TROPICAL CYCLONES

EDUCATIONAL MODULES FOR
THE ATMOSPHERIC SCIENCES

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I. Introduction

This educational module examines the life cycle and structure of tropical cyclones in conjunction with a portrayal of the 1983 Hurricane Alicia. The primary objective of the module is to enhance student understanding of the life cycle and specific features of tropical cyclones which videocomputer systems are particularly adept at displaying. References are made to other studies of tropical cyclones and related materials in an effort to stimulate the student to delve deeper into the subject.

Recent advances in high speed computer systems and in satellite technology have provided new information to the many scientists involved in tropical cyclone research (e.g., a global view of the genesis regions and life cycles of tropical cyclone). The Man-computer Interactive Data Access System (McIDAS) at the Space Science and Engineering Center of the University of Wisconsin-Madison is a videocomputer system which applies satellite information towards the study of meteorological phenomena. This module utilizes the capabilities of the McIDAS to portray and study the following areas dealing with tropical cyclones: 1) methods of investigation, 2) their life cycle, 3) their structure and circulation, 4) forecasting techniques, and 5) a case study of 1983 Hurricane Alicia. Other features of tropical cyclones are presented in lesser detail to complete the overall picture.

II. Description of the Module Contents

The module is composed of two components; a student manual and a 50 minute videocassette. The manual contains four major sections. The first two present an overview of tropical cyclones, the third examines tropical cyclone forecasting methods, and the fourth applies the discussion in the first three

sections towards an investigation of Hurricane Alicia. The videocassette utilizes a variety of data sources and display techniques to provide a visual presentation of the tropical cyclone and to enhance student understanding of tropical cyclone structure. Graphics were produced on an Apple microcomputer and satellite imagery and meteorological information were produced by the McIDAS.

III. Academic Considerations and Module Utilization

The module is designed for a senior level meteorology course to be used over a period of several weeks. However, the length is flexible and the satellite imagery should appeal to audiences of all academic levels. Instructors using previous modules at the University of Wisconsin-Madison and several other universities have found that the most helpful approach is to show specfic segments of the videocassette in augmenting particular lectures. The entire videocassette is then shown at the completion of the lecture series to provide an overall visual presentation. Student access to the videocassette for self study on their own time also proves helpful.

IV. Effects on Man and Property

The mature tropical cyclone is one of the most devastating of all meteorological phenomena. Strong winds, often in excess of 50 ms^{-1}, and flooding due to extremely high tides and large amounts of rainfall are capable of killing thousands of people and destroying coastal property. For the period 1964-1978, tropical cyclones accounted for more loss of life than all other natural disasters combined (Southern, 1979). In 1970, a single tropical cyclone killed approximately 300,000 people in Bangladesh as it made landfall

during high tide (Frank and Husain, 1971). The deadliest hurricane to strike the United States killed 6000 people in the Galveston, Texas area on 8 September 1900.

Tropical cyclones are perhaps best known for the damage caused by their very strong winds. However, other aspects of the storm are normally much more destructive. The storm surge, a sudden rise of water usually centered within or near the eye, has caused 90% of the total property damage in the United States associated with tropical cyclones (AMS, 1973). The storm surge may be as high as 10 meters at the shoreline and is primarily caused by wind driven waves as the cyclone makes landfall. This effect is enhanced if landfall occurs during a period of normally high tides. Damage from the storm surge includes coastal flooding, beach erosion, structural damage and loss of soil fertility due to saline intrusion (Southern, 1979).

The most destructive tropical cyclone to affect the United States was Hurricane Camille in 1969 (Simpson et al., 1970). Camille caused $1.4 billion in damages in striking the Mississippi coast with a storm surge in excess of 7 meters. Heavy precipitation can affect a much larger area than the storm surge, even after the cyclone moves inland and loses its tropical characteristics (Hebert and Taylor, 1979). Widespread damage due to severe flooding, especially in mountainous regions, can occur for several days after the cyclone makes landfall. The remnants of Hurricane Camille produced torrential rains of more than 60 cm over the mountainous regions of Kentucky, West Virginia and Virginia. The ensuing flash floods caused considerable loss of life and dollar damages that were comparable with the losses on the Gulf Coast (Simpson et al., 1970).

Tropical cyclones, especially those of a less severe nature, also have a beneficial impact. The rainfall associated with the storms frequently ends prolonged periods of severe drought (Sugg, 1968) and supply rainfall for irrigation purposes (Serra, 1971). Hurricane Camille, despite its excessive damages elsewhere, was largely beneficial to northern Mississippi and western Tennessee where the heavy rains from the storm ended a severe drought. Furthermore, Imberger et al. (1979) have suggested that in certain areas tropical cyclones induce upwelling and mixing in the underlying oceans, thereby producing nutrient-rich water which ultimately is beneficial for the fishing industry.

V. Global Distribution and Frequency

Satellite imagery has provided a global capability for viewing all tropical disturbances and cyclones throughout their life cycles. Tropical cyclone frequency charts have been updated since the advent of meteorological satellites. Prior to this technological achievement it was possible for tropical cyclones to go unnoticed, especially in sparse observational regions such as the Indian and East Pacific oceans.

Regions of tropical cyclone origin are quite distinct due to a number of conditions necessary for their formation. In general, oceanic regions located at least several degrees of latitude away from the equator with sea surface temperatures in excess of 26.5°C are potential areas for tropical cyclone genesis. Tropical cyclone formation occurs in all equatorial and subtropical oceans of the world except the South Atlantic Ocean, where the water is relatively cold (Gray, 1979) (see Fig. 1). Over 30% of all tropical cyclones originate within or just to the poleward side of the ITCZ. Approximately 15%
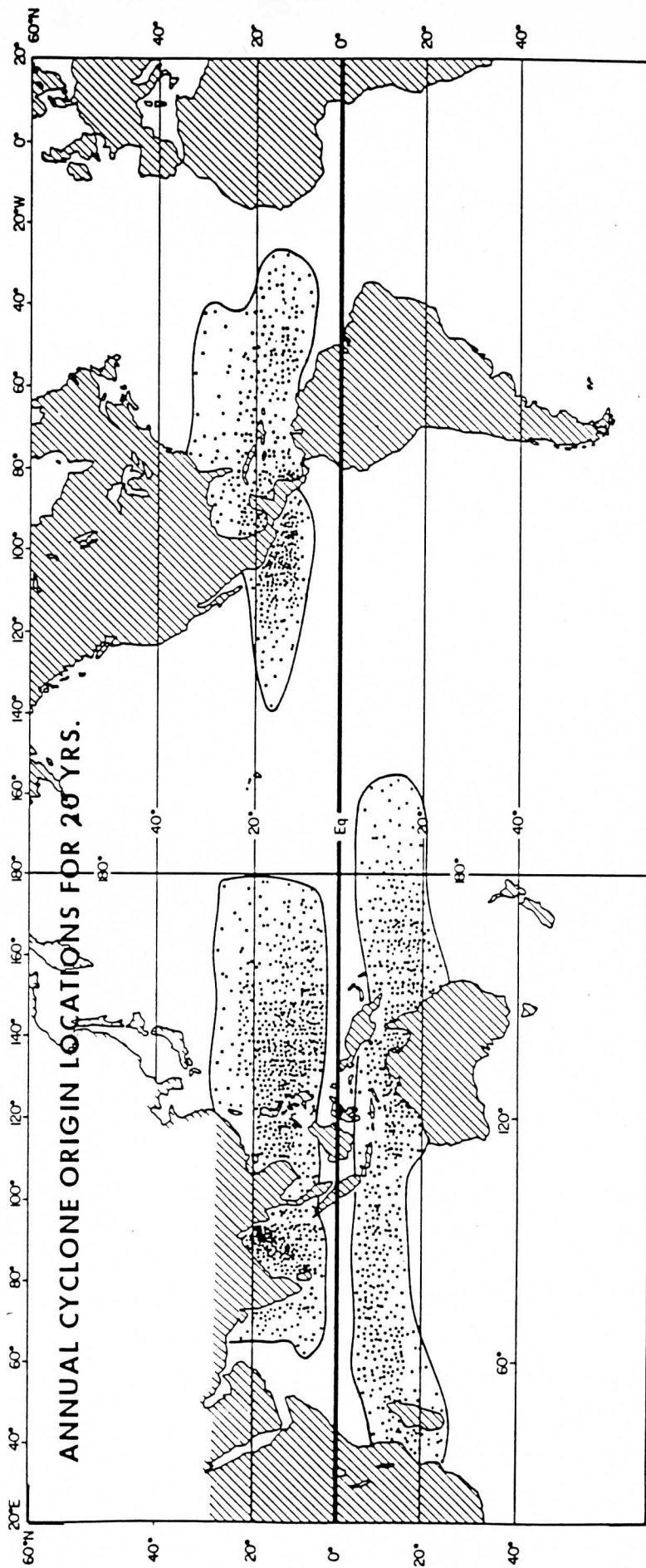
Fig. 1   Genesis locations for tropical cyclones during a 20-year period (Gray, 1979).

form in the easterly trade winds away from the ITCZ usually in association with an upper atmospheric trough within the easterlies. The remainder (about 3-5%) of the global total of tropical cyclones form in subtropical regions along stagnant frontal zones or to the east of upper troughs in the westerlies. Frank (1980) defines the first two groups as disturbances that primarily draw upon latent heating as their source of energy while the latter group initially feeds upon a baroclinic source of energy. Satellite imagery has shown that within the North Atlantic ocean basin a much larger percentage than the global average of tropical cyclones originate from easterly waves or baroclinic type disturbances. During the period 1967-1977 over one fourth of all North Atlantic tropical cyclones developed from baroclinic disturbances, while about half developed from disturbances originating in the northeasterly trade wind belt (Frank, 1980).

Gray (1979) has compiled global statistics on tropical cyclone activity for the 20 year period extending from 1958-1977. He found that approximately 80 tropical cyclones with maximum sustained winds of 20-25 ms^{-1} occur annually. Of these, about one half to two thirds reach hurricane strength (sustained winds > 33 ms^{-1}). While large differences in annual tropical cyclone occurrences exist within individual ocean basins, the global annual variance is only about 8%. Nearly one third of all tropical cyclones occur in the western north Pacific, with approximately twice as many in the Northern Hemisphere as in the Southern Hemisphere. Similarly, the number of occurrences in the Eastern Hemisphere is double the number in the Western Hemisphere. Tropical cyclones have a tendency to cluster in time and space. Active periods of one to two weeks in which two to six times the normal number

of cyclones occur are typically separated by non-active periods of two to
three weeks.

VI. Methods of Investigation

Obtaining sufficient data for the detailed study of individual tropical
cyclones is difficult since most of their lifetimes are spent over oceans
where conventional data are sparse. Even with the use of aircraft data, which
have provided information on the central core structure of tropical cyclones,
complete horizontal and vertical profiles over a large area for a single storm
have been difficult to produce. Thus, many studies have examined tropical
cyclone structure by compositing data from many similar storms over a number
of years. This method has several drawbacks including the inability to
resolve specific features within different storms and their environment. This
latter problem is alleviated somewhat by classifying the storms according to
several parameters (e.g., storm size, season, intensity).

A second method of investigation is the simulation of tropical cyclones
using a numerical model. With finite-difference approximations of the
primitive equations over a three-dimensional grid, numerical models have been
successful in simulating many of the features of hurricanes throughout their
life cycle. See Anthes (1982) for a summary of hurricane modeling studies.
These models are similar to mid-latitude operational forecast models, such as
the LFM (Limited Area Fine Mesh model), except that the spatial and temporal
resolution is higher and the relative importance of several physical
parameters is different. The effects of latent heating and friction, two
physical processes very important to the development and maintenance of
tropical cyclones, are difficult to numerically simulate realistically and

greatly affect the models performance. However, despite these difficulties a number of experimental and operational tropical cyclone models have achieved considerable skill in forecasting the track of actual tropical cyclones.

The recent use of advanced satellite techniques has made it possible to examine the structure of individual storms, even while they are over oceanic regions. Satellite derived atmospheric soundings provide information on the vertical and horizontal distributions of temperature, moisture and stability in tropical cyclone systems, as well as the temporal evolution of these quantities. In addition, methods which use only satellite information as input have been developed for empirical determination of the intensity of tropical cyclones located over mid-oceanic regions (Dvorak, 1975; Velden and Smith, 1983). Several of these satellite techniques are included in the accompanying videocassette presentation, and will be discussed further in the tropical cyclone forecasting and case study segments of the manual.

VII. Life Cycle and Basic Structure

The tropical cyclone life cycle is composed of three stages. The genesis stage consists of a disorganized area of clouds and squalls in conjunction with a small "initial" disturbance. Following a period of rapid intensification, the mature stage is characterized by a nearly calm central low pressure area surrounded by a well organized cloud pattern and a strong, nearly axisymmetric rotational circulation. The decay stage is denoted by a circulation which has weakened and expanded in size and has become asymmetric with respect to the storm center.

a. Genesis Stage

Pre-existing unorganized disturbances are essential for the development of the vortex of tropical cyclones. Such disturbances are regularly observed in the easterly flow of the tropics, but only about 10% of them organize and intensify to tropical storm strength (maximum sustained winds ≥ 20 ms^{-1}) (Shapiro, 1977). Development of the cyclone vortex requires a decrease in mass and an increase in angular momentum within the disturbance region. The combination of these conditions dictates the existence of both inward and outward branches of mass circulation. An outward branch must transport more mass away from the center than the inward branch transports towards the center, thus allowing a decrease in central pressure. At the same time, the inward branch must transport more angular momentum towards the storm's axis of rotation than the outward branch transports away from the vortex. The net convergence of angular momentum induces rotation and causes the formation and development of a cyclonic vortex.

Since deep cumulus convection is the primary mechanism for coupling the lower and upper tropospheric flow patterns, upward mass transport occurring within the convection is necessary for the inward and outward branches of mass circulation to exist within the stratification of the storm region. As such, the existence of deep cumulus convection is an essential component of tropical cyclone formation.

While an exact qualitative solution describing the initial stages of tropical cyclogenesis continues to elude meteorologists, some general requirements for tropical cyclone formation can be cited. Climatological studies by Gray (1968, 1979) have shown that several conditions, necessary but

not sufficient, must be fulfilled before the "initial" disturbance can intensify to tropical storm strength. These condition involve the following physical parameters:

Sea surface temperature

Convective instability ($\partial\theta_e/\partial z < 0$)

Middle tropospheric relative humidity

Low level absolute vorticity

Coriolis parameter

Vertical shear of the horizontal wind

Climatological studies have shown that tropical cyclones form only over oceans with surface temperatures in excess of 26.5°C. Why this threshold temperature is so critical is not well understood (Anthes, 1982). High sea surface temperatures induce more sensible heating and increase the equivalent potential temperature (θ_e) of the boundary layer, hence enhancing the convective instability of the atmosphere. Deep cumulus convection cannot exist unless the atmosphere is convectively unstable $\partial\theta_e/\partial z < 0$. In cases of tropical cyclogenesis Gray (1979) found typical decreases of 15 to 20 K for θ_e between the surface and 500 mb.

High relative humidities in the mid-troposphere are also necessary. Middle level relative humidities greater than 50-60% are typically needed for cumulus convection to occur over tropical ocean regions (Gray, 1979). If the mid-troposphere lacks sufficient humidity, convective clouds rising through this layer will erode by entrainment of dry air. In addition, large relative humidities above the boundary layer coupled with strong mass convergence will significantly increase the potential for strong latent heating throughout the vertical extent of the bands of deep convection within the storm's circulation.

Tropical cyclone formation occurs only in regions of positive low-level relative vorticity (Gray, 1968). More active convection within the "initial" disturbance intensifies the mass circulation and generates additional vorticity through low-level horizontal convergence. The generation of positive low-level relative vorticity by horizontal convergence is a signature of convergence of angular momentum. The areal integral of the relative vorticity is equal to the vortex's circulation while angular momentum of the vortex is the product of the circulation and the radius to the center of the vortex. The effect of friction at the lower boundary is important to the maintenance and development of the tropical cyclone. Negative frictional torques within the boundary layer force mass convergence within the vortex and at the same time transfer angular momentum of the vortex from the atmosphere to the earth. The resulting convergence intensifies the relative circulation through vertical stretching of vortex tubes. A feedback mechanism is initiated in that through the intensification of circulation, frictionally induced mass convergence within the planetary boundary layer also increases the intensity of the inward and outward branches of the circulation by providing a source of water vapor necessary for the intensification of the convection and latent heat release.

The additional heating enhances low-level convergence which further generates low-level vorticity. At some time the central pressure of the vortex falls through the net divergence of the mass, a condition that is necessary for the development of gradient wind balance within the vortex. This positive feedback effect, called Conditional Instability of the Second Kind (CISK), helps explain the growth of large-scale tropical disturbances (Charney and Eliassen, 1964).

Tropical cyclones do not develop within 4-5° the equator, however, on occassion pre-existing tropical cyclones will move across the equator once their relative circulation is well developed. With the earth's component of vorticity being negligible at these latitudes the effect of low-level horizontal convergence in intensifying the vorticity and circulation of the vortex is reduced, thus indicating the importance of the earth's rotation in tropical cyclogenesis.

Vertical variations in the speed and direction of the wind are also an important consideration in tropical cyclone formation (Anthes, 1982). Large vertical wind shear leads to a "ventilation" of the system through energy export, thereby not allowing heat and moisture to increase within the disturbance. If the vertical wind shear is small ("unventilated" case), increases of heat and moisture can occur that are important for the development of a vortex locally, thus allowing gradual surface pressure decrease and further cyclone development.

Synoptic and planetary scale motions also affect the potential for tropical large-scale wind regimes that favor storm formation as well. Upper-level divergence greatly enhances the potential for hurricane development; conversely, upper-level convergence minimizes the potential for development. Thus, tropical cyclone development is favored when a warm upper anticyclone is present while hurricane development is minimized when a cold upper trough exists (Gray, 1979). The tendency for tropical cyclones to cluster in time on a seasonal scale and the wide variation of storm occurrences within individual ocean basins on an annual scale also suggests that large scale flow patterns affect the potential for tropical cyclogenesis.

b. Mature Stage

The transition from genesis to maturity occurs rapidly if the horizontal and vertical circulations combine to produce a large net convergence of angular momentum and divergence of mass within the cyclone region. The central pressure of the cyclone rapidly falls below 1000 mb and a tight band of hurricane force winds ($\geqslant 33$ ms^{-1}) forms around the cyclone center as it reaches maturity. Cumulus convection and rain patterns transform from disorganized squalls to well-defined bands spiraling around and into the storm center. The formation of an eye within the inner core of the hurricane's vortex through subsidence indicates the transformation of a weak disturbance to an intense hurricane. The generation of extremely low central pressures with a warm core thermal structure and intense wind speeds characteristic of the mature tropical cyclone is not possible without eye formation (Anthes, 1982).

Figure 2, a vertical cross section of temperature anomaly for the 1966 hurricane Inez (Hawkins and Imbembo, 1976), shows the warm-core thermal structure throughout the troposphere within a mature tropical cyclone. These anomaly patterns compare closely with the composite anomaly distributions found by Gray (1979). Maximum values tend to occur at about 250 mb. Despite decreasing pressure towards the center, boundary layer temperatures are nearly uniform due to the strong sensible heat flux from the underlying warm ocean.

The wind structure of a mature tropical cyclone is characterized by low-level cyclonic winds spiraling inwards toward the low pressure center. The combinations of a strong radial pressure gradient force and friction induces mass transport towards the center of the storm within its planetary boundary layer.
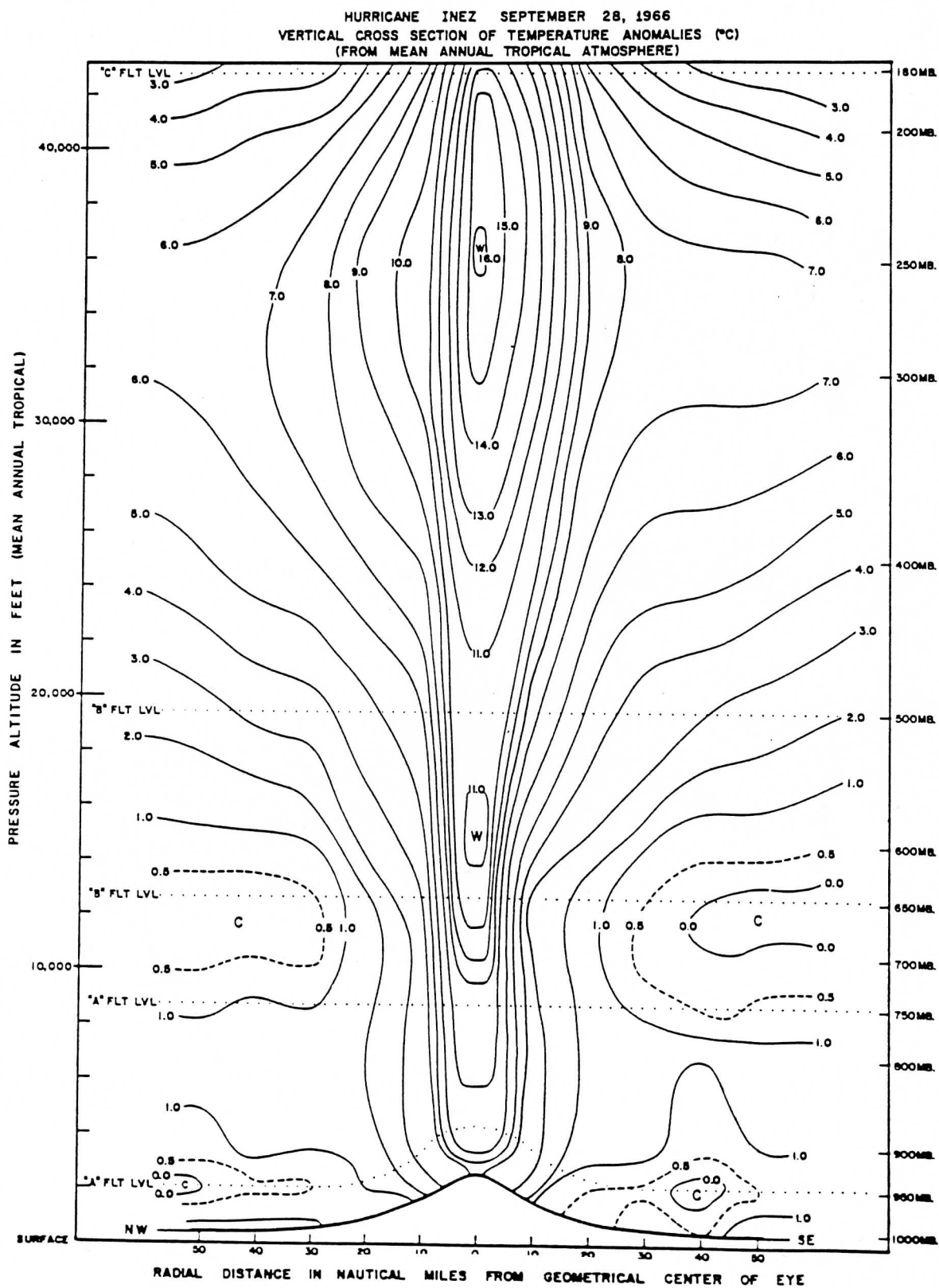
Fig. 2   Vertical cross section of temperature anomaly for Hurricane Inez on 28 September 1966 (Hawkins and Imbembo, 1976).

The rotational velocity of the hurricane increases from the convergence of angular momentum transport. At the same time the increased moisture convergence within the lower troposphere provides the source of latent energy that is released through precipitation. Within the spiral bands and eyewall, a ring of intense deep convection surrounds the eye with the convergence and accompanying upward vertical motion being greatest in the eyewall. The eyewall can vary in width from 10 to 100 km. Strongest winds and heaviest rainfall also occur within the eyewall. The rapidly ascending air within the eyewall is eventually transported outward within the layer of strong mass divergence just beneath the stable lower stratosphere. The diverging upper-level winds rotate cyclonicly initially, but become anticyclonic away from the center due to spindown from angular momentum constraints. Within the outflow layers of a vortex, the spindown of the relative circulation must occur with increasing radius, just as a skater or ballet dancer spins down at the end of a pirouette by extending their arms outward.

Cross sections of the radial and the tangential wind components for typical mature tropical cyclones (Fig. 3) illustrate the wind structure described above. Actual wind speeds in strong hurricanes may well exceed those depicted in the cross sections. Throughout most of the troposphere, the tangential wind component dominates the flow. Only in the boundary layer where surface friction retards the flow and causes a significant inward radial component is the radial component nearly equal in magnitude. Maximum inflow is centered at about 500 m above the surface with a typical radial speed of 3-10 ms^{-1} (Anthes, 1982).
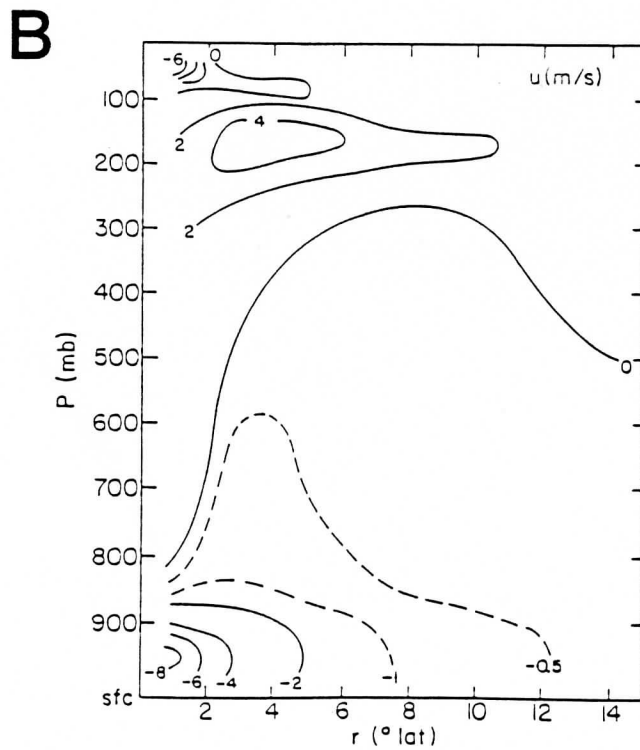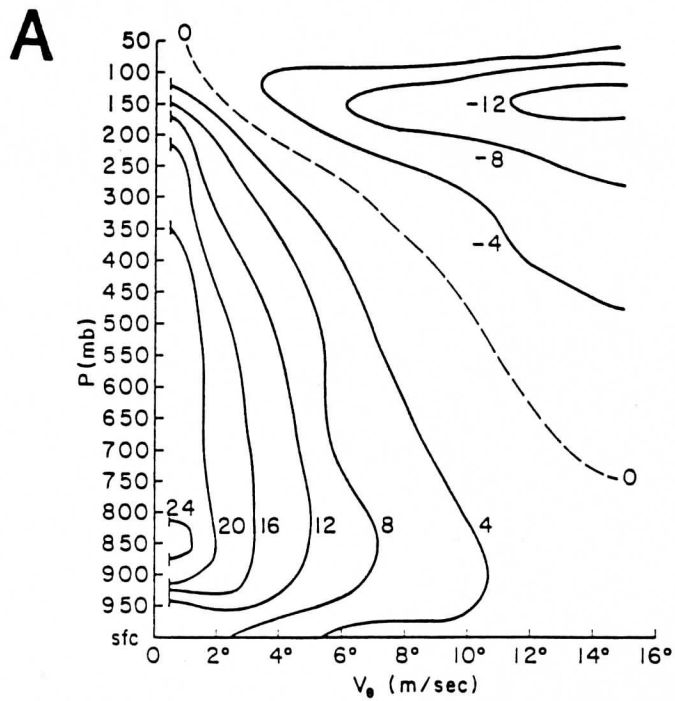
Fig. 3   Vertical cross sections of a) tangential winds and b) radial winds (ms^{-1}) for a composite mature tropical cyclone (Frank, 1977a and Gray, 1979).

c. Decay Stage

Several different conditions are associated with the decay of a mature tropical cyclone and the loss of its tropical characteristics. Decay nearly always begins when landfall occurs. However, tropical cyclones also decay over water as they travel poleward away from the warm, moist tropical air upon which they feed, and/or as they experience unfavorable large-scale flow aloft through relative movement and evolution. Rapid cyclone weakening following landfall results from a considerable reduction of sensible and latent heat transfer from the earth to the inflow layer of the hurricane and therefore a decrease in the amount of water vapor available for condensation and latent heat release. The decrease in latent and sensible energies also leads to a reduction of equivalent potential temperatures in the boundary layer of the circulation and thus the intensity and depth of the deep convection is suppressed.

Other factors which contribute to cyclone weakening include strong frictional retardation of the boundary layer wind flow over land and in flow of continental air which is typically cooler than ocean temperatures. As the hurricane moves inland over a colder earth's surface convective instability is suppressed. The cyclone often acquires subtropical or extratropical characteristics; however, it may still remain a destructive storm for some days, particularily if the vortex interacts with a mid-latitude baroclinic wave. Several decaying tropical cyclones within the United States have produced exceptionally heavy inland rainfall and consequential flooding damages far in excess of those caused during the earlier mature stage of the systems (Hebert and Taylor, 1979).

VIII. Forecasting of Tropical Cyclones

The accurate prediction of storm track, propagation speed, and intensity is a major goal of current tropical cyclone research. Given adequate time to prepare, storm damage and loss of life associated with tropical cyclones can be greatly reduced, especially in coastal regions directly affected by storm landfall. Since protective measures are time consuming and costly, overwarning causes unnecessary preparations to be made at great expense. Thus, a tradeoff exists between warning too small an area and possibly missing the landfall location and warning such a large area that time and money are wasted in unnecessary preparations. Frequent overwarning creates an apathy towards future warnings among inhabitants residing in unaffected areas and in turn increases the potential for human disaster in the future.

Given the existence of a hurricane, the most crucial aspect of tropical cyclone forecasting from the viewpoint of safety and economics is the accurate prediction of the storm track. Thus, the major emphasis of most objective forecast models has been to provide predictions of the storm track and landfall location.

Prior to about 1950, tropical cyclone forecasting relied primarily on subjective methods based on synoptic analyses and the regional climatology of tropical cyclones (Anthes, 1982). In order to predict the storm track, early forecasters established the concept of a "steering current." This concept, in which the smaller scale vortex is "steered" by the large scale wind field within which it is embedded, is still used today.

Since the 1950's, through utilization of high speed computer systems, forecast methods based upon objective techniques have been developed. These

objective forecast methods are classified under three main categories: statistical, dynamical, and hybrid. Statistical techniques use prediction equations generated from past information to forecast cyclone movement. Dynamical methods use the primitive equations (or approximations of the primitive equations) to numerically predict storm motion from an observed initial atmospheric state. Hybrid techniques produce cyclone forecasts by using forecast information from a dynamical model as input parameters for a statistical model. Of the various operational models currently in use, each has its own advantages but none appear to be clearly superior or inferior. See Anthes (1982) for an overview of commonly used objective forecast models.

With the advent of meteorological satellites in 1960, a new source of information became available to the tropical cyclone forecaster that has proven to be of great benefit. The most immediate and important benefit has been the ability to detect the existence of tropical storms globally and monitor their movement. This is particularily true in the Pacific and Indian Oceans where, prior to the advent of satellites, tropical storms frequently produced major human disasters with tens of thousands of fatallities. On several occasions hundreds of thousands have died in the tropical regions of the Eastern Hemisphere.

With the ability to detect and monitor essentially all tropical disturbances, several climatological methods based on satellite observations compiled over a number of years were developed to aid in the determination tropical cyclone intensity and to forecast storm movement (Dvorak, 1975; Fett and Brand, 1975; Ruprecht and Gray, 1976a, b). In the mid 1960's, the capability of inferring the atmosphere's vertical distribution of temperature and moisture from satellite observations was developed. However, the earliest

sensors were only able to probe the atmosphere successfully in clear or partial cloud-covered regions due to effects of clouds and also the attenuation of the radiation emitted by water vapor.

Newer operational polar orbiting satellites, NOAA-6 and NOAA-7, which house a TIROS Operational Vertical Sounder (TOVS) provide a capability to sound the atmosphere in cloudy regions through use of microwave sensors. While microwave radiation is not significantly attenuated by clouds, accurate microwave soundings are difficult to obtain because the atmosphere's outgoing radiation in these wavelengths is weak and attenuated by precipitation. At present, microwave sensing is in a relatively early stage of application in tropical analysis and prediction (Smith, 1983). However, indirect sensing of the tropics is a major emphasis of current satellite meteorology research and development.

The VISSR (Visible Infrared Spin Scan Radiometer) Atmospheric Sounder (VAS) was the first operational geostationary satellite with a capability of producing vertical atmospheric soundings. Since the location of the geostationary satellite is fixed with respect to the earth, VAS essentially produces time continuous three-dimensional probings of atmospheric temperature and moisture in cloud free regions. VAS itself does not have a microwave capability to probe the atmosphere in cloudy regions. Geopotential heights and gradient winds can be derived from analyses of the inferred temperature distribution from VAS. Methods to provide analyses of the structure and circulation of tropical storms from the combination of microwave and infrared sensing are becoming available (Smith, 1983). These include winds derived from cloud drift and water vapor motion in cloudy regions as well as gradient

winds from the thermal structure determined from satellite soundings in surrounding noncloudy areas.

The VAS/TOVS retrievals also provide real-time data over relatively large regions of the tropical ocean where conventional data is sparse. As mentioned earlier, tropical cyclone forecasters recognized long ago the need to accurately define a "steering current" to successfully forecast the storm track. One of the best indicators of this "steering current" is the deep-layer mean wind field around the storm (Chan and Gray, 1982). Veldon, et al., (1984) using VAS/TOVS data set have estimated a satellite derived deep-layer mean wind for forecasting tropical cyclone movement and have found it possible to accurately predict the short range storm track (12-14 hours) using this satellite derived "steering current" in two case studies.

As in the pre-computer and pre-satellite years, the official tropical cyclone forecast still remains a subjective one; however, it has become increasingly dependent upon information from various objective methods. An important step towards the further improvement of short range forecasts will likely be the continued development of improved forecast models that include improved methods of observing the atmosphere remotely and numerically simulating the development, maturation and decay of tropical storms. Statistical methods will also be used to correct for biases of numerical models and to include regional dependencies.

IX. Tropical Cyclone Case Study: 1983 Hurricane Alicia

Analyses from a particular case study in conjunction with video capabilities of the McIDAS provide an excellent means of illustrating the tropical cyclone scenario. Hurricane Alicia, which formed over the Gulf of

Mexico and made landfall along the Texas coast during August 1983 was only a moderate sized hurricane, yet it became the costliest storm in Texas history. Because of its major impact on the United States and the availability of both conventional and satellite data over the Gulf of Mexico and surrounding areas, Hurricane Alicia was the best candidate for this type of case study. The discussion which follows examines Alicia's life cycle from pre-development to decay, and corresponds closely to the case study segment of the accompanying module videocassette.

a.   Synoptic Conditions Prior to Genesis (12-13 August)

A well organized extratropical cyclone with a central pressure of 1006 mb at 0000 GMT 12 August was located over central Pennsylvania. A cold front extended southwestward from the low pressure center through West Virginia and Kentucky into Oklahoma. Diurnal convective activity displayed in the GOES satellite imagery sequences illustrates the location and progression of this frontal boundary as it moves slowly southward into the northern Gulf of Mexico. By 0000 GMT 14 the front had weakened and become nearly stationary.

All of the necessary conditions for tropical cyclone genesis existed over the northern Gulf region on 14 August. Sea surface temperatures in the area were in the 29 to 30°C range, well above the threshold for tropical cyclone development. Soundings from 1200 GMT for stations along the northern Gulf Coast display convective instability, high values of middle-level relative humidity and relatively weak vertical wind shear. The differences of the equivalent potential temperature between the surface and 500 mb were typically in the 15 to 20 K range found by Gray. Relative humidities between 500 and 700 mb were above 50-60% and favorable for the occurrence of deep cumulus

convection. Vertical wind shears in the region were weak, since both low and high level winds were generally westerly and of near equal magnitude.

b.   Genesis Stage (14 - 16 August)

High resolution visible imagery from 14 August indicates a well defined low level cyclonic circulation centered south of the Mississippi River delta at the western periphery of the decaying frontal boundary. Convective activity became concentrated in the vicinity of this system. The intensification and localization of the latent heat release provided the needed mechanism for increasing the upward vertical mass flux and the radial mass circulation. The cyclone vortex intensified through the convergence of angular momentum in the low troposphere within the inward branch of the radial mass circulation. The outward branch of the radial mass circulation in the upper troposphere is evident in the satellite imagery. Both the visible and infrared satellite imagery shows cirrus clouds propagating radially outward from the region of convection. The outward radial propagation of the cirrus clouds implies strong outward mass transport and thus mass divergence in the upper troposphere. Net mass divergence from the vortex is needed for development of the tropical cyclone.

A pronounced diurnal tendency in convective activity is evident in the satellite imagery during the early phases of Alicia's development. Such oscillations are commonly observed in tropical cyclones throughout their life cycle, but are particularly noticable during the genesis stage (Brower, et. al., 1977). Usually, a convective maximum occurs in the early morning hours while a minimum occurs during the late afternoon. Destabilization through emission of infrared radiation to space from high-level clouds during

the night time and stabilization through absorption of short wave radiation during the day appear to be primary mechanisms for this diurnal tendency (Anthes, 1982). Note that the oscillation in convective activity for tropical cyclones over the oceans is nearly exactly out of phase with the diurnal convection found over continental regions.

The tropical cyclone continued to gradually strengthen and was given tropical storm status (sustained winds $\geq$ 20 ms^{-1}) by the National Hurricane Center shortly before 1800 GMT 15 August. Some 18 hours later, by 1200 GMT 16 August, Alicia was a moderately intense tropical cyclone. Analyses of the 850 mb wind field for that time, based upon conventional and satellite data, show a well defined cyclonic circulation covering most of the Gulf of Mexico. The primary source of latent and sensible energy needed for the intensifying convection occurs through the inflow of maritime tropical air from the southern portions of the Gulf. Had the primary inflow been from the north or west, it is likely that Alicia would not have developed due to relatively dry continental air being drawn into its circulation.

Strong-upper tropospheric divergence remains evident in the outward spiralling of the cirrus over the Gulf at 1200 GMT 16 August. The analysis of 200 mb windflow for that time suggests that, along with the lower-tropospheric inflow, the primary outflow in the upper-troposphere is concentrated in the storm's southern sector. Soundings for 1200 GMT 16 August indicate that the environment remained favorable for development with weak convective stability, abundant mid-level moisture, and weak vertical shear. Under these conditions Alicia intensified to hurricane strength just before 0000 GMT 17 August (Fig. 4).
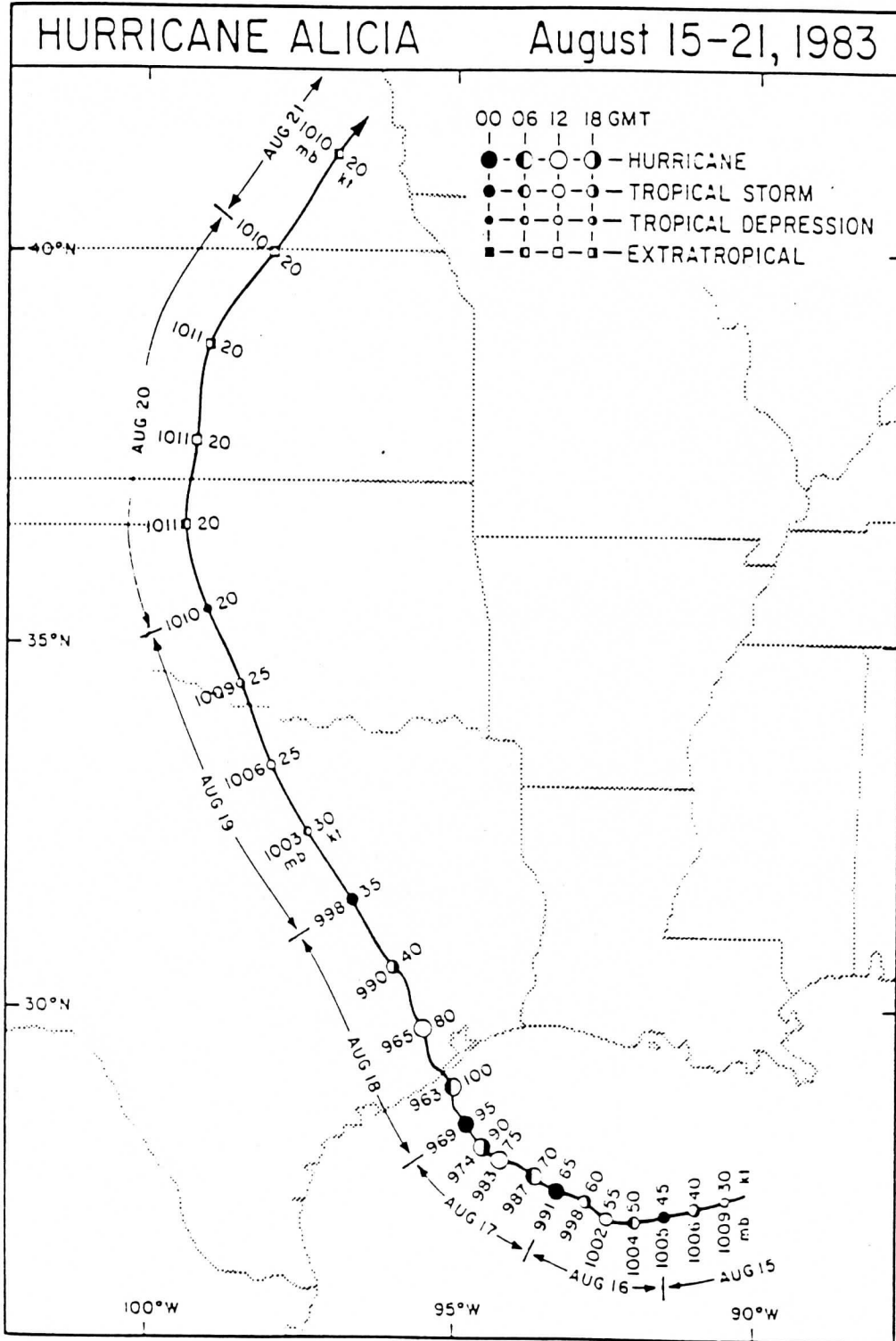
Fig. 4   Track of Hurricane Alicia 15-21 August 1983 (National Hurricane Center, Miami, Florida).

c. Mature Stage (17 - 18 August)

Hurricane Alicia attained peak intensity as it made landfall at approxiamtely 0600 GMT 18 August along the Texas coast just southwest of Galveston with a central pressure of 962 mb (Case and Gerrise, 1984). Maximum sustained winds at landfall were estimated to be 50-60 ms^{-1} (Stiegler, 1983). See figures 5 and 6. Visible and infrared imagery sequences spanning this period show the development of a well defined eye. As noted earlier, the extremely low central pressure and intense horizontal pressure gradient that are characteristic of mature hurricanes cannot be achieved without eye formation. One unusual aspect of Alicia's eye was its relatively large diameter of 30 km at landfall. Typically, diameters of eyes range between 10 and 20 km for tropical cyclones of Alicia's size and intensity.

Microwave soundings of the upper tropopsphere for 2100 GMT 17 August, obtained via the TOVS instrument aboard the NOAA-6 polar orbiting satellite, provide clear evidence of the hurricane's upper warm core structure. Estimates of central pressure and maximum winds for that period based upon satellite microwave sounding data (Dvorak, 1975) compared favorably with the values measured by reconnaissance aircraft. Techniques such as this are becoming widely used for estimating tropical cyclone intensities, while storms are over mid-oceanic regions and out of reconnaissance aircraft range (Velden and Smith, 1983).

In addition to satellite derived information, radar data provide an important means of remotely sensing and studying tropical cyclone structure and evolution. Radar observations from the National Weather Service at Galveston and from Texas A & M University at College Station clearly portray Alicia's circular, precipitation free eye and the surrounding eyewall
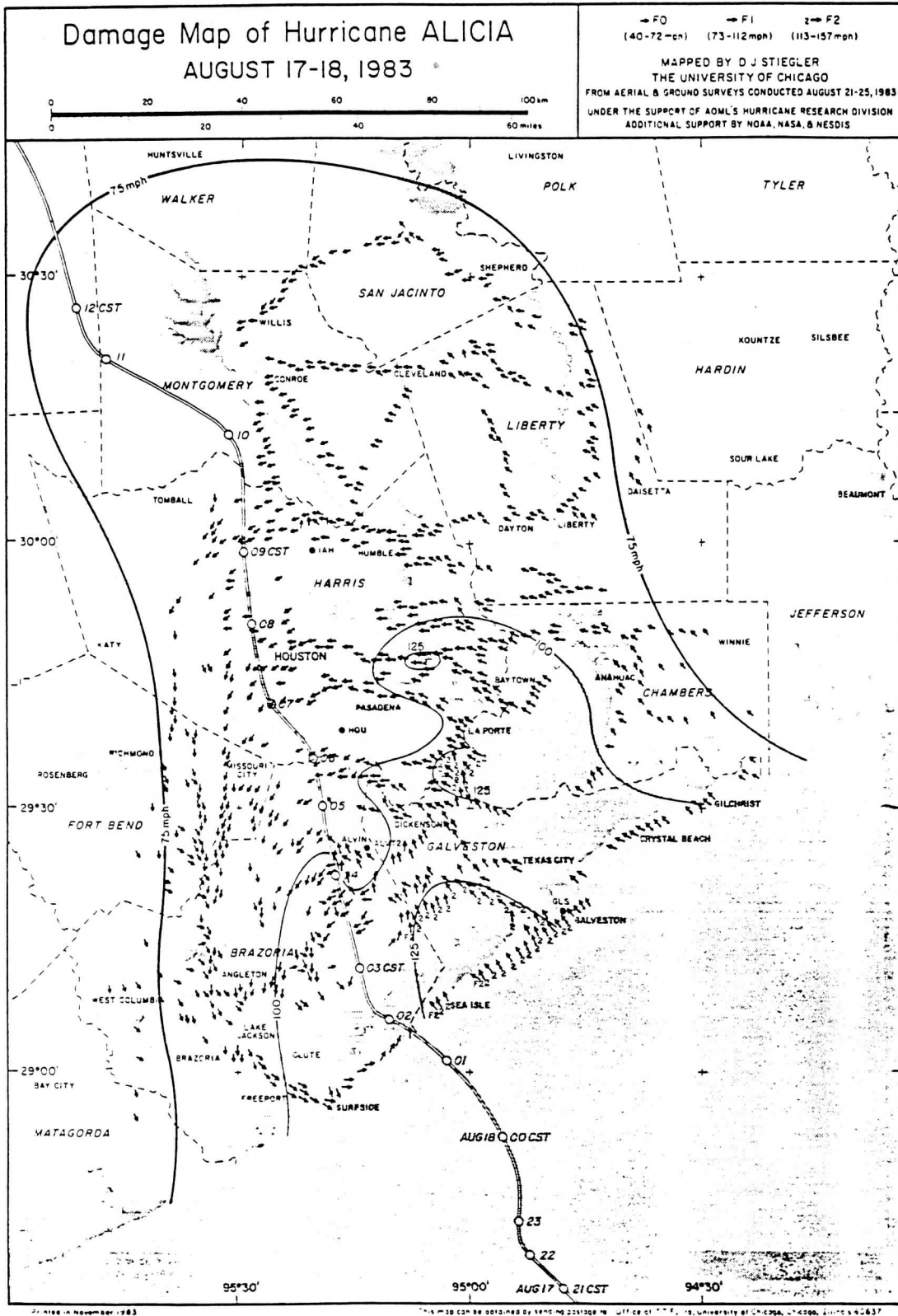
Fig. 5   Estimate of maximum winds experienced during the period 17-18
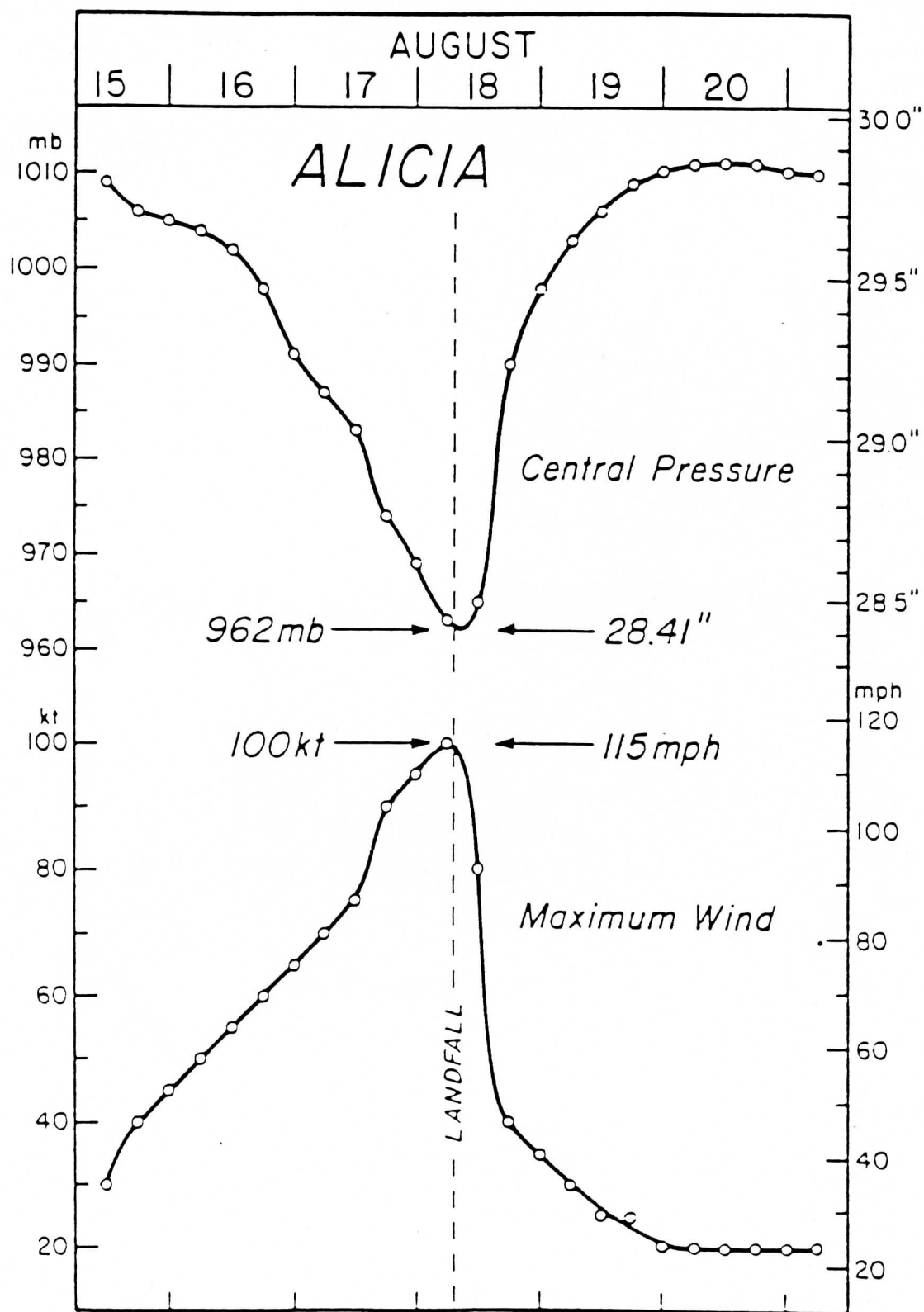   August 1983 (Stiegler, 1983).

Fig. 6   Time series of central pressure and maximum sustained winds for
Hurricane Alicia 15-21 August 1983 (National Hurricane Center,
Miami, Florida).

convection, along with the several spiral bands of enhanced precipitation embedded in the circulation. The radar imagery also shows the eyewall rupturing and the precipitation area becoming more asymmetrically distributed about the center after the hurricane crosses the coastline. A pronounced reduction in echo intensity occurred to the west of the center over land, while intense banded convection persisted to the east over the Gulf. The lack of sufficient water vapor within the dryer continental air in the western portion of the circulation is a likely cause for the rapid decrease in precipitation in this region. Meanwhile, the convection in the eastern portions of the storm continued to persist as the supply of tropical moisture through inflow over the Gulf of Mexico was better able to sustain activity. Both the radar and satellite imagery show a continued decrease in the overall circulation of Alicia as the hurricane moved inland. By 0000 GMT maximum winds had diminished to less than 33 ms^{-1} and the intensity of the system was downgraded to tropical storm status.

d. Decay Stage (19 - 21 August)

As with most decaying tropical cyclones, Alicia gradually lost the characteristics of a warm core vortex and evolved into an extratropical cyclone. During this period, the system continued to produce substantial precipitation throughout the southern and central Great Plains. The rainfall, although heavy, was largely beneficial to those areas since these areas had been experiencing a severe drought during the summer of 1983. Finally, the infrared sequence for this period shows the resumption of a continental type diurnal oscillation in the convective activity with a daytime maximum and night-time minimum as the cyclone moved more rapidly north-northeast and

merged with a middle latitude frontal system over the Great Lakes on 21 August.

Acknowledgments

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Appendix A: MODULE EVALUATION

The utilization of videocomputer technology in educational modules provides an innovative resource capable of enhancing classroom instruction. An important step in the development of these modules is feedback from instructors and students to evaluate the impact of this educational resource to facilitate improvements in module content and quality. Students are requested to evaluate this module using copies of the enclosed questionnaire. The instructor is requested to enclose a summary of how the module was utilized, the student's impression of its effects upon the course work and suggestions for improvement. Input from previous module utilization within the Department of Meteorology at the University of Wisconsin-Madison has led to revisions in the videocassette.

a. Instructor Evaluation form

In the development of educational modules a critique by faculty and students who have used the materials is essential. A student questionnaire is included in each module package. Student response will aid in modifications of the module being tested as well as help in future module development. A thorough instructor critique of the module is also indispensable. Therefore, faculty members involved in the utilization of the module are urged to complete this questionnaire and offer other comments that would make the module more effective.

Part I Summary

Please evaluate each of the following module components. Space is
provided after each statement to state briefly the basis for your response.
More detailed comments are sought in Part II of this questionnaire.

	Ex.	Very Good	Good	Fair	Poor
Videocassette visual quality					

Basis of rating:

	Ex.	Very Good	Good	Fair	Poor
Thoroughness and usefulness of the images, fields and graphics displayed in the videocassette					

Basis of rating:

	Ex.	Very Good	Good	Fair	Poor
Organization of videocassette materials					

Basis of rating:

	Too Long	Long	Just Right	Short	Too Short
Overall length of the videocassette					

Basis of rating:

	Too Long	Long	Just Right	Short	Too Short
Length of individual sequences					

Basis of rating:

	Ex.	Very Good	Good	Fair	Poor
Quality and usefulness of written material within the manual					

Basis of rating:

Map package and data base quality
(if applicable)

| | Very | | | |
Ex.	Good	Good	Fair	Poor

Basis of rating:

Audiotrack

| | Very | | | |
Ex.	Good	Good	Fair	Poor

Basis of rating:

Instructor evaluation forms

| | Very | | | |
Ex.	Good	Good	Fair	Poor

Basis of rating:

Student evaluation forms

| | Very | | | |
Ex.	Good	Good	Fair	Poor

Basis of rating:

Part II Instructor Discussion

1)   Please discuss how you utilized this module; include a) class description, b) how the module was integrated into the course structure, and c) the amount of classroom time and homework required.

2)   In what ways (if any) did the module assist you in achieving your classroom goals? What are the modules weaknesses?

3)   How would you change the module to make it more suitable for your needs? Why?

4)   Please suggest improvements to:

The manual:

The map package and data base: (If Applicable)

The videocassette:

5)   In your judgement does this type of material improve atmospheric science
education? If you found the modules to be an improvement, how was the
improvement attained (please cite examples)?

6)   How important do you feel this type of material will be in the future of
atmospheric science education?

7)   Additional comments.

b. Student Evaluation form

The module was constructed with the intention to support a series of lectures
and additional readings. It can present considerable difficulty if used in
too rapid a fashion. Please keep these ideas in mind as you complete the
evaluation. This evaluation is intended to judge the effectiveness of the
videotape as a teaching tool in atmospheric science. Your answers will help to
improve the quality of tapes such as this. Please write a short response in
the space provided below. Thank you.

1) What was the overall pace of the presentation of the material in the
    classroom

    Fast   _____

    All right _____

    Slow   _____

    Comments:

2) Was the visual quality of the tape acceptable (were you able to
    distinguish important features)?

    Good   _____

    All right   _____

    Needs improvement   _____   (please state where)

    Comments:

3)   Did the module help you to better understand the tropical cyclone?

     If yes, how?

4) Please indicate how helpful each of the following sections of the
   videotape was in aiding your understanding of the topic.

		Very Helpful	Somewhat Helpful	Knew all the material already	Not Helpful
I	Tropical cyclone development				
II	Tropical cyclone structure and circulation				
III	The use of satellite techniques for investigating tropical cyclones				
IV	Case study of a complete tropical cyclone life cycle: 1983 Hurricane Alicia				

     Comments:

5)   Is there other material you would like to see on this tape?

6)   Were there any portions of the videocassette that you feel did not
     contribute or did not present the material well? Explain.

s the audio track (if used) of value to your understanding of the tape
ntents?

s   _____

mewhat   _____

           _____

mment:

you think this tape has been an eduational aid to the material
esented in this class? Why?

y additional comments?