Chapter 25b

Tropical Meteorology: Panel Report

Edward Zipser, National Center for Atmospheric Research†*
Alan Betts, Middlebury, Vermont
Frank Ruggiero, Air Force Geophysics Laboratory
Barry Hinton, Space Science / Engineering Center, University of Wisconsin

1 INTRODUCTION

The subject of tropical meteorology can be defined in many ways. We prefer to follow Riehl (1954) in defining the tropics for meteorological purposes as those regions where weather sequences differ distinctly from those in middle latitudes, or roughly between the subtropical high pressure belts. Such flexibility is appropriate, permitting inclusion of important early radar studies of tropical cyclones at 42° latitude, while omitting consideration of equatorward intrusions of fronts and cyclones during the winter season.

By any definition, however, the subject includes an enormous range, which must be limited in discussions in this volume. Frank Marks, in his appropriately titled review, "Radar Observations of Tropical Weather Systems," (Chapter 25a) has chosen to concentrate on mesoscale convective systems and on tropical cyclones. He also has emphasized research since 1974, when digital radar systems were first applied to tropical meteorological problems on a significant scale.

The panel consensus is that Marks made a reasonable choice of subject matter, and we applaud his thorough, balanced, and up-to-date review of this important material. Our specific comments, presented to him in advance, are already incorporated into the review. This panel report, then, will comment on the connections between the subjects covered in the review and tropical meteorology as a whole, and on directions for the future.

One might have expected a review of tropical meteorology to include more emphasis on the convective scale than on the mesoscale, and more coverage of the weather systems of other geographic areas to balance the heavy emphasis Marks gives the GATE region. After much discussion, the panel agreed that Marks' choices are appropriate for the following reasons. First, it is now well known that deep convective clouds are often concentrated into organized mesoscale systems, in the tropics and elsewhere. Second, understanding the role of convection in the tropical atmosphere requires understanding the nature of these mesoscale systems, and the interactions between the convective scale, mesoscale, and larger scales; the Global Atmospheric Research Program, which included GATE and MONEX, aimed directly at these issues. Third, the explicit contributions of radar to tropical meteorology are especially great when radar is combined with other technologies in coordinated observing campaigns; in focusing on these, Marks conveys many of the most significant results of recent research with efficiency.

Nevertheless, before proceeding, we will pause to outline some of the important subject matter not covered by Marks' review.

In recent years, research on midlatitude convective systems has concentrated on their mesoscale properties as well as on their better known propensity to produce severe weather. Many similarities are being found between mesoscale convective systems (MCSs) in the tropics and in midlatitudes (Leary and Rappaport, 1987; Smull and Houze, 1987; Zipser, 1982). As discussed in the panel report on convective dynamics (Chapter 24b), it is important to seek common dynamical principles that can explain convective systems. We may be closest to an answer for squall lines, a form of MCS that seems to depend upon strong low-tropospheric shear in Oklahoma as well as in Africa. The panel hopes that the future will see a further erosion of artificial barriers between the meteorology of convection and mesoscale systems in the tropics and elsewhere in the world.

Tropical convective clouds are responsible for most tropical rain and are therefore important for subjects ranging from tropical climates to the general circulation (e.g.,

* Zipser served as panel chairman. Other panel members besides the authors listed above were Geoffrey Austin (McGill University), Ben Balsley (NOAA/ERL), Gary Barnes (NCAR), Jean-Pierre Chalon (Centre National de la Recherche Meteorologique, France), John Freeman (Institute for Storm Research), Michael Garstang (University of Virginia), Mort Glass (AFGL), Kenneth Hardy (AFGL), Robert Houze (University of Washington), Michael Hudlow (NOAA/NWS), Colleen Leary (Texas Tech University), and Margaret Pestaina-Jeffers (Caribbean Institute for Meteorology/Hydrology).

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Riehl, 1954). Indeed, since the classical paper by Riehl and Malkus (1958), release of latent heat in deep tropical convection has been accepted as an essential component of the general circulation, the "firebox of the atmosphere." The review and this report omit much important research on cumulonimbus convection per se. Fortunately, the dynamical aspects of this subject are covered elsewhere in this volume, and there are few fundamental differences in cumulus dynamics as a function of latitude.

During the 1960s and 1970s, stimulated in large measure by the possibilities of developing techniques for beneficial cloud modification, much research on cumulus dynamics and microphysics was accomplished in the tropics, notably in Florida. Reviews of this work include Simpson (1976) and Woodley et al. (1983). The properties of convective clouds were observed and compared with those of model simulations, beginning with simple one-dimensional models which later grew in sophistication (Simpson and Wiggert, 1971; Simpson and Van Helvoirt, 1980). Methods of estimating rainfall by gage-adjusted radars were developed and put to the test (Woodley et al., 1975). The role of boundary-layer convergence in initiating and organizing convective clouds was demonstrated by observations and models (Ulanski and Garstang, 1978; Pielke and Mahrer, 1978).

Marks' review also omits discussion of much relevant research for which radar is not the primary observational tool. We wish to note, however, that even nonquantitative radar observations are often the foundation of this research. Radar-observed echoes, and patterns of echoes, are used to define the type of system being studied and its environment, and to form a basis for compositing other types of data. Simpson et al.'s (1986) study of GATE waterspouts is one of many examples. Numerous studies of cloud microphysics, and of the interaction of airflow with topography or differential heating in cloud initiation, are also relevant.

Admittedly, by concentrating on GATE and hurricanes observed by the research aircraft, Marks' review also omits mention of much research pertaining to other geographical areas. This is not viewed as a serious omission for research in which fundamental physical processes are the object of study. Obviously, applied research results are often specific to particular regions, but such work is generally beyond our scope here. This panel report explores the future role of radar in tropical meteorology in the global context.

2 MAJOR UNSOLVED PROBLEMS IN TROPICAL METEOROLOGY

Marks' review devotes much attention to the organization of convection in the tropics. This is an important component of the problem that many would consider the key scientific issue in tropical meteorology and perhaps all of meteorology: How do tropical clouds, and convective clouds everywhere, feed back to and influence larger scale circulations in the atmosphere? This is often referred to as the scale interaction problem. It is no coincidence that Marks cites many results from the GATE (GARP Atlantic Tropical Experiment), which was organized for the express purpose of learning how scale interaction works in the intertropical convergence zone of the eastern Atlantic.

2.1 Scale Interaction in the Tropics

It is firmly established that tropical convection is a vital link in the global circulation (Riehl and Malkus, 1958; Riehl and Simpson, 1979). As a result of GATE and other programs, we know that tropical convection is not random but is highly concentrated in regions of forcing. Such forcing is commonly associated with synoptic disturbances such as waves in the easterlies or with active portions of the intertropical convergence zone. It is also common on the small mesoscale, as in land–sea breeze and orographically induced circulations. The GATE region featured very regular easterly wave disturbances, and clear relationships were evident between the waves and convective activity (Thompson et al., 1979). As Marks' review clearly states, deep convection, once formed, often becomes organized into mesoscale convective systems (MCSs).

Despite 15 years of research, the coupling between the large-scale tropical circulation and the convective (and radiative) fluxes is not well understood, and it is not well represented in global models. In essence, the problem of parameterizing the convection, layer clouds, and radiation fields in the tropics has not been solved. What we do know is that the models are highly sensitive to these processes. Betts and Miller (1986) report on preliminary testing of the ECMWF global forecast model comparing ten-day forecasts with a new convective adjustment scheme with those using the existing (modified Kuo) scheme. There were changes of order 20–30 percent in surface energy fluxes, convective precipitation, and strength of the Hadley circulation. There is every reason to expect similar sensitivity to modification of convection schemes to account for the stratiform components of mesoscale systems (Hartmann et al., 1984), which Marks' review has demonstrated to be so common in the tropics. Ramanathan et al. (1983) report on profound changes in the climatology of the NCAR Community Climate Model simply by altering the blackness of cirrus clouds.

Let us examine some aspects of the problem that illustrate its nature and importance and that also set the stage for future contributions to its solution from the radar community.

We depend upon four-dimensional data assimilation to obtain daily global analyses of kinematic and thermodynamic fields; these are the input data for global forecasts, climate studies, and a wide range of other basic and applied research. Yet this assimilation and the resulting analyses depend heavily upon the parameterization of convection, cloud distribution, and radiation, especially in the tropics. Tropical data are still sparse and largely inadequate to assess the accuracy of model analyses.

The fields forecast by global models (including climate models) in the tropics drift within a few days to model climatologies, which are in turn a function of the parameterizations of the physical processes. Assessing the performance of the models, therefore, is stymied by a fundamental deficiency: our lack of an adequate model-independent climatology of winds, thermodynamic parameters, and precipitation to assess the model biases independently and to develop an objective basis for improvements.

To study the coupling of physical processes such as convection and radiation to the larger-scale tropical flow, we must develop an adequate database and the means to make that database accessible to the community. This must include (i) a wind and thermodynamic climatology for the tropics, adequate to determine the mean fields and to resolve the energetics of tropical wave motions over a wide range of scales; (ii) a cloud and radiation budget climatology for the tropics; and (iii) a precipitation climatology for the tropics, to include the distribution of convective heating over land and oceans and through the diurnal cycle.

2.2 Precipitation Climatology for the Tropics

We have just emphasized the importance of improved precipitation estimates for the verification of global numerical models; these are of intrinsic importance. Precipitation climatology is poorly known over most of the tropics and is essentially nonexistent for the oceans, since accurate statistics are available only for limited areas for short-duration field programs such as GATE. Over many land areas such as jungles and mountains, observations are not merely scarce, they tend to be biased away from places with extreme rainfall. Coastline-dominated regimes such as the "maritime continent" (Ramage, 1968) defy description in terms of mean rainfall over an area, and exhibit diurnal cycles over land and water where mean day and night cloud areas can vary by a factor of 5 (Williams and Houze, 1987). We must develop the means to make accurate rainfall estimates from space, the only path to a unified global climatology, and we must improve on the current methodology of using proxy variables for rainfall such as outgoing longwave radiation. It is remarkable that a simple infrared thresholding technique remains our most consistently accurate method today, even though errors as large as 50 percent are reported for some long-term averages (Arkin and Meisner, 1987). Fortunately, we have an outstanding opportunity to improve the estimation of tropical precipitation from space; this is discussed at length in section 3.2.

2.3 Short-Term Forecasting Skill in the Tropics

Marks' review has demonstrated some of our recent successes in developing conceptual models of mesoscale convective systems, and in recognizing the relationship of those systems to larger scale disturbances. This new knowledge does not yet translate into significant skill in the forecasting of MCSs and their attendant weather, in the tropics or midlatitudes. For example, it is well known that extreme rainfall events and flash flooding can be associated with MCSs, but it is doubtful whether this knowledge alone can be used to improve forecasts of such events. The desired improvements in forecasts will require more than operational experience with advanced weather radar systems by line forecasters. In addition, archived radar datasets are required to be accessible for basic and applied research.

The case is somewhat different with respect to tropical cyclones. Marks has made a strong case in his review for the value of Doppler radar data in the study of hurricanes. The basic knowledge base is considerable. Prior to the time that NEXRAD systems are placed in the hands of forecasters, it is crucial to develop training programs in the use of coastal Doppler radars and to assist in the extremely critical nowcast and short-range forecast decisions that must be made. The panel believes that immediate steps are called for to develop techniques for application to this problem, and to acquire basic datasets that will be the basis for continued future improvements.

3 OPPORTUNITIES FOR THE FUTURE

The panel was excited about the prospects for radar to contribute to the solutions of the outstanding problems of the tropics, especially because the definitions of those problems have broadened and because the range of technological opportunities is greater than ever before. The scale interaction problem involves the physics and dynamics of convective and mesoscale weather systems as well as global numerical modeling. Despite the acknowledged broad scope and complexity of the issues, the panel has outlined strategies that may lead to major progress. This section will be organized by subject matter, and for each subject both short- and long-term opportunities will be identified.

3.1 The Scale Interaction Problem and Wind Profiling

We have described the critical need for an improved database in the tropics as a necessary, but not sufficient, condition for the development of improved parameterizations of essential physical processes in global models. Thirteen years after GATE, the only major experiment to address scale interactions in the tropics, the sensitivity of model simulations to physical parameterizations has been well demonstrated, but little progress has been made in incorporating the effects of MCSs into global models because of the complexity of the interactions, and, equally, because we are lacking the database for verification of proposed improvements.

The panel outlines a long-term strategy for applying existing and proposed technological advances to the solution of these problems. Essential elements are the use of radar wind profilers in the short term and satellite wind soundings combined with Doppler lidar in the long term. We can thus improve daily wind analyses in the tropics, provide a better wind climatology, and establish the basis for occasional more intensive observing campaigns in specific regions.

Current state-of-the-art wind profilers are already being deployed in the tropics and have proved their capability of providing data that quantitatively describe wind fields associated with tropical disturbances from the mesoscale to interannual scales. A profiler was installed on Christmas Island (2°N, 157°W) in 1985, and since 1986 its wind data have been transmitted operationally and assimilated into global numerical analyses and prediction models. On Pohnpei (7°N, 157°E) a vertically directed 50-MHz profiler has operated continuously since 1984, and the resulting data have been used to study the vertical velocity profiles on several scales of temporal averaging (Balsley et al., 1988). Boundary-layer systems are needed to supplement the tropospheric profilers for coverage of the lowest few kilometers, and prototypes of such systems have been developed and tested on Christmas Island (Eklund et al., 1988).

The panel recommends an early expansion of wind profiler use in the tropics. Even 10–20 systems would result in a quantum jump in our ability to describe the deep tropics and provide a basis for model verification. About eight systems deployed around the equator could provide unprecedented basic data for new knowledge of equatorial Rossby–gravity waves, Kelvin waves, the still-mysterious 30–60 day wave, the quasi-biennial oscillation, and the ENSO (El Niño–Southern Oscillation). Because the amplitude of many of these wind systems varies rapidly with latitude, it would also be important to deploy profilers along a few north–south lines across the equator, perhaps starting with the central Pacific and the Antilles–South American regions. On a longer time scale, wind data are required over the global tropics. No one system is likely to provide the total solution, but a satellite-based system is probably the best long-term answer, supplemented by increased deployment of profilers and other surface-based systems.

Carefully designed long-term regional "experiments," with a network of some 4–6 wind profilers, supplemented by thermodynamic and precipitation data, could provide the database to develop improved physical parameterizations for MCSs. We suggest this as an alternative and far less expensive initial approach to the problem, rather than a series of GATE-type scale interaction experiments. A few such networks could be created, strategically placed in different regimes, to obtain accurate wind, temperature, and moisture profiles, operationally, over an area of hundreds of kilometers in linear dimension. The interior of this area would require quantitative determination of precipitation and its vertical distribution, and the cloud and radiation distributions.

These regional networks would contribute to an improved tropical database, which would enter the global four-dimensional data assimilation system as well as provide data for research. Candidate areas for such regional networks include monsoon regions, the continental interior of Africa and South America, and the central Pacific and Caribbean regions where profilers could be established on islands.

These same regional networks, of course, would also be the obvious candidate locations for specific experiments, perhaps aimed at the scale interaction problem and improved physical understanding of mesoscale convective systems. The panel believes that while much is yet to be learned about the structure and organization of MCSs, there will be a marked shift toward questions of life cycle evolution of MCSs and their interaction with their environment; these are the issues that place the greatest demands upon the observing networks.

3.2 Quantitative Determination of Rainfall in the Tropics

We have already stressed the central importance of tropical rainfall and the need to develop methods for its accurate estimation from space. Radar meteorologists are well aware of the difficult challenges in rainfall estimation, and Chapter 29 of this volume (by Joss and Waldvogel) examines this subject in detail. Here, we emphasize the long-term opportunity represented by the Tropical Rain Measuring Mission (TRMM), and some important short-term opportunities during the preparation for TRMM.

To quote from Simpson et al. (1988), the priority science questions for TRMM are:

1) What is the four-dimensional structure of latent heating in the tropical atmosphere? How does it vary diurnally, intraseasonally, seasonally, and annually?

2) What is the role of latent heat released in the tropics in both tropical and extratropical circulations?

3) What is the relationship between changes in the boundary conditions at the earth's surface (e.g., sea surface temperatures, soil properties, vegetation) and precipitation?

4) What is the diurnal cycle of tropical rainfall and how does it vary in space?

5) What is the relative contribution of convective and

stratiform precipitation and how does the ratio vary in different parts of the tropics and in different seasons?

6) How can improved documentation of rainfall improve understanding of the hydrologic cycle in the tropics?

For the first time ever, these questions can be addressed in a meaningful way with the help of the rainfall estimates from TRMM. These will take the form of a three-year time series of monthly or semimonthly averages over areas of order 10^5 km^2. The TRMM satellite is to have the first quantitative precipitation radar in space. TRMM is to have a low altitude (300–350 km) orbit in order to have high spatial resolution data from passive microwave sensors (10-km footprint) and from the radar (4-km footprint), together with high-resolution channels in the visible and the infrared. It is to have a low inclination (30–35 degrees) orbit which will maximize coverage of the tropics and, by visiting each location at different local times, will permit documentation of the diurnal cycle.

TRMM by itself is not the total answer to the sampling problem at the time–space resolution of general circulation models, but it has a crucial and unique role as a "flying raingage." The radar and multichannel passive microwave radiometric measurements will be able to be compared continuously with the visible and infrared measurements on TRMM. When combined with "ground truth" over selected areas, the TRMM becomes a powerful calibration device that can be used to test and improve techniques for rainfall estimation from geosynchronous satellites. Thus, visible, infrared, and passive microwave radiometric methods can be calibrated and tuned for the inevitable regional differences. The opportunity will then be realized for rainfall estimates that can be used for validation of dynamic models of circulation systems on scales ranging from the mesoscale to the planetary scale. For further details of the TRMM scientific objectives and opportunities, the instrument complement, the sampling strategy and rationale, and the rain estimation algorithms, see Hildebrand and Moore (Chapter 22a), Simpson et al. (1988), or the report of the science steering group for TRMM (Simpson, 1988).

Long before the TRMM launch in 1994, there is both a need and an opportunity to develop additional datasets for tropical precipitation, and especially to undertake an extensive "ground truth" program involving combinations of remote and in situ measurements from the surface supplemented by special experiments from instrumented aircraft. Quoting from Simpson (1988), ". . . ground truth data gathering is already well under way to aid mission sampling analysis studies and to develop key regional climatologies. [Sites include] Florida, a monsoon site in northern Australia, and an ocean site in the western Pacific; i.e., Kwajalein Atoll, Marshall Islands. At the Florida site, centered near the Cape Canaveral area, both onshore and offshore (ocean) rain measurement research has begun to develop a standard rainfall measurement and data assimilation technology that can be transferred to a number of validation sites around the globe."

The combination of instruments at the primary ground truth site is to include standard and multiparameter radar, raingages, disdrometers, single and multifrequency attenuation measurements, and Doppler radar used in the Extended Velocity Azimuth Display mode (EVAD, Srivastava et al., 1986).

These activities are significant for several reasons. The GATE radar / rainfall dataset is excellent, but it represents a few weeks in a specific part of the tropics that may or may not have radar statistics comparable to those for other locations. The possible biases between oceanic and continental rainfall characteristics can be addressed at several of the test sites. Perhaps most important is the development and testing of methodologies for measuring rainfall averaged over time and space, including the capability for evaluating algorithms for estimates from remote sensing. The World Climate Research Program in cooperation with the World Meteorological Organization is sufficiently concerned about our admittedly shaky current rain estimation techniques that they have recommended reexamination of the past ten years of satellite data in the Global Precipitation Climatology Project.

3.3 Applications Research: Preparing for the NEXRAD Era

3.3.1 Hydrologic Applications of NEXRAD in the Tropics

It is commonplace in the atmospheric sciences to complain about inadequate data. Quantitative radars have indeed been all too scarce in the tropics. This is about to change, however. Within a few years, modern radar systems, mostly Doppler radars, will be active or planned at many tropical sites. These include the prospects for NEXRADs in Florida and at numerous sites along the coasts of the Gulf of Mexico and south Atlantic, Hawaii, Puerto Rico, and at military bases in Guam, Kwajalein, the Philippines, and other tropical locations. Other countries have already begun putting commercially available modern radars in operation, or will soon do so; these include Taiwan, Hong Kong, Japan, Australia, Panama, and Brazil.

The NEXRAD algorithms developed for estimating precipitation rate, precipitation accumulation, and flash flood potential relied heavily on experience gained during the GATE experiment. Consequently, performance of the algorithms for tropical locations should be good. However, to specify accurately site-adaptation parameters of the NEXRAD hydrology algorithms for locations in the tropics or elsewhere, an archived reflectivity database must be developed and made available. This raises the larger question of how the data from these radars will be archived for basic and applied research, so that they are available for study by researchers, forecasters, and hydrometeorologists, both locally and worldwide.

Radar technology is or soon will be ahead of our scientific understanding of the meteorological phenomena producing tropical precipitation. This is particularly true on the mesoscale where, for example, MCSs can develop in a few hours and die just as rapidly. These systems often produce extreme rainfall events over limited areas and we have little skill in predicting their occurrence and evolution.

The wealth of information the radars will provide about tropical MCSs can be tapped effectively for basic and applied research. As an example, current NEXRAD algorithms include a "nowcasting" projection of quantitative precipitation and flash flood potential, based almost exclusively on statistical extrapolation. It is imperative that arrangements be made to archive selected datasets from NEXRAD and other radars in the tropics to support basic and applied research directed at improving physical understanding and capability to integrate information from a variety of sources.

Last but not least, every quantitative radar in the tropics becomes a potential new data source for expanding our statistical knowledge of tropical rainfall, and a potential new ground truth site for satellite observations. As mentioned in the previous section, these radar data can and should be used in combination with visible, infrared, passive and active microwave satellite observations, at least in selected areas.

3.3.2 Tropical Cyclone Observations and Warnings in the NEXRAD Era

When NEXRAD deployment begins in about 1989 on U.S. coastlines, islands, and military bases, there will be extremely limited experience in the use of land-based Doppler radar for deriving tropical storm diagnostic or prognostic information. The panel believes that it is vitally important to expedite development of algorithms for tropical cyclones, and that in the meantime the temptation to implement untested algorithms must be resisted, whether at NEXRAD sites or the National Hurricane Center.

While severe storm algorithms were preceded by many years of field studies using Doppler radars, there is relatively little (land-based) Doppler radar data of tropical cyclones. The NEXRAD radars are the best potential source of such data if they are archived. Until such datasets are available, three sources of data can be identified for the development and testing of NEXRAD algorithms: 1) available cases of tropical cyclones observed by land-based Doppler radars; 2) conventional incoherent radar data; and 3) simulated tropical cyclone datasets. An important additional resource for both basic research and operational use is airborne Doppler radar.

Only three tropical cyclones have been observed by land-based Doppler radars in the United States, none of them typical of a full hurricane as seen by a coastal radar (Donaldson et al., 1978; Donaldson and Ruggiero, 1986; Bluestein and Hazen, 1987). In each case the radar was located some distance inland and each storm was losing its classical structure. Despite these problems Ruggiero and Donaldson (1987) were able to use observations of Gloria (1985) to develop a tropical cyclone strength index that had some of the characteristics of a NEXRAD-type intensity algorithm that could aid the forecaster.

A relatively large database of conventional reflectivity data of tropical cyclones exists, largely through the efforts of the Hurricane Research Division of NOAA, which has made special efforts to place digital recorders at National Weather Service radar sites in the path of storms. These data can be used now to help develop algorithms to identify storm center position. This is particularly urgent, because cyclone track algorithms will require storm center position as input. Improvements in current algorithms for accumulated precipitation could also be improved using these data. By adding storm track, one could also investigate the feasibility of storm-relative rainfall analyses and of extrapolation a few hours ahead near the coast for flood forecasting applications.

There are a host of potential algorithms that would use the Doppler velocity field, including circulation center position, wind field distribution, and mean vortex analysis. To assist in NEXRAD algorithm development while awaiting coastal Doppler datasets, Wood and Brown (1987) have created a simulated dataset of a mature hurricane close to the coastline. The dataset was developed based upon airborne Doppler radar observations of mature hurricanes in the Atlantic and in the Gulf of Mexico. Until actual NEXRAD hurricane data becomes available (which may be some years after the NEXRADs are in place) and independent testing can be done, such simulated datasets may be the best available testing ground for proposed NEXRAD algorithms.

The potential of the airborne Doppler radars deserves special mention. As Marks' review demonstrates clearly, they have greatly improved our understanding of tropical cyclones during the last five years. Regardless of the NEXRAD deployment schedule the airborne Doppler radar will remain one of our most valuable observing instruments for tropical cyclones (and other weather systems) for many years. Their mobility allows the cyclone to be observed while far out at sea and in all stages of development. In combination with coastal NEXRAD radars (or with each other) the airborne Doppler radars constitute a dual-Doppler pair that can yield estimates of all components of the wind field.

The future use of airborne Doppler radars with NEXRADs in dual-Doppler mode has potential to be one of the most important sources of complete wind field data for many atmospheric systems in the next decade. A long and expensive field program is not required—just the availability of a suitably equipped aircraft and the subject weather system within range of a NEXRAD radar. For more complete treatment of the airborne Doppler radar, including technical matters and research applications, refer to Hildebrand and Moore, Chapter 22a, and the accompanying panel report by Jorgensen and Meneghini, Chapter 22b.

Real-time use of airborne Doppler data in operations is now technologically feasible. The first step has already been taken with the implementation of the Airborne Satellite Data Link (ASDL) which transmits reflectivity data to the National Hurricane Center. The opportunity exists now to add velocity data in the form of user products much like those expected from NEXRAD. The real-time data could also be used to initialize operational tropical cyclone models.

Equally possible and probably more timely is the continuing need for the airborne Doppler as a basic and applied research tool. Just as important results followed the deployment of the Doppler radars on the NOAA aircraft, we can expect further advances to follow improvements in performance of the existing radars and the development of improved radars. More can and will be learned about the energetics of the hurricane's inner core and about the role of rainbands in the overall circulation and intensity of the storm. Future operational applications could include assimilation of the airborne Doppler data into a nested objective analysis describing the inner core wind structure and in multilevel analyses of the mean vortex and wavenumber-one asymmetry.

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