Modeling and Analysis of Global and Regional Hydrologic Processes and Appropriate Conservation of Moist Entropy

P.I.: Donald R. Johnson
Space Science and Engineering Center
University of Wisconsin – Madison

Research Objectives

The principal objectives of this research were to 1) advance the modeling of climate change by continued development and application of a hybrid isentropic coordinate model for global and regional climate simulations, 2) advance the understanding of physical processes involving the transport of water vapor, cloud water/ice and trace constituents including sources/sinks of entropy through diabatic heating, and 3) theoretically and diagnostically examine the limits of global and regional climate predictability imposed by inherent limitations in the simulation of transport and hydrologic processes, and cloud life-cycles.

Significance of Research

This research addressed the fundamental issues of understanding and modeling of hydrologic processes in relation to regional and global climate change. Hydrologic processes, including surface evaporation, long-range transport of water substances, release of latent heat involving evaporation/condensation and attenuation of the radiative flux of energy by water vapor and clouds, are crucial to the successful simulation of global and regional climate.

Major efforts have and are being devoted to advancing the accuracies of climate simulations through revisions and improvements in parameterizations and to some extent increased resolution. While these endeavors have advanced the realism of climate simulations, such efforts alone have not ascertained unequivocal accuracies needed to resolve global and regional climate change with respect to the atmosphere's hydrologic and chemical processes, and other anthropogenic impacts. Ensuring the accuracies of the transports of energy, entropy, water vapor, cloud water/ice and other trace constituents are fundamental to advancing the modeling of thermodynamic processes that force the climate state

Undisputable evidence has been set forth in Johnson et al. (2000; 2002), which illustrates the inherent difficulties of simulating the long-range transport of water vapor and other trace constituents within conventional sigma coordinate climate models. Long range transport throughout the atmosphere's global highly stratified circulation intrinsically involves three-dimensions, particularly within the amplifying baroclinic waves of extratropical/polar latitudes. The inaccuracies that develop stem largely from the inherent inaccuracies of sigma coordinate climate models in appropriately simulating the reversibility of moist thermodynamic processes including cloudiness. The source of these difficulties results from the numerical inaccuracies associated with vertical advection and the resulting inaccuracies of the transport of the three phases of water substances, vapor, water and ice as individual properties relative to the dry entropy. Given the combination of truncation errors from each of the components, the overall result is a failure to conserve moist entropy, which in turn leads to a failure to simulate accurately precipitation, cloudiness, the recycling of water substances over land as well as oceans, and the subsequent interaction of hydrologic/ biospheric processes, etc. As a result, large biases develop within the various climate models, particularly in the specification of regional climate change.

Since the long range transport of water vapor and trace constituents primarily remains two dimensional in isentropic coordinates except in limited regions of intense moist convection, Johnson et al. (2000, 2002) have established that moist entropy is appropriately conserved. As such, the reversibility of moist thermodynamic processes is retained with a high degree of accuracy in isentropic coordinates relative to sigma coordinate models. The following table lists the various RMS of the differences of moist equivalent potential temperatures at ten days as simulated by the model's combination of dry entropy and water vapor, water and ice versus the moist entropy transported as a inert trace constituent as extracted from the paper entitled, "Isentropic Diagnostic Assessments and Modeling Strategies Appropriate to the Development of Weather and Climate Models" . This paper was prepared and presented at the Symposium on the 50th Anniversary of Operational Numerical Weather Prediction by Johnson (2004, Pdf file available from NCEP and author).

	$S_G(\delta^*)$	$S_G(\hat{\delta}^*)$	$S_G(\hat{\hat{\delta}})$	$S_G(\delta)$
NCAR CCM T42				
CCM3 θ_e without physics	37.45 (6.12)	195.77 (13.99)	0.02 (0.15)	233.24 (15.27)
CCM3/2 θ_e without physics	27.88 (5.28)	0.09 (0.30)	0.03 (0.16)	28.00 (5.29)
CCM2(all spectral) θ_e without physics	10.83 (3.29)	2.12 (1.46)	15.03 (3.88)	27.98 (5.29)
NCEP GSF T62				
θ without physics	11.10(3.33)	0.28(0.53)	0.00(0.02)	11.39(3.37)
θ_e with physics	29.08(5.39)	1.22(1.10)	1.63(1.28)	31.93(5.65)
UW $\theta-\sigma$ (2.8°) θ_e without physics	0.70(0.84)	0.23(0.48)	0.13(0.35)	1.05(1.03)
UW $\theta-\eta$ (2.8°)				
θ_e without physics Van Leer numerics	0.12(0.35)	0.01(.10)	0.03(.16)	0.16(0.40)
θ_e without physics PPM numerics	0.10(0.31)	0.08(.10)	0.12(0.11)	0.12(0.34)
θ_e with moist convective parameterization only	0.45(0.67)	0.10(0.32)	0.00(0.02)	0.56(0.75)

The first three columns present the variance and RMS differences by components, deviations about the area mean at each level, deviations of the area mean from the global mean and the difference of the global means. The last column lists the total variance and RMS differences. See Johnson et al. (2000, 2002) for details of the Analysis of Variance. For the most part, the RMS differences in the fourth column for sigma models are on the order of 5 degrees while the RMS difference of the UW hybrid model is 0.34, a result which clearly illustrates the fidelity of a hybrid model relative to a sigma coordinate model.

The emphasis of this research effort was on the application of isentropic modeling and analysis to advance the accuracy of the simulation of all aspects of the hydrologic cycle including clouds and thus the climate state regionally and globally. Simulation of atmospheric hydrologic processes by the UW hybrid isentropic coordinate models provided fundamental insight into global monsoonal circulations, and regional energy exchange in relation to the atmospheric hydrologic cycle.

An inter-comparison of UW hybrid model simulations with those from the NCAR Community Climate Model and other climate and numerical weather prediction (NWP) models investigated the increased accuracies gained in modeling long-range transport in isentropic coordinates and isolates differences in modeling of the climate state. The intercomparisons clearly demonstrated advantages in the simulation of the transport of the hydrologic components of the climate system and provided insight into the more general problems of simulating hydrologic processes, aerosols and chemistry for climate.

Accomplishments

Our research efforts at the University of Wisconsin under this award have been primarily directed toward advancing the understanding of global water vapor and inert trace constituent transport in relation to climate change through the development and application of hybrid isentropic coordinate models. This research has achieved the objectives originally proposed. These key objectives were to:

<u>Direct the development of a hybrid isentropic coordinate model that more realistically simulates the transport of water vapor and other trace constituents, cloud amount, and other aspects of the hydrologic cycle toward the simulation of global and regional climate.</u> Over the period of the award, the UW hybrid isentropic coordinate model was transformed into a full-fledged climate model with robust capabilities (Schaack et al. 2004). The UW isentropic-eta model employs a vertical coordinate that smoothly transitions from terrain following at the earth's surface to isentropic coordinates in the middle to upper troposphere, while providing consistent vertical resolution in both the extratropical and tropical latitudes. This vertical structure retains the excellent conservation characteristics of the predecessor UW isentropic-sigma coordinate model and facilitates the implementation of advanced numerical schemes and data assimilation, and enables the model to be optimized for highly parallel computing systems. As part of this effort an all-sigma coordinate version (UW sigma model) of the UW isentropic-eta

model has been established and maintained to be as similar to the UW isentropic-eta model as possible except for the vertical coordinate.

Advance the modeling and understanding of transport processes and the hydrologic cycle. Research continued a series of experiments to investigate the capabilities of models to accurately simulate the long-range transport of water substances and inert trace constituents. The experiments involved simulations with the UW isentropic-sigma, UW isentropic-eta and UW sigma models, and the National Center for Atmospheric Research (NCAR) Community Climate Models. The results, focusing on numerics and appropriate conservations of dry and moist entropy and potential vorticity in relation to reversibility, have demonstrated remarkable advantages for simulating hydrologic processes and trace constituent transport in the hybrid isentropic models relative to sigma-based models.

Study the accuracy and theoretical limits of climate models in simulating transport processes and the hydrologic cycle. Johnson et al. (2000, 2002) developed and applied a statistical strategy utilizing the concept of "pure error" to assess the numerical accuracy of global models to simulate reversible processes including the explicit simulation of water vapor and cloud water/ice transport, as well as cloud condensation/evaporation in conjunction with heating/cooling from phase changes.

Study the impact of physical parameterizations on NWP and climate simulation. Over the past three years substantial effort was devoted to investigating the impact of physical parameterizations on climate simulations. The base version of the UW isentropic-eta model utilizes the full suite of physical parameterizations from the NCAR CCM3. In the last three year period, the moist convective parameterization scheme used operationally in the NCEP Global Forecast System (GFS) and the microphysics of clouds with a relaxed Arakawa-Schubert (McRAS) moist convective scheme have be implemented and tested in the model. The entire suite of physical parameterizations from the NCEP GFS has also been recently implemented. Impact tests for both NWP and climate are ongoing.

Improve the computational efficiency of the UW isentropic-eta and develop a version to execute on MPP machines. The speed and efficiency of the UW isentropic-eta model has been substantially increased over the last three year period. The model uses either OpenMP parallelism or MPI message passing. The effort to convert the code to use both MPI message passing and OpenMP to maximize the use of multiple nodes is 80-90% complete at this time.

UW Model Climate Simulation

In a recent paper, Schaack et al. (2004) presented results from a 14 year climate simulation from the UW isentropic-eta model. These results, which were validated against NCEP/NCAR reanalysis 4DDA data and other observed data, demonstrated the viability of the UW isentropic-eta model for long-term integration to simulate climate and climate change. Two numerical experiments presented in the manuscript's Appendix documented the ability of UW isentropic-eta model numerics to accurately simulate transport of moist entropy, potential vorticity and reversible isentropic processes. Overall, the study documented that no insurmountable barriers exist to simulation of climate utilizing hybrid isentropic coordinate models and provides impetus for continued development of hybrid isentropic coordinate models as a means to advance capabilities in the simulation of long range transport in relation to the planetary nature of heat sources and sinks.

Real Time Forecasts

The scientific community has come to recognize the link between weather and climate and how evaluation of bias errors in forecasts can be useful in diagnosing errors in climate models. As part of on-going model development and investigation of the impact of resolution and physical parameterization on model simulations, twice-daily 5 day forecasts from the UW isentropic-eta model were executed and validated for the past four years. Over this period, the NH 500 hPa geopotential height anomaly correlation (AC) for the UW isentropic-eta model (0.7 degree latitude-longitude, 28-layers) and the NCEP GFS are nearly identical. The average 500 hPa geopotential height AC for the UW isentropic-eta model (NCEP GFS) model is 0.81 (0.81) for the NH and 0.81 (0.79) for the SH. With respect to other global medium range forecast models, NCEP's scores are somewhat less than ECMWF's, but generally exceed the scores of the other centers. Considering that the NCEP GFS model is running at approximately twice the horizontal and vertical resolution of the UW model and the very limited resources devoted thus far to real-time forecasts, the results clearly document the feasibility and integrity of linking weather and climate modeling though utilizing hybrid isentropic/sigma coordinate models, given. Furthermore, these AC scores from the UW isentropic-eta model relative to the scores from the NCEP GFS are disadvantaged from the condition that the specification of the initial state for the hybrid model is determined by vertical interpolation from the GFS assimilated data, and assessing the hybrid model forecast involves interpolation to the verifying state as determined by the GFS model. There is also an implicit advantage that the GFS assimilated data against which the relative accuracy of the UW Hybrid Model was determined retains a GFS model climate which undoubtedly differs from that of the GFS Model.

Impact studies using the McRAS moist convective parameterization, which includes a prognostic cloud algorithm, have shown an 8% improvement in the above AC scores relative to the base version of the UW model employing the CCM3 moist convective parameterization.

Assessments of Numerical Accuracy

Johnson et al. (2000, 2002) developed a strategy to assess statistically the RMS pure error expressed as the difference of paired values of θ_e and $t\theta_e$ throughout the model domain. The strategy provides degrees of freedom to identify bias and random components within the fully developed global circulation of both weather and climate models. The emphasis of this strategy was to examine the capability of models to simulate explicitly the atmosphere's hydrologic cycle including clouds and to conserve moist entropy during the fully reversible processes of cloud generation, transport, and evaporation. Accurate simulation of reversible processes remains a critical challenge at all time scales from NWP to climate prediction.

The Gouy-Stodola theorem from thermodynamics, which is applicable for "analyzing loss mechanisms in complex processes", calls attention to the condition that heat transfer (energy exchange) even in the presence of diabatic heating requires that attention be given to the consideration of reversibility. The theorem in effect states that in thermally forced systems all “unnatural processes” require there be an additional work input above and beyond that required by natural processes. The net effect in accord with entropy and the Second Law is that the system must become cold in the regions from which net entropy is extracted by outgoing infrared radiation, a result consistent with the findings of Johnson’s (1997) study in the coldness of climate models. Others have supported this result, which still remains as a common difficulty in all IPCC climate models, with the possible exception of one (personal communication from R Anthes and D. Bader).

Johnson, D. R., 1997: On the "General Coldness of Climate Models" and the Second Law: Implications for Modeling the Earth System. *J. Climate*, **10**, 2826-2846.

Contributions to Development of DOE Climate Modeling Programs

The P. I. and his group had frequent interactions with scientists from DOE, NASA and NOAA concerning climate modeling and the importance of hydrologic processes. During the grant period, the P. I. served through a half-time IPA appointment as NOAA’s National Centers for Environmental Prediction Special Project Scientist. The P. I. attended all CCPP and SciDAC annual meetings. A member of our group attended the NERSC Users group meeting at Argonne National Lab on 29 May 2003.

The P. I.’s group has worked to facilitate the use and application of hybrid isentropic coordinate models and diagnostics at other research centers. The P. I.’s group has twice traveled to NCEP for discussions with NCEP scientists regarding the development of a global hybrid isentropic coordinate model. The group has also transferred to NCEP portions of a diagnostic packaged developed at the UW for use in diagnostic evaluation of the NCEP global model.

The P. I. was co-organizer and Chair of two Hybrid Modeling Workshops where 20-30 scientists either involved directly with or interested in hybrid isentropic coordinate modeling have presented and discussed results. The P. I. was on the program committee of the “Workshop on Atmosphere and Ocean Modeling with Isentropic and Other Quasi-Lagrangian Vertical Coordinates” held at NCEP on 17-19 August 2004.

Publications

Schaack, T. K., T. H. Zapotocny, A. J. Lenzen and D. R. Johnson, 2004: Global climate simulation with the University of Wisconsin global hybrid isentropic coordinate model. J. Climate, 17, 2998-3016. Available at www.ssec.wisc.edu/theta.

Johnson, D. R., A. J. Lenzen, T. H. Zapotocny and T. K. Schaack, 2002: Entropy, numerical uncertainties and modeling of atmospheric hydrologic processes: Part B. *J. Climate*, **15**, 1777-1804.

Presentations

Johnson, D. R., 2004: Isentropic diagnostic assessments and modeling strategies appropriate to the development of weather and climate models. Symposium on the 50th Anniversary of Operational Numerical Weather Prediction, College Park, Maryland, 14-17 June 2004

Johnson, D. R. 2004: Diagnostic Assessments and Modeling Strategies Appropriate to the Development of Weather and Climate Models. DOE Livermore Laboratory, Livermore, CA, March 4, 2004

Johnson, D. R., 2003: The relevance of water to civilizations, nations and sustainability: A critical issue regionally and nationally in the Near East. (Invited) Workshop: Medical Perspectives on Unconventional Disasters. Albuquerque, NM, Aug. 19-21, 2003.

Johnson, D. R., T. K. Schaack, A. Lenzen, and T. Zapotocny, 2003: Analysis and Modeling of Climate Globally Employing Isentropic Perspectives. Presented at the Climate Change Prediction Program Meeting, Charleston, SC, March 17-19, 2003.

Johnson, D. R., 2003: Analysis and Modeling of Weather and Climate Globally Employing Isentropic Perspectives. Invited, presented at the Institute of Global Environment and Society/COLA, Calverton, MD, January 29, 2003.

Johnson, D. R., 2002: Stratospheric Tropospheric Exchange Simulated by a Hybrid Isentropic Model. AGU Meeting, San Francisco, CA, Dec. 6-10, 2002.

Zapotocny, T. H., 2002: A chronological progress of physical parameterizations in the UW isentropic models. Presented at the Second Hybrid Modeling Workshop, Louisville, KY, April 18-20, 2002.

Schaack, T. K., 2002: Hybrid isentropic modeling at the University of Wisconsin. Presented at the Second Hybrid Modeling Workshop, Louisville, KY, April 18-20, 2002.

Johnson, D. R., 2002: Where have we been, where are we now, and where are we going. Presented at the Second Hybrid Modeling Workshop, Louisville, KY, April 18-20, 2002.

Lenzen, A. J., 2002: Conversion of UW-Hybrid coordinate model for MPP computers. Presented at the Second Hybrid Modeling Workshop, Louisville, KY, April 18-20, 2002.

Johnson, D. R., T. K. Schaack, A. Lenzen, and T. Zapotocny, 2002: Contrasting of numerical uncertainties of climate models in simulating reversibility. Presented at the AMS Annual Meeting, Orlando, FL, Jan. 12-18, 2002.

Johnson, D. R., 2001: The UW Global Hybrid Isentropic Model and Key Considerations in the Numerical Simulations of the Climate System. Presented at the Climate Change Prediction Program Meeting, San Diego, CA, October 1-3, 2001.

Johnson, D. R. 2001: Invited presentation. What is reversibility and how relevant is ensuring reversibility in the simulation of atmospheric hydrologic and chemical processes? Seminar at Langley Research Center, Hampton, VA, June 27, 2001.

Johnson, D. R., T. K. Schaack, A. Lenzen, and T. Zapotocny, 2001: Contrasting of numerical uncertainties of climate models in simulating reversibility. Presented at the Spring AGU Meeting, Boston, MA, May 28 - June 1, 2001.

Johnson, D. R., 2001: Invited presentation at the National Centers for Environmental Prediction. Challenges in Modeling and Analysis of Hydrologic Processes for Weather and Climate. March 2001.