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Modeling the Pan-Arctic Terrestrial and Atmospheric Water Cycle

Final Report

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1. INTRODUCTION

This report describes results of DOE grant DE-FG02-96ER61473 to Iowa State University (ISU). Work on this grant was performed at Iowa State University and at the University of New Hampshire, in collaboration with Dr. Charles Vorosmarty and fellow scientists at the University of New Hampshire's (UNH's) Institute for the Study of the Earth, Oceans and Space, a subcontractor to the project.

During project's second year, the Iowa State University postdoc on this project, Dr. Zekai Otles, left for a new position elsewhere. A search for a replacement started as soon as his imminent departure was confirmed. After some visa difficulties, the new postdoc, Dr. Helin Wei, arrived in February 1999, several months after Dr. Otles left. The transition created a gap in performance of many project tasks, as the primary responsibilities of Dr. Otles had running the atmospheric simulations and analyzing their output. For this reason, the PI requested and was granted a one-year, no-cost extension on this project.

2. PROJECT RESULTS

2.1 Model development

We acquired and implemented on our workstations the NCAR/Penn State Mesoscale Model, Version 5 (MM5). To drive the model, we acquired 15 years of reanalysis output produced by the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). We obtained output on the reanalysis model's gaussian grid and sigma levels to give us higher resolution output and greater processing flexibility compared to the standard 2.5° datasets. We also adapted NCAR codes for MM5 initial and boundary conditions to use the reanalysis output.

We performed initial simulations on a 120-km grid (81 x 71 gridpoints) chosen to encompass the land surface of the Arctic watershed while being as computationally efficient as possible (Fig. 1). Some test computations indicated that using a grid spacing of 60 km had only marginal impact on results, while requiring substantially greater computational resources.

Most of validations for previous climate simulations over the pan-Arctic region have been made by comparing simulations with model driven fields due to the lack of observed information. We used a number of data sets recently released that merged *in situ* measurement, satellite retrieval and reanalysis output over the polar region to provide observation-based data sets for evaluating model performance. We performed several one-month and a more limited number of one-year simulations with our MM5 version. A year with strong seasonal sea ice change (October 1985 – September 1986) was selected as a period to investigate model capability. The validation concentrated on atmospheric circulation, temperature, surface radiation fluxes, precipitation and evaporation over individual Arctic watersheds and the central Arctic Ocean.

We performed several upgrades to MM5 to make it more suitable for climate simulation, especially in the Arctic. Part of this development included modifying MM5's standard, weather diagnostics to produce compact output files more suitable for climate simulation and more specifically directed toward the diagnostics of water cycling and circulation dynamics needed for our research program. The modified diagnostics were directed toward comparison with several observational or quasi-observational sources, such as the Historical Arctic Rawinsonde Archive (HARA), NCEP/NCAR reanalyses and satellite retrievals. Further development included modifying the input data stream to include ongoing updating of the sea-surface temperature boundary conditions. We also tested various reasonable combinations of radiation and boundary-layer model options available in MM5 in a sequence of one-month simulations. All gave acceptable results, especially when recognizing that a limited-area model spanning the Arctic will be subject to much weaker control by horizontal boundary conditions than corresponding midlatitude simulations embedded in the westerly jet.

More significant changes involved implementing a sea-ice model, adding a much improved land-surface scheme, and adapting and implementing the parallel version of MM5 on a 64-node system (ALICE) operated by the Department of Energy's Ames Lab. The parallel version allowed fairly rapid testing of the model, but only in its parallel form, which ultimately became a limitation as we upgraded the model further. The sea-ice model was taken from the HIRHAM mesoscale climate model (Christensen et al., 1997), where it has been used successfully for Arctic climate simulation. This scheme was adapted to run in both the serial and parallel versions of MM5. Land surface modeling was improved significantly by coupling

the Land Surface Model (LSM) developed by Dr. Gordon Bonan for the NCAR Climate System Model. The LSM was chosen in part because it is especially appropriate for high-latitude use, with considerable care taken in its development to give appropriate thermal simulation of seasonally frozen soil. The LSM also offers flexibility in treating subgrid-scale variability in vegetation cover. The LSM-MM5 coupling was accomplished in the serial version of MM5. In the future we may try to implement it in the parallel MM5 code.

The final version of the model was attained by additional testing with all implementations in place. One last change was the addition of a new scheme to diagnose cloud cover, as tests showed excessive cloud cover when using MM5's standard scheme based on relative humidity. The adopted scheme instead used the model's predicted cloud liquid and ice water fields to diagnose cloud cover.

The model captured the general pattern of atmospheric circulation and its change throughout the one-year simulation period (Fig. 2). When model simulations and reanalysis output were compared to rawinsonde data, the root mean square error (RMSE) versus observation was more often smaller for the MM5 simulated wind than for the NCEP/NCAR reanalysis (Fig. 3). To some extent the model thus performed better than the data set providing its lateral boundary conditions. The model produced a reasonable annual cycle of surface temperature and radiation fluxes. The largest warm biases were found during the transition from late spring to early summer because surface albedo given by the simple surface scheme we use in this study decreased too fast. Though the model also simulated total precipitable water in the 900 hPa -100 hPa layer fairly well versus satellite estimates. An analysis of scale dependence of model precipitation and temperature errors showed that model errors are relatively small when output is average over large domains and remain as average domain shrinks, become excessively large for domains covering 10,000 km² or smaller. Figures of these results appear in Wei et al. (2001).

Parallel model development focused on land surface hydrology for the Arctic. A graduate student working under Dr. Vorosmarty at UNH developed a model to refine the partitioning of surface water routing and its timing for the Arctic region, where the landscape can vary between clearly defined river networks and broad, flat regions where the surface-water flow is not well-organized. This work included developing tools to create river networking models for somewhat arbitrary resolutions and map projections (Fekete et al., 2001). This will allow

adaptation of river networks developed at UNH on a standard latitude-longitude grid to coarser grids or other projections. (For example, the standard MM5 grid at high latitude is a polar-stereographic projection.)

Another UNH student completed a master's thesis (Holden, 1998) on adapting a local permafrost model for use in a spatially distributed model, such as MM5. The Permafrost Water Balance Model (P/WBM) (Rawlins et al., 2001) was developed, from the UNH group's original Water Balance Model (WBM) to incorporate improved representation of seasonal effects of frozen soil conditions found in the Arctic Regions, including effects on lateral water flow. P/WBM represents the soil zone as two compartments, the rooting zone and a deep soil zone. A dynamic active layer prevents melt water from entering into the soil zone thus increasing river discharge during the snow melt season. The model is driven by spatially distributed monthly time series of temperature and precipitation. The major water balance variables of evapotranspiration, soil water storage, and runoff, along with maximum active layer depth and permafrost extent, form the primary output surfaces. All are calculated for 30-minute grid cells and are later routed through a 30-minute river network developed by the UNH group (STN-30; Vörösmarty et al., 2000a,b; see below) to check on the efficacy of the water balance computations. The UNH group analyzed a 30-year monthly time-series of water balance elements to explore the parameterization of this model and link this understanding to the behavior of our version of the MM5 model. Further model and parameterization development was conducted (Vörösmarty et al., 1998) evapotranspiration algorithms that was partially supported by project funds and that advanced this project's development of the P/WBM.

The UNH group developed an optimized version of its Water Transport Model, which distributes runoff through entire drainage systems of the STN-30 and transforms this runoff into discharge hydrographs at any point within a simulated river network. The model is a finite difference formulation that handles both linear and non-linear flow dynamic formulations. We performed model calibration based on improved discharge hydrograph records (see below) that were assembled in selected basins of the region to develop a rule-based system for applying these parameters to all pan-Arctic basins resolved at 30-minute grid spacing. The UNH WTM applies idealized river geometries to solve the St. Venant equation for channel flow. An earlier version of the model used a simple formula to parameterize the river bed geometry. A group of UNH researchers, led by Drs. S.L. Dingman and D. Bjerklie, collaborated with UNH DOE-

project scientists on a NASA-funded study to demonstrate how well river bed geometry can be estimated from basic river flow information (such as discharge, river bed slope). They derived new formulas to parameterize riverbed geometry. This helped our effort, because now we do not have to specify an idealized configuration *a priori*. The new Dingman and Bjerklie formulae are to be implemented in a revised version of our WTM.

The UNH group also studied the impact of simulated river network resolution on how well the network can represent the characteristics, such as shape and width function. Coefficients were developed to correct for the river sinuosity lost at coarser resolution, which currently is at 30' longitude x latitude (Vörösmarty et al. 2000a,b). This work allows us to assess the impact of using coarser resolution simulated river networks, for example, in a global climate model.

2.2 Data Base

In order to compare water balance simulations over the pan-Arctic region, the UNH group generated a river routing topology for the entire land mass draining into the Arctic Ocean (Vörösmarty et al., 2000a,b; Lammers et al., 2001). The topology allows modeled runoff calculations to be "cascaded" downstream from each simulated grid cell to the Arctic Ocean. The river routing operates at a 30-minute (long. x. lat.) spatial scale and is referred to as the STN-30 (Simulated Topological Network at 30 minute spatial resolution; Fig. 4). The STN-30 was generated using an automated procedure based on a digital elevation model, followed by careful hand correction for consistency with assembled records of basin area. When compared to several hundred reporting stations, we found that the mean difference between simulated contributing areas and those assigned by the various reporting agencies was well under 10%, which allowed us to proceed with confidence as we simulated distributed water balances for the region. The river network also includes information about the boundaries of the different Arctic seas to permit interaction with the Arctic Ocean modeling community. The STN-30 was used for additional analysis of the role river networks play in organizing continental hydrology (Vörösmarty et al., 2000a,b) and for analyzing variability in freshwater flow into the Arctic Ocean (Shiklomanov et al., 1999).

We substantially increased our database of river discharge observations. In conjunction with a related project, the UNH scientists compiled river discharge measurements, associated

drainage-basin areas and flow characterization statistics collected through UNESCO. This data set has global coverage and was published in seven volumes (Vörösmarty et al., 1996) and also made available on the World Wide Web (Vörösmarty et al., 1998).

Over the project period, UNH scientists increased especially the discharge database substantially in the pan-Arctic. Through collaborative work under an NSF-Polar Programs project (Peterson et al. 1996), Dr. Vörösmarty and his UNH group have worked with Russian and Canadian post-doctoral fellows (A. Shiklomanov, R. Lammers) to develop historical time series of river discharge from observational records. Our original data set from the UNH RivDIS publication (Vörösmarty et al. 1996) yielded exactly 100 gauging station time series. Our current holdings total over 3700 individual site time series (Lammers et al., 2001). For those basins exceeding $15,000 \text{ km}^2$ in area (which we have discovered to be the most reliable for analysis at 30-minute spatial resolution, as in this study) RivDIS yielded 90 sites, whereas our update represents data from 668 sites. For the approximately 20 M km^2 pan-Arctic basin this produced a substantial increase in spatial sampling resolution, from $220,000 \text{ km}^2$ to $30,000 \text{ km}^2$ per station. The station-based discharge database was geographically co-registered to the STN-30, which permits several hundred comparisons of discharge to be made over the full size spectrum of rivers sampled. The pan-Arctic data river discharge base was released on a CD-ROM and made available on the Web (R-ArcticNet, 1999).

We used the STN-30 and the expanded river discharge database in a preliminary analysis of the atmospheric water vapor convergence produced by the NCEP/NCAR reanalysis. In the long-term average, the atmospheric convergence into a basin and river discharge out should balance. This analysis was an extension of a similar application to basins in the U.S. (Gutowski et al., 1997). Tentative results from 10-yr averages showed that convergence was within 30% of observed discharge for the largest basins (Ob, Lena, Yenisei, MacKenzie), but it quickly deteriorated to average errors greater than 30% for basins less than $500,000 \text{ km}^2$.

The UNH scientists also extended their land water balance assessment to develop composite, gridded runoff fields based on observed river discharge and simulated water balances. The work combined their STN-30 river network with best available gauging stations from the Global Runoff Data Centre archive. These stations were co-registered to the STN-30, which had the side benefit of exposing errors in either data set and providing information for error correction. The coupled data bases were used to calculate inter-station discharge and runoff,

which were then compared with output from a water balance model driven by long-term monthly climatology. The comparison yielded correction coefficients to the simulated runoff which were then applied to the simulations to yield the final product, monthly runoff on a 30 minute grid (Fekete et al., 1999a). The composite runoff fields were thus constrained by discharge observations but preserved the spatial and temporal distribution of runoff given by the water balance simulation. The composite is likely the most accurate spatially distributed runoff available and is available on CD-ROM (Fekete et al., 1999b). Examination of regional water balances using the composite runoff has shown the potential for identifying problematic regions in current precipitation data sets. Fekete et al. (1999a) have used such identification to develop a method for correcting regional precipitation estimates that appears applicable to monthly climatology.

2.3 Other work supported by the grant

Because we used the NCEP/NCAR reanalysis to supply atmospheric boundary conditions for our simulations, we performed an analysis of the atmospheric water transport it produces in comparison with river outflow in selected basins (Gutowski et al., 1997). The reanalysis water convergence fluctuated over weekly time scales in a coherent manner with lagged river outflow. However, when averaged over the 10-year period of the study, the reanalysis convergence agreed with time-average discharge only to within about 35%. We also published a supporting study of water-vapor layers in the atmosphere (Iselin and Gutowski, 1996), which pose challenges for modeling the atmospheric branch of the hydrological cycle. Relatively thin layers were found to be ubiquitous in the rawinsonde archive examined (Project STORM-FEST). (This DOE-supported work spawned a separate model development grant, from the National Science Foundation, to explore using adaptive-grid techniques to simulate such dynamic structures in atmospheric water vapor and to examine further the observational record.)

We published a paper (Gutowski et al., 19998) examining effects of sea-surface temperature (SST) spatial variability on scales that are typically subgrid to global climate models. We found that resolving such variability can yield surface latent heat fluxes that are as much as 50% stronger in summer, with weaker effect in winter. Simply resolving the SST

variability through surface tiling appears sufficient, though a scale analysis indicates that unresolved mesoscale circulations could arise with sufficiently strong, persistent SST gradient.

Finally, work was completed (Gutowski et al., 2001) on a single-column model developed primarily under the original grant to this project. This Coupled Land-Atmosphere Simulation Program (CLASP) was developed to explore issues of land-atmosphere coupling in a framework that would allow repeated multi-year simulation. Further work using has shown that two-way coupling of river flow and subterranean aquifer storage can have substantial impact on regional evapotranspiration during dry periods when the region includes phreatophytic vegetation (vegetation with roots impinging the water table).

3. PROJECT PRODUCTS

3.1 Refereed Papers

Fekete, B.M., C.J. Vörösmarty, and R. Lammers. 2001. Multiple-resolution stream networks for macro-scale hydrology: Algorithm development and analysis. *Water Resour. Res.* (In press).

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3.2 Data products and reports

- Fekete, B. M., C. J. Vörösmarty, and W. Grabs, 1999a: *Global Composite Runoff Fields Based on Observed River Discharge and Simulated Water Balances*. GRDC Report 22, Global Runoff Data Centre, Koblenz, Germany, 100 pp.
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4. FIGURES

Fig.1 - Model domain. Subregions for detailed analysis also shown [vertical line: Asian Arctic Watershed (AAW); horizontal line: North American Arctic Watershed (NAAW); italic line: European Arctic Watershed (EAW); North of 70°N: Central Arctic Ocean (CAO)]. Symbols mark locations of HARA soundings used for comparison with model output. Two areas for the analysis of scale-dependent errors are outlined by the frames with grid lines.

Fig. 2 - Monthly average wind vectors at 850 hPa for DJF (top row) and MAM (bottom row) in the reanalysis (left) and the simulation (right). Reference vector between lower panels is 15 m/s.

Fig. 3 - Root mean square difference versus HARA of daily 850 hPa u- and v-components for averaged for four months at four stations: Myszhelania (76.94N, 68.58E), Cambridge (69.1N, 105.13W), Tukvkhansk (65.78N, 87.95E), and Bodo (67.28N, 14.42E). White bars = NCEP; black bars = MM5. Only 6 days of HARA data available for Tukvkhansk in July.

Fig. 4 - STN-30 river routing for the pan-Arctic. River channel widths are scaled by their discharge