Satellite Observations of Hurricane Elena (1985) Using the VAS 6.7-μm "Water-Vapor" Channel

Christopher S. Velden

Cooperative Institute for
Meteorological Satellite Studies,
Space Science and Engineering Center,
University of Wisconsin-Madison,
1225 West Dayton Street,
Madison, WI 5370614

Abstract

Satellite imagery from the VISSR (Visible Infrared Spin Scan Radiometer) Atmospheric Sounder (VAS) 6.7-μm water-vapor absorption band is normally available to the National Hurricane Center (NHC) in real time (half-hourly intervals, 16 hours a day) through a remote Man-computer Interactive Data Access System (McIDAS) workstation located in the forecast center. Synoptic features that are not readily apparent in "visible" imagery or "11-μm–infrared" imagery are often well defined in the VAS "water-vapor" imagery with the help of special enhancement software that exists on McIDAS. A good example is Hurricane Elena (1985). Its erratic path in the Gulf of Mexico was responsible for the evacuation of nearly a million people in low-lying coastal areas during a three-day period. Imagery from the VAS 6.7-μm water-vapor channel clearly shows the interaction of a midlatitude trough with the hurricane, and supports other evidence that suggests this was responsible for altering Elena's course.

1. Introduction

The environmental flow field around tropical cyclones has been recognized as an important factor in determining tropical cyclone motion (George and Gray, 1976; Neumann, 1979; Chan and Gray, 1982). The synoptic patterns in the storm environment affect the steering currents in which the storm is embedded. Qualitative and quantitative observations provide important contributions to the analysis of the storm environment. Recent studies (Burpee et al., 1984; Velden et al., 1984) have shown the importance of observations in the vicinity of a tropical cyclone for identifying features in the storm environment that may affect the storm motion. The performance of the objective model guidance utilized by forecasters (Neumann and Pelisser, 1981) is related to the quality of the initial analyses. These quantitative analyses of the storm environment may be improved by new data sources such as VAS statellite soundings and dropwindsonde observations.

Qualitative satellite-image interpretation has been a useful tool in weather analysis for many years. In the last decade, timely imaging of water-vapor structure has become available. Recent studies with this data (Eigenwillig and Fischer, 1982; Rodgers and Stout, 1983; Nunez and Stout 1984; Dvorak, 1984) indicate the value of these observations. Features, which may not easily be observed in visible imagery or 11-μm infrared imagery, are sometimes very apparent in the VAS 6.7-μm water-vapor absorption-band imagery, which is most sensitive to radiation emitted from moisture in a broad layer of the middle troposphere (700-200 mb). A description of the 6.7-μm water-vapor channel is given by Nunez and Stout, 1984, and a complete description of VAS characteristics is given by Chesters et al., 1981.

An excellent example of the usefulness of this data is the Hurricane Elena scenario of 1985. Elena was a fast-moving system on a fairly smooth course when it gained hurricane strength as it emerged from Cuba and entered the Gulf of Mexico. The storm's path (Fig. 1) then became erratic in the eastern Gulf of Mexico, creating a difficult forecast situation. Elena meandered just off the southeast United States coast for three days, causing the evacuation of hundreds of thousands of people during Labor Day weekend.

In this paper, observations from the VAS 6.7-μm water-vapor channel during Hurricane Elena's trek through the Gulf of Mexico are presented. A specially enhanced image sequence (using McIDAS software, Suomi et al., 1983) clearly suggests that the interaction of Hurricane Elena with a midlatitude system was responsible for drastically altering Elena's course. The strength of the trough and the interaction with Elena was not readily apparent in "conventional" satellite imagery. "Conventional" upper-air reports were available every 12 hours in the vicinity of the trough and to the north and east of Elena, but did not offer a clear view of the interaction in the Gulf of Mexico. The high-spatial resolution and high-temporal resolution of the VAS water-vapor observations depict this interaction, and offer information that may be especially useful over areas that lack conventional data.

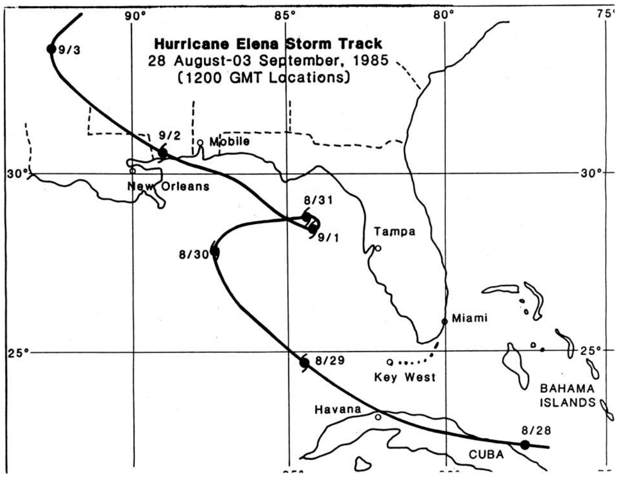
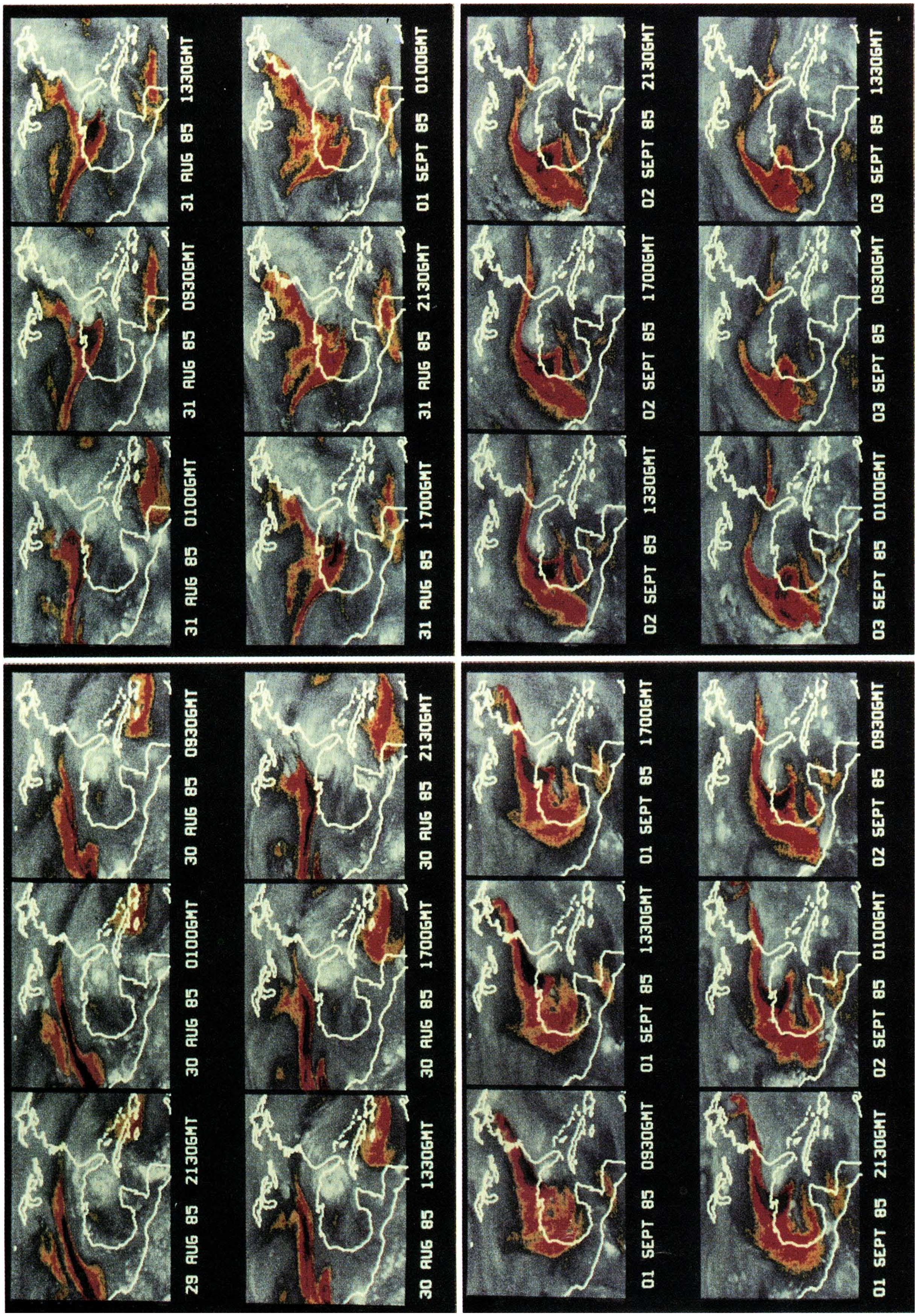


FIG. 1. Hurricane Elena's track.


29 AUG 85 2130GMT
30 AUG 85 0100GMT
30 AUG 85 0930GMT
30 AUG 85 1330GMT
30 AUG 85 1700GMT
30 AUG 85 2130GMT
31 AUG 85 0100GMT
31 AUG 85 0930GMT
31 AUG 85 1330GMT
31 AUG 85 1700GMT
31 AUG 85 2130GMT
01 SEPT 85 0100GMT
01 SEPT 85 0930GMT
01 SEPT 85 1330GMT
01 SEPT 85 1700GMT
01 SEPT 85 2130GMT
02 SEPT 85 0100GMT
02 SEPT 85 0930GMT
02 SEPT 85 1330GMT
02 SEPT 85 1700GMT
02 SEPT 85 2130GMT
03 SEPT 85 0100GMT
03 SEPT 85 0930GMT
03 SEPT 85 1330GMT

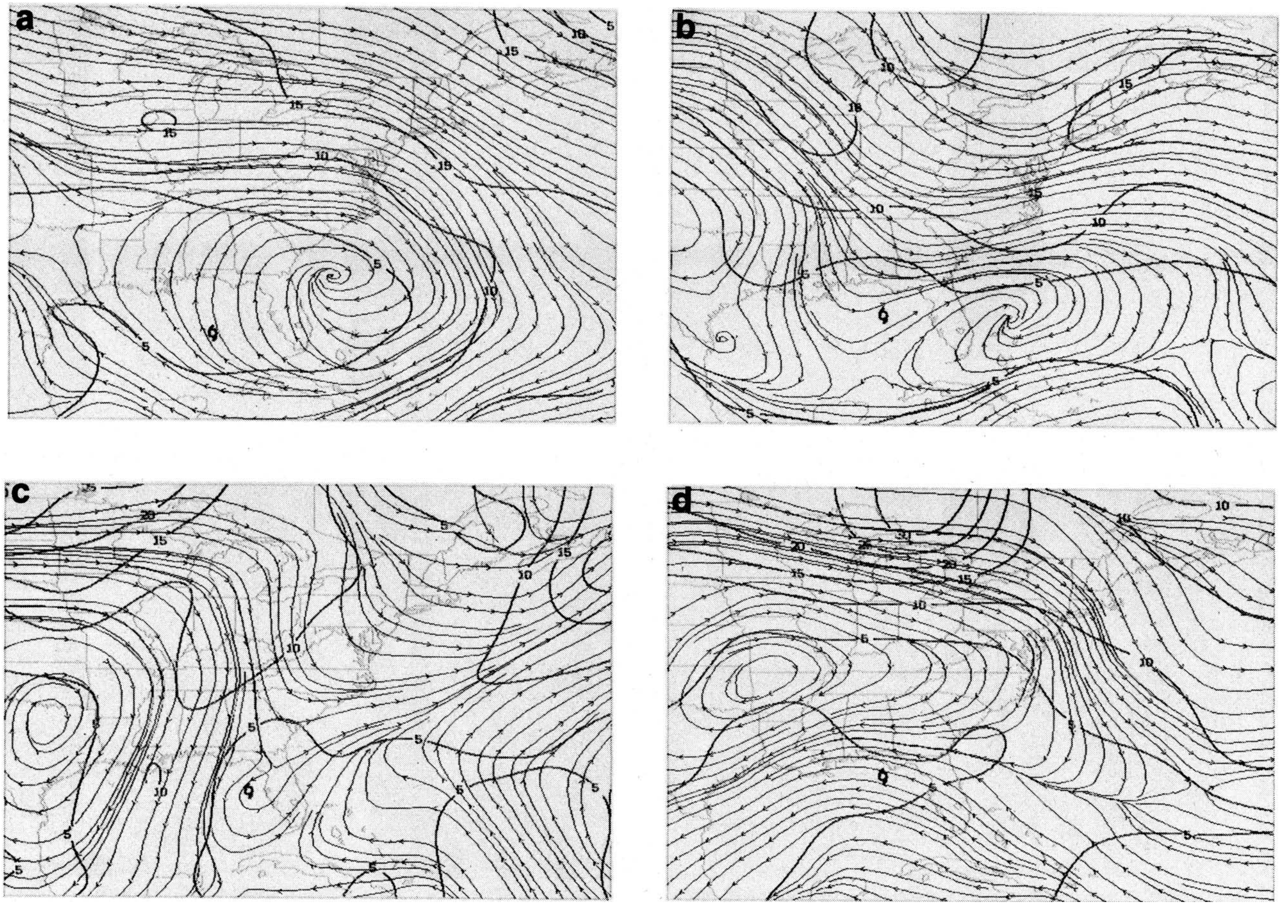


FIG. 2. a) Deep-layer-mean-wind analysis obtained from satellite-derived winds and rawinsondes (Velden et al., 1984) for 00 UTC 30 August 1985. b) Same as (a), except for 00 UTC 31 August 1985. c) Same as (a), except for 00 UTC 1 September 1985. d) Same as (a), except for 00 UTC 2 September 1985.

2. Elena's synoptic history and forecast problem

The tropical wave that eventually developed into Hurricane Elena was generated in the Saharan Desert and moved rapidly westward across the Atlantic Ocean at an unusually fast 30 kt. It moved across the Greater Antilles Islands as a well-organized cloud system and became Tropical Storm Elena on 28 August 1985 while over Cuba (for a complete description of the Elena scenario, see Case, 1986).

Elena continued on a west-northwest track into the Gulf of Mexico, and quickly gained hurricane strength on 29 August. Early on 30 August, steering currents (approximated by deep-layer-mean-wind fields as described by Velden et al., 1984 [Fig. 2a]) were well defined and suggested Elena would continue on a northwest course and make landfall within 30 hours in the New Orleans–Mobile area. The official forecasts supported this track. However, a marked decrease in Elena's forward speed took place late in the day in response to a mid-to-upper-level trough approaching from the northwest (Fig. 2b). As Elena began to interact with this trough, the hurricane turned and took an eastward course for the next 36 hours. The official forecast predicted this motion to continue with the storm crossing Florida and then heading out into the Atlantic. But, as can be seen from Fig. 3 (discussed in the next section), the trough axis had actually passed to the east of the storm center by 0930 UTC on 31 August. With Elena now on the back side of the trough late on 31 August (Fig. 2c), in weak steering currents, the hurricane proceeded to meander in the northeast Gulf of Mexico just off Florida's northwest coast. Elena was a fairly strong, well-developed hurricane at this point. It was evident now that the trough was moving too fast and/or was not strong enough to completely "pick up" Elena and "carry" it into the Atlantic Ocean. This interaction is represented in Fig. 3.

At 00 UTC 2 September the deep-layer-mean-wind steering currents (Fig. 2d) indicated Elena in weak easterly flow between an inverted trough to the south and an anticyclone to the northwest. During the day, Elena picked up speed to

FIG. 3. (facing page) Upper left) A color-enhanced 6.7-μm water-vapor-channel imagery sequence from 2130 UTC 29 August through 2130 UTC 30 August 1985. Black, Red, and yellow depict dry regions. Upper right) Same as (a), except for 0100 UTC 31 August through 0100 UTC 1 September 1985. Lower left) Same as (a), except for 0930 UTC 1 September through 0930 UTC 2 September 1985. Lower right) Same as (a), except for 1330 UTC 2 September through 1330 UTC 3 September 1985.

the west-northwest as the steering currents became stronger. Elena finally made landfall on the morning of 2 September ironically in the same area to which it was originally headed before its three-day "loop."

3. 6.7-μm water-vapor observations of Elena

A sequence of water-vapor images depicting the tropical cyclone-trough interaction is shown in Fig. 3a–d. The image sequence starts late on 29 August and runs through 3 September. The imagery is normally available to national forecast centers (including the NHC) every half hour (except between 0100–0900 UTC, when the VAS data are not available, but will be available around the clock starting in 1987), but due to space restrictions Fig. 3 is limited to imagery at approximately four-hour intervals. The imagery is color-enhanced, using McIDAS software to reveal very dry regions such as those associated with subsiding air behind the trough axis and those produced by Elena's dynamics.

A narrow band of dry air extends from the southwest United States into the Ohio Valley late on 29 August (Fig. 3a), associated with a weak upper-tropospheric trough. The short-wave trough that is to interact with Elena is located at this time in the upper midwestern United States, and is characterized by a "curl" in the water-vapor pattern with weak drying (subsidence) behind it. On 30 August, this trough becomes more distinct, and appears to strengthen slightly as it moves through the weak long-wave trough that existed over the area. Beginning around 0930 UTC, a deformation in the "dry" band can be seen, indicating the position of the trough axis, and providing information on the equatorward movement of the trough and the imminent interaction with Elena. It was just about this time (approximately 1200 UTC) that Elena began a turn to the east (Fig. 1) in response to the approaching system. It should be noted that the system that interacts with Elena is mainly mid-to-upper tropospheric, with only a weak surface cold front existing well to the north of Elena and not apparently involved in the storm-track deviation.

The equatorward surge of the southern end of the trough becomes very apparent late on 30 August and on 31 August (Fig. 3b). The August 31 0930 UTC image actually infers that the trough axis, depicted by the leading edge of the dry and/or subsiding surge of air to the south, has passed by the hurricane center. This image sequence provides a clue that the trough axis has passed to the south of Elena along with the mechanism apparently responsible for Elena's eastward movement flow ahead of the trough). The official forecasts, at this time, predicted Elena to make landfall on the west coast of Florida. Figure 4 depicts a sequence of "infrared-window" imagery during the trough interaction. From this imagery, it is very difficult to locate the approaching trough, or monitor the interaction with Elena.

A marked decrease in Elena's forward motion to the east did actually take place early on 31 August, and Elena virtually stalled about 120 km off the west coast of Florida early on 1 September. It was quite evident now that the trough would not pick up Elena and carry it across Florida into the Atlantic Ocean. The system appears to have been too weak and/or moving too fast to totally "absorb" the well-developed hurricane in its flow and carry it eastward. Elena seems to have "split" the trough, as evidenced by the image sequence in Fig. 3c. The northern branch of the trough moves rapidly eastward out of New England into the Atlantic. The surge of dry air behind the southern branch trough axis can be seen over Mexico and the Gulf of Mexico curving anti-cyclonically around a large high-pressure system building in from the southwest United States (Fig. 2).

On 1 September Elena was located in a relatively dry mid-tropospheric environment, probably characterized by weakly subsiding air behind the trough. An interesting feature in Fig. 3c is the pocket of dry air that develops to the north of Elena, and wraps around to the west side of the storm with time. This "dry pocket" is probably due to storm-induced subsidence (Rodgers and Stout, 1983; Nunez and Stout, 1984; Rodgers, 1984) and is coincident with about a 20-mb drop in Elena's central pressure from 0100 UTC 1 September through 0100 UTC 2 September. This dry area diminishes (Fig. 3d) as Elena weakens after making landfall early on 2 September.

Quantitative measurements of the VAS 6.7-μm radiance data are not dealt with in this paper. Qualitative interpretation of the specially enhanced imagery and its usefulness in explaining the loop in Hurricane Elena's track was the main focus here. However, other studies (Shenk and Rodgers, 1978; Rodgers, 1984; Velden et al., 1984; LeMarshall et al., 1985) have used quantitative measurements from the water-vapor channel to provide information in the tropical-cyclone environment. One promising data source for tropical applications is the tracking of water-vapor features to obtain mid-to-upper–level wind vectors using a sequence of 6.7-μm images on an interactive system. The reader is referred to Stewart et al. (1985) for detailed information on this technique. Water-vapor–tracked winds were derived using the McIDAS system during Elena, and were used in the production of the deep-layer-mean-wind analyses (Velden et al., 1984) shown in Fig. 2. These analyses are routinely provided to NHC during the hurricane season by the Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin as part of the NOAA Operational VAS Assessment Program. An example of the coverage and assigned heights of water-vapor winds produced during Hurricane Alicia (1983) is given in the Stewart et al. (1985) paper. The need for mid-tropospheric (approximately 500 mb) wind observations in data-void areas is vital to the prediction of storm motion (George and Gray, 1976; Neumann, 1979). Research is currently underway at the University of Wisconsin to determine if the VAS 7.3-μm water-vapor absorption-band channel (radiances emitting from 850 to 300 mb) can be used in the same manner as the 6.7-μm channel (which yields tracked winds in the 300 to 400 mb range) to produce mid-level (approximately 500 mb) motion vectors.

4. Summary

The VAS 6.7-μm water-vapor–channel imagery provides timely information depicting the interaction of a mid upper-tropospheric trough with Hurricane Elena. The interaction

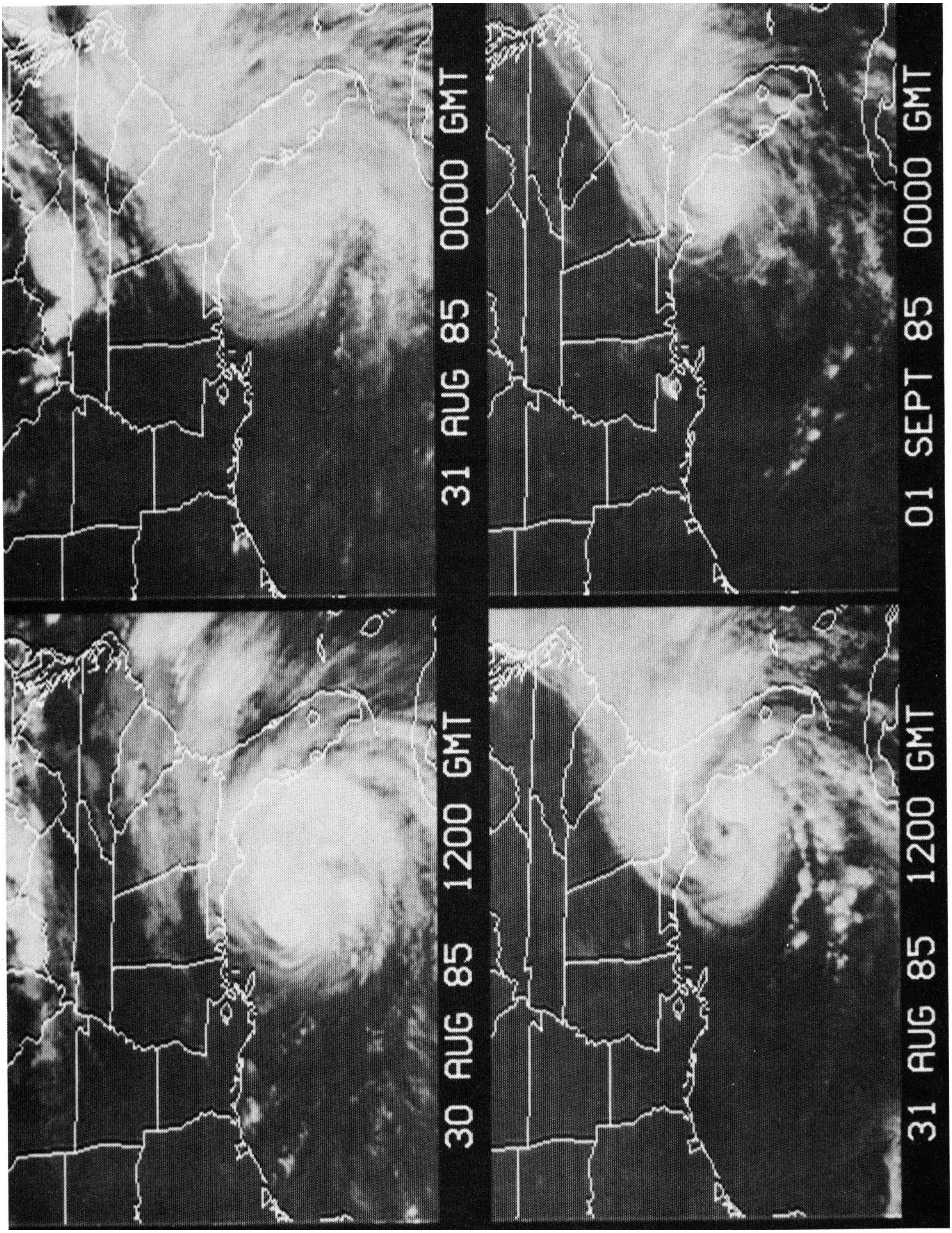


FIG. 4. Infrared-window imagery from 1200 UTC 30 August 1985. Same as (a), except from 00 UTC 31 August. Same as (a), except from 1200 UTC 31 August. Same as (a), except from 00 UTC 1 September.

appears to have caused a three-day loop in the storm track, prolonging the hurricane threat and warranting hundreds of thousands of people to be evacuated during Labor Day weekend due to hurricane warnings.

This imagery can be useful in depicting mid-to-upper tropospheric structure, and features in the tropical-cyclone environment that are not always apparent in conventional infrared or visible satellite imagery. The spatial and temporal resolution of the data makes for an attractive observing tool, and suggests it might aid in short-term forecasting. It certainly provides for a better qualitative understanding of atmospheric interactions. Better interpretation of the imagery and how to utilize it in forecasting tropical-cyclone motion should develop with increased examination of the data.[1]

Acknowledgments. I would like to express my gratitude to Gary S. Wade for help in putting together the enhanced satellite imagery. I wish to thank Dr. John Zapotocny for his contributions to the videocassette work. The reviews and comments from TSAC (Tropical Satellite Analysis Center) meteorologists at NHC and Dr. Hal Gerrish of NHC were much appreciated. Tony Wendricks is to be thanked for the excellent job, as usual, in preparing the figures; and Donna MacKenzie and Laura Beckett for the handling of the manuscript. This research was supported by NOAA contract #NA-84-DGC-0155.

References

Burpee, R. E., D. G. Marks, and R. T. Merrill, 1984: An assessment of omega dropwindsonde data in track forecasts of Hurricane Debby (1982). *Bull. Amer. Meteor. Soc.,* **65,** 1050–1058.

Case, Robert A., 1986: Atlantic hurricane season of 1985. *Mon. Wea. Rev.,* **114,** 1397–1405.

Chan, J. C. L., and W. M. Gray, 1982: Tropical cyclone movement and surrounding flow relationships. *Mon. Wea. Rev.,* **110,** 1354–1374.

Chesters, D., L. W. Ucellini, H. Montgomery, A. Mostek, and W. Robinson, 1981: Assessment of the first radiances received from the VISSR Atmospheric Sounder (VAS) instrument. NASA Technical Memorandum 83827. Goddard Space Flight Center, Greenbelt, MD 200771.

Dvorak, V. E., 1984: Satellite observed upper level moisture patterns associated with tropical cyclone movement. Postprints of the 15th Conf. on Hurricanes and Tropical Met., Miami, FL, American Meteorological Society, Boston, 163–168.

Eigenwillig, N., and H. Fischer, 1982: Determination of mid-tropospheric wind vectors by tracking pure water vapor structure in METEOSAT water vapor image sequences. *Bull. Amer. Meteor. Soc.,* **63,** 44–57.

George, J. E., and W. M. Gray, 1976: Tropical cyclone motion and surrounding parameter relationships. *J. Appl. Meteor.,* **15,** 1252–1264.

LeMarshall, J. F., W. L. Smith, and G. M. Callan, 1985: Hurricane Debby—An Illustration of the complementary nature of VAS soundings and cloud and water vapor motion winds. *Bull. Amer. Meteor. Soc.,* **66,** 258–263.

Neumann, C. J., 1979: On the use of deep-layer mean geopotential height fields in statistical prediction of tropical cyclone motion. Preprints Sixth Conf. of Probability and Statistics in Atmospheric Sciences, Banff, Alberta, American Meteorological Society, Boston, Mass., 32–38.

Neumann, C. J., and J. M. Pelissier, 1981: Models for the prediction of tropical cyclone motion over the North Atlantic: An operation evaluation. *Mon. Wea. Rev.,* **109,** 522–538.

Nunez, E., and J. Stout, 1984: Tropical storm moisture and subsidence patterns as revealed by the VISSR Atmospheric Sounder (VAS) water vapor channel. Postprints of the 15th Conf. on Hurricanes and Tropical Meteorology, Miami, Fla., American Meteorological Society, Boston, Mass., 256–260.

Rodgers, E. B., and John S., 1983: The infrence of tropical cyclone dynamics using GOES VISSR/VAS data. VISSR Atmospheric Sounder (VAS) Research Review. J. R. Greaves, Editor. NASA Conf. Publications 2253. Goddard Space Flight Center, Greenbelt, MD 20771.

——, 1984: The justification for using VAS data to improve tropical cyclone forecasting. Postprints of the 15th Conf. on Hurricanes and Tropical Meteorology, Miami, FL, American Meteorological Society, Boston, Mass., 151–158.

Shenk, W. E., and E. B. Rodgers, 1978: Nimbus 3/ATS-3 observations of the evolution of Hurricane Camille. *J. of Appl. Met.,* Vol. 17, No. 4, 458–476.

Stewart, T. R., C. M. Hayden, and W. L. Smith, 1985: A note on water-vapor wind tracking using VAS data on McIDAS. *Bull. Amer. Meteor. Soc.,* **66,** 1111–1115.

Suomi, V. E., R. Fox, S. S. Limaye, and W. L. Smith, 1983: McIDAS III: A modern interactive data access and analysis system. *J. Climate Appl. Meteor.,* **22,** 765–778.

Velden, C. S., W. L. Smith, and M. Mayfield, 1984: Application of VAS and TOVS to tropical cyclones. *Bull. Amer. Meteor. Soc.,* **65,** 1059–1067. ●

[1] Color-enhanced "loops" of water-vapor, infrared, and visible imagery from a satellite depicting Hurricane Elena on a three-quarter inch (U-matic) videocassette tape are available from the author (University of Wisconsin, Space Science and Engineering Center, 1225 W. Dayton St., Madison, WI 53706) on a cost-reimbursable basis. The interaction of the trough with Elena is quite dramatic in the color-enhanced, time-sequence loops.