A REGIONAL, INTEGRATED MONITORING SYSTEM FOR THE HYDROLOGY OF THE PAN-ARCTIC LAND MASS

NASA CONTRACT NAG5-9596

FINAL REPORT

Principal Investigator:

Mark Serreze: Cooperative Institute for Research in Environmental Sciences (CIRES), Campus Box 449, University of Colorado, Boulder, CO 80309-0449
email: serreze@kryos.colorado.edu

Co-Investigators:

Roger Barry, Anne Nolin, Richard Armstrong, Tingjung Zhang: CIRES, University of Colorado, Campus Box 449, Boulder, CO 80309-0449

Charles Vorosmarty, Richard Lammers, Steven Frolking: University of New Hampshire, Complex Systems Research Center, Morse Hall, 39 College Road, Durham, NH 03824-3525

David Bromwich: Byrd Polar Research Center, The Ohio State University, Columbus, OH 43210

Kyle McDonald: Terrestrial Science Research Element, Jet Propulsion Laboratory, Mail Stop 300-233, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109-8099

PROJECT GOALS

Work under this NASA contract developed a system for monitoring and historical analysis of the major components of the pan-Arctic terrestrial water cycle. It is known as Arctic-RIMS (Regional Integrated Hydrological Monitoring System for the Pan-Arctic Landmass). The system uses products from EOS-era satellites, numerical weather prediction models, station records and other data sets in conjunction with an atmosphere-land surface water budgeting scheme. The intent was to compile operational (at 1-2 month time lags) gridded fields of precipitation (P), evapotranspiration (ET), P-ET, soil moisture, soil freeze/thaw state, active layer thickness, snow extent and its water equivalent, soil water storage, runoff and simulated discharge along with estimates of non-closure in the water budget. Using "baseline" water budgeting schemes in conjunction with atmospheric reanalyses and pre-EOS satellite data, water budget fields were conjunction with atmospheric reanalyses and pre-EOS satellite data, water budget fields were compiled to provide historical time series. The goals as outlined in the original proposal can be summarized as follows:

1) Use EOS data to compile hydrologic products for the pan-Arctic terrestrial regions including snowcover/snow water equivalent (SSM/I, MODIS, AMSR) and near-surface freeze/thaw dynamics (SeaWinds on QuikSCAT and ADEOS II, SSM/I and AMSR).

2) Implement Arctic-RIMS to use EOS data streams, allied fields and hydrologic models to produce allied outputs that fully characterize pan-Arctic terrestrial and aerological water budgets.

3) Compile hydrologically-based historical products providing a long-term baseline of spatial and temporal variability in the water cycle.

The Arctic-RIMS web site is maintained by UNH (http://rims.unh.edu/). The website contains background material on the project and a tutorial for site navigation. The RIMS system contains a suite of visualization and analysis tools. For example, for a given watershed and selected time, one can easily generate maps different hydrologic variables (e.g., precipitation, net precipitation, temperature). Options are available to generate anomaly fields and time series.
All spatial fields in Arctic-RIMS are provided on a 25x25 km version of the National Snow and Ice Data Center (NSIDC) Lambert Azimuthal equal-area grid known as the EASE grid. In general, data are available at daily temporal resolution. The pan-Arctic drainage is defined as areas emptying into the Arctic Ocean and into Hudson Bay, James Bay, Hudson Strait and the Bering Strait. The Yukon and Anadyr rivers drain into the northern Bering Sea but supply a large amount of freshwater discharge to the Arctic Ocean via northward flow though the Bering Strait. They are therefore considered as part of the Arctic drainage.

Arctic-RIMS has been finding wide use by the Arctic research community. In turn, the RIMS system has and continues to be used by our group in studies conducted within the context of recent environmental change in the Arctic [see list of publications supported under this contract].

Arctic-RIMS evolved into a collaborative effort between NASA and the National Science Foundation (NSF). The original NSF component ("Collaborative Research: A Hydrological Observing System for the Pan-Arctic Landmass") is in its last year of funding. . This component involves researchers from University of New Hampshire (C. Vorosmarty, PI), University of Colorado (M. Serreze, PI) and The Ohio State University (B. Bromwich, PI). However, based on the success of Arctic-RIMS, new NASA funding has been obtained ("Assessment of Recent Hydrologic Change over the Arctic Terrestrial Drainage System") which in turn is complemented by a new line of NSF funding ("Collaborative Research: An Integrated Assessment of the Arctic Freshwater System: Analysis of Retrospective and Contemporary Conditions"). Consequently, while the NASA contract described in the final report has seen its sunset, the Arctic-RIMS system will continue to evolve.

Below we describe some of the key elements involved in the development Arctic-RIMS. While we of course highlight successes, we also articulate some of the challenges and problems involved in the system development. Discussion is broken down into the contributions from each participating institution.

University of Colorado

Precipitation Fields

A major challenge for Arctic-RIMS has been the provision of precipitation fields. The primary issues are as follows: 1) obtaining timely updates of station data is difficult due to delays in data posting; 2) the existing station precipitation network, while already sparse, has degraded further over the past decade due to the closure of many stations in the Former Soviet Union (FSU) and Canada, as well as a trend towards automation in Canada; 3) satellite-derived estimates over high-latitude land areas are of poor quality; 4) precipitation forecasts from atmospheric reanalysis, which might help to provide improved precipitation fields through blending with gauge data, are of variable quality often contain very strong biases.

The RIMS system presently contains two precipitation estimates. The first is based in interpolation of gauge data. The second is based on statistical methods that involve the re-scaling of precipitation forecasts from the NCEP atmospheric reanalysis to remove systematic biases (using gridded gauge data) and the use of a suite of other NCEP variables related to precipitation (e.g., precipitation less evaporation calculated from the vapor flux convergence, precipitable water, vertical motion, vapor fluxes, lower-tropospheric stability) in a multiple regression approach. Due to a change in computer systems, there have been delays in posting recent updates of reconstructed precipitation. Updates will be supported under the new NASA and NSF funding described earlier.

As the NASA contact came to a close, a great deal of progress had been made in the development of improved reconstruction techniques. One the biggest problems regarding the NCEP-based reconstructions is the generally poor quality of the NCEP precipitation forecasts, both with respect to biases (especially large in summer) and in the depiction of temporal variability. . It was expected that data from the next-generation ERA-40 atmospheric reanalysis (hopefully with improved precipitation forecasts) would become available soon after the NASA contract was awarded. However, due to a series of delays at the European Center for Medium range Weather Forecasts (ECMWF), fields from the production run of ERA-40 were not available until about a year ago, and then only for a low-resolution (2.5 degree) product.

Some insight regarding ERA-40 performance had nevertheless been available by November 2001 through the participation of M. Serreze and D. Bromwich in a workshop at ECMWF. For discussion at the workshop, ECMWF supplied four years of data from a "prototype" run of ERA-40. Precipitation forecasts from ERA-40 were indeed found to be much better than from the

NCEP reanalysis but are no better than those from the earlier ECMWF ERA-15 effort. While the lack of improvement over ERA-15 was initially puzzling, D. Bromwich identified a strong tropospheric cold bias, centered roughly over the Arctic Ocean. This essentially makes the polar vortex too strong. The cold bias was traced to a problem in the assimilation of HIRS satellite data over sea ice, apparently related to difficulties in cloud clearing. The problem was confirmed by ECMWF through an experiment in which HIRS data over sea ice were "blacklisted".

Once data from the production run became available, evaluation of ERA-40 began in earnest. The quality of ERA-40 forecasts was assessed against fields from NCEP, ERA-15 and from satellite-based retrievals from the Global Precipitation Climatology Project (GPCP). While ERA-40 precipitation forecasts from the production run were found to be highly superior to NCEP, again no improvement relative to ERA-15 was noted. It appears that the cold tropospheric bias introduced by sub-optimal assimilation of satellite data is still present. Interestingly, even the performance of NCEP was found to far superior to that of the GPCP. While it was hoped that a technique could be developed to blend the GPCP data with ERA-40 and gauge data, it was concluded that the GPCP retrievals, at least over Arctic lands and the ice-covered Arctic Ocean, are of little value.

Improved techniques have nevertheless been developed to blend ERA-40 with gauge data using optimal interpolation approaches. These approaches use the higher-resolution (approximately 125 km grid spacing) ERA-40 product that only recently became available. These fields will be ingested into the RIMS system under the new NASA and NSF funding.

MODIS Snow Product

A MODIS-derived daily snow cover data set (snow-covered area), provides fractional snow cover in each 25 km grid. The MODIS product provides coverage starting in October 31, 2000. As with all optical remote sensing products, cloud cover can obscure the land surface. Rather than simply flagging grid cells with partial or complete cloud cover, we provide the fractional cloud cover as a separate variable. This provides users with greater flexibility and recognizes that cloud cover is itself is a relevant hydrologic variable. Note that MODIS cannot provide coverage during polar darkness. While the MODIS products in RIMS are relatively up do date (available through February of 2004), the transition to our new computing system has delayed further processing.

Enhanced Microwave Snow Cover Algorithm

As outlined in previous reports, we compared Northern Hemisphere snow extent derived from passive microwave algorithms with snow maps based on visible-band satellite data. During the early winter season (October through December) most passive microwave algorithms significantly underestimate snow extent over high latitudes. This occurs because the current algorithms are not capable of detecting shallow discontinuous snow. As the snow cover builds during January through March, as well as into the melt season, agreement improves. This occurs because the snow cover not only becomes deeper but exhibits a more complex and varied stratigraphy (e.g. more melt-freeze crusts) which enhances the characteristic spectral signature of snow cover. As the snow cover retreats toward the Arctic Basin during April, May and June, the microwave data show very close agreement with the visible data. Daily snow water equivalent (SWE) fields the period 1987 to June 2003 from the prototype algorithm used in these earlier studies have been ingested into the RIMS system. Fields will continue to be updated under new funding.

Regarding validation of SWE retrievals, compared passive microwave algorithms with a gridded North American monthly snow depth and SWE data set provided by Dr. Ross Brown of the Meteorological Service of Canada. Other comparisons had already provided valuable, albeit variable, results. Work by Jim Miller (a student, who has left Colorado to pursue his PhD in Arizona) indicated a rather poor agreement between algorithm output and RIMS fields of both precipitation minus evaporation (P-E) and precipitation (both gridded RIMS fields and station data). Studies focused on the Ob, Yenisei and Lena river basins. In a separate study using RIMS data, Dr. Daqing Yang, University of Alaska, Fairbanks, found reasonable agreement between the SWE produced by the passive microwave algorithm and the snow cover melt and runoff over large northern river basins such as the Ob, Yenisei, Lena, Mackenzie, and Yukon. The emphasis here was on basin-scale snowmelt processes and associated peak flows.

Blended AMSR-E and MODIS Snow Product

A shortcoming of the MODIS product, apart from the problem of cloud cover, is that no coverage is provided during polar darkness. As this NASA contract ended, efforts were ongoing to combine the advantages of passive microwave (SSM/I and AMSR-E) (which provides all-weather coverage throughout the year) and MODIS to provide a blended 25 km snow cover product. A prototype of this product using SSM/I and NOAA data sets has been produced. Briefly, for grid cells where AMSR-E indicates snow, the grid cell is taken to be completely snow covered. Validation experiments indicate that this is a good assumption. AMSR-E in turn provides an estimate of associated SWE. For grid cells where AMSR-E indicates no snow, MODIS is used to estimate the fraction of the grid cell with snow cover. The MODIS data being used are in the Climate Modelers Grid (CMG) at approximately 5 km (0.05 deg.). Co-PI R. Armstrong is part of the AMSR-E instrument team.

Relationships between the percent area covered by snow as indicated by the MODIS data and the threshold for the appearance of snow as indicated by the passive microwave data are being generated. These relationships provide a method to estimate the error in early season snow extent derived from passive microwave which was described above. Both MODIS and AMSR-E data have enhanced spatial resolution compared to the earlier data sources. Examples of how this increased spatial resolution results in more accurate snow cover maps have been generated. Early results were presented at the 2003 Fall AGU conference.

Near-Surface Soil Freeze/Thaw Status

Efforts to assess the near-surface soil freeze/thaw status over the Northern Hemisphere have come to fairly high level of maturity.. For snow-free land surfaces, use is made of passive microwave data (SSM/I). Soil freeze/thaw status under snow-covered land surfaces is assessed via a one-dimensional heat transfer model.

Fields of daily freeze-thaw status for the pan-Arctic landmass were generated from 1987 onwards (the start of SSM/I coverage) and delivered to UNH for incorporation into Arctic-RIMS. Updates will continue to be generated. Statistical analysis of these data indicates that near-surface soil freezes for more than 9 months in high Arctic to less than six months in the upper reaches of the major river basins. Over the past 14 years (1987-2000), changes in the first and last day of surface soil freeze vary from a few days to more than two weeks. The duration of surface soil freeze varies by up to a month. These changes potentially have a significant impact on moisture exchange between the land surface and the atmosphere, surface and subsurface hydrology, and river runoff. This work is coordinated with a NOAA-funded project entitled Investigation of the seasonal freeze/thaw cycle of soils in the GCIP region" to Zhang and Armstrong at NSIDC.

Related studies show that active layer thickness has increased about 10 to 30 cm at ten observational stations and sites over the Lena River basin. Changes in active layer thickness may help to explain observed increases in cold-season discharge for Siberian rivers. Additional work is continuing to investigate recent changes in near-surface soil temperature.

Active Layer Monitoring

A finite difference model for one-dimensional heat conduction with phase change was adopted within Arctic-RIMS to monitor the active layer within Arctic permafrost. Enhancements to the original model include improving the forcing data sets and incorporating better parameterizations for the thermal conductivities of soil and snow. Weekly snow heights are calculated from SSM/I-derived snow water equivalents, using measured climatological snow densities for 5 different snow classes. Information from weekly NOAA snow charts improves identification of thin snow cover in spring. A topography-enhanced surface temperature data set was also created for model forcing. It uses NCEP reanalysis sigma-0.995 temperatures, atmospheric lapse rates and DEM-based surface elevation.

The model is divided into three major vertical layers, 0-30 cm, 30-80 cm, and 80-1500 cm. Soil bulk densities for these layers along with clay and silt contents are based on data from the SoilData System of IGBP. Calculations at each grid box are performed on 54 model nodes ranging from 10 cm at the surface to 1 m at 15 m depth. The model is run with a daily time step. Output is being used to assess the length of thawing season, the day of maximum active layer depth, and frozen ground depth.

Comparisons were made with about 60 measurements of active layer depth in the regions of continuous permafrost from the CALM project. There is reasonably good agreement between measured and modeled active layer depths although RMS errors are high. This is in part a function of scale differences. Active layer depths are mostly measured on 100 x 100 m grids, and even there the scatter is already comparable to that of the modeled values at 25 x 25 km scales. The active-layer thickness model has been used to assess temporal changes in the modeled soil thermal regime. When driven by RIMS temperature fields, the model indicates significant increases in soil temperatures over the last 30 years, in broad accord with observations.

Jet Propulsion Laboratory

SeaWinds Data Integration

We assembled a full two years of pan-arctic scatterometer data from the SeaWinds instrument on-board QuikScat. The SeaWinds data stream was initiated in June 1999 and continues through the present. Analysis efforts have focused on monitoring spring thaw and quantifying spatial and temporal thaw dynamics across the pan-arctic land mass. We have staged and assembled all data through late 2001, and are assembling data through spring 2002. Derivation of these freeze-thaw map products has utilized time series thresholding algorithms, classifying freeze-thaw transitions through comparison of the time series backscatter to a frozen or thawed reference state.

Validation and interpretation efforts involved two strategies: (1) testing, validation and improvement of freeze/thaw classification algorithms at local (25 km) scales utilizing in situ data collected at a series of ground measurement stations in Alaska, and (2) correlation of backscatter products with variables derived as part of other Arctic RIMS data sets. Emphasis was on developing improved freeze-thaw maps for application across regional and continental scales. For local scale testing, we assembled ecosystem biophysical data from eight in situ measurements stations extending along a north-south transect across Alaska. At each station, we monitored vegetation tissue and soil temperatures in a selection of trees. These data were used to validate the thaw status of the trees and soil at each site.

As a baseline, we implemented a class of thresholding algorithms following those previously derived using data from the NASA scatterometer (NSCAT). This approach examines the first difference (derivative) of the time series backscatter data. A transition from frozen to thawed surface conditions is present when the first difference is greater than a specified threshold value. Taking this further, we developed edge-detection techniques to better discriminate freeze and thaw transitions. These approaches have been widely used in computational edge detection in imaging systems and have superior handling of noisy signals. We adapted these techniques to detect a one-dimensional noisy step edge. Generally, these algorithms have performed better at detecting and locating a step edge than the differencing methods. They give clearer indications of transitional periods, capturing more general trends of transition and filtering out noise. However, they have mixed results for those regions where the freeze and thaw transitions are more gradual. Application of an integrated algorithm across the pan-arctic data set should allow significantly more accurate delineation of landscape thaw status.

We continued to develop scatterometer-based phenology products indicating dates of major thaw events estimated at regional scales across selected boreal regions. We compared results derived using various freeze-thaw detection algorithms to quantify improvement in mapping of landscape thaw.

The Ohio State University

Precipitation Minus Evapotranspiration (P-ET)

Monthly fields of P-ET were delivered for RIMS ingest on a monthly basis. They represent a standard Arctic-RIMS product and are used in the precipitation reconstruction scheme outlined earlier. As discussed in earlier reports, P-ET is calculated via the aerological method using wind and humidity data from the NCEP reanalysis. P-ET represents the vertically-integrated vapor flux convergence adjusted by the time change in precipitable water. On monthly time scales, P-ET is dominated by the flux convergence term. NCEP archives vertical integrals of the monthly-mean zonal and meridional fluxes and precipitable water (based on 6-hourly values at sigma levels), hence simplifying calculations. Using the P-ET in conjunction with P (based on either station data or the reconstructions) allows ET to be estimated as a residual.

Polar MM5 Simulations

This component of Arctic-RIMS uses a version of the Pennsylvania State University/National Center for Atmospheric Research fifth generation mesoscale model (MM5) that has been optimized for high-latitude applications (Polar MM5). The NCAR Land Surface Model (LSM) has been coupled to Polar MM5 with the aim of accurately simulating the land surface processes. LSM contains options for a detailed soil module (including frozen soil) and vegetation, as well as an option for snow cover. The Polar MM5 lowest model level meteorological variables and the near-surface radiative fluxes represent inputs to the LSM.

The latest version of the Polar MM5 (version 3.4) coupled to the NCAR LSM was used to generate fields of precipitation, evaporation, surface winds, temperature, cloud fraction, radiation and other variables. Each day the model is run over two domains, one centered at 65 deg. N and 95 deg. W longitude over North America and the other centered at 65 deg. N and 75 deg. E over Eurasia. The horizontal resolution is 60 km, and there are 28 terrain-following levels. The initial and boundary conditions are interpolated from the daily 00UTC run of the Aviation Model forecasts (AVN) obtained from the NCEP ftp site. The forecasts start at 00UTC every day and produce 48-h predictions. In comparison to observations, the Polar MM5 produces better predictions than the standard MM5, especially for near-surface temperature and mixing ratio over the North American and Eurasian regions. The time series of the modeled near-surface variables are in good agreement with the observed time series. Model development will continue under the new funding. Results are posted to the web at http://polarmet.mps.ohio-state.edu/ARCTIC. For use in Arctic-RIMS, the Polar MM5 as well as AVN output are also interpolated to the 25 km EASE grid. These data sets complement a suite of field fields generated for Arctic-RIMS based on the NCEP/NCAR reanalyses and provide alternative drivers for the UNH water balance and transport models (see below).

University of New Hampshire

River Network

A major effort under Arctic-RIMS was development of a pan-Arctic river network in a polar projection. Previous efforts to develop large scale-scale flow direction maps have concentrated on the global scale using cartographic projections that typically greatly distort high latitudes. The level of accuracy required for Arctic-RIMS required a more focused effort. Version 1.0 of STN-EASE, a digital river network on the 25 km EASE grid, contains are 39,926 grid cells in the pan-Arctic drainage for a total area of approximately 25 million square kilometers. There are a total of 3310 drainage basins in the pan-Arctic of all sizes and 170 large drainage basins (those with drainage areas greater than 10,000 km^2). Approximately 60% of the large basins are named within the data set. Under new funding, we intend to increase the number of large basins with names to make it easier for the casual user of the data set to locate basins of interest. Many basins, such as those defining the Greenland ice mass, have no name that we know of.

Real-Time Monitoring of River Discharge

Another major effort was to collect provisional river discharge data for many of the gauges closest to the ocean on the major drainage basins within the pan-Arctic. The number of gauges was extended to 57 sites (20 in Alaska, 15 in Russia, 12 in Norway and 10 in Canada). North American and Norwegian data are received on day after collection and the Russian data are delivered with a 5-7 day lag time. Software was developed perform automated data checking to look for errors in the real-time data.

Error assessments of discharge data have been performed at daily, monthly, and annual time steps and for large spatial aggregations (e.g. Eurasian discharge to the Arctic Ocean). Focus was placed on estimating the error in river discharge for the down-stream gauges (those closest to the ocean) of the largest Eurasian rivers. These gauges have very long time series (approximately 70 years) and contribute about 72% of total Eurasian discharge into the Arctic Ocean. We developed new methodological approaches to estimate discharge errors for various computational techniques. Errors in discharge data over the year and for the long-time period were estimated for both individual gauges and the spatially aggregated data.

Our error model applied to the major Eurasian gauges showed that the accuracy of daily discharge estimates for the large Arctic rivers is strongly variable over the annual cycle. During 4-5 months of the year, the well-behaved and mostly stable long-term stage-discharge rating curve can be used to convert stage measurements to discharge with low error not exceeding 10-15%. However, during ice and backwater conditions the stage-discharge relationship cannot be applied and we see daily maximum errors for the year exceeding 50% for some rivers. We established that one of major characteristics of the Arctic rivers is low winter stage values falling below minimal open-channel stage. This does not allow the use of the stage-discharge relationship with corrections and makes accuracy of the winter discharge estimates very sensitive to the frequency of discharge measurements. Fortunately, when integrated over the entire year, the annual discharge over the long-term is estimated to be accurate with approximately 3-10% error. More importantly, this level of error has not decreased in a significant way during the last 10-15 years during which the number of actual discharge measurements decreased.

Another part of the RIMS project is the collection of historical daily data for all real-time gauges. We eliminated the temporal gaps between the historical and the operational (provisional) data for 20 sites. This also provides us with data overlap of provisional and corrected data, allowing us to estimate errors in our correction algorithms. The remaining 37 gauges have a gap between the provisional and corrected data. In 34 of these gauges the gap is less than one year are filled (with data overlap) when national agencies release the corrected data. The remaining 3 gauges were closed and then re-opened, therefore there is no data to collect during this time. We are also collecting data for river discharge gauges located throughout the interior of the pan-Arctic. For these sites we are focusing on monthly time steps and so far we have data for 178 gauges up to and including December, 1999.

Model Development

Pan-Arctic Water Balance Model (P/WBM) used in Arctic-RIMS continued to be refined during the course of the project. This includes updating and improving the model to handle permanent ice conditions, as well as improved vegetation and subsurface components. Under the new NASA and NSF finding, appropriate processes will continue be added where they contribute to improved evapotranspiration and runoff.

A comparison with observed discharge data for 10 Arctic sea basins showed good correlation (r=0.84). In addition to evapotranspiration (ET) and runoff (R) products, estimates of storages such as snow water equivalent and soil moisture have been analyzed and archived. Comparisons between these data sets and those from other investigators allow us to validate the data and uncover systematic biases. For example, estimates of maximum active-layer depth from PWBM compare well with those from the soil heat conduction model. Estimates of ET from PWBM capture the seasonal cycle of moisture availability at high latitudes.

Internet-Based Applications

UNH was also responsible for developing the internet-based application to receive, process and serve RIMS data. The majority of RIMS data are received as gridded (25 km EASE-grid) daily fields. Data are processed to generate a set of spatial and temporal aggregations. Temporal aggregations are generated for monthly, annual and climatological time steps while the spatial aggregations focus on watershed, sea basin, continent and the pan-Arctic. The Arctic-RIMS web site (http://rims.unh.edu/) contains background material on the project and a tutorial for site navigation. The RIMS system contains a suite of visualization and analysis tools. For example, for a given watershed and selected time, one can easily generate maps different hydrologic variables (e.g., precipitation, net precipitation, temperature). Options are available to generate anomaly fields and time series.

PAPERS SUPPORTED UNDER THIS NASA CONTRACT

Bromwich, D.H, S.H. Wang and A.J. Monoghan, 2002: ERA-40 representation of the Arctic atmospheric moisture budget. In: *Proceedings, ECMWF Workshop on Reanalysis*, November 2001, Reading, UK, 287-297.

Forman, S. L., W. Maslowski, J. T. Andrews, D. Lubinski, M. Steele, J. Zhang, R. B. Lammers, and B. J. Peterson, 2000: Researchers explore Arctic freshwater's role in ocean circulation. *EOS Transactions, American Geophysical Union*, **81**, 169-174.

Holmes, R. M., B. J. Peterson, A. V. Zhulidov, V. V. Gordeev, P. N. Makkaveev, P. A. Stunzas, L. S. Kosmenko, G. H. Kohler, and A. I. Shiklomanov, 2001: Nutrient chemistry of the Ob' and Yenisey rivers, Siberia: Results from June 2000 expedition and evaluation of long-term data sets. *Marine Chemistry*, **75**, 219-227.

Holmes, R. M., B.J. Peterson, V.V. Gordeev, A.V. Zhulidov, M. Meybeck, R. B. Lammers, and C. J. Vorosmarty, 2000: Flux of nutrients from Russian rivers to the Arctic Ocean: Can we establish a baseline against which to judge future changes? *Water Resources Research*, **36**, 2309-2320.

Makkaveev, P.N., P.A. Stunzhas, P.V. Khlebopashev, V.V. Gordeev, R.M. Holmes, B.J. Peterson, and A.I. Shiklomanov , 2001: Flux of nutrients from Ob' and Yenisey rivers to the Arctic Ocean: results from June 2000 expeditions. In: *Proceedings of the Arctic Regional Centre*, pp. 97-106.

McGuire, A.D., J.S. Clein, J.M. Melillo, D.W. Kicklighter, R.A. Meier, C.J. Vorosmarty, and M.C. Serreze, 2000: Modeling carbon responses of tundra ecosystems to historical and projected climate: Sensitivity of pan-Arctic carbon storage to temporal and spatial variation in climate. *Global Change Biology*, **6**, 141-159.

Meybeck, M.M. and C. J. Vorosmarty. 1999: Global transfer of carbon by rivers. *IGBP Newsletter*, **37**, 18-19.

Oelke, C., T. Zhang, M. Serreze and R. Armstrong, 2003: Regional-scale modeling of soil freeze/thaw over the Arctic drainage basis. *J. Geophys. Res.*, **108**(D10), 4314, doi: 10.1029/2002JD002722.

Oelke, C., T. Zhang and M.C. Serreze, 2004: Modeling evidence for recent warming of the Arctic soil thermal regime. *Geophys. Res. Lett.*, **31**, L07208, doi:10.1029/2003GL019300.

Peterson, B. J., R. M. Holmes, J. W. McClelland, C. Vorosmarty, R.B. Lammers, A. Shiklomanov, I. Shiklomanov, and S. Rahmstorf, 2002: Increasing Arctic River Discharge Responses and Feedbacks to Global Climate Change. *Science*, submitted.

Rawlins, M.A., Lammers, R.B., Frolking, S., Fekete, B M., and Vorosmarty, C.J., 2003: Simulating Pan-Arctic Runoff with a Macro-Scale Terrestrial Water Balance Model. *Hydrological Processes* (in press).

Rawlins, M.A. , K.C. McDonald, S. Frolking, R.B. Lammers, M. Fahnestock, J.S. Kimball and C. J. Vorosmarty, 2003: Remote sensing of pan-Arctic snowpack thaw using the Seawinds scatterometer. Submitted to *Journal of Hydrology*..

Rogers, A. N., D.H. Bromwich, E.N. Sinclair, and R.I. Cullather, 2001: The atmospheric hydrologic cycle over the Arctic Basin from reanalyses. Part 2. Interannual variability. *J. Climate*, **14**, 2414.

Serreze, M.C., M.P. Clark, A.J. Etringer and D.H. Bromwich, 2001: Variability and trends in the hydro-climatology of the major Eurasian arctic drainages. In: Extended Abstracts, Second Wadati Conference on Global Change and the Polar Climate, March 7-9 2001, Tsukuba Science City, Japan, pp. 83-86.

Serreze, M.C. and A.J. Etringer, 2002: Representation of Arctic precipitation in ERA-40. *Proceedings, ECMWF Workshop on Reanalysis*, November 2001, Reading, UK, 317-331.

Serreze, M.C. and A.J. Etringer, 2003: Precipitation characteristics of the Eurasian Arctic drainage system. *International Journal of Climatology*, **23**, 1267-1291.

Serreze, M.C., A.H. Lynch and M.P. Clark, 2002: The Arctic frontal zone as seen in the NCEP/NCAR Reanalysis. *Journal of Climate*, **14**, 1550-1567.

Serreze, M.C., D.H. Bromwich, M.P. Clark, A.J. Etringer, T. Zhang, and R. Lammers, 2003a: The large-scale hydroclimatology of the terrestrial Arctic drainage. *J. Geophys. Res.*, **108**(D2), 8160, doi: 10.1029/2001JD000919.

Serreze, M.C., M.P. Clark and D.H. Bromwich, 2003b: Monitoring precipitation over the Arctic terrestrial drainage system: Data requirements, shortcomings and applications of atmospheric reanalysis. *J. Hydrometeorology*, **4**, 387-407.

Shiklomanov, A.I., R.B. Lammers, C.J. Vörösmarty, 2002: Widespread Decline in hydrological monitoring threatens pan-Arctic Research. *EOS Transactions, American Geophysical Union,* **83**, pp. 13, 16, 17.

Shiklomanov , I.A. and Shiklomanov A. I., 2002: Climate change and dynamics of river water input to the Arctic Ocean. Submitted to *Water Resources* (in Russian).

Shiklomanov, A.I., O Ph. Golovanov and R.B. Lammers, 2002: Status of the hydrometric monitoring network in the Arctic drainage basin. In: *Proceedings, The Conference for Hydrometeorology of the Commonwealth of Independent States*, 23-26 April 2002, 138-141 (in Russian).

Shiklomanov A. I., O. Ph. Golovanov O. and S.V. Golovanova, 2002: The Increase of river discharge in the Arctic Ocean and its possible consequences. In: *Proceedings, The Conference for Hydrometeorology of the Commonwealth of Independent States*, 23-26 April 2002, 147-149 (in Russian).

Vorosmarty, C., L. Hinzman, B. J. Peterson, D. H. Bromwich, L. Hamilton, J. Morison, V. Romanovsky, M. Sturm, and R. Webb, 2001: *The Hydrologic Cycle and its Role in Arctic and Global Environmental Change: A Rationale and Strategy for Synthesis Study.* ARCUS Report, ARCUS, Fairbanks, AK, 84 pp.

Vorosmarty, C., L. Hinzman, B. J. Peterson, D. H. Bromwich, L. Hamilton, J. Morison, V. Romanovsky, M. Sturm, and R. Webb, 2002: Arctic-CHAMP: A program to study arctic hydrology and its role in global change. *EOS Transactions, American Geophysical Union*, **83**(22), 241,244-245,249, 28 May 2002.

Zhang, T., R. G. Barry, and R. Armstrong, 2002. Application of remote sensing techniques to frozen ground study, *Progress in Physical Geography* (in press).

Zhang, T., R.G. Barry, K. Knowles, F. Ling and R.L. Armstrong, 2003: Distribution and seasonality of perennially frozen ground in the Northern Hemisphere. *In: Proceedings of the 8th International Conference on Permafrost,* Zurich, Switzerland, July 21-23, 2003.