NOAA Technical Report NESDIS 99



# THE USE OF WATER VAPOR FOR DETECTING ENVIRONMENTS THAT LEAD TO CONVECTIVELY PRODUCED HEAVY PRECIPITATION AND FLASH FLOODS

Washington, D.C. September 2000

U.S. DEPARTMENT OF COMMERCE National Oceanic and Atmospheric Administration National Environmental Satellite, Data, and Information Service

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## THE USE OF WATER VAPOR FOR DETECTING ENVIRONMENTS THAT LEAD TO CONVECTIVELY PRODUCED HEAVY PRECIPITATION AND FLASH FLOODS

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#### ABSTRACT

This Tech Report summarizes years of study and experiences on using GOES water vapor (6.7 micron and precipitable water) and Special Sensor Microwave Imager (SSM/I) from the Defense Meteorological Satellite Program (DMSP) derived Precipitable Water (PW) for detecting environments favorable for convectively produced flash floods. An emphasis is on the moisture. upper air flow, and equivalent potential temperature ( $\theta e$ ) patterns that lead to devastating flood events. The 15 minute 6.7 micron water vapor imagery is essential for tracking middle to upper tropospheric disturbances that produce upward vertical motion and initiate flash flood producing systems. Water vapor imagery at 6.7 micron is also used to detect surges of upper level moisture (called tropical water vapor plumes) that have been associated with extremely heavy rainfall. Since the water vapor readily depicts lifting mechanisms and upper level moisture, water vapor imagery is often an excellent source of data for recognizing patterns of heavy precipitation and flash floods. In order to analyze the depth of the moisture, the PW aspects of the troposphere must be measured. The collocation (or nearby location) of high values of PW and instability are antecedent conditions prior to the flash flood or heavy rainfall events. Knowledge of PW magnitudes have been used as thresholds for impending flash flood events; PW trends are essential in flash flood prediction. Conceptual models and water vapor products are used to study some of the characteristics of convective systems that occurred over the United States of America (USA) during the summer of 1997 and the 1997 - 1998 El Nino. PW plumes were associated with most of the west coast heavy precipitation events examined during the winter season of 1997 - 1998. In another study, conducted during the summer season of 1997, results showed that the collocation of water vapor (6.7 micron) and PW plumes possessed higher correlations with predicted rainfall amounts than when PW plumes occurred by themselves (i.e., without the presence of 6.7 micron water vapor plumes). Satellite Analysis Branch (SAB) meteorologists use the 6.7 micron water and PW products for their QPE's (Interactive Flash Flood Analyzer (IFFA) and Auto-Estimator precipitation estimates), Outlooks, and heavy precipitation briefings with the Hydrometeorological Prediction Center/National Center for Environmental Prediction. In the future, water vapor fields will continue to be used in the following ways: (a) by forecasters for anticipating heavy precipitation and flash floods. (b) in satellite Quantitative Precipitation Estimation (QPE) algorithms, and (c) by modelers to initialize numerical weather prediction models that will in turn improve Quantitative Precipitation

Forecasts (QPF). Many illustrations are used in this report to show the applicability of water vapor to the diagnosis and prediction of heavy precipitation and flash flood events. Examples and case studies are presented from the four Continental United States (CONUS) regions (western, central, southern and eastern) of the National Weather Service (NWS).

#### 1. Introduction

Heavy precipitation and flash floods are among the most devastating natural weather hazards in the United States of America (USA), claiming more lives and causing more property damage than lightning or tornadoes (NOAA, 1994, 1999). In addition, an average of more than 225 people are killed and more than \$4 billion in property is damaged by heavy rain and flooding each year. As a result, flash floods are one of our greatest challenges in weather prediction. Data from geostationary satellites and polar orbiters of the Defense Meteorological Satellite Program (DMSP) and NOAA 15 (National Oceanic and Atmospheric Administration) (Rao, et al., 1990) are primary sources of information for the diagnosis and prediction of heavy precipitation and flash floods (Bader, et al., 1995). The geostationary satellite (called GOES in the United States of America (USA) = Geostationary Operational Environmental Satellite) has the unique ability to observe the atmosphere and its cloud cover from the global scale down to the storm scale, frequently (every 15 minutes) and at high resolution (one km visible and four km infrared). This places GOES at the very heart of weather analysis and forecasting and is ideally suited for the "Satellite Forecasting Funnel" approach to the prediction of heavy precipitation and flash floods (Menzel and Purdom, 1994). The Satellite Forecasting Funnel represents a concatenation of meteorological scales and processes from the "global scale" to the "synoptic scale" to the "mesoscale" and finally to the "storm scale". Often, heavy precipitation and flash floods are a multi-scale and concatenating event (Scofield and Achutuni, 1996). Global to synoptic scale interactions involve a transfer of energy and moisture from the tropics into the middle latitudes. As a result, on the synoptic scale, the environment is being prepared for the heavy precipitation event either by moisture/energy transport or by moisture already being in place. Synoptic to mesoscale interactions determine where and when the precipitation system will initiate (by the presence of lifting mechanisms). Finally, the mesoscale to storm scale determines "how much precipitation has already occurred" and how the storm is expected to propagate with respect to location, intensity, and duration. The storm scale (especially Mesoscale Convective Systems (MCSs)) can produce energy feedback to the larger scales by altering the circulation, temperature and moisture fields over distances of hundreds of miles (160 km or more) (Maddox, et al., 1979, 1981). Manifestations of this feedback process from the storm scale to the other scales are: outflow boundaries produced by cold domes of air and mesohighs at low levels, a vortex produced at mid-levels and anticyclonic outflows aloft that can produce jet streaks to the north of the MCS.

Flash flood producing storms generally occur over a few hours where mesoscale processes have attained nearly a steady state condition. These conditions result in a tenuous balance where fronts, mesoscale boundaries, and cell intensity and motion are operating to produce congruent trajectories of rain cells; pulsating rains of heavy intensity are often the result. Changes in the

relative low level wind flow due to approaching upper level disturbances (synoptic to mesoscale in size) can terminate the heavy rains by disrupting these low level winds. Therefore, atmospheric processes and environments that lead to heavy precipitation and flash floods are multi-scale and range from global-synoptic-mesoscale.

This report will present some of the moisture, flow, and equivalent potential temperature ( $\theta e$ ) patterns that are associated with convectively driven heavy rainfall/flash flood events. Equivalent potential temperature is the temperature a sample of air would have if all its moisture were condensed out by a pseudo-adiabatic process (i.e., with the latent heat of condensation being used to heat the air sample), and the sample then brought dry-adiabatically back to 1000 mb. Some of the contents in this report are published in the World Meteorological Organization (WMO) document entitled "Estimating the amount of rainfall associated with tropical cyclones using satellite techniques" (Eric Barrett editor). Conceptual models, satellite products, and interpretation of features in the satellite data are used in detecting these patterns that promote environments conducive to heavy precipitation and flash floods. The emphasis in this report will be on heavy rainfall and flash floods produced by MCSs (Maddox, 1980). Forecasters at the Hydrometeorological Prediction Center (HPC) of the National Center for Environmental Prediction (NCEP)/National Weather Service (NWS) and forecasters in the field have stated that Precipitable Water (PW) and low level moisture transport/flux are two of the most important parameters for predicting heavy precipitation and QPF (Junker, 1990, Junker, et al., 1995, Junker, et al., 1997). A study of flash flood producing convective systems that occurred over the USA during the summer of 1997 will be discussed as well as some water vapor characteristics of the 1997 - 1998 El Nino event. Ingredients for Quantitative Precipitation Estimates (QPE) and Forecasts (QPF) are also briefly addressed.

#### 2. Precipitation Efficient Environments

Precipitation Efficiency (PE) is defined as the ratio of the total rainfall to the total condensation. Similar definitions of PE have been used by Weisman and Klemp, 1982 and Ferrier, et al., 1996. The following environmental conditions that effect PE have been noted by Chappell, et al., 1986, 1992 and 1994 notes from a COMET workshop. Doswell, et al., 1996, Fankhauser, 1988, and Marwitz, 1972. If the environment is dry, entrainment will cool the rising air parcels and reduce the buoyancy and upward vertical motion. Dry environmental air results in a reduction of the PE. Another factor, vertical wind shear, often produces entrainment and reduces PE, especially if the environmental air is dry; thus, some parameters related to PE are high PW and relative humidity (RH) values and weak vertical wind shear. The 6.7 micron water vapor (WV) (e.g. from GOES) imagery is an excellent source of data for: (1) determining flow fields that are associated with various intensities of vertical wind shear and upward vertical motion, and (2) locating middle to upper tropospheric moist (e.g. surges and plumes) and dry areas.

Another factor that increases PE is the depth of the cloud with a temperature warmer than  $0^{\circ}$  C; a depth of 3 km or greater appears to be a critical threshold. Such warm-based clouds enhance the collision-coalescence process (and thus the PE) by increasing the residence time of droplets in

clouds. Two additional factors that are related to PE are: (1) the storm-relative mean inflow and moisture transport into the storm. and (2) duration of the precipitation (moistening up of the troposphere). Satellite and forecast model-derived products of PW and RH are extremely useful for describing the environmental moisture conditions that are transporting moisture (or dry air) into the storm or acting as a precursor by preparing the environment for heavy precipitation: therefore, valuable information about the PE of a particular environment can be obtained from the satellite WV imagery and PW/RH products. Low level flow fields can be used with these PW/RH products to obtain some idea of the low level moisture transport and flux. Features in the WV imagery (6.7 micron) combined with the PW and RH products are being increasingly used in the production of QPFs and QPEs.

#### 3. Tropical Plumes Observed In Satellite Data

Several scientists have studied various aspects of tropical plumes in the satellite data. McGuirk, et al., 1987, 1988, and 1990 produced case studies and even described the evolution of tropical plumes over the tropical Pacific in VAS (VISSR (Visible Infrared Spin Scan Radiometer) Atmospheric Sounder) WV imagery. Many of the tropical plumes studied by McGuirk and others develop out of the ITCZ (Intertropical Convergence Zone). These plumes appeared to provide major synoptic scale interactions between the tropical Pacific and northern mid-latitudes. In addition, the relatively large transports of energy accompanying the plume evolution suggests that these northward surges of moisture constitute a large component of the Pacific circulation. A diagnostic budget of analyzed and modeled tropical plumes is an example of McGuirk's. et al., 1993 latest work. Recently, other scientists (Knabb, et al., 1998 and Mecikalski, et al., 1998) have provided additional investigations into the structure and dynamics of tropical plume formation. Mecikalski, et al., 1998 views the tropical plume as the upper branch of an enhanced thermally direct circulation driven by latent heat released along the ITCZ.

Tropical WV plumes (WVPs) have also been observed in the Alaskan area. In addition. forecasters in Alaska have observed that tropical water vapor plumes are one of the features that appear to interact with fronts and orography (over coastal Alaska) to produce flooding and mud slides (Saviers, 1999).

This report emphasizes the investigation of Scofield and others in National Environmental Satellite, Data, and Information Service (NESDIS) to use WVPs in: (1) detecting environments favorable for flash floods and heavy precipitation, (2) computing QPFs, and (3) deriving satellite-based QPEs. Two types of WV plumes are presented: (1) the 6.7 micron WVP that helps to locate lifting mechanisms and detect flow patterns and upper level moisture, and (2) PW plumes useful for detecting low-level moisture transport, i.e., moisture already "in place", and moisture trends and tendencies.

#### 4. Utility of the 6.7 Micron WV Imagery

A document that presents in detail the contributions of 6.7 micron WV imagery to weather and

forecasting is found in Weldon and Holmes, 1991. In addition, as mentioned in Section 2. GOES 6.7 micron WV imagery has been used to monitor tropical WVPs and to detect lifting mechanisms (Scofield and Funk, 1986, Funk, 1990, Ellrod, 1990). After studying three seasons of data (May-October over the forty eight contiguous states), Thiao, et al., 1993, 1995 determined that WVPs were present in eighty eight percent of the extreme rainfall events (125 mm or more within a 24 hour period); one hundred twenty nine events were used in this study. Eighty-three percent originated from the tropics and seventeen percent were subtropical or polar. WVPs are often parallel with the 300 mb flow and usually originate from the ITCZ and extend northward into the USA. Examples of tropical WVP are shown in Figures 1, 2, and 3. The WVP ("W - P") in Figure 1 was associated with only 1 or 2 inches of rain in central California. These lower amounts are partially due to rather low values of PW being transported into California (shown in the next section). However, this California event is notable because it was one of the first El Nino driven precipitation events along the west coast during the 1997 - 1998 season. The tropical WVP ("W - P") in Figure 2 was a classical precursor signature of extremely heavy rainfall that occurs in the southern and central regions of the USA; in this case, devastating flash floods occurred in south Texas. A discussion of the corresponding PW plume takes place in Section 5. An example of a tropical WVP in the eastern region is depicted in Figure 3. This illustration shows a cyclonic circulation (at "C") and an accompanying front (at "F - T") moving towards the east coast of the U.S.on October 18, 1996. Accompanying 500 mb analysis (Figure 4) depicts a rapidly deepening trough ("dashed line") that moves from the northern plains (of the US) to New England (where the low "cuts off" are between October 19 and 20). Tropical Storm Lili, with an abundance of high level moisture, is located in the tropical Atlantic Ocean at " L ". Over the next couple of days, the illustration shows the cyclonic circulation and accompanying front interacting with Lili as indicated by the transport of high level moisture ("W - L") from the tropical storm into the cyclonic circulation over New York (at " C " ). Over the New England area (near "W"), devastating flash floods were produced by 1 - 1 1/2 feet (300 - 450 mm) of rain. The transport of low level moisture will be considered in the next section.

Just why the WVP would be associated with extreme rainfall events is unclear. Some ideas have included that the plume: (a) enhances precipitation through cloud seeding and/or (b) makes the environment (at middle to upper levels) more efficient. More than likely, the WVP is a result of a specific synoptic pattern where the plume evolves (from the ITCZ, convective clusters, jet streams, etc) (see Section 3) in the western portion of an upper level ridge and downstream of the trough axis. Synoptically, the backside of a ridge also favors a southerly flow of low-level moist, unstable air. As the air moves northward a coupling can occur between this moist, unstable air and lifting mechanisms. As a result, conditions are created favorable for the initiation of heavy precipitation producing MCSs.

In addition to depicting middle to upper level moisture, as mentioned previously, the 6.7 micron WV imagery is an excellent source of data for detecting lifting mechanisms from the synoptic scale to mesoscale (Scofield and Achutuni, 1996 and Thiao et al., 1995). Lifting mechanisms are often called short wave troughs and are the features in the atmosphere that produce upward vertical motion that lead to clouds and precipitation. Features on the Synoptic Scale are usually best detected in the 6.7 micron WV imagery. Cyclonic circulations are key signatures in the



Figure 1. Water vapor imagery (6.7 micron) for November 26, 1997, 0000 UTC: 300 mb winds (mps) superimposed from the ETA model.



Figure 2. Water vapor imagery (6.7 micron) for October 16, 1998, 2345 UTC; 300 mb winds (mps) superimposed from the ETA model.



Figure 3. Water vapor imagery (6.7 micron) for October 18 (1915 UTC); 19 (1515 UTC); and 20 (2215 UTC), 1996.



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# WATER UAPOR SIGNATURES



Figure 6. Conceptual models of jet streaks in the 6.7 micron water vapor imagery.

satellite imagery that are associated with heavy precipitation. These circulations may or may not be connected to a WVP. Cyclonic circulations are readily identified in the WV imagery and are normally associated with a rather strong dynamical system in the westerlies. Not only can the heavy precipitation occur within the core of the cyclonic circulation but also along vorticity lobes and short wave troughs that often rotate around the center of the circulation producing elongated (north-south) areas of upward vertical motion; precipitation systems develop when these lobes intersect a low-level theta-e ridge axis (Figure 5). Short waves are also depicted by trackable dark areas in the 6.7 micron WV imagery that generally move along the jet stream. These short waves can be associated with: (a) mid-level cold air advection, (b) jet streaks (can appear cyclonically curved), (c) positive vorticity advection, (d) trough axes, and (e) meso-alpha waves. Jet streaks can also appear as streaks of cirrus that are anticyclonically curved (Figure 6).

Additional information from the Thiao (1993, 1995) study indicated that eighty four percent of the events were closely aligned with 850 to 700 θe ridge axes (Scofield, 1990). Many of these events possessed low-level wind maxima from a southerly direction. Such a wind direction was associated with a transport of warm, moist, and unstable air from the subtropics. With respect to the middle to upper levels (representative of the 6.7 micron WV), Thiao showed that the 300 mb jet maximum "played" a major role in initiating storms that produced heavy precipitation (Uccellini and Johnson, 1979 and Kocin, et al., 1986). Seventy seven percent of the events were associated with a double jet streak structure configuration that, if coupled with a lower-tropospheric jet maximum/streak, was shown to destabilize the atmosphere (Junker, et al., 1990, Corfidi, et al., 1990 and Funk, 1991). This jet streak configuration contributes to the development of an enhanced low-level wind maximum that transports moist, warm, and unstable air; such a scenario often leads to the initiation of heavy precipitation producing MCSs. Some of these double jet streak structures were the result of the MCS modifying the environment to produce a mesoscale-produced jet streak to the north of the convective system (Maddox, et al., 1981).

Although Thiao's study showed that WVP and upper level jet streaks appeared to be related to many of the extremely heavy rainfall events, twelve percent of these events did not have a well-defined WVP. On a few occasions, there was not an obvious jet streak (300 mb) at the time of the extreme precipitation event. Thus, differential temperature advection and/or low-level advection of warm, moist, unstable air were additional contributing factors for destabilizing the atmosphere and creating conditions favorable for the development of MCS that produced extreme precipitation events. Low-level moisture is readily detectable in the PW products and will be discussed in the next section.

#### 5. Precipitable Water and Relative Humidity Characteristics of Flash Flood Environments

Flash floods and heavy rainfall do not always occur with WVPs. In addition, it needs to be stressed that WVPs only indicate the presence of middle to upper level moisture. In order to analyze the depth of the moisture, total precipitable water (PW) must be measured. High values of PW and instability are often collocated and become antecedent conditions prior to the development of heavy rainfall and flash floods. Often, these high values of PW appear as

plumes, areas or surges of moisture. *When PW plumes become aligned with θe ridge axes and a lifting mechanism is present, heavy precipitation often occurs* (Scofield and Achutuni, 1996, Scofield, et.al., 1998 a, Scofield, et al., 1998 b). The equivalent potential temperature is a conservative meteorological parameter that combines temperature and moisture into a single quantity whose vertical distribution is related to convective instability.

Before examples of PW plumes are illustrated, an explanation of the type of satellite products for displaying PW are presented.

Daily rawinsonde data (conventional data) are available and provide accurate absolute measurements of PW. However, these conventional data observations are only available twice a day and are spatially inadequate to measure mesoscale features and gradients. In order to retrieve information on the mesoscale (flash flood/heavy precipitation scale), satellite data and forecast models (initialized by satellite information) are used. A most important feature in detecting environments that lead to heavy precipitation and flash floods are PW plumes. PW plumes are most detectable in satellite-derived products of PW. This includes satellite PW measurements from the Special Sensor Microwave Imager (SSM/I) instrument onboard the DMSP (Defense Meteorological Satellite Program) satellites (Kusselson, 1993), the Advanced Microwave Sensing Unit (AMSU) onboard NOAA 15 (Ferraro, et al., 1998) and the GOES Sounder and Imager products. SSM/I-derived PW is computed from the brightness temperatures of the following three vertically polarized channels: 19.35, 22.235, and 37.0 Ghz (Alishouse, et al., 1990). Accuracy of the SSM/I-derived PW, as determined by Ferraro, et al., 1996 are within ten percent of the observed. Since these frequencies are not sensitive to non-precipitating clouds. PW can be computed over clouds and clear areas. However, SSM/I-derived PW are limited to ocean areas. SSM/I PW is currently available approximately four times per day for a given location. Home Page addresses for obtaining SSM/I-derived PW and additional microwave information including AMSU (NOAA 15) may be found on: "http://orbit-net.nesdis.noaa.gov/arad/ht/leadin/main.html".

GOES-derived moisture profiles are computed over land and water using the sounder and imager channels (Hayden, 1988 and Hayden, et al., 1996). Accuracies range from five to ten percent when compared with rawinsonde data (Rabin, et al., 1991). Since these GOES channels are also sensitive to clouds, PW analyses are limited to regions that are determined to be cloud free. However, GOES PW, favored for timely qualitative tracking of moisture gradients and trends, is produced hourly. The GOES Sounder Temperature and Moisture product Home Page address is: "http://orbit35i.nesdis.noaa.gov/arad/fpdt".

A spinoff and positive impact of these satellite-derived water vapor fields is in the area of Numerical Weather Prediction (NWP). Modelers at NCEP and other institutions have used these water vapor analyses to initialize numerical weather prediction models (Mills and Hayden, 1983 and Wu, et al., 1995). Improved initialization should lead to more accurate QPFs.

Currently, water vapor data sets that blend satellite and conventional data are available on the climate scale (Randel, et al., 1996). However, to support the forecasting community.

NESDIS/National Severe Storms Laboratory (NSSL) scientists developed a satellite based, composite product that uses PW from the SSM/I, GOES 8/9/10 soundings and model output. The composite PW products (experimental at this time) are specifically designed to take advantages of the strengths of these polar and GOES satellites and are available four times per day (Scofield, et al., 1995, 1996). Since SSM/I is considered a higher quality product (microwave is a more direct measurement) compared to GOES PW, microwave PW is used first in the compositing process. If microwave is not available, the GOES PW is employed. When either of these satellite products are not available, PWs from NCEP's numerical forecast model (ETA or AVN) are used. At this time, the composited product is not smoothed in order for the user to determine which PW data source (satellite or model) is being applied in the PW analysis. SSM/I spatial resolution is around 25 km, GOES is 10 km, and the ETA and AVN models are 32 km and 110 km, respectively. One can determine which source is being used by how "blocky" the PW analysis appears. Model-derived PW would be the most blocky and GOES PW the least. This method of compositing is followed for the entire PW analysis system whether it be over water, land or coastlines. On the NESDIS Flash Flood Home Page (" http://orbit35i.nesdis.noaa.gov/arad/ht/ff/ "), two experimental real-time, products are available. The first product is designed for 0 to 24 hour forecasting of heavy precipitation that includes a region slightly larger than the continental U.S. and south to 20° N. This product is a composite

of both SSM/I and GOES data with the ETA model filling data voids. ETA model-derived 850 mb winds are superimposed to give some idea of the moisture transport. The second product utilizes SSM/I and AVN model data and is designed for medium range heavy precipitation forecasting and covers the northern hemisphere between 70 ° W and 170 ° W. Again, AVN model-derived 700 mb winds are superimposed.

Another useful product on the NESDIS Flash Flood Home Page is the ETA model-derived: "PW x RH (mean layer relative humidity)". This product has been used to adjust the precpitation from the GOES Auto-Estimator (Vicente, et al., 1998, 1997, 1996) for different environmental conditions (dry to moist). A similar rawinsonde PW/RH product is used to adjust estimates from the Interactive Flash Flood Analyzer (IFFA) (Scofield and Oliver, 1977, Scofield, 1987 and Borneman, 1988). "PW x RH" is also used to help diagnose the precipitation efficiency of the environment and used by forecast offices such as the Ohio River Forecast Center in simple locally developed QPF prediction algorithms (Jim Noel — unpublished manuscript).

Most of the above products discussed in this section are only available via internet; however there are plans to have many of them on the Advanced Weather Interactive Processing System (AWIPS) in the near future.

Examples of PW plumes are briefly discussed:

#### Southwest U.S.A. Monsoon

The southwest monsoon is associated with a change of the prevailing winds over the southwestern United States from westerly (early in the summer) to southeasterly (middle to late summer). Adang and Gall (1989) related the tropical plume and the formation of the monsoon

boundary to the onset of the southwest monsoon during the summer season. The monsoon season of the southwest is often associated with flash flood producing thunderstorms. Precipitable water observations derived from GOES (Bright and McCollum, 1998 and McCollum, et al., 1995) and SSM/I (discussed above) show that the main source of low level moisture for the southwest monsoon is from the Gulf of California. A couple of examples are used to illustrate both the occurrence of the tropical water vapor plume (6.7 micron) and the low level moisture surges from the Gulf of California. Satellite products or forecast models initialized by satellite data is the only source of information for detecting the location and transport of moisture into the southwest.

In the first example, the remnants of Hurricane Linda (at "L") was funneling upper level moisture ("T - P") into the southwest (Figure 7). As will be explained later in Section 7, the summer of 1997 was during the time of an El Nino event. The abnormally warm temperatures along the west coast of Mexico and California and anomalous southwesterly winds had the following effect. Hurricanes such as Linda, had the tendency to move north along the Mexican coast (instead of out to sea) and to maintain their intensity. As a result, an abundance of moisture was brought into the southwest providing precipitation efficient environments and flash flood-producing thunderstorms. The GOES digital product (Figure 8) for September 16, 1997, 0600 UTC shows high PW values over the Gulf of California and surrounding area. Clouds over southern California, Arizona and western New Mexico prohibit the computation of GOES PWs. A composite PW product (Figure 9) for the same time as the digital one displays the surge of moisture (PW plume) ("P - W - P") from the Gulf of California and eastern tropical Pacific northward into southern California and Arizona. As mentioned above, the environment in the southwest was prepared for flash flood producing thunderstorms.

Another example of the southwest monsoon depicts an upper level anticyclone over Arizona and New Mexico (Figure 10) funneling upper level moisture ("T - P") into the southwest. Thunderstorms are observed (Figure 10) embedded with this tropical WVP. The digital GOES PW product (Figure 11) indicates rather large moisture values from the Gulf of California northward into southern California and western Arizona. Unfortunately, the cloud cover inhibits the depiction of the tropical PWP ("P - W - P") that is displayed in Figure 12 (the composite PW product). The superimposed low level winds in Figure 12 do not show a significant transport of moisture (winds are not parallel to the PWP); however, the moisture is already in place in Arizona and New Mexico for precipitation-efficient thunderstorms and potential flash floods. Though not investigated, it is possible that flow at 700 mb could have been more parallel to the PWP; 850 mb winds, especially at 0000 UTC could have been influenced by terrain (mountains) and convective thermals. Figure 13 displays a similar plume of large PW/RH values ("P - R") from Mexico into Arizona. The units of the PW in this product (PW x RH) are inches. In order to expand the gray scale and obtain maximum use of the gray shades, this PW/RH product was multiplied by 10; therefore, 5.0 really represents 0.5, 10.0 is actually 1.0 and so forth. These two examples illustrate how essential moisture information is from satellites for predicting flash floods in the southwest.



Figure 7. Water vapor imagery (6.7 micron) for September 16, 1997, 0000 UTC; 300 mb winds (mps) superimposed from ETA model.



Figure 8. GOES digital precipitable water product (mm) for September 16, 1997, 0600 UTC.



Figure 9. Composite precipitable water product (GOES + SSM/I + ET.A)(mm) for September 16, 1997, 0600 UT; 850 mb winds (mps) superimposed from ETA model..



Figure 10. Water vapor imagery (6.7 micron) for July 27, 1999, 0000 UTC; 300 mb winds (mps) superimposed from ETA model; Flag = 25 mps.



Figure 11. GOES digital precipitable water product (mm) for July 27, 1999, 0000 UTC.



Figure 12. Composite precipitable water product (GOES + SSM/I + ETA) (mm) for July 27, 1999, 0000 UTC; 850 mb winds (mps) superimposed from ETA model.



Figure 13. Precipitable water X. Relative Humidity product (from ETA model) for July 27. 1999, 0000 UTC; 850 mb winds (mps) superimposed from ETA model.

#### Rainfall Event Over Central California: November 25 - 26, 1997

The tropical 6.7 micron WVP, shown in Figure 1, was associated with this early El Nino rainfall event over Central California. A tropical PW plume (at "P-W"), collocated with the 6.7 micron WVP, is shown in the northern hemispheric PW composite in Figure 14; 700 mb winds from the AVN model are superimposed to give some idea on the PW transport. Weak to possibly moderate PW transport is taking place as shown by the magnitude of the PW (20 - 25 mm entering into Central California) and 700 mb winds of 20 - 30 mps. Radar (Figure 15) and satellite estimates (Auto-Estimator) (Vicente, et al., 1998) indicated that 1 - 2 inches of rain had fallen within the 24 hour period between November 25 - November 26, 1200 UTC. Locally heavier amounts occurred in the mountains. The following day (November 27), as the atmosphere moistened up and disturbances continued to traverse the area, much heavier precipitation occurred along with floods.

#### South Texas floods of October 17 - 18, 1998

A pronounced tropical WVP is illustrated in Figure 2, as a precursor to the devastating floods that developed over south Texas. Middle to upper level jet streaks were located near the back edge of the WVP. Widespread extremely heavy rainfall occurred that produced amounts



Figure 14. Composite precipitable water product (GOES +SSM/I + AVN (mm) for November 25, 1997, 1200 UTC; 700 mb winds (mps) superimposed from AVN model; Flag = 25 mps.



Figure 15. "WSI" WSR-88D 24 hour derived precipitation amounts (inches) ending November 26, 1997, 1200 UTC.

between 15 to 20 inches; there was one report of 30 inches. As a result, deadly flash floods took place from San Antonio to Austin; 26 drownings were reported. As depicted in Figure 16, a tropical PW plume ("P - W") surged northward from the western Gulf of Mexico into southeast Texas; this PW plume is positioned in the eastern portion of the 6.7 micron WVP depicted in Figure 2. Winds at 850 mb are superimposed and illustrate the rather intense transport of high PW air; over 2 inches (50 mm) of moisture are being transported into southeast Texas.



Figure 16. Composited precipitable water product (GOES + SSM/I + ETA) (mm) for October 17, 1998, 1200 UTC; 850 mb winds (mps) superimposed from the ETA model; Flag = 25 mps.

The PW/RH product is illustrated in Figure 17 for the south Texas devastating flood event. Precipitation efficient air as shown by the PW/RH values of 1.5 to 2.0 are being transported into southeast Texas ("P - R"). In fact, the above PW/RH values indicate PWs > 1.5 inches and RHs near 100 % (extremely precipitation efficient air).

An additional feature is the location of the 850 mb theta-e ridge axis in Figure 18. As depicted by dashed lines, the 850 mb  $\theta$ e ridge axis is collocated with the 6.7 micron WVP in Figure 2 (the location of this WVP did not change for several days). Six-hour satellite-based rainfall estimates (figure 19) from the Auto-Estimator (Vicente, et al., 1998) indicated that over six inches of rain fell in south Texas ending at October 17, 1800 UTC; 24 hour gauge analysis (Figure 20) showed that over 16 inches occurred in the same areas.



Figure 17. Precipitable water x Relative Humidity product for October 17, 1998, 1200 UTC; 850 mb winds (mps) superimposed from the ETA model; Flag = 25 mps.



Figure 18. 850 mb equivalent potential temperature (\* K) for October 17, 1998, 1200 UTC.



Figure 19. Auto-Estimator 6 hour rainfall estimates (inches) ending October 17, 1998. 1800 UTC.



Figure 20. 24 hour rain gauge amount (inches) ending October 18, 1998, 1200 UTC.

#### October 18 - 20, 1996 Record Breaking Floods in New England

The 6.7 micron WV imagery (Figure 3) shows the eastward progression of an upper level disturbance and dramatic development of a tropical WVP. The SSM/I-derived PW analysis in Figure 21 illustrates a tropical PW plume ("P - L") connecting Tropical Storm Lili over the Atlantic Ocean to the record breaking rainfall event over New England. The 6.7 micron WVP (Figure 3) and the PWP (Figure 21) are all located with a 850 mb θe ridge axis (dashed in Figure 22) and strong 850 mb winds (Figure 23) transporting moisture from near Lili northwestward to New England. The four day rainfall totals are observed in Figure 24 (Keim, 1998). Over 400 mm (16 inches) of rain were measured in local areas over New England. Even though Tropical Storm Lili appears to have transported moisture to the cyclonic circulation and cutoff over New England (Keim, 1998), the interaction between these two storm systems is not completely understood and needs further investigation.



Figure 21. SSM/I derived precipitable water (mm) for October 21, 1996, 0000 UTC.



Figure 22. 850 mb equivalent potential temperature ("K) from the ETA model for October 20, 1996, 0000 UTC.



Figure 23. 850 mb winds (kts) from the ETA model for October 20, 1996, 0000 UTC.



Figure 24. Storm total rainfall (mm) (Keim, 1998) from October 19 - 23, 1996.

#### Precipitable Water Transport into Mesoscale Convective Systems (MCS) Over the Northern and Southern Plains (June 20, 1996)

On June 20, 1996, heavy rain was produced from two MCSs; one over northwestern Iowa and the other over western Louisiana. The 6.7 micron WV imagery in Figure 25 depicts the northern and southern MCS at "N" and "S", respectively. The following analysis in Figures 26, 27, and 28 show the southern MCS to be associated with a 500 mb relative vorticity maximum and the northern initiated by an approaching jet streak and upper level disturbance. These lifting mechanisms are also somewhat detectable in the WV (Figure 25). A dark area surging eastward in Figure 25 is associated with the northern jet streak. Animated 6.7 micron WV imagery would depict the cyclonic circulation/vorticity to the south. A PW plume ("P - W") is seen in the GOES sounding derived PW product (Figure 29) surging northward from the Gulf of Mexico and entering the upwind edges of the two MCSs. This PW plume is collocated with the 850 mb θe ridge axis (dashed in Figure 30) and the 850 mb maximum winds (Figure 31). All of these analyses illustrate moist, unstable air being transported into the individual MCSs (Figure 32) that resulted in the four or more inches presented in Figure 33. Notice the coldest and most active areas of the anvil (colder than -75 °C) are located in the extreme upwind edge portion of the MCS; this also locates the area of maximum moisture transport.

Soil conditions are another diagnostic feature available from satellite data. Soil moisture is an important parameter for hydrometeorological forecasts and Numerical Weather Prediction model initialization (Schmugge, et al., 1986). An experimental Surface/Soil Wetness Index (SWI) to identify soil surfaces that are either extremely saturated or flooded (Achutuni, et al., 1993, 1994, 1996 and Scofield and Achutuni, 1996) is shown in Figure 34. SWI uses the brightness temperature difference between the 85 GHz and 19 GHz horizontally polarized SSM/I data. For these northern and southern plains events, extremely wet to flooded conditions are shown over NW lowa; however, the SWI does not detect surface conditions where rain is occurring (at the time of the image in Figure 34) such as that associated with the MCS over western Louisiana. A potential application of the SWI is to locate land areas that are extremely saturated or flooded. Extremely heavy rainfall amounts falling over already saturated soils can accentuate the adverse impact of flash floods. A knowledge of antecedent soil conditions can assist forecasters in providing timely and reliable information to users regarding the potential for flash floods. Real time SWI information is available on the NESDIS Flash Flood Home Page.

#### θe, Water Vapor and a Conceptual Model

As mentioned in Section 5,  $\theta e$  is a conservative meteorological parameter that combines temperature and moisture into a single quantity whose vertical distribution is related to convective instability. As a result,  $\theta e$  gives an indication of the vertical distribution of the Convective Available Potential Energy (CAPE) that is representative of the convective instability in the troposphere. High  $\theta e$  values correspond to areas of high moisture and/or temperature and therefore represent favored regions for the initiation of thunderstorms (Shi Jiang and Scofield, 1987 and Xie and Scofield, 1989). Scofield and Robinson (1990, 1992) developed a conceptual model of WVP, PW plumes and low-level θe connections (Figure 35) over the USA. The schematic shows a tropical WVP (depicted by the dotted area) and consists of mid to upper level moisture that often extends northward from the subtropics and tropics. A θe ridge axis, at 850 to 700 mb, is depicted by dashed lines and the tongue of deep layer moisture is shown by the solid line. Notice in this conceptual model that typically the low level θe ridge axis is located in the western portion of the WVP and the tongue of deep layer moisture (the PW plume) is positioned to the east of the θe ridge axis. Jet streaks, short wave troughs, and other forcing mechanisms with their associated upward vertical motion fields are often observed near the back edge (western portion) of the tropical WVP. Sometimes vortices are embedded within the plume itself and produce enough lift to result in flash flood producing MCSs. The northern part of the WVP is often where the low-level forcing (θe ridge axes and warm air advection) becomes coupled with upper level forcing mechanisms (jet streaks) creating favorable conditions for development of MCSs. A cautionary note is that MCSs will not develop if there is a capping inversion present; small cumulus clouds in the visible imagery that are not growing indicate the presence of a cap or lid.

A typical scenario is that MCS tend to develop along the ridge axis of  $\theta e$  or its gradients (areas of positive  $\theta e$  advection). Often these developing MCSs are severe, producing tornadoes, hail, and strong winds. As these MCSs propagate to the east, the environment becomes more precipitation efficient with the presence of the PW Plume (associated with deep moisture). As a result, the MCSs tend to produce heavier rainfall and flash floods. These WVP and PW Plumes can be present, sometimes one or two days before a heavy rain event; and serves to pre-condition the environment. Moisture plumes also provide a feature that forecasters can monitor and track as potential areas of heavy precipitation and flash floods.



Figure 25. Water vapor imagery (6.7 micron) for June 20, 1996, 0515 UTC.



Figure 26. 500 mb analysis for June 19, 1996, 1200 UTC.



Figure 27. 500 mb relative vorticity analysis  $(10^{-6} \text{ sec}^{-1})$  from the ETA model for June 20, 1996, 0000 UTC.



Figure 28. 300 mb isotach analysis (kts) from the ETA model for June 20, 1996, 0000 UTC.



Figure 29. GOES derived precipitable water (mm) product for June 20, 1996, 0546 UTC.



Figure 30. 850 mb equivalent potential temperature ("K) from the ETA model for June 20, 1996, 0000 UTC.



Figure 31. 850 mb winds (kts) from the ETA model for June 20, 1996, 0000 UTC.


Figure 32. Enhanced infrared imagery (10.7 micron) for June 20, 1996, 0515 UTC.

6-20-96 1200 UTC



Figure 33. 24 hour rain gauge analysis (inches) ending June 20, 1996, 1200 UTC.



Figure 34. Soil (surface) Wetness Index (5 day moving averages) ending June 24, 1996.

### 6. A Study of Water Vapor Characteristics of Heavy Rainfall Systems Occurring over the USA During the Summer of 1997

During the summer of 1997, 93 convective events were collected over the 48 contiguous states. The events were selected during those occasions that rainfall estimates were being computed by Satellite Analysis Branch (SAB) meteorologists using the IFFA (Borneman, 1988); these rainfall estimates were supplemented by 24 hour gauge observations. A majority of the events occurred between the Rockies and the Appalachians and estimated (and observed) rainfall amounts ranged from 0.7 - 10.7 inches. The following parameters or signatures were examined prior or closest to the onset of the precipitation event: composited PW product, PW x RH product, 6.7 micron water vapor (flow patterns and presence of plumes and lifting mechanisms), 850 mb de, and 1000-500 mb thickness. Composited PW and PW x RH products are available in real time via the NESDIS Flash Flood Home Page (http://orbit35i.nesdis.noaa.gov/arad/ht/ff/). Some of these parameters were taken from a paper on Heavy Precipitation Branch's (HPB)/HPC/NCEP forecasting procedures for heavy precipitation (Funk, 1991 and Scofield and Kusselson, 1996). Average magnitudes were computed for several of the products collected during this study (93 events). Results were as follows: composited PW, 1.36 inches; 850 mb theta-e, 341° K; PW x RH, 1.03; 1000 - 500 mb thickness, 5758 GPM; and rainfall (IFFA or observed), 3.8 inches. Correlations between rainfall amounts and those products containing high amounts of PW were significant; low correlations existed for  $\theta e$  and thickness magnitudes. These findings are not surprising since the maximum are correlated with MCS initiation (Shi and Scofield, 1987 and Xie and Scofield, 1989) and not necessarily rainfall amounts. Similarly, thickness magnitudes are





associated with MCS development; not rainfall amounts (Funk, 1991). Of course, MCS initiation assumes that the environment is not capped and a lifting mechanism is present. However, whether or not the MCS will be a heavy precipitation/flash flood producer is dependent on the PE of the environment (already discussed in Section 2).

The following briefly discusses water vapor and  $\theta e$  (patterns) comparisons with observed rainfall.

### Water Vapor and $\theta$ e Comparisons to Observed Rainfall

All 93 convective events took place either in a  $\theta$ e ridge axis or its accompanying gradient. Most of the events (as depicted in the 6.7 micron water vapor) showed the presence of jet streaks either approaching or departing the area of heavy precipitation. The composited PW was best correlated with the ensuing rainfall that occurred. Figure 36 illustrates the scatter plot between the composited PW and rainfall amounts; again the rainfall amounts were obtained from both IFFA estimates and observations. A correlation of 0.58 existed between the PW and magnitude of precipitation. The regression equation derived for the scatter plot in Figure 36 was "P = -0.31 + 3.1 PW", where P = precipitation amount and PW is the magnitude from the composite PW product. Additionally, a 850 mb θe ridge axis accompanied most of these 93 cases. An interesting statistic is the correlation of the magnitude of rainfall with the PW x RH factor. For these cases, this factor gave a slightly reduced correlation to 0.51. This result may seem surprising but the cases selected in this study were biased toward heavy rainfall events when the RH is already quite large (60 % or more) and PW magnitude (by itself) is better correlated with heavy rainfall amounts. The RH becomes useful as a discriminator of the lighter rainfall events. As a result, the "PW x RH" factor is useful in computing satellite QPE's for different types of moist environments, especially reducing precipitation estimates when it is dry.

Another interesting aspect of this study was considering only those cases that were accompanied by a 6.7 micron water vapor plume (55 cases). As illustrated in Figure 37, including the presence of the 6.7 micron WVP with the PW plume reduces the scatter (as compared to Figure 36) and increases the correlation to 0.73. The regression equation derived for the scatter plot in Figure 37 was "P = -2.34 + 4.6 PW". Since a 850 mb theta-e ridge axis was present for most of these cases, this study seems to fit the conceptual model discussed in Section 5, Figure 35 — the relationship of water vapor (6.7 micron and PW),  $\theta$ e ridge axes and lifting mechanisms to precipitation efficient environments. An exact reason why or how the 6.7 micron WVP (Section 4) is associated with heavy rainfall is unclear. *However, experience and the above study have shown that for MCSs, the 6.7 WVP accompanied by a PW plume is a better predictor of heavy precipitation and flash floods than the PW plume by itself.* 

The following examines some validation of the composite PW product discussed in Section 5.



Figure 36. Scatter plot of the composite precipitable water (inches) versus precipitation (inches) (both from satellites and gauges).



Figure 37. Scatter plot of the composite precipitable water (inches) versus precipitation (inches) (both form satellites and gauges) when tropical water vapor plumes are present.

### Validation of Composite PW Product

The composited PW product is composed of SSM/I and GOES derived PWs; model-derived PWs from both the ETA and AVN are used to fill gaps. During the months of August - October, 1997, values from the composited PW product were compared with those (PWs) computed from collocated rawinsondes. A scatter plot that is representative of the statistics compiled during this 4 month period is shown in Figure 38. Statistics indicate that the composite PW has a slight dry bias but correlates well with rawinsonde observations. Some scatter is observed in Figure 38 where the composited PW is underestimating the observed rawinsonde observations. Correlations (r) are 0.92, r square is 0.84, the bias is - 0.15 inches and the per cent error, 15 %. A conclusion from this brief validation study is that the composite PW is accurate and can be used for diagnosing PW magnitudes, trends, and gradients that are used in pattern analysis for detecting environments favorable for flash floods.



Figure 38. Scatter plot of the composite precipitable water (inches) versus PW (inches) computed from rawinsonde data.

### 7. Some Water Vapor Characteristics of the 1997 - 1998 El Nino

The 1997-1998 El Nino has been described as this century's worst. Effects have been widespread from major droughts in Sumatra, Borneo, and New Guinea to record breaking rainfall and floods in the USA (western, southern and eastern regions), central and east Africa, and Peru. This

section will summarize some of the water vapor and precipitation characteristics of the 1997-1998 El Nino over the USA. The 1997-1998 El Nino was characterized (Liu, et al., 1998) by: (1) above normal sea surface temperatures and persistent convection along the equator in the eastern pacific, and (2) an anomalous cyclonic wind pattern in the northeast Pacific that created two effects: (a) anomalous warming along the west coast of Mexico to California and (b) a zone of anomalous southwesterly winds and above normal sea surface temperatures from the equator northeast past Hawaii to the west coast of California. As a result of the above phenomena, the satellite data readily showed: (1) a persistent subtropical jet (in the 6.7 micron WV) meandering from the tropical eastern Pacific to the southeast US where above normal rainfall occurred (in some cases record breaking) during the winter of 1998, (2) an abnormally large number of intense hurricanes that moved north along the Mexican coast (instead of out to sea) and brought an abundance of moisture and many flash floods to the southwest US from late August into early October (moisture plumes associated with the southerly flow ahead (east) of the hurricanes were readily detectable in the GOES 6.7 micron WV and PW products, an example in Section 5), and (3) many winter storms that effected California along with intrusions of PW plumes from the tropics. These PW plumes appeared to be associated with a low level jet that acted as a conveyor belt of moisture (from the tropics) and a focal point for moisture convergence. The west coast winter storms were detectable in the 6.7 micron WV imagery as jet streaks and cyclonic circulation patterns. As a result of these lifting mechanisms and the presence of the low level jet interacting with an abundance of tropical moisture, record-breaking rainfall occurred over California. Precipitation estimates from SSM/I depict the above normal precipitation accumulations that prevailed over portions of the southeast and west during the 1997-1998 El Nino episode.

Previous papers on using water vapor (6.7 micron) and other types of GOES imagery for flood forecasting in the west have been documented in Robinson and Scofield, 1994 and Fleming and Spayd, 1986. The latter paper describes 3 types of winter storm/extratropical cyclone events that occur in the Western region of the USA. These types or categories are based on satelliteobserved cloud signatures and synoptic weather patterns associated with: (I) cloud bands that can be sub-typed as being: (i) quasi-stationary, (ii) associated with a sub-synoptic wave, or (iii) curved anticyclonically over a large scale ridge (with short wave troughs passing over the ridge), (II) deep meridional troughs with embedded cyclonic circulations, and (III) active zonal jet streams. Category (I) above is most often associated with a very detectable feature in the 6.7 micron WV imagery called the WVP.

During this El Nino season, the predominate categories ranged from deep meridional troughs (Type II) to active zonal jet streams (Type III). As a result, even though the 6.7 micron water vapor imagery was able to detect middle to upper level surges of moisture (WVP), their lengths and fetches were small as compared to those that occur in category 1. However, many of these WVP were associated with synoptic scale flow patterns and lifting mechanisms as categorized in Types (II) and (III).

The 1997 - 1998 El Nino season was accompanied by high values of PW that frequently appeared as plumes, areas, or surges of moisture. Also, when these PW plumes became aligned

with or adjacent to  $\theta$  ridge axis and a lifting mechanism (category (II) and (III)) was present, heavy rainfall and floods occurred. Devastating floods will occur if mechanisms are in place to prolong the precipitation. Experience from analyzing PW patterns from the Pacific Ocean to the west coast has led to the development of the following criteria for heavy precipitation: (a) length of fetch (longer fetches are associated with heavier precipitation), (b) low to mid-level winds parallel to plume (often associated with a low level jet), (c) magnitude of moisture associated with plume is 30 mm or greater, and (d) a trend for the moisture to be increasing with time. In many of the 1997-1998 El Nino heavy rainfall events, the above PW patterns could be seen evolving over the Pacific Ocean while the plume was still several days from landfall along the west coast of the USA.

This section concludes with a brief discussion and examples of the western USA winter storms during 1997-1998.

### The Major West Coast Winter Storm Of February 23-24, 1998

One of the winter's fiercest El Nino-driven storms produced torrential rains in Southern California on February 23 - 24, 1998. This event raised the downtown Los Angeles rainfall total for the month to 13.68 inches, surpassing the previous record set in 1884 (13.37 inches). In addition, many homes were destroyed by mud slides and at least 7 people lost their lives.

The following is only a sample of the 6.7 micron water vapor and composited PW analyses available for this event. In Figure 39, the water vapor shows an intense cyclonic circulation ("C") with a surge of upper level moisture just to its east (at "M - S"); isotach analysis in Figure 40 displays two jet streaks (at "J" and "S") rotating around the cyclonic circulation into southern California. The depth of the moisture is shown in the Composted PW product seen in Figure 41. This figure shows a tropical PW plume ("T - P") transporting high values of PW (30 mm) into the Southern California area with very strong 700 mb winds. Not shown is the presence of a 850 mb be ridge axis parallel and collocated with the PW plume. The 300 mb wind field superimposed on the water vapor imagery in Figure 39 indicates that this winter storm is a category II (deep meridional trough) (dashed), and Figure 40 shows a jet streak (jet maximum) (at "S") just off the Southern California coast. All of these ingredients led to the above mentioned devastation and 24 hour rainfall amounts in excess of 10 inches (Figure 42). IFFA derived estimates (in Figure 43) were somewhat less; however, these estimates did not include orography in their computations. The experimental Soil Wetness Index (SWI) (Figure 44) also available in real time on the NESDIS Flash Flood Home Page indicated anomalously high values of surface wetness stretching from San Francisco to Los Angeles, California. As discussed in Section 5, the SWI is an excellent "tool" for detecting those areas that are already saturated and the occurrence of any more precipitation could be devastating.



Figure 39. Water vapor imagery (6.7 micron) for February 24, 1998, 0000 UTC; 300 mb winds (mps) from the ETA model superimposed; Flag = 25 mps.



Figure 40. Water vapor imagery (6.7 micron) for February 24, 1998, 0000 UTC; 300 mb isotachs (mps) from the ETA model are superimposed.



Figure 41. Composite precipitable water product (GOES +SM/I + AVN) (mm) for February 23, 1998, 1200 UTC; 700 mb winds (mps) from the AVN model are superimposed; Flag = 25 mps.



Figure 42. 24 hour rain gauge analysis (inches) ending February 24, 1998, 1200 UTC.



Figure 43. 24 hour Interactive Flash Flood Analyzer (IFFA) rainfall estimates (inches) ending February 24, 1998, 1215 UTC.



Figure 44. Soil (surface) Wetness Index (5 day moving averages) ending February 24, 1998.

### A PW Plume Connection To Heavy Rainfall in California March 22 - 23, 1998

An excellent example of a PW plume occurred with the heavy rainfall event on March 22-23, 1998. This event was typical of one type of west coast extra tropical heavy rainfall event — a cloud band passing over an upper level ridge (Type I in Fleming and Spayd, 1986). The band was located over the west coast and was composed of deep layered clouds; a baroclinic frontal zone accompanied this band. Jet streaks traversed from the trough to the west over the ridge (located over California); rainfall intensified with the passage of each jet streak. The 6.7 micron WV imagery shows this NE - SW cloud band (at "C - B") in Figure 45 that lies over northern California. Upper level winds (300 mb) are superimposed and show a strong jet stream flowing into California; 300 mb isotachs (Figure 46) indicated a strong maxima approaching California from the southwest. A PW plume ("P - W") (Figure 47) is positioned from the ITCZ northeastward into central and northern California. The 700 mb winds (superimposed in Figure 47) were parallel to the plume and were transporting plenty of moisture into California (over 30 mm of PW). The concurrence of moisture transport, lifting mechanisms (in the form of jet streaks), and orography led to the heavy rainfall observed and estimated (IFFA) in Figures 48 and 49, respectively. Observations ranged from 3 to 5 inches while the satellite derived IFFA estimates were just over 3 inches; these IFFA estimates did not include orography. SWI values (Figure 50) depicted anomalously surface wet conditions in northern California and surrounding locations. Especially notable was the very wet area north and northeast of San Francisco, CA.

Several cases have been collected for west coast winter storm events during the 1997 -1998 El Nino episode. Many of these events can be placed into the category of deep meridional troughs (Type II) or active zonal jet streams (Type III). In addition, the 6.7 micron WV imagery depicted pronounced cyclonic circulations and upper level moisture surges just to the east of the disturbance. With the persistent jet stream pattern, many disturbances affected the region from San Francisco to Los Angeles, California. The composited PW product showed the development of PW plumes over the Pacific Ocean; sometimes many days before landfall along the west coast. Finally, the alignment and collocation of these PW plumes with low level jets, the deep meridional troughs and an active zonal jet stream resulted in the devastation that occurred in the Western USA during the 1997-1998 El Nino episode.



Figure 45. Water vapor imagery (6.7 micron) for March 23, 1998, 0000 UTC; 300 mb winds (mps) from the ETA model superimposed; Flag = 25 mps.



Figure 46. Water vapor imagery (6.7 micron) for March 23, 1998, 0000 UTC; 300 mb isotachs (mps) from the ETA model superimposed.



Figure 47. Composite precipitable water product (GOES + SSM/I + AVN) for March 23, 1998, 0000 UTC; 700 mb winds (mps) from the AVN model superimposed; Flag = 25 mps.



Figure 48. 24 hour rain gauge analysis (inches) ending March 23, 1998, 1200 UTC.



Figure 49. 24 hour Interactive Flash Flood Analyzer (IFFA) rainfall estimates (inches) ending March 23, 1998, 1200 UTC.



Figure 50. Soil (surface) Wetness Index (5 day moving averages) ending March 24, 1998.

### 8. SAB: QPE, Outlooks, and Support for HPC/NCEP

The Satellite Analysis Branch (SAB) of NESDIS provides satellite derived QPEs (Borneman, 1988, Scofield and Oliver, 1977, Scofield, 1987, Ferraro and Marks, 1995, and Vicente, Scofield and Menzel, 1998) for heavy rain or snow (including Lake Effect) over the contiguous U.S. and Puerto Rico. SAB's efforts concentrate primarily on locations where there is a potential for or occurrence of flash floods or heavy precipitation. The estimates are sent via the Advanced Weather Interactive Processing System (AWIPS) as part of the satellite-derived precipitation message (SPENES). The SPENES message also contains guidance on satellite analysis, trends, and short range forecasts (Nowcasts). SAB's Home Page that contains graphics products of these estimates is located at: "http://www.ssd.noaa.gov". Heavy rainfall estimates from the Auto Estimator (Vicente, Scofield and Menzel, 1998) have replaced some of the estimates computed interactively on the IFFA. An advantage of the Auto Estimator is its ability to vastly improve the spatial and temporal coverage of satellite precipitation estimates while improving timeliness. As a note, the West Gulf River Forecast Center (RFC) in Fort Worth, TX also receives the Auto-Estimator and GOES Multi-Spectral Algorithm (GMSRA) (Ba and Gruber, 1998 and 2001) product in AWIPS for use in hydrological applications. The NESDIS Flash Flood Home Pages that contain these automatic estimates are:

"http://orbit35i.nesdis.noaa.gov/arad/ht/ff" and on the above-mentioned SAB Home Page.

Short range forecasts involve producing three hour precipitation outlooks (Spayd and Scofield, 1984, Scofield, 1987, Funk, 1989) using the following process: (a) the speed and direction of the coldest portions (or most active) of the convective systems are measured on the latest satellite imagery; (b) this speed and direction are used to extrapolate the current estimated rainfall rates out to 3 hours; (c) heaviest rainfall areas are correlated best to the mean cloud-layer shear vector (i.e., moves in the direction of 850-300 thickness isopleths (Merritt and Fritsch, 1984)); (d) for regenerative convective systems (e.g. back building, quasi-stationary, forward moving meso beta) (Shi and Scofield, 1987, Xie and Scofield, 1989, Corfidi, et al., 1996, Chappell, 1986), the growth and movement of individual clusters must be considered; and (e) the following "trend and expectancy" guidelines depicted in Figures 51 a, b, c are used to anticipate the evolution of the convective systems for the next 3 hours — these guidelines are used to adjust the extrapolated rainfall in (b) above.

In addition to the SPENES's, briefings are also provided to the HPB of HPC/NCEP. SAB is collocated with HPB so they can collaborate and interact more thoroughly on Nowcasts and QPFs. Satellite derived QPEs and guidance messages use GOES infrared (IR) and visible (VIS) imagery and various POES (Polar-orbiting Operational Environmental Satellite) microwave data. The messages are also derived from the 6.7 micron GOES WV imagery, GOES derived products and Sounder data, SSM/I data, the NOAA-15 AMSU data, and blends of various satellite data.

Two technical reports were written by SAB in which statistics were compiled for extremely heavy rainfall events (six or more inches in a 24 hour period) that occurred in 1992 and 1993. In the 1992 report (Kadin, 1993), 62 extremely heavy rainfall cases were identified. PW values and its per cent of normal ranged from 1.0 (minimum) to 1.5 (average) inches and 120 to 140%,

## **Trend and Expectancy Guidelines**

### Adjust amounts UPWARD if:

- The trend of the last 3 half-hourly estimates is upward
- The speed of the coldest tops is decreasing or if the tops are becoming quasi-stationary or building upwind
  - New convection is developing upwind of the coldest tops

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- Cluster/line mergers or intersections with a low level boundary are expected
- Warm, moist low-level inflow becomes increasingly perpendicular to the direction of movement of the coldest tops (increasing surface moisture convergence)
- If hourly surface data show low-level inflow increasing in dewpoint, precipitable water or increasing instability

## **Trend and Expectancy Guidelines**

### No Adjustments if:

- The trend of the last 3 half-hourly estimates is nearly constant
- The speed of the coldest tops is nearly constant, but not quasistationary
  - No mergers or intersections with boundaries are expected
    - The time of day is still favorable
- The system continues in the same topographic region
- The direction of the warm, moist, low-level inflow maintains its orientation with the direction of movement of the coldest tops
  - Hourly surface data show no change in dewpoint, precipitable water, or stability of low-level inflow

# **Trend and Expectancy Guidelines**

### Adjustments amounts DOWNWARD if:

- The trend of the last 3 half-hourly estimates is downward
- The speed of the coldest tops increasing
- The time of day is becoming unfavorable
- The system is moving into a different topographic region that is less moist and more stable
- and becomes increasingly parallel to the direction of movement of The warm, moist, low-level inflow points in the same direction as, the coldest tops
  - Hourly surface data show low-level inflow decreasing in dewpoints, precipitable water, or increasing in stability •

respectively. Surface to 500 mb relative humidity averaged around 75%. WVPs (6.7 micron) were present in 80% of the cases and positive theta-e advection in at least 70% of the events. The 1993 report presented a somewhat more in-depth study of extremely heavy precipitation events; this study was prepared by Borneman and Kadin, 1994. Sixty four events were identified and divided into summer (May to October) and winter (November to April). For the summer season PW and its per cent of normal had values between 1.1 (minimum) to 1.7 (average) inches and 120 to 161%, respectively. The winter season possessed PWs and its per cent of normal between 0.7 (minimum) to 1.3 inches (average) inches and 144 to 210%, respectively. WVPs occurred in 86% of the cases, and positive  $\theta$ e advection, 89%. All of the events took place within a  $\theta$ e ridge or its adjacent gradient. Jet streaks were noted for 89% of the cases.

### 9. Summary, Discussion and Outlook

This report illustrated the application of 6.7 micron WV and satellite derived PW for detecting environments that lead to heavy precipitation and flash floods. Examples were taken from the Eastern, Southern., Central and Western Regions of the USA. Concepts that are were developed for the continental USA are also applicable to Alaska and Hawaii. A number of the heavy rain (flooding) events in southern Alaska are caused by slow moving frontal boundaries and tropical water vapor connections that provide precipitation efficient environments (Saviers, 1999). WVP can also occur with heavy rainfall in the Hawaiian area, especially in association with the Kona Low (Businger and Morrison, 1999). Mean layer RH can be used in combination with the PW for QPE and QPF Techniques. Hydrometeorologists at the Ohio Valley and West Gulf RFC's are using PW/RH fields to develop QPF techniques for their local areas. PW and RH are also being used (as mentioned in previous sections) in mesoscale/heavy precipitation/flash flood satellite-derived precipitation estimation algorithms such as the IFFA (Scofield, 1987 and Scofield and Oliver, 1978), Auto-Estimator (Vicente, et. al., 1998) and the GMSRA (Ba and Gruber, 1998, 2001). Surges of moisture, especially the PW plumes, are often collocated or adjacent to a low level theta-e ridge axis; these plumes prepare the environment for heavy rainfall. In addition to analyzing the existence of middle to upper level moisture, the 6.7 micron WV imagery is an excellent detector of middle/upper tropospheric lifting mechanisms. A caution, as mentioned previously, is that even if all of the above ingredients come together. MCSs may not initiate if there is a capping inversion (lid) present.

Many aspects of this report can best be summarized by a checklist for predicting excessive rainfall:

- (1) the presence of 850/700 mb  $\theta$ e ridge,
- (2) the presence of PW plumes where the surface-500 mb RH > 70%; PW > 1 inch, and > 120% of normal,
- (3) the presence or anticipation of a short wave trough, cyclonic circulation or jet streak,
- (4) the presence of a 6.7 micron water vapor plume,
- (5) the presence of positive 850/700 mb  $\theta$ e advection, and
- (6) the presence of PW plumes where the surface-500 mb RH > 70% BUT  $PW \ge 1.5$  inches and 140% of normal.

According to Kadin, 1993 and Borneman and Kadin, 1994, if items 1 - 3 are present, that should alert the forecaster that the basic conditions exist for heavy rainfall. If, in addition, items 4 - 6 exist, the likelihood that at least 3 inches will occur and possibly more. Of course the forecaster needs to look at other meteorological variables before predicting heavy rainfall such as propagation characteristics, speed of the system, presence of a lid (capping inversion), and surface features (e.g. winds, dew points, boundaries). The values in the checklist are most applicable to areas east of the Rockies. In fact, in the west, PW values of over 1 inch and light winds at 500 mb typically result in high potentials for flash flood events. To summarize, the presence of the above features (1 - 5) would be associated with many of the heavy to extreme precipitation events observed in all sections of the USA.

Understanding the moisture characteristics of the sub-cloud layer is necessary for improving QPE's from satellite and radar and for QPFs; this is especially a big problem in the western region of the USA. A simplistic schematic of a convective cloud and sub cloud layer is illustrated in Figure 52. The lifting condensation level (LCL) is the height at which a parcel of air becomes saturated when it is lifted dry adiabatically and usually defines the cloud base. If the lapse rate is dry adiabatic from the surface to the cloud base, the LCL becomes identical to the convective condensation level (CCL). Precipitation efficient conditions are indicated in Figure 52 by the following conditions: depth of the warm cloud at least 3 or more km warmer than  $0^{\circ}$  C, and PW/RH criteria for the sub-cloud layer:  $RH \ge 70\%$  and  $PW \ge 1.0$  inches. A word of caution is that the schematic in Figure 52 suggests that the convection is rooted in the boundary layer. Elevated convection can also generate copious amounts of rainfall. Therefore, a broader utility of the schematic would be for elevated convection — an environment where the cloud base may be quite low and the sub-cloud layer quite moist, while the warm cloud depth may still be quite deep.



\* identical to Lifting Condensation Level (LCL) when dry adiabatic from the surface to cloud base

Figure 52. Conceptual model of sub-cloud layer environment.

In the future, PE environments would be better resolved through vertical profiles of WV that could be used by cloud models; in turn, these cloud models would provide information on the moisture characteristics of various layers of the troposphere with an emphasis on the sub cloud laver. From a satellite perspective, three layers (surface - 700 mb, 700 - 500 mb, and 500 - 300 mb) of WV can be produced from a blend of GOES 8/9, AMSU, SSM/I and the ETA model data. Both layer PW and RH will be produced for these three layers. These blended products along with collocated winds from the ETA model and satellite derived winds (SSM/I wind speeds and GOES tracking products) will be used to: (a) investigate the mesoscale distribution of WV transport/flux divergence and its role in QPF, and (b) to help initialize cloud models and NWP models. QPF is related to WV through the water budget equation that has the following terms: evaporation, WV convergence (or divergence), WV advection, and local change of water with respect to time (Gruber, 1970, and Rasmusson, 1967). A WV transport index has been developed by Jedlovec, et al., 1996 for climate research. A similar WV transport index could be generated for mesoscale applications since WV and its transport are key parameters in predicting heavy precipitation. Such a mesoscale WV transport index would use PW or layered WV products instead of the 6.7 micron utilized by Jedlovec. This mesoscale water vapor transport index will be used: (a) to develop regional and local scale climatologies (critical information for flash flood/heavy precipitation forecasting and QPF), and (b) to predict (and Nowcast) the evolution of PE environments.

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