ISENTROPIC DIAGNOSTIC ASSESSMENTS AND MODELING STRATEGIES APPROPRIATE TO THE DEVELOPMENT OF WEATHER AND CLIMATE MODELS

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1. INTRODUCTION

In this paper, background diagnostic and modeling strategies employed in the development and employment of the UW Hybrid Isentropic Model at the University of Wisconsin are summarized in some detail. One of these strategies which has been utilized at NCEP will be briefly discussed for purposes of emphasizing the importance of ensuring reversibility within long range transport. The aim of the summary and the formal presentation, however, will be: 1) to emphasize the relevance of entropy, 2) to raise key issues that must be faced in advancing accuracies in the simulation of weather and climate and, 3) to foster discussion on strategies to isolate the strengths and current limitations of weather and climate models within a unified modeling endeavor envisaged as a key component of the Earth System Modeling Framework.

2. BACKGROUND

In weighing the impact of isentropic theoretical and diagnostic strategies in advancing weather and climate models relative to conventional models as currently configured today, outwardly isentropic models have made limited impact relative to the wealth of studies based on analysis and modeling in isobaric and sigma coordinates. One exception is NCEP's operational mesoscale weather prediction with the RUC Hybrid Isentropic-Terrain Following Coordinate Model (Benjamin et al. 2004a, 2004b). Benjamin et al. (2004) provide a nice summary of modeling efforts that have led to the development of hybrid isentropic terrain following coordinate models which will not be repeated in this presentation. In this summary, Eliassen and Raustein (1968) are credited for the introduction of isentropic numerical atmosphere prediction. As far as interests of the Joint Numerical Weather Prediction Unit in these matters, Shuman (1962) proposed in a study entitled "Numerical Experiments with the Primitive Equation," to integrate the atmospheric equations utilizing the quasi-Lagrangian coordinate system proposed by Starr (1945). He comments that "one would intuitively expect the finite difference analogues to the quasi-Lagrangian equations to behave better than finite difference equations analogues to equations of higher degree and therefore greater mathematical complexity" and notes "that isentropic surfaces would be the natural choice for coordinate surfaces in the middle stratosphere and higher".

Considering that key scientists of yesteryear, including Shaw, Rossby, Eliassen, Naimas, Danielsen and others set forth perspectives utilizing isentropic theoretical constructs and analyses that were original and elucidating, the excitement over

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isentropic analysis has withered, at least in a relative sense. While the author has frequently followed contributions by these individuals and others, a particular interest of the author follows from Sir Napier Shaw's (1930) perspective utilizing entropy change and isentropic concepts in gaining insight into the thermally forced nature of the global circulation. Sir Napier Shaw, a student of Maxwell, emphasized that the heating forced mass upward through isentropic surfaces in tropical latitudes and downward in polar latitudes, the combination of which required poleward transport of mass and entropy in the overworld of higher valued isentropic layers and equatorward transport in the underworld of lower valued isentropic layers. In this system, the systematic meridional transport of mass, energy and entropy couples directly with heating in tropical latitudes and cooling in polar latitudes.

Following their study of the theory of available potential energy utilizing isentropic concepts (Dutton and Johnson 1967), a theoretical analysis of the isentropic mass, angular momentum and energy exchange within the general circulation viewed from isentropic coordinates was presented at the London Conference of the General Circulation (Johnson and Dutton 1969). This analysis, which was in essence an elaboration of Shaw's perspective, isolated the existence of thermally forced Hadley circulations spanning the troposphere of each hemisphere. Each hemispheric Hadley circulation provided for the direct transport of mass, absolute angular momentum, energy and entropy from tropical to polar latitudes within the overworld. The mass transport within the return branch of the underworld balanced that of the overworld. At the same time, the net transport of absolute angular momentum, energy and entropy was poleward from the excess of each of these properties within the poleward over the equatorward branch. Embedded within thermal structure of extratropical latitudes, absolute angular momentum was transferred from the poleward branch to the equatorward branch through pressure stresses acting on the inclined zonally undulating isentropes in combination with negative and positive pressure torques respectively. The sense and magnitude of the isentropically, zonally averaged mean negative and positive pressure torques were uniquely linked with poleward and equatorward geostrophic components of meridional mass transport. In essence, isolation of the systematic poleward and equatorward geostrophic mass transport as an intrinsic component of a thermally forced Hadley circulation provided insight into an outstanding question of that decade. This question raised by Lorenz (1967), Starr (1968) and others was why in a statically stable rotating atmosphere was the eddy relative angular momentum transport defined within isobaric coordinates directed against the mean gradient of zonally averaged zonal momentum, the combination of which maintain the westerlies against a coincident transfer of angular momentum to the earth's surface by pressure and viscous stresses. Starr (1968) figuratively characterized this process as "negative eddy viscosity."

The simple concept of a direct thermally forced hemispheric circulation originally set forth by Hadley had been discounted in the early part of the 19th century (Lorenz 1967), and thus Shaw's arguments in the early 20th century received little attention. The oversight must also be attributed to an over reliance on isobaric analysis and a failure to isolate systematic processes that were embedded within the atmospheric circulation. Even from a more fundamental perspective, this oversight must

be attributed to a failure to consider the relevance of entropy and reversibility within the framework of the planetary circulation.

In their emphasis on the relevance of entropy as a physical property, Tolman and Fine (1948) comment that if the energetics of a system are precisely specified and accounted for in terms of all the sources and sinks as well as exchange and transformations, there is no need to engage entropy as a property in detailing the system. Clearly, the earth and its atmosphere constitute an open system with an exchange of both energy and entropy across the upper boundary within which certain processes that link molecular with planetary scales remain to be precisely defined. Furthermore, within the concept of a temporally averaged statistically stationary state, there is the important difference in that the net flow of energy across the upper boundary vanishes, while there is an outward flow of entropy from the earth by infrared radiation that exceeds the inward flow by solar radiation. Thus, recognition of this difference precludes gaining a complete understanding of the underlying thermodynamics by simple reliance on an analysis of the energetics of the earth-atmosphere system. Viewed from statistical perspectives of inference, an analysis of the energetics including mass and momentum exchange does not constitute sufficiency in the sense that one has extracted all the information that can be gleaned from analysis and modeling.

The follow on questions then are: 1) what additional information can be gained by including analyses of the entropy exchange in diagnostics and modeling of atmospheric circulation, and 2) must we rely on the trust by many that simply increasing the spatial-temporal resolution and engaging robust parameterizations is the secret to increasing the accuracies of weather and climate predictions apart from the need to delve into the intricacies of understanding the flow of entropy through the earth-atmosphere system.

Concerning the first question, isentropic analysis has revealed that the scales of the temporally averaged irrotational modes of transport of mass, dry static energy and entropy not only correspond with each other, but also correspond uniquely with the spatial scales of the temporally, vertically integrated distribution of entropy sources and sinks. This unique coupling of the three properties enters from the degree of freedom for an isentropic zonally averaged mean mode of geostrophic mass transport that is determined through isentropic analysis, not so through isobaric analyses. More importantly its existence verifies that there is a direct atmospheric response of systematic geostrophic mass transport to differential heating in the presence of rotation; a condition that is basic for the existence of thermally forced Hadley circulations spanning each hemisphere. Note that the presence of rotation which forces geostrophic adjustment does not negate the direct response of a hemispheric scale of systematic mass transport, as has been presumed from isobaric studies.

In the author's view, the second question concerning trust of increased resolution and more robust parameterization lacks support in that the complexities of modeling and understanding the interplay of the hydrologic and chemical constituents including their impact of the radiative stream of entropy into and from the system constitutes a formidable barrier. This barrier will not be overcome without recognition of the importance of the internal sources and sinks of entropy in relation to the selective

absorption and emission by the radiatively active constituents and the need to ensure accuracies in the simulation of reversibility. There is the relevant consideration that positive definite physical sources of entropy by heat diffusion and viscous dissipation do not preclude energy conservation locally since in this case the organized energy locally degrades towards uniformity of internal energy. As such, ensuring energy conservation numerically must be distinguished from the issues of reversibility and the aphysical sources of entropy that stem from the limitations of discrete and spectrally truncated numerics and the imperfections of parameterizations. Very simply consider that the organized covariance of entropy sources and sinks with warm and cold temperatures relative to entropy surfaces expands the phase space of the reversible component of total energy against the contraction from positive definite sources of entropy from heat diffusion, kinetic energy dissipation and aphysical sources that abound in a discrete or spectrally truncated model (Johnson 1989, 1997 and 2000). The kinetic energy is maintained against viscous dissipation through the reversible processes of pressure work associated with the volume expansion and compression that occurs within the ascending and descending trajectories embedded in the equatorward and poleward branches of the isentropic Hadley circulation. Then apart from the current difficulties of simulating precipitation and cloudiness both of which are linked with entropy sources and sinks, there is the emerging challenge of including key chemical processes in global and regional models. The complexities introduced by the large number of chemical constituents, chemical families and the need to ensure accurate simulations of the relative concentrations for determining chemical reactions are manifold. Here, accuracy in specification of the entropy structure is of first order importance. Furthermore, the matter of aqueous chemistry together with entropy comes to the forefront in dealing with hydroxyls, sulfate and nitrogen compounds and resulting forms of acid precipitation in relation to advancing the accuracies needed to simulate the hydrologic and chemical dimensions of the water planet.

3. THE MOTIVATION TO DEVELOP ISENTROPIC MODELS FOR WEATHER AND CLIMATE

For my students and colleagues who were involved in isentropic analyses and diagnostics of weather and planetary scale phenomena at the University of Wisconsin for some forty years, there was always the fascination of the interesting insights gained from viewing the relations between the hyberbaroclinicity beneath jet stream maxima, ascending and descending trajectories of air including frontogenesis and deformation fields as waves amplified through scale interaction and baroclinic modes. There was the fascination of the three dimensional structures of cold and warm fronts that evolve with time during the occlusion of cyclones. Since the evolving nature of these phenomena and others occurs largely through isentropic motion and thus conservation of either dry or moist entropy, these phenomena were particularly interesting to diagnose followed by using isentropic models to gain insight into the underlying physics and dynamics of the various processes involved with baroclinic amplification and geostrophic modes of transport of mass, momentum, energy and entropy. In many ways, the complexities encountered were the manifestation of slant wise convection in a thin atmosphere (Hide and Mason 1975), that were in actuality embedded chaotic components of Shaw's

thermally forced isentropic meridional circulations.

These early diagnostics included studies of the differences in the stages of extratropical formation, maturation and decay utilizing the concepts of mass, angular momentum of storms and the energetics of open systems (Johnson 1970; Johnson and Downey 1975a, 1975b, 1976 and 1982). Following my discussions with Sverre Petterssen at the 1969 London Conference on the General Circulation, Professor Petersen visited the University of Wisconsin annually in the early 70's. During these month long visits, he shared insights from his extended studies of extratropical cyclones. He enjoyed commenting that extratropical cyclones were borne in a variety of ways, but in their death throes through occlusion, all appeared remarkable similar. He also enjoyed noting that if the origins of extratropical cyclones were from perturbations, the perturbations were formidable in extent and magnitude.

As a consequence of the influence of Lyle Horn, my major professor, early work with John Dutton and a later link in 1965 with Ed Danielsen and Frank Sechrist established through visits to the Pennsylvania State University, isentropic analysis efforts were established, or should I say re-established. Ed Danielsen was a key instructor in three quarters of classroom instruction in synoptics at the University of Washington in 1952-53 where I was initiated into meteorology as a student sponsored by the Air Force. In any accounting of the development of isentropic perspectives, Ed Danielsen must be acknowledged not only for his unique scientific contributions but his impact at Penn State and NCAR in carrying on with isentropic studies that were furthered through the studies by Dennis Deaven, Frank Sechrist, Rainer Bleck, and others. He was a key individual in ensuring a legacy devoted to isentropic diagnostics and modeling and was instrumental in the development of NASA's focus on the stratosphere circulation and chemistry.

Later during the 1968-69 year's visit at Penn State, friendships and common interest in isentropic analysis and modeling were developed with John Hovermale and John Cahir. Shortly afterward when John Hovermale re-joined NMC, these friendships and connections led to the establishment of the National Cyclone Workshop through efforts with John Hovermale and the blessing of Fred Shuman and Frank Eden of NSF. Wash (1978) carried out diagnostic studies of cyclones numerically simulated by NMC's Shuman-Hovermale model while Czarnetzki (1992) and Zapotocny (1990) followed later with studies of NMC's Eta Model. Preceding these diagnostic studies, Anthes (1970) and Gallimore (1973) developed numerical models of the thermally forced circulations based on azmithually and zonally averaged diagnostics of the differential heating occurring within hurricanes and the zonally averaged circulation, respectively. At about the same time Gall (1972) developed an early version of the UW channel model to simulate the propagation of a jet steak with precipitation embedded along the supporting baroclinic frontal structure. This channel model was further developed by Uccellini (1977) to study the development of favorable conditions for severe convection within the indirect circulation that is intrinsic to the propagation of jet streaks (Uccellini et al. 1979). Later Black (1984) included moist physics in a study of the pseudo geostrophic concept originally suggested by Rossby. In developing and employing isentropic models in these earlier years, the motivation was to address

scientific issues. Many of these efforts involved studies of the impact of latent heat on the development, maturation and even decay of phenomena.

About 1990 the thrust of my students and colleagues turned seriously to the study of whether weather and climate could be successfully simulated with hybrid isentropic models in conjunction with the issue of whether or not models expressed in isentropic coordinates would lead to improvements in the simulation of the atmosphere's hydrologic cycle. The advances that were made in the modeling of medium range weather prediction and data assimilation during and following the Global Weather Experiment were extraordinary (Summary of the Proceedings of the First National Workshop on the Global Weather Experiment, 1986.) However, a major disappointment was the limited progress in the simulation of the hydrologic components of the atmospheric system, in particular water vapor transport, precipitation, cloudiness, etc. There of course are the difficulties of gaining accurate observations of the water substances needed for initial conditions, the inherent complications that many of the scales at which condensation/evaporation occur which in the free atmosphere are frequently subscale to the resolution of the model and thus must be parameterized. Then there is the difficulty of accurately simulating the surface energy balance in dealing with partitioning what fraction of the incoming solar energy leads to sensible heating of the atmosphere as opposed to increasing the latent energy in the planetary boundary layer. Even apart from these complications, modeling atmospheric transport of water substances in isentropic coordinates is attractive in that to a first order approximation the coordinate surfaces within the free atmosphere are material surfaces.

3.1 Global Hybrid Isentropic Coordinate Modeling at the University of Wisconsin

Utilizing the heritage of the channel models expressed in spherical coordinates, model development in the 90's at the UW proceeded through a hierarchy of tests employing isentropic and sigma coordinates, first with the channel models and then with the full fledged global climate model now being utilized (Pierce et al. 1991; Zapotocny et al. 1991; Johnson et al. 1993; Zapotocny et al. 1993, 1994, 1996, 1997a, 1997b; Johnson and Yuan 1998; Reames and Zapotocny 1999a, 1999b; Johnson et al. 2000, 2002; Schaack et al. 2004). The companion sigma coordinate model simultaneously developed provides checks and balances on simulated structure and is still used to ascertain the impact of the vertical coordinate in the numerical simulation of both weather and climate (Zapotocny et al. 1993, 1994; Reames and Zapotocny 1999a and b). Model development has entailed studies of a wide variety of numerics employing both Eulerian and semi-Lagrangian numerics (Reames and Zapotocny 1999a and b) and different algorithms for boundary layer and dry and moist convective parameterizations migrated from NASA's GEOS Model, NCAR's CCM's and now NCEP's Global Forecast System.

Given the difficulties of modeling physical and dynamical processes at the earth atmosphere interface, there is now common agreement that to optimize accuracy of hybrid isentropic models, the PBL needs to be expressed in sigma coordinates at and near the earth surface, in a generalized coordinate above the PBL which provides for the transition from sigma to isentropic coordinates within the troposphere followed ideally by expression

solely in isentropic coordinates. For the model to be explicitly specified in isentropic coordinates, the potential temperature of the lower boundary of the isentropic domain as a closed undulating surface needs to exceed the value of any potential temperature observed at the earth's surface, a condition which is usually determined by temperature over Tibet in the summertime. Overall the results have documented realistic weather and climate simulations for both mesoscale and global models.

3.2 The Current UW Hybrid Model

The early global UW Hybrid $\theta - \sigma$ Model consisted of a PBL expressed in sigma coordinates and a discrete interface between the isentropic and sigma domains, above which the free atmosphere was expressed in isentropic coordinates. Early studies included assessment of accuracies in the simulation of long range transport of inert atmospheric constituents and conservative properties including stratospheric tropospheric exchange of potential vorticity and proxy ozone within the Southern Hemispheric circumpolar vortex. More recent studies have focused on the development of the UW $\theta - \eta$ Model with continuous transition from sigma to isentropic coordinates from the upper boundary of its sigma coordinate PBL to the 336 K isentropic surface which serves as the interface surface between the transition domain and the isentropic domain. This model has been employed in the successful simulation of weather and climate, the details of which are presented in Schaack et al. (2004) and available at www.ssec.wisc.edu/theta. The Model has also been joined with the NASA Langley chemistry model and successful experiments have been carried out in air quality simulations in support of NASA field campaigns. (Pierce et al. 2003).

The current UW θ–η model is a grid point model employing flux form piecewise parabolic method (PPM) numerics. The PPM scheme is a finite volume scheme capable of highly accurate advection both in the vicinity of sharp gradients and smooth flows. The monotinicity constraint employed in the scheme ensures the solutions remain free of spurious oscillations. Fields such as water vapor and mass within isentropic layers remain positive definite during integration.

The time integration is carried out with an explicit forward – backward scheme Fourier filtering is applied at high latitudes to overcome an undesirable restriction on the time step. An implicit formulation of fourth-order diffusion is applied to the wind components and specific humidity throughout the model domain, mass in the isentropic domain, potential temperature in the η domain and surface pressure.

The base UW θ–η model used in a recent 14 year climate simulation (Schaack et al. 2004) incorporates the full suite of NCAR's CCM3 physical parameterizations including radiation, moist convection, vertical diffusion, gravity wave drag, PBL scheme, surface fluxes, etc. The CCM3 land-surface model and OpenMP multi-taking capabilities have also been incorporated into the UW θ–η model.

3.3 Assessment of Numerical Accuracies

As a means to study the relative capabilities of models expressed in different coordinate systems and different numerics to ensure accuracies in the simulation of reversibility, 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 (Benjamin et al. 2004a).

In two earlier studies, a series of nine global simulations of paired values of equivalent potential temperature θ_e and it counterpart trace $t\theta_e$ were completed in which various versions of CCM2 and 3 --- mixed Eulerian spectral and semi-Lagrangian numerics, all Eulerian spectral numerics, all semi-Lagrangian numerics, all expressed in sigma coordinates --- were compared with the UW $\theta - \sigma$ grid point model (Johnson et al. 2000, 2002). Employing an analysis of variance of the differences of paired values partitioned into horizontal, vertical and global components, large bias and random errors were identified in the simulation of reversible processes in all of the models except for the UW θ-σ model. The structure of the zonal, vertical and temporal bias errors varied greatly in the sigma coordinate models. The only distribution of differences that remained unbiased and equilibrated over a ten-day period, in the sense that the distribution of pure errors remained statistically stationary, was from the simulation by the UW θ-σ model. In addition, Johnson et al. (2002) established that the equilibrating triangle form of the probability density functions (pdfs) for the pure error differences indicates the optimum numerical accuracy attainable in that the inferred distribution of numerical errors for θ_e and $t\theta_e$ were necessarily bounded and uniform. As evidence of the difficulties of NCAR's CCMs to ensure conservation of moist entropy, the results in Table 1 have been extracted from the Johnson et al. (2002) study of "Entropy, Numerical Uncertainties and Modeling of Hydrologic Processes: Part B" (see Johnson et al. 2002 for detailed discussion of the methodology and results).

For an analysis of variance, the grid point differences $(\theta_e - t\theta_e)$ between the simulated θ_e by the governing equations of mass, enthalpy or dry entropy, water vapor and cloud water and the proxy $t\theta_e$ as simulated by an appropriate continuity equation are summed and squared over a 10 day period. Thus the total sums of squares of differences $S_G(\delta)$ from all grid points in the far right column are a quadratic measure of numerical error which has been partitioned through an analysis of variance into three components; the sum of the squared deviations of differences from the horizontal mean difference $S_G(\delta^*)$, the sum of squared deviations of the horizontal mean difference from the global mean difference $S_G(\hat{\delta}^*)$ and the square of the global mean difference $S_G(\hat{\hat{\delta}})$. The quantities in the parentheses in Table 1 are the square root of the variances expressed in degrees K. As such these numbers estimate the standard deviation of the pure error difference for all grid points in the 10 day simulation and thus represent a measure of each model's numerical accuracy in simulating reversibility.

Included in Table 1 are more recent results from utilizing the concept of pure error differences to assess numerical accuracies in an NCEP Global Forecast

Model T62 and the UW $\theta - \eta$ Model. In these preliminary tests for the NCEP Global Model with horizontal resolution T62 and 28 layers, pure error differences were determined for the potential temperature θ minus its trace $t\theta$ with physics removed and then for equivalent potential temperature θ_e minus $t\theta_e$ with full physics included. Interestingly the standard deviation of 5.65 K for θ_e with full physics was comparable in value with those from CCM3/2 and CCM (all spectral), both without physics. Here the increased resolution of the GSF at T62 over the CCMs at T42 may account for the comparable values, given that one would expect higher values for GFS T62 given the inclusion of full physics. The comparison of the standard deviation of 3.37 K for θ without physics with 5.65 K for θ_e with full physics suggests that inaccuracies from numerics and physics are not substantial in magnitude.

Table 1: Results from analysis of variance globally for the differences of equivalent potential temperature minus its trace (θ_e-$t\theta_e$) and three components at day 10. Units of variance are the square of Kelvin temperature (K^2). Included is one experiment from the NCEP GSF T62 in which the difference is potential temperature minus trace $(\theta - t\theta)$. Units of quantity in parenthesis as the square root of the variance (standard deviation) are Kelvin temperature ($\pm$ K).

	$S_G(\delta^*)$	$S_G(\hat{\delta}^*)$	$S_G(\hat{\hat{\delta}})$	$S_G(\delta)$
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)

Now note the far right column of Table 1 reveals the estimate of the standard deviation of pure error differences for all grid points at day 10 for the UW $\theta-\eta$ model with PPM numerics is 0.34 K compared to 5.29 K, 5.29 K and 15.27 K for the CCM2 all spectral, CCM2/3 mixed and the standard CCM3 experiments all run without physics, but with explicit simulations of cloud condensation/evaporation and embedded diabatic processes of latent heating/cooling. While the earlier hybrid UW $\theta-\sigma$ model with a standard deviation of 1.03 K excelled in transporting dry and moist entropy and ensuring appropriate conservation relative to CCMs, the accuracies with the current UW $\theta-\eta$ model of 0.40 K with Van Leer numerics and 0.34 K with PPM numerics both without physics are even more striking. Finally the standard deviation of 0.75 K for the UW $\theta-\eta$ model with inclusion of moist convective parameterization substantiates the long held trust that employing isentropic coordinates would lead to increased accuracies in the modeling of hydrologic processes. See Schaack et al. (2004) for details.

Since the earlier comparisons with NCAR's CCM were completed several years ago, the development and application of global UW $\theta-\eta$ model in which the vertical coordinate smoothly transitions from terrain following at the earth's surface to isentropic coordinates in the middle to upper troposphere has been emphasized. Relative to the UW $\theta-\eta$ model, the vertical structure of the UW $\theta-\eta$ model reduces the complexity of the model, provides for computational efficiency and ensures a structure that is well suited to application of data assimilation techniques, higher order numerical schemes and massively parallel computing platforms. Benjamin et al. (2004a) also found the simulation of moist reversible processes to be much more accurate in the NOAA Rapid Update Cycle (RUC) hybrid $\theta-\eta$ model than in the RUC σ model.

These experiments document that the UW $\theta-\eta$ model appropriately conserves dry and moist entropy to a high degree of accuracy during transport and maintains a high degree of accuracy in the simulation of reversible processes within the atmosphere's hydrologic cycle involving condensation, evaporation and transport of clouds relative to the accuracies achieved with models employing sigma coordinates. Results for the UW $\theta-\eta$ model coordinate document that the minor systematic errors in simulation of reversible processes that develop from the discrete interface between the sigma and isentropic domains in the UW $\theta-\eta$ model were eliminated (Johnson et al. 2002).

3.4 A Contrast of Model Coordinate Representation of Isentropic Structure

The following meridional cross sections in Figures 1 and 2 present a snap shot comparison of model coordinate systems for the UW θ-η Model and a sigma coordinate representation of the potential temperature distribution between the earth's surface and 50 hPa along 104º E longitude for day 235 (early August) from a 14 year climate simulation by the UW θ-η Model. Horizontal resolution of the hybrid model simulation was 2.8125º by 2.8125º, while the vertical resolution was 28 model layers, one for the surface layer, 13 for the transition domain and 14 for the isentropic domain.

In Figure 1 the isentropes are dashed red while the model surfaces are solid black.

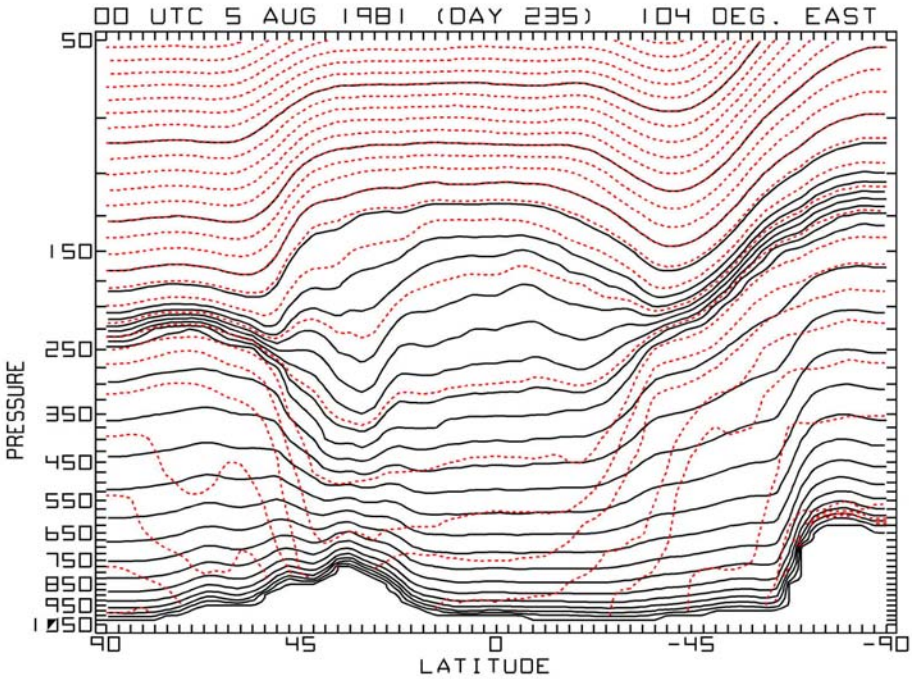

Fig. 1 Meridional cross section between the earth's surface and 50 hPa of UW $\theta - \eta$ model quasi-horizontal surfaces (black), and potential temperature (dashed red) along 104° E longitude for day 235 (early August) of a 14 year climate simulation. Model coordinates at and above 336 K are isentropic surfaces. Potential temperatures are plotted at 10 K resolution.

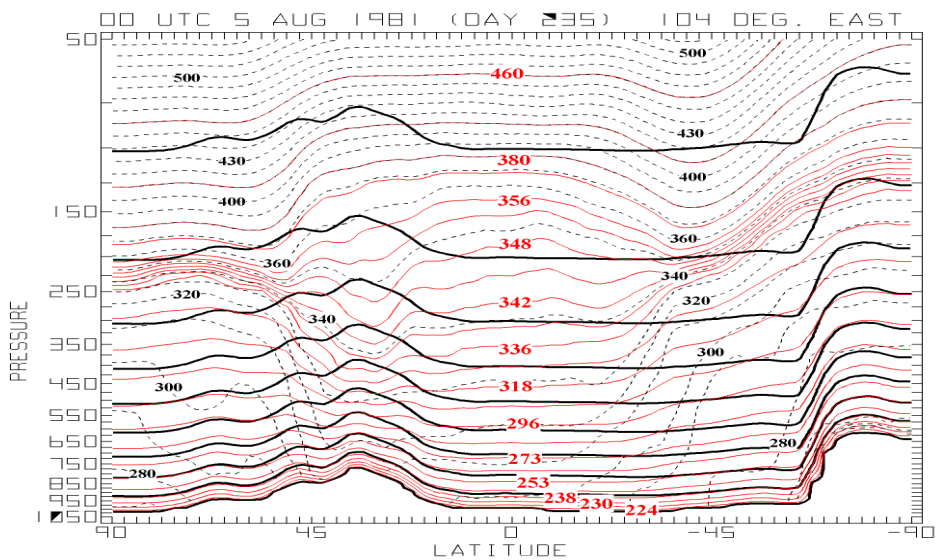

Fig. 2. Meridional cross section between the earth's surface and 50 hPa of UWθ–η model quasi-horizontal surfaces (red), potential temperature (K, dashed) and sigma surfaces (thick black) along 104° E longitude for day 235 (early August) of the climate simulation. Model coordinates at and above 336 K are isentropic surfaces. The units of the vertical coordinate below the isentropic domain are expressed as potential temperature (K) to facilitate the identification of isentropic surfaces within the upper domain as model coordinates even though such a designation for the vertical coordinate in the lower and middle domains has no immediate relation with potential temperature. Potential temperatures are plotted at 10 K resolution and sigma surfaces at 0.1 resolution.

Note in Figure 1 that the model surfaces transition gradually from being coincident with sigma surfaces in the PBL to being coincident with isentropic surfaces in the mid to upper troposphere. In Figure 2, the isentropes are dashed black, sigma coordinate surfaces are solid black and the Eta coordinates of the UW θ-η Model are red. The units of the vertical coordinate below the isentropic domain are expressed as potential temperature (K) to facilitate the identification of isentropic surfaces within the upper domain as model coordinates even though such a designation for the vertical coordinate in the lower and middle domains has no immediate relation with potential temperature. Potential temperatures are plotted at 10 K resolution and sigma surfaces at 0.1 resolution.

The effect of orography on sigma coordinates, which extends throughout the entire vertical structure is quite evident in Figure 2. Of particular interest are the out of phase relation of the curvature and structure of the sigma coordinates in the upper troposphere over the orography of southeastern Asia during the summer monsoon and the more or less perpendicular intersections of the sigma coordinates with the isentropes in baroclinic regions of both the stratosphere and upper troposphere.

The one to one correspondence of the Eta coordinates in the UW θ-η Model in the isentropic domain is evident in both Figures 1 and 2. Since the surface domain of the UW hybrid model is scaled in sigma coordinates, there is a one to one correspondence between sigma and hybrid model surfaces for representing processes within the PBL. The blending of the Eta coordinates in the transition domain from sigma in the PBL to isentropic surfaces at 336 K is determined by the scaling of the hydrostatic pressure from the lower interface boundary of the surface domain to the upper interface boundary at 336K. Inspection provides insight into why hybrid coordinate surfaces which blend into isentropic surfaces with increase of height leads to increased accuracies in the simulation of quasi-horizontal transport of atmospheric properties. Such blending with eventual transition into isentropic coordinates is essential for the accurate simulation of stratospheric/tropospheric exchange of potential vorticity and other atmospheric constituents. Note the complexity of the isentropic structure of the tropopause region over extratropical and polar regions and the sharp transition that occurs between extratropical and subtropical latitudes. At this point in time, no single strategy has emerged that identifies an optimum means to define the transition from sigma to isentropic coordinates. There are many different functions to consider, which for now remain subjects of investigation among those engaged in the development and application of hybrid isentropic models. However, the one utilized in the UW θ-η Model is remarkable for its simplicity.

The meridional cross section in Figure 3 presents the corresponding cross section of the potential temperature distribution between the earth's surface and 50 hPa along 104º E longitude for day 235 (early August) of a 14 year climate simulation of potential temperature simulated by CCM3, which utilizes a hybrid sigma isobaric coordinate system. In the cross sections, the isentropes are dashed red, hybrid sigma isobaric coordinate surfaces are solid turquoise. While the effects of orography on the model coordinate surface are reduced in the upper troposphere and stratosphere, there are substantial intersections of model coordinate surfaces

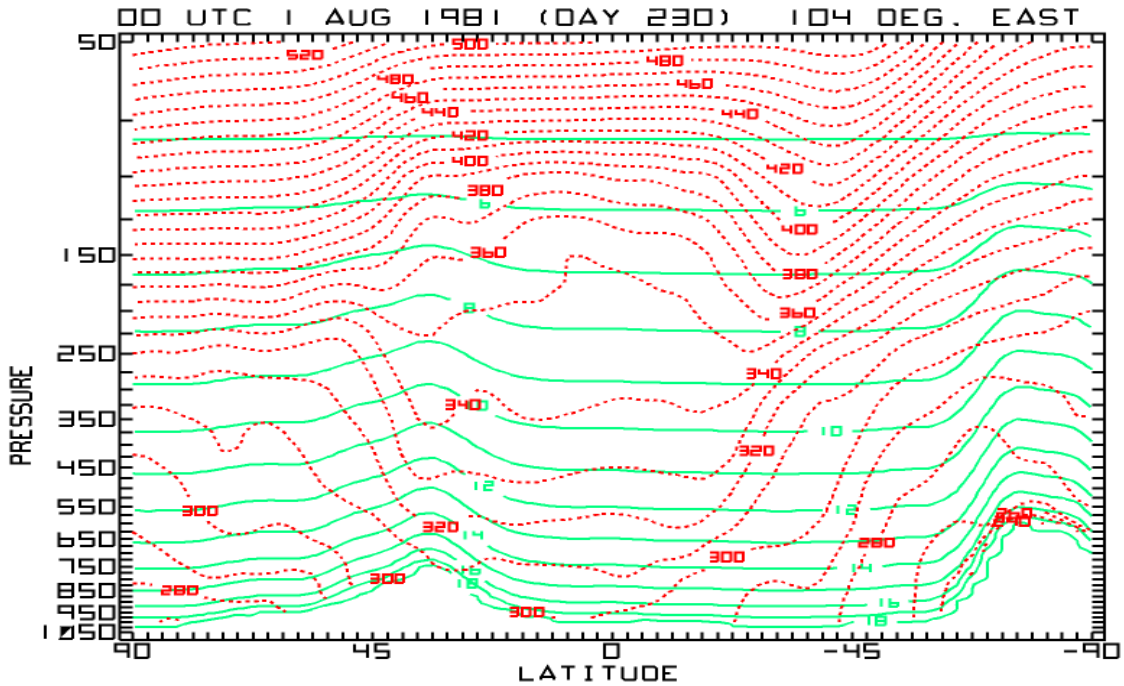

Fig. 3 Meridional cross section between the earth's surface and 50 hPa of the potential temperature distribution between the earth's surface and 50 hPa along 104° E longitude for day 235 (early August) of a 14 year climate simulation of potential temperature simulated by CCM3, which utilizes a hybrid sigma isobaric coordinate system. The isentropes are dashed red, and hybrid sigma isobaric coordinate surfaces are solid turquoise.

with potential temperature throughout the representation. Such intersections over extended regions pose difficulties in ensuring accuracies in simulation of reversibility and appropriate conservation of dry and moist entropies.

The full implications with respect to the increase of accuracies in the transport of water substances, clouds, trace and chemical constituents that stem from the correspondence of atmospheric isentropic structure with the coordinate surfaces of hybrid isentropic models versus sigma coordinate models remains to be determined. All models have a predictability limit, whether for weather or climate. A major part of the limit stems from the inadequacies of models to realistically simulate the thermodynamic processes associated with the hydrologic dimensions of weather and climate.

In this regard there is already a community of scientists developing hybrid isentropic models for the atmosphere and planetary atmospheres and hybrid isopycnic models for the ocean. This group of scientists with common and broad interests has come together for two hybrid isentropic modeling workshops, the first at the University of Wisconsin in August 1999 and the second at the University of Louisville in April 2002. While the author has failed to reference and acknowledge the noteworthy contributions by many of these individuals, the author trusts that his colleagues in these efforts will understand and not think unkindly for this failure. In an effort to increase interest in these matters and encourage participation in

the Third Hybrid Isentropic Workshop to be hosted by NCEP in Washington DC, August 17-19, 2004 with David Randall of Colorado State University chairing the Organizing Committee, the author now includes a brief summary of the events and findings from the 2nd Workshop. At the same time, he expresses his appreciation to his colleagues in these matters for the thoughtful and informative exchanges that he has enjoyed through personal interactions at the workshops as well as other occasions.

Wrap Up Summary for the 2nd Hybrid Isentropic Modeling Workshop Held at the University of Louisville Louisville, Kentucky, April 18-20, 2002

On behalf of the participants and organizing committee, David Randall, Akio Arakawa and Donald Johnson, we wish to express our sincere appreciation to Timothy Dowling, Thomas Hanley, Dean of Engineering, and their colleagues for hosting the workshop within the University of Louisville Rausch Planetarium including the pleasant luncheons at the University Club. The Planetarium provided an interesting and very pleasant environment for presentations and discussions.

The organizing committee also wishes to express appreciation to Louis Uccellini for his overview of where NCEP is headed and his challenge to the Hybrid-Isentropic modeling community. We express special appreciation to Chris Davis, who journeyed from NCAR at our request to summarize the status of mesoscale modeling of warm season precipitation and mesoscale convective systems, to Shawn Laatsch for the private showing of Oasis and to Hank Dietz for his presentation regarding latest developments in PC Cluster Supercomputing Solutions for Meteorological Computing Problems. Finally, we express appreciation to all those making presentations and to all who participated.

Overall the presentations revealed progress in the development of hybrid isentropic models for weather and climate ranging from meso through global scales including isopycnic models of the ocean. Among the highlights of the workshop were; descriptions of coupled atmosphere-ocean-land surface models, a planetary boundary layer formulation for hybrid models with emphasis on the diurnal nature of coupling with the free troposphere, decadal integrations with a global hybrid isentropic model, meso-scale atmospheric modeling at 10 to 20 kilometers, non-hydrostatic models including isentropic perspectives of deep convection, fully interactive atmospheric chemistry simulations with a global hybrid isentropic model and embedded non-hydrostatic regional model, progress on the hybridization of the Explicit-Isentropic (EPIC) model for planetary atmospheric simulations and century-scale climate simulations emphasizing CO_2 increase in a coupled atmosphere (sigma) ocean (isopycnic) model.

Considerable attention was given to various numerical methods in dealing with the representation of vertical structure and exchange processes associated with different moist convective parameterization algorithms, the horizontal representation utilizing geodesic and adaptive grids for both the ocean and the atmosphere and the maximization of isentropic representations in hybrid coordinates through utilization of ALE (Arbitrary Lagrangian-Eulerian) techniques in mesoscale atmosphere and global ocean models. While there are remaining challenges to improve the physics and dynamics of hybrid models, the results presented substantiate that there are no

insurmountable hurdles to successful prediction utilizing hybrid isentropic and isopycnic models for weather and climate.

The workshop concluded with the participants deciding to organize and sponsor a third workshop. The aim is to plan for an open meeting format with invitations to the broader scientific community and invited speakers covering an appropriate range of topics regarding hybrid isentropic analysis and modeling.

Again we express our appreciation to Timothy Dowling and his colleagues at the Comparative Planetary Laboratory and the University of Louisville for the exceptional pleasant surroundings and arrangements and to all those who participated.

Prepared by Donald R. Johnson, April 30, 2002.

4. THE COMMON CHALLENGE

For those who focus on the capabilities of global models to simulate monsoons, regional climate and medium range weather prediction and those who recognize the fundamental importance of water, moist thermodynamic processes, cloudiness and the related impact of clouds on both solar and infrared radiation on surface energy exchange, there should be common agreement that the scientific challenges in modeling weather and climate are one and the same. If not viewed as the same, they must be recognized as intimately intertwined. While the focus on carbon and global warming lies somewhat outside of the focus on medium range weather and seasonal climate forecasts, there is the emerging relevance of aerosols, the biosphere and related biogeochemical processes, diurnally varying land and surface boundary conditions and other processes being brought to the forefront that links all including the carbon cycle. Here, advancing accuracies in the simulation of weather and climate regionally and globally serves the nation's larger interests.

5. MODEL DIVERSITY AND DIAGNOSTICS IN RELATION TO THE EARTH SYSTEM MODELING FRAMEWORK (ESMF)

The following is a draft statement of principle concerning model diversity and the potential of diagnostics for model development utilizing the Earth System Modeling Framework (ESMF):

"Within the context of an umbrella for model diagnostics and validation, lets us strive to develop an assessment strategy and capability for advancing global models and the underlying science that is independent of the vested interests and developers of model, whether they be in the government, academic or private sectors. At the same time, the effort should also ensure the mutual interests and activities of the major centers and their scientists in a community effort that isolates deficiencies and shortcomings of global models while advancing modeling accuracies and understanding of global and regional modeling of weather and climate".

Underlying Considerations Concerning the ESMF

The following are several underlying considerations concerning the development of weather and climate models under the unified modeling effort envisaged within the ESMF:

An agreement that "model diversity within a community framework is required for progress in both weather and climate models" is predicated on the premise that no

single model or approach to modeling the weather climate state at this time or in the foreseeable future has achieved the level of accuracy needed for weather and climate prediction.

Strategies should focus on ascertaining the strengths and weaknesses of models in relation to advancing capabilities for weather and climate prediction broadly defined.

The underlying issue is how through collaborative utilization of the ESMF and working partnerships can major modeling centers and the larger scientific community in this county advance understanding and accuracies for weather and climate prediction.

Advancing understanding and prediction of weather and of climate are complementary to each other in implementing an environmental forecasting capability that serves the nation's larger interests.

Within the effort to advance weather and climate prediction for their own purposes and also to mutually complement each other in implementing an environmental forecasting capability, there must be recognition on the part of the science community, theoreticians, modelers, diagnosticians, and operational forecasters that all have a stake and need to contribute to this effort.

The challenge then is how to ensure the active engagement of not only those who were partners in the development of the ESMF, but also how to engage the larger scientific community.

Diagnostic Strategies Appropriate to the Development of Weather and Climate Models

Diagnostics of model simulations, model assimilated data, and observations both in situ and remotely sense are essential to advancing the accuracy of weather and climate models. Diagnostic strategies must include developing meaningful, robust and complementary measures of accuracy and inaccuracies in order to reduce uncertainty. Among these are:

1. Strategies to assess numerical accuracies of global models utilizing assimilated data as initial conditions:

a. Pure error differences of potential temperature, equivalent potential temperature, and potential vorticity in relation to appropriate conservation with and without moist convective parameterization for differing resolutions and with component and full physics included, differing numerics and differing orders of numerical accuracies, etc., examined in the form of scatter diagrams, empirical pdfs and profiles of systematic biases.

b. Global and regional analysis of variance of pure error differences including determination of systematic biases and component variances---zonal, horizontal, vertical and global.

c. Expansion of the variance of the pure differences, say V(g-tg), yields the sum of the variances V(g) and V(tg) minus two times the covariance Cov(g,tg). Since initially by specification, V(g) equals V(tg) and 2Cov(g,tg) is equal to the sum of the two variances, through normalization against initial values the error growth determined by the increase of pure error differences is readily related to the damping/amplification of each field and to the decrease of the integrity between the two fields as the covariance decreases. All three parameters provide relevant information on the relative accuracies of numerics as well

as the impact of parameterizations on the resolved flow as each are added singularly, and in multiple combinations.

c. Temporal and spatial integrity of filamentary transport of trace constituents and conservation of extremum within the vertically, horizontally wind sheared regions of the troposphere and stratosphere utilizing proxy initial state constituent conditions consisting of vertically invariant zonal ring and circular symmetric normal distributions as well as other specified distributions.

d. Integrity of transport of water, chemical and aerosol constituents including appropriate conservation in relation to families of chemical species and their interaction through chemical processes.

2. Validation of global and regional model simulations and also model assimilated data in relation to observed surface, radiosonde, satellite, aircraft and like measurements.

As part of this validation, both model simulated data and model assimilated data are compared against observations to assess how biases in the mean structure and spatial temporal variability of weather and climate models impacts assimilated data. For weather models the validation involves instantaneous and temporal comparisons with in situ and remotely sensed observations to determine forecast error spatially and temporally. For climate models, the validation involves comparison of simulated distributions corresponding with observed distributions; the form and modal nature of the distributions, measures of variation including second and higher order moments, etc. The key thrusts of both are to assess and determine reasons for model drift and resulting biases spatially and temporally for both model simulated and assimilated data relative to the actual atmosphere; --- numerics, filtering, sub grid scale parameterizations, numerical and physical dissipation, selective numerical damping, non linear interactions, orography, deficiencies in resolving scale dependency and diurnal forcing of dry and moist convection including interaction with solar and infrared radiation, etc. Here temporally averaged vertical profiles of diabatic and other processes including vertically integrated distributions of the various simulated processes over different geographical regions provide relevant information for the comparisons.

3. Comparative analyses of the global distribution of proxy water vapor brightness temperatures calculated from model simulated profiles of temperature, pressure and mixing ratio using forward radiance models versus observed satellite brightness temperatures

The comparison of the model's simulated water vapor brightness temperatures as determined by forward irradiance calculations is to assess drift of a model’s simulated water vapor distribution from reality for both weather and climate models. For weather models the comparison involves an instantaneous comparison with the corresponding satellite observation. For climate models, the comparison involves temporally averaged water vapor brightness temperatures as simulated versus corresponding temporally averaged satellite measurements over different seasons, different regions and different periods of simulations.

Similarly the temporally averaged global distribution of a climate model’s simulated upwelling irradiance within spectral intervals critical to the determination of the vertical distributions of temperature and the spatial distributions of other radiatively active constituents should

be compared with the corresponding temporally averaged observed spectral distribution of radiation by satellites.

4. Diagnostics of transport equations in model coordinates, sigma, isentropic, hybrid sigma isobaric, hybrid isentropic sigma coordinates – mass, angular momentum, energy, water vapor, atmospheric constituents, etc.

The following lists capabilities for diagnostics of transport processes that are embodied within the governing equations of weather and climate models. For maximum insight and accuracy in the determination of a model's simulation of the Eulerian components of transport and also Lagrangian sources and sinks of properties, the diagnostics should be carried out in the coordinate system employed in the model. Direct diagnostic comparisons of corresponding global simulations from model to model are only valid in general with integration over the entire vertical extent of a model's atmosphere.

a. Transport components, zonal mean and eddy, temporal standing and transient, combination of zonal and temporal components.

b. Lagrangian sources/sinks computed directly or estimated as a residual from evaluation of the transport equation for a property.

c. State structure, vertical averages, zonal averages, vertical-zonal averages, global averages, averages over regional domains, averages over arbitrary space and time.

d. Water vapor – P-E (precipitation minus evaporation), residence times, global, tropics, extratropics, continental domains, ocean basins, arbitrary regions.

Within these comparisons, it is essential to recognize the condition that the individual terms of the Eulerian expansion of the Lagrangian source of atmospheric properties are not invariant, that is, the tendency and divergence as simulated differs from model to model depending on the particular coordinate system employed in the representation of the governing equations. In addition, recognition must be made that the transfers of momentum and of energy across temporally and spatially varying inclined quasi-horizontal coordinate surfaces by pressure viscous stresses and by work, respectively, are coordinate dependent processes.

In the comparison of the vertical integral of the governing equations among global simulations for both weather and climate, efforts should be made to ascertain a given model's capabilities to globally conserve mass, momentum, total energy [kinetic, gravitational potential, and internal (including latent energy of phase changes)] and other constituents in relation to boundary fluxes. Discrepancies between the vertical integral of the interior transport of properties and the boundary fluxes are likely sources of bias and random errors within the model simulated atmosphere.

Beside the potential sources of error just noted, there is the issue of a model's capability to simulate reversibility of thermodynamic processes associated with transformations among the various components of total energy that is demanded from entropy principles in terms of dry and moist adiabatic processes internal to the atmosphere.

5. Three-dimensional distributions of the Lagrangian sources of entropy expressed as potential temperature change in degrees per day or specific heat addition determined from diagnostics employing the isentropic mass continuity equation.

a. Vertically averaged throughout the atmosphere

b. Layered and vertically averaged over specific layers

c. Zonal and temporally zonal averaged

d. Vertical profiles

e. Regionally averaged vertical profiles over continents, ocean basins, and subdomains of continents and oceans representative of different climate regimes

f. Arbitrary time and space domains or combinations thereof

6. Compare estimates of the Lagrangian sources of entropy diagnosed from assimilated data, first guess fields and model predicted heating from medium range, subseasonal and seasonal forecasts in accord with 5 above.

7.Determine rotational/irrotational components of transport of mass, energy, entropy, water vapor and constituent atmospheric properties by layer or arbitrary combination of layers by vertical integration.

One key purpose of this diagnostic transport calculation is to study the role of the temporally averaged mass transport in the long range transport of atmospheric properties in relation to the systematic sources of entropy by differential heating within monsoons. In isentropic coordinates, the systematic transport is global in extent, in other coordinates, the transport being by ageostrophic motion is more or less restricted to the tropics/subtropics.

8. Mean meridional zonally averaged mass circulations and their forcing in accord with Eliassen's concepts as determined for isobaric, sigma, isentropic, model, and hybrid model coordinates with partitioning into geostrophic and ageostrophic components

9. Additional considerations

While the emphasis has been on carrying out diagnostic assessments in the coordinate system of a model to preclude vertical interpolation errors, the generalized diagnostic capabilities described heretofore include the capability to interpolate the state structure of fields from one model coordinate system to another, as well as the capability to interpolate to isobaric coordinates. Traditionally diagnostic studies of the general circulation have been conducted in isobaric coordinates, and as such the 4DDA data sets from reanalysis and assimilation for medium range weather prediction include expression in isobaric coordinates to facilitate comparisons. Such comparisons are needed and deserve to be continued. Certain difficulties emerge however in determination of the accuracies of a given model. The most obvious is the difficulty that state variables and boundary exchange processes of the various forms of energy and atmospheric constituents as well as the transfer of momentum by pressure viscous stresses at the earth/atmosphere interface are not accurately specified by the isobaric representation. Neither are the state structure and energy fluxes at the model's upper boundary prescribed adequately. Then there are the difficulties that vertical interpolation errors negate the accuracies needed for assessment of pure error in the determination of conservation of moist and

dry entropies. For details concerning the generalized form of transport equations appropriate for the governing equations of atmospheric models discussed herein, see Johnson (1980).

Please recognize that the diagnostics listed above are not a complete set, thus additional listings remain to be added by others and also developed in the future.

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The author gratefully acknowledges the many individuals too numerous to name who have collaborated and contributed to the studies and efforts of the past 40 years that are summarized herein. The names of many are evident from the references to the thesis studies of former students and to fellow scientists. I have purposely included thesis titles in order to acknowledge their accomplishments. Later publications which followed from the thesis research are listed in the references. Unfortunately many remain unnamed simply because of lack of space and time in the effort to finish, most certainly not because of a lack of appreciation and enjoyment of their efforts as well. Students through research and discussions are the stimulus and life blood of creativity that professors enjoy. One who must be acknowledged is Judy Mohr for her technical typing assistance and secretarial support for more that 20 years.

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