CLIMATE CHANGE AND THE HYDROLOGIC CYCLE OF THE ARCTIC OCEAN

James R. Miller, Department of Marine and Coastal Sciences, Cook College, Rutgers University
71 Dudley Road, New Brunswick, NJ 08901 USA; miller@arctic.rutgers.edu

The long-term freshwater budget of the Arctic Ocean is maintained by inflow from the atmosphere and rivers and outflow through the ocean. The freshwater outflow consists of sea-ice export and an oceanic component which results from the transports of water masses of different salinities across the southern boundary of the Arctic Ocean. There are still uncertainties in the magnitudes and variability of all of the terms in this freshwater balance of the Arctic. Superimposed on these uncertainties is the possibility that the balance is changing in time either at shorter time scales associated with the North Atlantic and Arctic Oscillations or at longer time scales associated with climate change.

The powerful ice-albedo feedback mechanism in the Arctic region makes this region one of the most sensitive in responding to climate perturbations. Most global climate models find enhanced warming in the Northern Hemisphere polar regions in transient studies with increasing atmospheric greenhouse gases (Houghton et al., 1996). Potential changes in sea-ice cover will be occurring simultaneously with changes in precipitation, evaporation, and river flow. The combined effects of all these changes will alter the ocean circulation and the freshwater and salt budgets of the Arctic Ocean. In the North Atlantic, the thermohaline circulation is, in part, affected by the outflow of freshwater through Fram Strait, and according to Rahmstorf (2000) may be a system with dangerous thresholds to perturbations. A major component of the Arctic freshwater budget is river discharge which flows into the ocean primarily on shallow coastal shelves. It's necessary to know how this freshwater moves from the shallow shelves into the deeper basin and eventually out ot the Arctic. It is also of interest to know how these transfer mechanisms might change in the future in response to climate change.

To understand how the Arctic water budget varies naturally and how it might change in response to global climate change, we examine the components of the Arctic water budget from two 150-year simulations of the Goddard Institute for Space Studies (GISS) global coupled atmosphere-ocean-ice model. One simulation is for the present climate and the other is for a climate in which atmospheric greenhouse gases (GHGs) are increasing at a rate similar to today. The first simulation is a control with constant 1950 atmospheric composition, and the second is a GHG experiment with observed greenhouse gas concentrations from 1950 to 1990 and with compounded 0.5% annual increases in CO2 after 1990.

The GISS model used in this study is the global synchronously coupled atmosphere-ocean model developed by Russell et al. (1995) for climate studies at decade to century time scales. There are nine vertical layers in the atmosphere and 13 in the ocean. The horizontal resolution for both the atmosphere and ocean is 4 x 5 degrees in latitude and longitude. The resolution for heat, water vapor, and salt is finer than the grid resolution because those quantities have both grid-box means and directional gradients which are used in the advection by the linear upstream scheme. Atmospheric condensation and ocean vertical mixing are performed at 2 x 2.5 degree horizontal resolution. The model has several new features including a new ground hydrology scheme, four thermodynamic layers for glacial ice and sea ice, advection of sea ice, glacial ice calving off Antarctica but not in the Northern Hemisphere, and the k-profile parameterization (KPP) ocean vertical mixing scheme of Large et al. (1994). The model does not use flux adjustments.

For the present climate, the model's inflow of river water is about 10% too high. The net precipitation minus evaporation is consistent with some observations, although there is considerable variablity in the observations. The model's outflow of freshwater through the Canadian Archipelago appears to be somewhat high, although again there is uncertainity in the observed throughflow. The model's export of sea ice through the Fram Strait is about half of the observed transport obtained by Aagaard and Carmack (1989), although a more recent study by Steele et al. (1996) found that the annual observed transport through Fram Strait was significantly lower for the period from 1978 to 1990.

For the GHG experiment, the net inflow of freshwater to the Arctic Ocean increases, primarily due to an increase in river flow, sea level increases at a faster rate than the global average, and the net mass of water in the Arctic Ocean increases. During the last 50 years of the GHG experiment, the river discharge has increased by about 10% relative to the control. Relative to the control there is a small increase (0.029 mm/day) in P - E for the last 50 years of the GHG experiment. This increase accounts for 17% of the increase in freshwater inflow to the Arctic in the GHG experiment. The remaining 83% of the increase in freshwater inflow to the Arctic Ocean in the GHG experiment is due to the increase in river discharge. The 535mm increase in sea-surface height of the Arctic Ocean for the last half of the 21st century is due to both the increasing net mass inflow and to the loss of salt which increases the specific volume. The increase in sea level height in the Arctic Ocean is 62% greater than the global average.

The net outflow of freshwater also changes in the GHG experiment. The model's freshwater outflow due to sea ice decreases by 44% for the last 50 years. If the freshwater inflow increases and the sea-ice export decreases, then either the Arctic salinity will decrease or the liquid ocean freshwater export will increase. All of these occur in the GHG experiment. The liquid freshwater export increases by 25% for the last 50-years of the GHG experiment. The model's total freshwater outflow (oceanic liquid freshwater plus sea-ice advection) increases significantly in the GHG experiment.

The objective of this study has been to examine the water budget of the Arctic Ocean and how it might change in response to increases of atmospheric greenhouse gases. The results show that for the GHG experiment the inflow (P - E + R) increases primarily due to increased river discharge, the sea-ice export decreases by 44%, and the oceanic liquid freshwater outflow increases by 25%. The combined effects lead to increases in Arctic mass and sea level and a decrease in salinity.

The global hydrologic cycle is of critical importance in the climate system, and one rarely sees a detailed examination of it in climate models. This study indicates that an important and useful component of all future coupled model intercomparison projects should be a summary of the Arctic water budget. Cattle and Cresswell (2000) have done a similar analysis of the components of the Hadley Center global model’s Arctic freshwater budget. The Arctic Ocean is a self-contained subset of the global system where water occurs in all three phases. Modeling the hydrologic cycle in the Arctic region requires modeling the atmospheric precipitation and evaporation, the terrestrial system (river flow and continental ice), sea ice, and the ocean transports of salt, heat, and freshwater, and the exchanges between the shelves and the deeper basins.

This work will continue and be extended to examine the Arctic energy budget and how it might change in the future. A preliminary analysis indicates that for the GHG experiment there is increased absorption of radiation into the ocean due to the combined effects of increased absorption of short wave radiation and increased downward longwave radiation. The increased radiative flux is compensated for somewhat in the Arctic Ocean heat budget by increases in both the sensible and latent heat fluxes. New satellite data and other observations are being used to both validate the model for the present climate and to begin to assess whether the model's variability and trends are consistent with observed fields. These new satellite observations will help to reduce the errors in the observed data sets for water and energy budgets and will make model comparisons with observations more meaningful in the future.

References

Aagaard,K. and E.C. Carmack, 1989: The role of sea ice and other fresh waters in The Arctic circulation*. J. Geophys. Res.,* **94**, 14485-14498.

Cattle, H., and D. Cresswell, 2000: The Arctic Ocean freshwater budget of a climate general circulation model. In *The Freshwater Budget of the Arctic Ocean*, E.L. Lewis, Ed., Kluwer Academic Publishers, Dordrech, The Netherlands, 623 pp.

Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell, (Eds.), 1996*: Climate Change 1995: The Science of Climate Change*, Cambridge Univ. Press, 572 pp.

Large, W.G., J.C. McWilliams, and S.C. Doney, 1994: Oceanic vertical mixing: review and a model with non-local boundary layer parameterization. *Rev. Geophysics*, **32**, 363-403.

Rahmstorf, S., 2000: The thermohaline ocean circulation: A system with dangerous thresholds? *Climatic Change***,46**, 225-246,2000.

Russell, G.L., J.R. Miller, and D. Rind, 1995: A coupled atmosphere-ocean model for transient climate change studies. *Atmos.-Ocean*., **33**, 683-730.

Steele, M., D. Thomas and D. Rothrock, 1996: A simple model of the Arctic Ocean freshwater balance, 1979-1985*. J. Geophys. Res.*, **101**, 20,833-20,848.