Final Report
Modeling and Analysis of Global and Regional Climate Change in Relation to Atmospheric Hydrologic Processes
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This research was directed to the development and application of global isentropic modeling and analysis capabilities to describe hydrologic processes and energy exchange in the climate system, and discern regional climate change. An additional objective was to investigate 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.

Summary of Research Results

The above goals were addressed primarily through development and application of two complementary global versions of the UW hybrid isentropic coordinate models. Regional and global versions of the University of Wisconsin (UW) hybrid isentropic-sigma ($\theta-\sigma$) model have been developed. Papers describing their development and documenting results from both models have been published and presented at numerous conferences. More recently a global hybrid model (UW $\theta-\eta$ model) which has a continuous vertical transition from σ at the earth's surface to isentropic coordinates in the middle troposphere has been developed through modification of the UW $\theta-\sigma$ model. Relative to the UW θ-σ model, this vertical structure reduces the complexity of the model, makes it more computationally efficient and provides a structure that is well suited to application of data assimilation techniques, higher order numerical schemes and massively parallel computing platforms. The performance of the UW $\theta-\eta$ model has been examined through a series of daily 48-hour forecasts over a period of 5 months. In addition realistic simulations exceeding 5 years have been performed and analyzed.

To achieve accurate prediction of precipitation, cloudiness, energy exchange, etc., first-order considerations demand that a model be able to conserve numerically both dry and moist entropy (Johnson 1997). Building on Johnson's theoretical analysis and earlier studies concerning trace constituent transport (Zapotocny et al. 1996, 1997a, 1997b), Johnson et al. (2000, 2001) set forth 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.

The strategy ascertains numerical accuracy within the fully developed nonlinear structure of NWP and climate models throughout the entire model domain in relation to the appropriate conservation of moist entropy and related properties. The application of this strategy permits a statistical assessment of the impact of numerical bias and random errors and/or inconsistencies in thermodynamic and hydrologic processes that develop within NWP, medium-range forecasts and climate prediction. This strategy was applied in a series of numerical experiments performed with the UW $\theta-\sigma$, the nominally identical UW σ model, the UW θ-η model, and the National Center for Atmospheric Research (NCAR) Community Climate Models (CCM2 and CCM3). These experiments demonstrated decided advantages for simulating hydrologic processes in isentropic coordinates relative to sigma based models (Johnson et al. 2000, 2001; Zapotocny et al. 1997a, 1997b). The experiments document that both UW hybrid models are unusually accurate in long-range transport and conservation of water substances and inert trace constituents. The more accurate simulation of the long range transport of these fields in the UW $\theta-\sigma$ model relative to the other models provides the potential for improved simulation of condensation processes, precipitation, clouds, cloud-radiative feedback and surface energy balance. All of these processes are critical for improved predictions of global and regional climate.

In a theoretical analysis, Johnson (1997) focused attention on the importance of the atmospheric entropy balance and its time rate of change for modeling the climate system and has provided an explanation for "the general coldness" of current climate models. In a follow on study entitled "Entropy, the Lorenz Energy Cycle and Climate" Johnson (2000) reconciled the theoretical concepts of available potential energy with the classical thermodynamic concepts of thermodynamic efficiency and the Carnot cycle. He 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. Increasing the accuracy of climate model simulations through reducing aphysical sources of entropy and cold temperature biases is exceedingly difficult to realize.

Reames and Zapotocny (1999a and b) examined the accuracy of nine advection algorithms and twelve semi-Lagrangian algorithms to transport and conserve an inert trace constituent. Their results show that the conservation of second order moments scheme (Prather, Journal of Geophysical Research, 91, 6671-6681) and Lin's adaptation of the Van Leer scheme (Lin et al., Monthly Weather Review, 122,1575-1593) outperform the other advection algorithms. In the semi-Lagrangian transport experiments, the 6th order Lagrangian coupled with the "cascade" approach of Purser and Leslie (Monthly Weather Review, 119, 2492-2498) proved to be the most accurate and efficient.

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