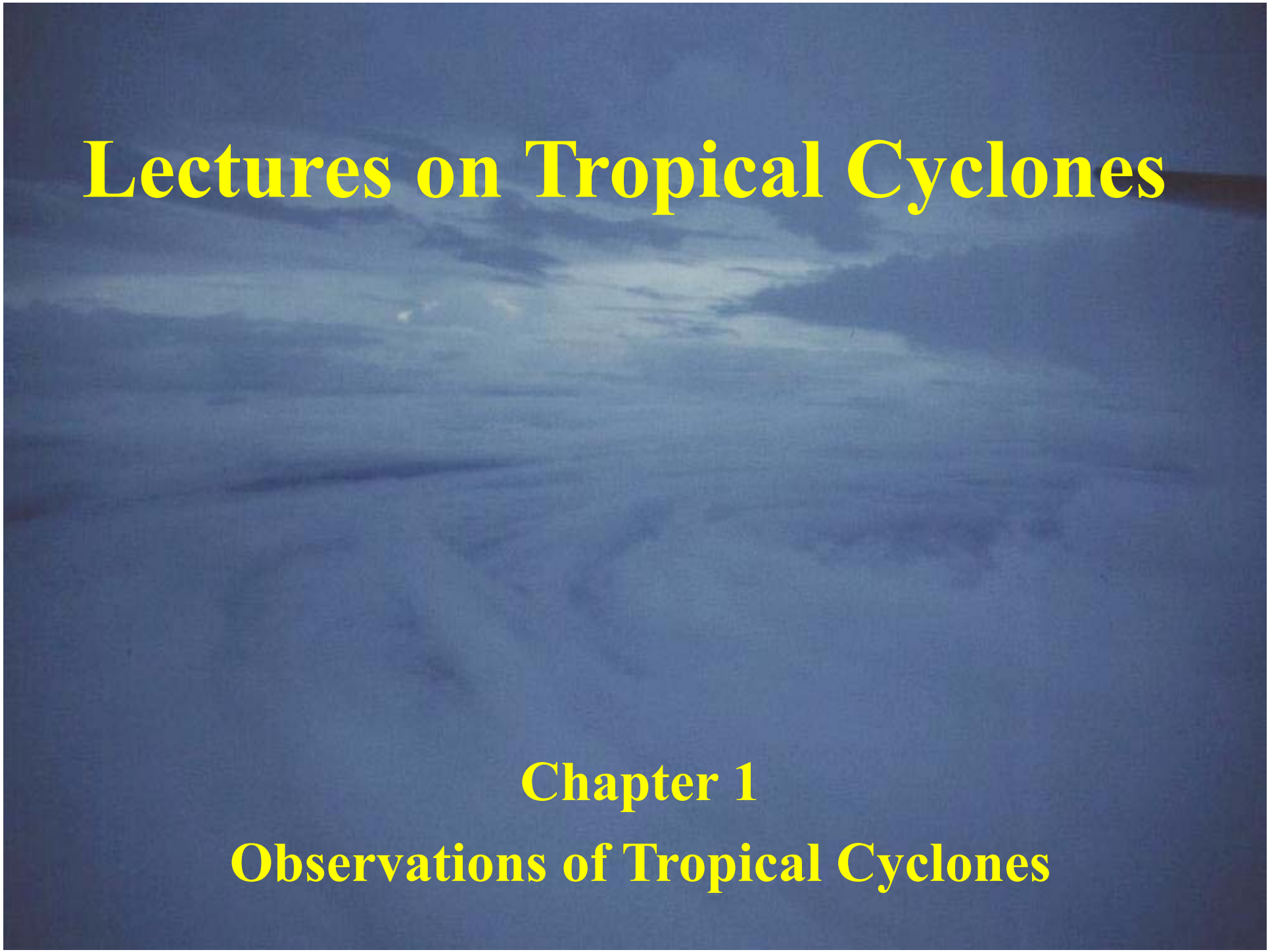


Lectures on Tropical Cyclones

Chapter 1

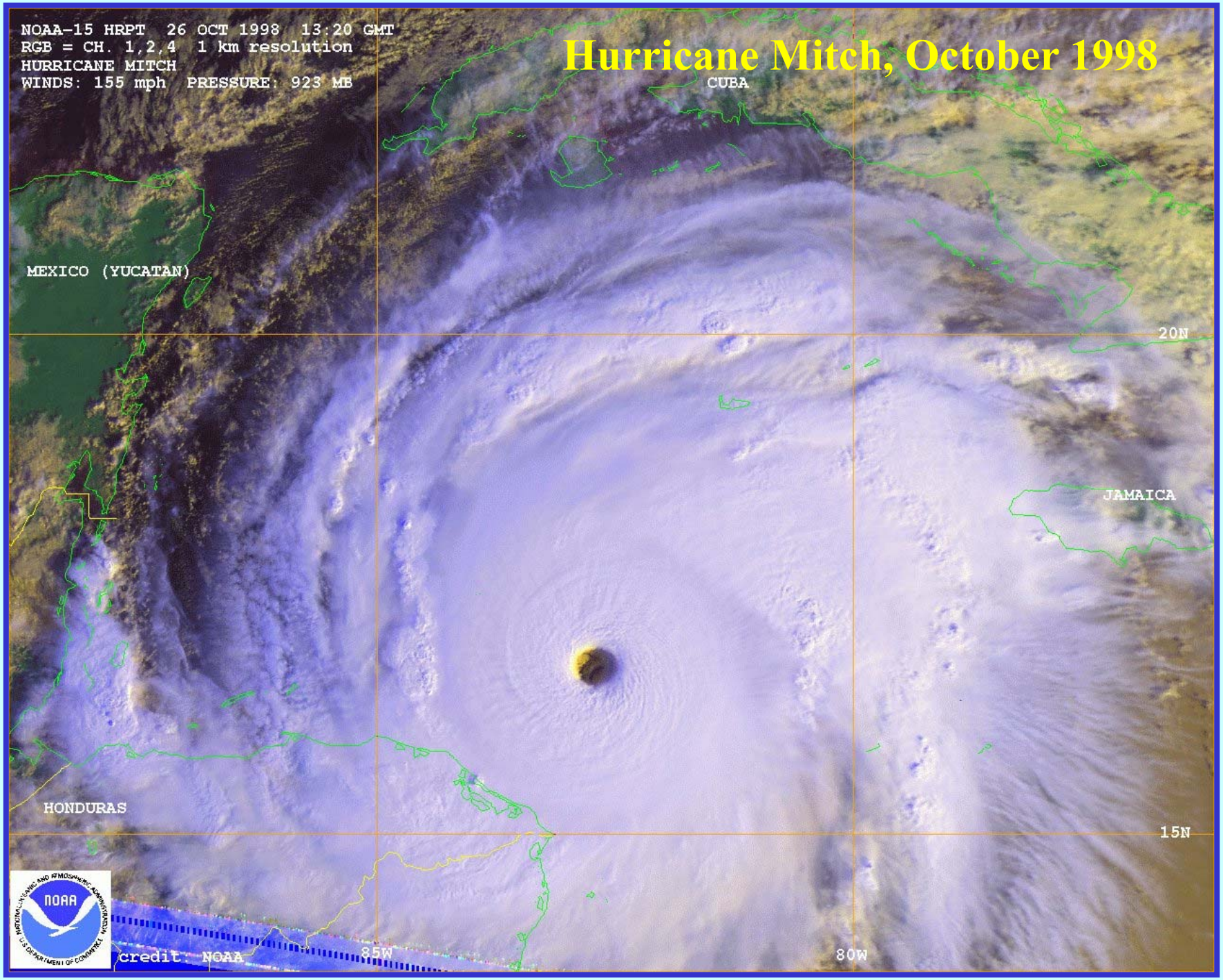
Observations of Tropical Cyclones

Course outline

- Introduction, Observed Structure
- Dynamics of Mature Tropical Cyclones
  - Equations of motion
  - Primary and secondary circulation
  - Tropical cyclone boundary layer
  - The role of moist convection
  - The sloping eyewall
  - The tropical cyclone eye
  - A model for the boundary layer
  - Tropical cyclone motion

Reading material

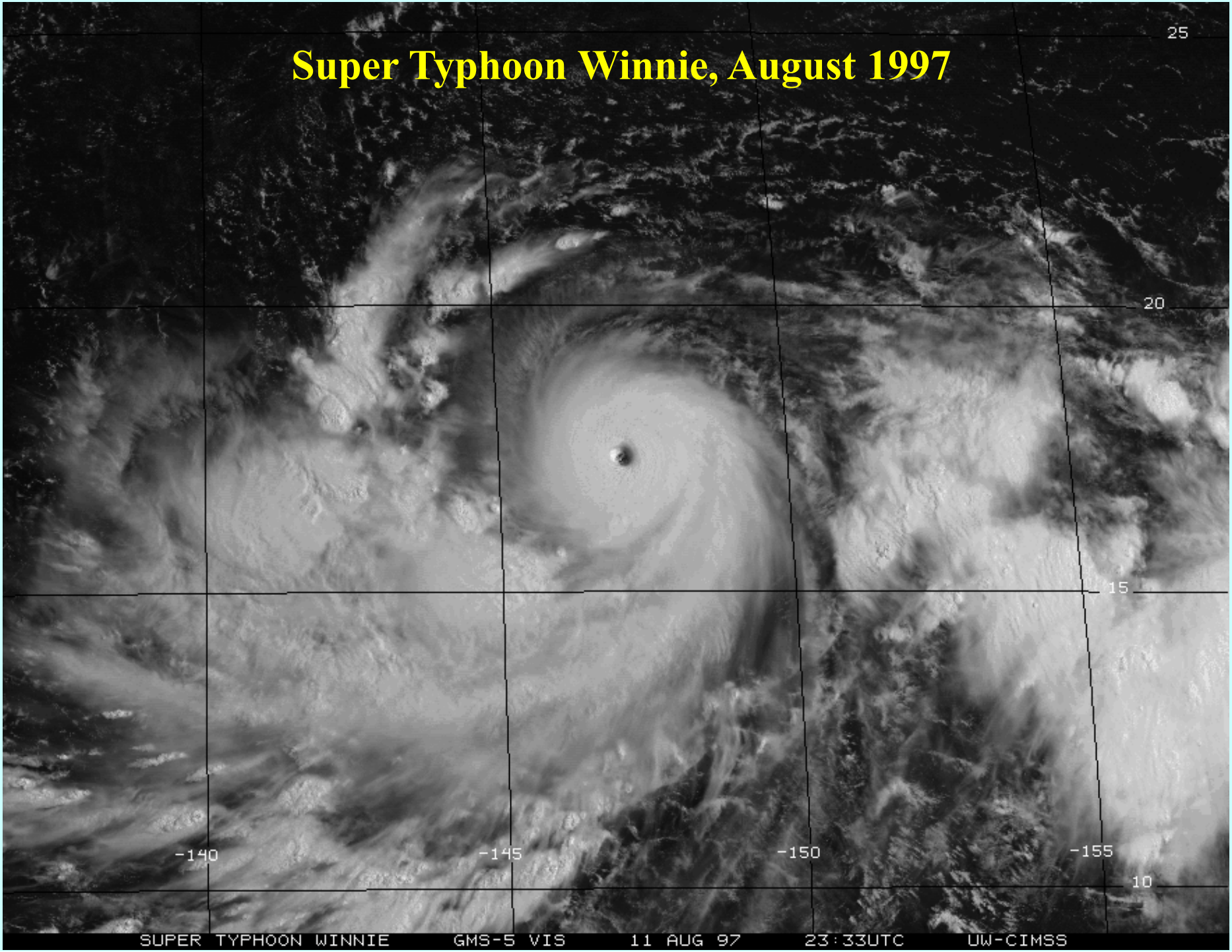
- **Anthes (1970), Tropical Cyclones, AMS Monograph**
- **Anthes (1974), The *dynamics and energetics of mature tropical cyclones, Rev. Geophys. Space Phys.*, 12, 495-522**
- **WMO Tech. Note (1995) *Ed. R. L. Elsberry***
  - ***H. E. Willoughby* Mature structure and evolution**
  - ***J. L. McBride* Tropical cyclone formation**
- **Paradigms for tropical-cyclone intensification. *(2014) Montgomery and Smith***
- **The fluid dynamics of tropical cyclones. *(2017) Montgomery and Smith***
- **Cloud Dynamics, 2nd edition *(2014) Robert Houze***
- **http://www.meteo.physik.uni-muenchen.de/~gerard.kilroy/**

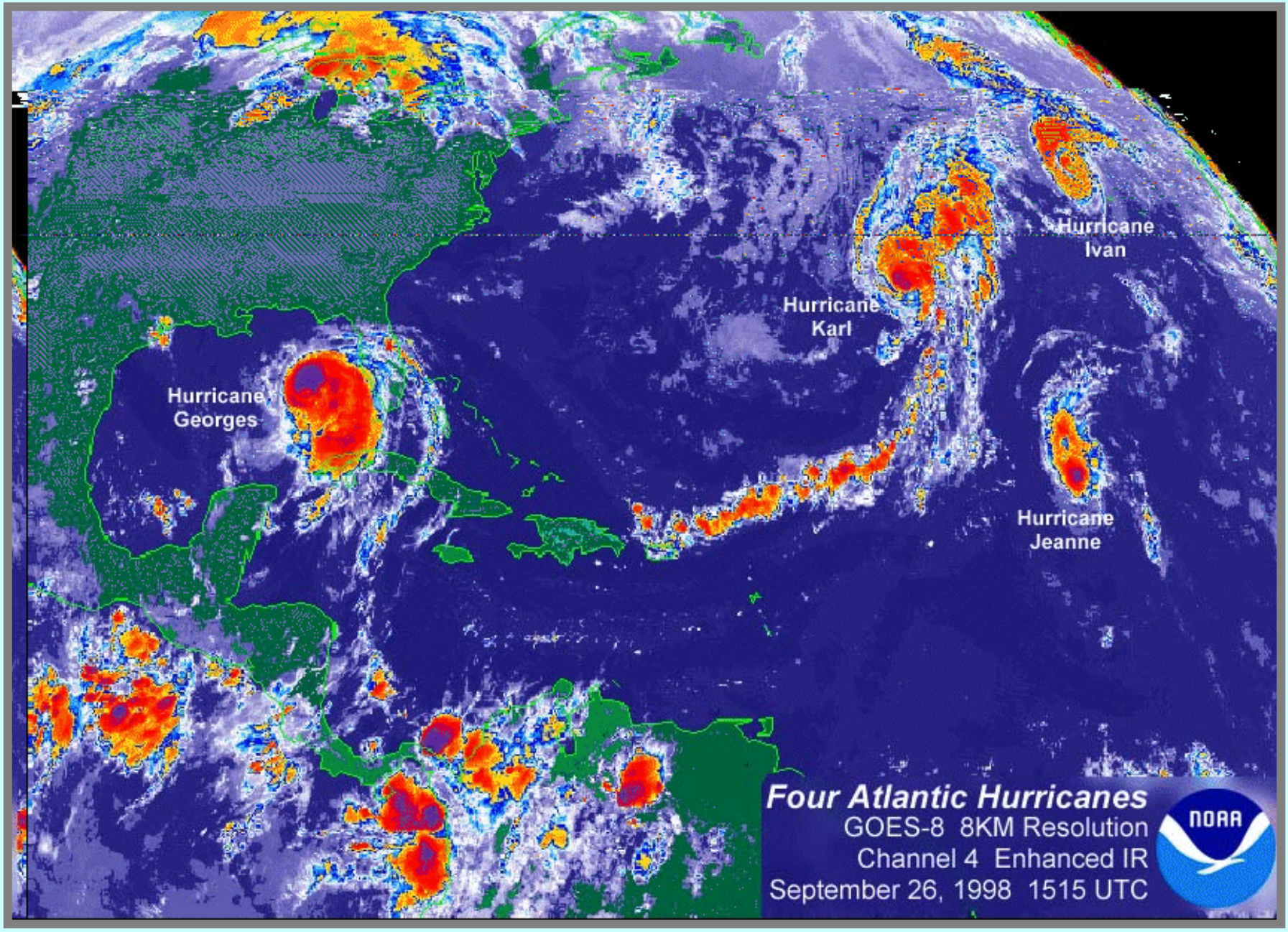

NOAA-15 HRPT 26 OCT 1998 13:20 GMT
RGB = CH. 1,2,4 1 km resolution
HURRICANE MITCH
WINDS: 155 mph PRESSURE: 923 MB
Hurricane Mitch, October 1998
CUBA
MEXICO (YUCATAN)
20N
JAMAICA
HONDURAS
15N
NOAA
credit: NOAA
85W
80W

Tropical Cyclones

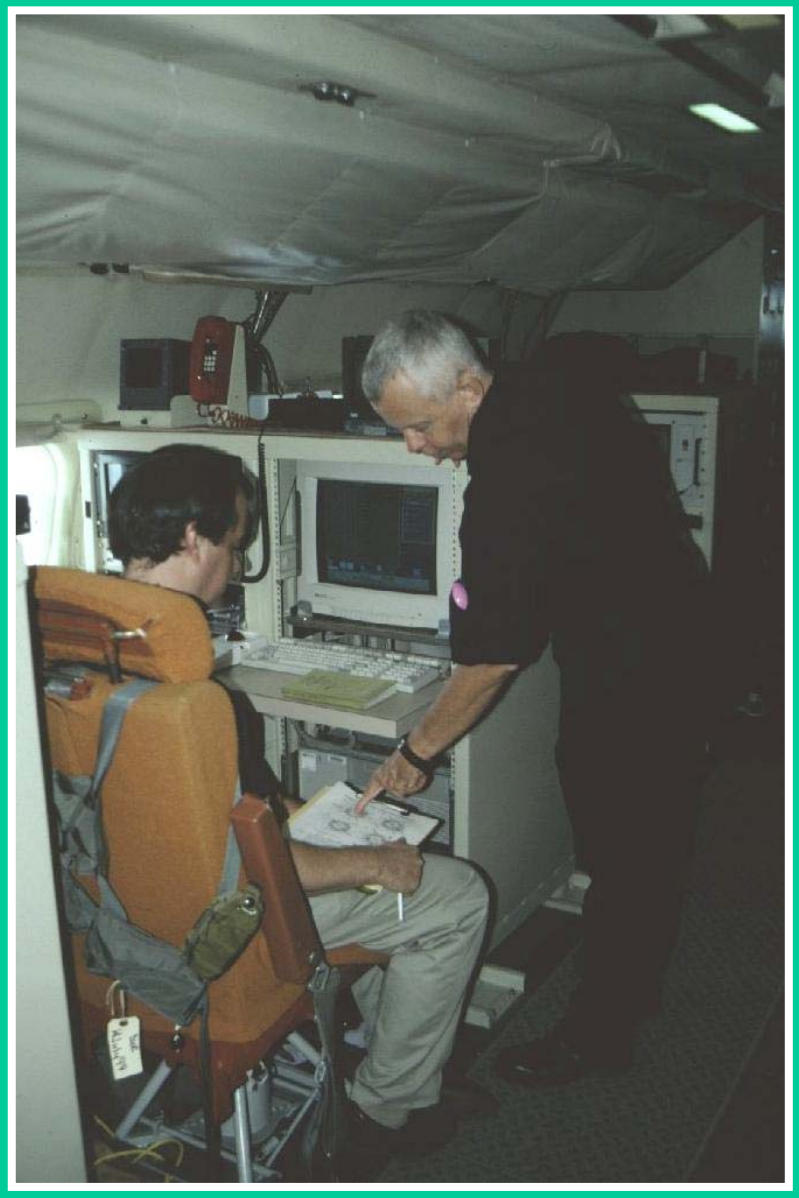
- Tropical cyclones are intense, cyclonically-rotating, low-pressure weather systems that form over the tropical oceans.
- Cyclonic means counter clockwise in the northern hemisphere and clockwise southern hemisphere
- Intense means that sustained wind speeds exceed 17 m/s (60 km /h, 32 knots) near the surface.
- Severe tropical cyclones have near surface sustained wind speeds equal to or exceeding 34 m/s (120 km/h, 64 knots): these are called hurricanes over the Atlantic Ocean, the East Pacific Ocean and the Caribbean Sea, and Typhoons over the Western North Pacific Ocean.
- Typically the strongest winds occur in a ring some tens of kilometres from the centre and there is a calm region near the centre, the eye, where winds are light.

Super Typhoon Winnie, August 1997




Hurricane
Ivan
Hurricane
Karl
Hurricane
Georges
Hurricane
Jeanne
Four Atlantic Hurricanes
GOES-8 8KM Resolution
Channel 4 Enhanced IR
September 26, 1998 1515 UTC
NOAA

Hurricane Research Aircraft, NOAA WD-P3




SONY
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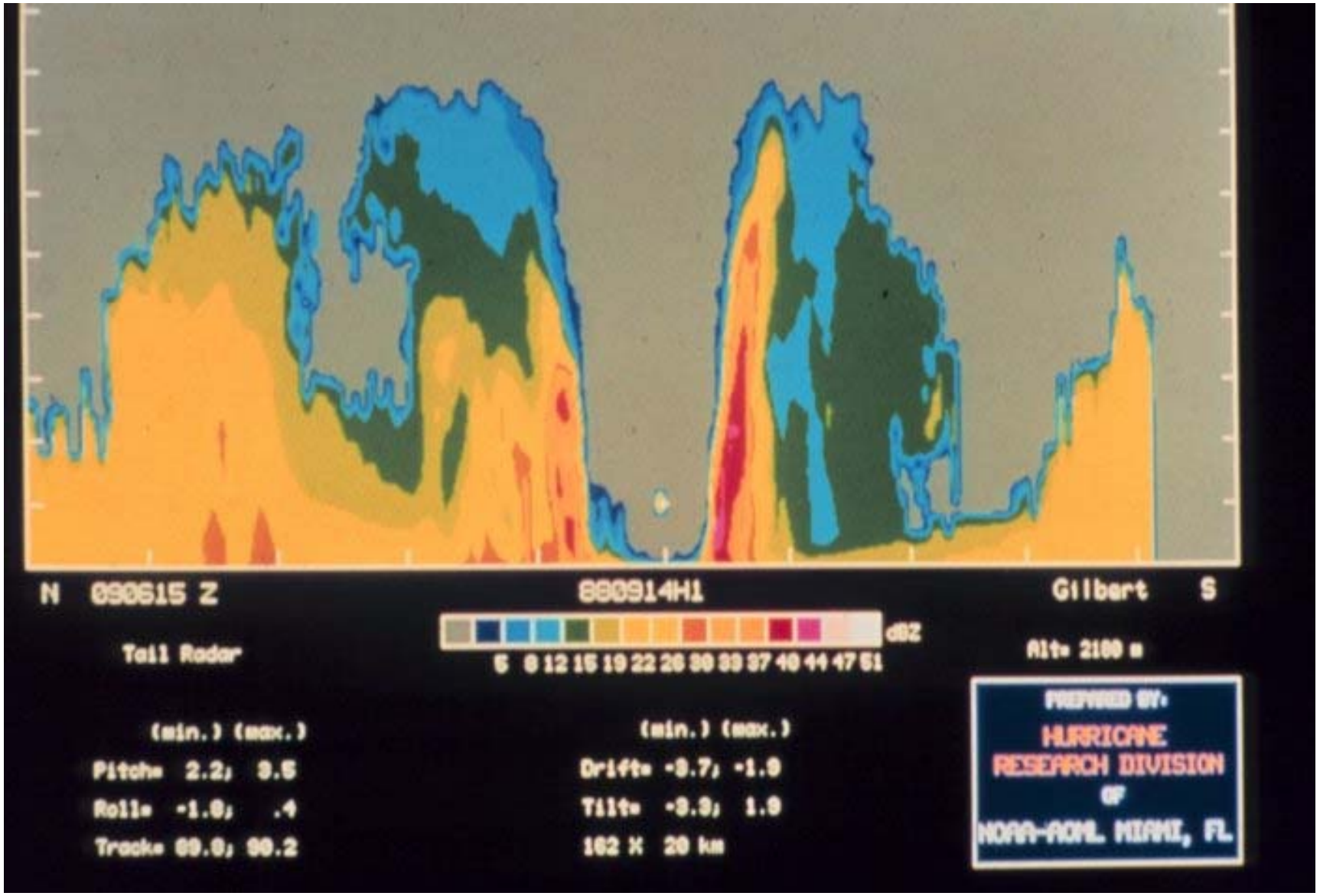
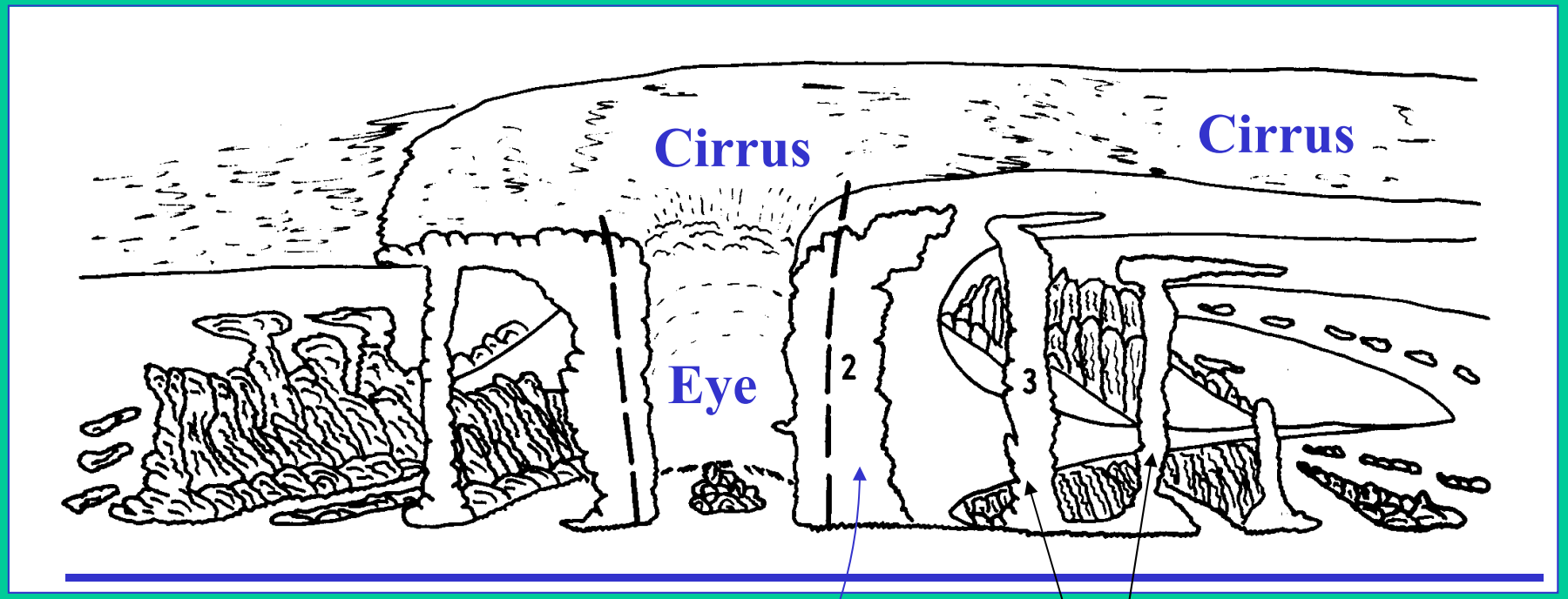
Structure

- The mature tropical cyclone consists of a horizontal quasi-symmetric circulation on which is superposed a vertical, or transverse circulation.
- These are sometimes referred to as the primary and secondary circulations, respectively.
- When combined, these two component circulations result in a spiralling motion with inflow at low and middle levels and outflow at upper levels.
- The secondary circulation is mostly thermally-direct, which means that warm air rising, a process that releases potential energy.
- However subsidence occurs in the eye and the circulation there is thermally indirect, a process that requires energy to be supplied.

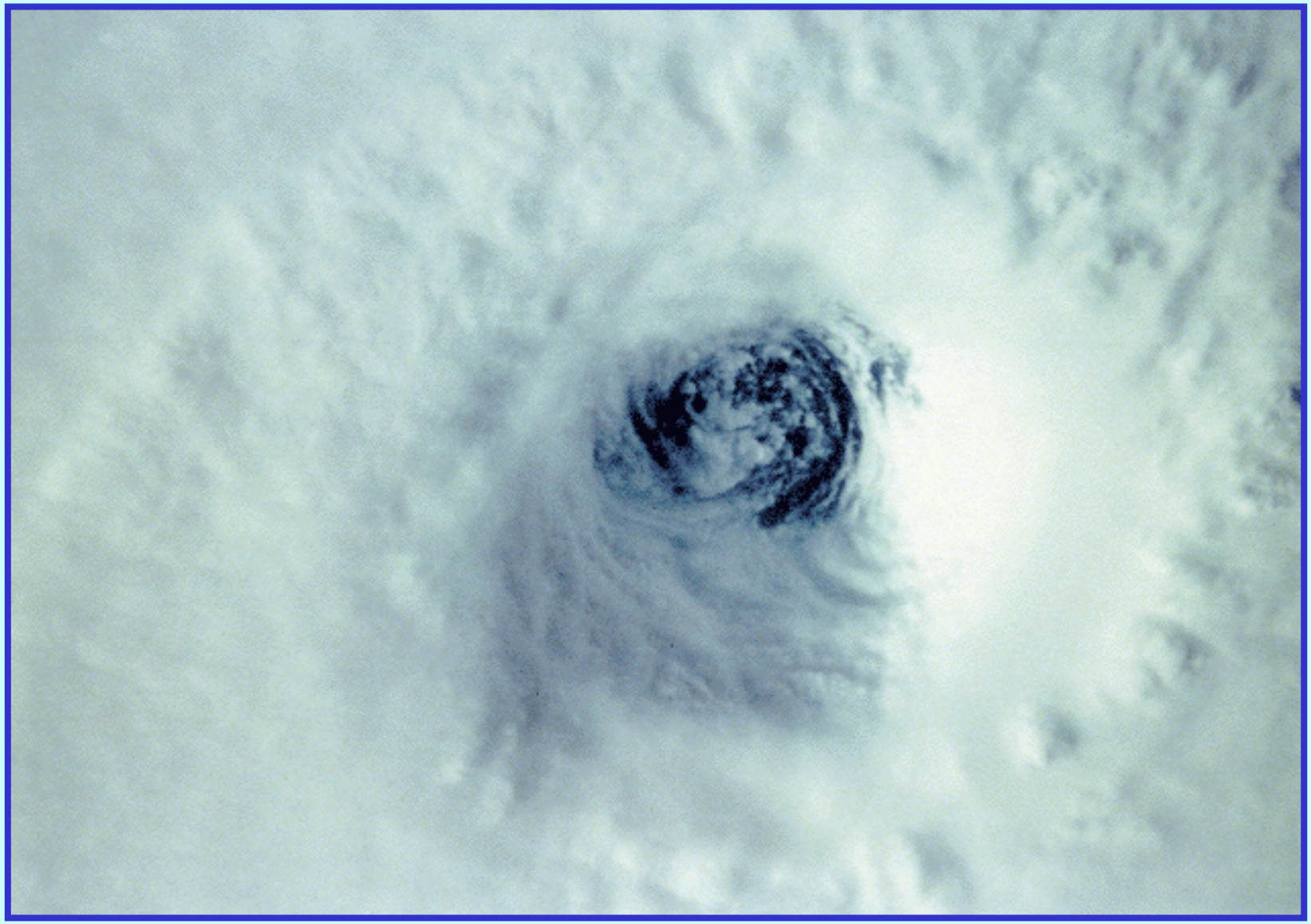
Radar display from the tail radar



Schematic cross-section through a hurricane

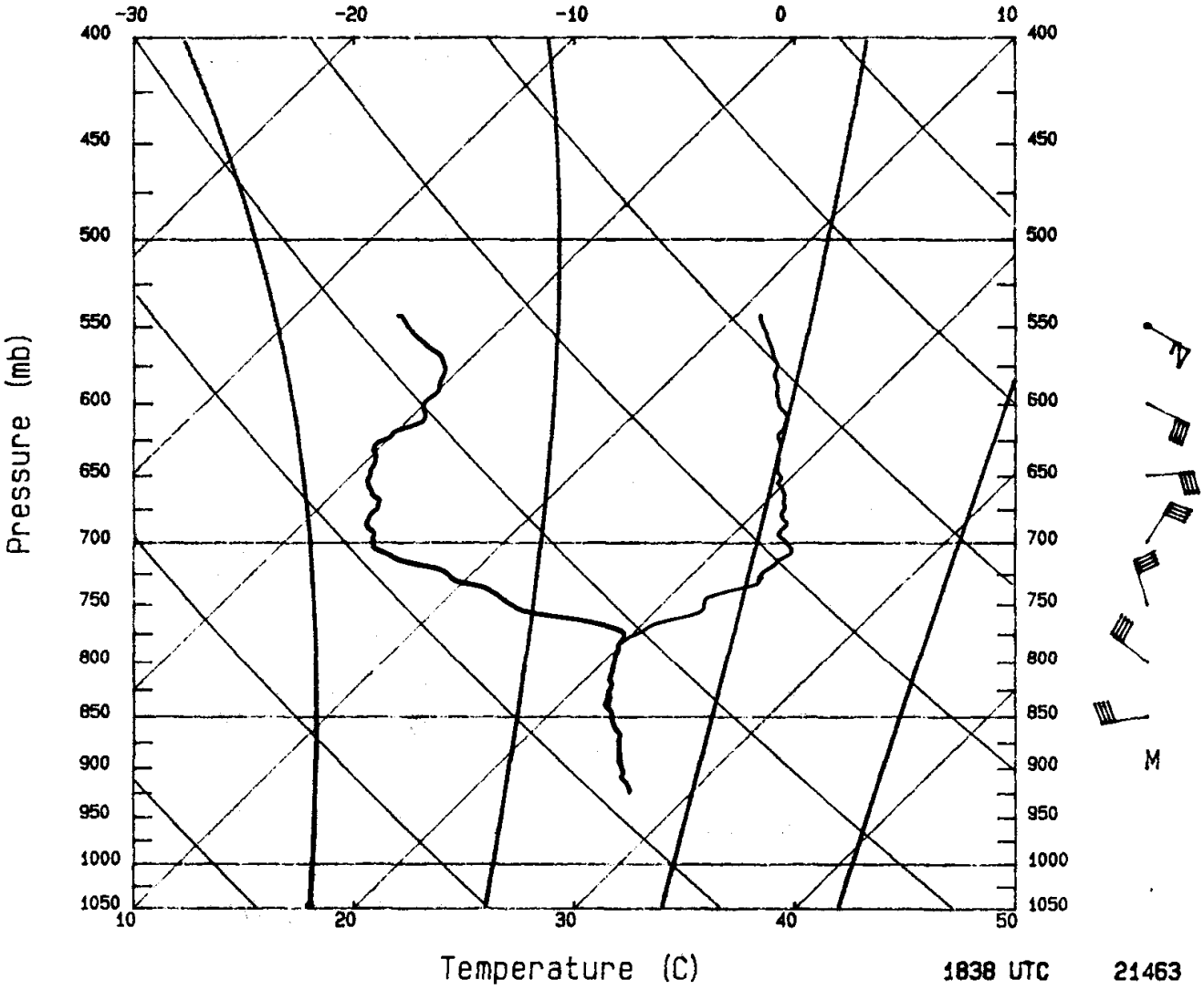


Close up photograph of the eye



The eye of Hurricane *Lili* (2002)

Dropwindsonde sounding in the eye of a hurricane



From Willoughby (AMM, 1988)

Radar PPI in Hurricane Gilbert (1988)

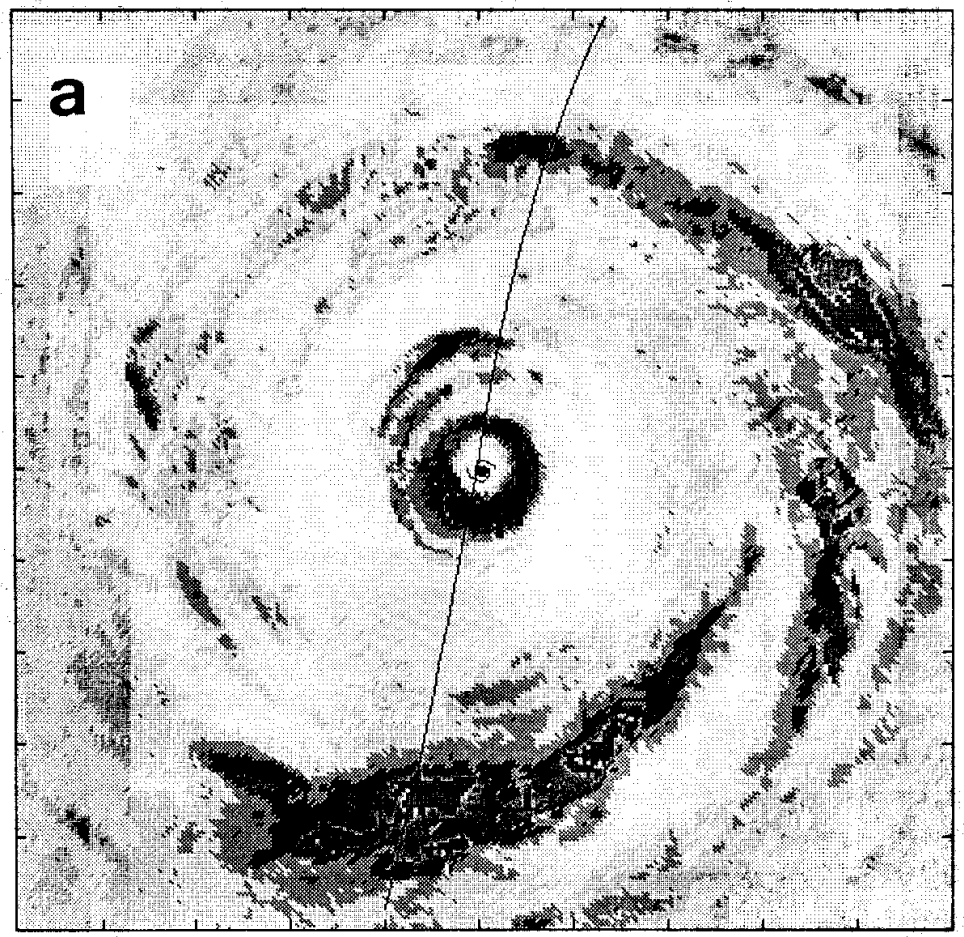
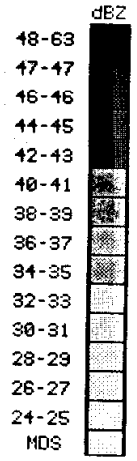
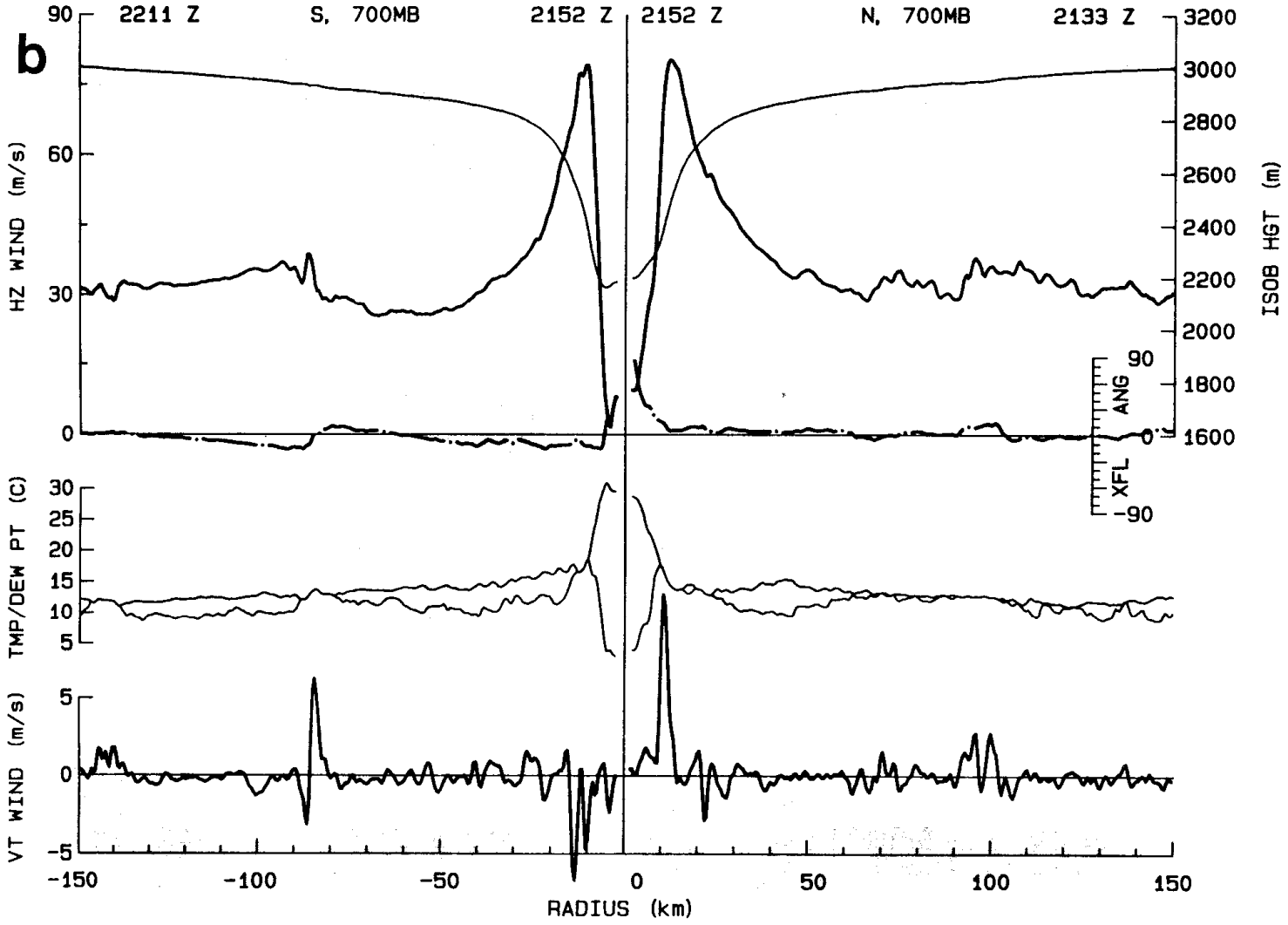


Fig. 2.4 (*a*) Plan-position indicator (PPI) radar reflectivity composite of Hurricane Gilbert at ~2200 UTC 13 September 1988, when it was at maximum intensity near 19.9°N, 83.5°W. (*b*) Flight-level measurements from research aircraft. The abscissa is distance along a north-south pass through the center. The top panel shows wind speed (dark solid line), 700 mb height (light solid line), and crossing angle ($\tan^{-1} u/v$, dash-dotted line). Winds are relative to the moving vortex center. The middle panel shows temperature (upper curve) and dewpoint. When $T_D > T$, both are set to $1/2(T+T_D)$. The bottom panel shows vertical wind (Black and Willoughby 1992).



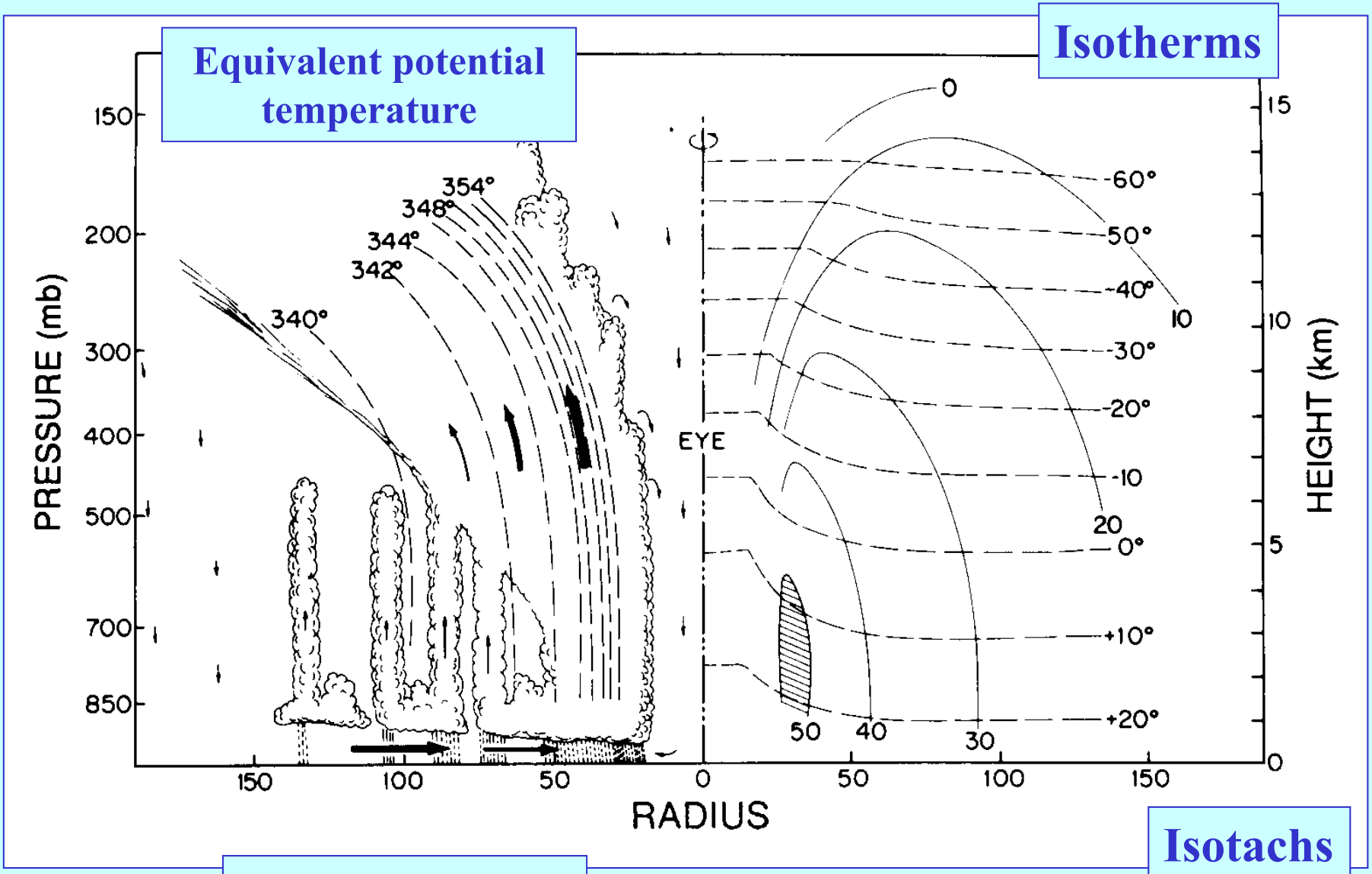
From Black & Willoughby (JAS, 1992)

Flight level data from a Hurricane traverse



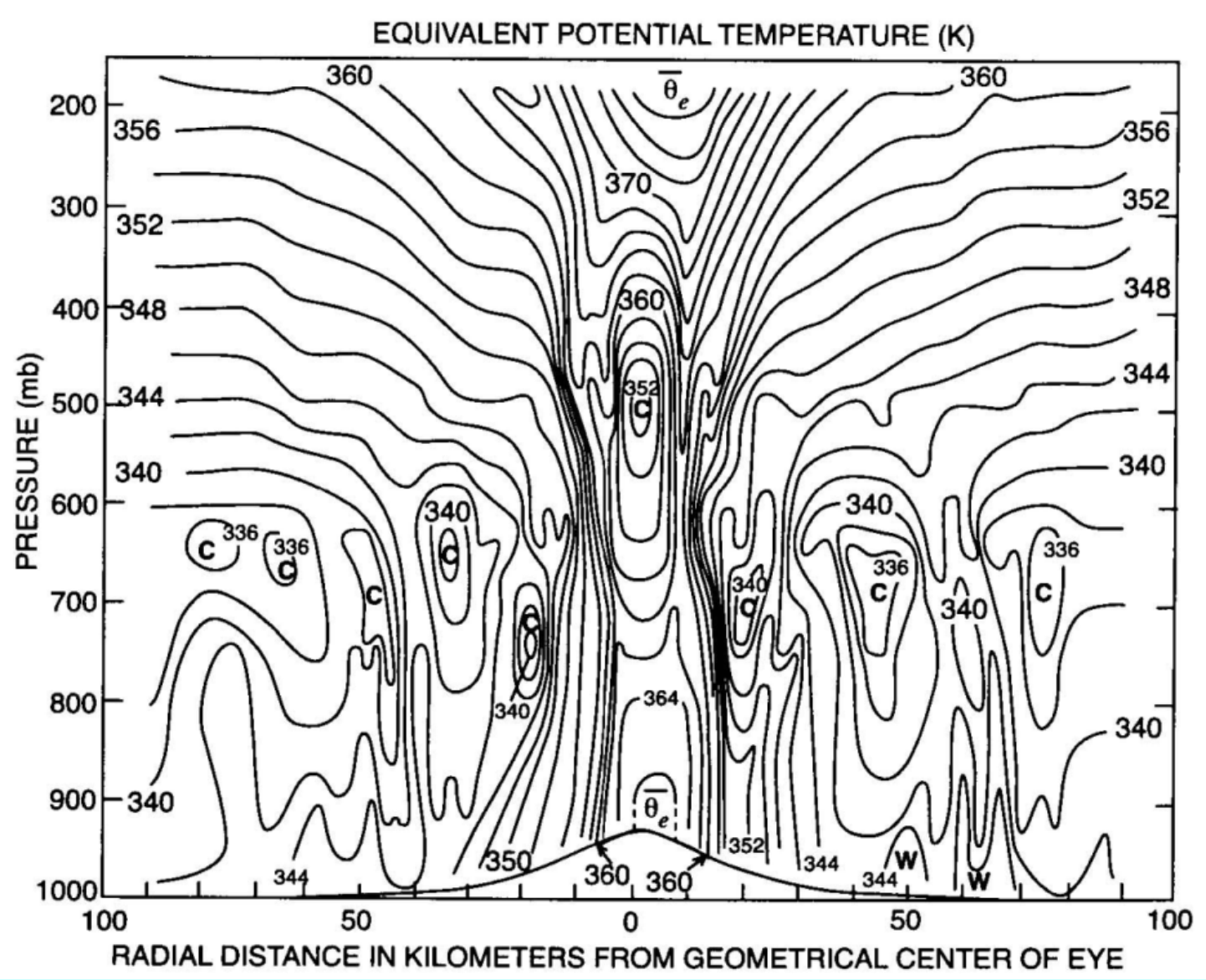
From Willoughby (WMO, 1995)

Vertical-radial cross-section through a mature hurricane



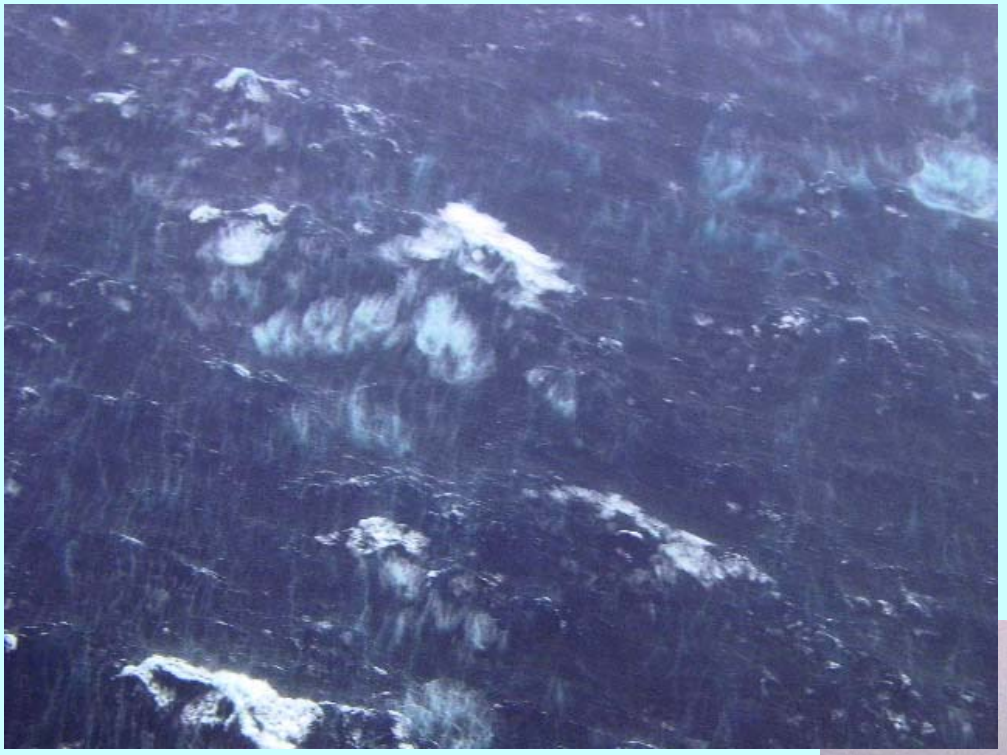
From Wallace and Hobbs (1977)

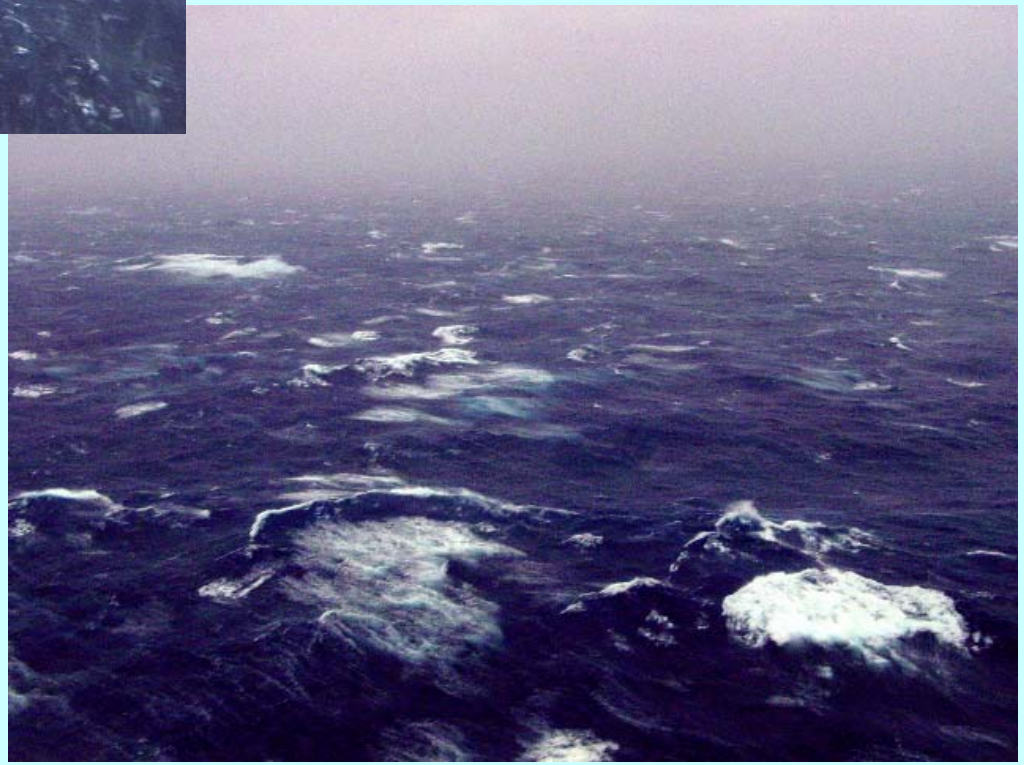
Vertical-radial cross-section through a mature hurricane



From Hawkins and Imbembo (1976)

Sea surface fluxes



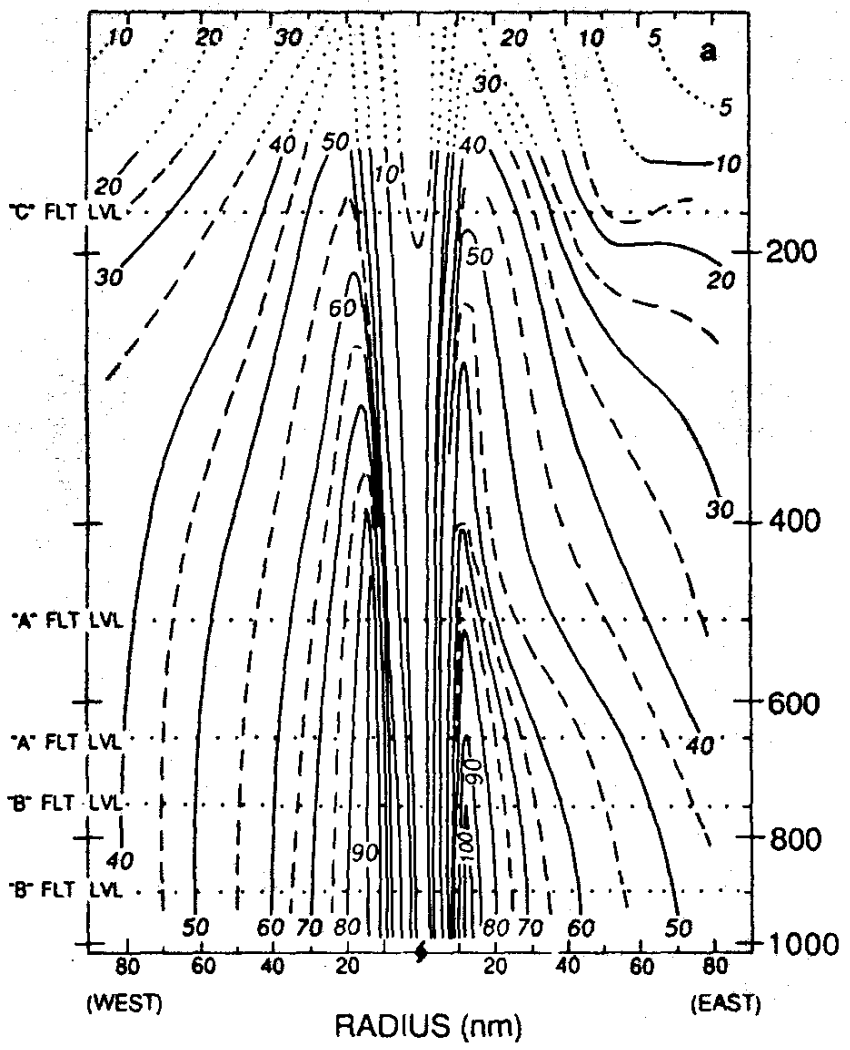


Strength, intensity and size

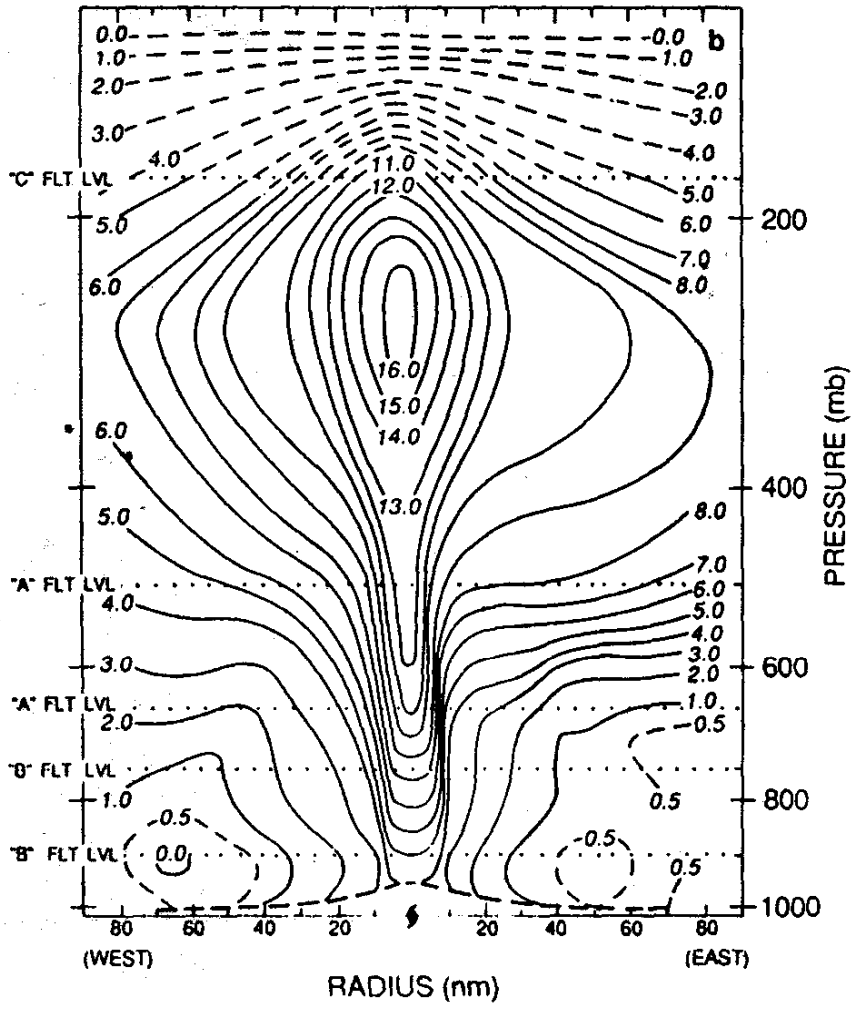
- Intensity is conventionally measured in terms of maximum wind or minimum sea-level pressure
- Strength is a spatially-averaged wind speed over an annulus between 100 and 250 km from the cyclone centre.
- Size which may be defined as the average radius of gale force winds (17 m s^{-1})
- Observations show that size and strength are strongly correlated, but neither is strongly correlated with intensity.

Vertical cross-section of Hurricane Hilda (1964)

From Hawkins and Rubsam (MWR, 1988)

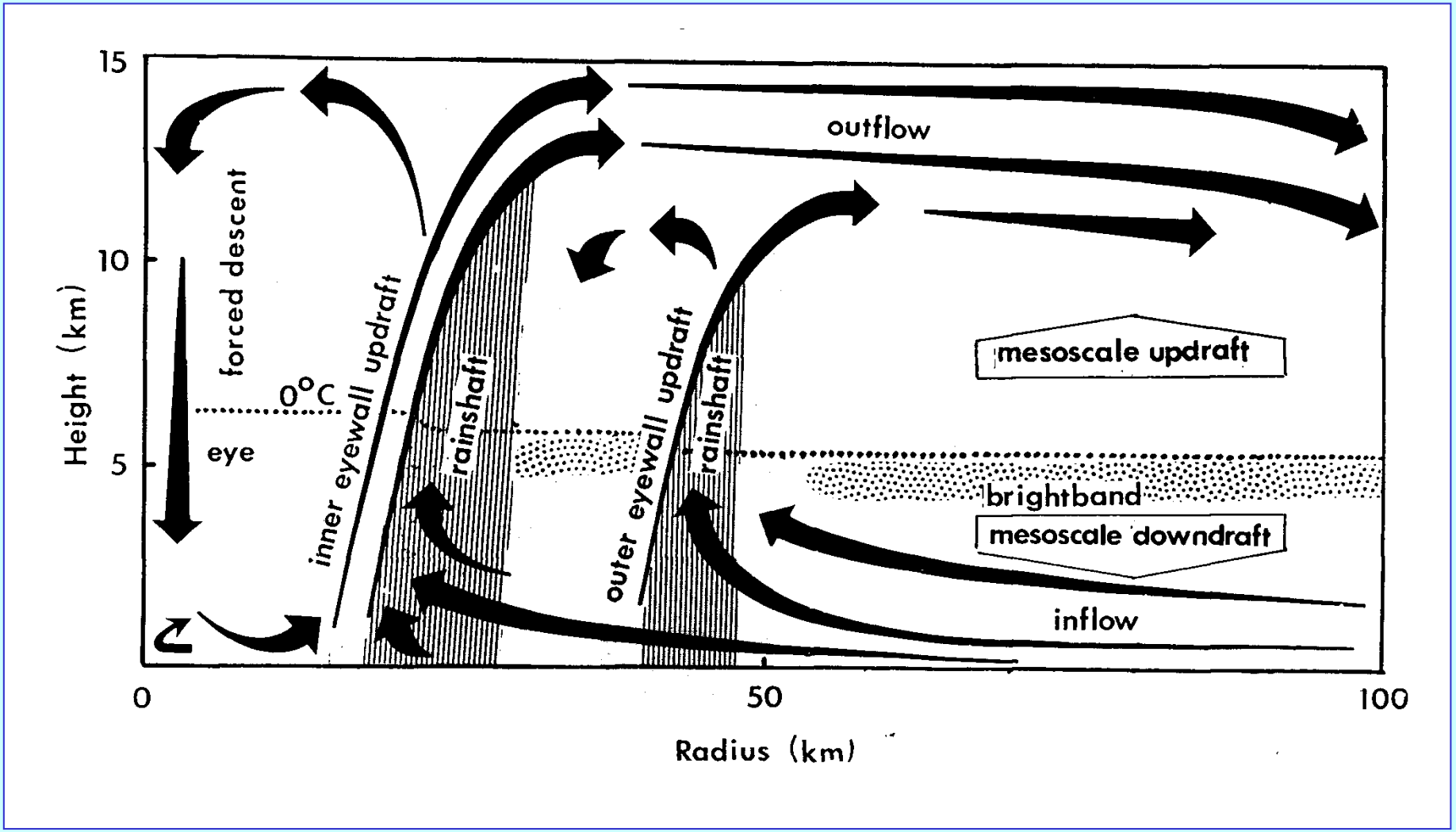


Azimuthal wind



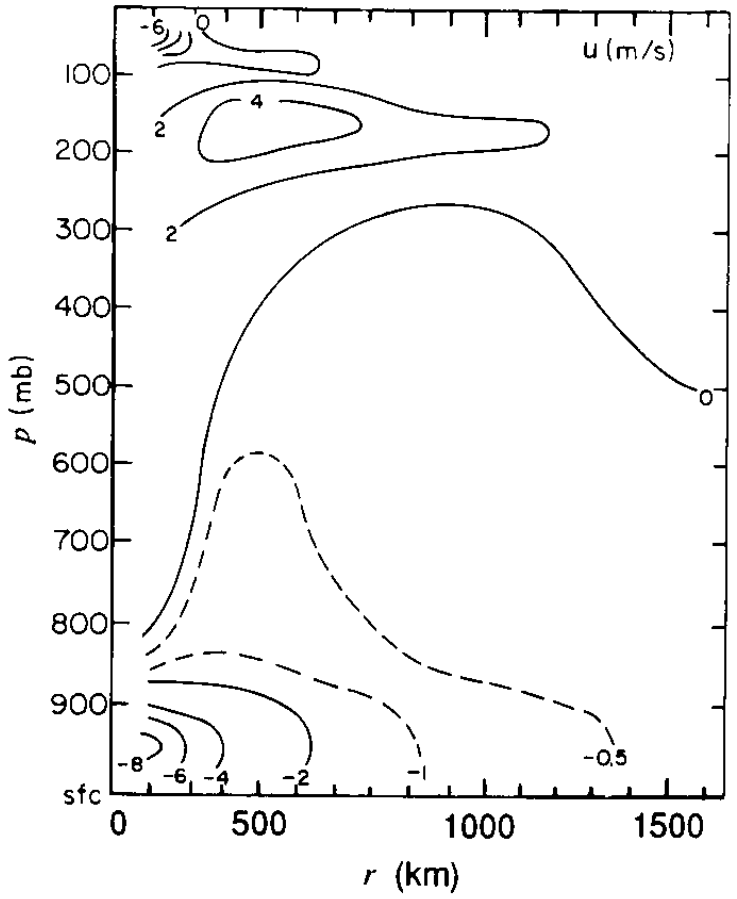
Temperature anomaly

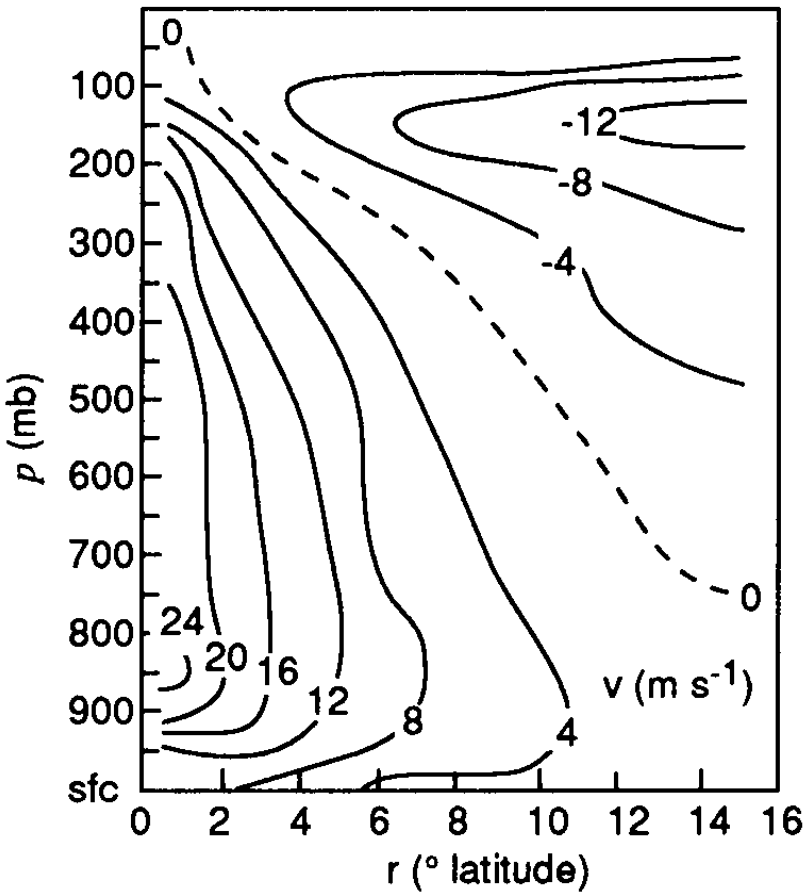
A TC with a double eyewall



From Willoughby, WMO (1995)

Cross-section from composite data



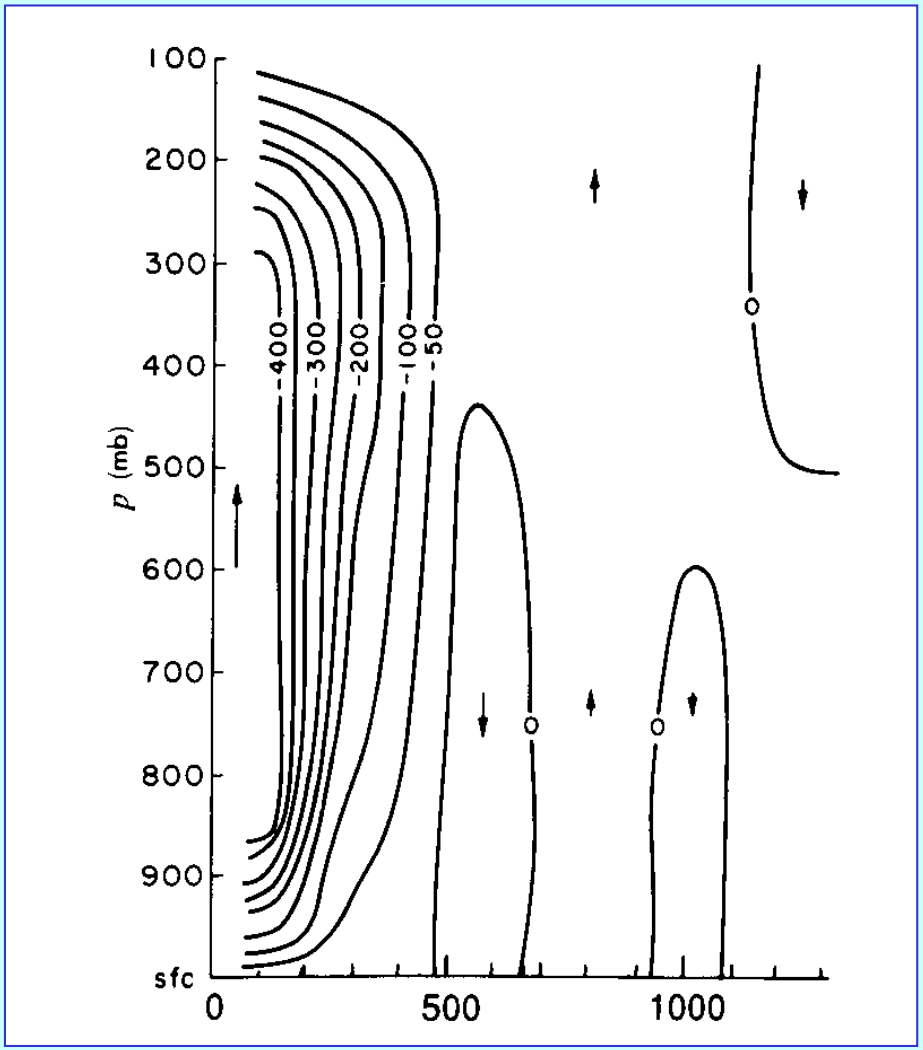


Radial wind

Azimuthal wind

From Gray (1979)

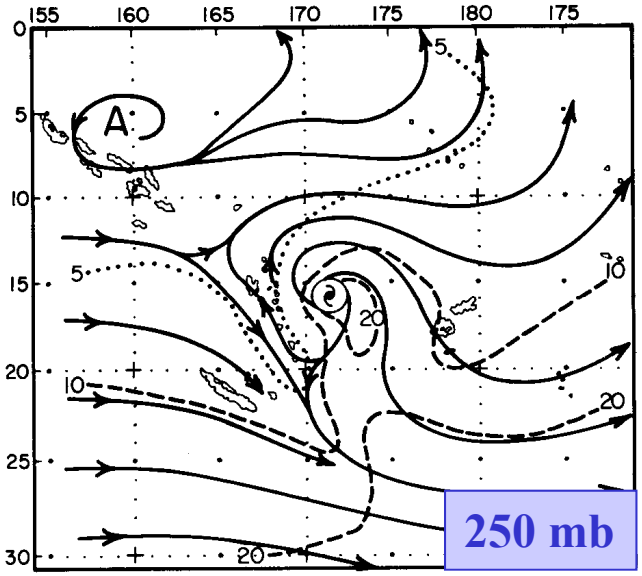
Vertical motion

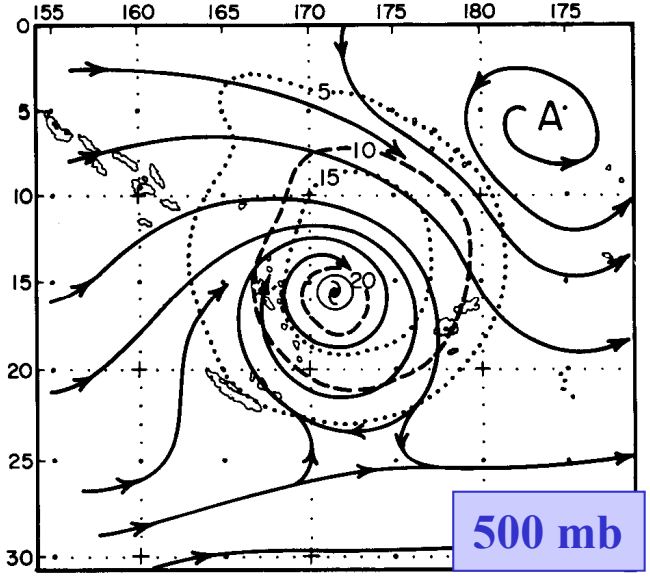


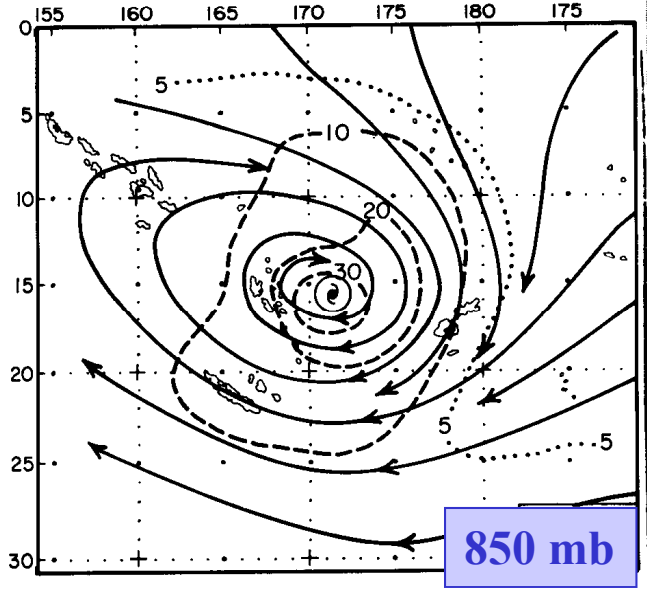
From Frank (MWR, 1977)

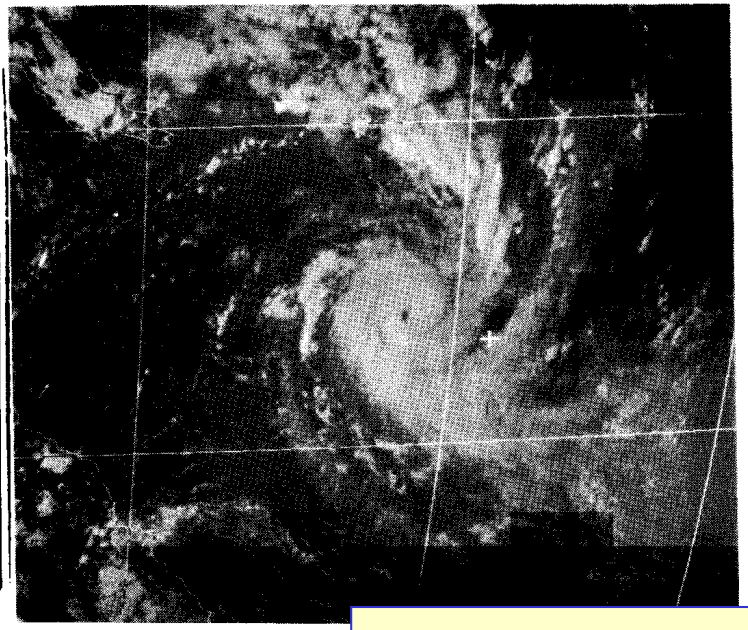
Vertical cross section of the mean vertical air motion (mb per day) in typhoons. Analysis is a composite of data collected in many storms.

Asymmetries



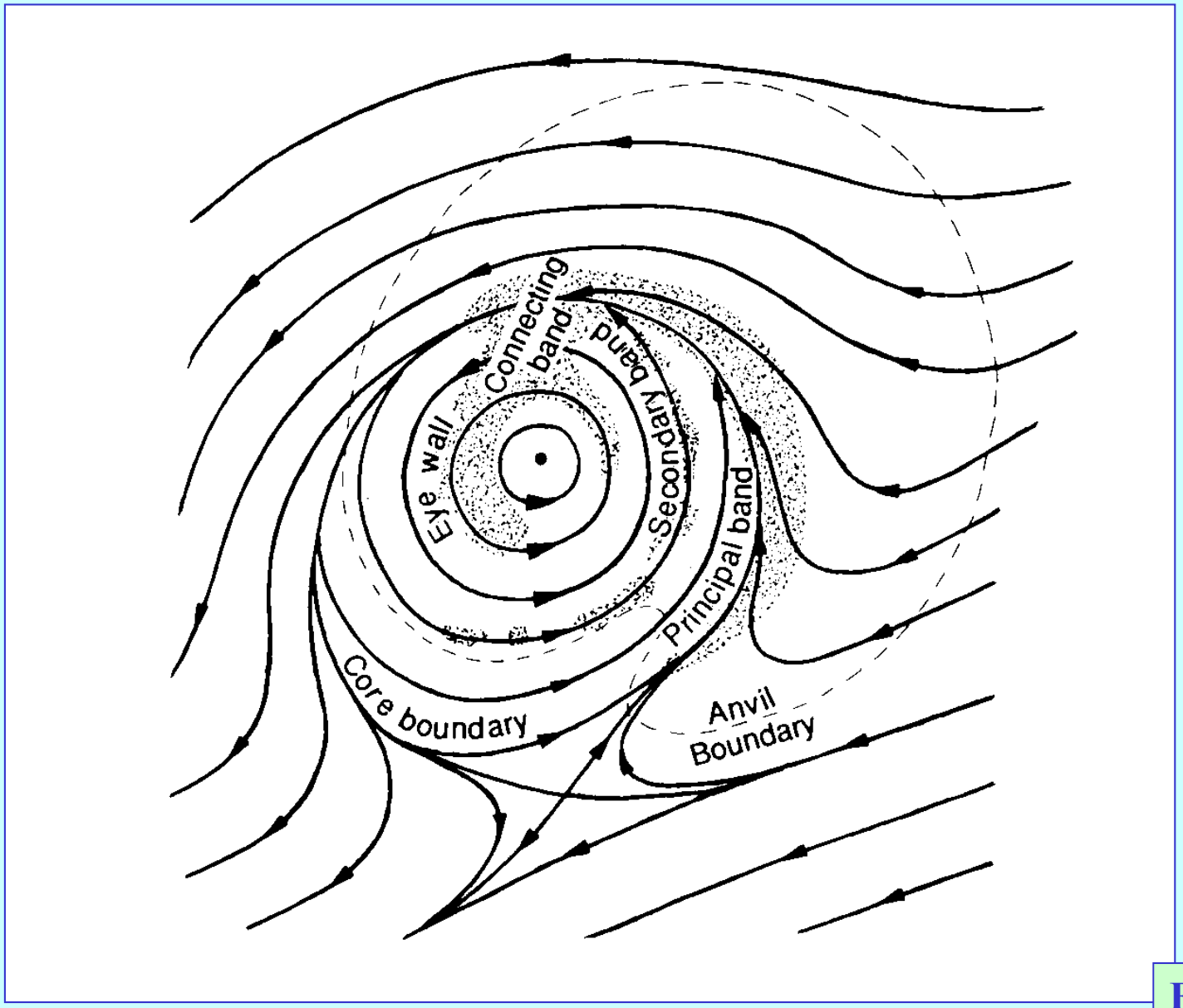






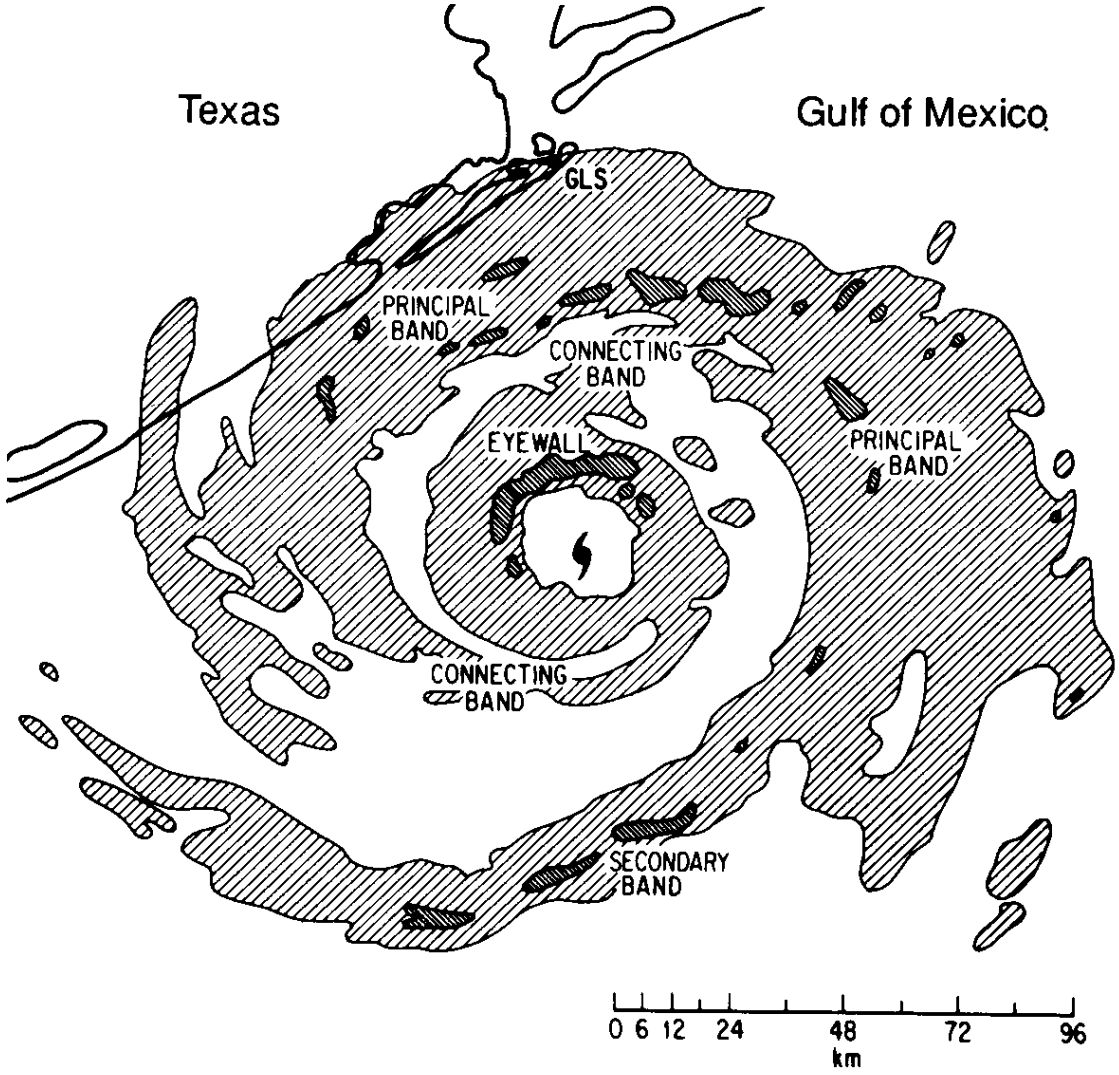
From Holland (AMM, 1984)

Asymmetric structure



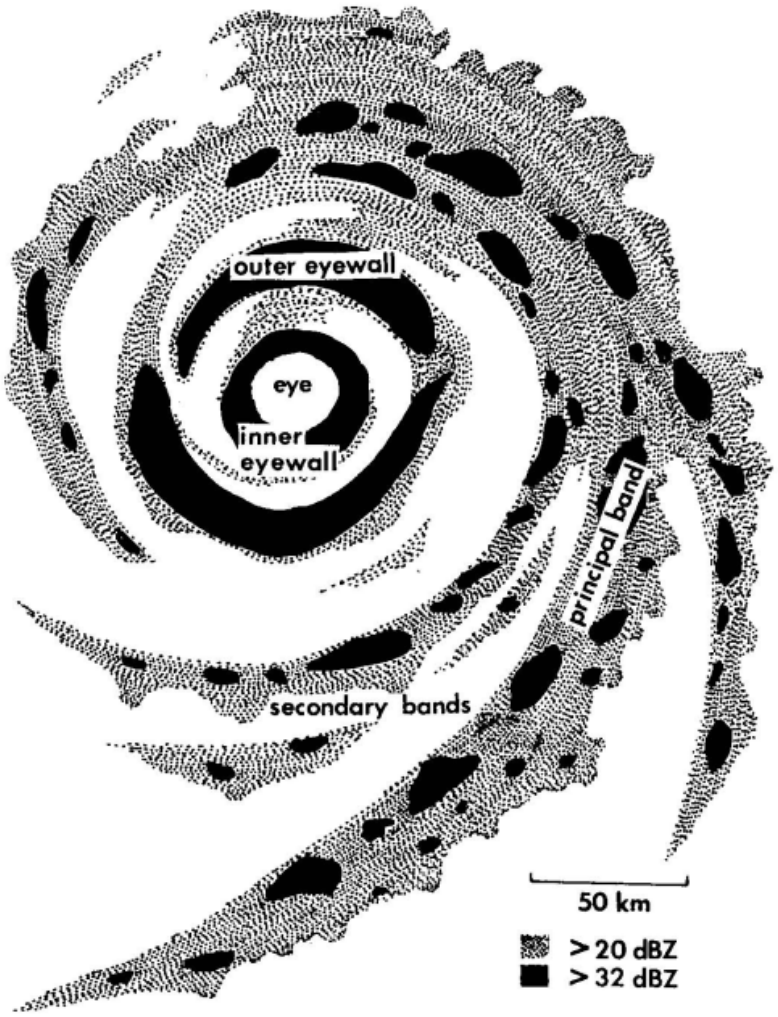
From Houze

Typical radar echo pattern



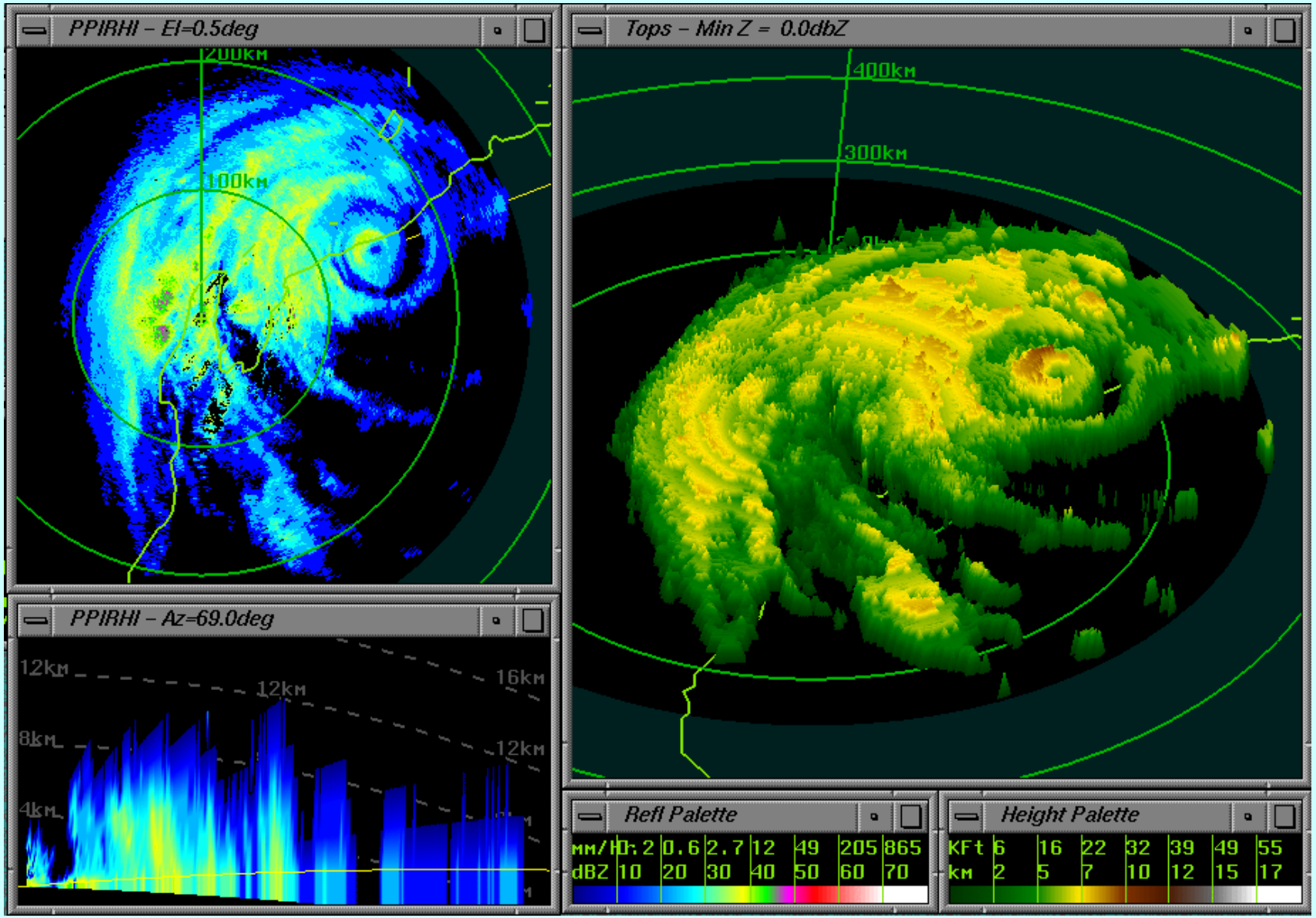
From Marks and Houze, 1987

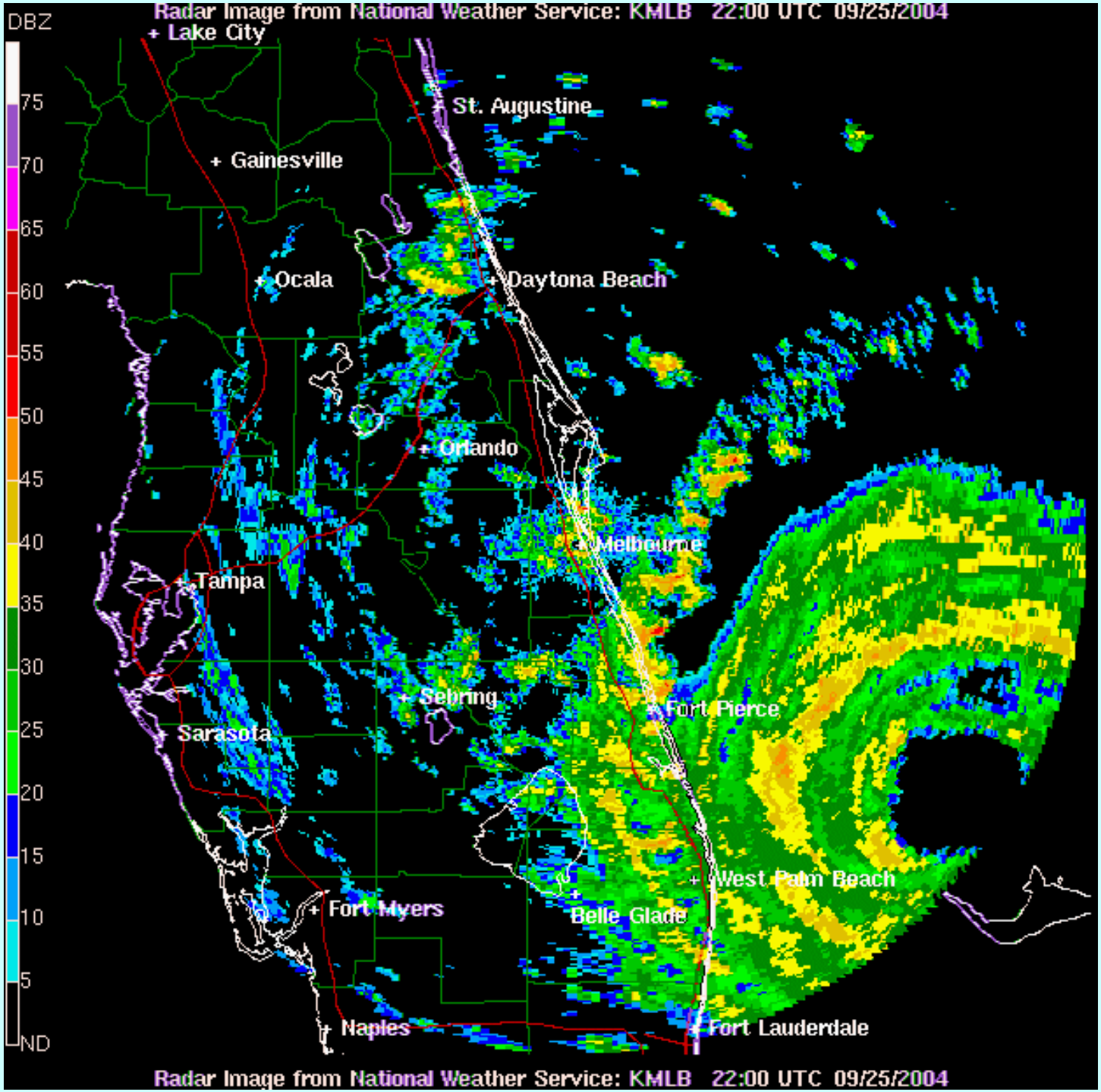
A TC with a double eyewall



From Willoughby, AMM (1988)

Western Australia: TC Bobby




Radar Image from National Weather Service: KMLB 22:00 UTC 09/25/2004
DBZ
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ND
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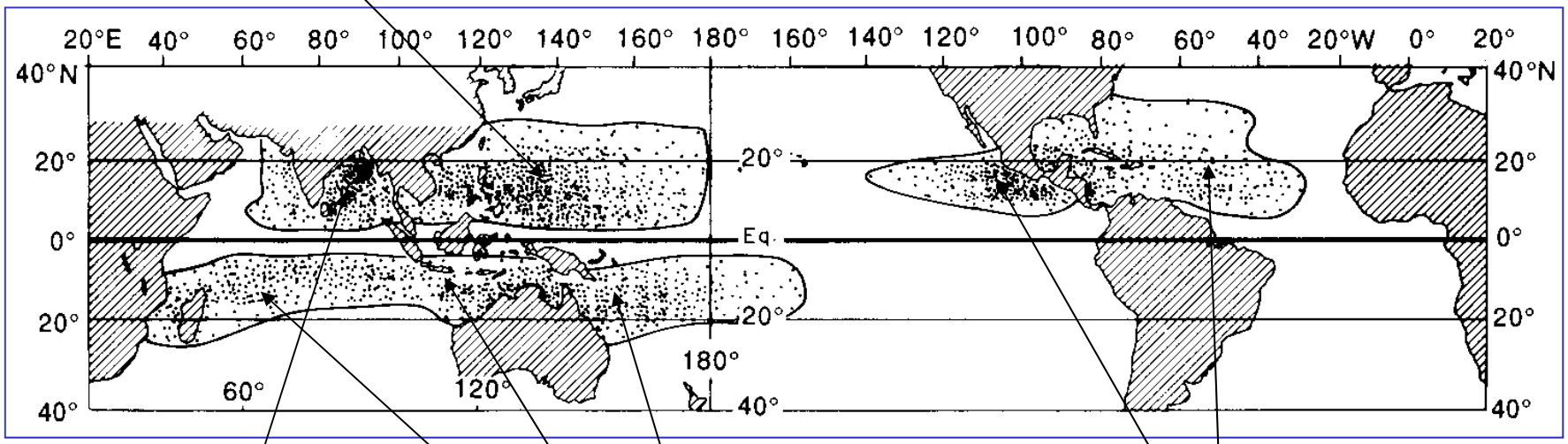
Gainesville
Ocala
St. Augustine
Daytona Beach
Orlando
Melbourne
Tampa
Sebring
Fort Pierce
Sarasota
West Palm Beach
Belle Glade
Fort Myers
Naples
Fort Lauderdale
Radar Image from National Weather Service: KMLB 22:00 UTC 09/25/2004

Genesis definition

- Tropical cyclones form in many parts of the world from initial convective disturbances sometimes referred to as cloud clusters.
- There has been much debate in the literature about the meaning of such terms as "tropical cyclogenesis", “TC formation", and “TC development
- Issue about when genesis has occurred and intensification has commenced.
- The existence of a (warm) core region can be identified by the time that the system is classified as a tropical cyclone (i.e., mean wind speeds exceeding 17 m s^{-1} or 34 kt).
- Further development of the maximum wind speeds beyond 17 m s^{-1} will be referred to as intensification. This stage includes the evolution of the core into a well-defined radar eye.
- Changes in wind speed of the outer vortex are referred to as outer structure change, or strength change, or size change.

Regions of TC formation

Typhoons



Cyclone

Tropical Cyclone

Hurricane

Tropical cyclogenesis requires a water temperature of at least 26.5 °C

From Gray (1975)

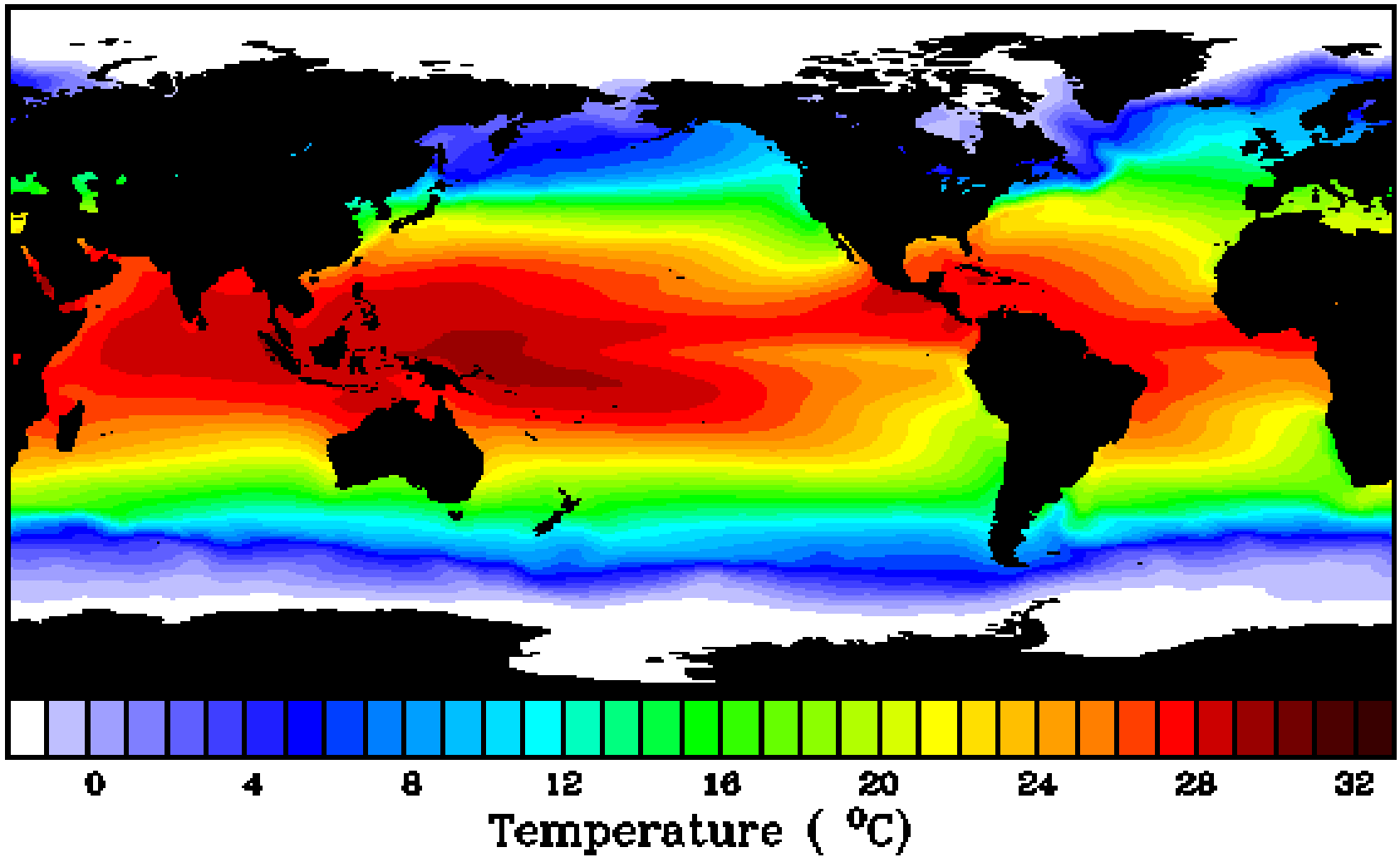
Genesis conditions

- The only region of cyclone formation not associated with a monsoon trough is the North Atlantic.

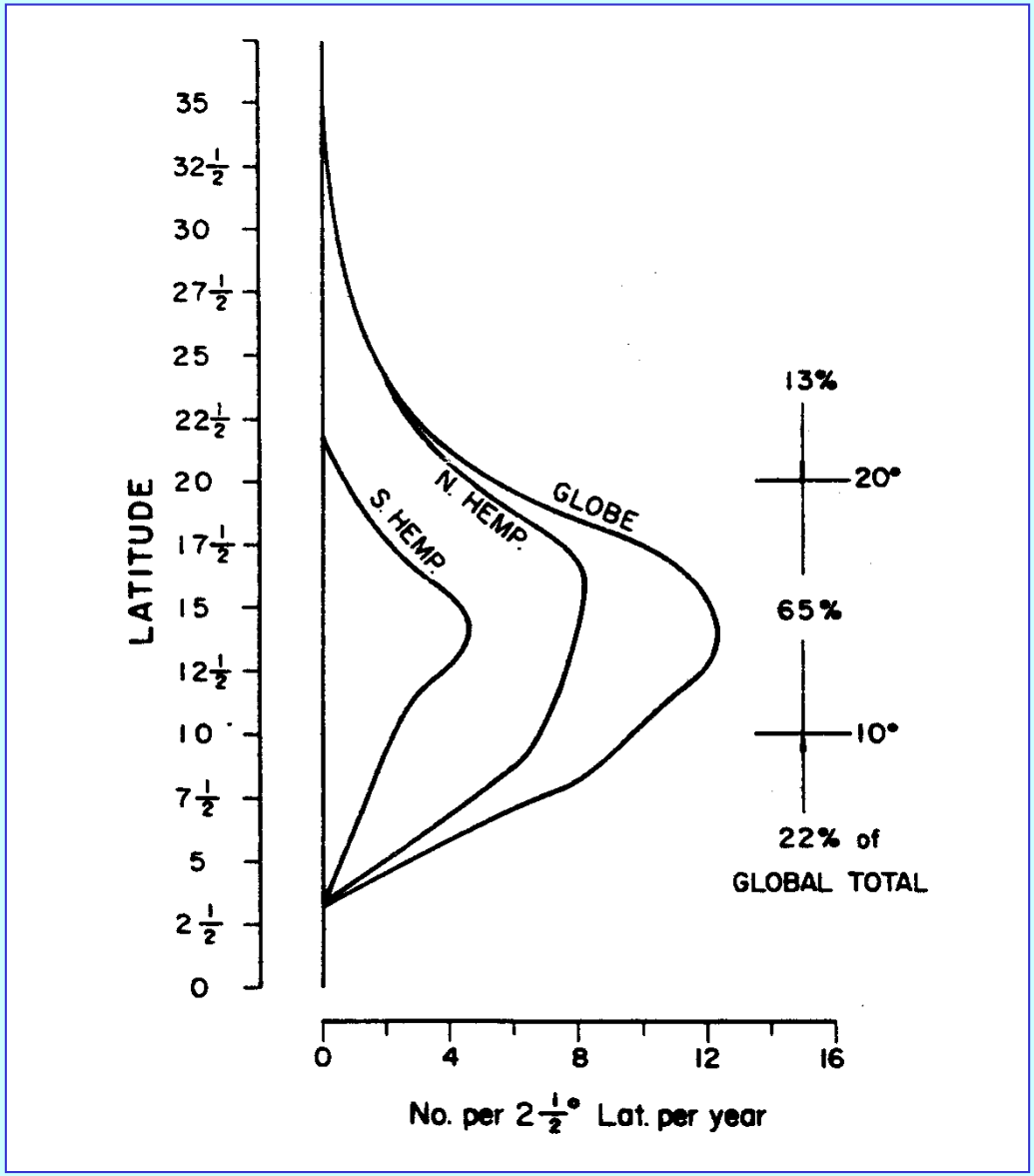
- In the first global climatology of tropical cyclogenesis found that cyclone formation is related to six environmental factors:

1. large values of low-level relative vorticity;
2. a location at least a few degrees poleward of the equator, giving a significant value of planetary vorticity;
3. weak vertical shear of the horizontal winds;
4. sea-surface temperatures (SSTs) exceeding 26°C, and a deep thermocline;
5. conditional instability through a deep atmospheric layer; and
6. large values of relative humidity in the lower and middle troposphere.

Annual mean sea surface temperatures



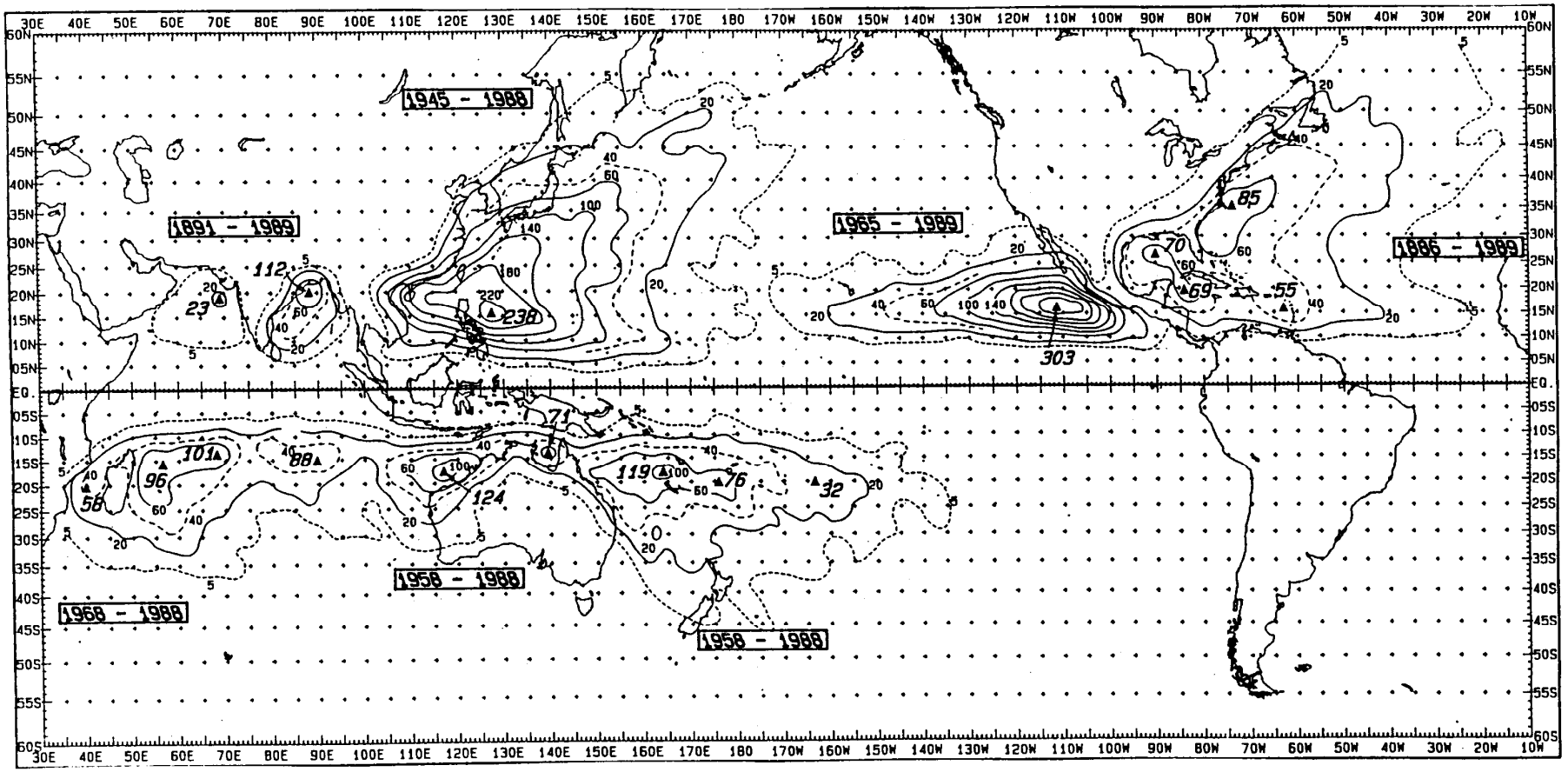
Mean latitude of formation



Latitudes at which initial disturbances later became tropical cyclones were first detected

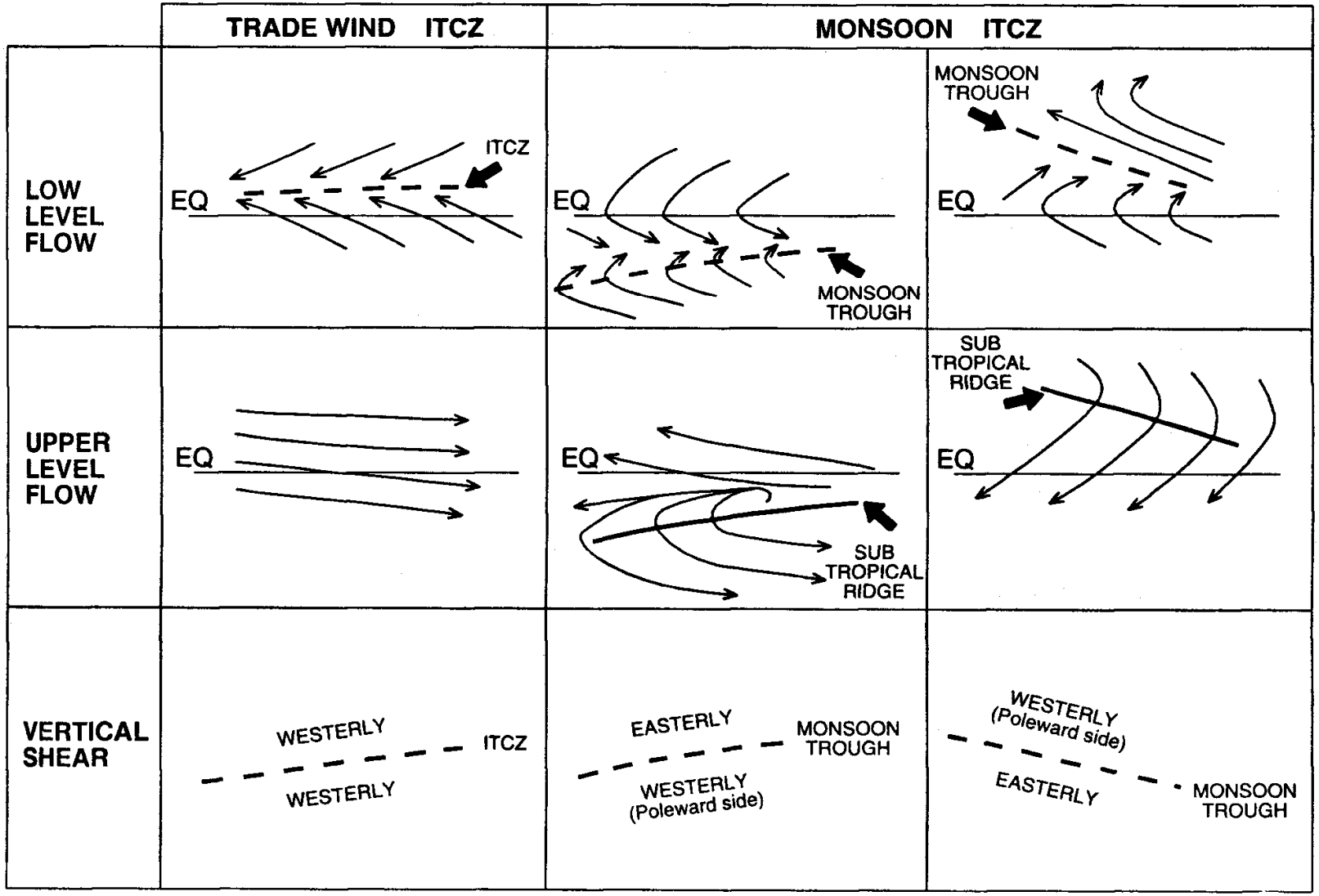
From Gray (MWR, 1975)

Frequency of TCs per 100 years

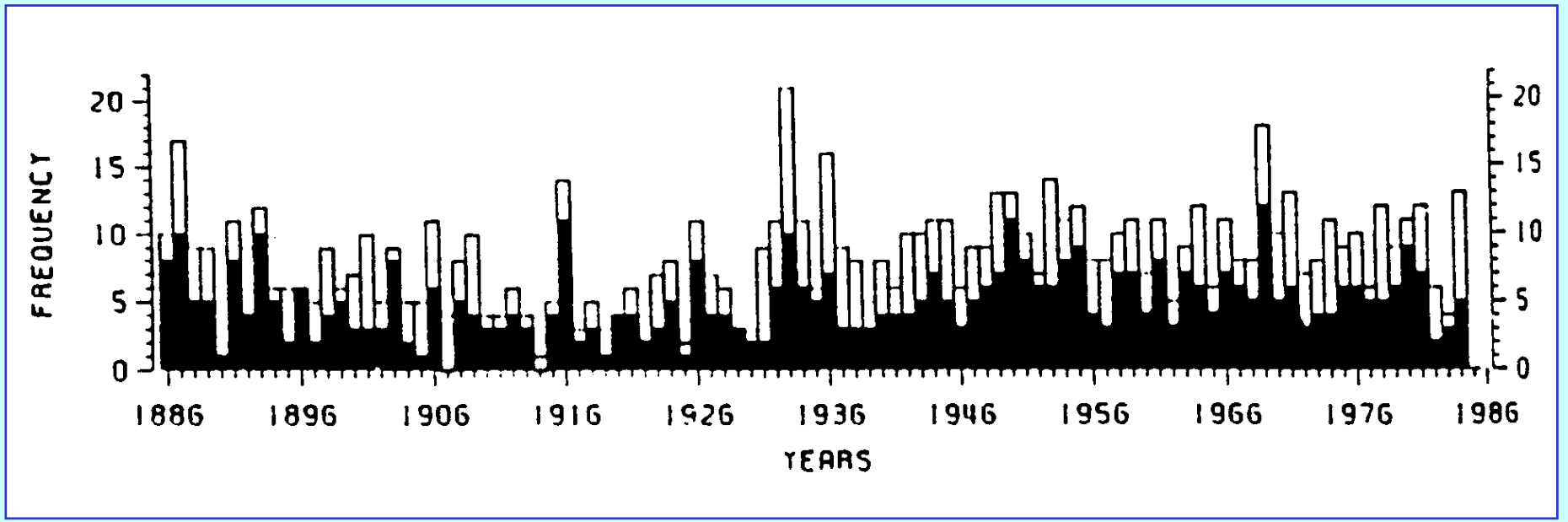


From WMO (1993)

Trade wind and monsoon flow regimes



Climatology in Atlantic Basin



Number of North Atlantic tropical cyclones reaching at least 17.5 **m** s^{-1} **(**34 **kt) intensity (open bar) and reaching at least** 33 **m** s^{-1} **(**64 **kt) intensity (solid bar) each year during** 1886-1985**. (From McBride, 1995)**

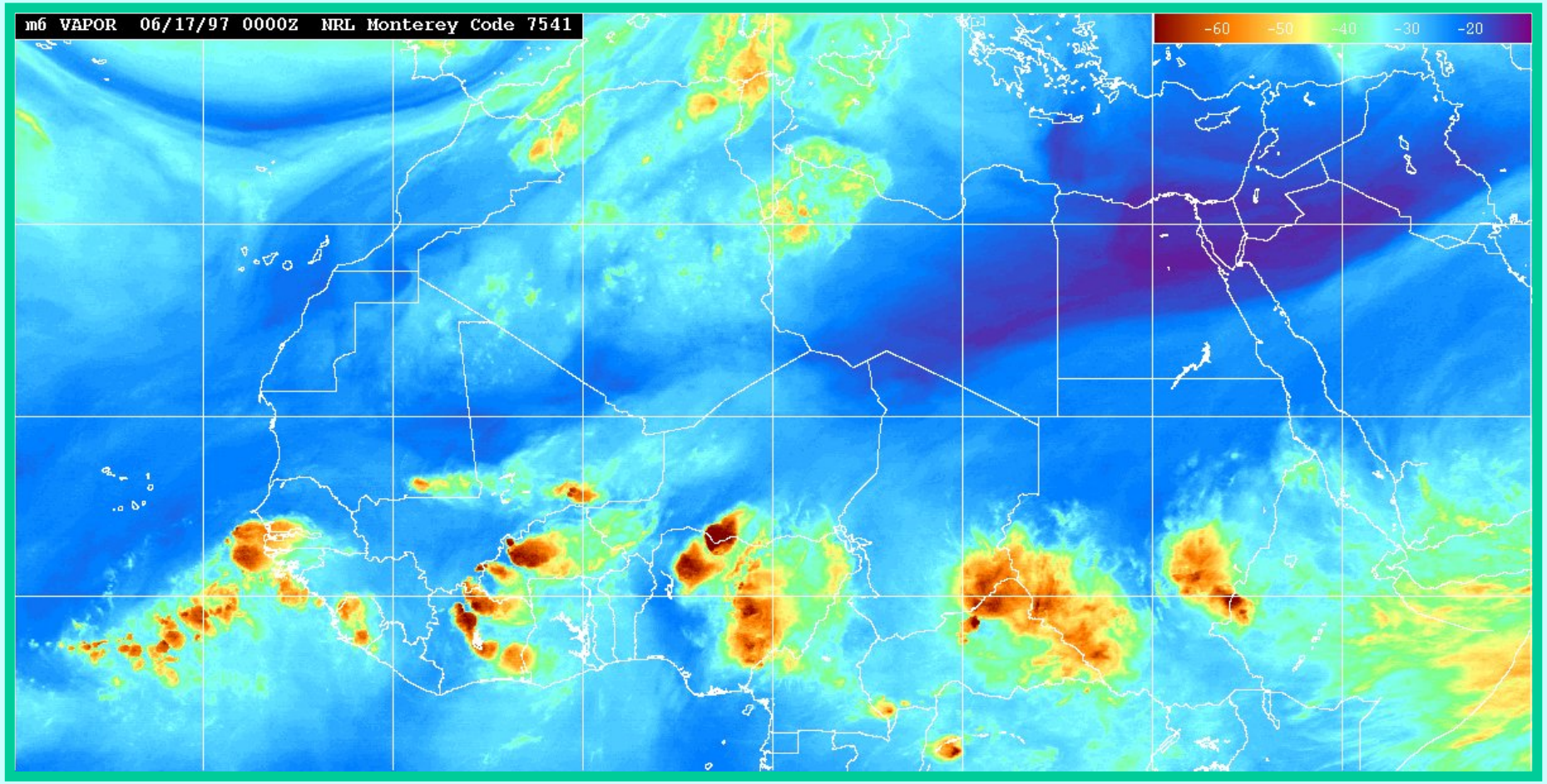
Large-scale conditions for formation

- Tropical cyclones form from pre-existing disturbances containing abundant deep convection;
- The pre-existing disturbance must acquire a warm core thermal structure throughout the troposphere;
- Formation is preceded by an increase of lower tropospheric relative vorticity over a horizontal scale of approximately 1000 to 2000 km;
- A necessary condition for cyclone formation is a large-scale environment with small vertical wind shear;

Large-scale conditions for formation (cont)

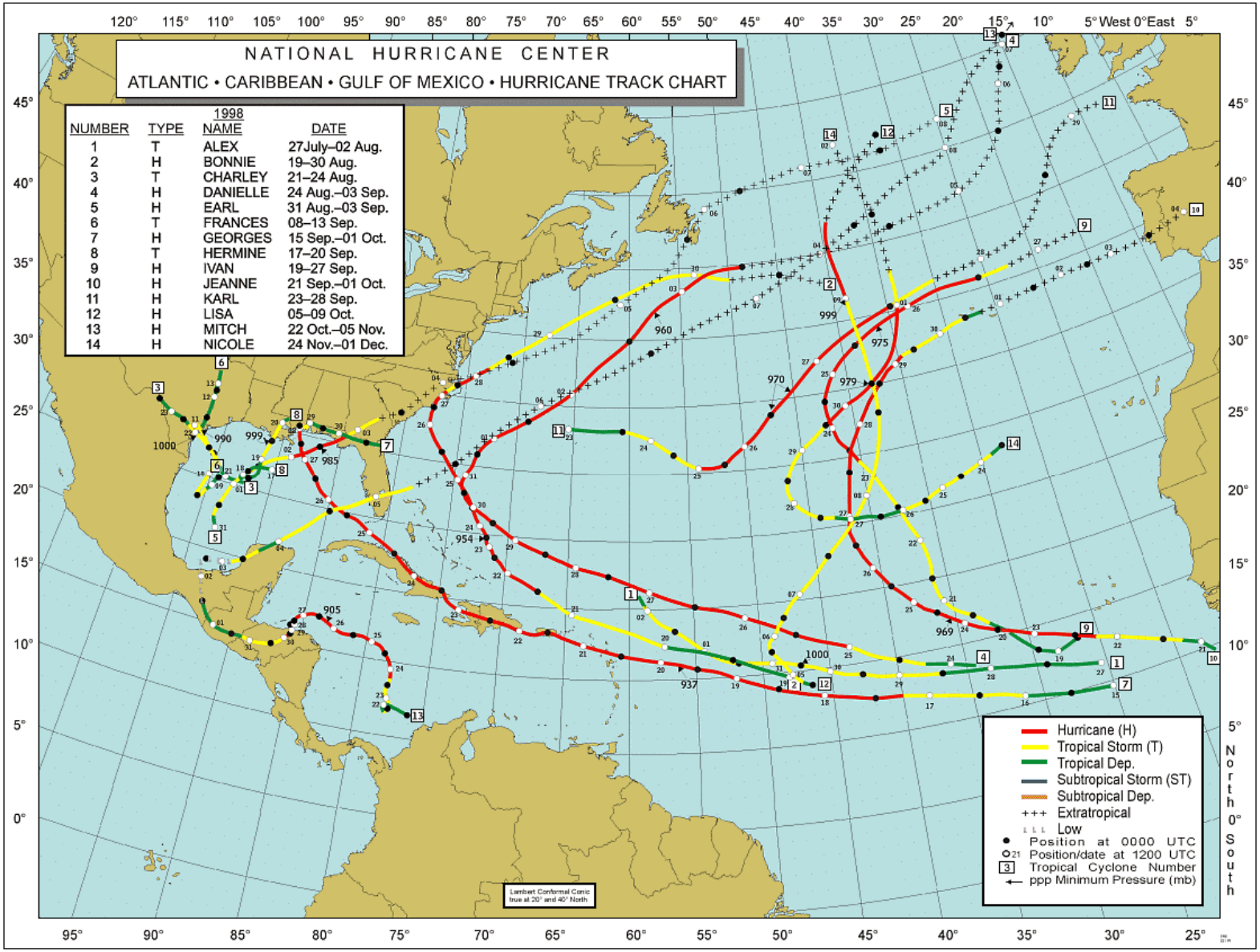
- An early indicator that cyclone formation has begun is the appearance of curved banding features of the deep convection in the incipient disturbance;
- The inner core of the cyclone may originate as a mid-level meso-vortex that has formed in association with a pre-existing mesoscale area of altostratus (i.e., a Mesoscale Convective System or MCS); and
- Formation often occurs in conjunction with an interaction between the incipient disturbance and an upper-tropospheric trough.

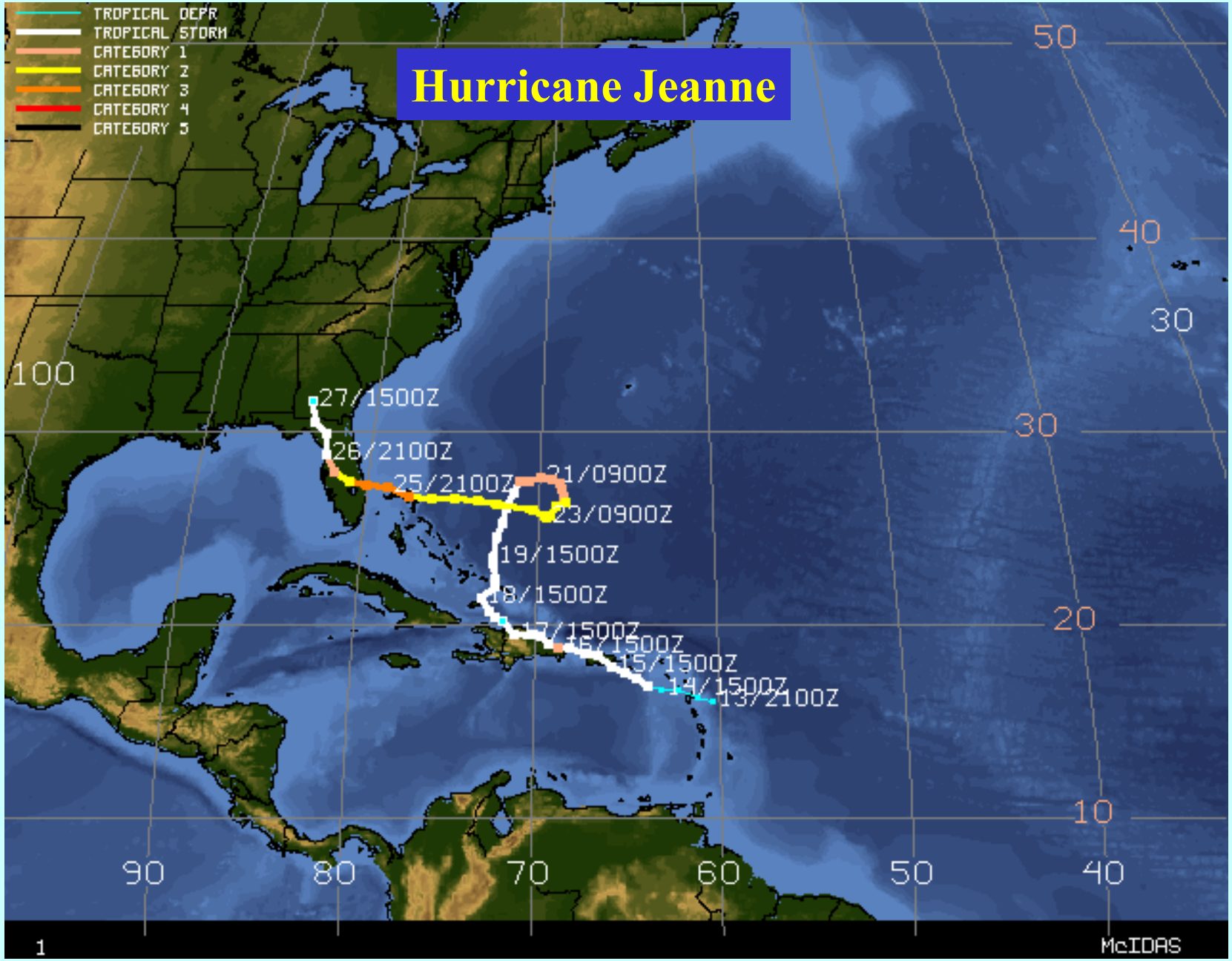
Easterly waves over Africa



WV Imagery 17 June 1997 00Z

Atlantic hurricane tracks in 1998




TROPICAL DEPR
TROPICAL STORM
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CATEGORY 2
CATEGORY 3
CATEGORY 4
CATEGORY 5
Hurricane Jeanne
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26/2100Z
25/2100Z
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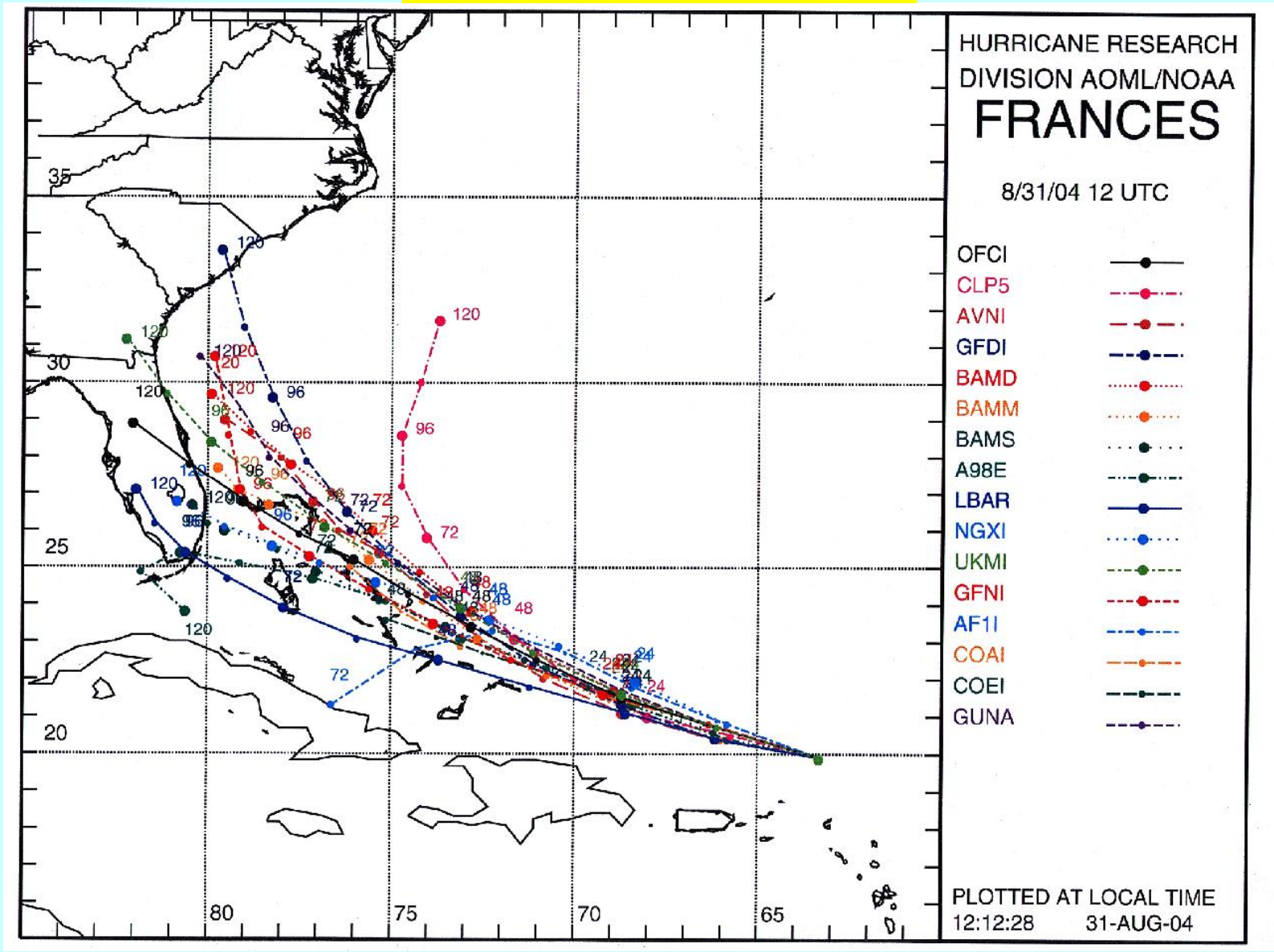
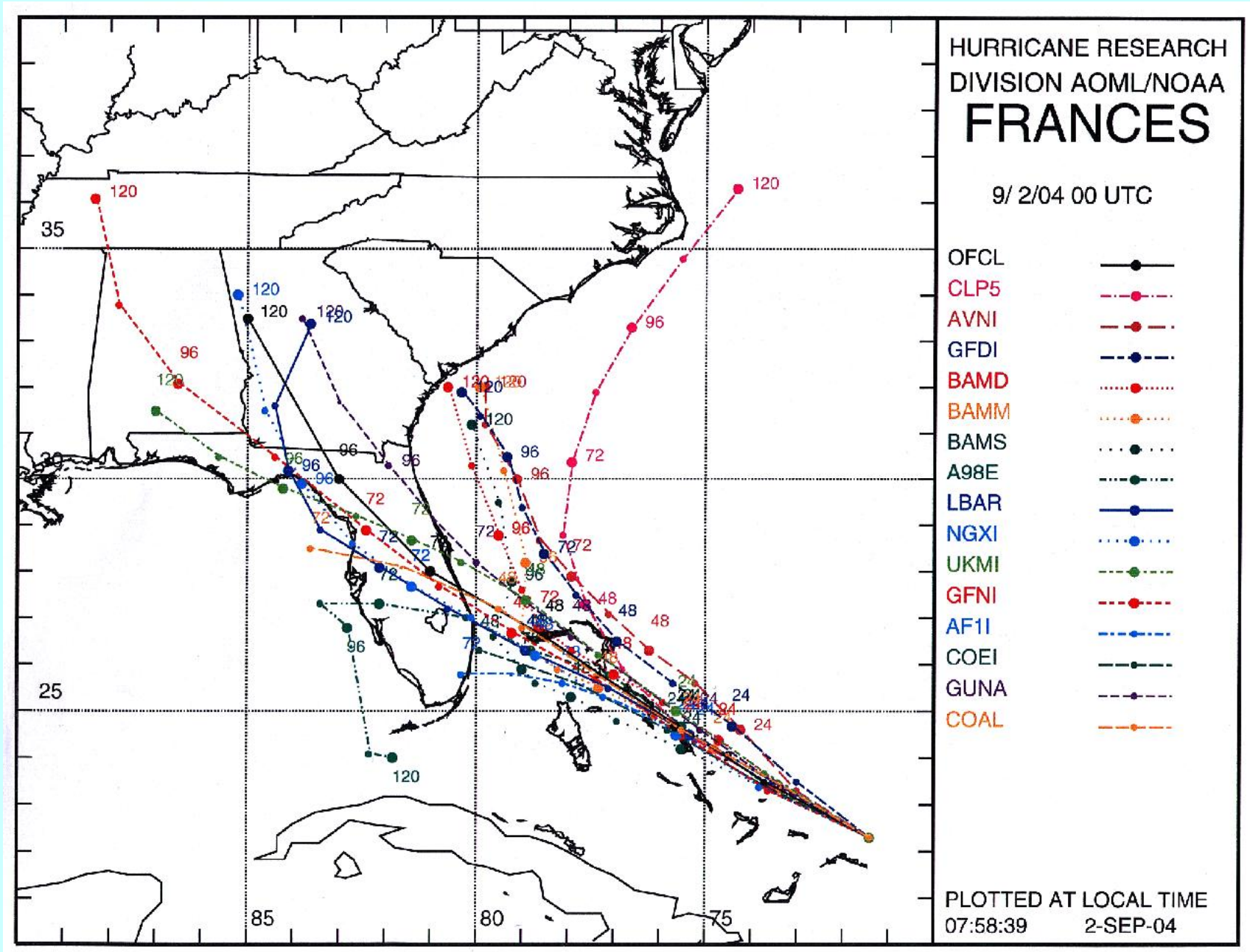
Track forecasting




HURRICANE RESEARCH
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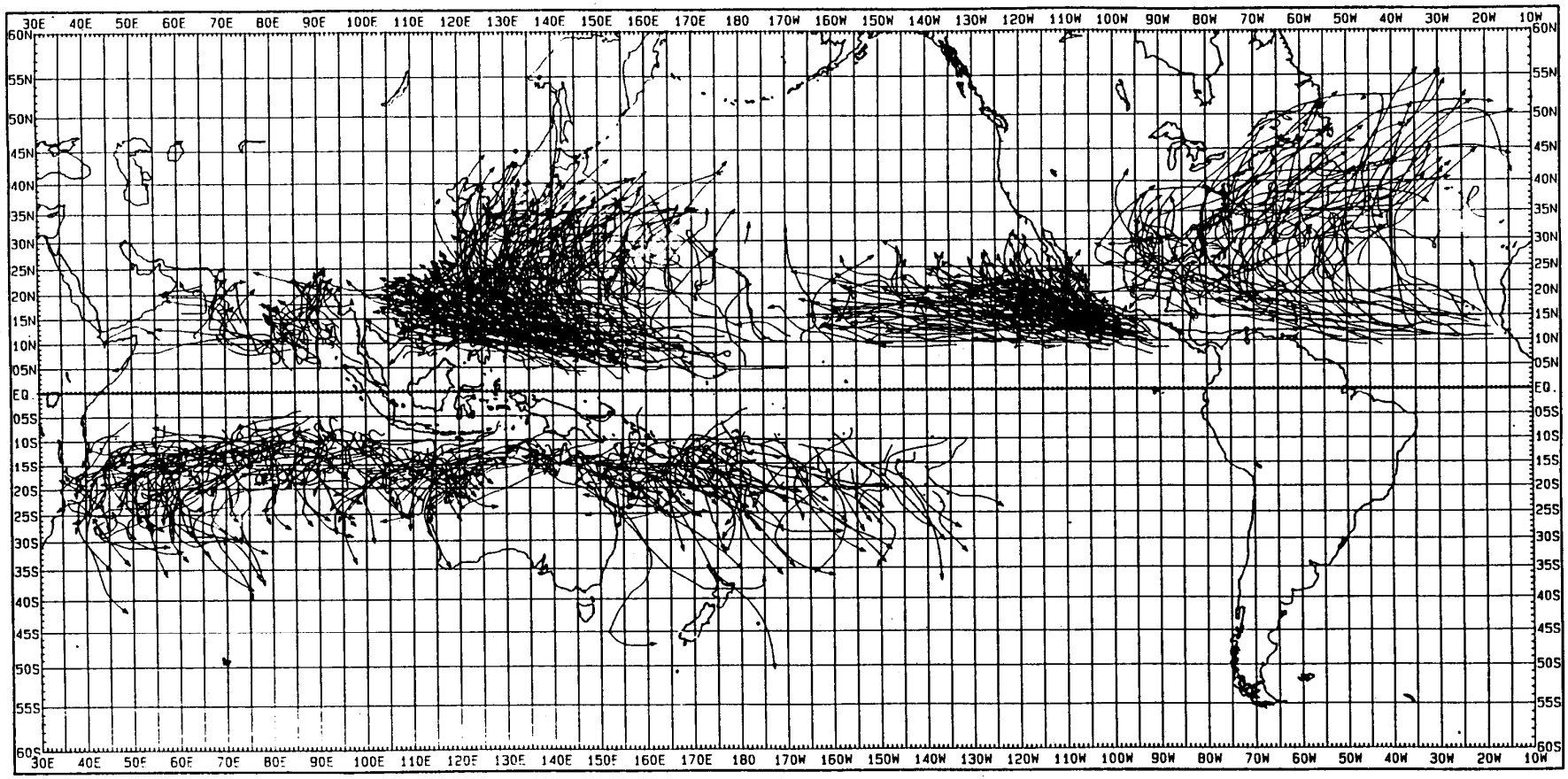
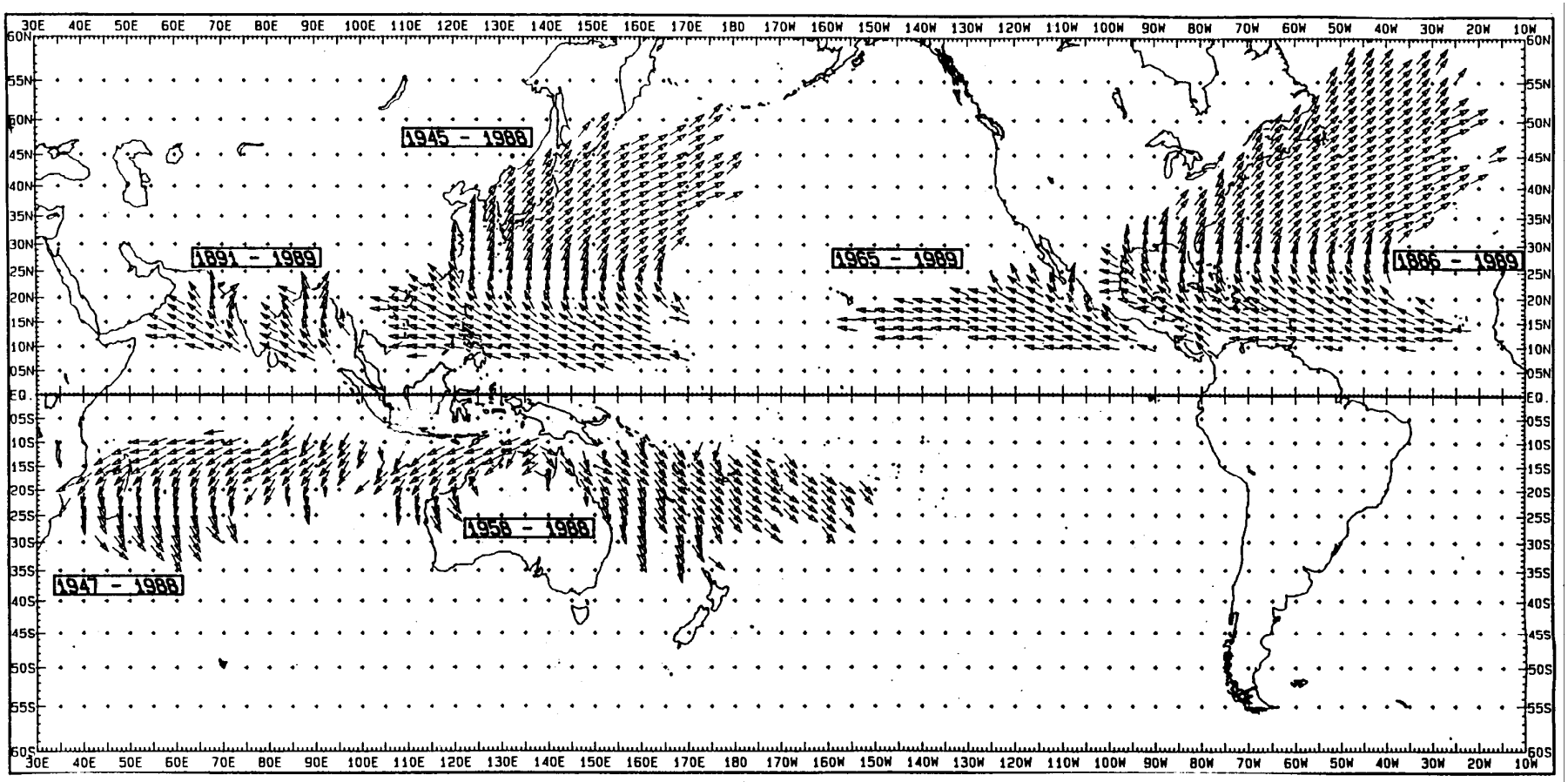
COEI
GUNA
COAL
PLOTTED AT LOCAL TIME
07:58:39 2-SEP-04
35
30
25
85
80
75

Tropical cyclone tracks (1979-1988)



From WMO (1993)

Mean direction of TC motion



From WMO (1993)

Satellite imagery - classification

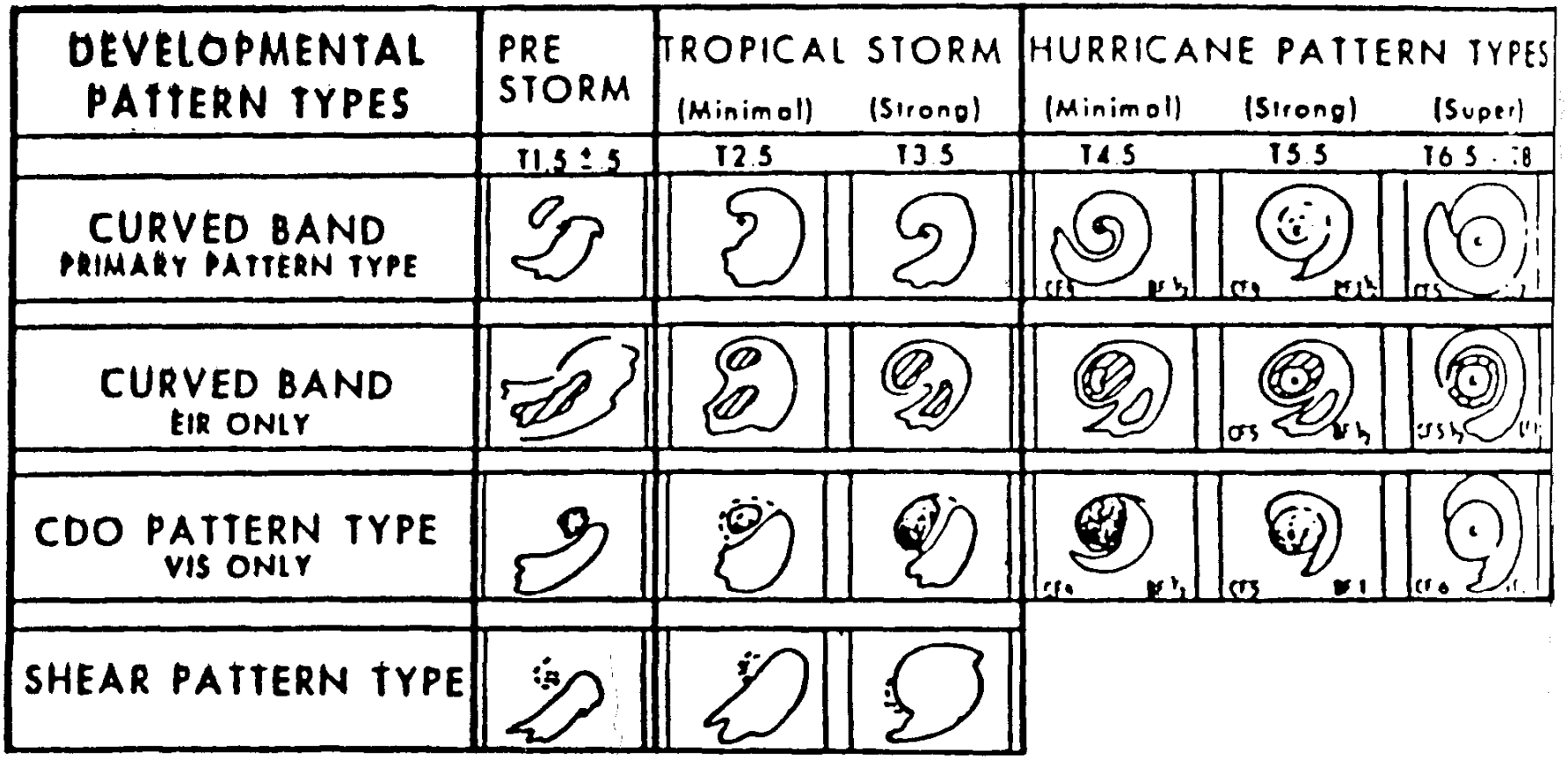
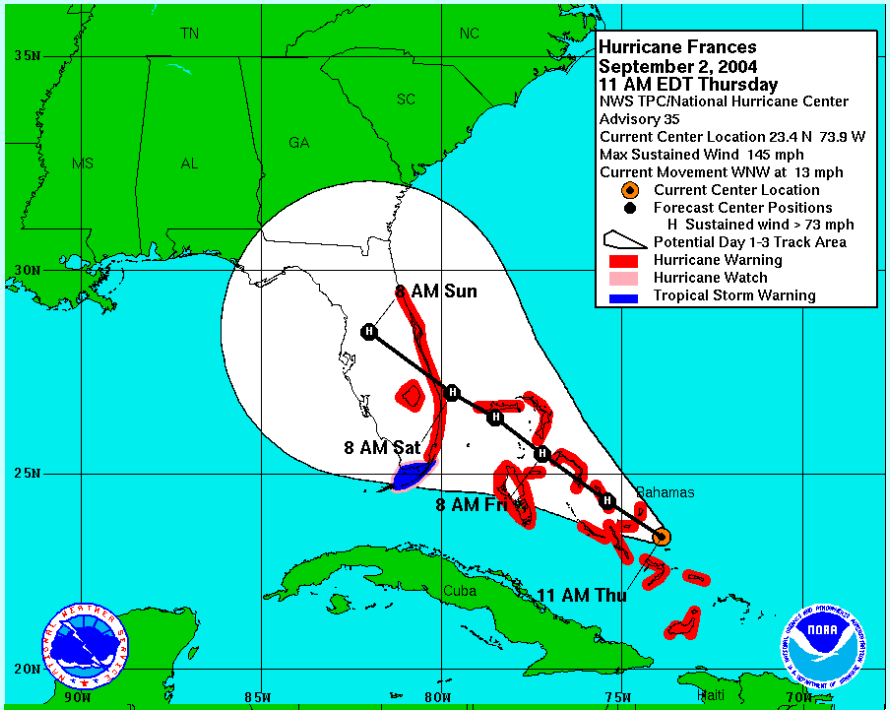
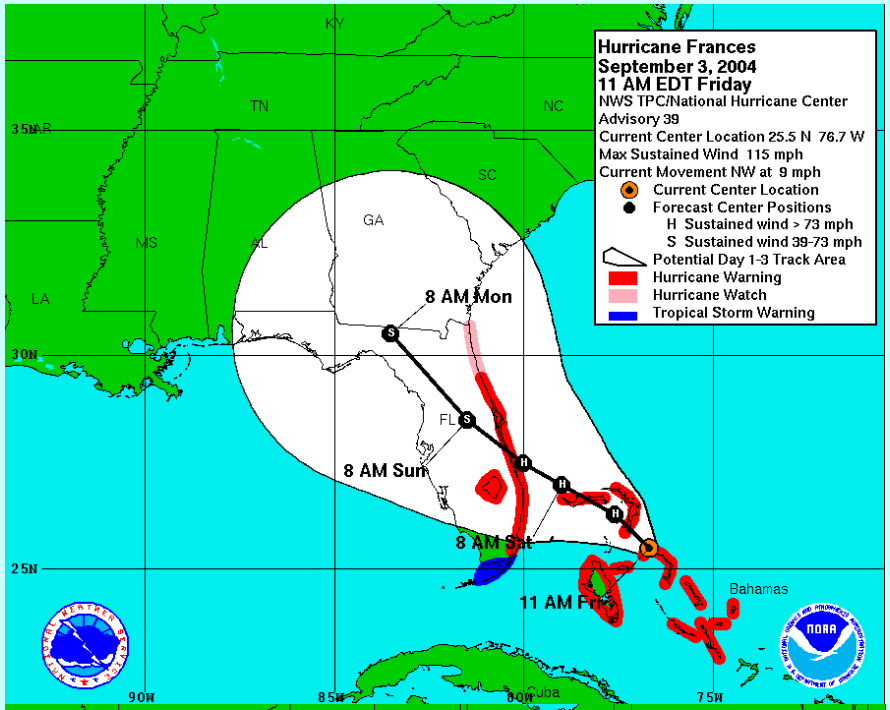
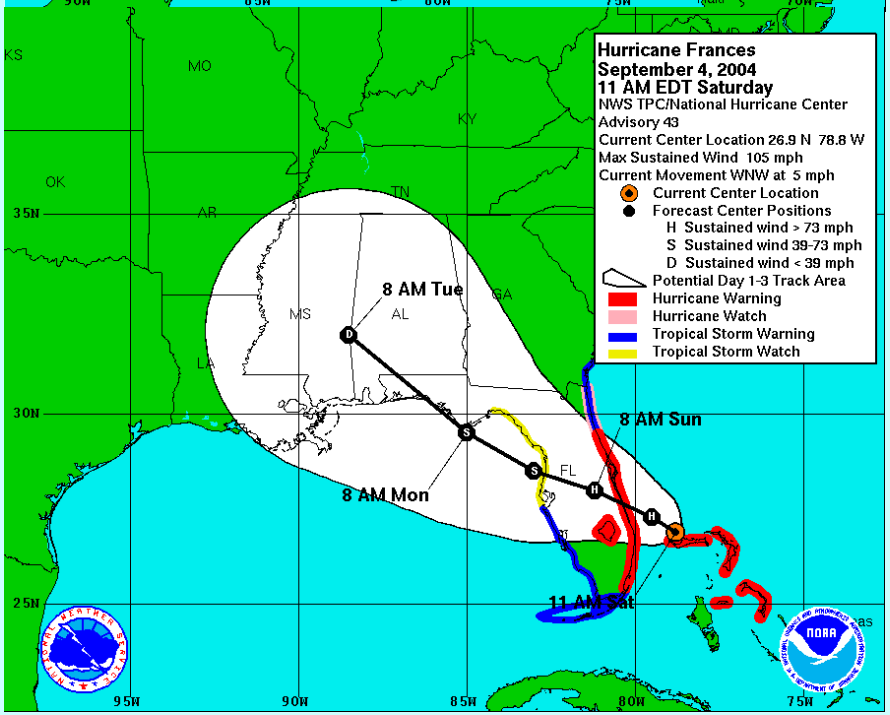
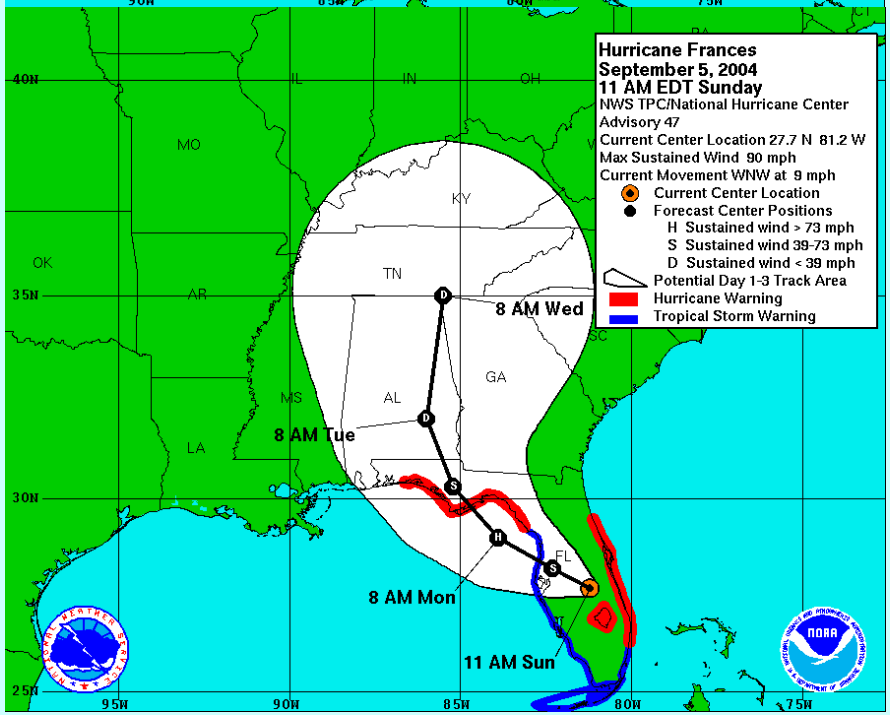


Fig. 3.20 Cloud pattern types in the tropical cyclone intensity analysis based on satellite imagery. Pattern changes from left to right are typical 24-hourly changes (Dvorak 1984).


Hurricane Frances
September 2, 2004
11 AM EDT Thursday
NWS TPC/National Hurricane Center
Advisory 35
Current Center Location 23.4 N 73.9 W
Max Sustained Wind 145 mph
Current Movement WNW at 13 mph
Current Center Location
Forecast Center Positions
H Sustained wind > 73 mph
Potential Day 1-3 Track Area
Hurricane Warning
Hurricane Watch
Tropical Storm Warning
8 AM Sun
8 AM Sat
8 AM Fri
11 AM Thu
Bahamas
Cuba
Haiti
TN
NC
SC
GA
MS
AL
35N
30N
25N
20N
90W
85W
80W
75W
70W

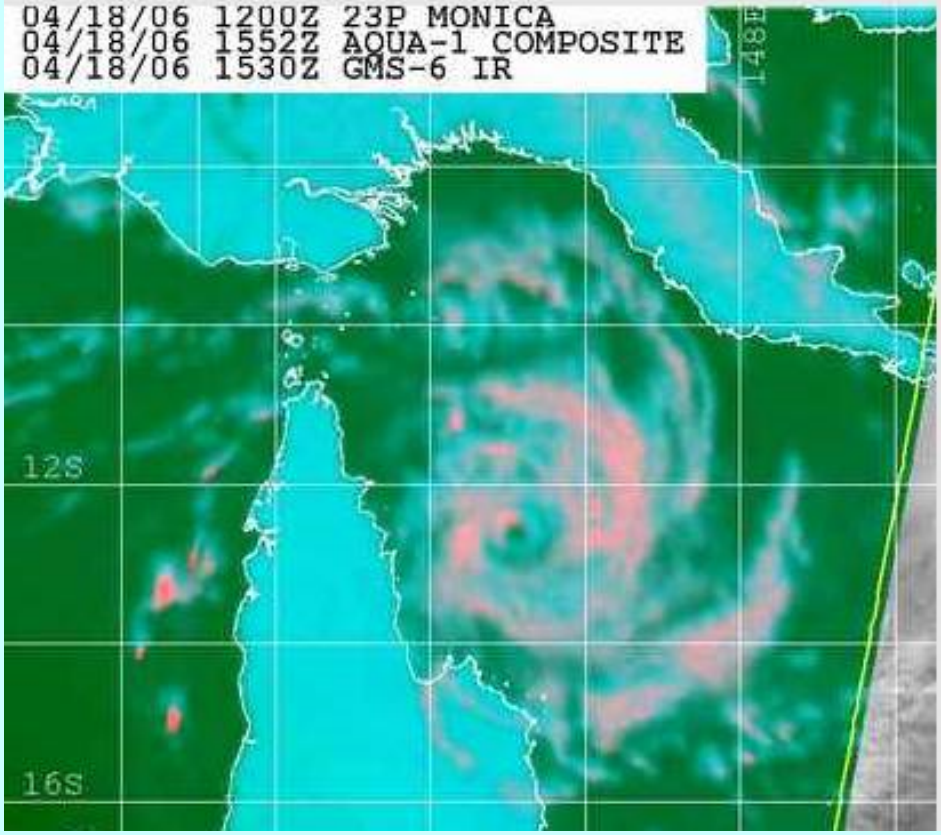

Hurricane Frances
September 3, 2004
11 AM EDT Friday
NWS TPC/National Hurricane Center
Advisory 39
Current Center Location 25.5 N 76.7 W
Max Sustained Wind 115 mph
Current Movement NW at 9 mph
Current Center Location
Forecast Center Positions
H Sustained wind > 73 mph
S Sustained wind 39-73 mph
Potential Day 1-3 Track Area
Hurricane Warning
Hurricane Watch
Tropical Storm Warning
8 AM Mon
8 AM Sun
8 AM Sat
11 AM Fri
Bahamas
Cuba
KY
TN
NC
SC
GA
MS
AL
LA
FL
35N
30N
25N
90W
85W
80W
75W

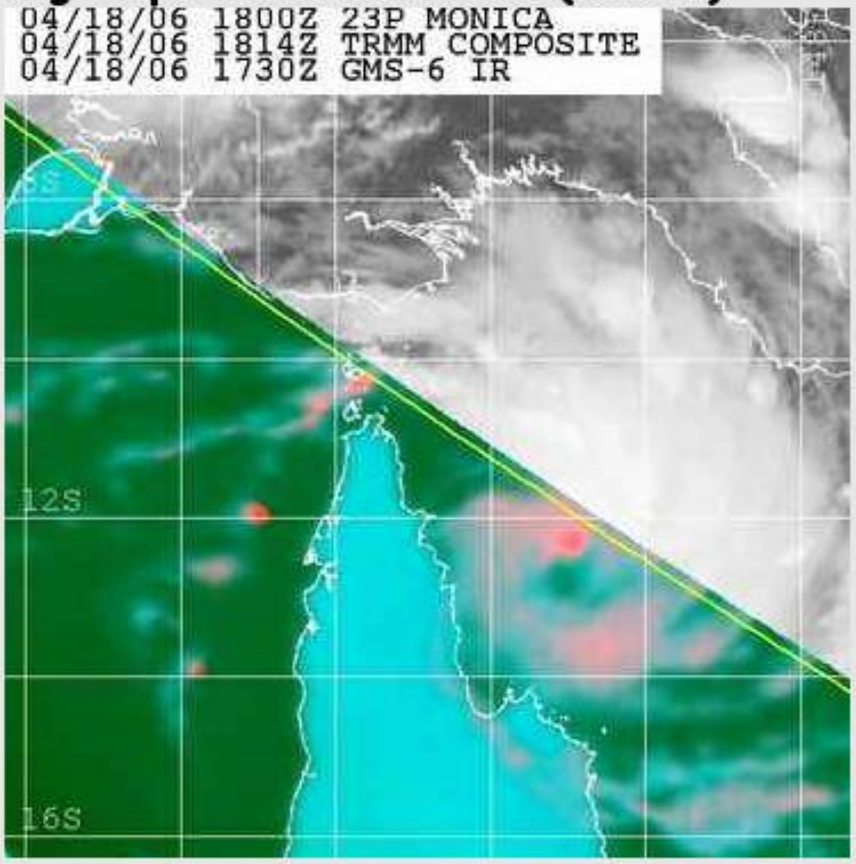

Hurricane Frances
September 4, 2004
11 AM EDT Saturday
NWS TPC/National Hurricane Center
Advisory 43
Current Center Location 26.9 N 78.8 W
Max Sustained Wind 105 mph
Current Movement WNW at 5 mph
Current Center Location
Forecast Center Positions
H Sustained wind > 73 mph
S Sustained wind 39-73 mph
D Sustained wind < 39 mph
Potential Day 1-3 Track Area
Hurricane Warning
Hurricane Watch
Tropical Storm Warning
Tropical Storm Watch
8 AM Tue
8 AM Mon
8 AM Sun
11 AM Sat
KS
MO
KY
OK
AR
TN
MS
AL
GA
LA
FL
35N
30N
25N
95W
90W
85W
80W
75W

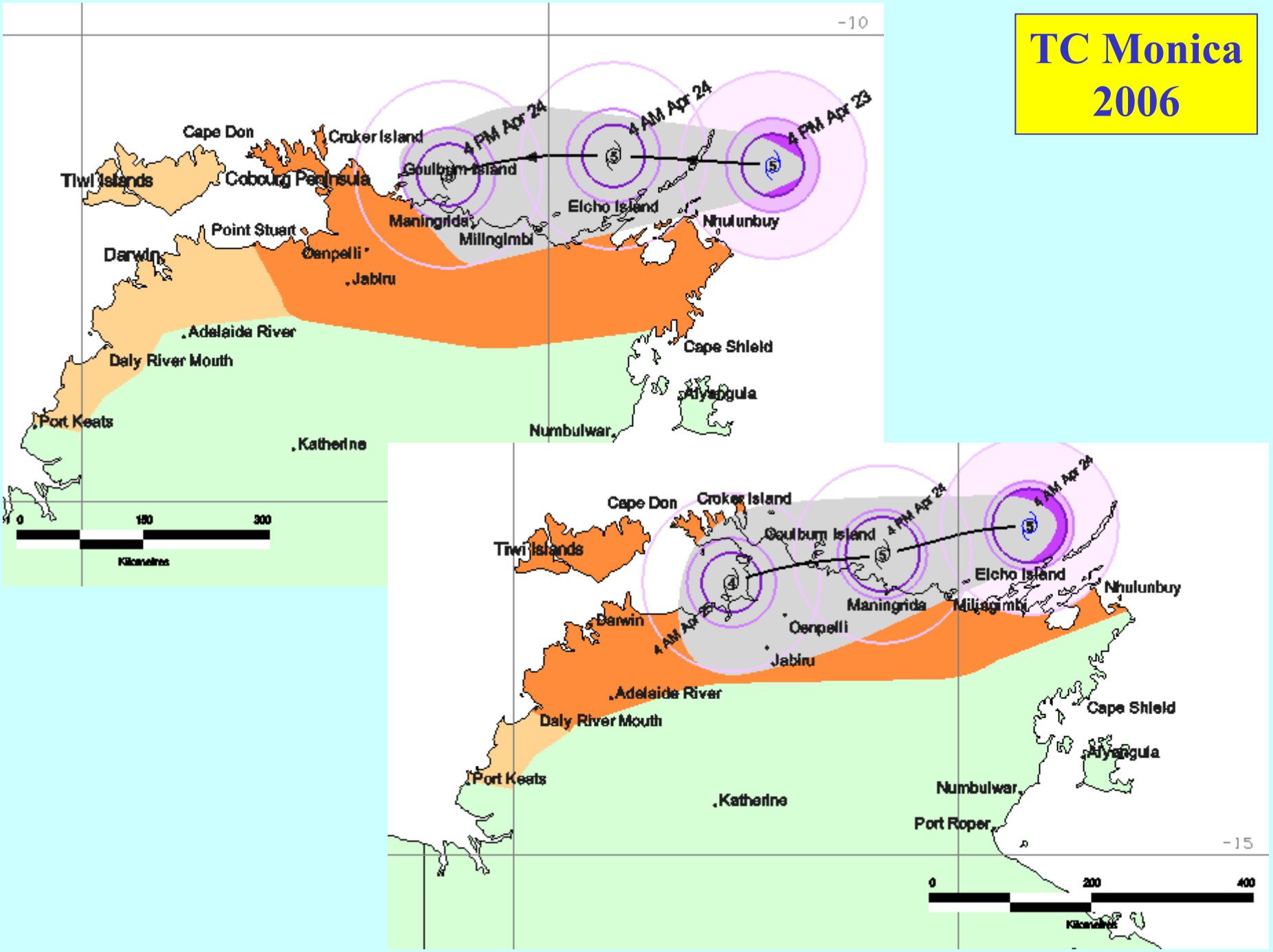

Hurricane Frances
September 5, 2004
11 AM EDT Sunday
NWS TPC/National Hurricane Center
Advisory 47
Current Center Location 27.7 N 81.2 W
Max Sustained Wind 90 mph
Current Movement WNW at 9 mph
Current Center Location
Forecast Center Positions
H Sustained wind > 73 mph
S Sustained wind 39-73 mph
D Sustained wind < 39 mph
Potential Day 1-3 Track Area
Hurricane Warning
Tropical Storm Warning
8 AM Wed
8 AM Tue
8 AM Mon
11 AM Sun
IL
IN
OH
MO
KY
OK
AR
TN
MS
AL
GA
LA
FL
40N
35N
30N
25N
95W
90W
85W
80W
75W

TC Monica 2006

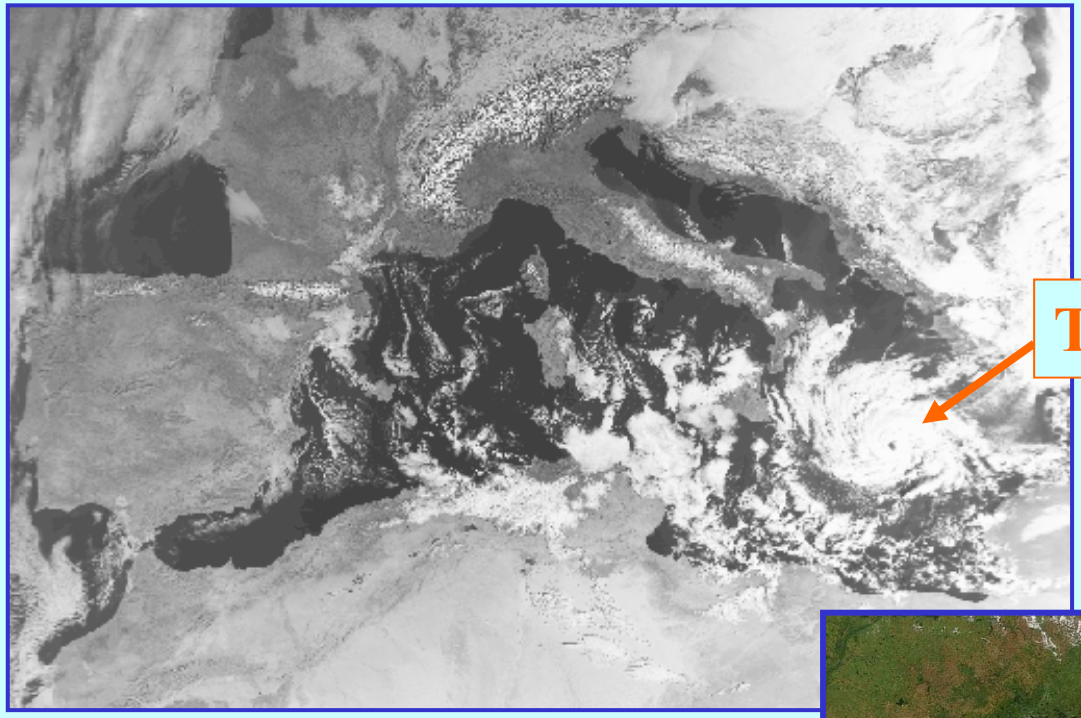
Tropical Cyclone Monica (23P) approaching Cape York Peninsula (36Ghz)



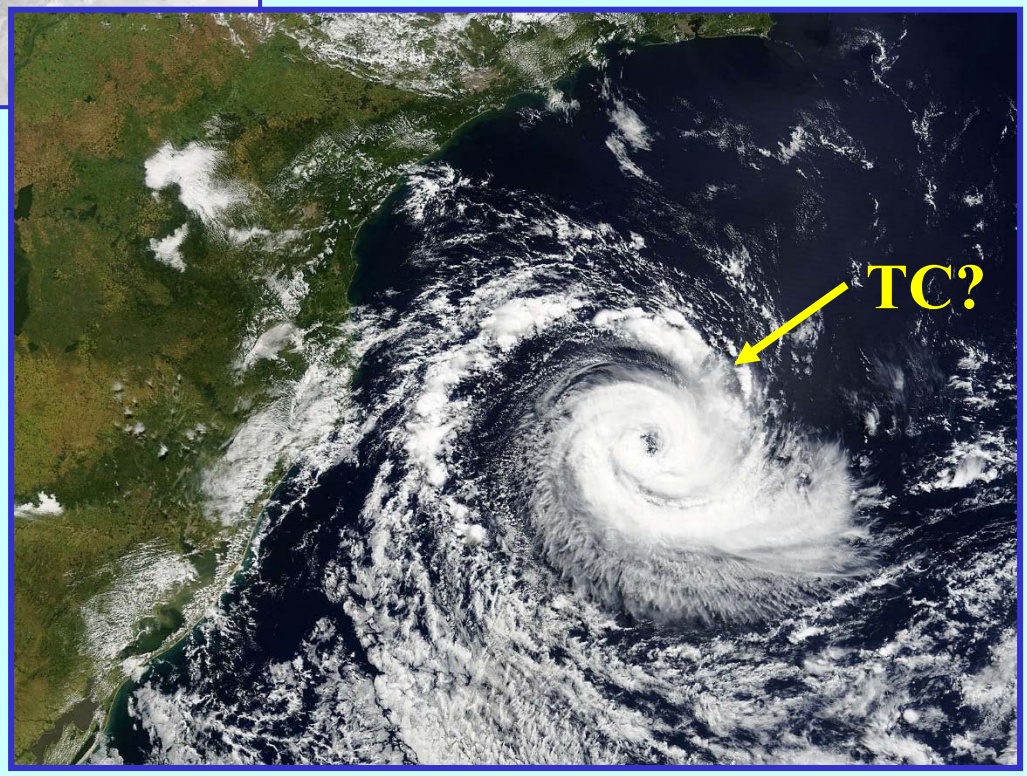



TC Monica
2006
-10
Cape Don
Croker Island
Tiwi Islands
Coburg Peninsula
Goulburn Island
4 PM Apr 24
4 AM Apr 24
4 PM Apr 23
Maningrida
Elcho Island
Nhulunbuy
Milingimbi
Point Stuart
Darwin
Oenpelli
Jabiru
Adelaide River
Daly River Mouth
Cape Shield
Alyangula
Port Keats
Katherine
Numbulwar
0
150
300
Kilometres
Cape Don
Croker Island
Goulburn Island
4 PM Apr 24
4 AM Apr 24
Tiwi Islands
Elcho Island
Nhulunbuy
Maningrida
Milingimbi
Darwin
Oenpelli
4 AM Apr 25
Jabiru
Adelaide River
Cape Shield
Daly River Mouth
Alyangula
Port Keats
Numbulwar
Katherine
Port Roper
-15
0
200
400
Kilometres

Damage TC Monica 2006

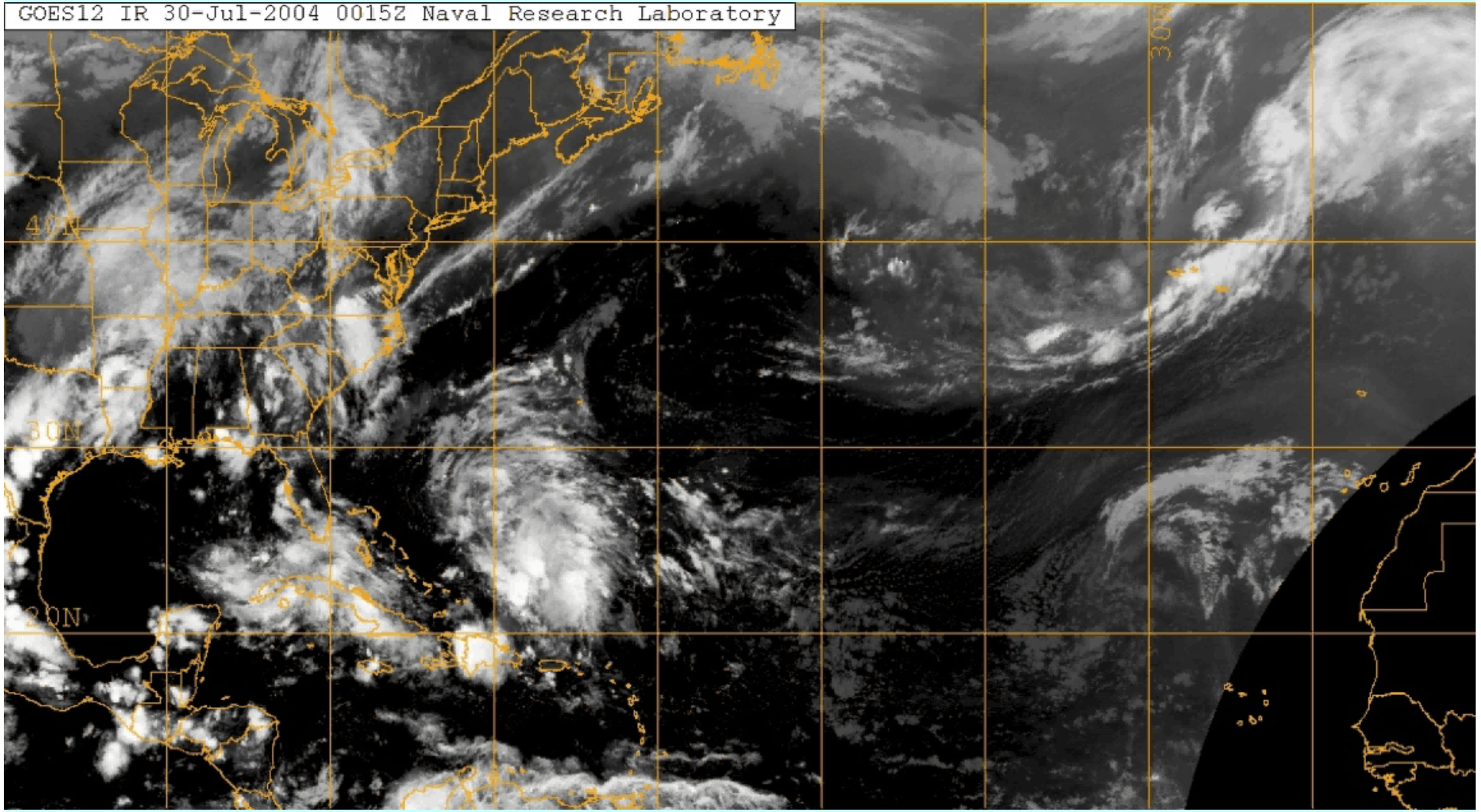


Related phenomena



End

Movies


GOES12 IR 30-Jul-2004 0015Z Naval Research Laboratory
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