Book title: ARCTIC Climate Change – The ACSYS Decade and Beyond edited by Peter Lemke

Chapter 9: Progress in hydrological modeling over high latitudes -- under Arctic Climate System Study (ACSYS)

Dennis P. Lettenmaier and Fengge Su

Mailing and e-mail address:

Dennis P. Lettenmaier
Department of Civil and Environmental Engineering
University of Washington
164 Wilcox Hall, Box 352700
Seattle, WA 98195-2700
E-mail: dennisl@u.washington.edu

Fengge Su
Department of Civil and Environmental Engineering
University of Washington
164 Wilcox Hall, Box 352700
Seattle, WA 98195-2700
E-mail: fgsu@hydro.washington.edu

Table of contents:

Abstract

We review achievements in hydrological modeling over high latitudes during ACSYS, including development and improvement of land surface schemes in representing cold processes, large-scale hydrological modeling over high latitude river basins, and estimates of freshwater river inflow to the Arctic Ocean. ACSYS hydrological modeling efforts were closely linked to the GEWEX Continental Scale Experiments (CSEs), and to the Project for Intercomparison of Land surface Parameterization Schemes (PILPS) Results in this review are mainly from PILPS 2(e), MAGS, BALTEX, GAME-Siberia (the latter three of which are CSEs), and other studies related to ACSYS. Based on these achievements from the ten years efforts, the ACSYS scientific strategy for hydrology, which included adaptation of macroscale hydrological modes developed in the framework of GEWEX to Arctic (high-latitude) climate conditions; and development of physical (conceptual) or parametric mesoscale hydrologic models for selected river catchments within the Arctic region, was implemented more or less as envisaged in the ACSYS Implementation Plan. In spite of major advances in high latitude hydrological modeling during the ACSYS era, there remain important problems in parameterization of snow, frost, and lake/wetlands cold processes within climate and hydrology models, and in linkages between atmospheric and hydrological models.

9.1 Introduction

Significant changes have been observed over the pan-Arctic land domain (defined for the purposes of ACSYS as all of the land area draining to the Arctic Ocean) in recent decades. These include increases in winter and fall precipitation (Wang and Cho 1997), reduction in spring snow cover extent (Armstrong and Brodzik 2001; Brown 2000), upward trends in permafrost active layer depth (Frauenfeld et al. 2004; Smith et al. 2005), and a later freezing and earlier breakup dates of ice on lakes and rivers (Magnuson et al. 2000). Strong trends have also been detected in seasonal and annual patterns of Arctic river discharge (e.g. Peterson et al. 2002; Yang et al. 2002; Ye et al. 2004). All of these changes are directly linked to the Arctic hydrologic cycle, which plays an important role in land, atmosphere, and oceans of the global climate system (Vorosmarty et al. 2001).

Runoff from Arctic drainage basins represents 50% of the net flux of freshwater to the Arctic Ocean (Barry and Serreze 2000) which makes the strong role of the land surface unique among the world's oceans. The total volume and temporal variability of freshwater discharge to the Arctic Ocean exerts a strong control on the salinity of the polar ocean and subsequently the thermohaline circulation of the World Ocean (Aagaard and Carmack 1989; Broecker 1997; Karcher et al. 2005), hence changes in the amount and timing of runoff from the land surface are of concern climatically. Accurate estimation of freshwater inflow to the Arctic Ocean and the spatial and temporal variations of Arctic river runoff in both gauged and ungauged basins are therefore of considerable concern not only to the land surface system, but to the coupled land-ocean-sea ice-atmosphere system of the Arctic.

These ongoing changes, and the connectivity of the Arctic freshwater system to global climate, motivated the objectives of ACSYS hydrological programme (WCRP 1994), which were to

- Develop mathematical models of the hydrological cycle under specific Arctic climate conditions suitable for inclusion in coupled climate models,
- Determine the elements of the fresh water cycle in the Arctic region and their time and space variability,
- Quantify the role of atmospheric, hydrological and land surface processes in the exchanges between different elements of the hydrological cycle;
- Provide an observational basin for the assessment of possible long-term trends of the components of the fresh water balance in the Arctic region under changing climate.

To respond to these stated objectives, the ACSYS hydrological programme was structured to include two major components. The first was the development of regional data bases for the main components of the fresh water balance of the Arctic region; and the second was the development of hydrological models of selected Arctic river basins and their validation using appropriate observational data sets. This review focuses on the second component, hydrological modeling of the arctic region conducted under the auspices of ACSYS.

Early in the evolution of ACSYS, a need was recognized for coordination of ACSYS hydrology activities with the companion World Climate Research Programme (WCRP) Global Energy and Water Cycle Experiment (GEWEX) project. GEWEX hydrological activities were initially formulated around a set of Continental Scale Experiments (CSEs), among which three –MAGS (Mackenzie GEWEX Study), BALTEX (the Baltic Sea Experiment), and GAME (GEWEX Asian Monsoon Experiment)-Siberia were all focused in part on the hydrology of portions of the pan-Arctic domain. Hence rather than embarking on a potentially duplicative hydrological modeling effort, ACSYS hydrological modeling efforts were closely linked to the three above-mentioned GEWEX CSEs.

Concurrent with the evolution of ACSYS and GEWEX came increasing recognition of the sensitivity of high-latitude land areas to climate change, and the need for better representation of cold region processes in the Land Surface Schemes (LSSs) used in numerical weather prediction and climate models. The Project for the Intercomparison of Land-Surface Parameterization Schemes (PILPS), initially an activity of GEWEX and later of the WCRP Working Group on Numerical Experimentation (WGNE), was designed to provide common data bases and protocols for testing of LSSs, and in so doing, to motivate improvements in the models. A key aspect of the ACSYS hydrological programme was co-hosting, with GEWEX, of Phase 2(e) of PILPS (see Bowling et al. 2003 for details). We summarize the key contributions of PILPS 2(e) in Section 2.

This paper reviews documented achievements in hydrological modeling over high latitudes under ACSYS, including development and improvement of LSSs, large-scale hydrological modeling, and estimates of freshwater river inflow to the Arctic Ocean. Results are mainly from PILPS 2(e), MAGS, BALTEX, GAME-Siberia, and other studies related to ACSYS. Summaries are then provided regarding what ACSYS did and what remains to be done in high-latitude hydrological modeling.

9.2 Evolution of land surface schemes

It has been widely recognized that the continental land surface processes and their characterizations play an important role in the accuracy of global climate and numerical weather prediction models (Dickinson and Henderson-Sellers 1988; Beljaars et al. 1993; Xue and Shukla, 1993; Gedney et al. 2000). LSSs describe the interaction of energy, momentum, and water flux between the surface and its overlying atmosphere. LSSs were originally developed to provide lower boundary conditions for General Circulation Models (GCMs) (Manabe, 1969). In the past two decades, there has been a great deal of attention focused on development of LSSs and evolution of their complexity from the simple “bucket” model to the more complicated soil-vegetation-atmosphere transfer schemes. There has also been an expansion in their applications from their original role in coupled land-atmosphere models used for climate and numerical weather predication to off-line, stand-alone use for hydrology, agriculture, and ecosystem studies. Although different LSSs have evolved from different heritages, and details differ, their representation of soil hydrology and runoff generation are of great significance regardless of their origins as the scheme used to partition water and energy in hydrological, ecological, and coupled land-atmosphere models (Henderson-Sellers 1996). PILPS was designed to assess the performance of LSSs in representing the hydrology, energy, momentum, and carbon exchanges with the atmosphere, and to achieve greater understanding of the capabilities and potential applications of LSSs in atmospheric models (Henderson-Sellers et al. 1993, 1995).

9.3 ARCTIC HYDROLOGICAL MODELING DURING ACSYS

As noted above, early in the history of ACSYS it was decided that hydrologic model development would be undertaken by the companion WCRP GEWEX program, and that ACSYS would primarily be a user of GEWEX-fostered hydrologic development. Hydrologic model development within the three GEWEX CSEs (MAGS, BALTEX, and GAME-Siberia) most relevant to ACSYS is discussed below.

9.3.1 MAGS

MAGS, the Canadian contribution to the GEWEX continental-scale experiments, was designed to understand and model the high-latitude water and energy cycles of the Mackenzie River basin (1.8×10^6 km^2), and to improve the ability to assess the climate changes to Canada's water resources (Stewart et al. 1998; Rouse 2000; Rouse et al. 2003). Development of hydrologic models, land surface schemes, and land-atmosphere coupled models, suitably adapted for northern conditions, was one of the initiatives of MAGS. Consequently, the outcomes of MAGS contribute directly to the objectives of the ACSYS hydrological programme.

A number of sites for intensive measurement were developed within MAGS to represent different biophysical facets of the Mackenzie River basin. Intensive hydrological process studies promoted the development of process models based on these field experimentations (Rouse 2000, Woo et al. 2000; Woo and Marsh 2005). Among the targets of these field activities were improvement of process-based models of snow accumulation, blowing snow, intercepted snow, and snowmelt infiltration on frozen soils (Pomeroy et al. 1997, 1998, 2002; Pomeroy and Li 2000; Hedstrom and Pomeroy 1998; Woo et al. 1998; Essery et al. 1999). Woo et al. (2000) and Woo and Marsh (2005) provided detailed reviews of Canadian research in snow, frozen soils and permafrost hydrology (including results from a first phase of MAGS) during the years of 1995-2002. They concluded that up to the date of their writing, few advances in comprehensive mathematical models that represent cold-region hydrologic processes had been incorporated into Canadian hydrological and atmospheric models despite the development of new process-based algorithms.

The Canadian Land Surface Scheme (CLASS) (Verseghy 1991; Verseghy et al. 1993), which was developed as a LSS for the Canadian General Circulation Model (CGCM), has been a participant in most PILPS experiments (including PILPS 2(e)). Development of improved parameterizations for CLASS was the ultimate objective of much of the MAGS hydrological modeling activity. A major effort within MAGS was to improve the ability of CLASS to simulate land surface hydrologic variables (especially runoff). This was accomplished by merging the surface energy flux (and vegetation) algorithms within CLASS with the hydrologic routing algorithms from WATFLOOD, a flood forecasting model (Kouwen et al. 1993). A three-level framework for hydrological modeling in MAGS was built in stages by combining CLASS and WATFLOOD as shown in Fig. 9.1 (Pietroniro and Soulis 2003; Soulis et al. 2005). The resulting model is termed WATCLASS (Soulis et al. 2000), and uses CLASS for vertical processes and the lateral algorithms from WATFLOOD. Off-line simulations using WATFLOOD, CLASS, and WATCLASS, which are driven by measured or forecast fields of near-surface data, represent Level 0, Level 1, and Level 2 efforts within the MAGS modeling strategy. The full coupling between CGCM/CRCM (Canadian Regional Climate Model) and land surface hydrology model (CLASS/WATCLASS) represents Level 3. During the course of MAGS, Levels 0, 1 and 2 were achieved and the framework for the progressing with Level 3 was established.

Results from small research basins showed marked improvements in the simulation of streamflow when using WATCLASS with its enhanced hydrology in comparison to the original version of CLASS 2.6, with Nash-Sutcliffe efficiency (NSE) increased from <0 to 0.6~0.8 (Soulis and Seglenieks 2007). However, the preliminary application of WATFLOOD and WATCLASS in the Mackenzie basin indicated that the traditional hydrological model WATFLOOD was better able to simulate hydrographs than WATCLASS both in the timing and volume of the peak (Fig. 9.2) (Snelgrove et al. 2005). The worse performance of WATCLASS in Fig. 9.2b (especially for the Athabasca River station) suggests that the increase of model complexity degraded model capabilities with respect to the timing and magnitude of simulated streamflow. Snelgrove et al. (2005) suggested that future work was required to bridge gaps in the current theory in order to improve model simulations. These include implementation of theories for infiltration and liquid moisture flow through frozen ground and examination of snowmelt processes within WATCLASS.

Fassnacht and Soulis (2002) examined the effects of variations in snow representations in WATCLASS on water and heat fluxes, and found that the inclusion of four enhancements to the CLASS snow process representations (occurrence of mixed precipitation, fresh snow density, maximum snowpack density, and canopy snowfall interception) strongly effected predicted heat fluxes, but had little impact on streamflow simulations. Davison et al. (2006) attempted to improve the simulation of the spatial variability of snowmelt in WATCLASS by including wind-swept tundra and drift classes based on topography rather than the traditionally used vegetation land classes.

A second five-year stage of MAGS, MAGS2 (which began in 2001) was aimed toward developing a fully coupled atmosphere/land-surface/hydrologic modeling system (Level 3) based on the three primary models (CRCM, CLASS, and WATFLOOD). CLASS had previously been coupled with CRCM, which was the primary regional climate model used in MAGS. The coupled model (CRCM/CLASS) along with the high resolution geophysical database was used to examine the mesoscale atmospheric circulations during the snowmelt period over the Mackenzie basin (MacKay et al. 2003a). Further evaluation of the coupled model was conducted by comparing the modeled surface water balance with observations during the water year 1998-99 (MacKay et al., 2003b). The results demonstrated a plausible simulation of precipitation, temperature, and snow cover through the Mackenzie. However streamflow was poorly simulated when the output was used to drive two offline hydrologic models. MacKay et al. (2007) summarize the development and application of the version of CRCM used within MAGS (denoted CRCM-MAGS), which is essentially a developmental version of the CRCM. The emphasis of regional climate modeling in MAGS was largely on land surface processes and the interaction between the land surface and the atmosphere. The impact of lakes on regional climate is currently an active area of research within MAGS (Rouse et al. 2007). A one-dimensional thermal lake model (DYRESM) was being embedded within CLASS, and was being tested over the Mackenzie River Basin at the completion of MAGS2.

9.3.2 BALTEX

The Baltic Sea Experiment (BALTEX) is a European contribution to the investigation of the energy and water cycle over a large drainage system (Baltic Sea and related river basins) (Raschke et al. 2001). Developing coupled atmospheric, oceanographic and hydrological models is a primary objective of BALTEX. The entire Baltic Sea drainage basin ranges from the subarctic climate in northern Finland (69° N) to the temperate and more continental climate in southern Poland (49° N). Although BALTEX, like MAGS, is not an ACSYS project, there are many interactions and common interests in modeling high-latitude hydrologic processes between these two projects (e.g., the PILPS 2(e) study area is part of BALTEX domain.).

The land-surface scheme SEWAB (Surface Energy and Water Balance) (Mengelkamp et al., 1999), which was developed for use in BALTEX, is designed both for use in coupled land-atmospheric models, and to be run off-line. It calculates the vertical energy and water fluxes between the land surface and the atmosphere and within the soil column. SEWAB's representation of runoff generation has been improved following its participation in PILPS phases 2(a) and 2(c) (Chen et al. 1997; Wood 1998). A variable infiltration capacity approach was included for surface runoff generation (Warrach et al. 1999) and a ponding at the surface was added to account for immediate streamflow response to precipitation events (Mengelkamp et al. 2001). The characteristic of seasonal snow cover and soil frost in the Baltic Sea drainage basin requires the inclusion of winter processes in the land surface model applied to this region. Soil freeze-thaw and improved snow accumulation and ablation representations were incorporated within SEWAB by Warrach et al. (2001). SEWAB overestimated the amount and duration of snow cover over the Torne-Kalix River basins in the PILPS phase 2(e) experiments, although it produced good streamflow simulations (Nijssen et al. 2003). As a first attempt to include horizontal water processes in an atmospheric land surface scheme for studies of the water and energy cycle in the climate system, SEWAB was used to simulate runoff and streamflow at a regional scale in the Odra drainage basin with a drainage area of 1.19×10^5 km^2 (Fig. 9.3) (Mengelkamp et al. 2001) by linking a horizontal routing scheme which describes the transport of locally generated runoff into river systems (Lohmann et al. 1996).

The HBV model is a distributed conceptual hydrological model which was originally developed for flood forecasting (Bergstrom 1995). Snow accumulation and snowmelt in HBV are normally modeled by a degree-day approach based on air temperature observations. Within the framework of BALTEX the large-scale hydrological model HBV-Baltic has been developed and used to simulate runoff of the entire Baltic basin (1.6×10^6 km^2) (Fig. 9.4) (Bergstrom and Graham 1998; Graham 1999), to evaluate the hydrological components of atmospheric models (Graham and Bergstrom 2001), and to assess climate change effects on river flow to the Baltic Sea (Graham 2004). These results suggest that continental scale water balance modeling for the Baltic Basin can be solved with the HBV-Baltic conceptual hydrological model. However, the lack of energy balance parameterizations within HBV is a major limitation, as the model is not appropriate for inclusion in coupled land-atmosphere models. In contrast, SEWAB is part of a coupled model system of land, atmosphere, and ocean developed in the context of BALTEX.

9.3.3 GAME-Siberia

The Lena River with a drainage area of about 2.43×10^6 km^2, is one of the largest rivers in the Arctic. Approximately 78-93% of the basin is underlain by permafrost (Zhang et al. 1999, 2000). The Lena River basin was chosen as a main field site within the GEWEX GAME-Siberia project. GAME-Siberia concentrates on observation and modeling of land surface processes, and regional analysis of energy and water cycle in permafrost region of eastern Siberia.

In GAME-Siberia, meteorological and hydrological observations were carried out at taiga and tundra areas within the Lena River basin during 1996-1998, followed by intensive observations during 2000 for various vegetation types (larch, pine, and grassland) (Ishii

2001; Ohta et al. 2001; Hamada et al. 2004). A one-dimensional land surface model was developed and improved to estimate water and energy fluxes in extremely cold regions based on the field data from GAME-Siberia (Yamazaki 2001; Yamazaki et al. 2004). Characteristics of snow cover and river runoff in a small watershed (5.5km^2) in Arctic tundra near the mouth of the Lena River were studied by observation and a new land surface model simulation (Hirashima et al. 2004a, 2004b). Ma et al. (1998) proposed a one-dimensional numerical model to estimate the heat transfer in permafrost regions by using the meteorological data obtained from observing sites in Lena River basin. These model implementations help to understand and explain observed land-surface processes and seasonal flux variations; however, all these models were basically only conducted at point or small-basin scales.

A macro-scale hydrological analysis of the Lena River basin was carried out to simulate snowmelt, evapotranspiration, runoff generation, and riverflow by using a combined model which is composed of a soil-vegetation-atmosphere transfer model, runoff model, and river routing model (Ma et al. 2000). Two kinds of grid sizes were prepared for the combined model, in which a 1°×1° grid was used for the SVAT model and runoff model, and a 0.1°×0.1° grid for the river routing model. Although this analysis was limited to only one year, it was one of the few macro-scale modeling studies from GAME-Siberia.

9.4 NATO ARCTIC FRESHWATER BALANCE WORKSHOP

A NATO Advanced Research Workshop (ARW) which focused specifically on the freshwater balance of the Arctic Ocean was held at Talinn, Estonia in 1998. As a contribution to this workshop (results of which were published in a 2000 NATO Science Series volume, see Lewis (2000) for an overview), Bowling et al (2000) made the first attempt to model in a comprehensive manner the land surface energy and water balance of the pan-Arctic drainage basin using the VIC (Variable Infiltration Capacity) LSS. VIC, as described by Liang et al. (1994, 1996) is a grid-based land surface scheme which parameterizes the dominant hydrometeorological processes taking place at the land surface-atmosphere interface. The model was designed both for inclusion in Global Circulation Models (GCMs) as a land-atmosphere transfer scheme, and for use as a stand-alone macroscale hydrologic model. The VIC model incorporates a two-layer energy balance snow model (Storck and Lettenmaier 1999; Cherkauer and Lettenmaier 1999) first used in the NATO study, which represents snow accumulation and ablation in both a ground pack, and in an overlying forest canopy (if any).

In their contribution to the NATO Arctic Freshwater workshop, Bowling et al. (2000) report applications of the VIC to the Mackenzie and Ob River basins at 2° spatial resolution and daily temporal resolution to examine the space-time structure of runoff, evaporation, soil moisture, and snow water equivalent. The work suggested that the VIC macroscale hydrologic model was able to replicate the timing and variability of discharge to the Arctic Ocean from large northern rivers, but also suggested the importance of the physical processes (e.g., sublimation from blowing-snow, surface storage in lakes and wetlands, and infiltration limitation by frozen soils) which were not represented by the model generation at that time. These finding motivated many of the VIC model improvements that were tested in PILPS 2(e), as described in the next section.

9.5 PILPS 2(e)

A small working group was established by ACSYS in August 1998 for the purposes of planning an Arctic hydrology model intercomparison project (WCRP 1999). The resulting project, PILPS 2(e), was jointly sponsored by ACSYS and GEWEX. It was intended to evaluate the performance of land surface models in high latitudes (Bowling et al. 2003). The project tested 21 land surface models with respect to their ability to represent snow accumulation and ablation, soil freeze/thaw and permafrost, and runoff generation. PILPS 2(e) contributed to the goals of both GEWEX and ACSYS by providing a test bed for model modifications and improvements in representing high latitude land processes, and by providing information about the accuracy with which land schemes can be used to estimate runoff from ungauged areas draining to the Arctic Ocean.

The PILPS 2(e) experiment used BALTEX data from the 58,000 km^2 Torne-Kalix River system (65.5°N-69.5°N) in northern Scandinavia to evaluate the performance of LSSs in an off-line setting, meaning that prescribed atmospheric conditions were used to drive the LSSs and that there was no mechanism for representation of feedbacks from the land surface to the atmosphere. In the PILPS 2(e) experiment, two sub-catchments of the Torne–Kalix system were selected for free calibration. Parameters were then transferred to two validation catchments, and to the basin as a whole, using methods of the participants' choice. The purpose of the calibration experiment was to test the extent to which calibration could improve the performance of the LSSs and the extent to which parameter transfer from such calibrated catchments can improve the estimation of runoff from similar, ungauged basins. Results of the experiment indicated that those models that participated in a calibration experiment in which calibration results were transferred from small catchments to the basin at large had a smaller bias in their daily streamflow simulations than the group of models that did not (Bowling et al. 2003).

Given the sparseness of observation sites in the Torne-Kalix River basin, the comparison of simulated results with observations largely focused on snow (extent, accumulation, and ablation) and streamflow (Nijssen et al., 2003). The results showed that in general, all 21 models captured the broad dynamics of snowmelt and runoff, but as shown in Fig. 9.5 and Fig. 9.6, there were large differences in snow accumulation, ablation, and streamflow. The greatest among-model differences in energy and moisture fluxes occurred during the spring snowmelt period, reflecting different model parameterizations of snow processes (e.g., fractional snow coverage, albedo, and land-surface roughness). Nijssen et al. (2003) indicated that one important source of among-model differences in water and energy balances was the large differences in simulated snow sublimation, many of which resulted from differences in snow surface roughness parameterizations. The among-model differences in the phase and magnitude of the spring runoff were primarily attributed to differences in snow accumulation and melt as well as to differences in meltwater partitioning between runoff and infiltration. In a series of experiments in the Torne-Kalix River basin using the CHASM model, which can be operated with different complexities of the land-surface energy balance, Pitman et al. (2003) demonstrated that the complexity of the representation of the land-surface energy balance could not explain the difference between the PILPS 2(e) model results, and instead attributed differences to variations in the hydrologic formulation incorporated in the participating models.

Results of the PILPS 2(e) experiment led to improvements in snow, frozen soil, and runoff process formulations in some of the participating models. These improvements were reported in part in a series of papers in a 2003 special issue of *Global and Planetary Change*. For instance, the Snow Atmosphere Soil Transfer (SAST) land-surface scheme had difficulty in the PILPS-2e experiments in accurately simulating the pattern and amount of spring snow-melt runoff. As a result, Jin et al. (2003) updated the subsurface runoff parameterization of the SAST and obtained better hydrograph prediction. Habets et al. (2003) describe the two-layer frozen soil scheme and the three-layer explicit snow model used by ISBA in PILPS 2e, as well as a new soil diffusion scheme of ISBA. Tests of ISBA using the PILPS 2(e) data showed that the new diffusion soil module performed well in terms of both hydrology and soil temperature, indicating a step forward in parameterizing frozen soils in ISBA.

Bowling et al. (2003) and Nijssen et al. (2003) concluded that the original ECMWF land scheme greatly overestimated sublimation, and underestimated spring snow accumulation, and hence snowmelt runoff. Van den Hurk and Viterbo (2003) reported improvements to the ECMWF land surface scheme in both timing and amount of runoff in the Torne-Kalix River basin that resulted from updates to the surface runoff scheme and the reduction of surface roughness. The Met Office Surface Exchange Scheme

(MOSES) produced excessive sublimation, and too early and too small peak runoff in the PILPS 2(e) simulations. Motivated by the PILPS 2(e) results, Essery and Clark (2003) improved the MOSES representations of snow processes in vegetation canopies and snow hydrology in the MOSES 2 land-surface model. The modifications improved runoff simulations for two subcatchments used in the PILPS 2(e) experiment by reducing the amount of snow lost through sublimation and delaying the runoff of melt water.

PILPS 2(e) was used as a test site for evaluation of various changes in the VIC model. These include testing of a frozen soil/permafrost algorithm (Cherkauer and Lettenmaier, 1999; Cherkauer et al. 2003) that represents the effects of frozen soils on the surface energy balance and runoff generation, a lake and wetland model (Bowling 2002) that represents the effects of lakes and wetlands on surface moisture and energy fluxes, and a parameterization of the effects of spatial variability in soil freeze-thaw state and snow distribution on moisture and energy fluxes (Cherkauer and Lettenmaier 2003). Although the flow attenuation by lakes and peat bogs in the Torne-Kalix basin appeared to be significant, predicted hydrographs using VIC with the lakes and wetlands algorithm did not differ much from those without lakes (Bowling et al. 2003). Bowling et al. (2003) also noted the apparent importance of sublimation during blowing-snow events in the Torne-Kalix basin, which was not represented by the version of VIC used in PILPS Phase 2(e). This finding motivated development of an algorithm that parameterizes the topographically induced subgrid variability in wind speed, snow transport, and blowing-snow sublimation. The algorithm was designed to work within the structure of the existing VIC mass and energy balance snow model (Bowling et al. 2004). Subsequent testing on the Alaska North Slope demonstrated that the VIC macroscale algorithm was consistent with estimates from two different high-resolution blowing-snow algorithms (Liston and Sturm 1998; Essery et al. 1999) and with limited observations at Barrow, Alaska.

Most of those new cold updates to the LSSs will require further evaluation and validation with more observations at an appropriate spatial scale. The impact of frozen soil and blowing snow schemes on large scale simulation of water and energy terms (e.g., soil moisture, runoff, and evaporation) is still not clear. Models with frozen soil mostly assume that the presence of frozen water limits infiltration into the soil and changes the soil thermal fluxes through the dependence of soil thermal properties on soil water and ice content. Therefore, in Cherkauer and Lettenmaier (1999, 2003), for instance, the VIC model tended to produce higher spring peak flows and lower winter baseflow when the model was run with the frozen soil algorithm; however the studies did not show apparent improvements (based on Nash efficiency) in streamflow simulations at basin scales. Results from PILPS 2(d), a previous cold regions experiment conducted at a grassland site in Valdai, Russia indicated that models with an explicit frozen soil scheme produced better soil temperature simulations than those without a frozen soil scheme (Luo et al., 2003). However, the difference in soil moisture simulations from models with or without frozen soil physics was not clear in that experiment. An earlier study by Pitman et al. (1999) found that including a representation of soil ice in land surface models degraded runoff simulations in the Mackenzie River basin. Field studies in MAGS demonstrated that the infiltration is unlimited for organic materials even in permafrost areas (Woo and Marsh, 2005).

Overall, the PILPS 2(e) experiment offered valuable opportunities for the land surface modeling community to identify problems in representations of snow cover, frozen soil, surface runoff, and other physical processes in cold regions. It is worth noting that the 21 participating land surface schemes included LSSs from many well known coupled models used for numerical weather and climate prediction. Furthermore, PILPS 2(e) was the first experiment to adhere to the ALMA (Assistance for Land Modeling Activities) data input and output protocols (based on NetCDF), one result of which is that the PILPS-2e data are available for future model testing. We are aware of one case in particular where the PILPS-2e data were used after the experiment to test three topography-based runoff schemes (Niu and Yang 2003), which did not exit at the time of the original experiment.

9.6 FRESHWATER INFLOW TO THE ARCTIC OCEAN

The goal of ACSYS Hydrological Programme was to determine the space-time variability of the Arctic hydrological cycle and the fluxes of freshwater to the Arctic Ocean. Numerous estimates have been made of the fresh water inflow to the Arctic Ocean based on available observed streamflow data (Prowse and Flegg 2000; Shiklomanov et al. 2000; Grabs et al. 2000; Lammers et al. 2001; Dai and Trenberth 2002). About 30% of the total drainage area to the Arctic is ungauged. Most of this area is along the Arctic coast downstream of the farthest gauging station in the major rivers, and in the Canadian Archipelago. Most estimates of total discharge to the Arctic from ungauged areas are based on the assumption that runoff per unit area is equivalent for gauged and ungauged areas within each basin. Application of hydrologic models offers one option for providing consistent estimation of the discharge of both gauged and ungauged areas.

Although ACSYS ended in December 2003, the goal of its Hydrological Programme continues to motivate macroscale hydrologic model developments and applications over the Arctic regions, and specifically to the problem of estimating total freshwater discharge. Recently, the VIC model with the cold land process updates described in Section 5 was applied to the entire pan-Arctic domain at a 100 km EASE-Grid system, to evaluate the representation of Arctic hydrologic processes in the model, and to provide a consistent baseline hydroclimatology for the region (Su et al. 2005). The model simulations of key hydrologic processes for the periods of 1979 to 1999 were evaluated using observed streamflow, snow cover extent, dates of lake freeze-up and break-up, and permafrost active layer thickness. The pan-Arctic drainage basin was partitioned into twelve regions for model calibration and parameter transfer according to geographical definitions and hydroclimatology. Twenty-seven individual and sub-basins within different regions were chosen for model calibration and validation. Results indicated that the VIC model was able to reproduce the seasonal and interannual variations in streamflow quite well (for 19 basins out of 27 monthly Nash efficiency exceeded 0.75, and for 13 it exceeds 0.8). However, almost all the baseflow from January to April was underestimated, which was mostly due to the nature of the frozen soil algorithm in the

VIC model. Although the primary purpose of the paper was to evaluate the ability of the model to reproduce hydrologic features of the major Arctic river basins, an evaluation was made of various estimates of freshwater discharge to the Arctic. In particular, the discharge simulated with the VIC model was used to estimate the total river inflow to the Arctic Ocean based on the farthest downstream outlets with the outflows to the Arctic Ocean in the 100 km river networks (Fig. 9.7). A 21-year average river inflow (1979-1999) to the Arctic Ocean from the AORB (Arctic Ocean River Basin) illustrated in Prowse and Flegg (2000), was estimated with the VIC model as 3354 km^3/yr, and 3596 km^3/yr with the inclusion of the Canadian Archepelago. The relationship between the inflow volume and contributing area resulting from various data sources and VIC simulations (Table 1) indicated that the VIC model was comparable to the previous estimates derived from the observed data (Fig. 9.8). More striking, however, was that a wide range of Arctic discharge estimates, when adjusted for differences in drainage areas, were shown to be closely equivalent – i.e., most of the differences in reported estimates of Arctic freshwater discharge can be attributed to differences in drainage areas used in the individual studies.

9.7 CONCLUSIONS: WHAT DID THE ACSYS ACHIEVE?

During its ten-year history, ACSYS and related GEWEX projects motivated a number of advances in high latitude hydrological modeling, particularly at large scales. The ACSYS scientific strategy for hydrology, which included adaptation of macroscale hydrological models developed in the framework of GEWEX to Arctic (high-latitude) climate conditions; and development of physical (conceptual) or parametric mesoscale hydrologic models for selected river catchments within the Arctic region was implemented more or less as envisaged in the ACSYS Implementation Plan [WCRP, 1994]. The followings achievements can be attributed at least in part to ACSYS:

1) Improvement of land surface models in terms of their ability to represent high latitude hydrologic processes, including snow accumulation and ablation, soil freeze/thaw and permafrost, and runoff generation (specific examples include the ISBA, ECMWF, CLASS, and VIC LSMs, but there are almost certainly other model improvements that are less well documented). These model improvements were motivated primarily by the PILPS 2(e) experiment in Torne-Kalix River basin;

2) Intensive field measurement under the GEWEX MAGS and GAME-Siberia projects promoted the development of improved process algorithms for snow accumulation, redistribution, and ablation, and water infiltration into frozen soil, and the development of one-dimensional land surface models for cold regions;

3) The VIC model and the macroscale hydrological models developed under the MAGS, BALTEX, and GAME-Siberia were used to simulate the surface water and energy balance of high-latitude river basins, and (subsequent to ACSYS) to estimate the freshwater balance of the pan-arctic land domain.

4) Riverine freshwater fluxes to the Arctic Ocean have been better estimated (and the existing estimates shown to lie within reasonably tight error bars) through use of macroscale hydrological models;

What remains to be done in the post-ACSYS era? Despite major advances in high latitude hydrological modeling during the ACSYS era, there remain important problems in parameterization of cold land hydrological processes within climate and hydrology models. Many of the key issues are identified in the Science Plan of the WCRP Climate and Cryosphere (CliC) project, which is the successor of ACSYS [Allison et al, 2001]. These include:

1) The role of frozen soil moisture and blowing snow parameterizations in the large-scale simulation of runoff, temperature, and evaporation are not completely clear.

2) Existing wetlands and lake models in land surface models need to be further improved and validated.

3) Many results from process investigations of snow and frost-related hydrological processes remain to be incorporated into large-scale hydrological models.

4) Continued development of hydrological models and linkages between atmospheric and hydrological models are needed in scientific studies of the interactions between climate, snow and frost hydrology.

Acknowledgments: This research was supported by NSF Grants 0230372 and 0629491 to the University of Washington.

REFERENCES:

Aagaard, K., and Carmack, E.C.: The role of sea ice and other fresh waters in the Arctic circulation. J. Geophys. Res. **94**(C10), 14,485-14,498 (1989)

Allison, L., Barry, R.G, and Goodison, B.E.: Climate and Cryosphere (CliC) Project Science and Co-ordination Plan, Version1. http://clic.npolar.no/introduction/science_plan.pdf (2001)

Armstrong, R. L., and Brodzik, M.J.: Recent Northern Hemisphere snow extent: a comparison of data derived from visible and microwave sensors. Geophys. Res. Lett. **28**, 3673-3676 (2001)

Barry, R.G., and Serreze, M.C.: Atmospheric components of the arctic ocean freshwater balance and their interannual variability. In: Levis, E.L. et al. (eds) The Freshwater Budget of the Arctic Ocean, pp.45-56. Springer, New York (2000)

Beljaars, A .C. M., Viterbo, P., Miller, M. J., Betts, A.K., and Ball, J.H: A new surface boundary layer formulation at ECWMF and experimental continental precipitation forecasts. GEWEX News 3(3): l, 5-8 (1993)

Bergstrom, S.: The HBV Model, In: Singh, V.P. (ed) Computer models of watershed hydrology, pp. 443-476. Highlands Ranch, CO (1995)

Bergstrom, S., and Graham, L.P: One the scale problem in hydrological modeling. J. Hydrol. **211**, 253-265 (1998).

Bowling, L. C., Lettenmaier, D.P., and Matheussen, B.V.: Hydroclimatology of the Arctic drainage basin. In: Levis, E.L. et al. (eds) The Freshwater Budget of the Arctic Ocean, pp.57-90. Springer, New York (2000)

Bowling, L. C.: Estimating the freshwater budget of high-latitude land areas. Ph.D. dissertation. Univ. of Wash., Seattle (2002)

Bowling, L. C., et al.: Simulation of high-latitude hydrological processes in the Torne-Kalix basin: PILPS Phase 2(e): 1. Experiment description and summary intercomparisons. Global Planet. Change **38**, 1-30 (2003)

Bowling, L. C., Pomeroy, J.W., and Lettenmaier, D.P.: Parameterization of blowing snow sublimation in a macroscale hydrology model. J. Hydrometeor. **5**(5), 745-762 (2004)

Broecker, W. S.: Thermohaline Circulation, the Achilles heel of our climate system: Will man-made CO2 upset the current balance? Science **28**, 1582-1588 (1997)

Brown, R.D.: Northern Hemisphere snow cover variability and change, 1915-1997. J. Clim., **13**, 2339-2355 (2000)

Chen, T., et al.: Cabauw experimental results from the Project for Intercomparison of Land- surface Parameterization Schemes (PILPS). J. Clim. **10**, 1194-1215 (1997)

Cherkauer, K. A., and Lettenmaier, D.P.: Hydrologic effects of frozen soils in the upper Mississippi River basin. J. Geophys. Res. **104**(D16), 19,599-19,610 (1999)

Cherkauer, K. A., and D. P. Lettenmaier, D.P.: Simulation of spatial variability in snow and frozen soil field, J. Geophys. Res. **108** (D22), 8858, doi:10.1029/2003JD003575 (2003)

Cherkauer, K. A., Bowling, L.C., and Lettenmaier, D.P.: Variable infiltration capacity cold land process model updates. Global Planet. Change **38**, 151-159 (2003)

Dai, A., and Trenberth, K.E.: Estimates of freshwater discharge from continents: latitudinal and seasonal variations. J. Hydrometeor. **3**, 660- 3687 (2002)

Davison, B., Pohl, S., Dornes, P., Marsh, P., Pietroniro, A., MacKay, M.: Characterizing snowmelt variability in Land-Surface-Hydrologic Model, Atmos. Ocean **44**, 271-287 (2006)

Dickinson, R. E., and Henderson-Sellers, A.: Modelling tropical deforestation: a study of GCM land-surface parameterizations. Q. J. R. Meteorol. Soc., **114**(B), 439-462 (1988)

Essery, R., Li, L., and Pomeroy, J.: A distributed model of blowing snow over complex terrain. Hydrol. Process. **13**, 2423-2438 (1999)

Essery, R., and Clark, D.B.: Developments in the MOSES 2 land-surface model for the PILPS 2e. Global Planet. Change **38**, 161-164 (2003)

Fassnacht, S. R., and Soulis, E.D.: Implications during transitional periods of improvements to the snow processes in the land surface scheme-hydrological model WATCLASS. Atmosphere-Ocean **40**, 389-403 (2002)

Frauenfeld, O. W., Zhang, T., and Barry, R.G.: Interdecadal changes in seasonal freeze and thaw depths in Russia, J. Geophys. Res., **109**, D05101, doi:10.1029/2003JD004245 (2004)

Gedney, N., Cox, P. M., Douville, H., Polcher, J., and Valdes, P.J.: Characterizing GCM land surface schemes to understand their responses to climate change. J. Clim. **13**, 3066-3079 (2000)

Grabs, W. E., Portman, F., and de Couet, T.: Discharge observation networks in Arctic regions: Computation of the river runoff into the Arctic Ocean, its seasonality and variability, In: Levis, E.L. et al. (eds) The Freshwater Budget of the Arctic Ocean, pp.249-267. Springer, New York (2000)

Graham, L. P.: Modeling runoff to the Baltic Sea. Ambio **28**, 328-334 (1999)

Graham, L. P.: Climate change effects on river flow to the Baltic Sea. Ambio, **33**, 4-5, 235-241 (2004)

Graham, L. P., and Bergstrom, S.: Water balance modelling in the Baltic Sea drainage basin-analysis of meteorological and hydrological approaches. Meteor. Atmos. Phys. **77**, 45-60 (2001)

Habets, F., Boone, A., and Noilhan, J.: Simulation of a Scandinavian basin using the diffusion transfer version of ISBA. Global Planet. Change, **38**,137-149 (2003)

Hamada, S., Ohta, T., Hiyama, T., Kuwada, T., Takahashi, A., and Maximov, T.C.: Hydrometeorological behaviour of pine and larch forests in eastern Siberia. Hydrol. Process., **18**, 23- 39 (2004).

Henderson-Sellers, A.: Soil moisture: A critical focus for global change studies. Global Planet. Change **13**, 3-9 (1996)

Henderson-Sellers, A., Yang, Z-L., and Dickinson, R.E.: The Project for Intercomparison of Land Surface Parameterization Schemes. Bull. Amer. Meteor. Soc. **74**, 1335-1350 (1993)

Henderson-Sellers, A., Pitman, A. J., Love, P. K., Irannejad, P., and Chen, T. H.: The Project for Intercomparison of Land-surface Parameterization Schemes (PILPS): Phase 2 and 3. Bull. Amer. Meteor. Soc. **76**, 489-504 (1995)

Hedstrom, N. R, and Pomeroy, J.W.: Measurements and modelling of snow interception in the boreal forest. Hydrol. Process **12**, 1611-1625 (1998)

Hirashima, H., Ohata,T., Kodama, Y., Yabuki, H., Sato, N., and Georgiadi, A.: Nonuniform distribution of tundra snow cover in Eastern Siberia. J. Hydrometeor. **5**(3), 373-389 (2004a)

Hirashima, H., Ohata, T., Kodama, Y., and Yabuki, H.: Estimation of annual water balance in Siberian tundra region using a new land surface model. Northern Res. Basins Water Balance **290**, 41-49 (2004b)

Ishii, Y.: The outline of the field observation at the right bank of the Lena River. Activity Report of GAME-Siberia 2000, GAME Publication **26**, 83-86 (2001)

Jin, J., Gao, X., and Sorooshian, S.: Impacts of model calibration on high-latitude land-surface processes: PILPS 2(e) calibration/validation experiments. Global Planet. Change **38**, 93-99 (2003)

Karcher, M., Gerdes, R., Kauker, F., Koberle, C., and Yashayaev, I.: Arctic Ocean change heralds North Atlantic freshening. Geophys. Res. Lett. **32**, L21606, doi:10.1029/2005GL023861 (2005)

Kouwen, N., Soulis, E. D., Pietroniro, A., Donald, J., and Harrington, R. A.: Grouping response units for distributed hydrologic modeling. J. Water Res. Manage. Plann. **119**, 289-305 (1993)

Lammers, R. B., Shiklomanov, A. I., Vorosmarty, C. J., Fekete, B. M., and Peterson, B. J.: Assessment of contemporary Arctic river runoff based on observational discharge records. J. Geophys. Res. **106** (D4), 3321-3334 (2001)

Lewis, E.L.: The freshwater budget of the Arctic Ocean – Introduction. In: Levis, E.L. et al. (eds) The Freshwater Budget of the Arctic Ocean, pp. xv-xxi. Springer, New York (2000)

Liang, X., Lettenmaier, D.P., Wood, E.F., and Burges S.J.: A simple hydrologically based model of land surface water and energy fluxes for general circulation models. J. Geophys. Res. **105** (D17), 14,415-14,428 (1994)

Liang, X., Wood, E. F., and Lettenmaier, D.P.: Surface soil moisture parameterization of the VIC-2L model: Evaluation and modifications. Global Planet. Change **13**, 195-206 (1996)

Liston, G., and Sturm, M.: A snow-transport model for complex terrain. J. Glaciol. **44**, 498-516 (1998)

Lohmann, D., Nolte-Holube, R., Raschke, E.: A large scale horizontal routing model to be coupled to land surface parameterization schemes. Tellus, **48A**, 708-721 (1996)

Luo, L. et al.: Effects of frozen soil on soil temperature, spring infiltration, and runoff: results from the POLPS 2 (d) experiment at Valdai, Russia. J. Hydrometeor. **4**, 334-351 (2003)

Ma, X., Hiyama, T., Fukushima,Y., and Hashimoto, T.: A numerical model of the heat transfer for permafrost regions. J. Jpn. Soc. Hydrol. Water Resour. **11**(4), 346-359 (1998)

Ma, X., Fukushima,Y., Hiyama, T., Hashimoto, T., and Ohata, T.: A macro-scale hydrological analysis of the Lena River basin, Hydro. Process. **14**(3), 639-651 (2000)

MacKay, M. D., Szeto, K., Verseghy, D., Chan, E., and Bussieres, N.: Mesoscale circulations and surface energy balance during sonwmelt in a regional climate model, Nordic Hydrol. **34**, 91-106 (2003a)

MacKay, M. D., Seglenieks, F., Verseghy, D., Soulis, E. D., Sneigrove, K. R. ,Walker, A. and Szeto, K.: Modeling Mackenzie Basin surface water balance during CAGES with the Canadian Rigional Climate Model., J. Hydrometeor. **4**, 748-767 (2003b)

MacKay, M. D., Bartlett, P., Chan, E., Verseghy, D., Soulis, E. D., and Seglenieks, F. R.: The MAGS regional climate modeling system: CRCM-MAGS. In: Woo, M.K. (ed.) Cold Regions Atmospheric and Hydrologic Studies: the Mackenzie GEWEX Experience. Vol. I: Atmospheric Dynamics, pp.433-450. Springer-Verlag (2007)

Magnuson, J. J., et al.: Historical trends in lake and river ice cover in the Northern Hemisphere. Science **289**, 1743-1746 (2000)

Manabe, S.: Climate and Ocean circulation: 1, The atmospheric circulation and the hydrology of the earth's surface. Mon. Weather Rev. **97**, 739-805 (1969)

Mengelkamp, H.-T., Warrach, K., and Raschke, E.: SEWAB-A parameterization of the surface energy and water balance for atmospheric and hydrologic models. Adv. Water. Resour. **23**, 165-175 (1999)

Mengelkamp, H.-T., Warrach, K., Ruhe, C., and Raschke, E.: Simulation of runoff and streamflow on local and regional scales. Meteor. Atmos. Phys. **76**, 107-117 (2001)

Nijssen, B., et al.: Simulation of high latitude hydrological processes in the Torne-Kalix basin: PILPS phase 2(e): 2. comparison of model results with observations. Global Planet. Change **38**, 31-53 (2003)

Niu, G.-Y., and Yang, Z.-L.: The versatile integrator of surface and atmosphere processes (VISA) Part II: Evaluation of three topography-based runoff schemes. Global and Planet. Change **38**, 191-208 (2003)

Ohta, T., Hiyama, T., Tanaka, H., Kuwada, T., Maximov, T., Ohata, T., and Fukushima, Y.: Seasonal variation in the energy and water exchanges above and below a larch forest in eastern Siberia. Hydrol. Process. **15**, 1459-1476 (2001)

Peterson, B. J., Holmes, R.M., McClelland, J.W., Vorosmarty, C.J., Lammers, R.B., Shiklomanov, A.I., Shiklomanov, I.A., and Rahmstorf, S.: Increasing river discharge to the Arctic Ocean. Science **298**, 2171-2173 (2002)

Pietroniro, A. and Soulis, E.D.: A hydrology modeling framework for the Mackenzie GEWEX program. Hydrol. Process., **10**, 1245-1261 (2003)

Pitman, A. J., Slater, A. G., Desborough, C. E., and Zhao, M.: Uncertainty in the simulation due to the parameterization of frozen soil moisture using the Global Soil Wetness Project methodology. J. Geophys. Res. **104** (D14), 16,879–16,888 (1999)

Pitman, A. J., Xia, Y., Leplastrier, M., and Henderson-Sellers, A.: The CHAmeleon Surface Model: description and use with the PILPS phase 2(e) forcing data, Global Planet. Change **38**, 121-135 (2003)

Pomeroy, J., Marsh, P., Gray, D.M.: Application of a distributed blowing snow model to the Arctic. Hydro. Process. **11**, 1451-1464 (1997)

Pomeroy, J.W, Gray, D.M., Shook, K.R., Toth, B., Essery, R. L. H., Pietroniro, A., and Hedstrom, N.: An evaluation of snow accumulation and ablation processes for land surface modeling. Hydrol. Process. **12**, 2339-2367 (1998)

Pomeroy J. W., and Li, L.: Prairie and Arctic areal snow cover mass balance using a blowing snow model. J. Geophys. Res. **105**(D21), 26,619-26,634 (2000)

Pomeroy J. W., Gray, D.M., Hedstrom, N.R., Janowicz, J.R.: Prediction of seasonal snow accumulation in cold climate forests. Hydrol. Process. **9**, 213-228 (2002)

Prowse, T. D., and Flegg, P.O.: Arctic river flow: A review of contributing areas. In: Levis, E.L. et al. (eds) The Freshwater Budget of the Arctic Ocean, pp. 269-280. Springer, New York (2000)

Raschke et al.: A European contribution to investigate the energy and water cycle over a large drainage basin. Bull. Amer. Meteor. Soc. **82**(11), 2389-2413 (2001)

Rouse, W. R.: Progress in hydrological research in the Mackenzie GEWEX study. Hydrol. Process. **14**, 1667-1685 (2000)

Rouse W. R., et al.: Energy and water cycles in a high-latitude north-flowing river system: summary of results from the Mackenzie GEWEX study-phase 1, Bull. Amer. Meteor. Soc. **84**, 73-87 (2003)

Rouse, W.R, Blanken, P.D, Duguay, C.R., Oswald, C.J., and Schertzer, W.M.: Climate-lake interactions. In: Woo, M.K. (ed.) Cold Regions Atmospheric and Hydrologic Studies: the Mackenzie GEWEX Experience. Vol. II: Hydrologic Processes, pp.139-160. Springer-Verlag (2007)

Shiklomanov, I. A., Shiklomanov, A.I., Lammers, R.B., Peterson, B.J., and Vorosmarty, C.J.: The dynamics of river water inflow to the Arctic Ocean. In: Levis, E.L. et al. (eds) The Freshwater Budget of the Arctic Ocean, pp. 281–296. Springer, New York (2000)

Smith, S. L., Burgress, M.M., Riseborough, D., and Nixon, F.M.: Recent trends from Canadian permafrost thermal monitoring network sites, Permafr. Periglacial Process. **16**, 19-30 (2005)

Snelgrove, K., Soulis, E.D., Seglenieks, F., Kouwen, N., and Pietroniro, A.: The application of hydrological models in MAGS: lessons learned for PUB. In: Spence, C., Pomeroy, J., and Pietroniro, A. (eds) Prediction in Ungauged Basins: Approaches for Canada's Cold Regions, pp.139-164, Canadian Water Resources Association (2005)

Soulis, E. D, Snelgrove, K.R., Kouwen, N., Seglenieks, F.R., Verseghy, D.L.: Toward closing the vertical water balance in Canadian atmospheric models: coupling the land surface scheme CLASS with the distributed bydrologic model WATFLOOD. Atmosphere-Ocean **38**, 251-269 (2000)

Soulis, E. D., Kouwen, N., Pietroniro, A., Seglenieks, F.R., Snelgrove, K.R., Pellerin, P., Shaw, D.W., and Martz, L.W.: A framework for hydrological modeling in MAGS. In: Spence, C., Pomeroy, J., and Pietroniro, A. (eds) Prediction in Ungauged Basins: Approaches for Canada's Cold Regions, pp.119-138, Canadian Water Resources Association (2005)

Soulis, E.D., and Seglenieks, F.R: The MAGS Integrated Modeling System. In: Woo, M.K. (ed) Cold Regions Atmospheric and Hydrologic Studies: the Mackenzie GEWEX Experience. Vol. II: Hydrologic Processes, pp.445-474. Springer-Verlag (2007)

Stewart, R.E., et al.: The Mackenzie GEWEX study: The water and energy cycles of a major North American river basin. Bull. Amer. Meteor. Soc. **79**(12), 2665-2683 (1998)

Storck, P., and Lettenmaier, D.P.: Predicting the effect of a forest canopy on ground snow accumulation and ablation in maritime climates. In: Troendle, C. (ed.) Proceedings of 67th Western Snow Conference, Colo. State Univ., Fort Collins (1999)

Su, F., Adam, J.C., Bowling, L.C., and Lettenmaier, D.P.: Streamflow simulations of the terrestrial Arctic domain. J. Geophys. Res. **110**, D08112, doi:10.1029/2004JD005518 (2005)

Van den Hurk, B., and Viterbo, P.: The Torne-Kalix PILPS 2(e) experiment as a test bed for modifications to the ECMWF land surface scheme. Global Planet. Change **38**, 165-173 (2003)

Verseghy, D. L.: CLASS-A Canadian land surface scheme for GCMs, Part1: Soil model. Int. J. Climatol. **11**, 111-133 (1991)

Verseghy, D.L, McFarland, N.A., and Lazare, M.: CLASS-A Canadian land surface scheme for GCMs, Part 2: Vegetation model and coupled runs. Int. J. Climatol. **13**, 347-370 (1993)

Vorosmarty, C. J., Hinzman, L.D., Peterson, B.J., Bromwich, D.H., Hamilton, L.C., Morison, J., Romanovsky, V.E., Sturm, M., and Webb, R.S.: The Hydrologic Cycle and Its Role in Arctic and Global Environmental Change: A Rationale and Strategy for Synthesis Study. Arct. Res. Consortium of the U.S. (2001)

Wang, X. L., and Cho, H.R.: Spatial-temporal structures of trend and oscillatory variabilities of precipitation over northern Eurasia. J. Clim., **10**, 2285-2298 (1997)

Warrach, K., Mengelkamp, H.-T., Raschke, E.: Runoff parameterization in a SVAT scheme: sensitivity tests with the model SEWAB, Regionalization in Hydrology. IAHS publ. 254, 123-130 (1999)

Warrach, K., Mengelkamp, H.-T., and Raschke, E.: Treatment of frozen soil and snow cover in the land surface model SEWAB. Theor. Appl. Climatol. **69**, 23-37 (2001)

WCRP: Arctic Climate System Study (ACSYS) Initial Implementation Plan. WCRP-No. 85, WMO/TD-No.627 (1994)

WCRP: Report on the hydrology models intercomparison planning meeting. Koblenz, Germany, 27-29 March 1999, WCRP Informal Report No. 12/1999 (1999)

Woo, M-K, Carey, S.K., Martz, L.W.: Effects of seasonal frost and permafrost on the hydrology of subalpine slopes and drainage basins. In: Strong, G.S., and Wilkinson Y.M.L. (eds) Proceedings of the 4th Scientific Workshop for the Mackenzie GEWEX study, pp. 66-73. Montreal, Quebec (1998)

Woo, M-K, Marsh, P., and, Pomeroy, J.W.: Snow, frozen soil and permafrost hydrology in Canada, 1995-1998. Hydrol. Process. **14**, 1591-1611(2000)

Woo, M-K, and Marsh, P.: Snow, frozen soils and permafrost hydrology in Canada, 1999-2002. Hydrol. Process. **19**, 215-229 (2005)

Wood, E. F.: The project for intercomparison of land-surface parameterization schemes (PILPS) phase 2(c) Red-Arkansas basin experiment: 1. Experiment description and summary intercomparisons. Global Planet. Change **19**, 115-135 (1998)

Xue, Y. , and Shukla, J.: The influence of landsurface properties on Sahel climate, Part I: Desertification. J. Climatol. **6**, 2232-2245 (1993)

Yamazaki, T.: A one-dimensional land surface model adaptable to intensely cold regions and its application in eastern Siberia. J. Meteor. Soc. Japan **79**, 1107-1118 (2001)

Yamazaki, T., Yabuki, H., Ishii, Y., Ohta, T., and T. Ohata, T.: Water and energy exchanges at forests and a grassland in Eastern Siberia evaluated using a one-dimensional land surface model. J. Hydrometeor. **5**(3), 504-515 (2004)

Yang, D., Kane, D.L., Hinzman, L., Zhang, X., Zhang, T., and Ye, H.: Siberian Lena River hydrologic regime and recent change. J. Geophys. Res. **107** (D23), 4694, doi:10.1029/2002JD002542 (2002)

Ye, H., Ladochy, S., Yang, D., Zhang, T., Zhang, X., and Ellison, M.: The impact of climatic conditions on seasonal river discharges in Siberia. J. Hydrometeor., **5**(2), 286-295 (2004)

Zhang, T., Barry, R.G., Knowles, K., Heginbottom, J.A., and Brown, J.: Statistics and characteristics of permafrost and ground-ice distribution in the Northern Hemishere. Polar Geogr. **23**(2), 132-154 (1999)

Zhang, T., Heginbottom, J.A., and Brown, J.: Further statistics on the distribution of permafrost and ground ice in the northern hemisphere. Polar Geogr. **24**(2), 126-131(2000)

Figure Captions:

Fig. 9.1 Atmospheric-hydrological coupled modeling strategy for MAGS.

Fig. 9.2 Monthly streamflow simulations over different Mackenzie subbasins with the WATFLOOD (a) and WATCLASS (b). Black is measured and gray is simulated (after Snelgrove et al. 2005).

Fig. 9.3 (a) The Odra drainage basin overlaid by an equidistant grid of 18 km mesh size. The dots indicate locations of gauging stations; (b) Daily observed (solid) and simulated (dotted) streamflow at gauging stations Gubin (river nysa Lucycka) and Gozdowice (river Odra) for the time period 1992- 1993 (from Mengelkamp et al., 2001).

Fig. 9.4 Monthly averages (in m3 s-1) of freshwater flow into the major subbasins of the Baltic Sea, calculated with the HBV model using meteorological input data. Note that major contributions are available during the melting season (Raschke et al., 2001).

Fig. 9.5 Observed (dots) and simulated (lines) snow water equivalent for five locations during the first part of 1995 (no observations were available for cells 4 and 5) (from Nijssen et al. 2003).

Fig. 9.6 Mean monthly observed (dots) and simulated (lines) discharge for the Kalix and Torne river basins (from Nijssen et al. 2003).

Fig. 9.7 Digital river networks for the pan-Arctic drainage basins at the 100 km resolution, showing the watershed boundaries of the Kolyma, Lena, Yukon, Yenisei, Ob, Mackenzie, and Nelson. Dots represent 200 the farthest downstream outlets with the outflows to the Arctic Ocean based on the river networks (from Su et al., 2005).

Fig. 9.8 Basin area-annual flow volume relationship for different estimations in Table 1 (from Su et al. 2005).

Table 9. 1 Estimates of Annual Continental Freshwater Into the Arctic Ocean (after Su et al. 2005).

Basin Definition	Contribution Area ($\times 1000\ km^2$)	Volume (km^3/yr)	Periods
“Arctic Ocean River Basin” in Prowse et al.[2000][a]	11045/15504	2338/3299	1975-1984
“All Arctic Regions” in Shiklomanov et al.[2000]	18875	4300	1921-1996
“Arctic Ocean Basin” in Shiklomanov er al.[2000]	23732	5250	1921-1996
“Arctic Climate System” in Grabs et al.[2000][a]	12868/18147	2603/3671	
AORB - Northern Greenland + Arctic Archipelago in [Lammers et al.2001]	16192	3302	1960-1989
The largest Arctic Rivers in Dai and Trenberth [2002]	16850	3658	
AORB –without Arctic Archipelago, VIC1	15017	3354	1979-1999
AORB – with Arctic Archipelago, VIC2	16397	3596	1979-1999

[a]The first area is the gauged area; the second area is the total contributing area in the definition; the second volume is the extrapolation over the total area.

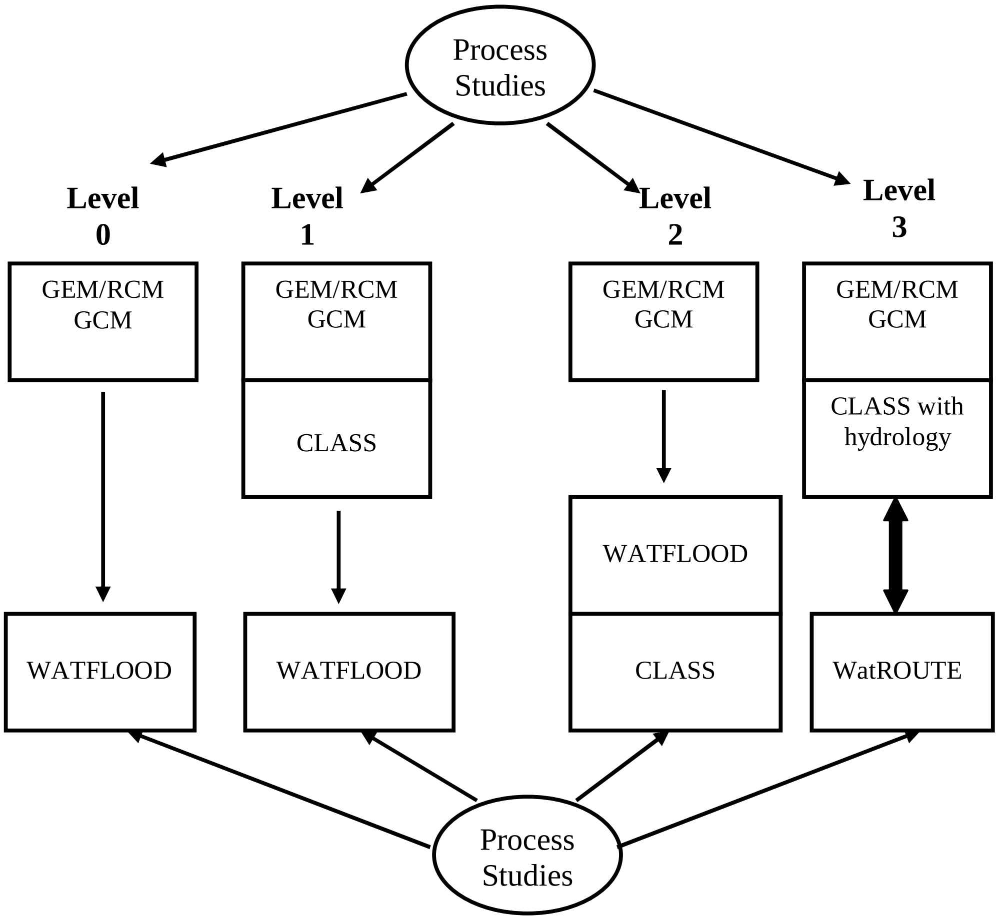
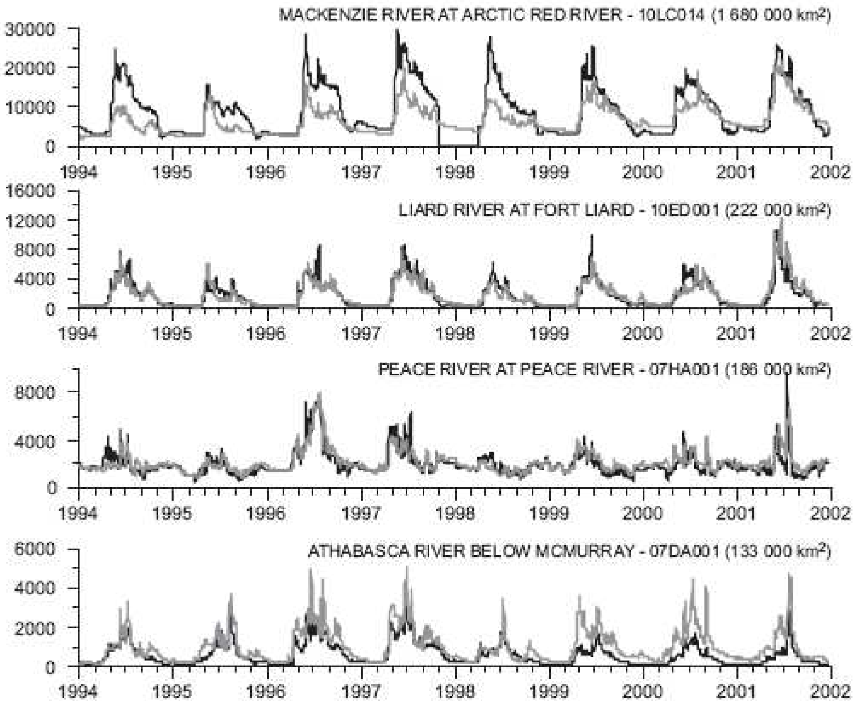


Fig. 9.1 Atmospheric-hydrological coupled modeling strategy for MAGS (after Soulis et al. 2005).

(a)


MACKENZIE RIVER AT ARCTIC RED RIVER - 10LC014 (1 680 000 km2)
LIARD RIVER AT FORT LIARD - 10ED001 (222 000 km2)
PEACE RIVER AT PEACE RIVER - 07HA001 (186 000 km2)
ATHABASCA RIVER BELOW MCMURRAY - 07DA001 (133 000 km2)

(b)

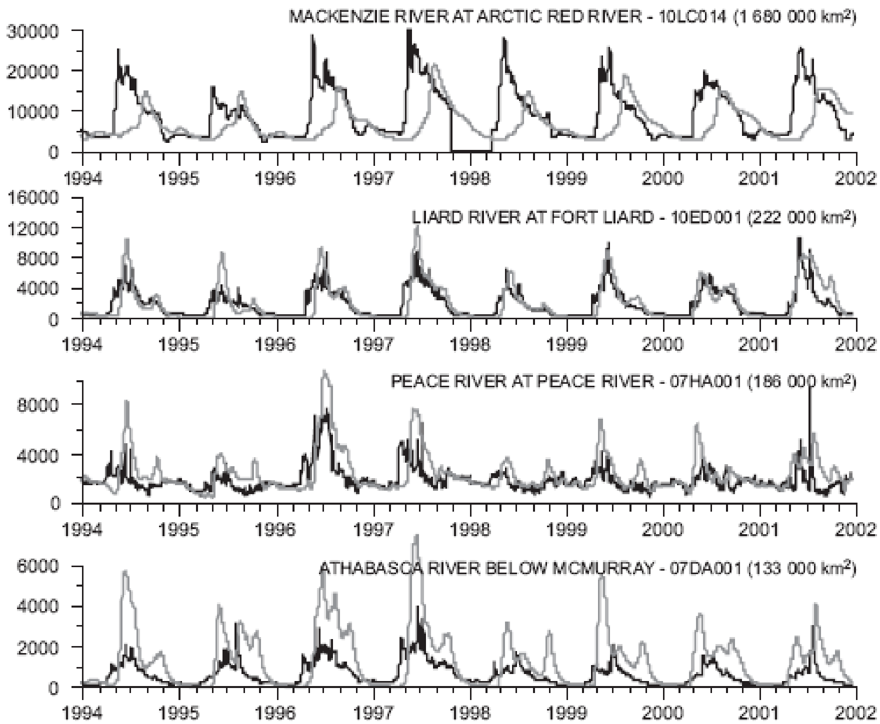

MACKENZIE RIVER AT ARCTIC RED RIVER - 10LC014 (1 680 000 km2)
LIARD RIVER AT FORT LIARD - 10ED001 (222 000 km2)
PEACE RIVER AT PEACE RIVER - 07HA001 (186 000 km2)
ATHABASCA RIVER BELOW MCMURRAY - 07DA001 (133 000 km2)

Fig. 9.2. Monthly streamflow (m^3/s) simulations over different Mackenzie subbasins with WATFLOOD (a) and WATCLASS (b). Black is measured and gray is simulated (from Snelgrove et al., 2005).

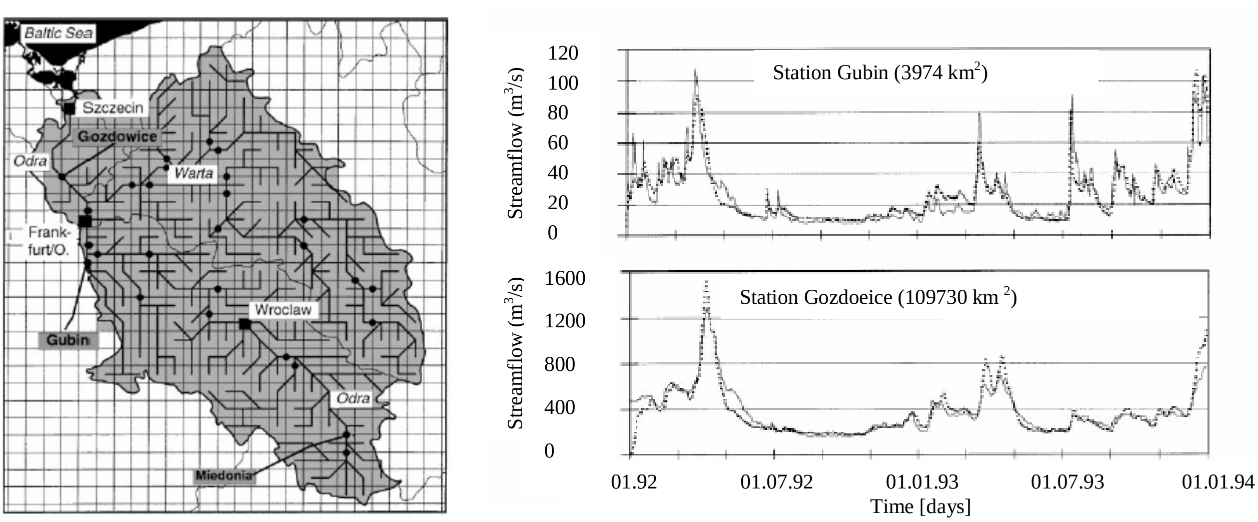


Fig. 9.3 (a) The Odra drainage basin overlaid by an equidistant grid of 18 km mesh size. The dots indicate locations of gauging stations; (b) Daily observed (solid) and simulated (dotted) streamflow at gauging stations Gubin (river nysa Lucycka) and Gozdowice (river Odra) for the time period 1992- 1993 (from Mengelkamp et al. 2001).

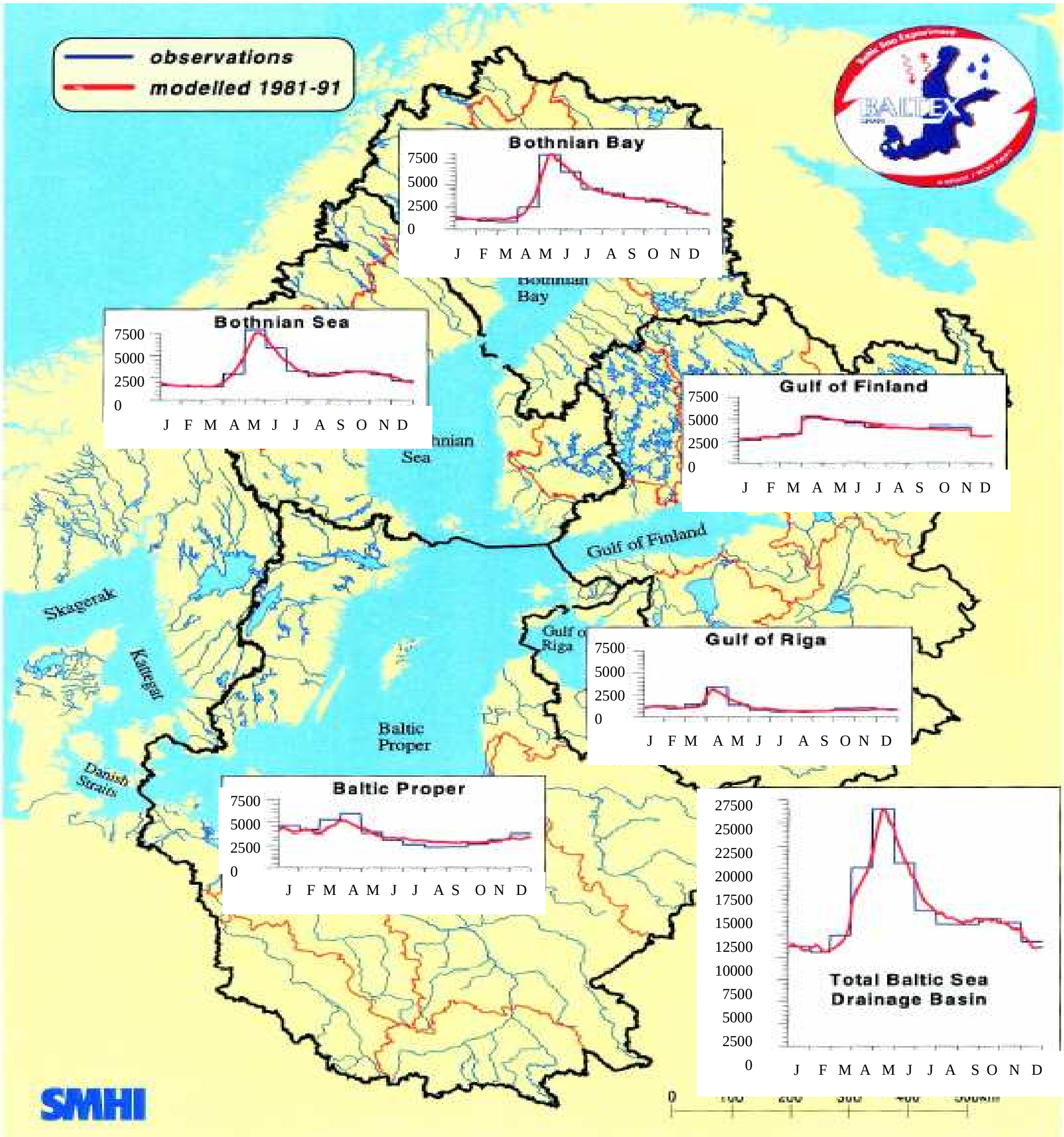


Fig. 9.4 Monthly averages (in $m^3\ s^{-1}$) of freshwater flow into the major subbasins of the Baltic Sea, calculated with the HBV model using meteorological input data. Note that major contributions are available during the melting season (Raschke et al., 2001).

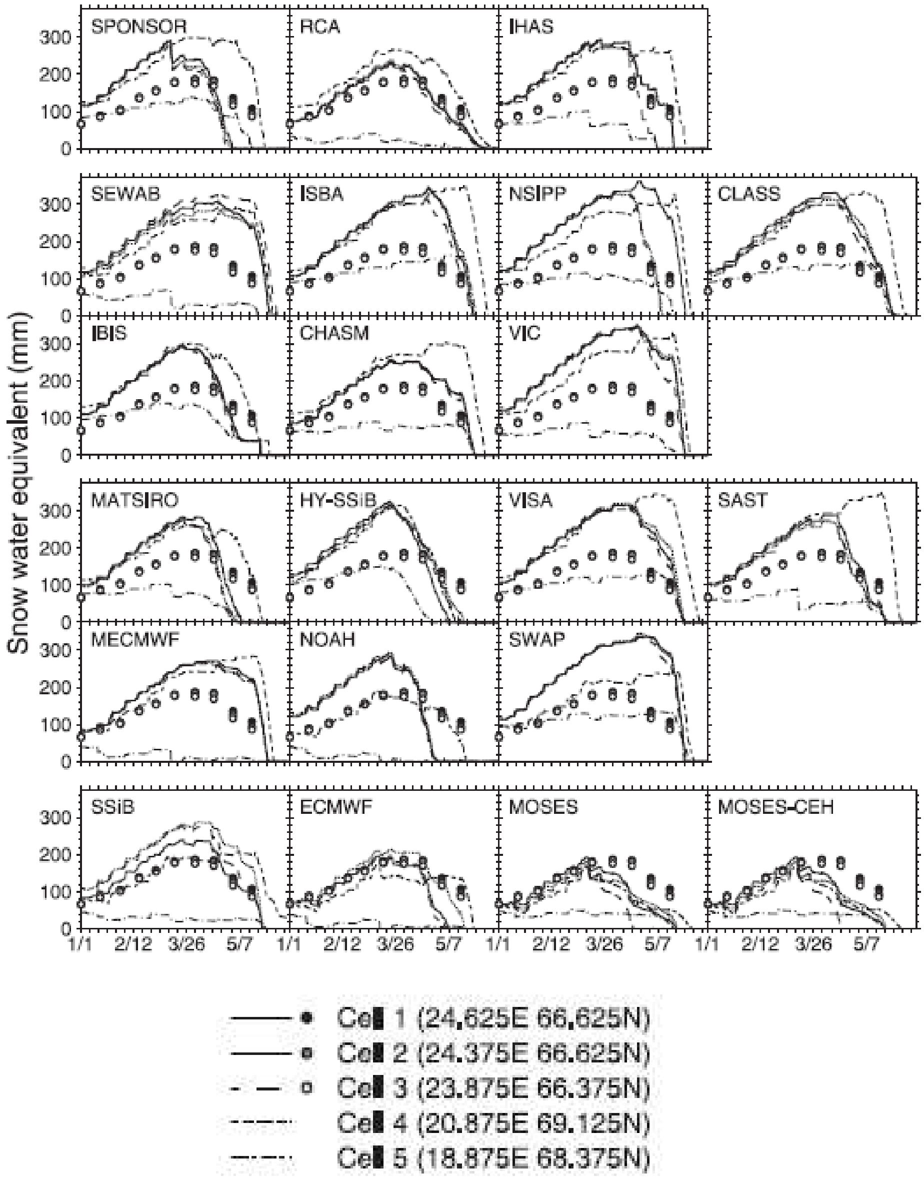


Fig. 9.5 Observed (dots) and simulated (lines) snow water equivalent for five locations during the first part of 1995 (no observations were available for cells 4 and 5) (from Nijssen et al. 2003).

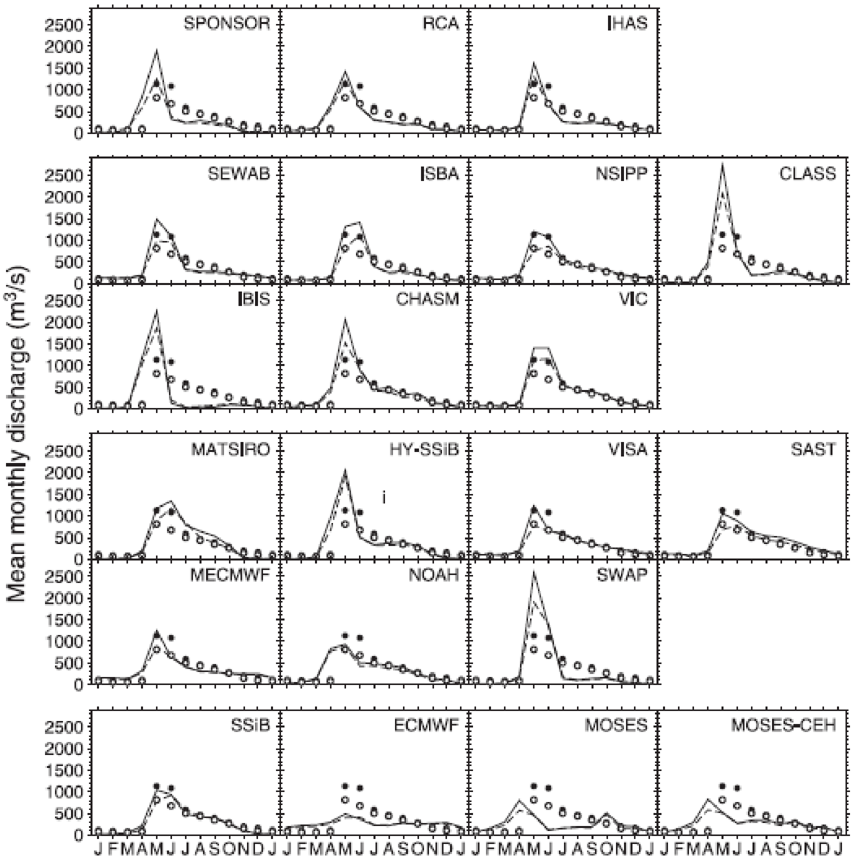


Fig. 9.6 Mean monthly observed (dots) and simulated (lines) discharge for the Kalix and Torne river basins (from Nijssen et al. 2003).

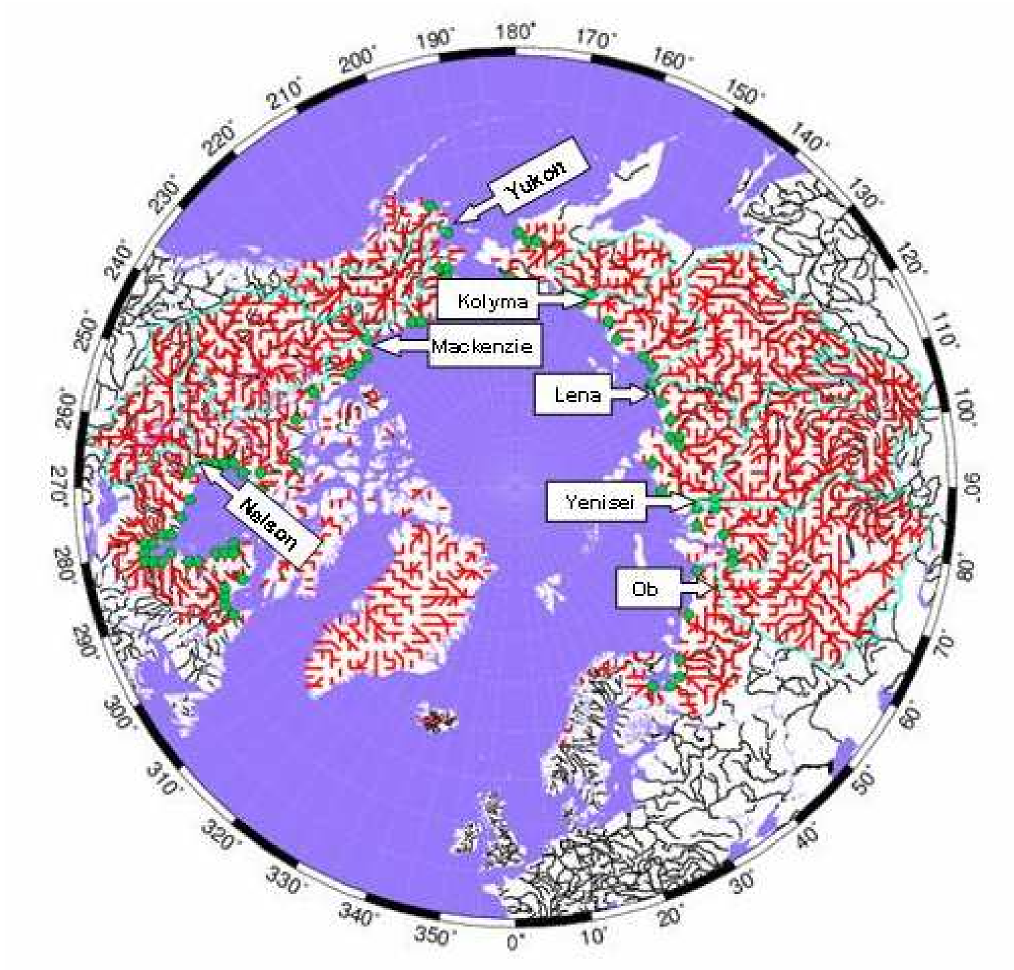


Fig. 9.7 Digital river networks for the pan-Arctic drainage basins at the 100 km resolution, showing the watershed boundaries of the Kolyma, Lena, Yukon, Yenisei, Ob, Mackenzie, and Nelson. Dots represent 200 the farthest downstream outlets with the outflows to the Arctic Ocean based on the river networks (from Su et al., 2005).

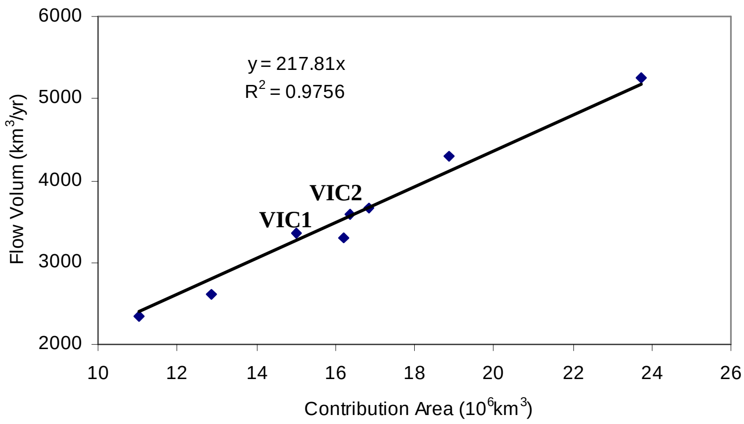


Fig. 9.8 Basin area-annual flow volume relationship for different estimations in Table 1 (from Su et al. 2005). VIC2 and VIC1 indicate the estimates with and without Arctic Archipelago, respectively.