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AN OVERVIEW OF NATIONAL WEATHER SERVICE QUANTITATIVE PRECIPITATION ESTIMATES

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1. INTRODUCTION

Accurate Quantitative Precipitation Estimates (QPE's) are needed for a wide variety of functions in meteorology, hydrology, and related areas of study. For example, long-term, large-scale precipitation records guide decisions related to water resource management; short-term, fine-scale measurements are vital for accurate prediction of flash flooding. Accurate QPE's are also necessary for improving precipitation forecasts through such means as diabatic initialization of Numerical Weather Prediction (NWP) models (Lin et al. 1997), evaluation of the model performance, and development of statistical forecasting tools such as Model Output Statistics (MOS).

This paper describes the three principal means of estimating precipitation that are used by the National Weather Service (NWS)--rain gauges, radar, and satellite. The current QPE contributions of each source are described, along with ongoing NWS efforts to improve QPE from these sources. To assist readers who are interested in obtaining QPE data for operational or research purposes, this paper also describes how these data can be obtained in real-time and from archives.

At the July 1996 meeting of the Hydrometeorological Information Working Group (HIWG), future requirements for hydrometeorological data were outlined, including requirements for QPE (Office of Meteorology 1997). These requirements are presented in Table 1 as an initial outline of NWS QPE products; these products will be described in more detail in the related sections of this paper.

2. RAIN GAUGE ESTIMATES OF PRECIPITATION

The standard technique for measuring rainfall has long been to use can-type gauges at discrete points. This method is quite robust--it directly measures the quantity of concern--and such gauge-based estimates of precipitation are often assumed to be "ground truth" for hydrologic forecasting.

However, even gauge-based estimates of precipitation contain errors. Sevruk (1985) describes possible sources of error in rain gauge measurements of precipitation--not including mechanical errors due to instrument failure and other factors. The first category includes systematic errors in the point measurements; two additional categories encompass representativeness errors for individual gauges and for the network as a whole.

The first category includes wind-related losses, wetting of the walls of the collector and container, evaporation, splash-out and splash-in, and blowing and drifting (in the case of snow). Wind-related losses occur because the rain gauge acts as an obstacle to the air flow and affects the wind field above the gauge opening, as described in Alter (1937) and Larson (1985). A number of studies cited in the latter paper found undercatch of 10 to 20 percent on average for liquid precipitation and as much as 75 to 80 percent for snow. The addition of shielding to reduce the windspeed in the vicinity

Table 1. QPE requirements in the NWS. Acronyms are defined in the text.

Data Type	Source	Requirement
Rain gauge	Multiple	Real-time, hourly precipitation data for a minimum of 50 all-season gauges for each radar umbrella.
	HOD	HADS bulletins containing hourly precipitation data from various gauge networks, including GOES DCP and CADAS.
	RFC	SHEF-encoded bulletins containing precipitation totals for the 24-h periods ending 0000 and 1200 UTC.
Radar	PPS	Stage I 1- and 3-h and storm total precipitation on a 2-km by 1-degree grid, updated every volume scan.
	Multiple	Near real-time, hourly Stage I (PPS), II and III (RFC), and IV (NCEP) precipitation estimates incorporating rain gauge, radar, and satellite data.
	RFC	HRAP-gridded 6- and 24-h Stage III post-analyses for the 0000 and 1200 UTC cycles.
Satellite	SAB	Current (manual): Graphics of half-hour QPE every hour and storm total every 3 hours for individual events; text bulletins every 3 hours. Future (automated): Nationwide gridded half-hour QPE every half hour; storm total every 3 hours; text products every 2 hours.

of the gauge can reduce the undercatch, but not eliminate it entirely (Larson 1985).

In addition to the wind-related losses, wetting of the collector walls can produce an undercatch of up to 10 percent. Losses from evaporation and splash-out are relatively minor (Sevruk 1985).

Although Sevruk (1985) states that these systematic gauge errors are the most significant source of error, representativeness errors can also be quite large. Representativeness errors occur in two forms. The first is associated with individual gauges: the amount of precipitation measured at a gauge may not adequately represent the rainfall amount in its vicinity because of localized climatological variations. The second is associated with the gauge network as a whole: if the network is not dense enough to completely describe the spatial variability of a precipitation field, assumptions must be made about the amount and timing of precipitation in those locations with no gauge coverage, and these assumptions can be significant sources of error. Huff (1970) describes the density of rain gauge networks required to adequately represent the distribution of precipitation over an area, and the errors that result from an insufficiently dense network.

A. Types of Rain Gauges

Three types of rain gauges are used by the NWS: weighing, tipping bucket, and storage. (The reader is referred to Nystuen et al. (1996) for a description of additional types that are not described here.) Weighing gauges and tipping bucket gauges are both recording gauges: gauge readings are taken automatically and are recorded on a paper tape or chart for later retrieval and/or transmitted via radio or satellite. By contrast, observations from storage gauges must be recorded manually.

Weighing Gauge

A weighing gauge is a collection bucket atop a scale; the bucket contains some antifreeze to melt any solid precipitation, and oil to retard evaporation (Office of Hydrology 1997). The weight of the bucket is recorded automatically; the depth of water can be estimated from the weight readings by accounting for the size of the bucket and the weight of the antifreeze and oil, and the density of water. The rate of precipitation can then be inferred from changes in the depth of water with time.

The weighing gauge records frozen precipitation more accurately than the tipping bucket gauge (see below); however, foreign objects falling into the gauge can produce incorrect readings. Also, pressures generated by wind currents near the gauge can produce oscillations in the weight readings; thermal expansion and contraction of the weighing equipment can have longer-term effects on the gauge readings (G. Goodge, National Climatic Data Center, personal communication).

Two types of weighing gauges are used by the NWS: the Universal gauge and the Fischer and Porter gauge. With the Universal gauge, observations are recorded by an inked pen that draws a trace onto an autographic chart--a piece of graph paper mounted on a rotating drum (Office of Hydrology 1997). This gauge records amounts in units of 0.01 inch (0.25 mm) (Higgins et al. 1996).

The Fischer and Porter gauge has a measurement resolution of 0.04 inch (1 mm), but it uses a punched tape recorder that limits the the resolution of reports to 0.1 inch (2.5 mm) (Higgins et al. 1996). There is significant uncertainty at this level of precision; a reading of 0.1 inch can correspond to an actual accumulation ranging from 0.01 inch (if the total accumulation in the gauge increases from 0.09 inch to 0.10 inch) to 0.19 inch (if the accumulation in the gauge increases from zero to 0.19 inch). Furthermore, several hours of light rain can occur unrecorded before the Fischer and Porter gauge reports the minimum 0.1 inch accumulation. Users of data from these gauges should keep these limitations in mind, especially when analyzing the timing of precipitation.

Tipping Bucket Gauge

The main components of a tipping bucket gauge are a funnel and a rocker mechanism with two small buckets on it that is located beneath the funnel. One bucket is below the funnel at any given time; when a set amount of water accumulates in the bucket, the full bucket tips, the empty bucket swings beneath the funnel, and a signal is sent. The total amount of precipitation can then be inferred from the number of tips in a given period of time (Office of Hydrology 1997).

One weakness of the tipping bucket gauge is that a discrete amount of time is required for the bucket to tip. Since this time required for tipping is essentially constant, the amount of precipitation that is lost during tipping will increase with rainfall intensity (Nystuen et al. 1996); this problem is often addressed through the use of a correction factor (Alena et al. 1990).

Tipping buckets can also experience double-tipping, failure to tip, and false tips from heavy dew. A serious difficulty can occur with measuring frozen precipitation if the funnel hole or the tipping mechanism freezes. Consequently, the funnel is heated in some gauges; however, this enhances evaporation and creates a weak updraft above the heated funnel that deflects snowflakes away from the opening (see, for example, the ASOS Trainer's Tool Box at http://www.nws.noaa.gov/asos/tipbuck.htm).

Storage Gauge

Storage gauges are quite simple, consisting of a large can, a funnel, and a measuring tube. The standard nonrecording storage gauge used by the NWS has a receiver can diameter of 8 inches (200 mm). The depth of precipitation in the tube is magnified according to the ratio of the cross-sectional areas of the mouth of the funnel and of the tube; this allows accurate readings to 0.01 inch (0.25 mm). Frozen precipitation is measured by removing the funnel and measuring tube, melting down the precipitation that is caught in the can, and pouring the contents into the measuring tube.

B. Rain Gauge Data Networks in the United States

Gauge-based measurements of precipitation amount are available from several different sources for well over 10,000 locations in the United States; this section describes the most significant sources.

ASOS

The Automated Surface Observing System (ASOS) network provides most of the basic hydrometeorological observations, including precipitation amount, at more than 400 locations as of this writing. The network will eventually cover a minimum of 868 locations. The ASOS network serves two primary purposes: one is to replace manual observations in locations where readings had previously been made using nonrecording gauges, and the other is to provide observations in locations where readings had not been previously available.

These platforms use Heated Tipping Bucket (HTB) gauges (National Weather Service 1992) to measure precipitation. In regions where snow accounts for more than 20 percent of the total annual precipitation, Alter shields (Alter 1937) are used to reduce wind-produced errors in measurement. The specifications of the HTB gauges are for an accumulation range of up to 10.00 inches per hour with a resolution of 0.01 inch (0.25 mm) and an accuracy of +/- 0.02 inches or 4 percent of the hourly total, whichever is greater. However, because tipping bucket gauges undermeasure during high rainfall intensities, a correction factor is applied to the measurements (Office of Hydrology 1992).

As stated previously, tipping bucket gauges perform rather poorly when measuring frozen precipitation; the NWS is presently investigating solutions to this problem. The use of weighing gauges is a potential solution

(D. Mannarano, ASOS Program Office, personal communication), and possible designs for an all-weather precipitation sensor are under consideration (Office of Hydrology 1996). In the meantime, ASOS precipitation observations can be corrected if a human observer is at the site (i.e., if the ASOS site is colocated with a Weather Forecast Office (WFO) and has access to observations from another precipitation gauge (B. Weiger, Office of Hydrology, personal communication).

Precipitation measurements are taken once per minute and are stored in the ASOS unit for up to 12 hours, and are available in two formats. Commissioned ASOS stations transmit METAR observations via the Automation of Field Operations and Services (AFOS) system that include hourly accumulations (PRRRR in METAR format, where RRRR is the amount in hundredths of an inch). Total precipitation amount for 6-h periods (6RRRR) are sent every 6 hours beginning at 0000 UTC, and 3-h totals (also 6RRRR) are sent midway between the reporting times of the 6-h totals. A 24-h amount ending at 1200 UTC is reported in the 1200 UTC observation as 7RRRR (National Weather Service 1992).

Hourly accumulations also are available at the top of each hour as Standard Hydrometeorological Exchange Format (SHEF) bulletins for weather radar precipitation processing (see below). They are sent under the AFOS header CCCRR7XXX, where CCC is the originating AFOS node, RR7 is the SHEF category, and XXX is the 3-letter identifier of the ASOS station. If the precipitation rate exceeds a certain threshold, four 15-minute totals covering the previous hour are provided in a SHEF bulletin under category RR6 (National Weather Service 1992). For sites operated by the Federal Aviation Administration (FAA), all of the hourly data (and 15-minute data, if conditions warrant) are sent as an AFOS collective message under the header NMCRR7NKA (Mannarano, personal communication).

Manual Observations

Regular manual observations of 3-h, 6-h, and 24-h precipitation amounts are still made at approximately 100 sites as of this writing, though they will eventually be replaced by ASOS observations (see above). These locations are classified as primary and secondary stations: primary stations provide observations 24 hours per day, but secondary stations do not provide observations during the overnight hours (Goodge, personal communication). For the most part, these observations are taken at the same time and transmitted in the same manner as the ASOS METAR observations.

In addition to the manual 6-h reports, hourly precipitation amounts are recorded on an automated gauge (usually a Universal weighing gauge). These amounts are not disseminated in real time but are sent to the National Climatic Data Center (NCDC) for processing, as explained in the section on hourly cooperative data below (Goodge, personal communication).

GOES DCP

Geostationary Operational Environmental Satellite Data Collection Platform (GOES DCP) data are collected from various sensors, including several different types of rain gauges, that are operated by a variety of different entities. The National Environmental Satellite, Data and Information Service (NESDIS) oversees the collection of these data, with information from approximately 10,000 DCP's in the Western Hemisphere collected via the GOES-8 and

GOES-9 satellites. Though the gauges record hourly or even sub-hourly precipitation amounts, many DCP's transmit the data less frequently--in some cases only every 6 hours (Office of Hydrology 1994). To meet the requirement for real-time data from 50 gauges per radar umbrella outlined in Table 1, the Office of Hydrology is working with the DCP owners to reprogram their DCP's to transmit more frequently (L. Cedrone, Office of Hydrology, personal communication).

Cooperative Network Data

Automated hourly observations of precipitation are taken at approximately 2700 climatic (cooperative observer) locations throughout the United States and some of its territorial possessions. These gauges are operated by the NWS or the FAA and consist of Fischer and Porter (approximately 90 percent of the network) and Universal rain gauges (Goodge, personal communication).

The paper tapes and autographic records from these gauges are retrieved once per month (less often for remote gauges) for processing and quality control at NCDC, so these data are generally not available in real time. However, approximately 1000 of these gauges have been equipped with telephone telemetry systems called Limited Area Remote Collectors (LARC's) that are polled by the Centralized Automatic Data Acquisition System (CADAS). These data are routinely collected four times per day (Office of Hydrology 1994).

In addition to hourly observations of precipitation by recording gauges, observations of 24-h precipitation amount and other variables are made once per day by a network of cooperative observers, mainly using standard non-recording gauges. These observations are recorded on paper forms and sent once per month to the local WFO and then forwarded to NCDC. Data from approximately 7,600 gauges are processed at NCDC; another 500-600 are received and archived in raw form by NCDC, but for various reasons are not quality controlled or processed in any other manner (Goodge, personal communication). As with the hourly cooperative observations, much of this data is not available in real time; however, a number of these observations are also transmitted in real-time to a collection system such as Remote Observation System Automation (ROSA). These systems collect the observations, encode them into SHEF format, and send them out as scheduled AFOS collectives under SHEF category RR3 or RR4 (Weiger, personal communication).

IFLOWS

The Integrated FLood Observation and Warning System (IFLOWS) network contains approximately 1500 precipitation gauges and other sensors in 12 states in the vicinity of the Appalachian Mountains. The network is the result of a cooperative venture between the NWS and several states to reduce losses from flash flooding by improving the observation and communication of precipitation data and other relevant information. In keeping with this objective, the resulting data are disseminated not only to NWS field offices via SHEF-encoded (category RRA) AFOS bulletins, but also to community-level users (Office of Hydrology 1997). A map of the gauge locations can be found on the IFLOWS Home Page at http://www.nws.noaa.gov/afws/raindata/htm.

The most common gauges in this network are tipping-bucket gauges with a resolution of 0.04 inch (approximately 1 mm) that report in real-time via a radio transmitter. Reports are made every tip (Office of Hydrology 1997). A serious limitation of the IFLOWS gauges is that they are unheated; consequently, they are typically not used during the winter months (J. Ostrowski, Mid-Atlantic River Forecast Center, personal communication).

SNOTEL

SNOwpack TELemetry data are available for approximately 600 high-elevation locations in the western U.S. This system is managed by the Natural Resource Conservation Service, and reports hourly and daily precipitation amount (using weighing gauges) as well as other hydrometeorological variables. SNOTEL platforms are polled at varying frequencies--some only once per day, but some as frequently as hourly (Office of Hydrology 1997). The data from these gauges are transmitted to base stations and then to the NWS, and are encoded in SHEF format via AFOS under the header NMCRRMXX, where XX is a 2-character state ID.

ALERT

Automated Local Evaluation in Real Time (ALERT) sensors are installed by local governments and other agencies to monitor rainfall and other variables at very high spatial resolutions over selected areas in order to support flash flood forecasting. Rainfall is measured by tipping bucket gauges with a precision of 0.04 inch (1 mm). The local agencies own and operate the systems and are the primary recipients of the data, but increasing amounts of the data are also being relayed to the NWS in real time and transmitted via AFOS in SHEF bulletins of various categories (usually RR1, RR2, or RRA). Coverage and level of organization vary widely; California, for example, has a very highly developed network.

Private networks

In addition to the observations described above, a significant number of private organizations take regular weather observations. These organizations include schools and interest groups such as the Association of American Weather Observers, as well as mesoscale observation networks such as that in the state of Oklahoma. Many of these data are already used locally by WFO's, and plans are being made to make these data available throughout the NWS. A number of issues must be addressed, however, including communication, instrument calibration, and data quality control (R. Leffler, Office of Meteorology, personal communication).

C. Precipitation Data Distribution Systems

Data from most of the real-time gauge networks described above are not transmitted on AFOS; procedures for ingesting and/or decoding the data are necessary in order to make the data available to field offices. Two present systems for doing so are described here, plus a future system that is planned for the Advanced Weather Interactive Processing System (AWIPS) era.

HADS

The Hydrometeorological Automated Data System (HADS) (Office of Hydrology 1994) is a data processing system that ingests GOES DCP and CADAS data. HADS was developed and is maintained by the Hydrologic Operations Division (HOD) of the Office of Hydrology (OH). HADS decodes the GOES DCP and CADAS data from a variety of formats, extracts the precipitation reports, and then encodes them in SHEF for transmission to field offices via AFOS in near real-time.

HADS precipitation data are also available from the Climate Prediction Center (CPC) of the National Centers for Environmental Prediction (NCEP) via the Internet at ftp://nic.fb4.noaa.gov/pub/gcp/precip/katz. All of the hourly reports for a given day are kept in the file hrly.prcp.day.*, where * is the month and the day with left-hand zeroes excluded (e.g., July 9 is 79, not 0709). Each file is in ASCII format and is typically 4-5 megabytes in size. HADS data are processed and added to the file every 3 hours at approximately 15-20 minutes after the hour. Each file begins with data reported at 0000 UTC. The files are kept online for several weeks; older data are maintained on tape at CPC. No quality control is performed on the HADS data.

Basic information about the sensors whose data are processed by HADS is also available at ftp://nic.fb4.noaa.gov/pub/gcp/precip/directories. The file hadstn.list lists all of the gauges in the HADS dataset, while the file hadstn.record explains the format of hadstn.list. More detailed information about individual gauges that are part of the HADS bulletins can be found on the HADS Home Page at http://hsp.nws.noaa.gov/oh/hads/hads.html.

NCDC Archives

The NCDC produces an hourly precipitation data archive that consists of cooperative observations, manual observations from the primary and secondary stations, and observations from those ASOS stations that have replaced manual observations. These precipitation reports are published as the Hourly Precipitation Dataset (HPD) (National Climatic Data Center 1995), and are available approximately two months after the end of the month for which the data are valid (Goodge, personal communication). A similar dataset is also available for daily cooperative gauge data. Archives of these two datasets are available on tape or on paper hard copy from NCDC; online archives containing a significant portion of the daily data and limited amounts of hourly data are available on the NCDC home page at http://www.ncdc.noaa.gov. In addition, a more complete dataset for 1993 and earlier is available for NWS internal use at the NOAA/NWS Hydrologic Data System (NHDS) Server for Historical Data at http://nhds2.ssmc.noaa.gov.

HYD Bulletins

Once per day in the early afternoon, each RFC transmits a daily hydrometeorological data bulletin in SHEF via AFOS that contains all of the available 24-h precipitation totals for the period ending 1200 UTC. Data from a variety of sources are included in this product, such as ASOS, IFLOWS, ALERT, and those cooperative data that are available in real time. The AFOS bulletin is identified by HYD as the middle three characters in the product identifier; the last three characters of the header identify the originating RFC (Ostrowski, personal communication). As noted in Table 1, HYD bulletins for the 24-h period ending at 0000 UTC will also be produced in the future.

As with the HADS data, the HYD bulletins are ingested by NCEP and posted online in ASCII format at ftp://nic.fb4.noaa.gov/pub/gcp/precip/katz. They are initially posted at approximately 1935 UTC, with an update at 0030 UTC to include any late data (S. Katz, Climate Prediction Center, personal communication). The files are named usa-dlyprcp-yyyymmdd, where yyyy is the year, mm the two-digit month, and dd the two-digit day of the data (including left-hand zeroes). The files are kept online for only a month; longer-term archives can be obtained on tape.

LDAD

The planned Local Data Acquisition and Dissemination (LDAD) system will be an AWIPS-based system that will greatly enhance the collection and dissemination of precipitation data within and outside the NWS. This network will ingest data from a wide spectrum of sources: LARC, ASOS (FAA and DOD only), IFLOWS, ALERT, and cooperative gauges, plus other sources that are not presently available to all NWS forecasters. In return, these data will be available in real time not only to NWS personnel, but also to local government agencies, utility companies, and other entities who form agreements with the NWS (National Weather Service 1994).

3. RADAR-BASED ESTIMATES OF PRECIPITATION

As noted by Wilson and Brandes (1979), a dense network of telemetered rain gauges would be ideal for estimating precipitation amount, but limited resources render it impractical for large areas. The spatial resolution of existing rain gauge networks is generally quite poor, resulting in incorrect representation of the spatial characteristics of rainfall areas, especially in convective situations where precipitation amounts vary significantly over small distances. This is especially evident in the findings of Smith et al. (1996) who found that rain gauge networks tend to seriously underestimate the coverage and intensity of heavy precipitation areas in comparison to radar estimates, even though the radar estimates themselves have a dry bias. The non-uniformity of the distribution of precipitation gauge data can also produce biases in areal estimates of precipitation, especially in mountainous regions where gauges tend to be located in valleys and the orographic influences on precipitation are largely undetected as a result. The rate of dissemination of rain gauge data (typically hourly or longer) also creates delays in responding to short, intense precipitation events and associated flash flooding.

In contrast to the relatively poor spatial and temporal resolution of rain gauge networks, radar offers high-resolution, more evenly distributed spatial coverage. In the United States, a network of over 130 Weather Service Radar-1988 Doppler (WSR-88D) radars provide coverage over most of the contiguous 48 states (Klazura and Imy 1993).

Rather detailed explanations of radar theory are found in Wilson and Brandes (1979) and Smith et al. (1996). In brief, each radar unit emits electromagnetic energy of a specified wavelength into the surrounding atmosphere, and a portion of that energy is reflected back by other objects, including hydrometeors. The radar reflectivity (Z), which is a function of the measured return power, is related to the rate of precipitation at ground level (R) in the corresponding region. The latter is estimated empirically from the former according to the so-called "Z-R relationship."

A. Problems in Measuring Precipitation via Radar

While the spatial and temporal resolution of radar data is clearly superior to that of rain gauge data, the radar data have the disadvantage of measuring precipitation rates indirectly. Consequently, any incorrect assumptions regarding the relationship between reflectivity and precipitation rate will produce errors in the estimates. Some of these assumptions, and the associated errors, are discussed in the following paragraphs. Wilson and Brandes (1979) classify these errors into three main categories: variations in the Z-R relationship, changes in the precipitation field between the bottom of the radar field and ground level, and anomalous propagation. These three classes of errors are discussed below.

Variations in the Z-R relationship

The conversion of reflectivity to precipitation rate assumes a constant Z-R relationship. This is not a valid assumption, however; the relationship is strongly influenced by a number of factors, including the size distribution of the raindrops. This distribution in turn varies considerably between stratiform and convective precipitation (Waldvogel 1974), and is also affected by evaporation, coalescence, and other microphysical processes (Wilson and Brandes 1979). It can even vary within a single cloud (Hunter 1996).

The Z-R relationship that is used to estimate precipitation rates from radar is also based on spherical, liquid hydrometeors, which again are often not what is observed. Melting snow reflects much more energy than raindrops and produces anomalously high returns called "brightband" (Hunter 1996) if the radar beam intersects a melting level aloft; hail produces similar effects. By contrast, snowflakes produce much lower reflectivity returns than raindrops. A number of authors have found rather consistent Z-R relationships that could be applied to snow situations (Collier and Larke 1978, Fujiyoshi et al. 1990), but brightband effects can be a serious problem in heavy, wet snow (Boucher 1978).

Also, the Z-R relationship assumes that the hydrometeors are uniformly distributed in space. If rain occurs in only part of the area covered by the beam, the energy return is assumed to be from the whole area and the maximum intensity of the precipitation is underestimated as a result. This effect becomes more pronounced with distance from the radar as the width of the beam increases (Hunter 1996).

Finally, the use of the same Z-R relationship for every radar assumes that all radars have the same calibration. However, calibration differences do occur: neighboring radars can give different reflectivity returns for the same region at the same scan height and distance from the radar, and thus give different estimates of precipitation rate. The differences can be significant: one study (Smith et al. 1996) found a mean difference of 30 percent between precipitation estimates from the Twin Lakes, Oklahoma, and Tulsa, Oklahoma radars.

Changes in the Precipitation Field before Reaching the Ground

The Z-R relationship assumes a consistent relationship between the reflectivity return at the level of the radar scan and the precipitation rate at ground level. However, the height of the radar beam increases with distance from the radar because the surface of the earth is curved, and because the radar beam must be at an angle to the ground to avoid striking obstacles and producing false precipitation returns. As the height of the radar beam increases, the difference in precipitation rate between the radar scan level and the ground becomes greater--in fact, at far ranges the radar beam often overshoots precipitation areas entirely (Kitchen and Jackson 1994; Smith et al. 1996).

Anomalous Propagation

The location of precipitation areas in radar fields is based on assumptions of where the radar beam will travel once it leaves the radar unit. In most cases, the beam behaves according to theory. However, when large vertical gradients of temperature and/or water vapor are present (such as those found in a nocturnal inversion or a thunderstorm outflow boundary), the beam may be refracted more than usual by the atmosphere. This is referred to as Anomalous Propagation (AP) of the beam. If the refracted beam strikes the ground as a result, false precipitation echoes are produced (Hunter 1996).

B. Stage I-IV Processing of the WSR-88D Data

Quality control of the radar data is performed, often with information from other sensor fields (i.e., rain gauge and satellite), in order to address the sources of error described in the previous section and thus maximize the accuracy of the WSR-88D estimates. Four steps of processing are applied to the WSR-88D data, known as Stages I through IV.

Stage I

Stage I (Fulton et al. 1997) is a multi-step processing of the radar data in the Precipitation Processing System (PPS) of the Radar Product Generator (RPG) of each WSR-88D unit. The processing performs basic quality control of the data, computes precipitation rates and bias-adjusted accumulated amounts, and generates graphic and digital products.

Reflectivity data at a resolution of 1 km by 1 degree azimuth are used in the Stage I processing, and these data are taken from a combination of tilts of the volume scan. This technique, called a "hybrid scan," uses a prescribed combination of the four lowest tilts such that lower tilts are used as distance from the radar increases. This is done in order to maintain a relatively constant scan height of approximately 1000 m above ground level. Two other conditions must be met: the bottom of the tilt to be used must be at least 500 ft (150 m) above any obstruction at the range of interest, and no more than 50 percent of the beam can be blocked by obstacles between the radar and the point of interest. If the prescribed tilt does not meet these requirements, then the lowest tilt that does meet them is used. One difficulty with the hybrid scan is that it can produce discontinuities in the radar field in regions where the tilt is shifted upward or downward. To alleviate this problem, some radars are now choosing the lowest tilt that meets the terrain requirements (Fulton 1997; O'Bannon 1997).

At far ranges, the higher of the reflectivity values from the two lowest scans is used; this algorithm is referred to as "bi-scan maximization." However, a study by Smith et al. (1997) found that brightband effects in the second tilt contribute to overestimation of precipitation amounts at middle ranges, so bi-scan maximization has been discontinued at some radars (J. Breidenbach, Office of Hydrology, personal communication).

Basic quality control is performed before converting the reflectivity values from the hybrid scan to precipitation amounts. Corrections for partial blockage of the beam by topographic features are made according to pre-defined blockage regions and correction factors. Extremely high reflectivity values and values that are inconsistent with their neighbors are adjusted in order to remove possible hail contamination or spurious noise in the return signal (Fulton et al. 1997). The PPS also employs a simple AP removal algorithm that compares reflectivity values from the lowest two tilts. If the reflectivity values of the two tilts differ too greatly, the lower scan is rejected. Smith et al. (1996) report good results from this scheme when precipitation is not occurring.

In addition to these quality controls, two new prototype schemes have been developed for the Stage I package. The first uses differences in reflectivity between different tilts to generate a range-dependent bias correction, while the second detects brightband effects based on the vertical precipitation rate profiles (Seo et al. 1997a).

These quality-controlled radar reflectivity values are converted to rainfall rates, and then to amounts with a precision of 0.1 mm. The default Z-R relationship is $Z=300R^{1.4}$; however, meteorologists at the WFO that is collocated with the radar can use a "tropical" Z-R relationship ($Z=250R^{1.2}$) when conditions warrant. The rain rates from adjacent pairs of radial bins are then averaged to reduce the resolution to 2 km by 1 degree azimuth. Additional quality control follows the rain rate conversion, including correction for hail contamination by specifying a maximum possible rain rate, and a time continuity test--if the rainfall field is excessively different from the previous field, it is discarded under suspicion that radio frequency interference or AP has contaminated the field (Fulton 1997).

To convert the precipitation rates to amounts, the rates from the current scan are averaged with the rates from the previous scan, and these average values are multiplied by the time between the scans to produce an accumulation. The PPS then uses these accumulations to compute totals for the past hour and for the entire precipitation event. The storm-total amount is reset to zero when no precipitation has occurred in the past hour (Fulton 1997).

The PPS contains an algorithm for computing a multiplicative bias for all of the rainfall estimates within the radar umbrella (Ahnert et al. 1986; Fulton 1997; Seo et al. 1997b). The values at each available rain gauge are compared to the values in the corresponding HRAP grid box and the eight adjacent boxes (to account for imprecision in the gauge coordinates, drift of hydrometeors, etc.), and the HRAP (Hydrologic Rainfall Analysis Project) bin with the value closest to that of the rain gauge is selected for bias computation. The observed bias is the total estimated rainfall in these grid boxes divided by the total observed rainfall at the corresponding gauges. A statistical filter is used to predict the present-hour bias based on observed biases from previous hours. A bias correction is then applied to the precipitation total for the previous hour, and is also used when incrementing the multi-hour totals. This algorithm is not operational as of this writing because the necessary gauge data are not available at the WSR-88D unit (Fulton 1997). However, a scheme called the Gauge Data Support System (GDSS) will soon be providing SHEF-encoded data from HADS and ASOS data to the PPS (W. Dice, Office of Hydrology, personal communication).

The final step in Stage I processing is the generation of products. A set of graphic precipitation estimates with 16 data levels is produced at the resolution of the reflectivity data as part of the Level III WSR-88D processing (Klazura and Imy 1993). These estimates are stored as raster graphic files that are available almost immediately after each radar scan (Breidenbach, personal communication), but can only be displayed in real-time on the Principal User Processor (PUP) units at field offices and by those entities who have entered into specific service agreements with the NEXRAD (**NEX**t-generation **RAD**ar) Information Dissemination Service (NIDS) (Klazura and Imy 1993). In addition to the 1-h and storm-total amounts described previously, a 3-h total is available that is updated at the end of each clock hour, along with a total accumulation covering a user-selected time period of up to 24 hours (Fulton 1997). Archives of the 1-h and storm-total graphic products are available both in hardcopy and electronic formats (tape and ftp) from the National Climatic Data Center (NCDC). Archive catalogs and information on ordering these products can be found at http://www.ncdc.noaa.gov/pub/data/nexrad/nexmain.html.

In addition to the graphic products, the PPS also produces a digital 1-h rainfall estimate called the Digital Precipitation Array (DPA) (National Weather Service 1993a; Fulton et al. 1997). This estimate is produced every volume scan, but is distributed on AFOS only once per hour as the Hourly Digital Precipitation (HDP) product. The estimates are produced on the HRAP grid (Schaake 1989)--a polar stereographic grid with columns aligned with 105°W. The grid resolution is 3.5-4.5 km over the continental U.S., but is often referred to as 4 km for simplicity. For comparison, the spacing between grid points on this grid is exactly 1/40 the spacing on the Limited-area Fine-mesh Model (LFM) grid and 1/10 the spacing of the Manually Digitized Radar (MDR) grid. Each radar produces estimates on a 131-by-131 portion of the HRAP grid centered on the radar location.

The HDP consists of a 131-by-131 matrix of dBA levels (Fulton et al. 1997), which relate to rainfall amounts in mm/h by the equation $R=10^{dBA/10}$ (National Weather Service 1993a). A total of 256 data levels are used, corresponding to dBA values ranging from -6 dBA (0.01 inch or 0.25 mm) to 26 dBA (15 inches or 400 mm). A data value of 0 or 255 is assigned to HRAP boxes that are outside the 230-km radius of the radar umbrella (Breidenbach, personal communication). In addition, the estimated bias and the gauge values used to compute it will be appended to the HDP when the bias correction becomes operational (National Weather Service 1993a).

The HDP is distributed to NWS forecast offices via AFOS in a binary format, and is available approximately 15 minutes after the valid time (Breidenbach, personal communication). Archives are available for NWS internal use from the NOAA/NWS Hydrologic Data System (NHDS) Server for Historical Data. The main server page is at http://nhds2.ssmc.noaa.gov; the Stage I data are located at http://140.90.20.144/nexrad.html. These data are in binary format; decoding instructions are found on the page.

Stage II

Each RFC performs Stage II processing for every radar site whose coverage area intersects the RFC's area of responsibility. Consequently, more than one RFC may perform Stage II analysis for a particular radar. The WFO's will soon have Stage II processing and display capability as well. This product is on the same grid and covers the same area as the HDP product, but has had additional quality control performed on it.

The Stage II algorithm (Hudlow et al. 1989; Office of Hydrology 1992; National Weather Service 1993a) ingests the HDP (including biases and rain gauge data when they become available), and applies 0/1 arrays of missing data (a static data field that accounts for beam blockage, ground clutter, etc.) and of bad data (a dynamic data field created by the RFC forecaster during Stage III processing--see below) to the precipitation field to mark grid boxes with unreliable values.

An algorithm had been developed to delineate areas of cloud and clear sky in order to remove clear-sky AP and other errors in the radar field, but it has been deactivated. This algorithm compared 11-micron (infrared) brightness temperatures from GOES-7 data to the lowest surface temperature observed within the radar umbrella. Since GOES-7 images are at 40-km resolution, comparisons were made over areas covering 10x10 HRAP bins. If the lowest brightness temperature on the three most recent images (they are taken every half hour) was significantly different from the lowest observed surface temperature within the radar umbrella (5°C is the default threshold), that area was assumed to be cloudy, and no changes were made to the radar data. If clear sky was assumed instead, all radar estimates in the central 6x6 box were set to zero, and the radar estimates in the 2-grid-box-wide borders were also set to zero if the adjacent 10x10 boxes were determined to be cloud-free. This algorithm was deactivated because the coarse resolution of the GOES-7 data caused a significant number of real precipitation echoes to be removed; Breidenbach (personal communication) is developing a revised algorithm that operates at the level of the individual HRAP boxes, using 4-km GOES-8/9 data and Rapid Update Cycle (RUC) model surface temperature forecasts.

Outliers are also removed from the HDP data. If the HDP value in a given HRAP bin exceeds a preset maximum (the default is 500 mm), that amount is replaced by the average of the estimates in those adjacent grid boxes that do not have bad or missing data. A set of Stage II biases are then computed based on the radar data and the available rain gauge data according to one of two available algorithms. The original procedure, a variant of the Stage I algorithm, computes the bias from a statistically filtered combination of present and previous observed biases. It is described in more detail in Hudlow et al. (1989), Smith and Krajewski (1991), and Office of Hydrology (1992). Seo et al. (1997b) have developed a new bias algorithm that is now being used by most RFC's (Breidenbach, personal communication); the advantage of the new algorithm is that it does not require a climatological mean bias estimate. The Stage II analysis is also re-run by the RFC's up to five times after the initial analysis, which allows additional gauge data (such as delayed reports from GOES DCP platforms) to be incorporated into the bias correction computation and also allows "future" biases to be used by the statistical filter when computing the time-filtered Stage II bias.

After re-analyzing the radar-only field, the Stage II algorithm generates a gauge-only field. One of two available algorithms for creating this field can be selected by the Hydrometeorological Analysis and Support (HAS) forecaster. The first (Hudlow et al. 1989, Office of Hydrology 1992) begins by delineating rain/no-rain areas. The gauge amounts for each HRAP bin are set to zero if the radar-only field shows no precipitation in that grid box and the eight that surround it and if no nearby gauges (within 6 km is the default) have precipitation amounts above a certain threshold (the default is 0.01 mm). The gauge-only values of the remaining HRAP grid boxes are computed by using a weighted average of all gauges within 25 HRAP boxes of the gauge of interest, with the weights based on the reciprocal of the distance from the HRAP bin to the gauge. This scheme also uses differences in normal precipitation amount between the HRAP grid box and the gauge of interest in order to account for orographic influences.

The alternative procedure for generating the gauge-only field is called Single Optimal Estimation (SOE) (Seo 1997a). Instead of using a distance-weighted scheme, this algorithm accounts for the spatial characteristics of the rainfall field by using a technique called kriging. This approach showed improved performance over the distance-weighting scheme, and produced more realistic-looking gauge-only fields. Most RFC's now use this new procedure; those in mountainous regions generally prefer to use the original algorithm in conjunction with a climatic data set generated by the Precipitation-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al. 1994) because the new scheme does not account for orographic influences (Breidenbach, personal communication).

The final step in Stage II processing is to merge the radar-only and gauge-only fields into a multi-sensor field. Again, two schemes are available. The first (Hudlow et al. 1989; Office of Hydrology 1992) uses a weighting scheme that accounts for the distance between the HRAP grid box and the nearest precipitation gauge (a measure of the confidence in the gauge-only analysis at that particular point) and the spatial correlation of the radar field (gauge-only fields tend to be less accurate when precipitation amount varies greatly in space). A second procedure for the multi-sensor field that is now operational at most RFC's is an SOE-based approach (Seo 1997b) that is similar to the gauge-only analysis algorithm.

Stage II products are produced approximately half an hour after the valid time. However, the RFC's that produce them do not distribute them externally and also do not archive them, since they can be re-created if necessary from the archived HDP data and corresponding gauge data (Breidenbach, personal communication).

Stage III

After Stage II processing is completed, the HAS forecaster produces a Stage III mosaic (National Weather Service 1993b) of the Stage II fields that are within the RFC's area of responsibility. In regions where radar coverages overlap, all non-zero and non-missing values for each HRAP bin are usually averaged; however, the HAS forecaster can instead use the maximum values in each bin. This approach compensates in part for the decrease in the radar's ability to detect precipitation as the distance from the radar increases (Breidenbach, personal communication). Furthermore, the multi-sensor grids are normally used for the mosaic, but the HAS forecaster can substitute the gauge-only field if the multi-sensor field is considered to be unsuitable.

The HAS forecaster also performs manual quality control on the gauges used in the Stage II/III analyses, changing or rejecting gauge values and adding new values as appropriate. The bad data arrays for the individual WSR-88D radar fields are constructed by identifying grid boxes whose values appear to be unreliable. Subsequent re-analysis of the Stage II/III products affected by these changes can be performed, if necessary. Furthermore, the HAS forecaster can manually adjust the bias value of individual Stage II fields if appropriate (Breidenbach, personal communication).

Since there is no routine overnight staffing of RFC's at the present time, an automated Stage III script is available that mosaics the Stage II products without any manual quality control. The HAS forecaster can examine the Stage III products and gauge data at a later time and perform retroactive quality control if needed. This may produce inconsistencies in the quality control of the nationwide Stage IV mosaic (see below) in the future (Breidenbach, personal communication). The automated version of Stage III takes approximately 10-15 minutes to run (Ostrowski, personal communication); the manual execution of Stage III takes longer, depending on the amount of manual quality control that is needed.

Finally, the HAS forecaster performs post-analyses to create 24-h total estimates of Stage III precipitation valid at 1200 UTC, and 6-h total estimates when necessary. This is done by aggregating the corresponding hourly Stage III products and merging them with a gauge-only field corresponding to the same time period that uses cooperative gauge data that were not available for any of the hourly gauge-only analyses. To ensure consistency with the hourly Stage III products, the precipitation amounts from the 6- and 24-h fields are disaggregated into the hourly mosaics; changes are made to the hourly products if their values differ by more than 5 mm from the disaggregated 6- and 24-h products.

The Stage III products are not usually distributed in real time by the RFC's, though some RFC's do post them on the Internet. For example, the Arkansas-Red River Basin River Forecast Center (ABRFC) home page (http://info.abrfc.noaa.gov) provides Stage III displays and helpful information about WSR-88D precipitation processing. Archives of Stage III data are available for internal NWS use at the NHDS Server for Historical Data on the same page as the Stage I archives (http://140.90.20.144/nexrad.html). The rain gauge data used for the Stage II/III processing are also available on this page, along with documentation.

Stage IV

The Environmental Modeling Center (EMC) of NCEP produces nationwide mosaics of 1-h precipitation amount (Baldwin and Mitchell 1997), with 6- and 24-h estimates to appear in the future. The eventual plan is for Stage IV to be a mosaic of Stage III data, and thus the final step in the Stage I-IV progression. However, transmission of all of the Stage III data from the RFC's to EMC will not be sufficiently timely until AWIPS becomes operational, so for now the Stage IV estimates are a fully automated processing of the Stage I data from WSR-88D radars across the continental U.S. that is similar to the Stage II processing.

In the current Stage IV processing scheme, a preliminary radar-only field is produced less than an hour after the valid time. However, multi-sensor processing does not begin until approximately 6 hours after the valid time because of delays in data transmission from some gauge data platforms (i.e., GOES DCP and CADAS). As with the Stage II processing, three fields are produced. The first is a bias-corrected radar field that is generated by applying the Stage II bias correction algorithm to each Stage I radar umbrella by using the previous 10 hours of data, and then mosaicking the resulting fields. The second field is a gauge-only field that is created by applying the Stage II gauge-only SOE algorithm to the HADS data. The two fields are then merged to create a multi-sensor field using the Stage II SOE technique. A re-analysis is performed 18 hours after the valid time with rain gauge and radar data over a 21-hour period (10 hours before validation time to 10 hours after) in the Stage II bias filter.

In the future, Stage IV processing will incorporate the new bias correction algorithm of Seo et al. (1997b) (K. Mitchell, NCEP, personal communication). More rigorous quality control of the rain gauge and radar data is also planned; as of this writing, only amounts that exceed 5 inches are removed from the rain gauge data, and the radar data are not quality controlled at all. Once AWIPS is operational, the original plan of mosaicking Stage III fields to create the multi-sensor Stage IV field will be implemented in place of the current independent processing scheme. This product will be available approximately two hours after the valid time--depending on the timeliness of the component Stage III products--along with the radar-only and gauge-only mosaics (Mitchell, personal communication). The automated satellite-based precipitation estimates from NESDIS (see below) will also eventually be incorporated into the Stage IV product (Baldwin and Mitchell 1997).

Stage IV estimates are available on the NCEP Stage IV home page at http://nic.fb4.noaa.gov:8000/research/gcp/hdpprec.html. These data include all of the most recent Stage IV fields: the radar-only fields with and without bias correction, the rain gauge-only field, and the multi-sensor field. They are in GRIdded Binary (GRIB) format on two grids: the 4-km HRAP grid, and a 15-km grid that is simply a 3x3 averaged remapping of the 4-km grid. In addition to the Stage IV fields, a field of 24-h total precipitation is available on a 40-km grid; this analysis is done by averaging all of the values within each grid box. Additional information on the Stage IV mosaic, one-week archives of Stage IV data, decoding software, and other useful information are also available on this home page.

C. Performance Evaluation of Radar Estimates

Quantitative evaluation of the accuracy of radar-based estimates of precipitation amount is difficult for a couple of reasons. First of all, although gauges are usually considered "ground truth," they are also subject to error. Furthermore, radars and rain gauges measure precipitation on two different scales of space and time. Radar measures spatially-averaged instantaneous precipitation rates over a region of significant size; rain gauges measure precipitation amounts over a discrete period of time at a point. The differences in temporal and spatial scales make direct comparison of the two difficult (Smith et al. 1996).

In spite of these difficulties, a number of studies of WSR-88D performance have been undertaken. A study by Smith et al. (1996) confirmed the range-dependent bias of the WSR-88D estimates, with significant underestimation at close ranges (within 40 km of the test radars) and at far ranges (beyond 100 km in winter and 150 km in summer). The latter occurs because of the beam overshooting problems described earlier--in many cases the radar fails to detect precipitation that is occurring. Overestimation occurs in middle ranges, presumably because of the brightband effects. Similar observations were made by Kitchen and Jackson (1993). In addition, shifts from one scan level to another as part of the hybrid scan were found to produce occasional ring-shaped discontinuities or holes in the estimated precipitation fields. This problem is at least partially addressed by the new hybrid scan algorithm described earlier (O'Bannon 1997).

Klazura and Kelly (1995) found that WSR-88D precipitation estimates tended to overestimate convective precipitation, probably because of brightband effects and hail, and perhaps because of evaporation of precipitation below the cloud base. Stratiform precipitation was almost always underestimated, most likely because of overshooting effects. The authors also point out that selection of the higher tilt in the Stage I AP removal algorithm may exacerbate the overshooting problems. Implementation of the range-dependent bias correction described in Seo et al. (1997a) should address many of the difficulties pointed out by these three studies.

No evaluations of the performance of the Stage III analyses have yet been published. However, for several case studies with independent gauge data, Breidenbach (personal communication) found that the Stage III multisensor product was superior to radar data with and without bias correction, and to gauge-only fields as well. The Stage III fields generally showed less bias and lower mean error than the other three fields. To evaluate the operational implications, a hydrologic model was run with mean areal precipitation estimates computed from the Stage III data and with the other three fields, and the Stage III data produced the best forecasts.

As a final note, significant improvement in radar-based estimates of precipitation may be offered by the use of polarimetric radars that alternate the polarity of the electromagnetic beam between horizontal and vertical (Zahrai and Zrnic 1993). It has been shown that the phase difference between the energy returns for the two polarities (specific differential phase) is much more strongly related to rain rate than reflectivity measure for a single polarity (Zrnic and Ryzhkov 1996). In addition to improving estimation of precipitation rates for heavy rainfall, Zrnic and Ryzhkov (1996) have also demonstrated that partial beam blockage and ground clutter effects can be largely mitigated by the use of polarimetric radars. The WSR-88D's in the present NWS network could be modified to include dual polarization (Zahrai and Zrnic 1993), and this option is currently being investigated by the NWS (Fulton et al. 1997).

4. SATELLITE-BASED ESTIMATES OF PRECIPITATION

A third method for estimating precipitation amount is to infer the rate of precipitation from the characteristics of clouds in infrared and visible satellite images. This approach offers some significant advantages, as well as disadvantages, compared to rain gauge and radar estimates. Satellite data provide uniform spatial coverage, whereas the poor spatial resolution of rain gauge data make it difficult to accurately represent the spatial variability of precipitation fields. Furthermore, satellites offer excellent coverage over mountainous areas where beam blockage restricts radar observations, and over ocean regions that are out of the range of land-based radar installations. However, as Scofield (1987) points out, satellites do not observe rainfall; they only can observe the characteristics of the clouds that are producing it. Consequently, precipitation can only be inferred in a less physically direct fashion than in either the rain gauge or radar approaches, and this affects the accuracy of the satellite-based approach.

A. Manual Satellite Precipitation Estimates

Satellite Precipitation Estimates (SPE's) are manually produced by the Synoptic Analysis Branch (SAB) of NESDIS (Borneman 1988). These products consist of maps of the region of interest showing estimated half-hour and storm-total precipitation in inches, along with text bulletins containing county-by-county precipitation estimates. The text also includes outlooks of precipitation expected for the next 3 hours. Both the maps and the bulletins are disseminated to field forecasters via AFOS, and also can be obtained in near real-time via the Internet at http://hpssdlen.wwb.noaa.gov/SSD/ML/pcpn.ndx.html. The maps on the home page are available in both graphical (gif) and digital format. Archives of the text products and the gif displays are kept online for 30 days; the digital files are kept online for only half as long because of their size (approximately 2 megabytes each). Long-term archives are maintained offline by SAB.

SAB meteorologists produce their estimates using the Interactive Flash Flood Analyzer (IFFA), an interactive computer system for manipulating and displaying data that is similar to the Man-computer Interactive Data Access System (McIDAS). The IFFA can be used to display single and multiple images, generate loops of consecutive images, and magnify particular areas of interest (Field 1985). The manual estimation technique requires approximately 15 to 20 minutes of work for each estimate (R. Scofield, NESDIS, personal communication), so SAB meteorologists focus on the following types of heavy precipitation events:

1) Heavy precipitation from convective activity (Scofield and Oliver 1977, Scofield 1987). Precipitation amount is estimated by using an empirical decision-tree method that considers cloud-top temperatures, cloud-top growth, overshooting tops, line and cluster mergers, the level of saturation of the environment, low-level inflow, the speed of the storm, and other factors.

2) Heavy rainfall and snowfall estimates for extratropical cyclones (Scofield 1984). Pattern recognition techniques are used to correlate satellite signatures to areas of light, moderate, and heavy precipitation, and these areas are then corroborated with radar and surface observations. Amounts are adjusted for the dryness of the environment. When necessary, a conversion from rainfall rates to snowfall rates is performed according to a temperature-dependent rain-snow relationship. Microwave precipitation estimates are also being used to analyze the rain bands approaching the west coast of the U.S., especially during the winter season.

3) Heavy rainfall from tropical cyclones (Spayd and Scofield 1984). This method also uses a decision tree that assigns rainfall rates to different tropical cyclone features such as the wall cloud and the spiral rainbands. A rainfall potential of the tropical cyclone is computed before the storm makes landfall. These rainfall potentials are now produced from microwave-observed precipitation estimates (Scofield, personal communication).

4) Lake-effect snow (Scofield, personal communication). This method, developed by SAB, has many similarities to the convective precipitation technique, but it accounts for factors that are unique to lake-effect

situations such as the length of the wind fetch over the lake, and the topography downwind from the lake. Rainfall rates are estimated and then converted to snowfall rates based on current temperatures.

A number of verification studies have been performed on SPE's by comparing the maximum SPE with the observed amount at the same location on an event-by-event basis. However, this is quite difficult because rain gauge observations are typically not available for the exact location of the region of maximum precipitation in the SPE. Field (1985) compared the maximum SPE rainfall to the maximum amount observed within 30 miles (50 km) of its location. For 268 cases in May through July of 1984, he found an average error of 29.6%, with a wet bias for amounts less than 99 mm and a dry bias for amounts of 100 mm or more. Similar percentage errors were observed by Borneman (1988) for April through November of 1986 and by Achutuni et al. (1993) for the May-August 1992 time period. However, those estimates were based on 40-km GOES-7 data; subsequent work by Achutuni et al. (1996a) using 4-km GOES-8 data for the period 15 May-9 June 1995 showed substantially smaller errors than the previous studies. Since SPE's are now based on GOES-8 images, the SPE's should be more accurate than the earlier studies indicate. In fact, recent work for 1997 shows an increase in accuracy (Scofield, personal communication).

B. The "Auto-Estimator"

As stated previously, SAB's manual precipitation estimates cover limited areas for limited periods of time, and can take a significant amount of time to produce. In order to improve the spatial and temporal coverage of satellite-based precipitation estimates while improving timeliness, SAB has developed and is currently testing an automated method, termed the auto-estimator, that uses GOES-8 data to estimate precipitation amounts throughout the continental United States and surrounding areas.

This algorithm, described by Vicente (1996) and Vicente and Scofield (1997) first estimates precipitation rates for each pixel according to an empirical relationship between cloud top temperature and surface rainfall rate. This relationship was derived by comparing satellite cloud top temperatures to radar-based estimates of rainfall (using the standard Z-R relationship to compute the rainfall rates). Adjustments are made according to the spatial characteristics of the cloud tops surrounding the pixel of interest, the temperature trends in the coldest cloud tops, and the moisture of the ambient environment, which is given as a scaled "precipitation efficiency factor." This factor is defined as the product of the early Eta model precipitable water and the average model relative humidity from the surface to the 500 hPa level, scaled to a value ranging from 0.0 (very dry) to 2.0 (very moist). Future modifications to the algorithm will include delineation of rain areas based on the difference in brightness temperature of the 3.9 micron and 10.7 micron channels (Vicente 1996); a prototype scheme that uses the visible channel imagery instead of 3.9 micron is available for internal use by SAB (G. Vicente, NESDIS, personal communication). An in-house version of the auto-estimator that uses the WSR-88D radar to locate rain/no rain areas (cirrus discriminator) is being tested. Other forthcoming modifications to the auto-estimator include a correction factor for orographic precipitation based on the wind fields and the underlying topography, and a parallax correction to improve the navigation of the satellite image to earth coordinates and thus make the locations of the precipitation estimates more accurate (Vicente, personal communication). The auto-estimator may eventually produce estimates every 15 minutes instead of every half hour, since GOES-8 images are available at that frequency (Scofield, personal communication). Ultimately, the auto-estimator will be integrated with microwave estimates from SSM/I and AMSU (Advanced Microwave Sensing Unit) in order to obtain the full benefits of GOES and POES (Polar Orbiting Environmental Satellite).

Despite the name, the auto-estimator is not entirely automated; SAB meteorologists can make some adjustments to the auto-estimator amounts as needed. The relation between brightness temperature and precipitation rate can be adjusted if the estimates for a particular precipitation event are too high or too low. SAB meteorologists can also choose to apply a warm-top correction similar to that described in Scofield (1987).

Table 2 lists the precipitation products being produced on an experimental basis; they can be found on the NESDIS Flash Flood Home Page (Achutuni et al. 1996b) at http://orbit-net.nesdis.noaa.gov/ora/ht/ff. These images are produced almost instantaneously and are immediately available to SAB forecasters, but there is a short delay in posting them on the home page. These images are also archived online in gif format as described in Table 2.

Table 2. Precipitation estimates available on the NESDIS Flash Flood Home Page.

Product	Frequency	Archives
Instantaneous rate	Half-hourly	Previous 24 hours
1-h accumulation	Hourly	Previous 24 hours
3-h accumulation	Hourly	Previous 24 hours
6-h accumulation	Every 6 hours	Previous 72 hours
24-h accumulation	Daily (1200 UTC)	Since 10/3/96

In addition to the national displays, regional close-ups of the 3-h precipitation estimates are available. Other parameters of interest on the page include the precipitation efficiency factor derived from the Eta model.

Evaluation by SAB meteorologists indicates that the auto-estimator is approaching the level of performance of the manual technique with its ability to adjust the rainfall rate for different types of precipitation systems (Borneman, NESDIS internal memorandum). However, the auto-estimator algorithm is based on the characteristics of deep, moist convective systems, so applications to other types of precipitation systems should be viewed with caution. As improvements to the scheme continue, SAB meteorologists will eventually transition from producing IFFA estimates manually to a full-time commitment to the auto-estimator by adjusting selected parameters and editing (when needed) the resulting estimates (Scofield, personal communication).

In addition to modifying the auto-estimator algorithm, NESDIS is investigating a number of other approaches to estimating precipitation from satellite data. These include using artificial neural networks to estimate instantaneous precipitation rates [refer to Zhang and Scofield (1987) for an example of early work in this area], and using data from other GOES-8 channels and microwave data from the Special Sensor Microwave/Imager (SSM/I) instrument aboard the polar-orbiting Defense Military Satellite Program (DMSP) satellite (Scofield, personal communication).

5. SUMMARY

Precipitation estimates are available to NWS forecasters and other interested entities from three main sources: precipitation gauges, radar, and satellite. Data from these sources are used by the NWS to produce a suite of products that serves a wide variety of hydrometeorological functions. Rain gauge data support climate studies, statistical model development, QPF verification, and hydrologic forecasting. Stage I-IV multi-sensor products support functions ranging from flash flood forecasting for small basins (Stage I) to river stage forecasting (Stage III) to numerical model initialization and verification (Stage IV). Satellite-based estimates of precipitation support local hydrologic forecasting and will eventually become part of the Stage IV national precipitation mosaic (Baldwin and Mitchell 1997). Satellite data may even be incorporated into the local Stage II processing in the future (Fulton et al. 1997).

All three data sources have strengths and weaknesses, and none stands alone as a definitive source of precipitation information. Rain gauges directly measure precipitation amount, but are subject to systematic errors and generally do not provide accurate spatial representation of precipitation fields because observations are not available at a sufficiently high resolution. By contrast, radar provides observations at high spatial and temporal resolution, but does not directly measure precipitation. Imperfections in the Z-R relationship, beam elevation changes, and other factors compromise the accuracy of radar-based estimates. Satellite data provide even wider spatial coverage than radar; however, satellite-measured irradiances are even less directly related to precipitation rate than radar reflectivities. Furthermore, navigation errors can displace precipitation areas by a significant distance.

Consequently, the NWS is continuing efforts to integrate data from all three sources into its precipitation estimates, primarily in the Stage I-IV multi-sensor processing. Integrating rain gauge data into the radar-based estimates can compensate for some of the errors in estimating precipitation rates from reflectivity returns. Radar data can be used to correct satellite navigation errors, and satellite data are very useful for those areas where high-quality rain gauge and radar data are not available, especially over oceans and in mountainous regions where the terrain makes radar estimates difficult or impossible to obtain.

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