

# **Tropical Cyclone Formation in Wind Shear: Climatological Relationships and Physical Processes**

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# Background

- Early studies of TC climatology identified the vertical shear of the horizontal wind as a consistently negative factor for TC formation (e.g., Gray 1968, 1975).

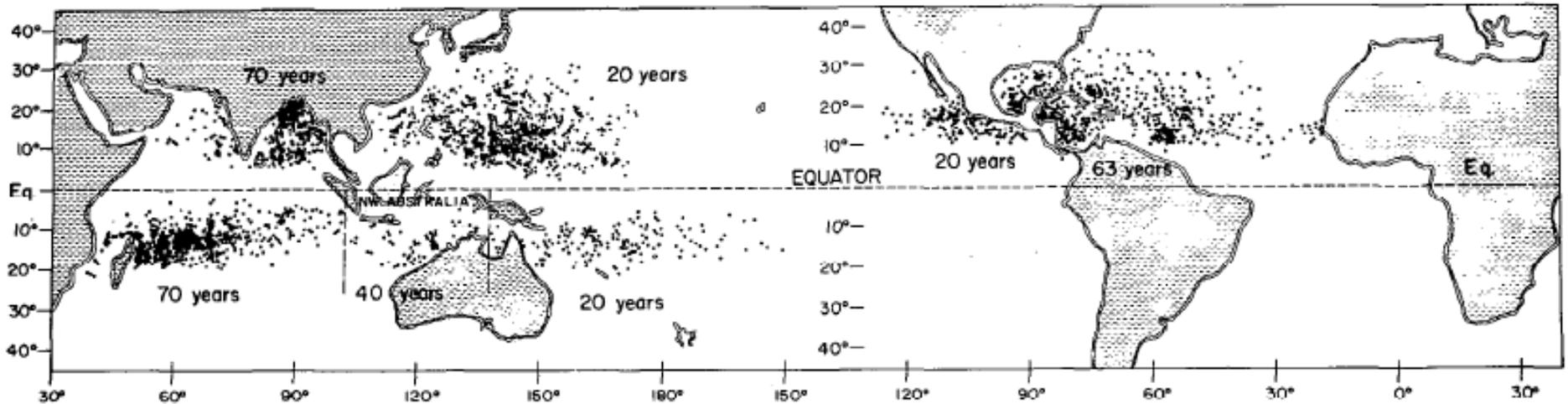


FIGURE 1.—Location points of first detection of disturbances which later became tropical storms.

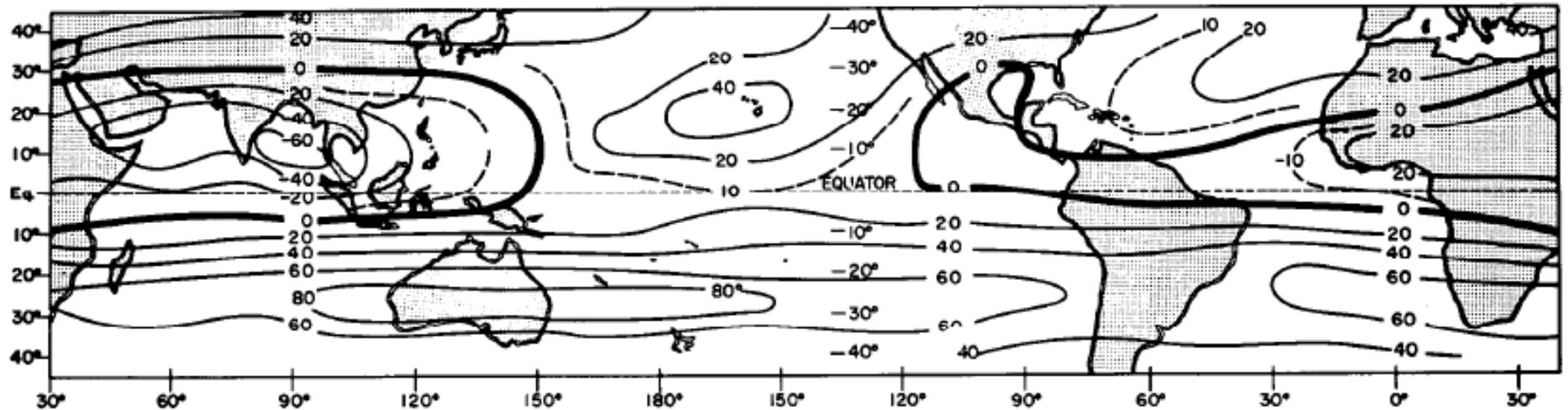
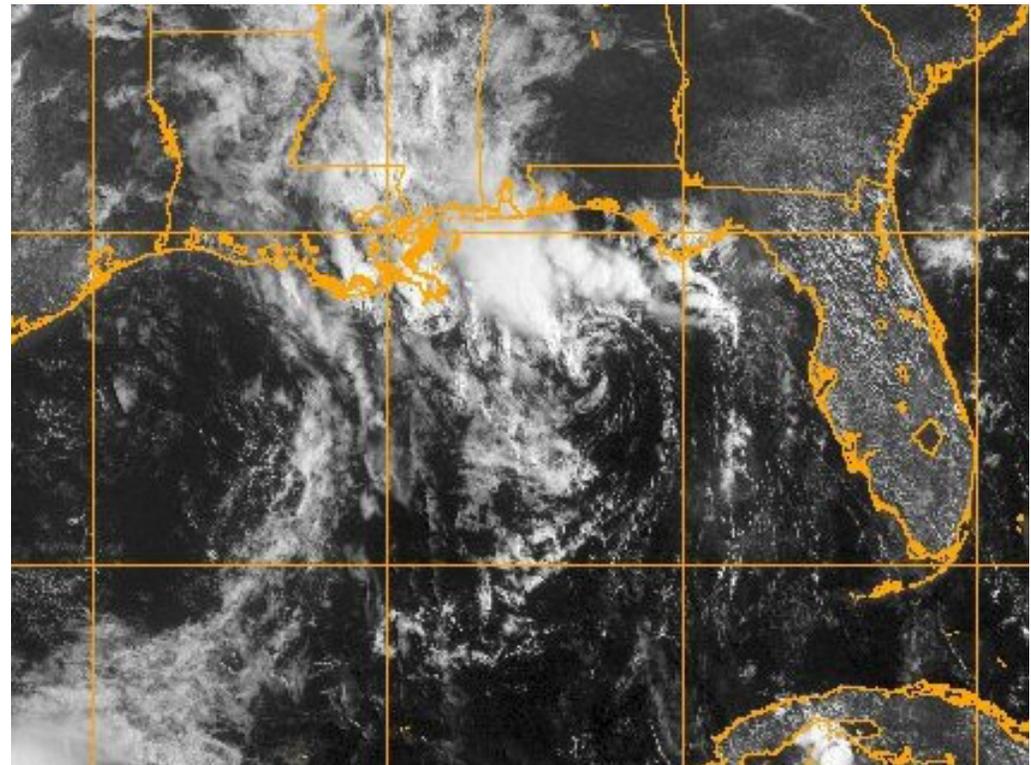
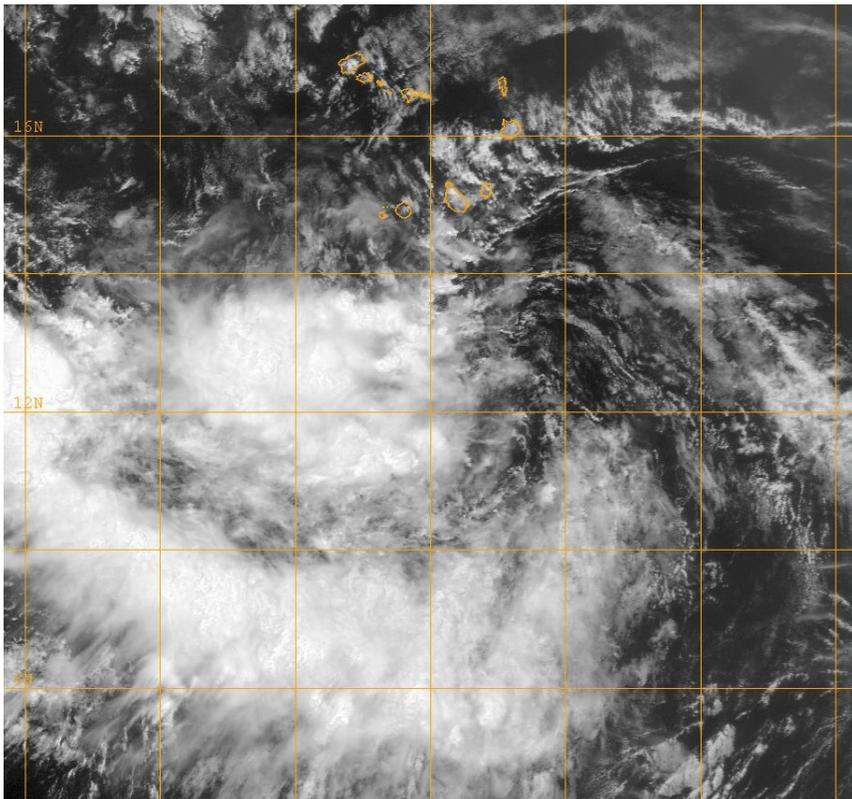


FIGURE 25.—Climatological average for August of the zonal vertical wind shear between 200 mb. and 850 mb. Positive values indicate the zonal wind at 200 mb. is stronger from the west or weaker from the east than zonal wind at 850 mb. Units are in knots (from U.S. Air Force data tapes, 1963).

- According to Gray (1968):

“Large vertical wind shears do not allow for area concentration of tropospheric distributed cumulonimbus condensation. Large shears produce a large ventilation of heat away from the developing disturbance. The condensation heat released by the cumulus to the upper troposphere is advected in a different direction relative to the released heat at lower levels. Concentration of heat through the entire troposphere becomes more difficult.”



- The composite wind fields of McBride and Zehr (1981) showed an axis of zero shear crossing near the center of “developing” disturbances.

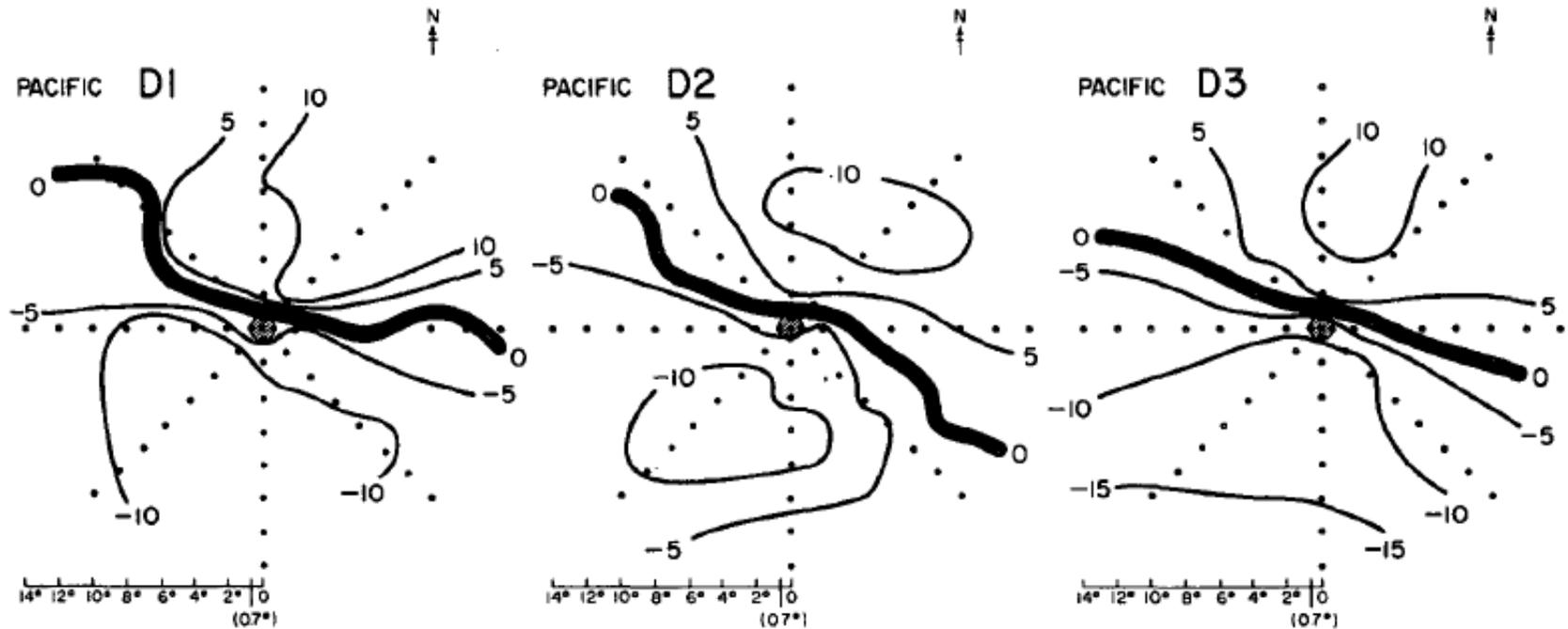
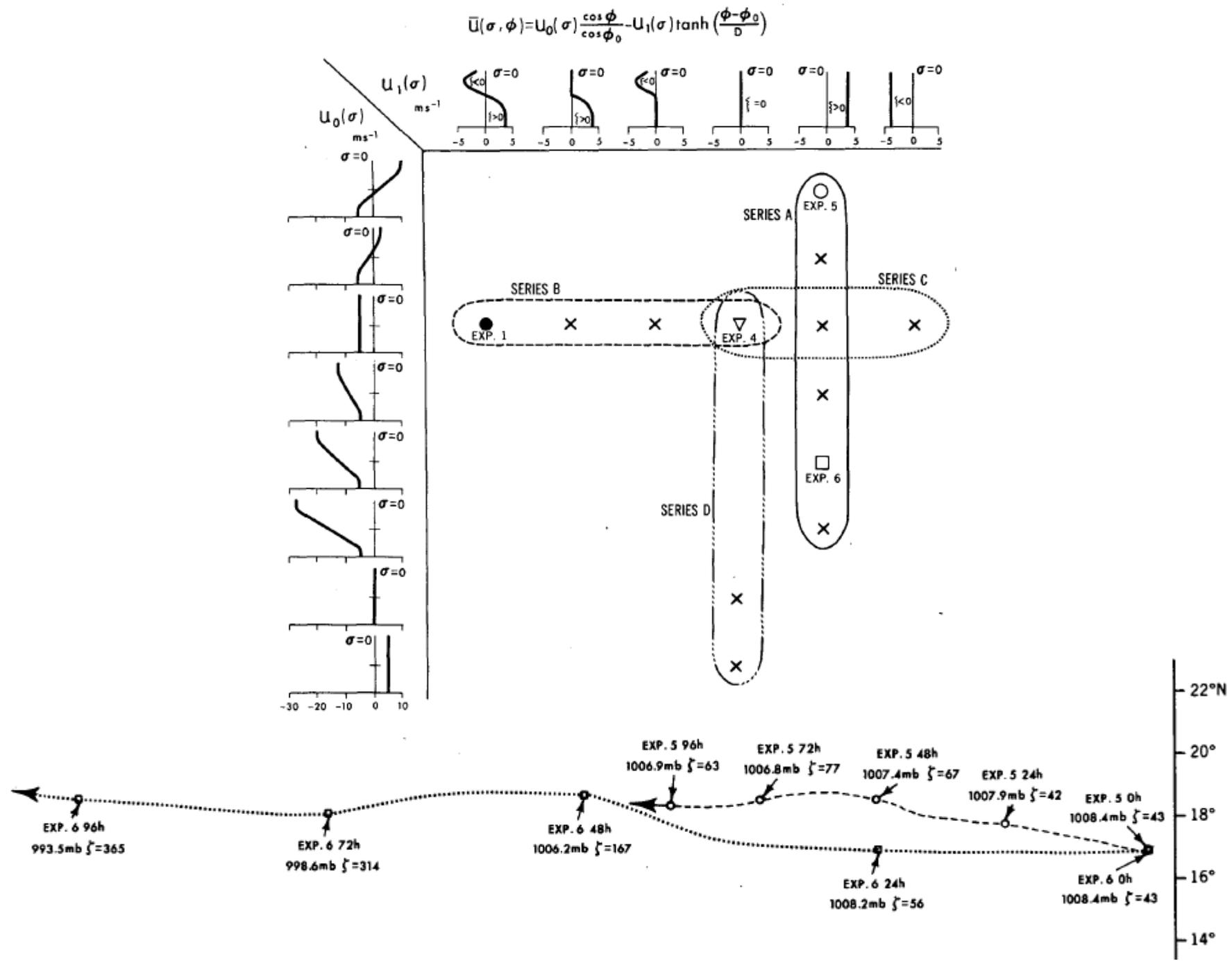


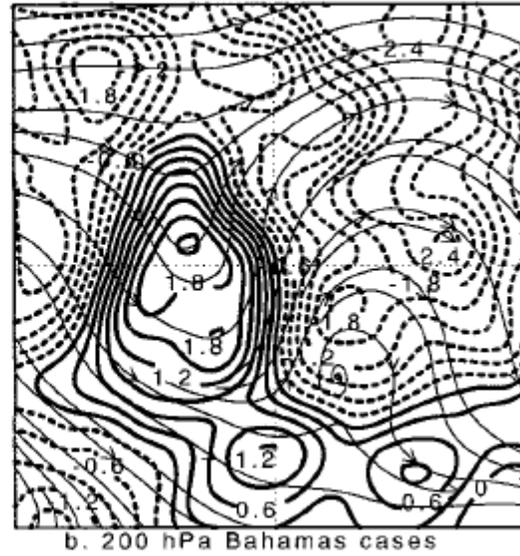
FIG. 18. Plan views of zonal shear,  $U_{200\text{ mb}} - U_{900\text{ mb}}$  ( $\text{m s}^{-1}$ ) for the Pacific data sets.

Until the 1990s, it was generally believed that very low shear was the most favorable state for TC genesis.

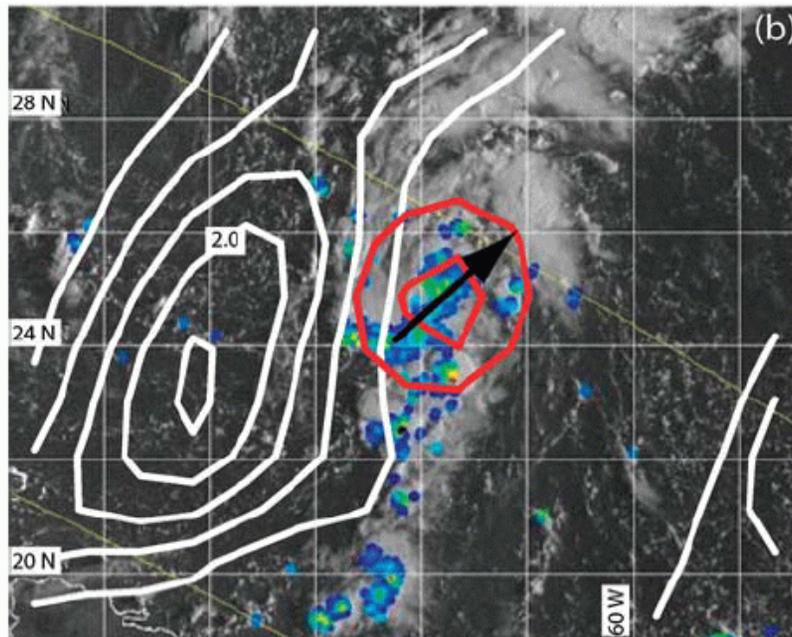
• In addition, a numerical modeling study by Tuleya and Kurihara (1981) suggested that easterly shear was more favorable than westerly shear.



- Since 1990, a substantive body of work has argued that wind shear *can promote* TC genesis in some cases, through large-scale ascent forced by the advection of upper-level vorticity:

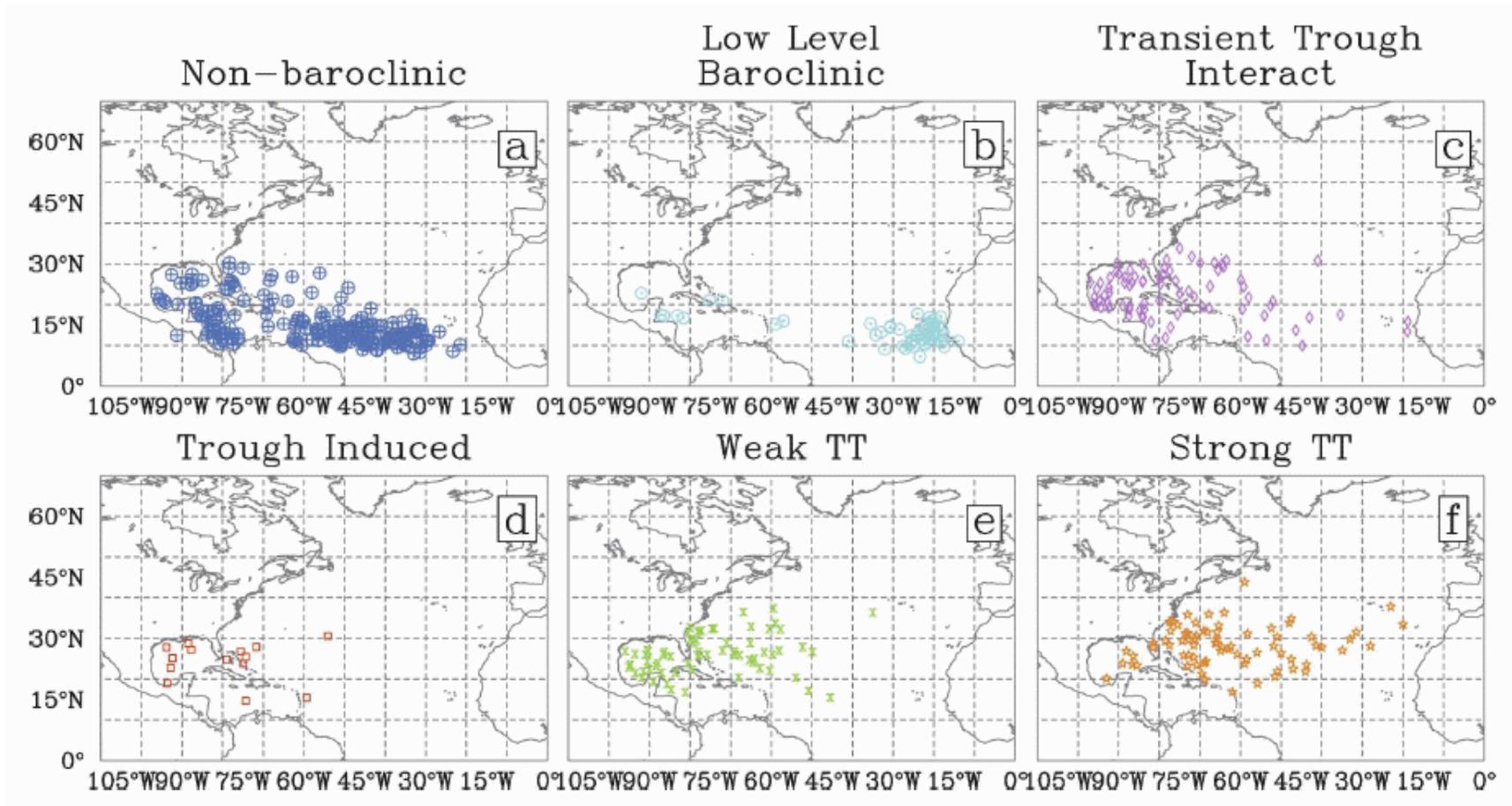


Bracken and Bosart (2000)  
genesis cases composite



Davis and Bosart (2004)  
“Tropical Transition”  
to become Hurricane Michael (2000)

- There are many cases of TC genesis that appear to be caused, or accelerated, by moderate wind shear, as documented below by McTaggart-Cowan et al. (2008):



- However, almost all of these cases are also associated with synoptic-scale, baroclinic forcing by the advection of upper-level troughs.

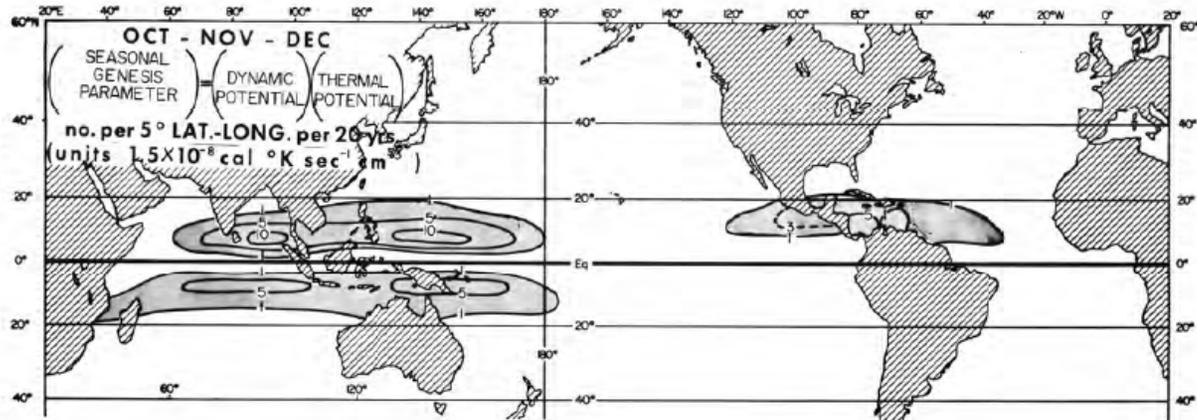
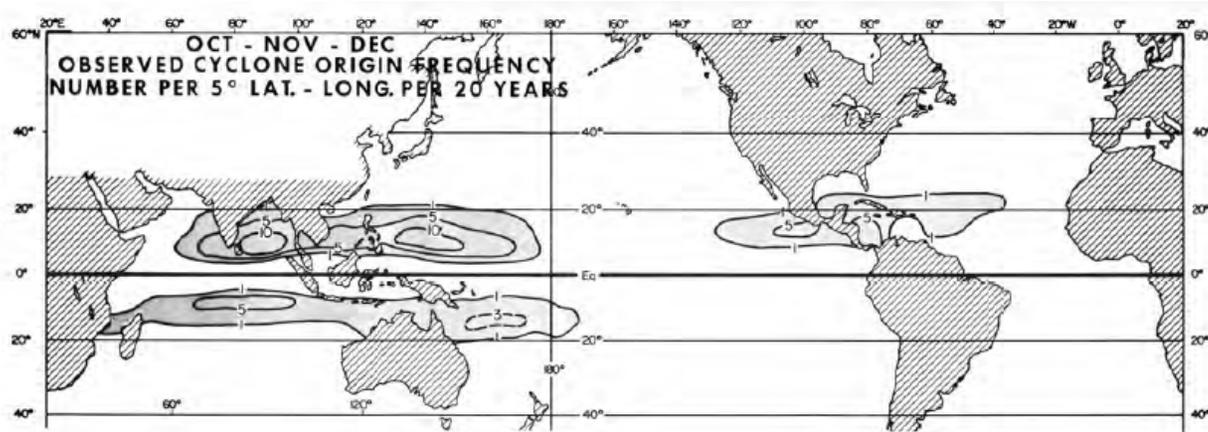
For today, we will focus on shear *without* baroclinic forcing.

## Some Open Questions...

- I. Is “some wind shear” more or less favorable for TC formation than no wind shear at all?
  
- II. Is easterly shear more or less favorable than westerly shear?
  
- III. Is TC genesis a different process in moderate shear?

## Empirical Analysis: Genesis Parameters

- “Genesis parameters” are an attempt to correlate large-scale, environmental variables with the seasonal frequency of TC formation, e.g., Gray (1975):



$$GP = \left\{ f \times (\zeta + 5) \times \left( \left| \frac{\delta V}{\delta p} \right| + 3 \right)^{-1} \right\} \times \left\{ E_{Ocean} \times \left( \frac{\partial \theta_e}{\partial p} + 5 \right) \times \max \left[ \frac{RH - 40}{30}, 1 \right] \right\}$$

- Since then, a number of other genesis parameters have been developed, e.g.,

Emanuel and Nolan (2004):

$$GP_{EN} = |10^5 \eta|^{3/2} \left(\frac{RH}{50}\right)^3 \left(\frac{V_{pot}}{70}\right)^3 (1 + 0.1 \times V_{shear})^{-2}$$

Emanuel (2010):

$$GP_{E10} = |\eta|^3 \chi^{-4/3} \{\max[(V_{pot} - 35)^2, 0]\} (25 + V_{shear})^{-4}$$

Tippet et al. (2011):

$$GP_T = \exp(b + b_\eta \eta + b_{RH} RH + b_{SST} SST + b_{shear} V_{shear} + \log \cos \phi)$$

Each genesis parameter has its own representation of the effect of wind shear on the frequency of TC formation.

- To compare them, we have to normalize each to maximum value of 1.0.

Gray (1975):

$$S = \frac{1}{S_z + 3} \quad \text{normalized} \rightarrow S_G = \frac{1}{1.0 + 0.385 \times V_{\text{shear}}} \quad (V_{\text{shear}} = 850 \text{ to } 200)$$

Emanuel and Nolan (2004):

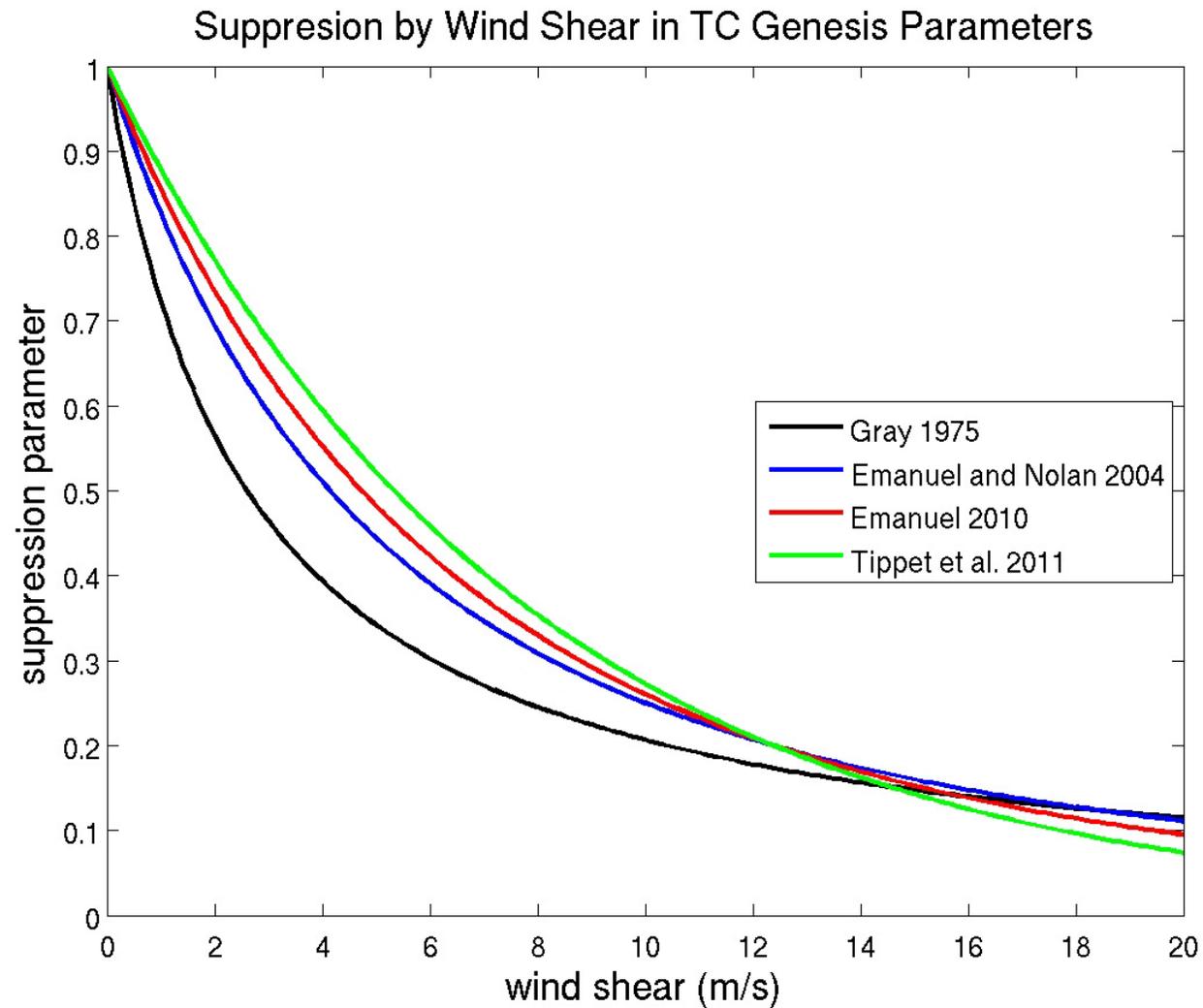
$$S_{\text{EN}} = \frac{1}{(1.0 + 0.1 \times V_{\text{shear}})^2}$$

Emanuel (2010):

$$S = \frac{1}{(25.0 + V_{\text{shear}})^4} \quad \text{normalized} \rightarrow S_{\text{E10}} = \frac{1}{(1.0 + 0.04 \times V_{\text{shear}})^4}$$

Tippett et al. (2011):

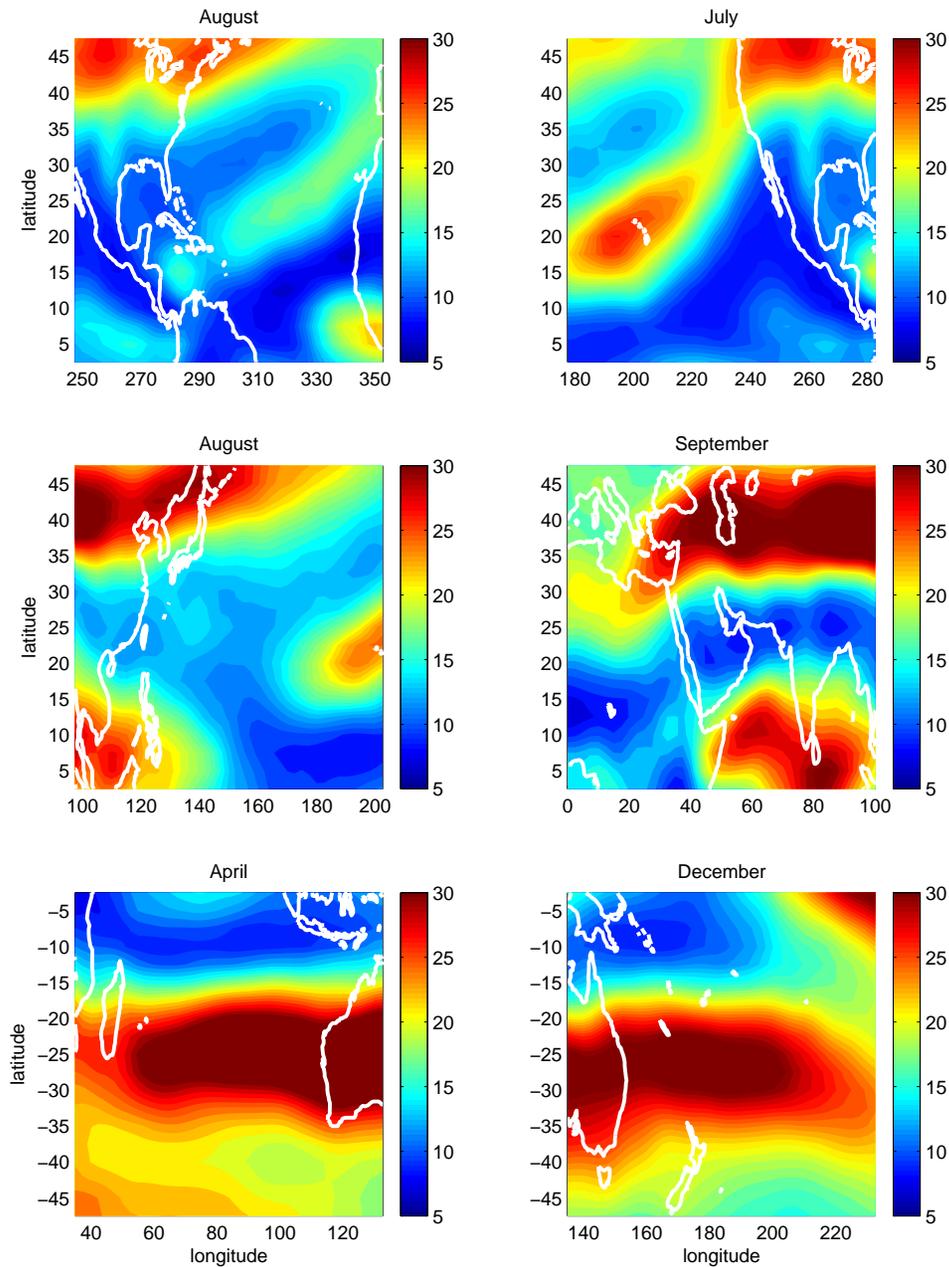
$$S_T = \exp(b_V V_{\text{shear}})$$



- They all indicate a strong maximum for genesis as shear goes to zero.

But this is deceiving...because these were designed on *seasonal* values.

In fact, the lowest local monthly shear values are all  $> 6$  m/s.



An example of a shear frequency distribution

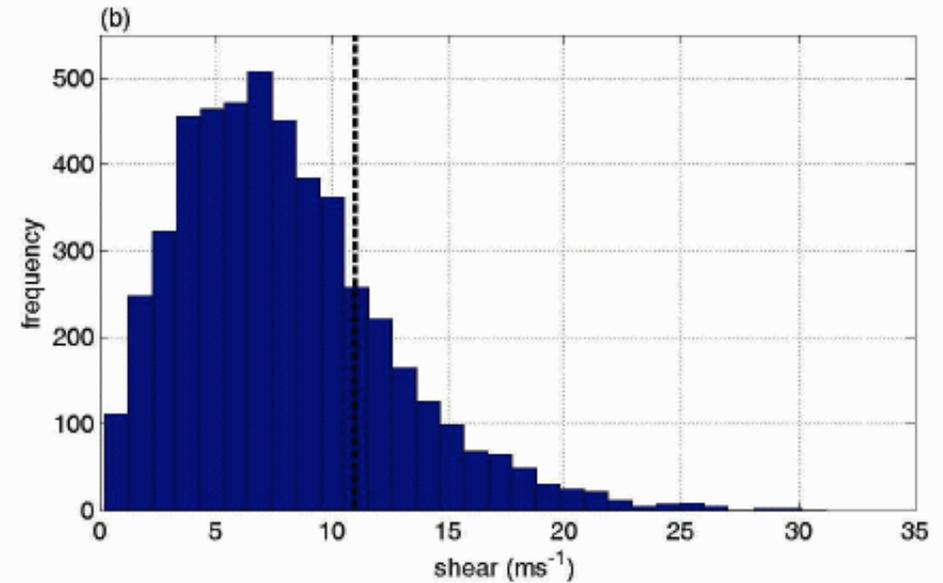
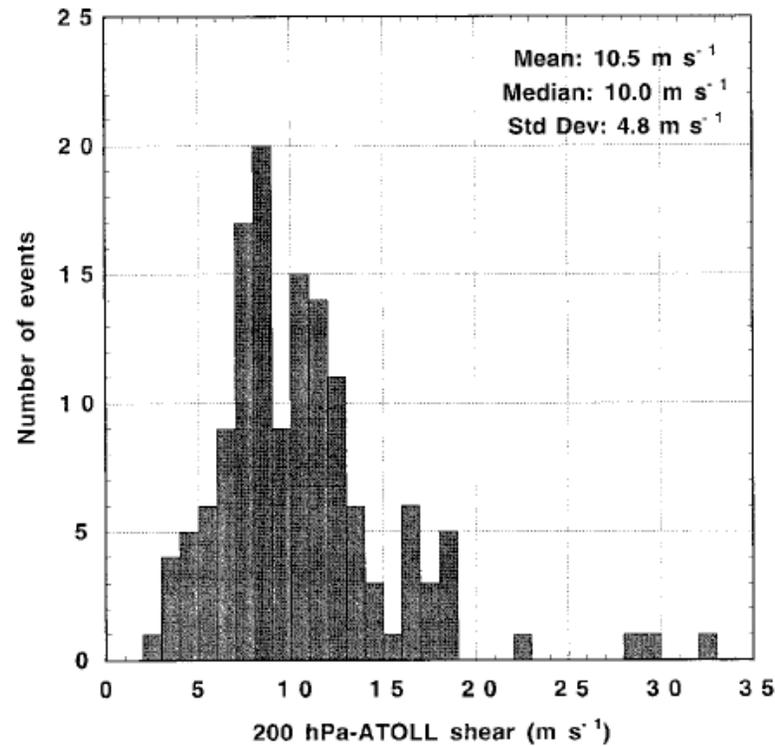


Fig. 26: July vertical wind shear distribution, 1969-2008. Coordinates centered at (a) Latitude  $15.0^{\circ}\text{N}$ , Longitude  $75.0^{\circ}\text{W}$ , mean shear value of  $17.0 \text{ ms}^{-1}$ ; (b) Latitude  $12.5^{\circ}\text{N}$ , Longitude  $45.0^{\circ}\text{W}$ , mean shear value of  $7.9 \text{ ms}^{-1}$ . Vertical dashed line at  $11 \text{ ms}^{-1}$  represents a shear threshold value.

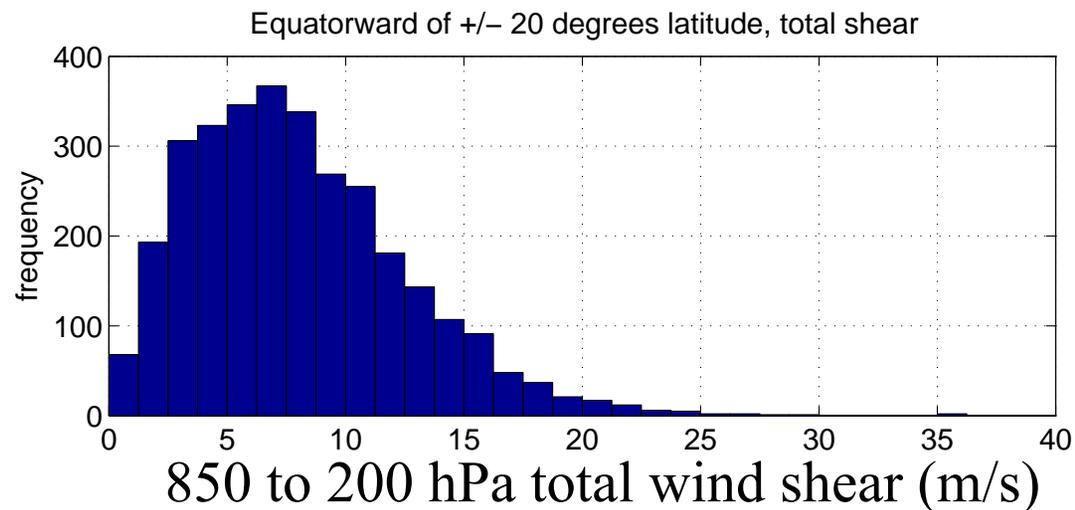
- A lower mean shear value means that even *lower* shear values will occur more frequently.

# Analyzed Wind Shear Around Individual TC Genesis Events

Bracken and  
Bosart (2000),  
Atlantic depressions  
1975-1993

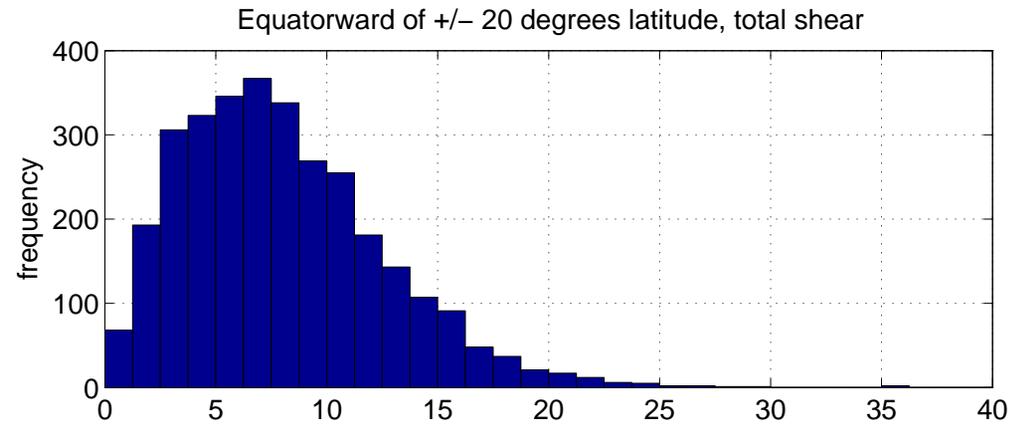


IBTRaCS  
plus  
NCEP/NCAR  
Reanalyses  
1969-2008,  
Lat < 20

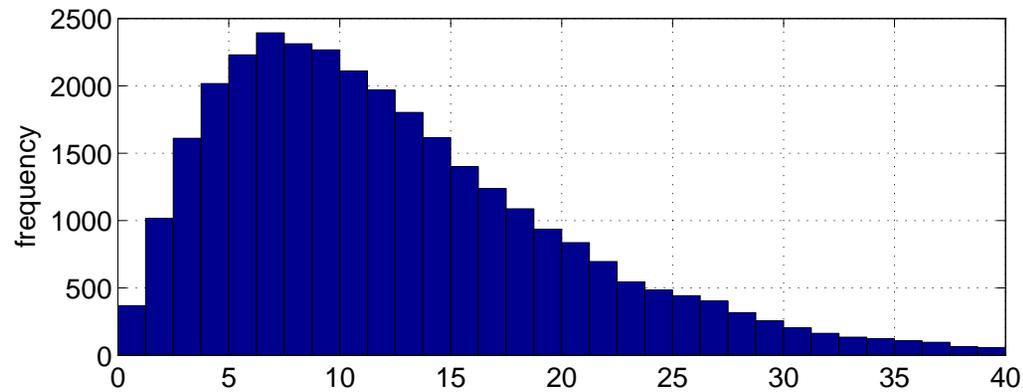


# Is 7 m/s of shear really the most favorable for TC genesis?

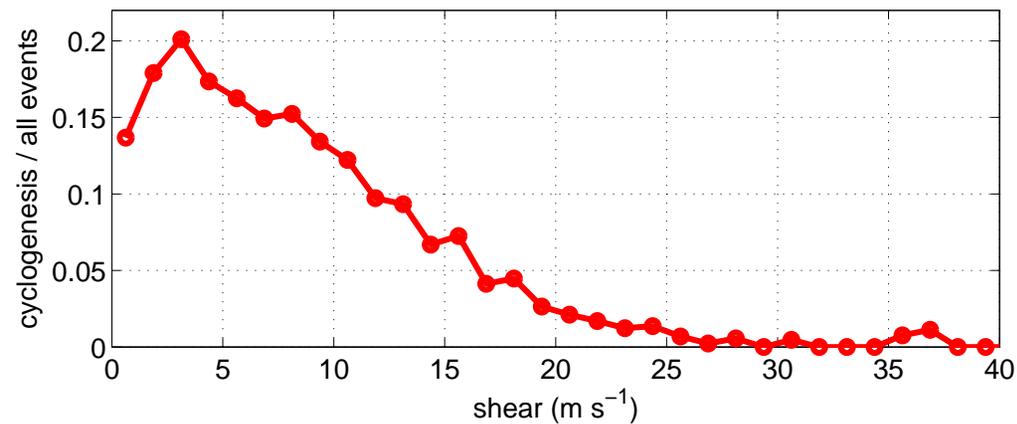
Shear for  
TC genesis events,  
Lat < 20



A random sampling  
of wind shear weighted  
to TC genesis regions  
and seasons



Divide the frequencies  
for “relative”  
favorableness



Tippett et al. (2011) show nearly the same result:

Note:  
log scale

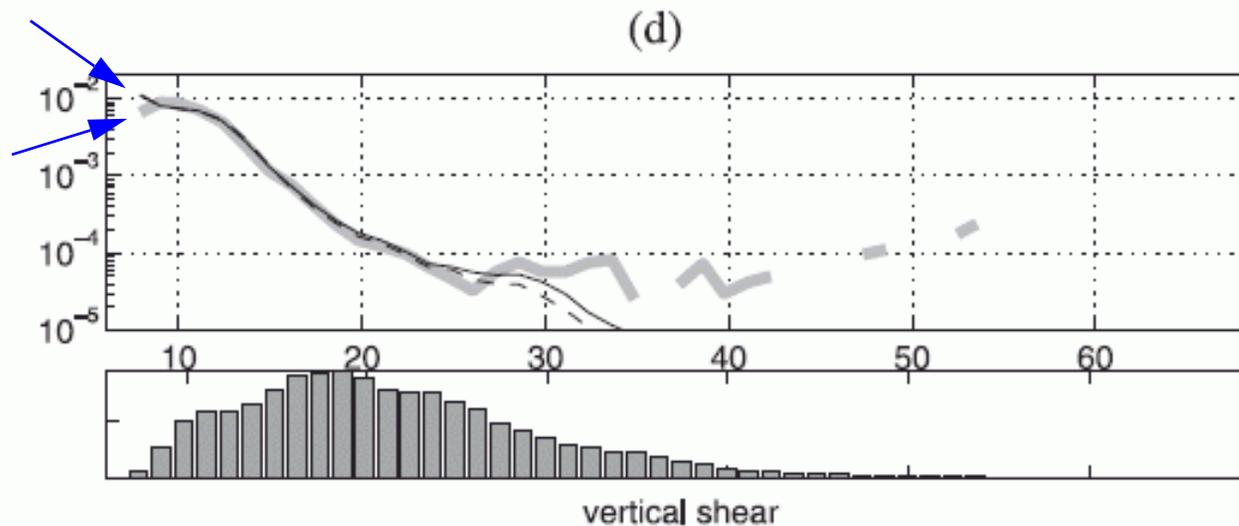
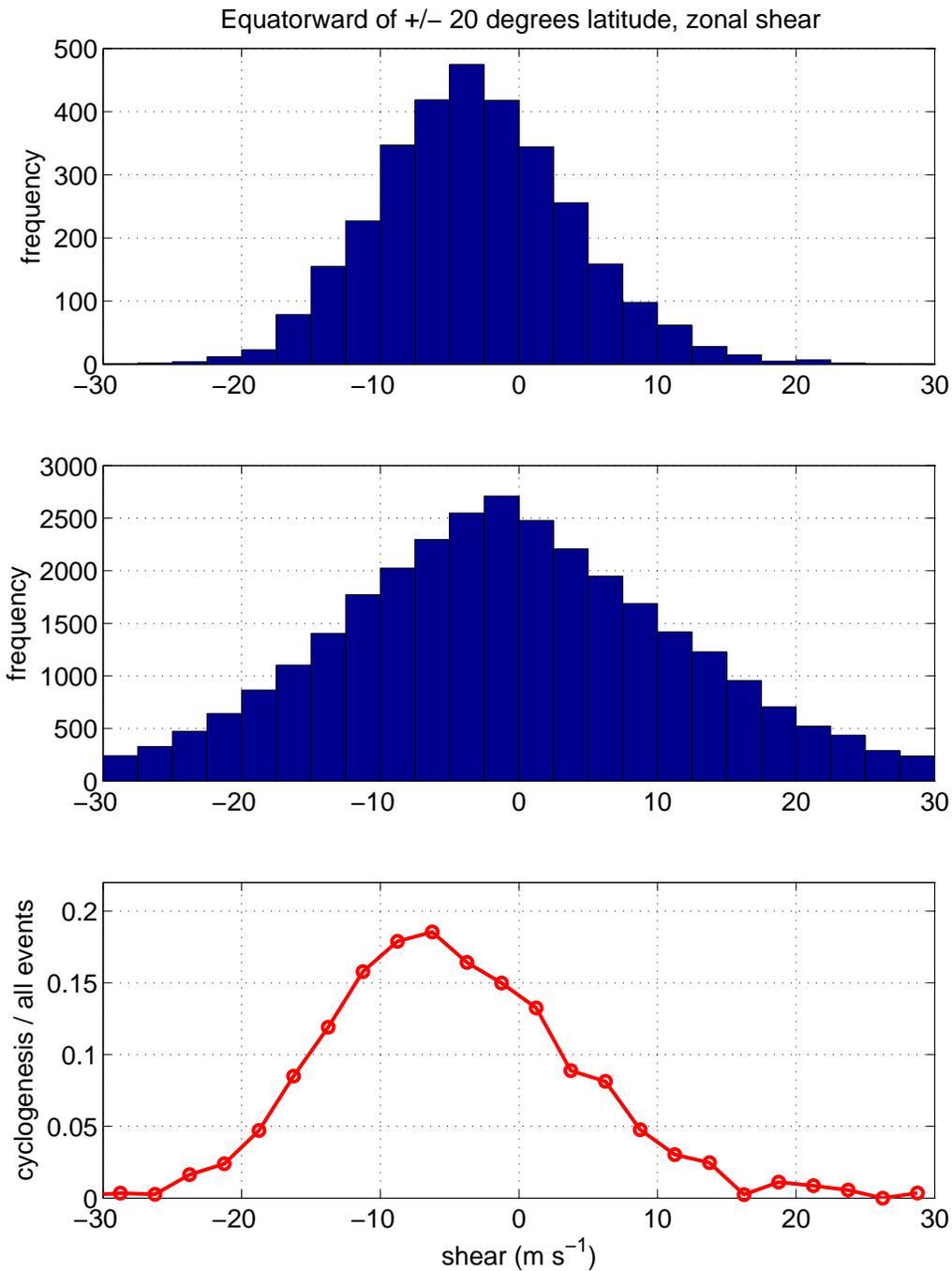


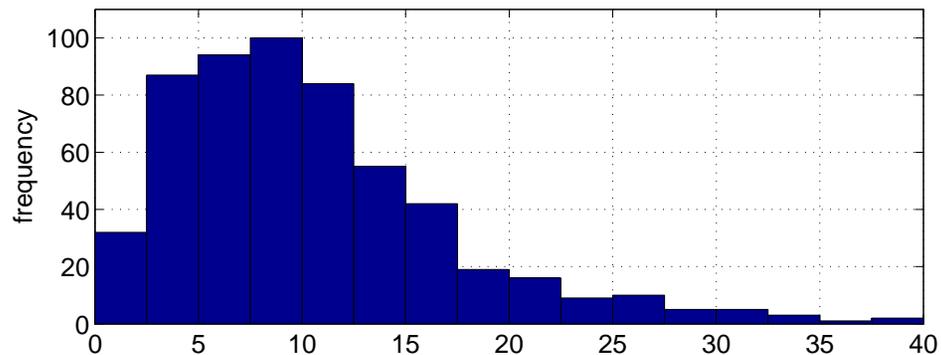
FIG. 11. Number of observed (thick line) and modeled (thin lines) tropical cyclones per year as a function of (a) absolute vorticity, (b) relative humidity, (c) relative SST, and (d) vertical shear. The solid (dashed) thin line is the model with the minimum ( $\eta, 3.7$ ) ( $\eta$ ) as a predictor. Histograms show the distribution of values of the climate variables.

- What about easterly versus westerly shear? (Lat < 20)

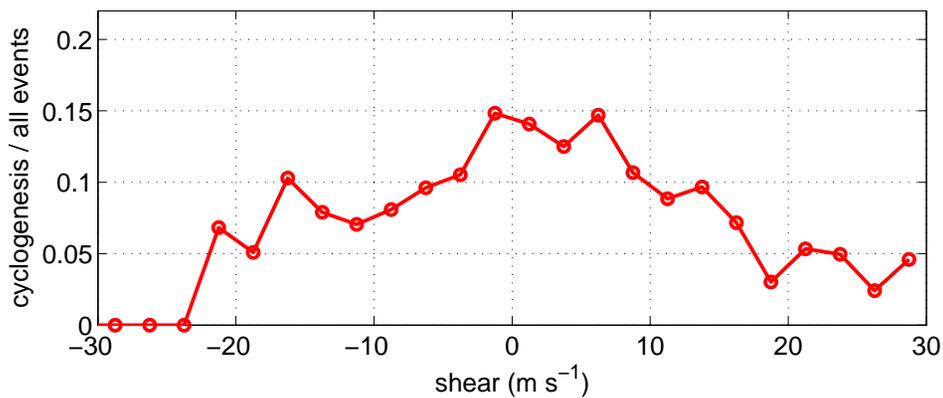
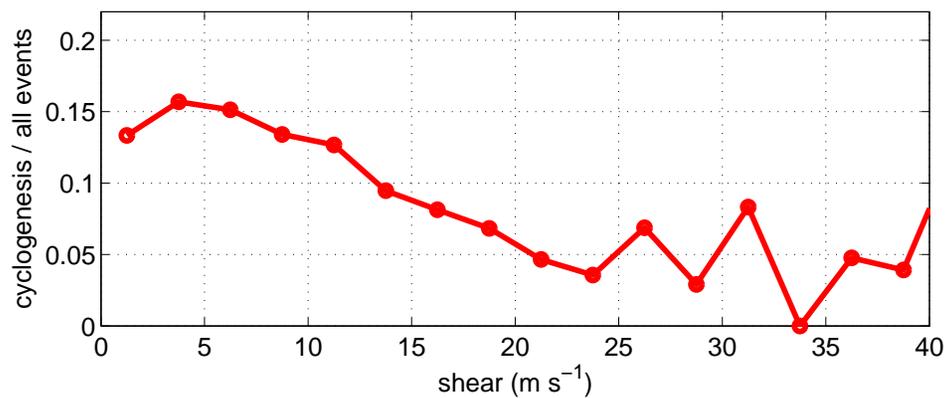
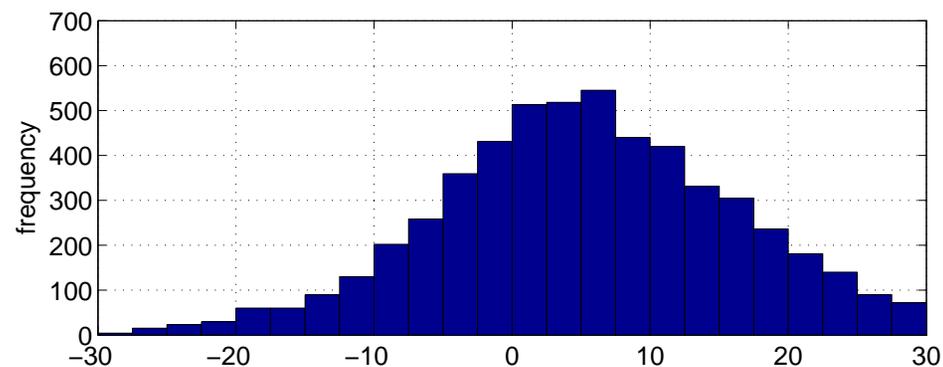
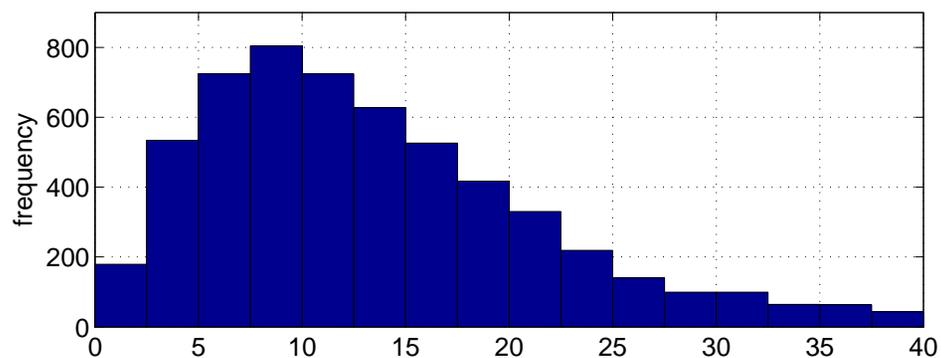
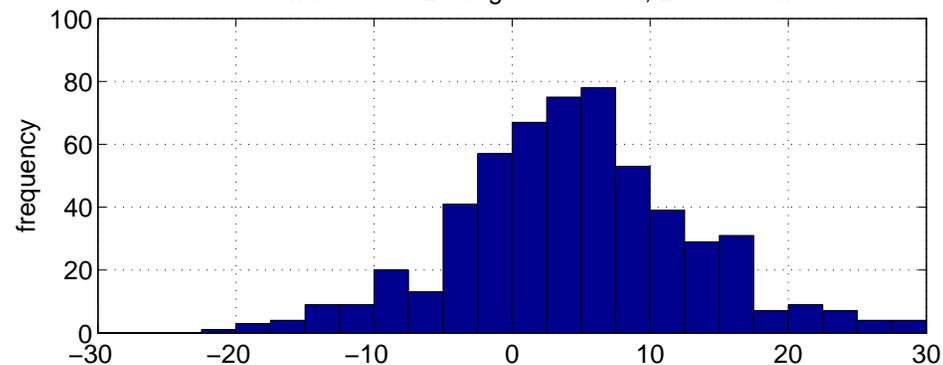


# Results for TC formation poleward of $\pm 20$ :

Poleward of  $\pm 20$  degrees latitude, total shear



Poleward of  $\pm 20$  degrees latitude, zonal shear

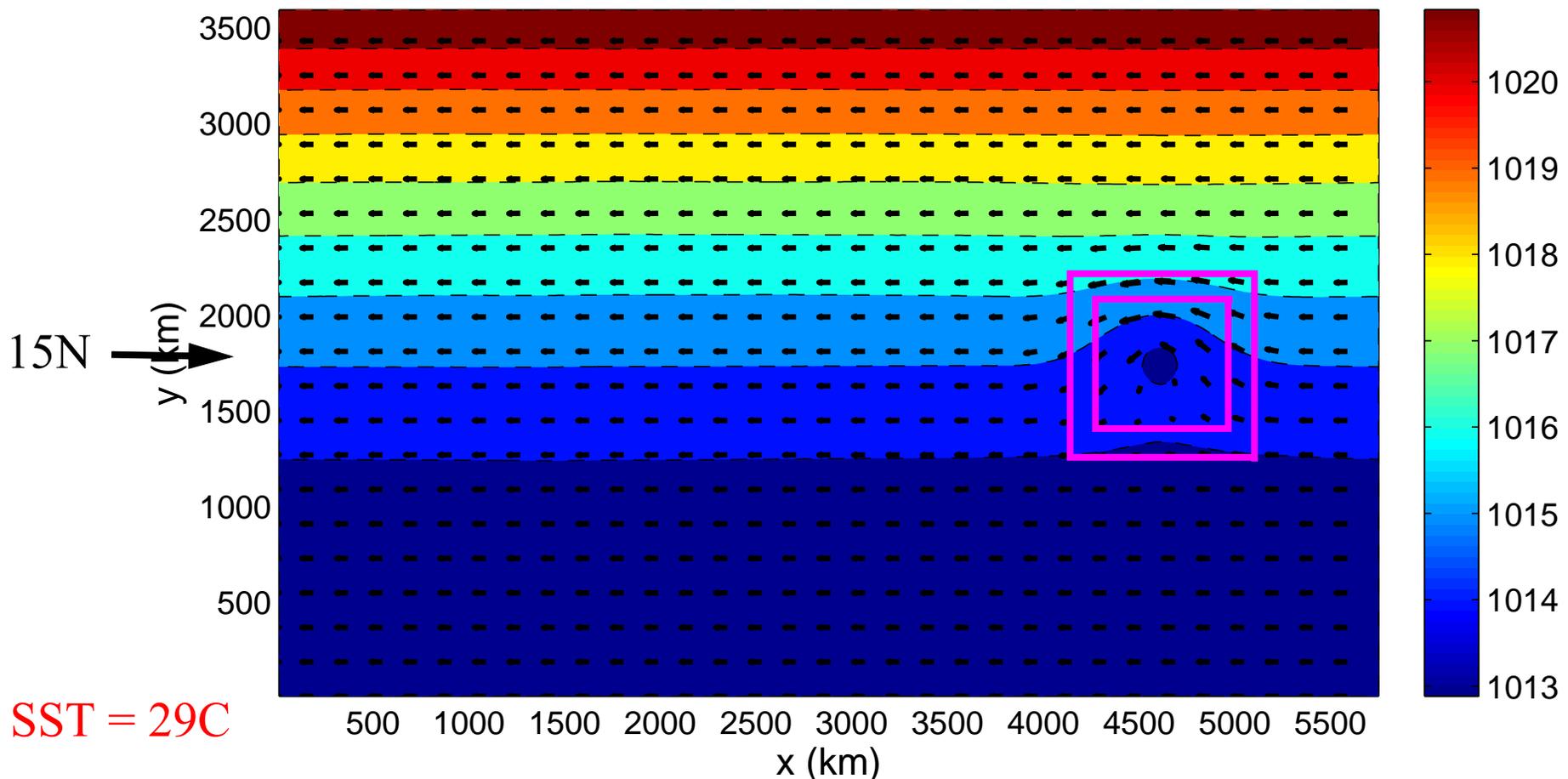


# Idealized Simulations of Tropical Cyclone Formation in Shear

- We use “tropical channel” domains with mean flow and wind shear.

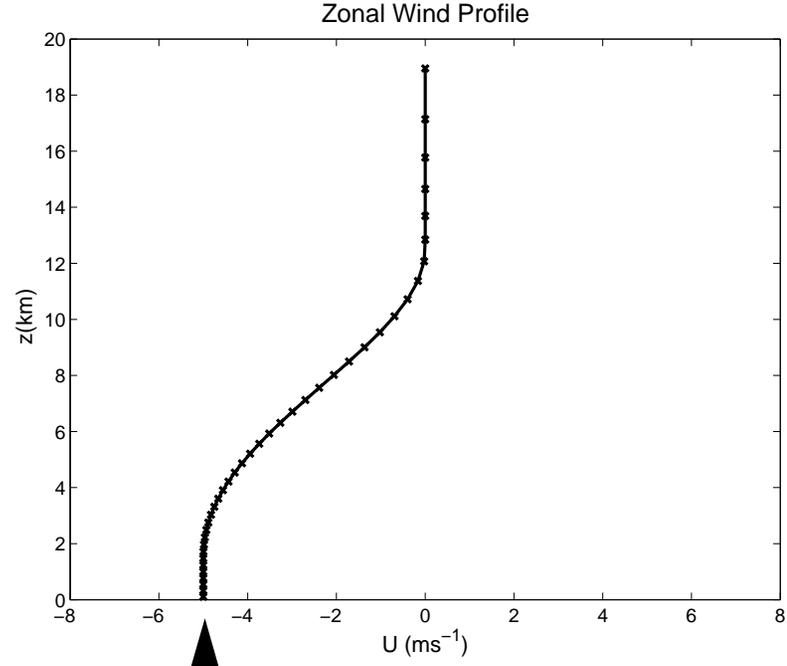
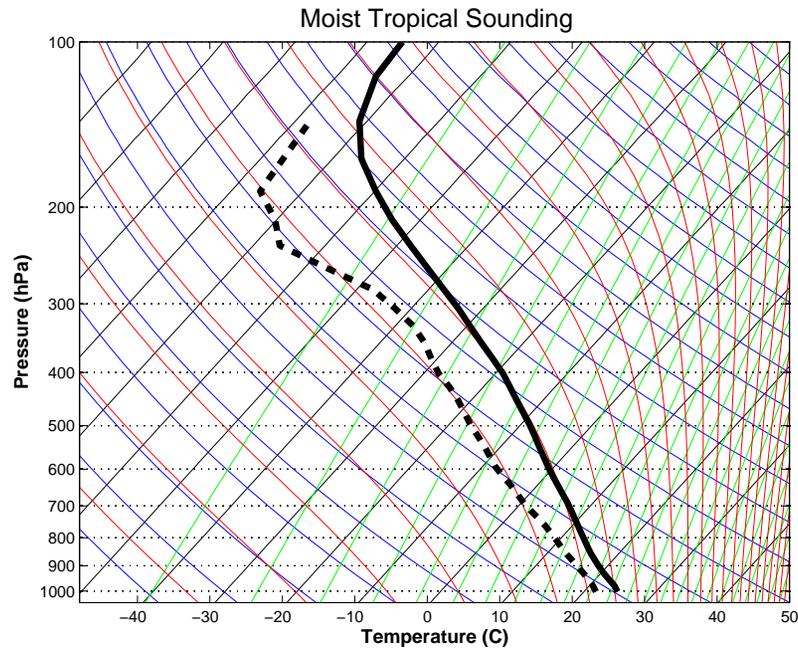
WRF 3.1.1, 18km/6km/2km resolution, on the beta-plane:

PSFC (hPa), 01-01-03 z=5.45e+02 max=1.02e+03 min=1.01e+03 int=8.84e-01

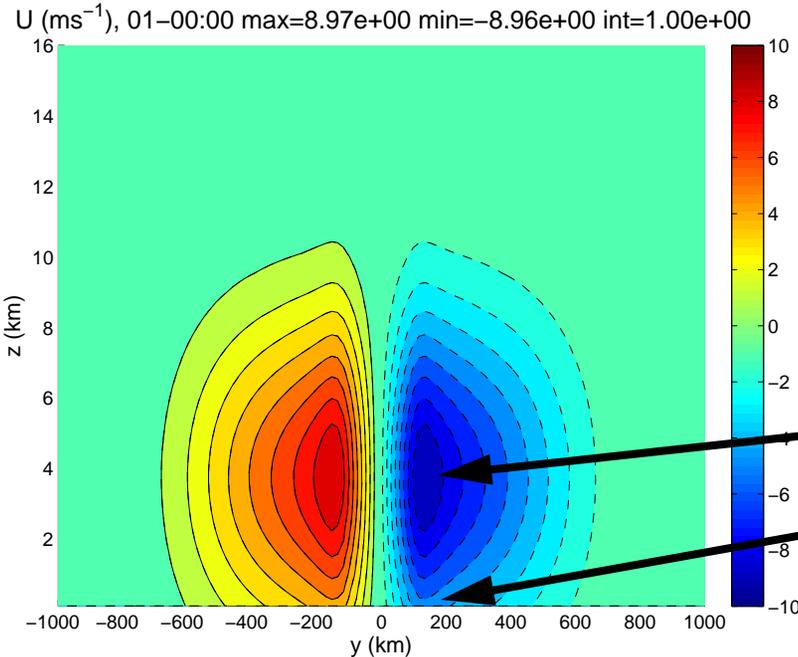


Free-slip walls; zonally periodic; mean flow balanced by temperature gradient.

# Initial Conditions:



5 m/s easterly flow plus shear

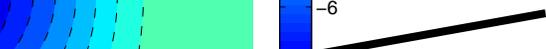


Initial "disturbance"

RMW = 126 km

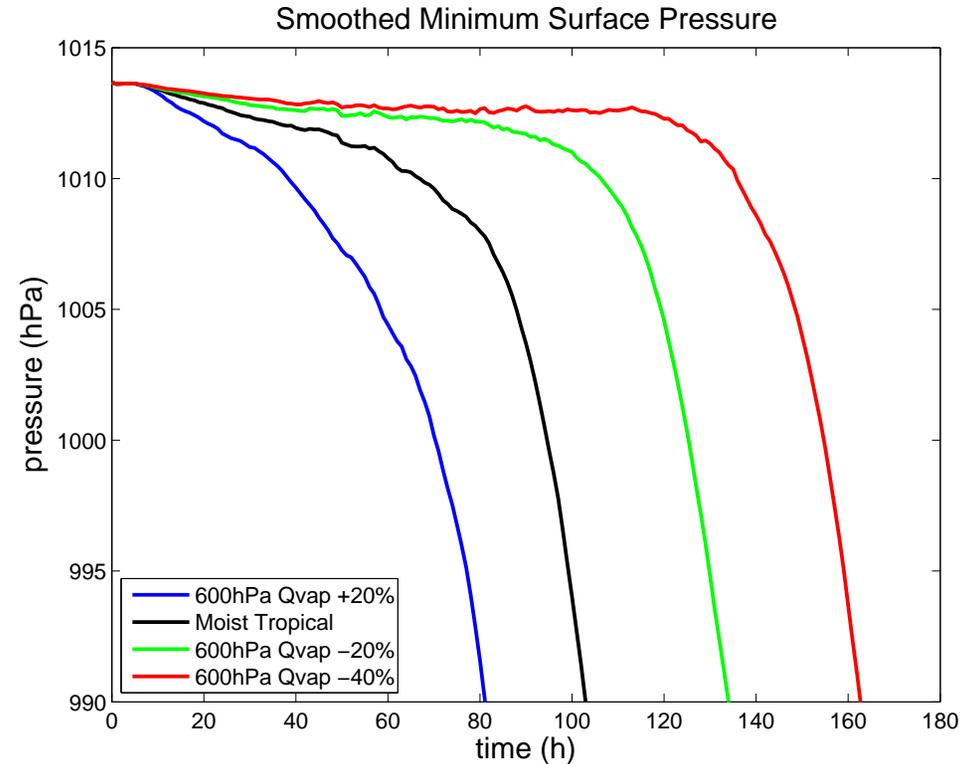
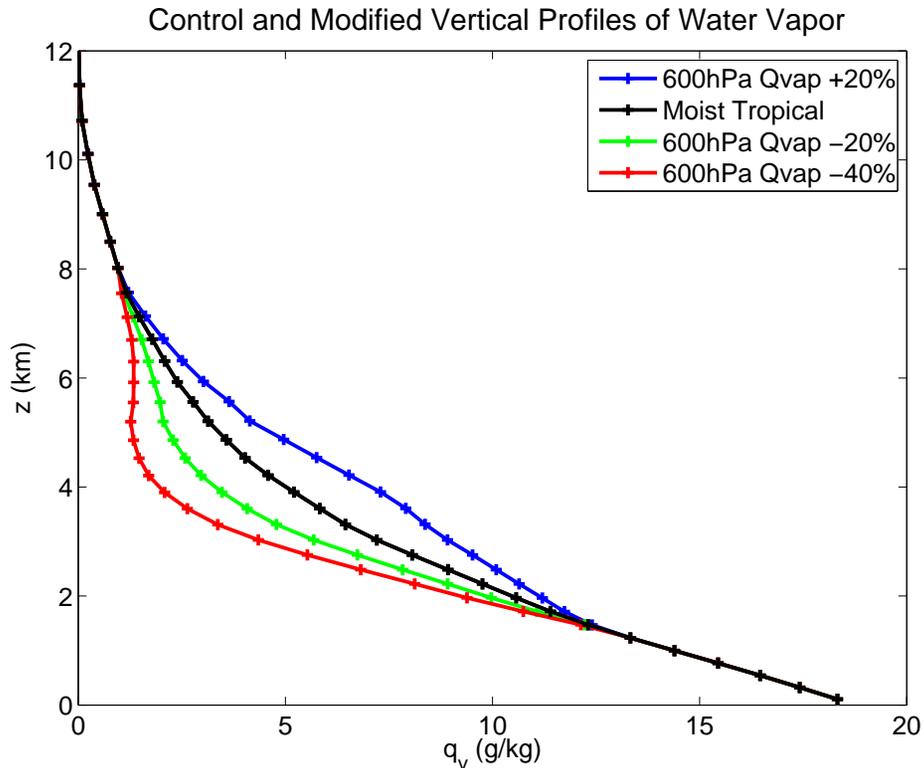
$V_{max} = 9$  m/s at  $z = 3.7$  km

= 4.5 m/s at  $z = 0$  km



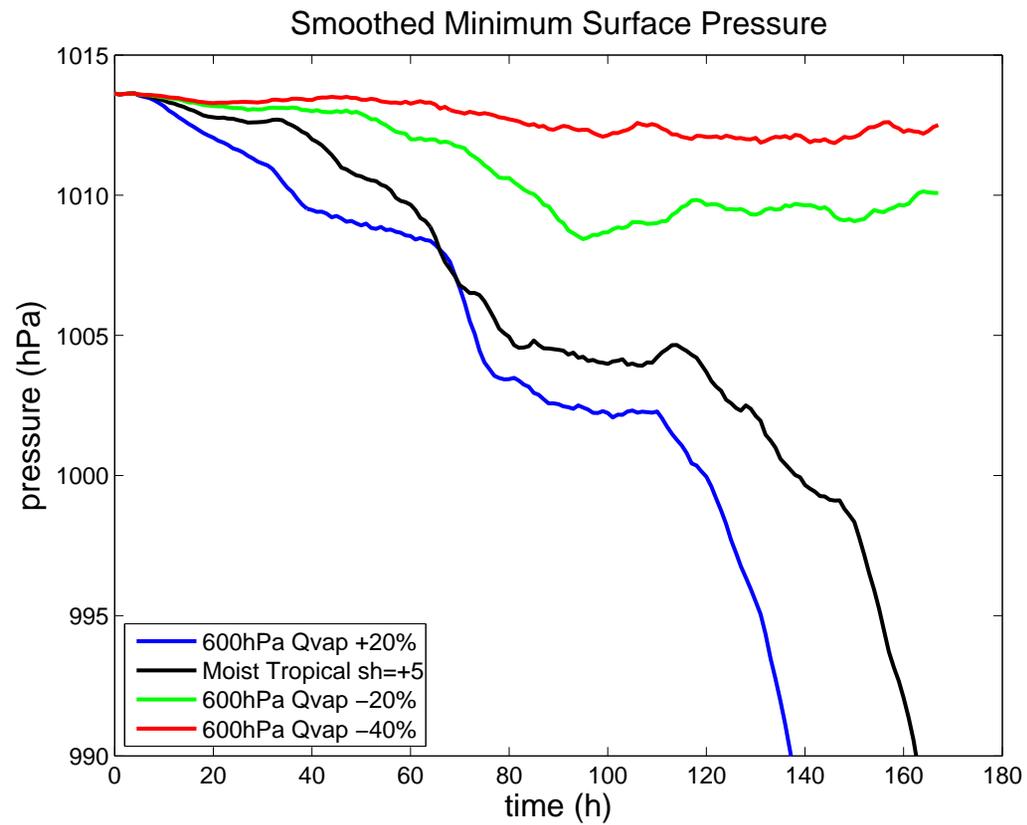
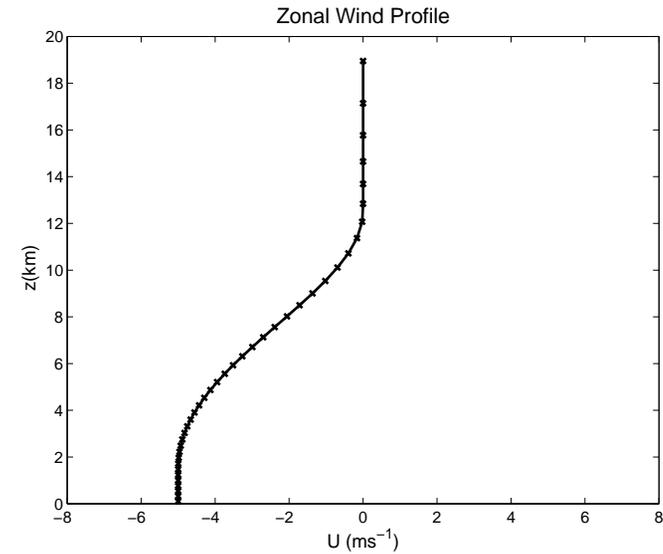
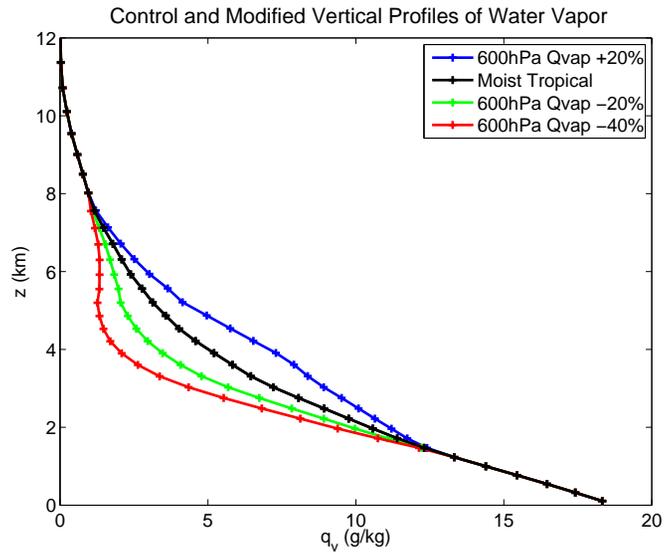
- But first...let's remember what simulated genesis is like with no flow, no shear, on the  $f$ -plane: the “hurricane in a box.”

Used in many studies: Montgomery et al. (2006), Nolan (2007), Nolan et al. (2007), Nguyen et al. (2008), Hill and Lackmann (2009), Sawada and Iwasaki (2010), and many others...:

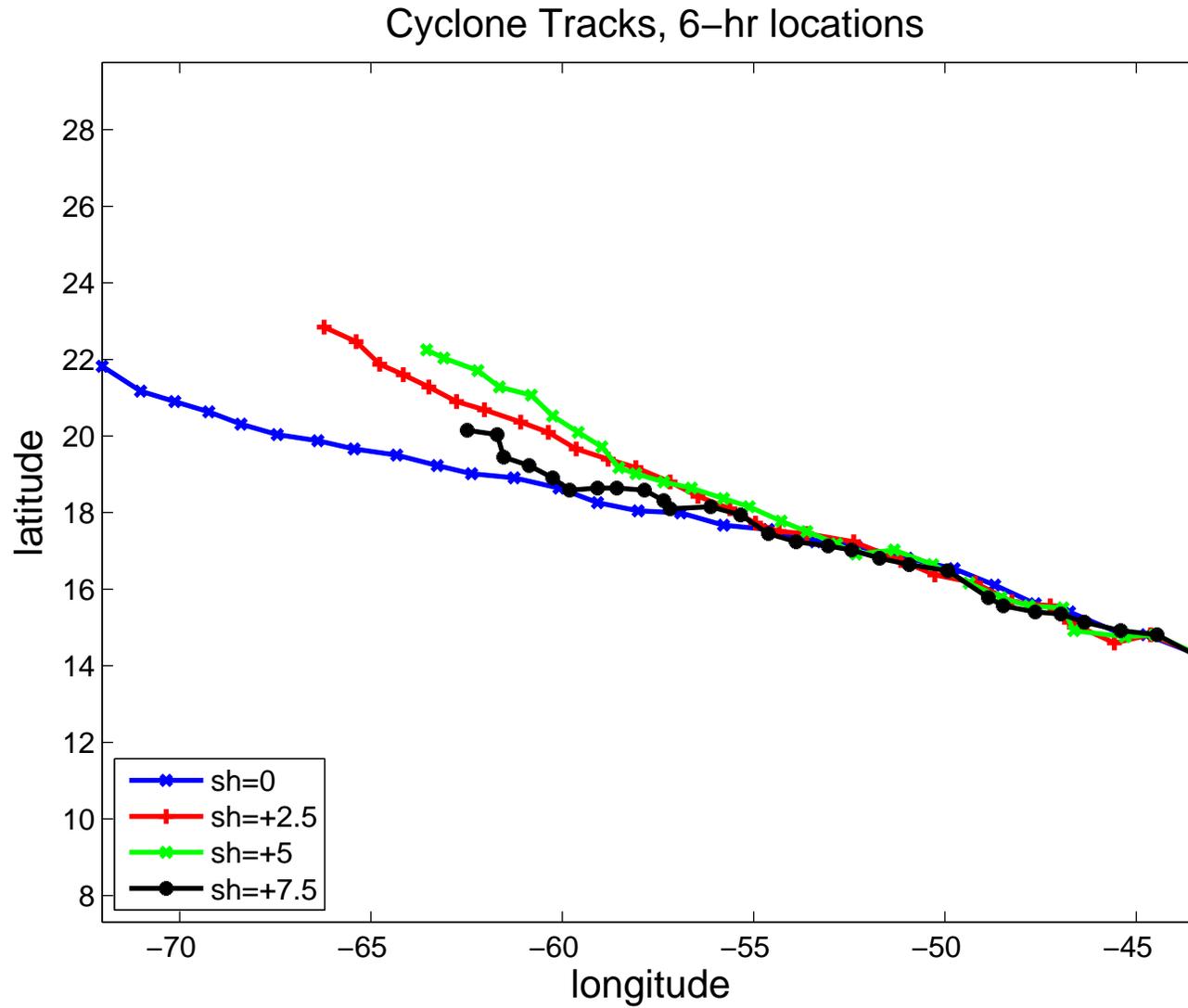


Regardless of humidity, end result is the same: Genesis, then rapid intensification.

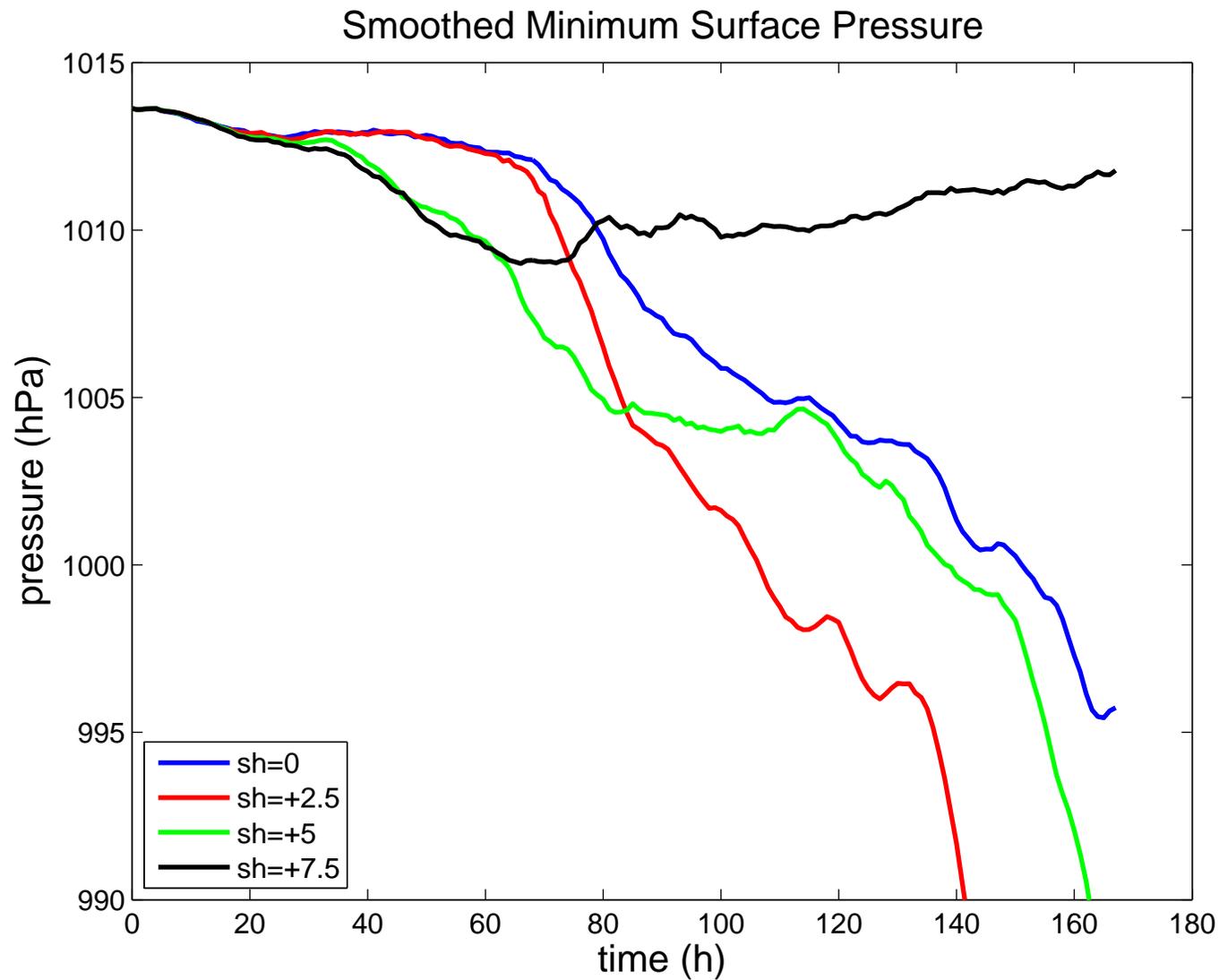
- Now let's use 5 m/s of easterly flow, and 5 m/s of westerly shear:



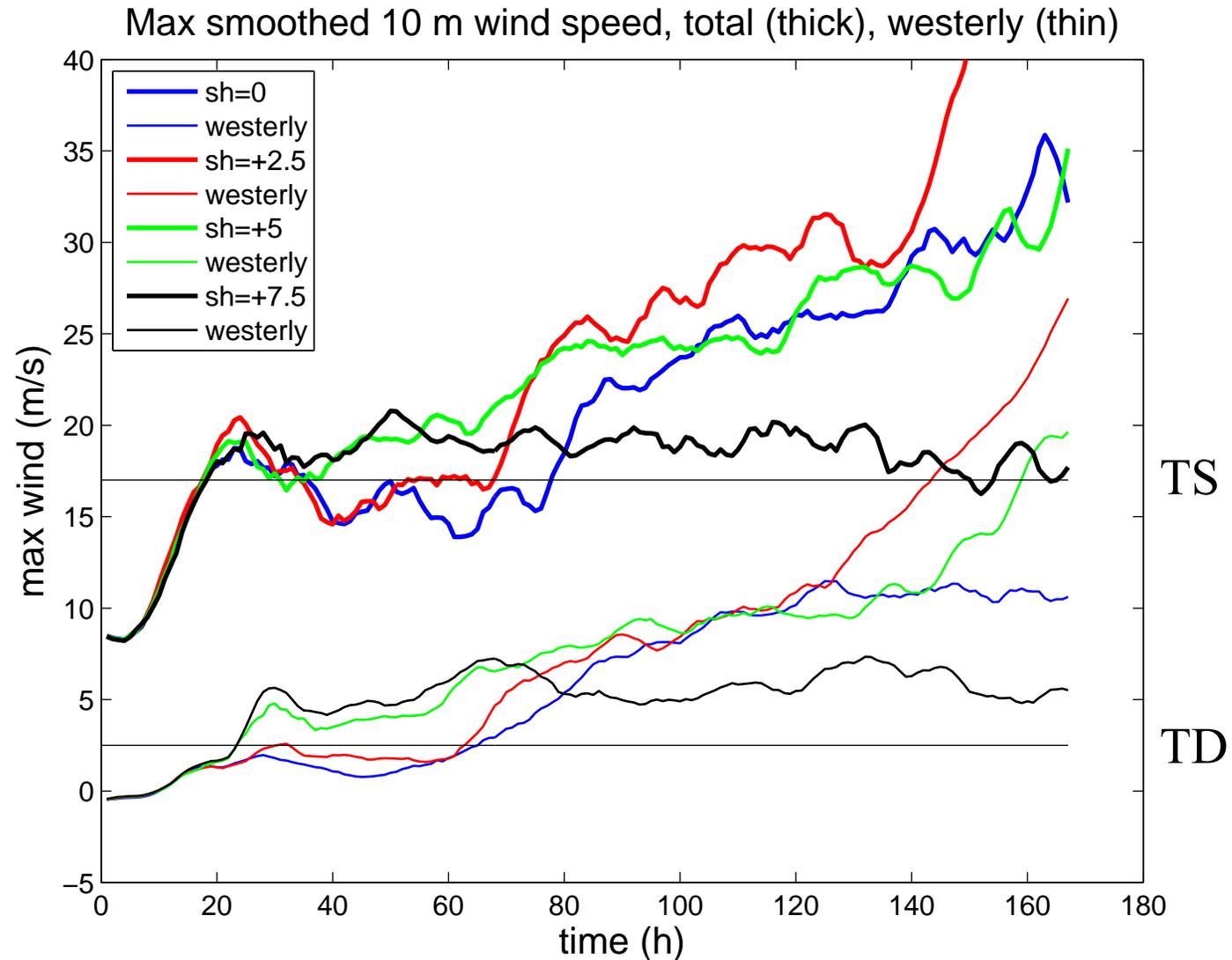
## Results: Control Sounding, Easterly Flow, Increasing Westerly Shear



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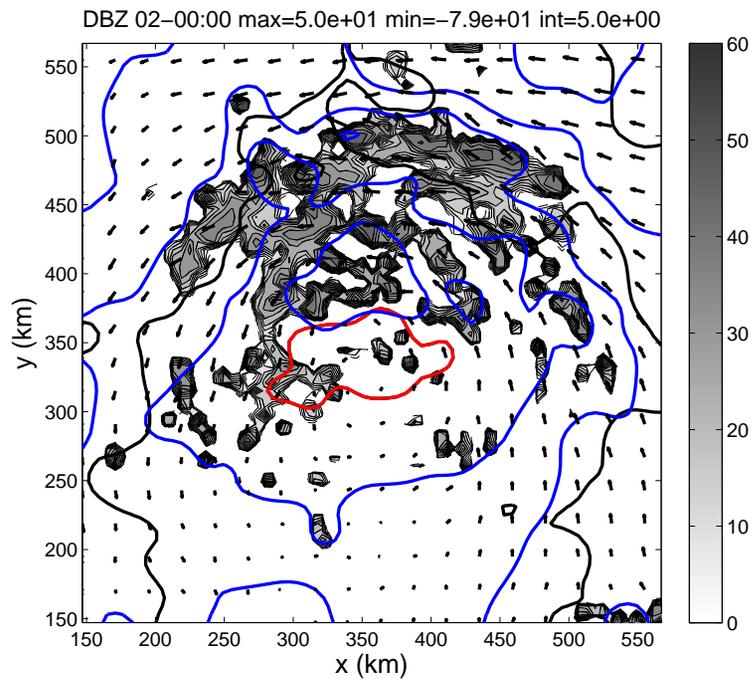


• Low shear: Delayed Genesis, Faster Development

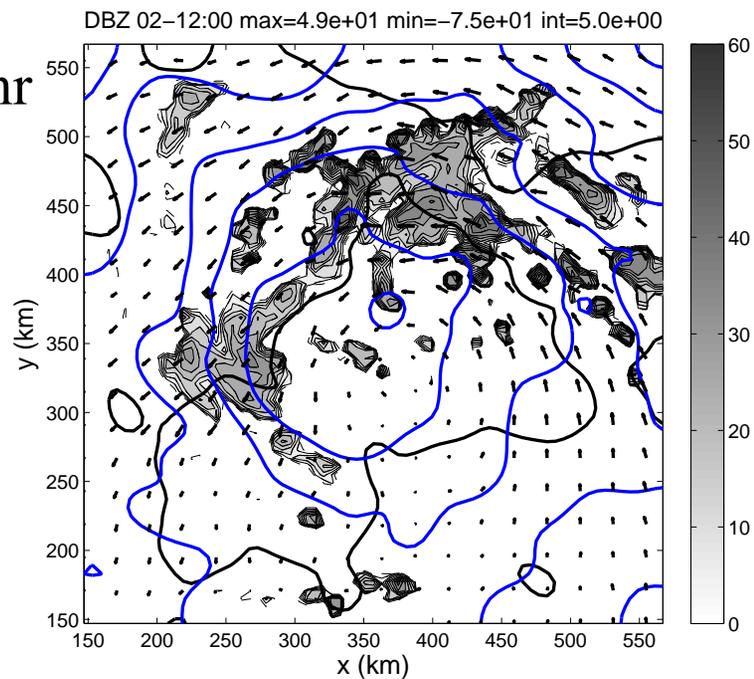
Moderate shear: Earlier Genesis, Limited Development

## Evolution: 5 m/s easterly flow, zero shear

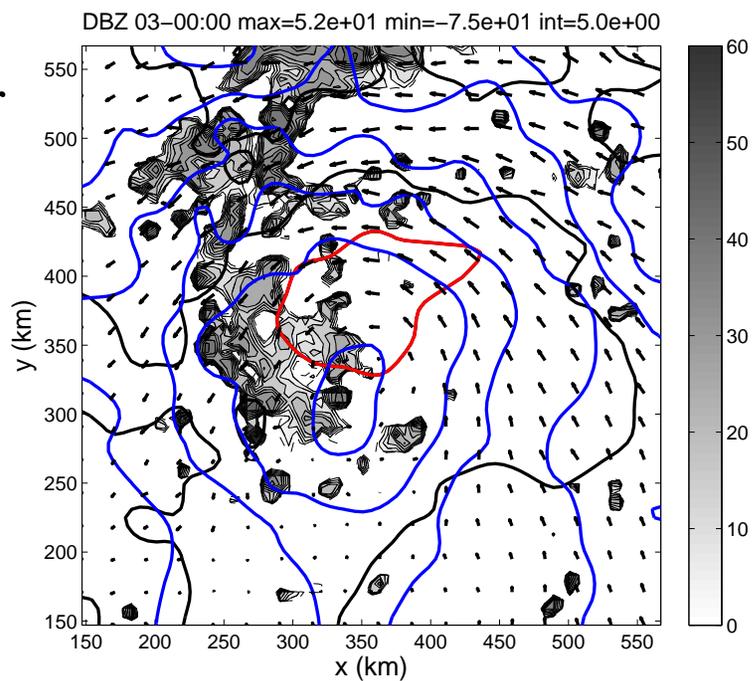
24 hr



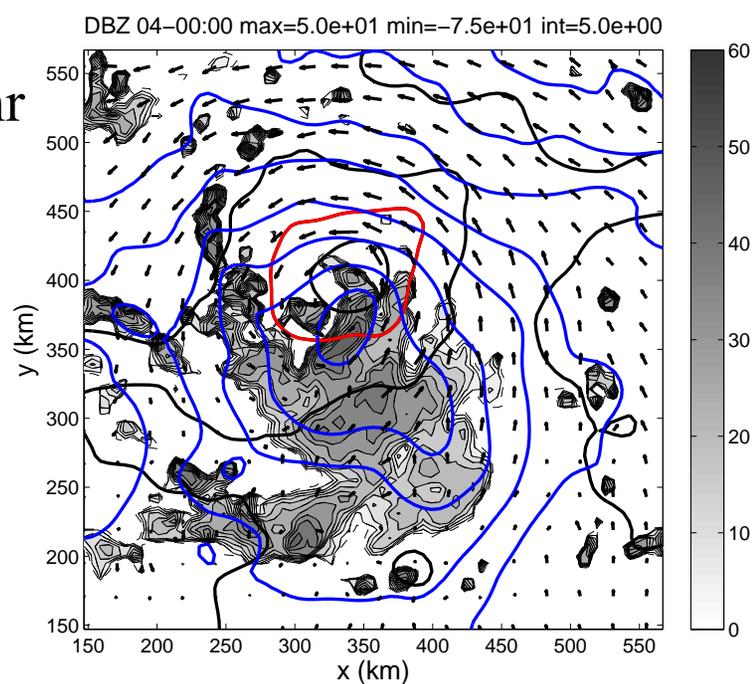
36 hr



48 hr

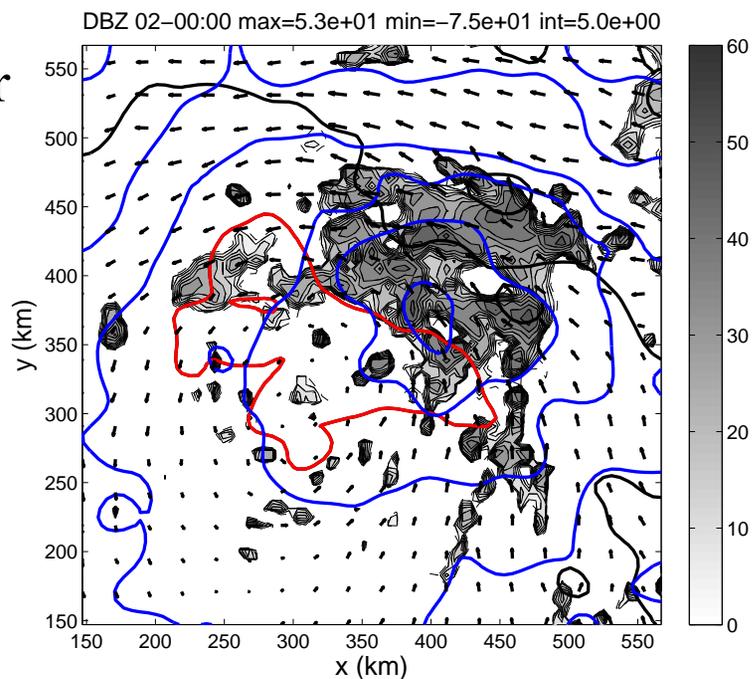


72 hr

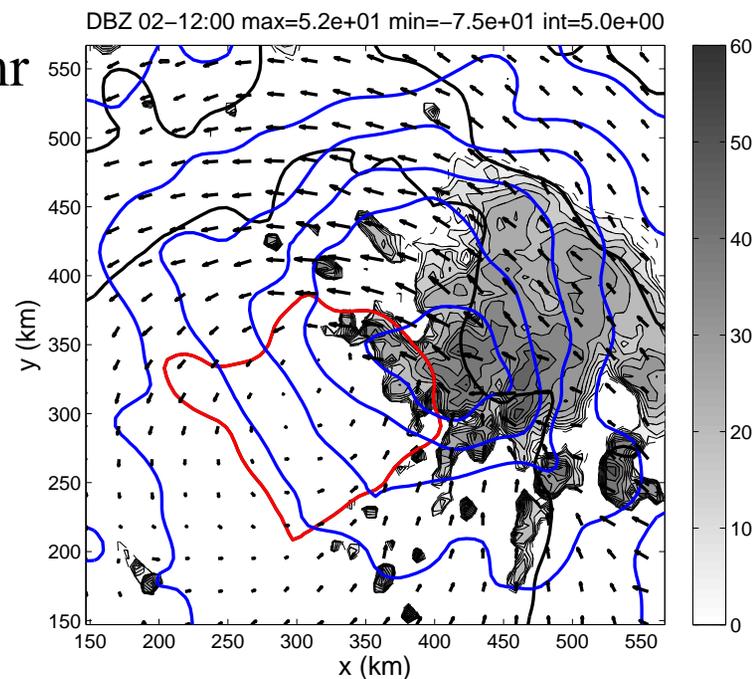


## Evolution: 5 m/s easterly flow, 5 m/s westerly shear

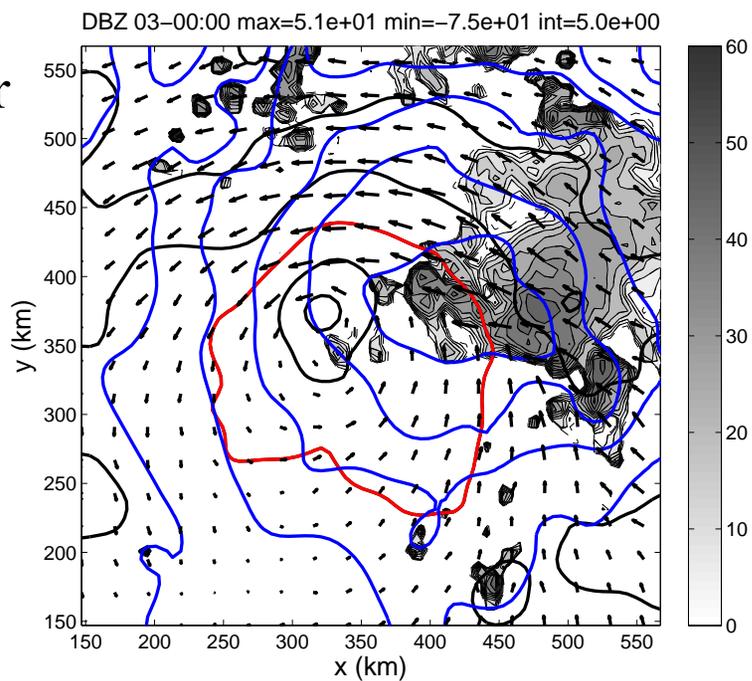
24 hr



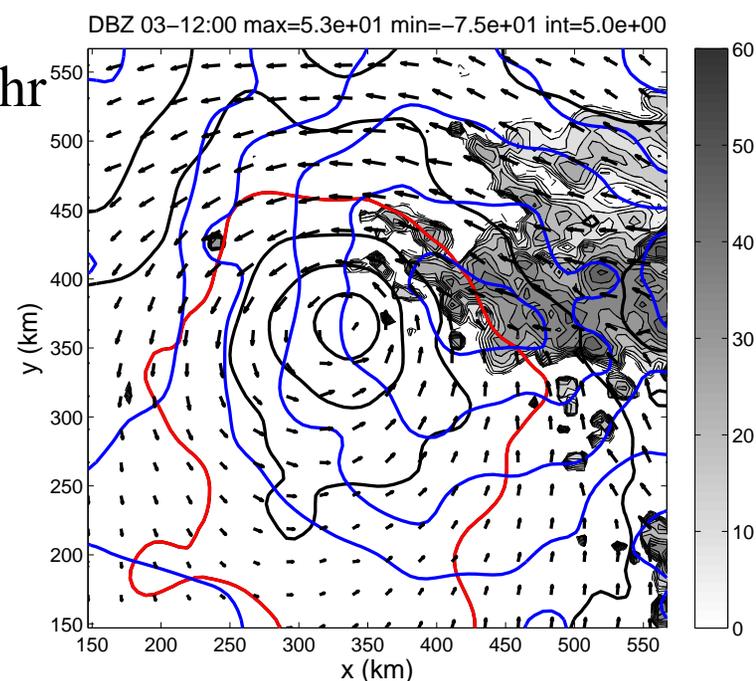
36 hr



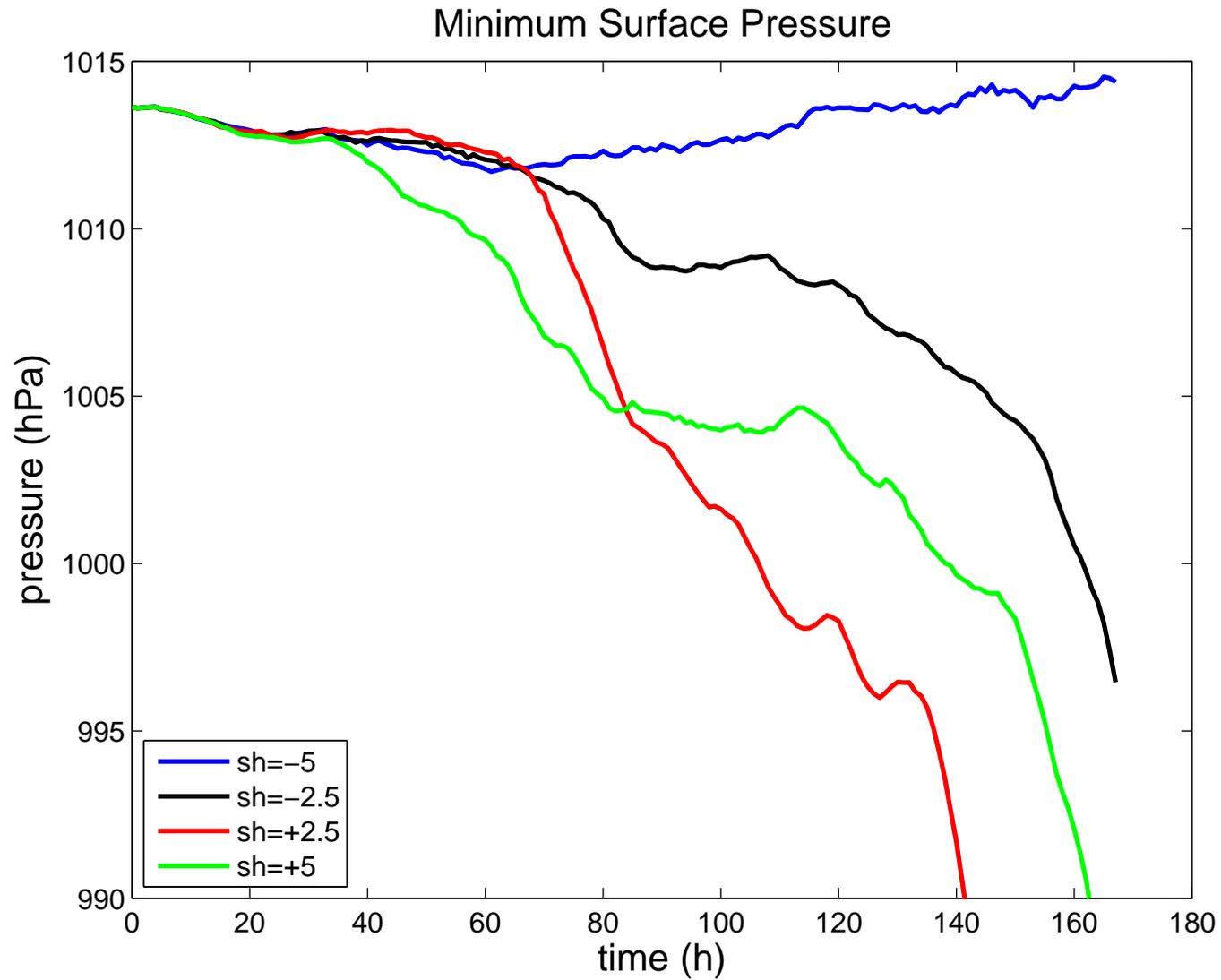
48 hr



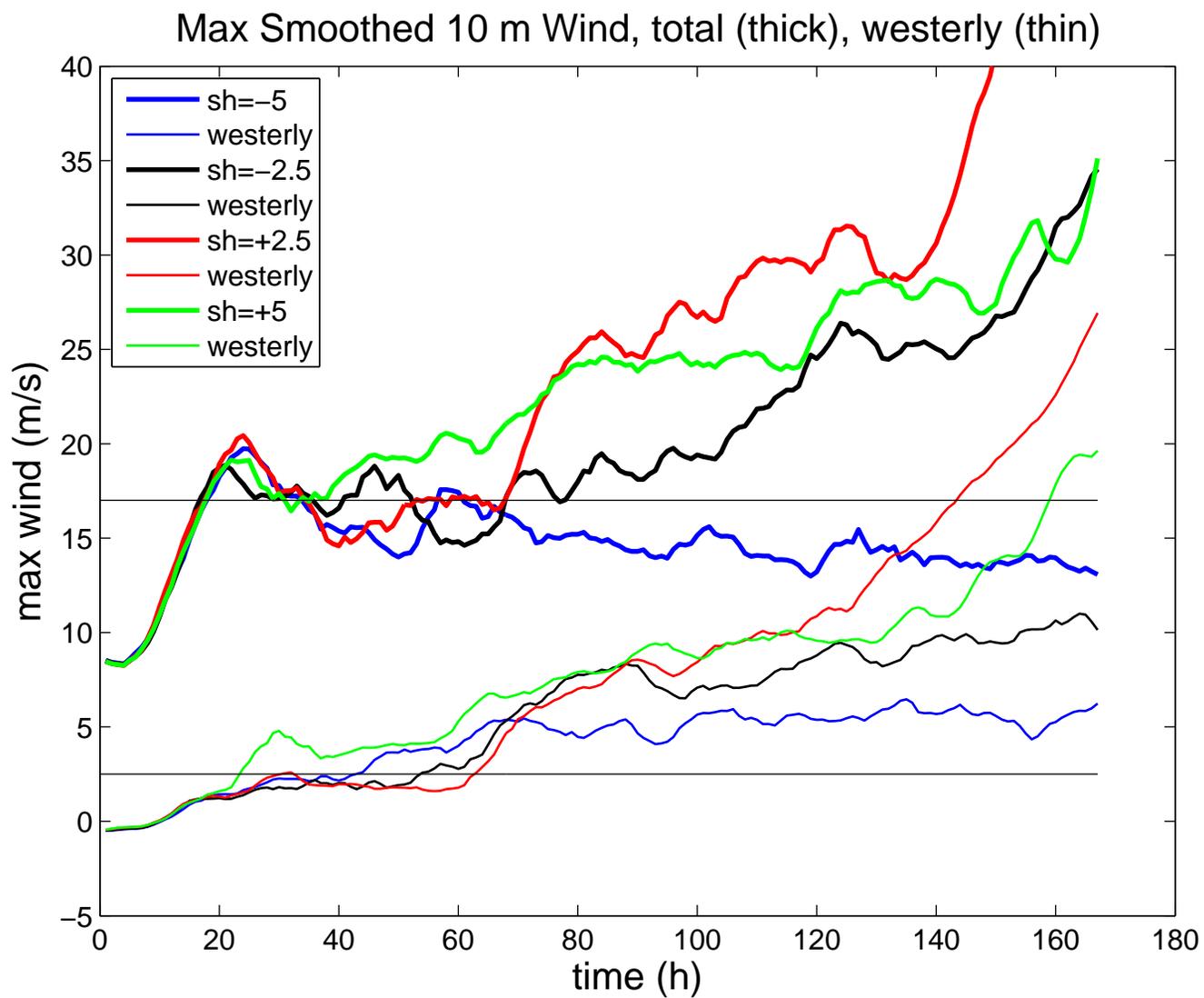
60 hr



## Results: Easterly Shear versus Westerly Shear



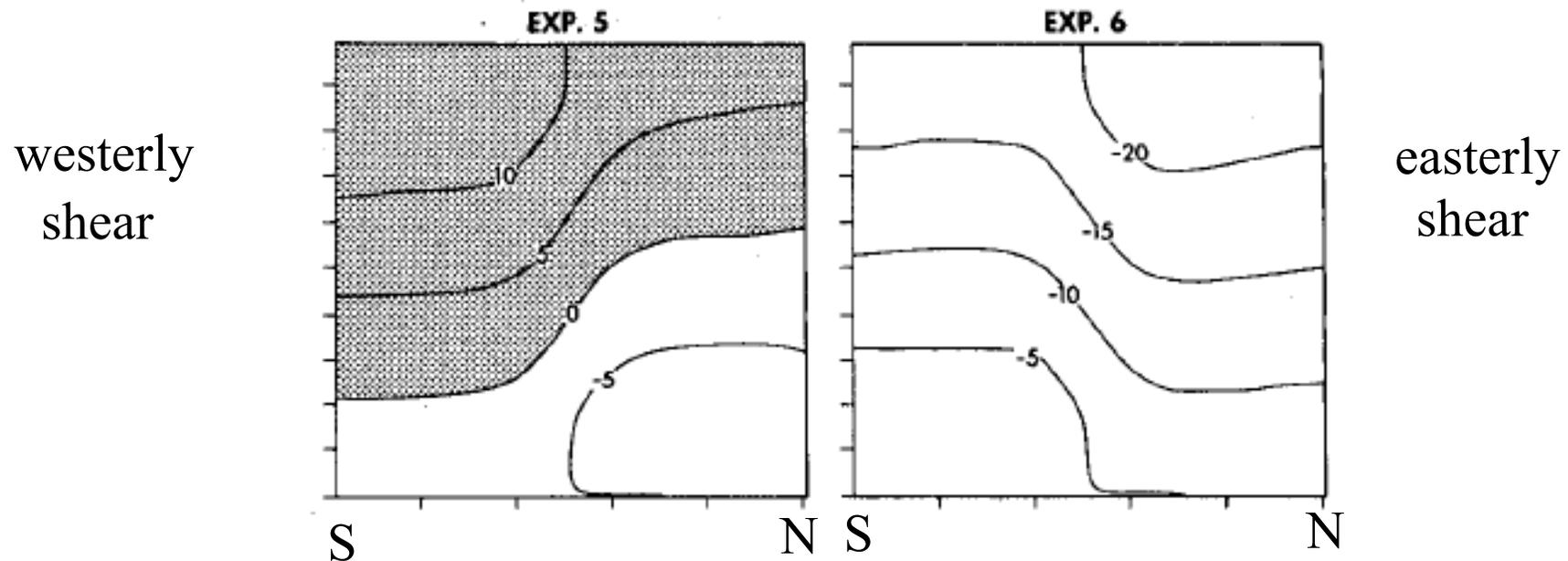
# Results: Easterly Shear versus Westerly Shear



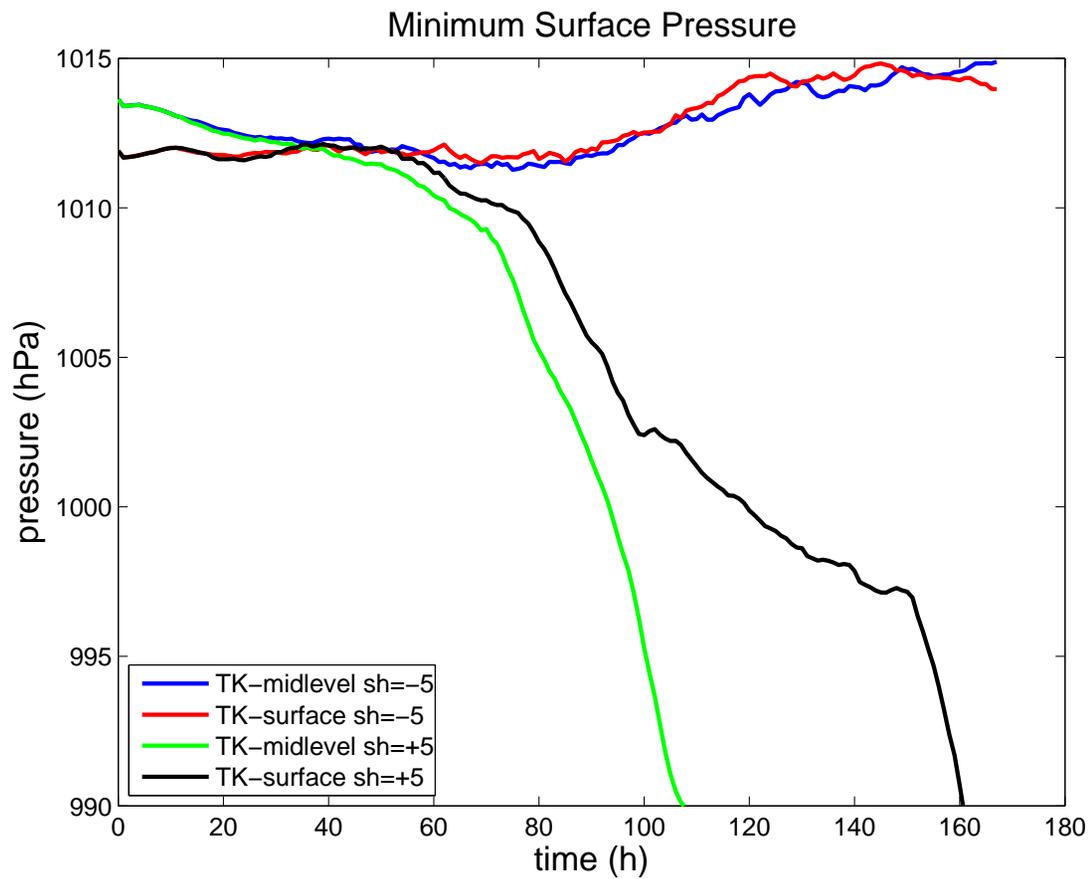
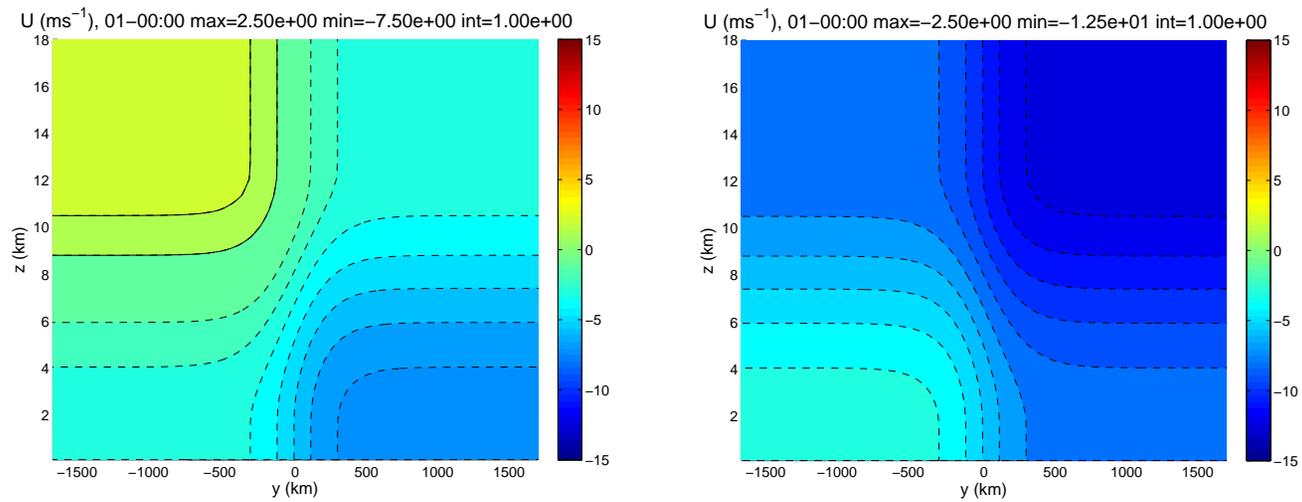
- Didn't Tuleya and Kurihara (1981) show that easterly shear is more favorable?

Yes, but...

- \* They used 70 km resolution and 11 vertical levels.
- \* Their initial vortex had maximum winds at the surface.
- \* They found 15 m/s of easterly shear was the most favorable!
- \* Their easterly shear was embedded in a deep cyclonic horizontal shear:



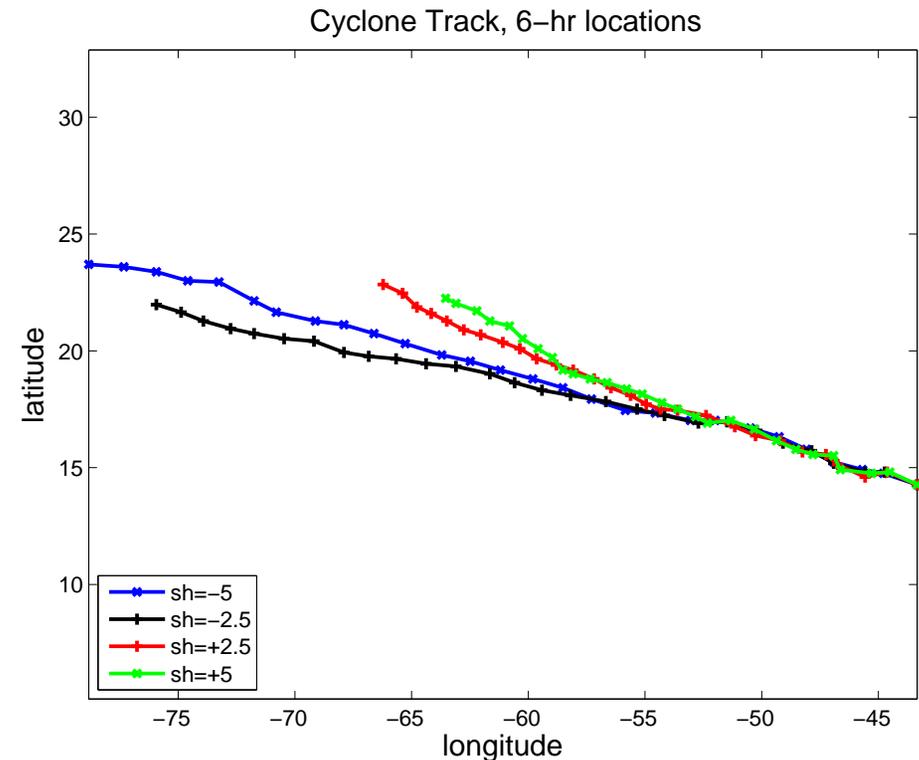
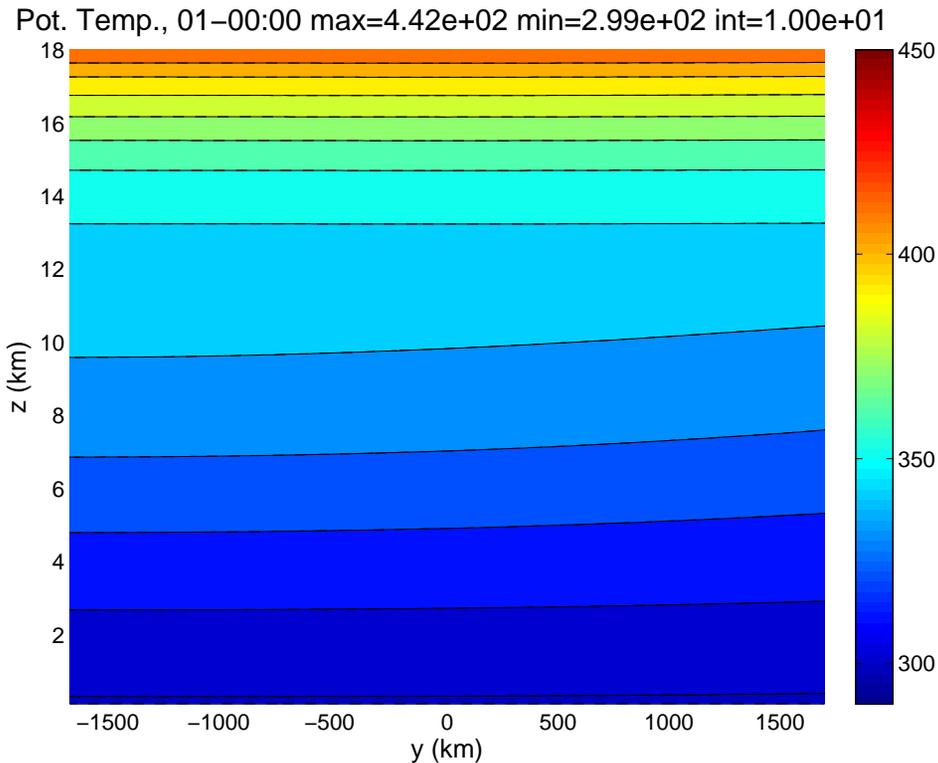
- We can do those things too...



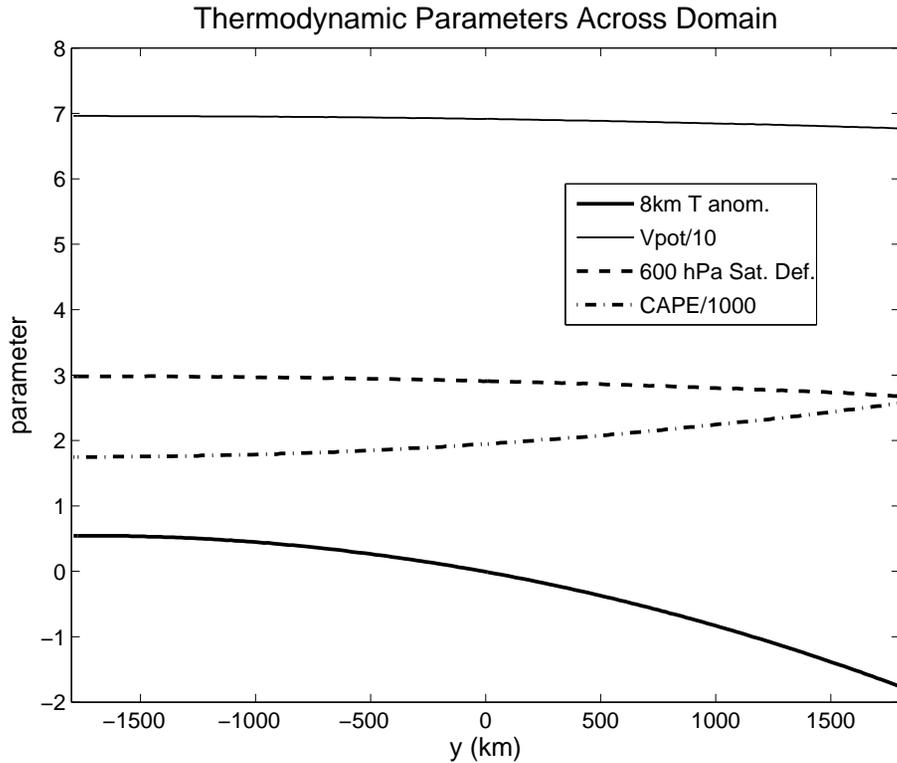
• In our simulations...why is westerly shear more favorable? At least two possibilities:

1) Westerly shear requires cooler upper-level air to the north.

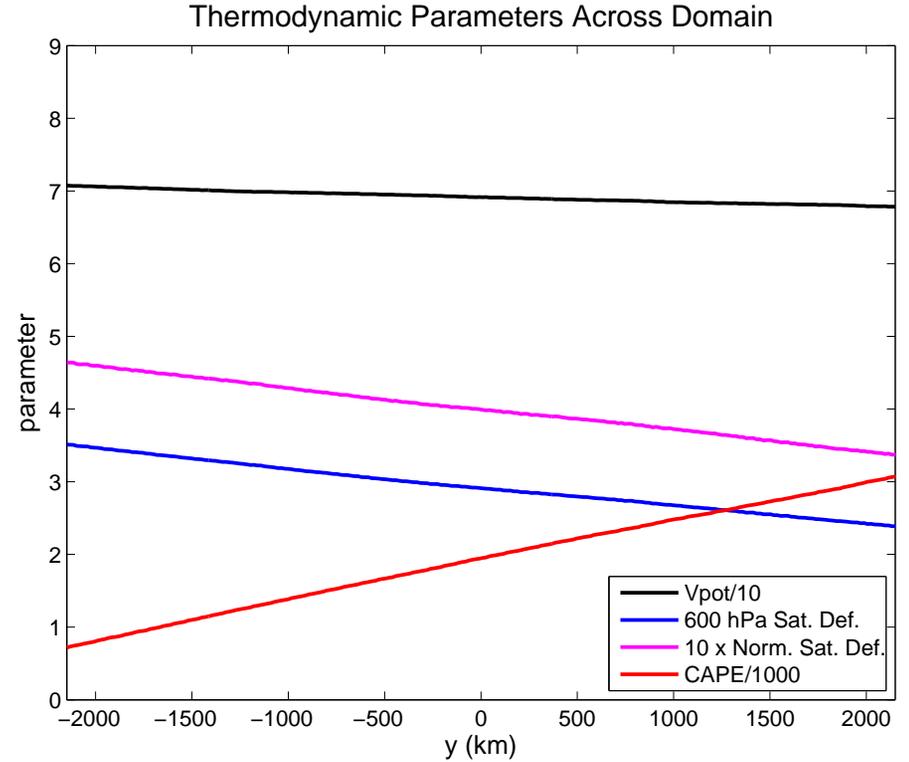
Thus, the storms are drifting into a more favorable environment.



•How much more favorable?

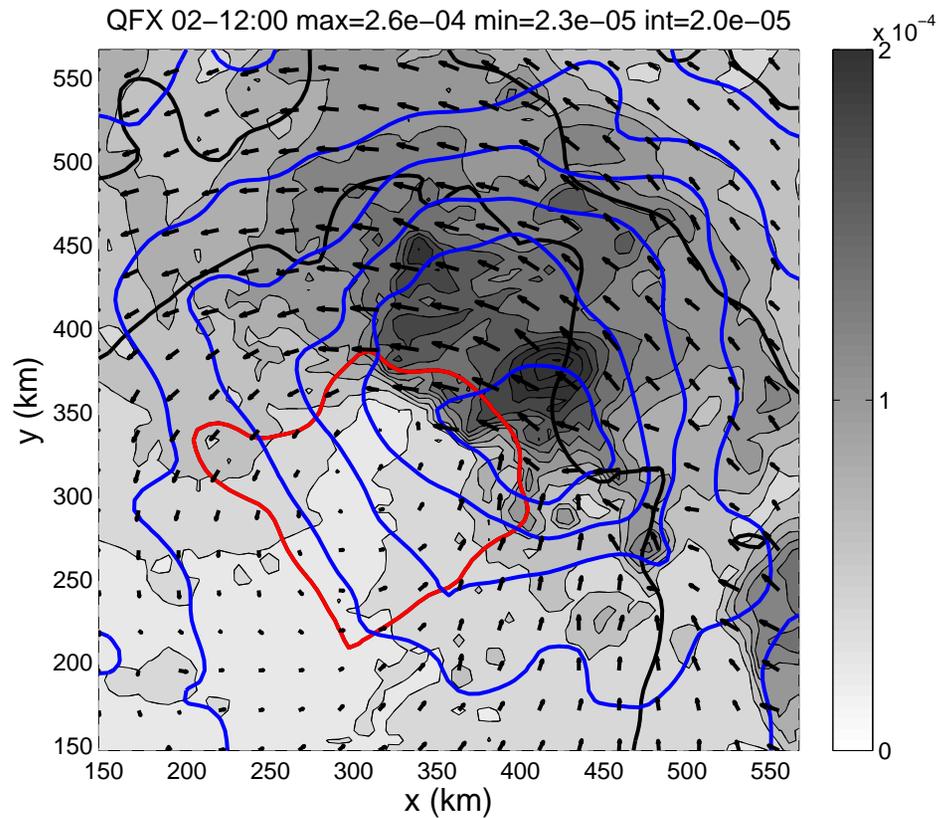


This study: 5 m/s shear  
15N  
Beta-plane

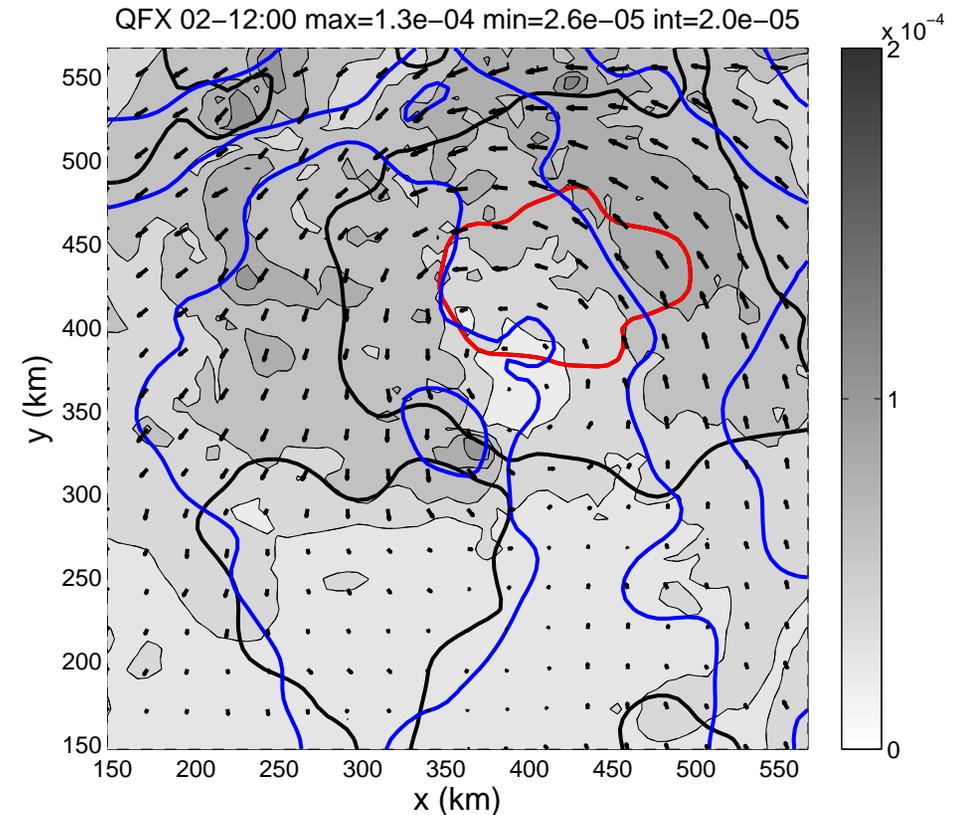


Previous study: 10 m/s shear  
20 N  
f-plane

2) When the low-level flow is opposite to the shear, there is a favorable configuration of increased surface fluxes.



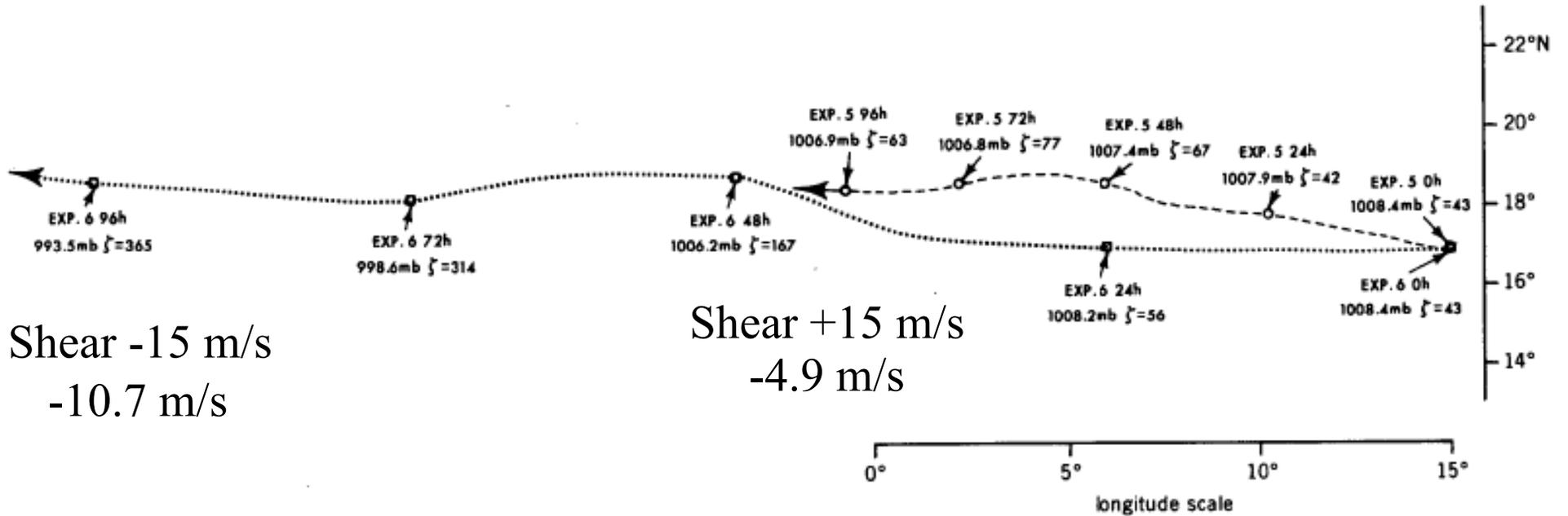
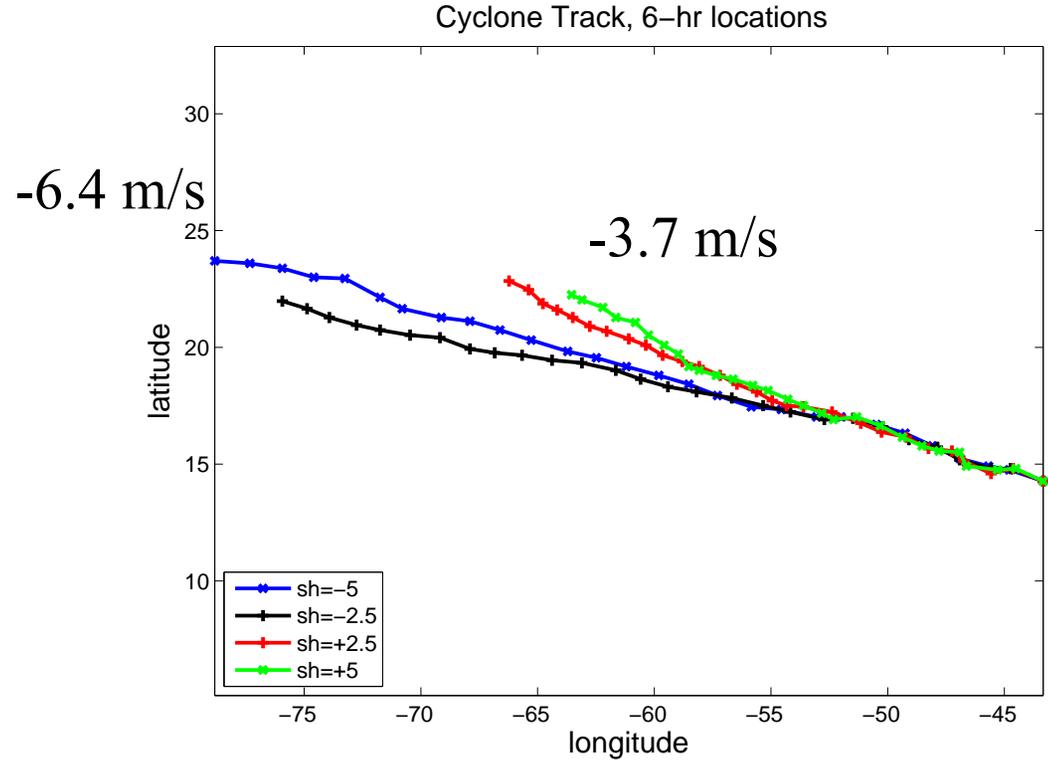
shear against low-level flow



shear with low-level flow

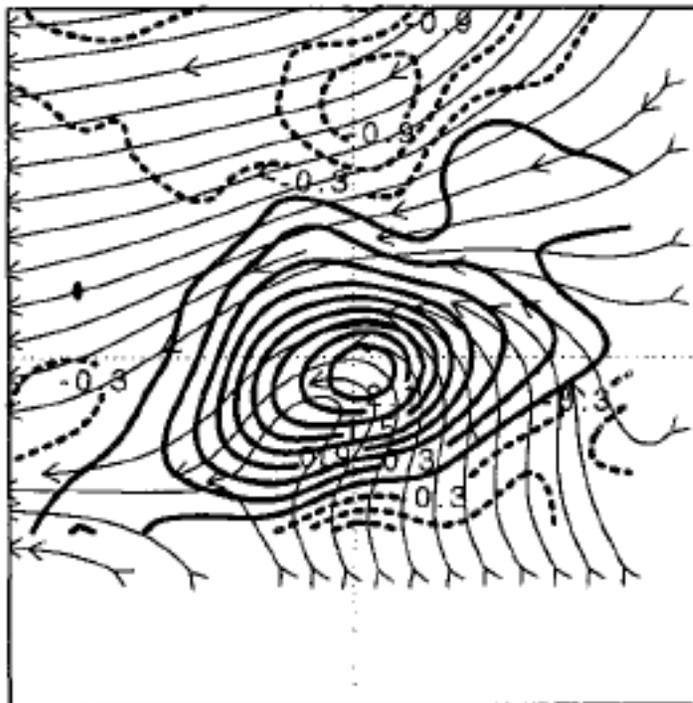
As discussed in Rappin and Nolan (2011).

- Was there something wrong with Tuleya and Kurihara (1981)?

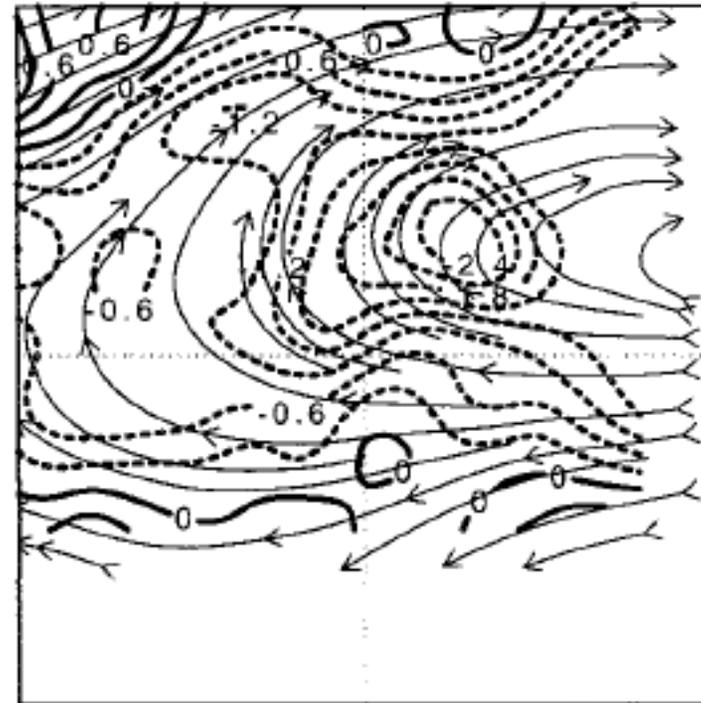


- If easterly shear really is more favorable, it may be because of other associated factors:

- \* Easterly shear may be more often associated with a nearby upper-level anticyclone, as shown in the composite by Bracken and Bosart (2000):

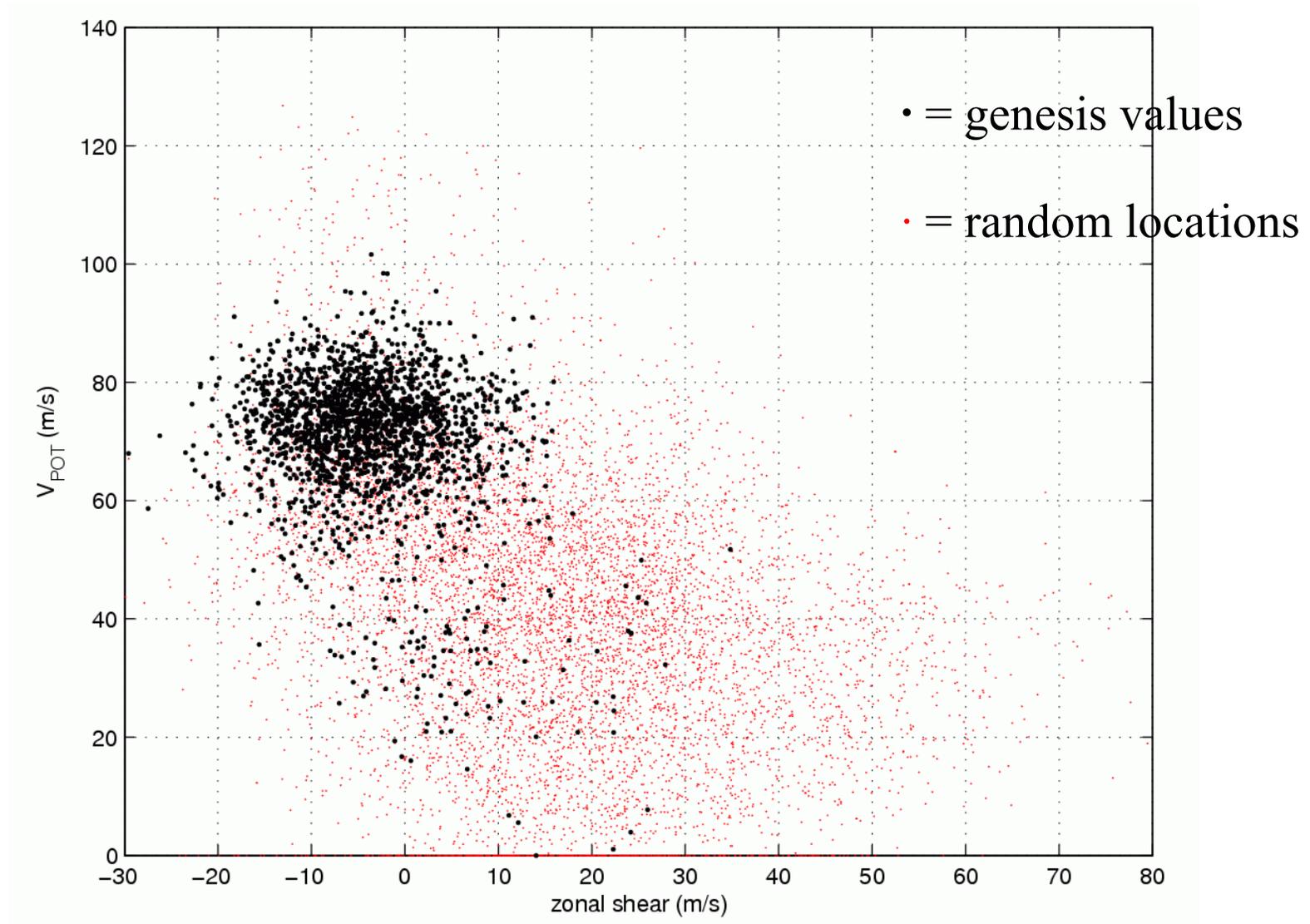


c. ATOLL level Cape Verde cases



d. 200 hPa Cape Verde cases

- \* Easterly shear happens more often at low latitudes, and in the Pacific, which are both thermodynamically more favorable



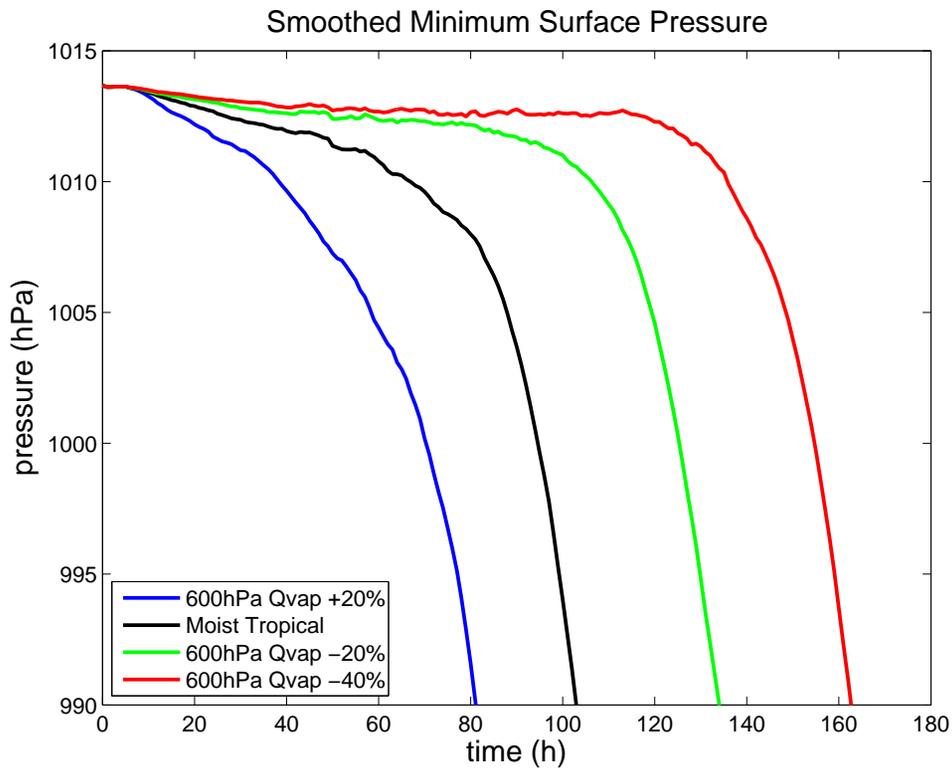
# Summary

- The vast majority of tropical cyclones form in weak or moderate shear.

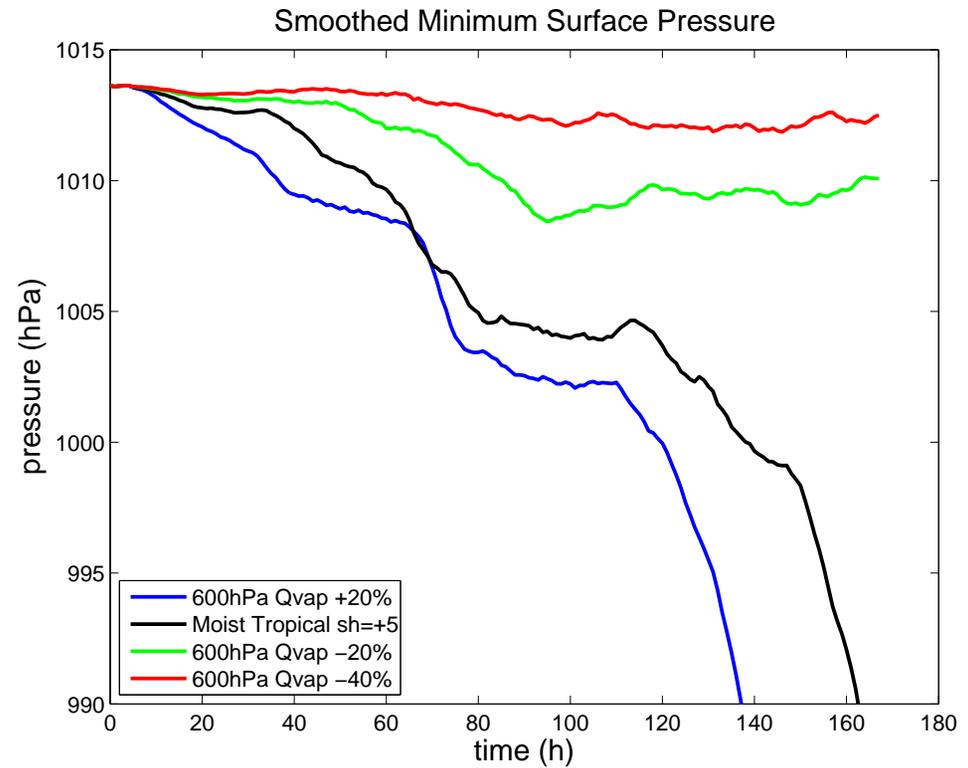
Theories of genesis will be incomplete until the interaction with shear is incorporated.

- As previously proposed, it does appear that shear helps to “organize the convection” and accelerates the formation of a more coherent low-level circulation.
- But, further development requires a local reduction of shear and alignment of the surface vortex and MCV.
- The relative effects of easterly versus westerly shear, or shear with or against the motion, in the real world, remain unresolved.

- Wind shear is the mechanism by which a tropical disturbance feels the favorableness, or unfavorableness, of the environment.



without wind shear



with wind shear