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NOAA WORKSHOP ON REQUIREMENTS FOR GLOBAL PRECIPITATION DATA

EXECUTIVE SUMMARY

Precipitation observations are vital to NOAA's monitoring and prediction missions in many ways. It is for this reason that NOAA maintains a wide variety of observing systems intended to provide those measurements, and continually plans to improve those systems. Despite these extensive efforts, however, there will inevitably continue to be requirements for precipitation data that exceed the data available from existing and planned systems. In recognition of this fact, a small group of NOAA scientists, all involved in some manner with the observation, analysis and use of precipitation information, convened a NOAA Workshop on Requirements for Global Precipitation Data. The meeting was held at the NOAA complex in Silver Spring, Maryland, on November 29-30, 2001, and this is the report of the meeting.

The workshop began with the goal of defining NOAA's operational and research requirements for global precipitation observations that will not be met by existing or planned systems. It brought together about 30 research scientists and operational users from three NOAA Line Offices, the National Weather Service (NWS), the National Environmental Satellite, Data and Information Service (NESDIS), and the Office of Oceanic and Atmospheric Research (OAR), to provide a report on NOAA's capabilities and needs, and to make recommendations to NOAA senior management. The stated objectives of the workshop were to:
Inventory NOAA's operational and research requirements for precipitation information;
Describe currently available precipitation observations and data sets, including their individual strengths and deficiencies; and
Provide pertinent recommendations to NOAA management.

NOAA's weather and climate requirements for precipitation data are described first. Weather requirements include numerical weather prediction, nowcasting and short-term forecasting, and the preparation of centralized forecast guidance. Critical aspects of these requirements include the timely and continuous availability of imagery and derived products, and the inclusion of information describing the error characteristics of the information. In NOAA's climate activities, precipitation data are required in the monitoring and prediction of seasonal-to-interannual variability, the modeling of climate change, and the diagnosis and understanding of the global water cycle. Primary needs for these activities include consistency and continuity of data sets, and an excellent understanding of the error characteristics of the information.

The report describes the characteristics of the observing systems and analysis techniques that provide precipitation information, including rain gauges, radars, satellites, and techniques for integrating data from varying sources. Rain gauges provide the most

accurate point measurements of precipitation at the ground, but with poor spatial coverage. Radar data can provide highly detailed information about the spatial and temporal distribution of precipitation, even in the vertical, but with significant uncertainties about absolute values and with limited coverage in a global sense. Various satellite-derived products provide exceptional spatial and temporal coverage, but with relatively poor absolute accuracy. Products based on combinations of several data sources offer significant advantages, but require extensive development and processing.

The report concludes with findings and recommendations that are intended to assist NOAA senior management in developing plans to address current and future NOAA needs. The recommendations emphasize the need for better understanding of the error characteristics of precipitation information, the need to ensure reliable and timely access to data and imagery, and the need for new observations, such as those offered by the proposed Global Precipitation Measurement (GPM) mission.

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1. Introduction/Background

Precipitation observations are vital to NOAA's monitoring and prediction missions in many ways. It is for this reason that NOAA maintains a wide variety of observing systems intended to provide those measurements, and continually plans to improve those systems. Despite these extensive efforts, however, there will inevitably continue to be requirements for precipitation data that exceed the data available from existing and planned systems. In recognition of this fact, a small group of NOAA scientists, all involved in some manner with the observation, analysis and use of precipitation information, convened a NOAA Workshop on Requirements for Global Precipitation Data. The meeting was held at the NOAA complex in Silver Spring, Maryland, on November 29-30, 2001, and this is the report of the meeting.

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Inventory NOAA's operational and research requirements for precipitation information;
Describe currently available precipitation observations and data sets; and
Provide pertinent recommendations to NOAA management.

The report begins by describing NOAA's weather and climate requirements for precipitation observations and data sets. Capabilities, including the characteristics, strengths and weaknesses of observing systems and analysis techniques, are described next and a set of findings and recommendations complete the report. It is our hope that NOAA senior management will find the recommendations and supporting discussion useful in developing plans to address current and future NOAA needs.

2. Requirements

The mission requirements for precipitation information can be separated into those supporting weather and those for climate. Here we describe the components of each mission and the requirements for supporting observations and data.

a) Weather

The weather forecasting mission of NOAA is carried out with the support of observations of current precipitation, projections of future weather derived from numerical models of the atmosphere, and forecast guidance developed by centralized components of NWS and NESDIS. Each of these efforts has different requirements and needs for precipitation information.

Numerical Modeling – Development and Operations

The mission of the Environmental Modeling Center (EMC) is to improve numerical weather, marine and seasonal predictions at the National Centers for Environmental Prediction (NCEP) through a broad program of research in data assimilation and modeling. The operational regional and global analysis/forecast systems at NCEP both assimilate precipitation data as part of the analysis cycle.

The regional system assimilates hourly precipitation from automated rain gauges and hourly precipitation estimates from WSR-88D (Weather Service Radar – 1988 Doppler) radars over the continental United States. Real-time precipitation observations from the rest of North America, especially Canada, would improve the assimilation, as would improvements in the accuracy and coverage of the automated rain gauges and radar estimates. At each time step model-predicted rainfall is compared to observations, temperature and humidity are adjusted to be consistent with the observed precipitation and model precipitation is readjusted. This iterative nudging corrects the model's precipitation bias, produces a much more realistic precipitation field during data assimilation, improves short-term precipitation forecasts and provides a better forcing for soil moisture in the coupled Land Data Assimilation System (LDAS). The regional system currently has a 12-km resolution and begins its analysis/forecast cycle 45 minutes after observation time (000, 0600, 1200 and 1800 UTC) 4 times a day. It is critical that data reach NCEP in time and in the correct format (World Meteorological Organization (WMO) standard, BUFR and GRIB) to be assimilated. Spatial and temporal resolution of the NCEP operational systems has increased (become finer) with time and that trend is expected to continue.

EMC also runs LDAS as a land data assimilation system uncoupled to any atmospheric model. In this version LDAS requires a high quality, high-resolution precipitation analysis. EMC also participates in a global LDAS collaboration with other agencies, requiring high quality precipitation analyses for all land areas globally. The regional data assimilation system is also being used for a regional reanalysis project to produce state of the art 32-km resolution regional analyses from 1979 to the present. The regional reanalysis uses satellite estimates of rainfall and rain gauges in its assimilation of precipitation. An accurate historical record of precipitation is needed for the regional reanalysis and independent precipitation estimates are needed for verification of the regional reanalysis.

The global system assimilates instantaneous satellite estimates of rain rates from the Special Sensor Microwave/Imager (SSM/I) and the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), although these estimates are given low weights (corresponding to less influence relative to other data) in the assimilation. The spatial resolution of the analysis is expected to increase from 75 km to 55 km this year. The global aviation analysis/forecast cycle is initiated two hours and 45 minutes after observation time (000, 0600, 1200 and 1800 UTC) four times a day, and the final global analysis (which is used as a starting point for the next analysis cycle of all global systems) begins six hours after observation time four times a day. Satellite observations of areas of no rain have had the greatest impact and have reduced a wet bias in the global system. Data can be used in the assimilation cycle to evaluate the forecast model; the fit of the data to the model's first guess can be calculated and accumulated even if the data are not assimilated.

Data at lower resolution than the global system can be assimilated; however, data at full model resolution is useful for developing error estimates. Error covariance matrices are essential for data assimilation. They are evaluated relative to the model to estimate the interaction of data with the model and with model error; the evaluation of error covariance matrices requires significant computational and human resources. The producers of rain estimates need to provide more information on the accuracy and uncertainties of their estimates, including biases and higher order moments as a function of rain rate and rain type. They in turn need more explicit requirements for error estimates from data assimilation experts. More dialogue between producers of data and data assimilation experts and modelers is needed; the recent establishment of a National Aeronautics and Space Administration (NASA)/NOAA Joint Center for Satellite Data Assimilation should help. Producers of satellite data also need to ensure that their estimates of precipitation, precipitation phase and type, and other cloud and hydrological parameters and profiles are consistent with each other. Both the global and regional systems assimilate daily analyses of snow cover and snow depth from NESDIS and the U.S. Air Force.

The very small spatial scales that characterize precipitation make it very difficult to estimate the error covariance. Satellite radiances would be easier to assimilate, but producing and applying an adequate adjoint of appropriate physics to convert model precipitation to radiances is difficult and too computationally expensive at present. It may be possible to provide additional information related to particular aspects of precipitation and atmospheric moisture from the improved use of particular satellite channels; greater dialogue on this topic between satellite retrieval and data assimilation experts may prove fruitful. Satellite retrievals can be improved by the use of more physically based retrieval methods. For example, microwave rain estimates have been improved by adding a freezing level to the retrieval algorithm.

Additional resources are needed to improve assimilation techniques to benefit in a timely manner from current and projected satellite data, including the development of error estimates and ongoing quality control and monitoring of satellite data and algorithms. Changes in the model physics used in the operational global analysis/forecast system have been shown to affect the assimilation as much as the introduction of precipitation estimates by itself, so additional improvements in model physics are needed to benefit from current and future data, especially data related to moisture. Additional resources are needed to achieve such improvements. Current model physics distinguishes between different precipitation phases and types, and thus observations of precipitation phases and types and their vertical distribution are needed to validate the model physics as well as for possible assimilation.

Evaluation of the model physics would be aided by observations of the three-dimensional structure of latent heat release in the atmosphere. The TRMM v.6 algorithm will soon produce vertical profiles of latent heat release. Such profiles are model-dependent and must be used with caution, but may be useful for model evaluation. Radar produces three-dimensional estimates of precipitation; these have not been seriously used in model evaluation.

Precipitation data are also required for model verification. Precipitation is one of the most important forecast elements and the skill of precipitation forecasts must be assessed. Precipitation forecasts over the continental United States are monitored for skill in the first few days of the forecast by comparison to daily reports from rain gauges at approximately 10000 stations; the network is rather sparse in the Rocky Mountains and needs to be supplemented. The global system's precipitation forecasts for other parts of the world are widely used. Greater availability of rain estimates (rain gauge networks, radar and satellite) from other countries would benefit both the verification and the assimilation of precipitation.

While the skill of precipitation forecasts beyond the first 3 to 5 days is usually small, precipitation in longer-range forecasts is monitored for its role in forcing the large-scale circulation, especially in the tropics. Forecasting the correct tropical precipitation is especially important in seasonal forecasts. Much of the skill in seasonal forecasting over the United States is related to sea surface temperature and precipitation in the tropical Pacific.

Verification of precipitation can also be used to assess the performance of model physics and the quality of divergent flow and diabatic heating in the model. For the validation of global precipitation, global data sets such as the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP), the Global Precipitation Climatology Project (GPCP), the Outgoing Longwave Radiation (OLR)-based Precipitation Index (OPI), and SSM/I are used (most of these merge satellite estimates and rain gauge measurements). Global patterns of monthly and seasonal precipitation are critically examined in model forecasts; increasing attention is now being paid to the model's ability to maintain and forecast variations in precipitation on shorter time scales, such as the Madden-Julian Oscillation (MJO) and the diurnal cycle. To verify the latter, precipitation observations every 3 hours or less are needed.

Satellite-based estimates appear to have trustworthy patterns of rainfall over the oceans; however, their magnitudes appear uncertain. Significant differences exist over the oceans between CMAP and GPCP, for example, and significant uncertainty exists even in the magnitude of climatological global mean precipitation. More accurate magnitudes are needed, especially over the oceans, but are difficult to obtain. The World Climate Research Programme (WCRP)/Scientific Committee on Ocean Research (SCOR)

Workshop on Ocean-Atmosphere Flux Fields found that new instruments were needed to provide direct precipitation measurements over the ocean. GPCP explored the use of coastal radars to evaluate its satellite-based oceanic estimates; the calibration of such radars needs to be checked. NOAA should establish a water super-site over an ocean area, in which all moisture-related quantities are measured as accurately as possible. Data from the Department of Energy Atmospheric Radiation Measurement (ARM) Program's Tropical West Pacific sites may also help evaluate the oceanic hydrological cycle.

The NCEP analysis/forecast systems also serve as useful sources of precipitation information. Currently, CMAP uses precipitation from data assimilation to complement its rain gauges and satellite estimates in regions where rain gauges are scarce and satellite estimates are more uncertain, such as high latitudes. Information from data assimilation may also help improve radar estimates of precipitation, especially in winter. For example, analyses based on data assimilation can help radar and satellite algorithms locate freezing levels.

Priorities for Advancement - Modeling:

Better error estimates from data producers, coupled with more explicit requirements for error estimates from data assimilation experts. Better communication between data producers and data assimilators and modelers. Additional resources are needed for travel and for personnel to meet this priority.

Additional resources for new personnel and additional computational resources to learn how to assimilate new satellite products in analysis/forecast systems in a timely manner, to develop error estimates, and to carry out quality control and monitoring of data.

Adequate resources to ensure that data reaches the analysis/forecast systems in time (45 minutes after observation time for the regional and 6 hours (preferably 2 hours and 45 minutes) for the global system) and in the proper form (WMO GRIB or BUFR format) to be assimilated.

Additional resources for new personnel and additional computational resources to improve model physics in order to improve the assimilation of data, particularly data related to moisture.

More accurate precipitation estimates (to within 1 mm/day or 20%, whichever is lower), particularly over the oceans. Better precipitation measurement techniques and additional in-situ measurements are needed over the oceans.

Better and timelier access to precipitation estimates from other countries.

Now-casting (0-3 Hour) and Short-Term (3-12 Hour) Forecasting:

A major concern of operational forecasters is the issuing of 0-3 hour now-casts and 3-12 hour short-term forecasts for severe weather, heavy precipitation and flash flooding, in which radar and satellite data play critical roles. Their major requirement is to have satellite data available promptly when needed. Data from polar satellites must be available within 30-60 minutes of picture time rather than the present 1.5-3 hours. They also recommend more coordination in the phasing of polar-orbiting satellites so that there could be at least four polar orbiting satellites spaced 3 or less hours apart. If combined with data from a precipitation radar in polar orbit, as proposed in the Global Precipitation Measurement (GPM) project, this would provide excellent coverage of high quality data.

Data from geostationary satellites should be available within 5 minutes of picture time and at 5 minute intervals rather than the current 15 minutes. There is presently a blackout period that can last as much as 6 hours for NOAA polar-orbiting satellite data that could be eliminated through the addition of a third ground station or a satellite relay such as is available for the Defense Meteorological Satellite Program (DMSP). An additional ground station (besides Wallops) should be built for the Geostationary Operational Environmental Satellites (GOES), if for no other reason than as a back-up in case security problems arise. The GOES currently have a 1-3 hour black-out period during local midnight during the month preceding and following the Spring and Autumn equinox. Efforts should be made to eliminate this gap on the next generation GOES slated for launch at the end of the current decade.

The following table summarizes the systems and instruments used to derive precipitation-related products for the use by the NESDIS Satellite Analysis Branch in the preparation of now-casts and short-term forecasts.

Current Sensors	Resolution	Timeliness (picture time to workstation)	Space (time between pictures)	Applications
GOES infrared (IR)/visible(VIS)	4 km or less	2-7 minutes	every 15 min.	NESDIS AE Exp. Blended AE Exp. TRaP from AE
DMSP SSM/I	15 km	1-3 hours	3 satellites/12 hrs	Exp. Blended AE TRaP from SSMI Analysis with GOES
NOAA AMSU-B (Advanced Microwave Sounding Unit-B)	16 km	1-3 hours	2 satellites/12 hrs	TRaP from AMSU Analysis with GOES
NASA TRMM	5 km	1-3 hours	1 satellite/3-24 hrs	TRaP from TRMM Analysis with GOES Exp Blended AE
WSR-88D	Nationwide 4 km	Instantaneous	every 6 min.	NESDIS AE (R vs. NR) Analysis with satellite
Future Sensors				
GOES IR/VIS/MW (Microwave)	4 km or less Min.15 km Ideal 4km	1-5 min.	Min. 15 min. Ideal 5 min.	NESDIS AE Blended AE TRaP from AE TRaP from GOES MW
POES (Polar Orbiting Environmental Satellite) MW	Min. 15 km Ideal 4 km	Min. 90 min. Ideal 30 min.	Min. every 3 hrs. Ideal every hr.	Blended AE TRaP from MW Blended TRaP from AE Analysis with GOES
POES Precipitation Radar	4 km or less	Min. 90 min. Ideal 30 min.	Min. every 3 hrs. Ideal every hr.	Blended AE TRaP from Precip Radar Blended TRaP from AE Analysis with GOES
Radar	4 km or less	Instantaneous	6 min or less	NESDIS AE ? R vs. NR Analysis with satellite

<u>Centralized Forecast Guidance from the National Centers for Environmental Prediction</u>

NCEP provides forecasts, forecast guidance and analysis products and services to support the daily forecasting activities of the NWS and its customers, and to provide tailored support to other government agencies in emergency and special situations. The products are delivered through the Service Centers, including the Hydrometeorological Prediction Center (HPC), Storm Prediction Center (SPC), Aviation Weather Center (AWC) and Tropical Prediction Center (TPC). Precipitation information is vital to the efforts of all these Centers; here we provide a description of the HPC requirements as an illustration.

An important focus of HPC is heavy precipitation forecasting. Currently forecasts are issued to 5 days, with 6-hour resolution through 72 hours and 48-hour resolution for days 4 and 5. Plans are, within 2 years, to issue forecasts to day 7, and, in 10 years, possibly farther, with 6-hour temporal resolution to day 7. HPC forecasts are currently produced on a 32 km grid.

The HPC requires observed precipitation information to assess the quality of issued forecasts, both to permit users to determine forecast utility and to assist forecasters in improving performance. Observed products are required principally over the U.S., but occasionally during emergencies may be needed in other parts of the world. High spatial resolution is needed. The National Digital Forecast Database is planned to support NWS forecasts at 2.5 km resolution, and verification data at that resolution will be necessary. At present, temporal resolution of 6 and 24 hours is needed; in the future 3-hour resolution will probably be necessary. Observations with total precipitation accuracy of ±2 mm on a 10 km grid should be available within 24 hours for the continental United States.

<u>Experimental Forecasting</u>

The West Coast is vulnerable to winter Pacific storms that bring huge amounts of rain and mountain snowfall and produce destruction with annual average losses of about three-quarters a billion dollars - mostly from flood damage. California, the nation's most populated state, supports one of then world's largest economies and most productive agricultural areas. It is hit particularly hard by winter flooding, but also depends on the winter precipitation to fill its extensive network of mountain reservoirs that serve as the primary annual water supply for the state. Thus, precipitation forecasting and management of the resulting water resources are of paramount importance there. Agencies that manage California's water supply depend heavily on precipitation and runoff forecasts from the NWS and its River Forecast Centers (RFCs) in their decision making. Small improvements in rainfall forecasts translate into huge savings in avoided flood damage according to an Army Corps of Engineers analysis. However, these winter storms are devilishly difficult to forecast because of the sparseness of upstream observations in the Pacific and the complex interplay of airflow and orography, as the storms encounter abrupt topography after thousands of miles of unimpeded fetch over the ocean. NOAA's PACJET program addresses this problem through advanced observing technologies (wind profilers, P3 research aircraft, special precipitation radars, new satellite products, etc.) strongly coupled with direct use by NWS forecasters and forecast

product users, including water managers. PACJET is exemplary in that it applies new methods to observe precipitation and related airflow features for improving short-term forecasts to a region where precipitation information is extremely valuable.
The West Coast winter storms have been more frequent and ferocious during El Niños. NOAA's new Climate-Weather Connection initiative seeks the origins and longer term predictability of these storms in seasonal climate patterns of the Pacific.

b) Climate

NOAA provides assessments of the current state of climate variability, outlooks for the coming year, and performs research on climate variability and change. The requirements for precipitation information to support these missions are generally similar to those for the weather mission with two exceptions: the need for long time series, and, in some cases, for superior absolute accuracy.

Seasonal-to-Interannual Monitoring and Prediction
NOAA provides climate services to assess and forecast the impacts of short-term (seasonal-to-interannual, or S-I) climate variability. Currently, assessments of the current state of short-term climate variability are provided by the CPC of NCEP/NWS and the Climate Diagnostics Center (CDC) of OAR. CPC issues outlooks of the probability of anomalous seasonal temperature and precipitation for the U.S. out to one year from the present.

The availability of timely and good-quality precipitation information is critical to these efforts. Information about the geographic distribution of precipitation amount is required for monitoring and forecasting and for input into soil moisture models, the output of which is useful for flood forecasting and initializing seasonal global forecast models. The monitoring of variations in tropical precipitation in particular is especially important because the interaction between variations in tropical sea surface temperature and the atmosphere is manifested through variations in convection and rainfall. Variations in the distribution of the latent heat exchange in the atmosphere that is associated with water phase change during the precipitation formation process have enormous impacts on the atmospheric general circulation, and rainfall over the tropical oceans can be thought of as the coupling mechanism in the tropical ocean-atmosphere system. Furthermore, tropical phenomena such as the El Niño/Southern Oscillation (ENSO) and MJO, which have well-documented impacts on weather in the U.S. and around the globe, are manifested by variations in precipitation distribution; thus, knowledge of the state of these oscillations has important implications for forecasting.

Two global climate data assimilation systems, using the same systems as were used for the NCEP-1 and NCEP-2 reanalyses, are executed regularly and assist CPC and CDC in assessing current climate events. The NCEP-1 reanalysis extends from 1948 to the present, while NCEP-2 extends from 1979 to the present. NCEP-2 corrects its soil moisture with 5-day mean precipitation values derived from a combination of satellite estimates and rain gauge observations. The NCEP-1 and NCEP-2 reanalyses are based on analysis and forecast systems several years old and have an effective resolution of 210 km, and several problems have been found in the hydrological cycles of both reanalyses. A new global reanalysis could produce a more accurate picture of the hydrological cycle, but would need additional data, data preparation and system development to deal with historical satellite data. Reanalysis is our best chance of improving the historical record of the hydrological cycle.

A version of the NCEP global atmospheric model makes seasonal forecasts out to 7 months, using sea surface temperature forecasts from a coupled ocean-atmosphere model. The ocean component of the coupled model is initialized by an ocean data assimilation system that includes the assimilation of salinity. Surface salinity is estimated from precipitation minus evaporation. Thus, reliable estimates of precipitation are needed for ocean data assimilation to initialize seasonal forecasts. Using precipitation estimates to improve the initialization of soil moisture in seasonal forecasts appears to improve summertime seasonal forecasts over the United States.

At present, traditional measurements of precipitation (rain gauges, radar) are extremely sparse over the oceans. Measurements from islands (which are often not representative of open-ocean conditions) are sparse. In situ measurements that are currently available over the Tropical Atmosphere Ocean (TAO) array of moored buoys employ technologies to measure rainfall that are experimental in nature and are deployed over a very limited area. Therefore, estimates of rainfall from space borne infrared and passive microwave sensors provide the bulk of information about precipitation over the oceans at the present time.

Because numerical model forecasts of precipitation are crucial tools for use in making short-range climate forecasts (6-10 day, week 2, monthly and seasonal), validation of the forecasts from these models is important so that forecasters can be aware of potential biases in the model forecasts that may vary seasonally. To this end, timely measurements of precipitation of the highest possible quality are necessary so that the model forecasts of precipitation can be validated and their biases determined.

Precipitation data and analyses are presently available to perform the monitoring and validation tasks stated above, but substantial improvements in this information are necessary to advance beyond our present capabilities. It is clear that instantaneous estimates of precipitation from passive microwave data are superior to those made from infrared data, but passive microwave sensors are presently deployed on only a few polar orbiting satellites. Thus, sampling issues are formidable with these data. Large differences among various satellite estimates of precipitation exist over the tropical eastern Pacific that need to be resolved since this important region is a major source of tropical moisture into the U.S. Measurement stability is a key issue for detecting and monitoring precipitation trends. However, the OLR data set, which is the longest global and spatially complete tool in the climate arsenal, is fraught with artificial variations and trends due to changes in instrumentation and times of observation. Rain gauge information is sparse over large portions of the planet and the time of observation for daily totals varies widely among countries. The technology to measure rainfall at the ocean surface directed is immature and needs to be validated. The sensors need to be deployed over more of the oceanic regions when the technology becomes mature.

Priorities for Advancement – S-I Monitoring and Forecasting

Global precipitation analyses with a spatial resolution on the order of 40 km and temporal resolution of 3 hours or less with a latency of less than 6 hours.
Observations from space borne passive microwave sensors every 3 hours or less.
Timely availability (daily totals no later than 1 day after observation) of more rain gauge data around the world. Many countries have internal rain gauge networks but the data are not disseminated.
Rigorous validation of in situ techniques to measure rainfall over the ocean surfaces and wider deployment of such instruments.
Wider availability of global 3-h or 6-h rain gauge data or attempt to persuade countries to adopt a universal standard for reporting daily precipitation totals.
Reconciliation of differences among satellite estimates of precipitation over the tropical eastern Pacific and elsewhere.
Consideration of climate concerns for observing systems in addition to weather concerns because measurement stability is fundamental to the accurate detection and monitoring of trends in precipitation.

Modeling of Climate Change

The prospective behavior of the global climate is investigated with the aid of General Circulation Models (GCMs) that simulate the behavior of the atmospheric component of the system. The principal requirement for precipitation data in general circulation modeling of climate change is for diagnostic evaluation of the lower frequency model variability (S-I to decadal time scales). Questions of particular importance to GCM modelers are:

How are changes in precipitation linked to changes in the radiative fluxes at the surface and top of the atmosphere?
How changes in global-mean precipitation are linked to changes in the frequency of extreme precipitation events?
How are changes in precipitation intensity (i.e., conditionally-averaged precipitation rates) related to changes in atmospheric moisture content? Precipitation products should include the monthly mean precipitation intensity as well as the precipitation rate.
What are the uncertainties in large-scale (i.e., tropical to global mean averages) precipitation measurements from satellite? This is perhaps the most important obstacle to answering the above model evaluation questions. It may be useful to look at precipitation variability within the context of other related variables, such as atmospheric radiative cooling, surface heating, etc., to examine the internal consistency of the observed variability from a coupled water/energy budget perspective. For example, are increases in precipitation associated with increased atmospheric radiative cooling (as expected by all models)?

One approach to GCM precipitation validation is a "forward approach" to the problem. That is, to actually simulate the passive microwave blackbody temperature (T_b) from a

GCM simulation of temperature, moisture, cloud water, ice and precipitation profiles and to compare the observed T_b with the simulated T_b; and then to invert both the observed and simulated T_b into precipitation "products". Such an approach requires a coordinated effort between the microwave retrieval experts and the modeling centers.

On the centennial time scales, the model-predicted increase in mid to high-latitude precipitation is of great importance because the freshening of the North Atlantic facilitates the shutdown of the Atlantic thermohaline circulation. This emphasizes the importance of mid to high latitude precipitation measurements.

Closing the Water Budget.

NOAA's mission requirements imply varying requirements for the spatial and temporal accuracy of precipitation observations. For extreme precipitation events, the spatial scale may be on the order of a few kilometers and the temporal scale on the order of minutes. Mid-latitude storms may have precipitation events with spatial scales on the order of hundreds of kilometers and temporal scales of days. Precipitation associated with the tropical monsoon systems has spatial scales of thousands of kilometers over seasonal time scales. One approach to determining the requirements for precipitation across this large range of time and space scales is to constrain the observation of precipitation by the conservation equation for atmospheric water.

The conservation equation for the atmospheric water budget states that the total time change of water in a vertical column (neglecting cloud water) is equal to the net sources, evaporation from the surface, minus the net sink, precipitation. This equation can be written as,

$$\frac{\partial W_a}{\partial t} = -\nabla \vec{Q} + E - P$$

Where W_a is the vertically-integrated water vapor, $\nabla \vec{Q}$ is the horizontal water vapor flux divergence, E is the evaporation plus transpiration, and P is the precipitation. This equation states that the observed precipitation amount at a given location must be balanced by the evaporation into the atmosphere and the flux of water vapor into the atmospheric column.

Precipitation is also constrained by the surface water budget which can be written as,

$$0 = -\Delta W_s / \Delta t + P - E - N + U$$

Where $\Delta W_s / \Delta t$ is the temporal change in surface water, N is the runoff (including the surface and subsurface flow), and U is a residual that helps account for processes such as soil water and the frozen hydrological budget.

Ideally, we could observe all the terms in both of these water budget equations and thus obtain required estimates for the accuracy of precipitation observations at a number of time and space scales. We should strive for such observations. In reality, we can not observe all these terms and so must rely on a combination of observations and analysis/model products (so-called re-analysis) to evaluate the relative accuracy requirements for each term, including precipitation. Analyses of the atmospheric water budget are underway and not yet published, but results differ by a factor of 2 or more between different analyses and observations.

Evaluations of the surface water budget for continental-size basins and for monthly and annual time scales show that random errors become small and systematic errors dominate budget constraints. Typical annual values for observed precipitation over the Mississippi basin of about 2 mm day^{-1}, runoff of about 0.55 mm day^{-1}, and evaporation of about 1.44 mm day^{-1}, assuming 10% error as a threshold, indicate that precipitation must be measured to about 0.2 mm day or less over the Mississippi basin on an annual basis. Large systematic biases between observations and analysis on both annual and monthly time scales are found. For example, the NCEP re-analysis has substantially higher precipitation relative to observations (2.47 versus 1.99 mm day-1) while the European Center for Medium-Range Weather Forecasts (ECMWF) re-analysis is much closer to observations (1.86 versus 1.99 mm day-1) over the Mississippi Basin. Examining the seasonal cycle of precipitation, they find the NCEP re-analysis overestimates summer precipitation and underestimates winter precipitation.

3. Capabilities

NOAA currently uses precipitation information inferred from observations of several different sorts. Rain gauges provide direct measurements of precipitation at the surface, while radars and satellites provide precipitation inferred from remote sensing. Here we describe the characteristics of each of these observing systems.

a) Rain Gauges

Rain gauges have been used for observations of precipitation for many hundreds of years, and many thousands of observing stations around the world have taken measurements with rain gauges. The length of this observing record provides a long-term, but problematic, picture of temporal and spatial precipitation patterns around the world.

In the United States precipitation is observed daily by more than 11,000 volunteer observers using equipment provided by NOAA. This constitutes the NOAA Cooperative Observer Network (COOP) which provides the best long-term, high spatial density observing network in the U.S. Additional NOAA networks include the Automated Surface Observing System (ASOS) that contains approximately 1000 sites operated by NOAA, the Department of Defense (DOD), and the Federal Aviation Administration (FAA). However, both networks contain a variety of measurement problems (discussed below) that degrade the observations for both weather and climate applications. More recently, however, the Climate Reference Network (CRN) being implemented by the National Climatic Data Center will have approximately 250 paired sites (a total of 500) over all 50 states and is designed to provide a homogeneous long-term picture of the climate of the U.S.

There are a number of advantages to the use of in situ rain gauge measurements compared to other precipitation measurement systems. First, unlike remotely sensed measurements (satellite and radar), rain gauge measurements are an observation of what is actually received at the surface and provide a point-depth measurement. Another advantage is that in situ measurements have been taken for hundreds of years, providing a long time series for specific locations, and are available for nearly all land areas providing near global land coverage. Rain gauge measurements also can have a high temporal resolution with measurements ranging from daily or longer totals to one minute totals. When compared to other methods, rain gauge networks are relatively cost effective and simple to implement.

Rain gauge measurements also suffer from a number of problems. They are very sensitive to changes in the environment around the gauge, in the gauge type and configuration, and methods of measurement. For example, in the U.S. first-order network a major discontinuity is present due to the change in location of stations, typically moving from the city to airport locations in the middle of the 20th century. This change usually resulted in a more open environment with higher wind speeds and thus a reduction in amount caught by the rain gauge due to wind-induced turbulence over the gauge orifice. This problem is particularly acute with solid precipitation, and can be addressed by installation of a wind-shield around the gauge. However in many networks, such as the COOP network, this practice has been inconsistent at best resulting in both temporal and spatial discontinuities.

A similar problem exists when rain gauge design is changed at an observing station. For example, in the U.S. First-order Network there have been at least four different gauge types in operation through history: the standard 8" rain gauge, a tipping bucket, universal weighing rain gauge, and the ASOS heated tipping bucket. Each gauge type has some unique properties: for example, tipping bucket gauges are notorious for under-catch at high rain rates, which causes both temporal and spatial discontinuities when compared with surrounding stations with different types of gauges. Furthermore, the heated tipping bucket has problems with measurements of solid precipitation such that a new all-weather rain gauge is scheduled to replace the ASOS tipping bucket in the near future.

Spatial fields of precipitation can be and are derived from networks of rain gauges. However, the distribution of gauges is generally not optimal for such a purpose, with poor spatial coverage in many areas, particularly poor coverage of higher elevation areas, and a general tendency for gauges to be located where people live. This often results in a poor analysis of the spatial structure of rainfall fields and the network can entirely miss isolated cells with high rain rates. Further, this is a problem not only in lesser developed parts of the world, but even in parts of the United States where population density is low and fewer observing stations are found. Observing time differences are also a problem, particularly for stations that take observations only once a day. This time may vary considerably: for instance, in the U.S. COOP network the ideal observing time is midnight LST (Local Standard Time), but in most instances the observing time is either in the morning (7 am LST) or evening (5 pm LST). This makes it difficult to create an accurate daily spatial field since the observed rainfall could have fallen at any time during the 24 hours prior to the observation, and may have occurred on the previous calendar day.

One network designed to address many of these measurement problems is the NOAA CRN. The CRN has been designed to provide high-quality climate measurements including point precipitation observations. Station design includes the installation of effective wind shields around each rain gauge to reduce problems of undercatch in windy conditions. Station site characteristics are also a strong consideration when establishing these stations and sites are being chosen to minimize exposure problems and in locations likely to remain unperturbed for the next 50-100 years. This network will provide high-quality rain gauge measurements suitable for documenting long-term variability and change in precipitation, as well as calibration and verification of remotely sensed measurements. Other efforts designed to address many of these problems include the development of a number of baseline data sets such as the Global Historical Climatology Network (GHCN) from the National Climatic Data Center (NCDC), Climate Anomaly Monitoring System (CAMS) data set from CPC, and a number of other gridded products from these and other sources.

b) Radars

Radar has been used for storm monitoring and research for almost half a century, but its full potential as an operational tool is still far from realized. Radar provides the highly detailed areal patterns of precipitation between and beyond rain gauge sites and quickly renders information on the three-dimensional structure of storms. In profiler form, radar provides incredibly detailed depictions of the vertical structure of precipitation. It has become an indispensable operational tool in the United States and several other nations for storm now-casting and for hydrometeorological quantitative estimates of precipitation.

Conventional Radars

The NWS nation-wide network of operational WSR-88D radars, completed in the 1990s as part of the NWS modernization, replaced 30-year-old radars with vastly improved technology. The improvements include heightened sensitivity to detect weaker or more distant storm clouds, Doppler measurement of storm winds, and automated real-time algorithms that provide life-saving warnings and compute dozens of useful meteorological parameters, including rainfall accumulations. WSR-88D rain estimates also serve as input to operational hydrological models. These radar applications represent tremendous advancements in the operational observation of precipitation. Yet crucial gaps and shortcomings still exist in current radar systems that NOAA should strive to remedy in order to derive maximum benefit from this exceptional tool.

Foremost among radar's shortcomings is that it has been almost entirely limited to observing precipitation over land in industrialized nations. Thus, vast areas of the planet suffer from complete absence of weather radar coverage, and a global radar perspective on precipitation is missing. This is especially true over the oceans, where until recently only radars on the hurricane-hunter NOAA P3 aircraft and a new Doppler precipitation radar on the NOAA's Ronald H Brown research vessel offer research-quality, albeit episodic, radar observations of marine storms.

Clearly, a satellite viewpoint is needed to address this deficiency by providing world-wide radar coverage of precipitation in three dimensions. Satellite radiometers currently monitor the horizontal global distribution of precipitation using passive space-borne methods that are less directly connected to basic rain properties than is true of radar. TRMM launched the first precipitation radar into orbit in 1997 to monitor rain across the data-sparse tropics. The follow-on GPM program plans to extend satellite-based radar coverage to higher latitudes (current plans call for an orbit covering from 65° N – 65° S), using a dual-wavelength radar on a core satellite to be launched in 2007. Ultimately, a constellation of cooperative satellites, including the National Polar-Orbiting Environmental Satellite System (NPOESS) co-sponsored by NOAA, will carry radiometers to improve the program's overall point-specific temporal sampling to approximately 3 hours. The potential benefits of the GPM observations to NOAA in terms of climate research alone are enormous and warrant a genuine, formal GPM partnership with NASA to attain the fullest benefit from these unprecedented observations for both agencies.

Another major radar shortcoming concerns a variable level of inaccuracy that arises from the current reliance on using reflectivity measurements to estimate rainfall rate. Reflectivity (Z) and rainfall rate (R) are fundamentally not proportional to the same moment of the raindrop size distribution. Thus, radar estimates of rain usually resort to empirical Z-R relations that can be highly inaccurate, depending on the specific drop size distribution (DSD) present in the beam. These reflectivity-based estimates of rain rate and accumulation may be degraded further by other circumstantial factors including inaccurate hardware calibrations, partial beam-filling, partial beam blockage by terrain, attenuation, and contaminations by hail, the melting layer bright band, and ground clutter. Some of these problems are accentuated with increasing distance from the radar site. In carefully controlled analyses, where most problematic factors can be ruled out, comparisons of radar-derived rainfall accumulations agree with coincident gage measurements to within about 20%. However, under more general conditions, comparisons frequently differ by more than a factor of 2. The situation is much worse for snowfall because highly variable sizes, shapes, and densities of ice crystals and snowflakes complicate the task.

Decades of radar meteorology research have developed promising methods to handle the problems related to reflectivity-based estimates of rain. Some methods are already being applied to WSR-88D observations, such as in the RFCs' Stage-III rain algorithms that adjust reflectivity rain estimates for range-dependent and melting layer effects to pre-condition the data for input to hydrological models. The original NWS plan also called for using real-time rain gauge measurements to locally tune the Z-R relation, as a means of coping with DSD variations, but this logical method has not yet been widely or routinely employed.

Among emerging radar technologies ripe for operational implementation, polarization offers the greatest promise. Polarization-diversity radar provides information about hydrometeor shapes that can be used to identify regions of rain, snow, hail, and other ice particles inside storm clouds. Polarization data from research radars are also used to obtain improved estimates of rain rate, in a method known as differential phase (or KDP). This technique uses radar measurement of phase rather than amplitude, thereby avoiding many of the problems that degrade reflectivity-based methods. National Severe Storms Laboratory (NSSL)'s Joint Polarization Experiment (JPOLE), plans to demonstrate the feasibility and benefits of upgrading the WSR-88D radars to polarization diversity. The significant potential benefits to hydrometeorology, storm nowcasting, and other applications warrant stronger support for this demonstration by NOAA and its partners (FAA and DOD).

Solutions to several other important radar/precipitation problems will require additional NOAA investments in research and technological innovations, as in the following examples.

Many coastal and mountain areas suffer from poor low-altitude storm coverage in the current WSR-88D network, leaving these areas more vulnerable to storm and flood disasters than most of the nation. Supplemental radars, perhaps in the form of smaller, less expensive, X-band systems, such as developed at the Environmental Technology Laboratory (ETL), may be needed to better protect vital coastlines and mountain and urban watersheds.

Knowledge of rain rate probability density functions is mainly based on the point data of gages. Its relation to similar distributions derived for areas from ground-based and space-based radars is poorly known, but is needed to properly merge these point and area observations.

The detailed vertical structure of storms overhead is measured by precipitation-profiling research radars developed at NOAA's Aeronomy Laboratory (AL). These, in combination with a collocated wind profiler, can simultaneously estimate rainfall rate, DSDs, and vertical air motions as a function of height. Used as anchor points, these hybrid profiler systems can provide validation checks that will help bridge the huge sampling-volume gap between gauges, scanning radars, and space-borne radars.

Snow is the dominant origin of water resources in the western United States and other parts of the world, but accurate radar estimates of snowfall have been very difficult to achieve. Revised reflectivity-based methods offer some promise, but polarization, dual-wavelength, or dual-remote-sensor methods may be required for greater success with snowfall estimation.

<u>Profilers</u>

A profiler is a Doppler radar with radar beams directed vertically and a few degrees off zenith. The fundamental difference between profilers and Doppler scanning radars is how the radar pulses are processed to produce the Doppler quantities. A profiler transmits thousands of low power pulses during a rather long dwell time (on the order 30 seconds) to produce a spectrum of Doppler velocities. In contrast, Doppler scanning radar transmits only a few high-power pulses with a short dwell time (of the order of milliseconds) and produces moments of the resolved volume. Profilers are complementary to scanning radars. The profiler can be calibrated with good accuracy using a collocated disdrometer. The profiler maintains accurate calibration due to the stability of its low power circuitry. The calibrated profiles of reflectivity from the profiler located in the view of a scanning radar can be used to calibrate a scanning radar.

A wind profiler is essentially a Doppler radar with fixed antenna beams. For wind measurement, most profilers operate by switching between antenna beams in a fixed cadence to sample the radial components of the wind field in orthogonal directions. The UHF (Ultra High Frequency) profilers originally developed by the AL for the measurement of lower tropospheric winds have now been applied to precipitation research. These UHF profilers are sensitive to hydrometeors and provide a highly resolved time-height cross section of precipitating cloud systems. For example, a unique precipitation data set was collected using UHF profilers at Integrated Sounding System (ISS) sites during TOGA (Tropical Ocean – Global Atmosphere) COARE (Coupled Ocean-Atmosphere Response Experiment). NOAA scientists analyzed the UHF profiler data from COARE to classify the precipitation into stratiform and convective components.

For precipitation measurements, a vertically pointing beam is essential in order to measure the fall speed of hydrometeors. The vertically directed beam of the UHF profiler provides the data needed to diagnose the vertical structure of convective systems passing overhead. The stacked Doppler spectra observed by the vertically looking beam of a 915 megahertz (MHz) profiler reveal the vertical profile of hydrometeor fall speeds above the profiler. For example, in stratiform rain, as the hydrometeors approach the melting layer, there is a noticeable acceleration of the particles, probably resulting from aggregation. As the hydrometeors pass through the melting layer, the ice particles melt and the resultant liquid drops accelerate rapidly, reaching terminal velocities as large as 5-7 ms-1 about 1 km below the zero degree isotherm. Some deceleration in the fall speed is evident below this level due to evaporation, drop breakup and increased atmospheric density. Algorithms developed at ETL use this information to provide NWS forecasters with automated determinations of the rain/snow transition altitude at wind profiler sites.

New methods recently developed in the AL enable the retrieval of drop-size distributions from the spectrum of fall velocities measured by the profiler. Profilers estimate the melting level by deducing the change in hydrometeor fall speed as the ice particles melt into raindrops. This freezing level information is available from every vertical beam observation and independent of the absolute calibration of the profiler.

The profiler observes the vertical structure of hydrometeor echoes, their Doppler velocity, and spectral width with excellent resolution. Classification of precipitation into stratiform and convective components is easily accomplished with the observations available from the profiler. The AL has developed low powered S-band profilers for precipitation research. Profilers are also being developed by several groups at higher frequencies (10 gigahertz (GHz), 35 GHz, and 95 GHz) to capitalize on the added information from the attenuation through the precipitation and the transition from

Rayleigh to Mie scattering processes. Combining the non-attenuating (UHF and S-band) profilers with these attenuating profilers will enable the drop size distribution and ice particle size distributions to be estimated using very short dwell times (on the order of a few seconds).

Profiler estimates of rain accumulation can be obtained using empirical Z-R relations and profiler observed equivalent reflectivities, similar to scanning radar techniques. However, a better approach is to utilize the profiler's ability to retrieve the vertical structure of the precipitation drop size distribution and apply it to determine rain rates. With knowledge of the drop-size distribution, the liquid water content and rain rate is easily obtained.

Profilers have been shown to be precise tools for measuring reflectivity and Doppler velocities of falling hydrometeors. They can be operated unattended in remote locations. These capabilities have been exploited for TRMM to retrieve drop-size distributions and related precipitation parameters. Individual profilers can be used to study the vertical and temporal variability of precipitation parameters. Multiple profilers can be used to examine in great detail the time-space variability of the same parameters. Such studies are needed to specify error covariance for numerical models that will assimilate precipitation measurements.

In field installations vertically resolving precipitation profilers should be located next to passive microwave sensors that are sensitive to the integrated column of liquid and solid precipitation. The passive microwave sensors will provide bounds for the vertical distribution of the profiler-retrieved quantities. Multiple frequency instruments need to be collocated to capitalize on the strengths and understand the weaknesses of the various instruments.

To achieve the full potential of profilers for hydrological applications, resources need to be devoted to improving the speed and automation of determining the precipitation products that combine different sensors in remote locations and transmit the products for assimilation into the numerical models. The lag between observation and transmission of precipitation products is determined by the needs and requirements of the models.

c) Satellites

Introduction

Satellites offer the perfect complement to ground-based radars and rain gauges in regions where these two ground measurements are inadequate. These include data-sparse areas over land, regions over land where radar suffers from beam blockage or beam overshoot, and over ocean, where virtually no ground information exists. Currently, NOAA satellites also offer global monitoring capability and regional monitoring capability as frequently as every 15 minutes.

Operational satellite rainfall retrievals are performed using data from both polar orbiting and geosynchronous orbiting satellites. Presently, the former provide measurements in the visible (VIS), infrared (IR), and microwave (MW) spectral regions while the latter provide VIS and IR measurements only. Additionally, there are a number of current and planned (non-NOAA) research satellite missions that will provide advanced sensors that are becoming increasingly important to operational users at NOAA. For example, the NASA TRMM and Earth Observing System (EOS) Aqua sensors include the "standard" VIS/IR/MW sensor suite, with TRMM providing space-borne radar as well. The Navy WindSat mission will provide additional microwave imagery, including those at never-before flown polarmetric channels, along with retrieved ocean wind products.

The table below summarizes some of the attributes of the current NOAA operational satellite systems in terms of a number of parameters important to users of the products. This information has been separated by satellite observing platform. It is clear that these POES and GOES systems complement one another.

Parameter	POES	GOES
Spatial Coverage	Global	Regional and Full Disk
Temporal Coverage	Every 12 hours per single satellite	15 min (regional) – 3 hours (full disk)
Data Latency	100 minutes or longer	5 minutes or longer
Finest Spatial Resolution	1 km (VIS/IR); 15 km (MW)	1 km (VIS); 4 km (IR)
Data Availability	1970s to present (1987 to present for MW imager)	1970s to present
Sensor Stability Issues	Satellite orbital drift and intersatellite calibration are major concerns.	VIS sensor calibration, intersatellite calibration and navigation are major concerns
Data Archive/Access	Relatively easy/low volume	Limited/high volume
Primary Retrieval Physics	Liquid (emission) over ocean Ice (scattering) over land	Primarily cloud top temperature and spatial texture, and their evolution.

At present, the major operational POES are maintained by the NOAA and DMSP programs, while the geostationary satellites are maintained by NOAA, the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and the National Space Development Agency of Japan (NASDA). The NOAA POES are sun synchronous and have orbital overpass times that are roughly 6 hours apart (approximately 0130, 0730, 1330, and 1930 LST) while the DMSP POES have orbital overpass times that are approximately 0600, 0830, 0930, 1730, 2030 and 2130 LST. Both POES programs contain a complement of VIS/IR/MW sensors that are comparable in capability for the retrieval of rainfall rate.

The U.S. GOES program consists of a dual-satellite mission that has one satellite centered at 75ºW longitude, the other at 135ºW. The European METEOSAT has two satellites operating at 0º and 63ºE longitude while the Japanese GMS has a single satellite centered at 140ºE. These satellites carry VIS and IR sensors with varying channel complements and sampling strategies.

Although not part of the operational satellite program, research satellites operated primarily by NASA are becoming instrumental in rainfall algorithm development and monitoring. For example, the current TRMM satellite, now expected to be available for several more years, is becoming more widely used by operational agencies such as NOAA for rainfall monitoring.

Current Retrieval Methods and Accuracy

Rain rate retrieval methods can be classified into three broad categories: instantaneous, mesoscale, and climate-scale. The first method relates the physics associated with the rain-producing cloud system to instantaneous surface rainfall: microwave-based techniques relate the radiative effect of cloud water or ice to the rate of rainfall associated with the cloud, while IR-based techniques, which were developed primarily for convective precipitation, relate the cloud-top properties to the rainfall rate. More recently, techniques have been developed to utilize VIS and near-IR along with IR data to obtain microphysical cloud properties to help detect raining clouds and corresponding rain rates. Mesoscale methods go a step beyond the instantaneous method by utilizing rapidly changing temporal characteristics of the rain system to make estimates of rainfall throughout the life of a regional storm system (e.g., mesoscale convective complex, squall lines, etc.) that produces extreme rainfall and flash flooding. Because of the usual short duration of these storms (6 hours or less), only GOES measurements can be used. The time variation of parameters obtained from the VIS and IR that are used in mesoscale applications include cloud top temperature and height, spatial texture, and cloud movement.

Climate-scale methods (e.g., monthly means at 250 km grids), which are primarily applied to IR data, utilize the climatological properties of the cloud systems over longer time and broader spatial scales to generate a time-area average rainfall. Microwave techniques (and some IR techniques) aggregate the instantaneous estimates to the desired larger time and space windows. Microwave techniques are generally considered to produce more accurate instantaneous estimates of precipitation than IR-based techniques. However, on climate scales the geostationary IR techniques, because of their frequent temporal sampling, are of comparable accuracy.

The absolute accuracy of the estimates is difficult to assess because surface reference data are difficult to come by, especially over ocean. The best hope for an absolute calibration comes from well-planned precipitation missions such as the highly successful (and ongoing) TRMM program and future GPM, both of which include extensive ground and airborne validation programs that yield insightful information on the microphysical aspects of the rain systems. More importantly, these missions are flown with a satellite borne radar that yields a three-dimensional view of the rain systems and is used as an on-board calibration for the more widely available passive microwave measurements.

Future Missions and Instruments

Within the next four years, there will be enhancements to the current POES and GOES systems that will lead to more accurate rainfall measurements. The DMSP program will begin operating an advanced microwave sensor package, the SSMIS. In addition, the NASA/Aqua satellite will be flying advanced VIS/IR/MW sensors suites. Finally, NASDA will initiate an operational polar satellite series with a full complement of VIS/IR/MW sensors. These satellite sensors will be used to the degree possible to enhance current operational rainfall products delivered by NOAA.

In the longer term, past 2005, improved versions of both GOES and POES satellite series are planned. The next generation of GOES satellites, known as the GOES-R series and scheduled for deployment around 2010, will offer a number of features that will enhance satellite-based rainfall estimation capability. These include enhanced spatial resolution (0.5 km in the visible and 2 km in the IR), improved temporal resolution (5 minutes over the continental U.S.) and additional IR imager channels that will prove helpful for both identifying precipitating cloud and estimating precipitation rate.

Both NOAA and DMSP are planning on a new series of POES that will be "converged" into a single U.S. POES satellite series known as NPOESS. NPOESS will have an entirely new series of VIS/IR/MW sensors that are anticipated to yield enhanced rainfall rate retrievals. The first NPOESS will be launched around 2007 and when fully deployed, will consist of a two satellite configuration will local crossing times at 0130, 0530, 1330 and 1730 LST.

In conjunction with EUMETSAT, the METOP polar satellite series will be placed into operation around 2006. The METOP satellite will contain a sensor package comparable to the current NOAA POES. EUMETSAT will maintain METOP in a 0930 and 2130 LST orbit time. This overpass time, in conjunction with NPOESS, will provide for four-hour temporal sampling for global precipitation measurement.

The rapid temporal evolution of precipitation, particular in association with extreme events such as flash floods, and the irregular spatial distribution and coverage of surface-based measurement systems, makes frequent temporal sampling from satellites essential. As described earlier, the combination of more frequent POES overpasses with microwave imagery and a precipitation radar in polar orbit, as proposed for GPM, would be of immense value to a wide variety of NOAA's weather and climate requirements. The combination of quantitative rainfall estimates from the radar, accurate estimates based on passive microwave imagery, and spatially and temporally dense, albeit less quantitatively accurate, information from geostationary imagery, should provide excellent precipitation data sets for many applications.

While microwave sensors on POES are extremely valuable, the sum of all planned missions will fall short of providing temporal sampling of precipitation that is consistent with its natural scale of development, that is, from a few to several tens of minutes between observations. This sampling problem will become worse in the tropics where overpasses will be relatively infrequent. From the standpoint of short-term weather forecasting, important changes can occur over short time periods at all times of the year. Climatological precipitation studies could also benefit from enhanced temporal resolution through better characterization of the evolutionary paths of individual precipitation events.

While the NOAA GOES series of sensors will help in this regard, the only means of providing high-temporal resolution imagery of precipitation on a synoptic basis is through the use of a geosynchronous microwave imager. An example of such a sensor, the GEosynchronous Microwave (GEM) observatory, has been studied in detail under the NASA-NOAA Advanced Geosynchronous Studies (AGS) Program and is currently ready for phase-B development. A single GEM sensor would provide hemispheric coverage of precipitation with refresh times of as little as 10-15 minutes for a ~1000km x 1000km region. The imagery provided by GEM would be complimentary to that provided by any POES configuration in that GEM would function as a temporal interpolator, tying together the information obtained from relatively infrequent (2-3 hourly) overpasses. The cost of adding a GEM sensor to GOES is expected to fall within the range of ~$50-75M.

d) Synthesis and Integration

Each of the observing systems described in this document provides a critical component of the full requirement for precipitation observations: rain gauges give quantitatively accurate point measurements; radars provide excellent spatial and temporal resolution in limited regions; and satellites provide near-global coverage. However, each is significantly limited in its ability to provide the complete measurements that NOAA requires. One strategy that has evolved to address these limitations is to combine observations from different platforms into a merged analysis of precipitation for selected time periods, regions and purposes. This strategy has been extensively applied in NOAA; a few examples of such synthesis and integration are provided here.

The CPC has developed a method through which gauge observations and estimates derived from geostationary and polar orbiting satellite are combined into complete near-global fields of area-averaged precipitation accumulated over periods of 5-days and months. This data set, referred to as the CPC Merged Analysis of Precipitation (CMAP) has proven extremely valuable in the study of precipitation variability associated with such climate phenomena as the El Niño/Southern Oscillation.

The operational use of radar observations is handicapped by the relatively poorly known details of the relationship between rain rate and the reflected energy measured by the instrument. Combining the excellent spatial and temporal sampling offered by the radar with the more accurate quantitative measurements of rain gauges makes it possible for the River Forecast Centers of the NWS to provide more accurate forecasts of river and stream flooding than would otherwise be possible.

Precipitation estimates from infrared sensors on geostationary satellites provide excellent spatial and temporal coverage, albeit with mediocre accuracy. Estimates based on passive microwave data from polar orbiting satellites provide much more accurate information, but with poor sampling in both space and time. Algorithms that attempt to combine the strengths of each method by using both geostationary IR and microwave estimates are being developed in several parts of NOAA, as well as in NASA and the Naval Research Lab.

4. Findings and Recommendations

The participants in the NOAA Workshop on Requirements for Global Precipitation Data, held at the NOAA complex in Silver Spring, Maryland, on November 29-30, 2001, have developed a set of factual findings and consequent recommendations that are described in the following two sections.

a) Findings

1. Precipitation observations on varying time and space scales are essential to NOAA's operational and research mission.
2. The application of current precipitation observations to the initialization and verification of numerical model forecasts is limited by inadequate understanding of the error characteristics of the observations.
3. Extended time series of near-global analyses of precipitation derived from all useful sources are essential to NOAA's climate monitoring and prediction mission.
4. The reliability and timely availability of satellite imagery is critical to NOAA's now-casting, short-term forecasting and climate monitoring missions.
5. NOAA lacks robust ground validation sites capable of quantitatively and accurately measuring areal rainfall accumulation over the scale of a WSR-88D pixel, a satellite pixel or a single column in a forecast model.
6. The proposed NASA/Global Precipitation Mission would provide data that would greatly improve NOAA's ability to monitor and predict weather and climate variability.
7. A microwave sensor in geostationary orbit would significantly enhance NOAA's capacity to monitor short time scale fluctuations in precipitation.

b) Recommendations

1. NOAA should become an active partner with NASA in the Global Precipitation Mission. This system will provide the global three hourly precipitation estimates required by the operational modeling centers. Furthermore, significant improvements in precipitation information for nowcasting, extreme precipitation events and flash floods will be achieved when geostationary data, gauges and radars are combined with GPM. Consideration should be given to the establishment of a science team or working group that would define NOAA's role in and relationship to GPM.
2. NOAA should sponsor a ground-validation super-site at a location that will complement the super-sites that NASA will establish for GPM. These sites would include concentrations of quality precipitation gauges (such as those of NCDC's Climate Reference Network) and advanced ground-based remote sensors to measure precipitation, clouds, and water vapor independently of the over-flying satellite instruments.

3. NOAA should accelerate assessments of the feasibility and scientific and economic benefits of polarization upgrades to the operational NEXRAD radars. The JPOLE project is the immediate avenue for these assessments, but it is presently funded at sub-critical level.
4. NOAA should ensure that adequate resources are available for the timely assimilation of new satellite data related to moisture and precipitation in analysis/forecast numerical weather prediction systems. Increased resources to develop error estimates and improve model physics are essential for the assimilation of such products.
5. NOAA should improve the timeliness of polar orbiting satellite data so that it can be used more effectively with geostationary satellite data to improve analyses and forecasts of heavy precipitation and flash flood events and thus enhance NOAA's core mission of Protecting Life and Property. The timely availability of POES data is affected by the current satellite-to-ground communication system. NASA has developed methodology that enables polar orbiting research satellites to transmit data through the Tracking and Data Relay Satellite System to ground stations, thus avoiding orbits during which the satellite cannot transmit data promptly. Future NOAA satellites should adopt this model of data transmission to make the data available to forecasters in real time.
6. NOAA should encourage the development of passive microwave instruments for geostationary satellites in order to provide the kind of high-temporal-resolution precipitation measurements that are required for short-term storm forecasting. NOAA should consider establishing a program office or a sub-program within its current GOES program office to facilitate the development of such an instrument.
7. NOAA should take advantage of opportunities to augment observations to improve short-term regional forecasting in areas that are particularly vulnerable to significant precipitation events, such as the U.S. West Coast in winter. NOAA's recent PACJET project in California provides an example of such an effort.
8. NOAA should support new regional and global reanalyses to improve our understanding of the hydrological cycle and to improve seasonal-to-interannual monitoring and prediction of changes in the hydrological cycle.

5. Workshop Participants

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