The Enduring Enigma of Tropical Cyclones and Climate

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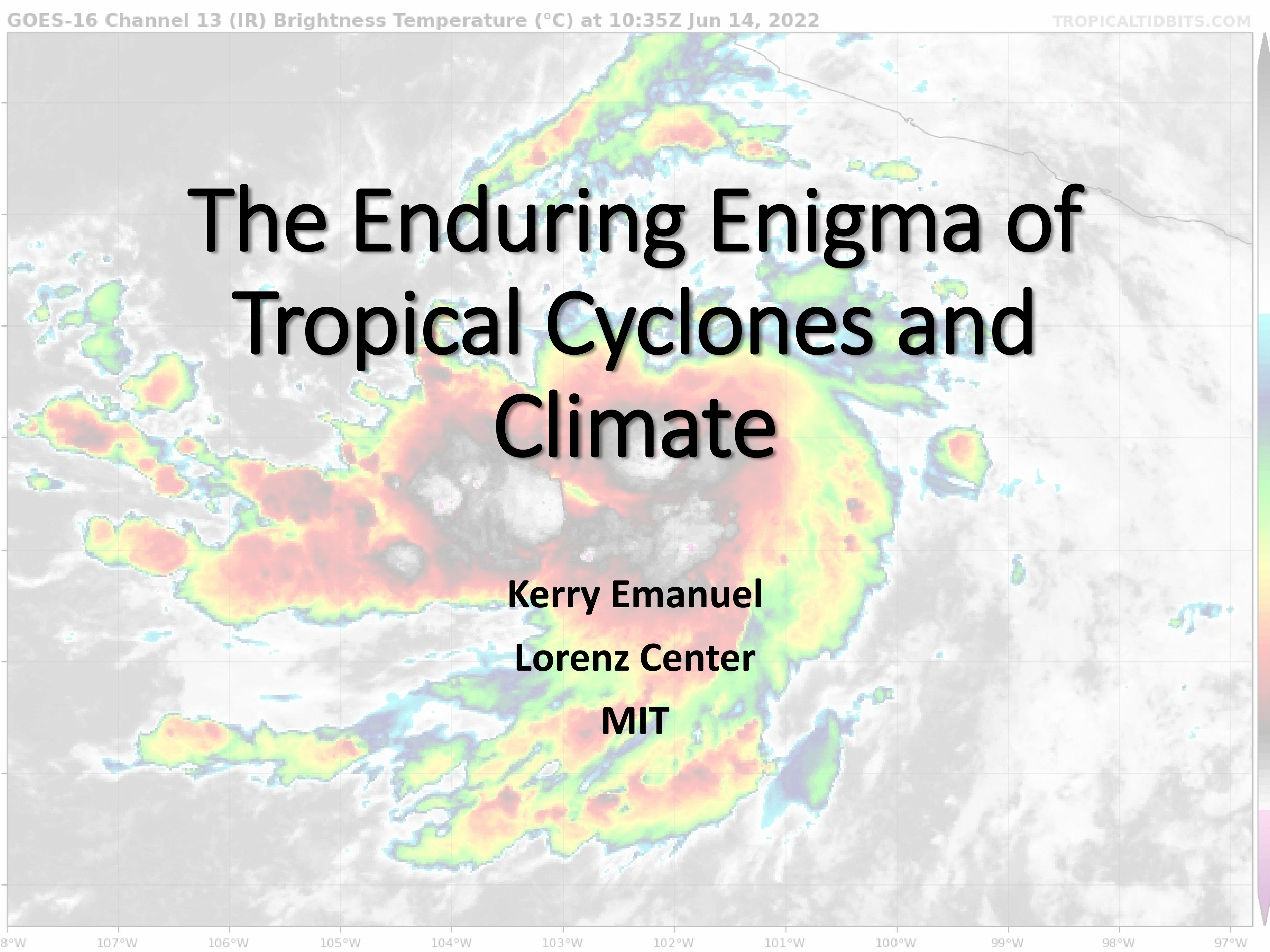


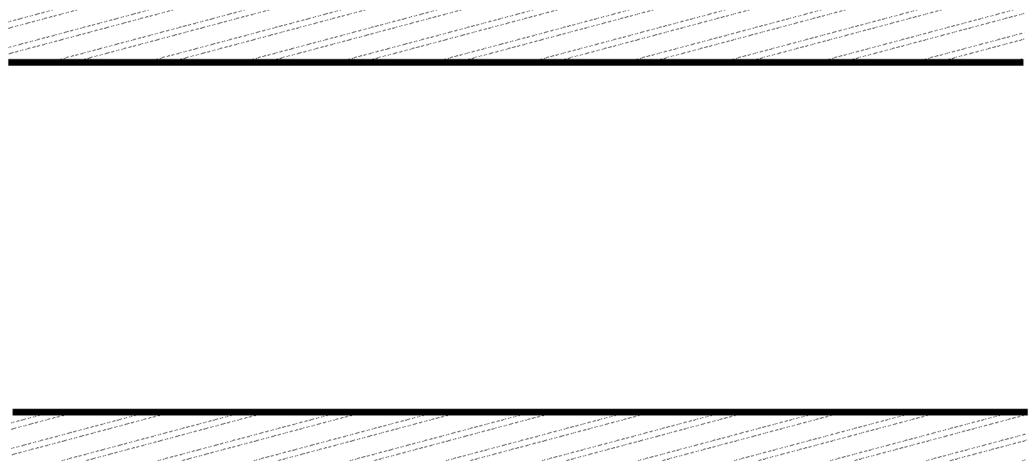
Program

- What distinguishes tropical cyclones from other forms of convection
- What we know about tropical cyclone intensity and rainfall
- History of genesis research
- The genesis enigma
- Summary

Program

- What distinguishes tropical cyclones from other forms of convection

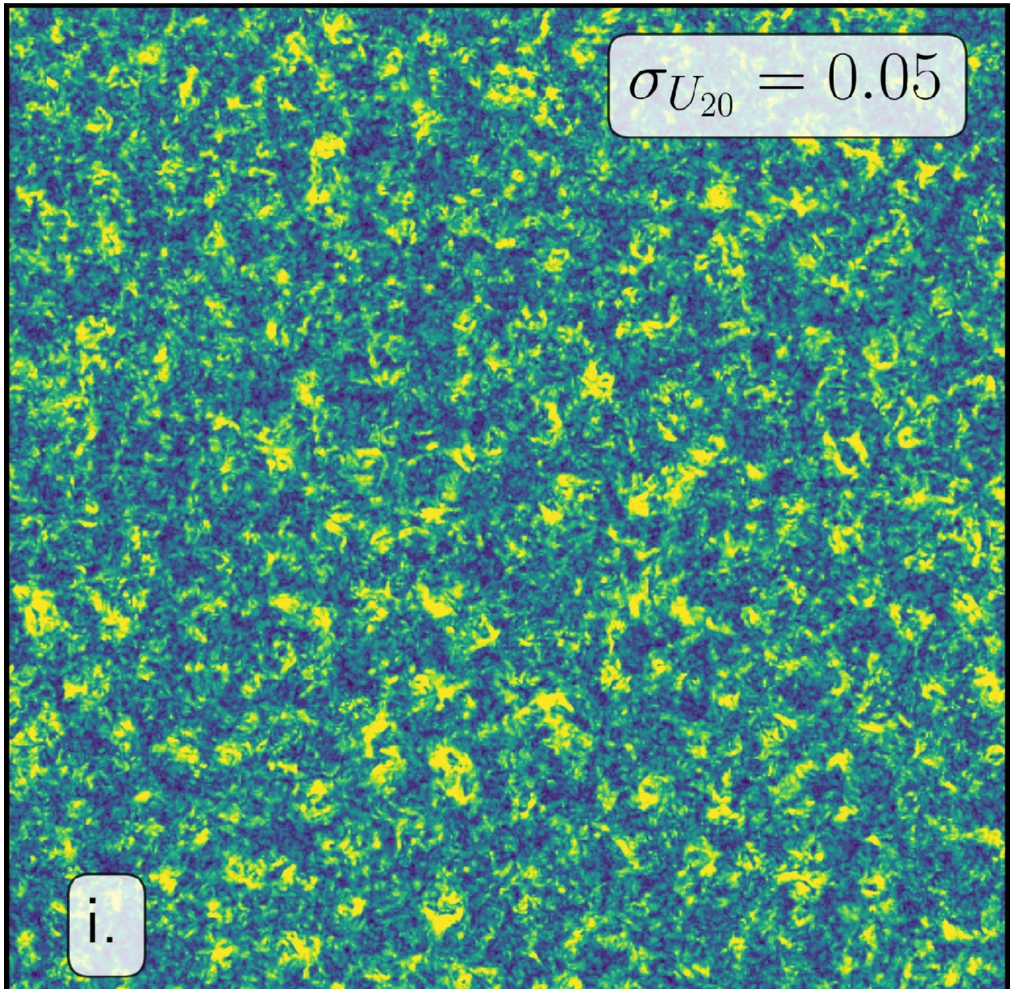
Back to Basics: Parallel-Plate Convection



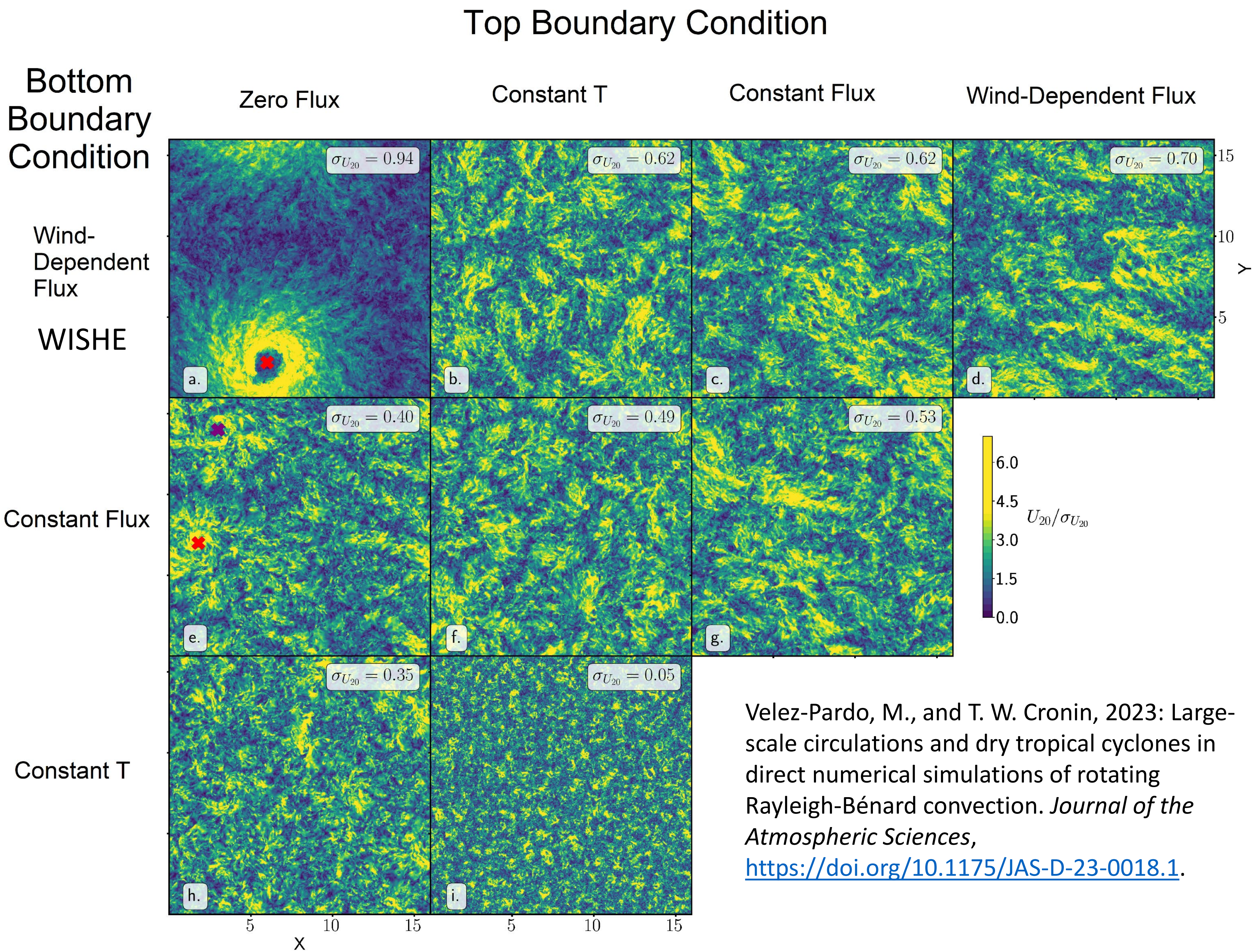
- Three types of boundary conditions:
  - Constant temperature (Rayleigh, 1916)
  - Constant heat flux
  - Aerodynamic (rough boundaries)

$$F = C_k \, |\mathbf{V}| \left(T_{boundary} - T_{fluid} \right)$$

Classical case with rotation (*f*)



Horizontal wind speed at 20% of domain height



Velez-Pardo, M., and T. W. Cronin, 2023: Large-scale circulations and dry tropical cyclones in direct numerical simulations of rotating Rayleigh-Bénard convection. *Journal of the Atmospheric Sciences*, https://doi.org/10.1175/JAS-D-23-0018.1.

Tropical cyclones are driven by wind-dependent lower boundary heat fluxes. They are NOT driven by latent heat release in clouds.

Program

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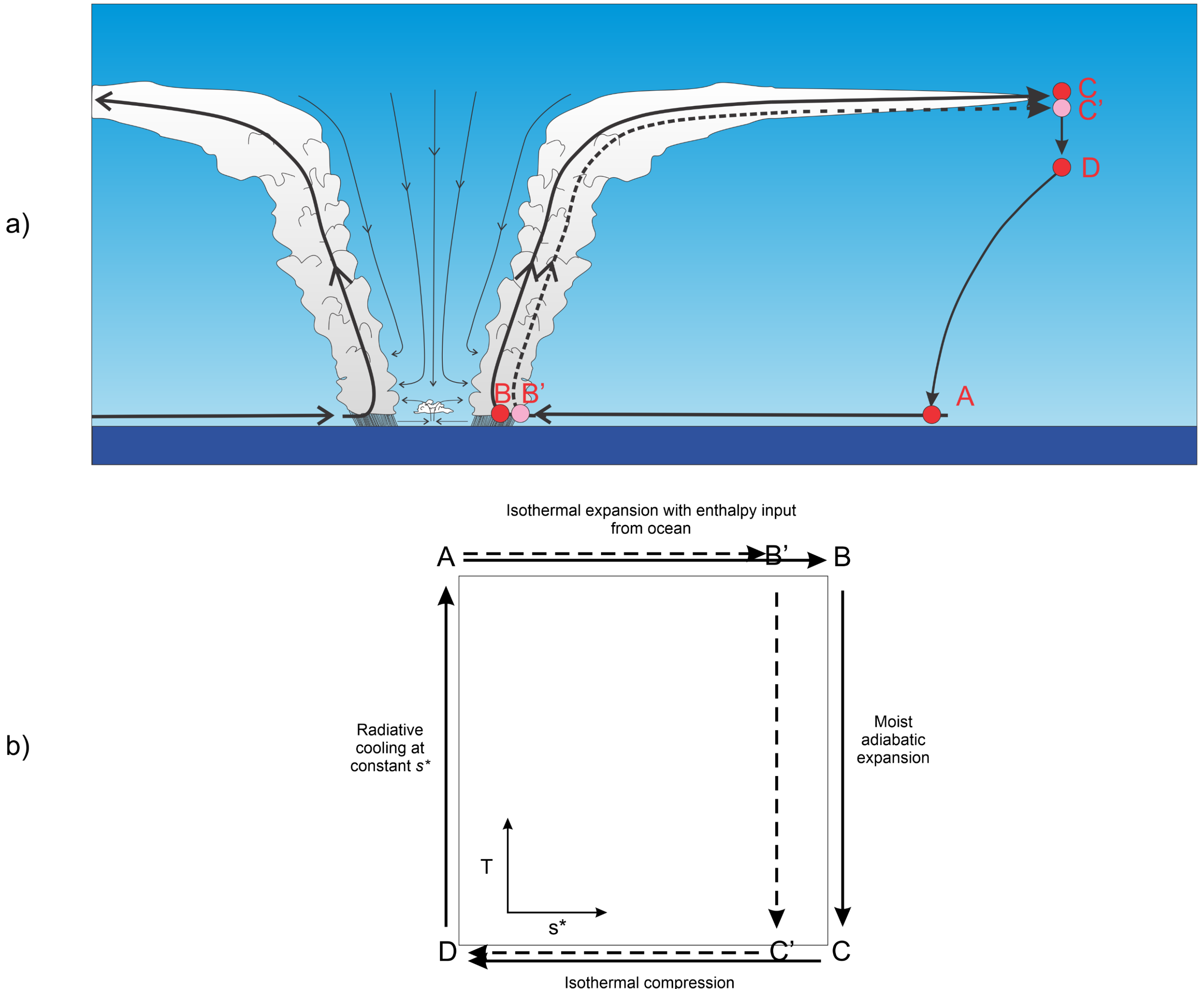
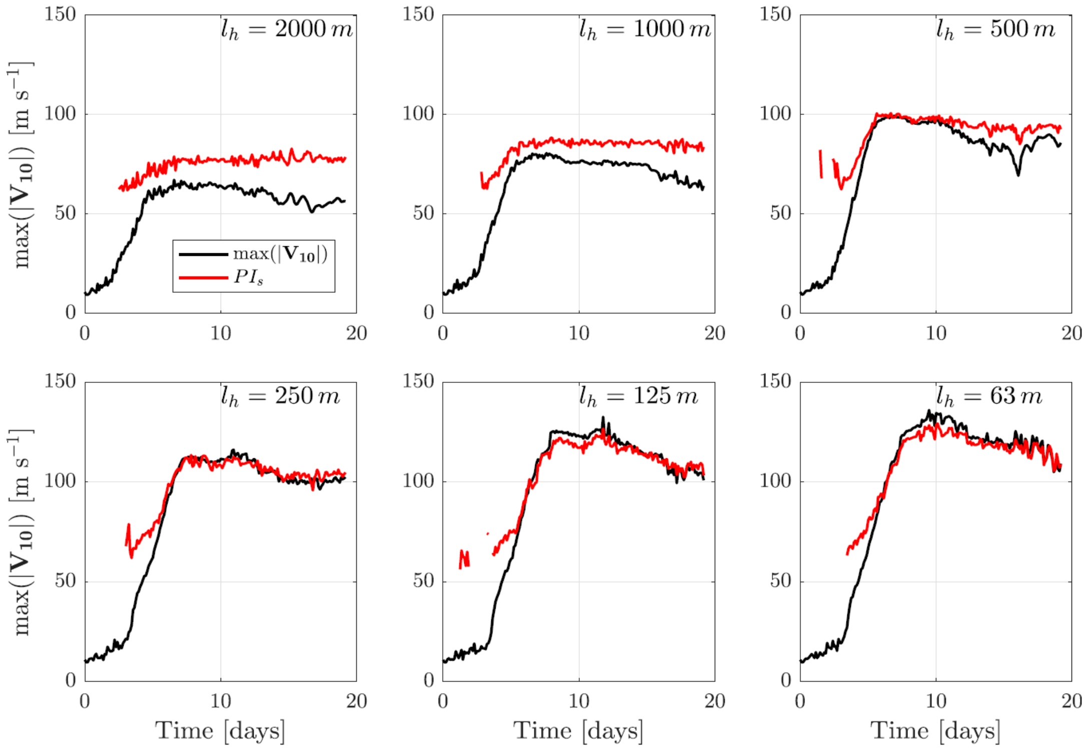


a)
C
C'
D
B
B'
A
b)
Isothermal expansion with enthalpy input from ocean
A
B'
B
Radiative cooling at constant s*
Moist adiabatic expansion
T
s*
D
C'
C
Isothermal compression

Potential Intensity

$$V_{pot}^2 = \left(\frac{1}{2}\frac{C_k}{C_D}\right)^{\frac{\frac{C_k}{C_D}}{2-\frac{C_k}{C_D}}} \frac{C_k}{C_D}\left(T_b - T_t\right)\left(s_0{}^* - s_e{}^*\right)$$

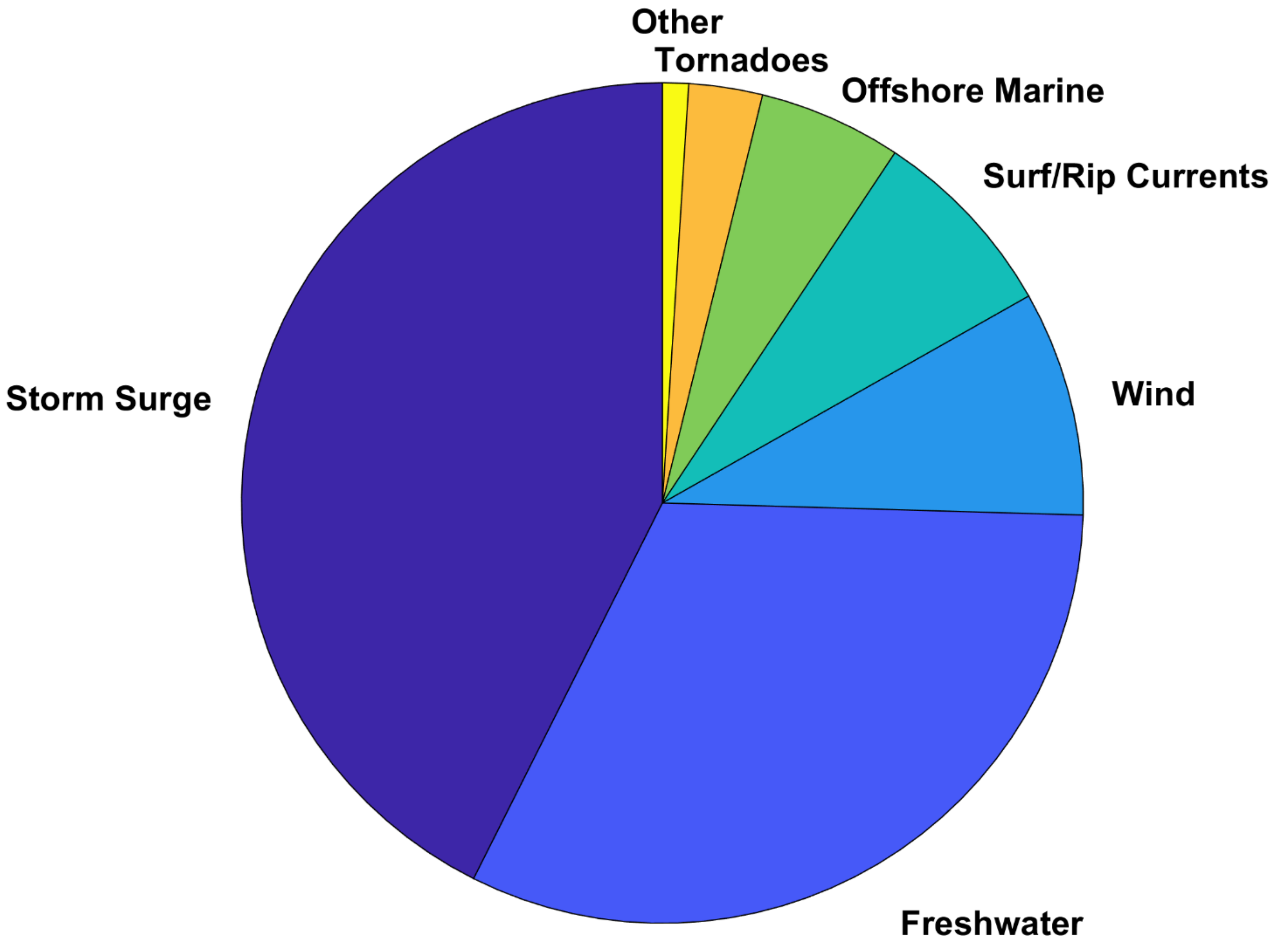


Rousseau-Rizzi, R., and K. Emanuel, 2019: An evaluation of hurricane superintensity in axisymmetric numerical models. *Journal of the Atmospheric Sciences*, **76**, 1697–1708, https://doi.org/10.1175/jas-d-18-0238.1.

Rainfall

- Responsible for large mortality and damage in tropical cyclones
- Increases *at least* as fast as Clausius-Clapeyron (6% K^{-1})

U.S. Hurricane Fatalities, 1963-2022



Program

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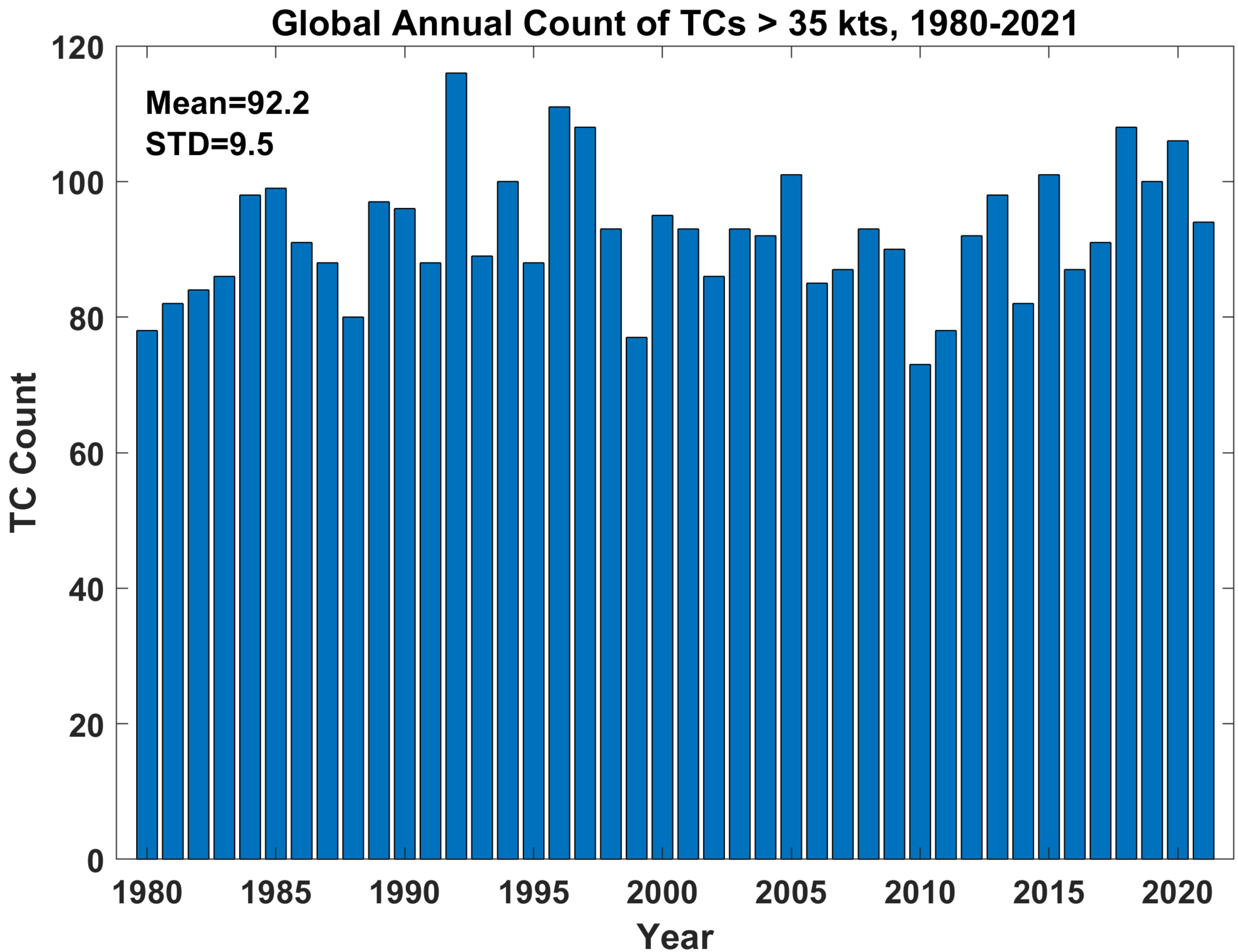
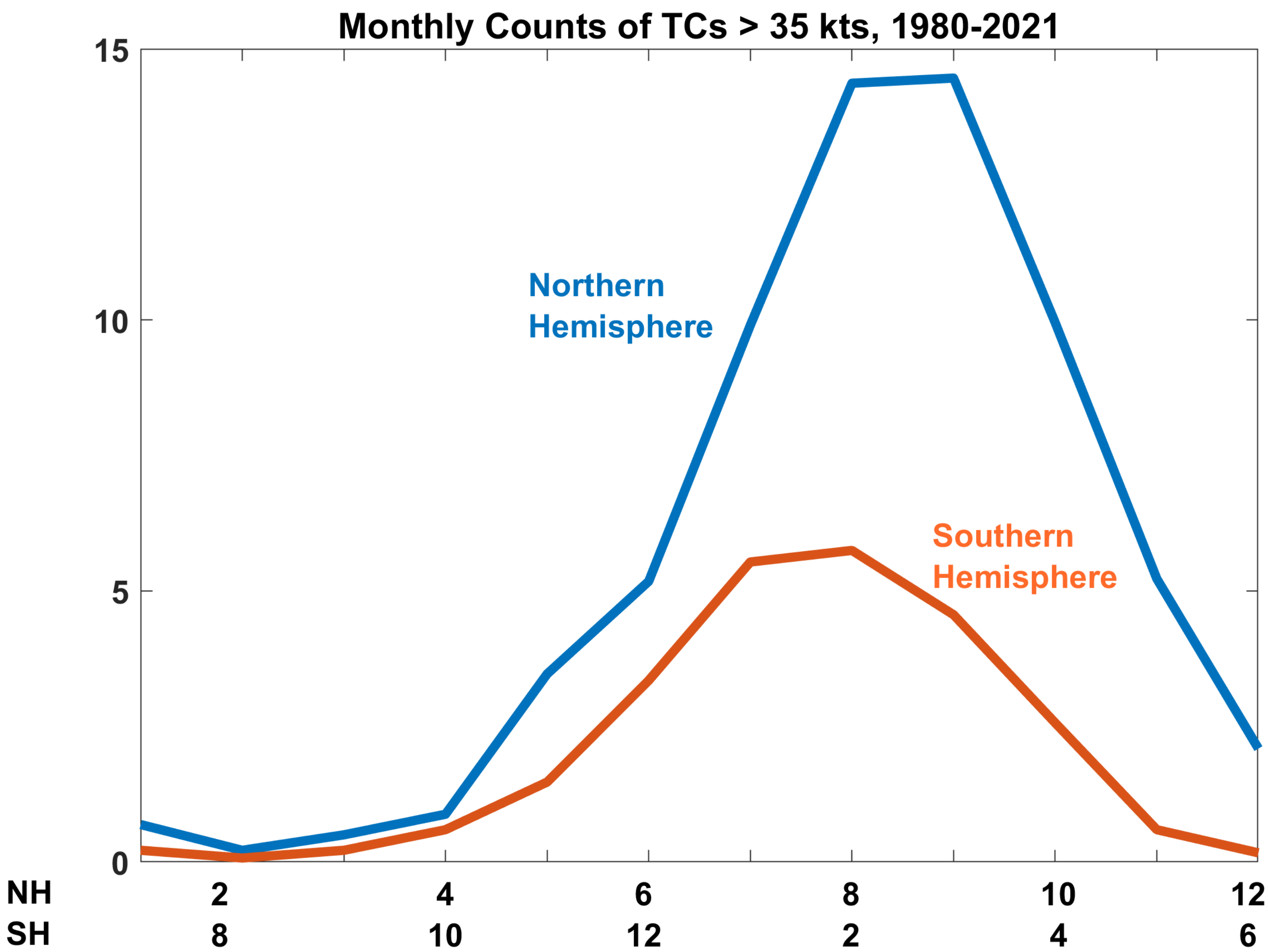
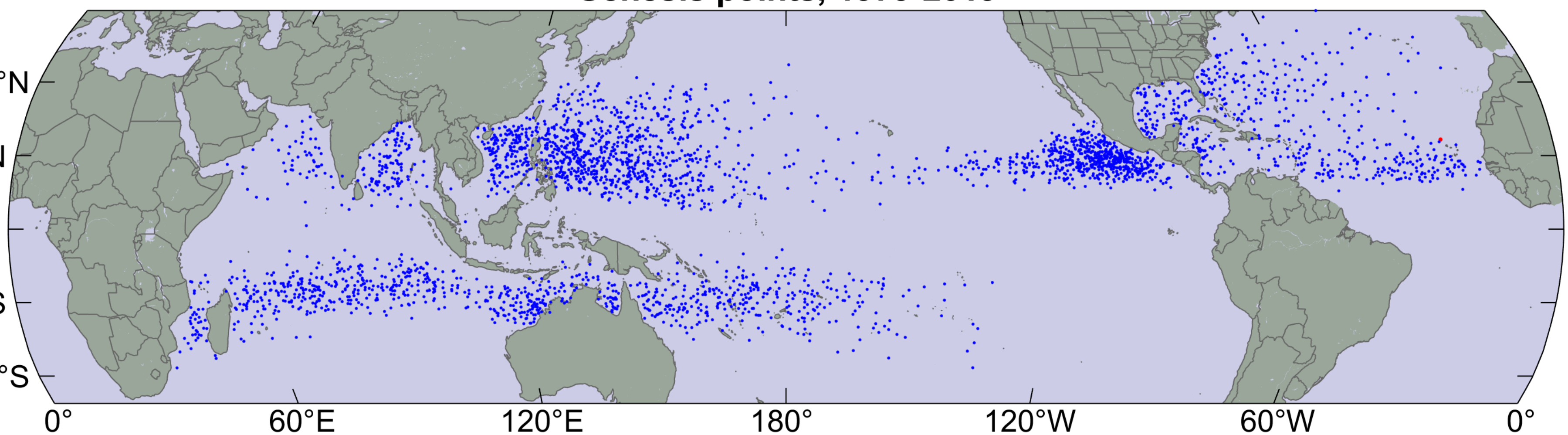
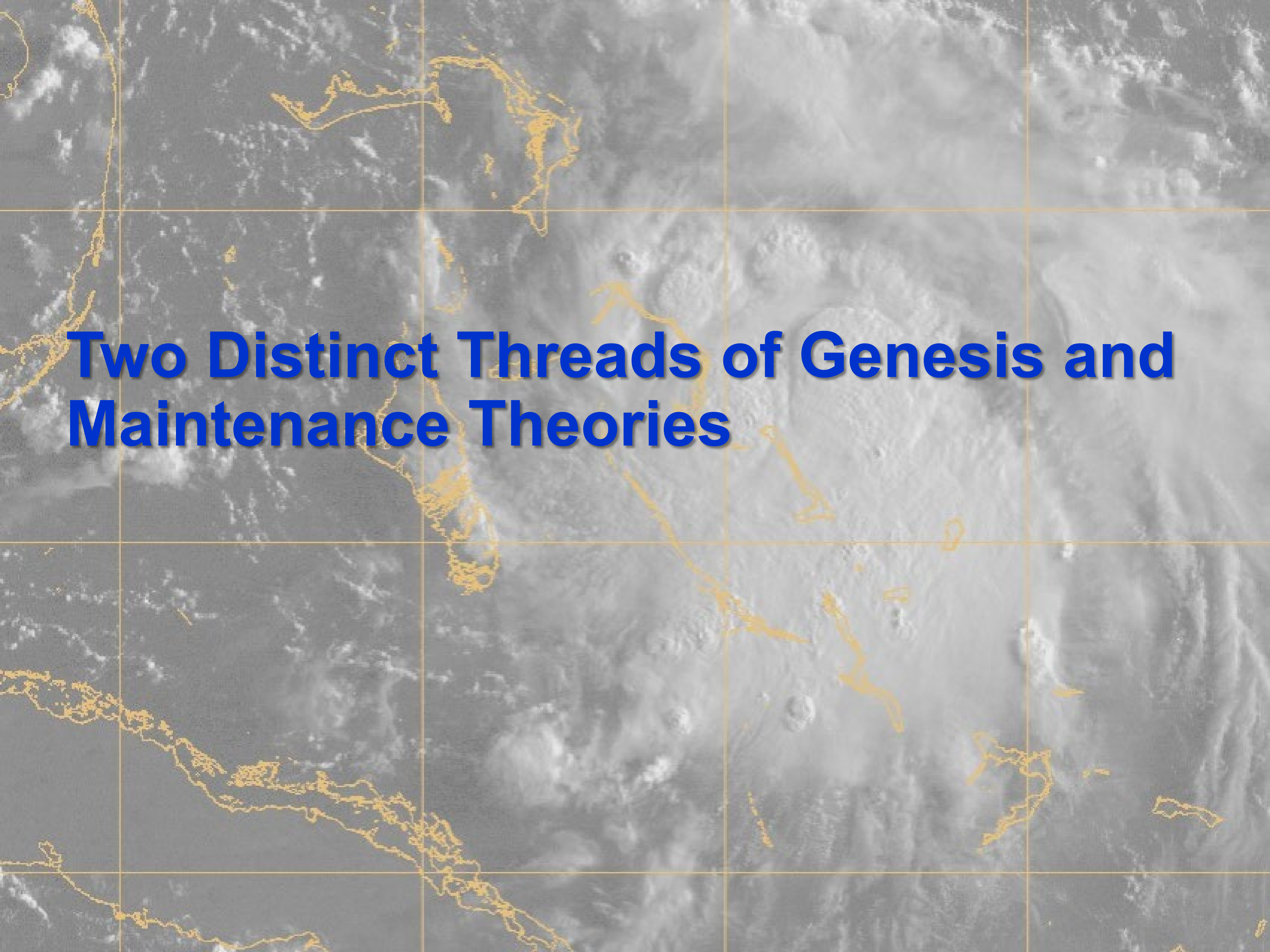

Global Annual Count of TCs > 35 kts, 1980-2021
Mean=92.2
STD=9.5
TC Count
Year
0
20
40
60
80
100
120
1980
1985
1990
1995
2000
2005
2010
2015
2020


Monthly Counts of TCs > 35 kts, 1980-2021
15
10
5
0
Northern Hemisphere
Southern Hemisphere
NH
SH
2
8
4
10
6
12
8
2
10
4
12
6

Genesis points, 1979-2019



Two Distinct Threads of Genesis and Maintenance Theories



- **TC formation as a mode of release of conditional instability**

  - Espy (1841), *The Philosophy of Storms*
  - Palmén (1948), *On the formation and structure of tropical hurricanes*
  - Charney and Eliassen (1964): *On the growth of the hurricane depression*
  - Yamasaki (1968): *Numerical simulation of tropical cyclone development with the use of primitive equations*

Example:

Numerous cumulonimbus clouds warm and gradually moisten their environment. This warming…produces a pressure fall at the surface, because warm air weighs less than cool air. The slowly converging horizontal winds near the surface respond to this slight drop of pressure by accelerating inward. But the increased inflow produces increased lifting, so that the thunderstorms become more numerous and intense. The feedback loop is now established.

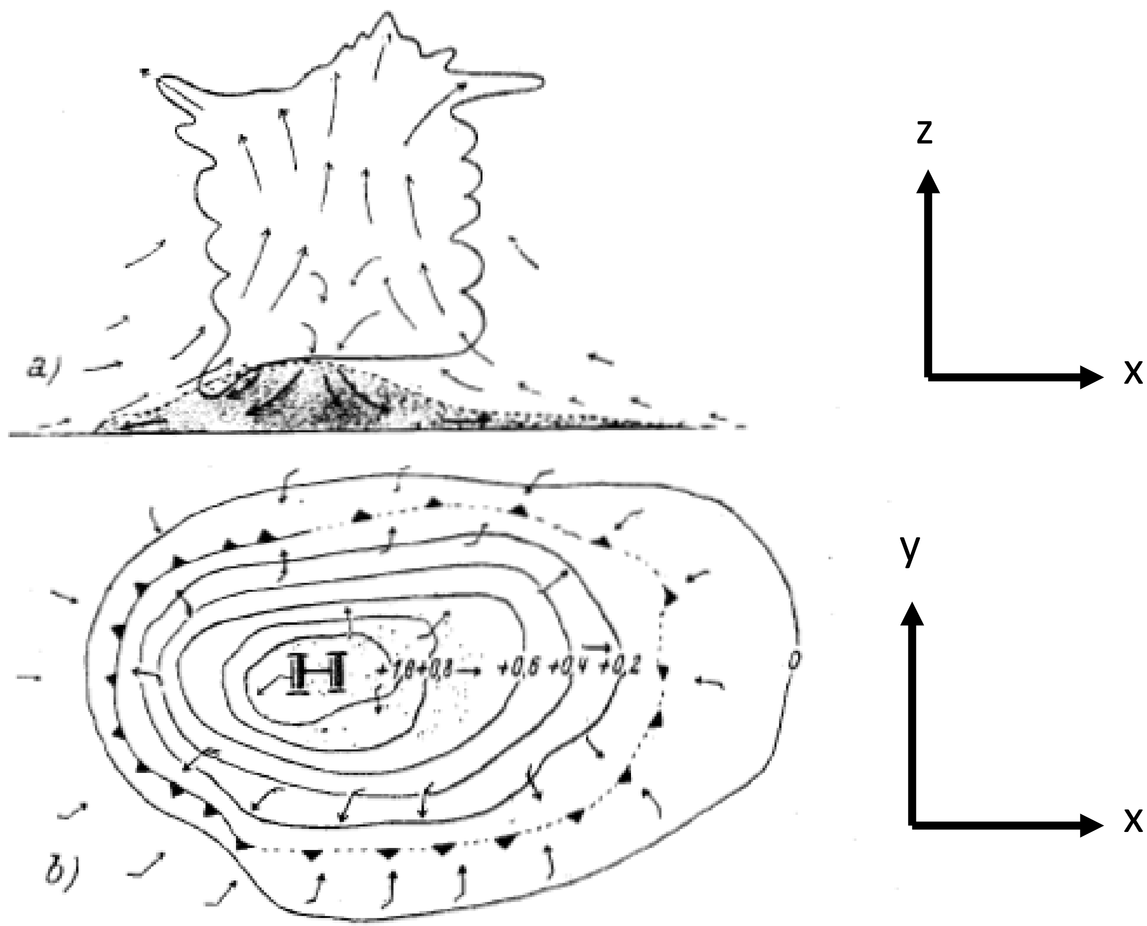
-- from a textbook published in the late 1970s

Already in 1901 Julius von Hann voiced an objection:

"Since a thundercloud does not give any appreciable pressure fall [at the surface] but even a pressure rise, it would be unreasonable to assume that a magnifying of this process would cause the strongest pressure falls known"

-- As paraphrased by Bergeron, QJRMS, 1954

Diagram from Bergeron, QJRMS, 1954



- **TC formation as a surface flux-driven phenomenon**
  - Riehl (1950): *A model for hurricane formation*
  - Kleinschmidt (1951): *Principles of the theory of tropical cyclones (in German)*
  - Ooyama (1969): *Numerical simulation of the life cycle of tropical cyclones* (Note: A foot in both camps)
  - Rosenthal (1971): *The response of a tropical cyclone model to variations in boundary layer parameters, initial conditions, lateral boundary conditions, and domain size*
  - Gray (1975): *Tropical Cyclone Genesis. (First to note role of cloud-radiation interactions)*

Example:

The heat removed from the sea by the storm is the basic energy source of typhoon. In comparison to it, the latent heat of the water vapor, which the air carries with it from the outside, plays no more than a secondary role.

- Ernst Kleinschmidt, 1951

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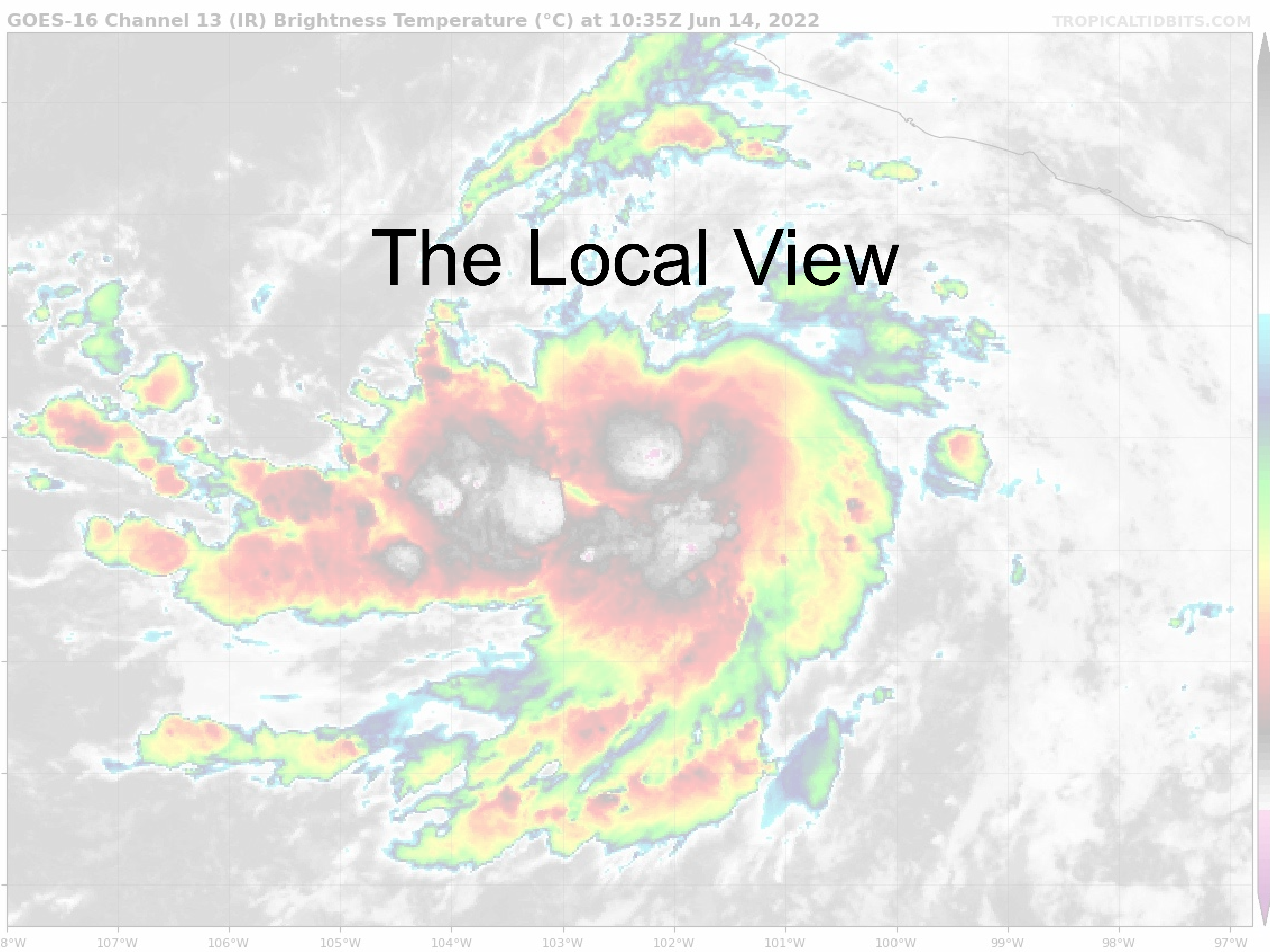
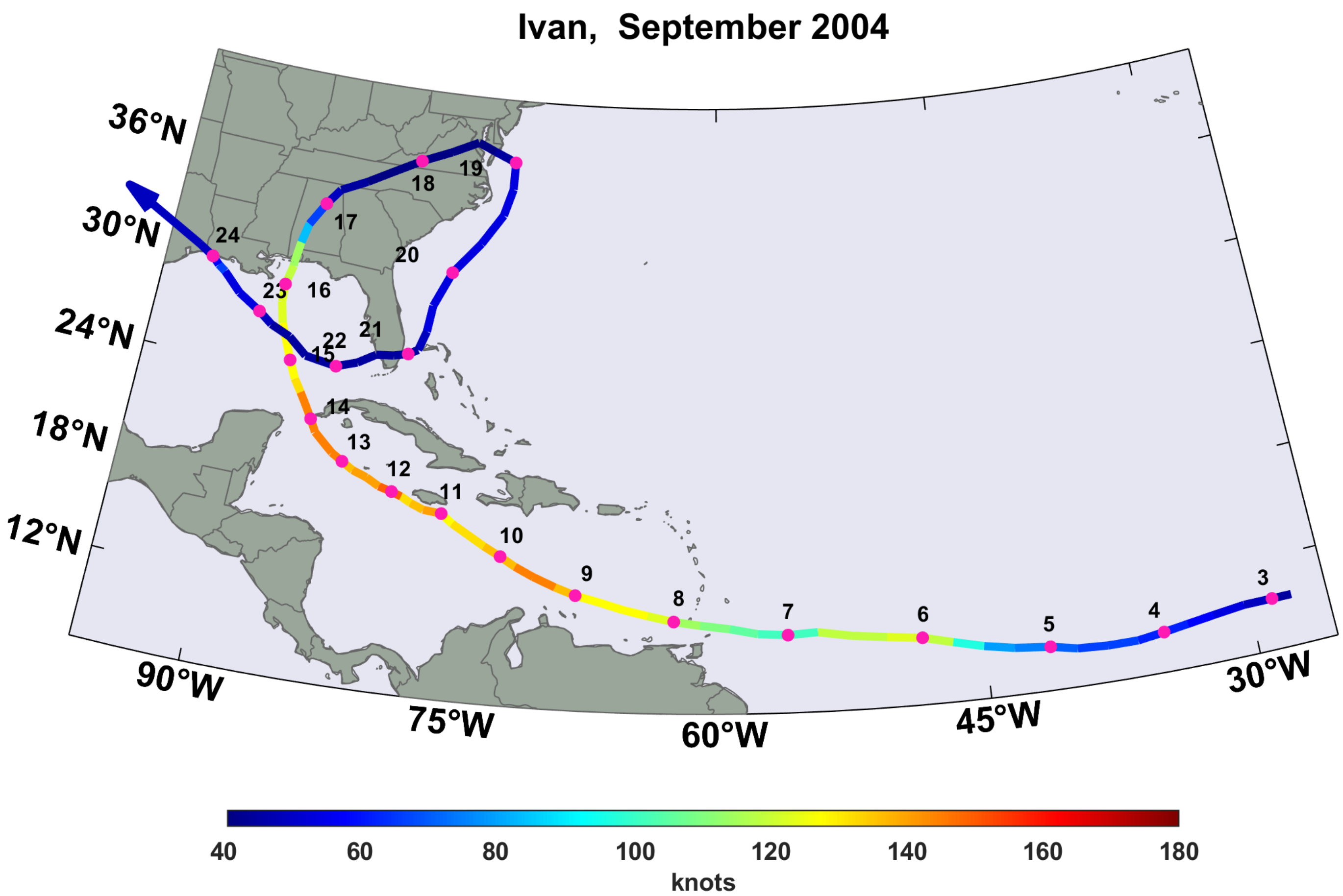
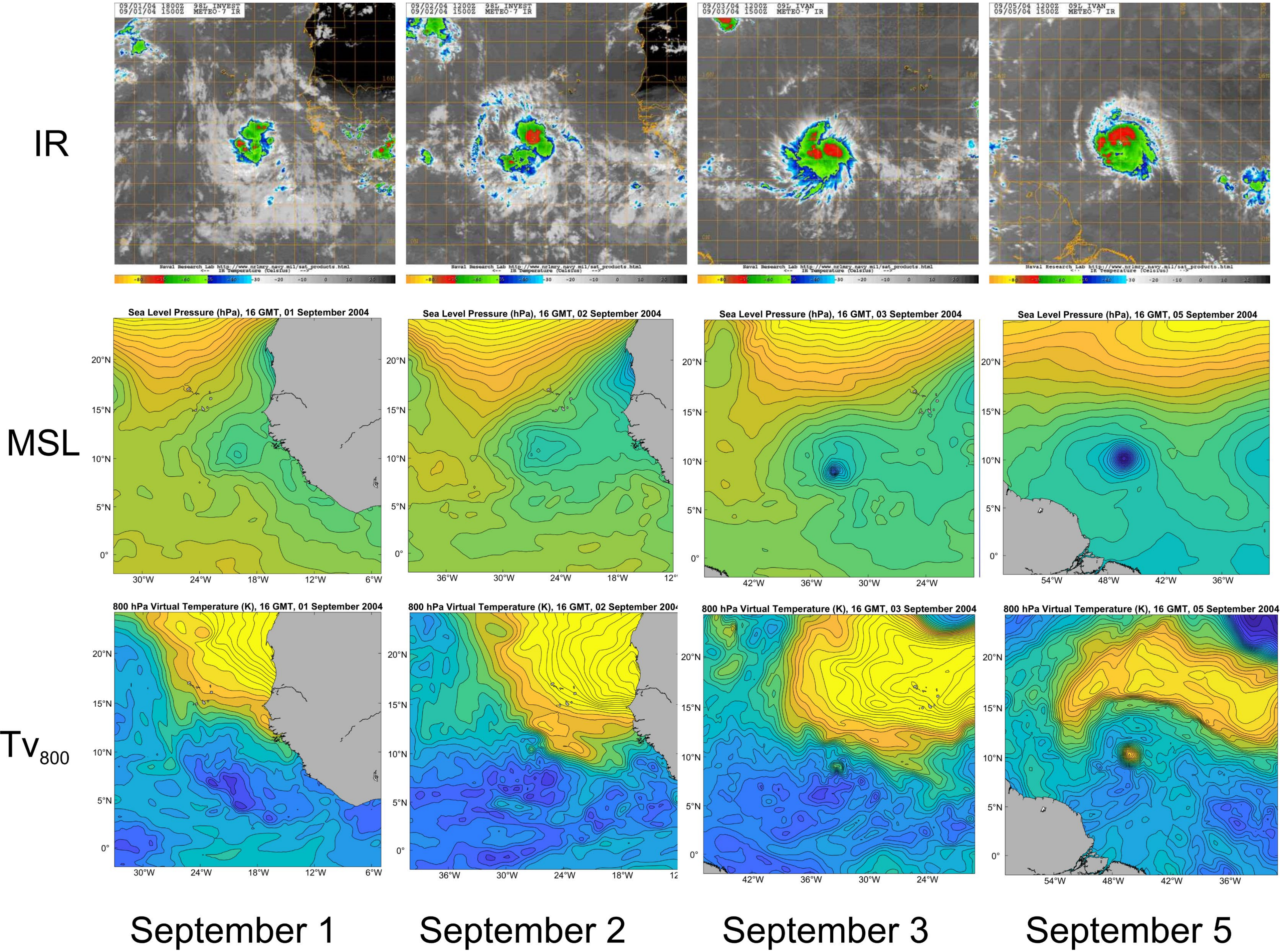
The Local View

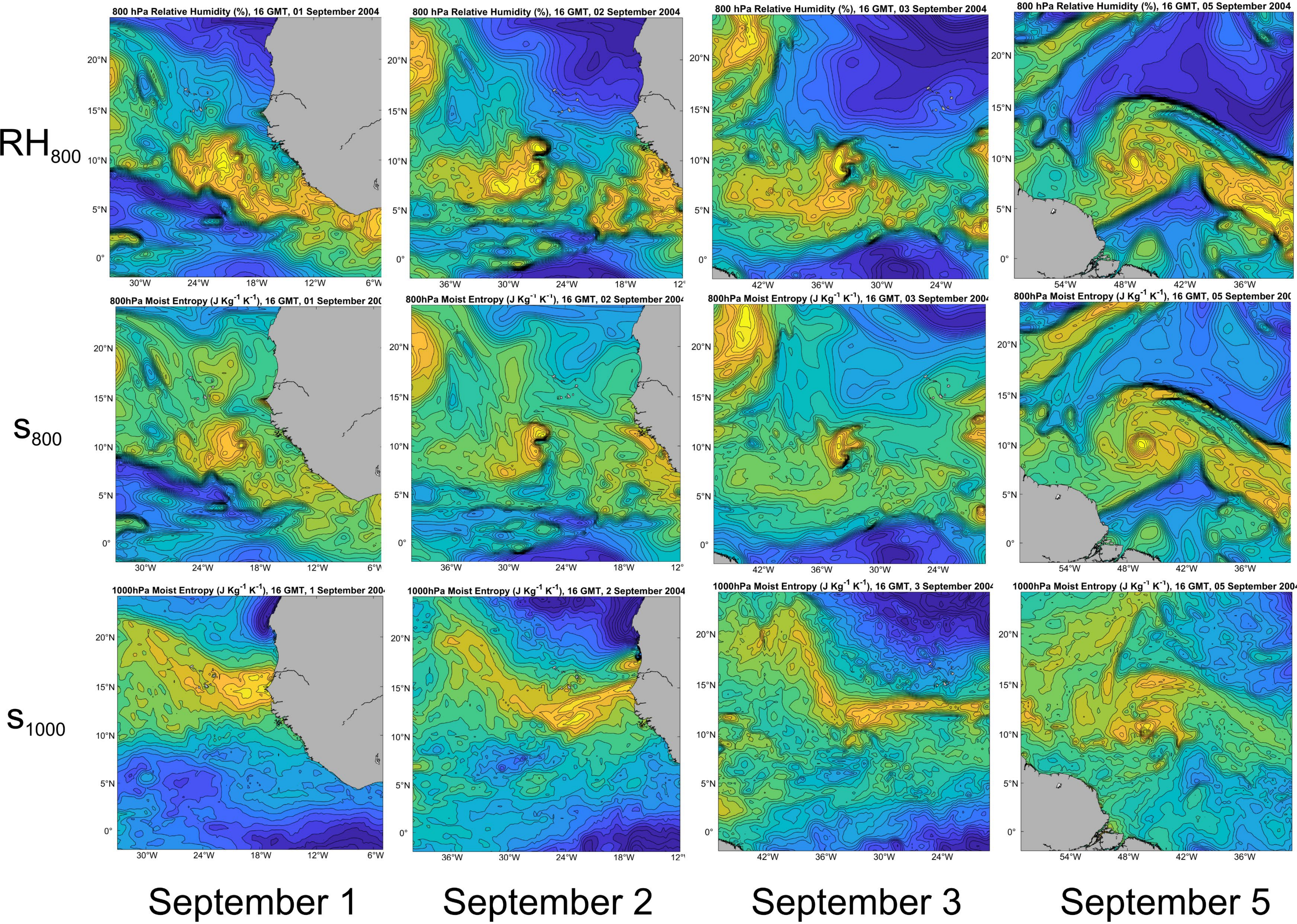


Case Study: Hurricane Ivan, 2004





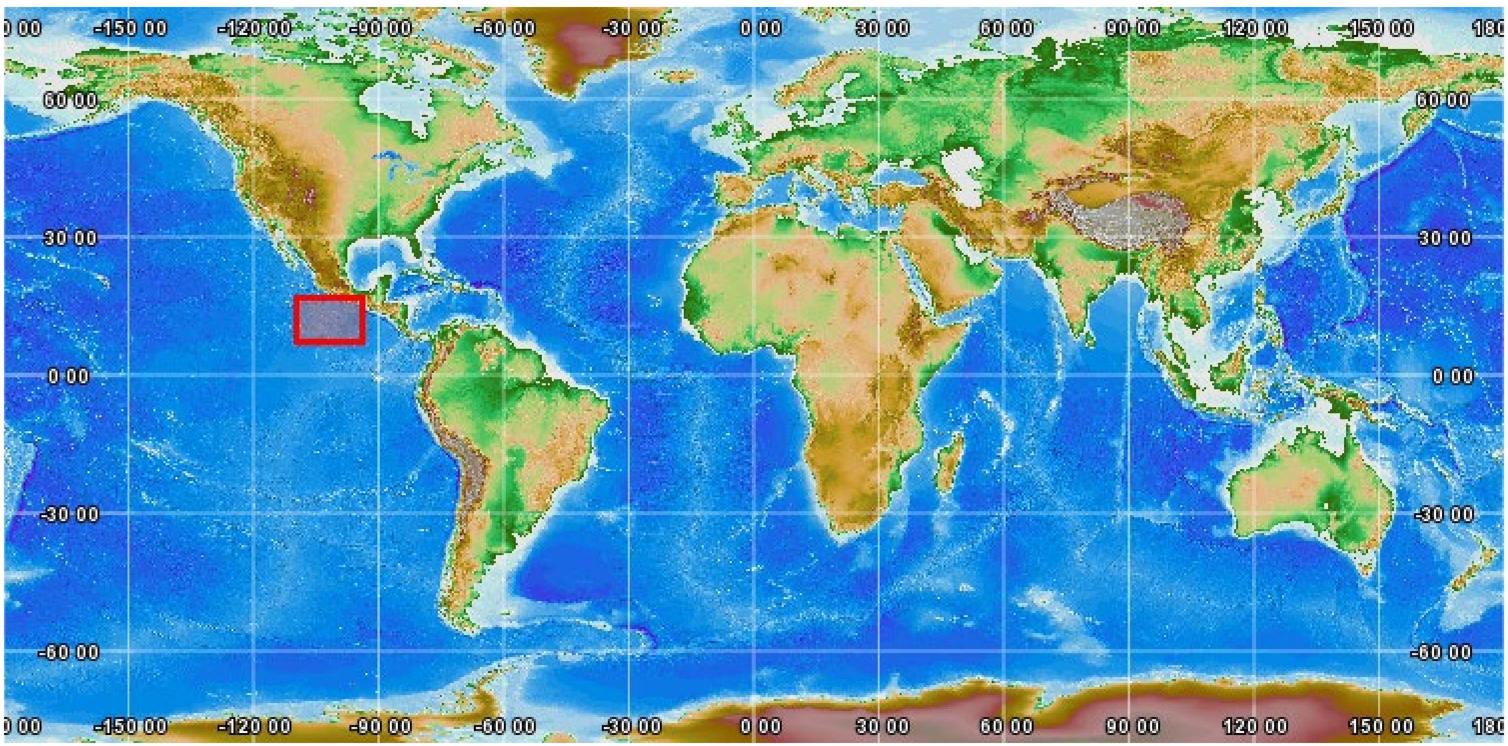
IR
MSL
Tv800
09/01/04 1800Z 98L INVEST
09/01/04 1500Z METEO-7 IR
09/02/04 1200Z 98L INVEST
09/02/04 1500Z METEO-7 IR
09/03/04 1200Z 09L IVAN
09/03/04 1500Z METEO-7 IR
09/05/04 1200Z 09L IVAN
09/05/04 1500Z METEO-7 IR
Naval Research Lab http://www.nrlmry.navy.mil/sat_products.html
IR Temperature (Celsius)
Sea Level Pressure (hPa), 16 GMT, 01 September 2004
Sea Level Pressure (hPa), 16 GMT, 02 September 2004
Sea Level Pressure (hPa), 16 GMT, 03 September 2004
Sea Level Pressure (hPa), 16 GMT, 05 September 2004
800 hPa Virtual Temperature (K), 16 GMT, 01 September 2004
800 hPa Virtual Temperature (K), 16 GMT, 02 September 2004
800 hPa Virtual Temperature (K), 16 GMT, 03 September 2004
800 hPa Virtual Temperature (K), 16 GMT, 05 September 2004
20°N
15°N
10°N
5°N
0°
30°W
24°W
18°W
12°W
6°W
36°W
42°W
54°W
48°W
September 1
September 2
September 3
September 5



800 hPa Relative Humidity (%), 16 GMT, 01 September 2004
800 hPa Relative Humidity (%), 16 GMT, 02 September 2004
800 hPa Relative Humidity (%), 16 GMT, 03 September 2004
800 hPa Relative Humidity (%), 16 GMT, 05 September 2004
800hPa Moist Entropy (J Kg-1 K-1), 16 GMT, 01 September 200
800hPa Moist Entropy (J Kg-1 K-1), 16 GMT, 02 September 2004
800hPa Moist Entropy (J Kg-1 K-1), 16 GMT, 03 September 2004
800hPa Moist Entropy (J Kg-1 K-1), 16 GMT, 05 September 200
1000hPa Moist Entropy (J Kg-1 K-1), 16 GMT, 1 September 2004
1000hPa Moist Entropy (J Kg-1 K-1), 16 GMT, 2 September 2004
1000hPa Moist Entropy (J Kg-1 K-1), 16 GMT, 3 September 2004
1000hPa Moist Entropy (J Kg-1 K-1), 16 GMT, 05 September 2004
RH800
s800
s1000
September 1
September 2
September 3
September 5

Tropical Experiment in Mexico (TEXMEX)

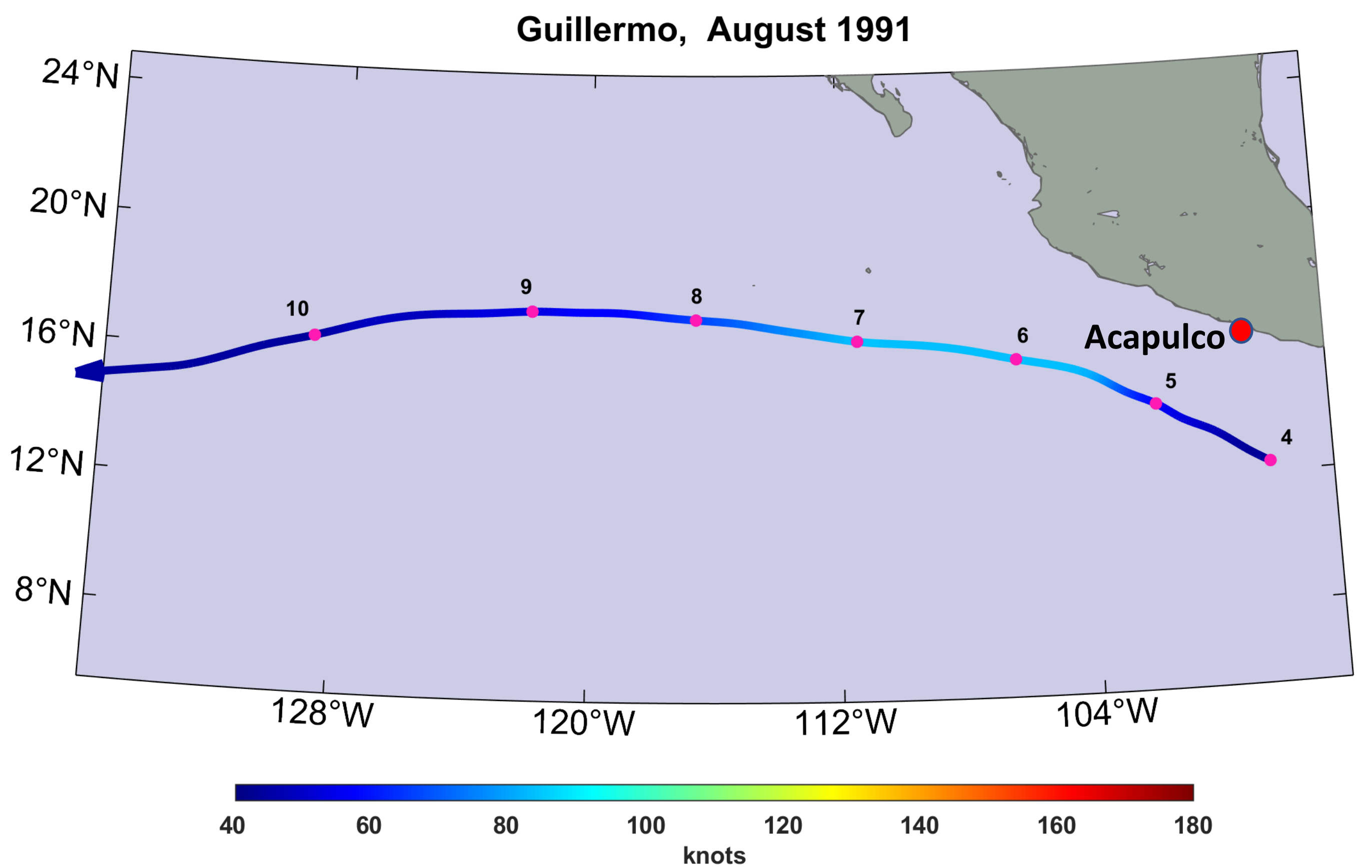
Summer of 1991



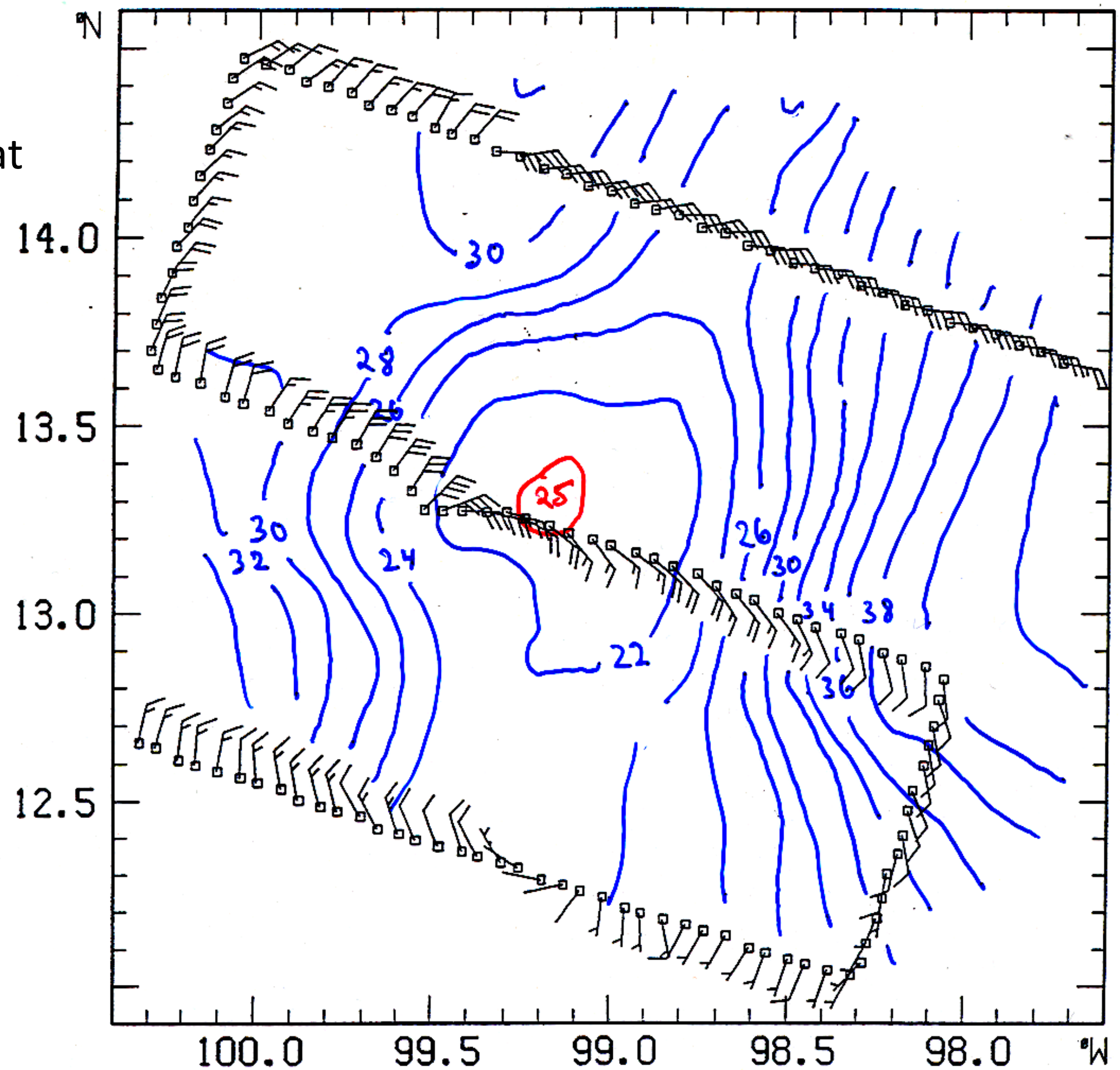
NSF/NCAR Lockheed Electra

NOAA Lockheed P3 Orion

Genesis of Eastern North Pacific Hurricane Guillermo, August, 1991

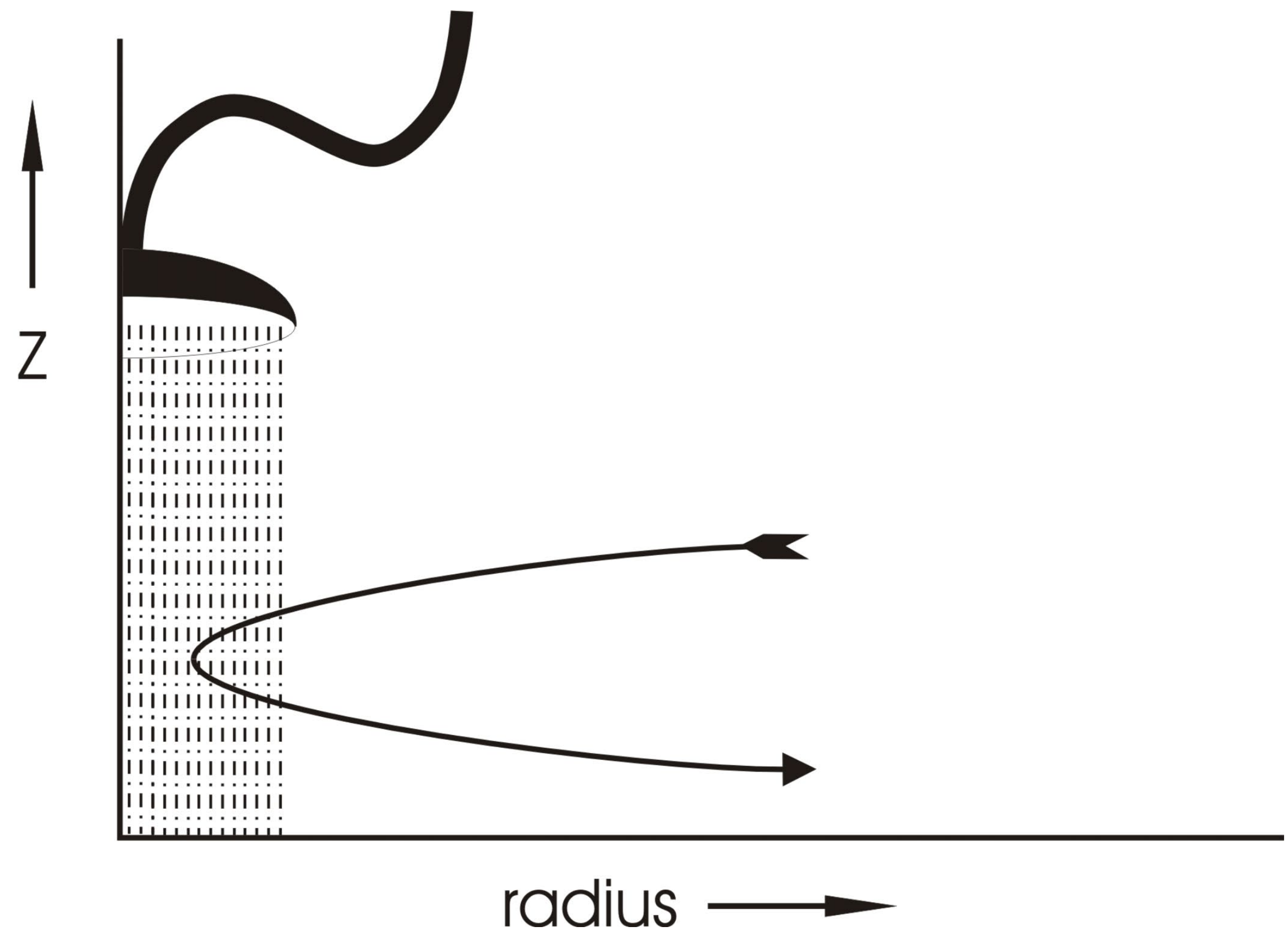


Flight level winds at 975 hPa and temperature (blue in tenths + 20)
August 4 1991
08-10 UTC

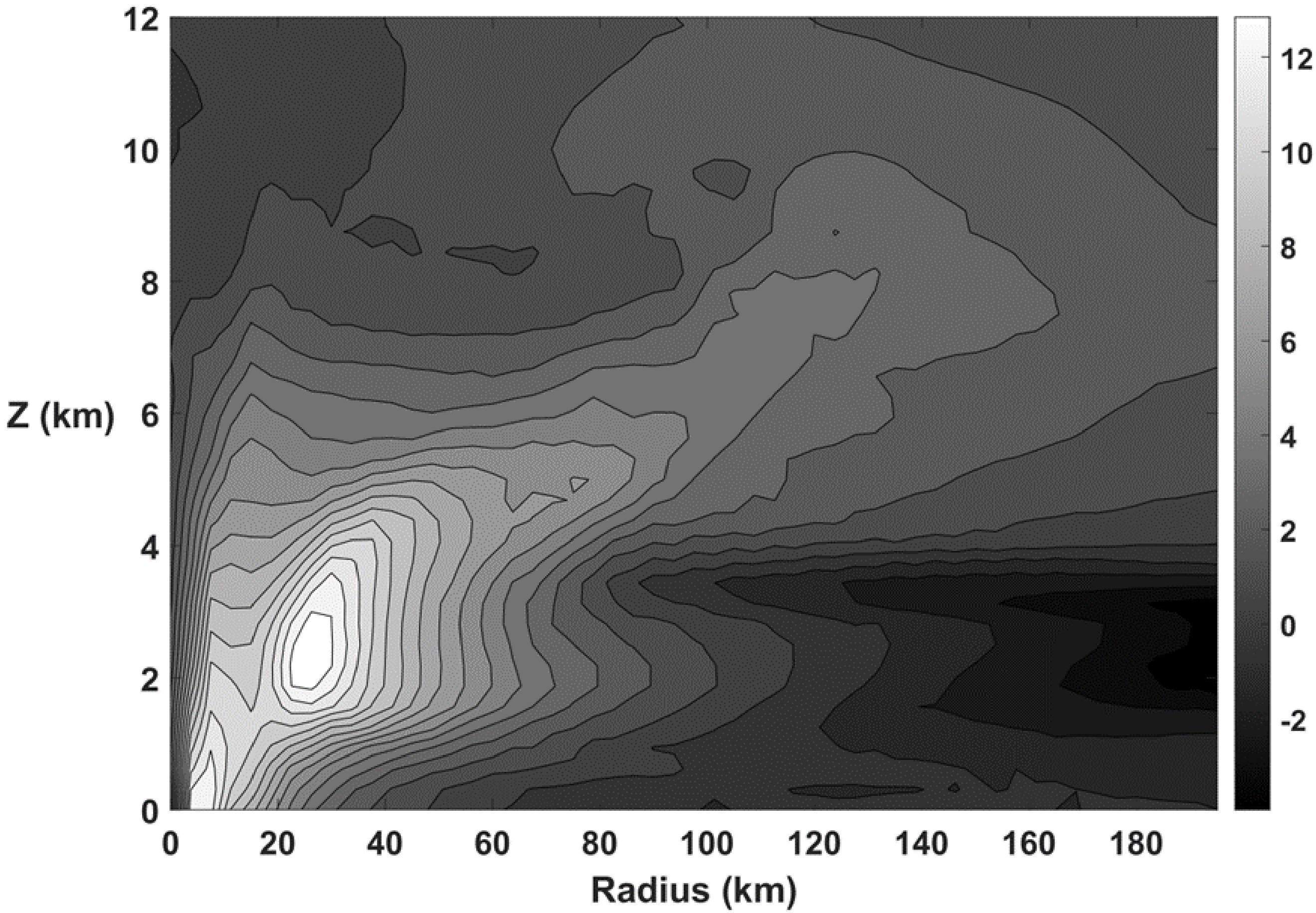


Analysis by Marja Bister
And K. Emanuel

Configuration of a “showerhead” inserted into the center of the nonhydrostatic, axisymmetric model of Rotunno and Emanuel (1987)

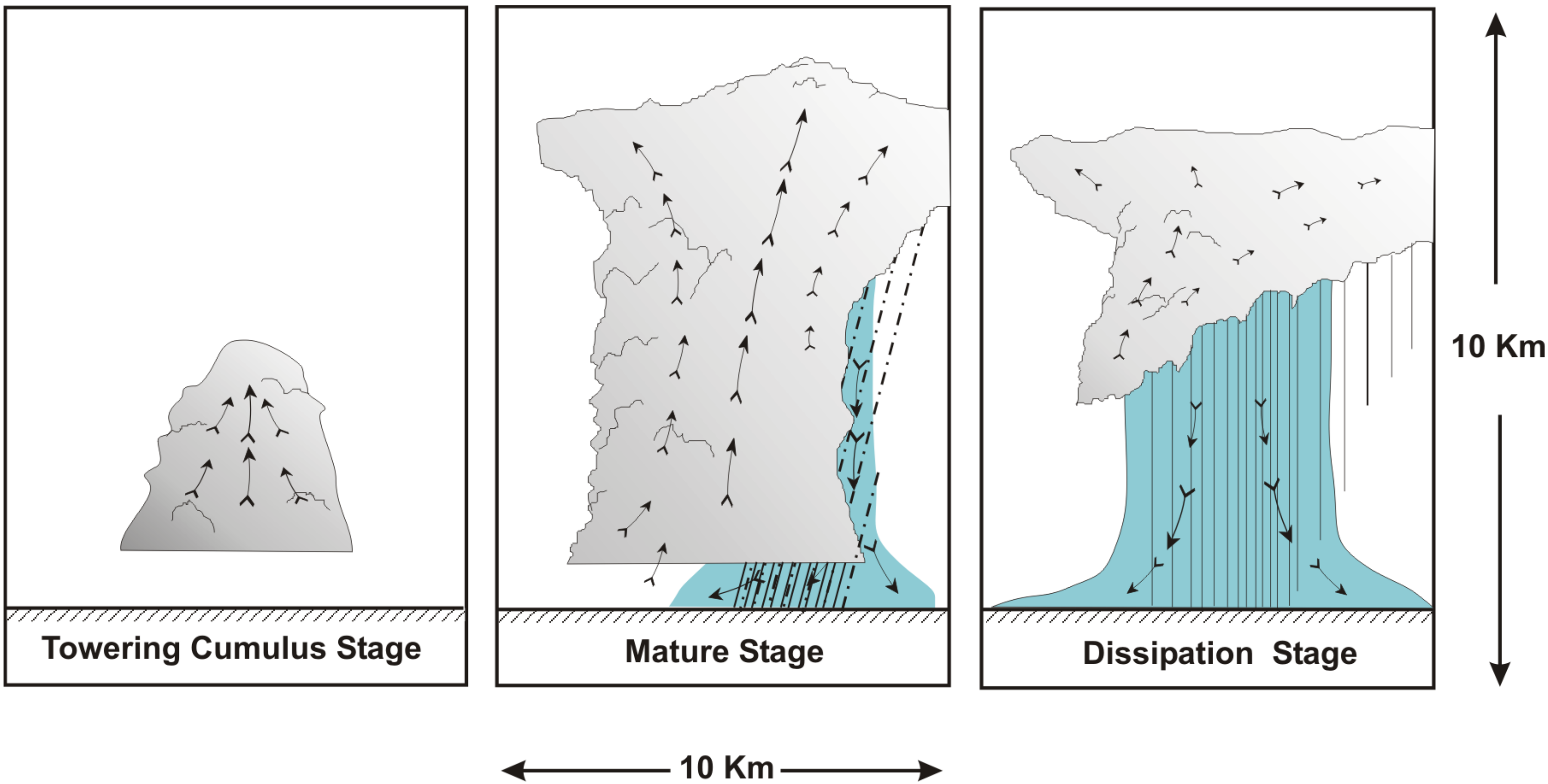


Cross-section of azimuthal wind speed (m s^{-1}) at about the time that a warm core vortex appears within the broader cold-core mesocyclone in a simulation using the non-hydrostatic, axisymmetric model of Rotunno and Emanuel (1987).



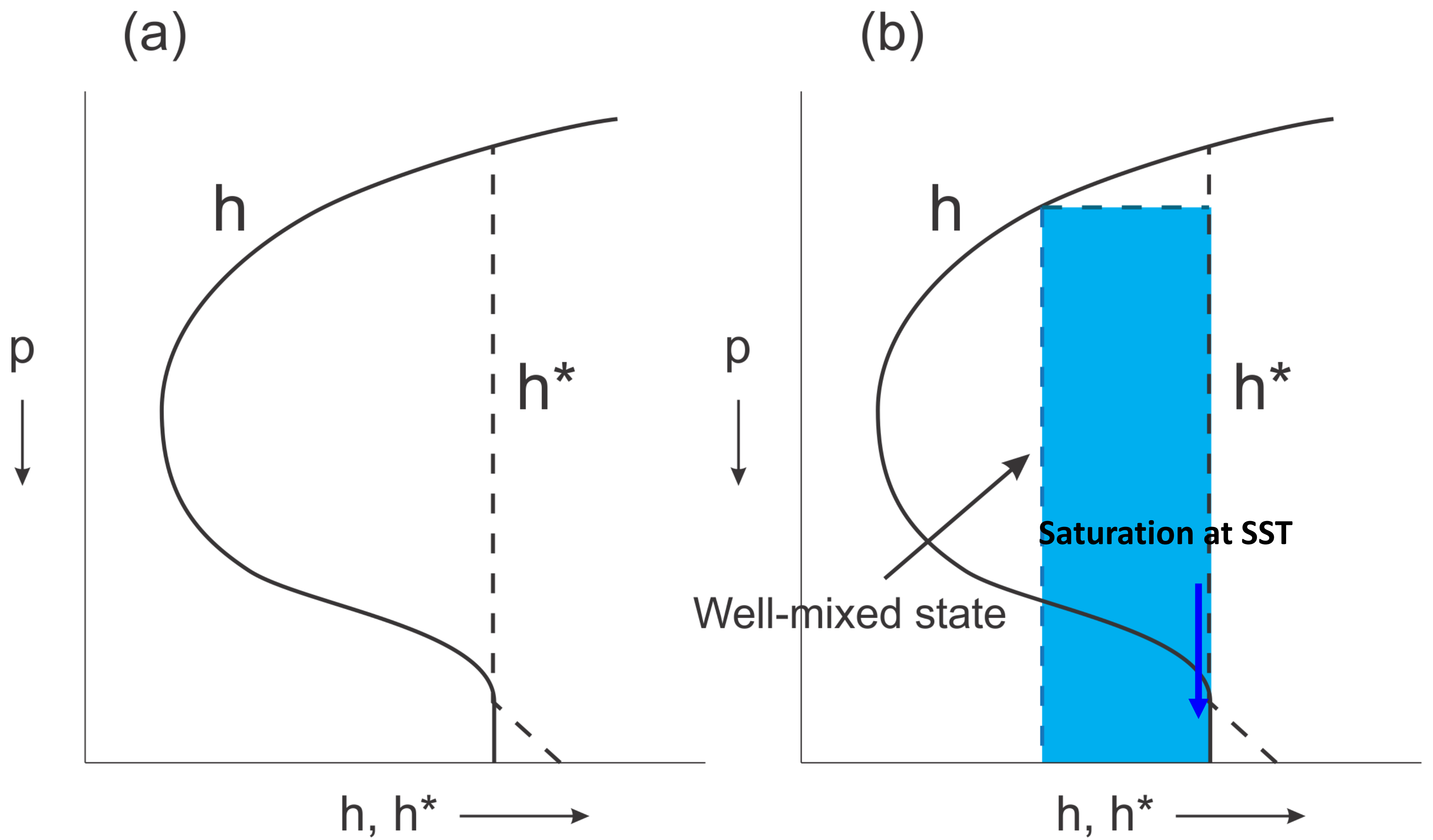
The Thermodynamic Inhibition to Genesis

“Air-Mass” Showers:



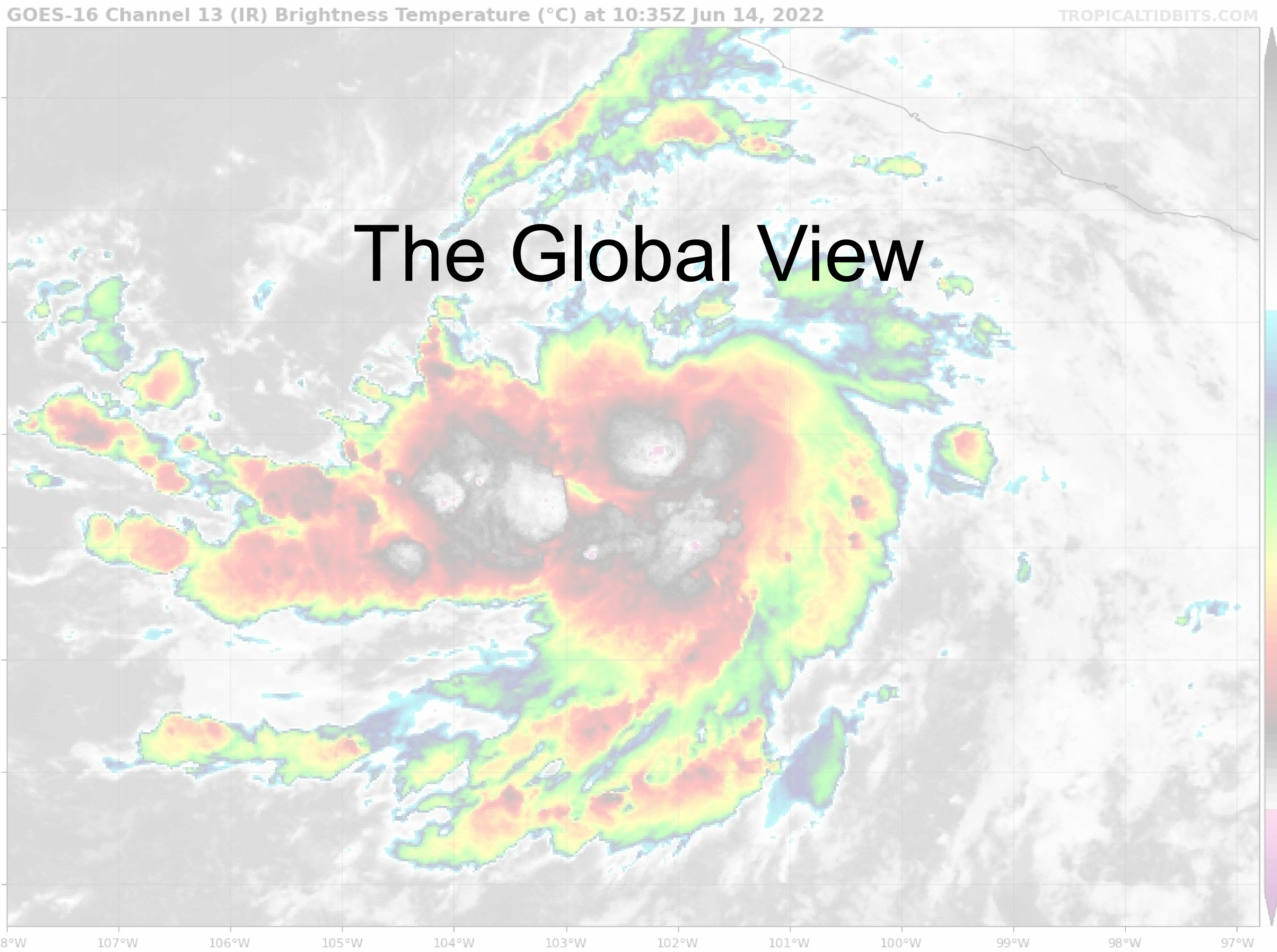
After Byers and Braham, 1948

To overcome thermodynamic inhibition, mesoscale column must come close to saturation. How does that happen?



Energetically advantageous to go through cold-core phase first

The Global View



Genesis Indices

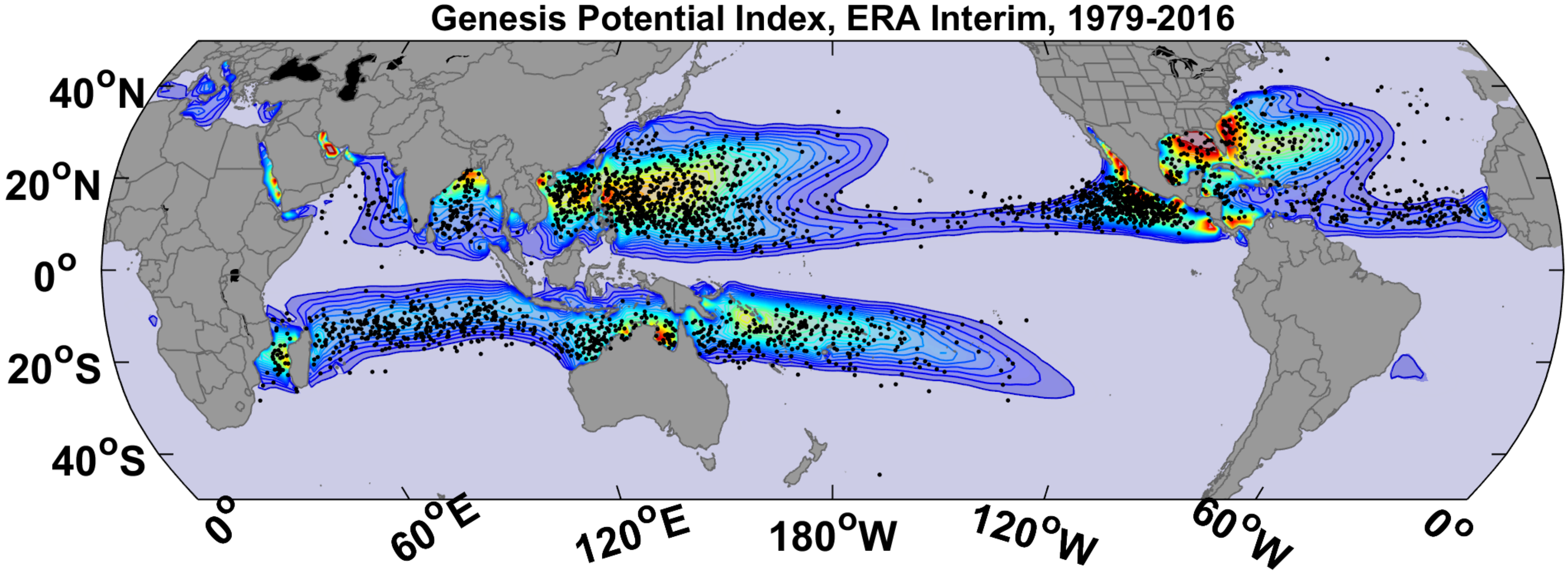
Pioneered by Bill Gray (1975)

A Genesis Potential Index:

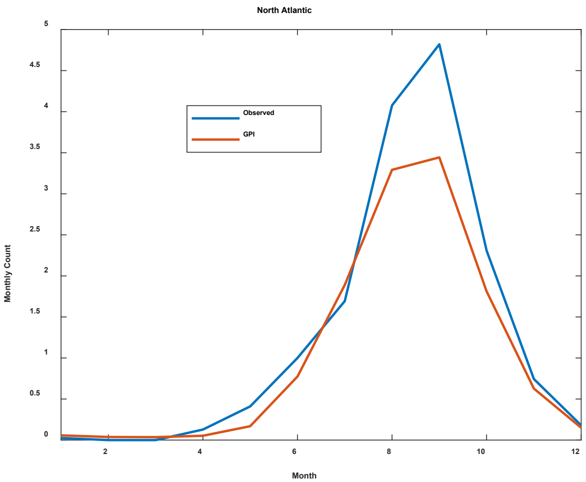
$$GPI \equiv \frac{|\eta|^3 \chi^{-4/3} \left(PI - 35\,ms^{-1}\right)^2}{\left(25\,ms^{-1} + S\right)^4}$$

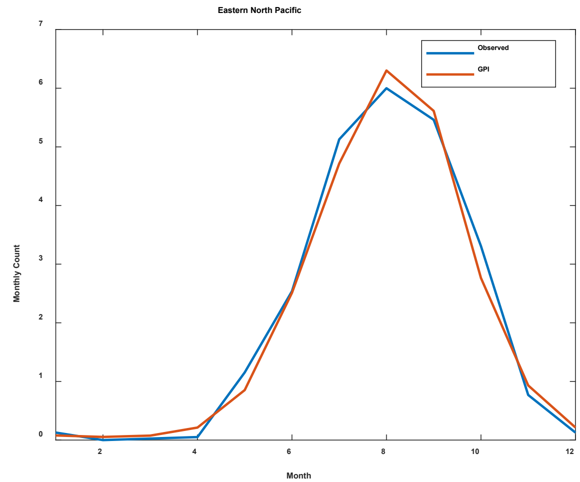
- 850 hPa absolute vorticity (η)
- 850 – 250 hPa shear (S)
- Potential intensity (PI)
- Non-dimensional subsaturation of the middle troposphere: $\chi \equiv \frac{s^* - s_{600}}{s_0^* - s^*}$

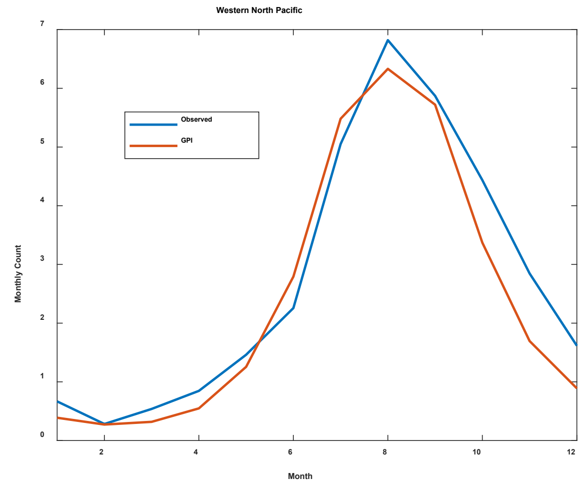
GPI from ERA-Interim Data, 1979-2016, with Observed Genesis Points



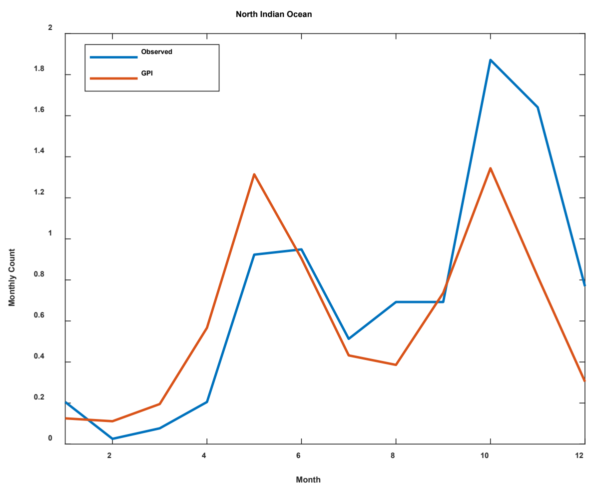
Seasonal Cycle

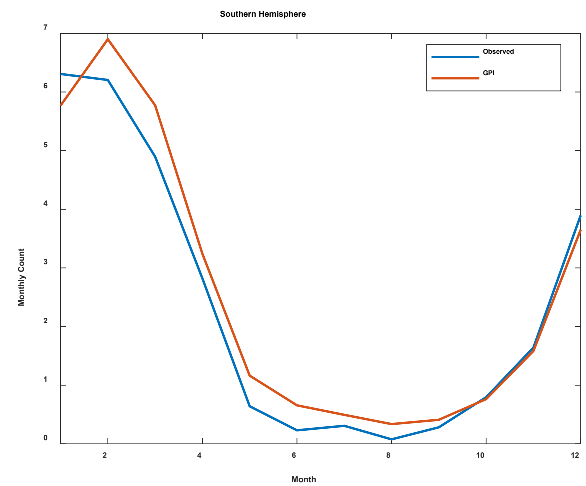






Genesis Potential Index from ERA5 reanalysis, 1979-2018 vs. Observed TCs, 1980-2018

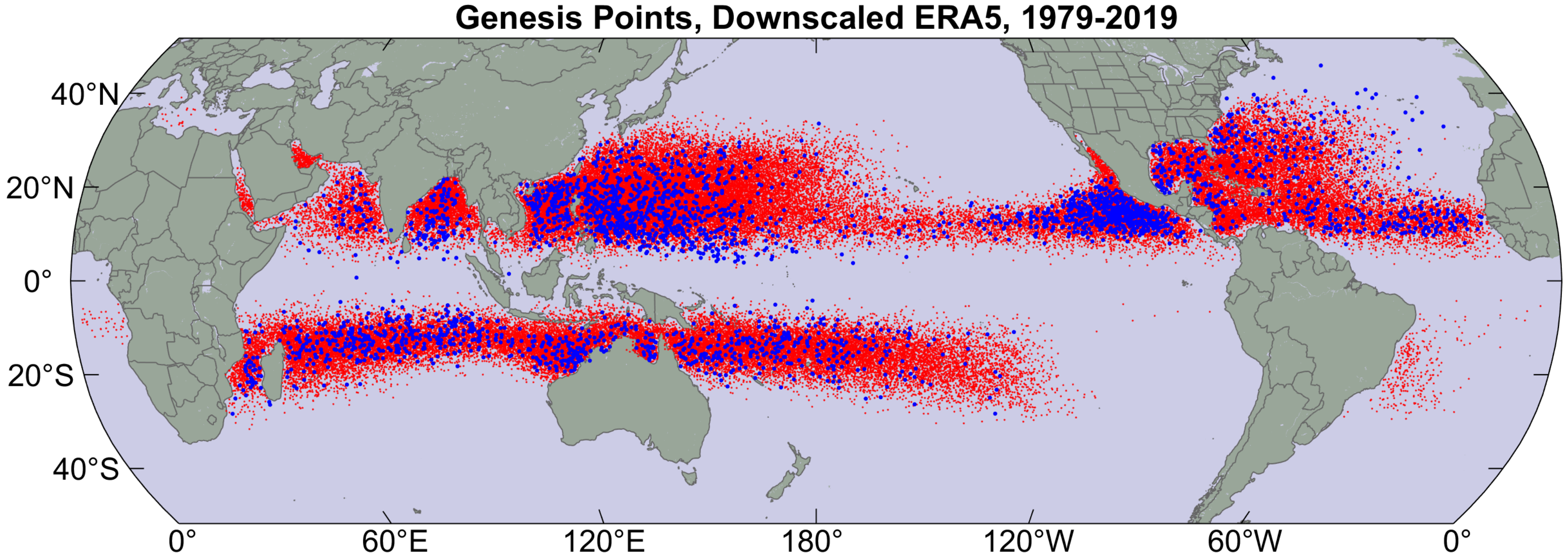


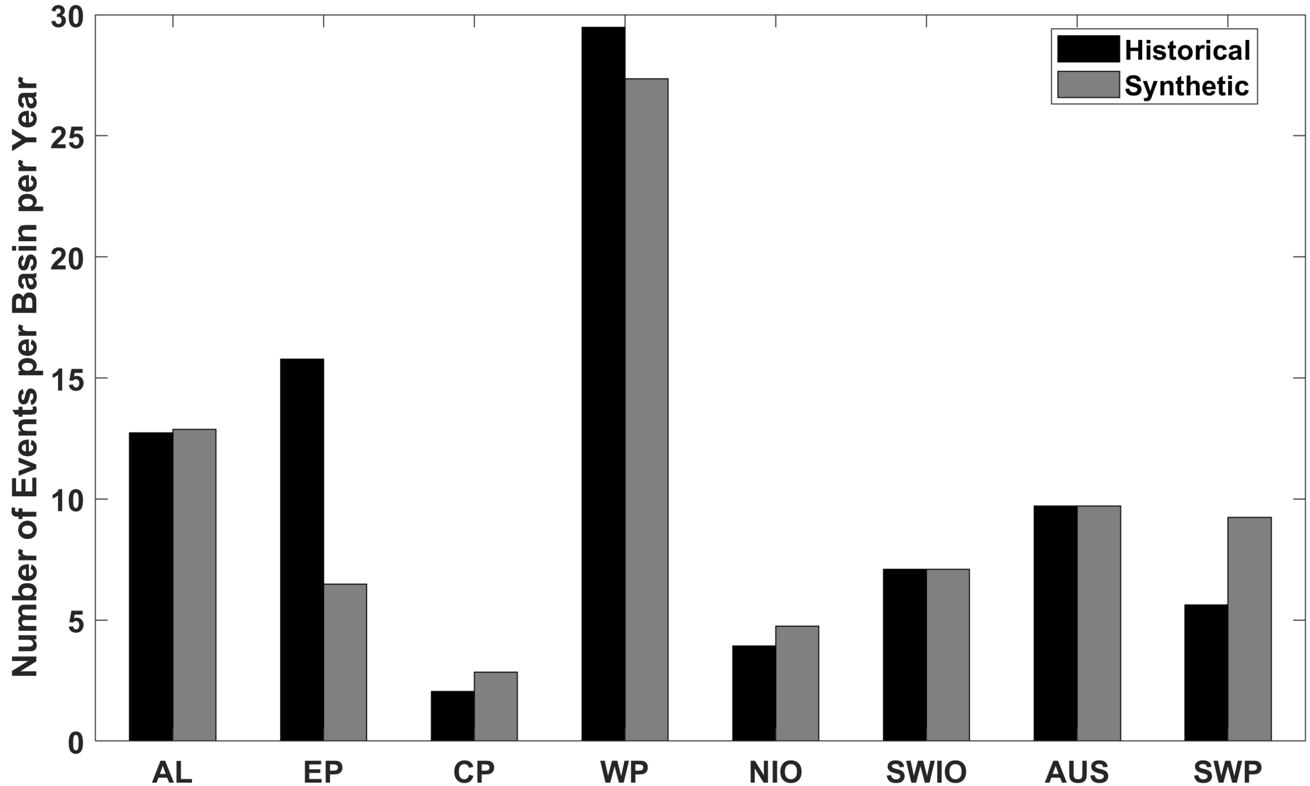


Random Seeding and Natural Selection

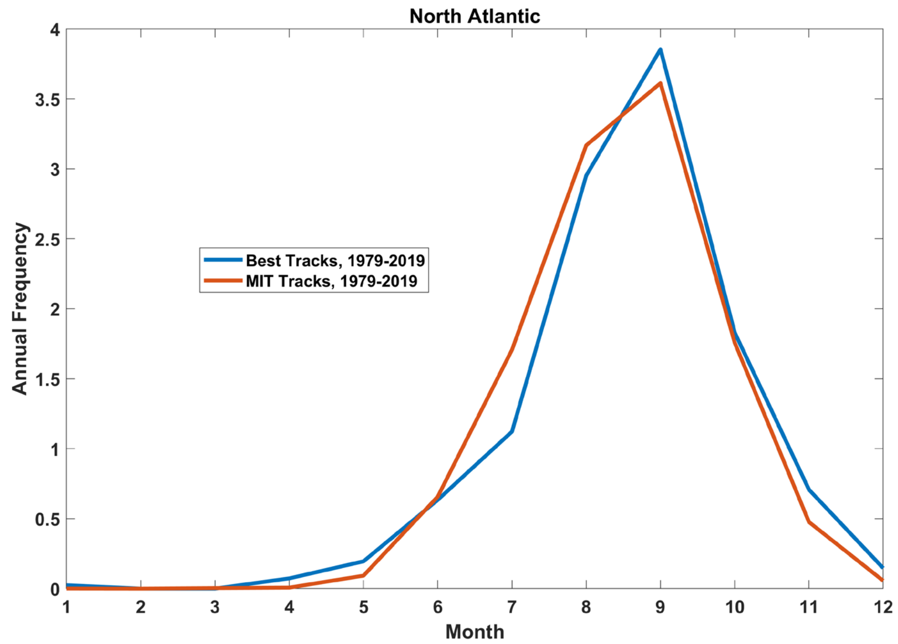
- Seed time-evolving, global state with very weak tropical cyclone seeds
- Random in space and time
- Seeds move with prevailing large-scale winds plus a correction for earth's rotation
- Coupled ocean-atmosphere, very high resolution model used to calculate disturbance intensity
- Throw out seeds that fail to develop

Origin points of successful seeds (red); observed genesis locations (blue)

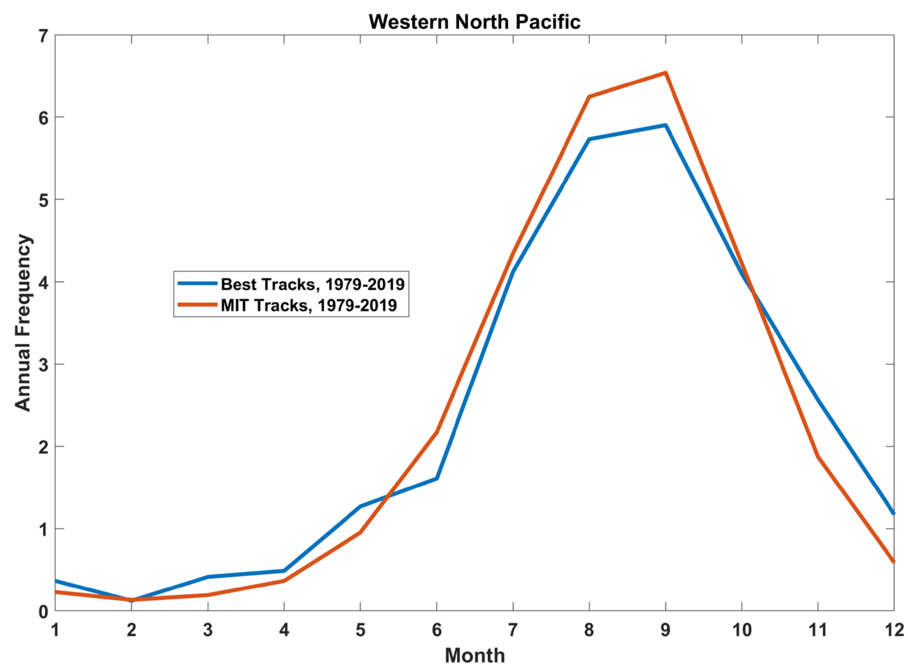




Average annual number of tropical cyclones over the period 1980-2020 in observations (IBTrACS; Knapp et al. 2010; black bars) and from random seeding of ERA-5 (gray bars)



Seasonal Cycle
North Atlantic



Seasonal Cycle
Northwest Pacific

Three Views on Genesis Rates

1) Genesis requires favorable large-scale environment and suitable initiating disturbances; rates affected by both

2) TC numbers reflect how many storms can be packed into a region of favorable large-scale environment, independent of triggering disturbances

3) Global TC numbers determined by a self-organized critical process involving feedbacks of TCs on climate

Early researchers recognized that genesis must depend on a combination of environmental favorability and the presence of initiating disturbances

- *"The origin of tropical disturbances cannot be explained solely from the local structure of the air masses in which the vortex motion develops. A suitable combination of external forces and local conditions is necessary"* – Riehl and Burgner (1950)

This is the prevailing view today

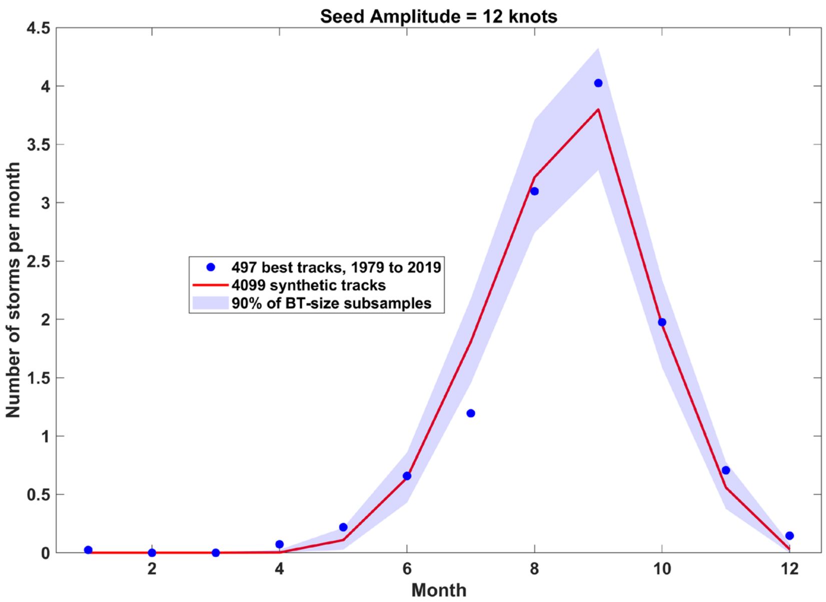
Contemporary support for this view:

- Sugi et al. (2020): Examined TCs in high-resolution global models; showed that TC rates largely determined by frequency of seeds, defined as disturbances with max winds of 20-35 kts
- Hsieh et al. (2020) used a 50-km resolution AGCM and showed that the frequency of simulated TCs can be well described by $n_{tc} = n_c \times P_1 \times P_2$, where
  - n_c = frequency of non-rotating clusters
  - P_1 = probability of transition to seeds
  - P_2 = probability of transition from seeds to TCs

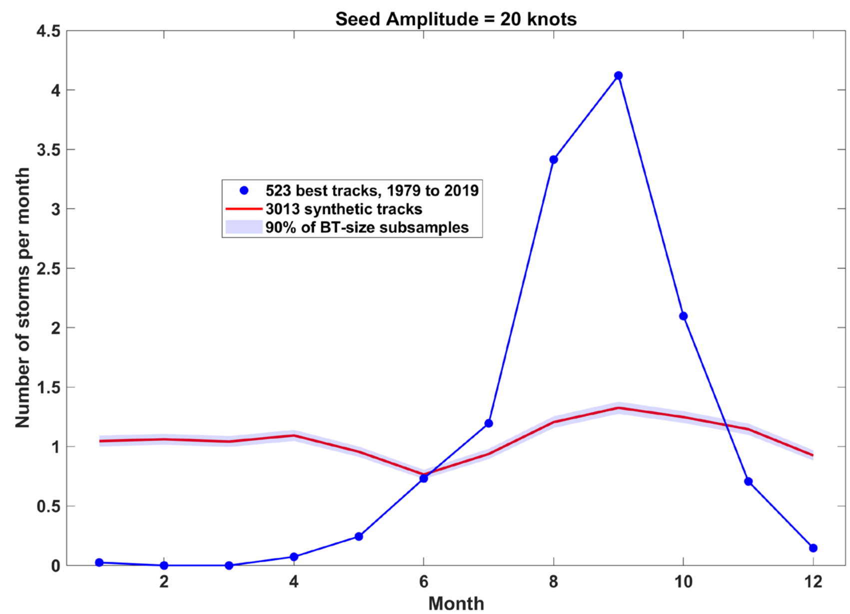
They formulated n_c, P_1 and P_2 as functions of large-scale model variables, so that *net rate could be regarded as a genesis index*. But innovation here is that different physics may operate at different stages of TC evolution.

BUT……….

In random seeding, selection does not work if seeds too strong

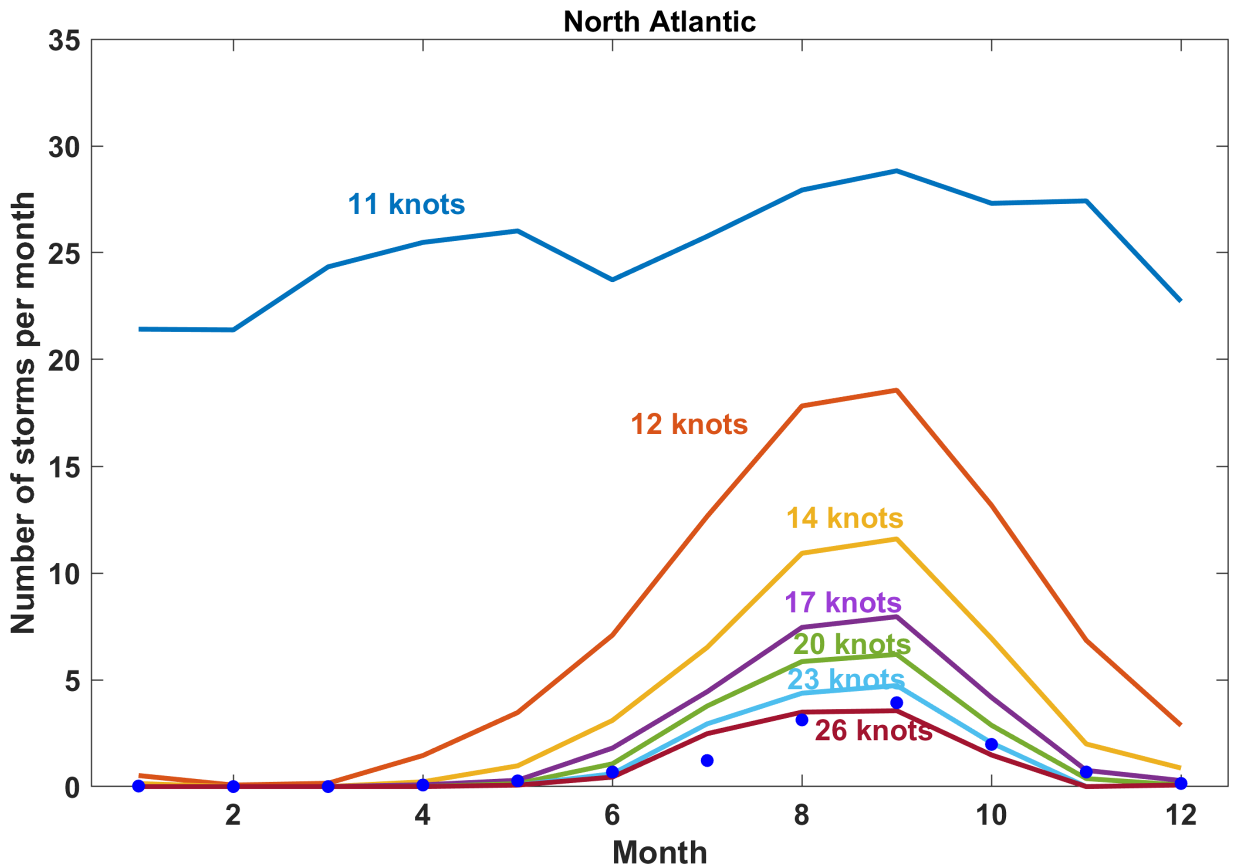


Seed amplitude = 12 knots



Seed amplitude = 20 knots

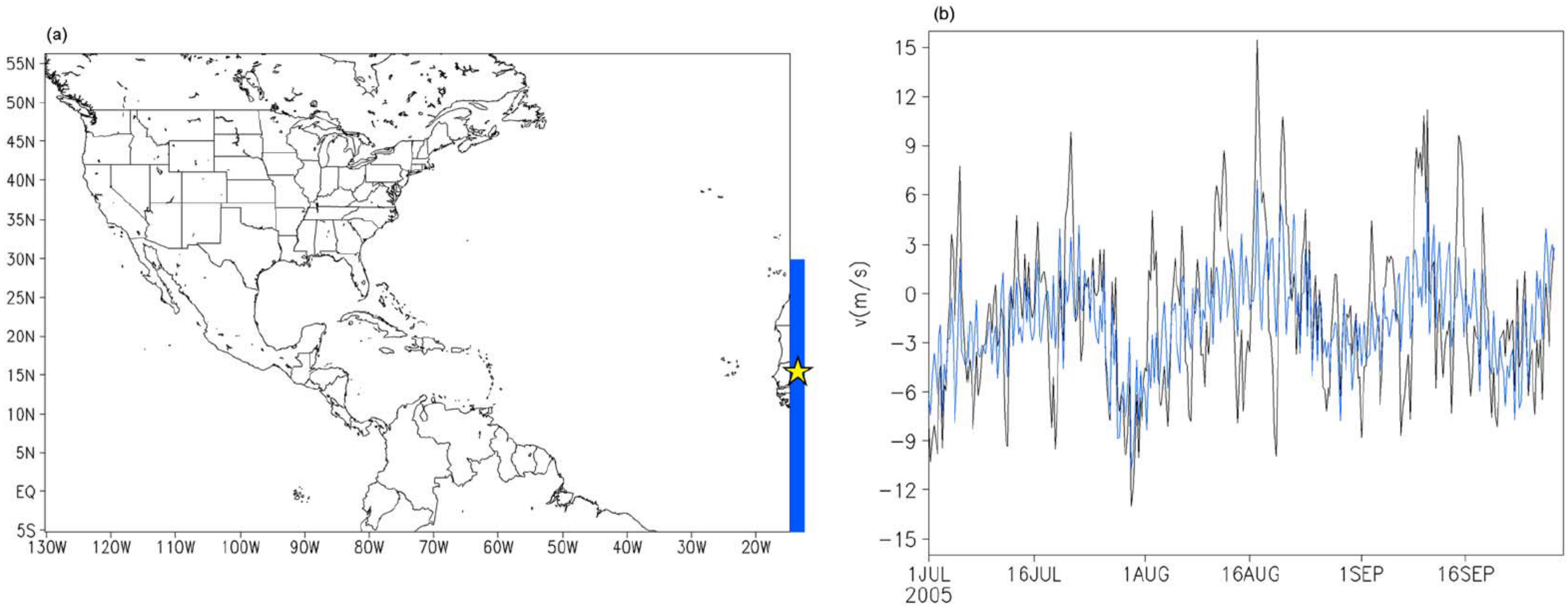
Selection in Action



The annual average monthly frequency of simulated storms whose lifetime maximum circular wind speed exceeds the values labeled on the curves, from the weak seed simulation. Blue dots are from historical observations.

Emanuel (2022)

Do African Easterly Waves Control Atlantic TC Frequency?
Experiments with a regional model forced by reanalysis boundary conditions



(a) The regional climate model domain. The blue rectangle denotes the latitude over which a 2–10 day Lanczos filter was applied to the eastern LBC in the AEW suppressed experiment. (b) The time series of 6-hourly meridional wind (m/s) at 15°N, 15°W (denoted by star in Figure 1a) and 700 hPa prescribed in the eastern LBC for the (black) control simulation and (blue) AEW suppressed experiment.

Patricola et al., 2017, *Geophysical Research Letters*, 45, 471–479

Results with 10-member ensembles

Table 1

Measures of Atlantic TC Activity From the Ensemble Average of the Control and AEW Suppressed Simulations

	Control	AEW suppressed	% change	*p* value
Number of TCs/season	19.5	20.2	+4%	0.64
Number of TC days/season	105	117	+11%	0.17
ACE (10^4 kt^2)	168	192	+15%	0.07

Note. This includes the percent change relative to the control simulation and the *p* value corresponding to a *t* test for difference of the means.

Note: *With African easterly waves*, location and timing of genesis highly correlated among the ten ensemble members.

Without AEWs, location and timing uncorrelated among the ensemble members

Inference: Seed disturbances determine timing and location of genesis, but not whether genesis occurs

Patricola et al., 2017, *Geophysical Research Letters*, 45, 471–479

If global TC rate is not controlled by “seed” frequency, then what does control it?

Hypothesis advanced by Hoogewind, Chavas, Schenkel, and O'Neill, 2020:

- Actual global TC count is a packing problem conditioned on places and times that large-scale environment is favorable

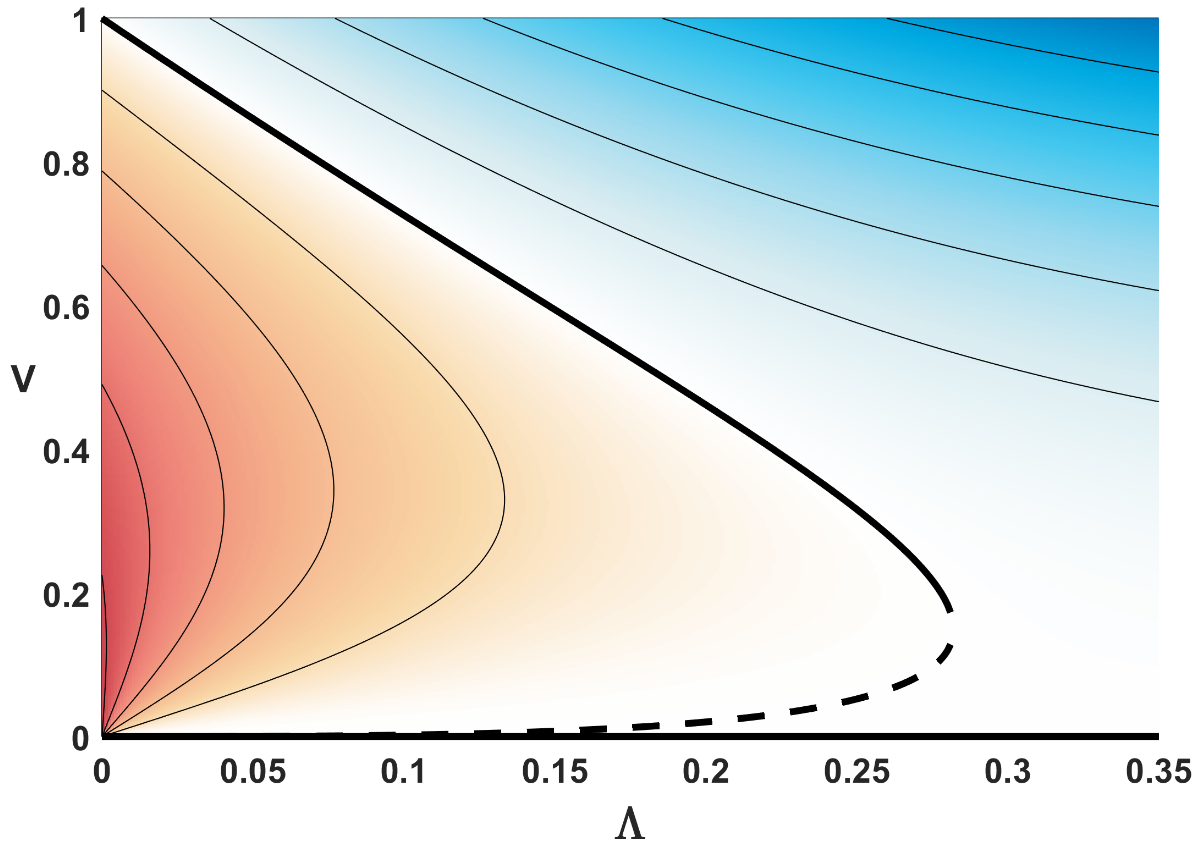
- Still overestimates the observed global tropical cyclone frequency by an order of magnitude

Third Possibility: TC-Climate Feedback

- TCs depend on high potential intensity, low shear, humid troposphere
- Aggregated convection dries out troposphere in models (Bretherton and Khairoutdinov, 2005), opening IR window, lowering both potential intensity and increasing genesis inhibition
- Aggregation is observed to dry out troposphere (Tobin et al., 2012, 2013; Holloway et al. (2017); Stein et al.,2017; Bony et al., 2020)
- Vu et al. (2021) used a tropical channel version of WRF to show that episodes of high TC activity are preceded by high GPI and followed by lower GPI, with much of the effect on GPI through mid-tropospheric water vapor
- In addition, strong TCs mix cold water to the surface, leading to an export of ocean heat energy to colder regions
- These are negative feedbacks on TCs themselves, possibly leading to self-regulation of both TCs and climate (Khairoutdinov and Emanuel, 2010, Mauritsen and Stevens, 2015)

Manifold of the FAST nonlinear hurricane intensity model

Warm colors indicate intensification; cold colors denote decaying solutions
Growth rates are for nullcline of core moisture variable



Non-dimensional Surface wind speed

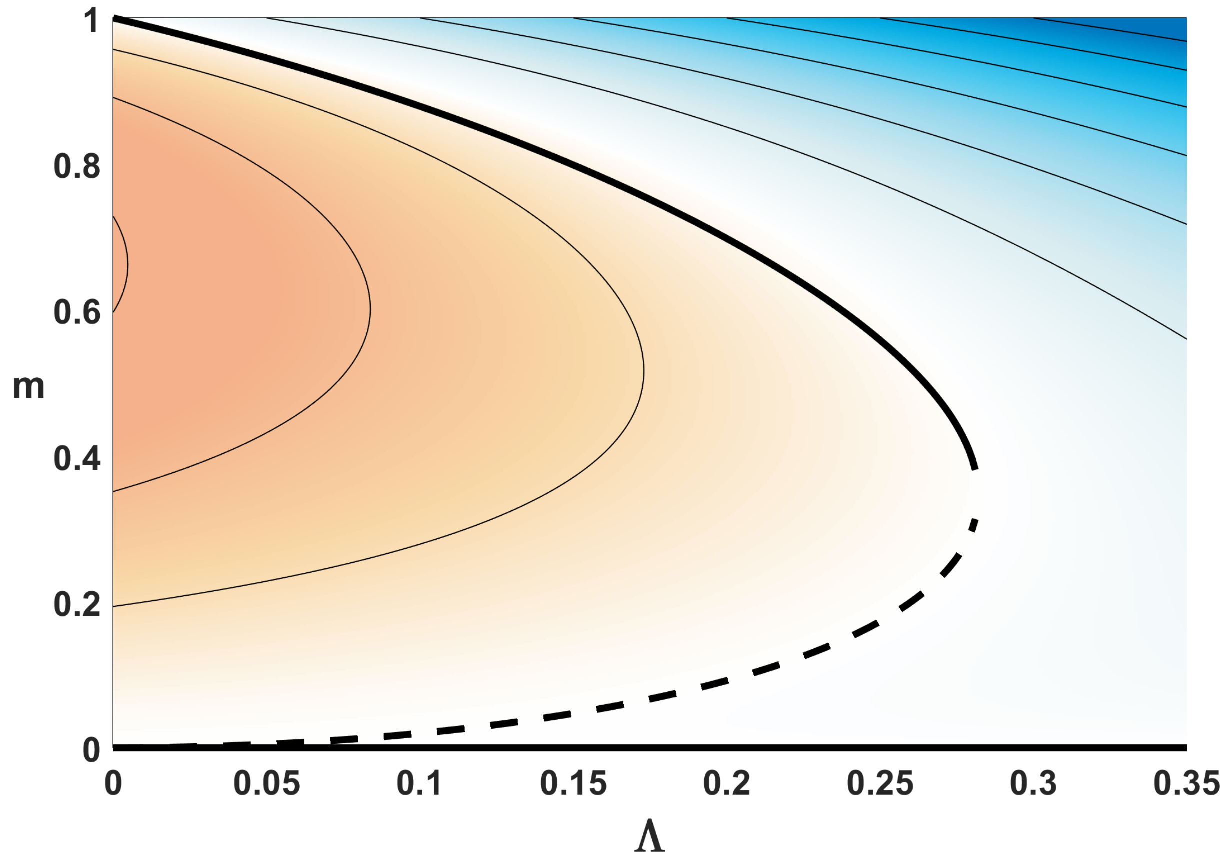
Non-dimensional ventilation parameter (shear)

Emanuel, K., 2017: A fast intensity simulator for tropical cyclone risk analysis. *Nat. Hazards*, https://doi.org/10.1007/s11069-017-2890-7.

Whole model available at https://github.com/linjonathan/tropical_cyclone_risk

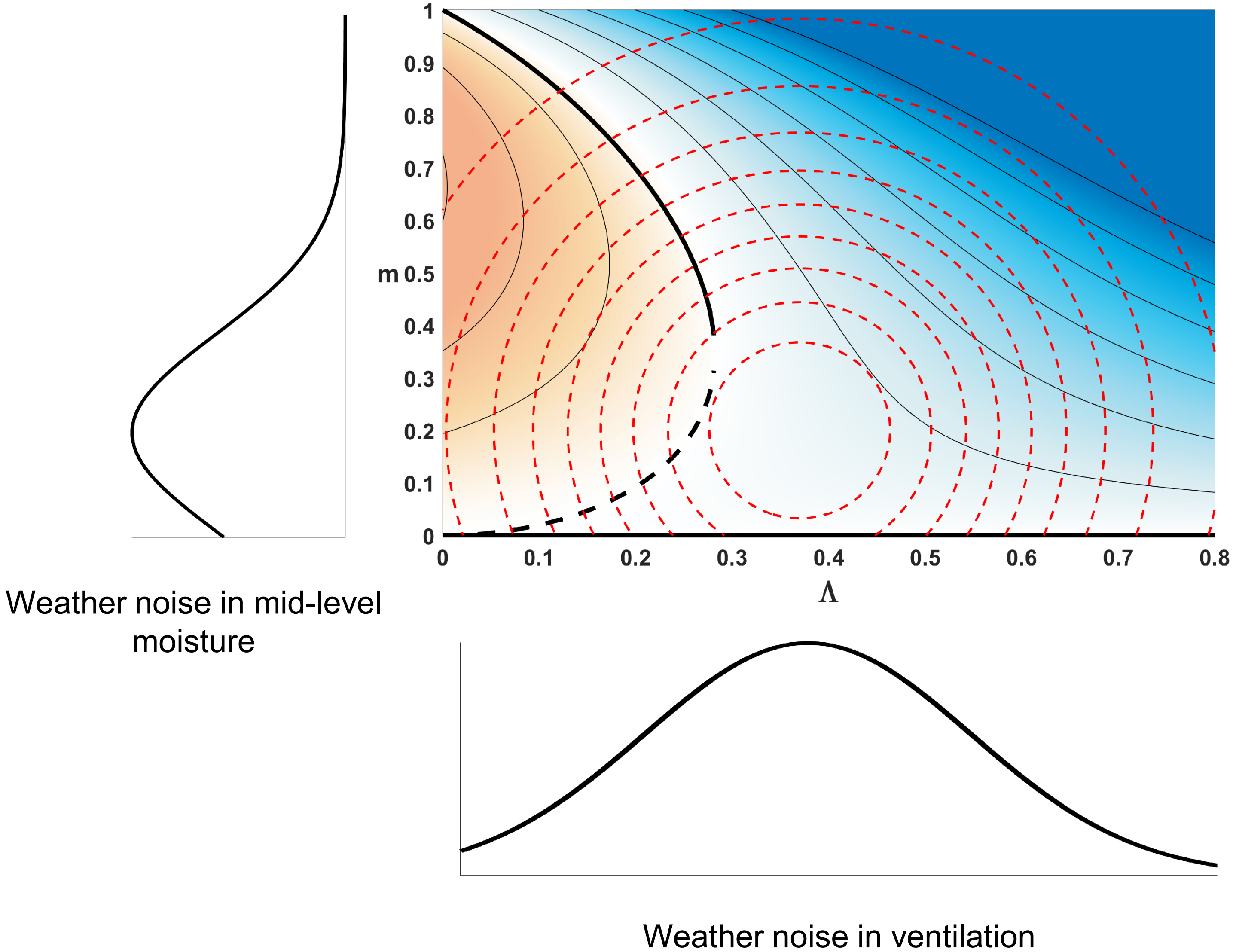
Warm colors indicate intensification; cold colors denote decaying solutions
Growth rates are for nullcline of surface wind speed variable

Non-dimensional core moisture



Non-dimensional ventilation parameter (shear)

Red dashed curves denote joint probability distribution of weather noise in mid-level moisture and ventilation



Summary

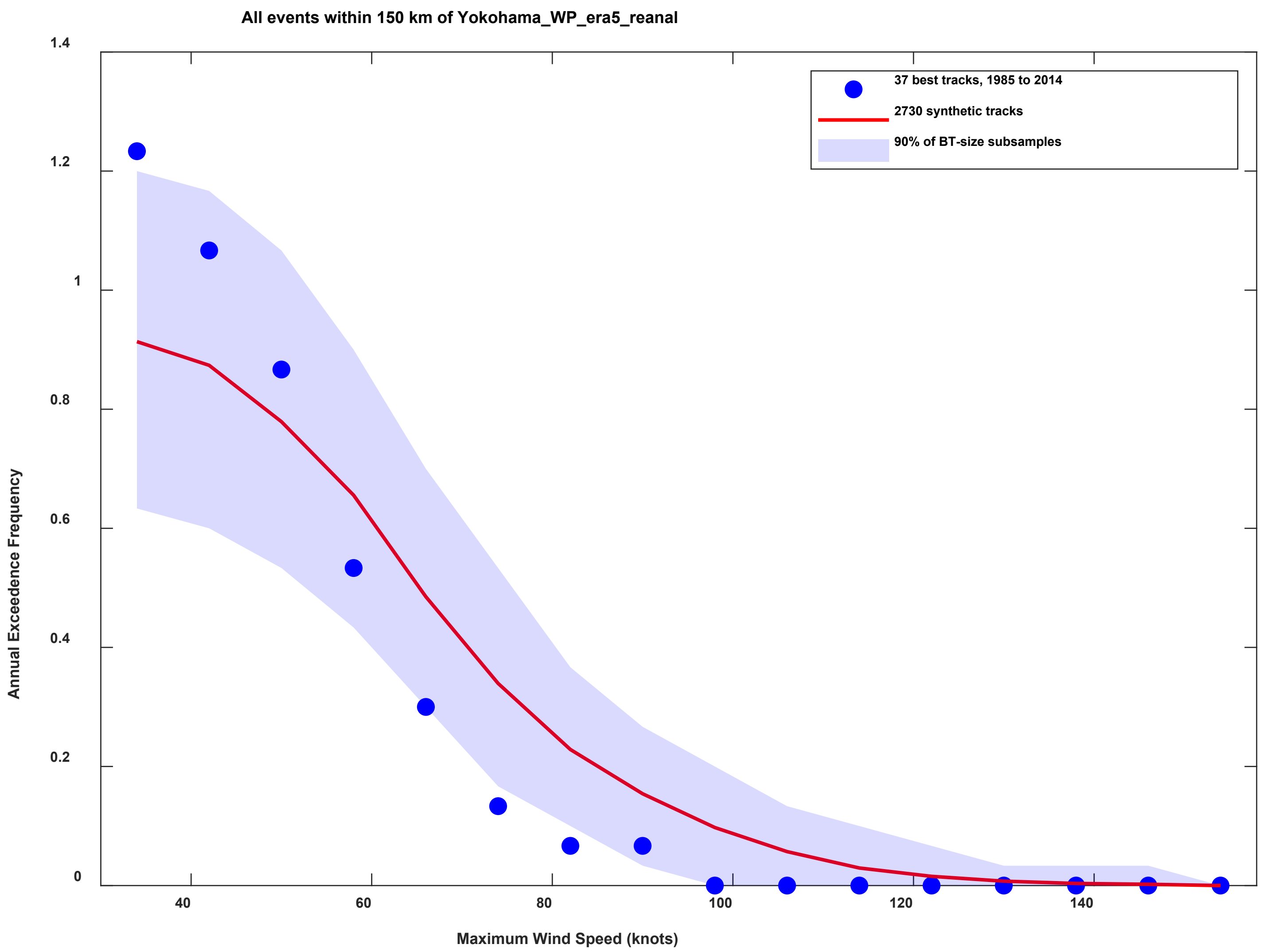
- Theory and observations strongly suggest that TC intensity and rainfall both increase in a warming climate
- Appreciable advances have been made in understanding both the detailed physics behind individual cases of genesis and the control of genesis statistics by the large-scale environment
- In spite of these advances, we still lack a generally accepted theory for the observed global rate of genesis
- Understanding genesis in the context of climate, including feedbacks of TCs on climate and the possibility of self-regulation of climate and TCs, may prove essential

Spare Slides

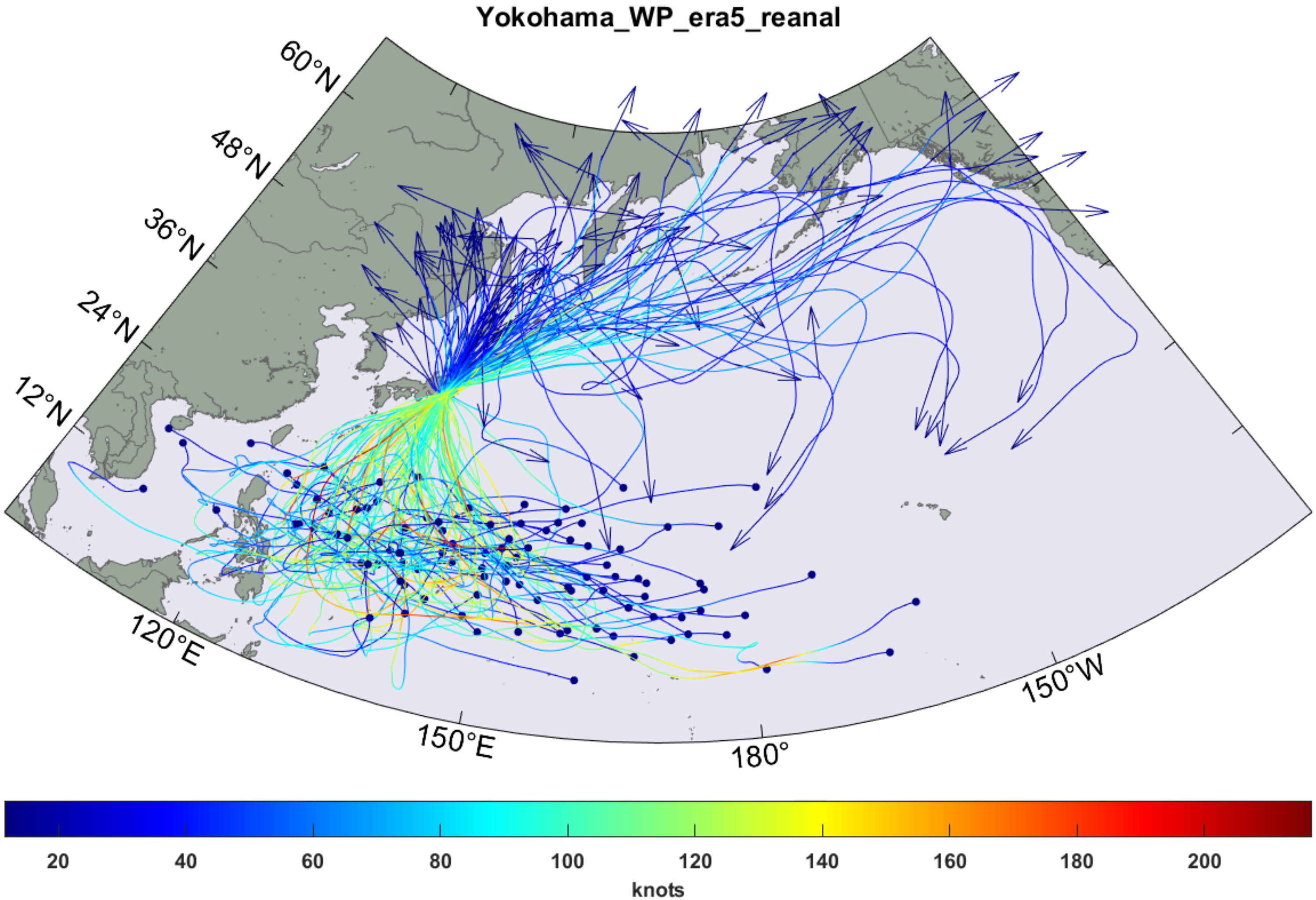
Yokohama

- Downscale 3000 events from ERA-5 reanalyses, 1985-2014, passing within 150 km of Yokohama
- Downscale 3000 events from historical simulations of 8 CMIP6-generation climate models, 1985-2014
- Downscale 3000 events from SSP3-7.0 simulations of 8 CMIP6-generation climate models, 2071-2100

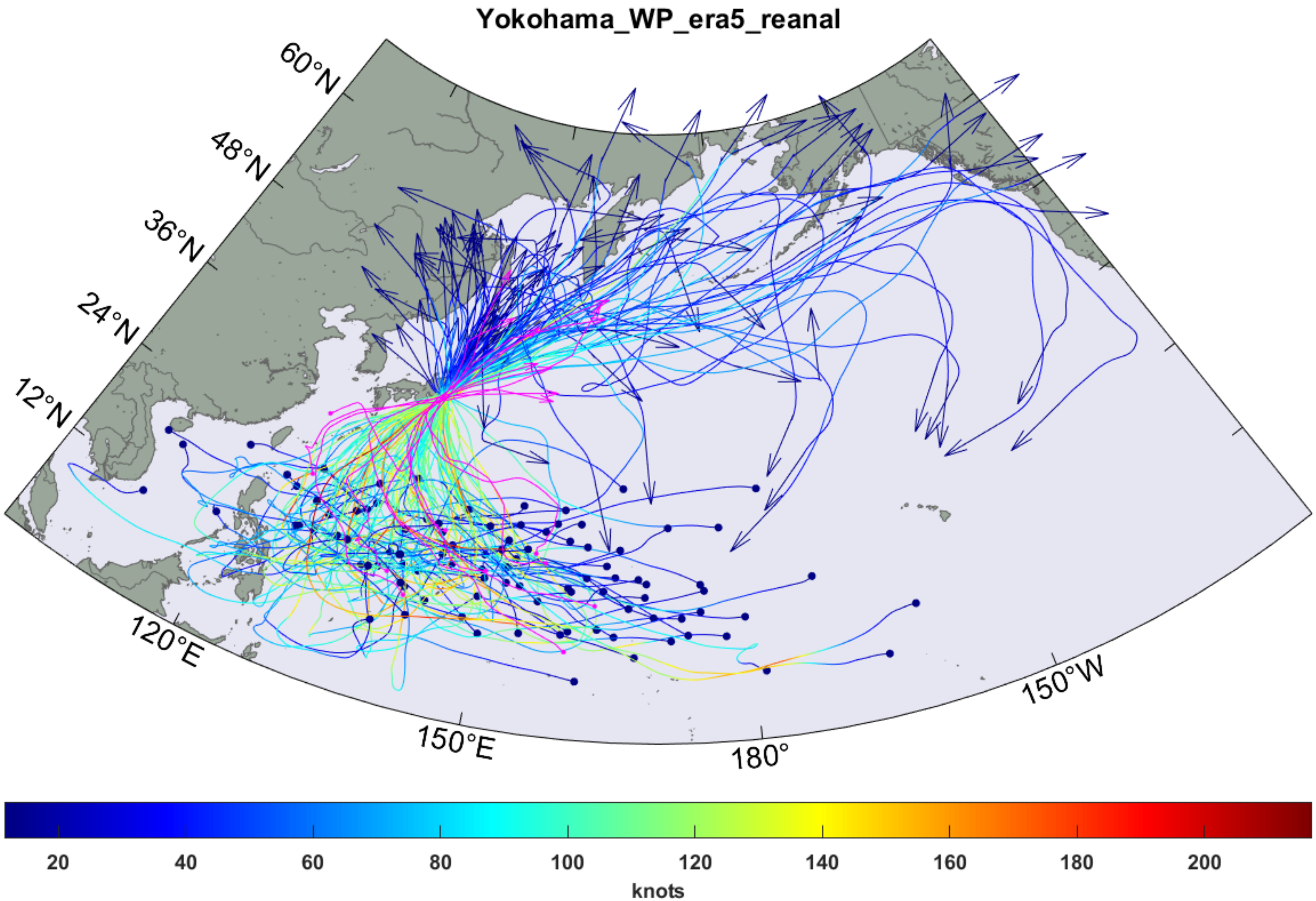
If you would like to use these tropical cyclone sets for research purposes, please write me (emanuel@mit.edu)

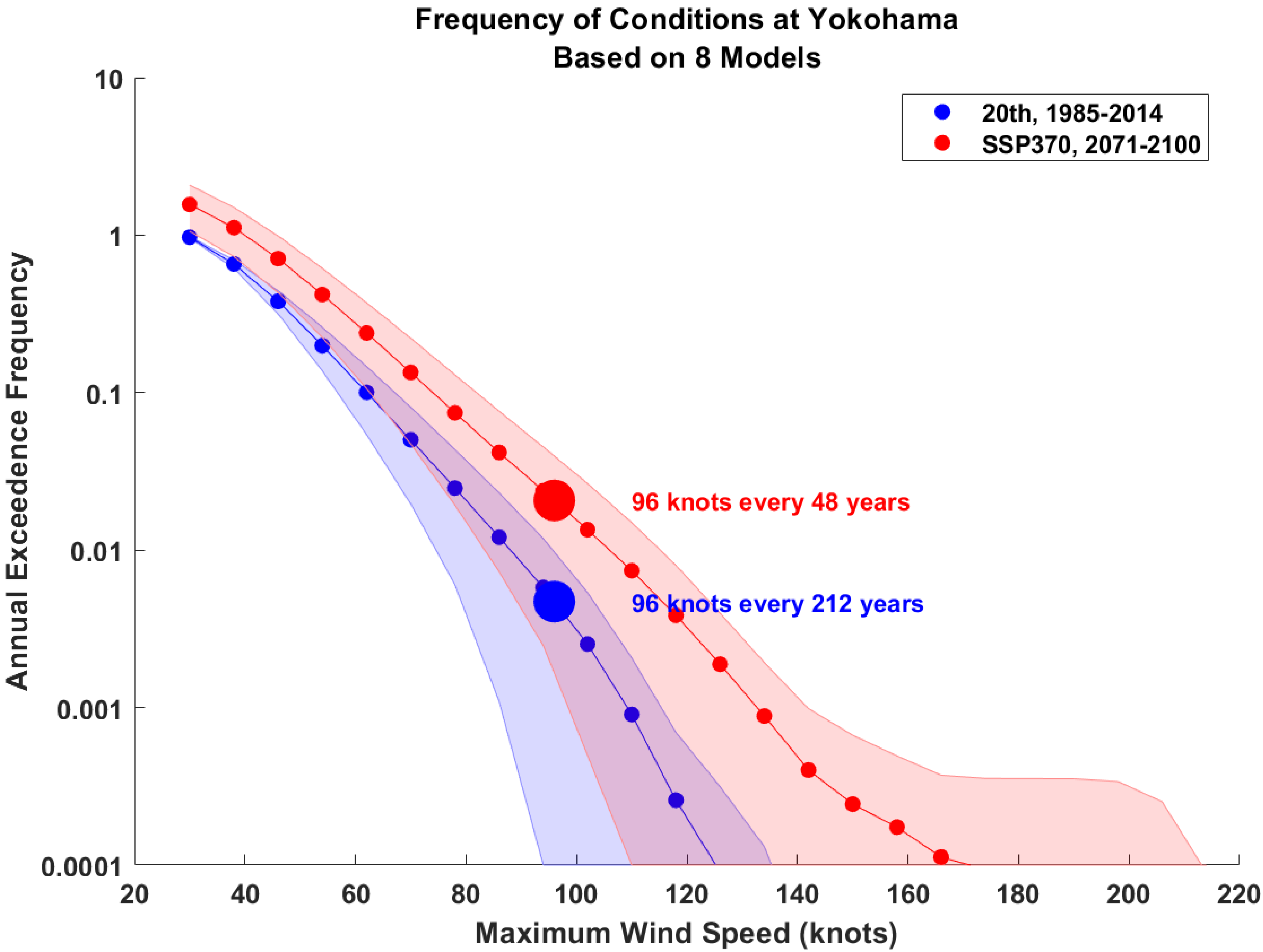

All events within 150 km of Yokohama_WP_era5_reanal
37 best tracks, 1985 to 2014
2730 synthetic tracks
90% of BT-size subsamples
Annual Exceedence Frequency
Maximum Wind Speed (knots)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
40
60
80
100
120
140

Top 100 out of 3,000 TCs passing within 150 km of Yokohama, downscaled from ERA-5 reanalyses

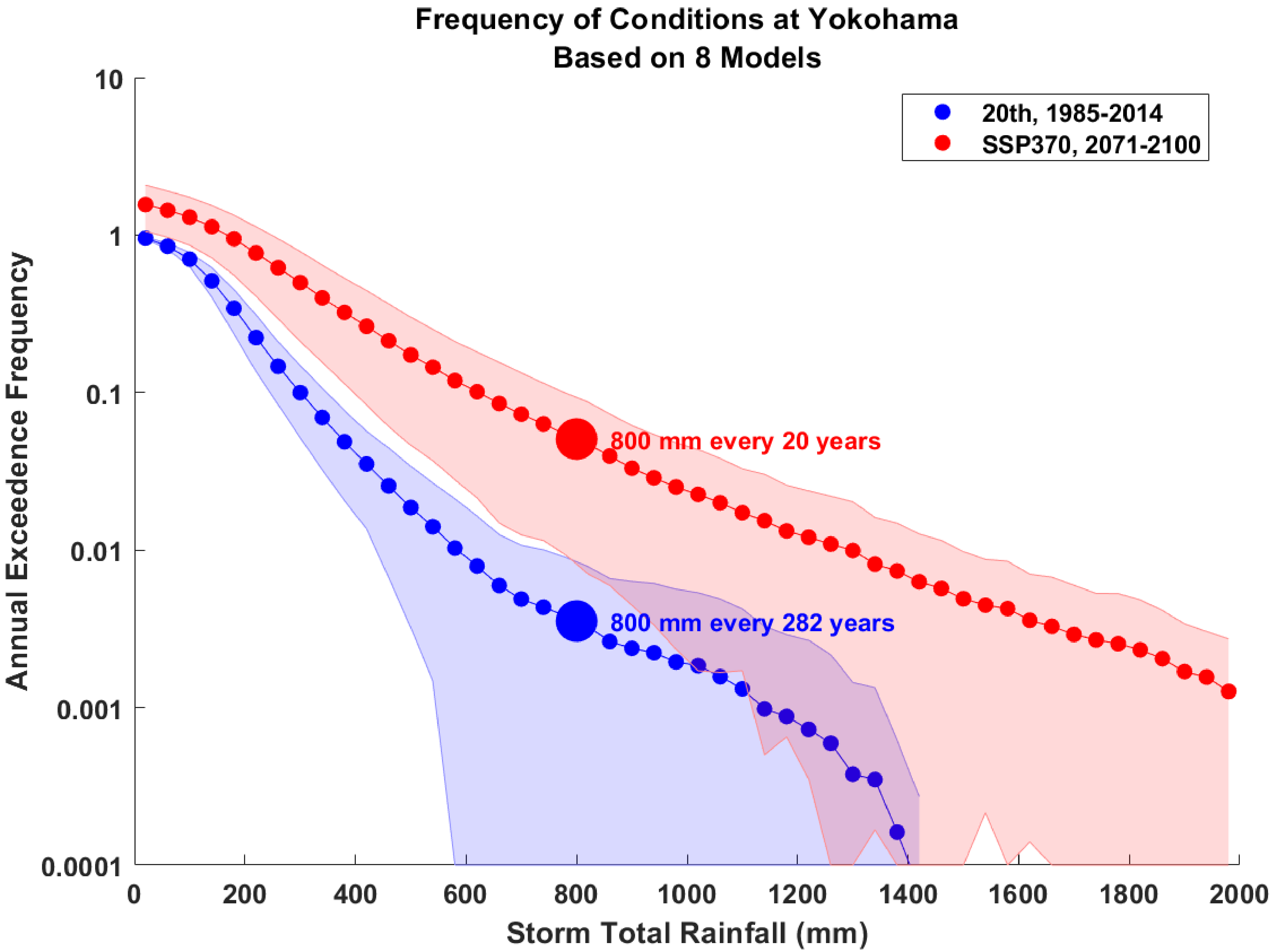


Same but with top 10 typhoons passing within 150 km of Yokohama, 1985-2014 superimposed (magenta curves)

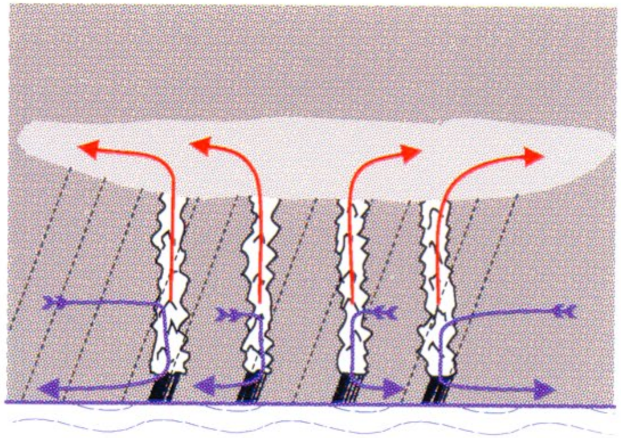




Frequency of Conditions at Yokohama
Based on 8 Models
20th, 1985-2014
SSP370, 2071-2100
96 knots every 48 years
96 knots every 212 years
Annual Exceedence Frequency
10
1
0.1
0.01
0.001
0.0001
20
40
60
80
100
120
140
160
180
200
220
Maximum Wind Speed (knots)

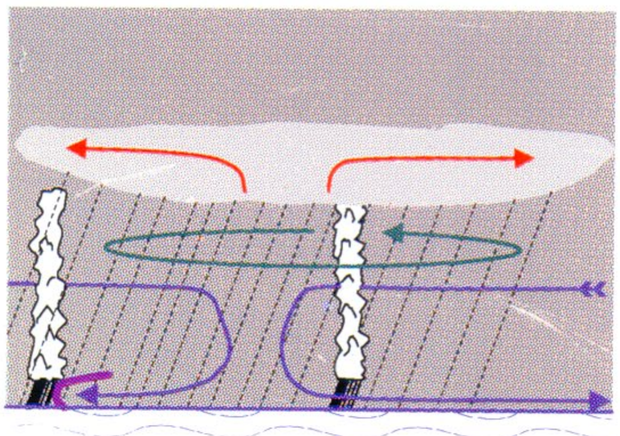

Frequency of Conditions at Yokohama
Based on 8 Models
20th, 1985-2014
SSP370, 2071-2100
800 mm every 20 years
800 mm every 282 years
Annual Exceedence Frequency
10
1
0.1
0.01
0.001
0.0001
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Storm Total Rainfall (mm)

1. TRIGGERING



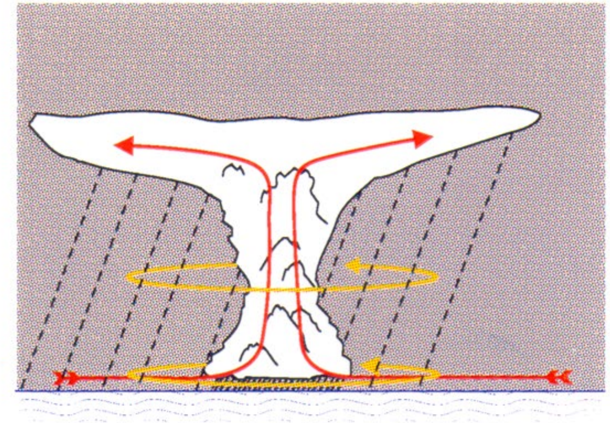
- Formation of long-lived mesoscale stratiform anvil
- Appears to require large-scale ascent in the upper troposphere
- Reduction of subcloud layer entropy by downdrafts

2. Gestation



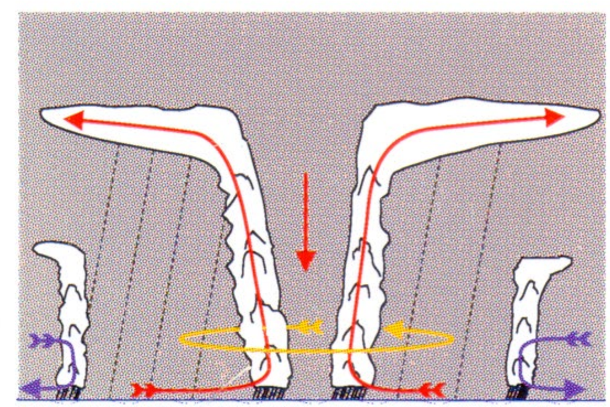
- Light to moderate stratiform rain; little deep convection, except at periphery
- Formation of middle tropospheric mesoscale cyclone cold core in the lower troposphere
- *High relative humidity* develops in core
- Subcloud layer entropy recovers

3. Ignition



- New episode of convection that is *free of downdraft* forms near core
- Strong surface *in*flow, strong surface heat fluxes
- Carnot engine switched on

4. Intensification

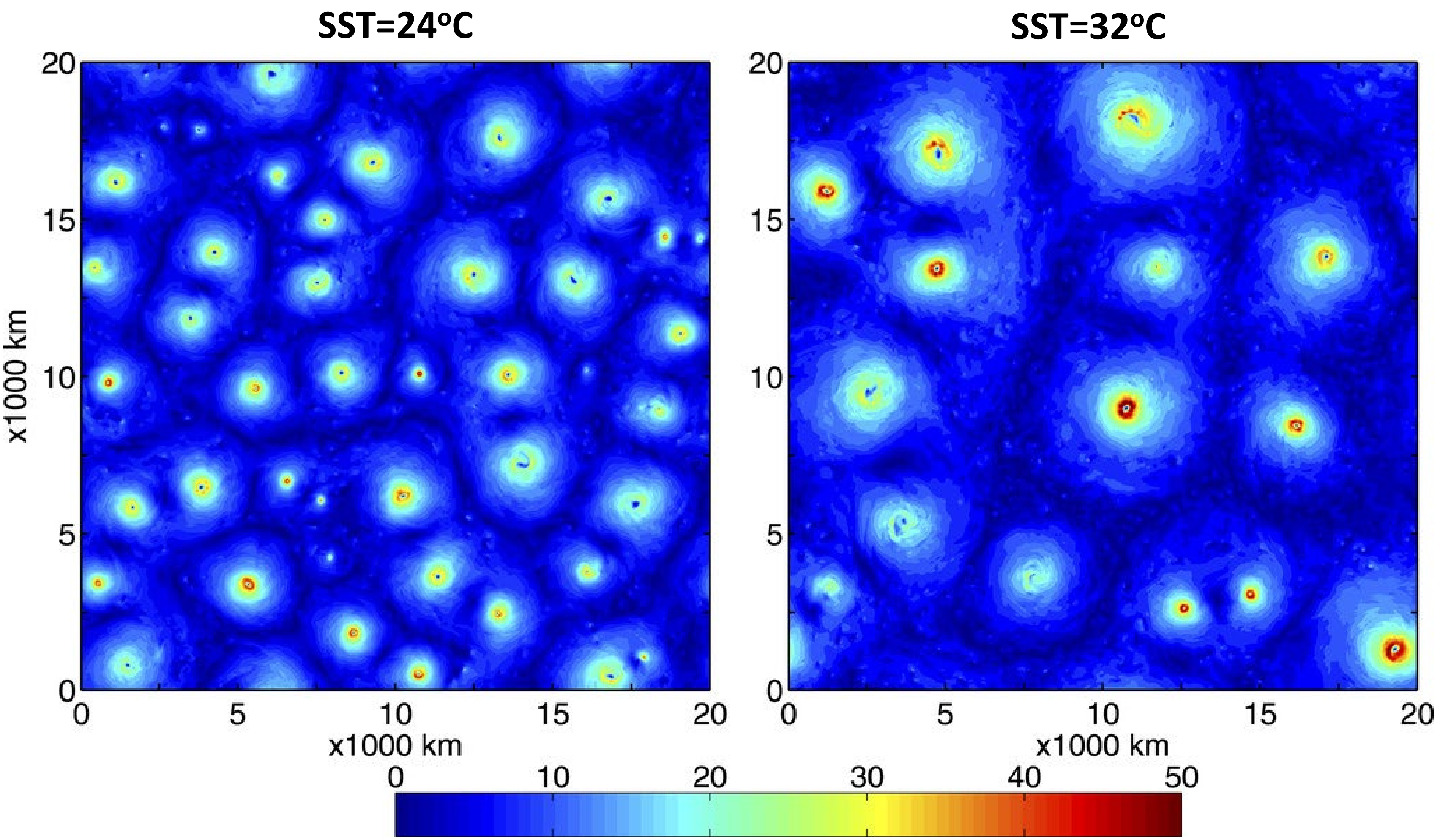


5. Maturity

6. Dissipation

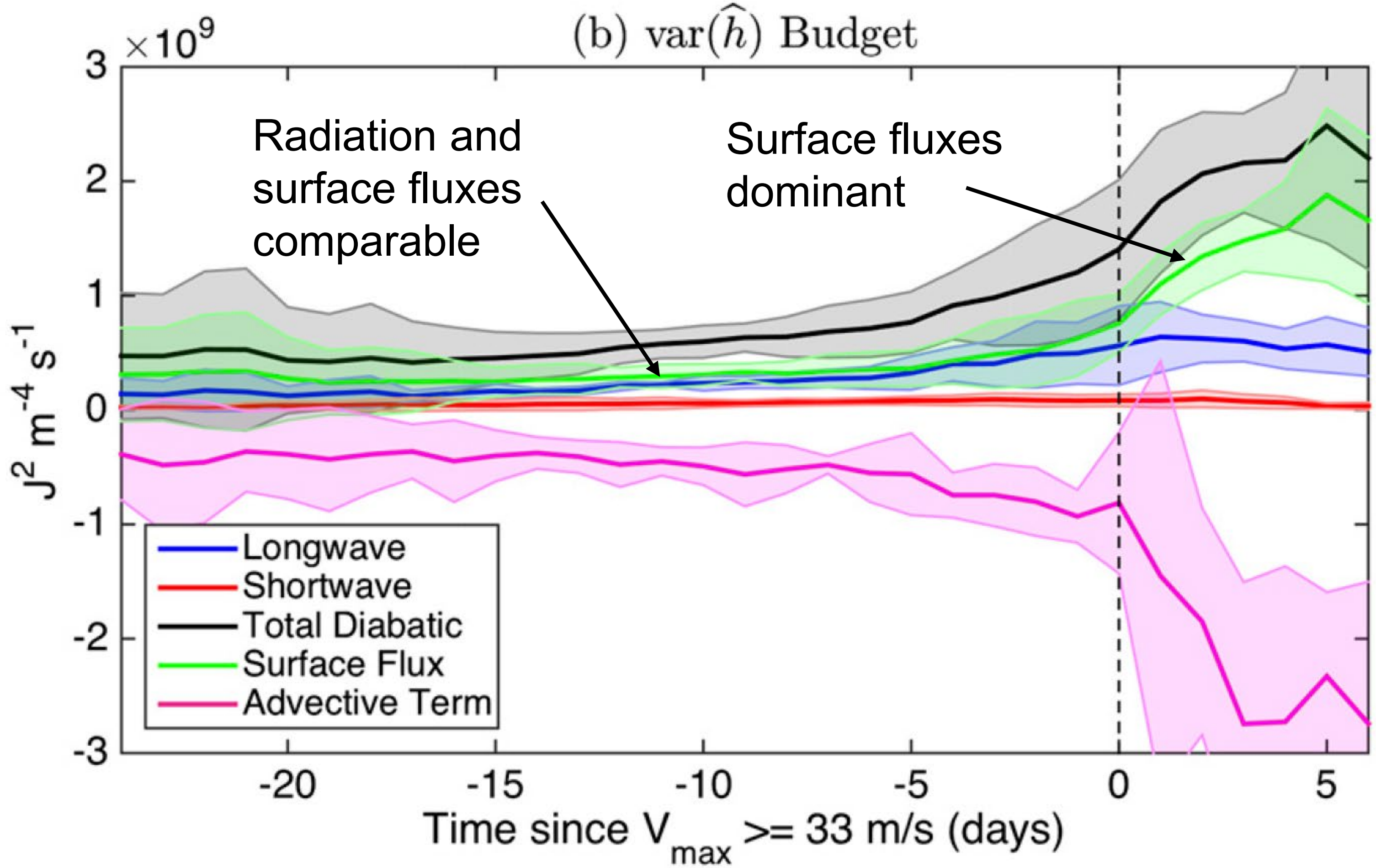
TC Worlds: f-plane Experiments in doubly-periodic boxes

Bretherton and Khairoutdinov (2005), Nolan et al. (2007), and many others



From Zhou, Held and Garner, 2014

Budget of variance of column moist static energy
(Lines: ensemble mean; Shading: Std. deviation)



Note: Genesis does occur with homogeneous radiation

Wing et al., *J. Atmos. Sci.*, 2016

Hurricane-World Scaling

- Radius of maximum winds: $$r_m \sim \frac{V_{pot}}{\Omega}$$
- Distance between storm centers: $$D \sim \frac{\sqrt{L_v q_s}}{\Omega}$$
- Number density: $$n \sim \frac{\Omega^2}{L_v q_s}$$

Note: I was able to show (2022) that the D scale above is consistent with the matched inner-outer radial profile developed by Dan Chavas and me, if it is assumed that the inner core radius scales as V_{pot}/f

Khairoutdinov and Emanuel, 2013

Dry Hurricanes in Dry RCE State

Cronin and Chavas, 2019

The idea that ‘triggers” are needed has a long history

- “*In all cases of hurricane formation noted in the course of this study, deepening began, without exception, in pre-existing tropical disturbances*” – Gordan Dunn (1951)

- “*Storms never develop spontaneously in the undisturbed tropical currents but always in a preexisting disturbance* – Herbert Riehl (1951)

Early researchers focused some attention on the nature of pre-existing disturbances:

- *"Tropical cyclones originate in easterly waves, in the intertropical convergence zone, and occasionally in the trailing southerly portions of old polar troughs….[but] there is as yet no generally accepted definition of exactly what synoptic situation is responsible for the formation of a tropical cyclone"* – Dunn (1951)