Hurricanes: Observations and Dynamics

Houze Section 10.1.
Holton Section 9.7.
Emanuel, K. A., 1988: Toward a general theory of hurricanes. *Amer. Scientist*, **76**, 371-379. (handout).
http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/hurr/home.rxml

Definition:

Hurricanes are intense vortical (rotational) storms that develop over the tropical oceans in regions of very warm surface water.

Hurricanes are called **typhoons** when they occur over the western Pacific.

Before they reach the hurricane/typhoon strength (when winds near the center of vortex is > 32 m/s), they are called **tropical cyclones**.

Horizontal scale ~ 500 km, vertical depth ~ 10 – 15 km

Although hurricanes have radial scales of several hundred kilometers, the horizontal scale of the region of intense convection and strong winds in a hurricane is typically only about 100 km in radius. Thus, it is reasonable to classify **hurricanes as mesoscale systems**.

Regions of formation:

- Between 5° and 20° latitude, but not at the equator (need Coriolis force)
- Sea surface temperature > 26.5°
- Moderately conditionally unstable atmosphere
- Weak vertical shear

Locations of formation over a 20-year period:

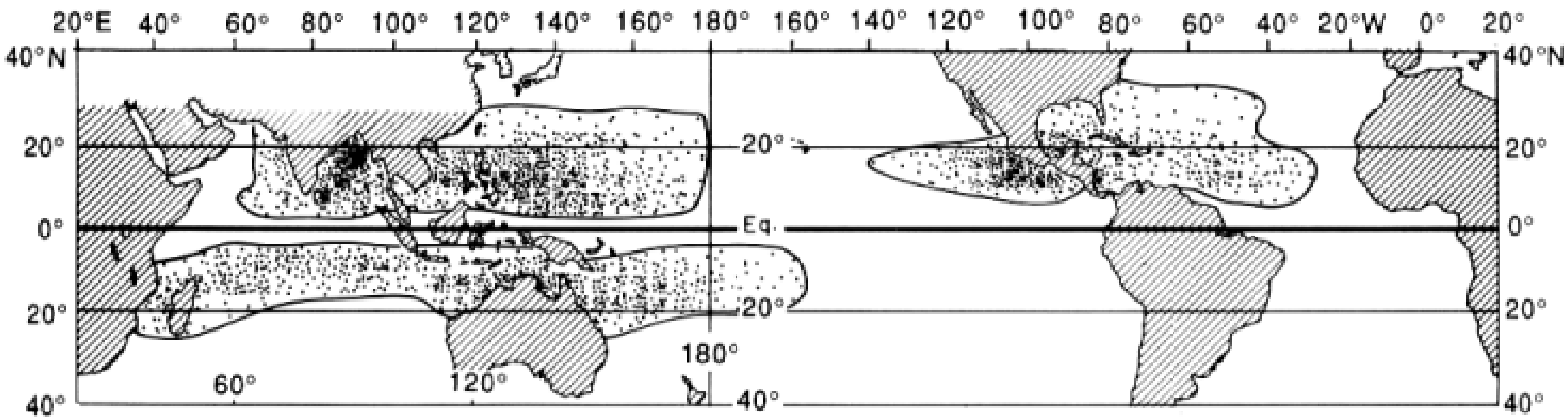


Figure 10.1 Locations of tropical cyclone formation over a 20-year period. (From Gray, 1979. Reprinted with permission from the Royal Meteorological Society.)

Tracks of tropical cyclones and sea-surface temperature

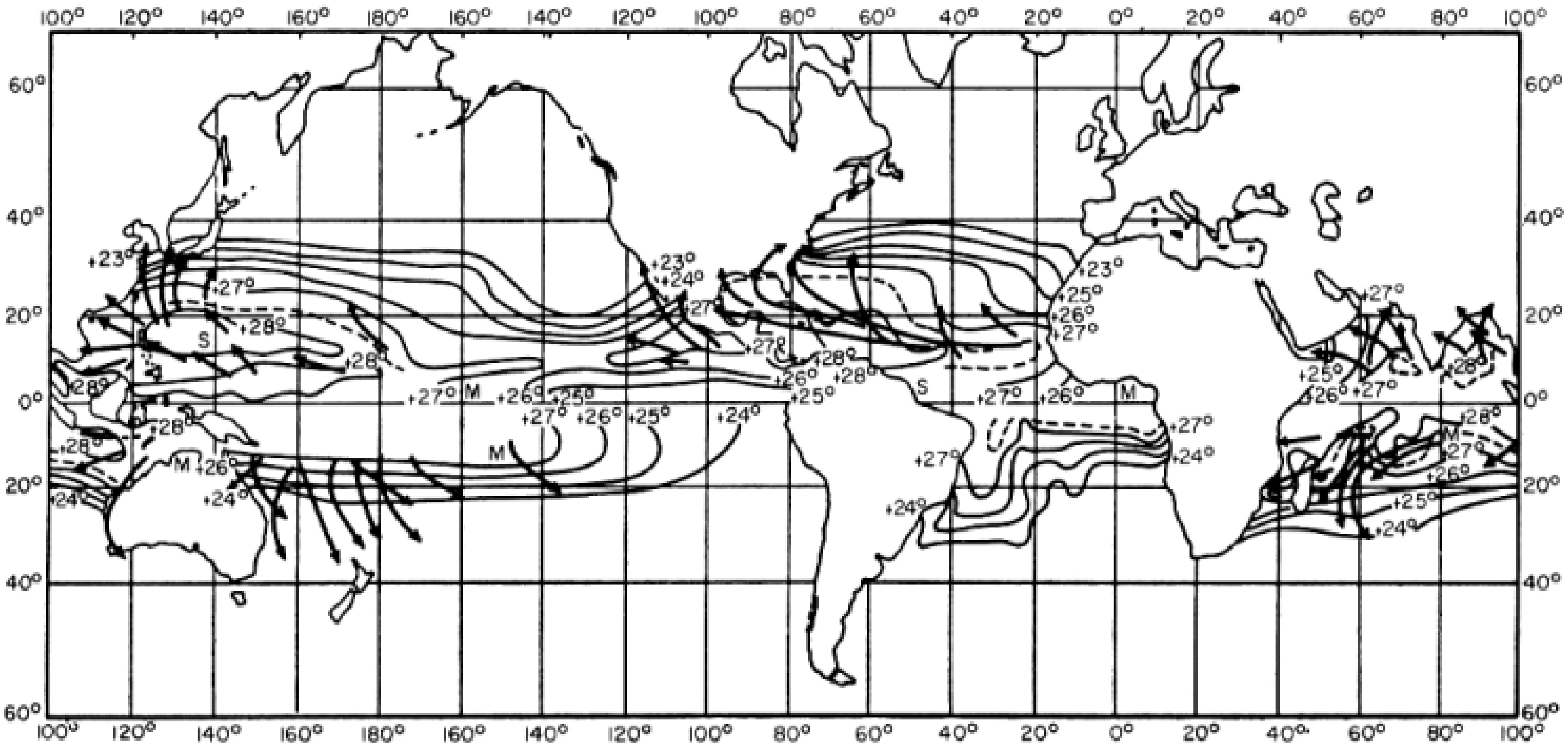


Figure 10.2 Tracks of tropical cyclones in relation to mean sea-surface temperature (°C). September temperatures are taken for the Northern Hemisphere. March temperatures are taken for the Southern Hemisphere. (From Bergeron, 1954. Reprinted with permission from the Royal Meteorological Society.)

General Patterns of Cloud and Precipitation in Hurricanes

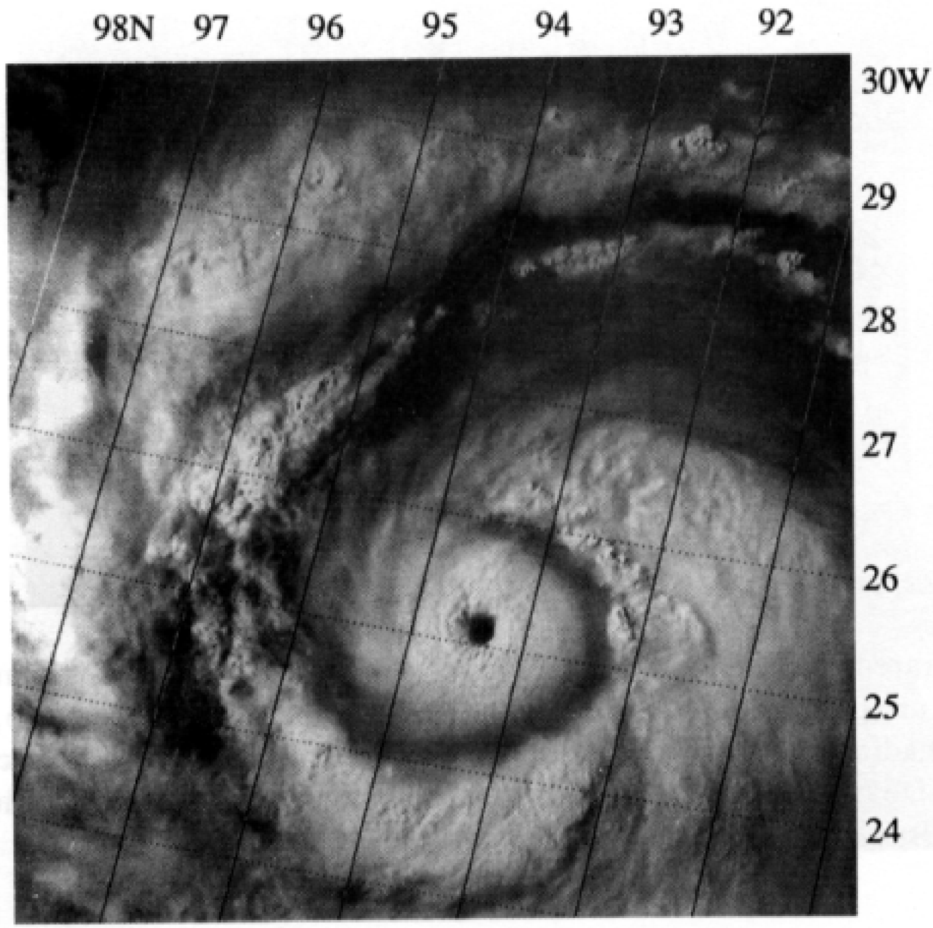


Figure 1.28 Visible wavelength satellite view of Hurricane Allen (1980). (Photo courtesy of Frank D. Marks, Jr.)

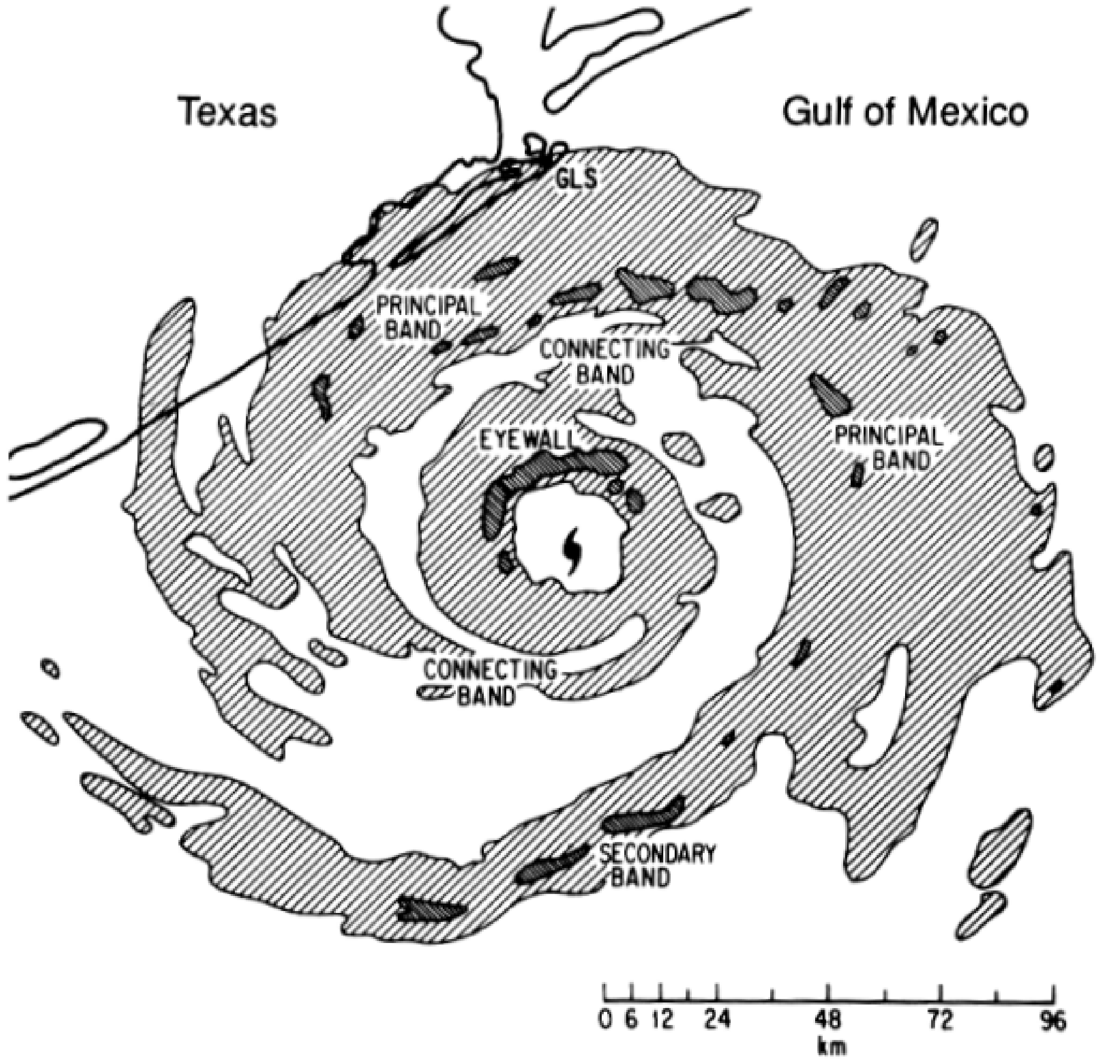


Figure 10.4 Radar echo pattern seen in Hurricane Alicia (1983) labeled according to the schematic of Fig. 10.3. Contours are for 25 and 40 dBZ. (From Marks and Houze, 1987. Reproduced with permission from the American Meteorological Society.)

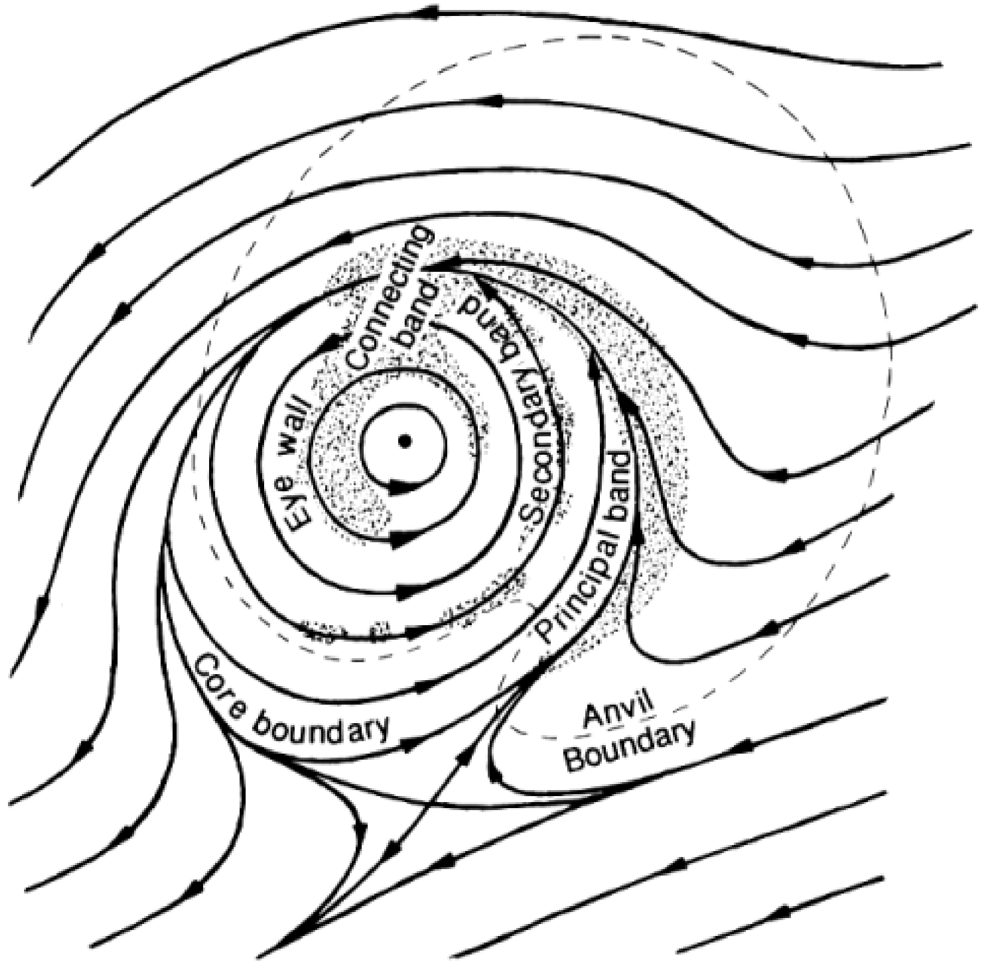


Figure 10.3 Schematic representation of the typical echo pattern seen by airborne radar in flights through hurricanes in relation to the low-level wind pattern. (From Willoughby *et al.*, 1984b. Reprinted with permission from the American Meteorological Society.)

Major Features:

- Cyclonic spiral convergent bands at the low-levels and anticyclonic outward spiral cirriform clouds at the upper levels

- Hurricane eye – typically a cloud free center of 10-50 km in diameter

- Eye wall – deep convection surrounding the eye. Slopes outward with height. Two-eye-wall structures had been observed.

- Rainbands – typically spiral bands of clouds outside the eye wall. Often propagate outwards from the eye.

- Reflectivity – even in eye wall, $R_{max} \sim 45 – 50$ dBz. 30-35 typical. In thunderstorms, $R \sim 55 – 70$ dBz.

The winds - In the horizontal cross-section

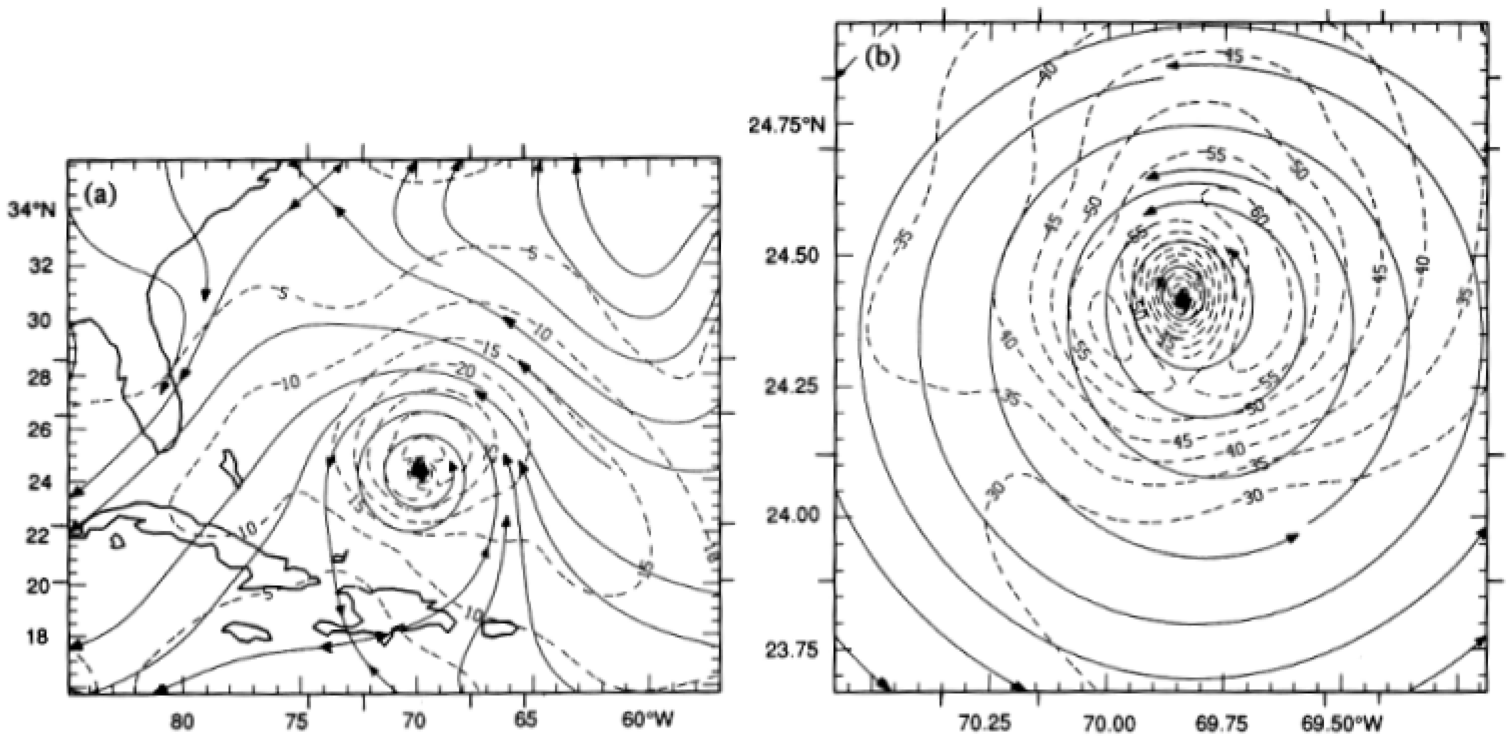


Figure 10.5 Low-level (900 mb) wind field associated with Hurricane Gloria (1985). (a) Large-scale flow analysis. Tick marks indicate boundaries of three nested rectangular domains defined for the analysis; in the inner domain, wavelengths less than about 150 km have been filtered out. In the intermediate and outer domains, wavelengths less than about 275 and 440 km have been removed. (b) High-resolution wind analysis, in which wavelengths less than about 16, 28, and 44 km have been filtered out in the three successively larger domains, whose boundaries are indicated by tick marks. Solid lines with arrows are streamlines. Dashed lines are isotachs labeled in m s^{-1}. (Courtesy of James Franklin, Hurricane Research Division, U.S. National Oceanic and Atmospheric Administration.)

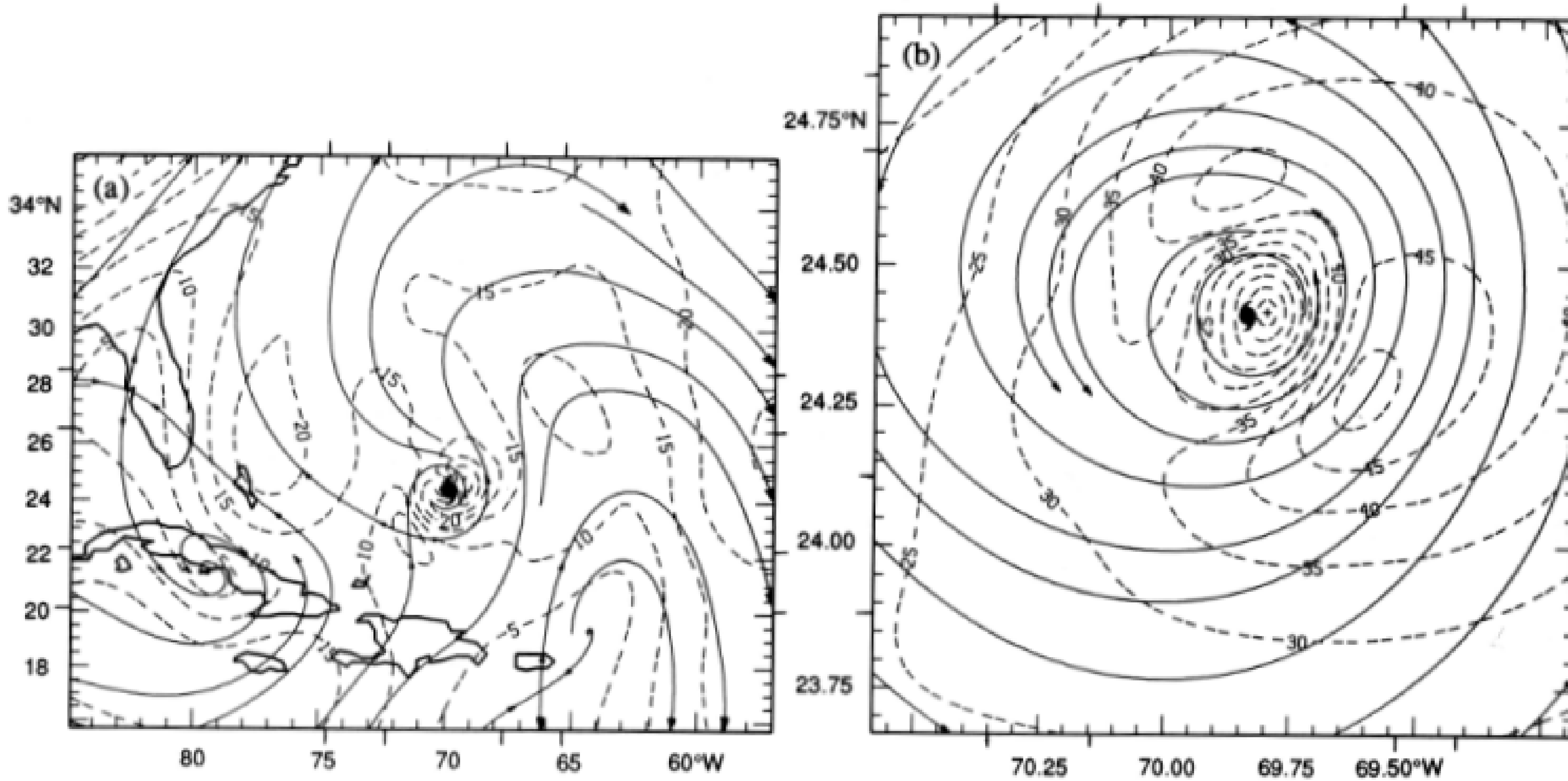


Figure 10.8 Upper-level (200 mb) wind fields associated with Hurricane Gloria (1985).

Horizontal Distribution of winds

Roughly symmetric in terms of system relative winds

Asymmetric in total winds due to the hurricane motion – stronger on the "forward" side.

Vorticity $= \frac{V}{R} + \frac{\partial V}{\partial r}$ in cylindrical coordinates.

Typical value ~ $\frac{50 m/s}{50 km} = 1 \times 10^{-3} s^{-1}$.

The winds - In the vertical cross-section

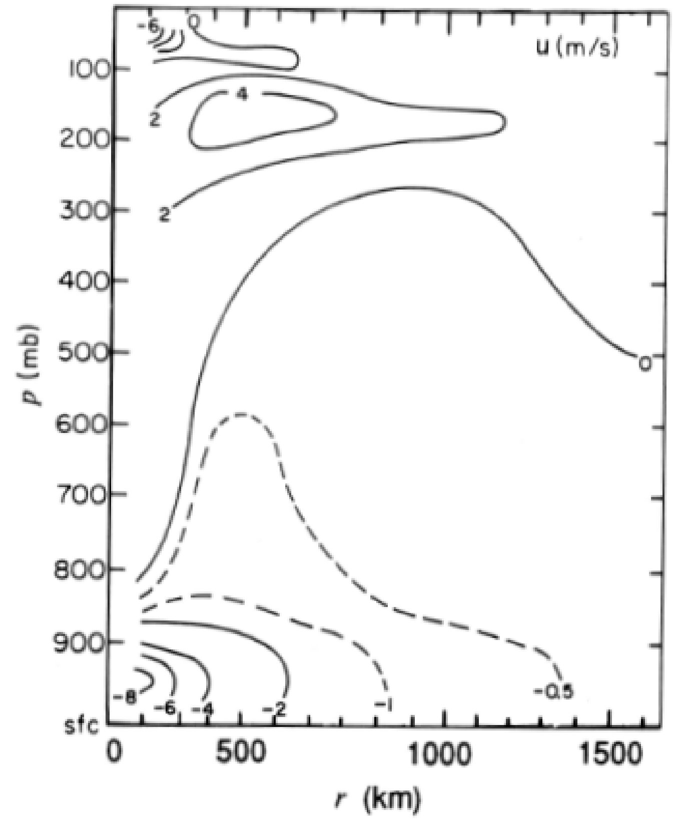


Figure 10.6

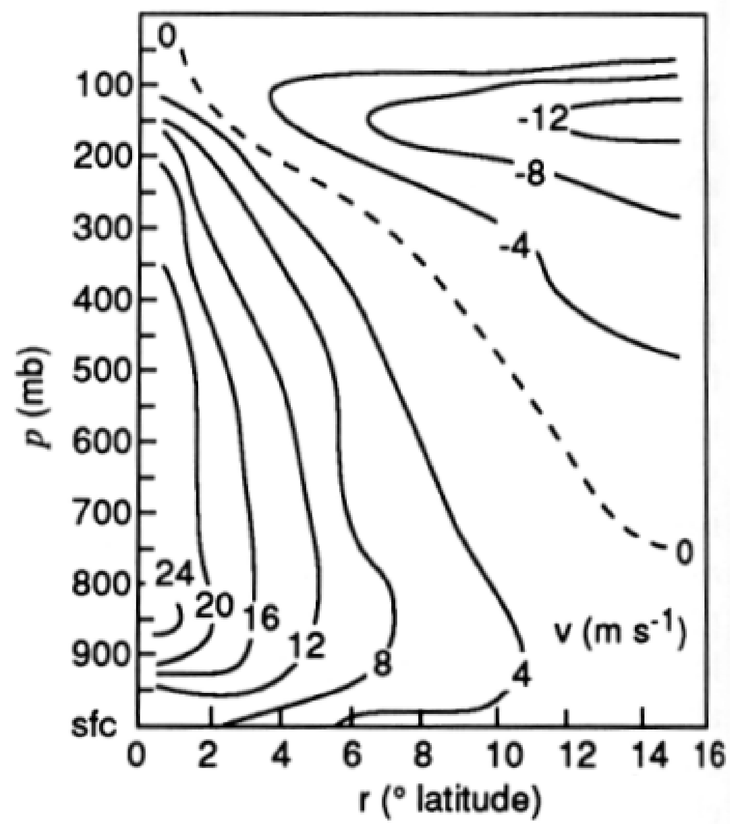
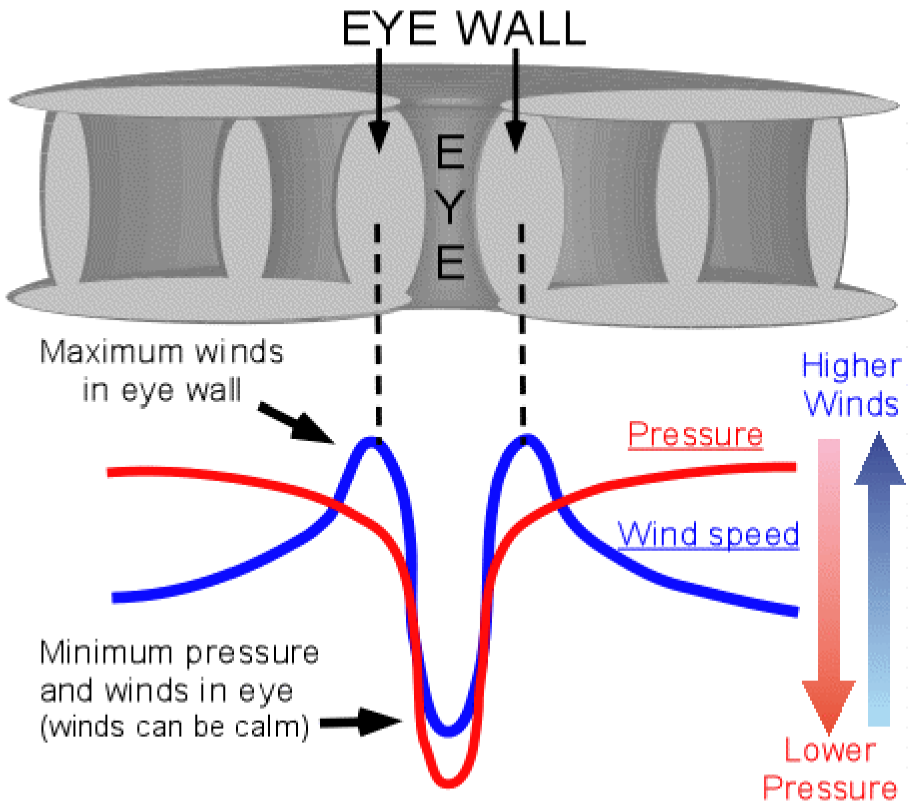


Figure 10.7

Figure 10.6 Vertical cross section of the mean radial wind (u) in western Atlantic hurricanes. Analysis is a composite of data collected in many storms. (From Gray, 1979. Reprinted with permission from the Royal Meteorological Society.)

Figure 10.7 Vertical cross section of the mean tangential component of the wind (v) in Pacific typhoons. Analysis is a composite of data collected in many storms. (From Frank, 1977. Reprinted with permission from the American Meteorological Society.)

- Maximum tangential wind at the edge of eye wall
- Max speed ~ 0.5 – 1.5 km above sfc
- Vertical shear < 0.0 since the thermal wind opposes the observed wind throughout the troposphere. Why – because hurricanes have warm code (see next figure)
- The vertical shear is relatively weak, though, due to vertical momentum mixing by Cb clouds


EYE WALL
EYE
Maximum winds
in eye wall
Higher
Winds
Pressure
Wind speed
Minimum pressure
and winds in eye
(winds can be calm)
Lower
Pressure

Thermodynamic Structure

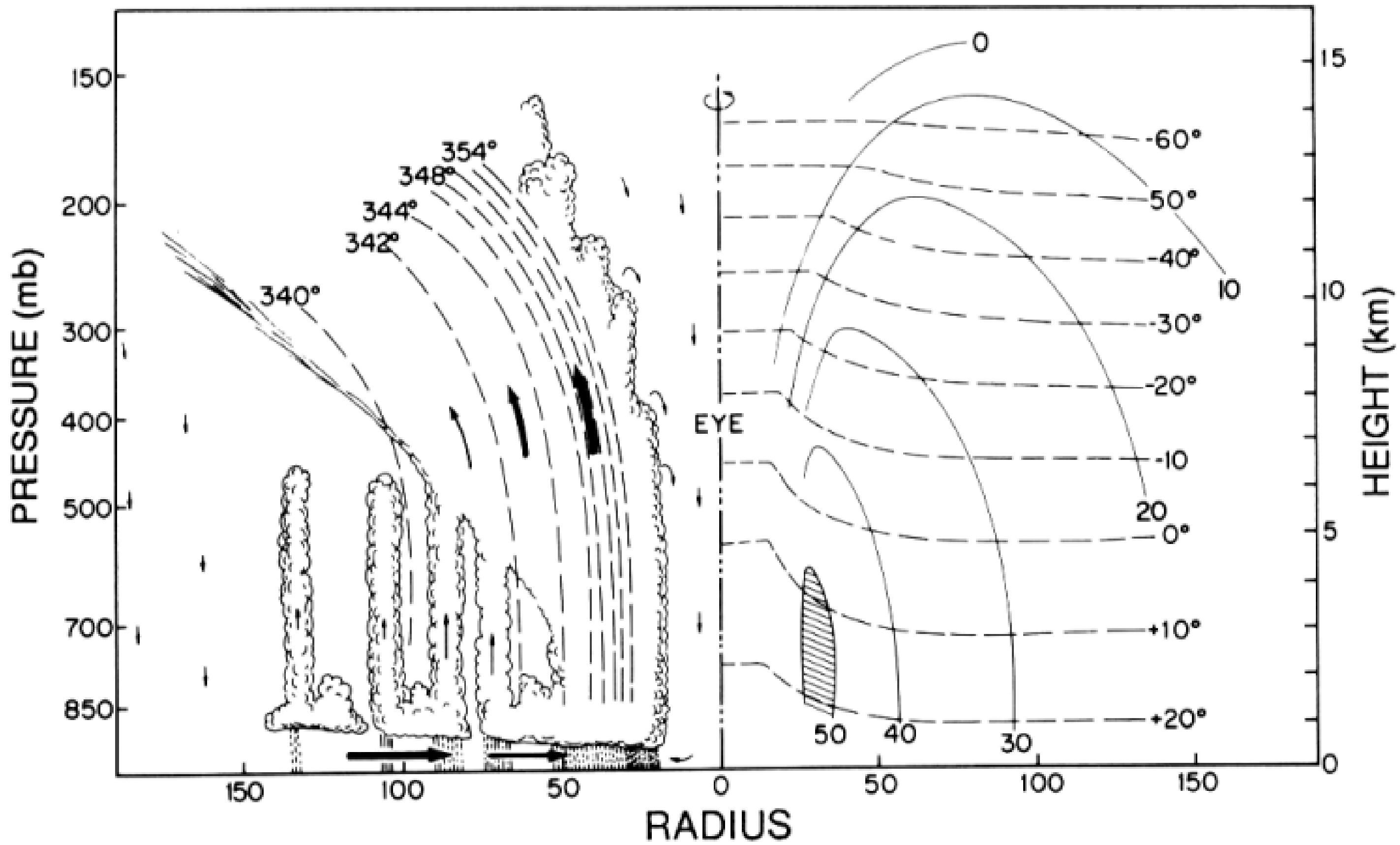


Figure 10.11 Radial cross section through an idealized, axially symmetric hurricane. On left: radial and vertical mass fluxes are indicated by arrows, equivalent potential temperature (K) by dashed lines. On right: tangential velocity in m s^{-1} is indicated by solid lines and temperature in °C by the dashed lines. (From Wallace and Hobbs, 1977, as adapted from Palmén and Newton, 1969.)

Temperature departure from the mean

- ~ 10° - 15° warmer inside eye due to subsidence
- Warm core causes surface low-pressure (hydrostatic balance)
- θ_e in hurricane more potentially stable than outside (since instability has been released)
- θ_e in eye much higher (15° - 30° more)

Note:

(a) If one starts with $\theta_e = 350K$ and go up along moist adiabat and $p_{sfc} = 1000mb$ (typical for most tropical disturbances), we can show

$$\Delta p_{sfc} = - 2.5\ \Delta\theta_e.$$

(b) Air from outside hurricane (where p ~ 1000mb) going towards the center (where p ~ 950 mb) should normally cool adiabatically – but observed temperature stays the same or increases slightly. This is due to sensible heat flux from the sea surface → θ_e increases substantially.

The air-sea interaction theory further points out that the latent-heat flux from the sea surface as the air flows towards the center at large wind speed is another major energy source.

Presence of warm-cored eye a key feature of hurricanes → pressure drop at the center.

Landfall

- greater frictional convergence
- convection may actually intensify because of enhanced Ekman pumping effect (but less high θ_e air from the surface cause pressure to rise)
- wind damage from large scale tangential winds but also from convective downdrafts
- weak to moderate tornadoes are common after landfall
- sfc winds now about 50% of 1 km winds (vs 70% over ocean) so vertical shear increases significantly
- CAPE in hurricanes relatively small

Damages:

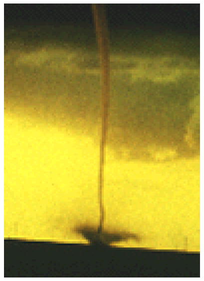
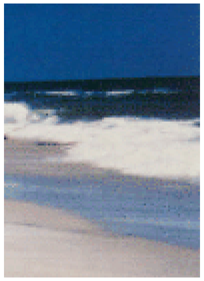
- Strong winds, convective gusts
- Sea level rise by 1-2 m due to low pressure
- Storm surge ~ 2 – 10 m, strongest in the right front quadrant
- Waves
- Tornadoes
- Flooding from rains

Damage
caused by hurricanes

With hurricanes being as powerful as they are, it is not surprising that upon landfall they cause damage and destruction. Even when the hurricane has yet to make landfall, its effects can be dangerous. However, most of the damage caused to man and nature occur as a hurricane makes landfall.



Strong Winds   Storm Surge   Flooding

Tornadoes   Rip Tides

Each of the above phenomena can turn a hurricane into a home-wrecker, a nature-destroyer, and even a killer. Some tropical storms that make landfall cause damage in these ways, but very rarely do they do so in as significant a manner as do hurricanes.

Strong Winds

determines the intensity of a hurricane

The intensity of a tropical cyclone is measured by the highest sustained wind speed found within it. Once it becomes a hurricane, the relative strength of that hurricane is also measured on a scale based on its greatest wind speed. This scale is named the Saffir-Simpson scale for the men who invented it. The scale is listed below.

Saffir-Simpson Hurricane Damage-Potential Scale

Scale Number Category	**Central Pressure** mb inches	**Wind Speeds** mi/hr knots	**Storm Surge** feet meters	**Observed Damage**
1	>=980 >=28.94	74-95 64-82	4-5 ~1.5	some damage to trees, shrubbery, and unanchored mobile homes
2	965-979 28.50-28.91	96-110 83-95	6-8 ~2.0-2.5	major damage to mobile homes; damage buildings' roofs, and blow trees down
3	945-964 27.91-28.47	111-130 96-113	9-12 ~2.5-4.0	destroy mobile homes; blow down large trees; damage small buildings
4	920-944 27.17-27.88	131-155 114-135	13-18 ~4.0-5.5	completely destroy mobile homes; lower floors of structures near shore are susceptible to flooding
5	<"920" <"27.17"	>"155" >"135"	>"18" >"5.5"	extensive damage to homes and industrial buildings; blow away small buildings; lower floors of structures within 500 meters of shore and less than 4.5 m (15 ft) above sea level are damaged

The Saffir-Simpson scale categorizes hurricanes on a scale from 1 to 5. Category 1 hurricanes are the weakest, and 5's the most intense. Hurricanes strong enough to be considered intense start at category 3 or with sustained winds exceeding 96 knots (111 mph). For reference, there have only been two category 5 hurricanes that made landfall on the mainland U.S. (Florida Keys 1935 and Camille 1969). Recent intense hurricanes to make landfall on the United States were Opal in 1995 and Fran in 1996.

Hurricane Dynamics

Hurricane vortex cannot be understood without including the **rotation of the earth** in the vorticity balance.

The rapid **rotation is produced** by concentration of the vertical component of absolute vorticity by vortex stretching/horizontal convergence.

Maximum tangential wind speeds range typically from 50 to 100 m s^{-1}.

Centrifugal force cannot be neglected compared to the Coriolis force.

The azimuthal (tangential) velocity in a steady-state hurricane is in **gradient wind balance** with the radial pressure gradient force.

Hydrostatic balance holds on the hurricane scale, which implies that the **vertical shear of the azimuthal (tangential) velocity** is a function of the radial temperature gradient (**thermal wind balance**)

The **kinetic energy** of hurricanes is **maintained** in the presence of boundary layer dissipation **by conversion of latent heat energy** acquired from the underlying ocean.

This potential energy conversion is carried out by a **transverse secondary circulation** associated with the hurricane, as shown below:

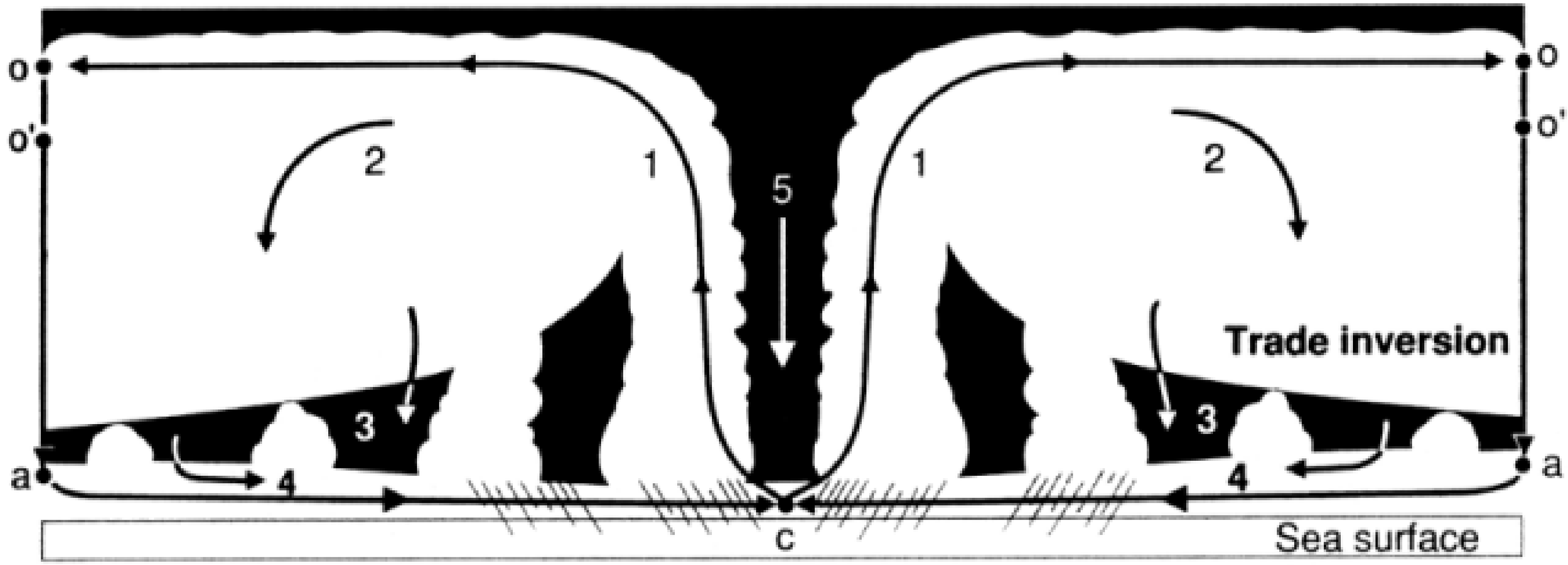


Fig. 9.14 Schematic cross section of the secondary meridional circulation in a mature hurricane. Air spirals in toward the eye (region 5) in the boundary layer (region 4), ascends along constant-M surfaces in the eyewall cloud (region 1), and slowly subsides and dries in regions 2 and 3. (After Emanuel, 1988.)

Hurricane Formation Theories

Two main theories:

CISK (Conditional Instability of the Second Kind) Theory and the Air-sea interaction theory

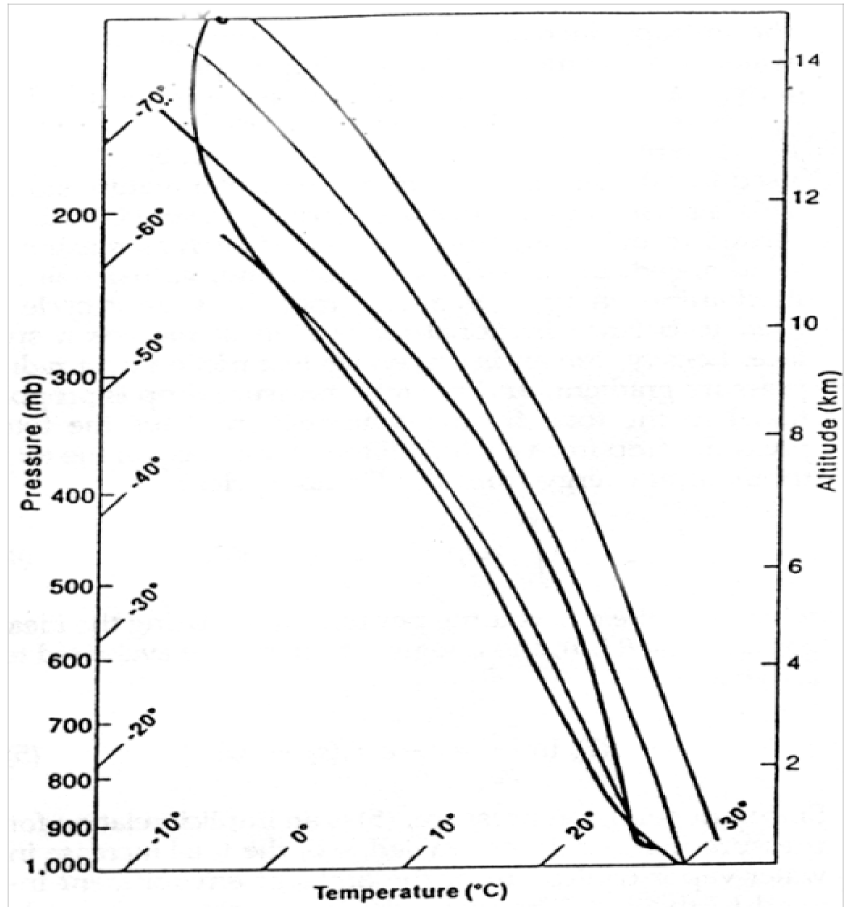
CISK (Conditional Instability of the Second Kind) Theory ((1960's – 1970's)

Represents a cooperation between convection and large-scale convergence:

- Weak disturbances containing vorticity
- Ekman layer (BL) convergence through Ekman pumping
- Increased convection
- Latent heat release
- Temperature increase
- Sfc pressure falls
- Increased vorticity
- Increased convergence
- A feedback loop - instability

Linear analysis to capture the above instability process has not been very successful, however, since there is little evidence that such interaction leads to a growth rate maximum on the observed scale of hurricanes.

Another problem is, as is pointed out by Emanuel (handout) that the tropical atmosphere is on average conditionally statically neutral to the low-level convective parcel, when the water loading is included. Therefore net buoyancy within a convective cloud is small relative to its environment. It is believed that it is the temperature difference between the hurricane center and the surrounding environment that drives the hurricane circulation.

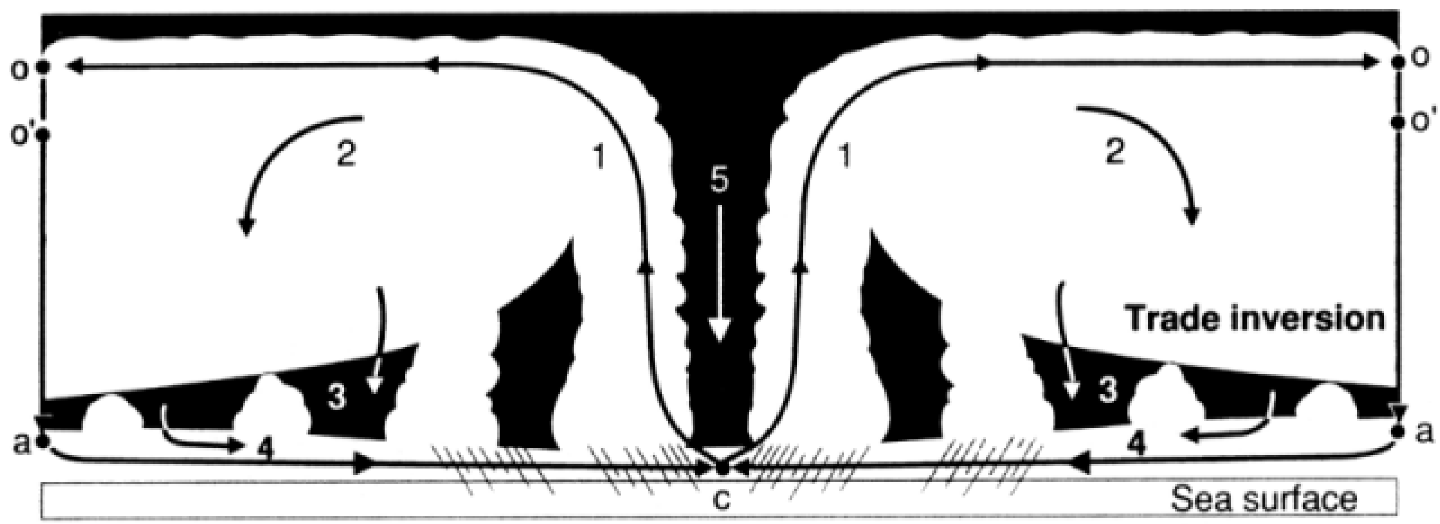


<u>Air-sea interaction theory</u> (Emanuel 1988, handout)

A dramatically different view has been proposed, mainly by Emanuel in the late 1980's which is referred to as the **air-sea interaction theory**.

It is based on the fact that the potential energy for hurricanes arises from the **thermodynamic disequilibrium between the atmosphere and the underlying ocean.**

Since the subcloud boundary layer is unsaturated, the BL air has a potential for significant increase in q_v therefore θ_e (or moist entropy), therefore the real energy source is believed to be the warm surface of the topical oceans.



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The air-sea interaction theory views energetics of the steady-state hurricane can be viewed as an example of a **Carnot cycle heat engine** in which heat is absorbed (in the form of water vapor) from the ocean at temperature T_s and expelled by radiative cooling to space at temperature T_o at the top of the storm.

With this theory, the circulation is driven by ΔT between region 1 (+5) and region 2. The temperature in region 1 is higher because of increase of water vapor of BL air as it flowed inward towards the eye and that in region 5 due to subsidence.

Quantitative investigation of energy source: Hoe does total moist entropy increase?

Recall (dry) entropy

$$ds = C_p\, dln(\theta)$$

where $\theta = T\left(\frac{p_0}{p}\right)^{R/C_p}$ —>

$$d\ln\theta = d\ln T - R/C_p\, d\ln p$$

or $$C_p d\ln\theta = C_p d\ln T - R\, d\ln p\,.$$

Now, for moist processes, we can show that

$$C_p d\ln\theta = -\frac{L dw_s}{T}$$ (equation for moist adiabat)

so, moist entropy is defined as

$$ds = C_p d \ln T + \frac{L dw_s}{T} - R d \ln p \, .$$

As air moves toward the hurricane center, **entropy increases** due to **increase in moisture** (dw_s term) via latent heat fluxes and ***p* decrease** (but temperature stays the about same as sensible heat flux from the ocean balances the expected adiabatic cooling – isothermal expansion, heat input at high T).

As the air ascends in the eye wall region (region 1 in Figure), s is conserved.

s decreases outside the hurricane at the upper-levels due to radiative cooling (at point O to O').

Carnot's Theorem says the total amount of mechanical energy available from a closed circuit through the storm is the total heat input multiplied by the efficiency:

$$E = \varepsilon T_s (s_c - s_a)$$ (c for center and a for ambient, outside)

where ε is the thermodynamic efficiency of the heat engine.

$$\varepsilon = \frac{T_s - T_o}{T_s}$$

Since $T_s \sim 300$ K and $T_o \sim 200$ K, the efficiency of the heat engine, given by the above equation can be as high as 30%, i.e., as much as 30% heat acquired at the low levels can be converted into kinetic energy.

In a steady state hurricane, almost all of the mechanical energy generated from the Carnot cycle is used to balance frictional dissipation at the ocean surface. Locally, the air is driven against the friction by a radial pressure gradient.

Equating the work done by the pressure gradient force when the parcel moves from point a to c, to E →

$$-\int_a^c \frac{1}{\rho}\frac{dp}{dr}dr = \varepsilon T_s(s_c - s_a) \rightarrow$$

$$-\int_a^c \frac{RT}{p}dp = \varepsilon T_s(s_c - s_a)$$

or $$RT_s\left[\ln p_c \text{-} \ln p_a\right] = -\varepsilon T_s(s_c - s_a)$$

Solving for p_c gives the minimum possible central pressure. Fig.7 in Emanuel is obtained this way. It is basically a function of sea surface temperature and temperature at the lower stratosphere. See Figure 8.

Since the air-sea interaction model depends on the sea surface fluxes, which depend on the wind speed. It has been demonstrated in a numerical model that the initial vortex has to have sufficient intensity (wind speed is large enough) a hurricane to form. See Fig.9.

The real difficulty is in determining which tropical disturbance can gain sufficient intensify to develop into a hurricane. This is a still an unsolved problem.

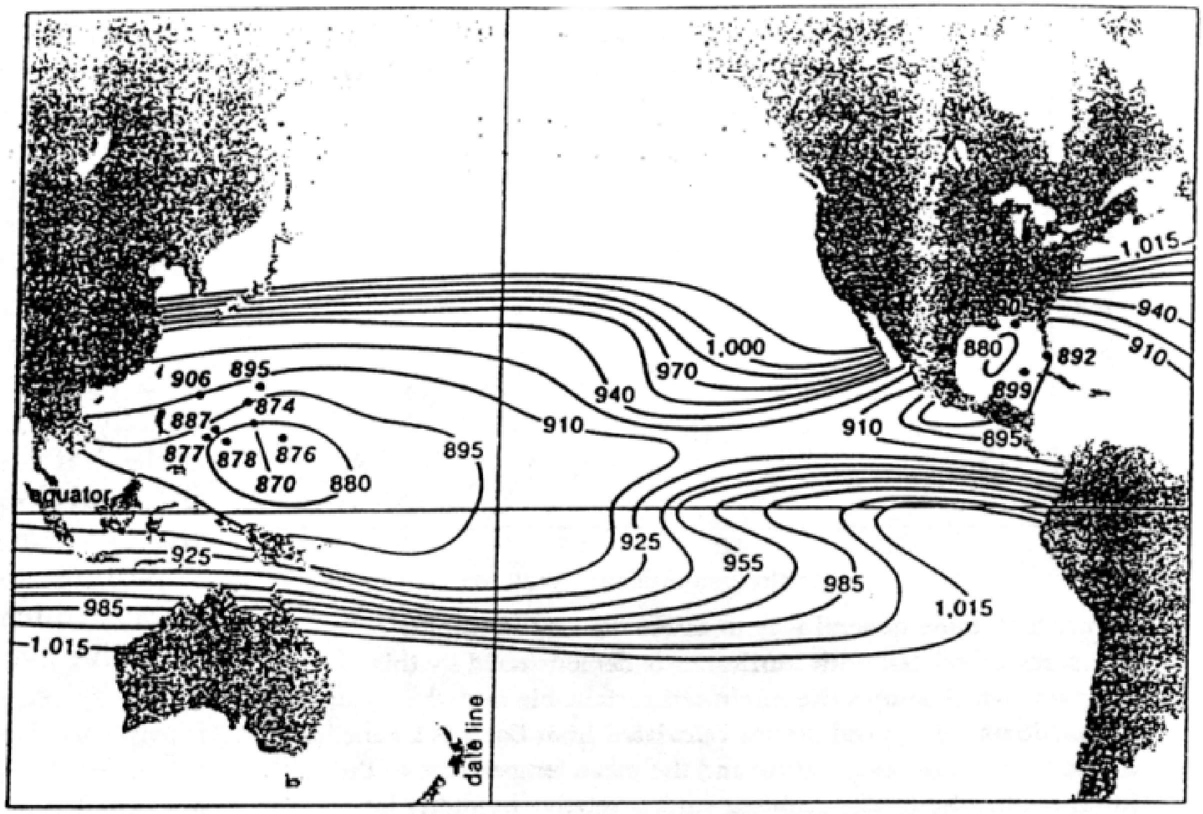

Figure 7. Hurricanes are areas of very low pressure. The tropical oceans are ideal spawning grounds for them, as demonstrated by this map, which shows the minimum sustainable central pressures in tropical storms under September mean climatological conditions over the Pacific Ocean and the Caribbean Sea. The pressures, which have been calculated using Eq. 5, are expressed in millibars, with 1,015 mb assumed to be the normal surface pressure. The dots and italicized numbers show, respectively, the locations and central pressures of some of the most intense hurricanes on record. Tropical storms in the Australian region are not indicated, because they occur during the late Southern Hemisphere summer (February–April).

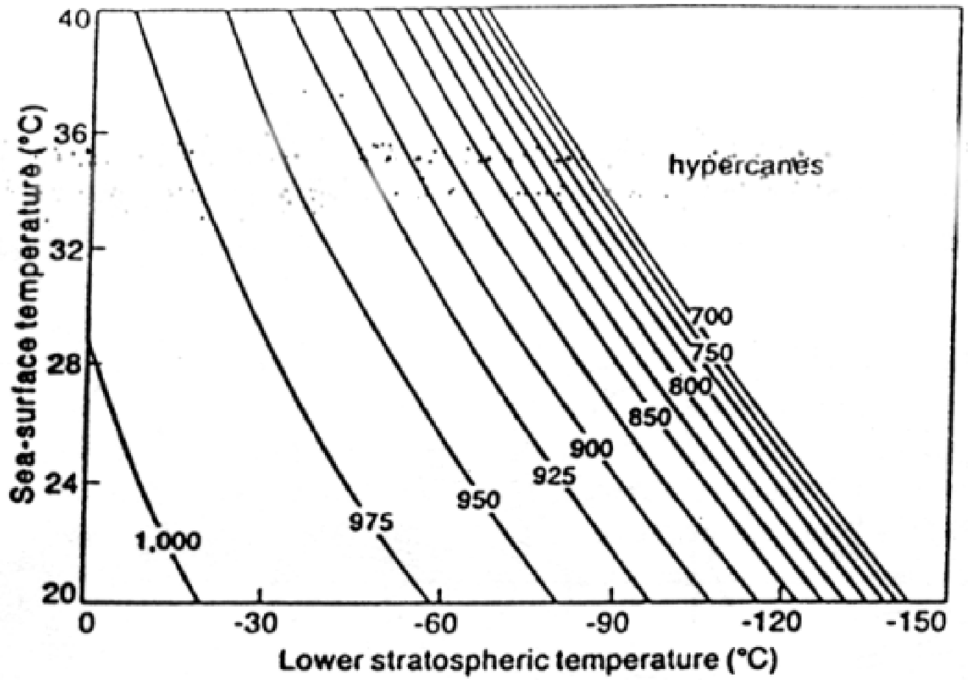

Figure 8. A more general way to assess the low atmospheric pressures associated with hurricanes is demonstrated by this diagram, which shows the minimum sustainable central pressure (in millibars) of tropical storms calculated from Eq. 5 as a function of the sea-surface temperature and the mean temperature of the lower stratosphere. The ambient surface relative humidity is assumed to be 75%. No solutions of Eq. 5 are possible in the region marked "hypercanes" because the mechanical energy produced by the Carnot heat engine is so large that it cannot be balanced by surface friction alone. The intensity of hurricanes in this regime would be limited by internal turbulent dissipation of kinetic energy, presumably at very high wind speeds.

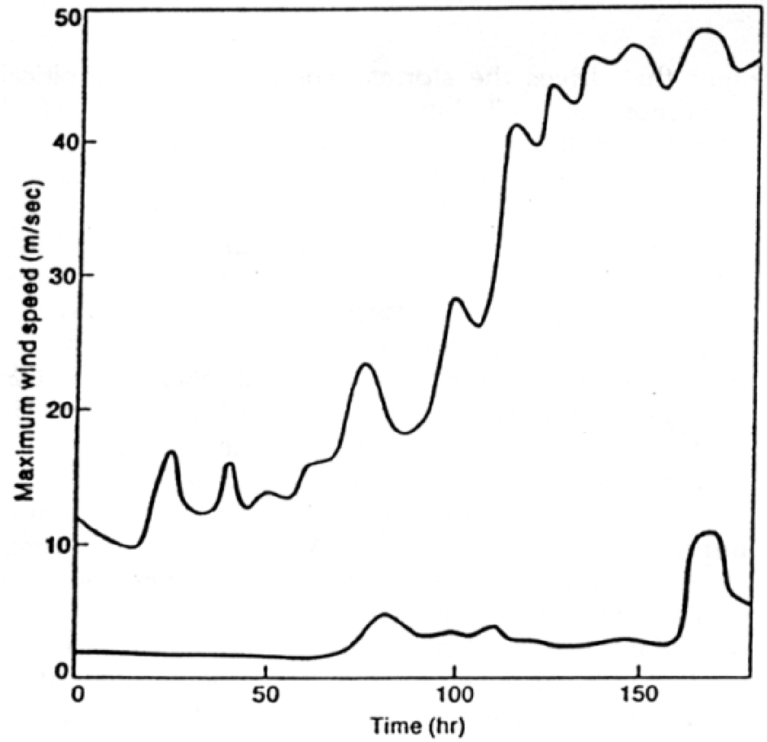

Figure 9. Computer models provide a partial answer to the question of why hurricanes are rare even though the tropical atmosphere has abundant energy to support them. This graph shows the evolution with time of the maximum surface wind speed produced by one such numerical model (Rotunno and Emanuel 1987). The red curve begins with a 12 m/sec amplitude vortex, while the maximum velocity in an experiment that starts with a 2 m/sec amplitude vortex, but is otherwise identical, is shown by the gray curve. The failure of the weak vortex to amplify demonstrates that hurricanes in this model cannot arise out of weak random noise; rather, a vortex of sufficient amplitude must be provided by independent means, such as a large-scale wave or a thunderstorm complex from a middle-latitude continent.

References:

Emanuel, K. A., 1986: An air -sea interaction theory for tropical cyclones. Part I: Steady state maintenance. *J. Atmos. Sci.*, **43**, 585-604.

Rotunno, R., and K. A. Emanuel, 1987: An air-sea interaction theory for tropical cyclones. Part II: An evolutionary study using a hydrostatic axisymmetric numerical model. *J. Atmos. Sci.*, **44**, 543-561.