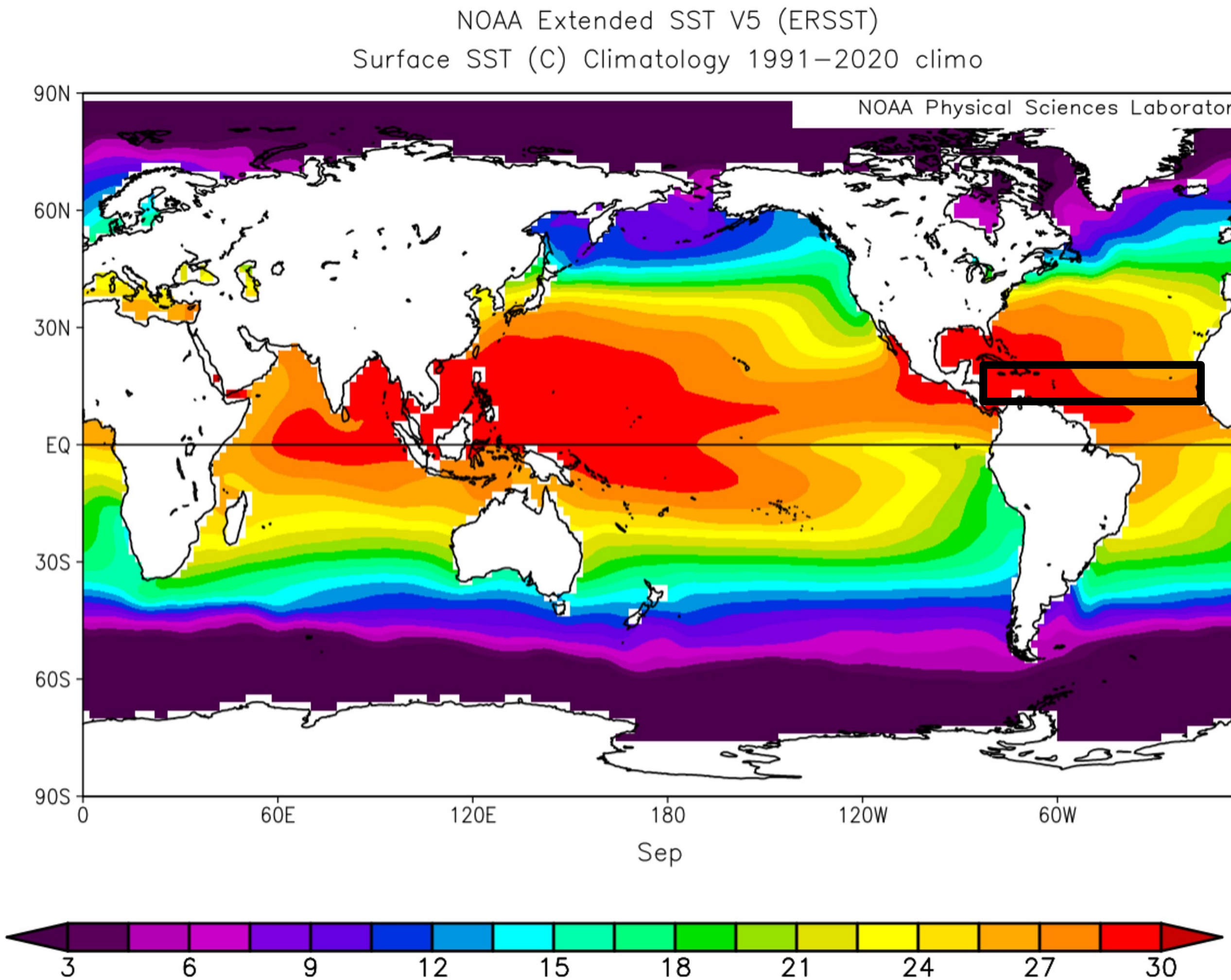
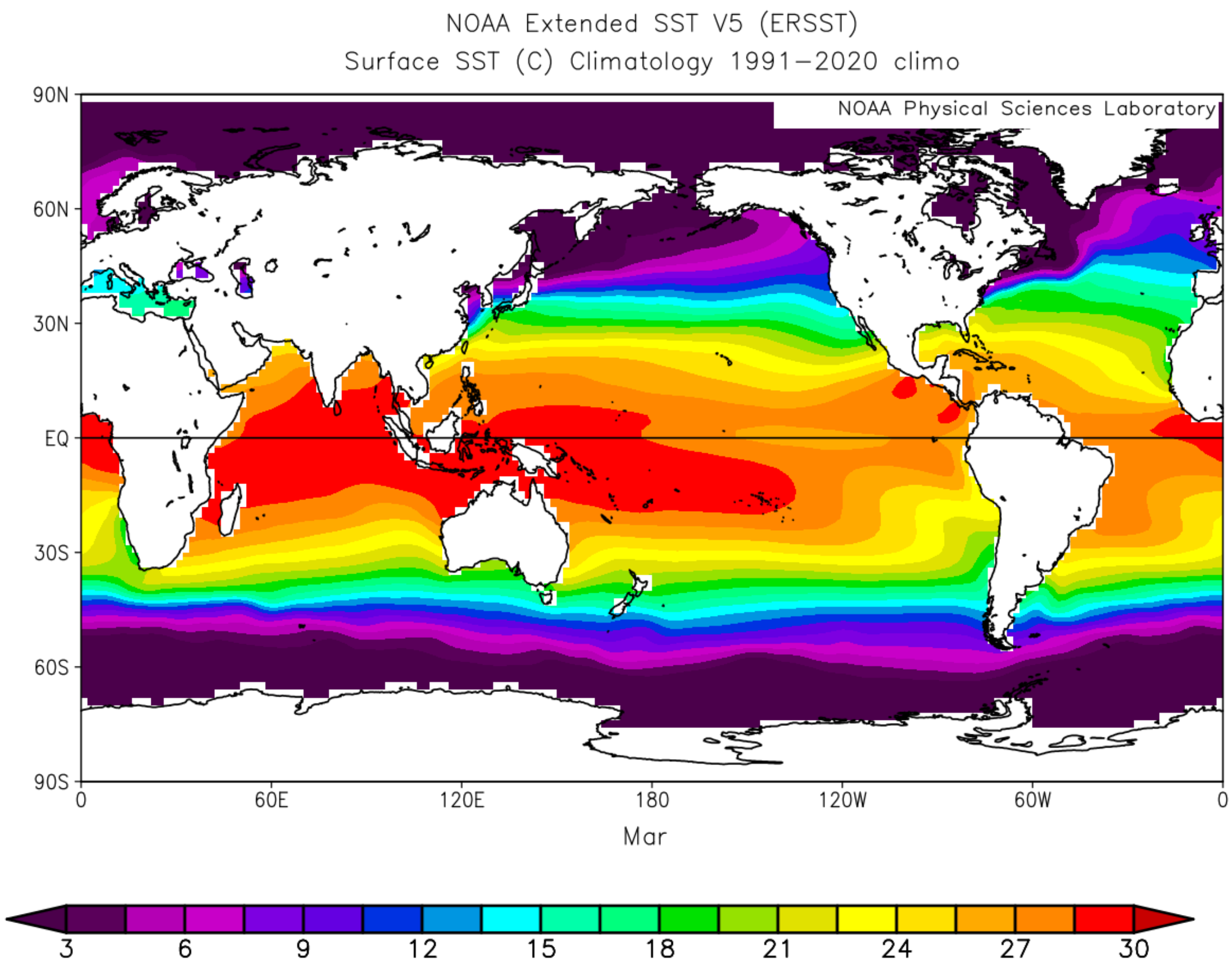
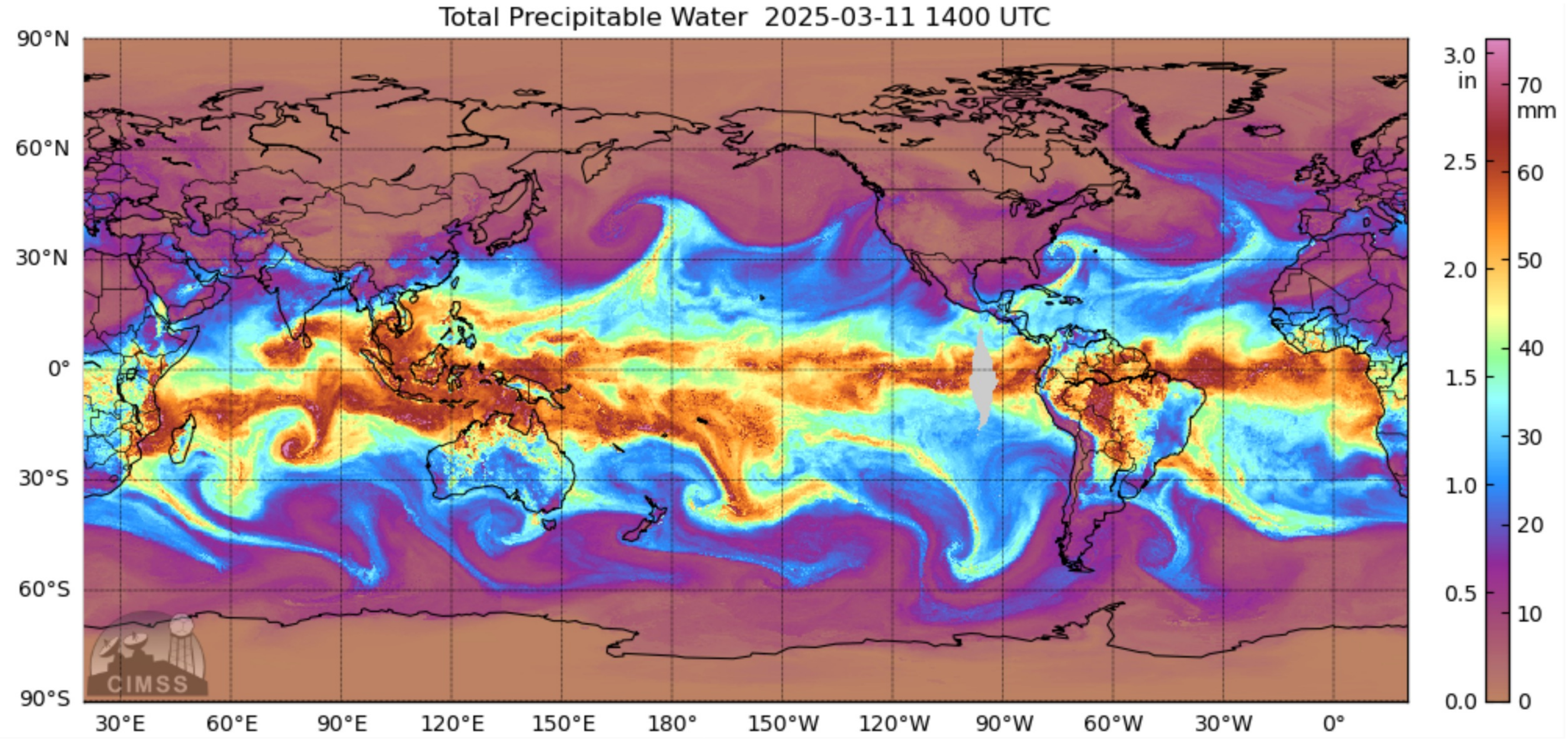
Necessary conditions for TC development:
1) Warm sea surface temperatures (> ~26° C)



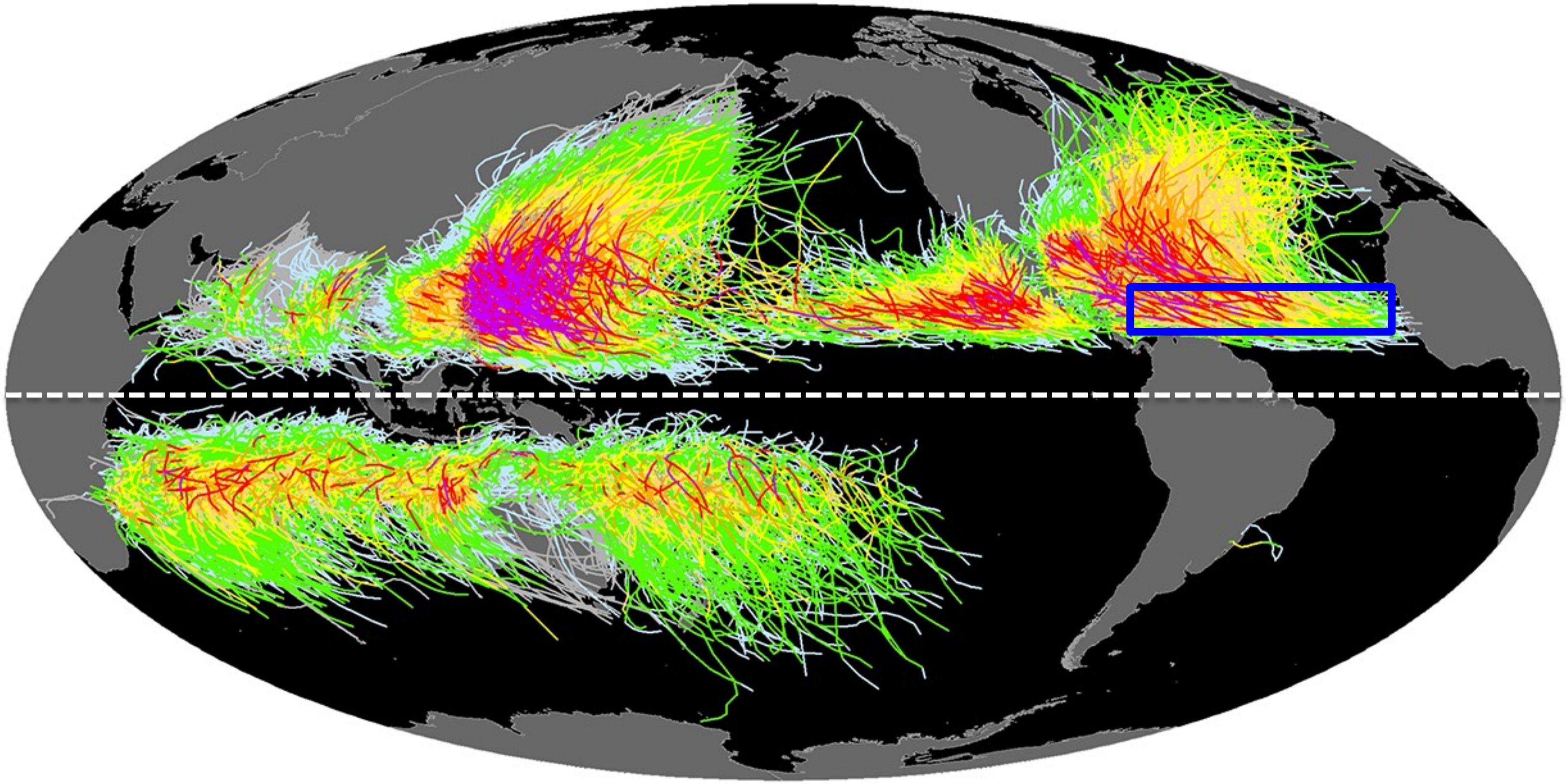
Necessary conditions for TC development:
1) Warm sea surface temperatures (> ~26° C)



Necessary conditions for TC development:
1a) Warm SSTs (> ~26° C) & a moist atmosphere



Necessary conditions for TC development:
2)Off equatorial location (Coriolis effect)



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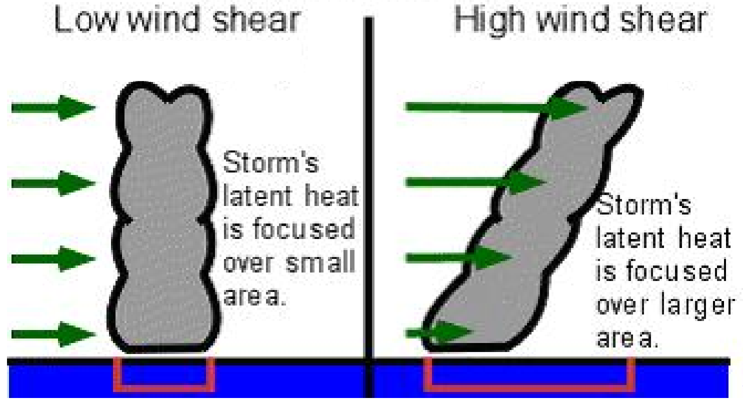
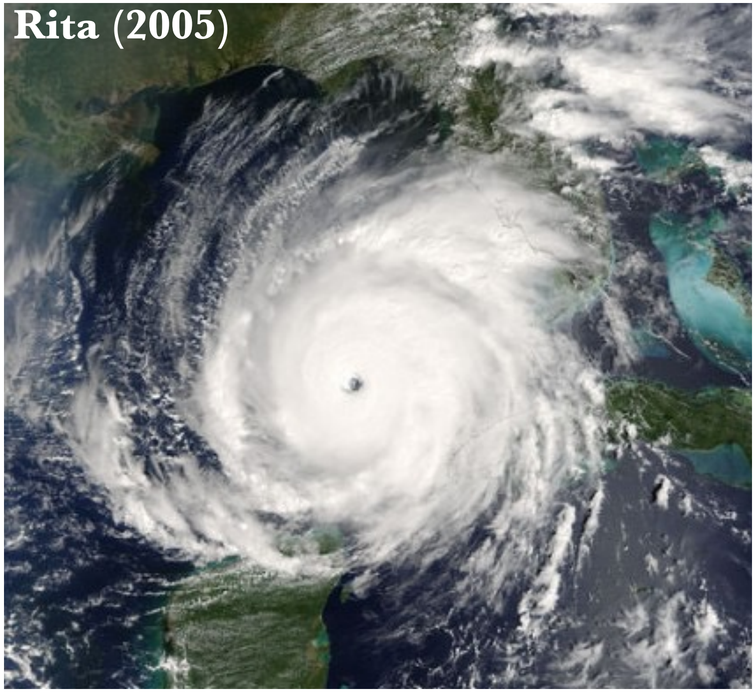
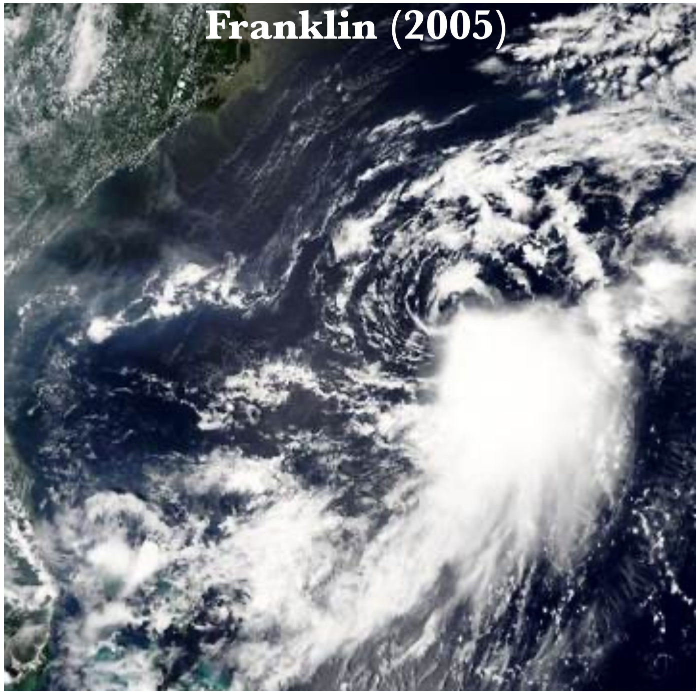
Saffir-Simpson Hurricane Wind Scale

Intensity Missing	Category 1
Tropical Depression	Category 2
Tropical Storm	Category 3
	Category 4
	Category 5

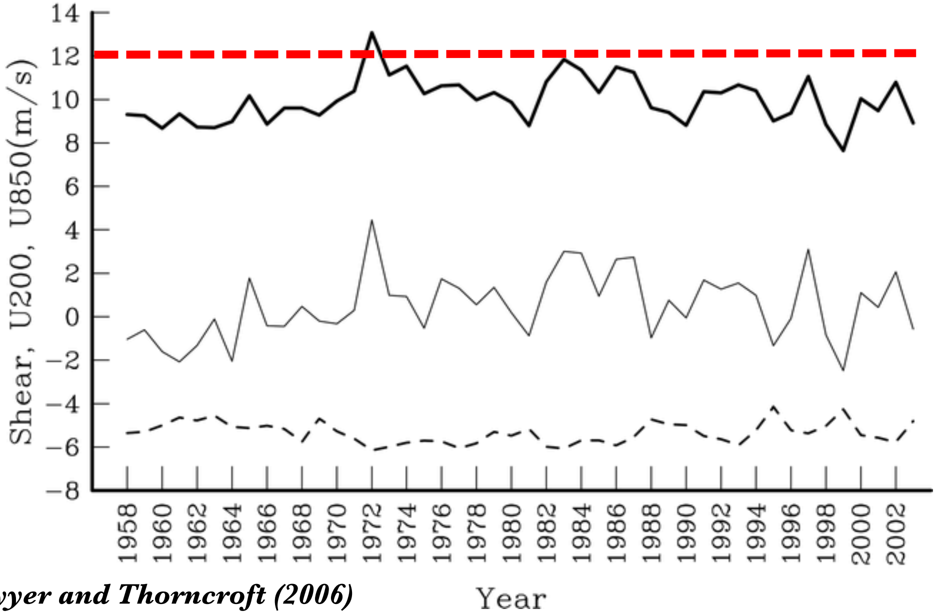
Necessary conditions for TC development:
3) Relatively "weak" vertical wind shear







Necessary conditions for TC development:
3) Relatively "weak" vertical wind shear

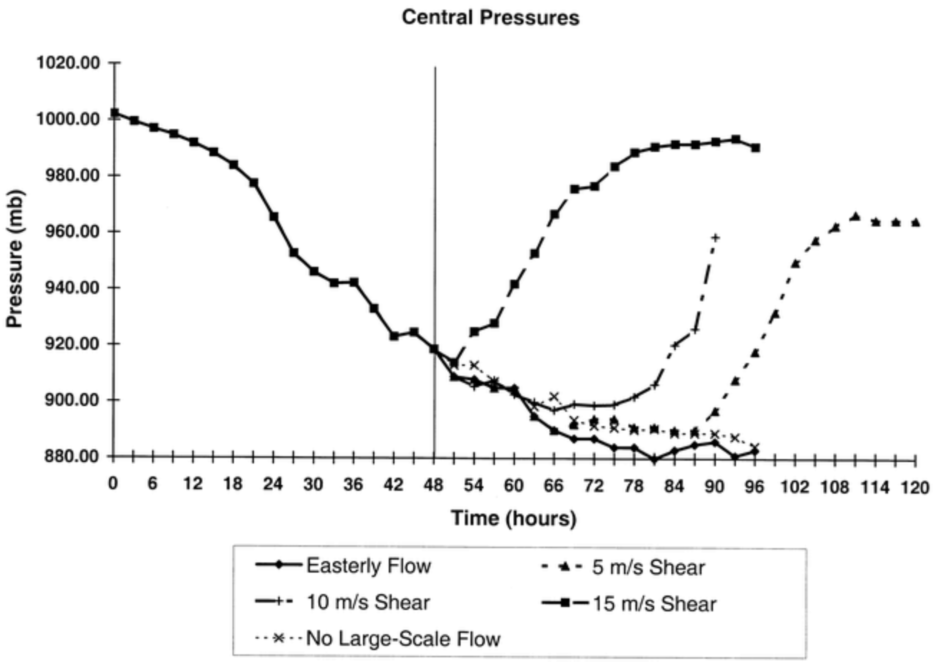


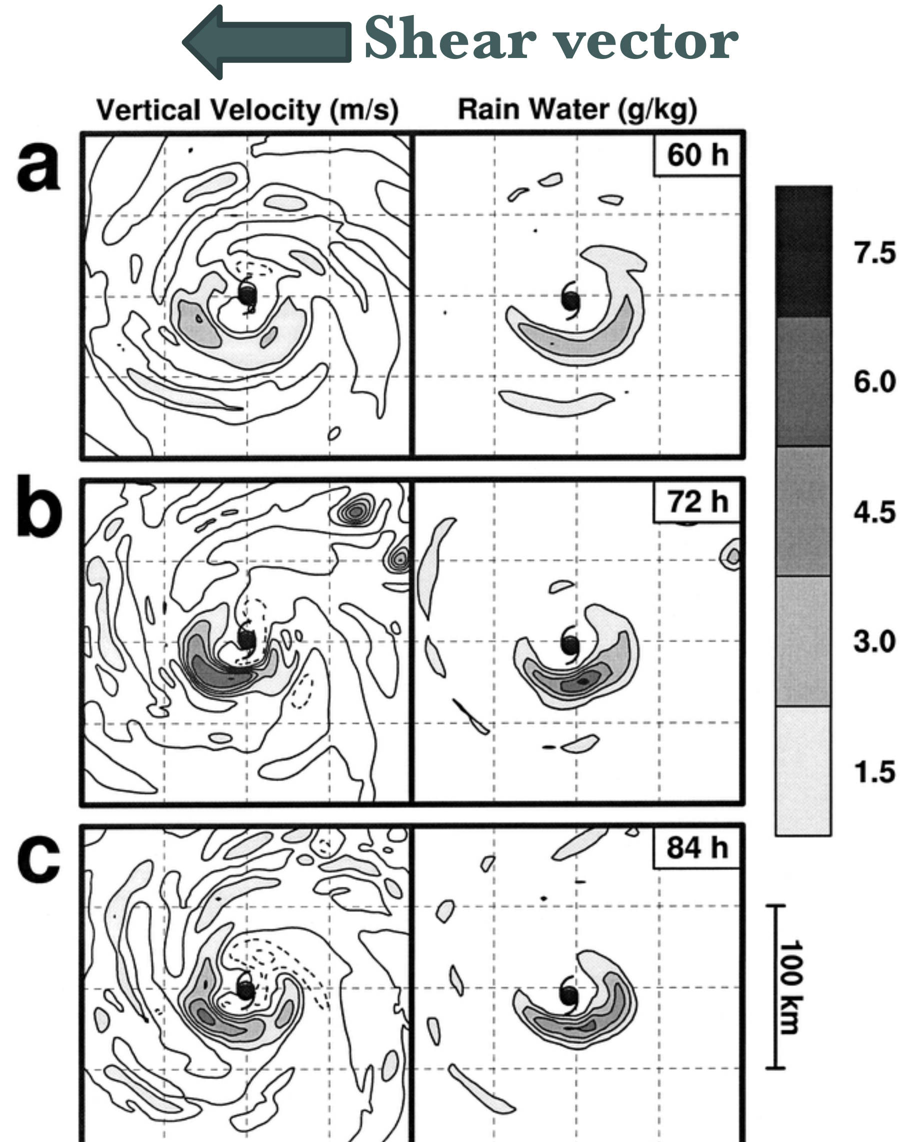
Aiyyer and Thorncroft (2006)

Vertical wind shear

Atlantic main development region (MDR) (left; bold solid line)

Necessary conditions for TC development:
3) Relatively "weak" vertical wind shear

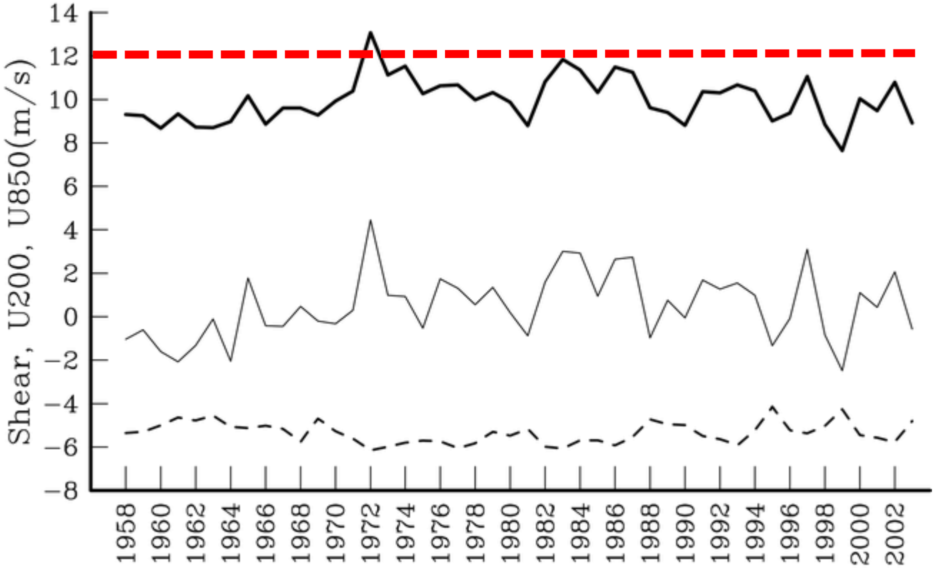




5 m s^{-1} of vertical shear is enough to generate significant asymmetries and weaken a TC after one to two days

Frank and Ritchie (2001)

Necessary conditions for TC development:
3) Relatively "weak" vertical wind shear



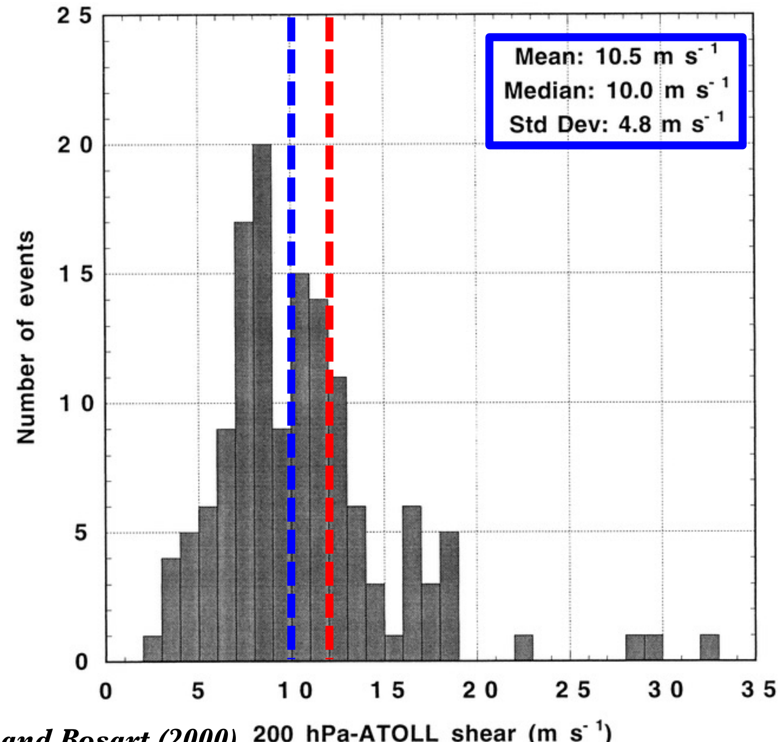
Aiyyer and Thorncroft (2006)

Vertical wind shear

Atlantic main development region (MDR) (left; bold solid line)

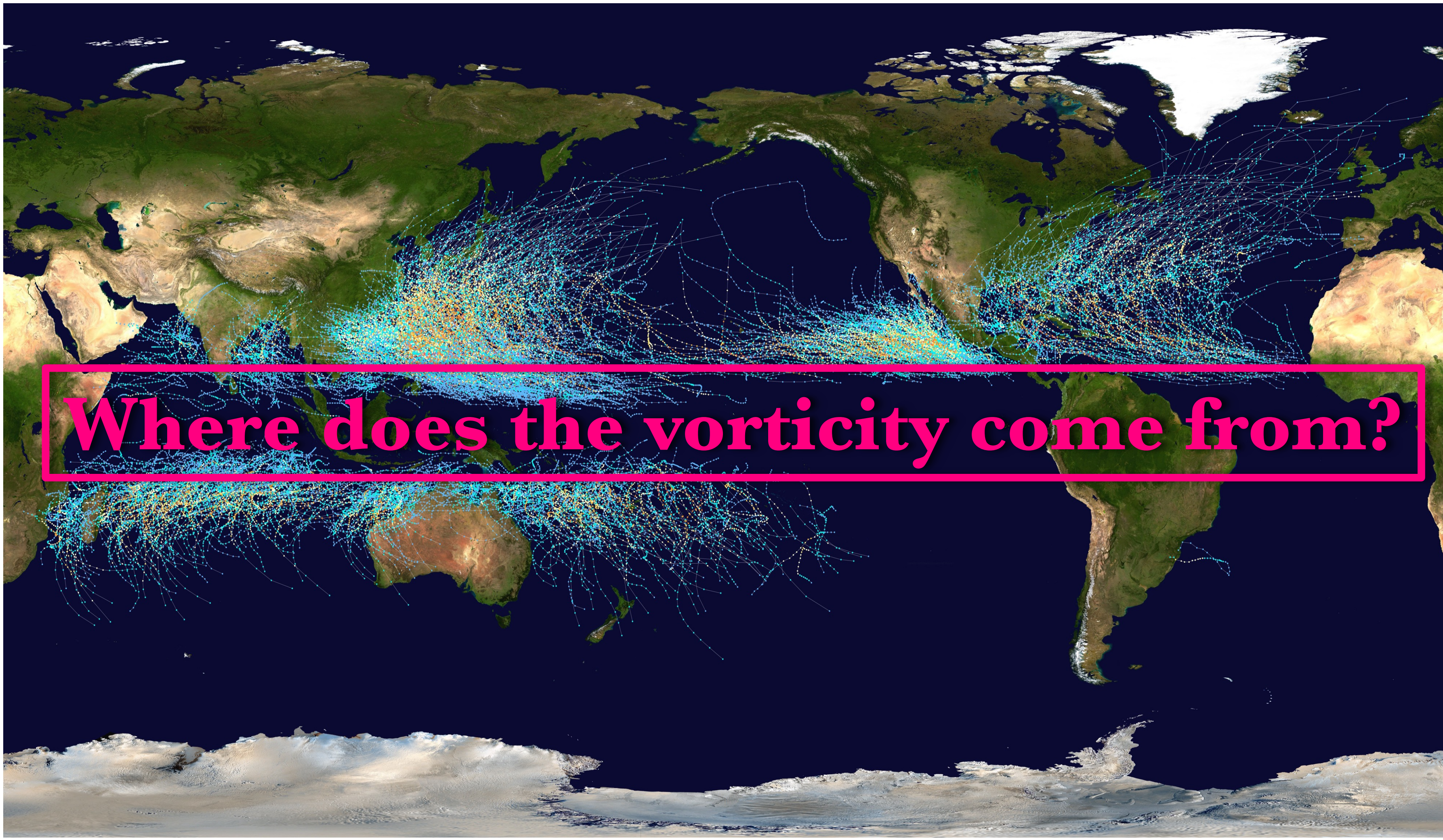
Vertical wind shear

At time of genesis for 139 Atlantic basin tropical depressions (ATOLL = ~900 hPa)

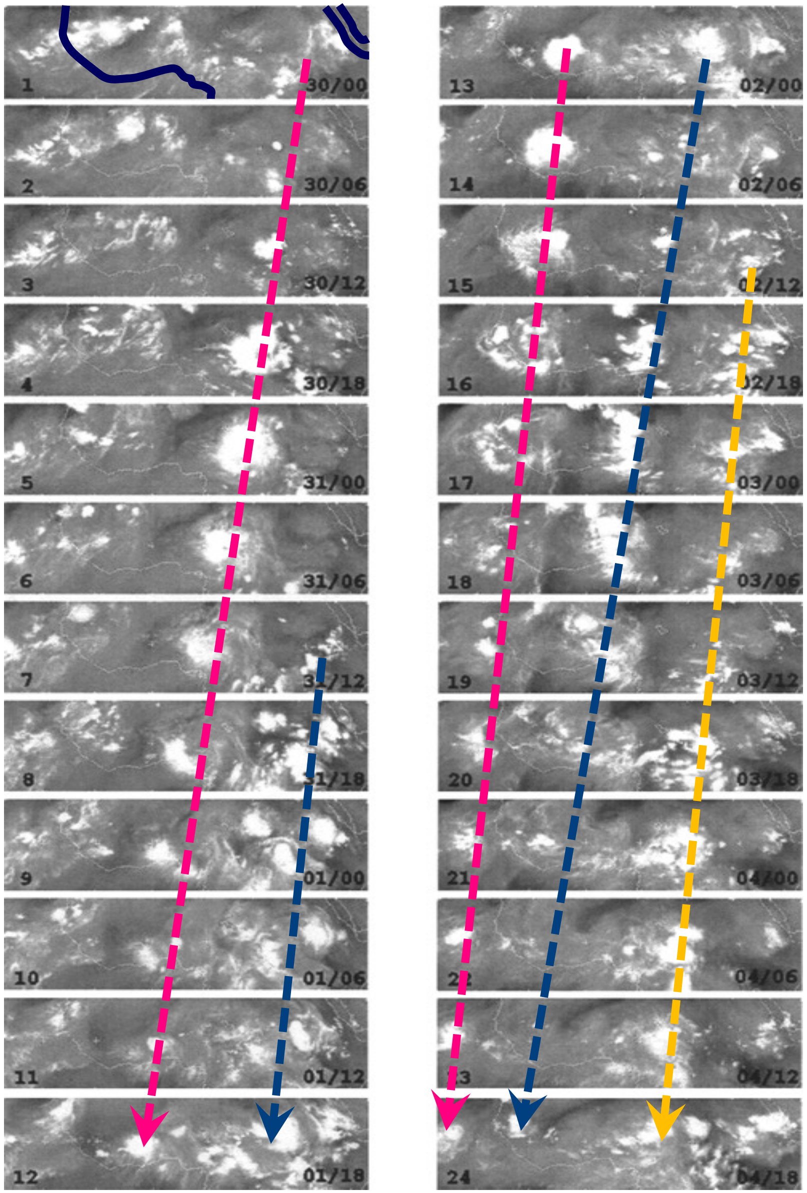


Bracken and Bosart (2000)

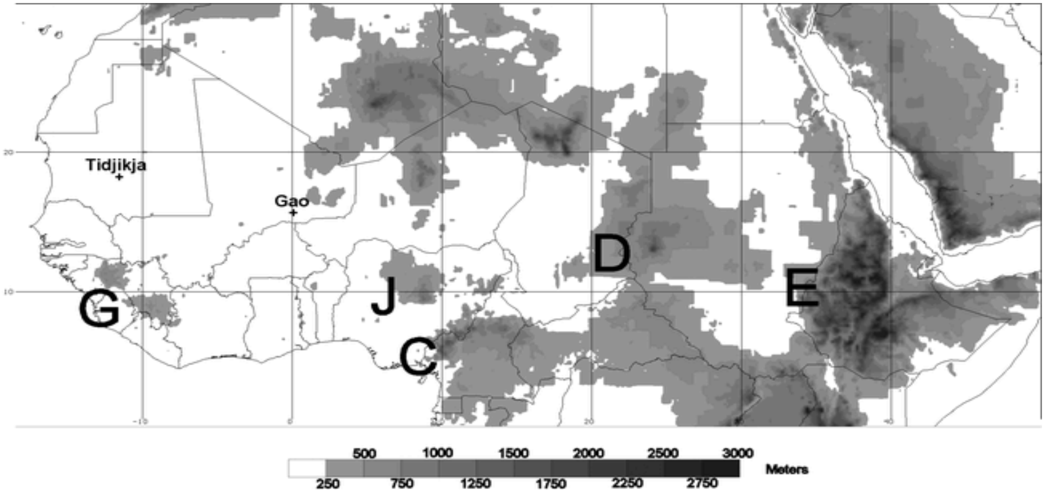
Necessary conditions for TC development:
4) Pre-existing finite amplitude cyclonic vorticity



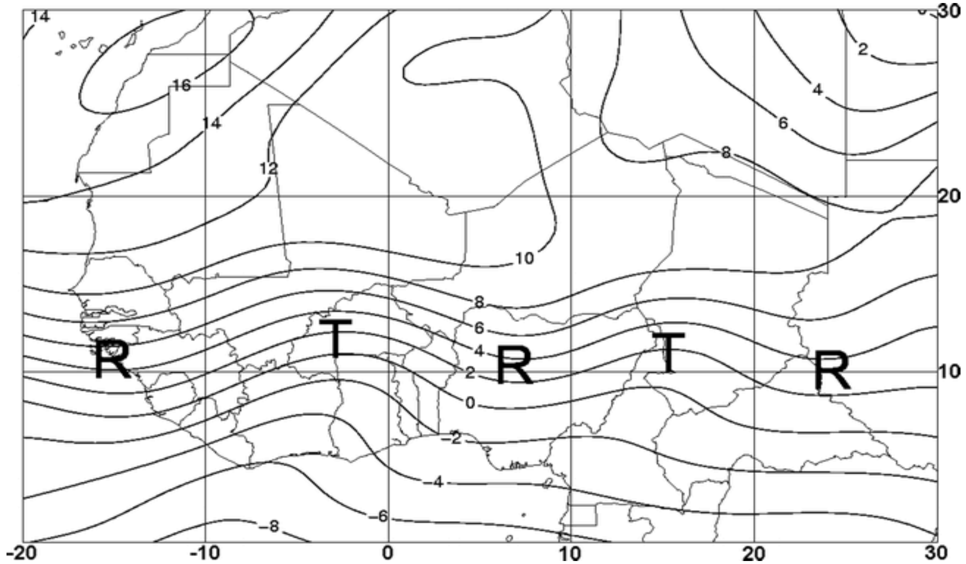
Necessary conditions for TC development:
4) Pre-existing finite amplitude cyclonic vorticity



Berry and Thorncroft (2005)

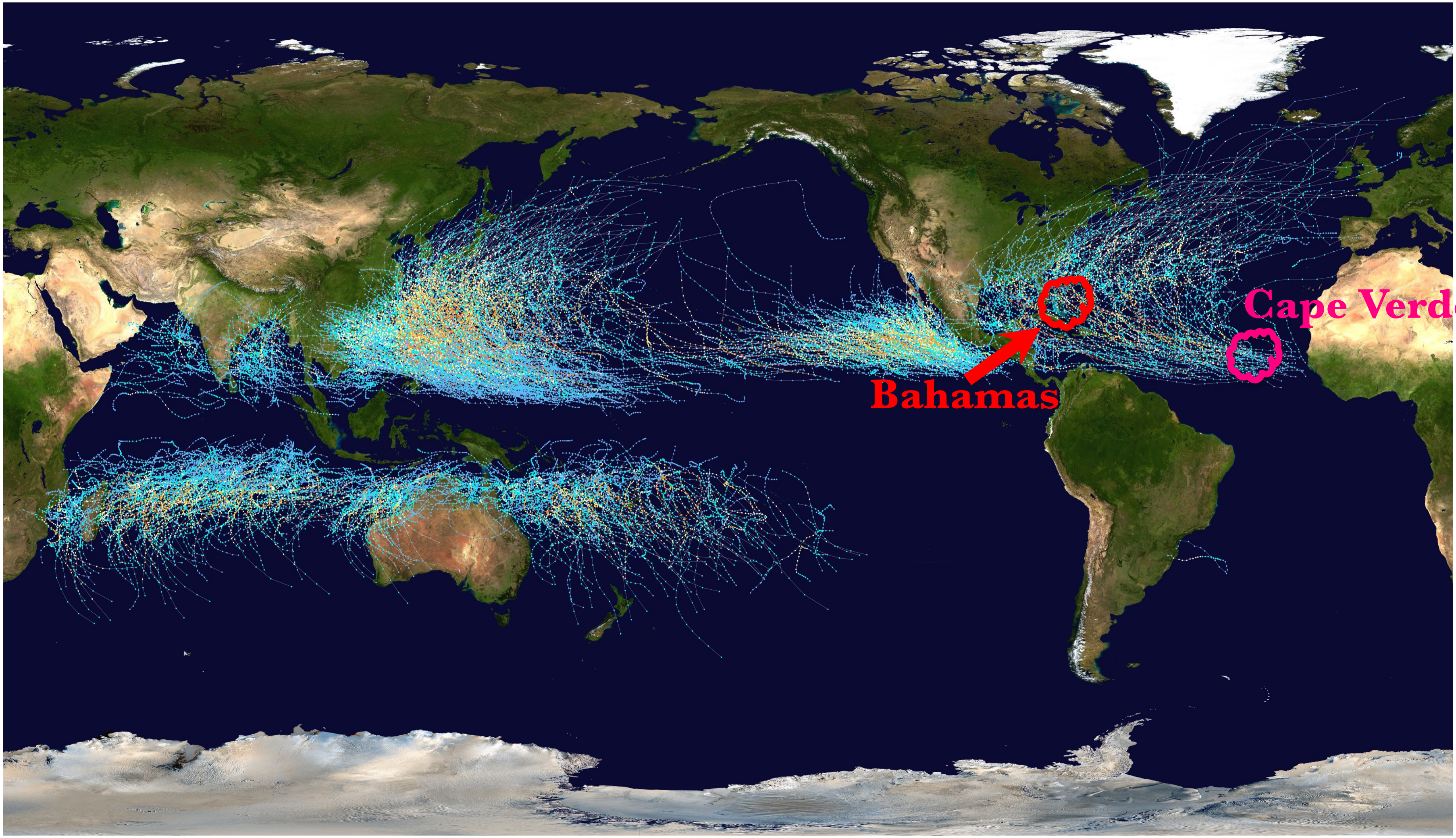


African easterly waves & PV



Berry et al. (2007)

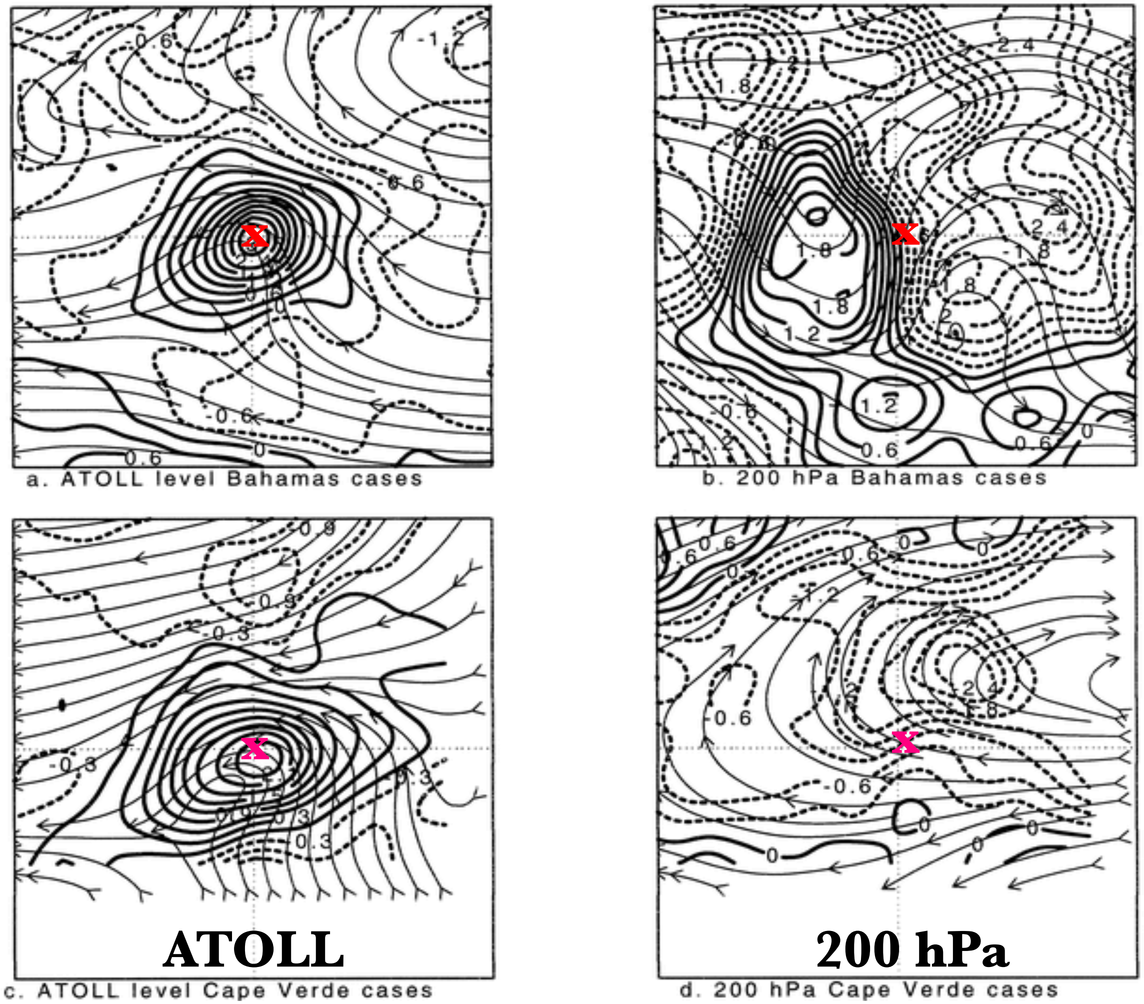
Necessary conditions for TC development:
4) Pre-existing finite amplitude cyclonic vorticity



Necessary conditions for TC development:
4) Pre-existing finite amplitude cyclonic vorticity

Bahamas

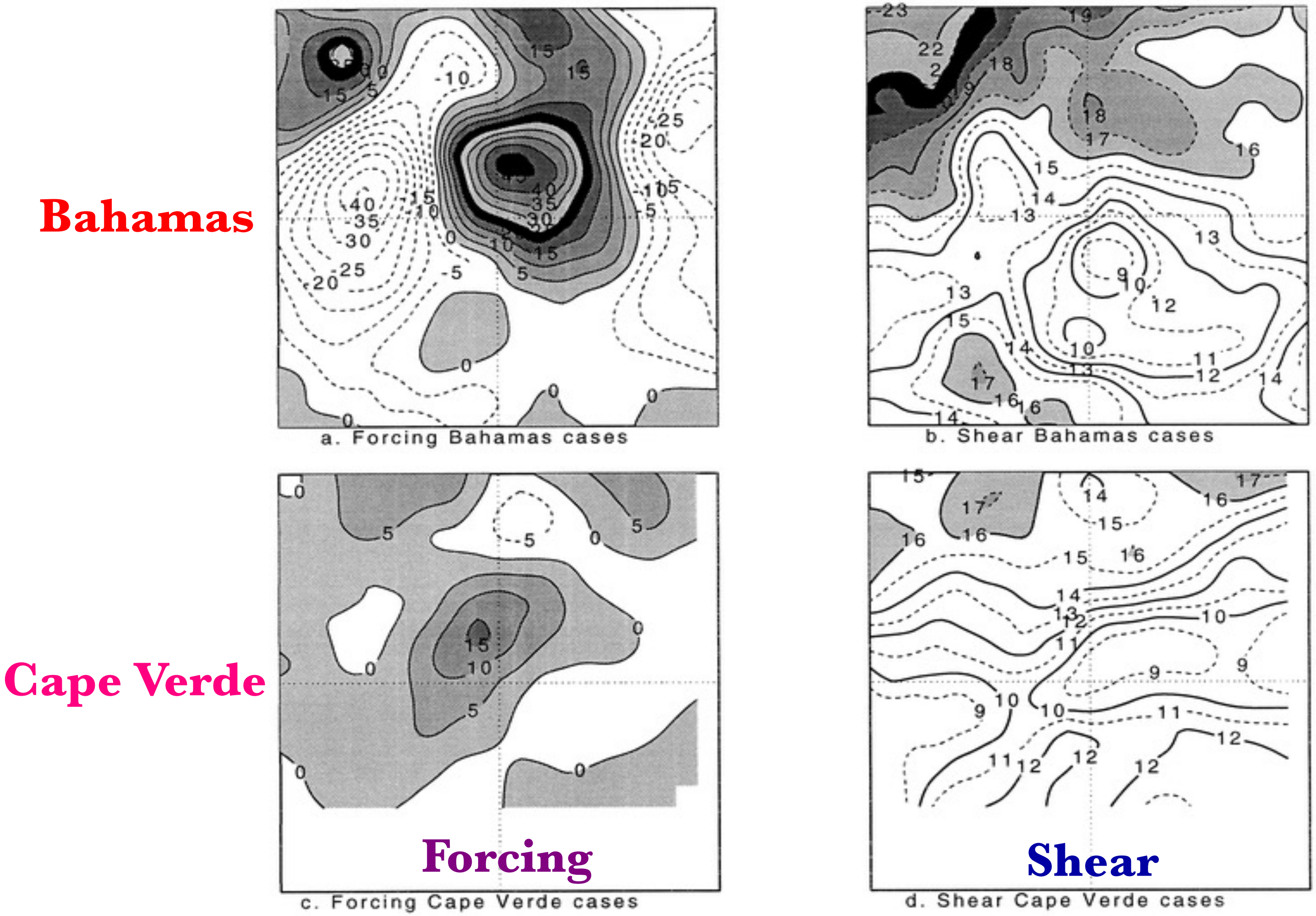
Cape Verde



Bracken and Bosart (2000)

Composite streamlines (thin solid) and relative vorticity (every 0.3 x 10^{-5} s^{-1}, cyclonic solid and anticyclonic dashed)

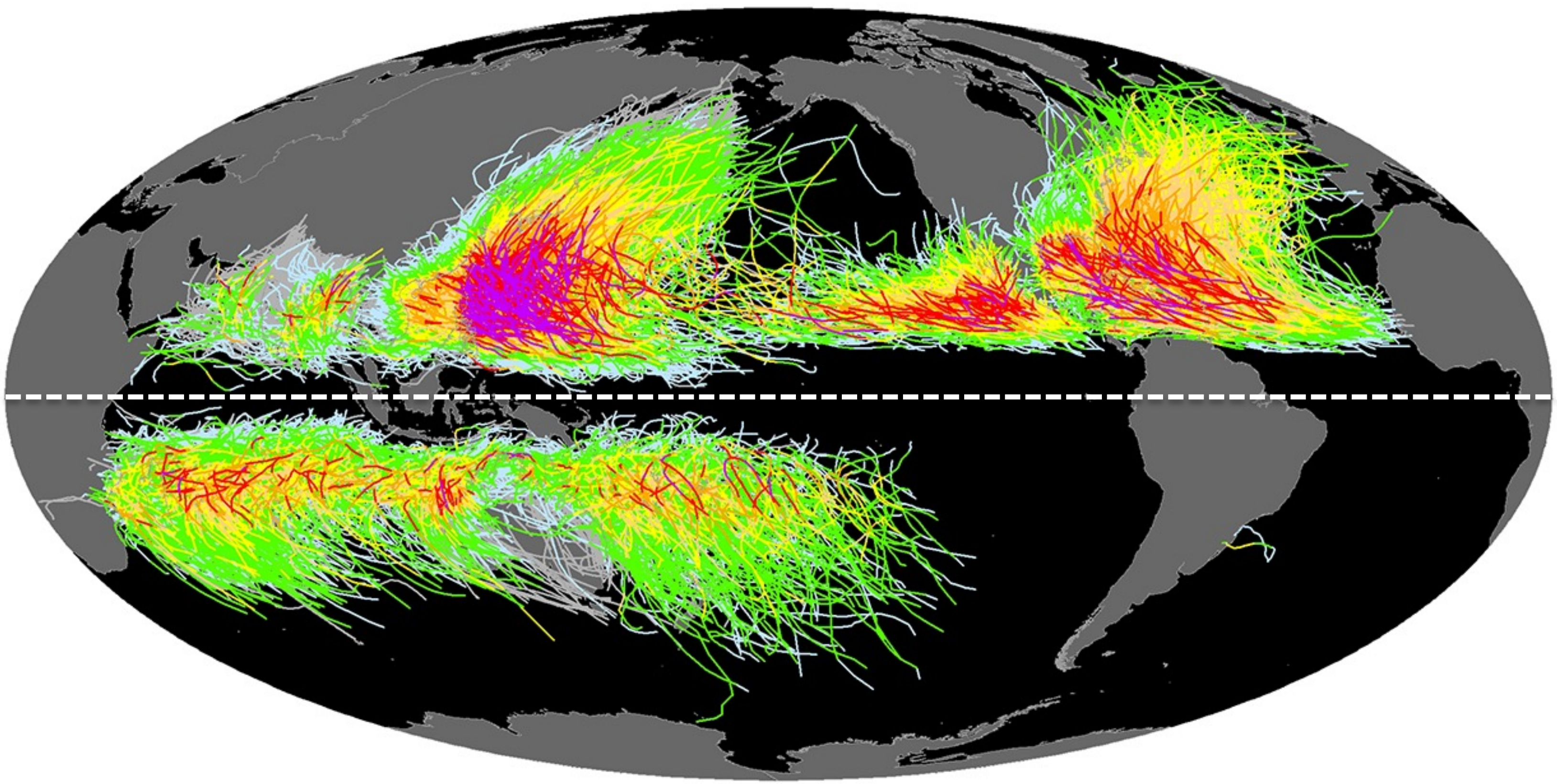
Necessary conditions for TC development:
4) Pre-existing finite amplitude cyclonic vorticity



Bracken and Bosart (2000)

Sutcliffe–Trenberth forcing for vertical motion and ATOLL–200-hPa vertical shear

Necessary conditions for TC development:
Putting it all together!



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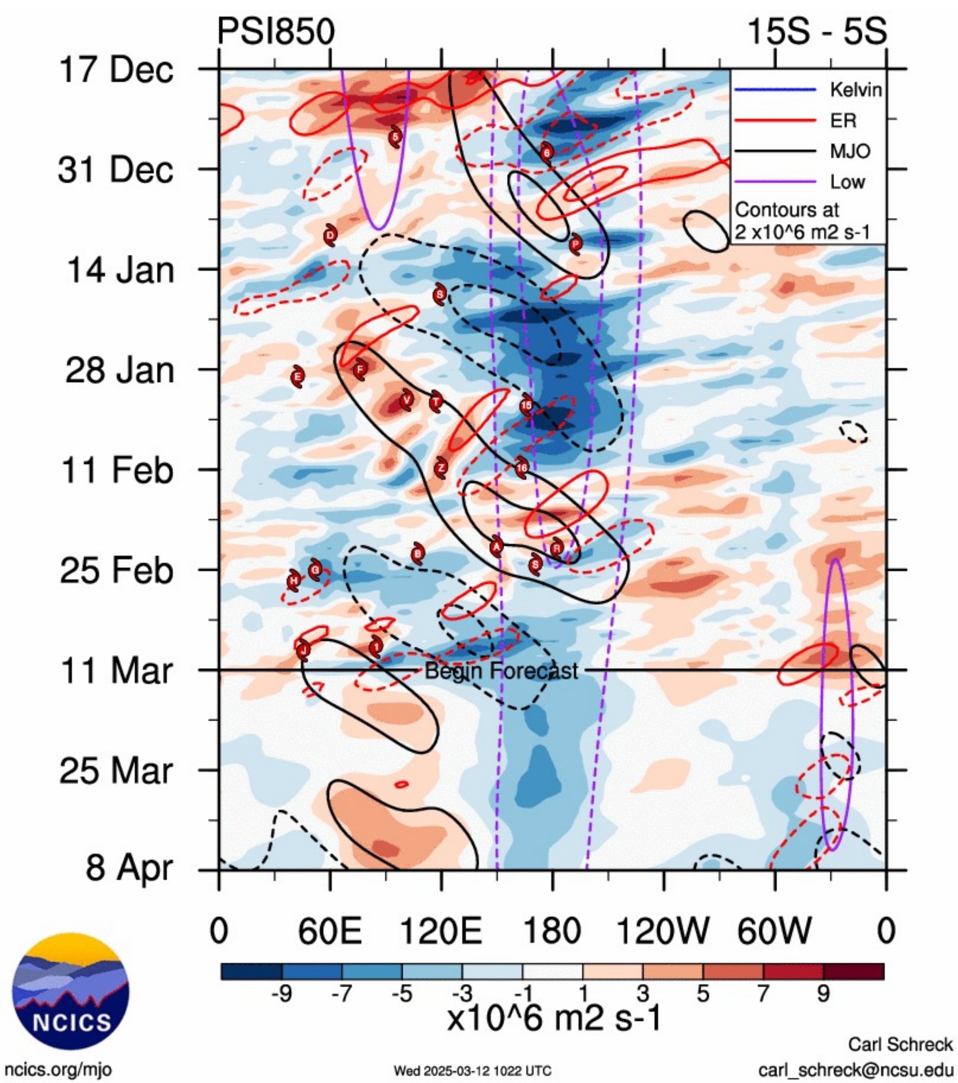
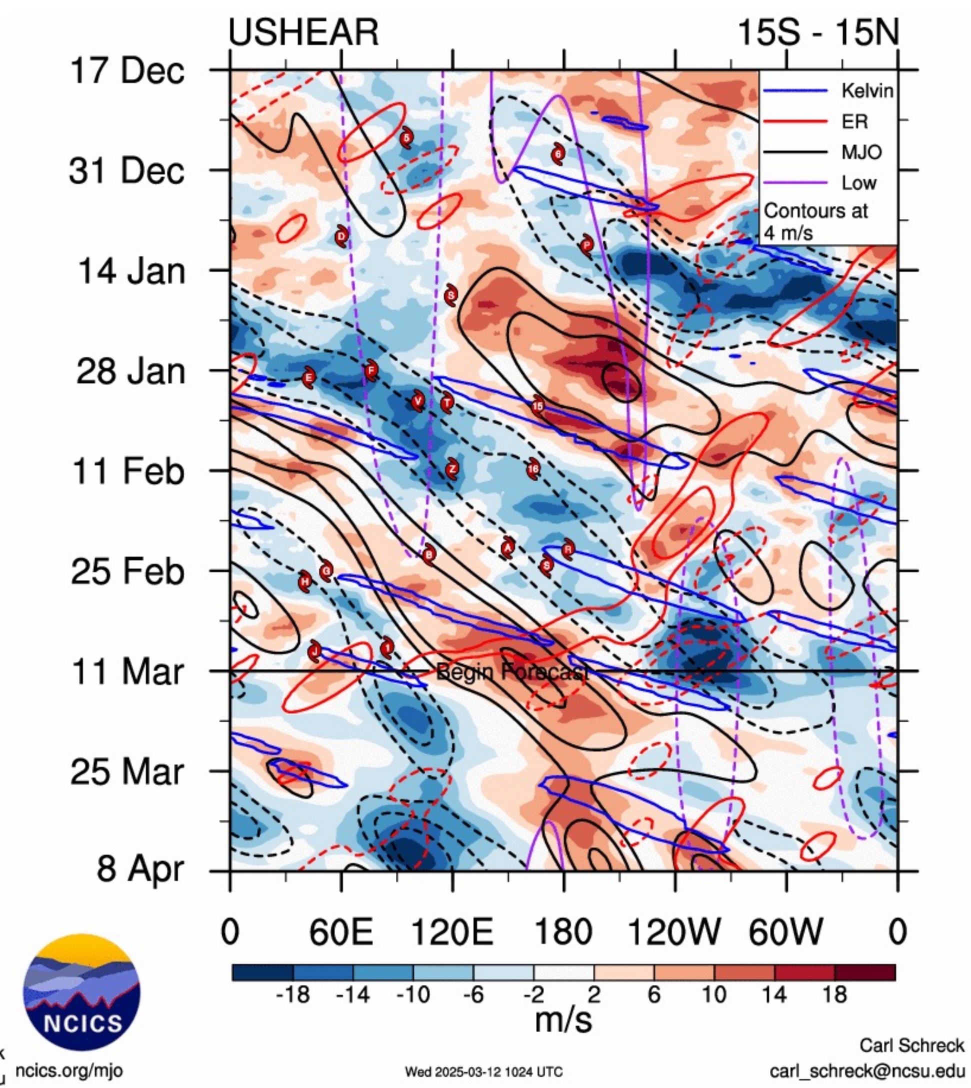
Saffir-Simpson Hurricane Wind Scale

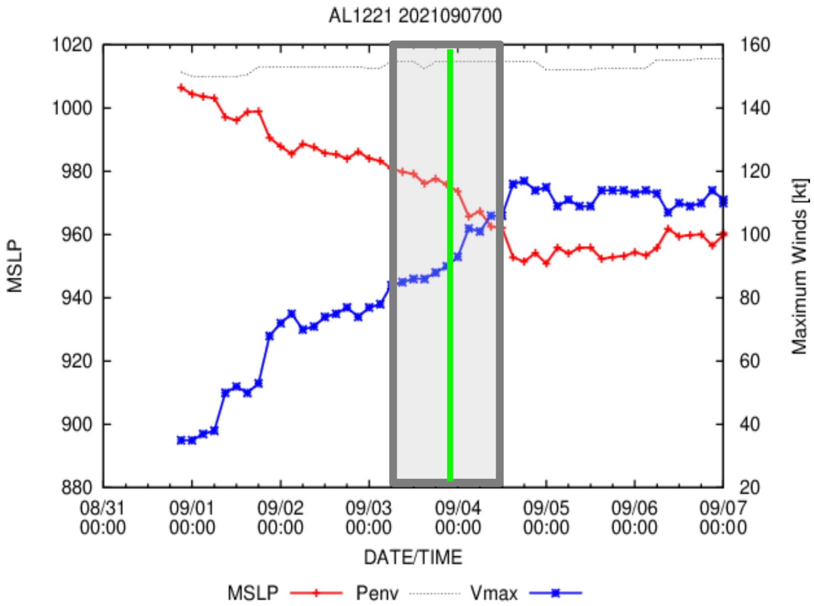
Intensity Missing
Tropical Depression
Tropical Storm
Category 1
Category 2
Category 3
Category 4
Category 5

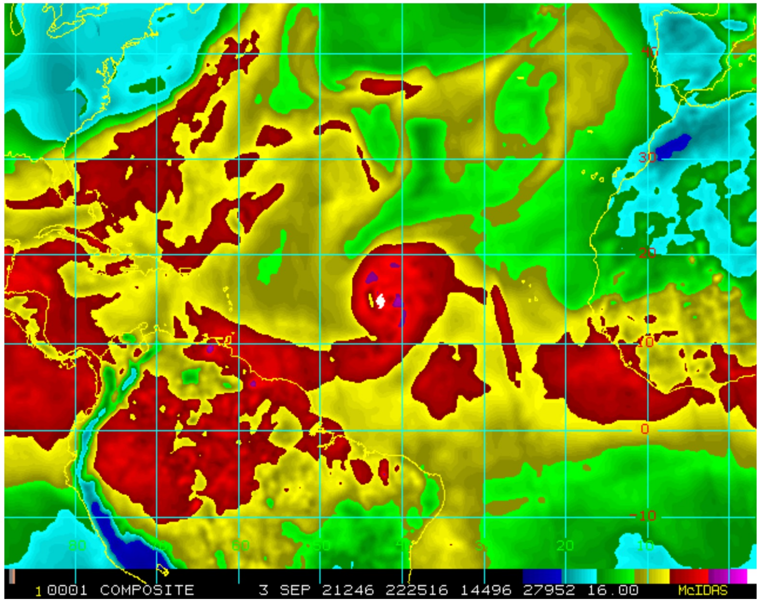
Necessary conditions for TC development:
Putting it all together with Carl's Hovmöllers!



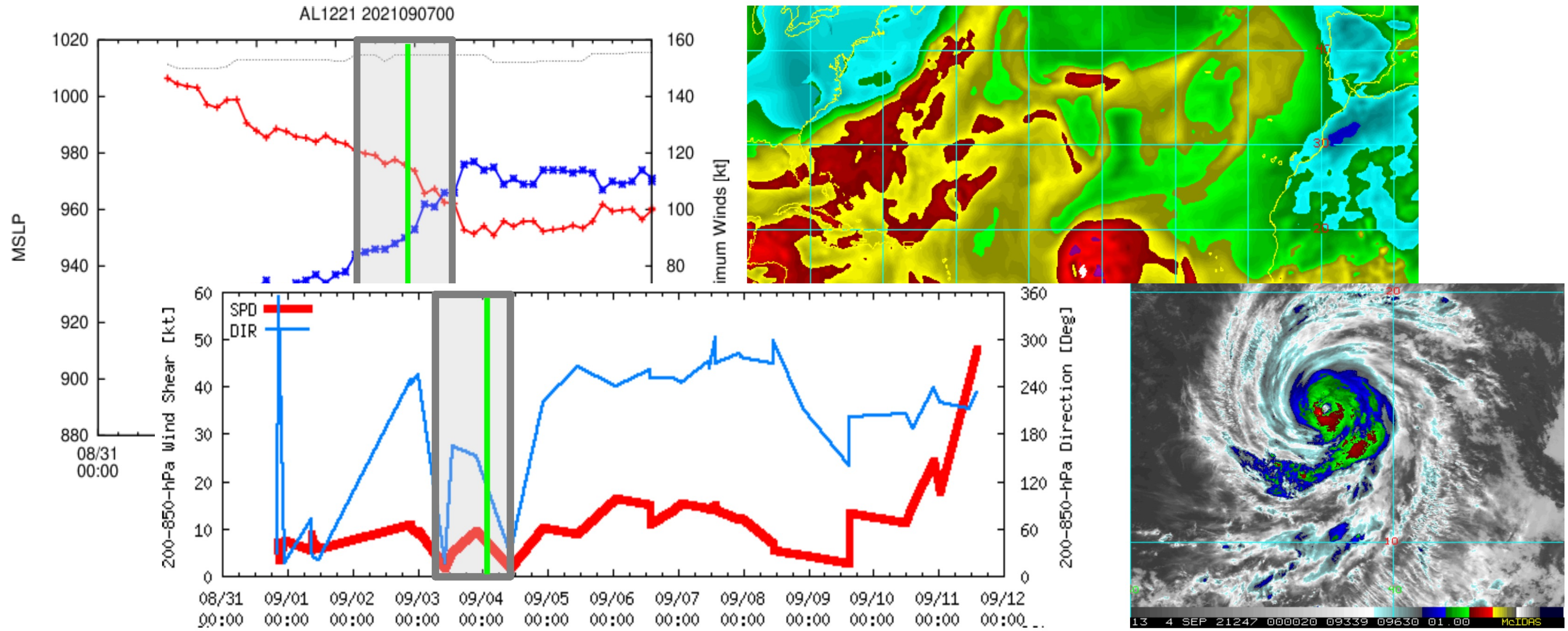


Necessary conditions for TC development:
Putting it all together with CIRA plots!

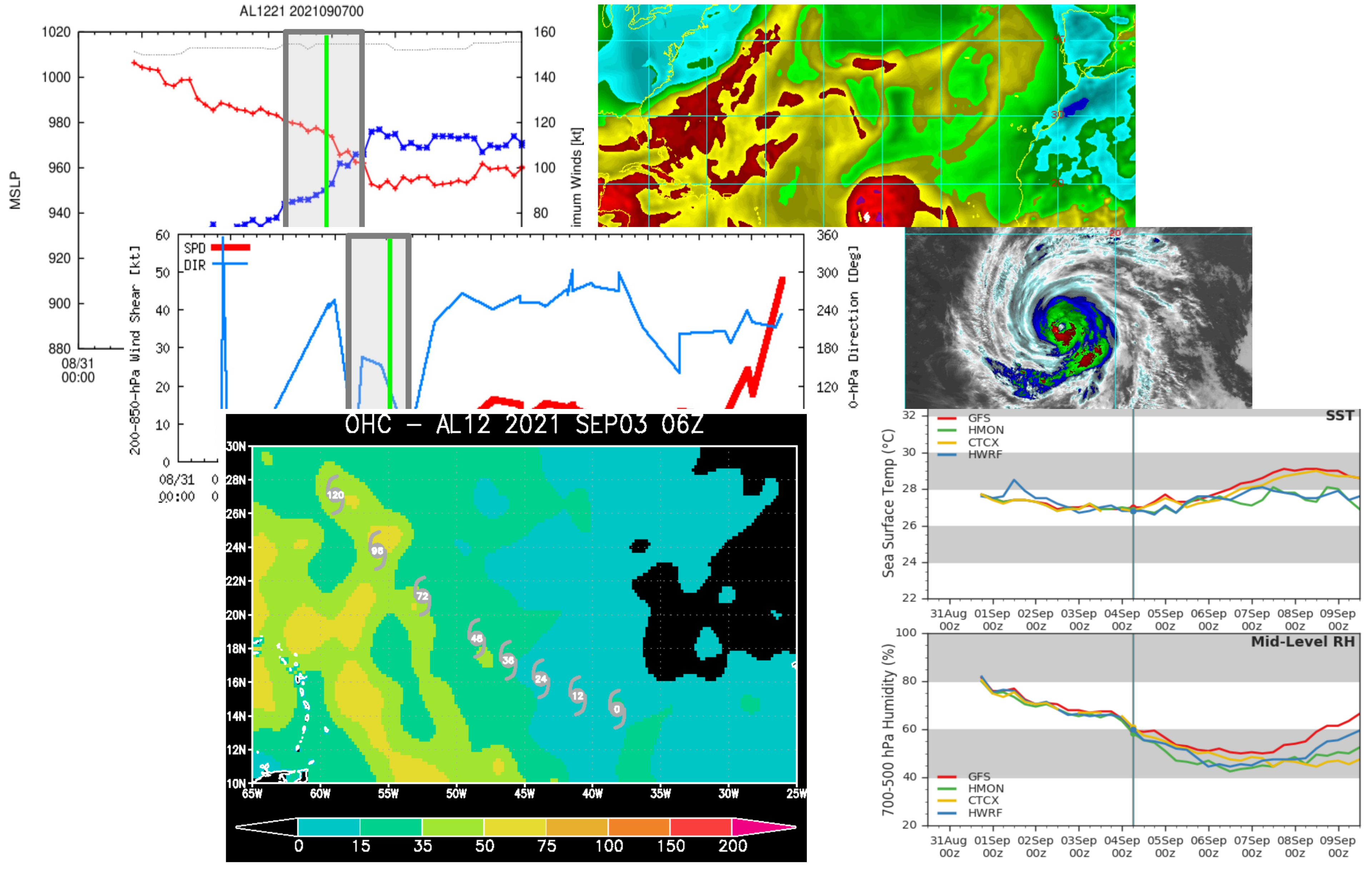




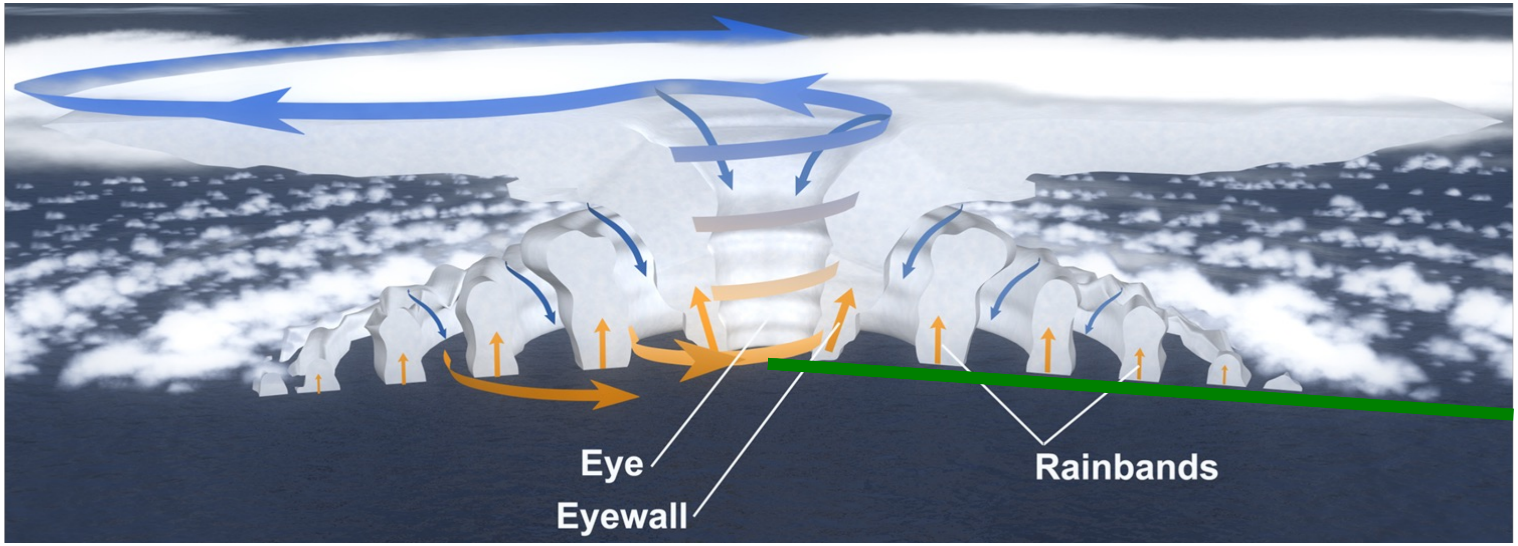
Necessary conditions for TC development:
Putting it all together with CIRA plots!

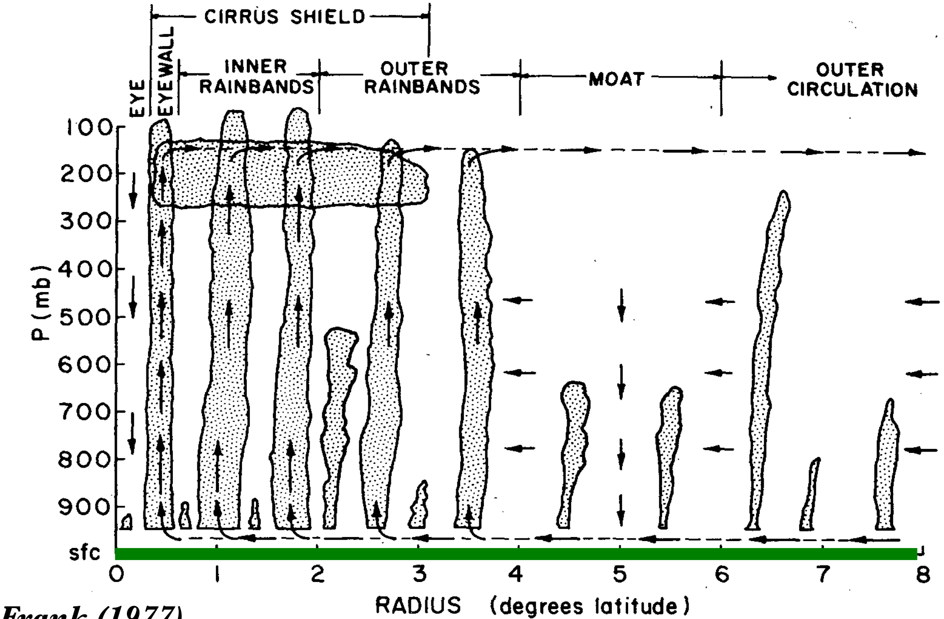


Necessary conditions for TC development:
Putting it all together with CIRA plots!



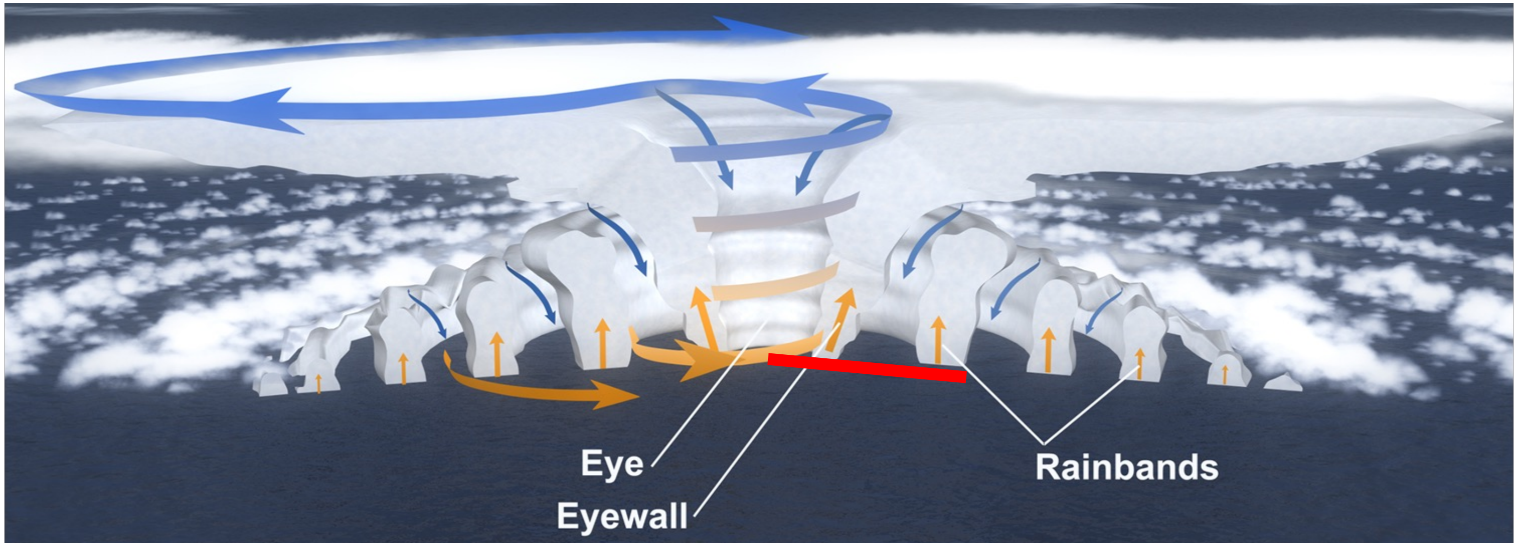
Tropical cyclone structure:
Primary and secondary circulations

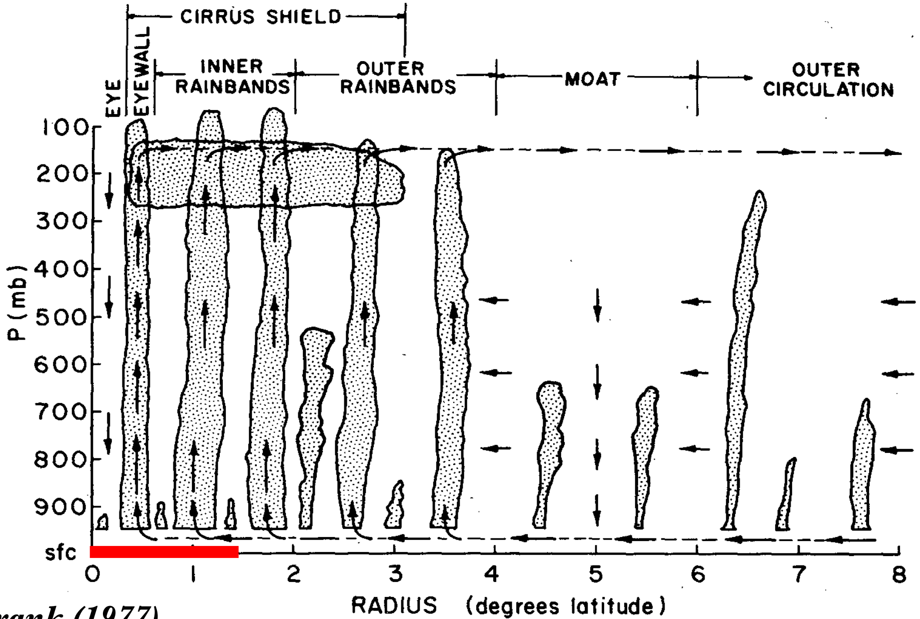




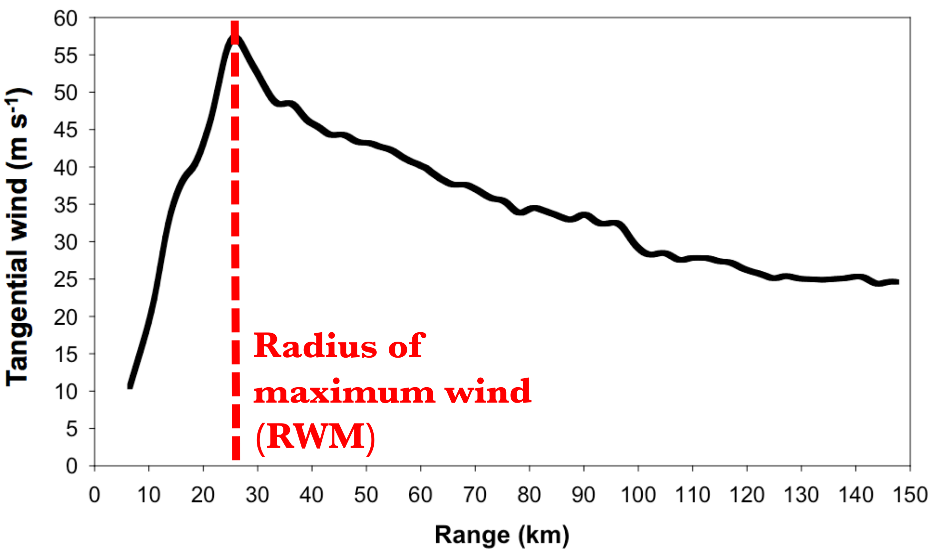
Frank (1977)

Tropical cyclone structure:
Primary and secondary circulations





Frank (1977)



Tropical cyclone structure:
Primary (tangential) circulation

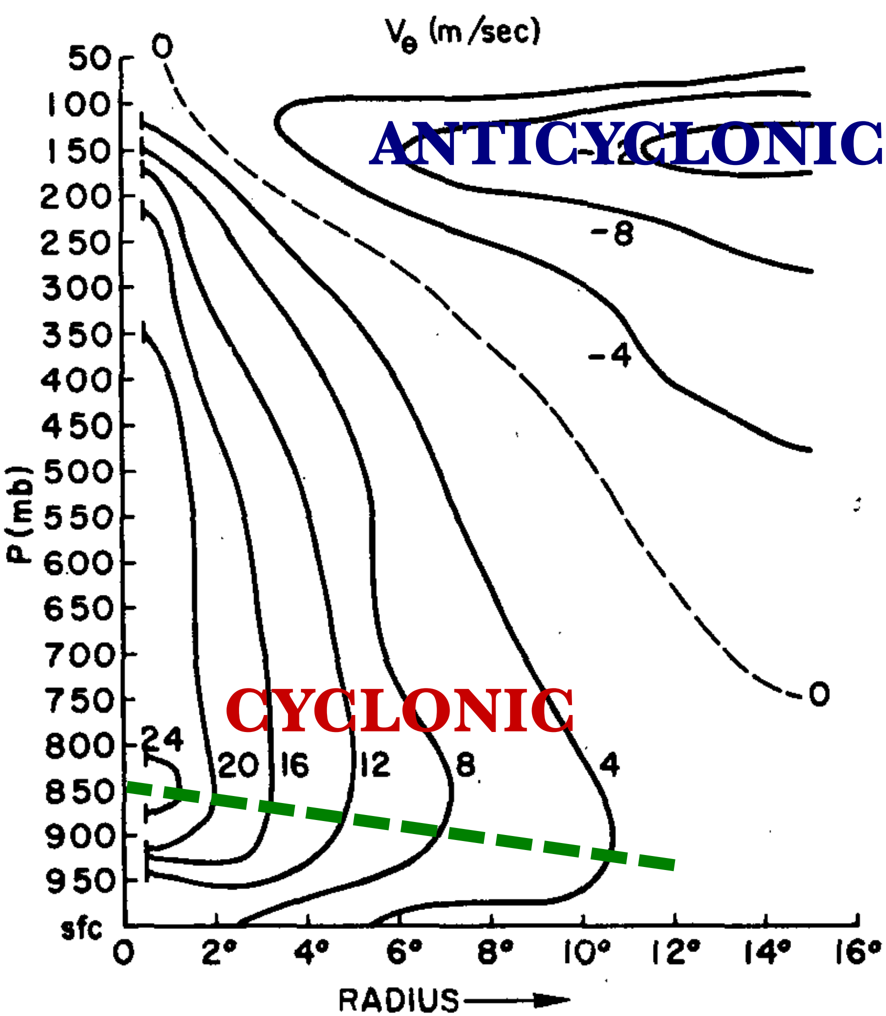


FIG. 9. Two-dimensional cross section of V_θ (m s^{-1}) in stationary (NAT) coordinates. Positive numbers denote cyclonic flow.

Frank (1977)

The **positive**, **cyclonic circulation** is **HUGE** (~10°), but **clouds** only extend out to a **radius** of ~3°–5°

Negative, **anticyclonic aloft** from 2° outward

Winds are **maximized** at the **top of the boundary layer**

Tropical cyclone structure:
Temperature anomaly

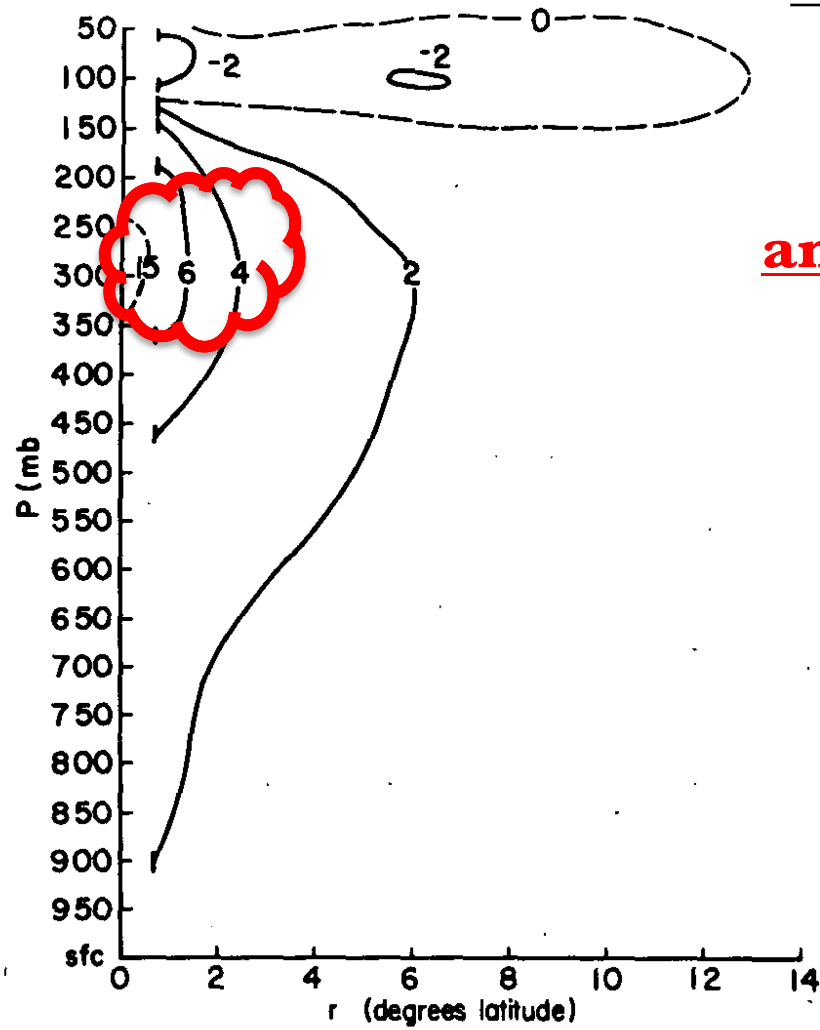
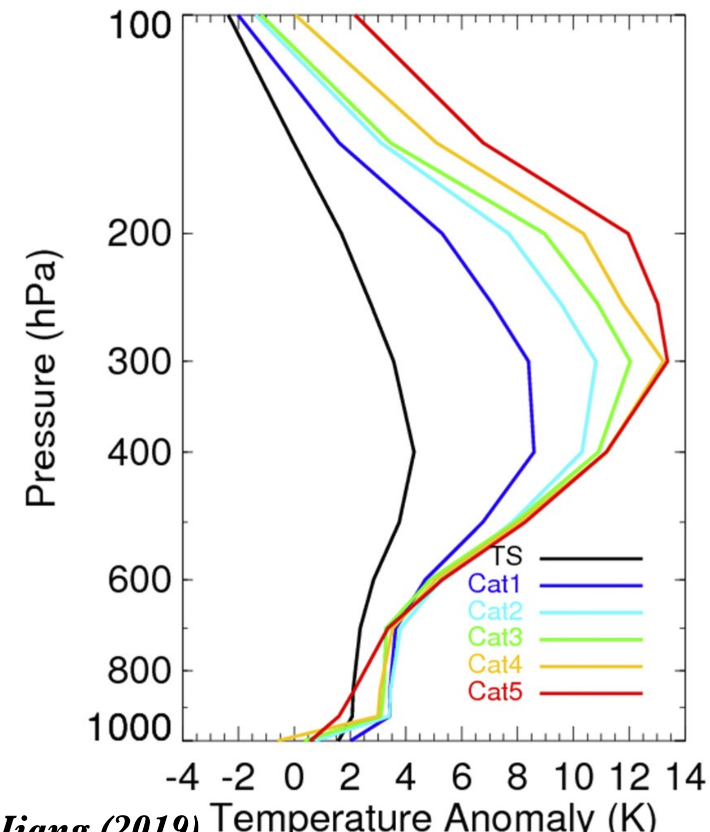


FIG. 3. Temperature anomaly $(T-\bar{T}_{r=14°})$ for mean steady-state typhoon. Units: °C.

Frank (1977)

<u>Latent heat release</u> makes tropical cyclones <u>WARM CORE</u>

The <u>maximum temperature anomaly</u> is in the <u>upper troposphere</u>



Wang & Jiang (2019)

Tropical cyclone structure:
Temperature anomaly: Warm core

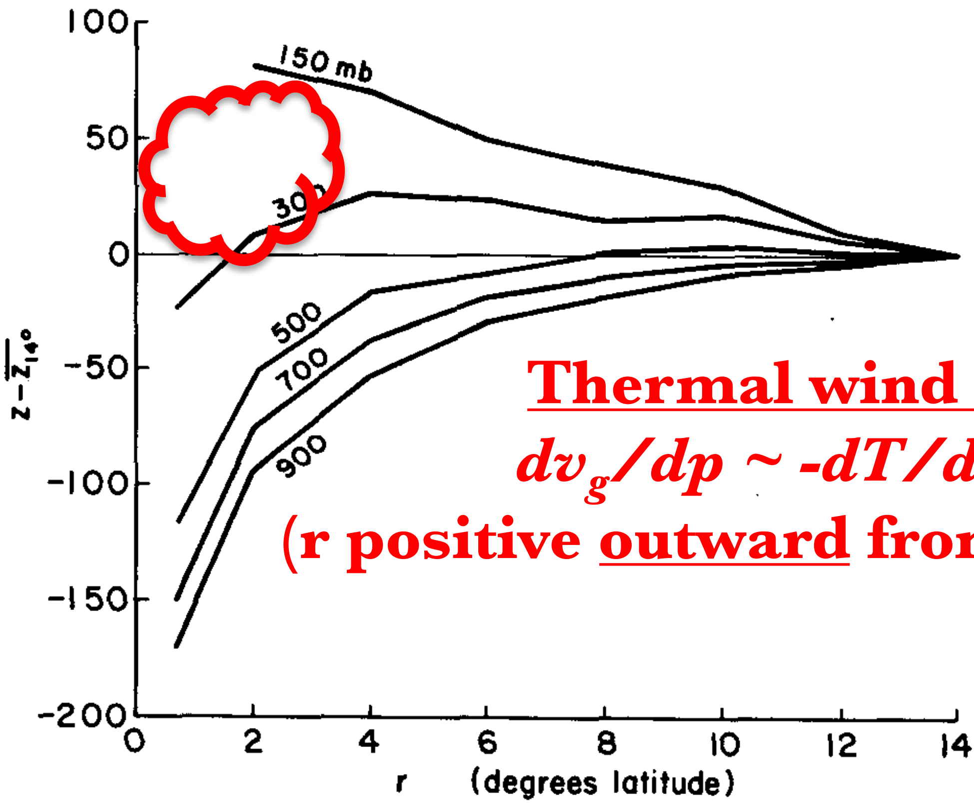


FIG. 4. D values ($Z-\bar{Z}_{r=14°}$) for mean steady-state typhoon at selected levels. Units: m.

Thermal wind :

$dv_g/dp \sim -dT/dr$

(r positive outward from center)

*** WARM CORE ***

A low pressure system with the strongest height gradients and, thus, winds, at low levels

Frank (1977)

Tropical cyclone structure:
Secondary (radial) circulation

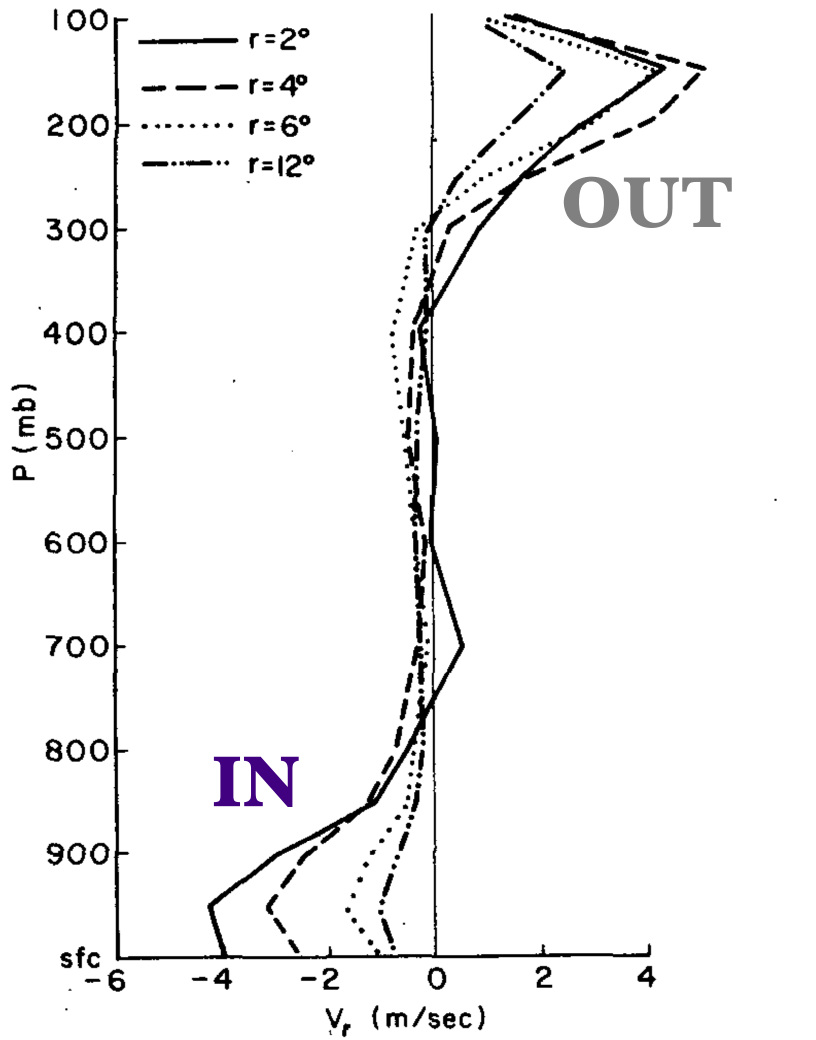


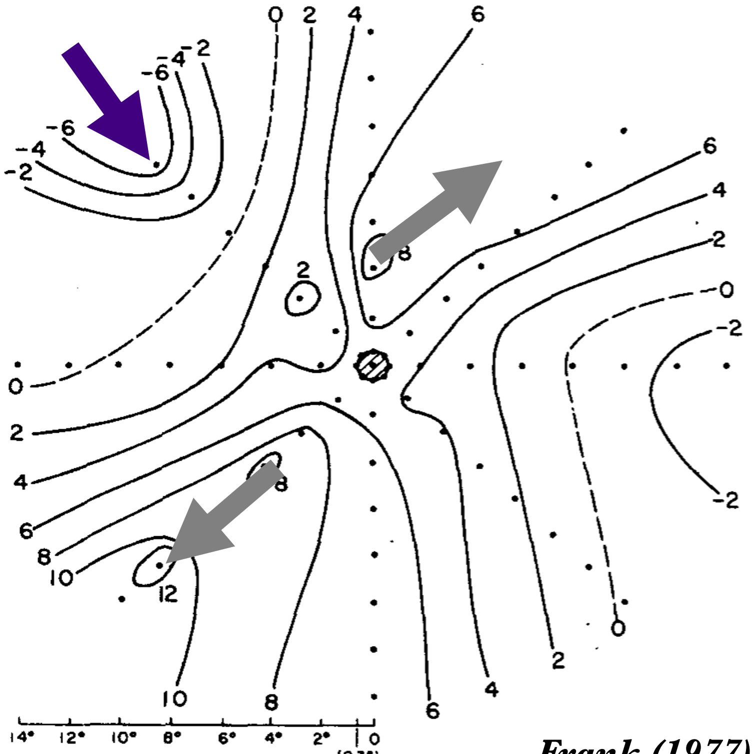
FIG. 12. Two-dimensional vertical profile of radial winds V_r (m s^{-1}) at $r = 2°$, 4°, 6° and 12°.

Frank (1977)

The maximum radial INFLOW occurs at ~950 hPa inside a radius of 2° from the center

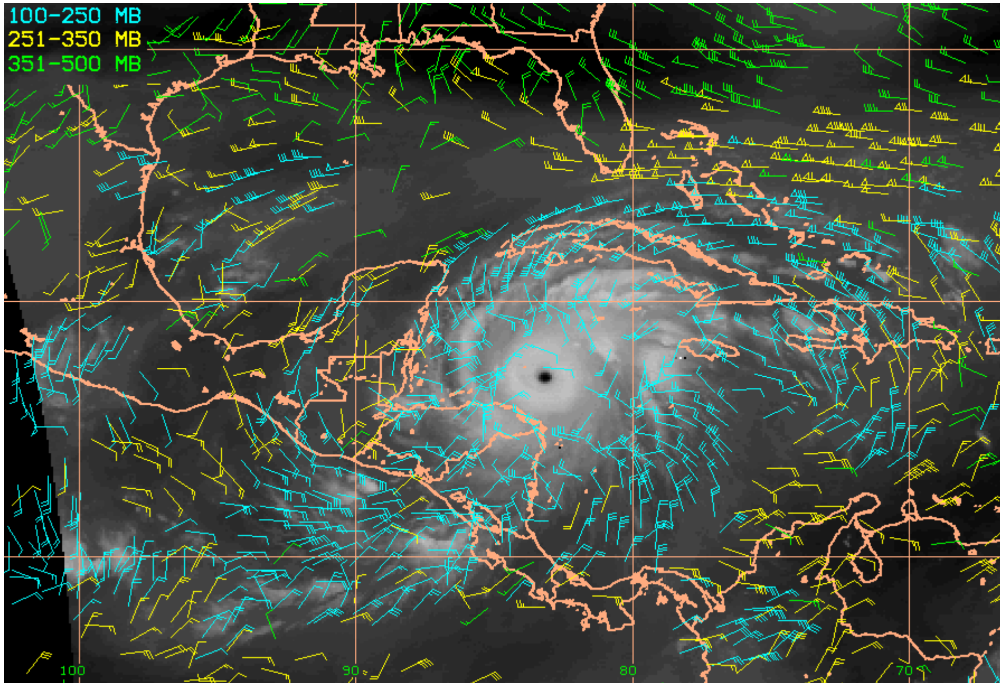
The maximum OUTFLOW occurs at 150 hPa at 4° from the center

Tropical cyclone structure:
Outflow jets



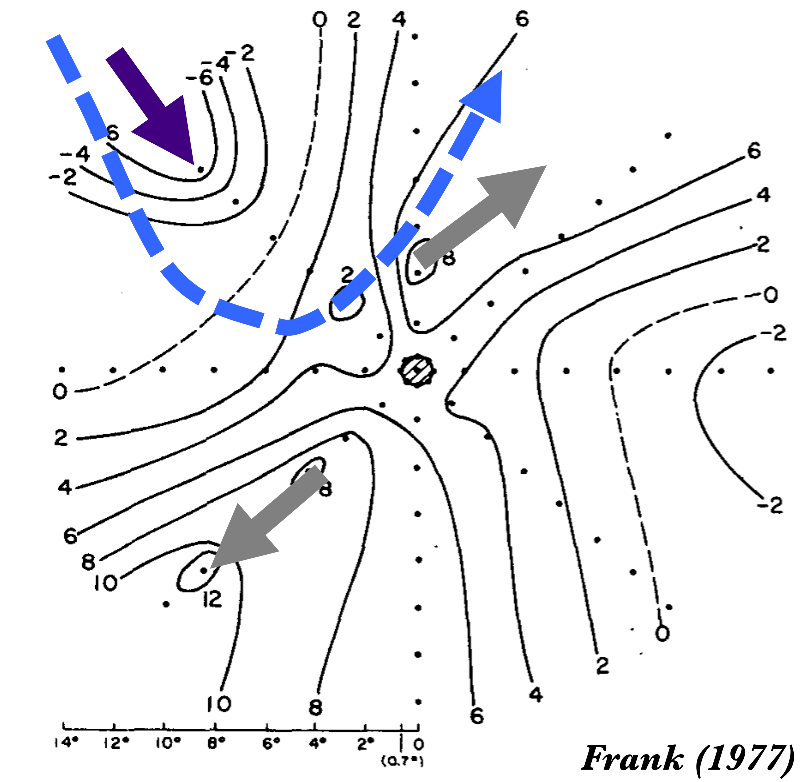
Frank (1977)

FIG. 15. Plan view of V_r (m s^{-1}) in NAT coordinates at 150 mb.



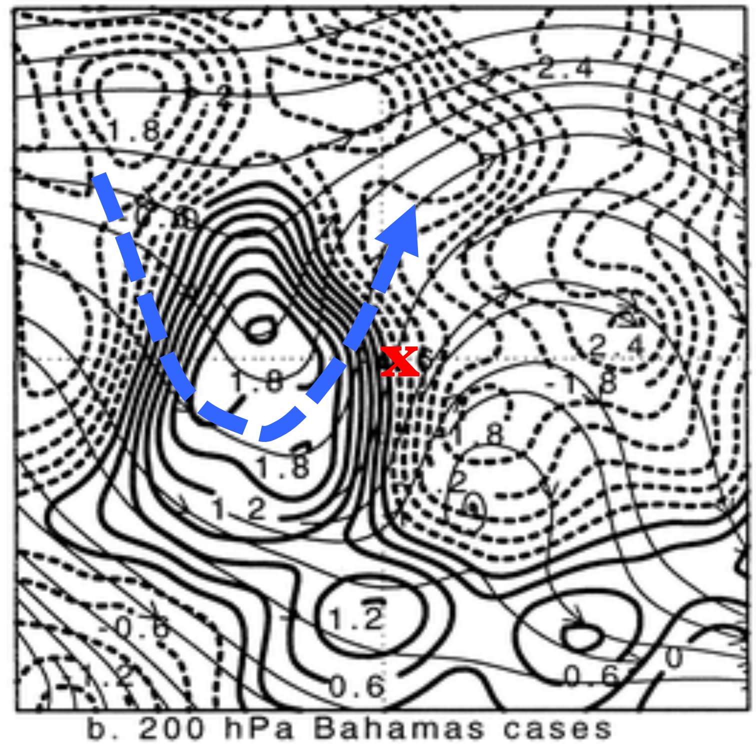
The upper-level OUTFLOW is concentrated in jets northeast and southwest of the center.

Tropical cyclone structure:
Outflow jets



Frank (1977)

FIG. 15. Plan view of V_r (m s^{-1}) in NAT coordinates at 150 mb.



Bracken and Bosart (2000)

The upper-level OUTFLOW is concentrated in jets northeast and southwest of the center.

In the composite, there is also evidence of a trough to the northwest of the TC like in Bracken and Bosart (2000).

Tropical cyclone structure:
Convergence and divergence

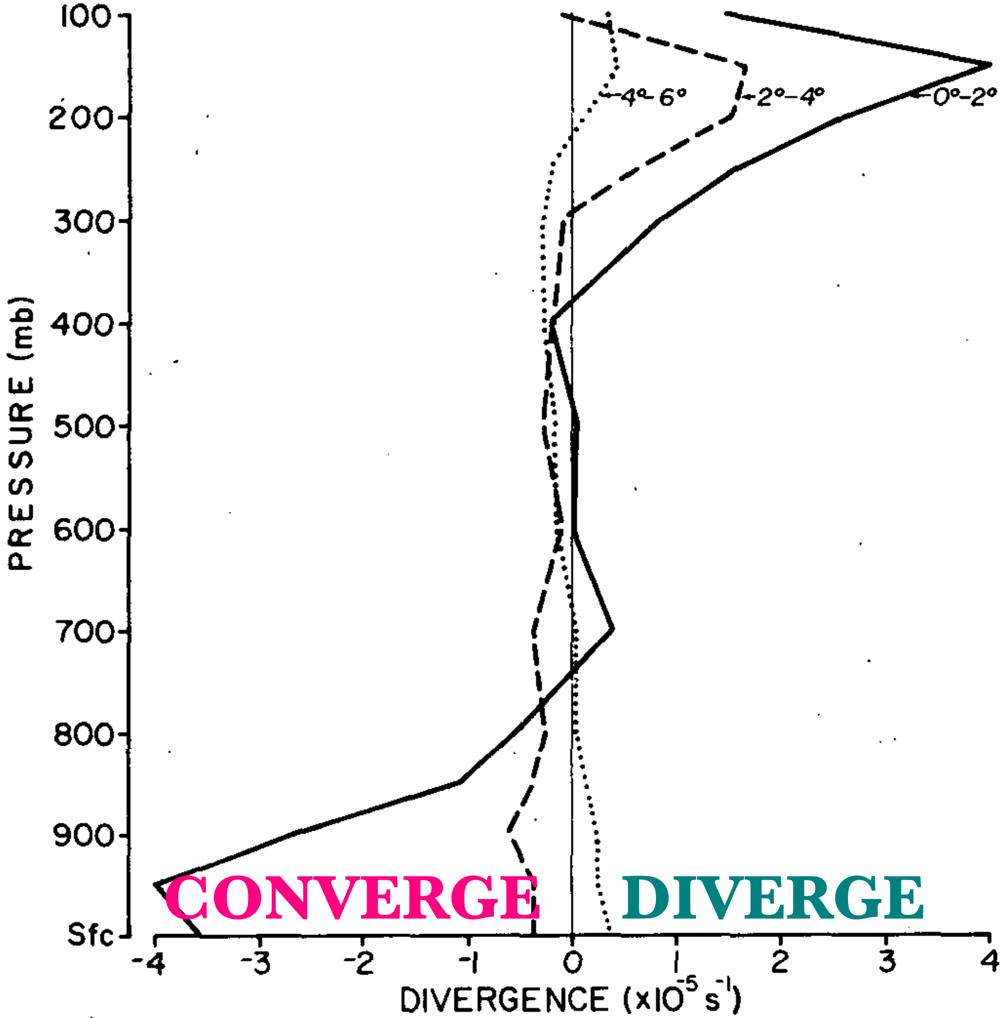


FIG. 18. Divergence for mean steady-state typhoon for the 0–2°, 2–4° and 4–6° regions.

Frank (1977)

Strong convergence is confined to the lowest levels and inner most radii

The 4°–6° ring shows convergence over divergence indicative of subsidence

Tropical cyclone structure:
Vertical motion

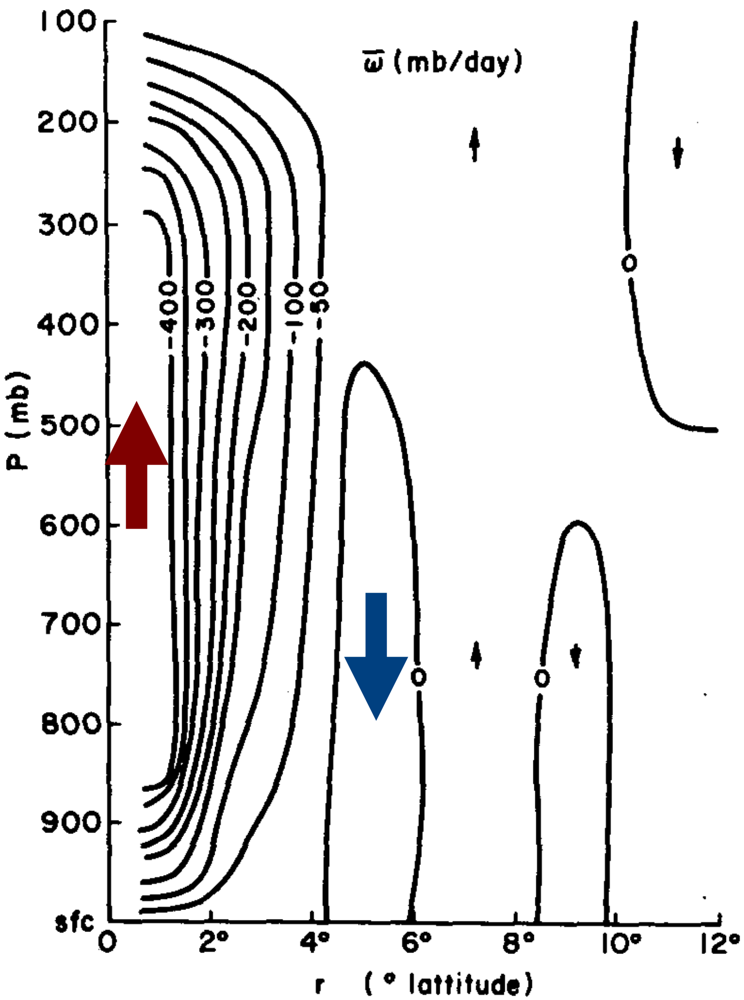


FIG. 19. Vertical motion (mb day^{-1}) from 0.7–12° for mean steady-state typhoon.

Frank (1977)

Weak SUBSIDENCE occurs 4°–6° from the center, at the edge of the cirrus cloud shield

Mean UPWARD motion is observed inside 4° through the depth of the troposphere