

# Satellite

## THE USE OF WATER VAPOR IMAGERY IN THE ANALYSIS OF THE NOVEMBER 1985 MIDDLE ATLANTIC STATES RECORD FLOOD EVENT

by Theodore W. Funk (1)

Satellite Application Laboratory

National Environmental Satellite, Data, and Information Service

Washington, DC 20233

### ABSTRACT

*The Middle Atlantic States were devastated by very heavy rainfall and catastrophic flooding during the first week of November 1985. Persistent light-to-moderate precipitation fell early in the week. However, very heavy rainfall occurred later in the week due to a low-pressure system that developed rapidly as it moved slowly northeastward from the Gulf of Mexico into the Middle Atlantic region.*

*The use of 6.7- $\mu$ m moisture channel imagery from VAS in detecting the rapid synoptic-scale intensification of the Low and the mesoscale development of convection that produced heavy rainfall is examined. The use of the imagery in supplementing numerical forecast models is discussed. Results indicate that the water vapor imagery was extremely useful for these purposes; this suggests that 6.7- $\mu$ m data appear to be a valuable new source of information for detecting moisture variations in the atmosphere and the development of heavy precipitation systems.*

### 1. INTRODUCTION

Record rainfall and flooding hit the Middle Atlantic states during the first week of November 1985. Generally light-to-moderate precipitation occurred across much of the region on 1-2 November; however, very heavy rainfall fell on 3-4 November as a major storm system affected the eastern United States. Extreme four-day rainfall totals saturated the soil and caused rivers and streams to rise at unprecedented rates resulting in disastrous flooding.

This paper will first present a synoptic overview of the event. The paper then will discuss the use of 6.7- $\mu$ m water vapor imagery as an indicator of both large-scale cyclogenesis and mesoscale convective development. The final section will focus on the use of the imagery as a supplement to numerical forecast guidance. Water vapor imagery is a product obtained from the multispectral imaging mode of the VISSR Atmospheric Sounder (VAS), housed onboard the most recent series of geostationary satellites, and is currently available every six hours.

### 2. SYNOPTIC OVERVIEW OF EVENT

Persistent light rainfall occurred across much of the Middle Atlantic region on the last day of October and the first two days of November 1985. However, over central and west-central Virginia, rainfall amounts were heavier, averaging 0.5-2.0 inches each day with locally higher amounts. Precipitation mechanisms included low-level moist, easterly flow from the Atlantic Ocean, weak low-level warm-air advection, and weak positive vorticity advection (PVA) at 500 mb. The steady onshore flow was generated by the extratropical remains of Hurricane Juan as it tracked from the Southeast into the Midwest, and a high-pressure system anchored in eastern Canada. The added effect of orographic uplift on the eastern slopes of the Appalachian Mountains caused the heavier precipitation in Virginia. Rainfall over several days caused soil to become saturated and rivers to rise.

During this period, a surface front, extending from the Ohio Valley southward to a weak low pressure system in the Gulf of Mexico, advanced very slowly to the east (top of Fig. 1). In addition, at 500 mb (and 300 mb), a jet maximum moved southeastward from the Midwest and injected energy into a short wave that was moving eastward across the southern United States (top of Fig. 1). In response, the weak surface Low in the Gulf came ashore and began to develop rapidly in southeastern Georgia on the evening of 3 November. The Low continued to develop rapidly into a major storm system as it moved slowly northeastward along the front into the Middle Atlantic states. The bottom of Fig. 1 presents a surface-and 500-mb analysis during the period of rapid development; Fig. 2 shows the track and intensity of the storm.

The Low caused steady rainfall as well as embedded thunderstorms within the storm's cloud system. As a result, heavy precipitation was observed from central North Carolina to central Virginia during the 24-h period ending 1200 GMT, 4 November (Fig. 3). Additional heavy rainfall, aligned along the nearly stationary front north of the Low (bottom of Fig. 1), caused extreme 24-h totals (ending 1200 GMT, 5 November) from eastern Ohio to west-central Virginia (Fig. 3). The rainfall was from a moist, southeasterly onshore flow, strong convergence along the front, warm-air advection, and PVA throughout this region. The precipitation was enhanced by upslope flow. However, embedded strong convection, which occurred on the southern

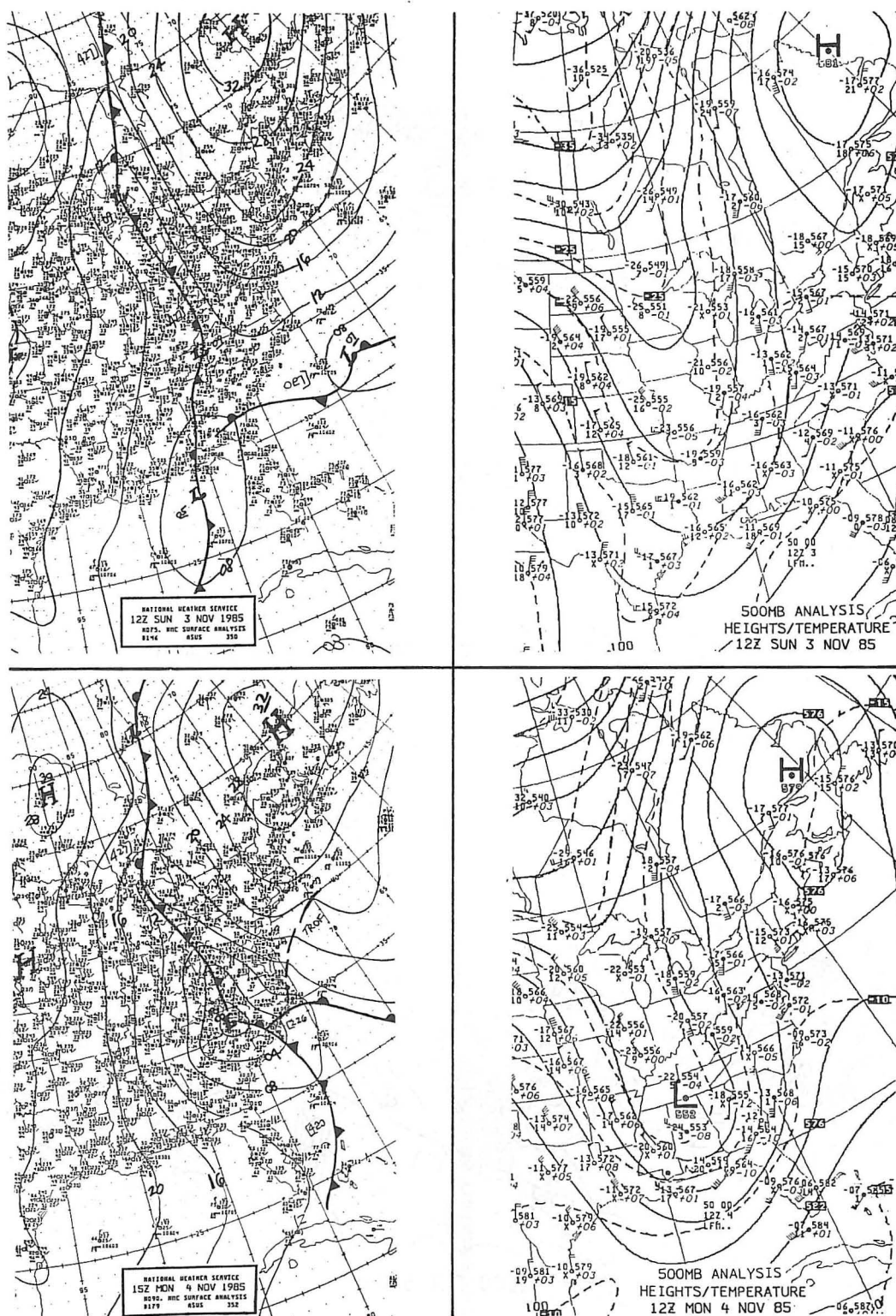


Fig. 1 Surface and 500 mb analyses for 1200 GMT 3 November 1985 (top); also surface analysis for 1500 GMT 4 November and 500 mb analysis for 1200 GMT 4 November (bottom).

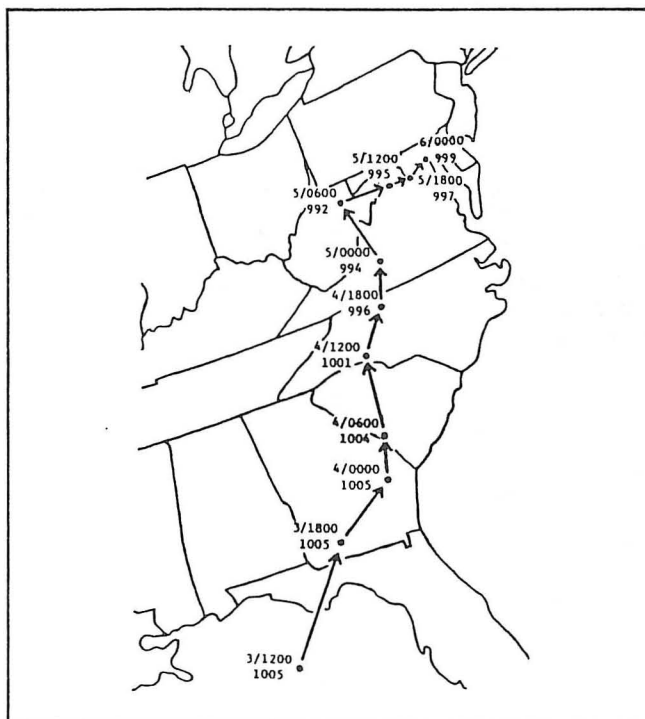


Fig. 2 Track and intensity (mb) of surface low pressure system between 1200 GMT 3 November (3/1200) and 0000 GMT 6 November (6/0000).

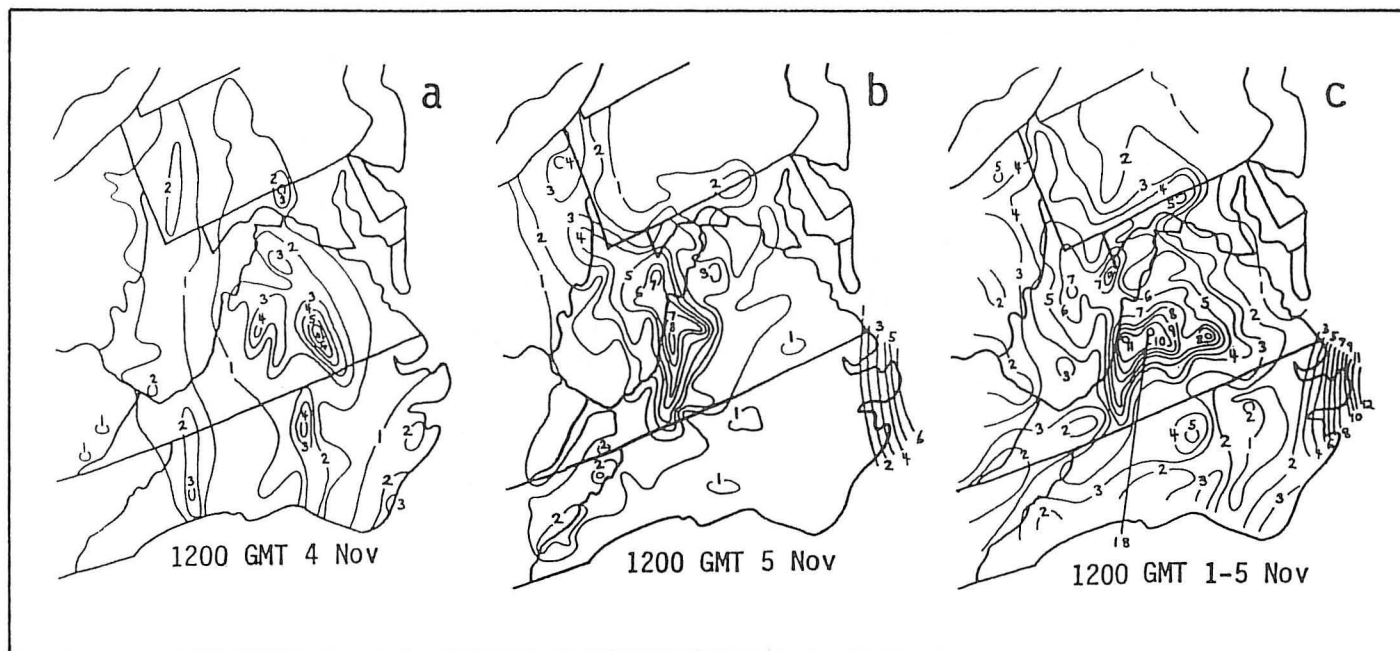


Fig. 3 Twenty-four hour (24h) observed precipitation totals ending at 1200 GMT 4 November (a) and at 1200 GMT 5 November (b); also, four-day observed rainfall totals for the period 1200 GMT 1 November to 1200 GMT 5 November (c). Values are in inches.

end of the general rainfall area, produced a pronounced rainfall maximum (up to 8 inches) over west-central Virginia (Fig. 3). By about 0600 GMT 5 November, most of the heaviest precipitation had ended across the region. By 1200 GMT 5 November, the surface Low began to weaken and move eastward (Fig. 2). Four-day precipitation totals from 1-5 November ranged from 5 to over 10 inches from central West Virginia to central Virginia with Montebello, VA, receiving over 18 inches (Fig. 3). (Other thunderstorms during the period caused the 12-inch maximum at Cape Hatteras, NC). The excessive rainfall caused devastating flooding. Damage estimates exceeded 570 million dollars in West Virginia and 800 million dollars in Virginia; over 60 people were killed in the two states (2).

The characteristics of water vapor imagery and how it clearly indicated the rapid synoptic-scale Low development and the mesoscale convective development in west-central Virginia between 1200 GMT 4 November and 0000 GMT 5 November are now examined. A discussion then follows of computer forecast guidance from this case.

### 3. WATER VAPOR IMAGERY CHARACTERISTICS

Water vapor imagery ( $6.7 \mu\text{m}$ ) depicts the total radiance emitted by water vapor in an atmospheric column, with a peak response in the middle troposphere from about 700-300 mb (Morel et al., 3). The imagery displays areas of middle-level moisture and cloudiness and is able to provide moisture information at a much finer resolution than conventional data sources. This finer resolution information is very essential since spatial moisture variations in the atmosphere can be quite extreme within the mesoscale range.

Very light shades (lightest third of shades) in the imagery indicate that (a) middle or high clouds are being detected as in standard infrared (IR) imagery or (b) a relatively deep layer of moist air (usually 300-400 mb deep) is present above about 700 mb. Very dark gray shades (darkest third of shades) indicate that (a) no middle or high clouds are present and (b) little or no water vapor is present in the middle or upper troposphere (above about 700 mb). Gray shades in the middle third of shades can be attributed to a wide range of combinations of moisture amount and vertical distribution (4). The various shades are related to features in the imagery that are associated with both synoptic and mesoscale advection and vertical motion, as described by Scofield and Funk (5). When animated, the features exhibit excellent spatial and temporal continuity.

### 4. DARKENING IN THE WATER VAPOR IMAGERY

Darkening in the water vapor imagery refers to a decrease in image brightness following a circulation system feature embedded in the airflow. In this paper, the emphasis is on darkening, not only the existence of dark regions. Physical processes leading to darkening are cold advection at middle and high levels and strong upper-level convergence; both processes lead to strong subsidence and a deepening of the dry layer. A deeper dry layer allows the satellite to sense further down to a warmer level in the troposphere.

Weldon (6) identified four types of darkening (warming):

- (1) Base darkening - occurs at the base of troughs and is often associated with jet maxima in "digging" situations.
- (2) Cyclonic surge darkening - a dark zone takes on an elongated shape as it moves into the storm slot in cyclonic flow; this often is associated with upper air cyclogenesis and surface Low deepening (surface deepening continues until the dark zone reaches the left or poleward side of the center).
- (3) Anticyclonic surge darkening - often is associated with upper air anticyclogenesis and closing off of a ridge.
- (4) Comma cloud head darkening - occurs on the poleward or upstream side of a comma head deformation zone and is associated with the opening up or shearing out of an upper air closed-contour Low and weakening of the surface system.

### 5. WATER VAPOR IMAGERY AS AN INDICATOR OF SYNOPTIC-SCALE CYCLOGENESIS

The November 1985 Middle Atlantic states record flood event provides an excellent example of how  $6.7\text{-}\mu\text{m}$  imagery can provide indications of rapid surface development and deepening. The imagery for this case at 2330 GMT each day 3-5 November is presented in Fig. 4. At 2330 GMT 3 November, the jet maximum that initiated cyclogenesis was located upwind and in the base of the 500-mb short wave trough (axis from Arkansas to Louisiana). The jet maximum was associated with a dark area, i.e., base darkening (6) (denoted by A) in Louisiana, which provided an indication that surface deepening may follow. The surface Low in southeastern Georgia had the same central pressure (1005 mb) as 12-h earlier (Fig. 2). However, by 1200 GMT 4 November, the Low began deepening rapidly to a pressure of 1001 mb in southern North Carolina. The corresponding water vapor image (Fig. 4) indicates the rapid development began as the jet maximum rounded the axis of the deepening 500-mb short wave and was oriented parallel and along the distinct moisture gradient across northern Florida northward to extreme eastern Kentucky (also see Fig. 1). The dark (dry) region previously in Louisiana had darkened and surged northeastward along the length of the jet axis, a phenomenon that Weldon (6) and Smigielski and Ellrod (6) have noted is associated with rapid surface cyclogenesis and deepening. Anderson et al. (7) believe that this dark slot region is due to sinking and drying associated with the jet circulation.

The comma configuration continued to develop markedly at 2330 GMT 4 November as the dry slot began to rotate into the Middle Atlantic states around the vortex (Fig. 4). A dual jet pattern was quite apparent. The polar jet dipped south through the Midwest along the distinct light-dark gradient and curved cyclonically around the trough base; the subtropical jet advanced northeastward from the Gulf of Mexico to just off the North Carolina



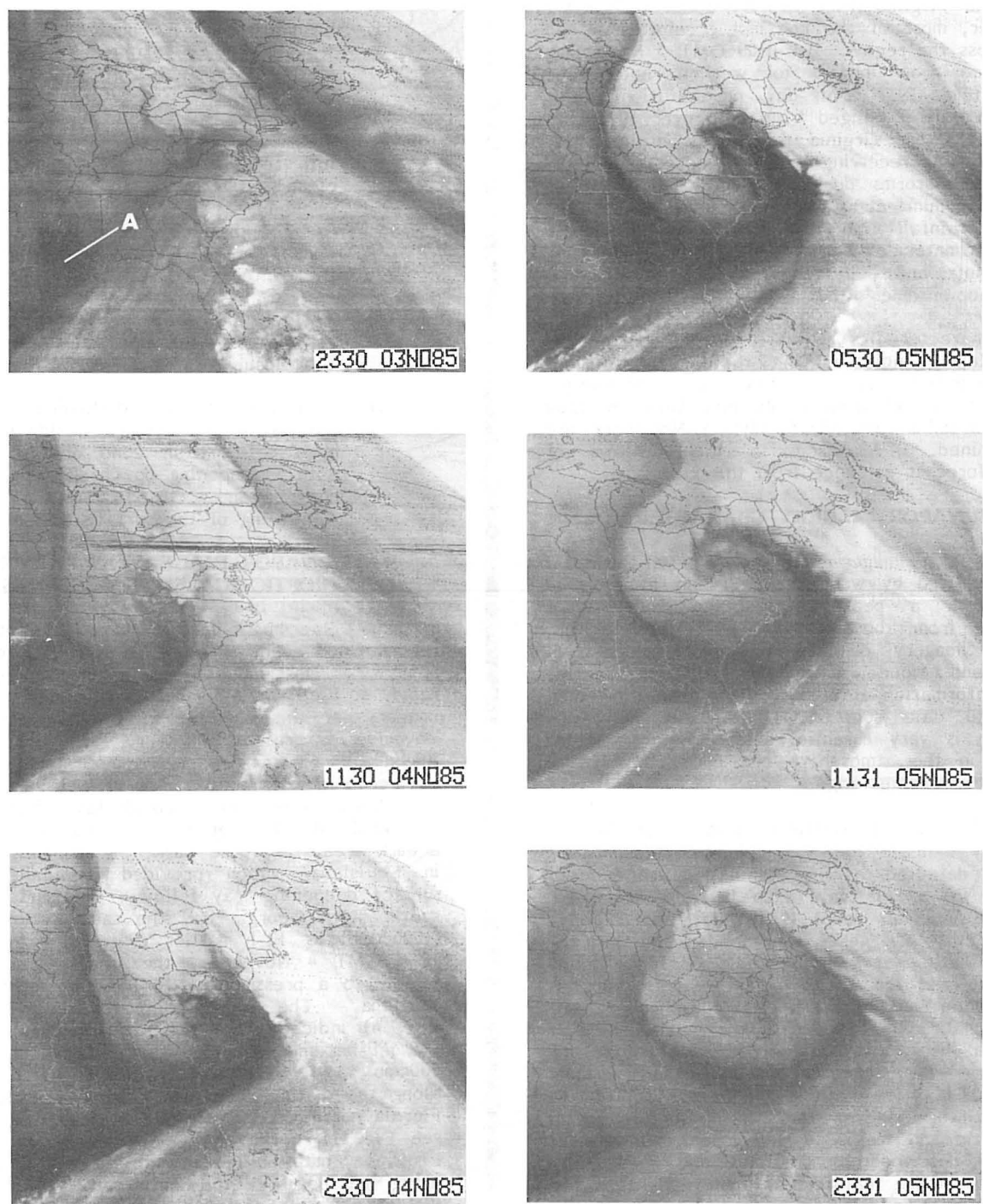


Fig. 4 Water vapor imagery ( $6.7\text{ }\mu\text{m}$ ) from the middle Atlantic states record flood event for the period 2330 GMT 3 November to 2330 GMT 5 November 1985.

coast. Resulting strong upper-level convergence apparently induced descent and drying behind the Low, which caused the dry slot to darken considerably from 12-h earlier. Ahead of the Low, compensating ascent and strong upper-level divergence caused explosive surface deepening. Therefore, the rapid slot darkening coincided with this deepening as the low-pressure center, located just south of Roanoke, VA, fell to 994 mb (Fig. 2). A closed circulation developed around the 500-mb Low center located in western North Carolina (not shown). The surface Low reached a minimum pressure of 992 mb at 0600 and 0900 GMT 5 November (Fig. 2) as the dry air continued wrapping around the vortex as depicted on the 0530 GMT 5 November image (Fig. 4). However, by 1130 GMT 5 November, its pressure rose to 995 mb as the dark slot reached the left or poleward side of the Low center (in northern Virginia) and began to diffuse. Weldon (6) and Smigielski and Ellrod (8) note that this slot position and diffusion are indications of a weakening surface Low. The 500-mb Low, however, continued deepening from 12h earlier, resulting in

the spiralling moisture pattern across the Middle Atlantic states. Finally, the surface Low's central pressure rose to 999 mb in eastern Maryland by 2330 GMT 5 November (Fig. 2) as the slot was no longer evident in the Middle Atlantic region (Fig. 4). Instead, a circular dark band, indicating the jet stream, completely encircled the center. The 500-mb Low began weakening as well by this time.

## 6. WATER VAPOR IMAGERY AS AN INDICATOR OF MESO-SCALE CONVECTIVE DEVELOPMENT

As this flood event also demonstrates, some of the boundaries in water vapor imagery are related to the development of heavy rainfall-producing convection. The  $6.7\text{-}\mu\text{m}$  image at 1130 GMT 4 November (Fig. 5) reveals bright cloud tops over West Virginia and eastern Ohio where general rainfall was occurring. However, strong thunderstorms were in progress over west-central and southwest Virginia (area A). In fact, a severe thunderstorm was reported at Roanoke, VA at 1500 GMT 4 November (Fig. 1). The convection occurred

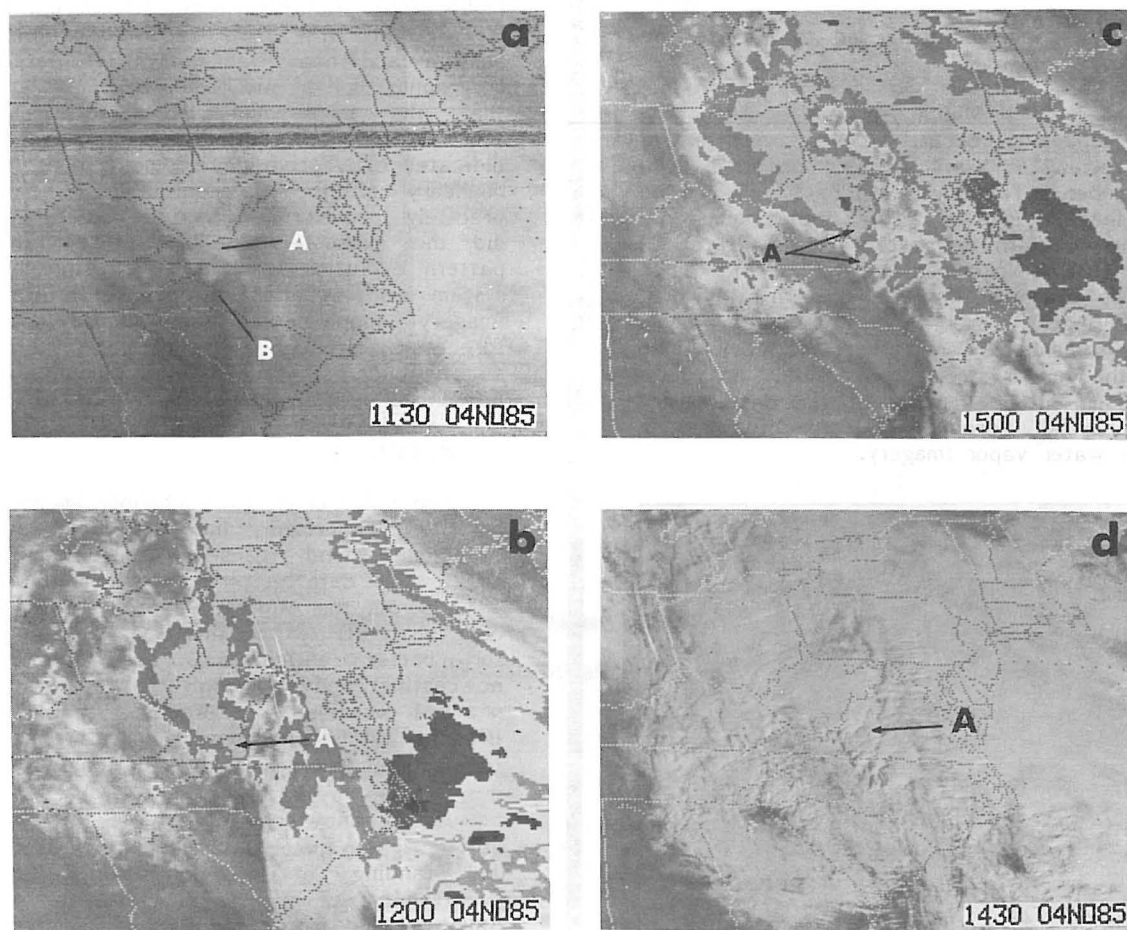


Fig. 5 Water vapor imagery ( $6.7\text{ }\mu\text{m}$ ) at 1130 GMT 4 November (a), enhanced infrared imagery at 1200 (b) and 1500 GMT 4 November (c), and visible imagery at 1430 GMT 4 November (d) depicting convection over west central and southwest Virginia at A and a dry region at B on the water vapor image.

on the moisture gradient along the eastern boundary of the rapidly developing and darkening dry air slot. The storms persisted until 1800 GMT over west central Virginia and produced 4.69 inches of rain at Roanoke between 1200 and 1800 GMT. This convection is difficult to detect in the corresponding enhanced IR images at 1200 and 1500 GMT 4 November (Fig. 5) (at area A on both images). Two reasons for this difficulty are that (1) the convective tops are "warm" (equivalent blackbody temperatures are warmer than  $-62^{\circ}\text{C}$ ) and (2) these tops cannot readily be delineated from the remaining widespread enhanced, but generally non-convective clouds. However, the visible image at 1430 GMT (Fig. 5) is useful in depicting the storms as bright, bumpy tops located at A in west central Virginia. However, the water vapor image is most useful in showing why the very "wet" convection developed just south of the general rain area and embedded within the cyclonic circulation just north of the synoptic-scale surface Low. The dark slot likely introduced middle-level dryness (as depicted at B on the 1130 GMT water vapor image) over abundant low-level moisture, resulting in convective destabilization. This instability, in an area of strong convergence, warm-air advection, and PVA, was the necessary ingredient needed to initiate the convection.

New thunderstorms, which produced another inch of rain at Roanoke, occurred over west-central Virginia between 1800 GMT 4 November and 0000 GMT 5 November. These cells (area C) formed on the distinct leading edge of a dark zone (looks like a finger) from southern to western Virginia (area D) on the 2330 GMT 4 November image (Fig. 6). Since the main slot extended through eastern Maryland, the dark "finger" may have resulted from compensating subsidence and, therefore, drying to the rear of the earlier strong convection. Spayd (9, 10) also has presented examples of the development of heavy rainfall producing convection along boundaries in water vapor imagery.

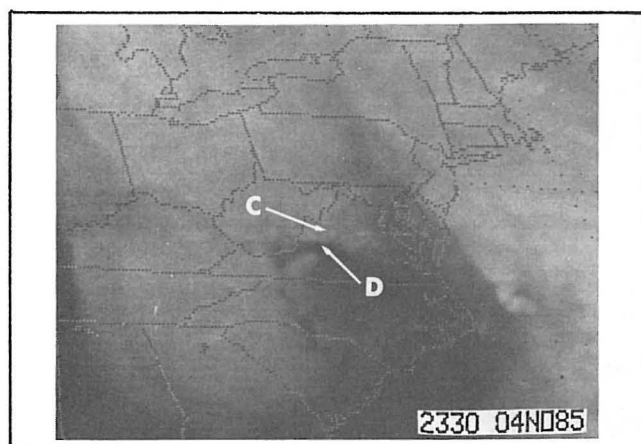


Fig. 6. Water vapor imagery (6.7  $\mu\text{m}$ ) at 2330 GMT 4 November depicting convection at C and a dark region at D.

## 7. WATER VAPOR IMAGERY AS A SUPPLEMENT TO NUMERICAL FORECAST MODELS

Water vapor imagery can be a valuable supplement to numerical forecast models for the accurate prediction of heavy precipitation events. For example, Gurka (11) has presented cases in which the imagery provided important information that improved Limited Fine-Mesh (LFM) and Nested Grid Model (NGM) forecasts that were deficient in predicting the movement of heavy rainfall producing winter storms. Similarly, the water vapor imagery can be used to supplement and improve LFM and NGM rainfall forecasts during the Middle Atlantic states record rainfall event.

The LFM and NGM 12-h forecasts predicted major storm system development, although both models, especially the LFM, consistently underforecast the strength of the surface Low by 1-6 mb. The models also indicated that a 2-4 inch broad-scale heavy rainfall event would result throughout the Middle Atlantic region. However, the observed heavy rainfall pattern was considerably more concentrated with maximum amounts much higher than predicted, especially across Virginia and West Virginia (Fig. 3). As discussed previously, the pattern and heavy amounts were largely due to orographic uplift and embedded strong convection that the LFM and NGM failed to predict accurately. The water vapor imagery, however, indicated convective development along the moisture boundary of the dry slot and, therefore, more precisely located the areas of heaviest rainfall than did the models. The jet stream and moisture pattern evolution associated with the synoptic-scale system also were indicated. In these ways, the imagery supplemented and improved the model forecasts, although the computer guidance only slightly underestimated rainfall amounts in areas not influenced by convection or orographic effects.

## 9. SUMMARY

The 6.7- $\mu\text{m}$  moisture channel imagery proved to be an important indicator of synoptic-scale cyclogenesis and mesoscale convective development during the catastrophic flood event of November 1985 across the Middle Atlantic states. The effort now is to utilize the imagery as an important tool for better anticipating and forecasting (also nowcasting) heavy precipitation events such as the one just described. A forecaster should use satellite imagery to supplement and "fine tune" model forecasts in heavy rainfall situations.

As our knowledge of how to fully interpret and utilize water vapor imagery increases, a better understanding of the initiation, focusing, and maintenance of heavy precipitation will result. Animated and more frequent 1-2-h interval imagery also will be necessary to increase this understanding.

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## NOTES AND REFERENCES

1. Theodore W. Funk received his B.S. degree in Meteorology from Parks College of St. Louis University in 1982 and his M.S. (Research) degree in Meteorology from St. Louis University in 1985. He currently is performing research in heavy precipitation and flash flooding in the Satellite Applications Laboratory at NOAA/NESDIS in Washington, DC.
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