A Study of the Effect of Synoptic Scale Processes in GCM Modelling

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by

Gerald F. Herman
Principal Investigator*
Department of Meteorology
College of Letters and Science

*Current affiliation: Merrill Lynch Capital Markets, N.Y., N.Y. 10281

1. Overview of the Grant.

In 1977 NASA's Goddard Institute for Space Studies and the Goddard Space Flight Center agreed with the Department of Meteorology at the University of Wisconsin to establish a position in the Department entitled Faculty Research Associate. The objective for establishing this position was to foster collaborative research between the University of Wisconsin and the Global Modeling Groups at NASA. Gerald Herman held this position in the Meteorology Department from 1977 to 1981 under a separate NASA Grant, NSG-5152. The current NASA Grant, NSG-5223 was originally proposed to support the actual costs of the research of Herman and his staff on subjects of interest and importance to the modeling effort at NASA. The research continued at Wisconsin for several years after the Faculty Research Associate program ended, and continued until Herman left the Meteorology Department in 1987.

The general objective of the research under this grant was to help the modeling groups at NASA develop better weather forecasting and general circulation models for their own activities relating to the meteorological applications of satellite data. The focus was on the so-called physical processes that were being simulated by the models: Radiative effects and latent heat release associated with clouds; orographic influences; and heat transfer at the ocean and ice surfaces. The diversity of the research activities over the lifetime of the grant reflects the fact that our research initiatives remained closely tied to the immediate needs of the modeling work at NASA. However, all of the research is unified by the central objective of improving model performance through a better understanding and representation of the physical processes.

GCM

2. Summary of Scientific Objectives and Results.

This presentation of the research results is organized according to the modeling problem that motivated the work. This subject-based approach integrates results that were obtained at various periods during the history of the grant.

A. Inferences about Diabatic Heating from GCM assimilations.

While reviewing the results of the pre-Global Weather Experiment Data Systems Test (DST) in 1977, Professor Yale Mintz, then a consultant to NASA, suggested that the data assimilation part of the numerical weather forecasting cycle could provide potentially valuable data for diagnostic studies, particularly in data sparse areas. Mintz, however, cautioned that this assimilated data was only a proxy for real atmospheric data since, first, it was derived from an imperfect model, and second, a new class of problems regarding the dynamical consistency of the data would arise as a consequence of the data insertion process. The assimilated data might always be an untrustworthy hybrid of actually-occurring atmospheric processes, model deficiencies, and initialization shocks. The fundamental research issued was to determine whether, at the margin, the assimilated data could provide new information about the true behavior of the atmosphere.

Our initial investigation of this subject was based on the data from the Data Systems Test, and was an attempt to deduce the role of diabatic heating North Atlantic Cyclogenesis and in the global heat budget.

i. Heat balance statistics from GCM assimilations. This work contributed to the development of the GCM as a diagnostic tool. The GLAS model was run in an assimilation mode for the duration of the wintertime Data Systems Test (DST), and model-generated fields of vertical velocity and diabatic heating rates were obtained shortly after the insertion of conventional meteorological observations. The sampling took place 6 and 9 hours after the data insertion, a time period over which the model forecast would not have departed significantly from the actual state of the atmosphere, particularly in data rich regions. The general circulation statistics thus produced were viewed as observationally-constrained model diagnostics, or alternatively, as model-generated atmospheric diagnostics.

A complete description of the analysis appears in Schubert and Herman (1981).

Salient features of the February, 1976 analysis included the following: Maximum rising motion in the mean vertical velocity field at 500 mb over South America, south central Africa, Australia, and the Indonesian archipelago. These regions were also characterized by large values of diabatic heating due to convective latent heat release. The cyclogenetically active regions over the north Atlantic and north Pacific oceans were characterized by maxima in latent heat release due to supersaturation cloud formation, and also maxima in the upward and northward transient eddy heat fluxes. In contrast, the continental west coasts showed a tendency for large downward and southward transient eddy heat fluxes.

The method developed had general applicability, and was useful in producing diagnostics from the FGGE (Global Weather Experiment) data sets. Hopefully, the method will eventually be employed in routine production of observationally-constrained diagnostics so that a long-term (e.g. 5-10 years) climatology of diabatic heating and vertical motion can be assembled.

ii. Dynamics of north Atlantic cyclones. The most useful applications of the DST and FGGE data were actually for case studies, since the short duration of the data collecting periods precluded the compilation of climatological statistics. We used the diagnostics from the DST assimilation to conduct an investigation into the role of diabatic processes in the development of north Atlantic cyclones. The complete description of this analysis appears Winston (1980).

In brief terms, the analysis investigated the role of diabatic processes in the generation of potential vorticity in six intense north Atlantic cyclonic events during the DST period. Large potential vorticity tendencies were observed in conjunction with each storm, indicating a strong correlation between simulated diabatic heating rates and cyclone intensity. Interactions between the boundary layer and the underlying surface were found to lead to large destruction of potential vorticity within the lower 100 mb of the troposphere. These destructions generally occurred to the rear of the surface cold front, where the greatest air mass modification was expected. Simulated dry convective adjustment and moist convection led to the generation of potential vorticity in the lower troposphere.

These studies confirmed the strong correlation between diabatic heating and cyclone development.

iii. "CAGE"-type Energy Budget Calculations.

The next application of the assimilated data was an attack on a somewhat traditional problem, i.e., the estimation of oceanic heat fluxes as a residual from atmospheric energy budget calculations. This approach, perhaps best exemplified by the work of Oort and Vonder Haar, had always been hampered by the fact that the atmospheric data was the most uncertain in the oceanic regions where it mattered the most. It seemed that the Mintz approach might prove the most useful for this problem.

The problem was tackled in the MS thesis research of Michael Alexander. The winter and summer energy balances of the earth-atmosphere system were examined for selected regions distributed around the globe. The column budget technique employed by Oort and Vonder Haar was used to obtain estimates of the atmospheric and terrestrial energy balance. These estimates were employed to determine the accuracy and physical consistency of the budget components and to assess the feasibility of using the column budget method to estimate the meridional ocean heat transport.

In the atmosphere, the net radiation at the top of the column was combined with estimates of the time change in energy storage and flux divergence of energy to obtain the flux through the surface as a residual. This surface flux became the input to the top of the terrestrial budget, and the energy it provided was either stored by the ocean or exported via ocean currents, as the energy stored by land and ice was considered negligible. The net radiation at the top of the atmosphere was generated by the GLA model physics. The GLA level IIIb analysis from the SOPs of the FGGE was used to compute the storage and divergence of energy in the atmosphere. A long term record of NODC oceanographic temperature observations was employed to calculate the ocean heat storage. The flux divergence of energy in the ocean was obtained as a residual from the difference between the surface energy flux and the time rate of change of the ocean heat storage.

Analyses of the budget components provided information about the seasonal circulation of the atmosphere and ocean. A surplus of net radiation at the top of the atmosphere was found for regions located between 35°N - 35°S. Both the oceans and the atmosphere exported significant amounts of energy from the tropics to midlatitudes. During winter between 30° - 60° in both hemispheres, a large quantity of energy (> 200 W m^{-2}) was transferred from the ocean to the atmosphere via fluxes of sensible and latent heat. This energy was supplied by poleward currents and the energy stored in the oceans during the summer. The atmosphere transported the energy to the continental and polar heat sinks. In the summer months, energy imparted from the warm continents to the overlying air was exported to the cooler oceanic regions. This seasonal exchange of energy between the continents and oceans was found to be much stronger in the Northern Hemisphere than in the Southern Hemisphere due to the limited land mass and therefore smaller air-sea contrasts in the Southern Hemisphere.

The flux divergence of energy in the atmosphere was partitioned into four constituents: kinetic, sensible, geopotential and latent energies. The sensible and geopotential energies were greater in magnitude but tended to balance one another. The flux divergence of latent energy also played a significant role in the atmospheric energy balance. A correction applied to conserve mass in the atmospheric column proved essential to obtaining reasonable energy flux divergence estimates. After the correction was incorporated, the energy flux divergence estimates differed by 15-30 W m^{-2} from the results of Swinbank, Bretherton et al. and Alestalo for various regions in the Northern Hemisphere.

The potential sources of uncertainty in the data, GLA model and the column budget method were discussed. Data deficiencies, instrument bias in multiple observing systems, and subgrid-scale processes may have a significant impact on the accuracy of the atmospheric flux divergence of energy and the ocean heat storage. Difficulties faced in using a GCM assimilation system included spurious gravity oscillations and spin-up error caused by data insertion, and potentially inaccurate representation of diabatic processes.

Several experiments were performed to investigate some of the uncertainties in the column budget method, the results of which indicated:

1) Small displacements in the regional boundaries affected all budget components and were shown to alter the flux divergence of energy in the atmosphere and the time tendency of ocean heat storage by as much as 20-30 W m^{-2}.

2) Differences between the atmospheric energy flux divergence computed in sigma and pressure coordinates were found to be less than 20 W m^{-2}. The mass imbalances were of similar magnitude when calculated using the two coordinate systems and thus no advantage was seen for using one system in place of the other.

3) The combined flux of sensible and latent heat across the earth-atmosphere interface was computed as a residual from the atmospheric budget and directly, by employing bulk aerodynamic formulae. On average, the two techniques different by 30 W m^{-2} during both winter and summer. These differences appeared to be randomly distributed.

4) Random errors introduced into the atmospheric variables were compensated for by the mass balance correction, causing a negligible impact (< 5 W m^{-2}) on the atmospheric flux divergence of energy. A 10% decrease in the wind speed over the oceans was shown to have a significant effect on the flux divergence of energy in the atmosphere. The wind biases altered the budget results by more than 20 W m^{-2} for regions in proximity to the polar and subtropical jets.

The oceanic meridional heat flux was obtained using Green's theorem by integrating the heat flux divergence over zonal segments extending the width of the ocean basin. The ocean heat transport was found to be very sensitive to systematic errors, as the integration procedure used to compute heat transport compounds inaccuracies in all the budget terms. The model generated shortwave radiation absorbed at the earth's surface was found to have a positive bias of approximately 25-40 W m^{-2} with the greatest error occurring during the summer months. This error propagated through the budget calculations causing excessive southward heat transport estimates in the Southern Hemisphere in January and February and at all latitudes during the Northern Hemisphere summer.

In the column budget method, the monthly mean ocean heat flux divergence is calculated from the difference between the surface energy flux and the rate of change of ocean heat storage. Through sensitivity experiments and comparisons with other studies, the uncertainty in the net surface flux was estimated to be on the order of 30 W m^{-2}, in agreement with the error evaluation of Hastenrath. The monthly change in heat storage was poorly known, with errors possibly as large as 100 W m^{-2}. Burridge et al. indicated that an error of 10 W m^{-2} or less in the ocean heat flux divergence was necessary to calculate the meridional ocean heat flux divergence was necessary to calculate the meridional ocean heat transport to within a desired accuracy of 20%.

The conclusion of the analysis was that it was not possible to obtain this level of accuracy using the column budget method. This conclusion was also reached by Holopainen and Fortelius and also by Boer.

iv. Grid-scale cloud formation.

The most commonly-used and simplest methods for predicting grid-scale cloudiness in numerical forecasting models have involved statistical relationships between a measure of cloudiness, such as fractional cloudiness, and relative humidity, vertical velocity, and static stability. However, data on the spatial and temporal distributions of these variables have generally not been adequate for the development of the cloud parameterizations. Once again, it was hypothesized that the assimilated data from the GCM, when used in conjunction with independently-derived cloud data, could provide useful statistics. James LeMunyon, as part of his MS thesis work, developed a Cressman-type analysis of cloudiness that was merged with the analyzed humidity and moisture fields to estimate the factors influencing grid-scale cloudiness.

The results of the 72 regression analyses of observed cloudiness and outputs from GCM assimilations were presented for the FGGE SOP-1 period of 5 January 1979 through 31 January 1979. It was found that, with few exceptions, the occurrence of large-scale cloudiness was most highly correlated with relative humidity rather than the other independent variables of vertical motion and static stability. Highest values of r^2 occurred over oceanic regions in the Northern and Southern Hemispheres and land regions at low levels in the tropics. In fact, it was found, based upon the r^2 values, that 850 mb relative humidity in the tropics was correlated more with tropical Cu and Cb clouds that nay other model variable
than any
and cloud type in the experiment.

An examination of the r^2 and coefficient values within and between the sectors indicated that the results were characteristic of the data quality and ambient atmospheric conditions of the sectors. For instance, the vertical motion fields were suspect based upon an independent analysis, and the results showed little correlation between six hourly omega data and cloudiness in the Northern Hemisphere. This was not true using averaged data and low-level cloudiness in the Northern Hemisphere. In two cases r^2 values for omega were actually greater than the values for relative humidity. This was probably due to the occurrence of synoptic-scale vertical motion associated with cloud-producing cyclogenesis.

In the tropics, neither mean nor six hourly omega data produced significant r^2 values, probably due to an absence of synoptic scale organization in the vertical motion fields. The small number of degrees of freedom in the Southern Hemisphere analyses prevented meaningful results from being achieved for the omega and cloud correlations.

Instances of significant r^2 values for static stability did not seem to concentrate in a particular sector or occur when particular cloud type or pressure level data were used in the regression. However, the minus sign on the stability coefficients, indicating a negative correlation between stability and cloudiness, occurred uniquely over land regions in the Northern Hemisphere. In all other cases, the static stability coefficient was positive. Similar to the results with omega, it was assumed that this occurred in association with cyclogenesis over land regions in the Northern Hemisphere.

Based upon the results presented here, we conclude that the ensemble average of micro-scale processes generated by the GLAS GCM provided a realistic diagnosis of synoptic-scale cloudiness. The relationships between model-generated variables and cloudiness were clearly more sophisticated than the threshold-type schemes, especially since more than one variable may often be a significant predictor.

However, the results showed that a cloud parameterization scheme which may be appropriate in the Northern Hemisphere may not be useful in the tropics or Southern Hemisphere because of different cloud types produced by different ambient atmospheric conditions. Likewise, schemes that predicted mid-level clouds over the land may not be appropriate for low-level and convective clouds over the sea. Complete cloud parameterizations schemes will probably require several schemes distinguished by cloud type, pressure level, and geographical location to provide meaningful simulations.

Finally, while the results suggest it may be worthwhile to reexamine GCM cloud parameterization schemes, it should be kept in mind that r^2 values in most cases (especially using six-hourly data) were well below .50. Hence, unless better data or a greater density of grid structure is employed, GCM cloud parameterization schemes, although improved, would still provide only rough approximations of reality.

The above-mentioned caveat concerning the potential impact of the dynamical adjustment to the initial conditions was addressed in a study by Dr. J. Young and his collaborator, J. Jhun. The focus of this study was on the impact of friction on the large-scale dynamical adjustment processes and the application to initialization of such flows. Three mechanisms of motion and mass coupling were found important: direct decay, energy dispersion, and spin-down mass adjustment. Their roles in transient imbalances and initialization techniques were determined for a one-layer model on the f-plane with linear friction. The results depended upon latitude, circulation scale, and type of initial data.

The free modes of frictional decay were derived and compared. Both slow and fast (oscillatory) modes show differential decay with inverse scale dependencies. At large scales the slow mode exhibits "dynamic diffusion" as the pattern spread horizontally decayed.

Three fundamental initial-value problems were solved numerically. They were interpreted in terms of analytic time scales and decomposition into fast and slow behavior. The influence of friction was shown to be dependent on initial data type as well as the relative adjustment time scales.

An exact frictional initialization procedure was developed, based upon the model solutions. The largest differences from traditional frictionless results were found for intermediate scales. In this case, the Ekman mass - motion constraint was retained well, but the use of motion information alone (particularly the divergent component) gave poor results.

The properties of approximate initializations were compared with the exact technique. A new high-order scheme was developed which gave superior results for the decaying modes. Poorest performances were found with large friction and large scales.

B. Atmospheric Variability and Structure.

This component of the research focused on the mechanisms that were responsible for the variability and structure of the atmospheric on a hemispheric scale. Variability and structure are both related to synoptic scale processes through baroclinic and barotropic energy transformations.

The approach to the problem of large-scale variability involved a hybrid of statistical analysis and theoretical modeling.

This long-term research effort to investigate the modes of variability of the atmospheric circulation was completed, and the results have been published in the Journal of the Atmospheric Sciences.

In this work, which represented the Ph.D. thesis research of S.D. Schubert, the observed wintertime intraseasonal variability of the Northern Hemisphere midtropospheric circulation was analyzed using a combined statistical and dynamical approach. The statistical analysis was based upon an empirical orthogonal function (EOF) expansion of the 500 mb streamfunction anomalies, and included a description and interpretation of their dominant modes. The dynamical analysis involved entering these modes into an equivalent barotropic model in an attempt to gain further insight into the important dynamical process governing their behavior. The importance of the terms involving boundary parameterizations was determined from a least squares fit.

Some of the dominant EOF's were found to be associated with the more familiar observed modes of variability. In particular, the first three EOF's exhibited a range of behavior encompassing an index cycle, the Pacific/North American pattern and the North Atlantic oscillation. The fourth and ninth EOF's seemed to be related to some aspects of North Pacific and North Atlantic blocking, respectively. A comparison with spatially and temporally uncorrelated noise suggested that the first twelve principal components (PC's) were significant; however, the limited temporal extent of the data allowed only a marginal resolution of the individual modes. The modeling results suggested that the terms involving the boundary parameterizations, in particular, the orographic term, contributed little to the observed tendency of the PC anomalies. However, it also suggested that orographic-type effects on the anomalies at 500 mb were dominated by a term of similar form involving the advection of mean flow vorticity.

A stability analysis of the zonally asymmetric winter mean flow showed that the mean flow was a potentially important energy source for the dominant EOF's. Together with the results of the model simulation, these findings supported the idea that barotropic instability may be the primary mechanism for producing the observed large scale intraseasonal variability of the Northern Hemisphere circulation.

An analysis of the nonlinear aspects of the model showed that the dominant interactions occurred between the ninth and second principal components. The former was associated with North Atlantic blocking and the latter was associated with fluctuations in the North American east coast jet. The North Atlantic blocking mode was found to be very unstable as a result of the nonlinear interactions between the dominant principal components, which acted to destroy this pattern.

A study of very low order models (without orography) showed that while multiple equilibria were possible, they were generally found for parameters values associated with unrealistically weak dissipation rates and/or unrealistically strong forcing. In the present model the blocking was most likely to occur as a quasi-linear response to the inhomogeneous forcing which entered into the model as a residual calculation due to the fact that the mean flow did not, by itself, satisfy the vorticity equation.

The second part of this investigation dealt with the interaction of orographic forcing and synoptic scale processes. One aspect of this work was the development of a linearized version of the NASA GCM, this based upon a request from Dr. E. Kalnay, then head of the Modeling and Simulation group. This work was carried out by R.B. Pierce as part of his MS and Ph.D. work, and was supported largely by a graduate student researcher's grant NGT-50-002-302, and was also done in close collaboration with Dr. Dean Duffy and the staff of the Modelling and Simulation group at Goddard.

A linear version of the Goddard laboratory for the Atmospheres General Circulation Model was developed to investigate the linear and nonlinear stability of a baroclinic zonal mean flow to small amplitude perturbations. The simulations replicated experiments conducted by Simmons and Hoskin jet at 30 degrees latitude. Simmons and Hoskins most unstable mode were considered, namely; wave number eight perturbations.

Differences between the linear and nonlinear adjustment, and early development of a single baroclinic wave were considered. Comparisons were made between linear and nonlinear phase speeds, growth rates, structure, and transport properties of the disturbances. Slight differences between the linear and nonlinear growth rates and phase speeds were found. Linear waves had larger phase speeds and smaller growth rates than the nonlinear waves. The differences were attributed to nonlinear advective processes, which allowed the perturbations to influence the phase speed and phase relationships of the disturbances. By maximizing the phase difference between the perturbation vertical velocity and perturbation temperature, the nonlinear disturbance was more effective at extracting available potential energy from the mean field.

The planetary-scale response to global orographic forcing was obtained within a nonlinear, steady-state primitive equation model. The orographic response was shown to account for the primary features of the Northern Hemisphere January climatology. Quasi-geostrophic theory was used to determine the physical processes which determined the structure of the orographic response. Residual vorticity tendencies in the quasi-equilibrium orographic response and the climatological planetary waves were shown to be due to planetary-scale divergence, which lead to retrograde motion.

The stability of the orographic response was investigated utilizing a nonlinear, time-dependent primitive equation model. Spectral kinetic energy budgets were used to determine the energy exchanges which were responsible for the amplification of the disturbances. Barotropic instability of the orographically forced planetary waves lead to the growth of synoptic-scale disturbances which were localized near the planetary-wave troughs. The maximum growth rates of these synoptic-scale disturbances were larger than the growth rates associated with linear, normal mode baroclinic instability. The orographically induced conversions of kinetic energy were determined within the primitive equation system. It was shown that the neglect of divergent motion lead to erroneous orographic conversion of kinetic energy in the quasi-geostrophic system.

In an ancillary investigation into the role of orography in mesoscale process, Dr. W. Raymond examined the dynamic processes within a steady viscous incompressible fluid that interacted with an isolated mesoscale obstacle. The topography was allowed to disrupt a variety of antitriptically balanced background states. A mesoscale antitriptic pressure gradient of a trough (ridge) was found to enhance lee side confluence when positioned just upstream (downstream) of the topographical center. Because of the obstacle, the barotropic flow was forced by the positive antitriptic pressure gradient. A repositioning of the trough downstream was found to enhance frictional drag. The influence of these mesoscale features was compared against that observed for constant frictional drag under mesoscale flow conditions, i.e., with the Rossby number near unity.

Publications Produced under NASA NSG 5223

A. Refereed Journal and Book Articles.

1. Schubert, S.D. and G.F. Herman, 1981: Heat balance statistics derived from assimilations with a global circulation model. J. Atmos. Sci., 38, 1981-1905.

2. Herman, G.F., 1986: Atmospheric modeling and air-sea-ice interaction. In: The Geophysics of Sea Ice (N. Untersteinter, ed.). Plenum. 713-754.

3. Schubert, S.D., 1985: A statistical-dynamical study of empirically determined modes of atmospheric variability. J. Atmos Sci., 42, 3-17.

4. Raymond, W.H., 1986: Topographically induced mesoscale motions in anti-triptically balanced barotropic flow. Tellus, 38A, 251-262.

B. Graduate Student MS and Ph.D. Theses.

1. Winston, H.A., 1980: A Diagnostic Study of Potential Vorticity Fields in the Vicinity of North Atlantic Cyclones. U. of Wisconsin MS Thesis.

2. Schubert, S.D., 1980: Maintenance of the Global Temperature Field as Deduced from Assimilations by a Global Circulation Model. U. of Wisconsin MS Thesis.

3. Alexander, M.A., 1986: On the Feasibility of Measuring the Earth-Atmosphere Energy Budget. U. Wisconsin MS Thesis, 107 pp. (Also appears as U. Wisconsin Meteorology Dept. Rept. #7).

4. LeMunyon, J.M., 1987: Relationships Between Large Scale Cloud Fluctuations and Atmospheric Processes Inferred from a GCM Assimilation. U. Wisconsin MS Thesis, 76 pp.

5. Pierce, R.B.,1985: A Comparison of Linear and Nonlinear Baroclinic Instability on a Sphere. U. of Wisconsin MS Thesis, 118 pp.

6. Pierce, R.B., 1988: Nonlinear Orographically Forced Planetary Waves and Their Interactions with Synoptic-Scale Disturbances. U. Wisconsin Ph.D. Thesis, 269 pp. (Also appears as U. Wisconsin Meteorology Dept. Rept. #9.)

C. Papers Submitted for Publication

1. Alexander, M.A., S.D. Schubert, and G.F. Herman, 1988: Regional Energy Balance Estimates Based on Assimilations with a GCM. J. Climatology.