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Modeling and Analysis of Global Hydrologic Processes and Moist Entropy for Climate with the University of Wisconsin Isentropic-Sigma Model

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1. Research Objectives

The primary objective of this research is to advance the modeling and understanding of atmospheric processes involving water substances and the transport of inert trace constituents in relation to climate change. To achieve this goal, a prototype climate model based primarily on isentropic coordinates in the vertical has been developed at the University of Wisconsin-Madison (UW). The model is hybrid in nature with approximately the lowest 15% of the model's atmosphere described by conventional sigma coordinates (normalized pressure) and the remaining 85% by isentropic (entropy) coordinates. The hybrid model is hereafter referred to as θ–σ in this report. For comparative purposes, a nominally identical global sigma coordinate model is under parallel development, channel and regional versions of each model also exist.

A further objective of this research is to examine the accuracy and theoretical limits of global climate predictability which are imposed by the inherent limitations of simulating trace constituent transport and the hydrologic processes of condensation, precipitation and cloud life cycles. This objective involves theoretical studies and a diagnostic comparison of results from the θ–σ and sigma models described above as well as other "state of the art" general circulation models, primarily the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM3).

2. Current Research

The results from theoretical and numerical studies have established that the UW θ–σ model more accurately simulates the transport of dry and moist entropy with appropriate conservation under reversible dry and moist adiabatic processes than sigma coordinate models.

A. Theoretical Studies

In addition to a more accurate numerical representation of water vapor transport and the hydrologic cycle, climate models based on isentropic coordinates or specific entropy coordinates enjoy a fundamental advantage over models based on sigma coordinates. Johnson (1997) established for a model without drift that a positive definite source of entropy requires that the simulated climate state be biased cold, and that sigma coordinate model simulations are subject to positive definite aphysical sources of entropy in association with the numerical diffusion/dispersion of energy. Also, since the implicit source of entropy in a sigma coordinate model is determined from a calculation of heating that is separate from the prognostic calculation of temperature, a prognostic error in temperature induces an erroneous aphysical source of entropy. Johnson (1997) further established that a similar positive definite source of entropy does not occur in a model based on isentropic or specific entropy coordinates since the vertical mass and entropy transport is a direct function of the Lagrangian entropy source itself.

In a follow on study entitled "Entropy, the Lorenz Energy Cycle and Climate" Johnson (1998) reconciled the theoretical concepts of available potential energy with the classical thermodynamic concepts of thermodynamic efficiency, the Carnot cycle, and verified that a climate model atmosphere must become cold, thus becoming more efficient in order to simulate a climate state without drift in the presence of spurious positive definite sources of entropy. Globally, an aphysical source of entropy from numerical diffusion/dispersion and other inadequacies of parameterization equivalent to 4% of the entropy source from kinetic energy dissipation corresponds with a biased temperature error of 10°C, thus limiting the accuracy of climate model simulations. Increasing the accuracy of climate model simulations through reducing aphysical sources of entropy and cold temperature biases is exceedingly difficult to realize. Theory substantiates that a major source of the positive definite source of entropy comes from the numerical diffusion of water substances and the spurious mixing of moist static energy.

B. Channel Model Experiments

As previously published (Johnson et al. 1993, Mon. Wea. Rev., pp 2088-2114), under adiabatic conditions the UW θ–σ and nominally identical sigma channel models produce virtually identical five-day predictions of standard meteorological fields. However, with hydrologic processes included, the timing, location and quantity of precipitation predicted by the two models is dramatically different. The underlying cause of the differences, that simulated transport of the water vapor prior to condensation is substantially more accurate in the θ–σ model, has been the subject of a series of experiments on the transport of an inert trace constituent. In an effort to examine the transport characteristics of a sigma model and a θ–σ model, a large number of commonly used advection and transport schemes have been implemented in both models.

Experiments have included two initial trace constituent distributions, nine advection schemes and twelve semi-Lagrangian transport (SLT) schemes. Of the nine advection schemes, the conservation of second order moments (CSOM) (Prather, J. Geophys. Res., *91*, 6671-6681) produced the most accurate and consistent results, while the 6th order Lagrangian coupled with the "cascade" approach of Purser and Leslie (Mon. Wea. Rev., *119*, 2492-2498) proved to be the most accurate and cost effective SLT algorithm. Furthermore, regardless of initial trace constituent distribution or scheme, the UW θ–σ model was more accurate at conserving the initial tracer maxima than the nominally identical sigma model for 84% of the cases examined. Overall, these results provide a substantive understanding of the difficulties of simulating transport processes in models based on sigma versus isentropic coordinates. Two publications describing these results are in press for publication in Monthly Weather Review (Reames and Zapotocny 1997a and b, copies available upon request).

C. Global Model Experiments

Global models based on both θ–σ and sigma coordinates have been developed that include orography and physical parameterizations for radiation, cumulus convection, skin friction, dry convective adjustment, moist adiabatic adjustment, vertical diffusion of heat and moisture, and surface snow, ice and frost covering. Model development during the past year included incorporating the physical parameterizations, land-surface model, optional slab-ocean model, history tape generation and multi-tasking capabilities from CCM3 into the UW θ–σ model. This recent addition, especially the consistent set of physical parameterizations and multi-tasking capabilities, greatly enhances the ability of the UW θ–σ model for extended climate integrations.

Several validation experiments, testing conservation of trace constituents and cloud production in the UW θ–σ and σ models and CCM2/CCM3, were published. The first (Zapotocny et al. 1997a) examined the models' abilities to transport an inert trace constituent and conserve the initial maxima. The second (Zapotocny et al. 1996) examined predictability by a comparison of the simulated joint distributions of isentropic potential vorticity (IPV) and a trace constituent related to the initial IPV. The third (Zapotocny et al. 1997b) compared simulated equivalent potential temperature (θ_e) and a trace constituent related to the initial θ_e. In all of these experiments, the UW θ–σ model simulations were superior to the other tested models: trace constituent conservation was higher in the first experiment and the joint distribution of the actual and proxy IPV and θ_e as calculated by their correlation remained greater in the second and third experiments.

These results and the research objectives outlined in section 1 provide substantial evidence that a model based on isentropic coordinates provides marked advantages over sigma models in producing more accurate long range transport of water vapor and other trace constituents and that the improved transport of these properties is important for accurately simulating and understanding condensation and precipitation processes.

An ongoing set of experiments involves extended length integrations with the UW $\theta-\sigma$ model. For these simulations, the model is usually initialized with December 15 GEOS-1 assimilated data and seasonal December-January-February and June-July-August distributions are diagnosed with an emphasis on hydrologic processes (e.g. atmospheric heating, precipitable water, and precipitation minus evaporation). All diagnostics, a subset of which were presented at the last CHAMMP meeting, compare well to the National Centers for Environmental Prediction (NCEP)/NCAR reanalysis. Finally, integrations longer than six years have also been completed. Diagnostics over the last 5 winter and summer seasons, also presented at the last CHAMMP meeting, agree well with the NCEP/NCAR climate reanalysis data.

Another significant development during FY98, as proposed, has been the development of a generalized coordinate model from the existing UW $\theta-\sigma$ model. Unlike the $\theta-\sigma$ model, which sharply transitions from sigma to isentropic coordinates, this model (hereafter called the UW $\theta-\eta$ model) has a smooth transition from sigma coordinates near the ground to isentropic coordinates in the middle to upper troposphere. The structure is represented completely by isentropic coordinates at and above the 336 K surface. Validation of this model has been carried out in a manner similar to the UW $\theta-\sigma$ model: numerical experiments replicating those in Zapotocny et al. (1996,1997a and b) have been performed, daily real time five day simulations have been run and validated against the NCEP Global Data Assimilation System (GDAS) data, and seasonal and annual simulations have been validated against the NCEP/NCAR climate reanalysis data. Numerical experiments with these two UW models document that they appropriately conserve dry and moist entropy to a high degree of accuracy during transport and therefore simulate reversible processes within the atmosphere's hydrologic cycle involving condensation, evaporation and transport of clouds with increased accuracy over models based on conventional sigma coordinates.

3. Project Schedule for the Coming Year

During the coming year, efforts will primarily be directed towards extending the UW $\theta-\sigma$ and $\theta-\eta$ models from prototype climate models to full-fledged climate models. This work will involve continued model development and evaluation, especially of the CCM3 physical parameterizations which were recently incorporated into the UW models. Particular attention will be given to:

a. Finish multi-tasking the dynamical cores of each UW model. Completion of this step along with the existing multi-tasking capabilities of the physical parameterizations enhances the ability of the UW models for extended climate integrations.

b. Examine conservation of dry and moist entropy in the dynamical core and physical parameterizations of the UW models, a necessary condition for simulation without drift which few if any climate models currently satisfy (Johnson 1997).

c. Evaluate for possible incorporation the Betts-Miller convective scheme or a modification thereof into the UW models. This algorithm seems particularly well suited for a model based on isentropic coordinates since it relaxes the profile of θ_e. Special attention will be directed at ensuring conservation of moist entropy during convection.

d. Diagnose global and regional energy balances in the UW models, with an emphasis on the role of atmospheric hydrologic processes. This will be accomplished by comparing results from seasonal, annual and interannual simulations by the UW $\theta-\sigma$ and $\theta-\eta$ models with multi-year diagnostics derived from assimilated data sets and satellite derived products from the Earth Radiation Budget Experiment and the International Satellite Cloud Climatology Project.

e. Initiate more in-depth studies of the relative abilities of isentropic and sigma coordinate models to predict explicitly cloud substances and diagnose the impact of the explicitly simulated clouds on cloud radiative forcing. As this study proceeds, increasingly more sophisticated algorithms including reversible moist adiabatic processes will be utilized.

The efforts discussed above reveal advantages in simulating long range transport utilizing isentropic coordinates over conventional sigma coordinates. The improved simulation of moist reversible processes involving water vapor and cloud water and ice and related hydrological processes will lead to increased accuracy and simulation of many important processes in climate models with strong dependencies on hydrological processes, for example, cloud radiative processes, surface energy balance, moist chemistry, hydroscopic aerosols, scavenging, cloud shading involving photosynthesis and photodisassociation etc.

4. Recent Publications and Invited Lectures Acknowledging DOE Support

A. Publications

Johnson, D. R., 1998: Entropy, the Lorenz Energy Cycle and Climate. Accepted for publication in General Circulation Modeling: Past, Present and Future. A volume dedicated to Professor Akio Arakawa to be published by Academic Press.

Reames, F. M. and T. H. Zapotocny, 1998a: Inert trace constituent transport in sigma and hybrid isentropic-sigma models. Part I: Nine advection algorithms. In press for publication in Mon. Wea. Rev.

Reames, F. M. and T. H. Zapotocny, 1998b: Inert trace constituent transport in sigma and hybrid isentropic-sigma models. Part II: Twelve semi-Lagrangian algorithms. In press for publication in Mon. Wea. Rev.

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.

Zapotocny, T. H., A. J. Lenzen, D. R. Johnson, F. M. Reames, and T. K. Schaack, 1997a: A comparison of inert trace constituent transport between the University of Wisconsin isentropic-sigma model and the NCAR community climate model. Mon. Wea. Rev., 125, 120-142.

Zapotocny, T. H., D. R. Johnson, T. K. Schaack, A. J. Lenzen, F. M. Reames, and P. A. Politowicz, 1997b: Simulations of Joint Distributions of Equivalent Potential Temperature

and an Inert Trace Constituent in the UW θ–σ Model and CCM2. Geophys. Res. Let., 24, 865-868.

Zapotocny, T. H., A. J. Lenzen, D. R. Johnson, F. M. Reames, P. A. Politowicz, and T. K. Schaack, 1996: Joint distributions of potential vorticity and inert trace constituent in CCM2 and UW isentropic-sigma model simulations. Geophysical Research Letters, 23, 2525-2528.

B. Invited Lectures

Johnson, D. R., 1998: Entropy, the Lorenz Energy Cycle and Climate. Presented at the General Circulation Model Development: Past, Present and Future Symposium in honor of Professor Akio Arakawa. Los Angeles, CA, January 20-22, 1998.

Johnson, D. R., 1998: GPS/MET, Integrated Observational Capabilities, Data Assimilation and Atmospheric Prediction. Presented at the U.S.-Taiwan Bilateral COSMIC Science Workshop, Taipei, Taiwan, February 26-28, 1998.

Johnson, D. R., 1998: Entropy, Predictability and Climate Simulated States. Presented at the DOE Center for Nonlinear Studies 18th Annual International Conference: Predictability, Quantifying Uncertainty in Models of Complex Phenomena, Los Alamos, NM, May 13-15, 1998.

Johnson, D. R., 1998: Challenges in Remote Sensing and Modeling of Hydrologic Processes in Weather Prediction and Climate. Presented to NESDIS, Camp Springs, MD, August 13, 1998.