the NASA collaboration Stieglitz will translate this modeling approach to arctic regions using lessons learned from the Arctic project "Key Connections in Arctic Aquatic Landscapes" in the modeling of freeze-thaw processes, snow physics, and arctic hydrologic processes.

3 Background

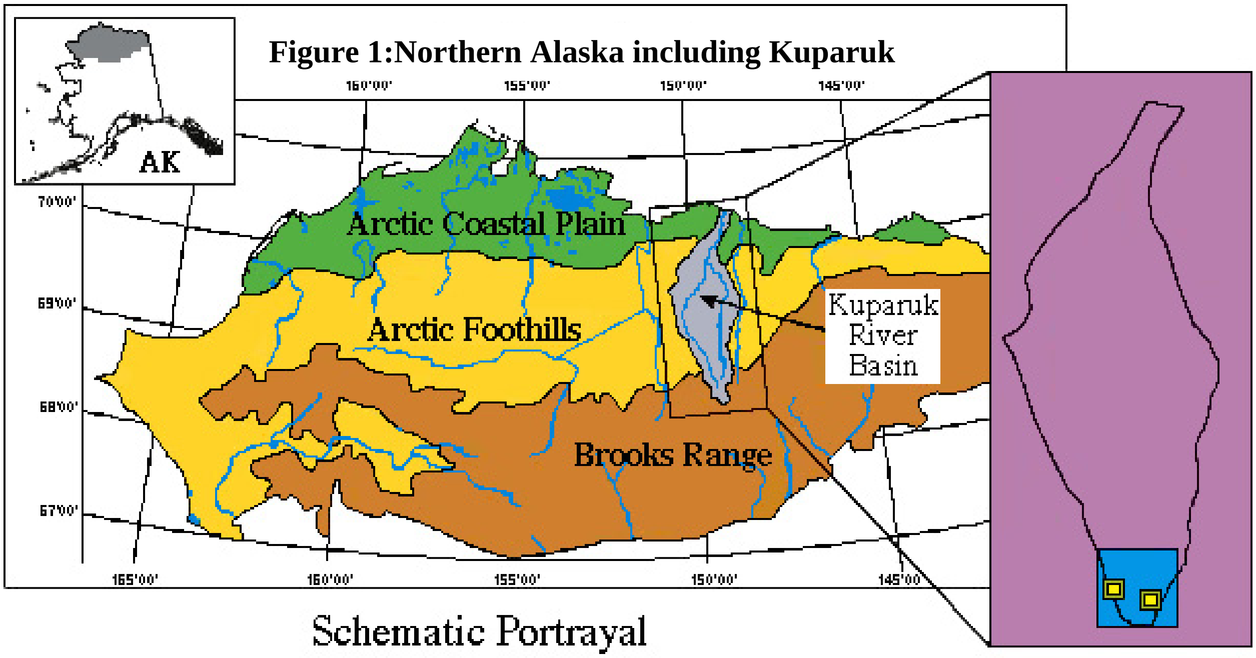
The arctic climate system responds to external forcing from low latitudes but is also driven by its own set of complex internal modes and feedbacks. Because these internal feedbacks are highly non-linear, the Arctic is thought to be very sensitive to climate change. For example, with its high albedo and large areal extent, snow cover on land can have considerable influence on regional and hemispheric conditions**.** Furthermore, since the snowpack is thermally insulating, and limits the otherwise efficient heat exchange between the ground and the atmosphere, it controls the evolution of seasonal ground temperatures. In turn, this thermal control over the evolution of the hydrologically active soil depths plays a large role in determining the magnitude and timing of spring melt water delivered to the Arctic Ocean, which impacts stability to the surface layer, and affects ocean circulation and seasonal sea ice formation. Finally, until the soil active layer deepen into mineral soils, much of the water soil flows through a narrow zone in contact with plant roots and soil organic matter, this having a direct influence on CO_2 and CH_4 fluxes, both greenhouse gasses. Hence, any long term forecast in a fully coupled climate system is dependent on an accurate simulation of the land snow-covered area, snow water equivalent, and permafrost dynamics.

Despite the acknowledged role that the arctic system plays in regulating the planetary climate, most land surface models intended for use in exploring the above mentioned feedbacks (i.e., coupled with atmospheric circulation models, ocean, and sea ice models) are inadequate. Originally designed for mid-latitudes, most do not adequately represent either snow physics or permafrost dynamics. Furthermore, no model to date includes the role that topography plays in the development of soil moisture heterogeneity and the critical, perhaps overwhelming, impact of this heterogeneity on surface energy, water, and trace gas fluxes. Our objective is to correct these deficiencies.

Given the constraint that we wish to work with a Land Surface Model (LSM) that is computationally efficient, can operate at large spatial and at high latitudes, and eventually, be fully coupled within a GCM, the are number of models available [*Abramopoulos et al.*, 1988; *Dickinson et al.*, 1993; *Koster and Milly*, 1997; *Koster and Suarez*, 1996; *Koster and Suarez*, 1992a; *Pitman and Desborough*, 1996; *Verseghy*, 1996]. However, if we do not wish to ignore the role topography plays in the development of soil moisture heterogeneity and the impacts that this heterogeneity has on surface water and energy fluxes, our options are limited. We can either account for the topographic control over surface hydrology by explicitly modeling the movement of water from the hillslopes to the valleys, which is computationally expensive at even small spatial scales, or the impacts of topography can be modeled with quasi-statistical techniques, such as those offered by TOPMODEL [*Beven and Kirkby*, 1979; *Sivapalan et al.*, 1987] or VIC [*Liang et al.*, 1994] formulations. Both TOPMODEL and VIC formulations have now been used in conjunction with sophisticated LSMs to successfully simulate the growth/ablation of the seasonal snowpack, permafrost dynamics, and snowmelt and storm discharge at scales ranging from small catchments to major river basins covering both the arctic and boreal ecosystems. Modeling results have been obtained for small arctic catchments [*Stieglitz et al.*, 1999b], large arctic basins including the Mackenzie [*Bowling and Lettenmaier*, in press; *Pauwels et al.*, 1996], and the BOREAS boreal area ranging from tower scales [*Nijssen et al.*, 1997; *Pauwels and Wood*, 1999a; *Pauwels and Wood*, 1999b] to regional scales [*Pauwels*, 1999]. Further, this type of modeling approach provides a significant conceptual improvement over current, GCM soil column models, as demonstrated by comparing site and simulated discharge [*Betts and Viterbo*, 2000; *Pauwels*, 1999; *Stieglitz et al.*, 1997].

The proposed work described here will begin with the land surface model currently under development by the NASA NSIPP program. This catchment-based LSM was developed to overcome a critical deficiency in standard General Circulation Model (GCM) based LSMs, namely, the neglect of an explicit treatment for spatial variability in soil moisture. From the outset this work has been a collaborative effort between NASA's Goddard Institute for Space Studies (GISS), Lamont Doherty Earth Observatory (LDEO: Marc Stieglitz, Colin Stark) and Goddard Space Flight Center (GSFC: Randy Koster, Max Suarez, Agnes Ducharne, and Praveen Kumar). Using this model presents numerous advantages to both NASA and NSF-OPP: (1) Leveraging off existing work avoids expensive duplication of effort. (2) Because the approach uses the statistics of the topography (via TOPMODEL formulations) rather than the details of the topography, it is computationally efficient and numerically tractable at the large spatial scales of today's regional and global climate models. (3) The limited validation performed to date indicates that the NASA LSM will be effective in regions with permafrost [*Stieglitz et al.*, 1999b] and significant snow cover (see Figure 3, [*Stieglitz et al.*, in preparation]. (4) In depth validation in arctic regions-will provide NASA with invaluable insights into the behavior of the model in a region that otherwise would receive only a cursory validation.

Figure 1:Northern Alaska including Kuparuk



4 Goals and Objectives

Research programs focused on understanding the physical climate of high latitude regions, and on predicting environmental change for these regions require a sound basis for predicting the terrestrial water and energy budgets across a range of spatial and temporal scales. Unresolved is a clear understanding of the small scale processes and features (e.g. topography, vegetation, soils) that must be included in such terrestrial hydrologic models, including the importance of these small-scale features for different seasons and the resulting errors if omitted. Thus, the research will develop an integrated program that combines field measurements, remote sensing observations and a terrestrial water-energy balance model with the objectives:

(i) To further our understanding of the relationship between the arctic ecosystem and the physical climate system, with particular attention on understanding spatial and temporal variability in water and energy fluxes.

(ii) To study approaches for scaling processes to arctic catchments and regional scales from relationships developed at the tower-scale through point measurements. Scaling to the basin scale will be through remote sensing and modeling of the water and energy fluxes (i.e., comparing model generated discharge into the Arctic Ocean with measured fluxes).

(iii) To identify the critical land-atmosphere interaction processes that need to be represented in modeling the arctic ecosystem at large scales and to determine the degree to which small-scale variability needs to be represented.

Initially we will focus on the Kuparuk Basin, located in the North Slope of Alaska (shown in Figure 1; Donald Walker, http://www.Colorado.Edu/INSTAAR/TEAML/atlas/chapters/geobot.html). We will force the LSM with historical climate data covering this basin and validate model-generated discharge, snow extent, snow depth, and snow water equivalent across a range of spatial scales.

5 Modeling of the Land Surface

5.1 A Catchment Based Approach

To put the proposed work in perspective, we present in this section the relevant accomplishments of the ongoing NASA NSIPP project and emphasize how these accomplishments can serve as the basis for new, valuable work.

Our catchment-based land surface model (LSM) was developed to overcome a critical deficiency in standard GCM-based LSMs, namely, the neglect of an explicit treatment for spatial variability in soil moisture. Standard LSMs employ a one-dimensional treatment of subsurface moisture transport and surface moisture and energy fluxes that effectively assumes homogeneous soil moisture conditions across areas spanning hundreds of kilometers. Much recent development work by various groups has focused on improving the 1-D representation itself, incorporating, for example, improved treatments of transpiration resistance and even carbon budget models into the evaporation calculation. Relatively little attention has been given to the spatial heterogeneity issue. This is unfortunate given that this heterogeneity can have a strong, even dominating, impact on surface energy and water budgets.

Our strategy [*Ducharne et al.*, 1998; *Koster et al.*, *in review*] calls for the partitioning of the land surface into a mosaic of hydrologic catchments, delineated through analysis of surface elevation data. When coupled to an atmosphere model, the effective "grid" used for the land surface is not specified by the overlying atmospheric grid. Within each catchment, the variability of soil moisture is related to characteristics of the topography and to three bulk soil moisture variables through a TOPMODEL-type formulation of catchment processes. Care is taken, however, to ensure that the deficiencies of the catchment model in regions of little to moderate topography are minimized. Many of the ideas underlying the strategy have been developed over a number of years by the Co-PI Wood and his students [*Famiglietti and Wood*, 1991; *Pauwels and Wood*, 1999a; *Peters-Lidard et al.*, 1997] and others [*Bowling and Lettenmaier*, in press; *Nijssen et al.*, 1997; *Stieglitz et al.*, 1997].

TOPMODEL formulations permit for dynamically consistent calculations of both the partial contributing area, and the baseflow which supports this area, from knowledge of the mean depth of the water table and a probability density function (pdf) of the soil moisture wetness index, χ, derived from topography digital elevation model (DEM) data. At any location, x, within the watershed, the wetness index, χ, defined to be $\ln(a/\tan\beta)_x$, is the ratio of the area, *a*, above any point on the catchment that drains to the point x (a measure of how much water can potentially flow through this location) to the local slope at that point, $\tan\beta$, (a measure of the potential driving water downslope through this location). As such, regions with a high topographic wetness index, along valley bottoms and flatter areas, are regions of convergent flow, a high water table, and in sum, constitute the bulk of the saturated fraction of the watershed. Regions with a low index, near the top of hills, are characterized by a suppressed water table, and are primary recharge zones.

A particularly unique aspect of our catchment model is the separation of the catchment into three subareas, each representing a distinct hydrological regime: one in which the surface is saturated, one in which the surface is unsaturated but transpiration proceeds without water stress, and one in which transpiration is stressed. Because these subareas are tied to the dynamically varying moisture variables in the catchment, their sizes vary with time. Key to the modeling strategy is the application of different formulations of evaporation and runoff in each subarea to reflect the fundamentally different physical mechanisms controlling these fluxes in the three regions. This is a far more physically consistent approach than is possible with traditional one-dimensional LSMs.

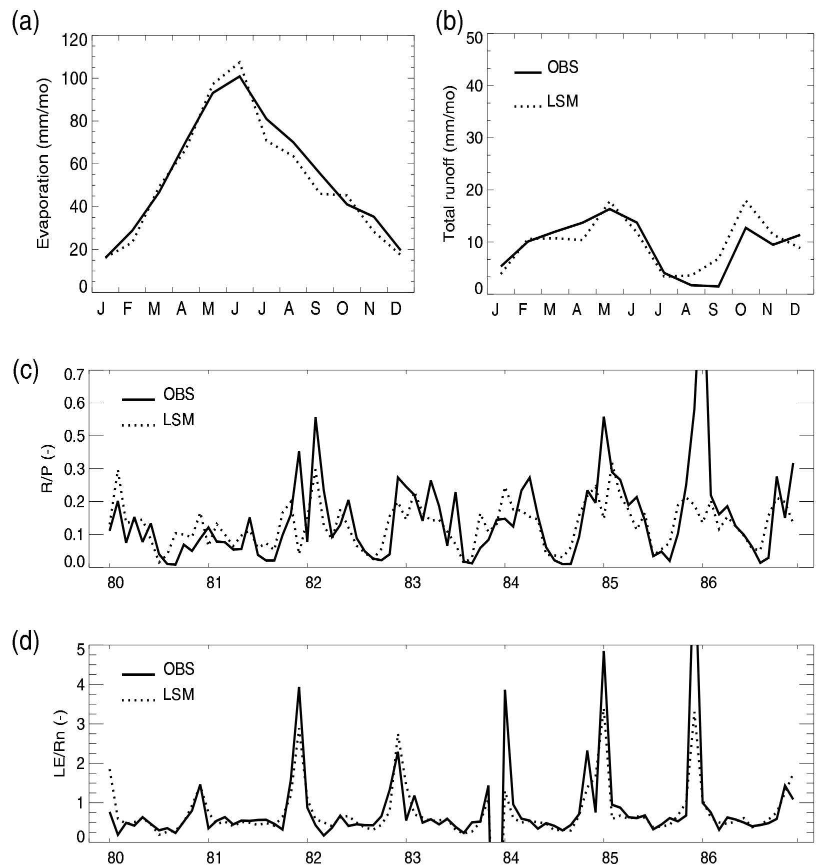


Figure 2: Comparison of simulated and observed fluxes for the Red Arkansas for the mean seasonal cycles for (a) evapotransipiration rates and (b) total runoff (mm/day); monthly ratios of (c) runoff to precipitation and (d) latent heat flux to net radiation (-)

The catchment model has some additional components worthy of mention. A detailed snow model is now incorporated into the code; this multi-layer model accounts for the coexistence of liquid and solid phases, changes in snow density due to melting, refreezing, compaction, density-dependent albedo, and other important processes [*Lynch-Stieglitz*, 1994; *Stieglitz et al.*, in preparation]. Ground thermodynamics are computed through a multi-level heat diffusion calculation. Transpiration and other surface energy balance calculations proceed using established and tested code from a standard ``SVAT-type" vegetation model [*Koster and Suarez*, 1996; *Koster and Suarez*, 1992b] that includes bare soil evaporation and canopy interception loss. The SVAT code used for one-dimensional energy balance calculations is applied over each of the three identified moisture regimes, and each regime maintains its own prognostic temperature.

The new catchment based model has been tested offline in two venues --- over the Red-Arkansas basin, using forcing established for the PILPS 2c intercomparison study [*Wood et al.*, 1998], and over North America as a whole, using forcing from the ISLSCP Initiative 1 CD-ROM [*Sellers et al.*, 1996]. The catchment boundaries and topographic-based model parameter values were derived from the processing of GTOPO30 (1-km) DEM data; some 5000 catchments cover North America, with 126 making up the Red-Arkansas basin.

Results for the Red-Arkansas are presented in Figure 2 [*Ducharne et al., in review*], which shows how model-simulated runoff and evaporation compare with observed values. (The evaporation ``observations" were derived from atmospheric water budget calculations.) The agreement between simulated results and observations is seen to be quite high, especially given that the observations, while reliable, are associated with some error. We must emphasize here that the Red-Arkansas dataset was used in the development of the model itself, so that some of the agreement seen in Figure 2 reflects a calibration of the model physics. This calibration was essentially limited, however, to the treatment of surface runoff generation over unsaturated soil and cannot by itself explain the general agreement in both the mean and variability of the simulated fluxes. Our main point here is that this model framework is capable of reproducing observed evaporation and runoff rates over large spatial scales. Note that because different catchments below a single atmospheric grid cell exhibit different, topography-dependent behavior, this modeling framework may be particularly valuable for downscaling applications.

5.2 Snow and permafrost dynamics

While sophisticated multi-layer snow models have been developed and successfully applied at the local scale [*Davis et al.*, 1995; *Hardy et al.*, 1998; *Jordan*, 1995], the treatment of snow processes, especially those used within GCMs, have been relatively simple. Some models consider the winter snow pack only as a store of soil moisture [*Abramopoulos et al.*, 1988; *Bonan*, 1996; *Koster and Suarez*, 1996], while others blur the distinction between the snow and the ground surface altogether by envisioning a composite soil and snow layer [*Dickinson et al.*, 1993; *Pitman et al.*, 1991]. Still others do distinguish between separate snow and ground layers, yet represent the entire pack with a single snow layer regardless of the actual pack depth [*Slater et al.*, 1998]. However, most of these simple schemes have considerable flaws. Lynch-Stieglitz [1994] demonstrated that an insufficient representation of snow processes can lead to a corruption of surface energy fluxes and a degradation of the snow insulation between the cold atmosphere and the warm ground; ultimately impacting the seasonal development of ground freeze-thaw processes, and compromising the normal hydrologic processes of runoff, ground water movement, infiltration, etc., for a good part of the year. Further, Betts *et al.* [1998] have recently shown that an insufficient representation of snow processes at high latitudes leads directly to a poor evolution of the atmospheric boundary layer in weather forecasting models.

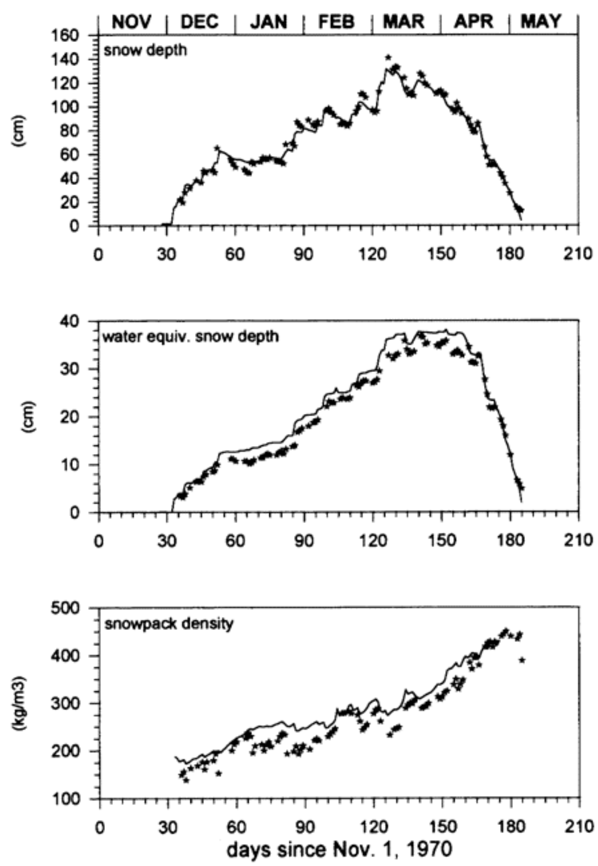


Figure 3: Model-predicted snow depth, water equivalent snow depth, and snow pack density for the 1970/71 snow season (solid line) and observed snow characteristics at the NOAA-ARS snow research station (stars).

Recently, sophisticated snow physics have been included in LSMs and demonstrate a clear improvement in the overall simulation of the hydrologic cycle, including ground freeze - thaw processes [*Loth and Graf*, 1998a; *Loth and Graf*, 1998b; *Loth et al.*, 1993; *Lynch-Stieglitz*, 1994; *Stieglitz and Giblin*, 1997; *Stieglitz et al.*, 1999b; *Yang et al.*, 1997]. Typically, these multi-layer snow schemes explicitly model the heat and mass (water) transport within the pack. Radiation conditions determine the surface energy fluxes, and the heat flow within the pack is accomplished via linear diffusion along the thermal gradient. Meltwater generated within a given layer can drain to a lower layer, where it will refreeze, remain in the layer in the liquid state, or pass through.

As mentioned earlier, we employ the snow model of Lynch Stieglitz *et al*. [1994] coupled to the global catchment-based LSM of the NASA NSIPP project. This three-layer snow model accounts for snow melting and refreezing, dynamic changes in snow density, snow insulating properties, and other physics relevant to the growth and ablation of the snowpack. As the boundaries of the snowpack move up and down under the influence of snowfall, mechanical and wet compaction, condensation, etc., three variables are needed to completely describe the system; layer thickness (Z_i), water equivalent (W_i), and heat content (H_i). The coupling to the catchment framework, however, necessitated some modifications to the original scheme [*Stieglitz et al.*, in preparation]. In particular, we now ensure a smooth transition between snow-free and snow-covered conditions in order to capture the gradual growth of a snowpack's spatial extent and to avoid abrupt (discontinuous) changes in the surface energy balance calculations. The approach used is straightforward. We assume a minimum local snow water equivalent, *SWE*, of 13 mm, a value that allows the resolution of the diurnal surface temperature signal yet still produces a stable solution with a 20-minute timestep. If a given volume of snow falls on a snow-free catchment, that volume is spread uniformly over a fraction of the catchment so that the local water equivalent at any snow-covered point is 13 mm. Thus, if the snow falling on a snow-free catchment during a timestep has a total water equivalent volume, V_s, and if the area of the catchment is A, then the snow-covered areal fraction, A_s/A, is taken to be $V/(A*SWE)$. The snow-covered areal fraction increases as more snow falls until A_s/A reaches 1, at which time the local snow water equivalents across the catchment start increasing uniformly. When the fractional coverage is less than one, the snow model is represented with a single snow layer, whereas three model layers are used when the snow coverage is complete [*Lynch-Stieglitz*, 1994]. The transition between the single layer and three layer representations involves a simple conservative redistribution of layer heat and water contents. Surface energy calculations are performed separately over the snow free and snow covered areas.

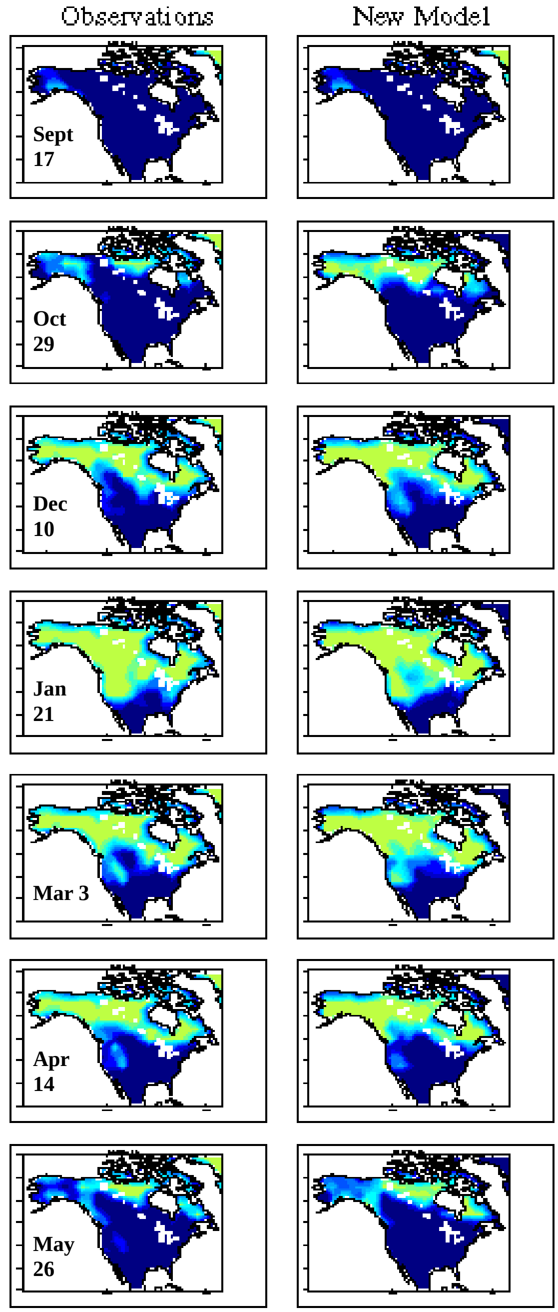


Figure 4: spatial snow cover for the 1987-1988 snow season.

To simulate ground freeze-thaw processes a multi-layer ground schemes is used in which heat transport is physically modeled via diffusion along the thermal gradient [*Abramopoulos et al.*, 1988; *Bonan*, 1996; *Stieglitz et al.*, 1997]. The scheme has been tested for seasonal evolution of ground temperatures in regions ranging from New England [*Lynch-Stieglitz*, 1994], to the Arctic [*Stieglitz et al.*, 1999b], where permafrost dynamics plays a large role in the seasonal hydrologic cycle.

Results at the Sleepers River watershed (8.4 km^2), located in the highlands of Vermont, demonstrate that all the features of snowpack ripening that characterize pack growth/ablation are well simulated (Figure 3) [*Lynch-Stieglitz*, 1994].

At the Basin scale we can evaluate the ability of the coupled catchment-snow model to simulate spatial coverage of snow, as well as snow amounts, over large areas. To this end, ISLSCP data was used to drive the model over North America for the period 1987 - 1988 and the Northern Hemisphere EASE-Grid Weekly Snow Cover data set was used to evaluate simulated snow coverage. This successful larger-scale application of the model at over the 5000 catchments comprising North America (Figure 4, [*Stieglitz et al.*, in preparation]) suggests that the global application of the model is within reach, and more specifically, application to the arctic will be successful.

6 Detailed Work Plan

The successful simulation of hydrologic and thermal processes using a land surface model has several requirements. These requirements are:

1. A high quality model of the land surface processes for forecasting of the LSM system states (ie. soil moisture, soil temperature, snow cover, etc.).
2. Observations of the land surface forcing (meteorological data) for driving the forecast of land surface system states when the LSM is running off-line.
3. An appropriate spin-up strategy for initializing the LSM system states.
4. Remotely sensed snow observation products, as well as ground observations, for validating the LSM hindcast simulation of snow cover, snow depth and snow water equivalent.
5. River discharge measurements, at a variety of scales for validating the LSM hindcast simulation of catchement outflow, and flow routing.

We will first outline our proposed approach and then detail the specifics in turn.

6.1 Proposed Approach

In this approach the LSM is important for establishing the relationship between snow, soil moisture, soil temperature, the energy and water budget. In order to run the model (off-line from a general circulation model), high quality meteorological data are required for forcing of the model. In addition to high quality forcing data, the model forecast is dependent on the initial state values given to the LSM. As the LSM states (other than snow which can be observed via remote sensing), the LSM must be spun-up to realistic initial state values prior to commencing the hindcast simulation. Hence, errors in the land surface initialization, forcing data and LSM physics all contribute to some errors in the forecast land surface states. However, as the forcing data sets are long enough (30 - 40 years), this problem should be mitigated as the run proceeds.

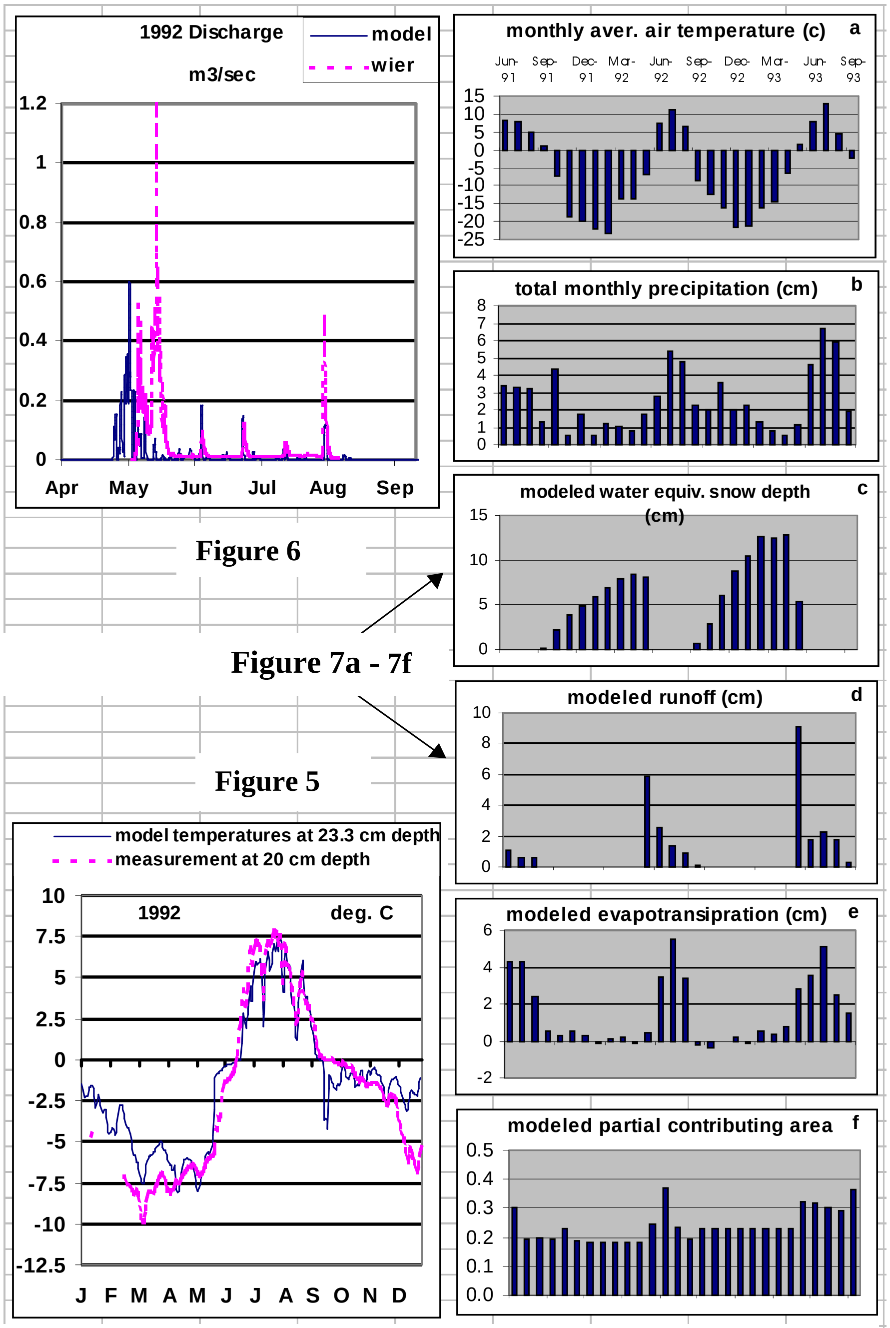
6.2 LSM Application to arctic regions

6.2.1 Snow Model Development

Here we focus on those snow processes operating at the small catchment scale which have a direct impact on our large Kuparuk basin scale simulations.

Stieglitz et al (1999) has demonstrated that this TOPMODEL based modeling approach can be used to successfully simulate the evolution of hydrologic and thermal processes operating in the North Slope of Alaska. Meteorological and hydrological data taken at Imnavait Creek from May 1991 through October 1993 (Hinzman and Kane) were used to force the land surface model. Figure 5-7 shows monthly averages of various watershsed water balance components for the period June 1991 through September 1993. With freezing of the soil column beginning in early fall, soil moisture does not change significantly until the onset of spring melt. As the pack ablates in late May and early June, melt waters infiltrate the still frozen ground. The soil is recharged and the mean water table depth rises from the previous summer value nearly to the surface. The associated partial contributing area increases from 20% to almost 40% (in good agreement with McNamara et al. [1997]. Surface runoff generated over the rapidly expanding saturated regions quickly enters the stream system. As the soil active layer deepens in the summer, evapotranspiration (and the latent heat flux) begins to increase, peaks in July and August, and falls rapidly as the snow season approaches. Finally, annual precipitation is partitioned 47% into runoff and 53% into evapotranspiration; the partitioning measured in the long-term field record. Modeled ground temperatures are in good agreement with measurements.

While the overall simulations of discharge is adequate (Figure 4), even at these small spatial scales snow heterogeneity significantly impacts the timing and quantity of snowmelt related discharge and poses a obstacle towards application on an arctic wide basis. Because the spatial distribution of snow cover is not represented in the model framework, modeled snowmelt consistently leads site data by five to ten days. With high winds and low vegetation height, snow in this region of the Arctic tends to blow into and accumulate in valleys [*Kane et al.*, 1991; *Liston*, 1986; *Liston and Sturm*, 1998]. As such, it takes longer to melt a snowpack whose depth is substantially increased over a reduced area compared to a pack that is uniformly distributed over the landscape. Further, as pointed out by Hinzman et al. [1996], where the snowpack is thick and dense on the valley floor, it functions as a dam and holds back the water until the bonding strength of the snow is overcome. As an ongoing part of this effort we will improve the models representation of sub-grid scale snow heterogeneity. To account for



Figures 5-7: Model predictions and measurements at Imnavait

the effects that wind, vegetation, and topography have on the distribution of snow cover, we will adapt the work of Liston and Sturm [1998] to our modeling framework. While their spatially explicit model is not directly compatible with the statistical treatment of topography presented here, the empirical equations governing wind blown snow can be used to treat snow distribution in much the same way we currently treat soil moisture heterogeneity; through a statistical representation in which valleys are regions of snow accumulation and uplands are regions of snow ablation. Hartman et al. [1999] has recently applied such a procedure, albeit without explicitly including for the effects of wind blown snow, and had success in improving snowmelt discharge. In this respect TOPMODEL formulations provide a clear advantage over more parameterized hydrologic models such as VIC in that the TOPMODEL pdf does retain quasi-explicit information about the landscape topography.

Finally, we may find that gradients in elevation are having an impact on snow heterogeneity. If so, a temperature lapse rate will be used along with binned elevation bands to distribute snow cover and snow melt throughout the landscape [*Bowling and Lettenmaier*, 1998; *Hartman et al.*, 1999].

6.2.2 Catchment Delineation

Prior to any water and energy balance simulations, two steps of data preprocessing must be performed; catchment delineation and the calculation of the pdf of the TOPMODEL wetness index, χ, for each catchment.

The NSIPP-LSM project currently uses the 1km resolution GTOPO30/HYDRO1k data to calculate catchement wetness indices. However, as demonstrated during the course of the NSIPP work and by others [*Wolock*, 1998], 1km resolution data is insufficient to capture hillslope processes. Systematic recalibration of topographic index pdfs are therefore required for the reliable estimation of TOPMODEL parameters. However, throughout the North Slope of Alaska, high resolution, 60-90m DEM data is available. Further, 10 m data is available for a region of approximately 1000 km^2 in the Upper Kuparuk. For this study, this high-resolution data will be used for catchment delineation and the estimation of TOPMODEL parameters, obviating the need for recalibration.

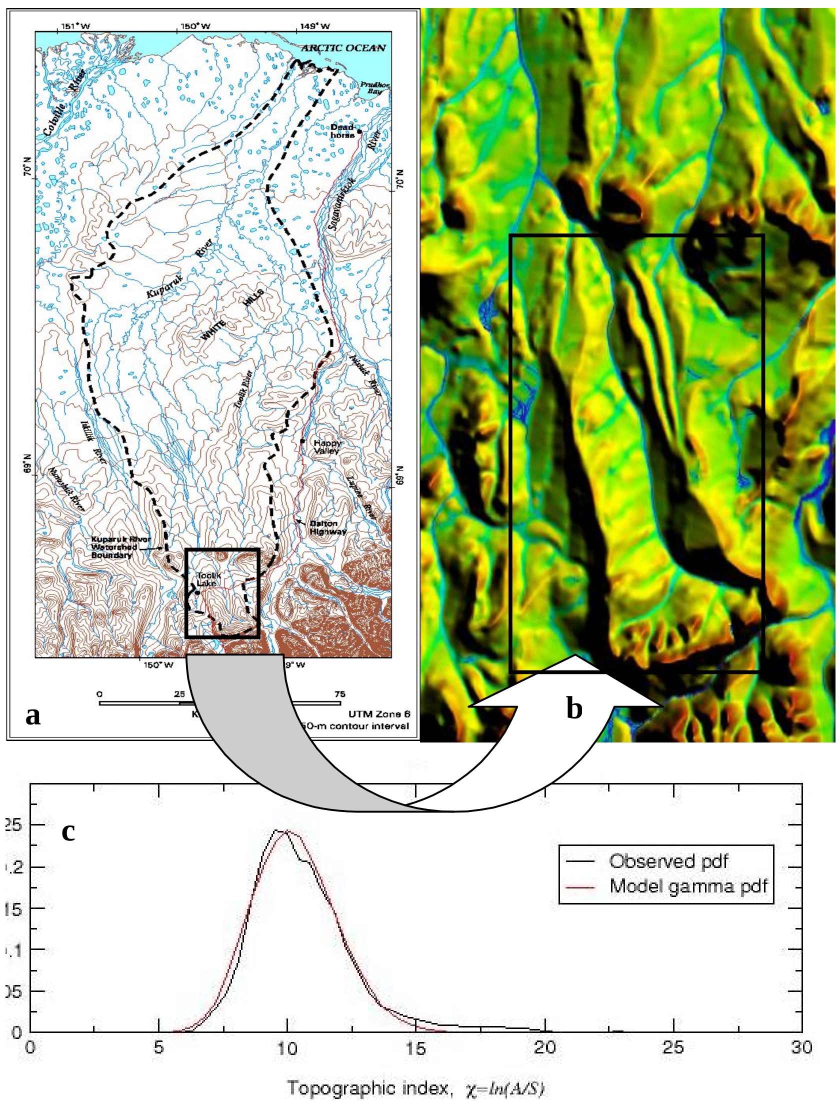


Figure 8: Catchment delineation and pdf generation for the Upper Kuparuk

The study region will be segmented into a mosaic of indexed sub-catchments using a delineation algorithm that includes a DEM error correction scheme. Each watershed index will permit access to a pdf of χ, a link into the drainage network template which permits river routing, and a sub-catchment boundary geometry which facilitates meshing with a GCM grid. The segmentation of sub-catchments will be performed in tandem with estimation of hillslope and channel network flow patterns using a multiple flow routing algorithm [*Quinn et al.*, 1991]. This methodology permits robust estimation of the topographic index in addition to establishing channel network structure and the along-channel properties required by routing equations.

The DEM flow routing algorithm is tied to an adaptive error correction (pit infill) scheme, something that is particularly necessary during delineation of flow on low relief areas such as coastal plains. Generally, error correction schemes perform crude "flooding" operations to force flow networks to join up, and to prevent internal drainage. In more difficult areas such as alluvial plains, the artifacts that arise from this approach can cause non-negligible errors in the estimated routing times along main channels. Our algorithm is similar to that of [*Martz and Garbrecht*, 1998]: a quasi-diffusive, stochastic interpolation is performed over pseudo-flat regions such that the interpolated flow routing is at least roughly consistent with the topography around the area of error. This technique has been shown to be successful for the delineation of braided flow patterns on error-prone DEMs of alluvial fans, and will provide a solid basis upon which to build a regional drainage model.

An application of the use of smoothed 90m resolution data, and of the algorithms for DEM correction and topographic index estimation, is shown in Figure 8 Figure 8a shows the Kuparuk drainage basin (Donald Walker, www.Colorado.Edu/INSTAAR/TEAML/atlas/chapters /geobot.html). Figure 8b shows a small area of the Upper Kuparuk, about 32km by 50km in size, which contains the Toolik Lake watershed in the center of the image. The colors in Figure 8b indicate the topographic index estimated from the DEM; low values of χ are shown in red (upslope regions), through green, to high values in blue (valley regions). The pdf of χ for the Upper Kuparuk River, which includes Toolik Lake, are plotted in Figure 8c. Both the color image and the pdf show that the DEM error, which is a potential problem in low relief areas to the north of Toolik Lake, and also along the river valleys, is largely suppressed, and that robust estimates of topographic index distributions can be obtained.

6.2.3 River routing

At each modeled timestep, and for each sub-catchment, runoff is generated; surface runoff plus baselow. This runoff is then routed thorugh a DEM-based channel network to provide model-estimated discharge at gauged discharge points within the basin. The inclusion of the river routing model, developed by Lohmann et al. [1998b] permits comparisons between the model-derived discharge and observations at gaging stations. This routing approach has been widely used with success in combining land surface models to catchments and their gauged discharges [*Lohmann et al.*, 1998c; *Maurer et al.*, in review].

6.3 Land Surface Model Forcing Data

An evaluation of the model will be undertaken over catchments in the Kuparuk basin. High quality historical climate data, available from 1960 through the present, will be used to force each of the sub-catchments within the Kuparuk Basin. Measurements of river discharge, snow extent, and snow depth, will be used to evaluate model performance. Test catchments across a range of spatial scales will be employed; across length scales where the channel routing transit time ranges from large to small compared to the time scale of observation. At the largest of scales we will evaluate model performance with respect to simulating discharge into the Arctic Ocean via the Kuparuk river.

6.3.1 Model-generated forcing data

The use of high quality global atmospheric forcing of the land surface is essential to produce reasonable land surface predictions. The off-line LSM requires wind speed, air temperature, humidity, precipitation, and radiation on a sub-hourly basis. Many of these forcing variables can be reliably provided by operational Numerical Weather Prediction (NWP) models at NCEP, ECMWF, or NASA-DAO, run in either a real-time or reanalysis mode. However, NWP models generally poorly predict precipitation and radiation because the complex prediction of cloud physics and dynamics, which can lead to gross errors in land surface simulations, have not been mastered. Therefore, when available, we will use observational products. Unfortunately most high-quality long-term global land surface observations have been processed on monthly time scales for use in climate variability studies, and therefore lack the high temporal resolution required by land surface modeling efforts. These low temporal resolution observations can still be used to improve land surface predictions by reducing the longer- term land surface forcing biases through a ratio correction. Essentially, NSIPP uses the NWP model forcing as high-resolution temporal weights on the longer-term observation averages when high-resolution observed forcing are unavailable. [*Pauwels*, 1999] and [*Pauwels and Wood*, in review] have investigated the effect of substituting ECMWF model data for observations over the BOREAS SSA and NSA. In their study, they found that the largest errors in the forcing data is spring-time radiation due to the well-discussed snow albedo bias problem [*Betts and Ball*, 1997] and precipitation, which is underestimated by about 40%. Betts and Viterbo [2000] have studied the water and energy balance from the ECMWF model products for seven sub-basins of the Mackenzie River basin. Their analysis will provide an additional basis for evaluating the use of NWP re-analysis products to force our LSM.

Generally land-surface precipitation and radiation forcing is most critical to land surface prediction, with surface winds, humidity, and air temperature being of second-order importance. Therefore, using precipitation observations based on gauges, GOES Precipitation Index (GPI) estimates [*Arkin and Meisner*, 1987], shortwave passive microwave (as available with the SSM/I instrument, TRMM, and AMSR) estimates, and ground-based Doppler radar estimates are a priority. The Global Precipitation Climatology Project (GPCP) [*McCollum et al.*, in review] has developed a long-term, globally continuous combination of microwave, infrared, and gauge measurements that is an attractive product for use in land surface modeling applications. Global downward shortwave radiation fluxes are available [*Pinker and Laszlo*, 1992] using surface solar irradiance models. This is a theoretical-spectral model and has shown success in producing the global surface solar radiation flux using ISCCP C1 data as input [*Whitlock et al.*, 1993], and has been extended to use ISCCP D1 data. [*Gupta*, 1989] developed a parameterization for longwave surface radiation using satellite measurements. Recently, he improved and modified the algorithm [*Gupta et al.*, 1992] for direct use of ISCCP D1 data. The use of air temperature, winds, and humidity surface observations are also being explored to improve land-surface predictions.

6.3.2 Observed forcing data

Monthly data: Under the auspices of the NSF project “Contemporary Water and Constituent Balances for the Pan-Arctic Drainage system: Continent to Coastal Ocean Fluxes", a Pan-Arctic 0.25 degree gridded monthly data seta of precipitation and temperature for the Pan-Arctic is now available for the period 1960 - 1990 (refs, http://climate.geog.udel.edu/~climate/html_pages/archive2.html). In total, 8818 independent weather stations north of 43N were used to produce the precipitation archive and 6487 stations for the temperature archive.

Daily data: Global Summary of the Day (GLOBALSOD) data contains precipitation, temperature, dew point, wind speed, sea level pressure, and daily total sunshine. Station coverage between latitudes 45N and 66N is extensive. Coverage above 66N is approximately 450 stations with nearly 100 stations in Alaska.

Hourly data: Alaskan surface weather observations from 1901 through 1990 at approximately 150 stations are available from the National Climatic Data Center (NCDC - DATSAV2 SURFACE). Data include precipitation, air temperature, dew point temperature, wind speed, precipitation, station pressure, and cloud cover. More specifically, since 1992 over a dozen meteorological stations have been set up throughout the Kuparuk, all recording the requisite data needed to run the LSM (ftp://arcss.colorado.edu/pub/projects2/climate/Alaska_NSlope_Met_1985-96/). With funding from AT-

LAS meterological stations have now been established at Ivotuk, Alaska. Finally, for all their deficiencies, two Wyoming snow gauges are located with the Kuparuk basin, one at Imnavait Creek and one near Prudoe bay.

6.4 Land Surface Model Spin-up

Initialization values for the system states of the LSM will be obtained by undertaking a land surface spin-up. This will involve running the catchment-based LSM repeatedly for a given year of forcing data, until the system states for the start of the year converge to consistent set of values. The spin-up will be undertaken for the first ten years of forcing data (i.e. 1960-1970). This will allow for validation of forecasted system states from 1970 through to the present.

6.5 Validation Products

An effective evaluation of any large scale modeling endeavor is always the most difficult and yet most important aspect of the project. In this project, we propose to evaluate the simulation using remotely sensed and ground observed snow products of the snow cover, snow depth, and snow water equivalent, as well as river observed discharge measurements throughout the Kuparuk basin.

6.5.1 Snow Observation Products

Since November 1978, the Scanning Multichannel Microwave Radiometer (SMMR) instrument on the Nimbus-7 satellite, and the Special Sensor Microwave Imager (SSM/I) on the DMSP series of satellites have been acquiring passive microwave data that can be used to estimate snow extent and snow water equivalent. The SMMR instrument failed in 1987, the year the first SSM/I sensor was placed in orbit. On SMMR, the channels most useful for snow observations are the 18 and 37 GHz channels. For the SSM/I, the frequencies are slightly different (19 and 37 GHz). Additionally, an 85 GHz channel is available on the SSM/I. This frequency has been demonstrated to be beneficial in detecting shallow snow packs (< 5 cm thick). Passive microwave data for most places on the globe are available for alternate days. The data are placed into ½ degree latitude by ½ degree longitude grid cells, uniformly subdividing a polar stereographic map according to the geographic coordinates of the center of the field of view of the radiometers. Overlapping data in a cell from separate orbits are averaged to give a single brightness temperature, assumed to be located at the center of the cell. Because when the snow pack is wet, snow water equivalent information is difficult to extract using passive microwave radiometry, only dry snow conditions will be examined. This necessitates using only the nighttime satellite overpasses so that there will be a higher probability that the snow pack is not actively melting.

Remotely sensed snow cover extent and snow water equivalent observations for all of the Kuparuk will be produced from the twenty plus years of microwave brightness temperature data. In addition to the passive microwave snow products, high resolution (1 km or less) visible and near-infrared satellite data from Landsat, the NOAA series of satellites and the DMSP optical sensors will be employed to look at snow cover extent in more detail where warranted. Moreover, airborne gamma data are available over much of the northern U.S. and southern Canada for the period from the late 1970s through the present time. This data set can be used to “spot check” the passive microwave snow water equivalent products.

The Northern Hemisphere EASE-Grid Weekly Snow Cover Extent data yields snow extent data from 1971 through 1995. This product is provided on a 25-km equal area grid and is available through NSIDC.

Daily snow depth climatologies based on sit observations are available for 61 sites throughout Alaska. The period 1949 through 1998 was used to construct the climatologies. The Data is available from the Western Regional Climate Center. Hourly/daily snow cover observations throughout Alaska from 1901 through 1990 at approximately 150 stations are available from the National Climatic Data Center (NCDC). Finally, snow depth is available from the GLOBALSOD data.

6.5.2 River discharge products

Monthly data: Monthly Pan-Arctic discharge data is now available from R-ArcticNet (http://www.R-arcticnet.sr.unh.edu/) covering the period 1960 - 1990. In total, this database encompasses 3700 gauged rivers. Unfortunately, this database does not include discharge measurements within the Kuparuk basin. We include the mention of this data with an eye toward eventual Pan-Arctic application of the LSM

Daily data: The USGS currently maintains about 88 full time stream-gauging stations in Alaska and about 40 "partial-record" stations used for peak flow data collection. Data for some of these sites are available in real-time. Historical surface-water data are available in a computerized database for about 2,600 sites. Daily measurements for discharge within the Kuparuk Basin go back 20 years and exist at three locations, the headwaters, the Kuparuk Crossing (where the Kuparuk river and the Dalton Highway cross), and at Deadhorse Alaska (Prudoe Bay). At the smaller catchment scale is continuous monitoring at the Toolik Lake inlet and at Imnavait Creek.

7 Simulations at ATLAS sites

In addition to validating within the Kuparuk basin, and specifically, the Kuparuk outflow into the Arctic Ocean, we will validate specifically at the ATLAS sites where are large suite of data will be collected; including Barrow, Atquasuk, Oumalik, and Ivotuk. Two sets of experiments will be performed: (1) We will use the 1960-1990 historical climate data mentioned above for regions near the ATLAS sites to force the LSM. The model will be validated against site-specific measurements of ground temperatures, soil moistures, snow depths, etc. Assuming a successful validation, this experiment will be used to provide ecology models with a historical record of sub-grid scale soil moisture and ground temperature against which they can be tested and calibrated. (2) Forcing the land surface model with the hydro-meteorological measurements currently being taken under the auspices of the ATLAS program, we will be able to validate model performance with a broad range of measurements, including the spatial distribution of soil moisture, ground temperature, snow cover, surface water and energy fluxes, and discharge. This will provide invaluable insights into improving model physics.

8 Relationship to other ATLAS projects

These and related results will be of broad interest across a range of disciplines, especially within the NSF Arctic Transitions in the Land-Atmosphere System (ATLAS) program and amongst other arctic researchers. It is our hope that this pilot study will develop into a core hydrologic component of the ATLAS program and serve the needs of ongoing ATLAS efforts. For example: We hope to eventually (1) expand the scope of this modeling effort to the entire Pan-Arctic, (2) couple our LSM with Amanda Lynch's ARCSyM regional climate model with the aim of improving seasonal and inter-annual variability in climate simulations, (3) use the model-generated sub-grid scale soil moistures and soil temperatures to force ecology models such as GEM [*Rastetter et al.*, 1991], TEM [*Raich et al.*, 1991], CENTURY [*Parton et al.*, 1987] and SPA [*Williams et al.*, 1996]. Finally, only through a proper accounting of arctic hydrologic and thermal processes, and the validation of those processes, will we be in a position to determine how the Arctic will respond to the expected warming in the next century. We feel this work leads us in that direction.

8 Schedule

This project will be three years in duration. Activity during the first eighteen months will focus on the catchment delineation, and the generation of TOPMODEL statistics using the 10 m and 90 m available in the arctic (the NSIPP project currently uses the 1 km DEM for catchemnt delineation), implementation of the river routing algorithm, the development and implementation of a new sub-grid snow scheme, and the processing of hydro-meteorological data. The second eighteen months will focus on simulation and validation at scales ranging from small catchments, including site specific validations at the ATLAS sites, to the entire Kuparuk basin.