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Proceedings of the First National Workshop on the Global Weather Experiment:

Current Achievements and Future Directions

Volume One

Woods Hole, Massachusetts
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First GARP Global Experiment (FGGE) Advisory Panel
U.S. Committee for the Global Atmospheric Research Program
Board on Atmospheric Sciences and Climate
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

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FOREWORD

After more than a decade of international and national planning, the Global Weather Experiment (GWE), formerly known as the First GARP Global Experiment (FGGE), was undertaken in December 1978 and continued through November 1979. This unprecedented and audacious venture was the work of many nations. Routine operational weather observing systems were thrown into high gear and were augmented on a massive scale by many special systems--satellites, aircraft, buoys, and ships. The year's effort culminated in a gathering of global observational data detailing the behavior of the atmosphere and ocean worldwide.

The primary motivation for the experiment was to explore the possibilities for greatly extended prediction of the atmosphere's behavior through the use of advanced observing techniques, computer capabilities, and numerical models, and on the basis of this experience, to design a global atmospheric observing system of the future.

Since completion of the observational phase, the global data sets have been in use by many research scientists, particularly to distinguish between prediction errors due to failures in observations and those due to failures in modeling and understanding. Their ultimate goal is to acquire better knowledge and understanding of the atmosphere so that better and more useful weather prediction services may be provided to the world.

The FGGE Advisory Panel of the U.S. Committee for the Global Atmospheric Research Program felt that a detailed assessment should be undertaken of the status of GWE research and the progress in meeting the previously established objectives of GWE. A two-week workshop was held at the National Academy of Sciences Study Center in Woods Hole, Massachusetts, in July 1984. Two reports have resulted from the workshop--one compiling the papers that were presented during the first seven days and one summarizing the proceedings. These reports are intended to inform researchers worldwide on what has been done and to present recommendations on what more should be done.

On behalf of the U.S. Committee for the Global Atmospheric Research Program, I wish to express our gratitude to Julia N. Paegle, Chairman of the FGGE Advisory Panel, to Donald R. Johnson, Chairman of the FGGE Workshop Organizing Committee, and to all those who continue to add to GWE's success.

Verner E. Suomi, Chairman
U.S. Committee for the Global
Atmospheric Research Program

PREFACE

The scientific results of the First National Workshop on the Global Weather Experiment (GWE) are presented in two volumes. The first volume presents the findings and a summary of the symposium presentations and discussions, while the second contains the papers given by participants. The objectives of the workshop were to (1) summarize research progress in meeting the GWE objectives, (2) identify future research needed to achieve these objectives, and (3) estimate the time and resources that will be needed in the future to fulfill the objectives. Two early international workshops sponsored by the World Meteorological Organization had been held shortly after the year of the Global Weather Experiment--one in Bergen, Norway, June 1980; the other in Tallahassee, Florida, January 1981. The results presented at these workshops were of a preliminary nature, since the Level III data sets just being prepared by the two major centers--the European Medium Range Forecast Center (ECMWF) and the Geophysical Fluid Dynamics Laboratory (GFDL)--were not yet available to the scientific community.

The objectives of the GWE, while determined through international efforts, are set forth for the U.S. scientific community in The Global Weather Experiment--Perspectives on its Implementation and Exploitation, a report of the FGGE Advisory Panel to the U.S. Committee for the Global Atmospheric Research Program, National Research Council, National Academy of Sciences.

Readers will recognize that the main body of the report of the workshop addresses five subject areas that reflect the stated scientific objectives of the GWE. Figure 1 portrays the interrelationship among the five areas. The observational system formed the basis for the unique experiment, data analysis and assimilation utilized the observations to construct the global structure of the atmosphere, the research thrusts of prediction experiments, and diagnostic and phenomenological studies follow from the data and analyses, and the final area of design of the future global observing system ultimately depends on all of the above. In the Executive Summary, however, these five subject areas have been combined under three headings dealing with the GWE observing system and future designs, analyses and predictions, and diagnostics and phenomenological studies.

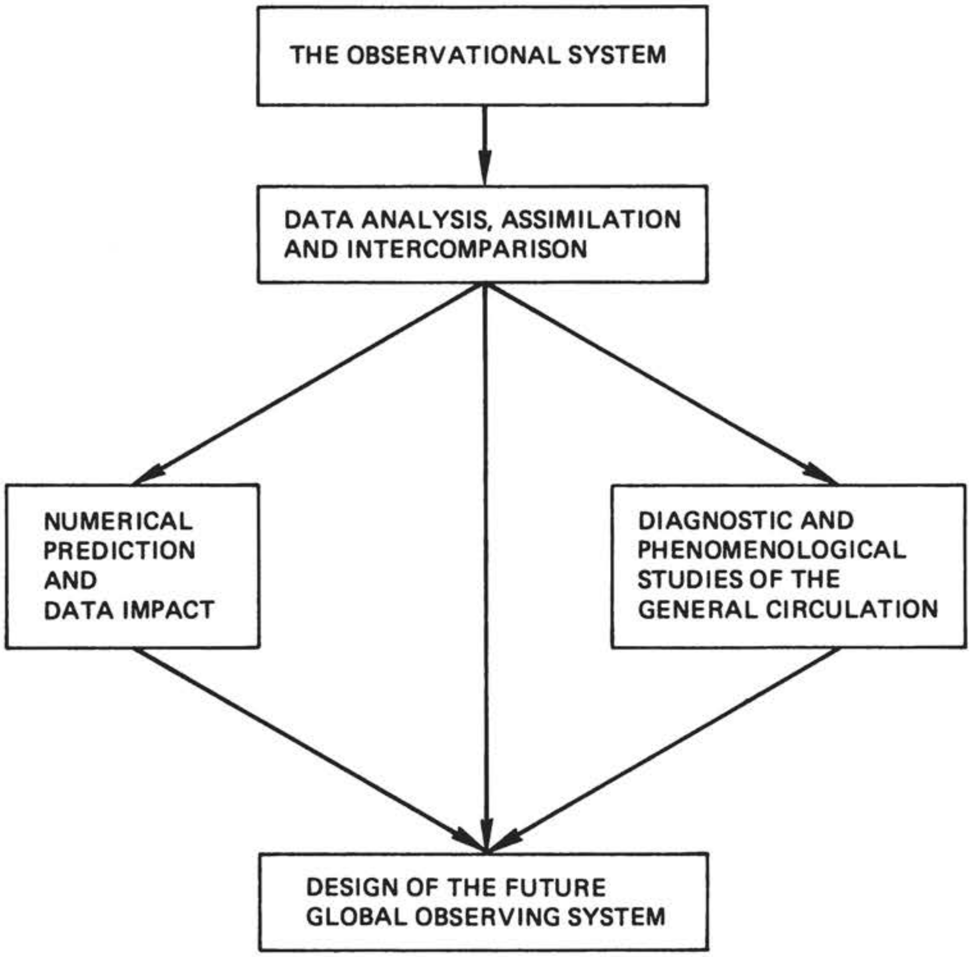
THE OBSERVATIONAL SYSTEM
DATA ANALYSIS, ASSIMILATION AND INTERCOMPARISON
NUMERICAL PREDICTION AND DATA IMPACT
DIAGNOSTIC AND PHENOMENOLOGICAL STUDIES OF THE GENERAL CIRCULATION
DESIGN OF THE FUTURE GLOBAL OBSERVING SYSTEM

FIGURE 1

Now, five years after the experiment, the results stemming from analyses and prediction for the GWE are comprehensive but not yet finalized in the sense that all the utility of the information gathered from the most extensive global weather observing system has been realized. The overall assessment of the participants was that important advances were made in observing, analyses, prediction, and diagnostics of the global atmosphere circulation through the GWE. Insight into the design of a future global observing system has been gained, but much remains to be accomplished. A primary purpose of the two volumes is to document the basis of this assessment.

In order to address the three objectives of the workshop and prepare findings, the FGGE Workshop Organizing Committee felt that a workshop format was essential in order to allow substantial time for discussion and exchange of ideas among the observationalists, analysts, theoreticians, and numerical modelers. Thus the seminar was organized by topical areas that covered the broad range of scientific efforts that were the foundation of the GWE. Session organizers for each topical area were assigned responsibilities to invite key speakers and enlist session chairmen and rapporteurs. With 20 sessions, the attendance at the workshop was limited primarily to active participants. Unfortunately, the size of the Academy's summer study facilities at Woods Hole and the need to prepare general findings that covered a broad range of scientific specialities limited attendance. In order to provide an opportunity for exchange among the larger community of scientists engaged in GWE research, the U.S. FGGE Committee has called for a national conference on the scientific results of the GWE to be held in conjunction with the 1986 annual meeting of the American Meteorological Society.

The first volume contains three summaries: the first, an executive summary that highlights the most important findings stemming from the GWE; the second, a supplementary scientific summary that covers additional key results and recommendations; and a third, a comprehensive summary of the presentations and discussion within each topical area. Detailed achievements, unresolved problems, and recommendations are included in each of the comprehensive summaries. These summaries were prepared by the workshop participants who were responsible for their respective areas.

The second volume contains the papers presented at the Workshop. Key speakers were invited to prepare and present a scientific summary of results within each topical area with the guideline that the summaries were to cover studies that addressed GWE research objectives and utilized GWE information.

It is hoped that the summaries, findings, and research thrusts reported in these two volumes will be informative to the general scientific community as future research is addressed to the GWE objective of both improving large-scale weather prediction and laying the foundation for a dynamical basis for climate.

The FGGE Workshop Organizing Committee expresses appreciation to all who contributed to the success of the workshop: To the organizers who arranged the sessions and prepared session summaries; to the speakers

who prepared and presented papers; to the rapporteurs for recording the highlights of the discussions; to the participants who engaged in lively discussion and debate; to Thomas H. R. O'Neill of the NRC staff for the planning, implementation, and documentation of the meeting; to Vicki Allaback of the University of Wisconsin and Doris Bouadjemi of the NRC staff for their secretarial assistance during the course of the workshop; and to Mike Moore for editing the two volumes of this workshop report. We also express our appreciation to all scientists at large who contributed to the success of the GWE. Finally, we express our appreciation to the individuals, organizations, and government activities of all nations that have provided support for the GWE.

Donald R. Johnson, Chairman
FGGE Workshop Organizing Committee

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EXECUTIVE SUMMARY

The Global Weather Experiment (GWE), held in 1979, represented a year long international effort to observe the earth's atmosphere to an extent not previously achieved nor likely to be achieved again within the foreseeable future. An enormous undertaking, the Experiment took more than a decade to plan and implement and cost the nations of the world a sum of over $400 million, half of which was contributed by the United States. The scientific objectives of the experiment were--

1. to provide data for numerical prediction experiments aimed at increasing predictive skill in the range of a few days to a few weeks;
2. to utilize the unique set of global observations in diagnostic and phenomenological studies aimed at increased understanding of large-scale atmospheric structure and processes and thereby lead to improving comprehensive prediction models; and
3. to define the necessary elements of the future operational global observing system taking account of the consequences of various alternative configurations on predictive capability.

Several remarkable accomplishments of the GWE include the following:

1. the implementation and operation of a global observing system that included the regular World Weather Watch network, two polar orbiting and five geosynchronous meteorological satellites, ocean buoys distributed mainly in the southern hemisphere, ships, aircraft, and constant-level balloons;
2. the development and utilization of global data assimilation models in real and delayed time to produce the best three-dimensional global description of the atmosphere that has ever been assembled;
3. the doubling of the useful time range of global numerical weather prediction within the decade from less than three days to six days in the northern hemisphere, from little skill to two days in the tropics, and from less than two days to four days in the southern hemisphere;
4. the determination of the impact of particular components of the composite observing system in numerical weather prediction, and the characteristics of the future global observational system required for more skillful weather forecasts; and

5. a marked increase in our knowledge of the major monsoon systems that has for the first time led to skillful forecasts of their onset from observations.

In July 1984, nearly 5 years after the conclusion of the field phase of the experiment, 60 scientists, representing a broad spectrum of the research community, gathered at the Woods Hole Study Center to discuss the progress that has been made thus far toward meeting the objectives of the Global Weather Experiment and to identify problems and needs requiring further attention if the objectives are to be fully satisfied. The main conclusions and recommendations that emerged from the workshop are summarized within this summary under the following three main headings: observational systems, analysis and prediction, and diagnostic and phenomenological studies.

A fuller summary of the main conclusions and recommendations of the workshop will be found in the body of the report. Also contained therein are summaries of the sessions held and a complete listing of the conclusions and recommendations, both major and minor, that emanated from each session.

OBSERVING SYSTEMS: THE GLOBAL WEATHER EXPERIMENT AND THE FUTURE

The observing system of the Global Weather Experiment provided, as intended, a description of the atmosphere's structure and behavior more complete and detailed than ever before. The space-based (satellite) system provided detailed temperature and moisture soundings; produced thousands of cloud-drift wind vectors over the tropics and oceans; and served as a data collection and location system for drifting ocean buoys, aircraft, and balloon platforms. In the tropics, a number of special observing systems were deployed in a concerted effort to observe the structure of that important part of the atmosphere. Five of the seven observational systems developed for the Global Weather System have already become part of the operational observing capability employed for routine weather support.

The task of collecting, collating, and managing the large amount of data produced by the observing system was enormous. Data produced by a number of the observing subsystems have undergone a reprocessing in order to correct deficiencies and improve the information content. Techniques for retrieving temperature and moisture profiles from satellite-measured radiometry have now improved to the point that a reprocessing of that data using better methods to produce significant improvements in quality and coverage is recommended. The utilization of the GWE data base has been, and will be, an iterative process as progress occurs in assimilation, global analysis, and numerical weather prediction. Only by this means can maximum utility and improvement of both the data base and the analysis product be achieved.

The specification of the components of the future global observing system can only be made after understanding what is important to observe both in the tropics and in higher latitudes and how to do it with economical and feasible observing systems. The research phase of GWE is in the midst of determining these components, and although some characteristics of the future observing system can be stated with some certainty, others are not yet so clear.

Observing system impact studies and system simulation experiments have demonstrated the importance of global measurements of the wind and temperature field. They have also demonstrated the necessity for a space-based observing system that is truly global. Surface and boundary layer information over the vast oceanic areas is necessary. It can most effectively be obtained in the southern hemisphere by a fleet of free drifting buoys.

Present knowledge concerning what is needed in the tropical regions is not complete, but agreement that observation of the wind field is essential poses very severe problems of how to observe it in adequate fashion. The field of moisture is also essential, but what moisture variables should be observed and on what scales are not now determined. Cloud cover and precipitation are likely to be important.

Overall, the more difficult task of determining the best mix of space-based and in situ measurements of the wind, temperature, and moisture fields in the tropics and in higher latitudes has only begun.

Because the specification of the components of an optimum observing system involves the feasibility of making observations of certain variables, it is imperative that system studies of the future global observing system should integrate results both from technological feasibility studies and from observing systems simulation studies.

ANALYSIS AND PREDICTION

The GWE objective analyses of meteorological information provide the best and most complete global representation of the atmosphere ever. The powerful new data assimilation methods developed to produce these analyses have been successful in assimilating many types of new and unconventional data. Much of the potential of these new schemes has been realized in the extratropics, although in the tropics their potential has not been fully exploited.

The GWE analyses produced by the various meteorological centers are consistent in the extratropical northern hemisphere suggesting an atmospheric representation that is virtually independent of the assimilating model. The tropical and southern hemisphere analyses are less consistent but, nonetheless, provide a more realistic representation than any previously produced.

The statistical covariance models employed in objective analysis of meteorological information are generally inappropriate in the tropics. Moisture analysis remains poor, and some diagnostic quantities derived from analyses show a stronger influence from the assimilating model's parameterization than from the observations. There are also serious deficiencies in the GWE objective analyses of stratospheric information. There remains much useful information in the GWE data set that has not been successfully assimilated into the GWE objective analyses.

The GWE data set should be reanalyzed using more advanced data assimilation systems to produce improved sets of GWE objective analyses of tropospheric and stratospheric circulation. Assimilation systems should be designed with an enhanced tropical capability that reduces the midlatitude bias evident in present statistical covariance models. The problem of moisture analysis should be attacked vigorously.

GWE has been an important stimulus in recent technological advances in numerical weather prediction (NWP). GWE, with its emphasis on the global atmosphere as a whole, coincided with a considerable advance in the skill and sophistication of numerical models and assimilation schemes. In particular, global assimilation schemes and forecast models became the rule rather than the exception after GWE.

Forecast impact studies performed with data from the GWE special observing system (SOS) have demonstrated that all components contribute to forecast accuracy. In particular, the GWE SOS added about two days of forecast skill in the southern hemisphere. Satellite temperatures were most important in the extratropics, satellite winds in the tropics, aircraft reports contributed to both regions, and buoys were valuable in the southern hemisphere. The use of GWE physical retrieval of satellite temperatures, in place of the archived GWE statistical retrievals, resulted in a significant forecast improvement over North America.

The useful time range of numerical prediction has been increased to six days in the northern hemisphere extratropics. This compares with a time of less than three days for numerical models of the early 1970s. Much of this improvement has been in the prediction of very long waves and in the winter season. The first successful real time forecasts of a stratospheric sudden warming were achieved during GWE. Useful numerical prediction of time-averaged anomalies at the range of two to four weeks has been elevated to a potentially obtainable goal.

Studies with the GWE data base have also been used to reveal shortcomings in both assimilation systems and forecast models. Cumulus parameterization schemes in forecast models are still not completely satisfactory and are not properly coupled with the radiation and planetary boundary layer (PBL) parameterizations. The tropical analyses, while much improved during GWE, remain far from satisfactory owing to deficiencies in both assimilating systems and forecast models. Tropical forecasts improved considerably during GWE but are still much less skillful than northern hemisphere extratropical forecasts. The results of predictability studies substantiate the fact that the overall forecast skill could be improved by several days through numerical model development.

A principal focus of future GWE research and model development should be directed toward realization of the potential increase in forecast skill. Particular emphasis should be put on the tropics where relatively little effort in analysis and modeling has been expended. Parameterization of PBL, cumulus convection, and radiative processes should be coupled consistently. Studies should be undertaken to separate the effects of initial analysis errors and forecast model deficiencies on forecast skill in order to help clarify the limits of deterministic forecasting and suggest where improvements could be made in the forecast system. Numerical prediction of time-averaged anomalies within the range of one month is a goal that should be cautiously pursued since apparently low frequency, large-scale signals in the atmosphere are potentially predictable when the effects of slowly varying boundary anomalies are taken into account. For time scales of a season or longer, ocean-atmosphere interactions play a crucial role.

DIAGNOSTIC AND PHENOMENOLOGICAL STUDIES

An understanding of the earth's planetary circulation and its momentum and energy balance is of fundamental importance for both weather prediction and climate. The GWE provided researchers with an important data set of unprecedented quality for diagnostic and phenomenological studies. From a broad spectrum of studies over the five years since the experiment, the atmospheric science community has obtained an unsurpassed global view of the planetary circulation of the atmosphere throughout one annual cycle. A markedly improved description of the southern hemisphere circulation has emerged. Diagnostics reveal that the Asiatic summer and winter monsoons, rather than being local phenomena, are strongly related to weather patterns around the globe. Mechanisms of interhemispheric exchanges have been ascertained and dependence of local predictability on remote events between tropical and extratropical latitudes has been quantified. GWE satellites provided the first global observations of sea-surface temperature and stimulated intensive analysis and modeling from which emerged an explanation of the seasonal response of tropical oceans to the annual wind stress. The drifting buoys provided the first synoptic observation of the Antarctic circumpolar current. This data set will continue to be the basis for studies of atmospheric circulation throughout the next decade and longer before full exploitation of this information is realized. No other data set of comparable quality for analysis and prediction will be formed within the coming decade.

The GWE has confirmed that differential heating plays a crucial role in driving the global circulation and the need for the domain of initial conditions to be global. Spatial and temporal distributions of the monthly and seasonally averaged atmospheric heat sources and sinks have been determined globally. Global analyses of the total energy exchange for the GWE year are in agreement with the distribution of heat sources and sinks. The primary energy source in the tropics is the release of latent heat associated with organized moist convection. This latent heat release and the induced concomitant tropical circulations affect the flow patterns of midlatitude regions within two to three days. In order to accurately predict and understand the influence of latent heat release on global circulation, accurate water vapor analyses are needed for the initial state of numerical weather prediction and for diagnosis of energy sources. There are a number of well documented shortcomings in the water vapor analyses. The inability to resolve these matters stems from the limitations of the GWE observational and analysis capabilities to adequately specify the water vapor distribution, its evaporation from the earth's surface, and its release as precipitation.

Research should be directed in the future to diagnosis of the global water vapor distribution, its transport, its evaporation, and its release as precipitation. This focus should include improvements in analysis and prediction of oceanic sources of latent and sensible heat flux, all of which are needed for resolving the global hydrological cycle. The focus should also include studies of total and component heating in order to resolve increased temporal and spatial structure of these fields and to investigate their influences on atmospheric motion.

Examples of the importance of a global observational capability are particularly evident from studies of the Asiatic summer monsoon and of the southern hemisphere circulation. The onset, maturation, and breakdown of the Asian monsoon constitutes one of the most important features of the atmosphere's circulation. The heat and moisture sources and sinks over the Tibetan Plateau and its vicinity have been more accurately calculated, and an understanding of the sudden monsoon onset has been sharpened. Interhemispheric exchange and tropical-extratropical interaction occur in the lower troposphere through strong mass and moisture fluxes from the southern to the northern Indian Ocean associated with the east African Somali jet. At upper levels, strong divergent motions generated over Asia flow across the equator into the southern hemisphere. The observed 30 to 50 day oscillation that is evident throughout the annual cycle has also been documented during the Asiatic summer monsoon.

The circulation of higher latitudes of the southern hemisphere for the GWE year was anomalously intense. The circumpolar trough was exceptionally deep. The surface pressure over the Antarctic was as much as two to three standard deviations below normal during winter. The anomalous low sea-level pressure of the southern hemisphere during its winter was accompanied by anomalous high sea-level pressure for several months in the northern hemisphere. The information from the southern hemisphere buoy system was a key observational component for the determination of the net interhemispheric mass exchange and its impact on the northern hemisphere's circulation.

While the progress from studies of the global exchange of mass, momentum, and energy has been impressive, particularly from those associated with the Asiatic summer and winter monsoons, emphasis should be given to diagnosis of monsoonal circulations over Africa and the Americas in concert with the Asiatic monsoon. The influence of continentality and oceanity on monsoonal circulations as the seasons evolve and interaction of tropical monsoon flow with the baroclinic wave regime of higher latitudes merits special attention. Within the global context of this problem, a clearer perspective of observed low frequency oscillations ranging from a month to years in time scale and their potential for prediction needs to be developed.

In the comparison of diagnostics and statistics from analyses derived from several data assimilation systems, differences in the analyses indicate that the assimilation models influence diagnostic results. These differences affect our conclusions and understanding of the global circulation. The differences are more pronounced in data-sparse regions where the analyses partly reflect the model's climatology and the degree of smoothing inherent in analysis and assimilation. In view of needs for accurate diagnostics and statistics in climatic studies of the future, the sensitivity of the analyzed fields and calculations of mass, momentum, and energy balance to data assimilation systems needs to be addressed. The accuracy required to determine interannual differences in fundamental processes are much more stringent than to determine the annual evolution of these same processes.

The differences in atmospheric structures and diagnostics of dynamical processes stemming from the impact of the different assimilation models on their analyses need to be understood and documented.

CONCLUDING REMARKS

By the end of the GWE year in November 1979, the political, logistical, and technological success of the GWE was already evident. The implementation and operation of a global observing system made possible through technological advances in satellite and computer systems of the past several decades was a monumental achievement. The information from this system is a resource to the 1980s comparable to what the information from the expanded World War II observational network was to the 1950s.

The information provided by this global network has focused the efforts of an atmospheric science community toward the equally monumental challenge of advancing the accuracy of global numerical weather prediction and understanding of the global circulation. The 60 scientists gathered at Woods Hole were excited over the progress being made. The major objectives of the experiment have been and are being addressed. Already the proof of need for a global observational system, the improved accuracy of global numerical weather prediction, and increase in understanding of the global circulation summarized herein and documented in the main body of this report justifies the investment in technological, scientific, and monetary resources committed to the GWE.

The workshop concluded with the belief that the potential for advancing the GWE objectives is still as challenging as before the experiment began. Increase in understanding sharpens our insight and directions for future work. In order to meet the challenge, it is imperative that programmed resources be committed to provide a focus throughout the remainder of the decade for the continuation of scientific research that advances global numerical weather prediction and understanding of the global circulation.

SUPPLEMENTAL SCIENTIFIC SUMMARY

The purpose of this summary is to highlight several key scientific findings and recommendations that are not contained in the executive summary, but ones that the workshop participants felt should be emphasized and brought forward from the detailed findings, unresolved problems, and recommendations of each session. This summary also provides additional scientific details regarding the most important findings and recommendations of the executive summary. The overall objectives that provided the foundation for the GWE are set forth in The Global Weather Experiment--Perspectives on its Implementation and Exploitation (a report of the FGGE Advisory Panel to the U.S. Committee for the Global Atmospheric Research Program, National Research Council, National Academy of Sciences, 1978) and are recommended for study.

THE OBSERVATIONAL SYSTEM

The space-based system of orbiting and synchronous satellites implemented for the GWE was an essential and highly productive part of the global observational capability. Operational temperature soundings from the TIROS-N series satellites provided a global picture of the atmospheric mass structure over large ocean regions that could not have been gathered by any other technique. A study of the precipitable water content shows that the accuracy of an analysis including satellite-based retrievals, bogus data, and conventional measurements is within 10 to 20 percent as judged from comparisons with data from aircraft dropsondes (themselves subject to some uncertainty). The thousands of wind vectors produced by the five geostationary satellites filled a void by specifying the wind field over the oceans and tropics. These winds, mainly concentrated in the upper and lower troposphere, were used effectively in global analysis/assimilation cycles. The main source of uncertainty, the altitude assignment, has been reduced by comparisons with other wind vector measurements and by refining height assignment techniques.

The extensive network of surface pressure observations provided by the drifting buoys over previously data-sparse oceans gave the first reliable routine sea-level pressure analyses for the southern hemisphere. The information from the GWE buoys showed sharper specification of the centers of surface high- and low-pressure centers, as well as much improved knowledge of the variations in the position and strength of the circumpolar trough and subtropical high-pressure belt. Sea-surface temperature measurements made by the drifting buoy network have also been used effectively in model forecasts.

The tropical observing system of the GWE included several new types of platforms. The complementary mix of observing subsystems was unprecedented in its ability to define the tropical circulation, particularly the large-scale divergent component of the wind field and its relation to large-scale organized convection.

Recommendations

1. Besides the need to reprocess the GWE data using the physical method for temperature and water vapor retrievals for at least the SOPs and preferably for the entire year, the scientific community is urged to pursue with vigor the extraction of useful information from satellite water vapor channels. This includes efforts to improve the accuracy of water vapor tracer winds to fill existing observational gaps, and of water vapor field analysis to improve initialization procedures and the determination of the hydrological cycle.
2. A small workshop should be held to improve methods of extracting and accommodating information from observing systems especially from tropical regions. This workshop should include discussion of objective assimilation procedures as well as more subjective methods of analysis.

DATA ANALYSIS, ASSIMILATION, AND INTERCOMPARISON

The GWE has been an important stimulus in recent advances in data assimilation and numerical weather prediction. With its emphasis on the atmosphere as a whole, the GWE coincided with a considerable advance in the sophistication and skill of global numerical models and assimilating schemes. Operational and research centers that participated substantially in GWE work have reaped a real benefit with improvements in accuracy of numerical weather prediction and in increased understanding of the atmospheric circulation and its numerical simulation.

Despite these remarkable achievements, problems still remain with the GWE IIIb analyses. Tropical analysis is still far from satisfactory owing to deficiencies in both forecast model and analysis systems. Serious differences in the various general circulation statistics stemming from differences in analyses, particularly second moment quantities, are present. Atmospheric structure within the planetary boundary layer is poorly resolved. This is particularly true with regard to water vapor distribution and its transport.

Recommendations

1. Well-organized analysis intercomparisons are worthwhile and should be encouraged. In particular, an experiment similar to the recent National Meteorological Center-European Centre for Medium Range Weather Forecasts-United Kingdom Meteorological Office (NMC-ECMWF-UKMO) analysis intercomparison should be conducted to determine separately the effect of quality control procedures, analysis or initialization scheme, and effect of the assimilating model. Data rejection lists are available and should be used in comparing GWE IIb data with GWE IIIb analyses.

2. More work needs to be directed toward tropical parameterization and its effect on tropical data assimilation. Present error covariance statistical models of both forecast and observation error are totally inadequate in the tropics. Present covariance modeling assumptions of non-divergence should be relaxed and statistics should be stratified by region and by synoptic situation (particularly with respect to convection) in the tropics. More general approaches such as Kalman filtering should be pursued.

3. Rainfall gauge information, satellite-based layer mean precipitable rates, and satellite infrared measurements have recently been used to infer the distribution of moisture and divergence in the tropics. This work should be encouraged and ways found to assimilate this type of information. In addition, ways should be found to include conventional information which is either not exploited or not properly assimilated such as surface pressure tendency or single-level winds.

4. The reanalysis of Level IIb data by techniques other than the forecast model related techniques of statistical interpolation and four-dimensional data assimilation may well be justified for the investigation of specific meteorological phenomena. This applies particularly for certain tropical phenomena such as stratospheric Kelvin waves.

NUMERICAL PREDICTION AND DATA IMPACT

Data Impacts on Forecasts

There was good agreement between the conclusions of the three groups--European Centre for Medium-Range Weather Forecasts (ECMWF), Goddard Laboratory for Atmospheriec Science (GLAS), and Australian Numerical Meteorological Research Center (ANMRC) --that performed studies to determine the impact of several components of the GWE Special Observing System (SOS).

The improvement of about two days of forecast skill from the GWE SOS was much larger in the southern hemisphere than in the northern hemisphere. The largest contribution to this skill was the information from satellite temperature retrievals (ECMWF and GLAS). Buoys improved the skill of short-range forecasting by more than 12 hours (ANMRC and GLAS). The use of GLAS physical retrievals of satellite temperatures in place of the archived statistical GWE retrievals resulted in a significant forecast improvement over North America.

Some problems were noted in the data impact studies. Satellite moisture data has not generally been used in global assimilation models. No use was made of the Meteosat water vapor winds, and no forecast study has been made to assess the importance of these data sets.

Recommendations

1. The potential for further improvement in the extraction of information and use of satellite data for NWP needs to be explored.
2. The impact of the use of moisture data and water vapor winds, which may complement cloud tracked winds, should be studied.
3. Data impact experiments with and without the buoys could be used to determine how much of the observed atmospheric variability in the southern hemisphere during the GWE was due to the enhanced observing system and how much was due to the anomalous circulation of 1979.

Tropical Forecasting and Cumulus Parameterization

The GWE tropical observing system has provided many new data, from several new types of platforms. This uniquely comprehensive data set will continue to be used for many years in the improvement of tropical analysis and forecasting. Research experiments in tropical forecasting have shown much more skill during the GWE than during previous years. However, tropical forecasts are still far from satisfactory. A need exists for more accurate temperature and moisture data in the tropics in order to resolve the structure of weak tropical disturbances and to avoid aliasing between perceived Rossby and Kelvin waves. It is not clear whether the necessary technology to provide this data is currently available. Systematic model errors that may corrupt tropical analysis need to be documented.

Cumulus parameterization studies and semiprognostic tests on GARP Atlantic Tropical Experiment (GATE), Monsoon Experiment (MONEX), and GWE observations have provided improved parameterization of heating-moistening profiles and rainfall rates. The impact of GATE on our understanding of cumulus convection was evident in the studies of cumulus parameterization. However, it was clear that the final GWE data sets should be useful in future parameterization studies for global models, particularly if information on rainfall distributions is available.

Recommendations

1. The present status of assimilation and forecasting in the tropics is far from satisfactory. Substantial research is required in tropical objective analysis, initialization, and physical parameterization.

2. The possibility of generating and using accurate temperature and moisture data to resolve the structure of weak tropical disturbances should be investigated. This data would also be useful in separating Rossby and Kelvin waves.

3. Wind information is vital in the tropics and the five geostationary satellites should be maintained to provide coverage of cloud tracked winds.

4. While investigating the sensitivity of forecasts to cumulus parameterization remains important, the FGGE data that directly address the problem of parameterizability and closure assumptions should be analyzed extensively. These analyses should include quasi-equilibrium states in which temperature lapse rates and humidities are highly coupled and also the regional dependency of fluctuations around such states. Cloud ensemble models should be used to test closure assumptions.

5. Testing a parameterization with the GATE data only, or with any data from the marine tropics, may give an overly optimistic view. Extensive studies on the macroscopic behavior of cumulus clouds over the tropical and midlatitude continents are needed. The possibility of conducting further field experiments over regions of heavy precipitation should be explored.

6. Global precipitation estimates during the special observing periods (SOPs), should be prepared from direct and indirect means.

Weather Prediction Present and Future

Six-day forecasts by ECMWF for recent winters are as accurate as some of the two-day forecasts made at other centers in the early 1970s. Useful height anomaly correlation values of 0.6 now extend to six days on the average. The useful time range of tropical forecasts has been extended from two to three days.

Thirty-day predictions of time-average anomalies made with the GFDL model were, on the average, slightly more accurate than persistence. There was evidence of skill in predicting low-frequency, large-scale structures such as the Pacific North American (PNA) teleconnection pattern. Improved physical parameterizations noticeably improved the forecast.

The results of predictability experiments suggest that improvements in the forecast system can potentially improve forecast skill by several days. However, it is not clear whether initial analysis error or forecast model deficiencies are the principal cause of present day forecast errors. There are also substantial variations in short and medium range forecast skill that occur on weekly, seasonal, and interannual time scales. The reasons for these variations are not currently understood. Despite improvements in tropical forecast skill, there is room for substantial improvement in cumulus parameterization and in the initial analysis.

DIAGNOSTICS

General Circulation, Monsoons, Heat Sources and Sinks, and Stratosphere

With a data set of unprecedented quality for comprehensive studies of the large-scale processes of the troposphere, GWE researchers have quantified a number of important atmospheric features such as the monthly and seasonally averaged distributions of the global heat sources and sinks, the eddy heat and momentum fluxes, zonal mean winds, and the energy cycles. The knowledge of major circulation features has been advanced as well. A significant achievement has been the improved understanding of the southern hemisphere planetary waves. A distinct southward divergent flow from the convective regions of the tropics into regions of kinetic energy generation over Australia, South America, and Africa has been found. It has been shown that the subtropical jet structure in the southern hemisphere is influenced by longitudinal gradients of tropical heating, which may, in turn, explain the standing wave pattern of the southern hemisphere winter. In addition, for the first time, global three-dimensional distributions of stratospheric water vapor, ozone, methane, and temperature were measured.

An important circulation that exercises considerable influence beyond its own region is the Asian monsoon. The planetary scale circulations of both the winter and summer phases of the monsoon have been documented. In addition, studies with GWE data have produced a more detailed description of the 30- to 50-day oscillation, including its interaction with the summer monsoon and association with convection.

Despite these accomplishments, some further investigations and problems remain. A detailed knowledge of the atmosphere's total heating and its components based on the analysis of GWE data is limited with respect to its temporal, horizontal, and vertical variations, in part because of the quality of the analyses themselves. Better analysis techniques in the vicinity of mountains are needed. In some cases, the differences among general circulation statistics from station data and the various IIIb analyses are substantial. Serious, well-documented shortcomings in the existing Level IIIb water vapor analyses limit their use in studies of, among other things, the balance of water vapor in the atmosphere. Reasons for these deficiencies and differences need to be determined. Better definitions of the heat sources are needed on the planetary scale as well as on smaller scales, in particular, during the onset, active and break, and withdrawal phases of the Asian summer and winter monsoons. A different but related problem is the lack of detailed information on the variability of monsoon rainfall and its relationship to disturbances on various space and time scales.

Finally, the stratosphere is only beginning to receive the attention it deserves. The impact of the state of the stratosphere on the accuracy of tropospheric forecasts has not been clarified totally, but appears to be quite important. Within the stratosphere, equatorial Kelvin waves are an important feature of the circulation and are believed to be excited in the troposphere; however, their energy source is poorly understood. Diagnostic studies of equatorial waves and the stratospheric warming would be greatly facilitated with improved stratospheric analyses.

Recommendations

1. Diagnostic, theoretical, and numerical studies of total and component heating should be conducted for the purposes of resolving increased temporal and spatial structure of these fields and investigating their influence on atmospheric motion.
2. Latent heating release should be assessed globally from the distributions of water vapor balance and compared with global estimates of total heating.
3. Detailed daily precipitation estimates for the tropical band for both winter and summer monsoon periods should be done. The estimates should be global if possible.
4. Experiments should be carried out using available GWE data to (a) determine the nature of the forcing mechanism for equatorial Kelvin waves and (b) clarify the role of the stratosphere in the evolution of the tropospheric circulation.

Concerning any reanalysis of the GWE data:

1. It is imperative that rejected observations be archived along with a code stating at which stage they were rejected.
2. Closer attention should be given to quality control of water vapor data in a reanalysis of the GWE data.
3. Analyses should be carried out at levels between 1000 and 850 mb to facilitate an incorporation of boundary layer processes into global diagnostics.
4. Surface pressure, temperature, and wind fields, which are important for research on energy diagnostics, boundary layer dynamics, and water vapor transport, should be archived.
5. Model generated total and component heating rates should be archived.
6. The reanalysis for the two SOPs should be extended to include the month of July for summer MONEX and December for winter MONEX.
7. Attention should be given to the full utilization of Limb Infrared Monitor of the Stratosphere (LIMS) and Television and Infrared Observation Satellite (TIROS) data to improve analyses above 100 mb.

Hemispheric Interactions, Cross-Equatorial Exchange, and Southern Hemisphere

The GWE year has clearly served to delineate the characteristics and provide new perspectives on the atmospheric processes associated with hemispheric interactions, cross-equatorial exchanges, and the general circulation of the southern hemisphere. The extensive data gaps, typical of the pre-GWE observational systems in the deep tropics and southern hemisphere, had hindered research in these areas.

Improved global analysis allowed better determination of the vertical structure of tropical and cross-equatorial flows. These were found to have a strong divergent component and to mostly arise from internal inertial-gravity and mixed Rossby-gravity waves. The importance of local diabatic forcing in the generation of tropical motions, which has direct implications for the development of assimilation systems in numerical models, has been established.

Furthermore, GWE data sets have provided quantitative estimates of the impact of initial data uncertainties in the tropics on extratropical prediction. While the predominantly barotropic spread of this error was anticipated from prior experiments, a realistic estimate of the magnitude of the effect could not be made before the GWE experiment.

The improved description of the characteristics of the predominantly oceanic southern hemisphere has advanced our understanding of the processes involved in the maintenance of its general circulation in comparison with those of the highly continental northern hemisphere. Anomalous circulations during the GWE year in the southern hemisphere included an exceptionally deep circumpolar trough with surface processes over the Antarctic as much as 2 to 3 standard deviations below normal during winter and amplitudes in the stationary components (waves 1 through 4) which were 20 to 50 percent larger than normal. The information from the southern hemisphere buoy system was fundamental to a reliable determination of the interhemispheric mass exchange occurring during the GWE. The anomalous low sea-level pressure of the southern hemisphere during its winter was accompanied by high sea-level pressure anomalies over the northern hemisphere.

Recommendations

1. Experiments with simplified models as well as numerical model simulations should be conducted to understand the effect of errors in tropical analyses on predictions at higher latitudes.
2. For limited periods of the GWE year, the IIIb data for all model levels of the boundary layer should be archived to assist in evaluating and intercomparing various boundary layer models.
3. Diagnostic and numerical experiments should be conducted to understand the anomalous behavior of the southern hemisphere during the GWE year.
4. Global, regional, and phenomenological studies of GWE IIIb analyses from different assimilation systems should be compared to determine reasons for the large differences in statistics computed from Level IIIb data (such as zonally averaged surface pressure and stationary temperature field). For this comparison a manual analysis for 2 to 3 weeks in each of the SOPs of sea level pressure (SLP), sea-surface temperature (SST), 850, 500, and 200 mb fields be made by analysts experienced with southern hemisphere circulations. These analyses would serve to check the different assimilations to isolate bias errors.

CONCLUDING REMARKS

Since 1979, the committed operational and scientific institutions have been hard at work processing GWE data to make it usable and accessible to the research community. The IIb sets have been in an almost continuous process of improvement, both in coverage and accuracy. Further upgrading is nearly at an end except for reprocessing of satellite temperature retrievals. A better global observing system and a better IIb data set is not likely to be available in the foreseeable future.

On the other hand, the IIIb sets, processed for the entire year or for more limited intervals, were based on global models and analysis/assimilation algorithms developed before or during the GWE year. It is clear that several iterations of improvements of the IIIb set will be attainable over the next decade or two.

Up until 1979, the primary factor limiting prediction in the week time range was inadequate global data, particularly in the tropics and the southern hemisphere. However, it is already becoming evident that, with a GWE-level observing system, the analysis/assimilation systems and the associated global prediction models are also limiting factors. Extratropical data requirements seem to be satisfied by the northern hemisphere GWE array. Steady progress in extending the accuracy of weather prediction in extratropical latitudes is being made by the major operational centers. In the tropics, however, progress is slower. All relevant components in the observational, assimilation, and prediction systems may be lacking. This is best exemplified by the essential differences between IIIb results obtained by different processing systems applied to the same IIb data sets. Only when better tropical assimilation and prediction models are developed, will it be possible to judge how adequate is the GWE tropical observing system and its ultimate impact on both tropical and extratropical prediction.

Provision must be maintained for extensive research to accelerate the improvement of IIIb sets and for their utilization in prediction experiments, phenomenological studies, and for guidance in designing the global observing system of the future.

SUMMARY OF SESSIONS AND DETAILED RECOMMENDATIONS

THE OBSERVATIONAL SYSTEM

The Global Weather Experiment (GWE) provided an unprecedented data set of observations over our planet. A number of summaries concerning the quantity of data available from the GWE have appeared in publications of the World Meteorological Organization (WMO) and in scientific articles, e.g., Fleming et al. (1979). The first session of the workshop concentrated on the quality of the GWE observing systems. The emphasis was on those space-based systems and the special observing systems that were not normally a part of WMO's World Weather Watch (WWW) system. The session was organized around review papers by Smith, McPherson, Fleming, and Julian (see Volume Two, Session 1). The discussion focused on evaluations of the data derived from these systems, and on recommendations for future use of the data produced by these systems.

Satellite Soundings

In a review paper entitled "Satellite Observed Thermodynamics During FGGE," Smith (see Volume Two, pp. 3-18) provided the basis for the discussion of the global atmospheric temperatures and moisture fields that were remotely sensed from space. The TIROS-N satellite was the first of a new series of operational polar orbiting satellites launched into orbit on October 13, 1978, just prior to GWE. The second spacecraft in the series, NOAA-6, was launched into orbit on June 27, 1979, midway through the GWE year. The complement of infrared and microwave instruments aboard each of the polar orbiting spacecraft provided complete global coverage of vertical temperature and moisture profile data every 12 hours. With the two spacecraft, complete coverage was achieved every 6 hours. The data were produced operationally with a horizontal resolution of 250 km for inclusion in the GWE Level IIb data sets. High resolution (75 km) sounding data sets were produced using man/machine interactive methods for the special pbserving periods (SOPs) of the GWE at the NASA/Goddard Space Flight Center and archived as supplementary Level IIb. Both data sets are included in the Final Level IIb.

During his presentation, Smith highlighted the major problems encountered during the processing of the TIROS Operational Vertical Sounder (TOVS) data. The participants were reminded that the soundings represent volume averages rather than point information. Thus, in attempting to compare the satellite derived soundings with the radiosonde observations, the colocation comparison technique contains a basic dichotomy. The windows for colocation are usually taken to be broad, both temporally and spatially. Smith attributed as much as $1^{o}C$ of the temperature "error" to the colocation comparison technique. The discussion also recognized that any measure of error must take into account the purpose for which the observation is to be used.

In discussion, the question was raised whether the relatively poor vertical resolution is a problem given the vertical resolution within numerical models. It was pointed out that the current models do not at present use all of the information from the radiosondes. However, as it was suggested, improved assimilation procedures might allow the models to use higher resolution data.

The main deficiencies of the GWE satellite sounding data were summarized by Smith as follows:

1. degraded accuracy in overcast cloud areas;
2. degraded horizontal gradient definition owing to the TOVS inherently low vertical resolution (approximately 5 km);
3. lack of globally produced moisture profiles in overcast cloud regions;
4. inability of the operational regression method to account for variable terrain conditions, thereby yielding unreliable results in mountainous regions; and
5. poor accuracy near the Earth's surface owing to the lack of utilization of conventional surface observations in the sounding retrieval process.

Many of the GWE sounding deficiencies have been alleviated through improved processing procedures, in particular through methods for handling clouds and the use of physical solutions rather than empirical regression procedures (McMillin et al., 1983; Smith et al., 1983; Susskind et al., 1984). Also, it was clear from the discussion that the divergent nature of the tropical atmosphere can be better handled by including the diabatic heating terms. The value of the water vapor information contained in the satellite radiances could contribute substantially to the tropical forecast problem but needs further scientific attention.

Achievements

1. The GWE would not have been possible without the TIROS-N system. The operational soundings from the new TIROS-N satellite system provided a vertical picture of the atmospheric mass structure over large ocean regions of the globe that could not have been gathered economically by any other technique. Nearly 20,000 satellite

temperature profiles per month were generated. The accuracy of the temperature profiles is better than 2.5°C rms, depending on level, as judged by comparisons with radiosondes. Horizontal gradient accuracy is better, approaching 1°C for deep layer mean temperature gradient over 250 km or greater distances.

2. A special effort to obtain high resolution soundings (75 km) during special observing periods of the GWE produced retrievals with more detailed thermal structure and more internal consistency than the operational satellite soundings.

3. The water vapor retrievals from TIROS-N provided the first substantial global view of this important atmospheric constituent. A number of case studies have appeared in the literature that demonstrate the value of these profiles.

4. In an analysis of precipitable water including TIROS-N humidity retrievals, bogus data, and conventional measurements, Cadet (1983) showed that the accuracy of the layer mean precipitable water retrievals is 10 to 20 percent as judged from comparisons with aircraft dropsondes. Krishnamurti et al. (1984), using Cadet's analysis, showed the value of this product in initializing tropical forecast models.

Satellite Winds

In a review paper entitled "Cloud-Drift Wind Estimates During FGGE," McPherson (see Volume Two, pp. 19-36) provided the basis for the discussion of the winds deduced by satellites during the GWE year. Five meteorological satellites were strategically placed in geostationary orbit during the GWE year. The satellites were situated to provide global coverage and were provided by the United States (three), Japan, and the European Space Agency.

Imagery from these satellites was used to produce estimates of wind by tracking identifiable cloud targets through a sequence of images. This generated a set of wind observations covering most of the Earth equatorward to about 45° latitude. The vector winds generally tended to be at two levels--low and high--corresponding to the two types of cloud targets (cumulus and cirrus) that are tracked by automated and manual methods. However, areas of satellite low-level winds tend not to overlap with areas of high-level winds since most of the high-level targets come from thicker cirrus which obscure lower targets.

Quantitative assessments of the cloud winds can be performed by a number of imperfect techniques. The problem with the assessment is in trying to locate "nearby" wind measurements of known quality. Nearby is defined as a prespecified colocation window in three-dimensional space and time. Since the observations are rarely at the same space and time (including winds derived from adjacent satellites that have different processing schedules), the atmospheric variability over this window tends to disguise the comparisons. Nevertheless, the following conclusions can be drawn from the review paper and the discussion about the satellite derived winds. The main source of error is the height assigned to the wind. The satellite winds of different operators tended to compare well against each other with the exception of those from the Japanese satellite. (The Japanese satellite winds were attributed to the wrong level by techniques that have since been changed. The University of Wisconsin has reprocessed the Japanese winds so that this problem has been virtually eliminated.)

Monthly averaged wind speed differences indicate that winds from U.S. satellites tend to be faster than their matched radiosonde counterparts while the European satellite winds are slower. The known limitations of rawinsonde sounding near jet streams may account for the U.S. results. However, the European satellite winds appear to be systematically slower, suggesting that the problem may be more complex.

Some time was spent discussing the future possibilities of using satellite water vapor channels to determine winds by tracking moisture features. It was agreed that this is a very promising and exciting observing technique since a high density of wind estimates can be achieved at midtropospheric levels. However, the accuracy and representativeness of wind estimates using this technique is not well known yet. The University of Wisconsin has agreed to document the accuracy of H_2O tracer winds and produce some limited data sets for model impact studies using Meteosat water vapor imagery.

Overall, the rawinsonde and automatic aircraft winds are considered more accurate than satellite cloud tracer winds (although perhaps satellite winds are more accurate than rawinsondes near jet streams). The satellite winds during the GWE are not uniform in quality. It appears that those winds from U.S. satellites are more accurate than those of the other two satellite operators.

Achievements

1. The thousands of wind vectors produced by the five geostationary satellites filled a major gap in obtaining the wind field over the oceans. The GWE showed that satellite derived winds provided by different operators could be used effectively in a global analysis/prediction cycle.

Buoy Systems

In a review paper entitled "Buoy Systems During the FGGE" (see Volume Two, pp. 37-50), Fleming provided the basis for the discussion of buoy data. Three general categories of new buoy systems were deployed during the GWE year. These buoys provided critical coverage of environmental phenomena in the Arctic Ocean basin, the tropical oceans, and the southern hemisphere. Each buoy system transmitted data to the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellite system, and the buoy positions were computed from the Doppler shift of the transmission as received by the satellite. All three types of buoy systems, each type uniquely engineered for applications in different regions of our planet, contributed to the broad objective of advancing weather and climate predictions in several special ways.

The southern hemisphere buoy program had 318 buoys deployed during the GWE year. The buoys were provided by 8 countries and deployment was shared by 14 countries. The southern hemisphere buoys measured pressure, sea-surface temperature (SST), and air temperature. Their contribution to the objectives of GWE was primarily to provide for the first time an accurate synoptic coverage of the southern hemisphere surface pressure fields, both for their intrinsic value and as a reference level for the satellite soundings so that the reconstructed atmospheric mass field would be independent of any model assumptions or first guess.

The buoys were equipped with a quartz oscillator pressure sensor, a very stable devise designed to minimize "drift" in the pressure measurement to less than 1 mb per year. With rare exception, when a buoy instrument failed during the GWE, it was obvious that it had done so. Zillman (1983) points out that at the end of SOP-1, of 156 buoys operating, 135 were considered by the Melbourne analysts to be producing reliable data and 21 were not. Even so, Zillman, speaking about the impact of the GWE systems on operational synoptic analysis, stated that the most outstanding contribution was made by the drifting buoy system. The extensive network of regular pressure observations over the previously data-sparse ocean areas removed the major hurdle that had prevented reliable routine surface pressure analyses over the entire hemisphere.

Pressure information from the GWE buoys permitted more confident specification of the centers of highs and lows, the variations in the position and intensity of the circumpolar trough, and the oscillations in the strength of the subtropical highs. The central pressures of the high-latitude cyclones were often analyzed 20 mb deeper than would have otherwise been estimated, and the westerly flow south of Australia was determined to be considerably stronger than otherwise would have been identified. From these results, Guymer and LeMarshall (1981) concluded that pre-GWE analysis procedures may have led to systematic underestimation of synoptic systems over the high-latitude oceans. The question arises, was the GWE year an anomalous one or is our existing southern hemisphere climatology deficient due to the poor data coverage? It now appears that both are true.

The Arctic Basin buoy program during the GWE was a modest effort to provide uniform coverage of the pressure field in the otherwise data-sparse region of the Arctic. Several countries (e.g., Canada, Norway, and the United States) reported improved analyses and forecasts resulting from the availability of this pressure information.

Moritz (1983) has evaluated numerical forecasts in the Arctic by comparing geostrophic winds derived from the analyzed and forecast pressure fields. He showed that the National Meteorological Center's (NMC's) 1000 mb height forecasts produce geostrophic winds that better persistence only out to 3 days, and that despite the higher persistence of the wind field in the Arctic, compared to midlatitudes, the forecast skill is smaller in the Arctic than in midlatitudes.

Achievements

1. The extensive network of regular pressure observations provided by the southern hemisphere buoys over the previously data-sparse areas provided the first reliable routine surface pressure analysis over the entire hemisphere. The pressure information from the GWE buoys provided invaluable support to subjective operational forecasts and major positive impact on numerical forecasts (see later workshop results). The semi-quantitative imagery interpretation techniques that had been developed by Guymer (1978) for ascribing numerical values to pressure fields based on satellite images was systematically improved by the southern hemisphere buoys.

2. The southern hemisphere buoys allowed Australia to begin operational production of 5-day and monthly SST maps for the entire southern hemisphere. Buoys in the tropical oceans during the GWE contributed accurate SST information and identified eddies that are associated with the cusp-shaped Legeckis waves seen in tropical oceans during non El Niño years (Hansen and Paul, 1984).

3. Several countries (e.g., Canada, Norway, and the United States) reported improved analyses and forecasts resulting from the availability of pressure information from the Arctic Basin buoys.

Tropical Observing Systems

In a review paper entitled "The Tropical Special Observing System" (see Volume Two, Session 1), Julian provided the basis for the discussion of the Aircraft Dropwindsonde System (ACDWS), the Tropical Wind Observing Ships (TWOS), and the Tropical Constant Level Balloon System (TCLBS). These systems, coupled with those satellite data systems; the automated aircraft reports (AIDS and ASDAR); surface, ship, land, and island reports; and the few conventional tropical upper air systems, comprised the total tropical observing system. It was noted that the task of establishing and meeting the observational requirements for the tropics during the GWE was formidable on both counts. The full dynamics of the tropics and its interaction with the higher latitudes were far less known in the days of planning for the GWE than they are now after the experiment. Further, the known methods of obtaining tropical winds were extremely expensive.

The ACDWS consisted of research and military transport aircraft of the United States flying missions along predetermined tracks in all three tropical ocean basins. The aircraft flew as long and as high as possible in order to deploy instruments via parachute to provide wind profiles of the tropical atmosphere. The dropwindsondes provided temperature and humidity information in addition to measuring omega navigation signals. Omega windfinding is a relatively complex process compared with radar or radio-direction finding techniques. Sources of uncertainty may be divided into those external to the system, mainly ascribable to various kinds of unsteadiness in the omega navigation net, and those internal to the system, mainly electronic and antenna noise. In spite of some apprehensions about deploying a sensitive system during sunspot maximum, only 10 drops out of nearly 5000 processed had to be eliminated because of the sudden ionospheric disturbances.

Another external source of error, longpath or anomalous propagation of the omega signals, caused a major uncertainty in the originally produced ACDWS data set. This longpath or anomalous propagation cannot be detected uniquely by the ACDWS system itself. (This is not the case in the TWOS-Navaid system because of the availability in that system of direct (local) omega recorded on the ship.) A number of solutions were investigated, and ultimately all drops for the final Level IIb were recalculated. Thus it should be emphasized that the ECMWF IIIb analyses, utilizing main IIb data, were assimilating less accurate data than Geophysical Fluid Dynamics Laboratory (GFDL) and GLAS IIIb, which used the recalculated data.

The TCLBS was instituted to fill a gap in the vertical coverage of the wind observation program in the tropics owing to the limited operational altitude of the ACDWS aircraft. The TCLBS consisted of 153 (and 157) platforms launched from 2 (3) sites within the tropics during SOP-1 (SOP-2). Because of air safety considerations, the float altitude was chosen to be above commercial airspace at 135 to 140 mb. Special tracking efforts to obtain single-level winds at the standard synoptic times resulted in very accurate winds at the level of the balloons. Uncertainties in the wind vectors were found to be less than 2.0 mps (vector rms) for 90 percent of the vectors produced. The TCLBS winds were usually accommodated into the analyses with a high degree of accuracy; however, occasionally an analysis scheme would needlessly reject such a wind.

Over 40 research vessels for oceanographic and/or atmospheric research were used as platforms for obtaining atmospheric wind profiles at some time during the GWE SOPs to fill gaps in the tropics. Two different wind measuring systems were used on the ships. One employed a standard balloon-borne sonde which used the omega windfinding system to track the balloon. The principles of calculating winds are identical to the Aircraft Dropwindsonde System, although different algorithms were used. Since the sondes were launched from slow moving or stationary ships, this ship system recorded direct omega signals together with sonde-retransmitted omega. This significant difference made the selection of omega signals for wind calculation less prone to error.

The ships contributed by the Soviet Union to the TWOS program carried a radar-tracking wind measurement system. Subjective comparison of these TWOS-radar observations with wind vectors obtained by other observing systems suggests that no major difficulties occurred.

There are examples of tropical analyses where good winds of various systems have been apparently ignored. There are other examples where the analyses have been drawn to apparently bad data. This situation can occur anytime, anywhere, even in the best analysis/forecast system. However it seems to occur often enough in the tropics for the GWE data to be of concern. A solution may require further significant research in that several factors are involved: identifying "proper" vertical structure functions in the tropical analysis schemes, minimizing difficulties experienced in initializing the tropical atmosphere, which has significant large-scale divergent components, and improving the model prediction errors, which are relatively high in the tropics. In the discussion the point was emphasized that more refined estimates of the proper observational uncertainty in the winds from the various tropical systems was needed so that users could assign consistent relative errors to observations from these systems in the assimilation schemes.

Achievements

1. The mix of observing systems comprising the Tropical Observing System produced a data set that was generally satisfactory for analyses of circulations in the upper and lower tropical troposphere. The data set was unprecedented in its ability to define regions of large-scale organized convection.

Recommendations

1. In view of what has been learned about processing satellite soundings and about new methods, an organization should be encouraged to reprocess the GWE satellite soundings using the physical solution approach, for at least the SOPs and preferably for the entire year.
2. The scientific community is urged to pursue with greater vigor the extraction of useful information from satellite water vapor channels. This includes efforts to improve the accuracy and acceptance of water vapor winds, which could fill existing observational gaps, and efforts to use water vapor analysis in improving tropical analysis and initialization procedures.
3. A small workshop should be held to improve methods of extracting further information from the tropical observing systems.

DATA ANALYSIS, ASSIMILATION, AND INTERCOMPARISON

GWE IIIb analysis for the entire GWE year was carried out by two institutions, ECMWF and GFDL. In addition, four other U.S. institutions (NMC, GLAS, Florida State University (FSU), and Naval Environmental Prediction Research Facility (NEPRF)) have produced some GWE IIIa and IIIb analyses. In this session Daley, Lorenc, Julian, Baumhefner, and Chen (Volume Two, Session 6) reviewed the work on GWE data analysis, assimilation, and intercomparison. The a priori characteristics (types of data used, error checking, initialization, assimilating model, objective analysis scheme, and analysis cycle) are shown in Tables 1-7 and Figure 1 (see Daley et al., Volume Two, pp. 71-82).

There are several a priori characteristics that were common to most of the six analysis systems, and there were also important differences. In particular, spectral assimilation models, nonlinear normal mode initialization, statistical interpolation (OI), and discrete insertion were widely used. Important exceptions are continuous insertion by GFDL and the successive correction method by GLAS.

There were also philosophical differences between the various GWE IIIb data producers. ECMWF opted for a highly constrained system, whereas GFDL's system was relatively unconstrained. The other schemes fell somewhere in between. Tightly constrained systems build many a priori assumptions into the system and are effective in noise control. Weakly constrained systems are potentially more effective in situations that do not fit the scientists' (and their models') preconceptions.

Analysis intercomparisons and the calculation of general circulation statistics revealed, a posteriori, many features of each of the analysis systems. By some measures, there was considerable agreement among the analyses, but there were also large and important differences. In general, there was much more agreement in midlatitudes than in the tropics. All analyses tended to fit the data acceptably in general, but there were exceptions (Hollingsworth et al., Volume Two, pp. 217-227).

The ECMWF analyses had a deficient vertical motion field owing to the use of adiabatic nonlinear normal mode initialization. This was reflected in a weak Hadley cell. In addition, the ECMWF analyses, being tightly constrained, had a divergent kinetic energy spectrum which dropped off rapidly at small scales (see Julian, Volume Two, pp. 211-216). In this way, the ECMWF analyses exhibited the weakest energy cycle, even when the vertical motion was calculated kinematically from the divergent component of the wind. The ECMWF analyses did, however, exhibit a -3 power law in the kinetic energy spectrum in the baroclinic waves (see Chen and Lee, Volume Two, pp. 247-266).

The GFDL analyses had the strongest energetics, particularly in the conversion terms. The divergent kinetic energy spectrum was much flatter than in the ECMWF case, but it was felt that much of the smaller scale divergence was noise. In fact, in the tropics, the GFDL wind analyses did not fit the data as well as the ECMWF analyses, despite being more loosely constrained (see Julian, Volume Two, pp. 211-216). There was some evidence that the GFDL analyses were inferior in the case of rapidly developing baroclinic systems.

There was considerable agreement between the various analyses when the basic quantities of temperature, wind, geopotential, surface pressure, or their time or space means were examined. For example, in the northern hemisphere extratropics, there was substantial agreement among the analyses for zonal wavenumbers less than 15. For the divergent wind however, this was only true for wavenumbers less than 5. There was much more disagreement with respect to inherently smaller scale fields such as moisture. The analyses also disagreed with respect to second-moment quantities, particularly those involving the divergent wind (see Chen and Lee, Volume Two, pp. 247-266). Despite considerable agreement in high latitudes, tropical differences could be greater than one-half the normal variance.

Although the ECMWF analyses extended into the stratosphere to 10 mb and the GFDL analyses to 0.4 mb, neither were very reliable above 30 mb. As noted in Daley et al. (see Volume Two, Session 2), very few observations were assimilated in the upper levels of the models.

It was found that many analysis differences resulted from different quality control or error checking procedures (see Hollingsworth et al., Volume Two, pp. 217-227). Although systematic analysis differences could be attributed to known system characteristics, it was not generally possible to predict how a particular analysis system would handle any given situation. Some of the difficulties in the tropics could be attributed to assimilation model deficiencies (lack of diurnal cycle, for example) or inappropriate analysis structure functions.

Analysis intercomparison showed up many analysis differences. It is not generally clear, a priori, whether these analysis differences will be significant in forecasts integrated from these analyses. A forecast model may act as an amplifier that turns small analysis differences into large, significant forecast differences (see Hollingsworth et al., Volume Two, pp. 217-227).

Some large analysis differences had virtually no effect on subsequent forecasts, particularly if they were associated with isolated or decaying systems. It was possible to relate directly analysis differences with much larger forecast differences 2 or 3 days later. It was found that the amplification in these cases was relatively independent of the amplifier (forecast model) used (see Hollingsworth et al., Volume Two, pp. 217-227).

The success of modern four-dimensional data assimilation techniques in advecting information from data-rich regions into data-sparse regions has been shown in recent data impact studies (see Kalnay et al., Volume Two, pp. 121-145). Impact studies have been performed by NOAA with the TIROS-N data using the Israeli Meteorological Service subhemispheric model and a 12-hour successive correction analysis as a first guess. They found that the TIROS-N data had more impact on these forecasts than in ECMWF and GLAS studies. This suggests that the ECMWF and GLAS first guess fields already provided some of the information in the data-sparse regions that was also available from TIROS-N.

There seemed to be more agreement among the analyses in the tropics than was evident in the Data System Tests (DST) of 1975-1976. However it is clear that there is a large amount of information in the GWE IIb tropical data set which has not been effectively used in any of the analysis schemes.

The analyses of the southern hemisphere were almost certainly superior to those produced prior to the GWE. This had a substantial positive effect on both forecasting and general circulation statistics in the southern hemisphere (see Kalnay and Puri, Volume Two, Session 4).

Achievements

1. The GWE IIIb analyses provide the best and most complete representation of the troposphere ever. The various GWE IIIb analyses are very consistent in the extratropical northern hemisphere, suggesting an atmospheric representation that is virtually independent of assimilating models. The tropical and southern hemisphere analyses are less consistent but, nonetheless, provide a more realistic representation than any previously obtained.

2. The powerful new data assimilation methods developed for the GWE IIIb analyses have been successful in assimilating many types of new and unconventional data. Much of the potential of these new schemes has been largely realized in the extratropics although in the tropics their full power has yet to be realized.

3. The GWE has been an important stimulus in recent technological advances in numerical weather prediction. The GWE, with its emphasis on the global atmosphere as a whole, coincided with a considerable advance in the sophistication and skill of numerical models and assimilating schemes. In particular, global forecast models became the rule rather than the exception after the GWE, and initialization and objective analysis methods with global rather than merely extratropical potential were developed. Operational and research centers that have participated substantially in GWE work have reaped real benefits in increased understanding of the atmospheric circulation and its numerical simulation.

Unresolved Problems

1. Analysis intercomparison shows that large analysis differences are products of differing quality control or error checking procedures.

2. Tropical analysis is far from satisfactory owing to deficiencies in both forecast model and analysis systems. There is still considerable midlatitude bias in both forecasting and analysis. There are serious differences in the analysis of various general circulation statistics, particularly second moment quantities. Some boundary layer diagnostics seem to reflect the assumptions made in the assimilating model's convective parameterization more than the observations. There are serious deficiencies in the analysis of the stratosphere.

3. Moisture analysis is still a considerable problem, and very little progress has been made since the GWE.

4. Analysis schemes are rarely described in the refereed literature, and their properties are difficult to discover.

5. Adiabatic initialization schemes have serious drawbacks in the tropics. Nonlinear normal mode initialization is widely used, but there are large differences in opinion (not based on much hard evidence) about which particular modes to initialize.

Recommendations

1. Well-organized analysis intercomparisons are worthwhile and should be encouraged. In particular, an experiment similar to the recent NMC-ECMWF-UKMO analysis intercomparison should be conducted to determine separately the effect of quality control procedures, analysis or initialization scheme, and effect of the assimilating model. Data rejection lists are available and should be used in comparing GWE IIb data with GWE IIIb analyses.

2. More work needs to be done on tropical parameterization and its effect on tropical data assimilation. Present error covariance

statistical models of both forecast and observation error are totally inadequate in the tropics. Present covariance modeling assumptions of non-divergence should be relaxed and statistics should be stratified spatially and by synoptic situation (particularly with respect to convection) in the tropics. More general approaches such as Kalman filtering should be pursued.

3. Rainfall gauge information and satellite infrared measurements have recently been used to infer moisture or divergence in the tropics. This work should be encouraged and ways found to assimilate this type of information. In addition, there is conventional information that is either not exploited or not properly assimilated such as surface pressure tendency or single-level winds.

4. Developers of data assimilation schemes should be encouraged to write up their work in the form of both detailed users guides and refereed journal articles.

5. It is possible to determine rationally which modes to initialize in normal mode initialization by examining the modal balance in long integrations of the forecast model. Procedures are now available for obtaining convergence for normal mode initialization even under diabatic conditions (Rasch, 1985). These should be exploited.

6. Simple spectral estimates of the initial analysis error or uncertainty (E_0) have already been obtained at ECMWF (Uppala et al., Volume Two, pp. 85-118). Bounds on E_0, spatial and spectral, would be useful in estimating the relative contributions of model error and errors due to the observational system. There are also important applications in stochastic-dynamic forecasting and Kalman filtering.

7. Operational centers should be encouraged to use the GWE IIb data set when debugging new data assimilation systems, in addition to their normal parallel mode for debugging new systems.

8. The reanalysis of Level IIb data by techniques other than the forecast model related techniques of statistical interpolation and four-dimensional data assimilation may well be justified for the investigation of specific meteorological phenomena. This applies particularly for certain tropical phenomena such as Kelvin waves or organized deep convection.

NUMERICAL PREDICTION AND DATA IMPACT

Data Impact on Forecasts

Three groups--ECMWF, GLAS, and ANMRC--have performed studies to determine the impact of several GWE observing systems on numerical weather prediction skill using four-dimensional analysis systems. In these sessions, Hollingsworth, Kalnay, and Puri (see Volume Two, Sessions 3 and 4) reviewed progress in prediction and GWE data impact.

ECMWF performed data impact studies for two periods of the GWE year: November 8 to 19, denoted OSE-1, and February 22 to March 7, 1979, denoted OSE-2, with about nine forecast comparisons in each period. The data impact periods chosen by GLAS were the special observing periods (SOP-1 and SOP-2), January 5 to March 5 and May 1 to

June 30, 1979, respectively, with about 14 forecasts in each period. ANMRC performed analyses confined to the southern hemisphere and to the period May 17 to 26, 1979, and two-day forecasts from May 20, 22, and 24.

Both ECMWF and GLAS performed comparisons between a "minimum" system, denoted "NOSAT" (no satellite data) by GLAS and "SO" (surface only data) by ECMWF, and a "maximum" system, denoted "FGGE" by GLAS and "AI" (all-included data) by ECMWF. In the minimum analysis only conventional data were assimilated, although SO also included drifting buoys and NOSAT included aircraft reports. The maximum system included, in addition to conventional data, the full Special Observing System (SOS) (GWE IIb) data.

The impact of individual components of the observing system was studied in two different ways: first, by adding the observations of a single system to the minimum system, and second, by deleting such observations from the maximum system. One of the purposes of these experiments was to explore the possible redundancy between these systems.

There was generally good agreement between the results of the different data impact experiments. Some of the main conclusions were as follows:

1. Forecast impacts of the GWE SOS (including as largest components satellite temperature soundings, satellite winds, and drifting buoys) are positive but small in the northern hemisphere and very large and positive in the southern hemisphere (ECMWF and GLAS).

2. In the northern hemisphere, the impact depends on season, synoptic regime, and data coverage. For example, ECMWF found a positive impact during OSE-1 and a much smaller impact during OSE-2. In the GLAS system, in which regional verifications over North America and Europe are made, both positive and negative impacts were observed, although the net impact was positive. The hemispheric verifications of ECMWF showed no negative impact.

3. All the main components of the GWE SOS were found to contribute significantly to forecast accuracy, with satellite temperatures being most important in the extratropics, satellite winds in the tropics, aircraft reports, when available, contributing to both regions, and buoys useful in the southern hemisphere.

4. Both ECMWF and GLAS emphasized that redundance of information from different observing system components is a strength of the composite observing system. The redundancy not only contributes to a reduction of the analysis errors but also reduces the risk of critical errors due to accidental gaps in one of the observing systems.

5. When GLAS physical retrievals were used in place of the archived GWE retrievals, no cases of negative forecast impact occurred over North America.

6. Forecast impacts with the Israel Meteorological Service subhemispheric model, and a 12-hour successive correction analysis using the previous analysis as first guess resulted in positive impacts in the northern hemisphere--larger than those in the GLAS and ECMWF analyses. This may be due to the use of forecast fields in the first

guess that was used; in the ECMWF and GLAS systems a forecast first guess advects information from data-rich to data-sparse regions and therefore alleviates the effects of data gaps in the conventional data.

Among the results pertaining to the southern hemisphere, the following should be mentioned:

1. The GWE SOS added about 2 days of forecast skill in the southern hemisphere, with the satellite temperature retrievals being the largest contributor (ECMWF and GLAS).

2. During SOP-2, the impact of removing the buoys is a deterioration of forecast skill of more than 12 hours, especially important in the 1-day forecast of sea level pressure. However, the removal of satellite temperatures has a much greater negative effect than buoys after the first day (GLAS and ANMRC).

3. Less impact from the loss of buoys was observed for SOP-1 (GLAS). The apparent redundancy of the buoy data during January and early February 1979 may be due to the fact that fewer buoys were available during that period, to the less intense summer circulation regime, or to the availability of VTPR satellite data during SOP-1 and not SOP-2. Furthermore, it was pointed out that the GLAS NOSAT assimilation also included a large number of ship observations not normally available during an operational analysis cycle, which may have also contributed to a reduction of impact.

Achievements

1. There was good agreement between the conclusions of the three groups--ECMWF, GLAS, and ANMRC--that performed studies to determine the impact of several components of the GWE SOS. Given the notorious difficulty of performing such studies, and the large discrepancies noted before the GWE, this is an important advancement.

2. Among those components of the GWE SOS that were tested, all were found to contribute significantly to forecast accuracy. Satellite temperatures were most important in the extratropics, satellite winds in the tropics; aircraft reports, when available, contributed to both regions; and buoys were useful in the southern hemisphere.

3. The use of GLAS physical retrievals of satellite temperatures in place of the archived GWE retrievals resulted in a significant forecast improvement over North America.

4. The forecast improvements from the GWE SOS were much larger in the southern hemisphere than in the northern hemisphere. The GWE SOS added about 2 days of forecast skill in the southern hemisphere, with the satellite temperature retrievals being the largest contributor (ECMWF and GLAS). Buoys improved the skill of short-range forecasting by more than 12 hours during SOP-2 (ANMRC and GLAS).

Unresolved Problems

1. Satellite moisture data has not generally been used in global assimilation models. There has been no use made of the Meteosat water vapor winds. No forecast study has been made to assess the importance of these data sets.

2. The forecast impact of other special observing systems, particularly those in the tropics, has not been studied in detail.

Recommendations

1. The impact of GWE data on tropical forecasting needs to be studied and documented in much more detail.

2. Further studies are needed to optimize the use of satellite data in NWP, e.g.,

- determination of optimal weights for satellite data over land and ocean, effect of orography and clouds;
- elimination of systematic errors and determination of error correlations in space and time;
- use of forecast first guess in the satellite temperature retrievals and in the assignment of cloud wind heights;
- use of horizontal temperature gradient information and three-dimensional temperature retrievals;
- optimal assimilation of single-level wind and pressure data;
- use of satellite moisture data;
- use of cloud, rain, radiances, and other nonconventional data in the assimilation cycle; and
- use of VAS retrievals.

3. The accuracy of the reprocessed GLAS physical retrievals, including moisture, and their impact on forecast skill should be studied in detail.

4. The impact of the use of water vapor winds, which may complement cloud tracked winds, should be studied.

5. The data impact experiments without the use of buoys should be used to determine the extent to which the buoy data has influenced the GWE analysis and perceived atmospheric variability in the southern hemisphere.

6. The abandonment of the present system of two sunsynchronous polar orbiters should be examined for its effect on the determination of the diurnal cycles in atmospheric parameters and on the reduction in the number of temperature retrievals.

7. Some redundancy between different observing systems is needed. This redundancy not only contributes to a reduction of the analysis errors but also reduces the risk of critical errors due to accidental gaps in one of the observing systems.

Tropical Forecasting

The work described in this session was mostly confined to experimental tropical forecasts performed at FSU and reported by Krishnamurti (see Volume Two, Session 5). Several GWE impact studies on tropical analysis and forecasting performed at ECMWF were reported by Heckley (see Volume Two, Session 5).

Krishnamurti first presented the results of an experiment to test the importance of the distribution of large-scale differential heating between the net radiative cooling over the Arabian Sea and the strong net heating over the foothills of the Himalayas that takes place at the time of the onset of the monsoon. In this experiment he made three 4-day forecasts in which the rotational wind, pressure, and temperature fields were identical and corresponded to a pre-onset circulation. The divergent wind and humidity fields however were taken to be those of three different stages of the monsoon evolution: springtime, pre-onset, and post-onset. The only strong monsoonal response that developed occurred in the third experiment, showing that the differential heating associated with the northerly position of the heat source and the corresponding divergence and moisture fields are crucial for the onset of the monsoon.

The ECMWF IIIb humidity analyses resulted in a rapid deterioration of the divergent field in short-range predictions with the FSU model. In order to alleviate this problem, a physical initialization scheme was designed. The humidity field is modified in such a way that it is consistent with rain gauge information and from satellite observations, according to Kuo's convective parameterization scheme. In rain-free areas, the modified humidity field satisfies a radiative-advective balance.

Experiments on the sensitivity of the forecast monsoon-onset vortex to different versions of the Kuo parameterization of cumulus convection, and to model resolution and orography were made at FSU, ECMWF, and by other groups. The best results at FSU were obtained using high horizontal and vertical resolution (rhomboidal 42 and 11 vertical levels) and an enhanced (envelope) orography. In these comparisons, the rms vector wind error in the tropics became comparable to that of persistence in about three days. Nevertheless, certain synoptic systems, such as the track of the monsoon-onset vortex, were predicted for up to 7 days.

In his presentation, Heckley emphasized the difficulties associated with tropical analysis, such as accuracy of the 6-hour forecast first guess, data quality checks and rejection, and nonlinear normal mode initialization. Some of the initial problems encountered in the ECMWF IIIb analysis have since been alleviated considerably with the introduction of diabatic initialization and with interpolation of the difference between analysis and first guess fields rather than the full analyzed fields.

Studies by Cats and Wergen (1982) showed that the optimal interpolation scheme now in use can seriously alias large-scale Rossby and Kelvin modes. This is due to the irregular distribution of the data, to the local and nondivergent character of the error correlation functions, and to the lack of high quality mass observations necessary to separate the Rossby and Kelvin modes. On the other hand, synoptic scale waves, primarily rotational, are reasonably well analyzed.

An ensemble of four forecasts with and without satellite cloud tracked winds, temperature soundings, and aircraft observations showed a clear impact of these data on the accuracy of tropical forecasting during the first four days. It was also pointed out that to evaluate tropical forecasting it is useful to separate systematic from transient errors. The former are dominated in the tropics by deficiencies in the model's simulations of large-scale stationary waves associated with thermal and orographic forcing. As a result, the quasi-stationary features of the tropical flow are difficult to forecast. Further work in improving the model's parameterizations, which determine the realism of the model's tropical climatology, is necessary to improve tropical forecasting.

Achievements

1. The GWE tropical observing system has provided many new data from several new types of platforms. This large data set will continue to be used for many years in the improvement of tropical analysis and forecasting.
2. With the establishment of global prediction, a significant improvement of NWP in the tropics occurred in operational centers.
3. Research experiments in tropical forecasting have shown much more skill during the GWE than during previous years.

Unresolved Problems

1. More accurate temperature and moisture data are needed in the tropics in order to resolve the structure of weak tropical disturbances and to avoid aliasing between perceived Rossby and Kelvin waves. It is not clear whether the necessary technology to provide this data is currently available.
2. Problems with the tropical analysis of data still remain, even for the largest scales. The structure functions in OI should be designed optimally. Systematic model errors that may corrupt tropical analysis should be documented.

Recommendations

1. The potential for medium-range predictability in the tropics, as well as for longer-time averaged forecasting, should be investigated.
2. Forecast and simulation studies of the various phases of the monsoon (e.g., transitions between active and break monsoon) should be made.
3. Verifications should be made using a common system, e.g., rms vector wind errors in the tropical belt, verifying against observations, not analysis.

4. Systematic and transient errors should be examined separately.

5. The possibility of generating and using accurate temperature and moisture data to resolve the structure of weak tropical disturbances and to reduce aliasing between perceived Rossby and Kelvin should be explored.

6. The five geostationary satellites should be maintained to provide global coverage of cloud tracked winds.

7. Studies on the sensitivity of tropical forecasting to initialization and model parameterizations should be performed.

8. The possibility of using climatological or recent observed moisture and heat sources during a model forecast could be explored.

9. Systematic model errors that may corrupt tropical analysis should be documented.

Cumulus Parameterization

The work described by J. Molinari, Ogura, and Betts (see Volume Two, Session 16) included recent prognostic studies made with various parameterization schemes and a study that demonstrated the utility of using a cloud ensemble model to test cumulus parameterizations. The impact of GATE on our understanding of cumulus convection was evident in the work described. It was clear that the final GWE data sets should be useful in future parameterization studies, particularly if the information on rainfall distributions is available.

A number of questions were raised during the discussion regarding the possible impact of mesoscale circulations on cumulus parameterizations. Such circulations were clearly documented during GATE. One comment noted that relatively weak forcing, such as diurnal effects over oceans, can affect the organization of convection. It is still not clear, however, if such features as convective-scale and mesoscale downdrafts need to be explicitly considered in parameterizations used in forecast and general circulation models. It was noted that if more complicated schemes are used, more closure assumptions are needed. One must also be able to determine for a given situation if observations will or will not support the more complicated structure in some clouds. A question was also raised on the importance of parameterizing momentum transport by cumulus convection. However, no consensus was reached on the importance of including these effects in models. It was suggested that the errors in tropical forecasts from the Level IIIb data could be used to determine what cumulus parameterization schemes should be used and that more prognostic testing of the parameterizations be made.

Ogura (see Volume Two, Session 16) described a study made with a cumulus ensemble model. He investigated the statistical properties of cumulus clouds that occur in response to the imposed large-scale forcing for both tropical and midlatitude conditions. A strong drying process was found to occur in the boundary layer in association with deep convection in a midlatitude case. The Arakawa-Schubert cumulus parameterization scheme was tested semi-prognostically against both the model results and the observations in a tropical rain event that occurred during GATE. The cloud heating and drying effects predicted by the Arakawa-Schubert scheme were found to agree well with both the observations and the model. However, it was also found that the Arakawa-Schubert scheme underestimates both condensation and evaporation rates substantially. An inclusion of the downdraft effect, as formulated by Johnson (1976), appears to alleviate this deficiency. This downdraft effect may be important in predicting the behavior of the boundary layer accurately.

J. Molinari (see Volume Two, pp. 689-705) described a simulation of a mesoscale convective complex (MCC) made with a modified version of the Kuo scheme. This study, which evaluated the effect of cloud-scale and mesoscale downdrafts on the simulation of a convective complex, noted that the predicted total rain volume is most accurate when cumulus and mesoscale downdrafts are incorporated. A strong divergent circulation extends 600 km from the narrow heavy rain region of the MCC in only 6 hours, much like those observed. A realistic life cycle behavior occurs only in the integration with downdrafts. The results indicate that (1) Kuo's closure, linking rainfall to a fraction of the instantaneous moisture supply, may be useful in mesoscale models and (2) the incorporation of downdrafts into Kuo's approach appears to be essential to reproduce the life cycle of convective disturbances in nature.

Betts (see Volume Two, pp. 706-724) described a new convective adjustment scheme in which the temperature and moisture are adjusted simultaneously with a time lag toward empirically obtained quasi-equilibrium structures. The parameterization was tested using GATE, BOMEX, and AMTEX data, and the scheme does well in reproducing the structure of the convective source terms and the precipitation. Preliminary 10-day forecasts using the ECMWF gridpoint model show that the scheme improves the forecast of the tropical temperature and surface fluxes.

Albrecht showed the effect of cumulus transports of moisture on the climate simulated with the NCAR Community Climate Model. The inclusion of these transports resulted in an increase in tropical upper tropospheric temperatures and better definition of tropical circulations and precipitation distributions.

Arakawa showed observational evidence for the existence of a set of quasi-equilibrium states, in which temperature lapse rates and humidities are highly coupled, as the cloud-work function equilibrium indicates. Fluctuations around the quasi-equilibrium states show large regional differences, especially between the oceanic and continental regions. Predictability (or parameterizability) of such fluctuations require further studies.

Achievements

1. Semi-prognostic tests based on GATE, MONEX, and GWE observations have provided improved parameterization of heating-moistening profiles and rainfall rates.
2. Cloud ensemble models have provided a scientific rationale for closure assumptions (quasi-equilibrium) and provided a verification for the bulk methods.

3. Simple applications of the Arakawa-Schubert, Kuo, and adjustment schemes have enabled extended range predictions with some promising results.

4. Promising improvements have been made in the areas of cumulus downdrafts within existing parameterization schemes.

5. Diagnostic studies of heat sources (Q_1, Q_2) have complemented cumulus parameterization studies (GATE, MONEX).

6. Diabatic initialization methods have steadily improved. Cumulus parameterization methods are being included within the initialization with some success.

Unresolved Problems

1. Modeling and impact of mesoscale organization of clouds need to be studied within forecast models and GCMs.

2. The dependence of parameterization schemes on grid size should be studied.

3. Further work is necessary on the vertical transport of vorticity and momentum and its parameterization.

4. Parameterization of planetary boundary layer, cumulus convection and radiative processes should be coupled consistently.

5. Better estimates of global daily precipitation rates should be obtained as a function of raingauge and satellite-based observations. At present no such data sets exist.

Recommendations

1. While investigating the sensitivity of forecasts to cumulus parameterization remains important, extensive analyses of the GWE data that directly address the problem of parameterizability and closure assumptions should be made. The analyses should include those of quasi-equilibrium states and fluctuations around such states. Cloud ensemble models should be used to test closure assumptions.

2. Testing a parameterization with the GATE data only, or with any data from the marine tropics, may give an overly optimistic view. Extensive studies on the macroscopic behavior of cumulus clouds over the tropical and midlatitude continents are needed. (Explore the possibility of conducting further field experiments over regions of heavy precipitation.)

3. Parameterization studies should be conducted with high-quality Level III data that give reliable spatial and temporal distributions of the cumulus heating and drying rates from large-scale budgets of heat and moisture, Q_1 and Q_2, that have been prepared for this purpose. The scope and limitations of reprocessed Level III data for these purposes should be addressed.

4. The model-dependence of the analysis should be minimized to develop an improved model.

5. Global precipitation estimates, during the SOPs, should be prepared from direct and indirect means.

Improvements in Forecast Skill

The European Centre for Medium-Range Weather Forecasts started to make daily 10-day weather forecasts in 1979. This forecast range was longer than the several days that formed the limit of numerical weather prediction for most operational centers at that time. Since 1979, the ECMWF procedures have been continually improved in many aspects--data checking, analysis, initialization, numerical integration methods, the representation of physical processes, and output procedures. These developments at ECMWF and at other centers, although often justified by an immediate need for improvement in operational predictions, were stimulated by planning for the Global Weather Experiment, by the advent of global data in 1979, by the preparation of Level IIIb analyses for the GWE archives, and by the use of IIb data for studies of the impact of different types of data on the accuracy of forecasts. Forecast improvements of the type reported at the workshop by Bengtsson for ECMWF have also appeared in operational forecasts from other centers, although not so dramatically.

The results reported by Bengtsson (see Volume Two, Session 7) may be summarized as follows.

1. Six-day forecasts by ECMWF for recent winters are as accurate as some of the 2-day forecasts made at other centers in the early 1970s.
2. There has been a gradual increase in accuracy by ECMWF since 1979, to the point where "useful" height anomaly correlation values of 0.6 now extend to 6 days on the average.
3. Most of this improvement has been in the prediction of very long waves and in the winter season.
4. In agreement with earlier predictability studies, very long waves are more predictable than the cyclone scale disturbances, the extra-tropics are more predictable than the tropics, and the northern hemisphere is more predictable than the southern hemisphere. Summers, however, are characterized by less forecast skill than winters, when measured against the variability of the system.
5. In addition to the seasonal variations of forecast skill, there are large variations of forecast skill within one month and in the monthly-averaged scores for different years. Episodes of enhanced or lessened forecast skill of several weeks duration are not uncommon.
6. The routine examination of the fit of objective analyses to data from individual stations has uncovered many examples of systematic errors in data from particular stations.
7. Tropical forecasts are not only sensitive to the initial analysis, but also to the parameterization of convection and to the presence or absence of a diurnal cycle in the model. Skill has increased in the last several years so that the average 850-mb vector wind correlation in the tropics now takes 3 days instead of 2 to decrease to a value of 0.6.
8. The dominant errors in 10-day forecasts in the northern hemisphere appear as an underestimate of the ridges over western Canada and Europe and as a weakening (4 m/s) and upward migration (40 mb) of the principal zonally averaged jet stream. Weakening of the large

scale features is accompanied by an overprediction of shorter-scale transient systems. These features are found in both grid-point and in spherical harmonic transform models.

9. Inclusion of a diurnal cycle has increased the upward (turbulent) flux of sensible heat from the ground and slightly decreased evaporation from land surfaces. Precipitation has been improved, most notably in the convection center over Africa.

10. Inclusion of an enhanced ("envelope") orography has reduced somewhat the systematic underpredictions of the western Canadian and European ridges, but it has also increased the local forecast error in some locations near major mountains.

11. A new spherical transform model with triangular 106 truncation promises increased skill over that from a triangular 63 truncation.

12. Incorporation of the effect of latent heat into initialization procedures has increased the strength of the Walker and Hadley circulations in the tropics.

13. In spite of the typical error referred to in 10 above, the forecast model seems to have now reached the point where there is little or no systematic change during a forecast in the standard energy transformations.

Bengtsson concluded by expressing the opinion that "models are doing better than the data" and that improvements in data will further increase the skill of medium-range forecasts. This quotation led to much exchange of opinion.

Miyakoda of the Geophysical Fluid Dynamics Laboratory presented preliminary results of 1-month forecasts from seven different January dates from 1977 through 1983 (see Miyakoda et al., Volume Two, pp. 292-296). These forecasts were made with the 9-level N48 GFDL model, with three different initial analyses made at GFDL, at ECMWF, and at NMC. The effects of three different parameterizations were also tested. These monthly prediction experiments are a continuation of research begun at GFDL in 1975.

The results may be summarized as follows. (The correlation coefficient between predicted and observed isobaric height anomalies between 25°N and 90°N was used as a measure of skill. Averages over 10-day and over 20-day means were taken before computing the correlation coefficient. A persistence forecast was defined by the 10- (or 20)day average completely preceding the initial date.)

1. For 10-day means centered on day 25 the skill at 1000 mb ranged from 0 to 0.5. The skill of a persistence forecast had a larger range, from -0.2 to 0.5. The numerical predictions were therefore, on the average, slightly more accurate than persistence.

2. The average skill for a 20-day mean centered at 20 days was 0.5 at 1000 mb and 0.2 at 500 mb.

3. Forecasts from the three different analyses varied most in the location and amplitude of the principal ridges.

4. Skill was improved by averaging forecasts from the three different analyses.

5. There was some evidence of small skill in predicting the large-scale structures associated with low frequency variability, such as the PNA pattern defined by Wallace and Gutzler (1981).

6. A very promising result was evidence that improved physics, such as a turbulence closure model, soil heat conduction, the Arakawa-Schubert cloud parameterization, and the enhanced "envelope" orography developed at ECMWF noticeably improved the forecasts.

7. The mean forecast errors for days 10 to 30 were often similar to the known patterns by which the forecast model deviates from climatology. (The improved physics referred to above did not however greatly reduce these systematic errors.)

8. The spectral model (rhomboidal 30 and 42) developed at GFDL is not yet competitive with the N48 gridpoint model at this range.

Achievements

1. Six-day forecasts by ECMWF for recent winters are as accurate as some of the 2-day forecasts made at other centers in the early 1970s. Useful height anomaly correlation values of 0.6 now extend to six days on the average. Most of this improvement has been in the prediction of very long waves and in the winter season. The useful time range of tropical forecasts has been extended from 2 to 3 days.

2. Thirty-day predictions of time-average anomalies made with the GFDL model were, on the average, slightly more accurate. There was evidence of skill in predicting low frequency, large-scale structures such as the PNA pattern. Improved physical parameterizations noticeably improved the forecast.

Unresolved Problems

1. Substantial variations in short- and medium-range forecast skill occur on weekly, seasonal, and interannual time scales. The reasons for these variations are not presently understood at all.

2. Despite improvements in tropical forecast skill, substantial improvement is needed in cumulus parameterization and the initial analyses.

Recommendations

1. Numerical prediction of time averaged anomalies at the range of three weeks is a potentially attainable goal. Work should proceed in this area, but the subject must be approached with caution.

Prospects for Improved Weather Prediction

Two speakers, Lorenz and Ghil, discussed this problem from the viewpoint of theoretical possibilities (see Volume Two, Session 19).

Lorenz (1982a,b, 1983) addressed the application of theoretical concepts of predictability to an interpretation of current operational forecast skill and the relative roles of errors in initial data and errors in forecast models. Studies in the 1970s had focused attention on global estimates of the growth rate of initial errors (as in the pre-GWE planning studies) and on the theoretical-numerical modeling of nonlinear error growth in idealized atmospheres with simple assumed power spectra. The existence of a long series of 10-day forecasts with a "good" model at ECMWF enabled Lorenz (1982b) to obtain some separation of the relative roles of initial and model error in the range 1 to 10 days. This separation is based on the fact that the differences between (say) 4- and 6-day forecasts for a given day are less than the error of 6-day forecasts. A complete elimination of model error could (optimistically) reduce the forecast error to the growth-rate curve of the difference between 1 and 2 day forecasts, 2- and 3-day forecasts, ..., 9- and 10-day forecasts. This reasoning would lead to an upper limit of 3 days increase in skill obtainable from improvements to the ECMWF forecast model. A caveat in this reasoning however is that elimination of the error in the forecast model will probably involve model improvements (such as finer resolution) that will increase the instability and error growth rate; the differences between 1- and 2-day forecasts (etc.) will then increase. (A doubling time of 2.4 days for rms 500-mb height errors was characteristic of the ECMWF forecasts.) Improvement of the initial data (actually the 1-day forecast errors) might lead to a further improvement of several days.

Lorenz also reported on the effect of introducing a "spectral gap" into his original study of nonlinear error growth that was based on an assumed -5/3 power spectra. This does slow up the upscale propagation of errors by several days. He cautioned however that recent evidence (e.g., that summarized by Lilly) does lend support to the -5/3 assumption at scales as large as 100 km.

With respect to extended range forecasts, Lorenz emphasized that the above studies not only applied to deterministic prediction, but also ignored the possibility and usefulness of variations in predictability in space and time. (For example, theoretical constructs such as modons, which are very stable, might exist to some extent in atmospheric flows.) Certain averages, such as time-means, might also have more predictability because of small but persistent effects on the atmosphere from anomalous sea-surface temperature, snow cover, etc.

In an earlier session, Baumhefner reported the results of forecasts made with the NCAR Community Climate Model from a variety of GWE year analyses. His results are quite compatible with Lorenz's study of the ECMWF forecasts. The rms height difference between analyses after initialization for the Community Climate Model was 20 m at 500 mb. The difference between forecasts from the different analyses reached the climatological variance value in 7 to 10 days. These results enabled Baumhefner to conclude that at the present time model deficiencies contribute as much to forecast error as do uncertainties in initial conditions.

Ghil (see Volume Two, pp. 794-802) discussed the problem of improving initial analyses by a more careful combination of observations with model predictions (often referred to as "first guesses") through the application of Kalman filtering. This procedure is very much like the current practice of optimum interpolation, except that covariance structure of the first guess errors is predicted (by linearized equations) instead of being derived empirically as an average result from a long series of previous forecasts (and then applied uniformly over the globe.) In this way the relative weights assigned to the observations and to the first guess would change in response to the local distributions of data that had entered preceding analyses and in response to the local advective and instability properties of the flow.

Against the seemingly overwhelming computational requirements needed for this approach, he pointed out the promise of vastly increased computer power and the possibility of useful approximation techniques to greatly simplify the very large matrices that are involved. (Some exploratory work in this direction is under way at NMC.) Experiments with a linear one-dimensional model (reported by Ghil and his colleagues in the literature in recent years) have already demonstrated certain advantages of Kalman predicted covariances to the conventional error covariance models in this simple case. These advantages seem especially significant in regions of sparse data and at the borders of data-rich and data-sparse regions. He concluded by pointing out that methods exist for estimating the "system noise" and for stabilizing the performance against erroneous assumptions in the linearized equations used to predict the error covariances.

Achievements

1. Predictability studies indicate that improvements in the forecast models and reduction of initial analysis error can potentially improve forecast skill by several days.

Unresolved Problems

1. It is still not clear whether initial analysis error or forecast model deficiency are the principal cause of present day forecast errors.

Recommendations

1. The implementation of advanced assimilation methods such as Kalman filtering should be encouraged.

DIAGNOSTIC AND PHENOMENOLOGICAL STUDIES OF THE GLOBAL CIRCULATION

Heat Sources and Sinks

Information on the global distribution of heating gained through the use of the GWE data sets is useful for study of the global heat budget, for improvement in short- to medium-range forecasts as an aid to verify the parameterization schemes in forecasting models, and for the design of a better objective analysis--initialization formulation. The use of the GWE Level II data and Level III analyses made possible the evaluation of the global distribution of heat sources and sinks.

The Planetary Distribution of Heat Sources and Sinks during GWE

The monthly average heating from one such study was presented by D. Johnson (see Volume Two, Session 8) who compared heating distributions estimated from NMC IIIa and ECMWF IIIb gridded data. The results showed that the dominant feature of the planetary scale heating distribution is the extensive heat source over the western Pacific and Southeast Asia that migrates seasonally with the Asiatic-Australian monsoonal circulation. Other primary features showed (1) a region of summertime heating within the western hemisphere over Brazil, Columbia, and Central America that also migrates seasonally, (2) cooling within the eastern portions of the major subtropical anticyclonic circulations, (3) heating within the Intertropical Convergence Zone, (4) wintertime heating and summertime cooling over the Asiatic and North American continents, and (5) wintertime heating over midlatitude oceanic regions along the east coasts of the Asian and North American continents. Johnson and his colleagues have also calculated mass circulations within isentropic coordinates, which are directly related to heating distributions. The results of these calculations were reported also at the workshop.

Kasahara (see Volume Two, Session 8) presented briefly the results of the global distribution of heating calculations performed by him and Mizzi using the ECMWF IIIb analyses with the isobaric method. Although the results using the NMC IIIa and ECMWF IIIb data show some differences, there are more similarities than differences within the patterns of heating. By reviewing the global distributions of diabatic heating rate calculated by various investigators, it seems clear that the large-scale diabatic heating rate distributions calculated from the GWE Level III analyses contain significant meteorological information, implying that the same is true for the large-scale horizontal divergence field.

Despite general agreement among various heating distributions calculated from the GWE Level III analyses by various investigators and with different methods, some differences in the patterns of heating among the GWE data sets and among the methods of analysis are apparent. Computational difficulties exist in the calculation of horizontal divergence and vertical motion in the vicinity of high mountains, such as the Tibetan Plateau. These shortcomings tend to produce systematic errors in the heating distributions.

Heat and Moisture Budgets over the Tibetan Plateau and Surrounding Areas

Since the GWE Level III analyses are produced by an analysis scheme that utilizes forecast values as an initial guess, various GWE Level III gridded data sets are different from each other. These differences are important since the accuracy of heating estimates depends strongly on the accuracy of wind analysis. It is important then to perform the evaluation of heat sources and sinks by using only the GWE Level II data. Yanai presented the results of heat and moisture budgets over the Tibetan Plateau and surrounding areas using the GWE Level IIb data during the onset of the 1979 summer monsoon (Luo and Yanai, 1984). His main objectives were (1) to determine the horizontal and vertical distributions of the tropospheric heat sources and (2) to identify the heating mechanisms operating in this region. The fields of horizontal wind, temperature, moisture, and vertical motion were analyzed objectively without resort to the use of model simulation for an initial guess, since the density of observations in this region is high over most of the area.

The results show clearly that the distributions of heat source Q_1 calculated from the thermodynamic equation and Q_2 from the latent heat component are different, implying different physical mechanisms of heating operated in the various sub-regions of the Tibetan Plateau and surrounding area. Yanai also reported a large diurnal change of the air temperature and noted its role in the heating mechanism over the Plateau.

Energy Associated with Tropical Heat Sources

The use of the GWE Level III analyses provided the first opportunity to evaluate the characteristics of large-scale gravity waves as well as those of Rossby waves. Silva-Dias (see Volume Two, pp. 331-360) first discussed theoretical results based on the equatorial beta-plane linear primitive equations in which Kelvin and mixed Rossby gravity waves are generated just as intensely as Rossby waves by thermal forcing in the tropics. A misrepresentation of such gravity waves in initial conditions for the primitive equation prediction models by inappropriate initialization will have a detrimental impact on the quality of numerical forecasts. Silva-Dias then presented the results of normal mode analyses with the ECMWF Level IIIb data. One of his notable findings was that the amplitude of the external vertical mode is dominant in the midlatitudes, but very small in the tropics, whereas the amplitude of the internal vertical mode, corresponding to the equivalent depth of a few hundred meters, is dominant only in the tropics.

The decomposition of the divergence field in terms of the normal modes of the linearized global primitive equations in sigma coordinates was presented by J.N. Paegle (see Volume Two, pp. 331-360) for one of the study periods considered by Silva-Dias (January 29 to February 16, 1979). The major contributions to the divergence field over the tropical areas were the vertically reversing internal gravity and Kelvin waves, with the gravity waves contributing about 40 percent and the Kelvin waves 30 percent at central values of the South Pacific Convergence Zone.

J.N. Paegle further reported comparisons of the normal mode decomposition for the ECMWF and GFDL analyses at January 15, 00Z. These showed that divergence values and gravity wave contributions for the GFDL analysis are, respectively, about 2 times and 20 percent larger than for the ECMWF analysis at central values of the South Pacific Convergence Zone. The general patterns of the gravity wave contributions were similar in both the analyses, though the Kelvin wave contributions showed differences consistent with the higher values of divergence at the equator produced in the GFDL analysis.

Normal mode decompositions are clearly useful for the evaluation of wave characteristics in different GWE Level IIIb analysis data sets. Significant correlations exist between the geographic distributions of heat sources and the horizontal structures of fast modes (i.e., Kelvin and other gravity waves).

Satellite Measurements of Quantities Related to Heat Sources and Sinks

GLAS has developed a physically based algorithm for analysis of HIRS2/MSU data on the TIROS/NOAA operational satellites (Susskind et al., 1984) that currently provides not only atmospheric temperature profiles but also sea and land surface temperatures, cloud heights and cloud amounts, and ice and snow cover. An algorithm to retrieve humidity profiles has just been developed and is being tested.

The GLAS temperature retrievals, generated using a 6-hour NOSAT analysis first guess, are shown to be significantly more accurate than both the 6-hour forecast and the official GWE data base satellite temperatures, when compared to colocated radiosondes. In addition, accuracy of the retrievals is relatively insensitive to cloudiness, except that retrievals are not produced in areas of greater than 80 percent cloud cover.

Susskind compared sea-surface temperatures obtained from HIRS2/MSU with those obtained from AVHRR, SMMR, and ships and buoys (see Susskind and Kalnay, Volume Two, pp. 361-384). Results showed the HIRS2/MSU SSTs to have a monthly mean accuracy of about 0.6^{o}, on a 2 x 2 grid, compared to ships and buoys. The errors are primarily random and excellent anomaly patterns are produced, even in the tropics. Land temperatures are hard to verify but do show all climatological and topographical features. Day minus night land temperatures, obtained by subtracting averages of the 3:00 a.m. and 3:00 p.m. local time soundings, showed that patterns correlated extremely well with the amount of high clouds and expected rainfall. Mintz et al. (1985) have derived an expression relating day-night ground temperature difference to soil moisture and have obtained very reasonable soil moisture and evapotranspiration fields from the HIRS2/MSU sound temperatures.

Global fields of total fractional cloudiness--high, middle, and low cloud fractional cloudiness, cloud top pressure, and cloud top temperature have been produced for January 1979 and July 1979. The results are consistent with model generated fields of rainfall and vertical velocity obtained from the GLAS model when driven by the assimilation cycle.

The day minus night cloud amounts show consistent features in which (1) stratus clouds to the west of continents are predominantly nocturnal but those close to the shore are more prevalent at 3:00 p.m., (2) in areas of high convective activity clouds are predominantly nocturnal over land but are more prevalent during the day over the ocean, and (3) midlevel clouds over land are generally more of a daytime phenomenon, especially over the United States. The current system, which is an improved version of Susskind et al. (1984), has been used to analyze January and July 1979 and March and July 1982. Fields are available for all of these months.

Achievements

1. Monthly and seasonally averaged spatial distributions of the atmosphere's heat sources and sinks for the planetary scale inferred from GWE data sets were analyzed for the first time and have been shown to be realistic. The patterns are consistent geographically and temporally in accord with the march of the seasons.
2. The tropospheric heat sources and moisture budget over the Tibetan Plateau during the Asiatic summer monsoon have been quantitatively determined.
3. Global distributions of sea and land surface temperatures, cloud heights, cloud amounts, and ice and snow cover have been estimated from analyses of HIRS2/MSU satellite data.

Unresolved Problems

1. Our detailed knowledge of the atmosphere's total heating and its components from the analysis of GWE data is limited with respect to its temporal, horizontal, and vertical variations. The temporal and spatial consistency of the heating patterns among the Level III analyses in the northern hemisphere is greater than in the southern hemisphere. Systematic errors in the heating distributions can be introduced in the analyses by topography.
2. Detailed temporal and regional distributions of heat sources and sinks over Asia, Africa, and the Americas and their relation to planetary scale monsoonal circulations remain unresolved.

Recommendations

1. Diagnostic, theoretical, and numerical studies of total and component heating should be conducted for the purposes of resolving

increased temporal and spatial structure of these fields and investigating their influence on atmospheric motion, particularly in regard to planetary scale monsoonal circulations.

2. Latent heating release should be assessed globally from the distributions of water vapor balance and compared with global estimates of total heating. Global distributions of surface heat fluxes, sensible and latent, should also be estimated.

3. Heating should be compared from Level II and Level III data using different methods of computing, and the degree to which the heating and moisture distributions in Level III analyses are model rather than data dependent should be determined.

4. Model generated total and component heating rates should be archived in Level IIIb analysis.

5. The effects of including heating in the initialization of primitive equation models should be investigated.

General Circulation and Planetary Waves

The behavior of the atmosphere as determined by studies of the general circulation and planetary waves has provided valuable insights for the development and testing of atmospheric prediction models. Indeed, the fourth GWE objective is to define diagnostically the structure, variability, energetics, and transport mechanisms of the general circulation for the GWE year. The first two papers by Rosen and Pfeffer (see Volume Two, Session 9) in this session report on diagnostic studies address this objective directly. The first GWE objective is to provide initial and verifying conditions for experiments to enlarge predictability in medium- and extended-range forecasts. Toward this objective the third paper, by Baker (see Volume Two, Session 9), reports on research with the augmented observational data base provided by the GWE to improve predictability of atmospheric planetary waves, and the fourth paper, by Baer (see Volume 2, Session 9) provides an assessment of the historical development and current status of several important areas relevant to atmospheric predictability.

Diagnostics

The availability of the GWE data sets, in particular the Level IIIb data, has provided researchers with an unprecedented opportunity to study diagnostically the planetary-scale circulation of the atmosphere. Not only are these global data available on an unprecedented spatial scale, but they have been objectively analyzed by a number of centers and thus are of high quality, facilitating many detailed analyses.

In the first paper of this session, Rosen (see Volume Two, Session 9) compared monthly mean zonal winds, eddy heat and momentum fluxes, zonal mean mass stream functions, energy cycles, and moisture fields obtained from various Level IIIb analyses and obtained directly from station observations. In each quantity he found fair agreement among the various analyses, but there were some important differences as follows:

1. In zonal winds, the ECMWF and GFDL data differed by up to 10 m/s in the monthly mean near the exit region of the Pacific subtropical jet.

2. The transient eddy fluxes often differed significantly.

3. The Hadley cell strength differed among the various objective analyses with, for instance, the ECMWF cell usually much weaker than the others. Large spurious net mass flows exist in all the analyses.

4. The GFDL analyses are unduly noisy in certain fields.

5. Level IIIb moisture analyses are inadequate for studying the hydrological cycle.

Rosen concluded that while the station analyses often missed regional patterns in data-sparse areas, they agreed quite well with the objective analyses in the zonal mean statistics. Regional differences among IIIb analyses are sometimes large, reflecting model biases used to assimilate the data.

An important question raised in the discussion was whether more data or better data are needed to improve the reliability of the GWE data. The consensus seemed to be that a better distribution of data would alleviate many of the problems. It was also pointed out that there may be some problems introduced into the objectively analyzed fields, especially the mass stream function, by the use of satellite winds. There is a need for further study of this problem.

Pfeffer (see Volume Two, pp. 422-437) focused on comparing the diagnosis of zonal wind accelerations using conventional and transformed Eulerian diagnostics. He found that, whereas the transformed diagnostics give a clearer picture of the dynamics of stratospheric warmings, the conventional diagnostics give a clearer picture of tropospheric dynamics and the acceleration of the primary zonally averaged jet in the upper troposphere. In the transformed Eulerian diagnostics, the acceleration of the zonal current is obtained as a small difference between the Eliassen-Palm (E-P) flux divergence and the Coriolis force acting on the residual meridional circulation. The Coriolis force dominates at jet stream level, largely owing to the fact that much of the residual circulation at this level is induced by sea level poleward heat fluxes. As a result, the E-P flux divergence correlates poorly with the zonal acceleration. The two forms of diagnostics can be brought together by solving the diagnostic equation for the eddy induced meridional circulation in either system and by calculating the eddy induced zonal acceleration as the sum of the eddy forcing and the Coriolis force.

In the discussion it was pointed out that comparison of diagnostic techniques is difficult with the currently available Level IIIb analyses. A more definitive data set is needed in which some of the discrepancies between the current sets are reconciled. Pfeffer's comparisons for the troposphere were performed with December 1978 data, and it was stated that most of the new GWE observing systems were not operating at that time and thus his comparisons should be performed at another time also.

Prediction

The unique and rich data base available for the GWE year has offered an opportunity to improve our understanding and ability to predict the behavior of atmospheric planetary waves.

In the third paper of this session, Baker (see Volume Two, pp. 438-450) reviewed research on the prediction of planetary waves using GWE data. Baker found that substantial progress has been made, but a number of problems remain to be solved. He reported the following:

1. Successful 8-day predictions were made by ECMWF and GLAS utilizing GWE data. Both sets of predictions occurred during periods characterized by blocking patterns.
2. The sensitivity of extratropical, planetary-wave forecasts to the assimilation of tropical wind data has been examined using GWE data. The extratropical planetary-wave predictions were found to be sensitive to tropical wind data. After 72 hours significant differences in forecasts of the rotational component developed at all latitudes. Forecast differences in the divergent component remain largely restricted to the tropics. The results were consistent with those obtained with a barotropic model.
3. Possible planetary-scale teleconnections between the tropics and midlatitudes have also been investigated. The enhancement of a convective heat source over the equatorial central Pacific was found to coincide with the intensification of the subtropical jet stream and the amplification of the upper-level trough/ridge system extending from the equatorial central Pacific to the west coast of North America.
4. Understanding of the southern hemisphere planetary waves has been significantly advanced with GWE data. A distinct southward divergent flow from the convective regions of the tropics into regions of kinetic energy generation over Australia, South America, and Africa has been found. This has suggested the possibility that the subtropical jet structure in the southern hemisphere may be determined by longitudinal gradients of tropical heating and may explain the standing wave pattern of the southern hemisphere winter.
5. Analyses of GWE data have confirmed the existence of Rossby waves, characterized by irregular vacillations, whose wave periods agree closely with theoretical estimates.
6. A few, highly successful forecasts (skillful out to 8 days) have been presented in which the atmosphere was characterized by quasi-stationary planetary wave behavior.

During the discussion, Baumhefner noted that predictability is higher when standing waves dominate and lower when transients dominate. This led to a discussion about selecting additional cases from time periods during which the circulation was quasi-stationary as well as from periods during which the circulation was highly transient.

Also during the discussion period, Reed asked to see documentation of circulation changes from January to February 1979. Baker responded with difference maps (January to February) showing that the rotational component decreased by 1.5 m/s in the western Pacific in February but increased 10 m/s over the Atlantic. The divergent component was also much stronger in the western Pacific in January. Virji commented that Weickmann (University of Wisconsin) has documented the January-March difference fields.

GWE activities have been a catalyst for global prediction model development with respect to improvements in the preparation of initial fields that are so essential for advances in large-scale forecasting. In addition, the GWE data set itself has been successfully applied to improve atmospheric predictability. This has been achieved through model initialization, improved parameterization of model forcing, and through validation of model forecasts.

In the final paper of this session, Baer (see Volume Two, pp. 387-397) summarized the impact of the GWE on several aspects of numerical weather prediction. Baer provided an historical perspective for numerical weather prediction and for the theoretical limits placed on such deterministic prediction. He then discussed the current status of predictability in the context of model development, covering such areas as methodology, model initialization, and the testing of prediction models by their ability to reproduce observed atmosphere structure and mode interactions. He pointed out that the detail available from the GWE data has resulted in improvements in these areas that have in turn resulted in improved forecasts. He cautioned however that in evaluating model output we must understand that no model can achieve "real" truth. Model truth is not "real" truth, which is related to observations. We must answer the question, what is the model's best output and how does this depend on the input data? Baer also urged that we develop model verification schemes more creatively than we have in the past.

Finally, Baer discussed the potential offered by the GWE data set in addressing the question, does the atmosphere have characteristic modes? Baer had described the use of model normal modes in model initialization and also as a means to gain insight into model forcing. He pointed out that, indeed, a few atmospheric modes seem to be identifiable (and these have been discussed elsewhere in this report). He speculated that, for example, perhaps models could produce improved predictions if integrations were performed in vertical modes rather than on pressure surfaces, particularly if those modes reflected the statistical properties of the atmosphere. He highlighted the importance of identifying the most important and active modes in models and comparing them with those of the atmosphere where possible. In discussion, several questions were asked about the normal mode analysis. The first was whether normal mode analysis is meaningful, given that the transient modes change very rapidly. Baer responded by pointing out that the observational data can be separated into the time mean and transient components. The transients may also have a characteristic structure that would be determined by the analysis. The other two questions were related: to what extent is the normal mode analysis useful and representative, and what is the advantage gained from the application of characteristic structure? Baer responded by saying that advantages include the use of both vertical and latitudinal modes for model prediction, the possibility for truncating unimportant modes, the opportunity to calculate exchanges from model properties, and the determination of verification statistics from properties of model forecasts. Finally, he said that observed structures can be compared to model modes to see if the model and the mean atmosphere have common characteristics.

Achievements

1. Successful 8-day predictions by ECMWF and GLAS were presented utilizing GWE data. Both sets of predictions occurred during periods characterized by blocking patterns.
2. Extratropical planetary-wave predictions were found to be sensitive to the inclusion of actual wind information in the tropics with the differences being seen primarily in the rotational component of the wind. Differences in the divergent component were largely restricted to the tropics.
3. Among the planetary-scale teleconnections between the tropics and midlatitudes that were investigated, the enhancement of a convective heat source over the equatorial central Pacific coincided with the intensification of the subtropical jet stream and the amplification of the upper-level trough/ridge system extending from the equatorial central Pacific to the west coast of North America.
4. Understanding of the southern hemisphere planetary waves has been significantly advanced with the GWE data. The subtropical jet structure and kinetic energy generation in the southern hemisphere is influenced by longitudinal gradients of tropical heating, which may explain the standing wave pattern of the southern hemisphere winter.
5. The detail available from the GWE data has resulted in improvements in the preparation of initial fields for large-scale forecasting. In particular, GWE data have been used to test methods of initialization, to identify characteristic atmospheric structure, and to evaluate various filtering techniques. These applications have resulted in improved forecasts.

Unresolved Problems and Recommendations

1. Differences among general circulation statistics from station data and from the various IIIb analyses are in some cases substantial. During any reprocessing of Level IIIb analyses, it is imperative that rejected observations be archived along with a code stating at which stage they were rejected.
2. Existing Level IIIb water vapor analyses from the ECMWF and GFDL have a number of serious, well-documented shortcomings that limit their use in studying the balance of water vapor during the GWE. During the reprocessing of Level IIb data by the analysis centers, close attention should be paid to quality control of the water vapor data and the ensuing analyses. Special efforts should be made to archive analyses at those model levels between 1000 and 850 mb.

3. Future Level IIIb analyses should be carried out at levels between 1000 and 850 mb to facilitate an incorporation of boundary layer processes into global diagnostics.

4. Surface pressure and temperature fields are important for future research on energy diagnostics, boundary layer dynamics, and water vapor transport and should be archived in the Level IIIb reanalyses. Topography fields should be archived as well.

5. It has been suggested that data inadequacies could result in the improper partitioning of the initial stationary and transient components of the flow, producing large errors early in the forecast. It has also been suggested that the regional coherence of the errors later in the forecast may indicate incorrect external forcing such as land/sea contrasts or topography. Significant effort should be devoted to identifying sources of systematic error in the planetary waves of models.

6. Current verification schemes are inadequate and are often based on a single parameter. Better, more meaningful means of verification should be developed.

7. A few highly successful forecasts (skillful out to 8 days) have been carried out for periods when the atmosphere was characterized by quasi-stationary planetary-wave behavior. It is recommended that additional cases during the GWE year be selected and studied for periods when the circulation was highly transient.

8. The abundant GWE data provide an opportunity to gain further insight into atmospheric teleconnections. High priority should be given to studying teleconnections within the context of the GWE objectives.

Interhemispheric and Cross-Equatorial Exchange

The lack of knowledge of the initial state of the atmosphere was identified in the earlier planning documents of the GWE as a major cause that limits the predictability of numerical forecasts. It was therefore recommended that diagnostic studies be conducted to obtain an improved understanding of the large-scale dynamics of the atmosphere and of critical physical processes. Research devoted to this effort now includes analyses of pronounced and complex interhemispheric interactions between global scale motions of the northern and southern hemispheres. The research regarding interhemispheric and cross-equatorial exchange was summarized by J. Paegle, Somerville, and Young (see Volume Two, Session 10).

GWE data sets indicate strong coupling between regions of enhanced tropical convection of the summer hemisphere and subtropical jet stream maxima of the winter hemisphere. The possibility that this connection is produced by direct forcing of local Hadley circulations with their ascending branches over the convective regions and descending branches on the entrance jet regions was examined. Also the possibility of meridional wave propagation through tropical latitudes was discussed.

It was noted that though there are many cases for which this propagation occurs through regions with tropical westerly winds, in other instances this interhemispheric connection occurs through regions of easterly winds. This implies that the latitudinal interaction occurs through processes other than Rossby wave propagation. Alternative mechanisms include gravity wave propagation and non-linear energy transfers. The former possibility is supported by the finding that the meridional tropical wind field receives as much contribution from the divergent wind as from the rotational wind and independent findings that the tropical divergence projects mainly on the internal gravity-inertial and Kelvin modes of a linearized primitive equation model. Thus for purposes of representation in terms of linear modes, the gravity mode contribution to the wave pattern may not be negligible.

In order to establish these waves as a mechanism of energy transfer, it is necessary to compute their energy flux, to isolate their effect in circumstances of a variable basic state flow, and to sort out the linear and essentially nonlinear components of the flow dynamics. These studies are in progress and may require more carefully recomputed tropical wind and thermal fields. An indirect indication that Rossby wave transfer may not play a dominant role in the region is that the absolute vorticity and its horizontal gradient are very small between the convective heating source of the summer hemisphere and the subtropical jet enhancements of the winter hemisphere.

An experiment was run with the GLAS GCM to test the influence of tropical latent heating in the model. Although the tropical heating is greatest in the summer hemisphere, its removal produces the greatest changes of divergent wind in the winter hemisphere. The divergent wind field, including the entire Hadley cell, collapses in 12 hours after the tropical latent heating is removed. Possibly because this divergent effect is greatest in the winter hemisphere, the subtropical jet of the winter hemisphere reacts more strongly than the summer hemisphere jet stream.

Other possible explanations for this meridional propagation were suggested, such as transient motions, mean meridional circulations, and nonlinear effects. The large heating rates over extensive horizontal domains in the tropics would generate spurious strong circulations unless the numerical models are capable to properly disperse and dissipate their effect. This problem was noted to occur in mesoscale modeling at NMC when large heating rates are included in the model. The proper initial incorporation of tropical condensation heating and the ability of numerical models to properly disperse this effect horizontally was identified as a key issue in this session.

Erroneous initial conditions in the tropics were shown to be sources of errors in higher latitudes. Results of numerical simulations with global and hemispheric models have reported cases with both positive and negative impact in predictability when the integration domain is extended to include both hemispheres, with an average of 0.65 day improvement in predictability reported by ECMWF for eight cases. Benefits from global domains in numerical modeling will only be obtained if the tropical initial state is adequately defined. Numerical simulation impact studies of the effect of tropical data indicate that spurious barotropic modes are generated in higher latitudes. The stationary response of the model is of importance to the characteristics of the resulting error field. Normal mode analysis of forecasts and verification fields are useful tools to understand the impact of tropical errors in extratropical latitudes.

High priority was given in the planning of the GWE to research aimed at clarification of the more localized motions, such as the east African Somali jet that produces strong mass and moisture fluxes between the northern and southern Indian Ocean. This flow is a key element of the seasonal cycle in the tropics, especially in monsoonal regions.

A complete set of surface winds from ships and satellites for the GWE tropical belt has shown typical winds of 3 m/s or more over the eastern Pacific and Atlantic. The strongest case is found in the Somali jet region, which maximizes around 900 mb, but significant flows are also found in the upper troposphere.

The "cold surge" is another form of boundary layer interaction between hemispheres--rises in sea-level pressure that occur behind vigorous wintertime cold front passages can often be tracked to the equator and beyond into the opposite hemisphere. Surges often cause an increase in the cross-equatorial wind and a strengthening of the monsoon westerly flow of the summer hemisphere.

Significant results have been obtained for strong cross-equatorial motions associated with the Asian monsoon. Flows become increasingly unbalanced as the equator is approached with a major nonlinear adjustment region downwind of the equator. This has been characterized as essentially an inertial transition from cyclostrophic to geostrophic motions. This transition region contains extensive areas of negative absolute vorticity.

Some of the most important cross-equatorial flow is concentrated at low levels in the planetary boundary layer where turbulent exchange processes affect its distribution and strength. It has been determined that inertial regimes near the equator have vertical depths that depend on latitude. Preliminary results indicate that the vertical variation of friction is larger than previously thought, with cloud base values of the order of 20 percent of the surface values. This suggests the need for better estimates of the vertical structure of the boundary layer wind. It would be useful to archive all boundary layer levels of IIIb data and to assess the influence of this data on surface fluxes derived from boundary layer models.

Achievements

1. GWE studies have suggested that there is a strong coupling between regions of enhanced tropical convection of the summer hemisphere and subtropical jet maxima of the winter hemisphere.
2. GWE data have provided observational evidence for inter-hemispheric connections through regions of both easterly and westerly winds. The easterly cases display greatly reduced gradients of absolute vorticity.
3. GWE studies have shown that a substantial contribution to the cross-equatorial and meridional tropical flows resides in the divergent wind component and arises mostly from the vertically reversing gravity-

inertial and mixed Rossby gravity waves. This indicates the importance of local diabatic forcing in the generation of tropical motions and has direct implications for the development of assimilation systems in numerical models.

4. GWE data sets have provided quantitative estimates of the impact of initial data uncertainties in the tropics on extratropical prediction. While the predominantly barotropic spread of error was anticipated from prior experiments, a realistic estimate of the magnitude of the effect could not be made before the GWE.

5. Cold surges of the Asiatic winter monsoon often cause an increase in the cross-equatorial wind and a strengthening of the monsoon westerly flow of the southern hemisphere.

6. It was found that strong low-level cross-equatorial flows associated with the Asian monsoon displayed extensive areas of negative absolute vorticity on both sides of the equator and an apparent nonlinear adjustment process.

7. Preliminary results have clarified the magnitude of the vertical variation of friction indicating that it is larger than previously thought with cloud base values of the order of 20 percent of the surface value.

Unresolved Problems and Recommendations

1. Studies should be pursued to delineate the modes of energy dispersion and dissipation in strongly heated circulations.
2. Idealized model experiments as well as numerical model simulations should be pursued to understand the effect of initial errors in the tropics on higher latitudes.
3. Comparisons should be made of surface energy budgets obtained from Level IIIb data with those obtained from Level IIb data.
4. Estimates of surface heat, moisture, and momentum fluxes should be made for the tropical oceans during the entire GWE year.
5. Studies of gross boundary layer structure over the tropical oceans are needed to assist efforts in large-scale analysis and numerical modeling.
6. For limited periods of the GWE year, Level IIIb data for all levels of the boundary layer should be archived to assist in evaluating and intercomparing various boundary layer models.

Global Aspects of Monsoons

A major goal of the GWE planning effort was to study the couplings between the tropics and the extratropics. In his summary, Murakami (see Volume Two, Session 12) pointed out that these couplings possess both local and global characteristics. Cold surges moving southward out of east Asia are relatively localized shallow circulations that may trigger deep convection above the tropical western Pacific Ocean through enhancement of low level convergence. In the upper troposphere, the tropical cloud masses resulting from the deep convection are associated with strongly divergent flows that stream poleward and modify the subtropical jet stream structure and related wave activity. Asiatic winter monsoonal outbreaks were relatively weak, and the coupling processes were not especially active during the Winter MONEX, but the sequence was still observable in this and other years. Further studies are needed to elucidate the space-time variability of the winter monsoon rainfall.

Significant theoretical advances have been accelerated by Winter MONEX and have clarified our understanding of the response of tropical waves to heating in different locations. Responses to transient forcing (monsoon surges) are mainly in Rossby and Kelvin modes. When the forcing time scale is short, significant gravity modes are also excited. The responses closely resemble observed winter monsoon flow. Responses to stationary forcing show that deep (barotropic) motions propagate energy away into high latitudes and that shallow (baroclinic) motions are trapped around the equator. While both Rossby and Kelvin modes are important, the former is always dominant, even in the case of Walker-type circulations. It is shown that the barotropic teleconnection-type response to tropical sources found in previous numerical studies was due to the specified vertical wind shear and surface friction. Furthermore, comparison between the baroclinic stationary responses and the transient responses suggests that monsoon surges play an important role in the maintenance of the mean tropical motions.

Further studies should explore the sensitivity of these conclusions to the strong vertical shear accompanying the subtropical jet. Additionally, numerical weather prediction efforts need to address the prediction of local phenomena such as surges, surge vortices, the role of diurnal changes, and numerous complexities associated with the "maritime" continent. These include land versus ocean structure of clouds, convection within monsoon disturbances, radiative effects on convective development, and the vertical distribution of heating.

The global aspects of the summer monsoon onset are better delineated now than ever before. Specifically, the large-scale heat and moisture sources and sinks have been computed far more accurately during the GWE than they were previously, and the understanding of the sudden transition of the monsoon onset has been sharpened.

Numerical experiments of the monsoon onset during the GWE illustrate the crucial role of the divergent flow and of the moisture field in the initial state.

As a consequence, deterministic predictability of the tropics is now appearing, and a consistent quantitative estimate of the tropical energy cycle is emerging. It remains to be determined whether the summer monsoon onsets are similar in the northern and southern hemispheres though the topography is different.

The Tibetan Plateau separates distinctly different regions of sensible and latent heating and appears to generate vortices peculiar to the region. These shallow vortices form on the edge of the Plateau, propagate eastward, and produce heavy rains. In an attempt to more closely delineate these structures, Chinese scientists mounted a field study during 1979 that complemented the GWE data. It is desirable to include this data set in the GWE analyses.

Recently, several investigations documented the nature of long period (40- to 50-day) oscillations during the GWE year. These low frequency oscillations appear to propagate slowly northward, upward, and eastward during the northern summer monsoon. They are characterized by a zonal wavenumber 1 and are strongly divergent. The amplitude of this divergent wave is largest during the summer season over the monsoon region and the western Pacific. Detailed analyses suggest that the 40- to 50-day oscillation resembles in many aspects the interannual variation associated with the Southern Oscillation, but further study is needed to describe the details of its structure from year to year and possible stratospheric and midlatitude coupling.

Achievements

1. One- to six-day global forecasts of monsoonal circulations made with GWE/MONEX data sets have accurately described the onset of strong winds, deep moist westerlies, the onset vortex, and the initial rains over the Kerala Coast.
2. GWE/MONEX observations have provided the most comprehensive description of the Asian summer and winter monsoon ever. The planetary scale of these monsoonal circulations has been documented.
3. The data sets have clarified relationships among divergent circulations of the winter monsoon and the subtropical jet stream of winter.
4. Monthly mean heating rates and divergent circulation as well as heating rates during selected periods were better defined.
5. A better description and understanding of the onsets of both the summer and winter monsoon have been attained.
6. Studies with GWE data have produced a more detailed description of the 40- to 50-day oscillation, including its interaction with the summer monsoon and its association with convection.

Unresolved Problems and Recommendations

1. The reanalysis of the IIb data should be extended to include the months of July for Summer MONEX and December for Winter MONEX.
2. Research on onset, dry and wet spells, and related heat sources and sinks should be continued in greater detail.
3. Efforts should be made to map daily precipitation fields for the tropics for the Summer and Winter MONEX periods. The estimates should be global if possible.
4. Research on low frequency modes or oscillations should be encouraged since they appear to modulate monsoon activity.
5. Theoretical and modeling studies should work toward resolving the roles of both vertical and horizontal wind shear within winter monsoonal circulation.
6. Better techniques for data analyses in the vicinity of mountains should be developed.

The Stratosphere

An important objective of the Global Weather Experiment is "to define diagnostically the structure, variability, energetics, and transport mechanisms of the general circulation for [the GWE year]" in order to "provide the basis for interactive studies such as between the stratosphere and troposphere...." (U.S. Committee for GARP, 1978). That objective has motivated many investigations. The speakers of this session, Mechoso and Leovy (see Volume Two, Session 14), presented some of the major findings of those investigations. These findings are summarized in what follows.

A minor and a major stratospheric warming occurred in the northern hemisphere during the winter of 1979. These events have motivated several diagnostic and numerical studies. The diagnostic studies have shown the usefulness of the Eliassen-Palm (E-P) diagnostic to describe wave-mean flow interaction processes in the stratosphere at the time of the warmings. Numerical studies with stratospheric models with prescribed forcing at the lower boundary have contributed to establishing the sensitivity in the evolution of the warming to the configuration of the zonal mean flow and to the phase speed of the forcing. There are also, for the first time, successful medium-range (10-day) numerical forecasts of stratospheric warming events. They were performed with a modified version of the operational model at the ECMWF and with the 15-layer version of the University of California at Los Angeles (UCLA) general circulation model. The two models have comparable vertical resolutions between 100 mb and 10 mb (the highest level of the ECMWF model). The UCLA model extends up to 1 mb. The ECMWF and UCLA forecasts reveal that, in general, stratospheric warmings are predictable from several days in advance. The UCLA forecasts for the major warming of February 1979 show that the accuracy of stratospheric forecasts can be very sensitive to the accuracy in predicting zonal mean tropospheric wind (and consequently to the model resolution and parameterization of physical processes).

Three Nimbus-7 satellite instruments successfully provided new data relevant to the GWE objectives: the total ozone mapper (TOMS), the Limb Infrared Monitor of the Stratosphere (LIMS), and the Stratosphere and Mesosphere Sounder (SAMS). In addition to the global high resolution measurements of total ozone provided by TOMS, the latter two instruments have provided global synoptic measurements of temperatures, ozone, water vapor, and several other constituents in the stratosphere and lower mesosphere, and supplement other GWE data sets by providing information above 10 mb, and adding the constituent information. These additional data sets are currently being used to diagnose and interpret stratospheric processes. It was pointed out that the equatorial wind estimates from LIMS temperature retrievals are fairly good for the zonal component although not for the meridional component.

Utility of these types of observations for assessing interannual variability in the stratosphere with long-term measurements has been clearly demonstrated. Data from LIMS have been used to perform detailed studies of the thermal structure in the tropical stratosphere and lower mesophere, revealing details of Kelvin wave structure and possible inertial instability.

Several important points were raised during the discussions following the presentations. It is believed that the unstable wind shears in the equatorial stratosphere are produced by seasonal changes in the flow. The vertical resolution needed to represent stratospheric phenomena depends on latitude. In the tropics, a 3-km vertical resolution seems to be required. At higher latitudes the requirement is not so stringent. The vertical momentum transports were measured and were found to account for 1/3 to 1/2 of the westerly acceleration. The impact of the stratospheric representation on the accuracy of tropospheric forecasts was discussed, and it was concluded that extensive research is needed on this important subject. It was suggested that Level IIIb analysis could be extended above 10 mb. The importance of determining the nature of the forcing responsible for the generation of observed equatorial Kelvin waves was discussed. It was suggested that an analysis of GWE wind fields by methods other than purely model dependent methods was advisable to attempt to more clearly define equatorial waves.

Achievements

1. For the first time, global three-dimensional distributions of stratospheric water vapor, ozone, methane, and temperature have been measured.
2. Successful numerical forecasts of a stratospheric warming were carried out using GWE stratospheric data as input.
3. GWE satellites have provided detailed measurements of thermal structure in the tropical stratosphere and lower mesosphere, revealing details of Kelvin wave structure and possible inertial instability.

Unresolved Problems and Recommendations

1. The impact of the state of the stratosphere on the accuracy of tropospheric forecasts should be clarified.
2. Equatorial Kelvin waves are an important feature of the stratospheric circulation which are believed to be excited in the troposphere. The energy source of these waves is poorly understood and should be investigated with GWE data.
3. Level IIIb analyses should be archived up to 10 mb.
4. Reanalyses should incorporate LIMS and TIROS data to improve analyses above 100 mb.

The Southern Hemisphere

The GWE has provided unique data sets to study the behavior of the southern hemisphere atmosphere. The atmospheric circulation over the southern hemisphere during the GWE had, as most years do, its peculiar set of anomalies. Review papers by Trenberth and Van Loon (see Volume

Two, Session 15) provided the basis for discussion regarding the southern hemisphere.

Australian analyses and station data have delineated several noteworthy differences between 1979 and other years. Specifically, exceptionally deep cyclones accompanied an increase in westerlies south of 50°S. The extent to which this is a consequence of the enhanced GWE observing systems can be investigated by studying the impact of buoy density in assimilation systems and numerical models.

During winter (May to September), the subtropical jet was weaker than normal, but the polar jet was considerably enhanced, and a double jet structure prevailed. During summer (November to March), there was a southward shift in the jet by about 3° latitude and a southward shift of storm tracks. For both seasons, anomalous convergence of momentum by eddies into the jets helped sustain the abnormal distribution of westerlies against surface friction (consistent with expectations based on baroclinic theory).

This anomalous behavior should be investigated in conjunction with anomalous forcing (surface effects, diabatic heating, northern hemisphere influences, etc.). Also, studies should be undertaken to isolate reasons for the incorrect simulation of the strength of the westerlies and of seasonal changes by nearly all models.

ECMWF IIIb analyses, Australian analyses, and station data indicated large intra-annual variations in the amplitude of monthly averaged zonal harmonic wavenumbers 1 to 4. The amplitude of the stationary 3-month average component was 20 to 50 percent larger than normal; the vertical meridional structure of these waves conformed to the long-term mean structure in terms of the position of peak amplitudes and the barotropic structure.

It was also determined that the surface pressure over the Antarctic was as much as 2 to 3 standard deviations below normal during winter. As a result, the usually dominant half yearly wave in surface pressure over this region was suppressed. In midlatitudes, on the other hand, a large half yearly wave was a dominant feature of the seasonal cycle in the surface pressure field over the oceans. The dominant equatorial-tropical half yearly wave in the wind and temperature of the upper troposphere was somewhat stronger than normal. Analysis intercomparisons showed pronounced differences in the amplitude of the stationary temperature field.

Diagnostic global and regional studies of GWE IIIb data sets should be done using different assimilation systems (at least five sets are available) to address this and other processes of interest.

Comparison of ECMWF IIb, NMC IIIa, and Australian analyses of the zonal mean surface pressure indicated that in midlatitudes the ECMWF IIIb and NMC IIIa analyses are comparable, while at high latitudes, NMC analyses show values considerably larger than the other two data sets. The Australian analyses yielded consistently the lowest zonal mean surface pressure of the three analyses in middle and high latitudes.

Achievements

1. Through the unique data set provided by the GWE, a markedly improved description of the southern hemisphere circulation has emerged. The improved description has advanced our understanding of important mechanisms involved in its maintenance and its uniqueness as an ocean hemisphere in comparison with the continentality of the northern hemisphere.

2. The improved global analyses have enabled the determination that the circulation of high latitudes for the GWE year was anomalously intense. These anomalies included:

o an exceptionally deep circumpolar trough,

o a polar jet stronger than normal (therefore, a double jet structure prevailed), and

o the amplitude of the stationary components (waves 1 through 4) 20 to 50 percent larger than normal.

3. The information from the southern hemisphere buoy system was fundamental to a reliable determination of the interhemispheric mass exchange occurring during the GWE. The anomalous low sea-level pressure of the southern hemisphere which was as much as 2 to 3 standard deviations below normal during its winter was accompanied by high sea-level pressure anomalies over the northern hemisphere.

Unresolved Problems and Recommendations

1. The anomalous behavior of the southern hemisphere should be related through diagnostic studies with various types of forcing (surface effects, diabatic heating, northern hemisphere influences, etc.).

2. Global, regional, and phenomenological studies of GWE IIIb analyses from different assimilation systems should be compared to determine the reasons for the large differences in statistics computed from IIIb analyses, such as the zonally averaged surface pressure and stationary temperature field. For comparison, a manual analysis for two to three weeks in each of the SOPs of SLP, SST, 850, 500, and 200 mb fields should be made by analysts familiar with southern hemisphere circulations. These analyses would serve to check the different assimilations to isolate bias errors.

3. Results from numerical models should be studied to determine why the strength of the westerlies is underpredicted, especially in the southern hemisphere summer.

4. Studies should be conducted to better describe and understand the nature of diurnal variations over lands and oceans. In this context, it may be of value to separate heavy and light precipitation.

Oceanography

Oceanographic research was carried out during the GWE in the three tropical oceans in the spirit of the GARP climate objective. It was internationally coordinated by three autonomous panels of the ICSU Scientific Committee on Oceanic Research (SCOR) Working Group 47. A review of the results is available in McCreary et al. (1981). This work laid "the foundation, within the limitation of a single year's sampling, for the development of a modeling capability to explore the nature of climatic variation" (Objective 5 of the Global Weather Experiment (U.S. Committee on GARP, 1978)). This objective has also driven several national programs since 1980 (EPOCS, SEQUAL, Tropical Heat in the United States; FOCAL in France; SECTIONS in the Soviet Union) and is of primary importance to the international TOGA program (a 10-year program beginning in 1985). The success of GWE oceanography and the subsequent programs has led the community to begin the difficult development of interactive air-sea models.

Since 1979, dynamical models of the tropical ocean circulation, forced by prescribed wind stresses, are steadily and significantly increasing our understanding of the oceanic response. What distinguishes these efforts from the pre-GWE decades, is the increasing availability of quasi-synoptic observations against which to evaluate the modeling development. What is needed next are sustained observations over many years with which to quantify correlated interannual variations and from which models can be developed to accurately predict climatic variations.

At the workshop, Bernstein, R. Molinari, Sarachik, and Stommel (see Volume Two, Session 18) reported on the impact of the GWE on observing and modeling SST and estimating the best balance in the surface mixed layer. It was reported that satellites launched just prior to the GWE have proved capable of providing SST data accurate to about 1°C. The generally accepted need for climate studies is an accuracy of 0.5°C and that seems within reach by identifying and eliminating systematic errors introduced by geophysical phenomenon. Thus atmospheric modeling can expect an adequate lower boundary condition in the near future. In the discussion Bernstein recommended that 20 calibration sites, well distributed around the global ocean, would help ensure absolute accuracy.

The GWE data sets in the equatorial Atlantic and Indian Oceans were extensive enough to estimate the heat balance in the surface mixed layer during the year. At best, it was found that 75 percent of the variance of the mixed layer temperature could be explained by surface fluxes. This was not true, of course, in regions of coastal or equatorial upwelling, where one needs to include a parameterization of vertical mixing across the base of the mixed layer to explain a comparable percentage of the variance. Finally, it was implied from the comparisons that the error in estimating the surface fluxes was of the order of 20 to 30 W/m^2, or half as much as one would expect summing the errors of individual contributors.

R. Molinari pointed out three remaining gaps in the type of flux analyses presented here: a statistical description of the surface fields would allow interpolation into data-sparse areas, an improved parameterization of surface fluxes would increase the accuracy of the heat fluxes into the ocean, and a coordinated ship-of-opportunity program would increase data coverage over the tropical ocean.

It was pointed out that other sources of error in the calculation resulted from the errors in estimation of mixed layer depth since the error in the rate of change of temperature is directly proportional to the fractional error in mixed layer depth (MLD).

Modeling the SST from oceanographic models (with specified wind stress boundary conditions) has received much attention, particularly in the tropical oceans. At the present time, coupled models of the ocean-atmosphere, where SST needs to be derived rather than inputted, are limited by our ability to model the observed variations in SST. Progress is being made despite the fact that getting SST "right" is one of the more difficult problems in the modeling. For example, one can get reasonably mixed layer depths from one-layer reduced gravity equatorial models, but the correlation between MLD and SST is unreliable.

It was pointed out during the discussion that an operational SST prediction effort is going on at the Naval Postgraduate School using a mixed layer model and simple Ekman advections, and that sensitivity studies have been done with this model to assess the tolerable errors of the winds needed for given errors in SST.

In the discussion, Sarachik stressed that coupled atmosphere-ocean models will be required in the future, that before such coupling is done, the quality of each model can be assessed by looking at the surface and by examining the surface winds and heat fluxes, and that surface winds and fluxes be standard diagnostics of atmospheric models and of the GWE data sets. Operational modelers in attendance described large uncertainties in model forecasts of surface winds and fluxes, which, as Sarachik noted, is a strong argument for presenting and evaluating these fields.

Two caveats should be added to the comments of Sarachik. One concerns his statement that the characteristics of the annual signal of SST variability are sufficiently known for comparisons with modeling results, while the characteristics of the interannual signal are not adequately defined for this purpose. This statement does not preclude the possibility that in many situations interannual signals may merely represent enhancements or weakening of the annual signal caused by changes in phase or amplitude of the annual signal of those processes which drive SST variability (i.e., no new dynamics may be required to model interannual variability). The second caveat concerns his statement that model results of SST variability resemble SST fields. Unless detailed and quantitative verifications of models are performed, it cannot be confirmed that model physics are correct. For example, a model may amplify the effect of horizontal advection on SST fields while underestimating the effects of surface fluxes. Since both factors can induce similar patterns of SST variability, comparisons with observations of currents and SST fields are required to determine the credibility of the model results.

Achievements

1. The GWE data set in the tropical oceans stimulated an intensive and ongoing modeling activity that has done much to explain the seasonal response of these oceans to the annual wind stress.
2. The drifting buoys in the southern hemisphere have provided the first synoptic observation of the circumpolar current.
3. GWE satellites yielded the first global observation of SST, and intercomparison with GWE in situ measurements suggests that achievement of the 0.5°C requirement for climate variability with existing technology is likely.

Unresolved Problems and Recommendations

1. Improvements are needed in the parameterization of surface energy fluxes through intercomparison of different observing systems.
2. Daily values of surface fields are needed to develop statistics describing the variability of wind speed, SST, SSP, humidity, etc., for use in analysis algorithms.
3. The sensitivity of sea-surface temperature derived from oceanic models to errors in the wind field needs to be better defined.
4. Improvements are needed for atmospheric boundary layer simulation in analysis models to better assimilate surface wind observations and produce verifiable surface wind sets.
5. Surface wind and surface fluxes should be standard outputs of both operational analysis-forecast atmospheric models and general circulation models.
6. a. All original TIROS-N and subsequent NOAA-series polar orbiter radiometer data need to be saved. (According to current plans only a spatially subsampled set will be held permanently in the national archives.)
b. The full resolution (nominally 4 km) Global Area Coverage data from the Advanced Very High Resolution Radiometer (AVHRR) should be organized in an archive to provide convenient access by oceanographic researchers.

DESIGN OF THE FUTURE GLOBAL OBSERVING SYSTEM

The second objective of the Global Weather Experiment is to define the necessary elements of an operational global observing system with a reliable measure of the consequences on predictability from various compromises. The principal research tools used to achieve this objective are observing system impact studies, or observing system experiments (OSE), and simulated observing system experiments (SOSE). The former uses a given assimilation model complex to study the variation in forecast skill, evaluated against that complex's own analyses of different combinations of components of an observing system. The latter is an attempt to minimize the amount of forecast error attributable to model error and predictability error by utilizing a model simulated atmosphere or "truth" from which observations are generated and used by a different model. It is only with SOSEs that the impact of future observing systems can be estimated.

Halem (see Volume Two, Session 17) presented three examples of simulation of future global observing systems. The first one was a comparison of the accuracy of temperature retrievals from HIRS instrument, currently part of TIROS-N satellite series, and the Advanced Moisture and Temperature Sounder (AMTS), one of the proposed future satellite observing systems. The simulation was performed by NOAA/NESS, NMC, GLAS, and the University of Denver. Four hundred real radiosonde soundings, selected by Phillips (NMC) for their global representativeness, were used to generate "satellite observed radiances," including instrumental and atmospheric noise in clear air. Forty more soundings were used to simulate cloud conditions, with cloudiness varying from 5 to 95 percent. Two different temperature retrieval systems, one based on statistical regression and the other on the inversion of the physical radiative transfer equations, were used to retrieve the atmospheric temperature profiles. The results indicated that the AMTS will produce temperature soundings about 0.5° more accurate than the HIRS, and about 1° more accurate near the surface. The physical retrieval method proved to be somewhat more accurate than the statistical method, and it was not much affected by clouds.

The second simulation study (Halem and Dlouhy, 1984) was a comparison of idealized single global observing systems assumed to determine the three-dimensional fields of either wind or temperature, as well as surface pressure. These observations were used in a 12-hour assimilation cycle, with a simple direct insertion at all grid points. The simulated observations were extracted from three different model-simulated atmospheres: a long run of the GLAS fourth order model also used in the simulation, a 20-day simulation using the ECMWF model, and the operational NMC analyses. The principal result was that three-dimensional wind and surface pressure observations were about twice as effective in reducing the 12-hour forecast errors as three-dimensional temperature and surface pressure. Only the three-dimensional wind observations were effective in reducing forecast error in the tropics.

The third study is an attempt to produce the most realistic study of the impact of future observing systems on numerical weather forecast skill. The experiment was designed in a Workshop on Simulation of Future Observing Systems held at NMC in 1983, with the participation of ECMWF, GFDL, and GLAS. This experiment uses as "nature" a 20-day ECMWF model run, from which synthetic observations are extracted at their proper geographical and temporal locations and with appropriate observational errors. An important element of this simulation system is that the results are calibrated against a real data impact study, OSE, using the GWE Special Observing System. Results obtained so far indicate that both wind profiles and more accurate temperature retrievals will further improve forecast skill, even in the northern hemisphere.

The future extension of the current space-based component of the Global Observing System can be viewed on a short-term basis (1980s) and a longer term (1990 and beyond). On a shorter time scale, improved vertical sounders are planned that will provide temperature profiles with a reduction in errors from present levels of 0.5 to 1.0°C. In addition, better humidity, total precipitable water, and surface temperature measurements will be possible. On the longer time scale, satellite-based lidar probing systems promise to give measurements of wind profiles, and recurrent scanning remote tomography could be the basis for improved and more versatile (microwave) sensing systems.

While SOSE and OSE results are converging on the basis for a Global Observing System (GOS) design, we do not know at present the optimum mix of wind and temperature measurements, however obtained, nor do we understand what exactly should be done in the tropics. Moreover, the question of the inclusion in a future space-based GOS of non-standard variables, such as precipitation, clouds, and infrared imagery, needs to be addressed.

Achievements

1. There was good agreement between the data impact conclusions of three groups (ECMWF, GLAS, and ANMRC). (See detailed list in section on Data Impacts on Forecasts.)
2. Simulated Observing System Experiments (SOSE) have been carried out that are in general agreement with the results of the data impact experiments (above). These simulation experiments indicate that wind observations are more effective in reducing forecast error than temperature measurements. They also indicate that future temperature sounders can reduce the rms temperature error over present capability by 0.5 to 1.0°C.

Unresolved Problems and Recommendations

1. Both SOSE and the real data impact experiments (OSE) provide valuable information to guide the design of improved future observing instruments. More experiments need to be performed to explore the effects of single-level data versus three-dimensional observations, observational error correlations, the use of nonconventional data such as cloud imagery and precipitation, and other specific questions.
2. System studies of the future global observing system should integrate results from technological feasibility studies and from observing systems simulation studies.

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GLOSSARY

ACDWS	Aircraft Dropwindsonde System
AIDS	Aircraft Integrated Data System
AMTEX	Air Mass Transformation Experiment
ANMRC	Australian Numerical Meteorological Research Center
ASDAR	Aircraft to Satellite Data Relay
AVHRR	advanced very high resolution radiometer
BOMEX	Barbados Ocean Meteorological Experiment
DST	data system tests
ECMWF	European Centre for Medium Range Weather Forecasts
EPOCS	Equatorial Pacific Ocean Climate Studies
FGGE	First Global GARP Experiment
FSU	Florida State University
GARP	Global Atmospheric Research Program
GATE	GARP Atlantic Tropical Experiment
GCM	global circulation model
GFDL	Geophysical Fluid Dynamics Laboratory
GLAS	Goddard Laboratory for Atmospheric Science
GOS	Global Observing System
GWE	Global Weather Experiment
HIRS	high resolution infrared sounder
LIMS	Limb infrared monitor of the stratosphere
MCC	mesoscale convective complex
MLD	mixed layer depth
MONEX	Monsoon Experiment
MSU	microwave sounding unit
NCAR	National Center for Atmospheric Research
NEPRF	Naval Environmental Prediction Research Facility
NESS	National Earth Satellite Service
NMC	National Meteorological Center
NOAA	National Oceanic and Atmospheric Administration
NOSAT	no satellite (data)
NWP	numerical weather prediction
OI	optimum interpolation
OSE	observing systems experiment
PBL	planetary boundary layer
PNA	Pacific North America
SAMS	stratosphere and mesosphere sounder

SCOR	Scientific Committee on Oceanic Research
SEQUAL	Seasonal Equatorial Atlantic Experiment
SLP	sea level pressure
SMMR	scanning multifrequency microwave radiometer
SO	surface only (data)
SOP	special observing periods
SOS	special observing system
SOSE	simulated observing systems experiment
SSP	sea surface pressure
SST	sea surface temperature
TCLBS	Tropical Constant Level Balloon System
TIROS	Television and Infrared Observation Satellite
TOGA	Tropical Ocean/Global Atmosphere
TOMS	total ozone mapper
TOVS	TIROS operational vertical sounder
TWOS	Tropical Wind Observing Ships
UKMO	United Kingdom Meteorological Office
VAS	vertical atmospheric sounder
VTPR	vertical temperature profile radiometer
WMO	World Meteorological Organization
WWW	World Weather Watch

APPENDIX

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