Tropical meteorology

Textbooks and web sites references for this lecture:

- Dennis L. Hartmann, Global Physics Climatology, Academic Press, 1994, ISBN 0-12-328530-5 (§ 6)
- Robert McIlveen, Fundamentals of Weather and Climate, Chapman & Hall, 1995, ISBN 0-412-41160-1 (§ 11)
- Joseph M. Moran e Michael D. Morgan, Meteorology, The Atmosphere and the Science of Weather, Mc Millan College Publishing Company, 1994, ISBN 0-02-383341-6 (§ 10)
- James R. Holton, An Introduction to Dynamic Meteorology, Academic Press, 1992, ISBN 0-12-354355-X (§ 9.5-9.6)

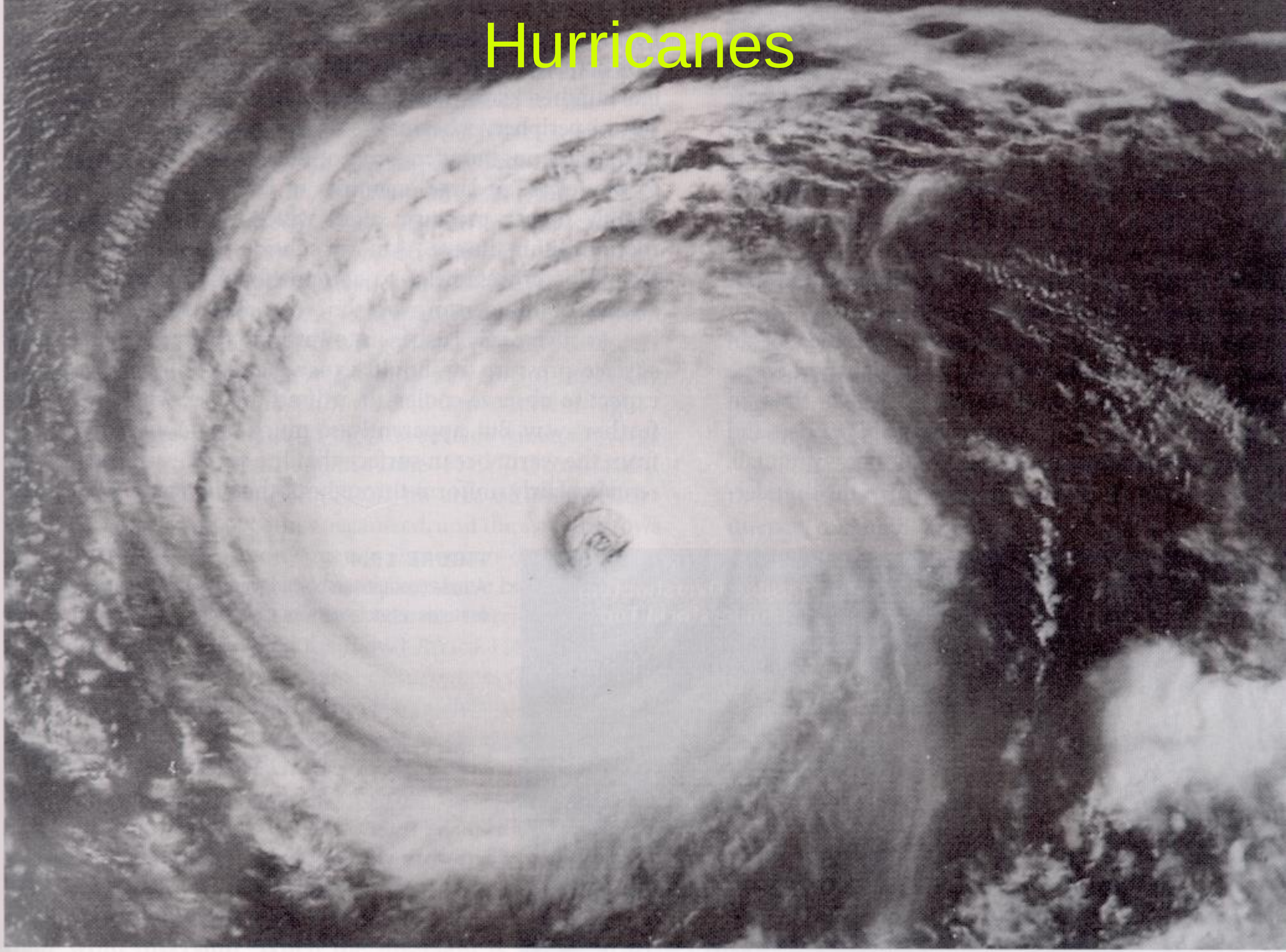
Tropical meteorology

- Low latitude: small f (but not β)
- High solar azimuth: Q with diurnal periodicity
  $\Rightarrow$ barotropic (relatively high horizontal homogenuity)
  relatively weak seasonal variation
- High humidity: Q by latent heating
  $\Rightarrow$ cloud convection, intraseasonal variations
- Complex geography: sea-land, mountain-valley, ...
  $\Rightarrow$ local circulation
- Interaction with ocean
  $\Rightarrow$ interannual variations

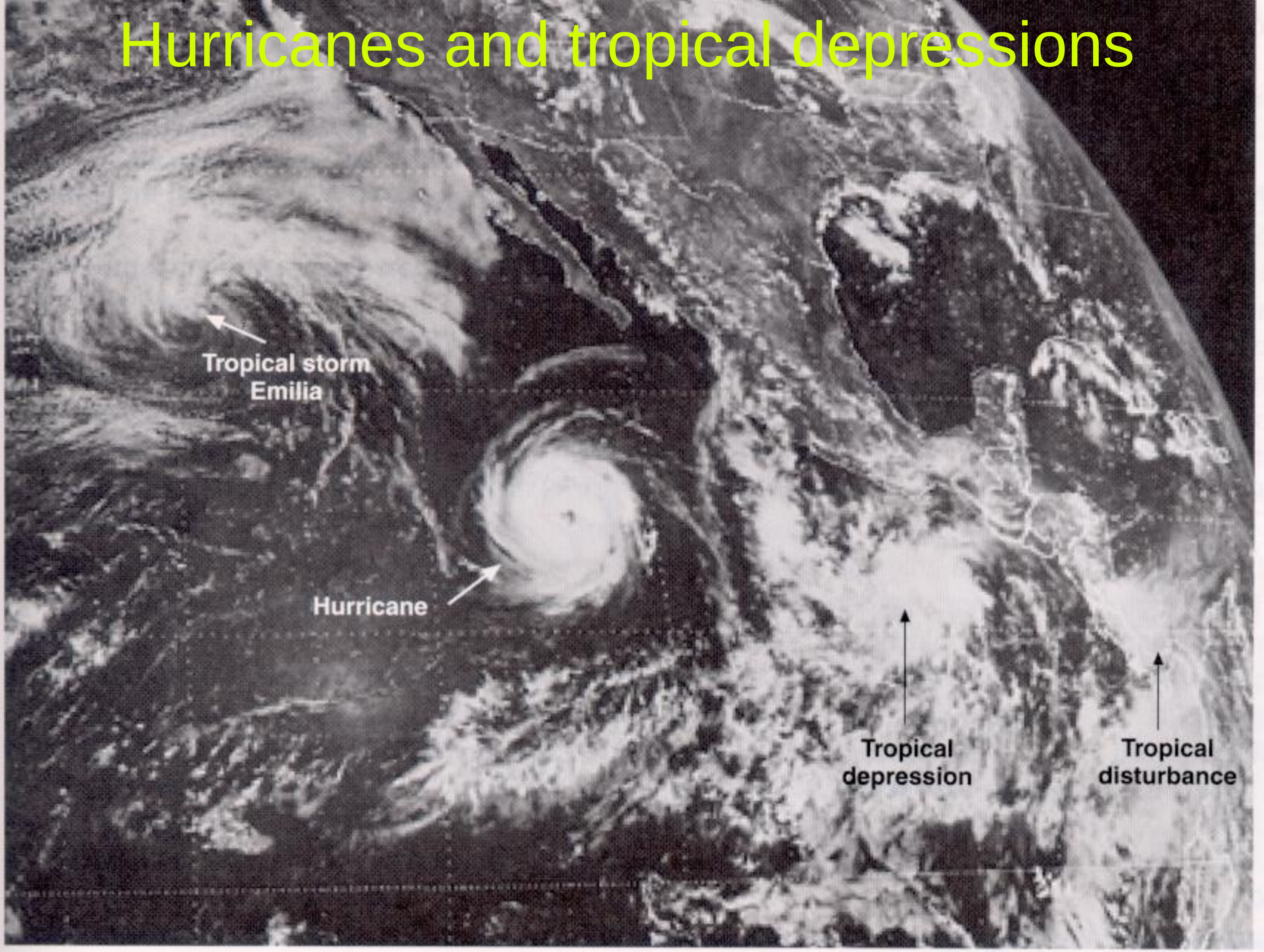
↓

Seemingly less usefulness of atmospheric dynamics

Hurricanes

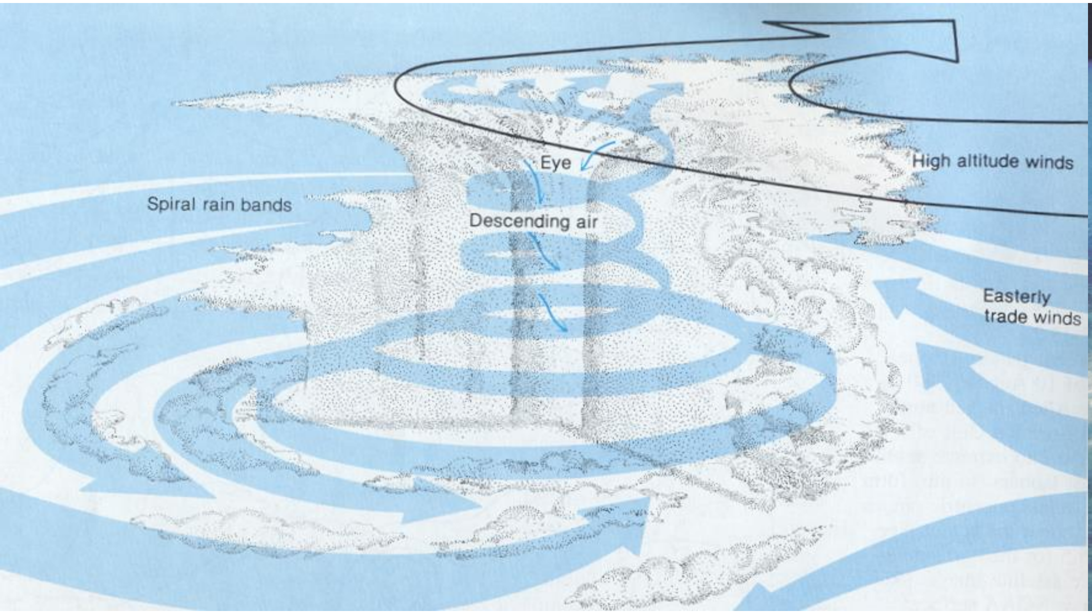


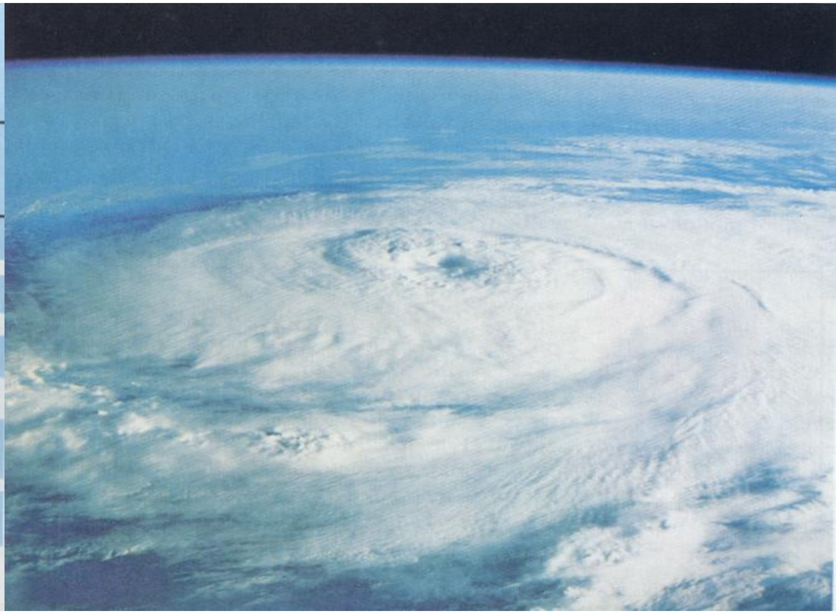
Hurricanes and tropical depressions

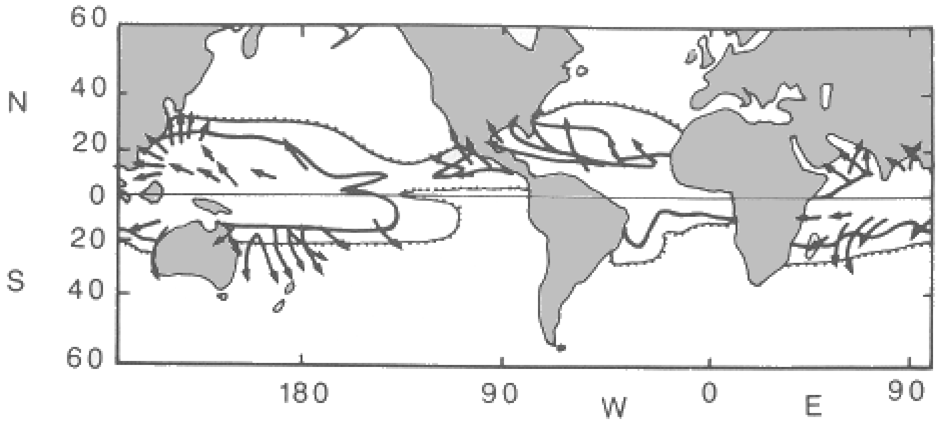


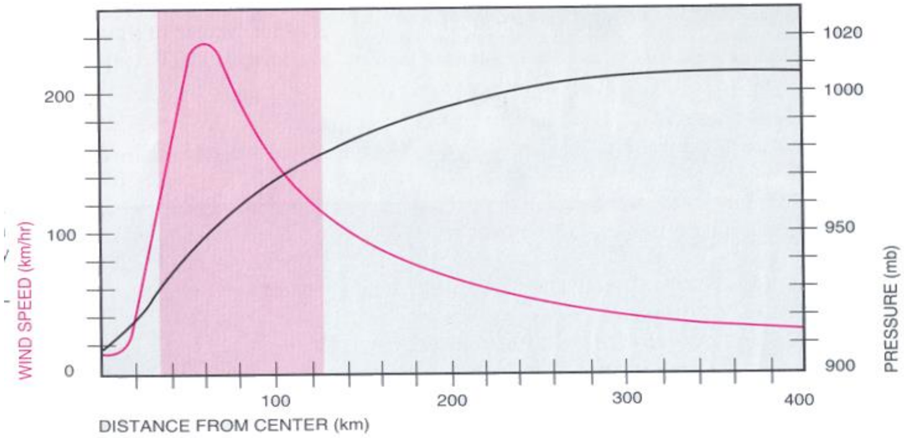
The tropical cyclones

- For definition, in a **tropical cyclone** (hurricane, typhoon) |U|>33 m/s (hurricane)
- They form prevailingly in the tropical areas at latitudes < 25° N,S (~80/years) but not in the Southern Atlantic Ocean

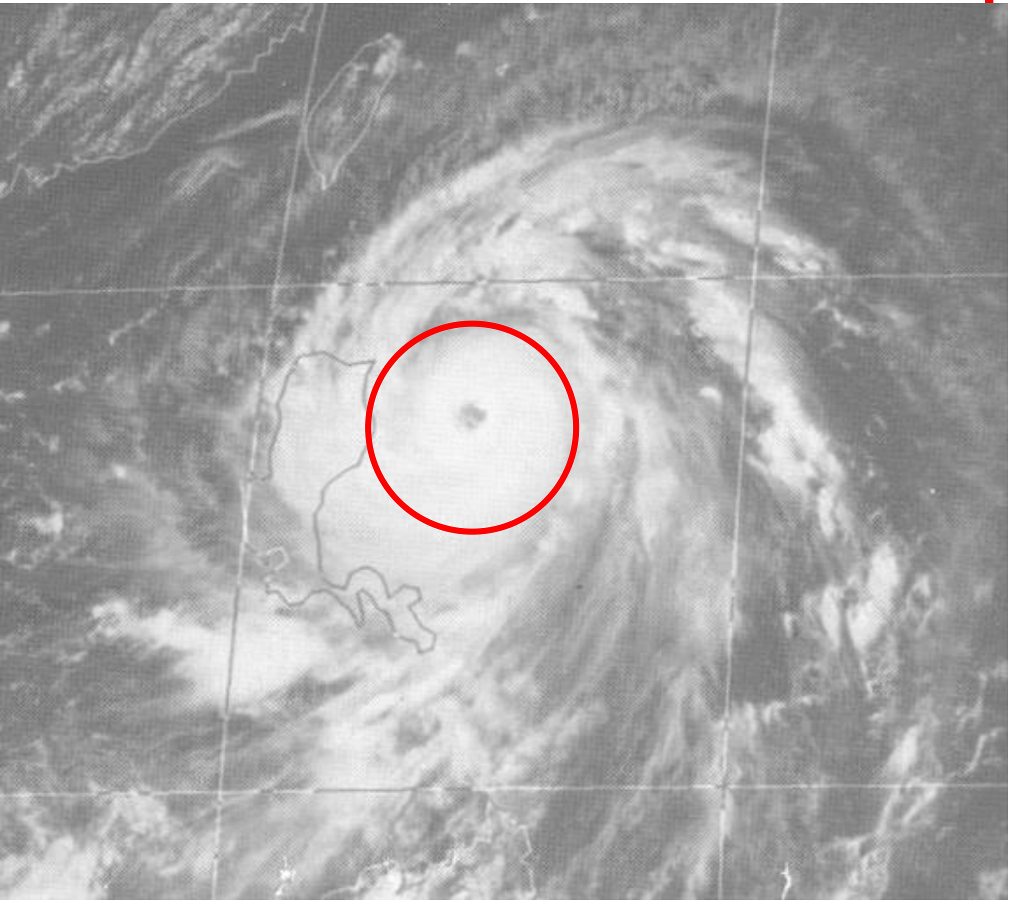








Structure of tropical cyclones



- They have a circular structure with a central area of low pressure with calm wind
- Ring of ~200 Km around the center
- Ci are clearly seen (due to the spread of Cb in the tropopause), even if the cyclone is formed almost entirely by Cb in fast rotating motion
- Cb are thicker around the eye (eye wall)

- At the center p≤950 hPa in an area of few tens of Km; horizontally |dp/dx|~1 hPa/Km (at synoptic scale normally |dp/dx|~0.1 hPa/Km)
- In the central area of the cyclone (~10-50 Km) U>33 m/s (sometimes U~75 m/s) → the wind is the main destructive factor of a tropical cyclone (directly or indirectly), especially in the proximity of the coasts (for U>50 m/s waves 10 m above the tide are seen)

Rotation velocity in tropical cyclones

- Concentration of strong rising motions near the eye → horizontal convergence
- Let consider a circular disc of air of radius R_0 at rest: the angular momentum per unit of mass dur to the terrestrial rotation is:

$$L/m = \left|\vec{v} \times \vec{R}_0\right| = vR_0 = \omega R_0^2 = fR_0^2/2$$

being ω=f/2 the planetary vorticity

- If the disc shrinks at $R<R_0$, it will start rotating at tangential speed U; the specific angular momentum is:
- The angular momentum conserves so:

$$L'/m = (\omega + \omega')R_0^2 = \left(\frac{f}{2} + \frac{U}{R}\right)R^2$$

from which, being U~50 m/s and R~30 Km:

$$L = L' \Rightarrow U = \frac{f}{2R}\left(R_0^2 - R^2\right) \xrightarrow{R_0 >> R} \frac{fR_0^2}{2R} \quad \Rightarrow \quad R_0 \approx \sqrt{\frac{2RU}{f}}$$

NB: $R_0^2 \propto 1/f$ → at the equator f~0 → R_0 (and then U) much greater

for ϕ~20° → R_0 ~145 Km but for ϕ~5° → R_0 ~500 Km

[previous values are underestimated as **friction has not been considered**]

The warm nucleus in the tropical cyclones

- In rotating motions centrifugal force U^2/R equiklibrates the pressure gradient force:

$$U^2/R = -\frac{1}{\rho}\, dp/dZ$$

- Being $dp/\rho = -g\,dZ$ thus $\frac{U^2}{R} = -g\frac{dZ_p}{dR}$ i.e. in the layer p_1-p_2

it is: $U_2^2 - U_1^2 = gR_d \frac{d}{dR}\left(Z_{p_2} - Z_{p_1}\right)$ and as $Z_{p_2} - Z_{p_1} = \frac{R_d \overline{T}_v}{g}\ln\frac{p_1}{p_2}$ thus:

$$\frac{U_2^2 - U_1^2}{Z_{p_2} - Z_{p_1}} = \frac{gR_d}{\overline{T}_v}\frac{dT_v}{dR}$$

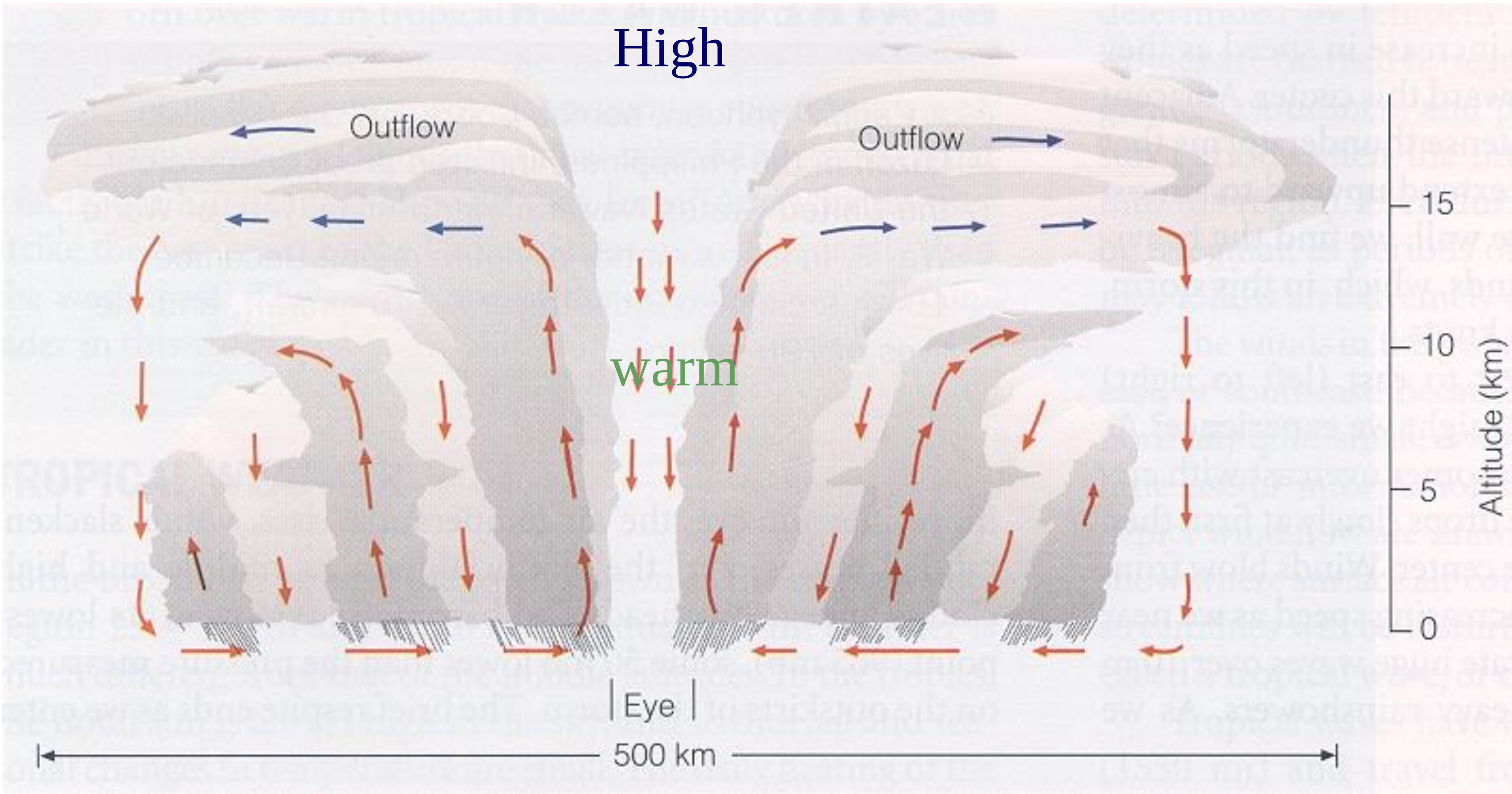
i.e.:

$$\frac{dU^2}{dZ} = \frac{gR_d}{T_v}\frac{dT_v}{dR}$$

which is known as **relation of thermal cyclostrophic wind**

➔if $dT_v/dR > 0$ there is a positive shear of U^2

- As in the tropical cyclones wind speed DECREASES with the heigth (negative shear), thus $dT_v/dR < 0$ → **the central nucleus of tropical cyclones** (eye) **is warm**

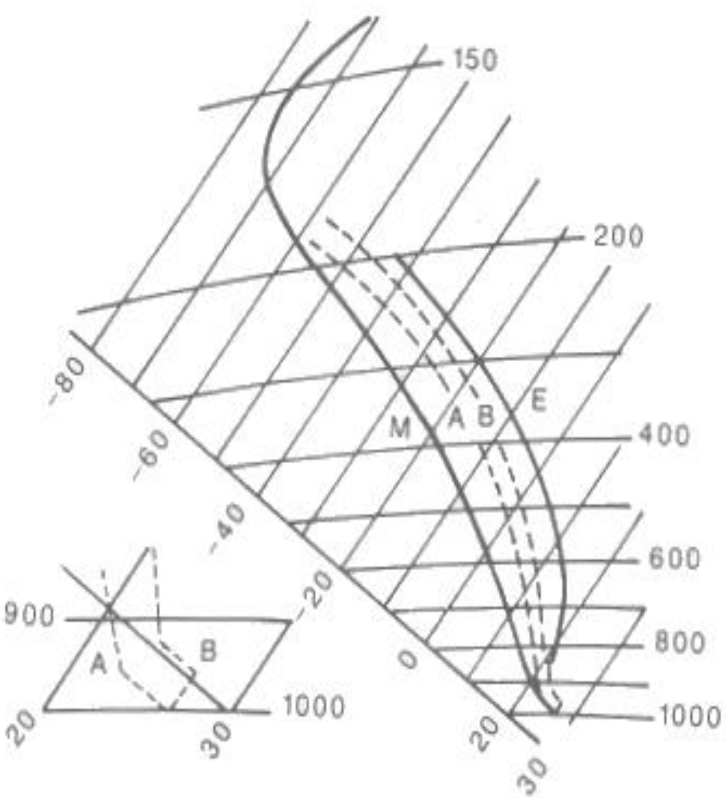


Low

Note where rising and sinking motion occurs.
Hurricane is a “warm core low”.

How tropical cyclones form?

- The formation mechanism is still unclear. Certainly the experimental evidence says that cyclomes form over oceans **in the presence of warm surface temperatures (≥ 26 °C)**
- The mean typical sounding of tropical troposphere (M) is **potentially unstable** → if there is local convection, Cb develop; energetically the convection is enhanced by friction surface



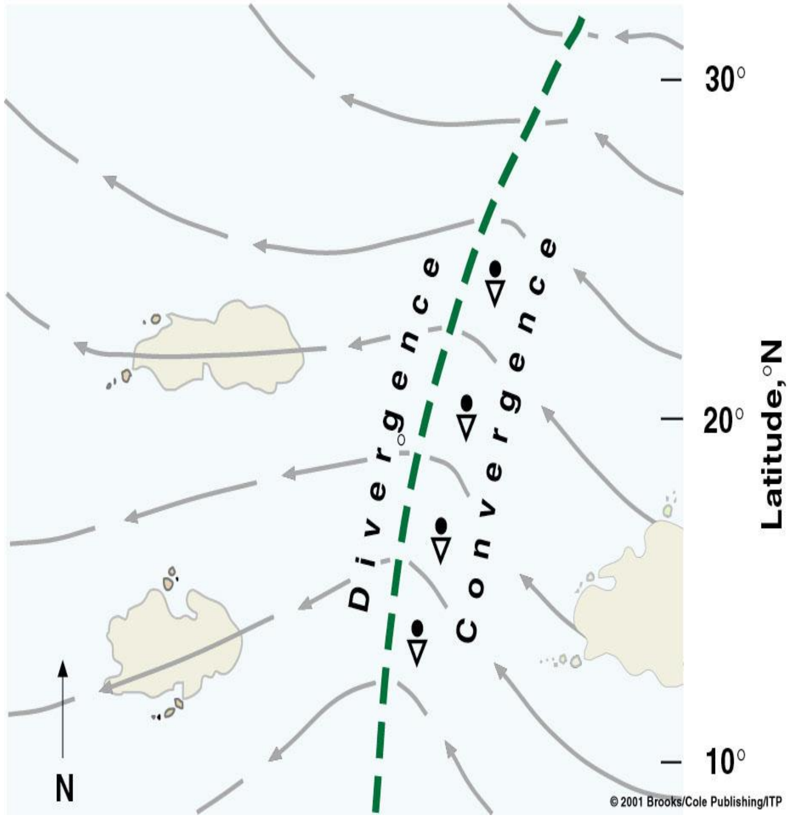
- If a depression of ~20 hPa forms, the 500m surface layer is heated by the ocean and becomes **almost isothermal** (since the pressure decreases, the buoyancy forces are higher) ➔ this causes **warming at all levels** → most instability → convection most active
- At the uppest levels further energy is produced by the latent heat of fusion in the clouds due to the crystallization of water vapor

A theory for hurricane development

1. surface convergence leads to rising motion → increase in moisture content
2. rising air condenses, releases gobs of latent heat
3. latent heating aloft leads to high pressure and divergence aloft (organizes the large scale circulation); divergence aloft leads to lower surface pressure
4. lower surface pressure increases surface convergence
5. stronger surface winds increase wave height; increase friction and convergence; also increase ocean-air moisture flux
6. rotation serves to organize flow

Tropical weather and eastern winds

- Tropical waves
  - » The streamlines possesses clockwise curvature and create a ridge
    - Isobars show small variations and weak trough
    - Wavelength is 2500 Km; systems move eastwards (W to E)
  - » There is surface divergence at W and surface convergence at E

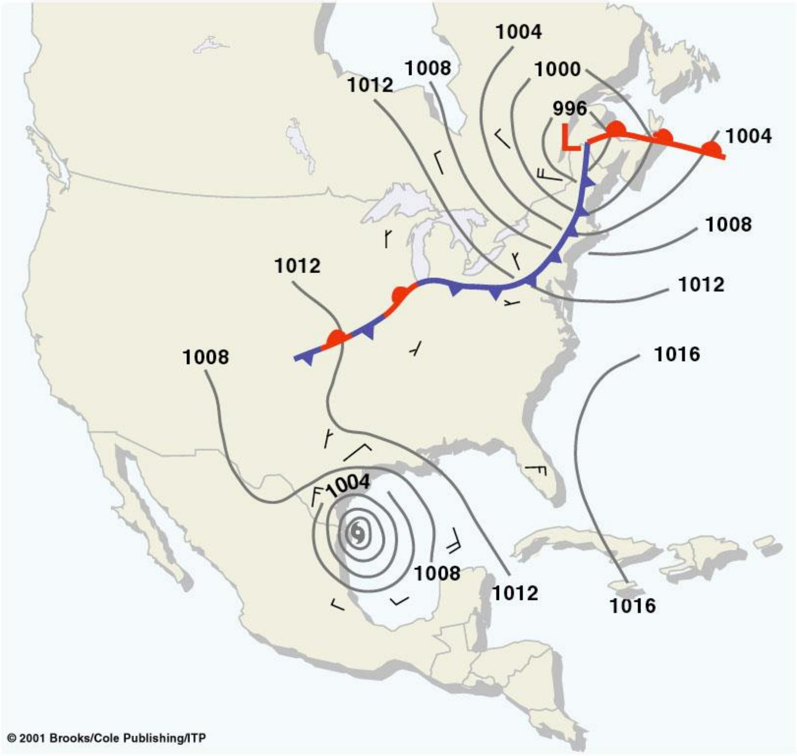


Hurricane development initiated by the passage of a wave disturbance in the subtropics (e.g., easterly waves).

Tropical and extratropical cyclones: differences

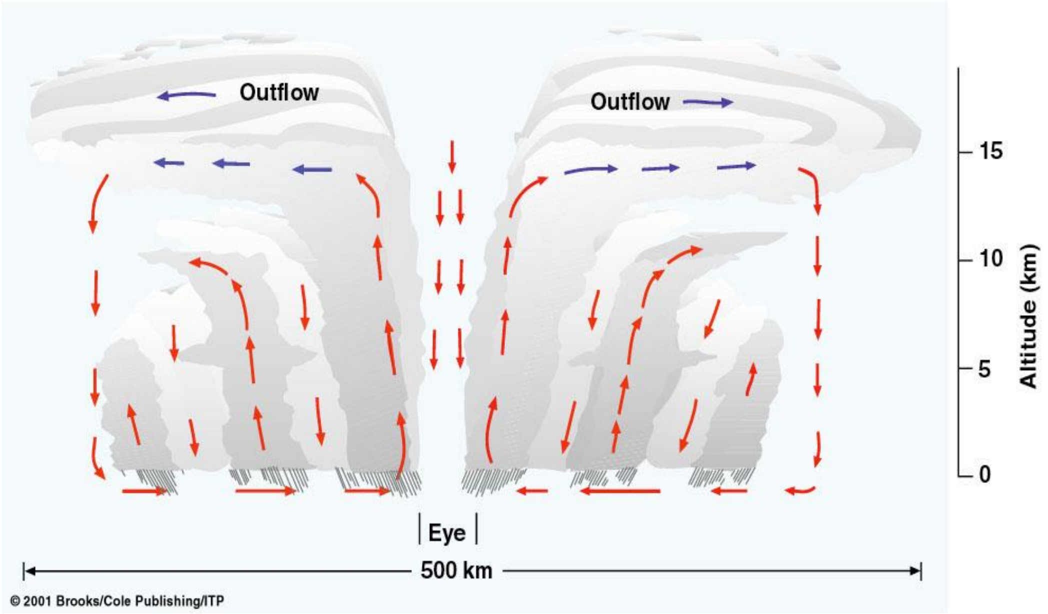
- Energy source: warm water VS horizontal thermal contrast
- Vertically: warm nucleus of low pressure VS W vertical speed intensifies with heigth
- Eye: downward (W<0) VS upward (W>0) motions
- Isobars: circular VS cumulated

- NE flows:
  - Internal nuclei and warm winds
- Polar lows
  - Simmetrical bands ofd systems



Tropical cyclones and thunderstorms

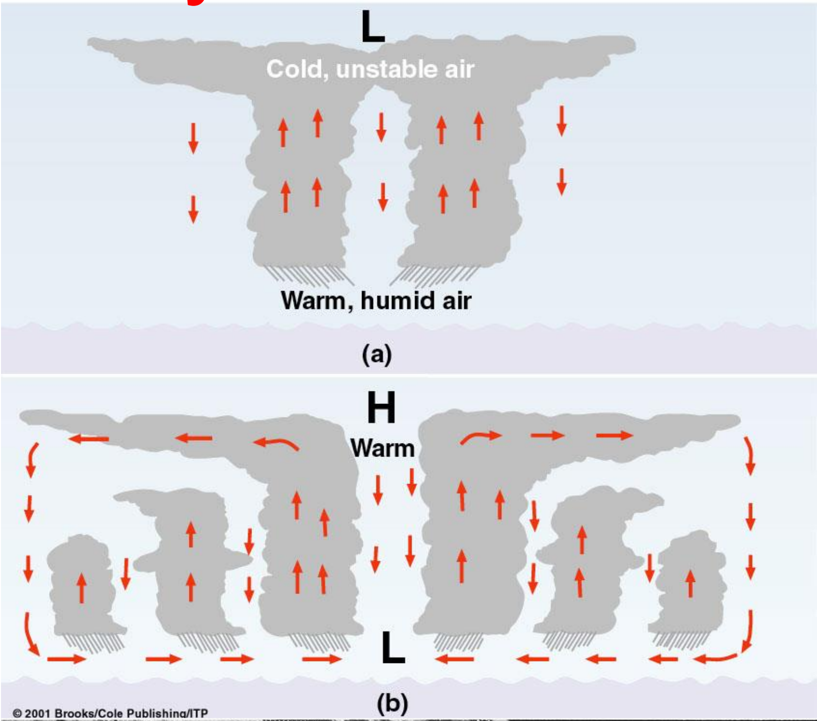
- Favorable mechanisms
  - Coriolis force (not at the equator) & conservation of angular momentum
  - Warm water temperature (26 ºC) in the first 200 m of ocean
  - Convergence of fronts (waves form depressions along the ITCZ)
  - High pressures and high level divergence
  - Absence of trade wind inversions
  - Presence of very humid air

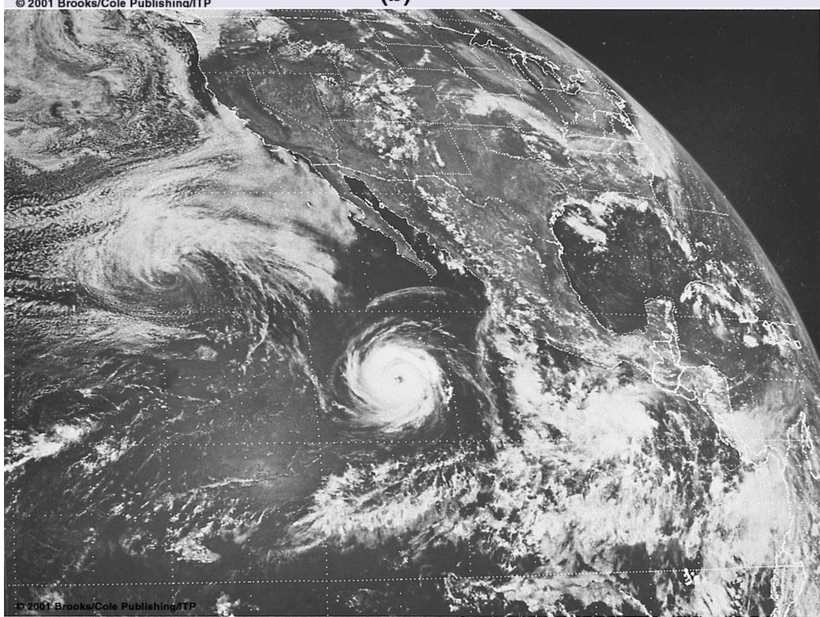


- El Niño effect
  - Most intense winds → less cyclones in Atlantic Ocean
  - Warmest surface water → more cyclones in the Pacific Ocean
  - Opposite situation during La Niña conditions

Energy in the tropical cyclones

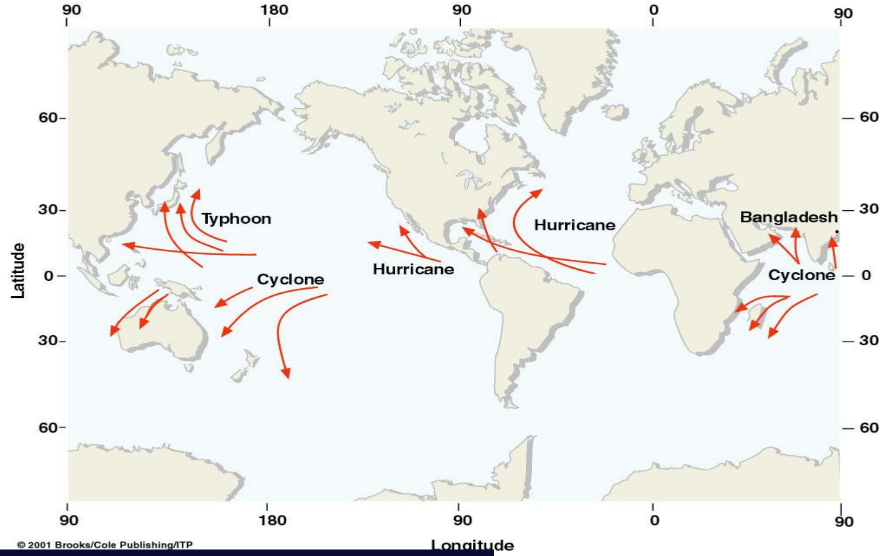
- Theory of organized convection:
  - System Organization
  - Cold air at high levels →unstable
  - Latent heat warms upper atmosphere
  - high altitude downward winds below H
  - Surface pressure decreases
  - Converging air rises
  - Latent heat warms upper atmosphere ....
- Theory of heat pump:
  - Small eddies transfer sensible and latent heat to the upper air
  - Higher wind speed and warmer surface water transfer more heat
  - The transfer rate grows at the heart of the system which is (and becomes) warmer
  - Horizontal pressure gradients at the top push the air away
  - Heat loss at uppest levels by radiation
- Dissipation
  - Loss of energy above the land or cold water

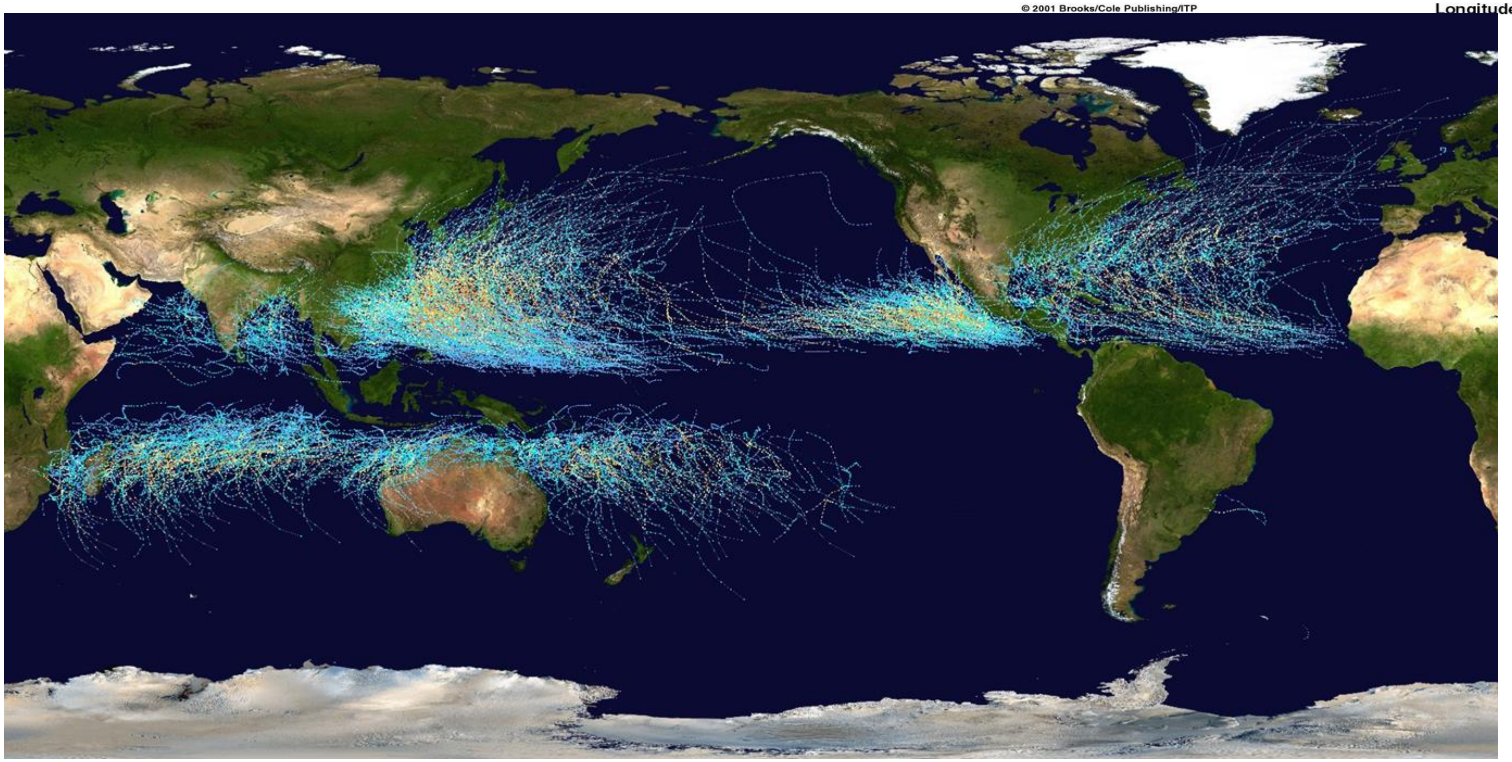




Development and movement of tropical cyclones

- Stages
  - Tropical wave (weak winds <20 knots)
  - Tropical depression (20-34 knots)
  - Hurricane (35-64 knots)

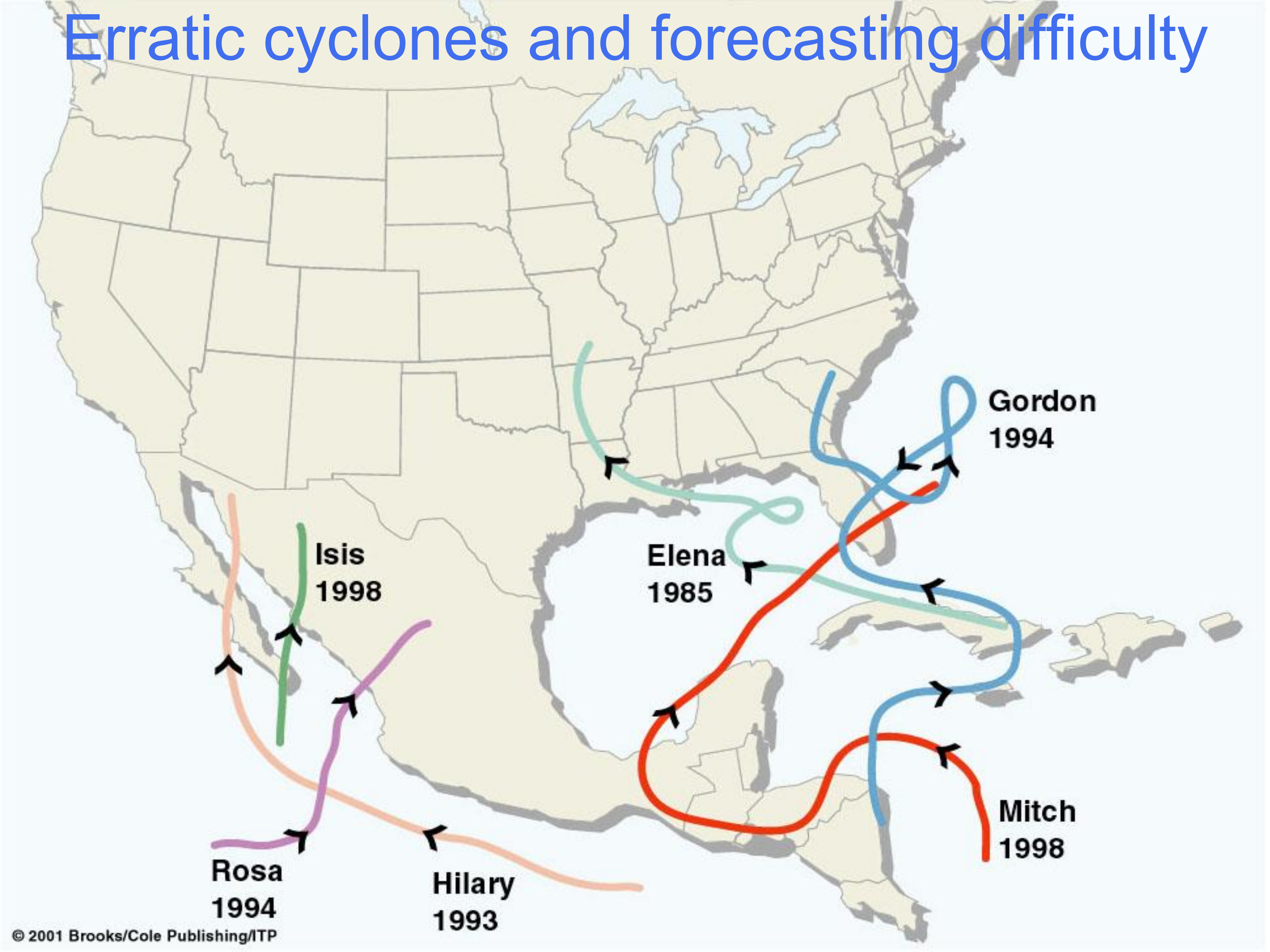




Typical trajectories

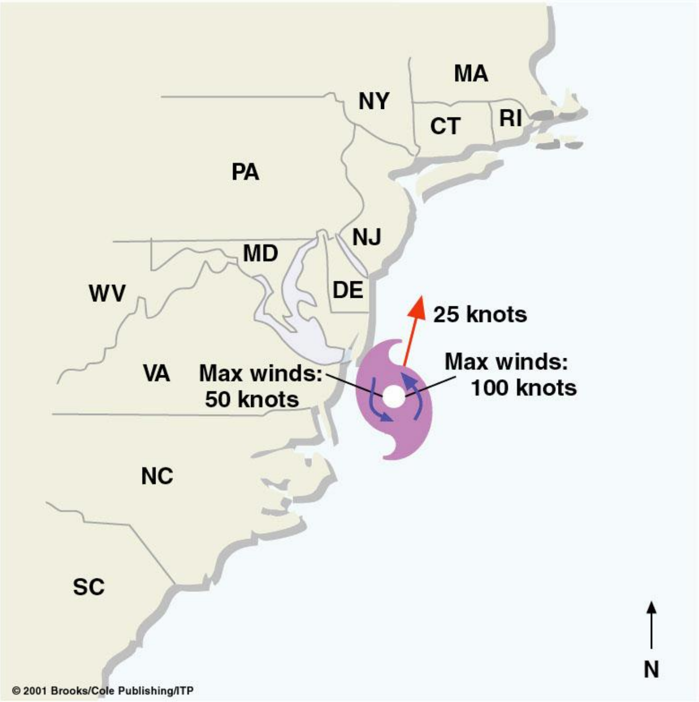
- W to E & around anticyclones

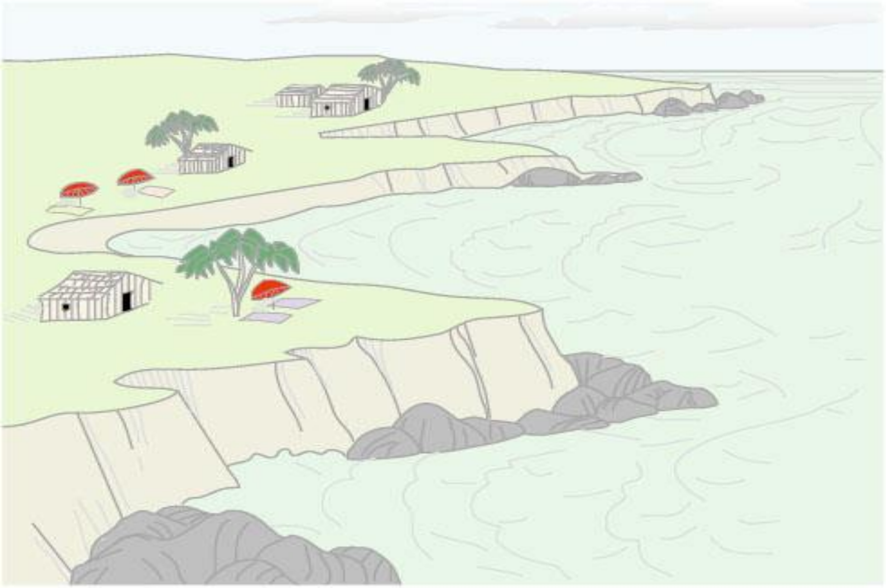
Erratic cyclones and forecasting difficulty

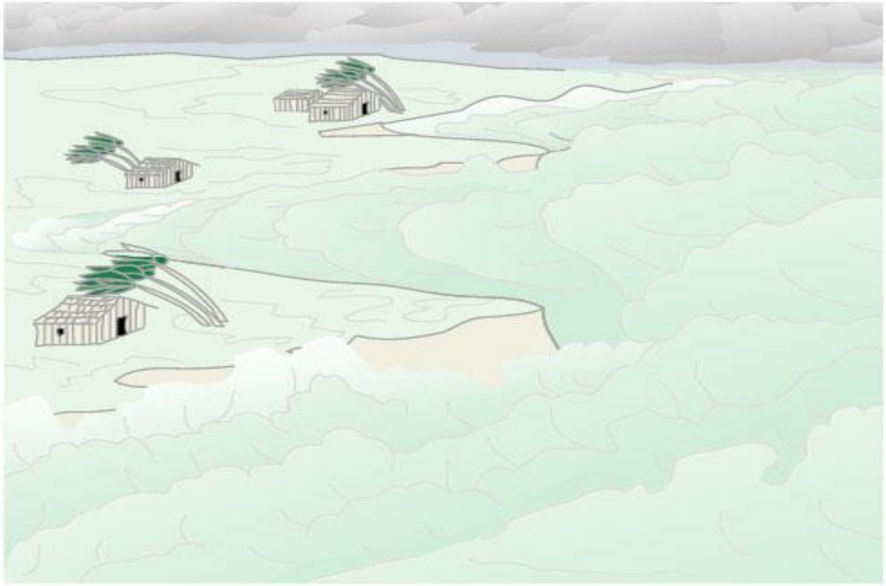


Effects

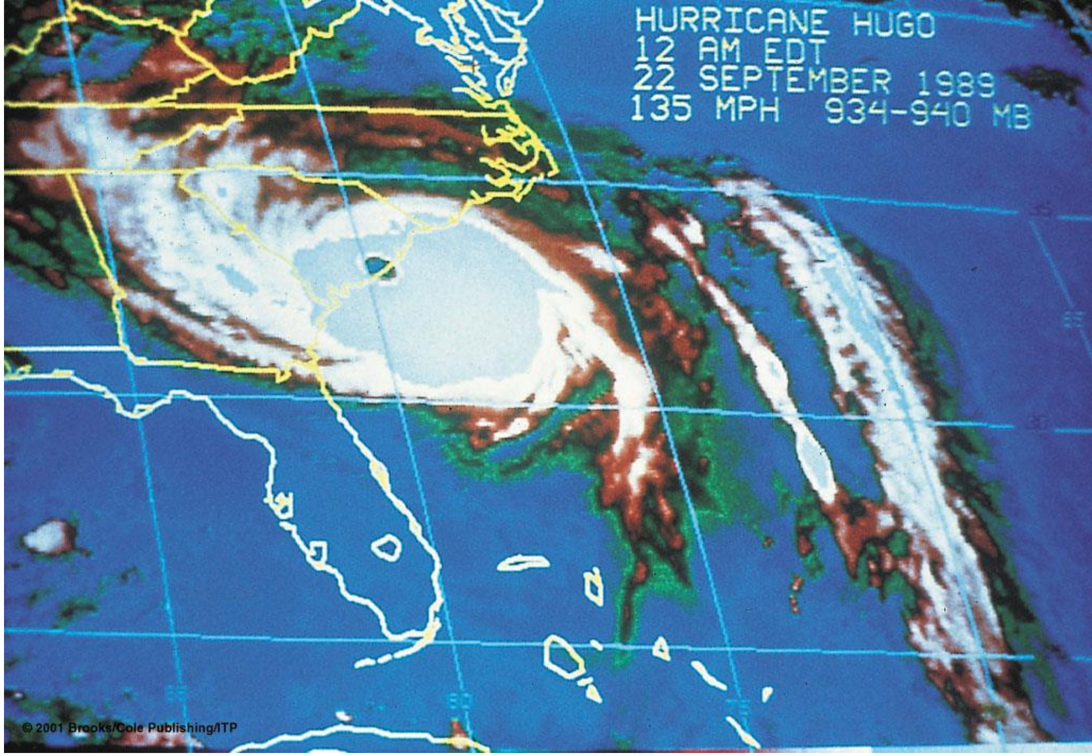
- Flooding & storm surge
  - » Strongest winds
    - Path +/- Spin
  - » Elevated sea levels
    - Low pressures
    - 1 mb = 1 cm
  - » Water transport
    - Ekman spiral to right
    - Bending w/ depth
- – Tornado generation
  - » Spin-up vortices







Effects of Hugo hurricane, 1989



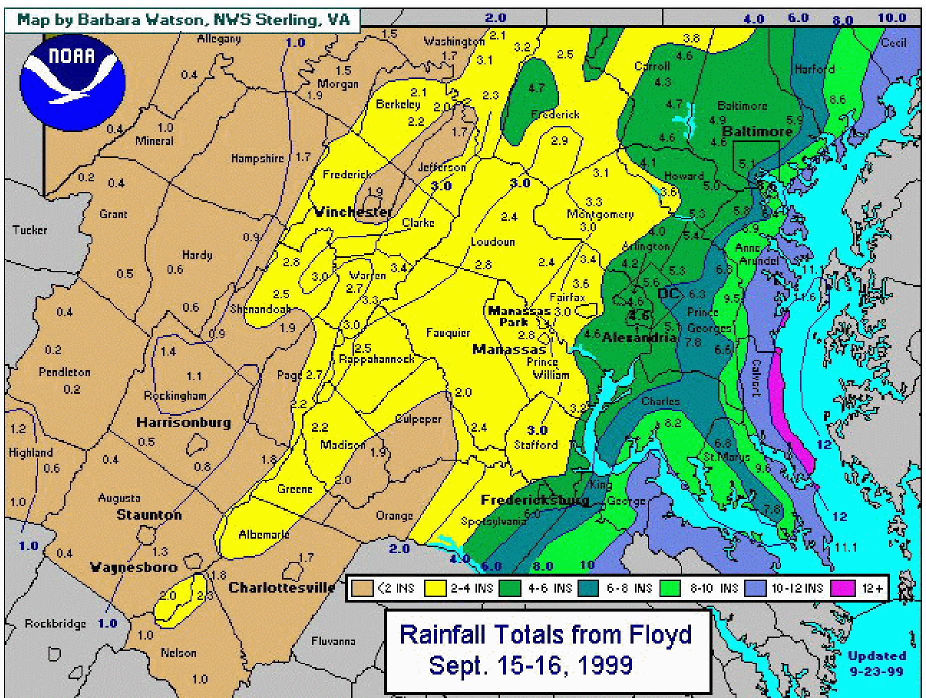
Excessive Rainfall from Tropical Cyclones

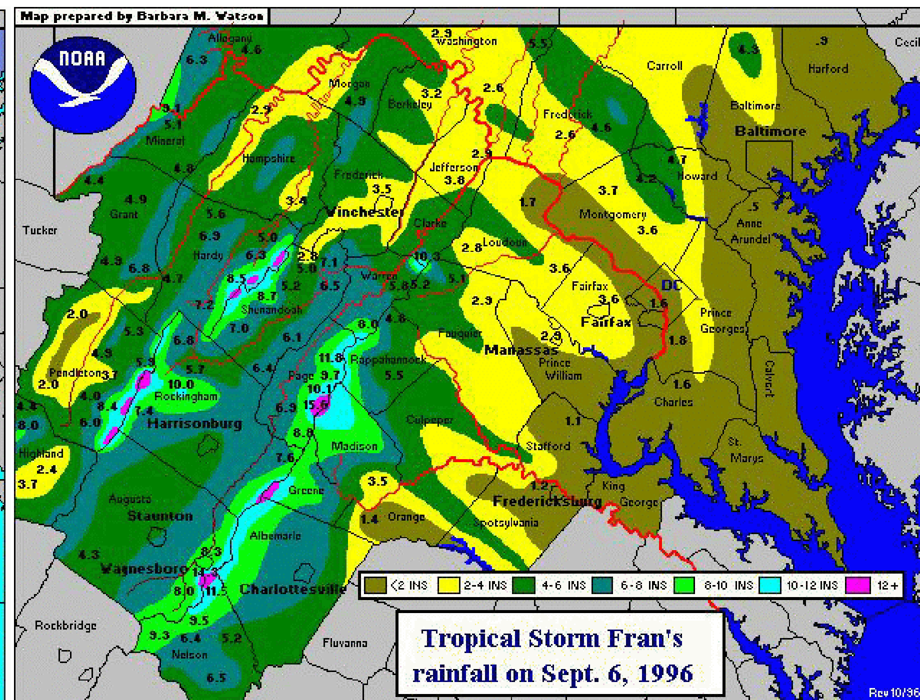
- In recent decades the greatest number of hurricane-related fatalities have been from **inland flooding**. Three situations (or combinations of) to watch for are:

1. **Slow movement (Alberto 1994, Mitch 1998),**
2. **Interaction with topography (Camille 1969, Fran 1996, Mitch 1998),**
3. **Interaction with midlatitude system (Camille 1969, Tico 1983, Floyd 1999).**

Excessive Rainfall from Tropical Cyclones

- South of about 35º latitude
  - **typically from slow movement/terrain influence**
  - **typically associated with eyewall convection (especially where wind is perpendicular to coastline) and feeder bands.**
- North of about 35º latitude (western US too)
  - **often associated with midlatitude interaction (most intense rainfall north & west of track).**
  - **Terrain focus**





TLC - Medicanes

- TLC (Tropical-Like Cyclone) or

Medicane (Mediterranean Hurricane)

  – Some vortices that occurred in the Mediterranean Sea have features similar to tropical cyclones: they originate and develop over the sea, present a warm-core structure and in most of the cases they have a quasi-circular eye surrounded by a convective cloud wall and a roughly axisymmetric cloud pattern.

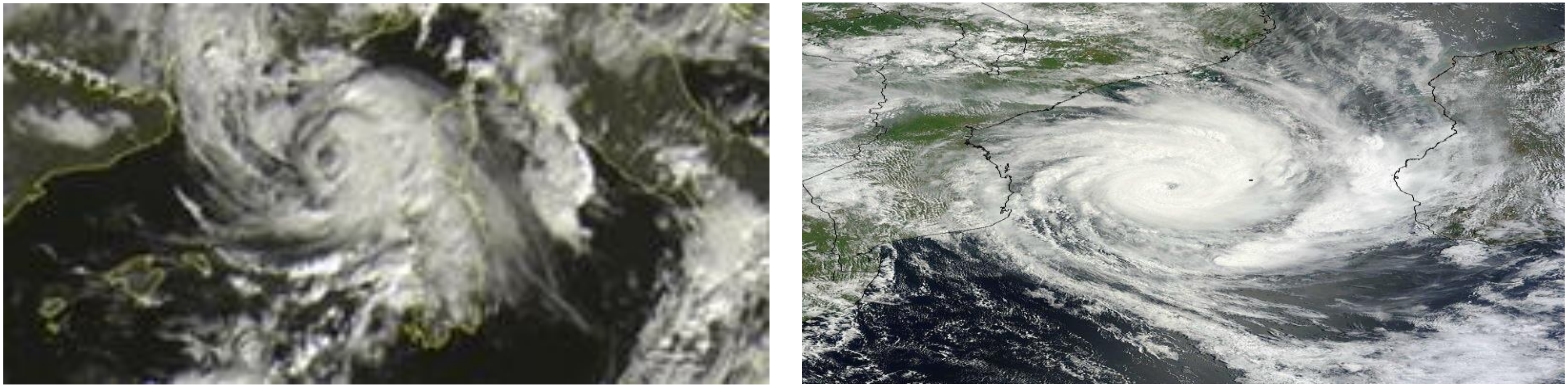
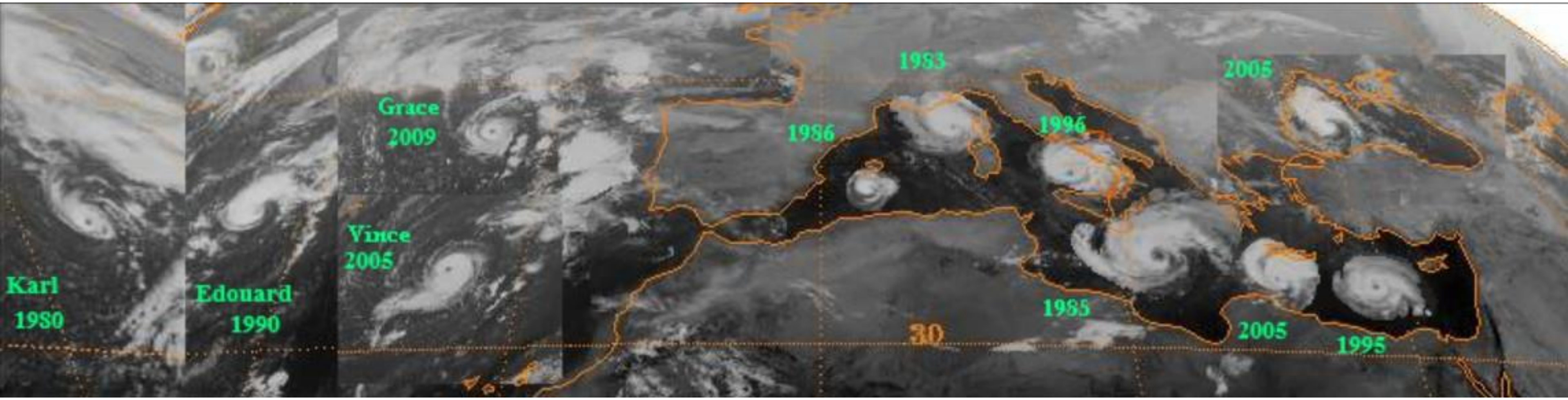


Fig. 1. a) (left)The satellite image in the visible channel of medicane that occurred in the Mediterranean Sea on 8 November 2011 at 10:00 UTC (source: sat24.com); b) (right)The MODIS visible image of tropical cyclone that occurred in the India Ocean on 25 January 2012 at 7:40 UTC (source: NASA/Goddard Space Flight Center)

Historical Medicanes



Triggering factors of TLCs

- The Mediterranean Sea surface temperature is too cold and the atmosphere is usually far too dry to permit the medicane development.
- The medicanes develop underneath an unusually deep, cut-off low at upper levels, and on the west side of a pre-existing disturbance region (Emanuel, 2005).

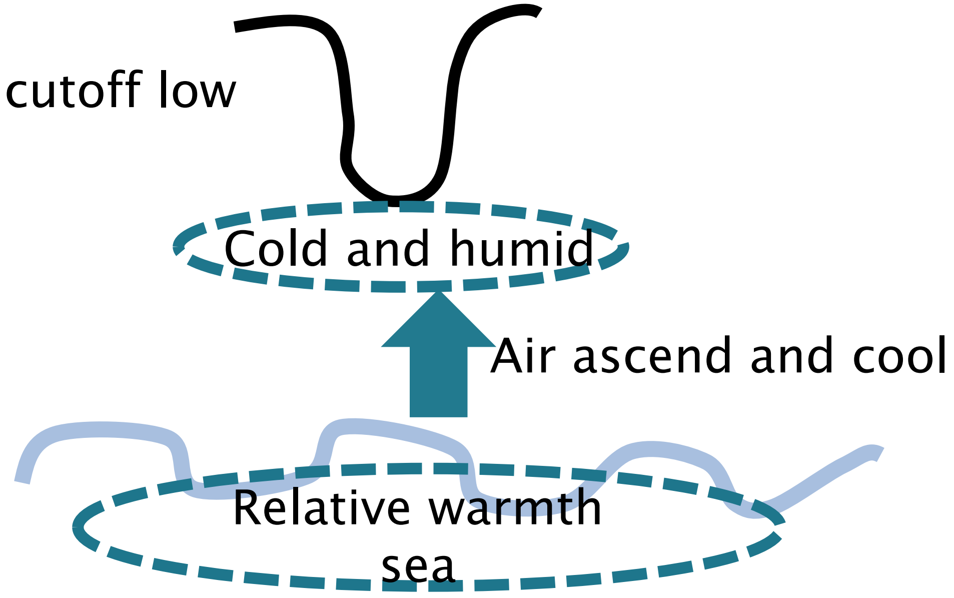


Fig. 2. A upper-level cut off low

Vertical structure of TLCs

The Phase-Space Diagram (Hart, 2003)

■In order to determine whether the cyclones have tropical or extratropical characteristics, an objective evaluation is applied based on the phase-space diagram introduced by Hart (2003).

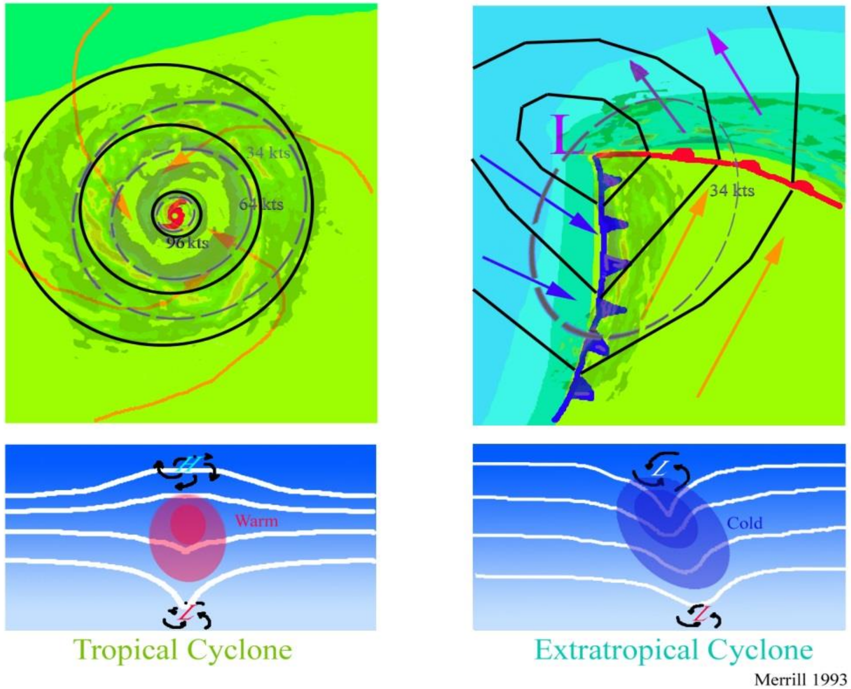


Fig. 5. The top schematics show horizontal maps of the surface temperature, pressure, and wind fields associated with a tropical cyclone (left) and an extratropical cyclone (right). Colors indicate temperature (blue 15 ˚C, blue green 20 ˚ C, green 25 ˚ C). Dashed lines indicate surface wind speeds : 34 kts, 64 kts, and 96 kts. Solid lines are isobars. The bottom schematics show vertical maps of the pressure surfaces, temperature anomalies, and circulation at the surface and tropopause.

Table 2. Characteristics of extratropical and tropical cyclones

Tropical	Extratropical
Symmetric (non-frontal)	Asymmetric (frontal)
Warm core	Cold core

The Phase-Space Diagram (Hart, 2003) - B

- **Parameter B** : Cyclone thermal symmetry
  - » The storm-motion-relative 900–600 hPa thickness asymmetry across the cyclone within 150 km radius

$$B = h\left(\overline{Z_{600\,hPa} - Z_{900\,hPa}}|_R - \overline{Z_{600\,hPa} - Z_{900\,hPa}}|_L\right) \quad (1)$$

R : The right of current storm motion

L : The left of current storm motion

overbar : The areal mean over a semicircle of radius 150 km

h : Hemisphere [+1 = Northern Hemisphere (NH), -1 = Southern Hemisphere (SH)]

  - » B>10m, asymmetric, showing extratropical characteristics, and vice versa

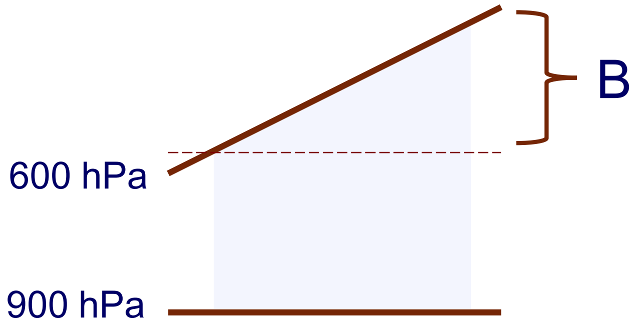


Fig. 6. Parameter B. The dark blue solid lines are isobaric height.

The Phase-Space Diagram (Hart, 2003) - B

➢ **Parameter $-V_T^L$ and $-V_T^U$** : Cyclone thermal wind — Cold versus warm core

$$\Delta Z = Z_{MAX} - Z_{MIN} \quad (2)$$

$$\Delta Z = \mathrm{d}g|V_g|/f \quad (3)$$

$$\left.\frac{\partial(\Delta Z)}{\partial \ \ln p}\right|_{900\,hPa}^{600\,hPa} = -V_T^L \quad (4)$$

$$\left.\frac{\partial(\Delta Z)}{\partial \ \ln p}\right|_{600\,hPa}^{300\,hPa} = -V_T^U \quad (5)$$

ΔZ : The cyclone height perturbation within a radius of 150 km

d : The distance between the geopotential extrema.

f : The Coriolis parameter

g : The acceleration of gravity

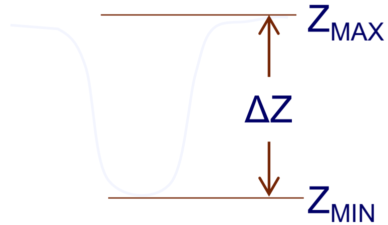


Fig. 7. The green solid line is isobaric height.

- Since the cyclone radius is limited, the larger ΔZ becomes, the stronger geostrophic wind (V_g) is.
- $\Delta Z \propto V_g$

- Numerator < 0 , V_g magnitude of the lower level is larger → Warm core
- Numerator > 0 , V_g magnitude of the upper level is larger → Cold core
- Denominator, always < 0
- $-V_T^L$ or $-V_T^U > 0$, warm core, showing tropical characteristics, and vice versa

Potential vorticity distribution

- Potential Vorticity (PV) on an isentropic surface
  - In large scale, adiabatic atmospheric motions, PV conserve

$$\mathrm{PV} \equiv -g(\zeta_\theta + f)\frac{\partial \theta}{\partial p} \qquad (6)$$

g : The acceleration of gravity
f : The Coriolis parameter
θ: Potential temperature
p : Pressure
ζ_θ : Relative isentropic vorticity

$-\frac{\partial \theta}{\partial p}$: static stability
$(\zeta_\theta + f)$: absolute isentropic vorticity

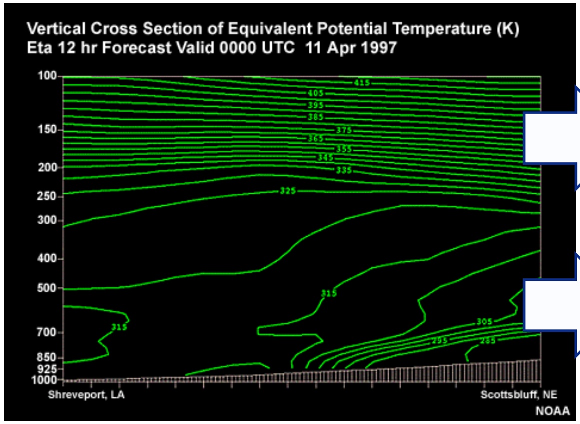


Fig. 11. Vertical cross section of equivalent potential temperature.

Stratosphere
$: -\frac{\partial \theta}{\partial p} \uparrow$

Troposphere
$: -\frac{\partial \theta}{\partial p} \downarrow$

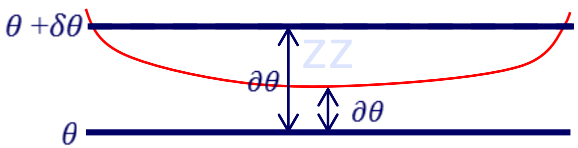


Fig. 12. Stratospheric air intrudes into the troposphere

$$-\frac{\partial \theta}{\partial p}\downarrow \rightarrow (\zeta_\theta + f)\uparrow$$

Therefore, PV is a conservative tracer that serves as a marker for the intrusion of stratospheric air into the troposphere, thus it is considered as a useful synoptic diagnostics (Wallace and Hobbs, 2006)

Potential vorticity distribution

- The upper-level cut off low

1200 UTC 05 November 2011

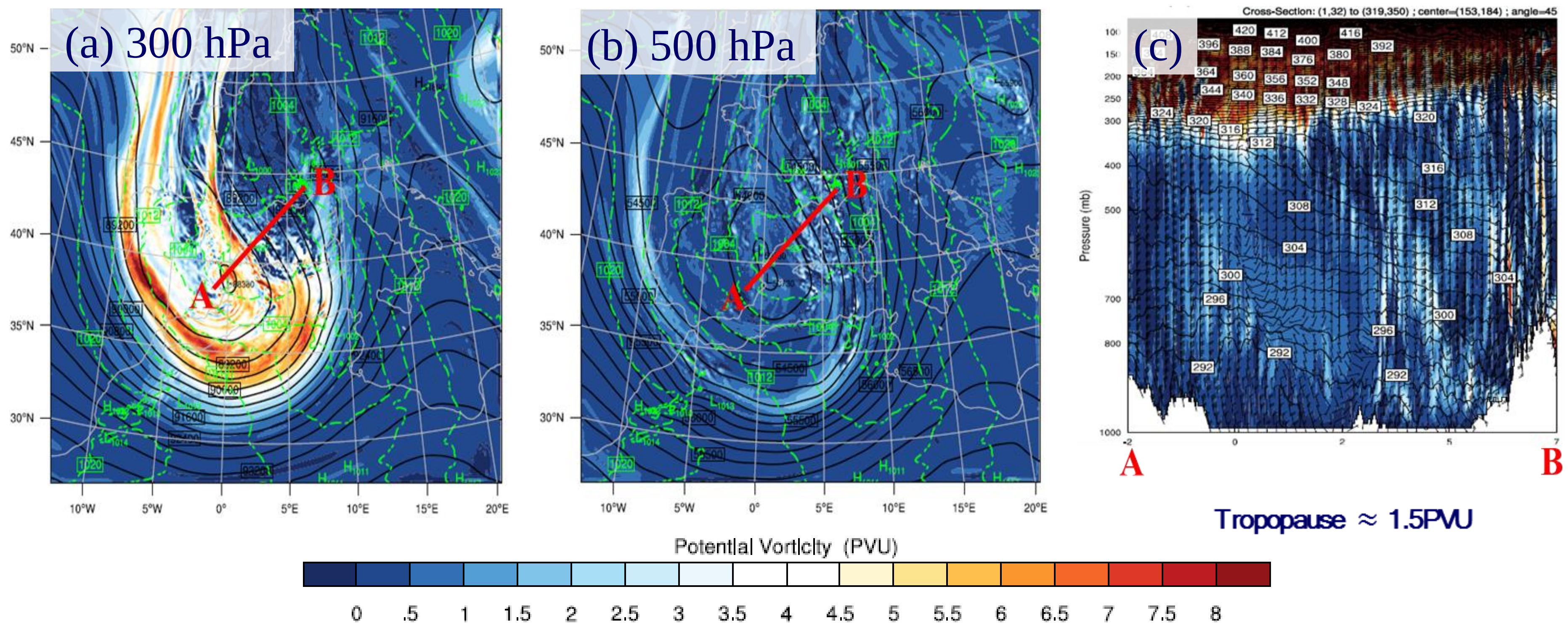


Fig. 13. DOMAINCHG: (a) mean sea level pressure (dashed green line contours; interval is 4 hPa), potential vorticity (plot is shaded at intervals of 0.5 PVU) and geopotential height (solid black line contours are plotted at intervals of 400 gpm) at 300 hPa at 1200 UTC 05 November 2011. (b) Same as top but at 500 hPa. These Fields were extracted from the outer grid (7.5 km horizontal resolution), and thick red lines represent the orientation of the cross-sections shown in the bottom. The letters A and B denote the start and end points of cross-sections. (c) Vertical cross-sections of PV (shading; interval 0.5 PVU), potential temperature (black; interval 2 K) and wind vectors (kts) at 1200 UTC 05 November 2011 from the inner grid (2.5 km resolution).

Potential vorticity distribution

- The upper-level cut off low

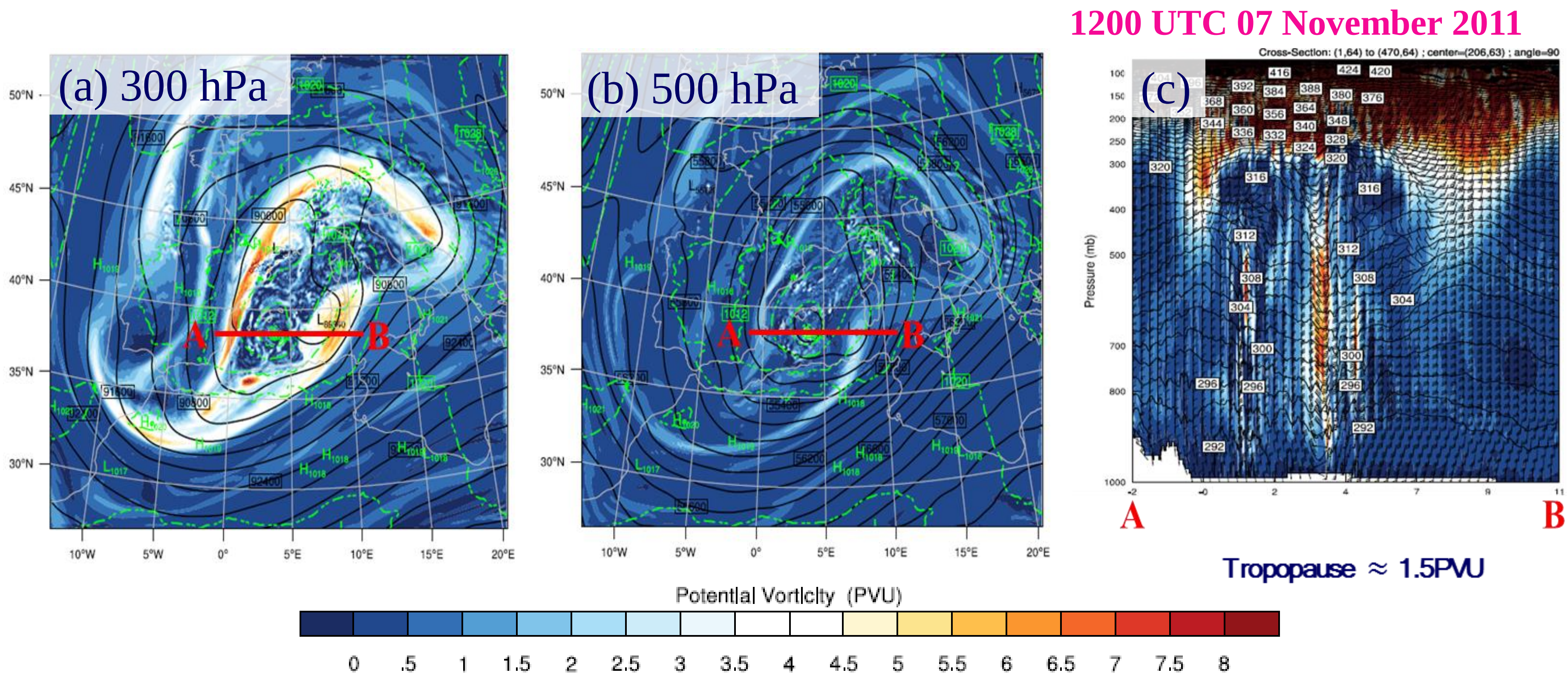


Fig. 14. Same as Fig. 13, but at 1200 UTC of 07 November 2011.

The case of Medicane Rolf (November 2011)

Synoptic parameters (Cavicchia et al., 2013)

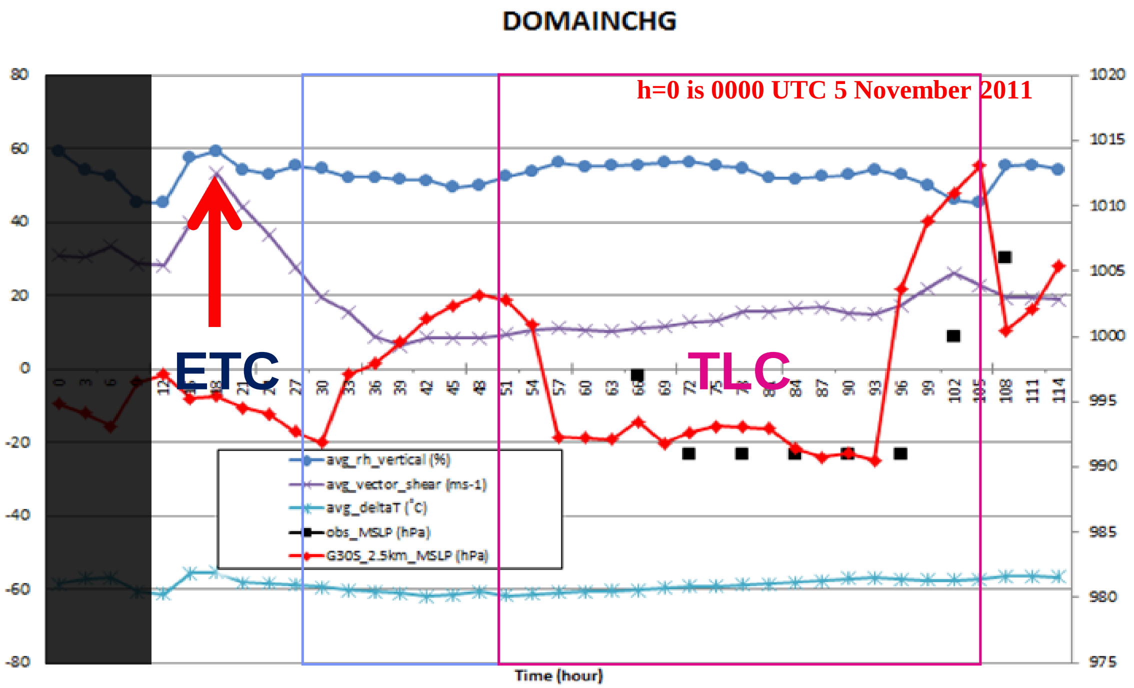


Fig. 16. DOMAINCHG: The vertical wind shear between 850 hPa and 250 hPa (purple; ms-1), the temperature difference between the sea surface and 350 hPa (light blue; ˚C), and average relative humidity in the troposphere (dark blue; %) averaged in a box of 3˚ x 3˚ around the minimum pressure. The mean sea level pressure (hPa) values are from experiment DOMAINCHG (red) and observations from NOAA (black) (http://www.ssd.noaa.gov/PS/TROP/DATA/2011/tdata/med/01M.html). Numbers on the left hand side of y axis denote the values of medicane formation synoptic factors and those on the right hand side of y axis indicate mean sea level pressure. The values are evaluated in the inner grid (resolution 2.5 km).

- Except vertical wind shear, the other two parameters do not seem to play an evident role, being almost constant during all the time.
- The evolution of the vertical wind shear throughout the troposphere shows that the transition from a baroclinic environment to a barotropic atmosphere is associated to the genesis of the tropical-like cyclone.

ETC : Extratropical cyclone
TLC : Tropical-like cyclone

Monsoon formation mechanism

Year	Hazelrigg (UK) 54.0°N, 2.8°W	Year	Canton Island (China) 2.48°S, 171.43°W
1975	223	1957	1269
1976	99	1958	1597
1977	218	1959	759
1978	305	1960	492
1979	229	1961	508
1980	295	1962	402
1981	254	1963	713
1982	276	1964	519
1983	152	1965	1433
1984	165	1966	1101
<P>	**222**	**<P>**	**879**
σ_p	**63 (28%)**	σ_p	**414 (47%)**

- ITCZ displacement related to the position of thermal equator, with speed ∝ to inverse of heat capacity → largest over land
- On land solar radiation → evaporation [over wet surfaces larger than over oceans as they are warmer] → scattered convective clouds (Cb)
- The circulation of the Hadley cell favors the development of towering clouds distributed discontinuously along the ITCZ
- Rainy season is the season in which a region is crossed by the ITCZ (at the equator there are 2 r.s., only 1 in the tropics); generally precipitations are irregular in the short and long term ($\sigma_p \geq$ 50% <p>)

Seasonal Migration of ITCZ

- Mean position is somewhat north of Equator
- Strong departures from zonal mean position driven by seasonal heating over land

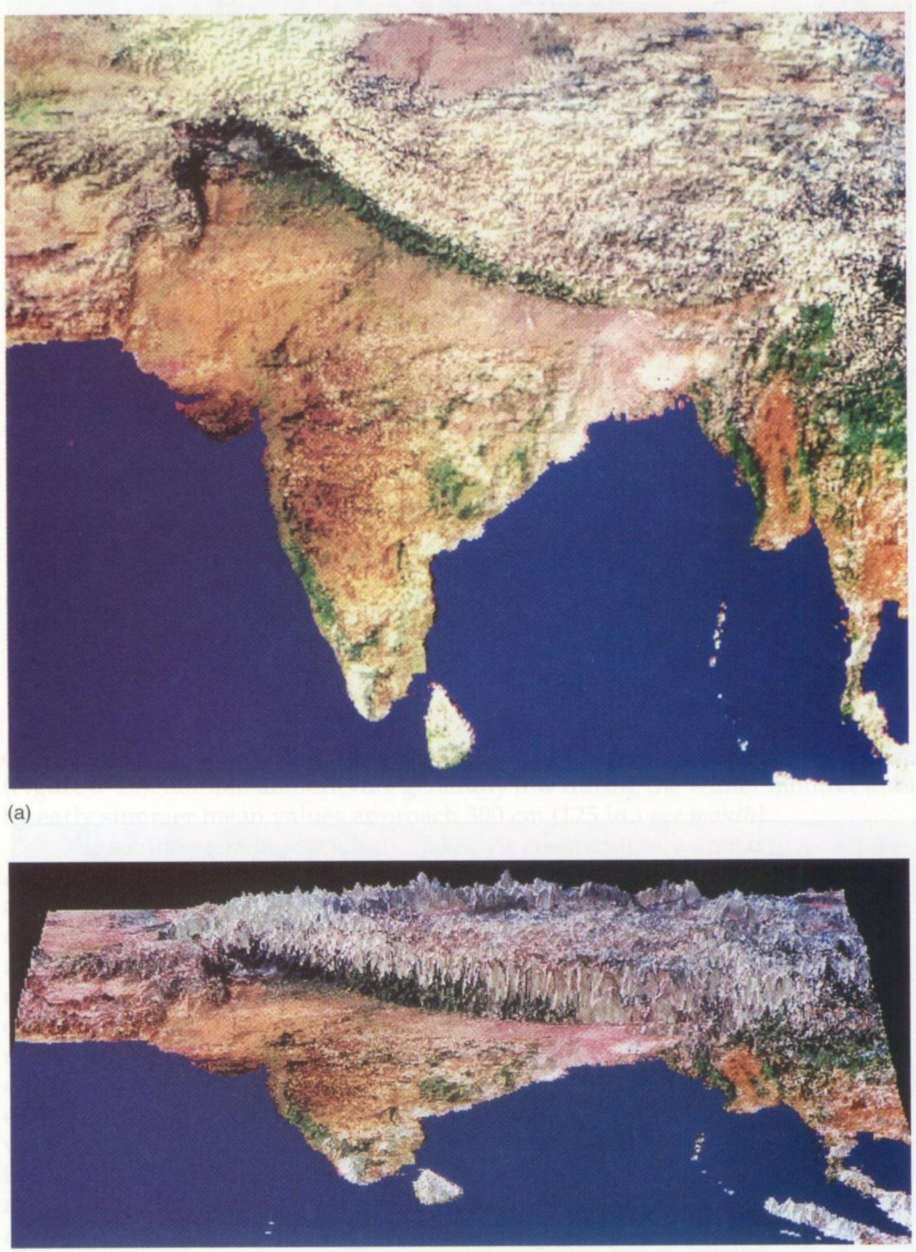
(Especially over Asia, S. America, Africa)

Monsoon Circulations

(a)

- "monsoon" = "season"
- Like a giant "sea breeze"
- Winter monsoon flow off the continent, turns with Coriolis forcing to accelerate Trade Winds
- Summer monsoon flow onto continent
  - Cross-equatorial!
  - Strong tropical westerlies!
- A regional intensification of the Hadley Cell
  - Consider [v*u*], [v*T*], [v*q*]

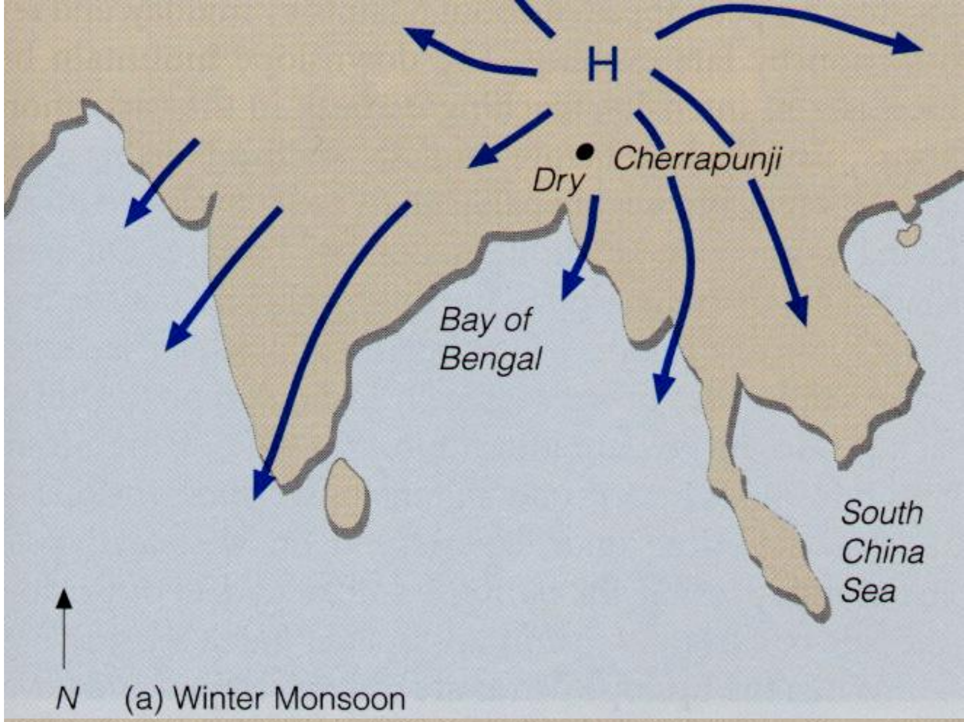
South Asian Topography



- Tibetan Plateau and Himalayas act as a giant elevated heat source in subtropics
- Warming of this region in summer causes associated divergence aloft
- Creates a huge low pressure area (monsoon low) in JJA
- Strong cooling in winter contributes to a huge high in winter

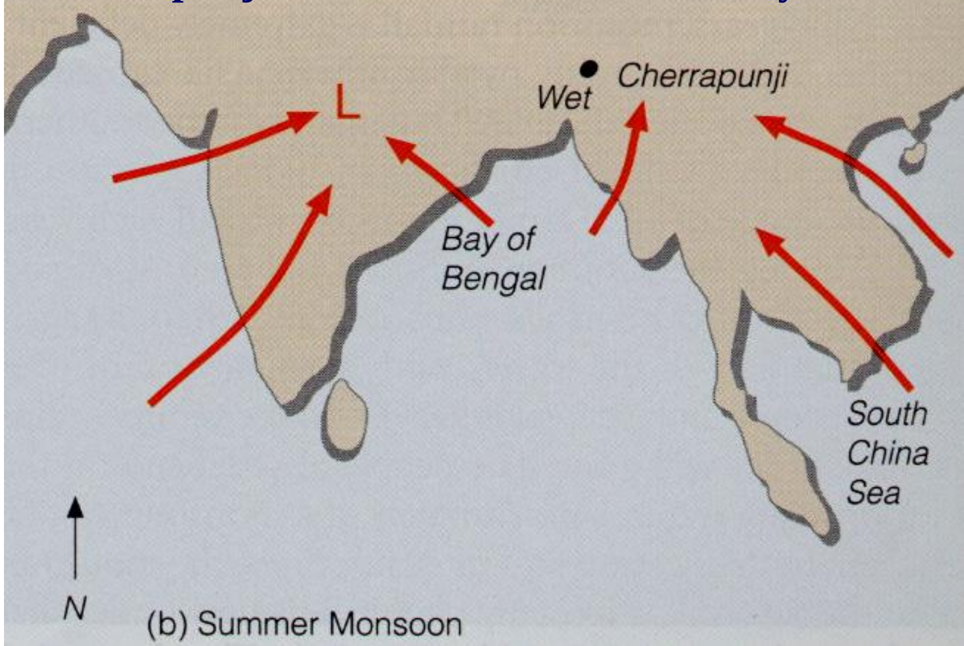
Indian Monsoon

- Monsoon winds are
  - Seasonal
  - Common in eastern and southern Asia
  - Similar to huge land/sea breeze systems
- During winter strong cooling produces a shallow high pressure area over Siberia
  - Subsidence, clockwise circulation and flow out from the high provide fair weather for southern and eastern Asia
- During summer, air over the continent heats and rises, drawing moist air in from the oceans
  - Convergence and topography produce lifting and heavy rain formation



(a) Winter Monsoon

Cherrapunji received 10 m of rain in July 1861!



(b) Summer Monsoon

Asian Monsoon Circulation

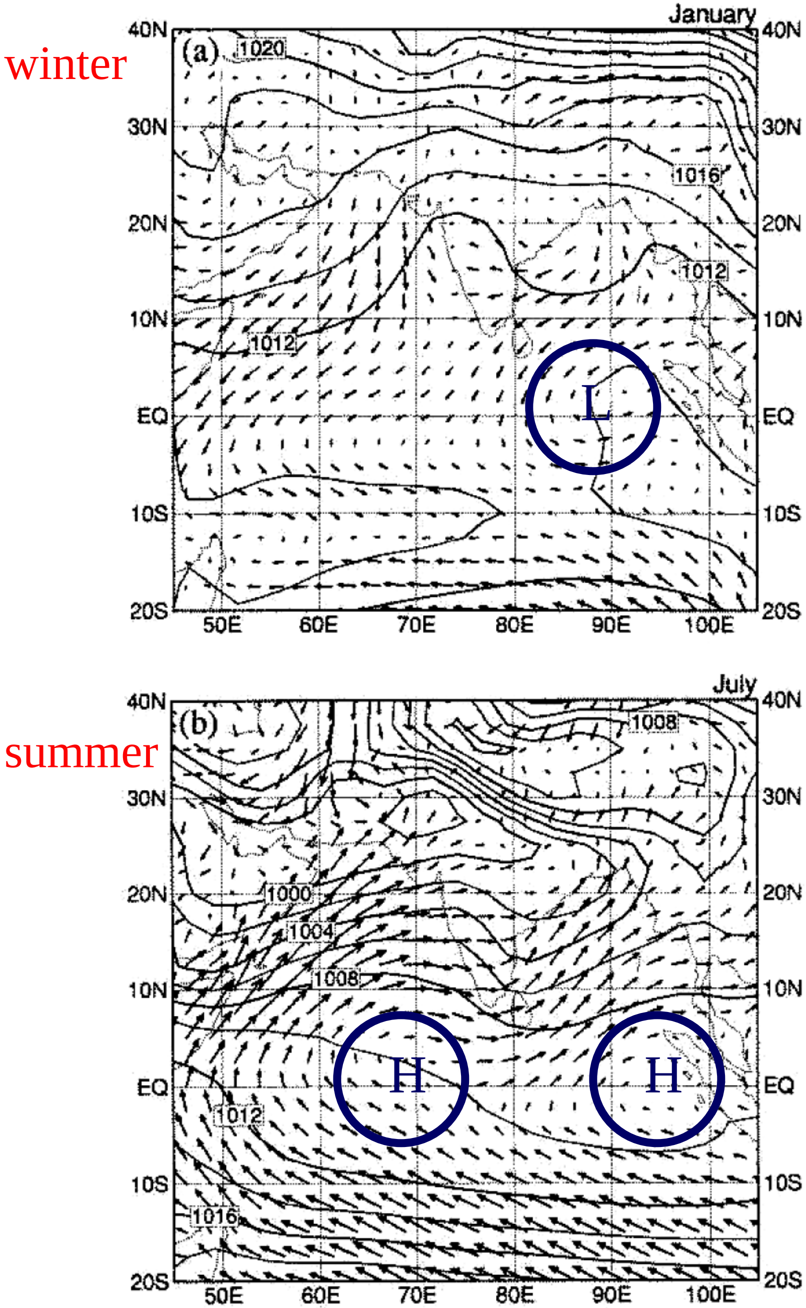


Fig. 6.19 Maps of mean sea-level pressure and 1000-mb winds in the region of the Asian Monsoon during (a) January and (b) July. Contour interval is 2 mb and largest vector represents a wind speed of 17 m s^{-1}.

- Cross-Equatorial flow in both seasons
- Tropical westerlies in summer hemisphere, both seasons
- “Somali jet” and strong SW flow in Bay of Bengal are important for regional dynamics and inter-hemispheric transport

Indian Monsoon Precipitation

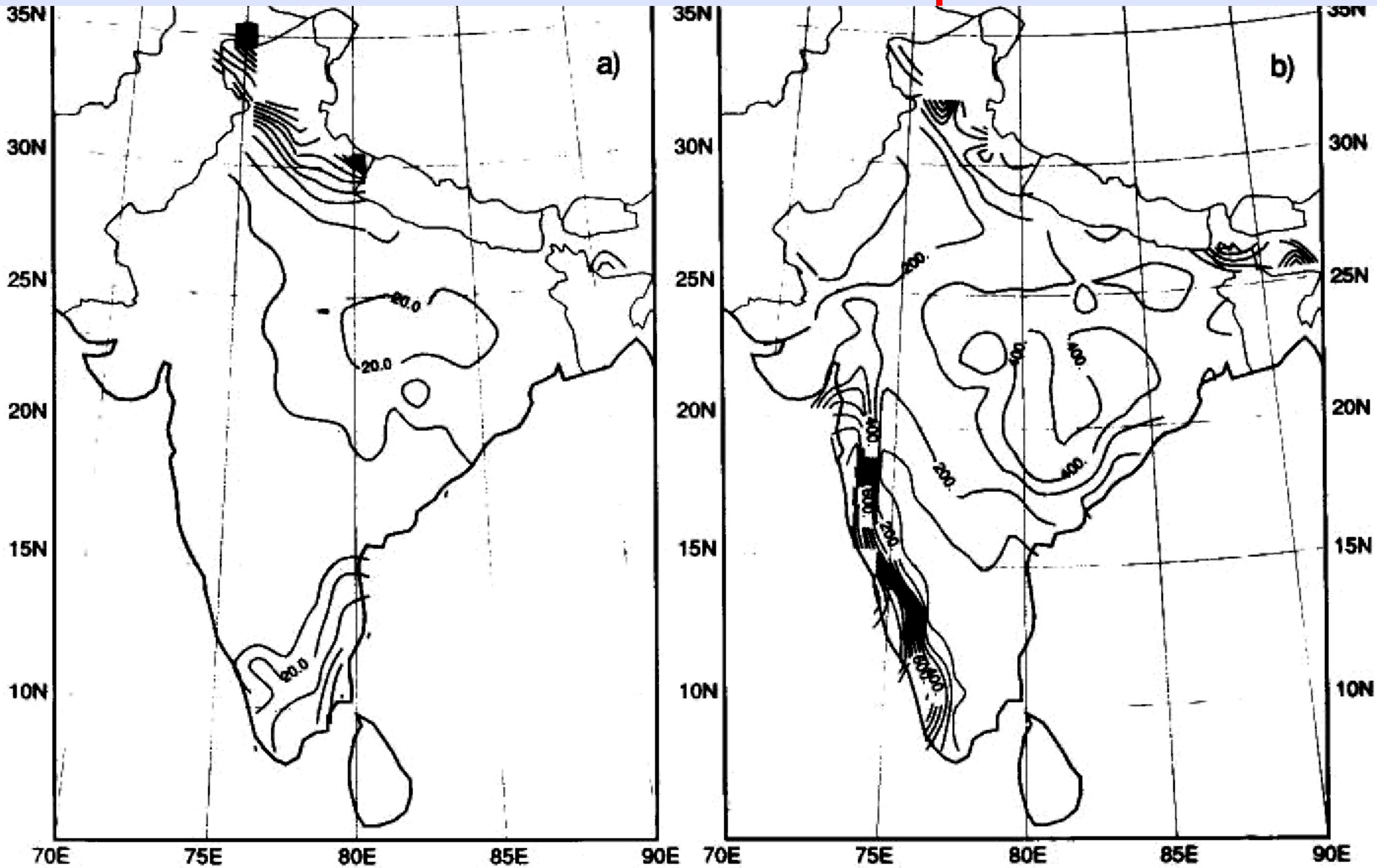
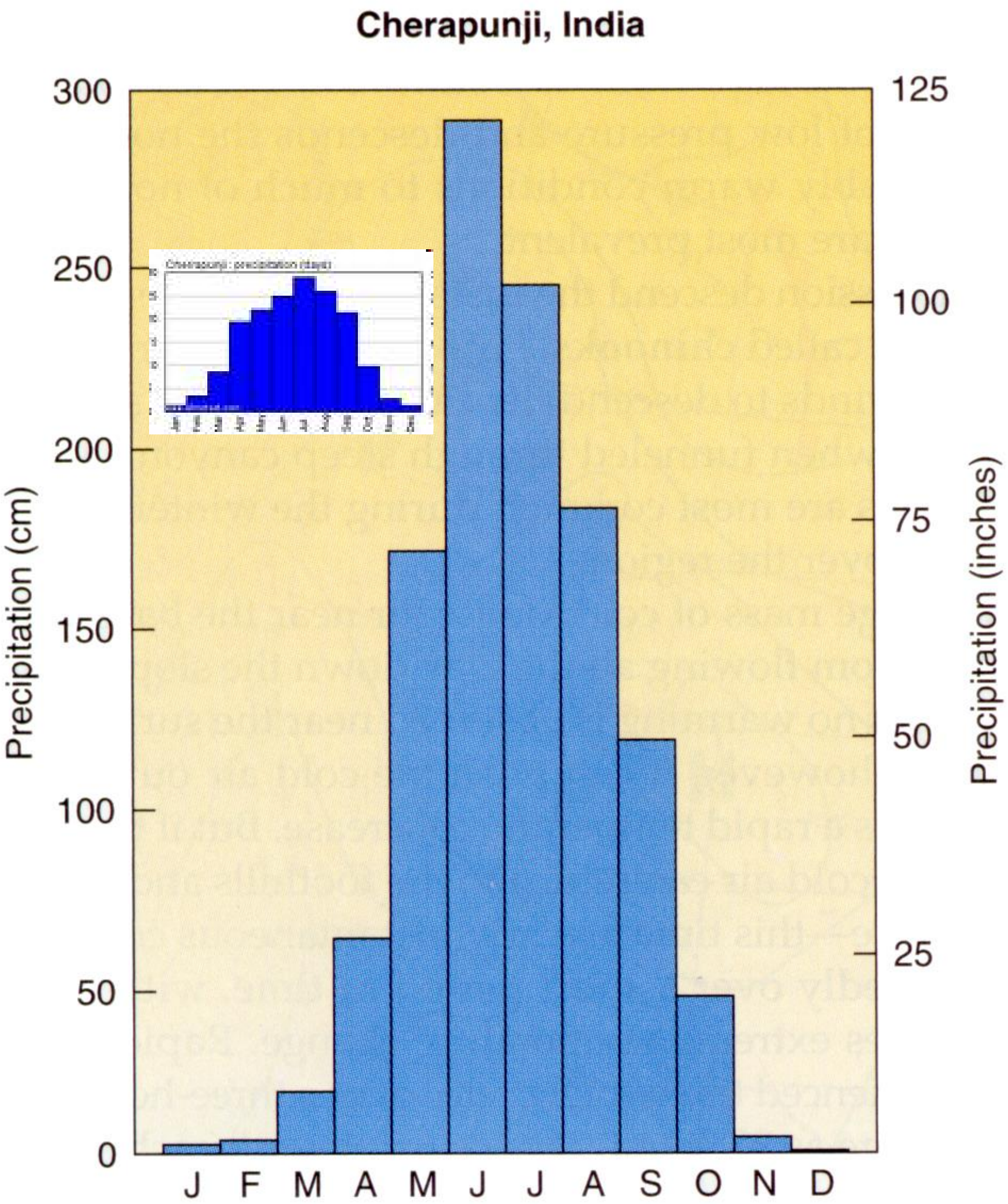
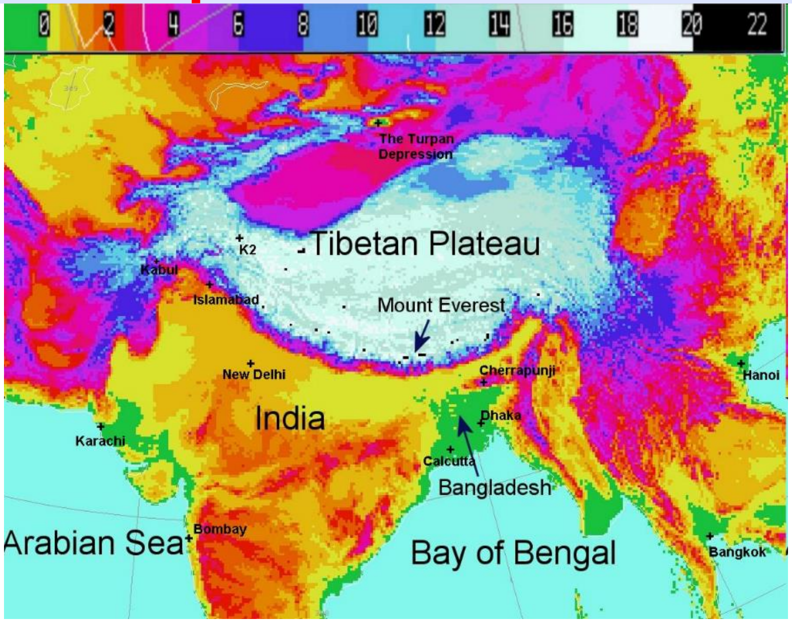


Fig. 6.20 Maps of the mean monthly precipitation over India during (a) January (contour interval 10 mm) and (b) July (contour interval 100 mm).

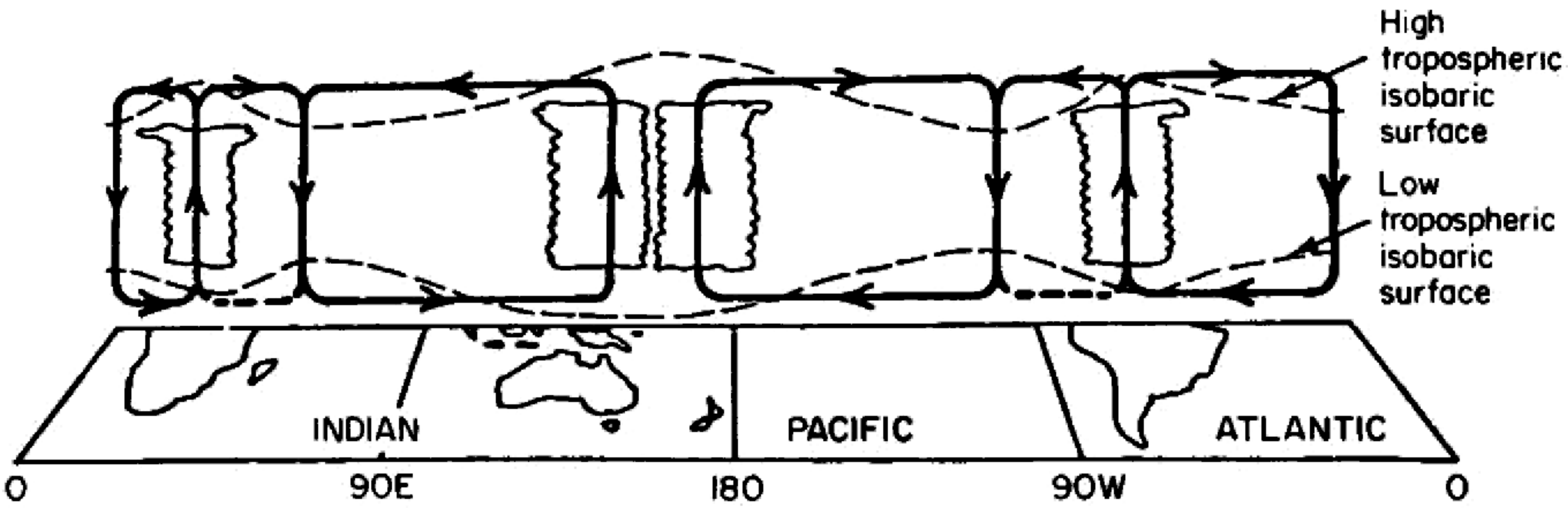
Indian Monsoon Precipitation





Nearly all the annual precipitation in this part of the world is associated with the SW monsoon

Walker Cell



$$\Psi_Z = \frac{a}{g} \int_{\phi_S}^{\phi_N} \int_0^p \overline{u}^* \, dp \, d\phi$$

- Monsoon convergence and lifting is linked to upper level convergence and subsidence over eastern Pacific
- Similar, weaker centers of deep convection over South America and Africa are also linked to subsidence over oceans

African Monsoon

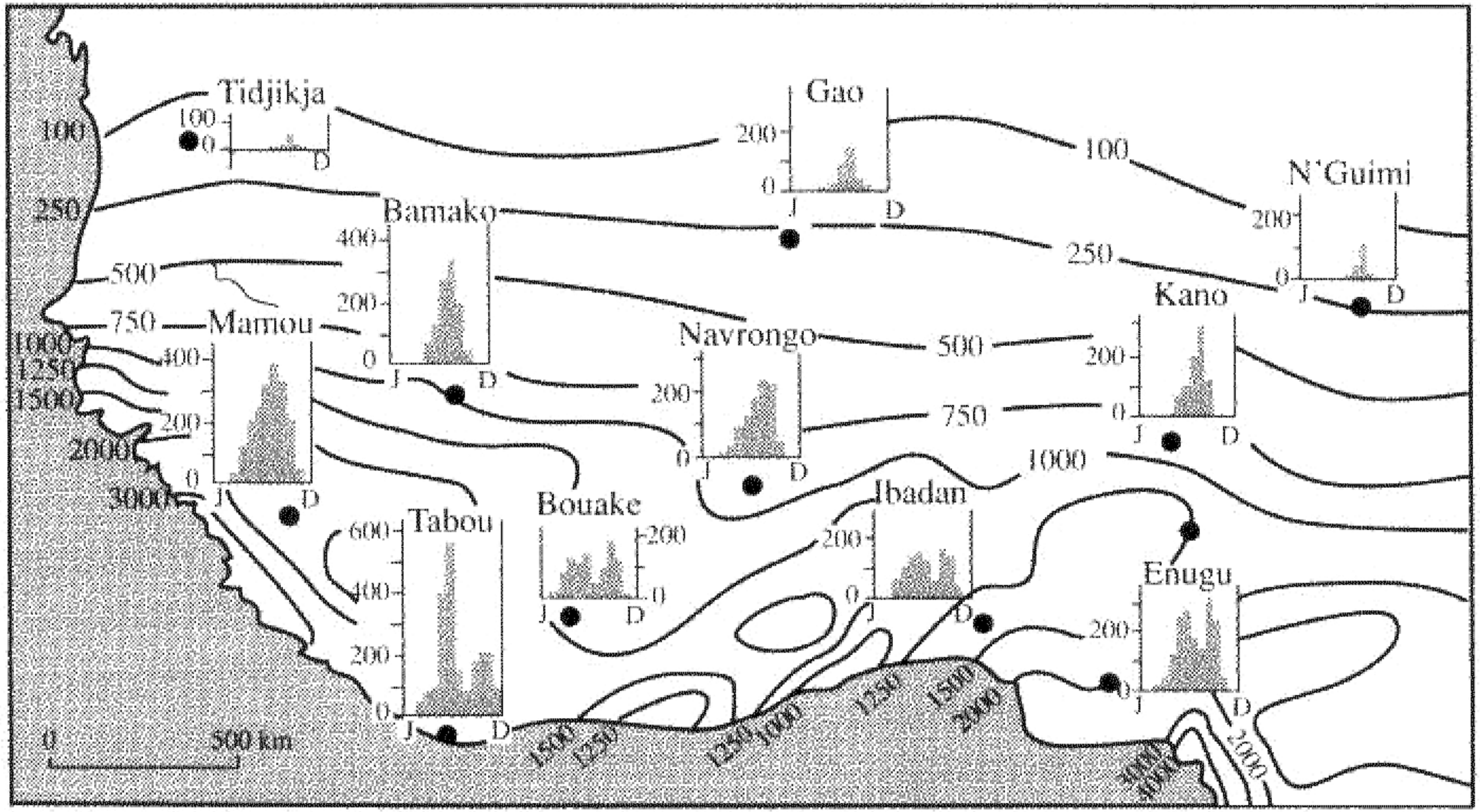


Fig. 6.24 Precipitation and seasonality of precipitation in NW Africa. Units are mm/year for contours of annual mean precipitation and mm/month for bar graphs showing the monthly precipitation from January (J) through December (D). [From Ledger (1969). Permission granted from Methuen and Co.]

Australian and Indian Monsoon

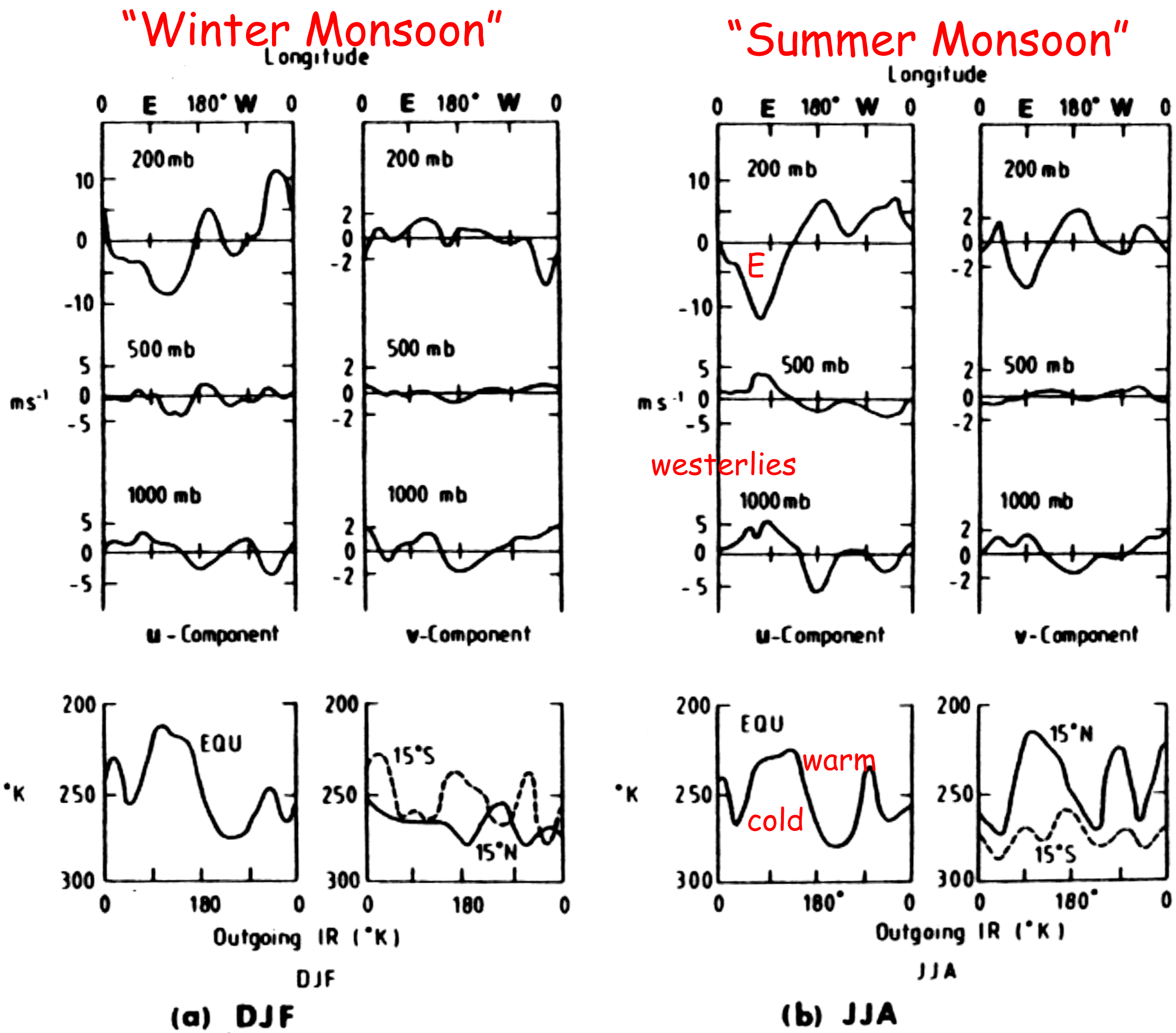
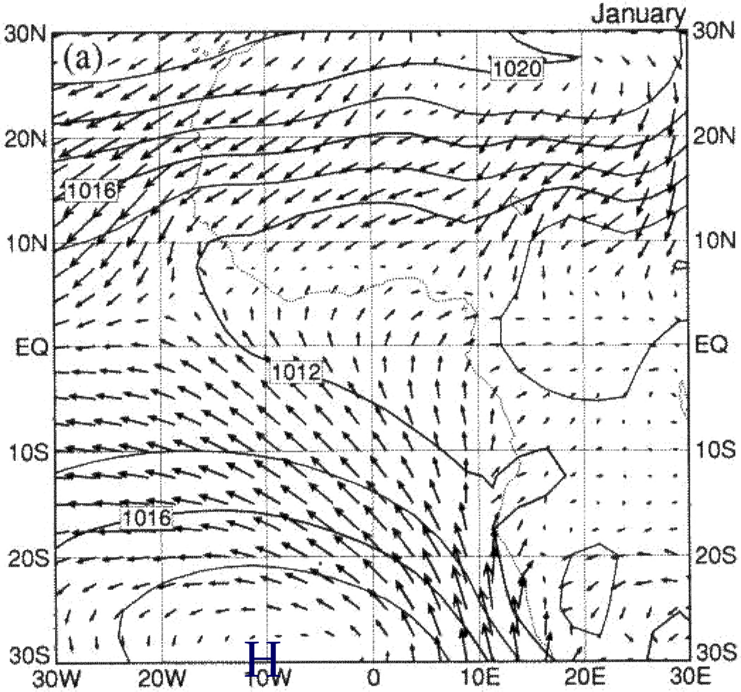


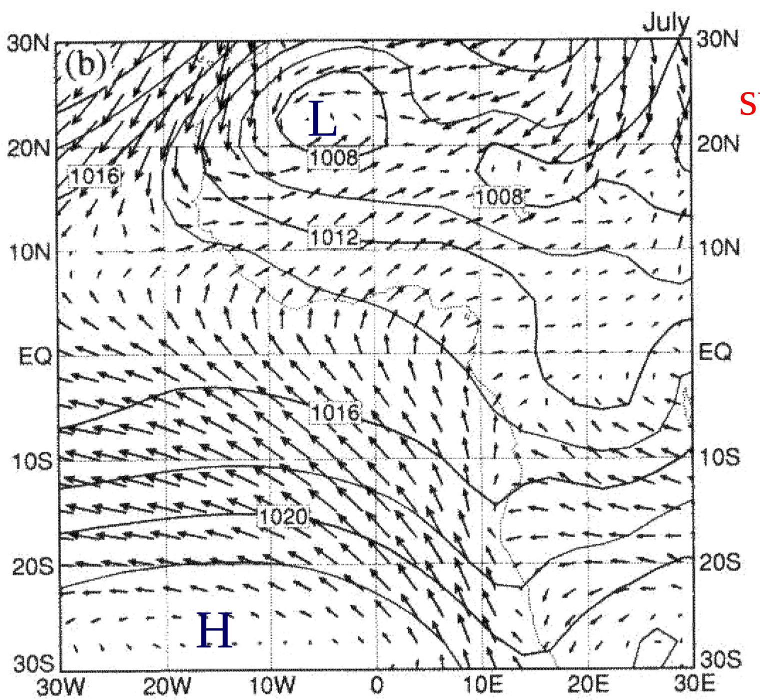
Figure 11.3. The seasonal mean east–west (*u*) and north–south (*v*) velocity components in the 5°N–5°S latitude belt along the equator for (*a*) DJF and (*b*) JJA. The zonal average wind has been removed. The lower graphs show the infrared radiating temperatures (scale inverted) determined from satellite along the equator and at 15°N and 15°S.

- Very strong asymmetry across Pacific
- Surface westerlies, easterlies aloft
- Warm ocean, very cold TOA

African Monsoon Circulation



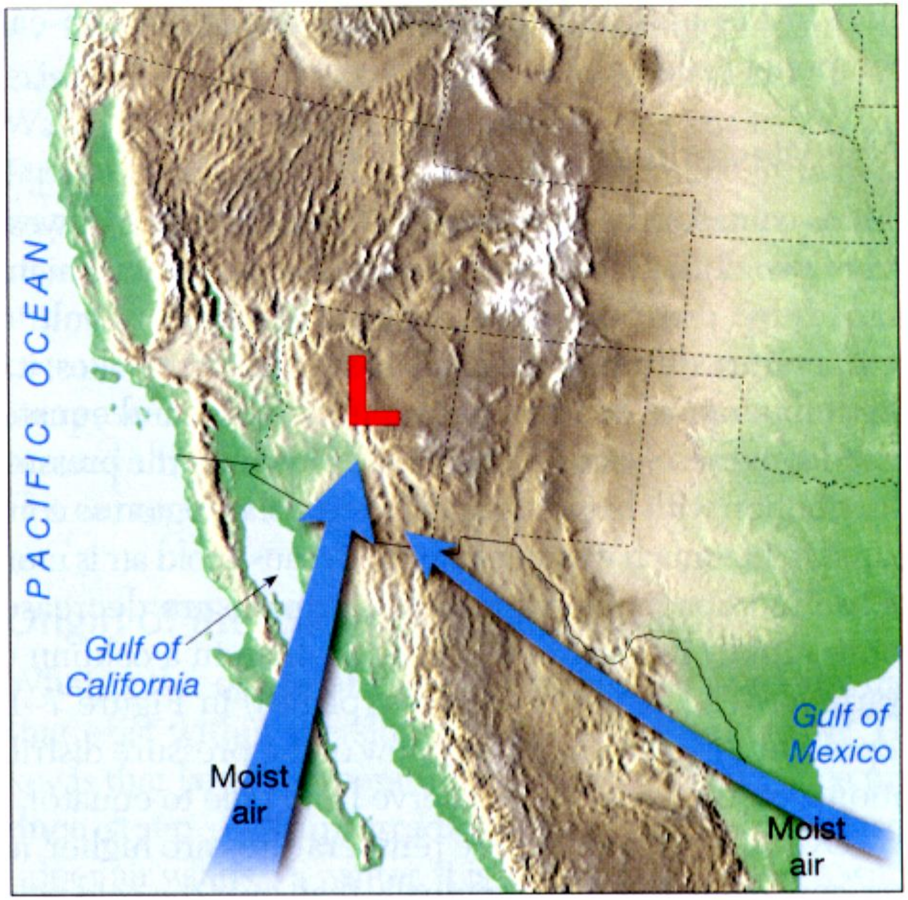
winter

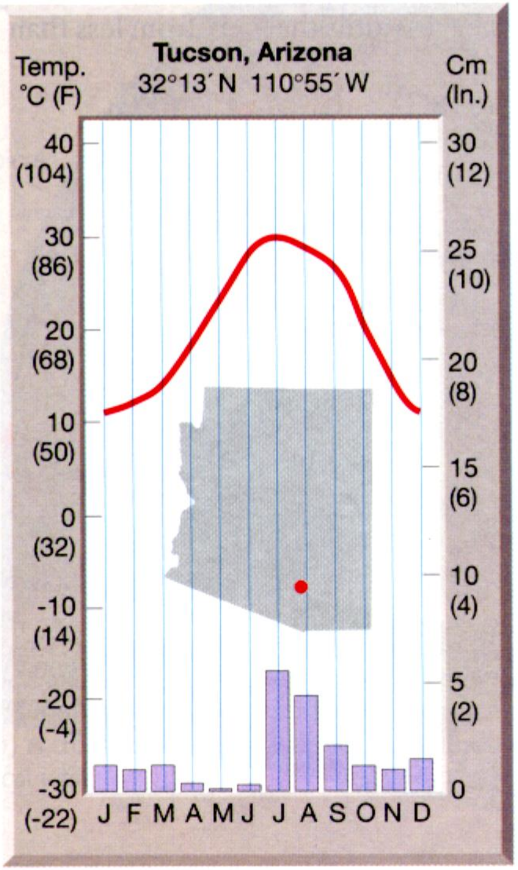


summer

- Cross-Equatorial flow mainly summer season
- Easterly trade winds in both seasons oscillating with ITCZ
- Persistent southeasterly flow along western border of African coast governed by high pressure area located in Atlantic ocean at 25° S

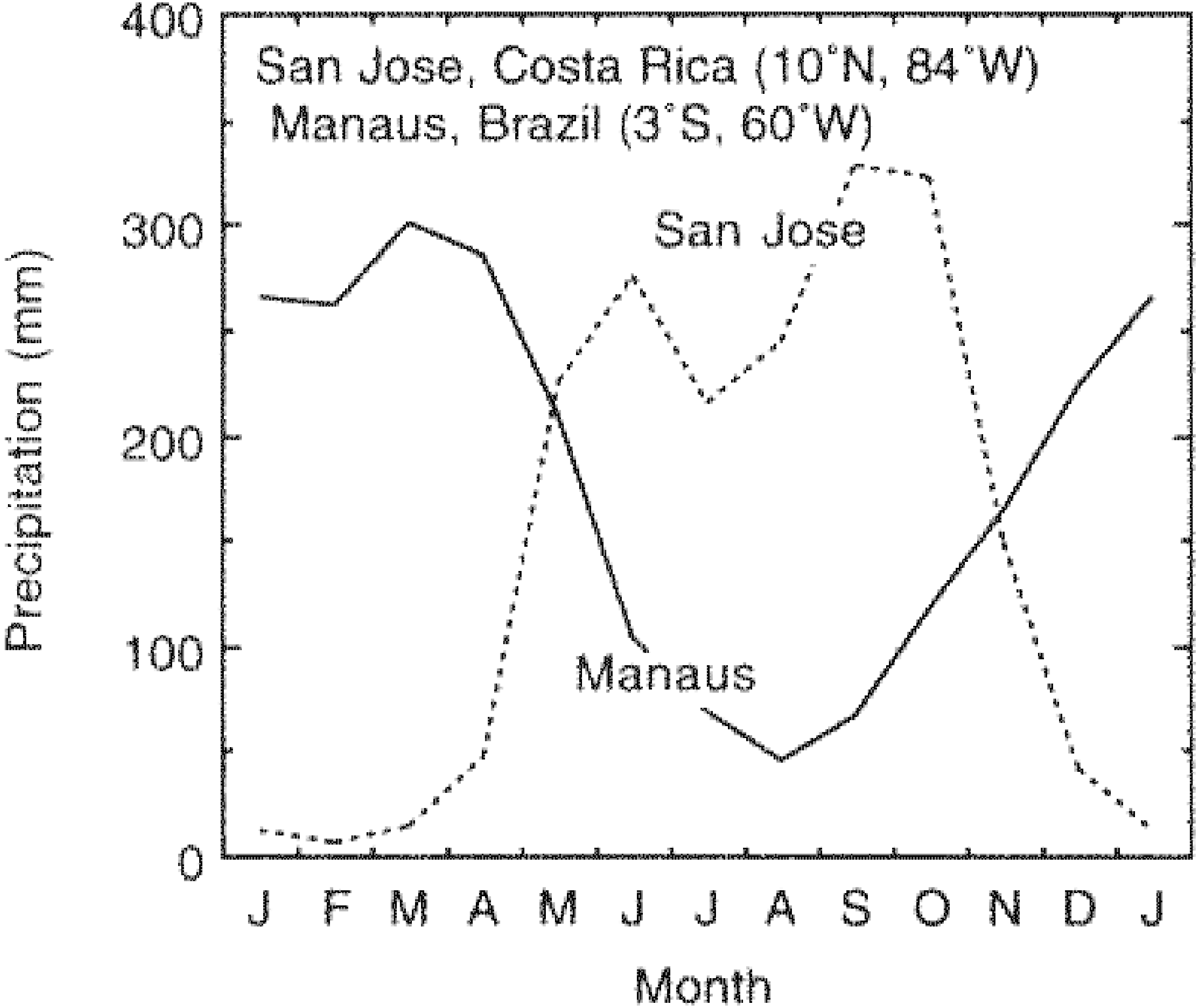
North American Monsoon





- Summer heating over SW desert produces divergent flow aloft
- Leads to a "thermal low" at the surface
- As with Asian Monsoon, effect is amplified by elevated terrain
- Convergent flow of moisture produces a late summer precipitation maximum that often reaches Colorado

South American Monsoon



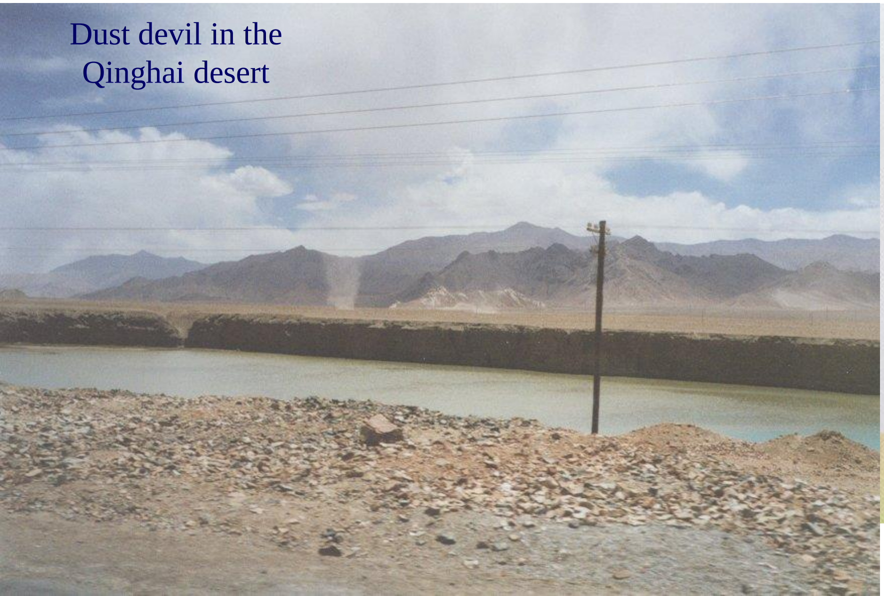
Desert winds

- The surface temperature in desert areas can reach even 50-55 °C
- A **superadiabatic** layer very unstable creates at contact with the soil which generates strong convection (γ~10°C/100m >> γ_a~1.0°C/100m)
- Convective eddies cannot form clouds because the surface moisture is too low ($Z_{LCL} > Z_i$) and since there is the thermal inversion typical of thermal anticyclones; but they produce turbulence
- Dust storms develop in correspondence with transitions in surface characteristics (diameter ~ 1 m, duration ~ 1 min) and sometimes amplify (~ 100 m) producing very strong wind speeds

Dust devils

Dust devils (=miniature tornadoes) develop mainly in desertic and dusty areas, where convection is very strong due to the intense surface solar heating (SL is extremely superadiabatic), but where humidity is generally low and insufficient to produce rainy clouds

- Mechanism:
  - Surface heating produces convection
  - Wind blowing past object twists rising air
  - Air rushes into rising column lifting dirt and debris


Dust devil in the Qinghai desert