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**NASA/MSFC FY88 GLOBAL SCALE ATMOSPHERIC
PROCESSES RESEARCH PROGRAM REVIEW**

Edited by G. S. Wilson, F. W. Leslie, and
J. E. Arnold

Space Science Laboratory
Science and Engineering Directorate

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16. ABSTRACT <p>This document describes the research supported by NASA's Global Atmospheric Processes Research Program at the Marshall Space Flight Center. There has been much interest recently in environmental issues such as the ozone hole, the global warming of the atmosphere, etc. Debate about the magnitude of these environmental changes continues. One problem is that measurements of the atmosphere are concentrated near large cities or airports of which virtually all are located on land representing only a small part of the Earth's surface. One way to gain more understanding of the atmosphere is to make measurements on a global scale from space. One of NASA's new initiatives is the Earth Observation System, a series of new sensors to measure globally atmospheric parameters such as temperature, moisture, wind, lightning, etc. Analysis of satellite data by developing algorithms to interpret the radiance information improves our understanding and also defines requirements for these new sensors. One measure of our knowledge of the atmosphere lies in our ability to predict its behavior. In order to predict future states of the atmosphere, one must know not only the current state but also the physics which govern change. Use of numerical and experimental models provides a better understanding of these processes. This work describes these efforts in the context of satellite data analysis and fundamental studies of atmospheric dynamics which examine selected processes important to the global circulation.</p>					
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STRATIFORM CLOUDS AND THEIR INTERACTION WITH ATMOSPHERIC MOTIONS

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During the 1987-1988 academic year, we have finished three projects and we have made plans to redirect and focus our work in a proposal now being reviewed. The completed work involves study of waves on an equatorial beta-plane in shear flow, investigation of the influence of orography on the index cycle, and analysis of a model of cloud street development in a thermally-forced, sheared environment. Our proposed work involves study of boundary layer circulations supporting stratocumulus decks and investigation of how the radiative effects of these clouds modulate larger-scale flows such as those associated with the index oscillation.

Significant Accomplishments in the Past Year

1. Waves on an Equatorial Beta-Plane

The equatorial region of the oceans and atmosphere has been shown to support a variety of large-scale wave-like oscillations that are unique to this region of the globe. These waves have been shown to play important roles in such *in situ* phenomena as the Walker - El Niño circulation and the 50-day oscillation. In addition, these waves are critical in setting up so-called teleconnection patterns between the tropics and mid- and high-latitudes (Horel and Wallace, 1981). Thus, these waves, although confined to the tropics, are important in the general circulation of the atmosphere.

Numerous studies have been carried out to determine the linear structure of these oscillations in shallow water models assuming motionless background states or allowing for background winds that vary linearly with latitude (Matsuno, 1966; Bennet and Young, 1971; Lindzen, 1971). The problem with these studies is that the background flow used was highly idealized and thus was unrepresentative of the observed profile of the zonally-averaged east-west flow in most seasons. We (Aberson and Clark) have extended the above studies by allowing for much more representative background wind profiles (Aberson, 1987). One purpose of this work was to determine whether the generic Kelvin and mixed Rossby-gravity wave structures determined with the simpler zonal wind profiles still more or less remained intact in the more realistic background atmospheres. Furthermore, we sought new equatorially-trapped wave structures that could only be supported with the more realistic wind profiles. Possibly these structures could have some relevance to observed equatorial large-scale dynamical phenomena.

The profiles that we used were hyperbolic tangent and Gaussian functions for $U(y)$, where y is north-south distance from the equator. These profiles turned out to be quite accurate representations of actual winds in certain sectors of the tropics. A broad spectrum of eigenmodes resulted from our numerical solution to the stability problem. A radiation condition was imposed as y approached \pm infinity. Some of these waves were slightly modified versions of the Kelvin and mixed Rossby-gravity waves of earlier studies. A variety of new wave structures was found, however, that was unique to the background wind profile used. Some, we argued, could be

discarded since they were highly sensitive to the details of $U(y)$ or would be rapidly dissipated by friction if it were present. Others, however, could be meteorologically significant. For example, with the hyperbolic tangent wind profile with westerlies (easterlies) in the northern (southern) hemisphere and as the magnitude of U approached 10 m s^{-1} as the magnitude of y approached infinity, a disturbance that slowly propagated westward with a critical latitude near 10 degrees was found. It was mainly confined to the southern hemisphere and was slightly unstable with an e-folding time of about one month. It is very similar to the wavenumber-two structure observed by Hirota (1976) and could play an important role in driving the easterly phase of the semi-annual oscillation. With the westerly Gaussian wind profile centered at the equator, an eastward propagating mode with two amplitude maxima near critical latitudes on either side of the equator occurred. We speculate that it could be important to the Walker circulation and might also resemble some of the teleconnection patterns observed by Horel and Wallace (1981).

2. The Influence of Orography on Index Cycles

It has been shown by Lindzen et al. (1982) that index-like oscillations can occur in the atmosphere because of destructive and constructive interference between traveling free waves and topographically forced stationary waves. We (Clark and Wilson) reasoned that in a realistic atmosphere where baroclinic and barotropic instability, in addition to nonlinear wave-wave and wave-mean flow interactions can occur, it is not at all obvious that the linear Lindzen mechanism could still prevail to drive an index oscillation. We chose to use a quasigeostrophic two-layer spectral model to address the general question of what role the orography has in precipitating and fostering low frequency oscillations in eddy as well as zonally-averaged energies. A synoptic, as well as a planetary, scale disturbance was represented in the model and a Newtonian approximation to radiative driving was included. Runs of 200 and 300 days were carried out with and without orography.

Very little variance in the 20- to 30-day periodicity range was found when topography was excluded. Rather, sharp spikes in the spectrum at 7 and 10 day periods were observed. The former was due to a cyclical baroclinic exchange of energy between the synoptic-scale wave and mean flow. The latter was due to the Lindzen mechanism, that is, interference between the forced stationary wave and the traveling planetary scale wave. The problem here was that the latter mechanism did not produce slower index-like oscillations. Introduction of topography into the model broadened the energy spectrum considerably and, most significantly, introduced a peak in the variance spectrum at a period near 25 days. This peak, however, was not caused by the Lindzen wave interference mechanism. Rather, the process of form-drag instability proposed by Charney and DeVore (1979) seemed to cause the periodic, mainly barotropic, exchange of kinetic energy between the planetary wave and the mean flow. We find that, although the mechanism is not yet entirely understood, the planetary wave periodically becomes almost stationary and subsequently grows by form-drag instability. Its energy is then transferred barotropically to the mean flow. This numerical result may confirm the observations by us (Clark and Schlaak, 1988) concerning the primarily barotropic nature of the observed wintertime well-defined index oscillation of 1974/1975.

3. Cloud Street Development from Dynamic and Thermal Instabilities

At least three fundamental mechanisms leading to the development of boundary layer rolls have been proposed. The inflection point and parallel instabilities are the two dominant dynamic mechanisms and the Rayleigh-Bénard instability is the primary thermal mechanism. Under NASA sponsorship, for the past several years we have been developing nonlinear boundary layer models capable of accepting observed data in order to determine for particular atmospheric cases the mechanisms underlying roll development. We have recently published (Stensrud and Shirer, 1988) a study of the circulations developing from the inflection point instability. Hirschberg (1988), in a thesis to be completed in August 1988, has extended their model to the case of linearly varying thermal stratification. Finally, in a study sponsored by the Air Force, we are extending the Hirschberg model to the case of an arbitrarily varying stratification, with an emphasis on the influence of inversions.

In all these spectral models, the background profiles of wind or temperature are represented via their lowest order Fourier coefficients. Analysis of the stability properties of the solutions to these models allows identification of the possible modes leading to secondary circulations in the boundary layer. Preferred values of both the horizontal spacing and the orientation of the rolls are determined via the standard method of minimizing the critical values of the dynamic and thermodynamic forcing parameters. In addition, the expected values of the frequencies of the periodic solutions are determined. Hirschberg (1988) compared her model results against observations taken during the West German KonTur experiment. In two cases, when the roll circulations extended significantly into an inversion layer, her model revealed that the roll circulations were likely given by a new mode, the shear mode, that she had identified. The expected roll orientation and critical forcing values were modeled very well, but the expected street spacing and propagation rates were poorly represented. We have hypothesized that these poor results are related to the fact that the background temperature gradient is constant, and so we are now testing this hypothesis in a model with a more general background temperature profile so that the effects of the inversion can be included.

Proposed Work

1. The Index Oscillation

Our continuing study of the index oscillation will concentrate on two aspects that we consider crucial in understanding its strength and longevity, especially during the northern hemisphere winter. They are:

- the role of orographic forcing in establishing as well as maintaining the hemispheric oscillation, and
- the role of mid- and high-latitude radiative heating as modulated by periodically changing cloud cover in maintaining the oscillation against dissipative mechanisms.

Charney and Strauss (1980) demonstrated that wave-like topography in a two-layer quasigeostrophic atmosphere could stimulate growth of stationary

disturbances by inducing them to tilt vertically such that they can tap the available potential energy associated with the sheared background flow. The instability occurs once the vertical shear, driven by a north-south gradient of heating, exceeds the value for which a free Rossby wave first becomes stationary (there is no mean flow in the lower layer).

Our first order of business will be to determine whether the above mechanisms can work in a simple nonlinear two-layer spectral model on a mid-latitude beta-plane to give a long-term periodicity like the index oscillation. We will also use the hemispheric spectral model to investigate in detail the mechanisms of the low-frequency oscillation noted above. Furthermore, we will introduce simple parameterizations of stratocumulus development and dissipation and the ensuing modulations of radiative heating based on our study of FIRE and global ERB data to assess diabatic feedbacks on the dynamically-driven cycle.

We have observed that stratocumulus over mid- and high-latitudes respond to periodic incursions of warm air associated with the zonal index oscillation in such a way as to modulate the field of infrared cooling. Our preliminary conclusion as to the implications of this cooling is that it reinforces the dynamically-driven oscillation. We wish to gather satellite radiance as well as conventional data for at least three years in order to more closely investigate this possibly important mechanism for coupling cloudiness with low-frequency oscillations in the atmosphere.

2. Stratocumulus Modeling

Cloud streets are one manifestation of stratocumulus decks that exist in the upper portions of the secondary circulations in the boundary layer. However, the mechanism by which these decks break up into streets remains uncertain. It is important to understand this mechanism, because, as noted in the previous section, the areal coverage of the stratocumulus deck plays an important role in modulating the index oscillation through the influence of the clouds on the large-scale radiative heat budget. Thus, we seek a detailed understanding of the dynamics of these boundary layer circulations in order to provide crucial information for modeling the structure and response of large-scale flows.

In order to provide a dataset for the study of the structure and break up of marine stratocumulus, a coordinated series of ground-based, aircraft, and satellite observations was conducted last summer west of San Diego, CA. NASA was the lead agency for this experiment, which was part of FIRE (First International Cloud Climatology Project Regional Experiment). One of us (Shirer) participated in this experiment as an observer on the NCAR Electra; indeed the data measured on this aircraft are being analyzed at Penn State. It was apparent that a common feature of marine stratocumulus is the existence of a cumulus layer below the stratocumulus. At times, these cumulus clouds penetrated into the stratocumulus deck, which coincided with the occurrence of breaks in the overcast. We propose to investigate whether the break up process may be in part dynamically caused by the coupling of the subcloud and cloud layers. We will extend a model presently being developed under the sponsorship of NSF; an early version is summarized in Laufersweiler and Shirer (1988). This new model will contain representations of net radiative heating, latent heating in two cloud layers, and arbitrary

background temperature and wind profiles. We will determine the expected roll circulation spacing and orientation, and we will calculate the associated vertical transports of heat and momentum. We will attempt to identify those large-scale conditions under which stratocumulus will break up, and we will compare our results with the observations taken during FIRE.

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TITLE: Synoptic/Planetary-Scale Interactions and Blocking Over the
North Atlantic Ocean

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SIGNIFICANT ACCOMPLISHMENTS IN THE PAST YEAR:

Work this past year has continued to focus on the development of a blocking anticyclone that formed over the North Atlantic in January 1979 and a marine cyclone that deepened explosively prior to the onset of the block. The "extended" height tendency equation has been used as the primary diagnostic tool. Focusing on the domain encompassing the migrating ridge that eventually formed the block, we have found that vorticity advection played the dominant role in the development of the ridge and the formation of the block. This negative vorticity advection was especially pronounced during the 48 h period prior to initial block formation and immediately following the upstream explosive cyclone development. This advection was attributed primarily to the northward advection of negative relative vorticity on the anticyclonic side of jet that formed east of the cyclone system.

Also of interest has been an attempt to evaluate the relative importance of synoptic-scale, planetary-scale, and synoptic/planetary-scale interactions as the block developed. To accomplish this, all data fields were partitioned into synoptic and planetary-scale components using a Barnes-type filter. Results of this work indicate that during explosive cyclone development the height tendencies were dominated by planetary/synoptic-scale interactions. However, as the migrating ridge became stationary, built northward, and finally formed a closed high, the interaction forcing diminished and became comparable to the synoptic-scale forcing. Throughout this time period the planetary-scale forcing was one-half or less than the other two partitioned forcing components.

Finally, we began a diagnosis of the cyclone by examining the low level static stability fields associated with the cyclone's development. Low level static stabilities decreased throughout the explosive development period and then increased. This is in sharp contrast to two continental cyclone cases that we had previously studied. In these, the low level static stabilities increased as the cyclones developed. This contrast suggests that boundary layer sensible heat transfer, which in turn acts to decrease the low level static stability, may play a more significant role in marine than in continental cyclone cases.

FOCUS OF CURRENT RESEARCH AND PLANS FOR NEXT YEAR

Of course we are continuing toward completion of the blocking anticyclone study. In addition, we are giving more attention to the upstream cyclone. In particular we are now and will continue to examine the role of boundary layer sensible and latent heat transfer, horizontal moisture transport, and latent heat release. The latter two are coupled through diagnoses now in progress of the convective latent heating as revealed by the Kuo parameterization scheme. In this scheme the horizontal moisture convergence plays a key role. Initial calculations suggest good placement of the latent heating compared with satellite cloud images but with magnitudes that are often too small. We are hypothesizing that a portion of this underestimate is attributed to underestimates of the moisture convergence, which in turn results from moisture gradients that are too weak. In the coming year we will be attempting to use satellite data to improve the moisture fields.

In addition, we will be initiating a study designed to assess the overall impact of satellite data included in the GLA SOP-I analyses. In this study we will use GLA analyses prepared without the inclusion of satellite information (known as the NOSAT analyses) to do some of the same diagnostic calculations already done with the standard GLA analyses. The two sets of calculations will then be compared to see the influence of satellite data on higher order diagnostic quantities.

PUBLICATIONS

1. Refereed paper

Smith, P.J., and C.-H. Tsou, 1988: Static stability variations during the development of an intense extratropical cyclone. Monthly Weather Review, vol. 116, in press.

2. Non-refereed papers

Tsou, C.-H., and P.J. Smith, 1988: The role of synoptic/planetary-scale interactions during the development of a blocking anticyclone. Preprints of the Palmen Memorial Symposium on Extratropical Cyclones, Aug. 29 - Sept. 2, 1988, Helsinki, Finland, in press.

Smith, P.J., C.-H. Tsou, and M.N. Baker, 1988: Static stability variations during a winter marine cyclone development. Preprints of the Palmen Memorial Symposium on Extratropical Cyclones, Aug. 29 - Sept. 2, 1988, Helsinki, Finland, in press.

TITLE: Global Atmospheric Moisture Variability

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SIGNIFICANT ACCOMPLISHMENTS IN THE PAST YEAR:

Research efforts during FY88 have focused on completion of several projects relating to analysis of FGGE data during SOP-1 and on expanded studies of global atmospheric moisture. In particular, a revised paper on the relationship between diabatic heating and baroclinicity in the South Pacific Convergence Zone (SPCZ) was submitted to the QJRMS. A summary of completed studies on diagnostic convective parameterization was presented at the Satellite Meteorology and Oceanography Conference last February. These investigations of diabatic heating in the SPCZ have demonstrated the requirement for a more quantitative description of atmospheric moisture. As a result, we have directed our efforts toward use of passive remote microwave measurements from the Nimbus-7 SMMR and the DOD's SSM/I as critical sources of moisture data. Our activities this year are summarized as follows.

1. Use of IR gradient information in rainfall estimation

In an attempt to extend infrared (IR) rainfall estimation techniques to middle latitude stratiform rain situations, an algorithm has been developed which incorporates gradients of IR brightness temperature, T_b . The premise of this approach is that in vertically sheared flows typical of middle latitudes, horizontal gradients of T_b can help discriminate vortical cloud bands and comma clouds in which there is a tendency for slantwise ascent of air parcels with precipitation concentrated on the upstream flank of the cloud shield. A data set consisting of over 1500 3-hour cumulative rainfall amounts and collocated GOES-E IR T_b s and gradients of T_b has been compiled. Results suggest that T_b and its horizontal gradient possess *independent* information on rain rate and that consideration of the T_b gradient adds significantly to the skill of the algorithm.

2. SMMR Precipitable Water During FGGE SOP-1.

Because the convective intensity of the SPCZ during FGGE SOP-1 was apparently modulated by processes acting on intraseasonal time scales, it is of interest to determine how the associated moisture fields (precipitable water) also behaved. We conducted a pilot study to assess the ability of SMMR to detect variability of large scale tropical moisture over weekly and longer time scales. For the period 10 January through 13 February 1979 composites of the difference between 22 and 18 GHz (horizontal polarization) have been produced. Prabhakara *et al.*, (1982 JAM) has developed a quantitative relationship between these T_b differences and precipitable water. During this period, significant changes in the global structure of precipitable water over tropical oceans were observed. In mid January the SPCZ and that portion of the ITCZ associated

with the Australian Monsoon were quite moist with precipitable water values in excess of 5 cm. By early February the SPCZ had weakened (dried) somewhat. Concurrently the ITCZ east of 180° and the southwest Indian Ocean had shown considerable moistening. This sequence of events is consistent with the results from studies which indicate convective anomalies in the Indian Ocean being out of phase with those in the mid-Pacific and SPCZ regions.

This variability has been confirmed in the ECMWF and GLA analyses for the same period. An examination of 160 colocated values of grid point data and SMMR precipitable water averaged over a 4.0° square showed high correlations: SMMR/GLA, .81; SMMR/ECMWF, .83; and GLA/ECMWF, .87. Given that the SMMR data are totally independent from the GLA and ECMWF values, and that the SOP-1 period provided an unequaled observational density, the passive microwave data base seems to be a substantially under-utilized resource.

3. Analysis of SSM/I geophysical retrievals

We have recently begun an examination of precipitable water, total liquid water and wind speed derived from the Special Sensor Microwave Imager (SSM/I) launched in June 1987. These geophysical retrievals have been produced by Dr. Frank Wentz of Remote Sensing Systems, Santa Barbara, CA. To date we have been working with data for September 1987 (descending nodes only). The monthly mean precipitable water shows anticipated patterns of a moist ITCZ, dry "oceanic deserts" west of continents, and strongly resembles climatological sea surface temperature patterns. Because SSM/I coverage per unit time is four times that of SMMR owing to duty cycle and swath width, analysis of evolving synoptic scale structures will be possible. Several instances of extratropical cyclone development and a case of a tropical cyclone recurving and merging with a mid-latitude baroclinic wave have been identified.

Total liquid water (cloud and rain water) during the same period is largest over the ITCZ and western tropical Pacific. However, there are some regions in the tropical Southern Hemisphere which, although high in precipitable water content, are relatively free of cloud liquid water. These may possibly be descending branches of local Hadley circulations.

Surface wind speeds determined from SSM/I exhibit considerable coherence. In cases where vortical structure in precipitable water suggests a mature or deepening cyclone, wind speeds form a "bullseye" pattern increasing radially inward. During September, the Antarctic circumpolar trough exhibits persistently high wind speeds, evidence of weak frictional effects due to the lack of continents at these latitudes. One potential problem with SSM/I winds is an apparent high bias in regions of large liquid water content.

FOCUS OF CURRENT RESEARCH AND PLANS FOR NEXT YEAR:

We are currently directing most of our efforts toward developing the SSM/I data base, associated image processing routines, and statistical analysis programs. We are also examining NMC gridpoint analyses for comparison to SSM/I geophysical quantities. During the next year we plan to apply spectral analysis techniques (e.g. power, coherence, phase, bandpass filtering) to quantify the structure and variability of moisture and surface wind speed on synoptic to intraseasonal scales. This analysis will also be performed on global gridpoint data sets (NMC or ECMWF analyses) to assess current capability of assimilated global data to quantitatively describe the atmospheric component of the global water cycle.

These results should also be of interest to other researchers in the 146 RTOP area who are investigating global moisture and diabatic processes. We plan to coordinate with these groups relative to observational periods, case study selection and numerical modeling strategies. We will also finish producing IR rainfall estimates for use in several other 146 RTOP efforts. Production of regional 12h precipitation estimates at 2.5° resolution for several case studies for Drs. Colucci

and Smith is underway.

PUBLICATIONS:

(Referred)

Robertson, F. R., D. G. Vincent and D. M. Kann, 1988: The role of diabatic heating in maintaining the upper-tropospheric baroclinic zone in the South Pacific. (Revised and submitted to Quart. J. Royal Meteor. Soc.).

(Non-referred)

Huang, H.-J., D. G. Vincent and F. R. Robertson, 1988: Precipitable water derived from Nimbus-7 SMMR measurements and its comparison to FGGE III-b data during January 10- February 13, 1979. Preprints of Third Conference on Satellite Meteorology and Oceanography, January 31-February 5, 1988, Anaheim, CA, American Meteorological Society, Boston, MA, 64-69.

Robertson, F. R. and D. G. Vincent, 1988: Vertical profiles of heating derived from IR-based precipitation estimates during FGGE SOP-1. Preprints of Third Conference on Satellite Meteorology and Oceanography, January 31-February 5, 1988, Anaheim, CA, American Meteorological Society, Boston, MA, 334-339.

Title: Application of Dynamical Systems Theory to Global Weather Phenomena
Revealed by Satellite Imagery

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Significant Accomplishments in the Past Year:

1) Theoretical studies of low frequency and seasonal weather variability. As part of our effort to treat extratropical weather in terms of stochastic-dynamical systems analysis, we have developed a thermally-forced, low-order model of the atmosphere that seems capable of accounting for many of the statistical properties of the long-wave structure including the main seasonal and planetary-monsoonal variations. In its most simplified form this model can be reduced to a 3-variable forced, dissipative dynamical system exhibiting a "folded resonance" equilibrium structure that admits multiple steady-states in a realistic parameter range. This structure can explain the observed bimodality and vacillation of long-wave amplitude in winter and the more steady monsoonal circulation characteristic of summer (Saltzman, Tang, and Maasch). In other theoretical studies the criteria for "baroclinic adjustment" and the role of interactions between planetary and cyclone-scale waves in accounting for the observed zonal mean and wave structure have been elucidated in a series of three papers (Ebisuzaki).

2) Dynamical properties of observational (e.g., satellite) and GCM-generated records. The newly developed techniques for determining "attractor dimensionality", and the presence of multiple regimes and "jump" phenomena have been used and improved in a series of studies applied initially to paleoclimatic data (Maasch). The ultimate aim is to apply these same techniques to the long, continuous time-series being made available for the first time by satellite borne instrumentation, and being made available theoretically by extended GCM runs. A first order task is to determine the extent to which those series can be ascribed to an identifiable deterministic process (that may however be "fractal" or "chaotic"), having an attractor that can be modelled by a low-order system. Our preliminary results, for example, indicate that the weather variability exhibited by a complex GCM can be modelled with a reduced low-order system containing a minimum of six variables (Maasch and Saltzman).

3) Effects of the hydrologic cycle and latent heat release on extratropical weather. Using a general circulation model we have determined that extratropical Northern Hemisphere weather is extremely sensitive to variations of sea surface temperatures in the Gulf of Mexico which is the most significant source of water vapor fueling the latent heat release in the North Atlantic storm track. The consequences of the cooling of this Gulf region during the deglaciation phase of the last ice age cycle, about 10,000 years ago, are corroborated by the geologic and paleoclimatic evidence available for this period (Oglesby, Maasch, and Saltzman).

4) Earth-system science studies. In a series of papers we have explored the degree to which the major changes in terrestrial climate associated with the Pleistocene "ice ages" can be accounted for internally by complex nonlinear interactions involving the atmosphere, bio-hydrosphere, and cryosphere. In our most recent contribution we show how positive feedback in the global carbon cycle, as controlled by the deep ocean state, can provide the instability to drive the major ice age cycle. When additive external forcing (e.g., due to earth-orbital, Milankovitch variations) is applied much of the inferred global variations of climate over the past 2 million years, including the "jump" about 900,000 years ago, can be accounted for with a relatively small number of adjustable parameters (Saltzman and Maasch).

Focus of Current Research and Plans for Next Year:

1) Continuing Study of Low-Order Weather Systems. We are presently performing numerical calculations to explore the robustness of the results of our 3-variable model described above for a full range of parameters. Our objective will be to establish the relevance of the results of this thermally-forced model as an explanation of the observed bimodality of the long-wave amplitude structure. In addition, the model will be expanded by the successive addition of new features such as wave-wave interactions and orographic forcing. Concerning the former additional considerations, Dr. W. Ebisuzaki will be continuing his promising numerical modelling work on baroclinic adjustment and the interactions of planetary and cyclone scale wave motions; interesting work on the latter, orographic, considerations is already underway by Lionel Pandolfo, in the contexts of both barotropic and baroclinic models. Furthermore, it remains our goal to include hydrology and clouds into these low-order models in order to connect these models more directly with satellite observations.

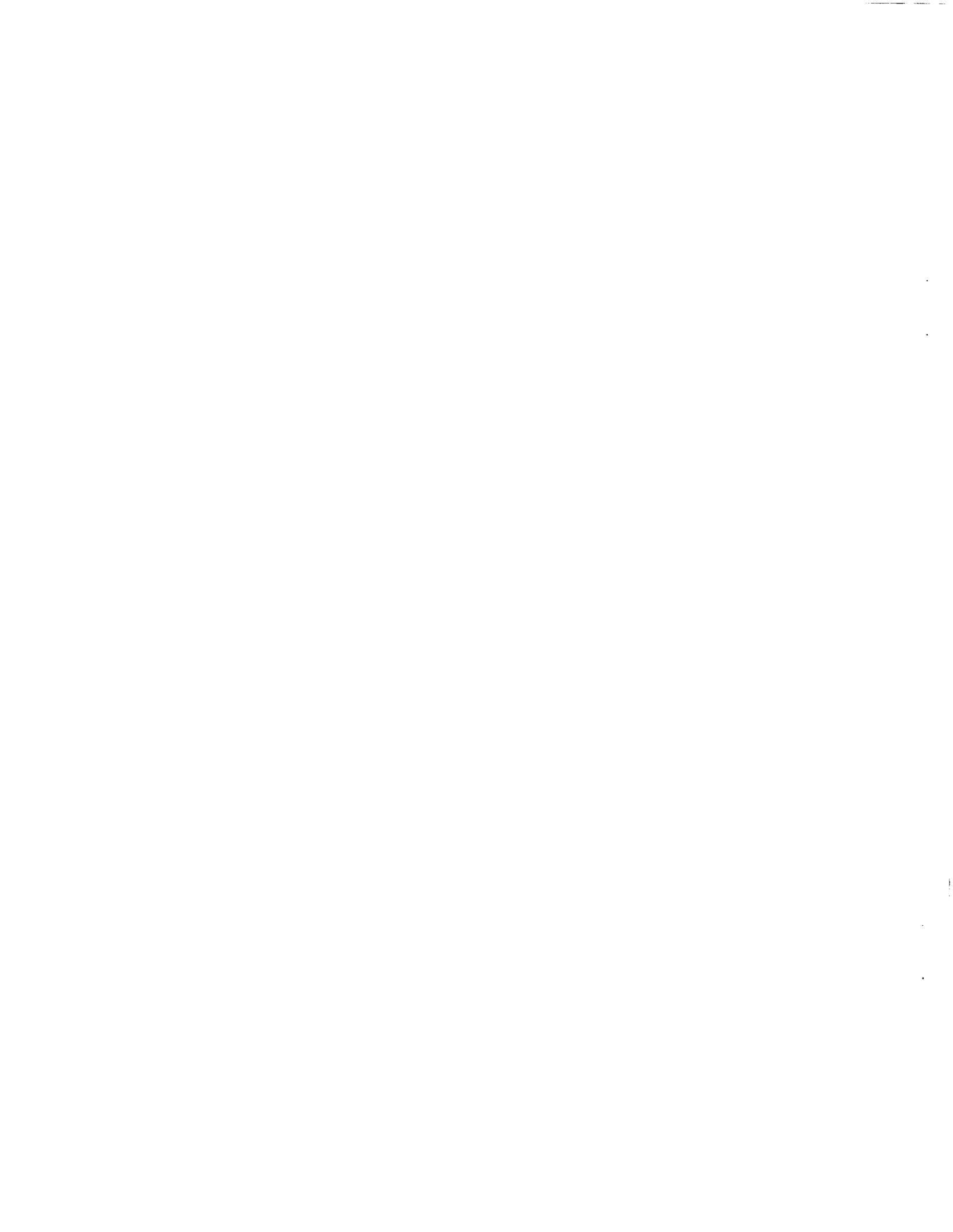
2) Observational studies. Dimension analysis of satellite OLR and cloud records are being pursued, in conjunction with similar analyses of the output of general circulation models. A more general observational goal will be to use satellite data to help quantify the "cloud and latent heat forcing" in the storm tracks associated with the long baroclinic waves, as embodied qualitatively in our present low-order dynamical model.

Publications Since June 1987:

- 1) Tang, C.-M., 1988: The meridional scale of baroclinic waves with latent heat release. Atmósfera, 1, (in press).
- 2) Saltzman, B. and C.-M. Tang, 1988: Folded resonance and seasonal vacillation in a thermally-forced baroclinic wave model (abstract). Ann. Geophysicae, European Geophysical Society, XIII General Assembly, Bologna, p. 107.
- 3) Ebisuzaki, W., 1988: Dynamical criterion for a marginally-unstable, quasi-linear behavior in a two-layer model. J. Atmos. Sci., 45, (in press).
- 4) Maasch, K.A., 1988: Statistical detection of the mid-Pleistocene transition. Climate Dynamics, 2, 133-143.
- 5) Maasch, K.A., 1988: Dimension from a time series: application to deep sea $\delta^{18}O$ records (abstract). EOS, 69, 376.
- 6) Saltzman, B. and K.A. Maasch, 1988: Carbon-cycle instability as a cause of the late-Pleistocene ice-age oscillations: modelling the asymmetric response. Global Biogeochem. Cycles, 2, (in press).
- 7) Saltzman, B., 1988: Modelling the slow climatic attractor. Physically Based Modeling and Simulation of Climate and Climatic Change (M.E. Schlesinger, ed.), Reidel Publ. Co., Dordrecht (in press).

Manuscripts Submitted for Publication or in Preparation

- 1) Saltzman, B., C.-M. Tang, and K.A. Maasch, Folded resonance and seasonal vacillation in a thermally-forced baroclinic wave model. (submitted for publication).
- 2) Ebisuzaki, W., Interactions between long and synoptic-scale waves: Part I. Instability of a non-zonal flow. (submitted for publication).
- 3) Ibid., Part II. Growth rate of long waves. (submitted for publication).
- 4) Maasch, K.A., On the practicality of calculating dimension from $\delta^{18}O$ records. (in preparation).
- 5) Pandolfo, L. and A. Sutera, The effects of form-drag and wave-wave interactions on the equilibrium solutions of topographically-forced barotropic and baroclinic models of atmospheric planetary waves. (in preparation).
- 6) Oglesby, R., K.A. Maasch, and B. Saltzman, Glacial meltwater cooling of the Gulf of Mexico: GCM implications for Holocene and present-day climates. (submitted for publication).



TITLE: Variational Objective Analysis for Cyclone Studies

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SIGNIFICANT ACCOMPLISHMENTS DURING THE PAST YEAR:

Five major components of this project are:

1. **MODEL I.** Requires satisfaction of the two nonlinear horizontal momentum equations, the integrated continuity equation, and the hydrostatic equation.
2. **MODEL II.** Requires satisfaction of MODEL I plus the thermodynamic equation for a dry atmosphere.
3. **MODEL III.** Requires satisfaction of MODEL II plus the radiative transfer equation. Brightness temperatures and skin temperature are introduced as dependent variables.
4. **MODEL IV.** Requires satisfaction of MODEL III plus a moisture conservation equation and a parameterization for moist processes. Moisture is introduced as a dependent variable.
5. **INITIAL ANALYSIS.** Makes the variational models more responsive to the observations. Thorough analysis of all phases of the data representation, gridding and initial analysis/model interface.

Significant accomplishments during 1987-88 are summarized with regard to each of the major project components.

I. MODEL I

A. The completion of MODEL II allowed for the testing of the variational method for the complete set of dynamic equations. The tests were determined whether the MODEL I vertical velocity formalism was posed correctly as it wasn't as rigorous as are the other model formalisms. The results of the test revealed that there was little or no coupling of the "observed" vertical velocity with the other adjusted variables. In other words, the adjustment simply didn't "see" the divergent part of the observed wind. It was found that the adjusted vertical velocities converged toward a solution of the vorticity theorem that gave vertical velocity patterns similar to those of one of the NMC numerical prediction models that was operational during 1979.

This information was used to develop a new MODEL I that includes as constraints the two nonlinear horizontal momentum equations, the hydrostatic equation, and a particular solution of the vorticity theorem that satisfies

the constraints that the vertical integrals of the vorticity theorem and of the divergence vanish at the top of the model domain. In theory, this formulation strongly couples the divergence of the observed wind into the adjustment for the winds and there are no "variational models within variational models" as was required for the first version of MODEL I.

The variational equations for the new version, MODEL I.2, are more complex than for the old version, MODEL I.1. After the higher order terms are moved into forcing functions, the equation set reduces to three diagnostic equations; geopotential height, divergence, and vorticity. The latter two are solved for the velocity potential and stream function in order to get the adjusted winds. Boundary condition problems inherent in these Poisson equations are well known. We tested four methods for retrieving the velocity potential and stream function (Bijlsma, 1986, MWR 114, 1547-1551; Shukla and Saha, 1974, MWR 102, 419-425; Endlich, 1967, J. METEOR, 6, 837-844; Schaefer and Doswell, 1979, MWR 107, 458-476.) The method of Schaefer and Doswell seems to work best for the staggered grid of MODEL I.2. This problem of boundary conditions is a subject of continuing investigation including personal communications with R. Endlich.

Theoretical development and programming of MODEL I.2 (extensive programming was required to implement MODEL I.2) have been completed and tests will begin soon.

B. Precision moduli sensitivity testing was done with MODEL I.1 to determine which variables are crucial to the convergence of the method. Fifteen runs of MODEL I.1, beginning with "standard" precision moduli calculated from observations or formulas linking with observations, were done with standard precision moduli selectively multiplied by 0.1 or 10.0. RMS residuals, a measure of how well the constraints are satisfied, were plotted for each cycle out to four cycles. The MODEL I.1 solution method was found to be sensitive to the horizontal velocity (if too accurate) and the developmental component of the horizontal velocity tendencies (if too inaccurate); the solution for the horizontal momentum equations diverged. A similar sensitivity test will be done for MODEL I.2.

II. MODEL II.

MODEL II was completed near the end of the first year of the current 3-year effort. As reported in the NASA MSFC FY87 Global Scale Atmospheric Processes Research Program Review, slow divergence was found in the solution for the middle layers of the model atmosphere. Subsequent analysis of the behavior of MODEL II has revealed the following:

a) The adjusted vertical velocities in MODEL I were weakly coupled with the initial vertical velocities. The solution wandered toward the vorticity equation rather than the continuity equation. The solution order that readjusted the winds to satisfy the continuity equation did not force the solution toward the initial vertical velocity. A solution for the problems with vertical velocity coupling has been briefly described in connection with MODEL I.2.

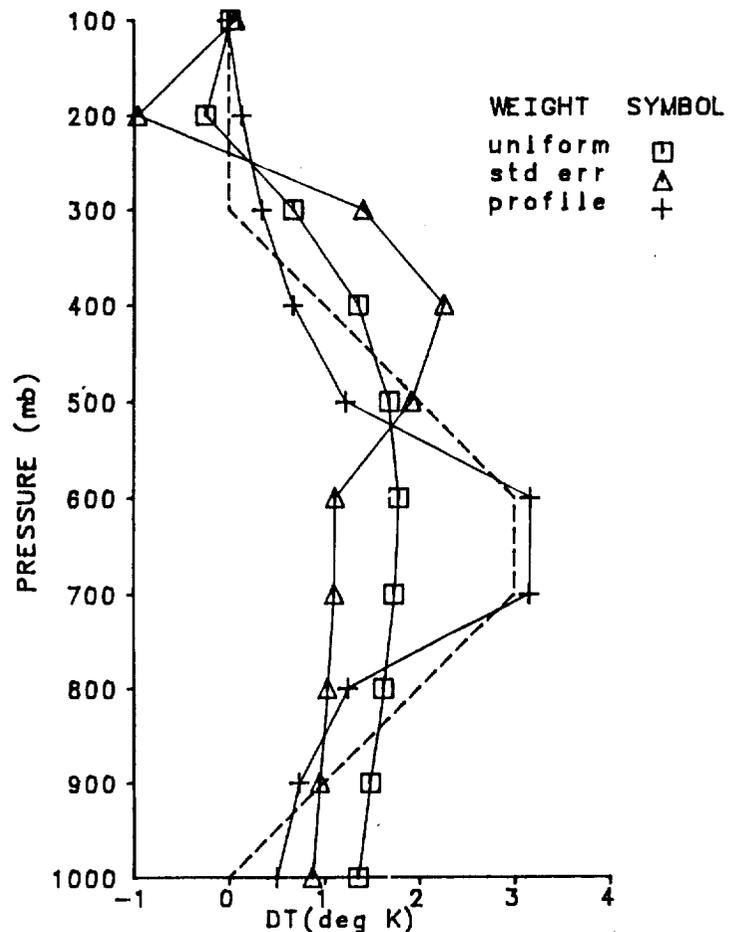
b) The initial vertical velocity must not have large error or else the adjusted temperature tendencies will have large error. Kinematic vertical

velocity methods make no allowance for the discontinuity in stability between the troposphere and stratosphere. Large stratospheric kinematic vertical velocities produce large erroneous temperature tendencies. In an attempt to correct this problem, Barb Chance coupled adiabatic vertical velocities with the kinematic divergence of the horizontal wind through a variational algorithm that weighted the velocities through static stability, relative humidity and cloudiness. Her method was modified to blend adiabatic and kinematic vertical velocities through static stability alone.

III. MODEL III.

Three variational models that incorporate the four radiative transfer equations for the four TOVS microwave channels as constraints and the four brightness temperatures and the skin temperature as new dependent variables are in various stages of development. These models are:

a) MODEL 3a consists of the radiative transfer equations with rawinsonde temperature and brightness temperatures as adjustable variables. It was apparent that this formalism would be just another retrieval algorithm. Therefore the main reason for derivation of MODEL 3a was to gain understanding of the behavior of four integral equations as dynamic constraints. Solutions were by matrix inversion and an iterative technique. An unexpected result from MODEL 3a was that the retrieval is sensitive to the vertical distribution of the temperature weights. Figure 1 gives an example of the response of the adjustment to the vertical distribution of temperature weights. The



standard atmosphere was used as the true temperature and the true brightness temperatures were calculated from it. Then a 3C temperature anomaly (dashed line in Fig. 1) was introduced into the first guess temperature and MODEL 3a was asked to retrieve the true temperature. The best retrieval more closely matches the anomaly curve. The curve connected by the squares in Fig. 1 shows the results of this effort when the temperature weights were uniform (as is done with most retrieval methods). If the temperature uncertainty is doubled at the location of the anomaly, then the retrieval follows the line given by

the pluses; the correct temperature profile has been mostly restored. This finding may be useful for retrievals across the tropopause.

b) MODEL 3b consists of MODEL 3a plus the u and v geostrophic equations and the hydrostatic equation. This model couples the satellite temperatures to the three dimensional wind and height fields. It was tested with the 00 GMT 11 April 1979 SESAME data with the result that the SAT analysis filled a deep trough over the high plateau areas of the southwest U.S. by 30 m. This anomaly may be traceable to high skin temperatures. (Skin temperature was treated as true in MODEL 3b.)

c) MODEL 3c consists of MODEL 3b but with skin temperature as an adjustable variable. Varying the skin temperature increases the complexity of the variational equations. MODEL 3c is still under development.

IV. MODEL IV.

No significant progress has been made to date.

V. INITIAL ANALYSIS

a) A three-pass version of the Barnes objective analysis method has been implemented. This method has been found to reduce short wavelength noise in derivatives of gridded fields by up to 70% (Laplacians of height fields.)

b) A vertical velocity method that blends adiabatic vertical velocities with the divergence of the observed wind has been implemented. The blending is done as a function of the static stability.

RESEARCH PLANS FOR THE NEXT YEAR

1. Complete MODEL I.2, run, and verify (top priority)
2. Combine the new MODEL I.2 with the thermodynamic equation to produce a new MODEL II.
3. Complete the studies with the radiative transfer models (3a-3c) and develop theory to combine with model II into model III.
4. Develop a variational methodology for moisture.
5. Investigate a new objective interpolation method developed by F. Caracena (JAS 44, 3753-3768) that allows for the direct interpolation of derivatives from the observations and modify the vertical velocity algorithm to include vorticity advection.

LIST OF PUBLICATIONS PREPARED IN 1987-1988

Achtemeier, G. L., 1987: On the Concept of Varying Influence Radii for a Successive Corrections Objective Analysis. Mon. Wea. Rev., 115, 1760-1771.

Achtemeier, G. L., 1987: A 3-pass near optimum Barnes method for the univariate objective analysis of mesoscale phenomena. 3rd Conf. Mesoscale Proc., Vancouver, B.C., Canada, 21-26 Aug. 1987, 126-127. (Poster paper)

Achtemeier, G. L., 1988: Variational Blending of Space Observed Radiance with Conventional Weather Data Through Coupling Radiative Transfer with the Truncated Navier-Stokes Equations. European Geophysical Society XIII General Assembly, Bologna, Italy, 21-25 March 1988, Annales Geophysicae, 6, 97.

Achtemeier, G. L., and H. T. Ochs III, 1988: A Variational Objective Analysis - Assimilation Method, Part I: Development of the Basic Model. (Submitted to Tellus 20 April 1988)

Achtemeier, G. L., S. Q. Kidder, and R. W. Scott, 1988: A Multivariate Variational Objective Analysis - Assimilation Method, Part II: Case Study Results with and without Satellite Data. (Submitted to Tellus 20 April 1988)

Achtemeier, G. L., 1988: Modification of a Successive Corrections Objective Analysis for Improved Higher Order Calculations (Submitted to Mon. Wea. Rev. 15 April 1988)

Annual Report for NASA GSAPRP*
(1 July 1987 - 30 June 1988)

Dynamics and Energetics of the South Pacific
Convergence Zone During FGGE SOP-1
Contract NAS8-35187 (1 July - 31 December 1987)

and

South Pacific Convergence Zone and Global-Scale Circulations
Contract NAS8-37127 (20 July 1987 - 30 June 1988)

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* report prepared for GSAPRP Review
in Huntsville, AL, August 2-3, 1988

Significant Accomplishments in Past Year

1. Two articles by Huang and Vincent were published: one in Tellus and the other in Beitrage zur Physik der Atmosphere (see attached publication list).
2. An article by Hurrell and Vincent was published in the Monthly Weather Review (see attached publication list).
3. Three papers were given at the Third Conference on Satellite Meteorology and Oceanography in Anaheim, CA, February 1988 (see attached publication list).
4. One manuscript was revised and resubmitted to the Quarterly Journal of the Royal Meteorological Society, by Robertson, Vincent and Kann, "The role of diabatic heating in maintaining the upper-tropospheric baroclinic zone in the South Pacific".
5. Dr. Huang spent the summer of 1987 and is spending the summer of 1988 as a visiting scientist, USRA, at MSFC/NASA, Huntsville, conducting research on water vapor and precipitation estimates from satellite measurements.
6. Dr. Robertson, Dr. Vincent, and Mr. Hurrell visited the GSFC/NASA in Greenbelt, MD and the National Meteorological Center and Climate Analysis Center in Camp Springs, MD on 17-19 November 1987. They discussed some of the research objectives of the contract with Drs. Baker and Lau at GSFC, Drs. Kalnay and Kann at NMC, and Dr. Mo at CAC.
7. A computer account at NSESCC/GSFC/NASA was established so that Dr. Vincent and Mr. Hurrell could use the Goddard Laboratory for Atmospheres (GLA) General Circulation Model (GCM) on the CYBER 205 to perform some of the research objectives of the contract.
8. Mr. Hurrell successfully passed his Ph.D. preliminary examination and is now working full time, as a Ph.D. candidate, on his doctoral research. Mr. Hurrell's work involves using the GLA GCM to examine the global-scale physical processes responsible for maintaining the South Pacific Convergence Zone (SPCZ). With the assistance of Mr. Larry Takacs at GSFC, Greenbelt, MD, a successful control forecast was produced on the CYBER-205 using the GLA general circulation model. This forecast was a 15-day average of selected variables, initialized at 10 January 1979, which we are comparing with FGGE observations for the same time period. The observed state was well simulated by the model and we plan to examine cause/effect relationships in the future, particularly as they relate to the SPCZ, which was very intense during the 15-day period.
9. Ms. Pedigo gave a departmental seminar on her M.S. research on 11 April. The title of her seminar was, "Moisture and Precipitation Analyses During the Global Weather Experiment (GWE)". Her research is progressing well and she should finish her M.S. thesis in the Fall 1988 semester.
10. Dr. Vincent, Mr. Hurrell and Ms. Pedigo visited Dr. Robertson at MSFC, Huntsville, 6-11 March 1988, to discuss our research work.

11. Three graduate students have accepted offers to come to Purdue in the Fall 1988 and work on research problems within our contract. Dr. Vincent will serve as their major professor.
12. Dr. Peter Speth of the University of Cologne, FRG visited Dr. Vincent on 8 April to discuss collaborative research, as well as Dr. Vincent's plans for sabbatical leave next year in Germany.
13. Dr. Robertson visited Dr. Vincent, Mr. Hurrell and Ms. Pedigo at Purdue University on 15-18 June 1988 to discuss their collaborative research.

Focus on Current Research

1. Computer scientists at GSFC/NASA, Greenbelt, MD, have now produced a second control run on the GLA GCM for Mr. Hurrell to diagnose. This forecast is averaged over the 15-day period, 28 January - 11 February, 1979, initialized on 28 January. During this period the SPCZ was considerably less active, convectively, than during the prior 15-day control run period (10-24 January). Both runs appear to be successful in that the forecast fields are in good agreement with the observed fields, except over the Indian Ocean during the second period. Mr. Hurrell is now in the process of reading the history tapes provided by GSFC so that further analyses can be achieved and comparisons can be made between the active and inactive SPCZ periods.
2. Ms. Pedigo is diagnosing the heat and moisture budgets over the tropical oceans during January and February, 1979, which was part of the period of The Global Weather Experiment, FGGE. She is using FGGE Level III-b analyses produced by GLA and will compare her results to those obtained using satellite techniques. She currently is producing daily global results of precipitation using the Q_1 (heat) and Q_2 (moisture) budget techniques. A preliminary assessment of the results looks very promising.
3. One abstract was recently accepted for presentation of a paper at the 7th Extratropical Cyclone Workshop to be held in October 1988 at Drexel University, PA.
4. One new graduate student, Captain Keith North, arrived in June 1988 to begin in M.S. degree work and research on our project.

Plans for Next Year

1. We have one manuscript in the review process which may require further work before it is acceptable.
2. Mr. Hurrell and Ms. Pedigo will continue to work on their Ph.D. and M.S. research; Ms. Pedigo should finish her M.S. thesis and receive her degree in the Fall 1988 semester. A manuscript on her research will be submitted for publication.

3. Mr. Hurrell's work should progress toward culmination within the coming year and, if he completes his dissertation, one or more papers on his research would be submitted for publication.
4. Our department moved to a new building in June 1988 which required a careful review and scrutiny of all research materials. The research space in the new building offers an improvement over our previous facility.
5. We are eagerly anticipating the arrival of two more new students, Messrs. Ko (M.S.) and Ramsey (Ph.D.). They will begin graduate work in August 1988 and their addition will bring the number of graduate students working on the project to five.

List of Publications (at Purdue only)

- Huang, H.-J. and D.G. Vincent, 1988: Daily spectral energy conversions of the global circulation during 10-27 January 1979. Tellus, 40A, 37-49.
- Huang, H.-J. and D.G. Vincent, 1988: Active and inactive phases of the South Pacific convergence zone and changes in global circulation patterns: A case study. Beit. z. Phys. d. Atmos., 61, 123-134.
- Hurrell, J.W. and D.G. Vincent, 1987: Significance of the SPCZ in the energy budget of the Southern Hemisphere tropics. Mon. Wea. Rev., 115, 1797-1801.
- Huang, H.J., D.G. Vincent and F.R. Robertson, 1988: Precipitable water derived from NIMBUS-7 SMMR measurements and its comparison to FGGE III-b data during January 10-February 13, 1979. Preprints of Third Conference on Satellite Meteorology and Oceanography, January 31 - February 5, 1988, Anaheim, CA, American Meteorological Society, Boston, MA, 02108, 64-69.
- Miller, D.K. and D.G. Vincent, 1988: An example of estimates of precipitable water derived from NIMBUS-7 SMMR satellite measurements and FGGE upper air data. Preprints of Third Conference on Satellite Meteorology and Oceanography, January 31 - February 5, 1988, Anaheim, CA, American Meteorological Society, Boston, MA, 70-73.
- Robertson, F.R. and D.G. Vincent, 1988: Vertical profiles of heating derived from IR-based precipitation estimates during FGGE SOP-1. Preprints of Third Conference on Satellite Meteorology and Oceanography, January 31 - February 5, 1988, Anaheim, CA, American Meteorological Society, 02108, 4 pp.

TITLE: Low Level Remote Sensing: Orographic winds

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SIGNIFICANT ACCOMPLISHMENTS:

The orographic flow data set was obtained from a flight program to measure the influence of orographic features on turbulence momentum, heat, and moisture fluxes. The flights were carried out in Boulder, Colorado, February 1984. The NASA B-57 aircraft instrumented with probes for measuring the three fluctuating wind speed components, temperature, and humidity was the primary measuring vehicle. Ancillary measurements were made with several ground-based sensors provided by NOAA and NCAR. These include the NOAA radar wind profilers, the Boulder wind network, the PROFS mesoscale surface network, the Boulder Atmospheric Observatory 300 m tower, special rawinsonde observations, and the NOAA/WPL Doppler lidar. The major objective of the flight program was to provide planetary boundary layer parameter information for new and current general circulation computer models.

Data were gathered on February 1 and 10, 1984, while the upper level winds (above 10,000 ft msl) were blowing from west to east (perpendicular to the mountain range) and on February 2 and 6, 1984, when the upper level winds were blowing at 301° and 312° from true north. This direction represents prevailing winds which are oblique (approximately 50°) to the mountain range. Characteristic wake flow patterns were observed for the differing wind directions. Analysis of the data suggest a shear layer emanating from the mountain peak and propagating downstream and a recirculation region reattaching about 6 mountain heights downstream.

Observations from the February 2 and 6 events (flow oblique to the mountain range) showed a very unique wake flow pattern. The data indicate a strong vortex causing recirculation at the surface. Based on the heat flux measurements made with the aircraft, there is no evidence that these flows are thermally driven. The flow patterns for the February 2 and 6 events correspond with those observed by Zipser and Bedard [1]. Strong vortices shed from isolated mountain peaks were embedded in the overall vortex wake produced by the composite mountain range. The data clearly show an intense wake shed by the semi-isolated peak of Boulder Mountain.

To develop a fundamental and scientific understanding of this flow phenomenon, which may be the cause of severe upslope and strong vortex-like wind conditions in Boulder, Colorado, a water tunnel simulation of flow over a mountain range was carried out. A triangular mountain barrier with a conical peak was used to simulate the mountain range. This simple geometry was utilized primarily to understand the interaction between horseshoe vortices produced by the conical peak and recirculating wakes induced by flow separation behind the large barrier to the flow. Preliminary experimental results have been completed and clearly demonstrate strong wake interactions.

A numerical code, WINDER, based on a discrete element technique [2] has been run to numerically model the water tunnel simulated flow. Comparison of the analytical model with the experimental results is very good. Physical fluid dynamic principles embedded in the computational model and visual and hot wire anemometer measurements from the simulation are being rationalized to develop a physical understanding of the vortex flow. The results will be interpreted as they pertain to full scale atmospheric flows.

STATUS:

This effort has been completed.

REFERENCES:

1. Zipser, E.J., and A.J. Bedard, Jr. "Front Range Windstorms Revisited: Small Scale Differences Amid Large Scale Similarities," Weatherwise, pp. 82-85, April 1982.
2. Eraslan, A.H. "A Transient, Two-Dimensional, Discrete-Element Model For Far-Field Analysis of Thermal Discharges in coastal Regions," Progress in Astronautics and Aeronautics, ED.: J.A. Schetz, Vol. 36, AIAA publication, MIT press, Cambridge, MA, 1975.

Title: Low Level Remote Sensing: The Doppler Radar Wind Profiler

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Significant Accomplishments:

A research study is in progress to investigate mesoscale phenomena such as thunderstorm and sea breeze frontal circulations using a 50 MHz Doppler wind profiler at the Kennedy Space Center. The profiler installation will begin October 1, 1988 and will be completed by February 17, 1989. A proposal is currently being reviewed, and a research grant is expected to be awarded before fiscal year 1989.

Focus of Current Research and Plans for Next Year:

- (1) Examine vertical velocities associated with local thunderstorm activity and sea breeze frontal circulations and compare the vertical velocities to conceptual mesoscale models.
- (2) Implement space-time conversion analysis techniques to blend profiler data with National Meteorological Center's model output and other wind data such as jimsphere, windsonde and rawinsonde for mesoscale analysis.
- (3) Develop suggestions for use of wind profiler data in mesoscale analysis and forecasting at Kennedy Space Center.
- (4) If problems are detected in the quality of the profiler data during this research project, researchers will work closely with MSFC to identify and solve the data quality problems.

Publications:

1. Byers, H. R. and R. R. Braham, Jr., 1949: *The Thunderstorm*. The Government Printing Office, Washington, DC, 287pp.
2. Dodge, J., J. Arnold, G. Wilson, J. Evans, and T. Fujita, 1986: The Cooperative Huntsville Meteorological Experiment (COHMEX). *Bull. Amer. Meteor. Soc.*, 67, 417-419.
3. Forbes, G. S. and L. A. Carroll, III, 1987: Initial results from the Penn State wind profiler in MIST/SPACE. *Vaisala News* 111-112/87, 20-23.
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5. Strauch, R. G., B. L. Weber, A. S. Frisch, C. G. Little, R. A. Merritt, K. P. Moran, D. C. Walsh, 1987: The precision and accuracy of profiler wind measurements. *J. Atmos. Oceanic Tech.*, 4, 563-571.
6. Syrett, W., 1987: Some applications of 50 MHz wind profiler data: detailed observations of the jet stream. M.S. Thesis, The Pennsylvania State University, 135pp.
7. Watson, A.I., R. E. Lopez, R. L. Holle, and J. R. Daugherty, 1987: The relationship of lightning to surface convergence at Kennedy Space Center. *Weather and Forecasting*, 2, 140-157.
8. Weisman, M. and J. Klemp, 1986: Characteristics of isolated convective storms. Chapter 15 in *Mesoscale Meteorology and Forecasting*, P. Ray, ed., Amer. Meteor. Soc., Boston, 331-358.

Title: Studies of Baroclinic Instability in the Presence of Surface Topography and Stratospheric Ozone

Investigator: Nathaniel D. Reynolds, Department of Mathematics and Statistics, University of Alabama in Huntsville, Huntsville, AL 35899

Research Objectives:

Major goals of this study are to gain a better understanding of the planetary-scale tropospheric / stratospheric circulation and to better utilize global-scale routine measurements from satellites. The focus on the latter goal for this study is determining the relationship between total column ozone measurements and the tropopause altitude. (A proposal to NASA Headquarters for the ozone/tropopause work was submitted in early June, 1988.)

Significant Accomplishments:

Work has been accomplished on the problem of the interaction of a wave with an idealized topography of the same wavenumber in a two-layer quasi-geostrophic channel flow. The topography is a major portion of the linear dynamics, in which the eigenmodes exhibit a coupling between various spectral components, i.e., wavenumbers. Although various investigators have emphasized wave/mean flow interactions in the sense of a decomposition of the flow into zonal averages and departures, there seems to be merit in using the linear eigenmodes to study the nonlinear evolution. A scheme has been devised to project the nonlinear solution onto the linear eigenmodes, and has been briefly described in a paper submitted for the preprint volume of the Palmen Memorial Symposium.

An approach to the study of the relationship between the tropopause height and total column ozone has been defined and presented in the proposal mentioned in the "Research Objectives." Some of the data has been gathered, and some development of multilayered models has been carried out.

Current Activity:

A small portion of the investigator's Ph.D. dissertation has been prepared. It was submitted once and rejected due to the absence of a couple of pertinent references. It is now undergoing significant modification and it is planned to resubmit this paper this summer.

A manuscript based on a more significant portion of the investigator's Ph.D. dissertation, concerning the influence of an idealized topography on waves of wavelengths different from that of the topography is also under preparation. The investigator is convinced that dynamical systems theory has much potential for yielding insight into nonlinear dynamics and has spent a significant amount of time attending and preparing lectures on the subject.

Future Plans:

Plans for FY89 are to commence the data analysis and preliminary modeling studies for the proposed ozone / tropopause study. Initially, it is planned to consider a model similar to that of an earlier model of Hartmann and Garcia, with the addition of a total ozone calculation. Data analysis will focus on the question of whether the tropopause height variations can be studied by means of quasigeostrophic theory. The possibility of using a general circulation model to help answer this question will also be addressed.

Publications (Peer-Reviewed Scientific Journals):

Fichtl, G. H., N. D. Reynolds, A. E. Johnston, S. I. Adelfang, W. Batts, L. Lott, P. J. Meyer, O. E. Smith, M. S. Swint, and O. H. Vaughan (1988), "Analysis of the Ascent Meridional Winds for Mission 51-L", J. Clim. Appl. Met., in press.

Reynolds, N. D. (1988), "A Note on Linear Baroclinic and Orographic Instability, to be submitted to J. Atmos. Sci..

Reynolds, N. D. (1988), "Topographic Modulation of Free Unstable Baroclinic Waves", in preparation.

(Non-refereed Publications)

Reynolds, N. D. and T. L. Miller (1987): "Linear Baroclinic Instability in the Presence of Large-Scale Topography." Poster presented at the Sixth Conference on Atmospheric and Oceanic Waves and Stability, Seattle WA, August 25, 1987.

Reynolds, N. D. (1988) "Baroclinic Wave-Mean Flow Interaction due to the Presence of Large-Scale Topography." In preparation for the Palmen Memorial Symposium on Extratropical Cyclones, Aug., 1988.

Global Distributions of Moisture, Evaporation-Precipitation,
and Diabatic Heating Rates

Investigator: John R. Christy
Atmospheric Science and Remote Sensing Laboratory
University of Alabama in Huntsville

Accomplishments:

1. Global archives were established for:
 - ECMWF 12-hour, multilevel analyses beginning 1 January 1985
(U, V, RH, Z, T, Omega on 2.5 degree grid)
 - Day and Night IR temperatures (OLR on 2.5 degree grid)
 - Solar incoming and solar absorbed (for albedo calculations)
2. Routines were written to access these data conveniently from NASA/MSFC MASSTOR facility for diagnostic analysis.
3. Calculations of diabatic heating rates were performed from the ECMWF data using 4-day intervals. A major component of the calculation is the vertical divergence of the heat flux due to the mean vertical velocity. After several methods were examined, it was determined that the best results were obtained using the ECMWF archived values of vertical velocity rather than by any method using the divergent wind. Considerable variability over periods longer than 20 days is evident in the results when viewed in time-lapse animation, especially in the Indian Ocean to South Pacific sector of the tropics.
4. Calculations of precipitable water (W) from 1 May 1985 were carried out using the ECMWF data. Because a major operational change on 1 May 1985 had a significant impact on the moisture field, values prior to that date are incompatible with subsequent analyses. Global mean values of W range from 28.3 mm in late July to 23.3 mm in early January. This variability in W affects the global mean surface pressure by about 0.5 mbar in the course of a year.

Regional results indicate that monsoon areas are very moist, as expected, with point values of W up to 60 mm. The moisture budget equation reveals that in these rainy areas, Evaporation-Precipitation (E-P) drops below -20 mm/day while in broad areas of the subtropical oceans E-P exceeds +6 mm/day. The zonal mean moisture flux, when the constraint of conservation of mass is applied, agrees with accepted notions that the main moisture divergence occurs out of the summer subtropical oceans.

Focus of Current Research:

The present goal in data analysis is to determine what is the current state of the global atmosphere. The moisture component is of intense interest because of its non-trivial feedback into the circulation.

Plans for the coming year:

Continued diagnostic analysis of the ECMWF archive and comparisons with satellite data will be carried out. Again, the focus will be on the global atmospheric hydrologic cycle as well as the areas of large scale heating and cooling. Modeling efforts using the NCAR CCM1 will concentrate on simulation of the present climate, as determined in the ECMWF analyses, rather than on prediction.

Publications:

Christy, J. R., K. E. Trenberth, and J. R. Anderson, 1988: Large-scale redistributions in atmospheric mass. accepted, J. Climate.

TITLE: Tropical Pacific Moisture Variability

INVESTIGATORS : James P. McGuirk
Department of Meteorology
Texas A&M University
College Station, TX 77843-3146
(409) 845-4431

RESEARCH OBJECTIVES:

1. To describe the synoptic scale variability of moisture over the tropical Pacific Ocean.
2. To describe the systems leading to this variability.
3. To develop and implement satellite analysis procedures to facilitate (1) and (2) over the data sparse Pacific.

SIGNIFICANT ACCOMPLISHMENTS IN FY-87/88:

1. Radiative transfer model (RTM) based efforts. The NASA GLA RTM has been modified for operationally oriented research at TAMU. Significant results from the use of this tool are:
 - a. The disparity between TIROS- and radiosonde-observed moisture has been identified as a tropopause level contamination by meteorologically insignificant moisture. The sensitivity of TIROS moisture channels to observed and hypothetical moisture profiles has been mapped.
 - b. Vertical synoptic structure is being identified and quantified using a synthetic data base generated through the RTM. Several data sets, based on fictitious and actual conditions, have been analyzed and statistical tools have been developed which objectively classify a sounding type and quantify its features. The procedure can be implemented independently from operational retrieval methodologies. Clustering and classification techniques are used to sort synthetic "observations" into specified sounding classes; the variance structure within the sounding class can then be used to infer features, like inversion strength and height.
 - c. Calculations have been set up to generate synthetic TIROS N channel radiance maps from ECMWF (and other) operational analyses.
2. Outgoing longwave radiation (OLR) based studies. This research extends OLR capability to synoptic scale systems, an application not well studied:
 - a. Disturbances generated by east Asian cold surges have been tracked across the Pacific and their evolution and characteristics in OLR data and operational analyses described. Why these systems normally are not found in the east Pacific is hypothesized. The relationship between cold surge phenomena and moisture bursts is clarified--the former triggers over 40% of the latter.
 - b. Large synoptic scale variations of the Pacific ITCZ are documented over an 8-yr OLR record. Local ITCZ activity possesses large meridional scales. Systematic ITCZ variations are described; for example, ITCZ intensification is related to a southward displacement of convection.

3. Observational tropical TIROS-N radiance data. Studies extending the interpretations of satellite observations continue:

a. Complete statistical properties of satellite radiance fields are not well known. Horizontally and vertically oriented statistical structure differs strongly between satellite observations and model analyses. The "temperature", "moisture" and "lapse rate" eigenfunctions of TIROS data are not reproduced in ECMWF eigenfunctions. Similar disparity exists in horizontal structure functions. These structure functions contain information not being utilized currently.

b. Satellite moisture observations have been documented further. They possess a bimodal character, with a small portion of exceedingly dry tropical observations linked unambiguously to moisture bursts; these systems provide significant dry air to the mid-tropospheric tropics. EOF and filtered individual channel radiance fields describe a typical equatorial wave associated with developing moisture bursts. The signal is subtle, but repeatable, and requires careful compositing of events; results are consistent with OLR and VAS water vapor composites and provide new horizontal and vertical system structure.

4. Dynamics of moisture bursts. Study of dynamical mechanisms has been curtailed due to funding. Both moisture and momentum budgets of tropical analysis contain unacceptably large errors. For moisture, not even the right sign on the local change can be computed reliably, even using available radiosonde data. For momentum, subjective analyses which better fits observations provide more physically interpretable balances; uncertainties have important consequences regarding moisture burst and subtropical jet development.

FOCUS OF CURRENT RESEARCH AND PLANS FOR FY 88/89:

The following tasks will be initiated or continued this year:

1. Continue a recently initiated moisture burst case study utilizing SMMR microwave moisture and precipitation data.
2. Conclude the RTM-based development of a technique to specify synoptic features in tropical soundings. Explore applications with real data.
3. Conclude a comparative study of horizontal and vertical structure of TIROS and ECMWF analysis data. Included in this study will be new analysis of synthetic satellite data (generated from ECMWF analysis and the RTM). Quantification of the sensitivity of analysis procedures and clouds on resultant analysis and satellite data is the goal.
4. Initiate a study to relate tropical moisture fields to wind fields. Even if moisture analysis in the tropics is perfected, if it is not consistent with the wind fields, model integrations quickly destroy the accuracy of the moisture analysis.
5. Intensify documentation efforts. A number of studies of been completed and are not yet published. A major effort will be expended to rectify this situation.

PUBLICATIONS:

Refereed:

McGuirk, J. P., A. H. Thompson and L. L. Anderson, 1988: Synoptic scale moisture variation over the tropical Pacific Ocean. Accepted for Mon. Wea. Rev.

_____, _____, and J. R. Schaefer, 1988: An eastern Pacific tropical plume. Accepted for Mon. Wea. Rev.

Conference Proceedings:

Blackwell, K. G., J. P. McGuirk and A. H. Thompson, 1988: Temporal and spatial variability and contamination in 6.7 and 7.3 micrometer water vapor radiance data, *op. cit.*

Thompson, A. H., J. P. McGuirk and D. J. Ulsh, 1988: Tropical synoptic signatures in composited 6.7 micrometer water vapor imagery, Third Conf. on Satellite Meteorology and Oceanography, AMS, Feb., 1988, Anaheim.

White III, G. A., J. P. McGuirk and A. H. Thompson, 1988: Identification and recovery of discontinuous synoptic features in satellite-retrieved soundings using a radiative transfer model, *op. cit.*

McGuirk, J. P., 1987: Climatology of various synoptic systems over the tropical North Pacific, 12th Climate Diagnostics Workshop, Salt Lake City, Oct., 1987.

_____, and A. H. Thompson, 1987: Tropical synoptic scale momentum budgets during FGGE SOP 1, 19th IUGG General Assembly, Vancouver, Aug. 1987.

Thompson, A. H., J. P. McGuirk and K. G. Blackwell, 1987: Synoptic scale moisture transports using ECMWF analysis and satellite data, *op. cit.*

White III, G. A., and J. P. McGuirk, 1987: Canonical discriminant analysis of synoptic signatures in satellite channel brightness temperature data, Tenth Conf. on Probability and Statistics in Atmospheric Science, Edmonton, October, 1987.

Theses:

Blackwell, K. G., 1987: Synoptic scale sensitivity of TIROS-N moisture channels in the tropics. Master's Thesis, Texas A&M University, 125 pp.

Ulsh, D. J., 1988: Moisture burst structure in satellite water vapor imagery. Master's Thesis, Texas A&M University, 101 pp.

Hayes, P. M., 1988: Active modes of the Pacific ITCZ. Master's Thesis, Texas A&M University, 90 pp.

Sautter, D. C., Synoptic-scale east Asian cold surge-induced phenomena. Master's Thesis, Texas A&M University, 104 pp.

[Totalling 4 refereed publications, 20 conference papers, 9 M.S. theses, and 1 PhD. dissertation under 5 yrs. of NASA sponsorship, commencing April 1983]



Disturbances in the Arizona Monsoon

Robert Gall, Benjamin Herman, and John Reagan

I. Significant Accomplishments During the Past Year

1. We have submitted two manuscripts for publication and have 2 more manuscripts in preparation. These publications are listed at the end of this report.
2. We have begun numerical modeling simulations of tropical squall lines to determine the role of large scale terrain features over Arizona and Mexico in their initiation and propagation.
3. We have completed the installation of a short-base, high resolution lightning location and detection network in and around Tucson.
4. Data from a Doppler wind profiler, on loan for 6 weeks last summer from Penn State University is being analyzed to determine the role of large scale heating over the inter-mountain plateau region in governing local diurnal wind variations and possible relationships to the monsoon flow.
5. We have completed development and calibration of the portable solar photometer for determining high temporal resolution values of the local precipitable water vapor.
6. We have nearly completed assembly of a multi-channel microwave passive radiometer to determine local temperature and water vapor profiles.

II. Focus of Current Research and Plans for Next Year

1. We will continue our simulation studies of tropical squall lines.
2. We plan to collect data (lightning location and local radar data) this coming summer during the passage of tropical squall line types of disturbances in the monsoon flow.
3. We will collect solar photometric precipitable water data and microwave temperature and humidity data to aid in the analysis of passing mesoscale disturbances.

III. Summary of Presentation to Review Panel

The Arizona Monsoon is a seasonal reversal of the mean winds over the southwestern U.S. and Mexico from generally westerly during most of the year to generally easterly during July, August and part of September. This reversal of the winds satisfies the usual definition of a Monsoon. In addition, in this area this reversal is accompanied by a considerable increase in rainfall. Most of this rainfall results from thunderstorms and in the past it has been assumed that these storms could be forecast simply by examining certain airmass parameters such as precipitable water. When these parameters indicate that the airmass is both fairly unstable and wet then thunderstorms will be widespread, otherwise they will be scattered or absent. This technique works well at times; however there are other times when it doesn't. On some days there are no storms even though airmass parameters say there should be and vice versa. It is apparent on those days that there must be some sort of disturbance present to either enhance or inhibit thunderstorm activity.

In the past it has been virtually impossible to either study or forecast these disturbances due to a lack of conventional data. With the recent availability of satellite derived data this is no longer the case. Thus we have spent the last two years attempting to use this new data from satellites, as well as any other non-conventional data, to describe the structure and dynamics of some of these disturbances. We have described a number of these disturbances in other review sessions. These include the monsoon boundary (Adang and Gall 1988), disturbances that form along the monsoon boundary (Moore, Gall and Adang 1988) and a system that forms over the mountains of Arizona and Mexico in the late afternoon, propagates westward after sunset and has many of the properties of tropical squall lines (Smith and Gall 1988). All of these studies have benefited from data sources in addition to those given by satellite and conventional devices. For example we have made extensive use of lightning location information to show the location and motion of convective systems. We recognize that any additional data source that we can develop may also prove important in our understanding of systems such as those described in the above mentioned references as well as others. Thus in this review, rather than again summarizing the work we have completed on the structure of monsoon disturbances, we will instead summarize our development work on a simple system to determine precipitable water.

As has been described in Adang and Gall 1988, the monsoon boundary is frontal-like and separates an extremely dry air mass, generally to the west and north of the boundary, from a very moist air mass to the south and east of the boundary. This boundary frequently lies over Arizona and its meanderings, or oscillations are extremely important determining the total precipitable water over any given region. Thus measurements of precipitated water are very useful in determining the location and motions of their boundary. The normal radiosonde data does not yield the required temporal resolution for tracking this boundary, and the spatial resolution is inadequate for determining the presence of many mesoscale disturbances

along the boundary. The technique to be described here is capable of yielding daytime temporal resolutions on the order of minutes, providing the sun is not observed by clouds (on most days, there are adequate breaks in the monsoon cloud cover to provide at least some data). This temporal resolution may then be interpreted in terms of a spatial resolution for moving disturbances.

The solar photometric technique for determining precipital water utilizes the Langley method for determining the total atmospheric extinction of the direct solar beam at any wavelength, λ . Thus, if $F_{o\lambda}$ is the solar irradiance at the top of the atmosphere, then an instrument at the surface will measure an irradiance F_λ given by

$$F_\lambda = F_{o\lambda} e^{-m\tau_\lambda} \quad (1)$$

where τ_λ is the total vertical optical depth and $m = \sec \theta_0$, where θ_0 is the solar zenith angle. Writing eq. (1) logarithmically yields

$$\ln F_\lambda = \ln F_{o\lambda} - m\tau_\lambda \quad (2)$$

If a series of measurements at various solar zenith angles are made, and the logarithm of the measurements, $\ln F_\lambda$ is plotted against m , the points should fall on a straight line with intercept $\ln F_{o\lambda}$ and slope, $-\tau_\lambda$. In this manner the total optical depth at any wavelength may be determined. In a water vapor absorption band, the total optical depth may be written as

$$\tau_\lambda = \tau_{R\lambda} + \tau_{a\lambda} + \tau_{w\lambda} \quad (3)$$

where τ_λ is the known Rayleigh optical depth, $\tau_{a\lambda}$ is the aerosol optical depth, and $\tau_{w\lambda}$ is the desired water vapor optical depth. If other measurements are made outside the water vapor band (and without any other gaseous absorption) then, at these wavelengths,

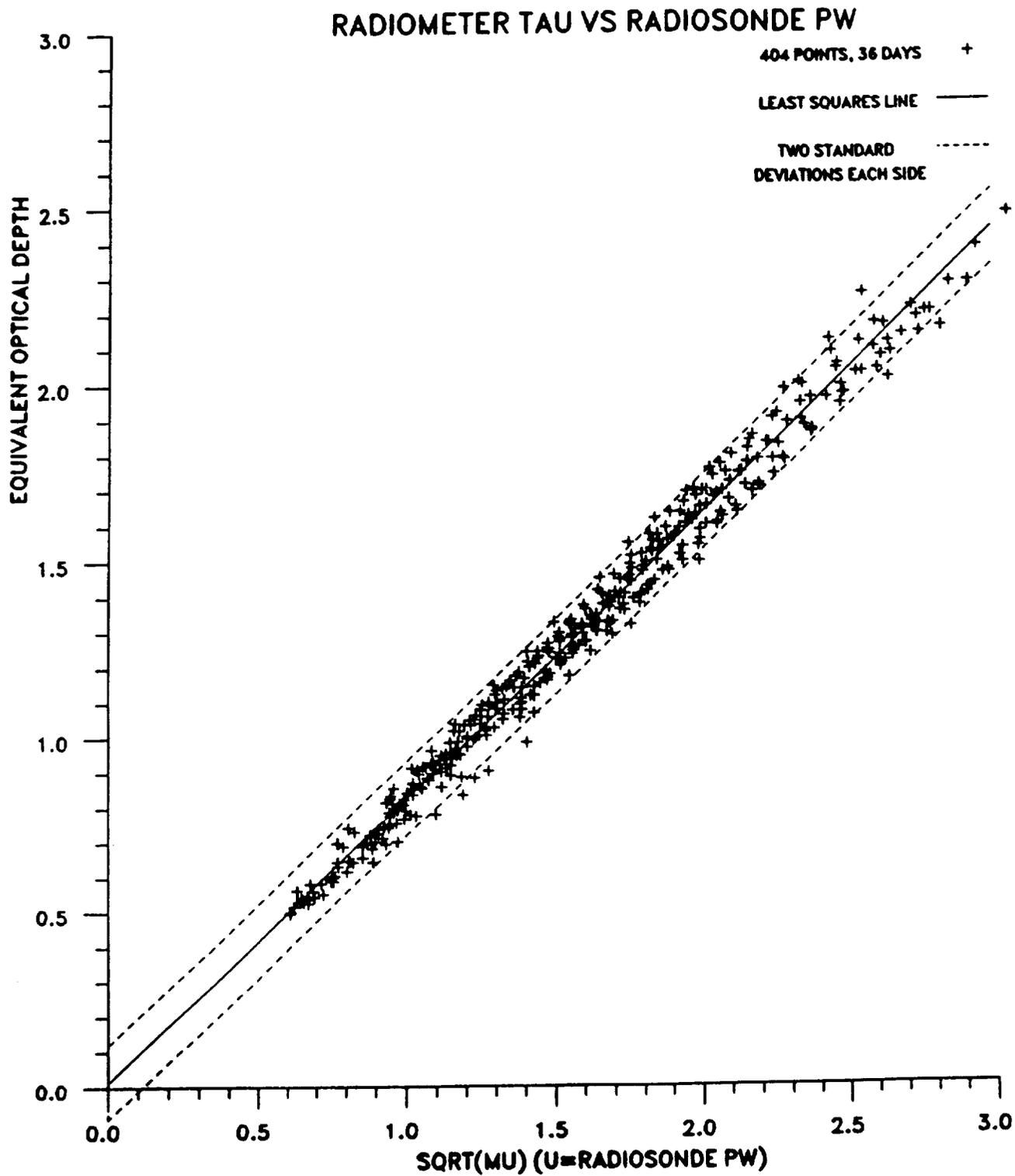
$$\tau_\lambda = \tau_{R\lambda} + \tau_{a\lambda} \quad (4)$$

and since the only unknown is $\tau_{a\lambda}$, the aerosol optical depth, this may readily be solved for at these wavelengths. From the known aerosol optical depth at non-absorbing wavelengths, the aerosol optical depth within the water vapor band may be inferred ($\tau_{a\lambda}$ in eq.(3)) by interpolation and then eq.(3) may be solved for $\tau_{w\lambda}$, the water vapor optical depth.

Once $\tau_{w\lambda}$ is known, it must be converted into a value for the total precipitable water (P.W.) Several techniques, both experimental and theoretical, have been tested (Twomey et al.). All methods give results which agree with each other to within the experimental errors (i.e., to within about $\pm 10\%$). One method we have employed utilizes the twice daily radiosonde P.W. Fig (1) shows a plot of the slant path optical depth, $m\tau_\lambda$ v.s. the square root of the total P.W., $\sqrt{\mu}$ where μ is the vertical P.W. determined from the radiosonde data. The best fit straight line has a slope of 0.807 and an intercept of 0.013. The theoretical technique gives a slope of 0.802 with a zero intercept. Both methods yield total P.W.'s generally within 10% of one another.

Fig. 2, 3, 4 show the P.W. determined in this manner as a function of time, together with the radiosonde P.W. as measured at 0600 and 1800 LST. As can be seen from these figures, the P.W. can, and often does, show great temporal variations that cannot be determined from the radiosonde data. During the present monsoon season, we will be employing this data, together with all of our other data sources, to help us obtain a better analysis of the various meso-scale disturbances within the monsoon flow that we are trying to study.

Figure 1. Least squares fit between radiometric slant path water vapor tau and radiosonde precipitable water.



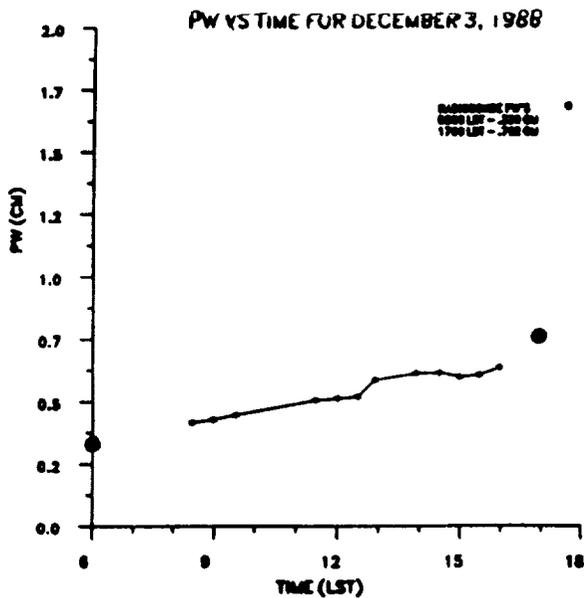


Figure 2. Radiometer precipitable water versus time for the five different models for case 1. Also shown are the radiosonde precipitable water.

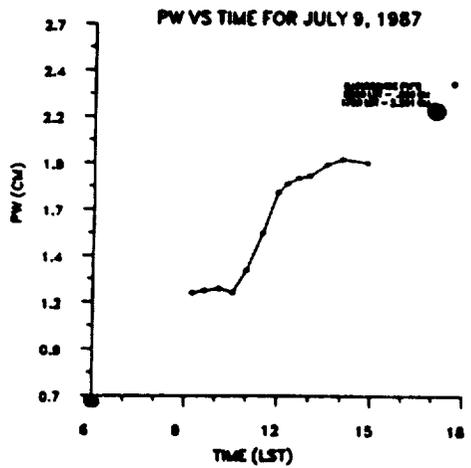


Figure 3. Radiometer precipitable water versus time for the five different models for case 3. Also shown are the radiosonde precipitable water.

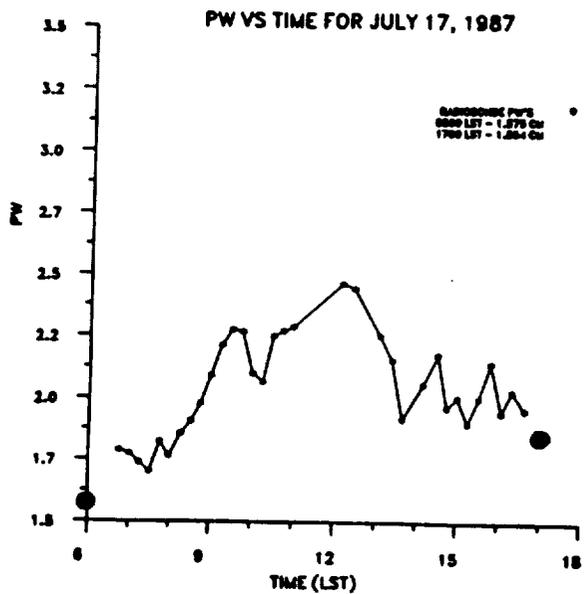


Figure 4. Radiometer precipitable water versus time for the five different models for case 4. Also shown are the radiosonde precipitable water.

ORIGIN: DATA
 OF NCAP QUALITY

IV. Publications

Adang, T. and R. Gall, 1988: "Structure and Dynamics of the Arizona Monsoon Boundary." Submitted to Monthly Weather Review.

Moore, T., R. Gall and T. Adang, 1988: "A Linear Stability Analyzer of the Arizona Monsoon Boundary." Submitted to Monthly Weather Review.

Smith, W. and R. Gall: "Tropical Squall Line in the Arizona Monsoon." In preparation.

Twomey, S., B. Herman and J. Reagan: "The Determination of Precipitable Water from Solar Transmission." Manuscript in preparation.

Title: Dynamics of Baroclinic Wave Systems**Investigators:**

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Significant Accomplishments in the Past Year:

The research carried out in the past year dealt with nonlinear baroclinic wave dynamics. The model consisted of an Eady baroclinic basic state and uneven Ekman dissipation at the top and bottom boundaries with/without slopes. The method of solution used a truncated spectral expansion with three zonal waves and one or two meridional modes. Numerical experiments were performed on synoptic scale waves or planetary scale waves with/without wave-wave interaction.

- (1) **Wave-wave vs. wave-mean flow interactions in an Eady-type model.** The relative importance of wave-wave interaction versus wave-mean flow interaction in the dynamics of baroclinic flows is examined by means of numerical experiments. It is shown that in some parameter regions where both solutions with and without wave-wave interaction have the same steady single-wave state, wave-wave interaction does not play a role in determining the equilibrium state of the flow at that parameter setting. This region is not necessarily near the marginal curves. In some other parameter regions, wave-wave interaction may destabilize a baroclinic flow, resulting in more temporal and spatial degrees of freedom of the flow. Therefore, wave-wave interaction may reduce the region of steady waves while enlarging the region of aperiodic flows in the parameter space. The experiments also show that, in a multi-wave system, the dependency of the final state on the initial condition is generally larger in a flow with wave-wave interaction than that in a flow without.
- (2) **The effect of sloping boundaries with Ekman dissipation in a nonlinear baroclinic system.** A modified Eady channel model with sloping top and bottom Ekman layers is used to examine the effect of sloping boundaries on baroclinic flows in a linear and nonlinear systems with/without wave-wave interaction, respectively. In the linear system, the sloping boundaries render the linear waves dispersive, stabilize unstable waves, and may shift the most unstable wavenumber to a higher one. In nonlinear systems, when wave-wave interaction is absent, the sloping boundaries reduce the region of vacillation and aperiodic flows, and enlarge

the region of single-wave steady wave where the preferred nonlinear wavenumber may also be shifted to a higher one by the slopes. When wave-wave interaction is included, most flows are destabilized. At some parameter settings, multi-steady wave states are observed in which the resultant flow exhibits vacillation. This additional mechanism of vacillation, besides the mechanism due to pure baroclinic instability, is caused by the interference of these steady waves which translate with different phase speeds. In contrast to the system without wave-wave interaction, the region of vacillation in a nonlinear system with wave-wave interaction is enlarged. The effect of sloping boundaries on both linear and nonlinear baroclinic waves is similar, in some sense, to the β -effect due to variation of Coriolis parameter with latitude in two-layer models.

Focus of Current Research and Plans for Next Year:

We are not currently supported by NASA. The new research for the next fiscal year, starting October 1988, is **Potential Vorticity Index**.

- (1) We will calculate potential vorticity on specific isentropic surfaces (IPV) for Northern Hemisphere, from both GLA and ECMWF FGGE data sets. The comparison between these two data sets will be performed through all the proposed data analyses.
- (2) We will do data analyses of the IPV climatology and try to find the relationship between IPV systems and blocking and cyclogenesis for Northern Hemisphere.

Papers supported by NASA grant NAG 8-075 in the Past Year:

- (1) Weng, H.-Y. and A. Barcion, 1988: Wavenumber selection for single-wave steady states in a nonlinear baroclinic system. *J. Atmos. Sci.*, **45**, 1039 – 1051.
- (2) Weng, H.-Y. and A. Barcion, 1988: Wavenumber transition and wavenumber vacillation in Eady-type baroclinic flows. *Quart. J. Roy. Meteor. Soc.*, in the July issue.
- (3) Weng, H.-Y., 1988: Wave-wave interactions in an f -plane baroclinic model. Submitted to *Tellus*
- (4) Weng, H.-Y., 1988: The effect of sloping boundaries with Ekman dissipation in a nonlinear baroclinic system. Submitted to *Quart. J. Roy. Meteor. Soc.*

Presentations:

Some of the above work was presented by A. Barcion at: Imperial College, Cambridge University, Bristol University, University of Reading, UK; Laboratoire de Meteorologie Dynamique, Paris; NCAR, University of Miami.

The Effect of Latent Heat Release on Synoptic-to-Planetary Wave Interactions and Its Implication for Satellite Observations: Theoretical Modeling

INVESTIGATORS: Dr. Lee E. Branscome and Dr. Rainer Bleck, University of Miami, Rosenstiel School of Marine and Atmospheric Science, 4600 Rickenbacker Causeway, Miami, FL 33149, (305) 361-4075

SIGNIFICANT ACCOMPLISHMENTS IN PAST YEAR:

The project objectives are as follows:

- Develop simple models to simulate interaction of planetary and synoptic-scale waves incorporating the effects of:
 - a. Large-scale topography
 - b. Eddy heat and momentum fluxes (or nonlinear dynamics)
 - c. Radiative heating/cooling
 - d. Latent heat release (precipitation) in synoptic-scale waves
- Determine the importance of latent heat release in oceanic storm tracks for temporal variability and time-mean behavior of planetary waves.
- Compare the model results with available observations of planetary and synoptic-scale wave variability and time-mean circulation.
- Ascertain the usefulness of monitoring precipitation in oceanic storm tracks by satellite observing systems.

The modeling effort includes two different low-order quasi-geostrophic models:

- a. *Time-dependent* version to study intraseasonal variability, anomalous circulations and seasonal cycle. This version will explicitly resolve a few planetary and synoptic waves and their interaction and the transport of water vapor by wave motions.
- b. *Climatological mean* version to study response of planetary waves to slow variations in external forcing. This version will explicitly resolve stationary planetary waves only, while parameterizing average effects of transient synoptic-scale waves and latent heat release.

The modeling also includes a low-order primitive equation model. A time-dependent, multi-level version will be used to validate the two-level Q-G models and examine effects of spherical geometry. It will explicitly resolve a few planetary and synoptic waves and include specific humidity as predicted variable, moist convective parameterization and large-scale precipitation.

Since the beginning of the grant in July 1987, we have constructed a two-level model of the extratropical atmosphere which has an arbitrary truncation of meridional and zonal modes. A complete package of diagnostics were developed for the model to examine heat and momentum balances, time-mean fields, energetics, energy

spectra, persistent anomalies, etc. Tests with this model form the dissertation of Ph.D. student Enda O'Brien, who was supported by this grant. The results answer outstanding questions regarding the usefulness of low-order models of the general circulation and provide a foundation for our modeling effort. The results are reported in a paper in press for Tellus, a second paper accepted for Tellus and a third paper submitted to J. Atmos. Sci.

The first paper deals with variability within a low-order ("2 by 2" or 2 zonal waves plus a mean flow, 2 meridional modes) version of the model in the presence of planetary-scale topography. We examined the viability of theories of persistent circulation anomalies. We found that the two distinct "weather regimes" (i.e., extremely long-lived configurations of planetary waves) reported by other investigators vanish when realistic physical parameters are used in the model. These regimes are replaced with a more random temporal distribution of the planetary wave in phase space. Persistent anomalies are found that more closely simulate observed anomalies than the weather regimes.

The second paper examines the resolution and processes needed in a low-order model to accurately represent basic features of the extratropical general circulation, e.g., the time and zonal mean circulation, eddy variability and energetics. To achieve this end, the model must have sufficient resolution (at least three wave modes in both the zonal and meridional directions) to represent wave-wave interactions and eddy momentum fluxes, as well as appropriate, but simple, parameterizations to represent radiative driving and dissipation. A "3 by 3" model is capable of representing the mean zonal flow including surface winds, a three-cell meridional circulation, realistic heat and momentum budgets and energy cycle, and a simple K^{-3} energy spectrum where K is total wavenumber. These features are also present in higher resolutions with small quantitative differences. However, a model with only one even and one odd meridional mode is incapable of reproducing the momentum budget, time-mean surface zonal winds and the three-cell structure.

The third paper examines the effect of large-scale topography on the interaction of synoptic and planetary waves in the model, using various truncations. This paper discusses basic elements of stationary wave forcing by topography and the role of synoptic-scale eddies in the variability and time-mean maintenance of the planetary-scale waves. We found that a "5 by 5" truncation provided a reasonable low-order representation of time-mean stationary waves. We also found that wave-wave interactions act to reduce the amplitude of the short stationary waves and alter the phase of the topographically-forced long wave. Stationary waves and persistent anomalies in the model have about one-half the amplitude of observed features. Latent heating appears to be the missing ingredient and, based on satellite-derived observations of diabatic heating over the oceans, will make an order one contribution to the heat budget of the planetary waves.

Thus, a major tool in the project has been developed and tested, using observed atmospheric behavior as a standard. We have also prepared computer code for a low-order, primitive-equations model on a sphere. This

model is a subset of the spectral model used by the National Meteorological Center for medium-range forecasts. We have prepared the model for idealized experiments with water vapor and topography and are currently in the testing stage with this model. A complete package of spectral energetics and wave-mean flow diagnostics was developed in the first year. The model includes parameterizations of large-scale condensation and moist convection.

FOCUS OF CURRENT RESEARCH AND PLANS FOR NEXT YEAR:

The results to date demonstrate the usefulness and success of low-order modeling. We are currently working on incorporating moisture effects into the general truncation, quasi-geostrophic model so that the influence of latent heat release on the wave interactions can be examined in that model. During the second year of the grant we will be performing a number of long-term integrations with this model.

In the second year of the project we will examine the effect of moist processes in two different low-order models of the atmosphere, the two-level quasi-geostrophic model with a limited number of zonal and meridional modes in a periodic channel and the multi-level primitive-equations model on a sphere with three or four zonal wavenumbers (3,6,9 and 12) and several meridional modes. These models will include large-scale topography and allow for the development of both planetary and synoptic-scale waves. We will investigate the importance of latent heat release on the synoptic scales in the forcing and variability of planetary-scale waves. In particular, we anticipate that latent heat release in preferred locations (i.e., storm tracks) will be important in organizing or modifying the larger scale waves.

The results will assess the need for observing precipitation over extratropical oceans. In our experiments with the primitive-equations model we will compare the effects of moist convection and condensation by large-scale uplifting. This comparison will provide insights into the nature of the precipitation and its impact on the motion. It is expected that the method of observation of precipitation over the extratropical oceans will depend on the precipitation process. We hope to provide information regarding which type of process is important in the evolution of the large-scale circulation. Comparisons will be made between the behavior in the quasi-geostrophic and primitive-equations models to evaluate the limitations of the simpler, but more efficient quasi-geostrophic model.

PUBLICATIONS:

- O'Brien, E. and L. Branscome, 1988: Modes of variability in a low-order, two-level model. In press for Tellus.
- O'Brien, E. and L. Branscome, 1988: Minimal modeling of the atmospheric general circulation. Accepted for Tellus.
- O'Brien, E. and L. Branscome, 1988: The effect of large-scale topography in minimal general circulation models. In review for J. Atmos. Sci.

TITLE: The Effect of Latent Heat Release on
Synoptic-to Planetary Scale Wave
Interactions: Observational Study

INVESTIGATORS: Stephen Colucci
Steven Greco

AFFILIATION: Department of Environmental Sciences
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SIGNIFICANT ACCOMPLISHMENTS IN THE PAST YEAR:

We are completing an investigation of a blocking pattern which formed over eastern North America following the landfall of Hurricane Juan during November 1985. We hypothesize that latent heat released in the Hurricane's rainfall was either directly or indirectly responsible for the large observed 500 mb height rises over eastern Canada during the formation of this block. This idea is evaluated with a diagnostic model for the height tendency field which includes latent heat release as a forcing function. The total column heating is calculated using satellite-derived precipitation estimates provided by Dr. Pete Robertson of the Marshall Space Flight Center. These estimates are qualitatively congruent with observations, but overestimate light rainfall (in magnitude and aerial extent) and underestimate heavy rainfall (in magnitude). The heating is distributed sinusoidally in the vertical direction with a maximum at P=550 mb.

The calculations reveal that the direct contribution of the heating to the 500 mb height tendency field is small relative to the quasigeostrophic forcing. However, maxima in heating (i.e. rainfall) coincide with regions where anticyclonic potential vorticity is generated. Once such region is just upstream of the location of large 500 mb height rises in the incipient block. We therefore propose an indirect role of the heating in this case. Specifically, anticyclonic potential vorticity is generated near the heating maxima; this vorticity is then advected downstream, forcing the 500 mb heights to rise and the block to develop.

FOCUS OF CURRENT RESEARCH AND PLANS FOR NEXT YEAR:

Currently we are testing the sensitivity of the above findings to the shape of the vertical heating profile, recognizing that a sinusoidal shape may be too simplistic. Once this is done, a paper now in preparation which describes this work will be submitted for consideration for publication.

Now that we have tested Robertson's satellite precipitation algorithm with a continental case, we wish to investigate blocking examples over the Atlantic Ocean where there is no precipitation data against which to compare the satellite estimates. We have requested the satellite data for blocking cases during January and February 1983 and April 1982, each associated with intense surface cyclone activity. While we await this data as Dr. Robertson refines his algorithm to ameliorate the inaccuracies noted earlier, we have begun to investigate the observed adiabatic dynamics of these cases, focusing upon the effect of static stability variations. We hope to complete this work within the next year.

PUBLICATIONS:

No papers have yet to be published from the above work. The following paper is in preparation for submission to the Journal of the Atmospheric Sciences:

"Large-scale circulation changes during the landfall of Hurricane Juan (1985): The Importance of latent heat release during the formation of a block".

The following paper based upon the above work was presented at the American Meteorological Society's Conference on Atmospheric and Oceanic Waves and Stability in August 1987:

"The importance of diabatic heating in the formation of a block".

Finally, the following paper, co-authored with Robert B. Jacobson of the United States Geological Survey (USGS), has been submitted for consideration as a chapter in a USGS technical report:

"Meteorology of the storm of November 3-5, 1985 in West Virginia and Virginia".

Title: USE OF SATELLITE DATA AND MODELING TO ASSESS THE INFLUENCE OF STRATOSPHERIC PROCESSES ON THE TROPOSPHERE

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Our research is comprised of the following tasks:

- 1) use simple analytical and numerical models of a coupled troposphere - stratosphere system to examine the effects of radiation and ozone on planetary wave dynamics and the tropospheric circulation;
- 2) use satellite data obtained from the Nimbus 7 Limb Infrared Monitor of the Stratosphere (LIMS) instrument and Solar Backscattered Ultraviolet (SBUV) experiment, in conjunction with National Meteorological Center (NMC) data, to determine the planetary wave vertical structures, dominant wave spectra, ozone spectra, and time variations in diabatic heating rate;
- 3) synthesize the modeling and observational results to provide a better understanding of the effects that stratospheric processes have on tropospheric dynamics.

Below we summarize our research carried out during the period 1 August 1987 to 15 June 1988, describe the research currently in progress, and outline our research plans for the period 1 August 1988 - 31 July 1989.

SIGNIFICANT ACCOMPLISHMENTS: 1 August 1987 - 15 June 1988

Our research during the past eleven months has focused on the following:

- * **Examination of the barotropic stability of realistic stratospheric jets on a sphere in which the jet profiles are taken from observational data.**

Results show that approximately nondispersive modes are associated with a region of negative basic state absolute vorticity gradient on the poleward side of the jet. In particular, broader jets and those which peak at higher latitudes produce poleward modes that are less dispersive. The jet profiles were derived from observational data at 10, 5 and 2 mb for three Southern Hemisphere months, and the stability characteristics of these profiles were compared with quasi-nondispersive features which have been observed in satellite data in the Southern Hemisphere winter stratosphere. Characteristics of the barotropically unstable modes compare remarkably well with those of the observed modes. The barotropic model results for a month in which these features were not observed indicate the presence of equatorward modes at zonal wavenumbers 3 and 4 which grow considerable faster than the quasi-nondispersive poleward modes. Also identified are westward moving modes in the summer hemisphere during June, and in analytical jet profiles with a realistic global structure (details concerning this work are described in Mannney, Nathan and Stanford, 1988a).

This work serves as a basis from which we can now examine whether realistic vertically and horizontally sheared stratospheric jet structures in a baroclinic atmosphere can significantly alter the reflection and transmission properties of the planetary waves, and thus affect the tropospheric circulation.

*** Examination of the role of dissipation in the finite amplitude interactions between forced and free baroclinic waves.**

The effects of dissipation on the weakly nonlinear interactions between a marginally unstable wave and a resonant topographic wave were examined using multiple time scales in a quasigeostrophic, two-layer model on a midlatitude beta-plane channel. The lower boundary is characterized by sinusoidal bottom topography. The dissipation was chosen as one or a combination of the following forms: Ekman dissipation at the lower and upper boundaries, interfacial Ekman dissipation, thickness damping, and potential vorticity damping (PVD).

In the absence of topography the baroclinic wave always equilibrates irrespective of the form of the dissipation. If the dissipation is sufficiently weak and due solely to PVD, the baroclinic wave exhibits a damped vacillation symmetric about its steady value. If the form of the dissipation is different from PVD, the baroclinic wave evolves through three distinct stages: initial exponential growth, a damped vacillation in which the overall envelope of the vacillation increases on an intermediate time scale and, finally, an asymptotic approach towards equilibration.

In the presence of topography, numerical integrations of the asymptotically derived wave and mean flow evolution equations were carried out for the case where the topographic wave is taken zero initially. It is shown that depending on the form and/or the strength of the dissipation, the asymptotic state of the system is characterized by either a single (stationary) topographic wave state or a mixed wave state. Weak PVD favors the single wave states while, in sharp contrast, other dissipation forms, provided they are sufficiently weak, favor the mixed wave states. Perpetual vacillation was not obtained (details concerning this work can be found in Nathan, 1988b).

The degree to which these results are changed with the explicit incorporation of diabatic heating/cooling due to oxygen only photochemistry in a continuous model of the atmosphere is currently under study. Preliminary results indicate that such explicit photochemical coupling to the dynamics may have important implications regarding the stability of planetary waves and the coupling between the stratosphere and troposphere.

*** Examination of the influence of short-term variations of solar ultraviolet radiation on stratospheric ozone and temperature.**

This work examines the influence of variations in solar UV radiation flux on ozone and temperature in the middle to upper stratosphere for the time scale of the solar rotation period. The problem is formulated within the context of a coupled, one dimensional radiative-photochemical model. Negative ozone phases relative to the UV flux are predicted for the upper stratosphere in accord with recent observational and theoretical results. The increase in temperature phase with decreasing height results from a shift from direct forcing by solar flux variations at 1 mb to indirect forcing by sun induced ozone perturbations at 10 mb. The strength of damping strongly affects the response of the system to changes in the solar forcing period. (Results of this work are described in White and Yarger, 1988)

CURRENT RESEARCH ACTIVITIES

*** Examination of satellite-derived ozone and temperature field data.**

A reconstruction of synoptic ozone fields from asynoptic satellite ozone data is currently under study. The method of Salby (1982a,b; JAS), as applied to observational data by Lait and Stanford (1988; JAS), has been adopted. The Salby method was modified for use with only one scantrack and only ascending nodes, such as the backscattered ultraviolet ozone data of the Nimbus 4 BUV or Nimbus 7 SBUV experiments. Preliminary analyses of BUV ozone data have been carried out to obtain daily maps of ozone mixing ratio north of 30° at 1 mb for April through October 1970. SBUV ozone data have been obtained for analysis by this technique. The reconstructed ozone fields and temperature fields will be used for comparison with our numerical model results. These reconstructed ozone fields will also be analyzed to better understand the time dependent behavior of stratospheric ozone over the period of satellite observations.

*** Examination of the effects of radiation and ozone on the linear stability properties of external Rossby waves in a continuously stratified model of the atmosphere.**

The role of ozone in the linear stability of Rossby normal modes was examined in a continuously stratified, extratropical baroclinic atmosphere. The flow is described by coupled equations for the quasigeostrophic potential vorticity and ozone volume mixing ratio. A perturbation analysis has been carried out under the assumption of weak diabatic heating, which is generated by Newtonian cooling and dynamics-ozone interaction. An expression for the propagation and growth characteristics was obtained analytically in terms of the vertically averaged wave activity, which depends on the wave spatial structure, photochemistry, and basic state distributions of wind, temperature and ozone volume mixing ratio. A qualitative analysis of the results suggests that coupling of the dynamics with ozone has a destabilizing influence on external Rossby waves (results of this study can be found in Nathan, 1988c).

The possible effects of chlorofluorocarbons (CFCs) on the stability of traveling normal modes, and implications for the tropospheric circulation, are currently under investigation.

*** Examination of the effects of radiation, ozone advection, and ozone photochemistry on the linear stability properties of transient normal modes in a multilevel, quasigeostrophic, midlatitude beta plane channel model.**

We are currently investigating to what extent diabatic heating induced by the advection of ozone and ozone photochemistry can alter the vertical structure, propagation characteristics and growth rates of transient planetary waves based on realistic basic state distributions of zonal wind, temperature and ozone. Variable opacity and temperature dependent ozone absorption have also been incorporated into the model. Standard reference profiles of ozone and temperature have been obtained for calculation of the photochemical variables. The numerical code for determining the structure and stability properties of the transient planetary waves is currently being developed.

RESEARCH PLANS: 1 August 1988 - 31 July 1989

Our research plans for the next year are:

- * Determine analytically the effects of radiation and photochemistry on the linear stability properties of internal Rossby waves and compare with our results obtained for the external Rossby waves.
- * Develop analytically the wave - mean flow interaction equations for travelling normal modes in the presence of radiation and ozone photochemistry.
- * Complete development of the numerical code for the multi-level, linearized quasigeostrophic model which incorporates radiation and ozone photochemistry. The model will be used to confirm our analytically derived results and to consider more realistic basic state flow structures.
- * Continue to analyze satellite derived ozone and temperature fields, and compare our observational results with our analytical and numerical model results.
- * Begin an extensive description of stratospheric ozone characteristics based on satellite observations.

PUBLICATIONS/PRESENTATIONS: 1 August 1987 - 15 June 1988

a) Refereed Publications

- 1) Nathan, T. R., 1988a: "Finite amplitude interactions between unstable baroclinic waves and resonant topographic waves." J. Atmos. Sci., 45, 1052-1071.
- 2) Manney, G., T. R. Nathan, and J. Stanford, 1988a: "Barotropic stability of realistic stratospheric jets." J. Atmos. Sci. (in press).
- 3) Nathan, T. R., 1988b: "On the role of dissipation in the finite amplitude interactions between forced and free baroclinic waves." Geophys. Astro. Fluid Dyn. (in press)
- 4) White, R., and D. Y. Yarger, 1988: "Influence of short term variations of solar UV radiation on stratospheric ozone and temperature." (submitted to Pure and Applied Geophysics)
- 5) Manney, G., T. R. Nathan, and J. Stanford, 1988b: "Barotropic instability of basic states with a realistic jet and a wave." J. Atmos. Sci. (in revision)
- 6) Nathan, T. R., 1988c: "On the role of ozone in the stability of Rossby Normal modes." (submitted to J. Atmos. Sci.)

b) Refereed Abstracts/Conference Presentations

- 1) Nathan, T. R., 1987: "Interactions between unstable baroclinic waves and quasistationary waves in the presence of topography and periodic forcing." Sixth Conference on Atmospheric and Oceanic Waves and Stability, Seattle, Washington.
- 2) Barcilon, A., and T. R. Nathan, 1987: "Dynamics of Forced and Free Finite Amplitude Baroclinic Waves." Sixth Conference on Atmospheric and Oceanic Waves and Stability, Seattle, Washington.
- 3) Nathan, T. R., 1988: "Chaos in Physical Systems." Physics Section, 100th Session of the Iowa Academy of Sciences."
- 4) Manney, G. L., T. R. Nathan, and J. Stanford, 1988: "Stability of stratospheric zonally varying flow." Southeast Geophysical Fluid Dynamics Conference, Huntsville, Alabama.
- 5) Nathan, T. R., 1988: "Seasonal forcing of finite amplitude baroclinic waves." Southeast Geophysical Fluid Dynamics Conference, Huntsville, Alabama.

**LABORATORY AND THEORETICAL MODELS OF
PLANETARY-SCALE INSTABILITIES AND WAVES**

June 30, 1988

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Meteorologists and astrophysicists interested in global planetary and solar circulations have long recognized the importance of rotation and stratification in constraining the character of these flows. In particular, the effect of latitude-dependent Coriolis forces, the so-called beta-effect, is thought to play a crucial role in such phenomena as differential rotation on the Sun, cloud band orientation on Jupiter, and the generation of magnetic fields in thermally driven dynamos. Most theoretical works, and all prior laboratory studies on these problems, have treated the curvature effects only locally, and the laboratory efforts have only been able to consistently study beta-effects in layered quasi-geostrophic models.

The continuous low-g environment of the orbiting space shuttle provided a unique setting for conducting geophysical fluid model experiments with a completely consistent representation of sphericity and the resultant radial gravity found on astrogeophysical objects. This is possible because in zero gravity one can construct an experiment that has its own radial buoyancy forces. The dielectric forces in a liquid, which are linearly dependent on fluid temperature, give rise to an effectively radial buoyancy force when a radial electrostatic field is applied. The Geophysical Fluid Flow Cell (GFFC) experiment is an implementation of this idea in which fluid is contained between two rotating hemispheres that are differentially heated and stressed with a large a-c voltage. The GFFC flew on Spacelab III in May, 1985. Data in the form of global Schlieren images of convective patterns were obtained for a large variety of configurations. These included situations of rapid rotation (large Taylor numbers), low rotation, large and small thermal forcing (ie. a range of Rayleigh numbers based on the electrostatic gravity and the statically unstable radial temperature contrast), and situations with applied meridional temperature gradients. Our group has been involved with the analysis and interpretation of the GFFC-85 data. We have also developed improvements to the GFFC instrument that will allow for real-time (TV) display of convection data and for near-real-time interactive experiments. These experiments, on the transition to global turbulence, the breakdown of rapidly rotating convective planforms (banana cells) and other phenomena, are scheduled to be carried out on the International Microgravity Laboratory (IML-1) aboard the shuttle in June, 1990.

Research Accomplishments over the period June 1987 - June 1988

Planform Selection

The plane parallel model of nonlinear planform selection was extended to spherical geometry. In planar geometry, the (GFFC) observed tendency for down-center hexagons at low Taylor number was generated by the fact that the inner GFFC spherical surface has stronger gravity. In spherical geometry, a similar effect is present. However, numerical simulations (using Glatzmaier's model) have indicated a preference for down-center hexagons even with inverse r -squared gravity, with a small enhancement for inverse r -fifth gravity. The weakly nonlinear model does not have this property, suggesting that the GFFC experiments may have been influenced by more than one desymmetrizing force. Future GFFC experiments, looking again at a range of low Taylor numbers with better thermal boundary control than on SL-3 shall re-address this planform selection issue.

Spiral Waves

The rather astounding superposition of spiral waves alongside strong north-south columnar convective rolls at moderate Taylor number was addressed by studying the linear stability properties of local Hadley circulations (Hart, 1988). The locally planar, exact, Hadley circulation changes with latitude. At the poles the zonal flow is strong, whereas at the equator it is very weak (with the bulk of the basic state flow being tied up in a simple meridional circulation). Linear eigenfunctions tended to line up with the ambient shear (for the moderate Prandtl number of the GFFC experiment). As one approaches the pole, the linear modes are locally at an angle of up to 45 degrees with respect to a meridian. Whereas near the equator, the axes of the most unstable modes are within 10 degrees of a meridian. This tendency may explain the different characteristics of the polar and equatorial modes observed in the SL-III GFFC data.

Columnar Convection

We have studied the GFFC flight data in detail in order to understand the competition between columnar cells (banana cells) at lower latitudes and strong disturbances at higher latitudes (e.g. Toomre, Hart, and Glatzmaier 1987). Under the most nonlinear conditions considered with GFFC, we find that there remain distinct signatures of banana cells at low latitudes, and this suggests that similar giant convection cells may indeed be present deep within the solar convection zone. The GFFC data provides the only experimental means to directly study such rotationally-constrained convection, and thus our data is of great interest to the observational and theoretical efforts in helioseismology which will use the oscillations of the Sun to probe the interior dynamics of this star (Toomre, 1986, Hill et al. 1988). We are providing our GFFC imaging data on the banana cells, along with velocity and thermal fields from our three-dimensional simulations of these GFFC experiments, to the helioseismology working groups dealing with both the ground-based GONG project and the now-approved NASA/ESA SOHO spacecraft solar oscillations imager experiment. Our simulation data will permit frequency splittings to be calculated for potential oscillation modes to be used to search for the flows of the giant cells.

Numerical Simulations

We have continued our major efforts in the numerical modelling of fully compressible convection, for it is essential to understand the effects of stratification on flows that can readily span multiple density scale heights in the vertical (Hurlburt, Toomre & Massaguer, 1986, 1988a, 1988b). Such work is vital in making the link between results from our GFFC experiment and real convective flows in the Sun or in the giant planets. We have recently begun the first substantial three-dimensional simulations of compressible convection (employing 64x64x64 modes) with Dr. Fausto Cattaneo, and we find that the pronounced asymmetries between strong, concentrated downflows and weaker, broader upflows seen in our 2-D simulations are retained. However, the sheets of downflow at cell peripheries, evident near the top of the layer, turn into distinct plumes at greater depths, and thus the topology of the cells changes noticeably with depth. The compressible code has been further used to investigate convection in the presence of strong magnetic fields, and of buoyancy instabilities of intense fields, as might be occurring near the base of the solar convection zone (e.g. Cattaneo & Hughes 1987, 1988, Hughes, 1987, Hughes and Cattaneo, 1987, Cattaneo, 1988). We have also studied the properties of travelling and modulated waves in convection, dealing with doubly diffusive convection with its remarkably rich bifurcation structure (Deane, Knobloch & Toomre, 1987, 1988). This latter problem is analogous to that for rotating polar convection, and solutions found will be useful in interpreting GFFC data.

Experiment Modifications

A design for converting the GFFC film camera into a combined 16mm film and real-time TV downlink camera has been developed following the ideas of the PI (J.E. Hart). The PDR for the Univ. of Colo. Video Acquisition Module was held in April, and the Critical Design Review is scheduled for Aug. 9. All circuits have been breadboarded and successfully tested. An approved parts list has been generated. Delivery and integration of the Video Module is scheduled for Fall, 1988.

Research Plans

Theoretical Modelling

Instability calculations using the exact parallel flow Hadley circulations as basic states will be continued. Prandtl numbers other than the previous GFFC flight value will be considered. The results will be compared to numerical calculations using a full (nonlinear) axisymmetric state by Miller et. al. at UAH.

Data Analyses

Using much higher resolution TV-imaging technology, with the capability of extensive noise reduction (through real-time averaging and smoothing), the Spacelab-III data films will be redigitized. This time we intend to use the original films rather than copies, in order to capture subtle details and to expand the dynamic range of the secondary data products such as the longitudinal wavenumber spectra. The data films will be archived in digital form on read-only laser discs. These data will be used to analyze the

Rayleigh number evolution of spiral and cross waves in situations with moderate to strong north-south heating.

Numerical Simulations

We are planning to undertake a major new series of direct three-dimensional simulations of GFFC convection, and use these to help guide the experimental parameter values to be employed during the IML-1 reflight of GFFC. We will be using a refined version of the pseudo-spectral code devised by Dr. Gary Glatzmaier, employing spherical harmonics in the horizontal and Chebyshev polynomials in the radial direction. Dr. Nicholas Brummell from Imperial College, London will be joining us as a postdoc to participate in these simulations, and we expect to carry out much of the work on the NASA-Ames NAS Cray-2 supercomputers. Those machines with their 256MWord memories are essential if we are to use the 4000 or more spherical harmonics in the nonlinear simulations, and such modal resolution is required to begin to make contact with the parameter values that we can readily attain with the GFFC. These Cray-2 machines are accessible by fast network links from Boulder, and we now have available Unix-based IDL software for interactive analysis and display of the planned simulations. Such modelling is not only very demanding of computing resources, but the data sets to be produced are massive and the techniques for visualizing the flows are challenging. We have developed considerable experience with many aspects of these challenges through our current three-dimensional compressible simulations, and thus we are confident that together with Drs. Cattaneo and Glatzmaier we can learn a great deal from these new simulations of GFFC flows.

Experiment Integration

The real-time television module shall be installed into the current GFFC instrument. The system shall be calibrated (optically) and tested as a functional unit, complete with the interactive display and experiment control software that shall enable the astronaut to change experiment parameters in response to particularly interesting convection data.

Planning for IML-1

The GFFC real-time software shall be updated to include a set of experiment scenarios selected on the basis of extensive numerical integrations and analyses of the previous flight data. The IML-1 flight runs will concentrate on the breakup of banana cells, the transition to unsteady (turbulent) convection, especially in situations (ie heating distributions) not investigated during SL-III. A backup set of executable scenarios will be set in GFFC ROM's for use in case there is a breakdown of the GFFC-GRID computer datalink. The Univ. of Colorado team will also be involved in astronaut science training, and in extensive preparations for launch and mission operations support. These activities will be coordinated by the PI's and Mr. Scott Kittelman who will re-join the project in September and who shall be in charge of ground support equipment and data analysis.

List of Publications

- Cattaneo, F., "Compressible magnetoconvection: linear theory." Submitted to Geophys. and Astrophys. Fluid Dyn., (1988).
- Cattaneo, F., and Hughes, D.W., "The nonlinear breakup of a magnetic layer: instability to interchange modes." J. Fluid Mech., in press (1988).
- Cattaneo, F., Hughes, D.W. and Proctor, M.R.E., "Mean advection effects in turbulence." Geophys. and Astrophys. Fluid Dyn., 41, 335-342 (1988).
- Cattaneo, F., and Hughes, D.W., "Magnetic fields in the overshoot zone: the great escape." Theoretical problems in high resolution solar physics II, NASA Conf. Pub 2483, 101-104 (1987).
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- Hill, F., Gough, D.O., Toomre, J., and Haber, D.A., "Solar equatorial rotation rate inferred from inversion of frequency splitting of high-degree modes." Advances in helioseismology, J. Christensen-Dalsgaard and S. Frandsen Eds., IAU, 45-48 (1988).
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- Knobloch, E., Deane, A.E., Toomre, J., and Moore, D.R., "Doubly diffusive waves." Contemp. Maths., 56, 203-209 (1986).
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LABORATORY AND THEORETICAL STUDIES OF BAROCLINIC PROCESSES

Principal Investigator: Dr. Timothy Miller
MSFC/ED42

Collaborators:

Experiments:

Dr. Fred Leslie, MSFC/ED42
Dr. Dan Fitzjarrald, MSFC/ED43
Dr. Nathaniel Reynolds, UAH

Numerical modeling:

Dr. Shih-Hung Chou, NRC (MSFC/ED42)
Ms. Karen Payne, NTI (MSFC/ED42)
Dr. Joseph Fehribach, UAH

Theoretical/analytical:

Dr. Nathaniel Reynolds
Dr. Shih-Hung Chou

OBJECTIVES:

This research is aimed at developing an understanding of fundamental processes which may be important in the atmosphere, and at supporting the definition and analysis of baroclinic experiments utilizing the GFFC apparatus in micro-gravity space flights. Included are studies using numerical codes, theoretical models, and terrestrial laboratory experiments. The numerical modeling is performed in three stages: calculation of steady axisymmetric flow, calculation of fastest-growing linear eigenmodes, and nonlinear effects (first, wave-mean flow interactions, then wave-wave interactions). The code can accommodate cylindrical, spherical, or channel geometry. It uses finite differences in the vertical and meridional directions, and is spectral in the azimuthal. The theoretical work has been mostly in the area of effects of topography upon the baroclinic instability problem. The laboratory experiments are performed in a cylindrical annulus which has a temperature gradient imposed upon the lower surface and an approximately isothermal outer wall, with the upper and inner surfaces being nominally thermally insulating.

SIGNIFICANT ACCOMPLISHMENTS IN THE PAST YEAR:

Although the PI has been at NASA Headquarters for the year, work has proceeded in all areas. Dr. Fehribach has utilized the axisymmetric/linear wave code to analyze flows which would occur in a GFFC apparatus which had "Earth-like" meridional temperature gradients, i.e., heated equator and cooled pole, with vertical stability imposed by having the outer sphere warmer than the inner. A transition curve was computed in thermal Rossby number (Ro), Taylor number (Ta) space. (The transition curve separates the region in which the axisymmetric flow is stable from that which is unstable.) Similar to the experiments that would actually be performed in space, Ro was varied by fixing the boundary temperatures and varying the artificial radial gravity. The transition curve for relatively low rotation rate (Ta) was very similar to that computed for the heated

pole (which is how the current hardware must be operated) by the PI the previous year, but for faster rotation there is a big difference. Centrifugally induced buoyant instabilities occur for small enough Ro , which give rise to another transition curve which intersects the baroclinic instability curve. This causes the axisymmetric flow to be unstable regardless of Ro (for large enough Ta). Thus, there appears to be an advantage to heating the pole and cooling the equator, at least in terms of performing analysis near the transition curve.

Ms. Payne and Dr. Chou have worked on further development of the numerical code. Ms. Payne implemented wave-mean flow feedback, so that the amplitude of a single unstable wave could be determined. The results were carefully checked against the only available published results, those of Williams and Quon. The present code disagrees with Williams and Quon for the single case they analyzed in the sense that wavenumber 5 (which is the only one they considered) equilibrates at a lower amplitude than theirs. Our wave number 4 case looks very much like their wave number 5. We have obtained some output and diagnostics from Quon's code supplied to us by Dr. Richard Pfeffer, FSU, with which we can compare our code. Most of the numerical techniques used by the codes are identical, and the numerical values of the terms should be the same. We suspect that the difference is in the advection of meridional and vertical momentum, where there are differences in the formulation. Detailed comparison and determination of the cause for the difference may be completed by the time we have our review meeting. Dr. Chou has begun work to include multiple azimuthal waves with wave-wave interactions. This will allow fully nonlinear simulations of fluid flow in a broad range of applications.

Theoretical studies by Drs. Chou and Reynolds consider the effects of topography on baroclinic instability. Dr. Reynolds was partially supported by this task, but he is proposing to expand his work separately, and the description of his work is not included here. Dr. Chou has developed a spectral numerical model for a rotating infinite channel to study the effect of topography on nonlinear baroclinic disturbances. Both its effect on exciting a disturbance of the same scale and its ability to modulate disturbances of another scale are examined. He finds that topography generates a short period modulation which superimposes on a long time nonlinear baroclinic evolution pattern that could be produced in the absence of topography. The topography has a tendency to phase-lock the disturbance, especially the topographic mode, while the baroclinicity leads to the propagation of the disturbance, especially the most unstable mode.

Further work on the cylindrical annulus laboratory experiments has been hampered by leakage problems with the turntable supplied by Contraves-Goertz. Currently, the table is back at the factory for repair. In the past year, Drs. Reynolds and Leslie completed calibration of the thermistors in the cylindrical apparatus (so that boundary temperatures can be determined), and wrote software for an Apple IIe computer so that the boundary temperature profile can be easily computed from resistance data. Preliminary experiments performed before the turntable malfunctioned showed interesting development of the spin-up process, which begins with small-scale convection arranged in rings around the annulus, and ends with smooth,

baroclinic waves. Transition to longer wavenumbers after the baroclinic waves form was observed, which occurs due to the combining of two waves and the spreading out of the others. It is hoped that these experiments will point to interesting cases which can be done in spherical geometry using the GFFC apparatus, and that they can be simulated in detail by the numerical code.

FOCUS OF CURRENT RESEARCH AND PLANS FOR NEXT YEAR:

As stated above, the new developments in the numerical code are being checked against other codes and sources for discrepancy are being sought. Depending upon the results of that analysis, changes in the code may or may not be made. After that process, the code will be used to more precisely define baroclinic experiments with GFFC on the IML-1 mission. The code will also serve as a valuable general research tool for studying dynamical processes in spherical and cylindrical geometry, hopefully better tying together much of the past laboratory work with the cylindrical annulus with the spherical atmosphere. The code will be used to analyze the results of the terrestrial laboratory studies, as well as being further verified by comparison with the laboratory results.

To investigate the topographically induced short-period modulation, a low truncation version of the spectral model will be employed to identify its source and physical mechanisms. The nonlinear interaction between a resonant topographic wave and a weakly unstable baroclinic wave, similar to that studied by Nathan, will also be examined. Preliminary results show a very good agreement between our numerical results and Nathan's analytical results. In the future, we will relax Nathan's parametric restrictions (e.g., weak supercriticality and small topographic height) to examine the validity of the analytical solutions and to extend the results in a broader parameter space.

When the turntable is returned from the factory, we will perform the experiments to determine a regime diagram for one set of external parameters (vertical depth, Prandtl number). This diagram will include the wave/axisymmetric transition curve as well as observed equilibrated wavenumber. The spin-up process will be documented and can be compared with the results of numerical simulations.

PUBLICATIONS:

T. L. Miller, "Baroclinic instability in a spherical space laboratory experiment," in process of revision (further work, including possible expansion of scope and adding authors, is pending PI's return to MSFC).

T. L. Miller, "On the design of baroclinic space laboratory experiments in spherical geometry," Sixth Conference on Atmospheric and Oceanic Waves and Stability, Seattle, August, 1987.

J. Fehribach and T. L. Miller, "Numerical stability analysis for a geophysical fluid flow cell" Southeastern Geophysical Fluid Dynamics Conference, April, 1988.

S.-H. Chou and A. L. Loesch, "Effect of topography on supercritical baroclinic disturbances" to present in Palmen Memorial Symposium on Extratropical Cyclones, Helsinki, Finland, August, 1988.

TITLE: AEROSOL IN THE PACIFIC TROPOSPHERE

INVESTIGATOR: ANTONY D. CLARKE

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Overview

The objective of our research in support of the NASA/GLOBE program emphasizes the use of near real-time optical techniques for the measurement of mid-tropospheric aerosol over the Central Pacific. The primary focus is on measurement of the aerosol size distribution over the range of particle diameters from 0.15 to 5.0 μm that are essential for modeling CO_2 backscatter values in support of the LAWS program.

The measurement system employs a LAS-X (Laser Aerosol Spectrometer-PMS, Boulder CO.) with a custom 256 channel pulse height analyzer and software for detailed measurement and analysis of aerosol size distributions. A thermal preheater system (Thermo Optic Aerosol Discriminator-TOAD) conditions the aerosol in a manner that allows the discrimination of the size distribution of individual aerosol components such as sulfuric acid, sulfates and refractory species (soot, salt or dust). This allows assessment of the relative contribution of each component to the BCO_2 signal. This is necessary since the different components have different sources, exhibit independent variability and provide different BCO_2 signals for a given mass and particle size. Our field activities involve experiments designed to examine both temporal and spatial variability of these aerosol components from ground based and aircraft platforms.

Significant Accomplishments During the Past Year

1) The LAS-X TOAD system was configured for deployment at Mauna Loa Observatory (MLO) and operated during the springtime transition from a relatively "clean" period of "background" aerosol to one displaying the characteristic transport of dust from Asia. MLO is one of four NOAA stations monitoring atmospheric constituents in remote sites as part of its Geophysical Monitoring for Climatic Change (GMCC) program. During nighttime downslope air flow the 3,500 m elevation at MLO provides an opportunity for the sampling of "background" mid-tropospheric air from a ground based platform. A preliminary analysis of our data suggest that dust present during periods of Asian dust transport (approximately one half of the year) dominates the BCO_2 backscatter signal expected for LAWS but is reduced to a secondary contributor when compared to sulfates during the "clean" low-dust periods (see publication below for details). Characterization of these "clean" periods is important since they are expected to be more characteristic of conditions at higher altitudes and they reflect conditions where signal to noise considerations for LAWS operation may be most critical.

2) We have also designed and built a virtual impactor that can increase the relative contribution of dust particles by a factor of ten prior to sampling with the LAS-X TOAD system. This effectively reduces sampling time under "clean" conditions and improves sampling statistics. Tests and calibrations of this impactor are ongoing.

Current Research & Plans for Next Year

- 1) We are currently modifying a CLIMET-252 optical particle counter for the analysis of coarse particles ($>5 \mu\text{m}$) not readily measured by the LAS-X. We hope to have this new instrument operational for a new MLO study in November 1988.
- 2) We are currently designing and building an isokinetic aerosol sampling inlet for our participation in the Pacific flight series scheduled for Spring 1989.
- 3) A new LOPC-TOAD system is also being designed in preparation for the Pacific flight series.
- 4) We are preparing for participation in a new MLO intensive comparison study in November 1988. Data analysis for the spring and winter 1988 MLO studies will be continued and integrated into a report.
- 5) We intend to participate with our instrumentation in both the spring and fall Pacific flight series scheduled for 1989.

Publications

A. D. Clarke, Preliminary Results of Aerosol Measurements Made at Mauna Loa Observatory in Support of the NASA/GLOBE Program, (submitted Jour. Geophys. Research-Atmospheres, May 1988).

TITLE: Aerosol Backscatter Studies Supporting LAWS

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SIGNIFICANT ACCOMPLISHMENTS TO DATE:

1. Aerosol backscatter algorithm development.

- A. Optimized Royal Signals and Radar Establishment (RSRE), United Kingdom (UK), Laser True Airspeed System (LATAS) algorithm for low backscatter conditions. Algorithm converts backscatter intensity measurements from focused continuous-wave (CW) airborne Doppler lidar into backscatter coefficients.
- B. Evaluated performance of optimized algorithm under marginal backscatter signal conditions.

2. CO₂ backscatter climatologies. Statistically analyzed 10.6 micron CO₂ aerosol backscatter climatologies compiled by RSRE, Wave Propagation Laboratory/NOAA (Boulder, CO), and Jet Propulsion Laboratory (Pasadena, CA). Climatologies reveal "clean background" aerosol mode near 10^{-10} kg⁻¹m²sr⁻¹ (mixing ratio units) through middle and upper troposphere, "convective mode" associated with planetary boundary layer convective activity, and "stratospheric mode" associated with volcanically-generated aerosols. Properties of clean background mode are critical to design and simulation studies of Laser Atmospheric Wind Sounder (LAWS), a MSFC Facility Instrument on the Earth Observing System (Eos).

3. Backscatter - water vapor studies. Previous intercomparisons suggested correlation between aerosol backscatter at CO₂ wavelength and water vapor. Field measurements of backscatter profiles with MSFC ground-based Doppler lidar system (GBDLS) were initiated in late FY88 to coincide with independent program of local rawinsonde releases and overflights by Multi-spectral Atmospheric Mapping Sensor (MAMS), a multi-channel infrared radiometer capable of measuring horizontal and vertical moisture distributions. Design and performance simulation studies for LAWS would benefit from the existence of a relationship between backscatter and water vapor.

FOCUS OF CURRENT RESEARCH AND PLANS FOR FY 89:

1. Backscatter algorithm development.

- A. Refine LATAS algorithm to improve performance under marginal signal conditions.
- B. Provide expertise to RSRE during debugging phase following installation of LATAS on new research aircraft; analyze forthcoming measurements; update UK climatology.

2. Global Backscatter Experiment (GLOBE) data base. Participate in implementation of GLOBE data base on desk-top computer; incorporate and periodically update CO₂ backscatter climatologies.

3. GLOBE survey flight preparations. Provide expertise on implementation of surface acoustic wave (SAW) spectrum analyzer to MSFC 9.1 and 10.6 micron CW backscatter lidars; apply LATAS algorithm to analysis of measurements from these systems during debug and field phases.

4. Backscatter - water vapor studies. Continue contemporaneous backscatter measurement program begun in late FY88. Define empirical relationship between backscatter and water vapor using (1) aforementioned field measurements and (2) carefully selected backscatter and water vapor measurement sets from, e.g., Joint Airport Weather Studies experiment and from VISSR Atmospheric Sounder (VAS) data archives.

PUBLICATIONS:

- Bowdle, D.A., J. Rothermel, J.M. Vaughan, D.W. Brown and M.J. Post, 1988: Aerosol backscatter measurements at 10.6 micrometers with airborne and ground-based CO₂ Doppler lidars over the Colorado High Plains, 1, Lidar intercomparison. Submitted to *J. Geophys. Res.-Atmospheres*.
- Bowdle, D.A., J. Rothermel, J.M. Vaughan and M.J. Post, 1988: Aerosol backscatter measurements at 10.6 micrometers with airborne and ground-based CO₂ Doppler lidars over the Colorado High Plains, 2, Backscatter structure. Submitted to *J. Geophys. Res.-Atmospheres*.
- Rothermel, J., D.A. Bowdle, J.M. Vaughan and M.J. Post, 1988: Evidence of a tropospheric aerosol backscatter background mode. Submitted to *Nature*.
- Rothermel, J., D.A. Bowdle, J.M. Vaughan, D.W. Brown and A.A. Woodfield, 1988: Calculation of aerosol backscatter from airborne CW focused CO₂ Doppler lidar measurements, 1, Algorithm description. Submitted to *J. Geophys. Res.-Atmospheres*.
- Rothermel, J., D.A. Bowdle and J.M. Vaughan, 1988: Calculation of aerosol backscatter from airborne CW focused CO₂ Doppler lidar measurements, 2, Algorithm performance. Submitted to *J. Geophys. Res.-Atmospheres*.
- Rothermel, J., D.A. Bowdle and J.M. Vaughan, 1988: Aerosol backscatter variability at 10.6 microns over Colorado High Plains during JAWS experiment. Presented, 3rd Conf. Sat. Meteor. Ocean., 1-5 Feb., Anaheim, CA, sponsored by Amer. Meteor. Soc.
- Vaughan, J.M., R. Callan, D.A. Bowdle and J. Rothermel, 1988: Spectral analysis, digital integration, and measurement of low backscatter in coherent laser radar. Submitted to *Appl. Optics*.

TITLE: Global Backscatter Assessment

N90-12080

INVESTIGATOR: David A. Bowdle, University of Alabama, Huntsville

SIGNIFICANT ACCOMPLISHMENTS IN THE PAST YEAR:

The activities described below have been performed as part of the GLOBE Backscatter Experiment (GLOBE), an international/interagency program coordinated by NASA to support NASA's Laser Atmospheric Wind Sounder (LAWS).

Global Backscatter Model The focus of this effort is the development of a global-scale model of aerosol backscatter for LAWS design and performance studies. The model is being developed in stages, the first of which is the determination of a design baseline backscatter magnitude. This objective is being attained assuming a global-scale background aerosol with an invariant geometric mean backscatter mixing ratio. Background parameters are derived from aerosol data sets with global-scale spatial and/or temporal coverage, using objective statistical decomposition and/or *a priori* stratification based on supplementary data. Backscatter coefficients at the LAWS design wavelength (currently envisioned to be 9.11 μm) are derived from background aerosol physical, chemical, and optical data, or from direct backscatter measurements at other wavelengths, using background conversion factors. Results to date confirm the background hypothesis to first order. Background backscatter magnitudes appear to be near the expected design threshold for LAWS. Critical uncertainties in the analysis involve lidar calibration procedures, conversion factors, sampling statistics, inter-hemispheric variability, and the effects of massive aerosol injection from volcanoes and dust storms.

Aerosol Data Analysis Direct measurements of aerosol backscatter at 10.6 μm from the Royal Signals and Radar Establishment (RSRE) and the Wave Propagation Laboratory (WPL) were selected for special study. This Investigator assisted in the optimization of the RSRE backscatter data processing code under low backscatter conditions, performed detailed analyses of collocated intercomparisons between the two lidars, and assisted in the analysis of the long-term backscatter climatologies from the two lidars. The intercomparison studies showed sufficient agreement to warrant the climatology study. Both climatologies showed similar background backscatter magnitudes, despite large spatial separation, further confirming the background hypothesis.

GLOBE Special Issue Timely presentation of GLOBE research results to the global geophysical community is required: 1) to ensure a rigorous scientific review of the GLOBE results and their impact on LAWS, 2) to ensure that the community bases its response to LAWS on appropriate evidence, 3) to support aerospace contractor studies for LAWS, and 4) to support national scientific and administrative reviews of LAWS. This objective is being met by a special GLOBE issue of the Journal of Geophysical Research - Atmospheres, for which this Investigator is Lead Guest Editor. The special issue was approved by the GLOBE Scientific Working Group (SWG) in September 1987, a Call for Papers was issued in October 1987, and paper submission was completed in July 1988. Approximately 20 papers are currently being considered for the special issue. Publication is expected in late winter, in time to support critical phases of the LAWS development effort.

Mission Planning Evaluation and screening of existing aerosol data and designing of new aerosol research in support of GLOBE must be consistent with the background aerosol concept if they are to be useful to the LAWS development activity. In the earlier phases of GLOBE, this investigator was instrumental in the design of the GLOBE research effort, using this concept. This activity gradually evolved into evaluation of prospective instrumentation for GLOBE, detailed design of GLOBE field experiments (particularly the 1989 Pacific survey flight on the NASA DC-8), continuing technical liaison with the various GLOBE investigators, and documentation of the overall GLOBE research program.

Eos Proposals Two proposals based on LAWS were submitted to NASA's Earth Observing System (Eos): 1) as Principal Investigator on a LAWS Team Member proposal, involving an extension of the GLOBE backscatter modeling work, and 2) as Co-Investigator on an Interdisciplinary proposal, involving dust plume mapping and dust transport modeling.

Meetings and Communication Regular meetings of the GLOBE SWG are required for updates and critical reviews of the GLOBE data base and the various research elements of the GLOBE program. Six of these meetings have been held since the inception of GLOBE in 1986, including three within the past twelve months. This Investigator has organized and coordinated the technical sessions for these meetings, coordinated and prepared full meeting documentation, including proceedings and technical assessments, and also prepared periodic newsletters between meetings. This activity will continue during the next year with full SWG meetings approximately every six months.

FOCUS OF CURRENT RESEARCH AND PLANS FOR NEXT YEAR:

Background Backscatter Analysis Analysis is continuing on backscatter data sets from the RSRE and WPL lidars. Analysis is beginning on backscatter data from the JPL CO₂ lidar and on aerosol scattering coefficient data from the Mauna Loa Observatory climatology. The focus of these studies will be on the spatial and temporal variability of the background, physical mechanisms for generating and maintaining the background, and the use of surrogate (tracer) data (such as water vapor from rawinsondes and infrared imagers) in extending the global coverage of the background model. Other data will be incorporated as they become available.

Field Experiments Planning is underway for the Mauna Loa Aerosol Backscatter Intercomparison Experiment (MABIE) during late Fall 1988. This experiment will involve many of the instruments that will be used on the NASA DC-8 in the Spring 1989 Pacific Survey flight. MABIE-1988 will be used for instrument shakedown, sampling protocol development, and interim backscatter data supply from low backscatter conditions in the free troposphere over the central Pacific. The Survey flight will provide critical backscatter data over a wide range of meteorological and geographical settings. This Investigator will participate in the planning, coordination, execution, and data analysis phases of both of these experiments, as well as in the calibration of the MSFC continuous-wave CO₂ Doppler lidar to be used in these efforts.

GLOBE Data Base A centralized, user-friendly GLOBE data base, with rapid access capability, is required to support aerospace contractor studies on LAWS, and also to perform in-house performance simulations for prospective LAWS design concepts. The data base has matured from the conceptual phase (SWG meeting, September 1987), to the preliminary design phase (Spring 1988). Detailed design will be completed in late summer 1988, and implementation will commence in Fall 1988. The data base will utilize a microcomputer version of the ORACLE relational data base manager on a dedicated IBM AT, with optical disk storage.

PUBLICATIONS - JOURNAL:

Bowdle, D.A., and D.E. Fitzjarrald, 1989: "The GLOBal Backscatter Experiment (GLOBE): measurement and modeling." To be submitted to special GLOBE issue of J. Geophys. Res.

Bowdle, D.A., J. Rothermel, J.M. Vaughan, D.W. Brown, and M.J. Post, 1989: "Aerosol backscatter measurements with airborne and ground-based CO₂ Doppler lidars over the Colorado High Plains, 1, lidar intercomparison." Submitted to special GLOBE issue of J. Geophys. Res.

Bowdle, D.A., J. Rothermel, J.M. Vaughan, and M.J. Post, 1989: "Aerosol backscatter measurements with airborne and ground-based CO₂ Doppler lidars over the Colorado High Plains, 2, backscatter structure." Submitted to special GLOBE issue of J. Geophys. Res.

Patterson, E.M., and D.A. Bowdle, "Use of aerosol microphysical measurements to model IR backscatter in support of GLOBE." Submitted to special GLOBE issue of J. Geophys. Res.

Rothermel, J., D.A. Bowdle, J.M. Vaughan, and M.J. Post, 1988: "Evidence of a tropospheric aerosol backscatter background mode." Submitted to Nature.

Rothermel, J., D.A. Bowdle, J.M. Vaughan, D.W. Brown, and A.A. Woodfield, 1989: "Calculation of aerosol backscatter from airborne CW focused CO₂ Doppler lidar measurements, 1, Algorithm description." Submitted to special GLOBE issue of J. Geophys. Res.

Rothermel, J., D.A. Bowdle, and J.M. Vaughan, 1989: "Calculation of aerosol backscatter from airborne CW focused CO₂ Doppler lidar measurements, 2, Algorithm performance." Submitted to special GLOBE issue of J. Geophys. Res.

Vaughan, J.M., D.A. Bowdle, R. Callan, and J. Rothermel, 1989: "Spectral analysis, digital integration, and measurement of low backscatter in coherent laser radar." Submitted to Appl. Opt.

PUBLICATIONS - CONFERENCE:

*Fourth Conference on Coherent Laser Radar:
Technology and Applications, Aspen, CO, July 25-31, 1987*

Bowdle, D.A.: "A global-scale model of aerosol backscatter at CO₂ wavelengths"

Bowdle, D.A. and D. E. Fitzjarrald: "The GLOBal Backscatter Experiment (GLOBE) program" (invited paper)

Bowdle, D.A., W. D. Jones, A. D. Clarke, S. A. Johnson, and D. E. Fitzjarrald: "Mauna Loa Aerosol Backscatter Intercomparison Experiment (MABIE)"

Patterson, E.M., and D.A. Bowdle: "Use of aerosol microphysical measurements to model IR backscatter in support of GLOBE"

Rothermel, J., J.M. Vaughan, and D.A. Bowdle: "Algorithm to calculate aerosol backscatter from airborne CW focused CO₂ Doppler lidar measurements"

Vaughan, J.M., D.W. Brown, J. Rothermel, and D.A. Bowdle: "Measurements of aerosol backscatter at CO₂ wavelengths with the airborne Laser True Airspeed System (LATAS)"

*Symposium on Aerosols and Climate
International Association of Meteorology and Atmospheric Physics
International Union of Geodesy and Geophysics
Vancouver, British Columbia, August 11-18, 1987*

Bowdle, D.A., J. Rothermel, and J.M. Vaughan: "Micro-scale to global-scale variability of atmospheric aerosol backscatter at 10.6 micrometers wavelength"

*Third Conference on Satellite Meteorology and Oceanography
Anaheim, California, February 1-5, 1988*

Bowdle, D.A., 1988: "The GLOBal Backscatter Experiment (GLOBE) measurement and modeling program"

PUBLICATIONS - OTHER:

Bowdle, D.A., and D.E. Fitzjarrald (Eds.), 1988: GLOBE Survey Flight Program Test Plan. In preparation.

Bowdle, D.A., W.D. Jones, A.D. Clarke, S.A. Johnson, and D.E. Fitzjarrald, 1987: "Mauna Loa Aerosol Backscatter Intercomparison Experiment (MABIE)", in Geophysical Monitoring for Climatic Change, No. 15. Summary Report 1986, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Research Laboratories, Boulder CO, December 1987. 137-139.

Vaughan, J.M., D.W. Brown, P.H. Davies, R. Foord, J. Cannel, C. Nash, A.A. Woodfield, D.A. Bowdle, and J. Rothermel, 1987: Atmospheric Backscatter at 10.6 um: A Compendium of Measurements Made Outside the United Kingdom by the Airborne LATAS Coherent Laser Radar Velocimeter; RSRE Report 87002, Royal Signals and Radar Establishment, Great Malvern, United Kingdom, May 1987.

PUBLICATIONS - GLOBE SWG

Proceedings

Bowdle, D.A.(Ed), 1987: Proceedings: Third Meeting of the GLOBE Scientific Working Group, Guntersville, Alabama, May 4-6, 1987, Birch and Davis Associates, Silver Springs, Maryland, 223 pp.

Bowdle, D.A. (Ed), 1988: Proceedings: Fifth Meeting of the GLOBE Scientific Working Group, Oakland, California, February 8-10, 1988, Birch and Davis Associates, Silver Springs, Maryland, 190 pp.

Summaries

Bowdle, D.A., 1987: Summary of Third GLOBE Meeting, Guntersville, Alabama, May 4-5, 1987, University of Alabama at Huntsville, Huntsville, Alabama, 9 pp.

Bowdle, D.A., and D.E. Fitzjarrald (Eds), 1988: Technical Session Summaries, Fifth Meeting for the GLOBAL Backscatter Experiment (GLOBE), Oakland, California, February 8-10, 1988, Birch and Davis Associates, Silver Springs, Maryland, 9pp.

Newsletters

Bowdle, D.A., 1987: GLOBE Newsletter, Vol. 1, No. 1, June 1, 1987, University of Alabama at Huntsville, Huntsville, Alabama, 6 pp.

Bowdle, D.A., 1987: GLOBE Newsletter, Vol. 1, No. 2, December 15, 1987, University of Alabama at Huntsville, Huntsville, Alabama, 6 pp.

TITLE: LAWS Simulations - Sampling Strategies and Wind Computation Algorithms

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ACCOMPLISHMENTS in 1987/88:

In general, work has continued on developing and evaluating algorithms designed to manage the LAWS lidar pulses and to compute the horizontal wind vectors from the line-of-sight (LOS) measurements. These efforts fall into three categories: 1) Improvements to the Shot Management and Multi-Pair Algorithms (SMA/MPA); 2) Observing System Simulation Experiments; and 3) Ground-based simulations of LAWS.

Shot Management and Multi-Pair Algorithm Improvements

Various forms of shot management have been examined. In particular, several combinations of scan angle, scan rate and pulse repetition frequency (PRF) were simulated and evaluated for shot coincidence and shot density (spatial). Although it is possible to achieve shot intersections by controlling all three of the scanner/lidar parameters, mid-scan or scan to scan variations in scan angle and scan rate have been ruled out because of engineering considerations. However, shot timing or a variable PRF has been kept as a viable option.

Prior to invoking a variable PRF, the Multi-Pair Algorithm (MPA) was revised for use with a fixed PRF by improving the matching of nearest shots to form shot pairs. MPA I used a look-up table to match shots and did not consider the effects of the earth's rotation. MPA II includes the change in sampled volume displacement as a function of latitude. A comparison of MPA I, MPA II and the least squares approach for 100 x 100 km² areas is shown in Table 1.

While the advantages of the MPA (I or II) over the least squares approach are significant the MPA II showed modest improvement 10-50% over the MPA I. Further improvement may be possible with an "assumed" coincidence shot schedule yet to be developed.

Table 1
RMS Speed Error
(Input: Gradient* and Random** Wind Field)

	<u>150-650</u>	<u>600-1250</u>	<u>1200-1450</u>	<u>150-1450 km</u>
Least Squares	32.680(33.12)	8.963(10.05)	11.294(9.400)	17.387(23.41)
MPA I	1.241(0.988)	0.615(0.314)	0.626(0.324)	0.826(0.692)
MPA II	0.890(0.761)	0.577(0.319)	0.552(0.459)	0.724(0.551)

$$*u_o = v_o = 2.0 \text{ m s}^{-1}, \frac{du}{dx} = \frac{dv}{dy} = 10^{-5} \text{ sec}^{-1}, \sigma_u = \sigma_v = 0.15 \text{ m s}^{-1},$$

$$**\sigma_w \text{ (vertical velocity variations)} = 0.05 \text{ m s}^{-1}, \sigma_{\text{noise}} \text{ (LOS measurement uncertainty)} = 1.0 \text{ m s}^{-1}$$

Observing System Simulation Experiments

Efforts to assess the potential impact of LAWS on global scale weather forecasts are on-going in a set of GCM experiments being conducted by SWA and NASA/GSFC. The amount of data generated by the LAWS Simulation Model (LSM) has required modifications to the assimilation/analysis programs that provide input to the forecast models.

Figures 1-3 show the simulated LAWS winds and their sampling related errors using ECMWF Nature Run data as input. The along and cross track errors are obvious in Figure 3. The absence of data near the sub-satellite ground track is due to a cut-off for wind estimates made from shot pairs having angular separation 175-180°. In simulations used as input to the forecast impact studies, cloud fields and topography are included.

Ground-based Simulations of LAWS

During the period November 16-19, SWA conducted a series of experiments at MSFC using the ground-based scanning CO₂ Doppler lidar. The experiments were designed to answer some questions regarding lag-angle compensation, optimum pulse length, single shot signal quality, and space-based lidar shot management. Review of the data collected shows that we have enough data to work on three of the primary objectives of those tests:

- i) downwind/crosswind line-of-sight (LOS) variance comparisons;
- ii) single-shot/poly-shot velocity comparisons; and
- iii) LAWS sampling simulations.

We completed the sampling simulation using 10 sequential VADs obtained on 17 November when the winds aloft were between 20 and 30 m s^{-1} . This block of VADs allowed us to simulate shots taken 20 to 25 km apart (we assumed Taylor's hypothesis). The results of these simulations were presented at the CLEO '88 meeting in April in Anaheim, CA.

The quality of the VADs, in terms of data loss, required substantial editing before trying to fit a sine wave to the LOS velocities. In Figure 4a a typical VAD is shown without any editing. If the data losses were easily identifiable (and unambiguous) from the velocity information, then editing would be straightforward as it often is with other types of sensors. In our case a positive but varying velocity is reported when the SNR is insufficient to get a good peak detection. A low band pass filter on the velocity data was tried but good data were often filtered out and if a large contiguous section ($\sim 90^\circ$) of the sine wave was bad, then the band pass filter performed very poorly.

Instead of using FFT's and band pass filtering we chose a method that uses the amplitude of the signal for editing the winds. Figures 4a-c demonstrate the method for extracting useful LOS wind information from noisy Doppler lidar measurements. The method uses the maximum signal amplitude at the 90th range gate as a threshold value to be compared with signal amplitude at range gates where good data are expected. Part a) shows the signal drop-out for a VAD of LOS wind velocities as a function of lidar azimuth at range gate 22. Part b) shows the corresponding SNR (solid line) for range gate 22 and the threshold SNR (dotted line) found at range gate 90. The circles in part c) depict LOS wind velocities after filtering out the noise. A sine fit to the data is also shown.

This approach is conservative in so far that it uses only the best velocity data. While the sine fitting part of the software cannot handle biased noise very well, it can handle a VAD made up of very few good values including clustering in partial sectors.

The sine fitted VADs provided the "true" wind speeds and directions against which shot-pair estimates of the winds could be compared. The individual LOS measurements (processed through the Poly-pulse pair processor) were paired so as to simulate the relative perspectives through the boundary layer that would be achieved from a polar orbitor. In order to obtain enough pairs to make a meaningful statistical statement on errors, the shot pair estimates were grouped by angles into 12 bins. In Figures 5-7, the errors in the estimates of the U (cross track in this instance) and V (along track) components as well as the total wind speed indicate the same pattern of errors resulting from the numerical simulation. However, the amplitude of the errors are slightly large, i.e., 3-5 m s^{-1} in the mid-range.

CURRENT RESEARCH AND PLANS FOR 1988/89

During the next six months, efforts will be focused upon the following three areas:

- * Develop a fully documented set of gridded wind/clouds/aerosol fields for use in the Phase a/b LAWS feasibility and trade studies. Included in the set would be:

Pure structures - divergence
vorticity
deformation
random (u,v,w)

Model outputs - global scale with clouds
with aerosols
regional scale with clouds
with aerosols

- * Use single shot data from MSFC's (or NOAA's) ground based lidar system to assess errors associated with incorrect height assignment of LOS velocities obtained in regions of known wind shear and aerosol gradients. Software will be developed for rapid assimilation of backscatter data collected during the 88/89 globe missions.

- * Complete the Baseline and Bracket OSSES being run at GSFC.

PUBLICATIONS

- Emmitt, G.D. and J.W. Bilbro, 1987: Error analysis for horizontal wind vector computation using line-of-sight component measurements from a space-based Doppler lidar. Submitted to special issue of Appl. Optics.
- Emmitt, G.D., 1987: Contributor to Laser Atmospheric Wind Sounder (LAWS); Instrument Panel Report (Chairman R.J. Curran), NASA Earth Observing System, Vol. IIg, NASA Headquarters, Washington, D.C.
- Emmitt, G.D. and J.W. Bilbro, 1987: Assessment of error sources for one component wind measurements with a space-based Doppler lidar. Paper presented at the Optical Society's Fourth Conference on Coherent Laser Radar: Technology and Applications, Aspen, CO, July.
- Emmitt, G.D., 1987: Error analysis for total wind vector computations using one component measurements from a space-based Doppler lidar. Optical Society's Fourth Conference on Coherent Laser Radar: Technology and Applications, Aspen, CO, July.
- Emmitt, G.D. and S.H. Houston, 1987: Impact of a space-based Doppler lidar wind profiler on our knowledge of hurricanes and tropical meteorology. AMS 17th Conference on Hurricanes and Tropical Meteorology, Miami, FL, April.
- Emmitt, G.D., 1988: Direct measurement of boundary layer winds over the oceans using a space-based Doppler Lidar Wind Sounder. AMS Third Conference on Satellite Meteorology and Oceanography, Anaheim, CA, February.

Emmitt, G.D. and S.A. Wood, 1988: Ground-based simulation of a space-based Doppler lidar atmospheric wind sounder. Optical Society's Conference on Lasers and Electro-Optics, Anaheim, CA, April.

Emmitt, G.D. and S.A. Wood, 1988: Subvisible cirrus in space-based Doppler lidar simulations. Atmospheric Transmission Conference, AFGL, Hanscom, MA, June.

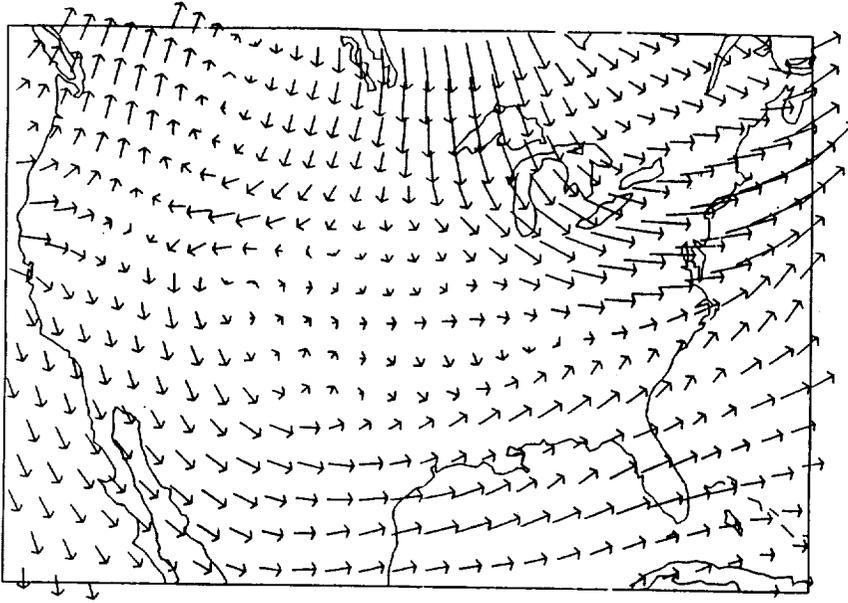


Figure 1.

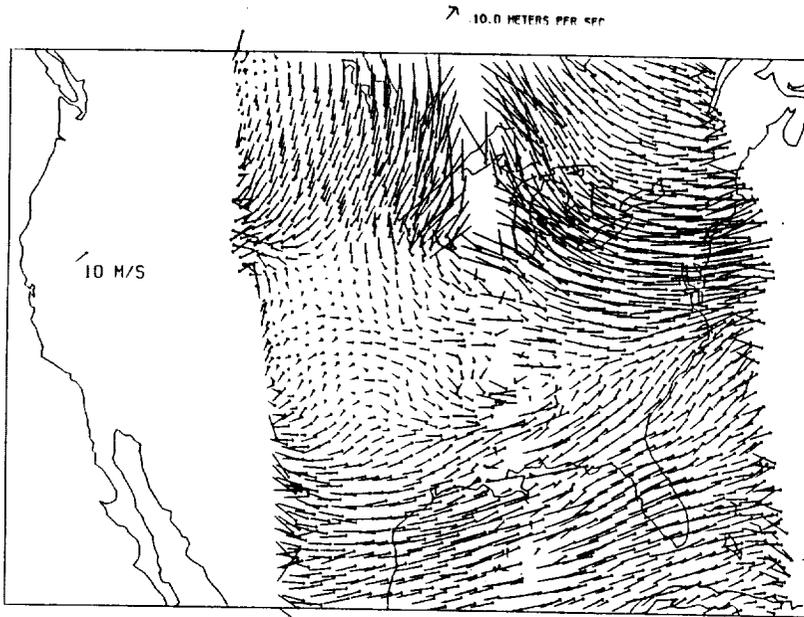


Figure 2.

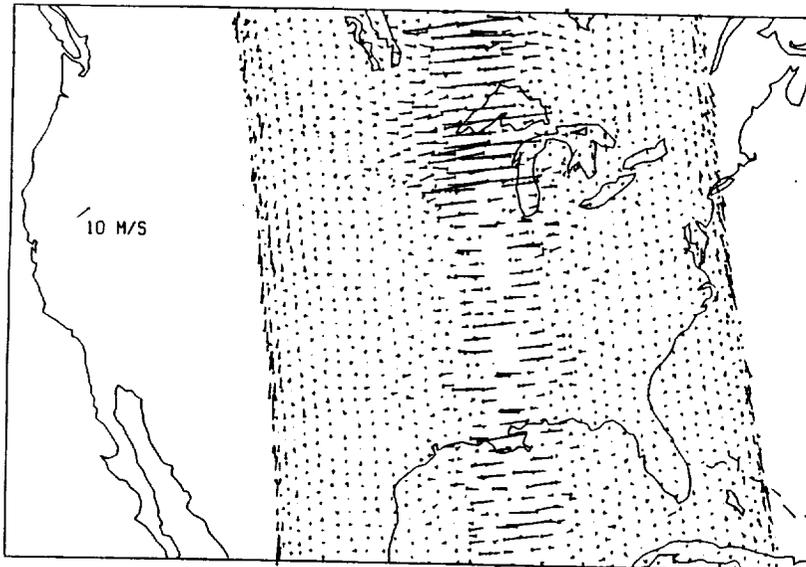


Figure 3.

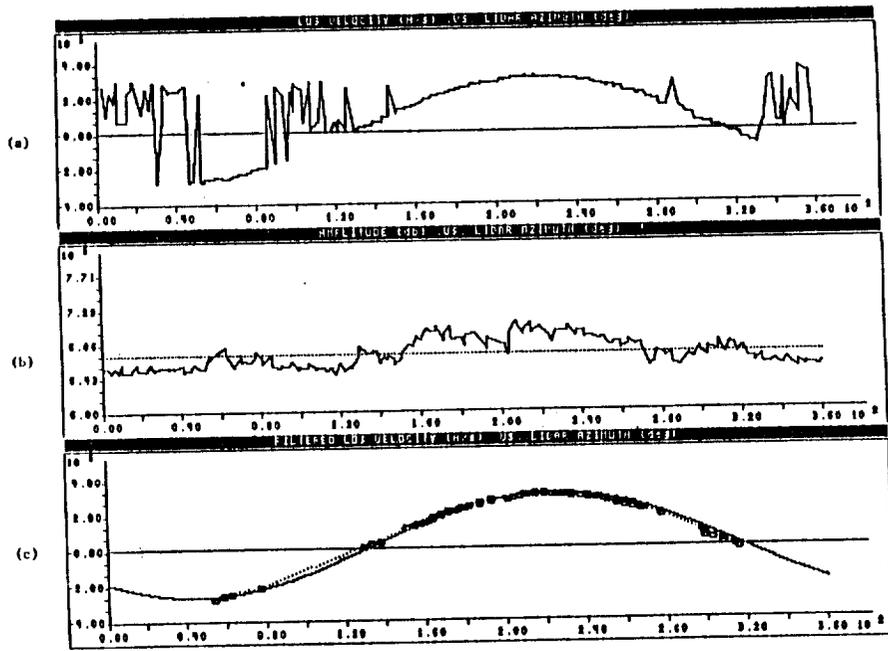


Fig. 4 An example (18 Nov, 13:10) of VAD editing and sine fitting to recover u, v and w components of the wind from a ground-based lidar. Panel (a) unedited VAD display of LOS velocity ($m s^{-1}$) vs azimuth in degrees; Panel (b) amplitude (db) in the 22nd range gate vs azimuth compared to the amplitude threshold at the 90th range gate; and Panel (c) edited and sine fitted VAD.

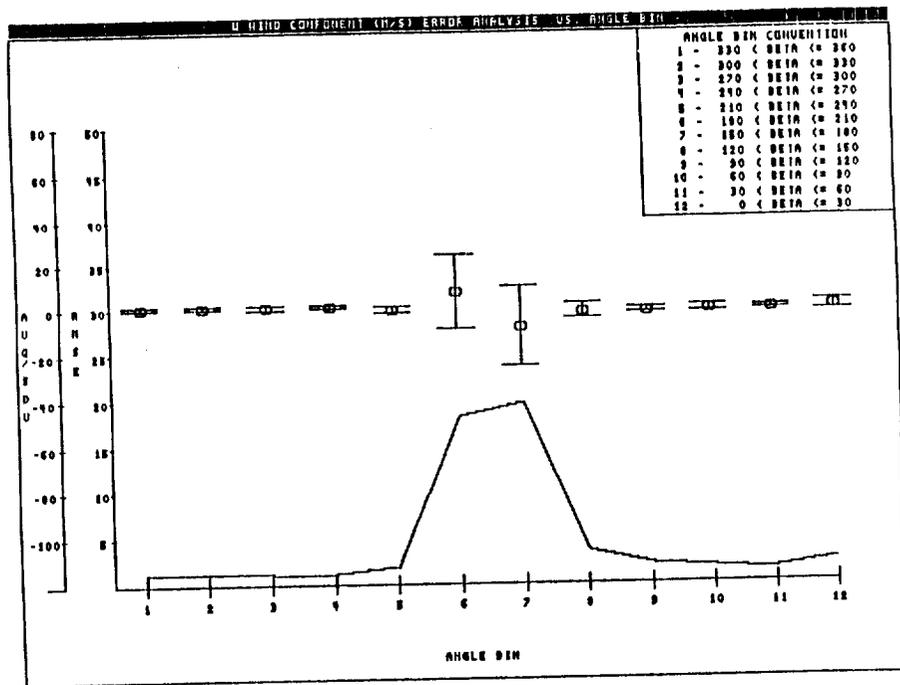


Fig. 5 U component errors across the track of a simulated spaced-based lidar scan.

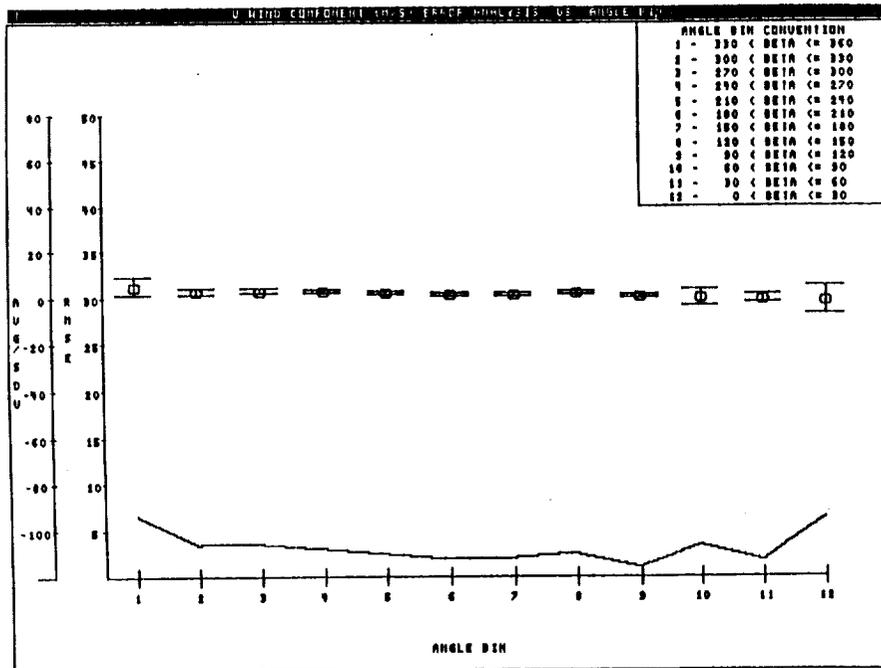


Fig. 6 V component errors along the track of a simulated spaced-based lidar scan.

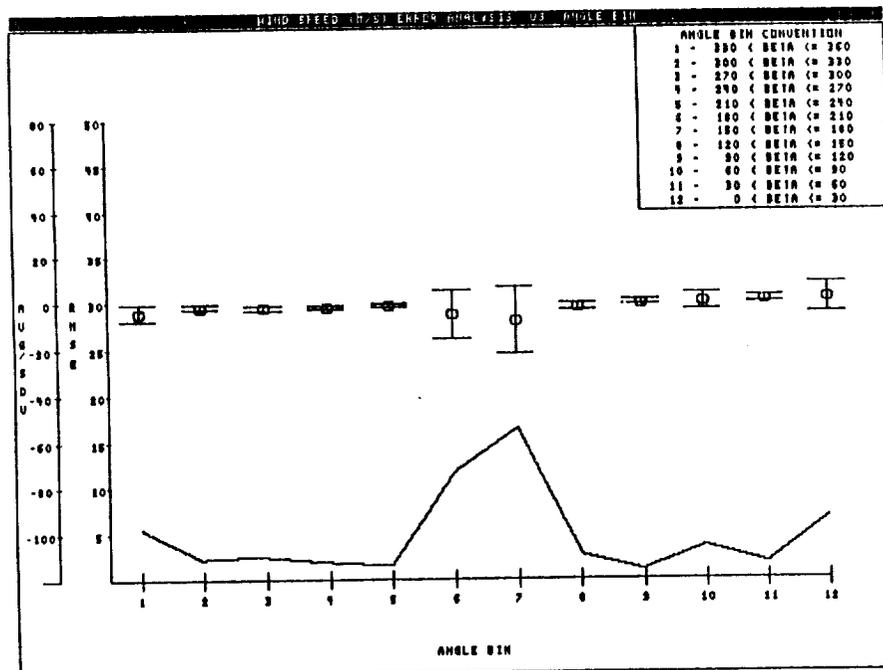


Fig. 7 Errors in total wind speed estimates from a simulated space-based lidar scan.

Measurements of Aerosol Properties needed to Infer
Backscatter Characteristics in Support of the
NASA Doppler Lidar Program

Principal Investigator: E. M. Patterson
Co Investigators: M. S. Black
C. O. Pollard

SIGNIFICANT ACCOMPLISHMENTS

During the first year of this program two areas of work were emphasized, analysis of aerosol data to provide improved estimates of backscatter over the Pacific ocean and to develop a global model for backscatter at different wavelengths and preparation and planning for the aircraft flights of the GLOBE program. Significant progress was made in each of these areas.

The analytical work is a continuation of the GAMETAG analysis, and has been directed toward the development of a backscatter model for the Pacific oceanic free troposphere. This has included a further evaluation of relationships between the optical effects at different wavelengths, a comparison of modeled optical effects at differing temporal resolutions, and an investigation of the effects of sampling on the modeled results. We have also made an initial investigation of the predictability of 9 to 10 μm β values from other data sets as well as some preliminary comparisons of our modeling results with experimental data.

The comparison of the optical effects has been extended to make the comparisons for different sets of time bases between 1 and 20 minutes. The longer time period comparisons have provided a reduced scatter in the data relative to the one minute comparisons. These other comparisons have strengthened the idea that there are consistent relations in the data for the aerosol measurements over the Pacific. These data also suggest that short wavelength data, including appropriate combinations of short wavelength data, are of use in predicting the backscatter values at CO_2 wavelengths. The comparisons do indicate, however, that the relationships are non linear and depend on the concentration of materials.

The modeling results at the different temporal resolutions had another goal, the investigation of the uniformity of aerosol populations, as measured during the Pacific flights. This investigation was undertaken because of the observation that the data, especially the southernmost data, had many very small backscatter values, and we wanted to determine whether these values were a statistical artifact of

the data or whether the low values were characteristic of large areas of the southern hemisphere free troposphere. This question was investigated by a calculation of backscatter distribution means and 10% values for the different time bases and by determinations of the log-normality of the different distributions. The results of each of these approaches indicated that the very low values calculated were an artifact of the aerosol measurement process and that on volume scales comparable to that to be measured by the LAWS system the aerosols are log-normally distributed. These results have been presented at GLOBE panel meetings and are discussed in detail in the attached paper (Patterson and Bowdle, 1988) which has been submitted to the Journal of Geophysical Research.

One of the questions that is asked of any atmospheric model is how well it matches actual conditions. Although there are limited experimental data with which to compare the model, limited comparisons of northern hemispheric model means and standard distributions with NOAA and with JPL long term data show a good deal of consistency. In addition, a set of simultaneous measurements of RSRE backscatter data and SAGE II sensor attenuation data have been reported. These data sets have provided a basis for comparisons between the modeled optical effect ratios and the experimental data. To date, only preliminary comparisons have been made; but these comparisons indicate that our modeled optical values are quite consistent with the experimental data. In addition, our modeled relationship between 1 micron attenuation and 10.6 micron backscatter agrees with the relation inferred from the SAGE II-RSRE comparison.

Results of these modeling efforts were presented at the Topical Meeting on Coherent Laser Radar: Technology and Applications, held at Aspen, Colorado July 27-30, 1987 in a paper entitled "Use of Aerosol Microphysical Measurements to Model IR Backscatter in Support of GLOBE."

The planning and preparation for the aircraft flights included further sensitivity analysis of the flows needed to achieve the required particle concentrations, a redesign of some of the sampling equipment to take advantage of some of the capabilities of virtual impactor designs, and coordination of our air flow needs with those of other microphysical experimenters.

PLANNED ACTIVITIES

The following specific activities have been planned for the following year of the project:

Completion of the preparation of the aircraft sampling equipment for the GLOBE flights and installation of the equipment on the Aircraft.

Participation in the aircraft flights.

Participation in a set of ground based measurements with our equipment in Hawaii in the fall 1988.

Participation in a set of calibration studies at the Marshall Space Flight Center in the fall of 1988.

Participation with NASA Ames personnel in the initial analysis of the aircraft particle counter data.

Extension of optical modeling efforts to additional wavelengths for comparisons with NOAA integrating nephelometer data.

The major experimental effort will be in the preparation for and the participation in the series of GLOBE flights. The goal of these air chemistry measurements is to provide micro-physical support for the Lidar measurements to better relate modelling results to the experimental efforts. Such efforts are needed because the GLOBE flights are survey flights rather than an attempt to determine a climatology for backscatter. The survey flight results must then be extended to develop a long term climatology by means of modelling results as well as direct experimental comparisons.

The planned Mauna Loa experiment may be viewed as a paradigm for the GLOBE flights. One of the goals of this experiment is the determination of relationships between short wavelength scattering data and 10 micron backscatter data. Microphysical measurements will be used to model beta values as well as to model relationships between short and long wavelength optical values. The result will be a set of beta estimates to compare with actual measured values. These data will aid in the interpretation of the mauna Loa data set in terms of a backscatter climatology.

PUBLICATIONS

E. M. Patterson and D. A. Bowdle, 1987: Use of Aerosol Microphysical Measurements to Model IR Backscatter in Support of GLOBE. presented at the Topical Meeting on Coherent Laser Radar: Technology and Applications, Aspen, Colorado, July 27-30.

E. M. Patterson and D. A. Bowdle, 1988: Use of Aerosol Microphysical Measurements to Model IR Backscatter in Support of GLOBE, submitted to J. Geophys. Res.

Title: Infrared Backscattering

Investigators: Craig F. Bohren (Timothy J. Nevitt is a consultant and Shermila Brito Singham is an unpaid collaborator)

Recent Work:

All particles in the atmosphere are not spherical. Moreover, the scattering properties of randomly oriented nonspherical particles are not equivalent to those of spherical particles no matter how the term "equivalent" is defined. This is especially true for scattering in the backward direction and at the infrared wavelengths at which some atmospheric particles have strong absorption bands. Thus calculations based on Mie theory of infrared backscattering by dry or insoluble atmospheric particles are suspect.

To support this assertion, I note that peaks in laboratory-measured infrared backscattering spectra show appreciable shifts compared with those calculated using Mie theory. One example is ammonium sulfate. We have had some success in modeling backscattering spectra of ammonium sulfate particles using a simple statistical theory called the CDE (continuous distribution of ellipsoids) theory. In this theory, the scattering properties of an ensemble are calculated. Each member of the ensemble, an arbitrary ellipsoid, does not necessarily correspond to each particle in a suspension of naturally occurring nonspherical particles. Nevertheless, the properties of the two ensembles are similar. Spectra calculated with the CDE theory are in better agreement with measurements than those calculated using Mie theory.

In the original version of the CDE theory, all ellipsoidal shapes had equal probability. Recently, Tim Nevitt applied a modified version of this theory to measured spectra of scattering by kaolin particles. The particles were platelike, so the probability distribution of ellipsoidal shapes was chosen to reflect this. As with ammonium sulfate, the wavelength of measured peak backscattering is shifted longward of that predicted by Mie theory. Even the original CDE theory, in which no information about the shape distribution is used, predicts more accurately the position of peak backscattering. When the shape distribution is accounted for, agreement between theory and experiment is even better.

The CDE theory is only a first tentative step. It is limited to particles small compared with the wavelength of the incident light. Although this condition is satisfied, at CO₂-laser wavelengths, for some particles in the atmosphere, it is not satisfied for all such particles. Thus a better theory is needed.

There are two aspects of the problem of calculating infrared backscattering by irregular particles: (1) Constructing a theory capable of accurately calculating backscattering by an arbitrary particle (or at least some range of nonspherical particles); (2) Deciding what is meant by "irregular" and how to treat irregularity statistically.

For about the past two years, my colleague Shermila Singham and I have been tackling the first of these two problems using a method originally developed by Purcell and Pennypacker. We call this method the coupled-dipole method, although it recently has acquired other names. In this method, a particle is approximated by a cubic array of point dipoles, the polarizabilities of which are determined by the refractive index of the particle of interest. Each dipole is excited not only by the incident field but by the fields of all the other dipoles. If the array contains N dipoles, $3N$ linear equations for the cartesian field components at each lattice site must be solved, from which the scattered field is readily obtained. If N is less than about 300, the $3N \times 3N$ coefficient matrix of the $3N$ linear equations can be inverted using standard techniques. When N is greater than about 300, however, the matrix inversion approach fails because of insufficient computer storage. In an attempt to overcome this limitation, we reformulated the coupled-dipole method in such a way that the field at every dipole site is a series, each term of which can be interpreted as arising from multiple (coherent) scattering of different orders. This enables us to calculate scattering for N greater than 300, but eventually the scattering-order series diverges. At what point it diverges depends on the particle refractive index and shape; $N = 5000$ is a good approximate upper limit. Thus we have run into the same problems that plagued Purcell and Pennypacker and others who have adopted their method.

This summer, Shermila and I reformulated the coupled-dipole method in such a way that we obtain a series that must converge. Unfortunately, this method is impracticable given the speed of the present generation of computers. It works, but at the expense of a staggering amount of computer time.

Recently, several papers on the coupled-dipole method (which they call the digitized Green's function method) were published by George Goedecke and Sean O'Brien of New Mexico State University. Once the mathematical decorations are expunged from their work, what remains is no more than the coupled-dipole method. Moreover, they compute fields by matrix inversion, thus are limited to arrays of at most a few hundred dipoles.

Recently, other papers, either in press or to be submitted, have been sent to us by their authors. Bruce Draine, at Princeton, has applied the coupled-dipole method (which he calls the discrete dipole approximation)

to the calculation of scattering and absorption by interstellar grains. Draine was able to treat particles of fairly high refractive index with size parameter up to about five. Yet to do so he had to restrict himself to particles with a high degree of symmetry. Draine is now collaborating with Graeme Stephens and Piotr Flatau at Colorado State University.

Although it is frustrating for us to have reached a size-parameter barrier, it is comforting to know that no one else has been able to surmount it. To date, no one who has worked on the coupled-dipole method has been able to overcome its limitations. To surmount the size-parameter barrier will require either radically new approximations based on physical reasoning or an increase in computer speed of at least a factor of ten, preferably much more. Computers are likely to become faster, but this will not occur overnight.

Fortunately, as a practical matter, the size-parameter limitations of the coupled-dipole method are of no serious consequence to calculating infrared backscattering by irregular atmospheric particles. At a wavelength of 10 μm , for example, the size parameter is less than 2 for particles with characteristic linear dimension less than about 2 μm . We can treat such particles using the coupled-dipole method.

Plans for Further Work:

I have been hampered in the past by the lack of a capable graduate student. The original proposal was written by Tim Nevitt, then a graduate student working on a doctoral degree in meteorology at Penn State. Our intention was that his doctoral research would be supported by the NASA grant. Unfortunately, by the time we received it--two years after submission--Tim had left Penn State to take a position at 3M. This left me without a graduate student. After a year of floundering by myself, I went on sabbatical leave for a year. During the past year I have been working with Shermila Singham on the coupled-dipole method. Tim Nevitt has continued to work on the problem of infrared backscattering, but he cannot devote much time to it since he has a full-time, demanding job.

Recently, my situation has improved. Tracy Moore has left the Air Force to work with me. He has a degree in physics so we speak the same language. He did a second BS degree, in meteorology, at Penn State while an Air Force officer. He was the best student in all of my classes. When he left, he told me that he was going to return, and he has made good on his word. Despite the fact that he now has three children, he resigned his commission in the Air Force to take up voluntarily the exiguous life of a graduate student. Thus he is highly motivated and I expect great things of him. When I return to Penn State in

August, I am going to put him to work at using the coupled-dipole method for calculating infrared backscattering by irregular particles. Penn State now has a Supercomputer link, which we hope to make use of.

Publications:

Singham, S. B. and C. F. Bohren, 1988: Light scattering by an arbitrary particle: The scattering-order formulation of the coupled dipole method. J. Opt. Soc. Am. A (in press).

Bohren, C. F. and S. B. Singham, 1988: Backscattering by nonspherical particles: A review of methods; suggested new approaches. J. Geophys. Res. (submitted).

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Singham, S. B. and C. F. Bohren, 1988: A hybrid method in light scattering by an arbitrary particle. Appl. Opt. (submitted).

NASA/MSFC GLOBAL SCALE ATMOSPHERIC PROCESSES RESEARCH PROGRAM

FY88 REVIEW

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**John Theon, NASA HQ,
Greg Wilson and
Fred Leslie, MSFC**

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Ramesh Kakar, NASA HQ

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Atmospheric Motions*

**John Clark, Nels Shirer,
Penn State**

*Synoptic/Planetary Scale Interactions and
Blocking Over The North Atlantic Ocean*

Phil Smith, Purdue U.

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S. H. Chou, NRC**

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**Antony D. Clarke, Hawaii
Institute of Geophysics**

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Jeffry Rothermel, USRA

Global Backscatter Assessment

David A. Bowdle, UAH

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Wind Computation Algorithms*

**G.D. Emmitt, S.A. Wood, and
S.H. Houston
Simpson Weather Associates, Inc.**

*Measurements of Aerosol Properties Needed
to Infer Backscatter Characteristics in
Support of the NASA Doppler Lidar Program*

**Edward M. Patterson
Georgia Inst. of Tech.**

Infrared Backscattering

**Craig F. Bohren
Penn State University**

APPROVAL

NASA/MSFC FY88 GLOBAL SCALE ATMOSPHERIC
PROCESSES RESEARCH PROGRAM REVIEW

Edited by G. S. Wilson, F. W. Leslie, and J. E. Arnold

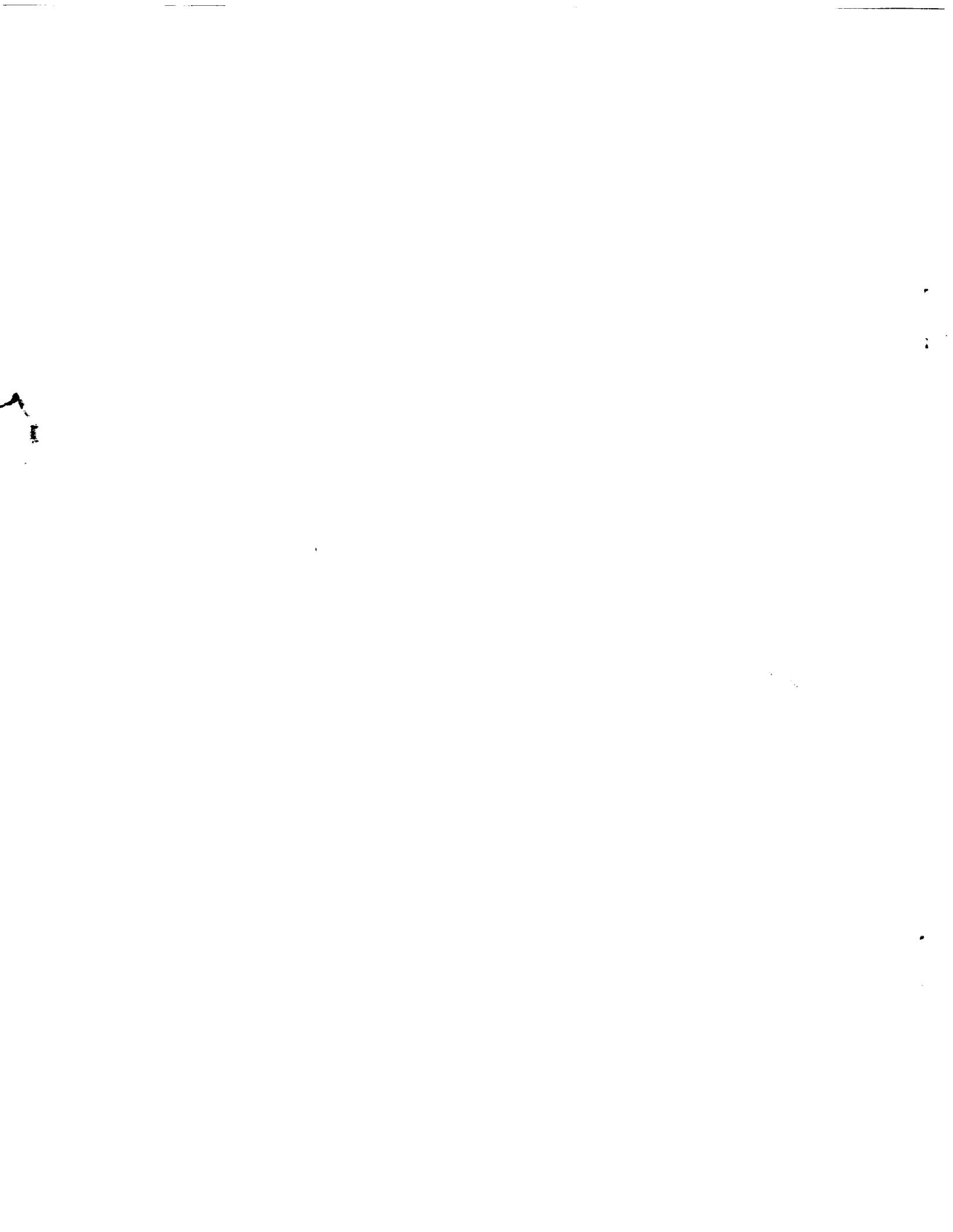
The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.



E. TANDBERG-HANSEN
Director
Space Science Laboratory







**NASA
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