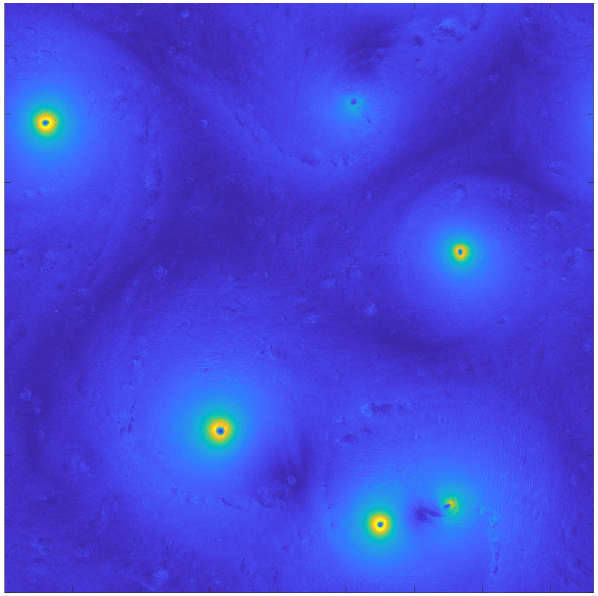
12.307
Hurricane worlds, from moist to dry



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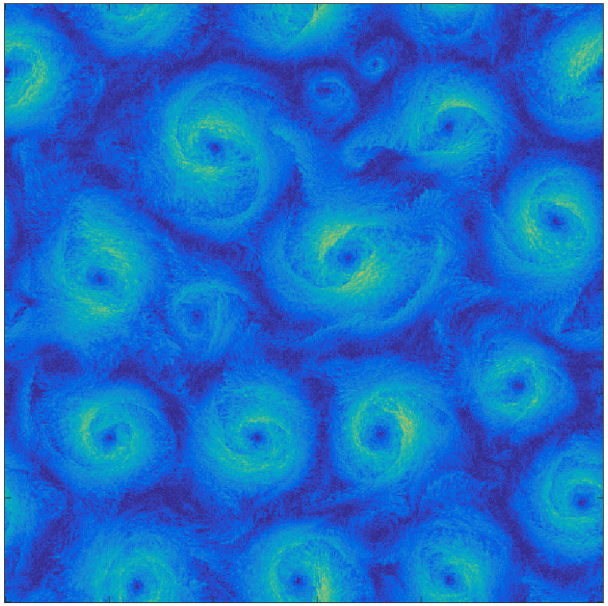
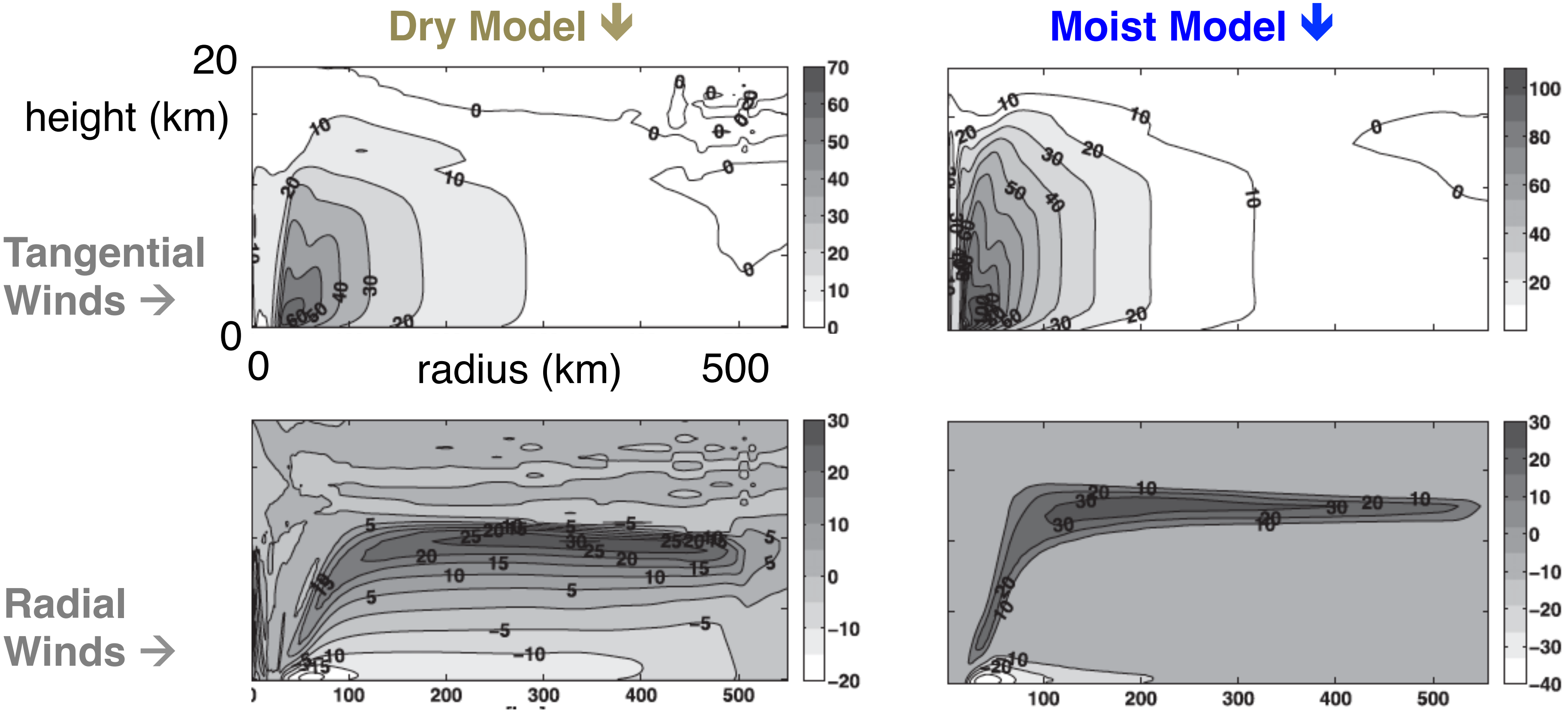
(collaborative work with Dan Chavas (Purdue)



Hurricanes are largely dangerous because of how they move water

Is moisture required for a hurricane?

Is moisture required for a hurricane?



Dry Model ↓

Moist Model ↓

Tangential Winds →

Radial Winds →

Mrowiec, Pauluis, and Garner (2011):

No, it’s not!

Dry hurricanes raise many questions and we have few answers

Are dry storms even stable in 3D?

What controls their intensity, size, and structure?

What does the transition from moist to dry dynamics look like?

Little work has been done to address these questions.

Why should we care about dry hurricanes if they don’t exist on Earth?

Simplicity: dry fluid dynamics is far simpler than moist dynamics

Prospect of studying dry vortices to better understand their real moist counterparts

Experimental tractability: possibility of “hurricanes in a tank”

Analytic linkage to rotating Rayleigh-Benard convection?

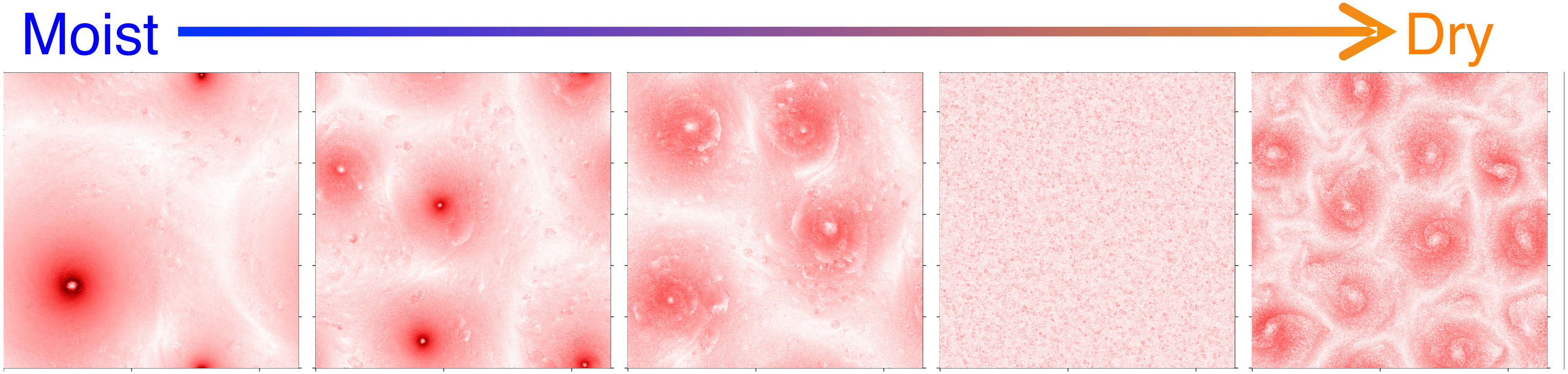
Universality: convective vortices on other worlds?

My work: simulate moist-dry transition of hurricane-worlds

Dry or cool the surface to reduce the role of evaporation and condensation

Look for similarities and differences with theories for real (moist) hurricanes

Dry hurricanes readily form under the right conditions*



Dry storms are less intense than familiar moist counterparts

Moist-dry transition appears discontinuous for storm genesis, but smooth for established storms

*These conditions are unlikely to be found in Earth's current climate!

Overview

I) Background on Tropical Cyclones/Hurricanes

II) Simulation of dry hurricanes and moist-dry transition

What is a hurricane?

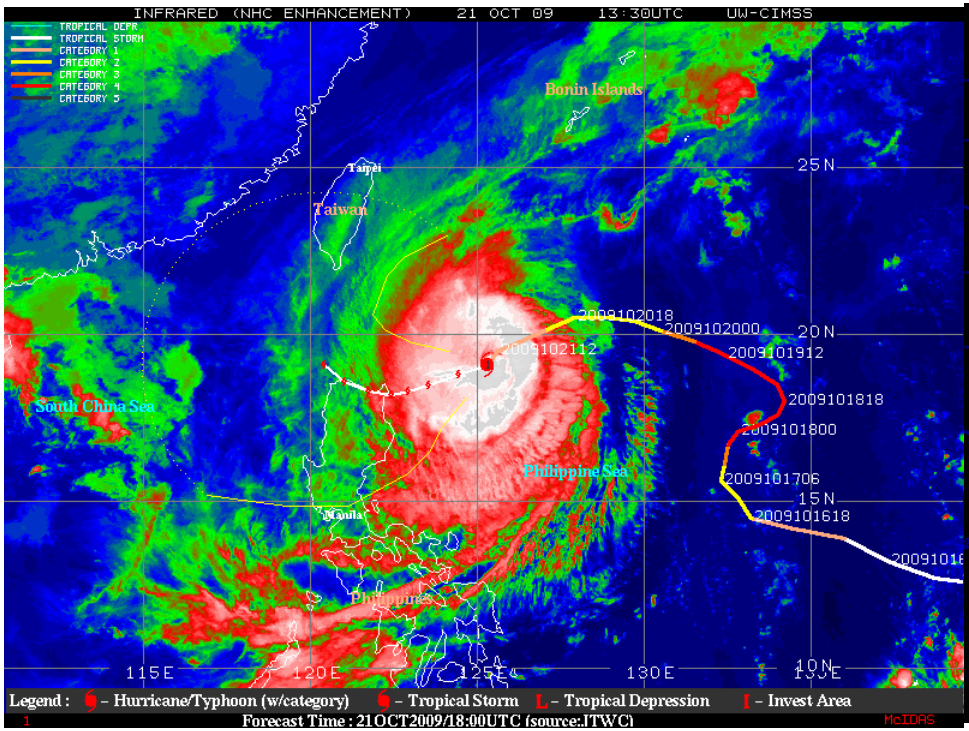
For the purposes of this talk:

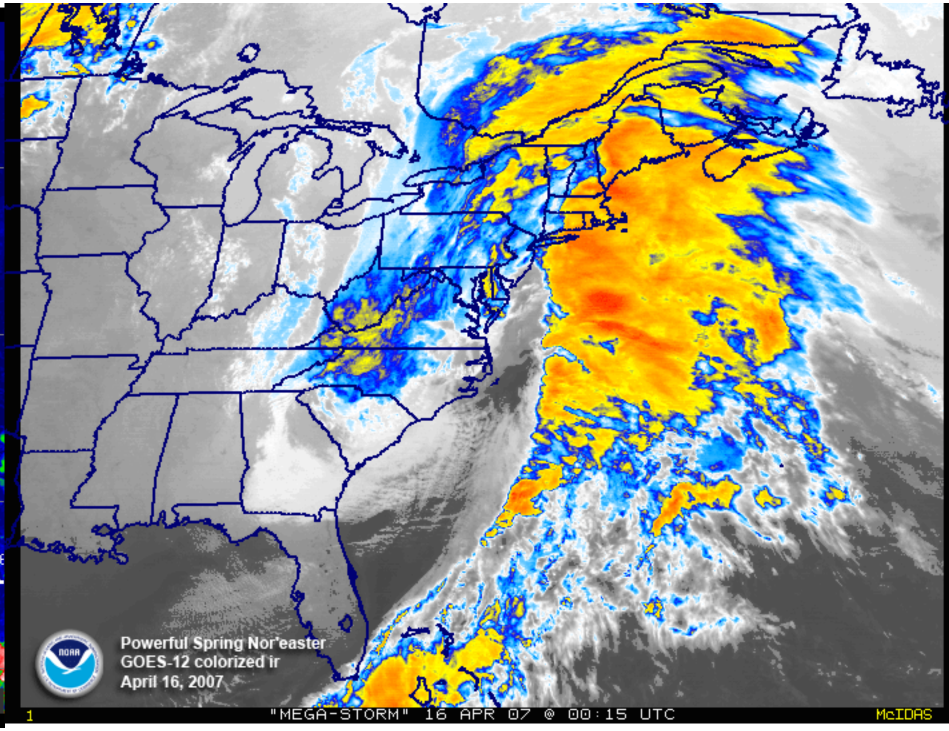
hurricane = tropical cyclone

The “tropical” essence of “tropical cyclone” lies in the energy source:

Surface-flux driven convection, *not* baroclinic instability

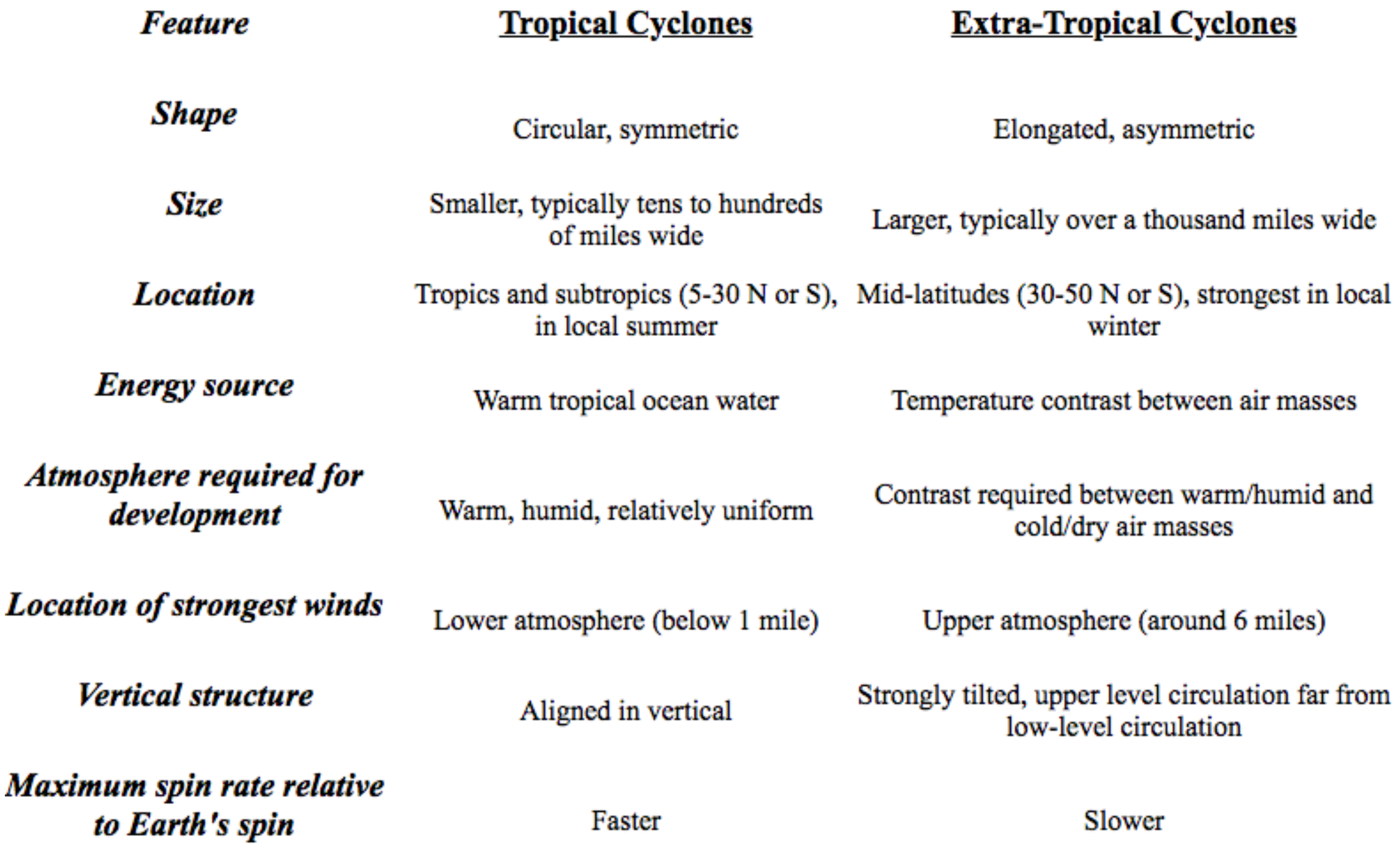
A class project I did from Lodo's graduate class 12.818





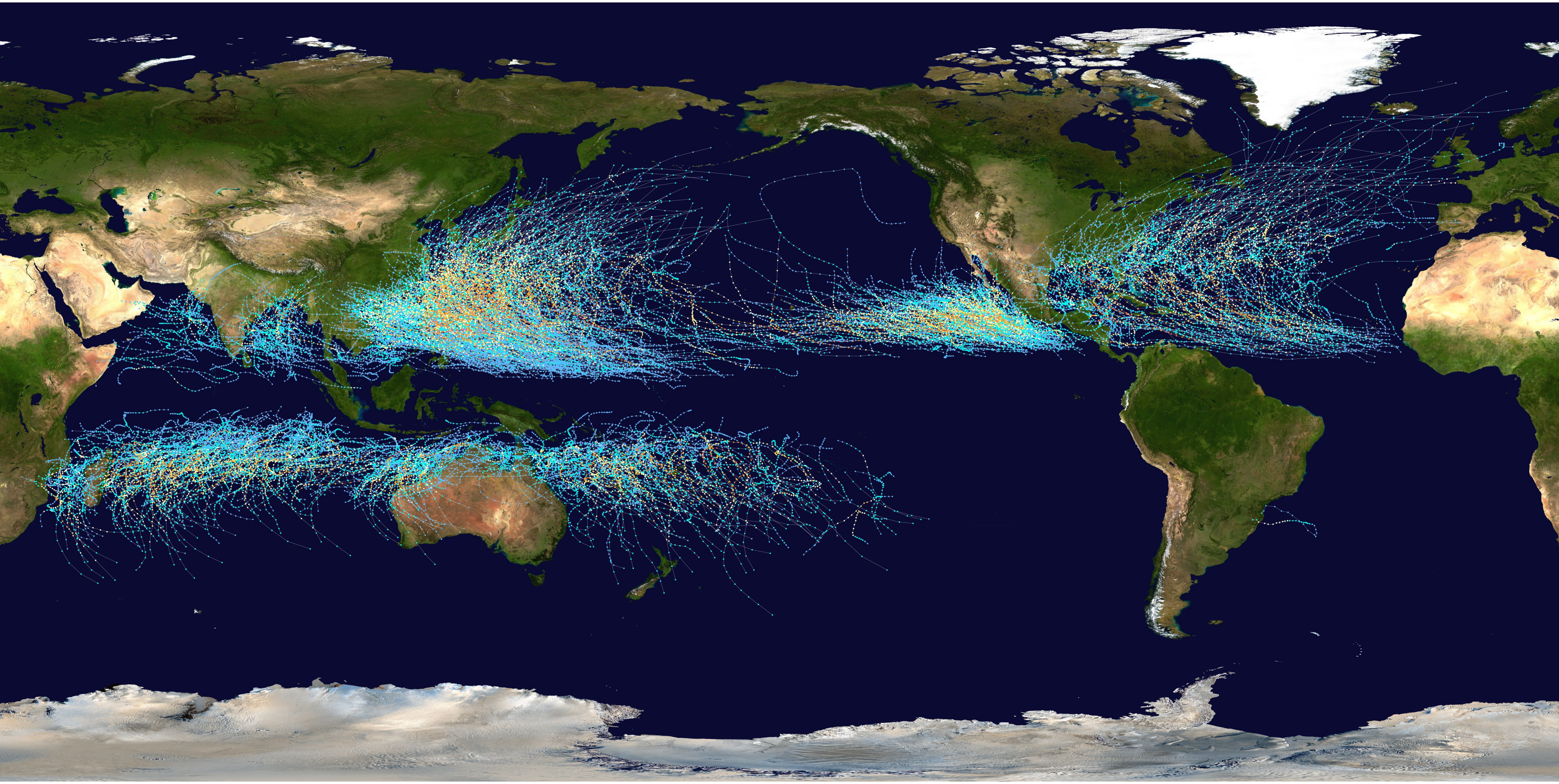
http://mit.edu/~twcronin/Public/Cyclone_Comparison.html

Comparison of tropical and extratropical cyclones



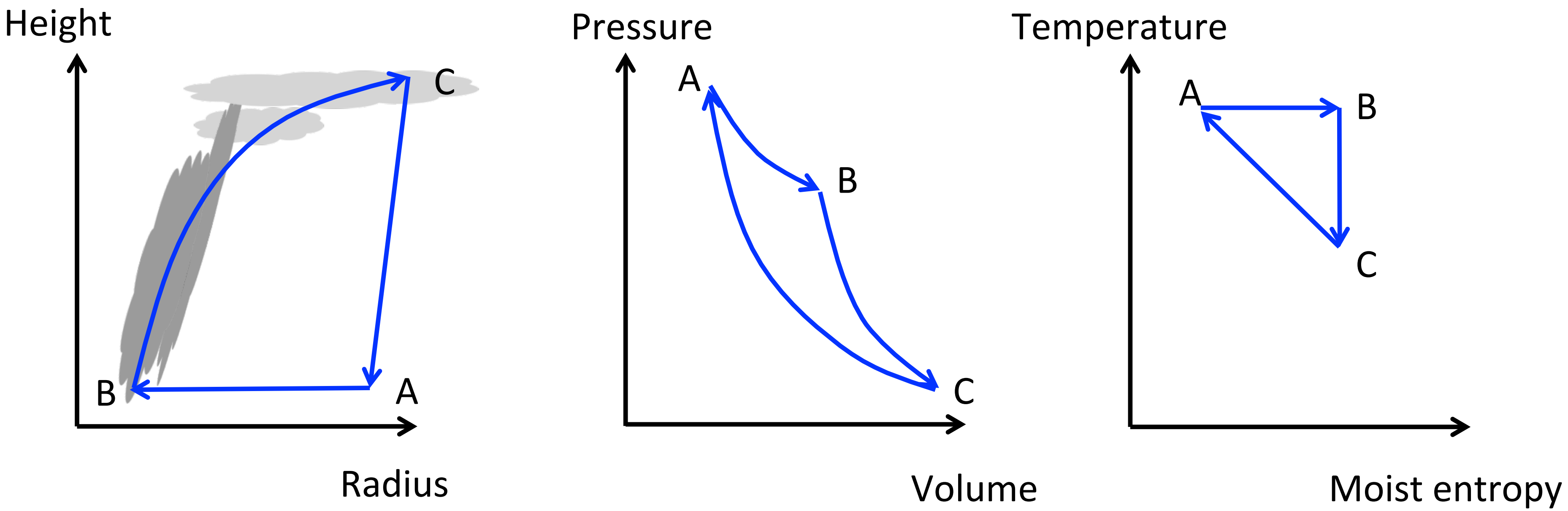
Feature	Tropical Cyclones	Extra-Tropical Cyclones
Shape	Circular, symmetric	Elongated, asymmetric
Size	Smaller, typically tens to hundreds of miles wide	Larger, typically over a thousand miles wide
Location	Tropics and subtropics (5-30 N or S), in local summer	Mid-latitudes (30-50 N or S), strongest in local winter
Energy source	Warm tropical ocean water	Temperature contrast between air masses
Atmosphere required for development	Warm, humid, relatively uniform	Contrast required between warm/humid and cold/dry air masses
Location of strongest winds	Lower atmosphere (below 1 mile)	Upper atmosphere (around 6 miles)
Vertical structure	Aligned in vertical	Strongly tilted, upper level circulation far from low-level circulation
Maximum spin rate relative to Earth's spin	Faster	Slower

Hurricanes are limited to off-equator tropical* oceans in Earth’s present climate

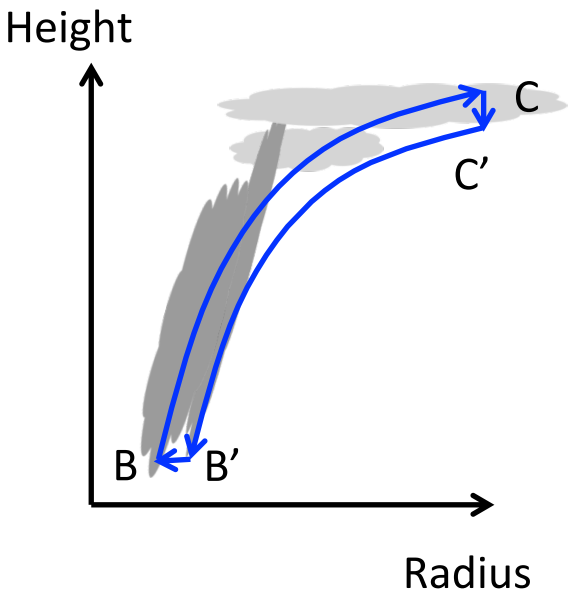


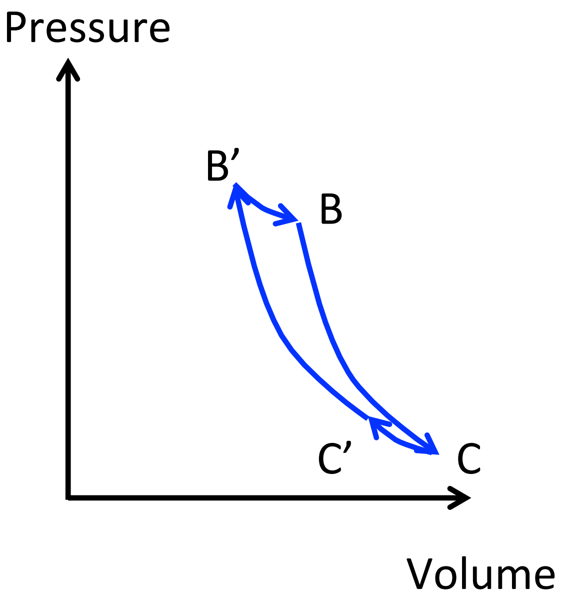
* some rare small cyclones with mid- or high-latitude genesis may also be essentially hurricanes

Theory:
Hurricanes act as heat engines



“Potential intensity” = speed limit for hurricane winds





Thermodynamic sub-cycle B’-B-C-C’ near center of storm:

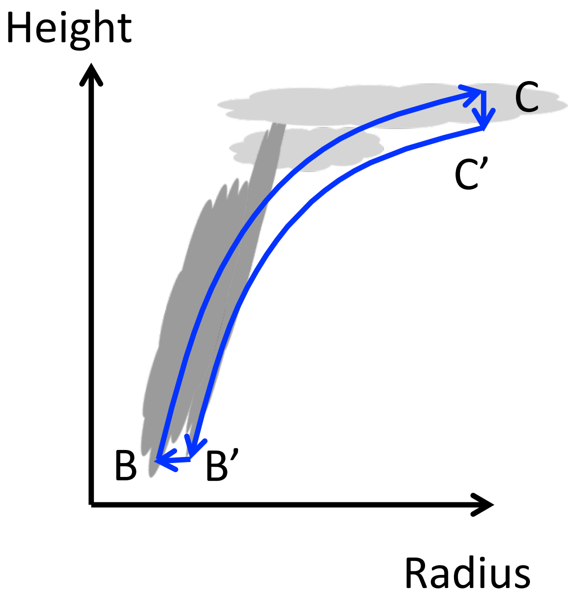
Heat input rate per unit mass of air: Q = $c_k\, v\, (k_0{}^{*}-k)$

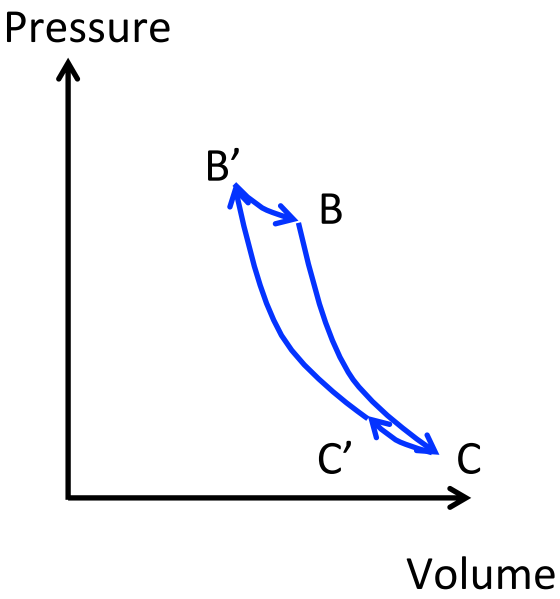
[k = moist enthalpy]

Potential work done: efficiency × Q

Efficiency = $(T_S-T_0)/T_S$ [This is a Carnot cycle!]

“Potential intensity” = speed limit for hurricane winds





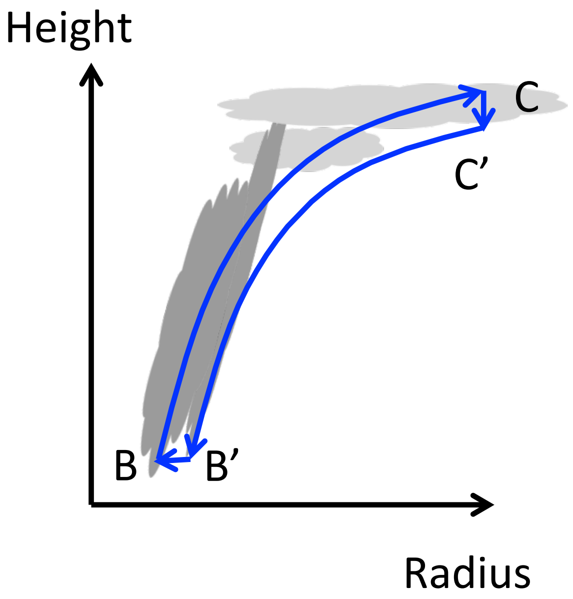
Potential work done per unit mass: $(T_S - T_0)/T_S \times c_k\, v\, (k_0^* - k)$

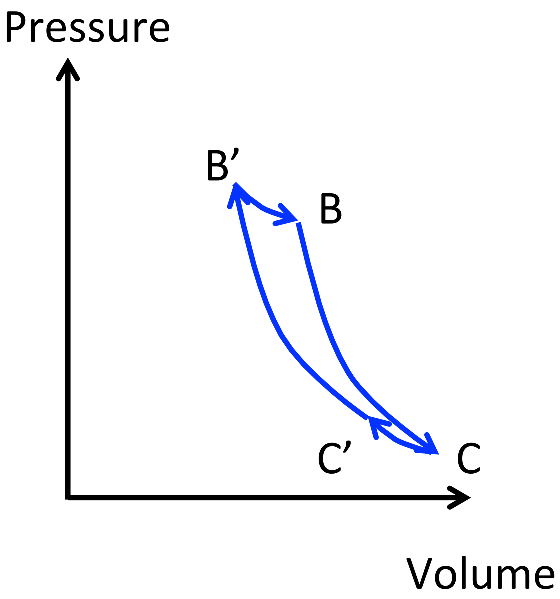
Assume all of this work goes into frictional dissipation of winds at the surface = $c_d\, v^3$

Equate these two:

$$c_d\, v^3 = (T_S - T_0)/T_S \times c_k\, v\, (k_0^* - k)$$

“Potential intensity” = speed limit for hurricane winds





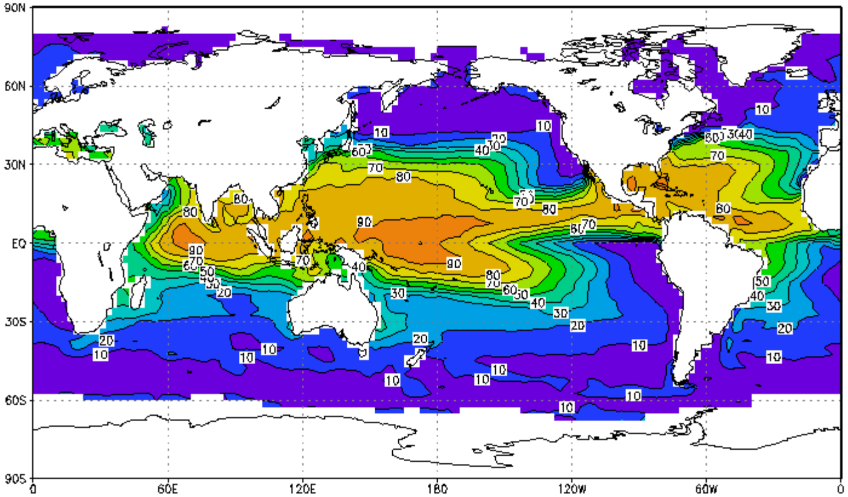
Solve for the wind speed and call it “potential intensity” v_p:

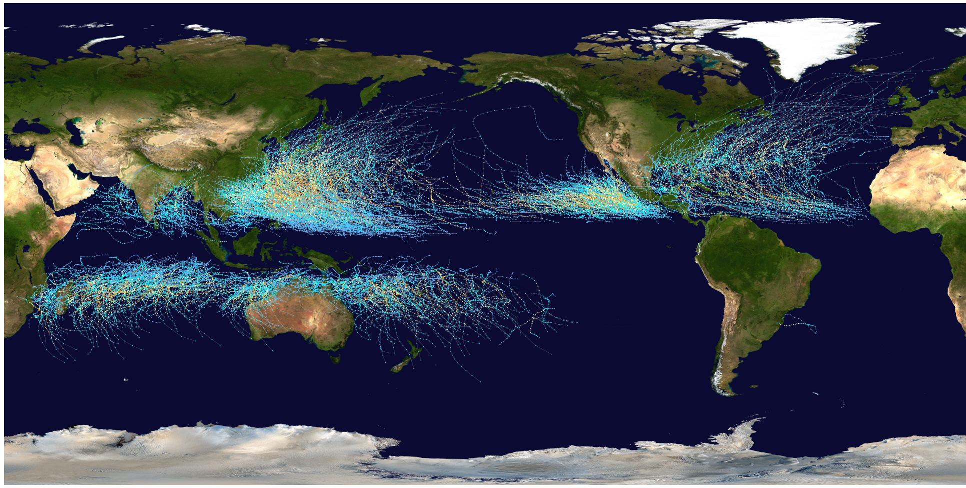
$$v_p = [c_k/c_d (T_S - T_0)/T_S \, v \, (k_0{}^* - k)]^{1/2}$$

Major body of work by Kerry Emanuel, e.g.,

Bister & Emanuel (1998); Emanuel & Rotunno (2011)

Potential intensity and hurricane tracks





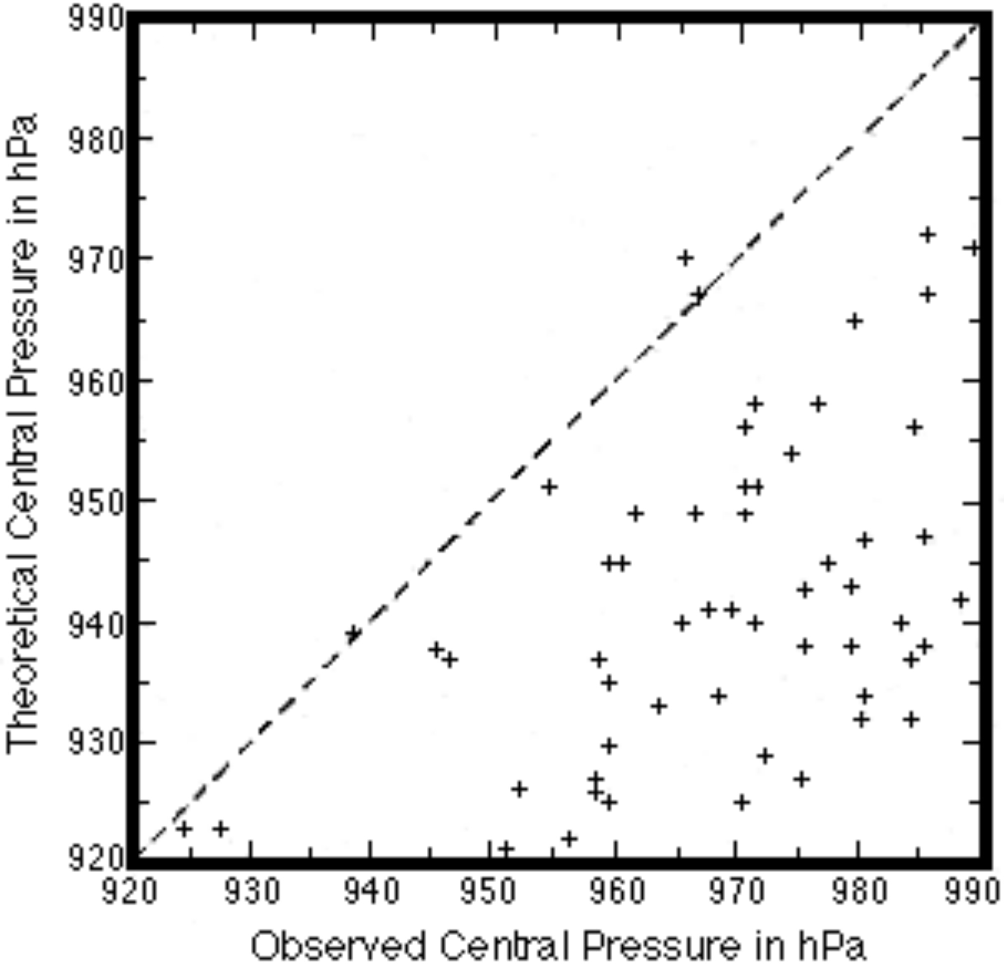
September average v_p

Contours 10 m/s up to 90 m/s

http://wind.mit.edu/~emanuel/pcmin/climo/avv09.gif

Observed TCs (all times of year!)

Real storms rarely exceed their potential intensities



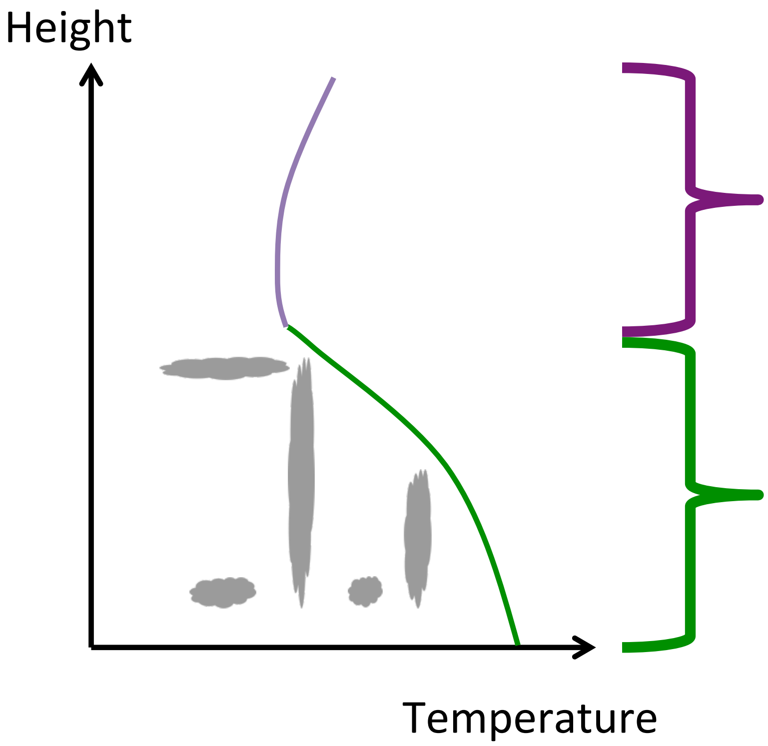
https://emanuel.mit.edu/hurricane-potential-intensity-maps-0

How do you make hurricanes in a model?

Easy (with enough processing power): there are two ingredients

1) Deep convection
2) Planetary rotation

Radiative-convective equilibrium



Stratosphere: radiative equilibrium, essentially no mixing

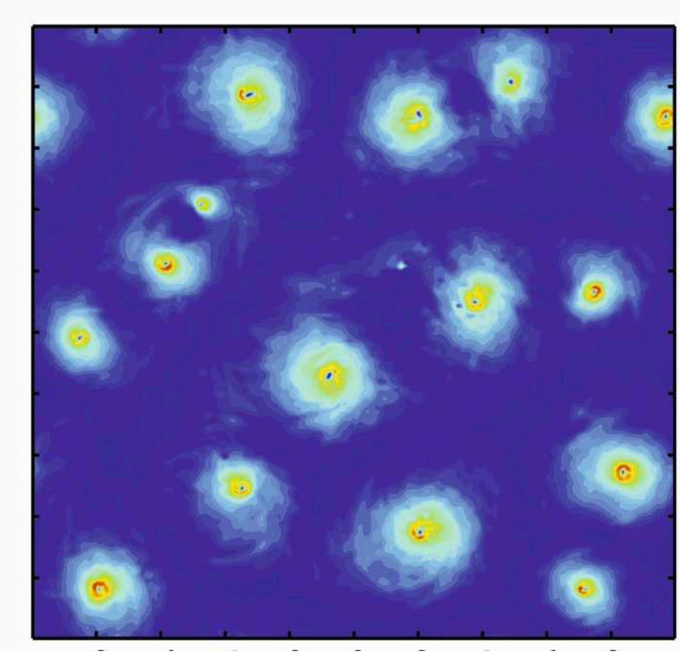
Troposphere: radiative cooling balanced by convective heating, surface evaporation balanced by precipitation

Simplest basic-state notion of tropical atmosphere

A movie of radiative-convective equilibrium

(movie made by Tristan Abbott)

Larger-scale radiative-convective equilibrium + rotation



Simple to simulate: just add a coriolis acceleration in the horizontal momentum equations

Previous studies have found that rotating moist RCE fills up with hurricanes ("TC-worlds")

(Held et al, 2008; Khairoutdinov and Emanuel, 2013; Reed and Chavas, 2015, …)

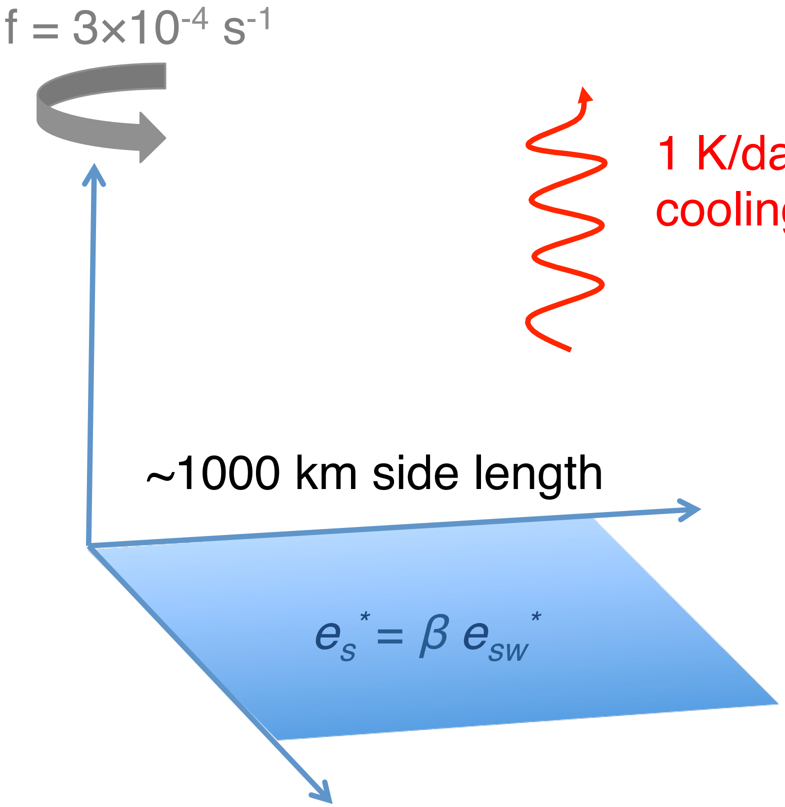
Nothing in theory just presented precludes dry or semi-dry hurricanes

Overview

I) Background on Tropical Cyclones/Hurricanes

II) Simulation of dry hurricanes and moist-dry transition

Two ways to dry out the surface



- SAM, rotating, doubly-periodic square domains, side length ~1000 km
- Constant tropospheric radiative cooling (1K/d)
- Start simulations from equilibrated f=0 RCE

1) Scale surface saturation vapor pressure by varying β ($0 \leq \beta \leq 1$) with SST = 300 K

2) Vary the SST between 240 and 300 K to span dry to moist limits

Dry and moist systems with f=3e-4 s^{-1}

Moist surface (β=1)

60 m/s

Dry surface (β=0)

40 m/s

1000 km

- Dry hurricanes readily form and persist
- Dry hurricanes have big eyes, weaker peak intensity
- Surface KE dissipation is similar for dry and moist systems

Dry storms are more uniform in size and outer winds fall off more quickly

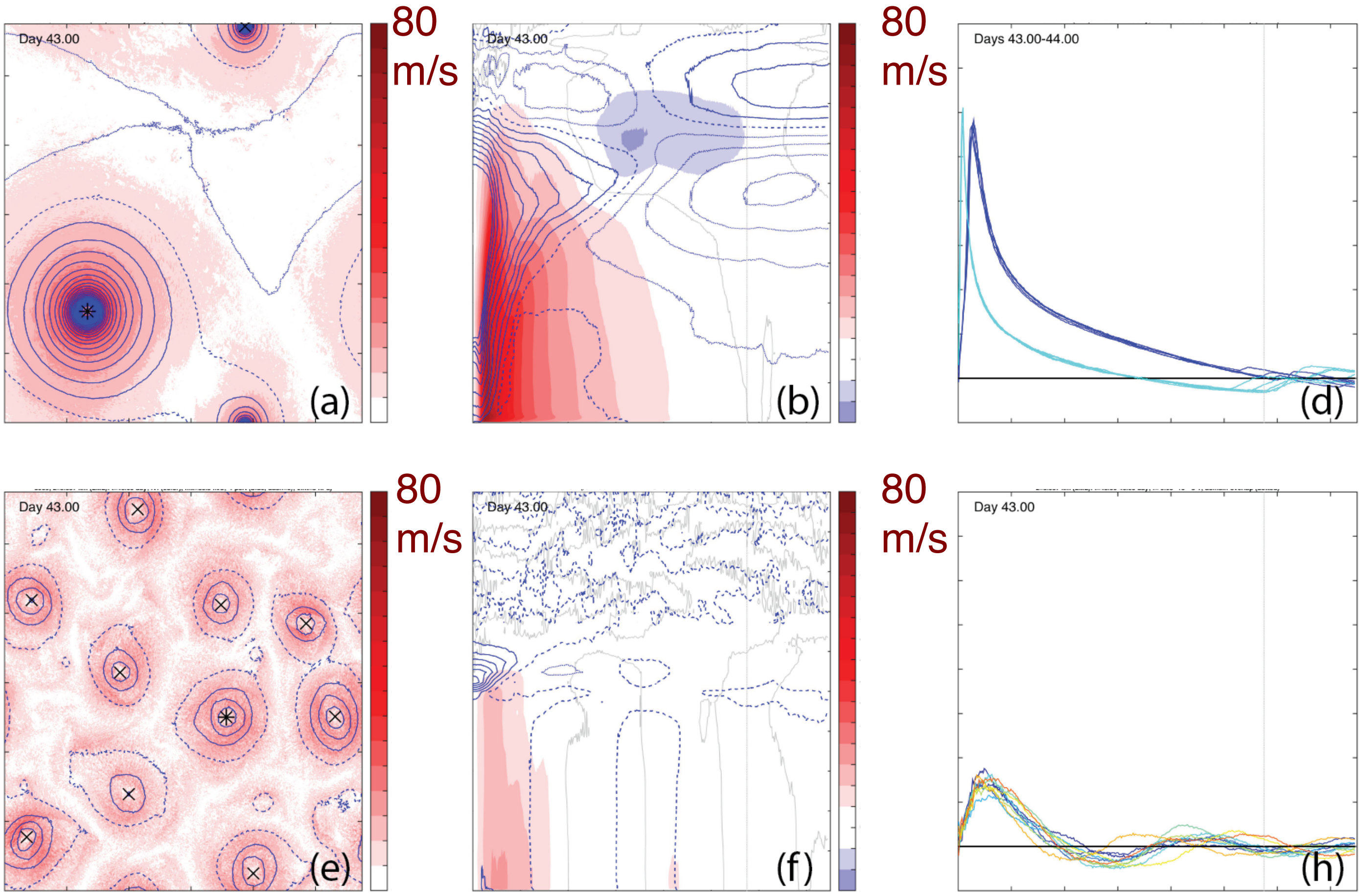
MAP,
Surface winds (colors),
pressure (lines) ↓

r-z section,
Azimuthal winds (colors),
T’ (lines) ↓

Azimuthal winds
plotted against
radius ↓

Moist TC
World →

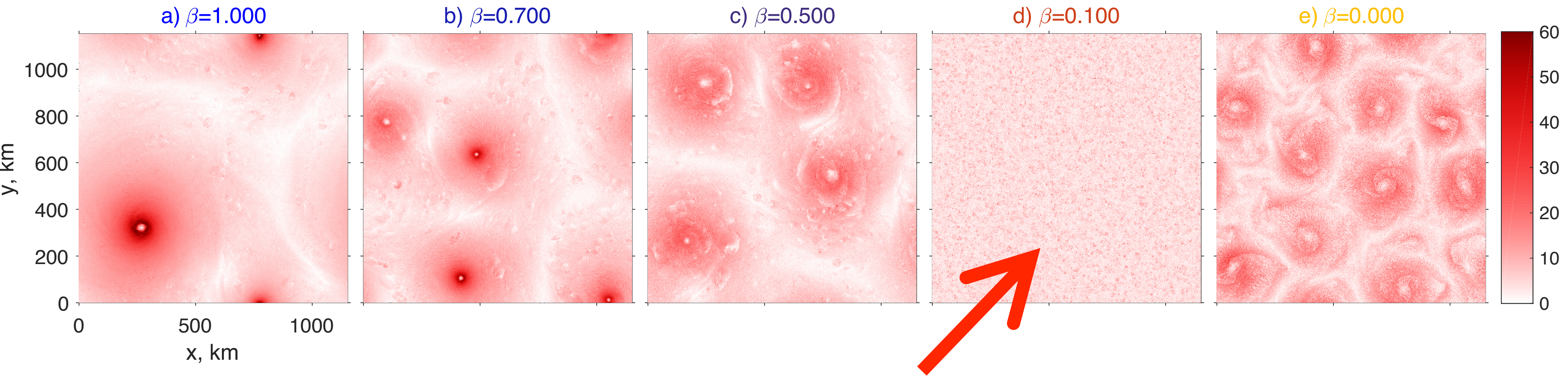
Dry TC
World →



BUT: moist-to-dry transition is not continuous

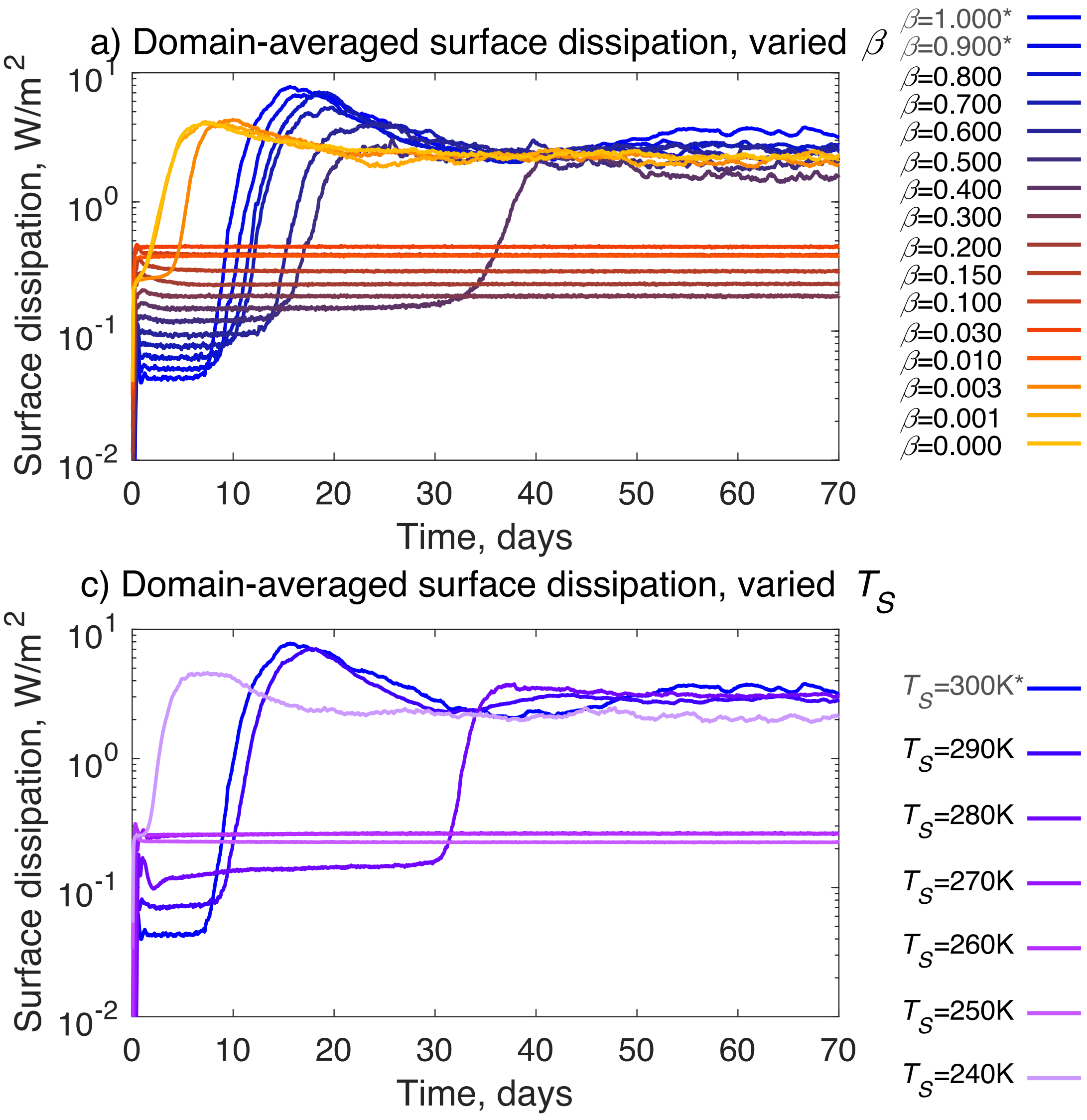
Storms gradually transition in size, intensity, and inner structure…

Moist → Dry



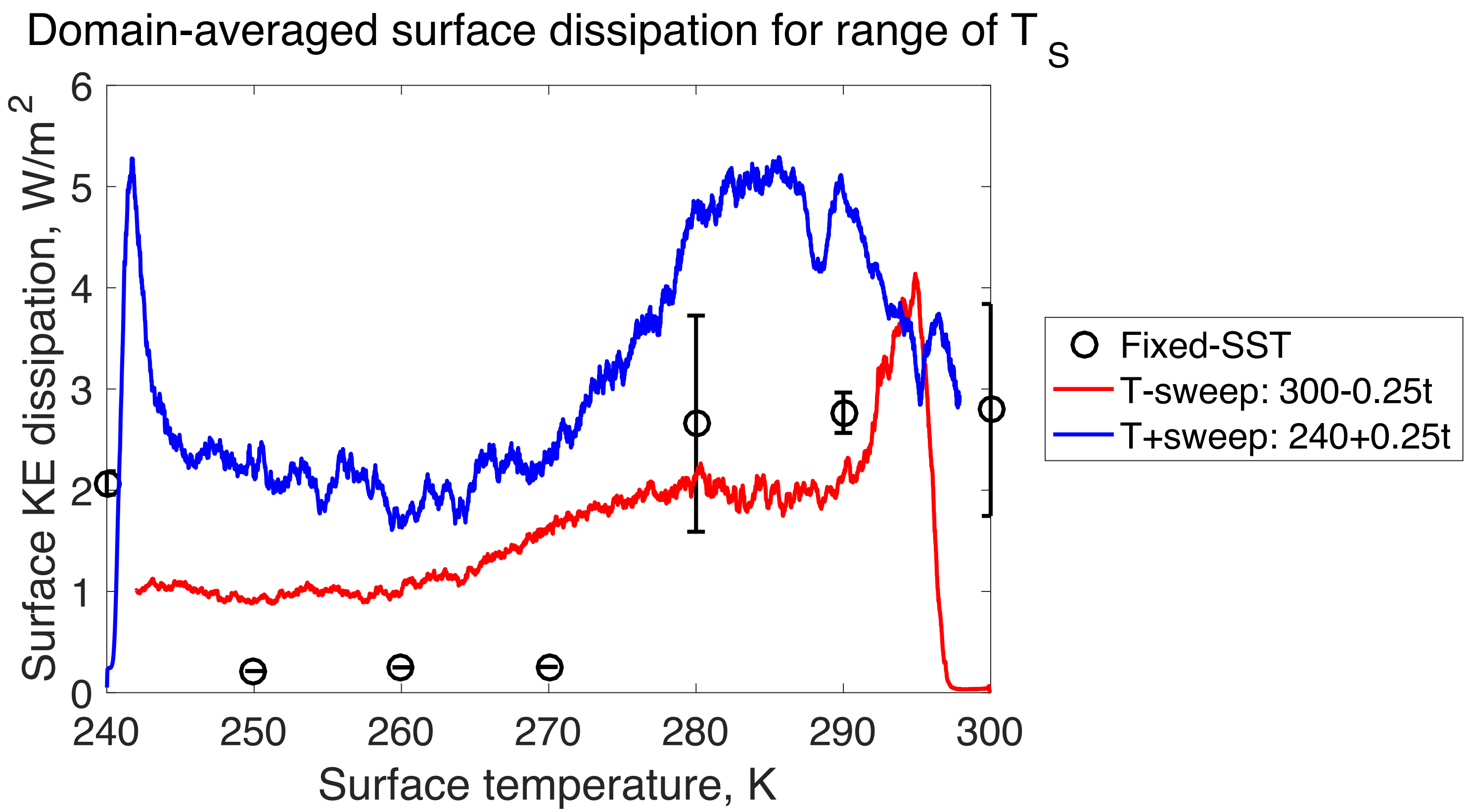
… Except for a no-storms-land where storms don't form at low but nonzero β!

Surface KE dissipation timeseries



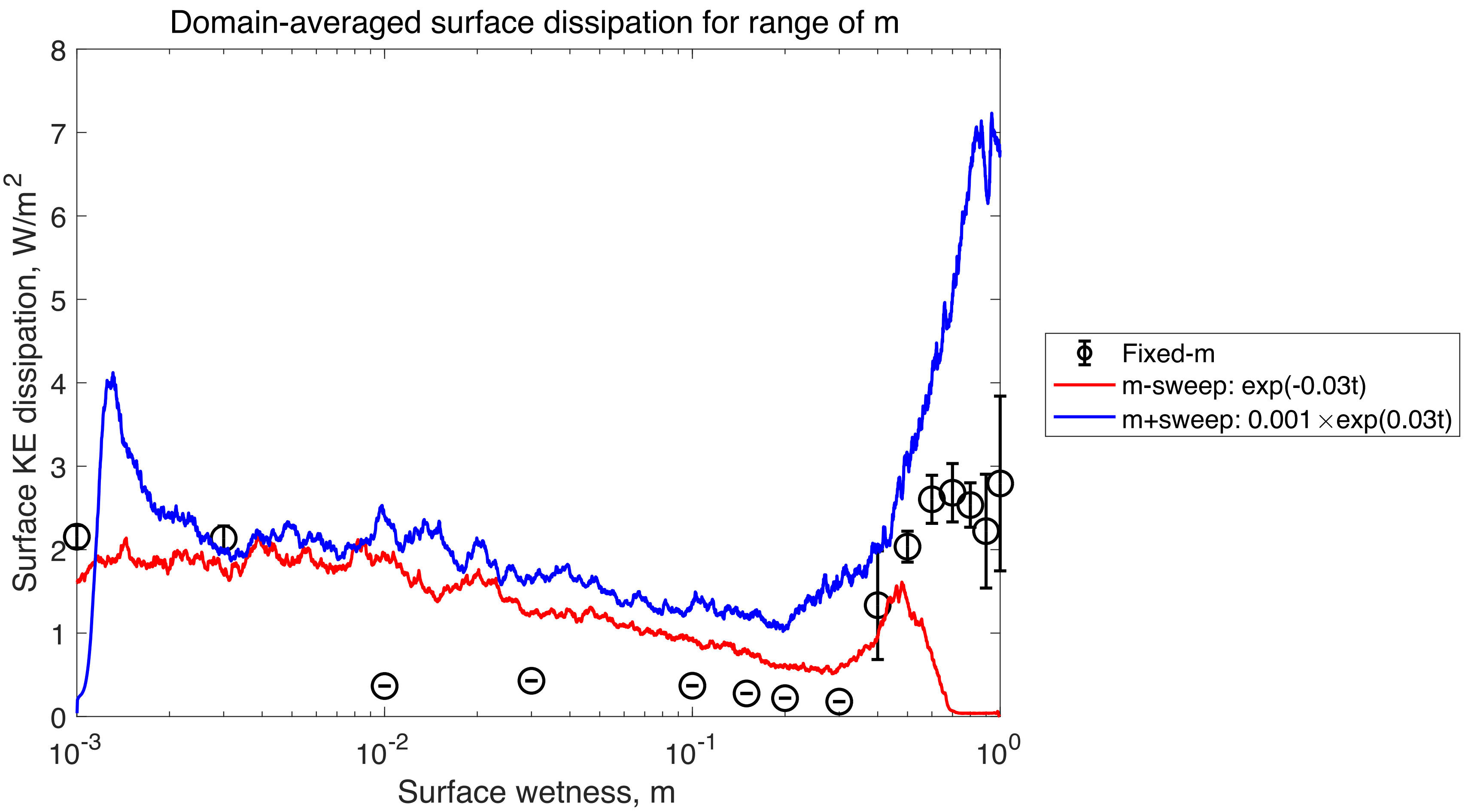
- Varied β: No spontaneous genesis from 0.3 to 0.01
- Varied T_s: no spontaneous genesis from 250 to 270 K
- But dry TCs form almost immediately at T_s = 240 K!
- Striking similarity between two sets of simulations

But no-storms-land is only a barrier to spontaneous genesis



- Simulations with SST ramped up or down in time keep cyclones across whole range of surface temperatures

Similar picture for moist-dry ramps



- Simulations with surface wetness ramped up or down in time keep cyclones across whole range of β

Nondimensional cyclone properties

Left

Intensity:

v_m/v_p

Middle

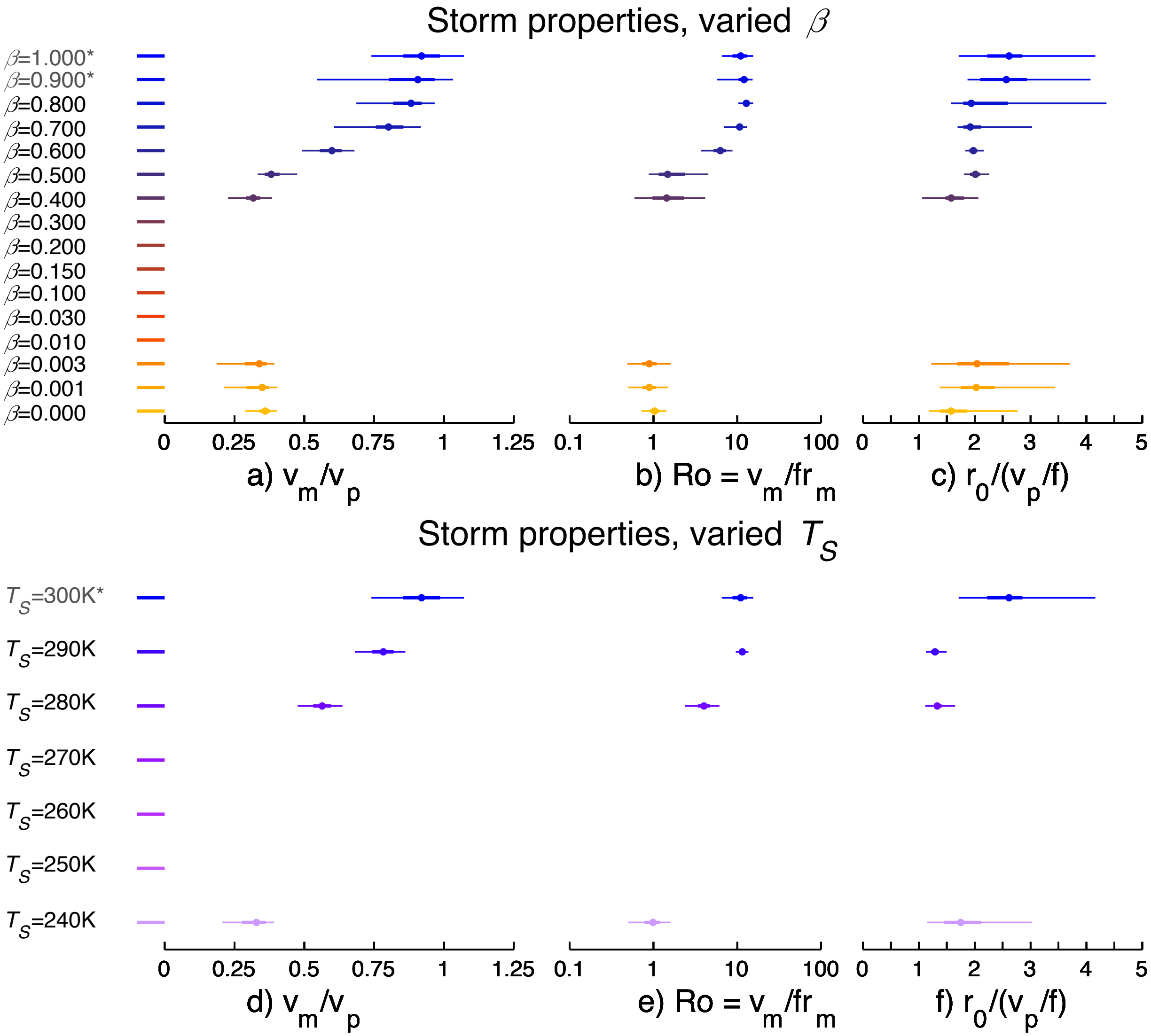
Inner core vortex regime:

$Ro=v_m/(fr_m)$

Right

Outer size:

$r_0/(v_p/f)$



Main results

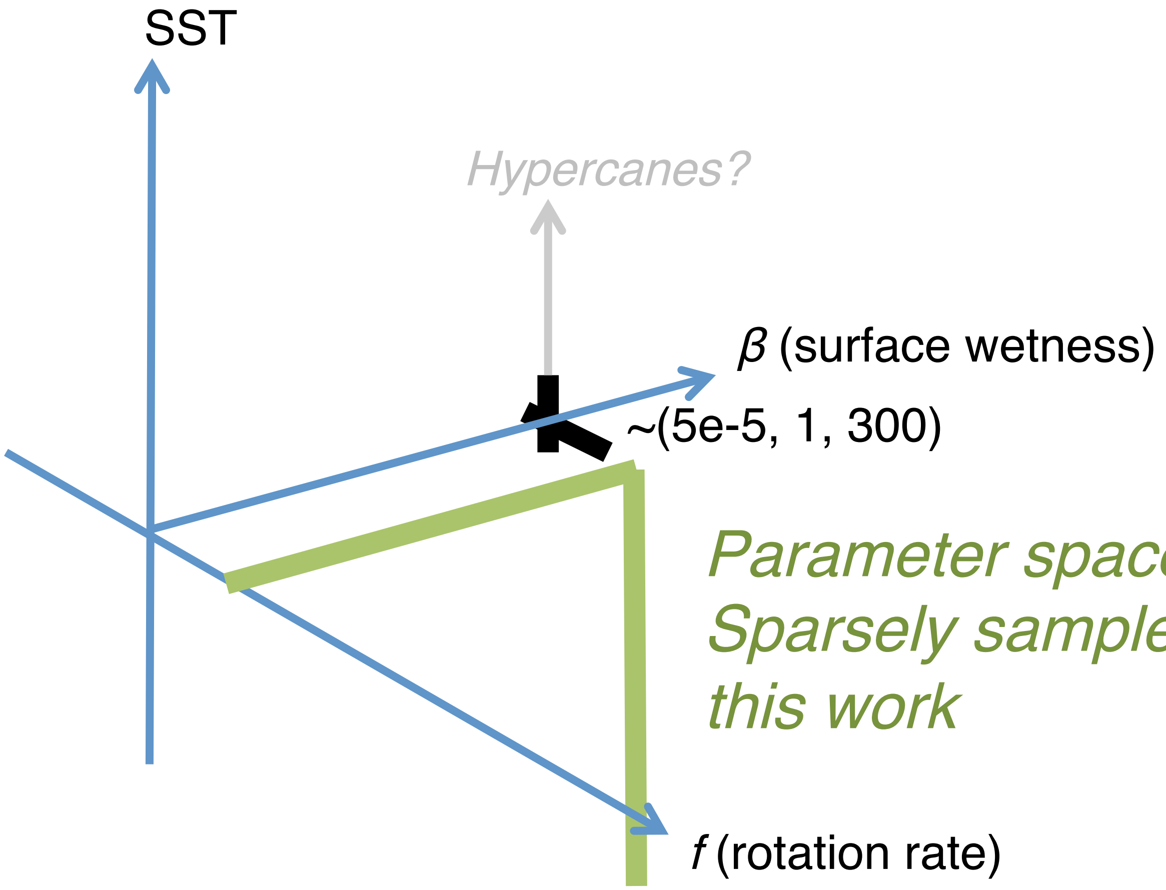
Dry hurricanes readily form in rotating RCE

Properties differ from moist counterparts – weaker peak winds, larger radius of maximum winds

Transition appears relatively continuous except for “no-storms-land” barrier to spontaneous genesis

Cronin & Chavas, *JAS*, in review

There's a lot to explore…

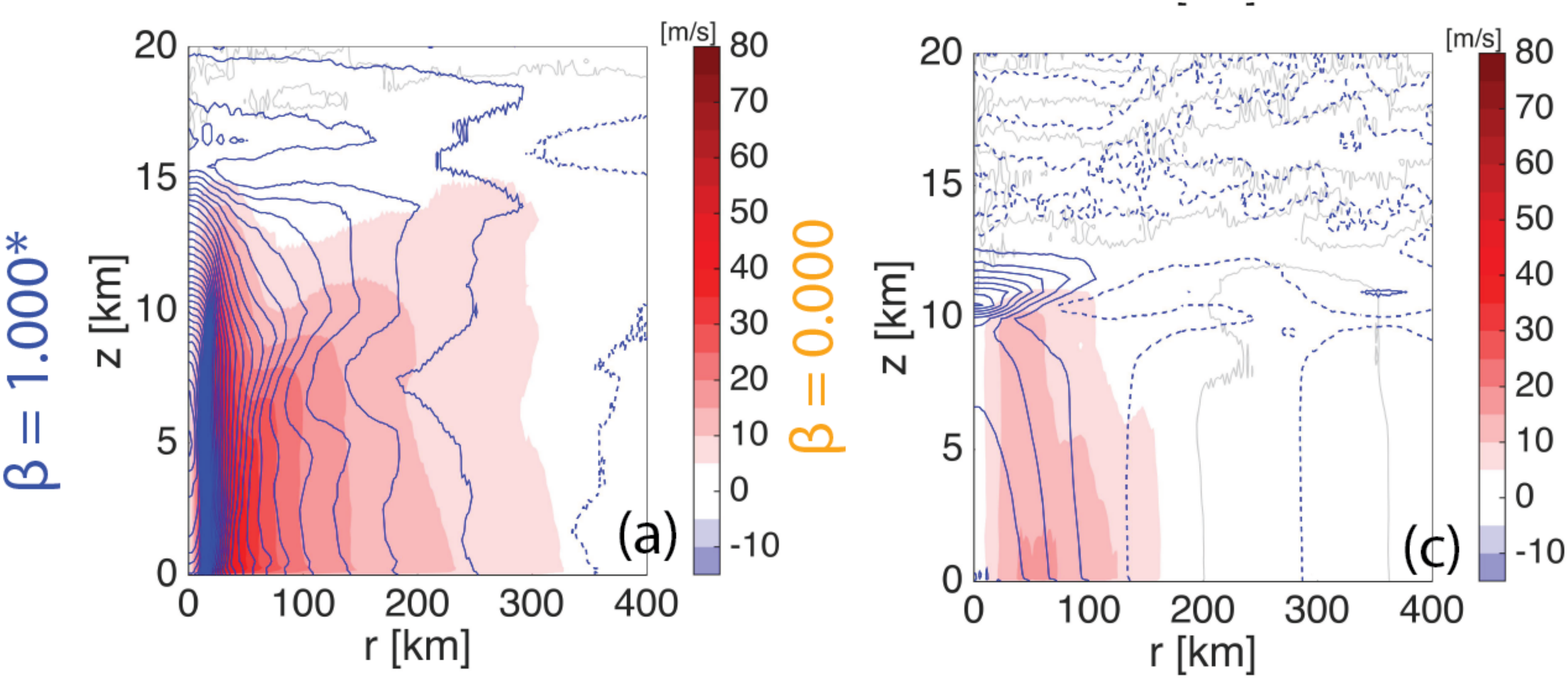


Parameter space Sparsely sampled in this work

…and interesting territory in all directions!

Cronin & Chavas, "Dry and semi-dry tropical cyclones" *JAS,* submitted. twcronin@mit.edu

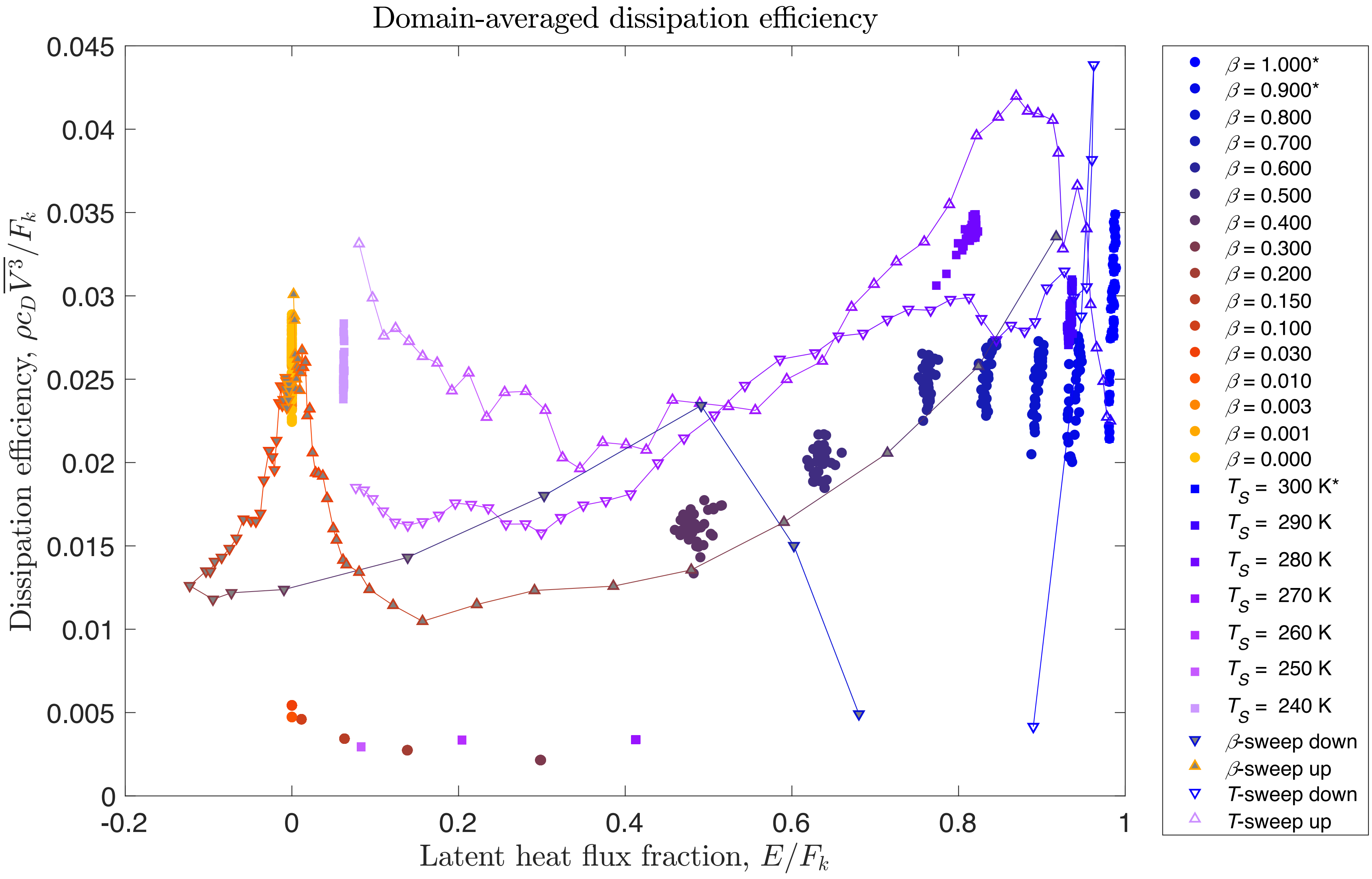
Dry storm cores are buoyant but not warm at fixed *z*



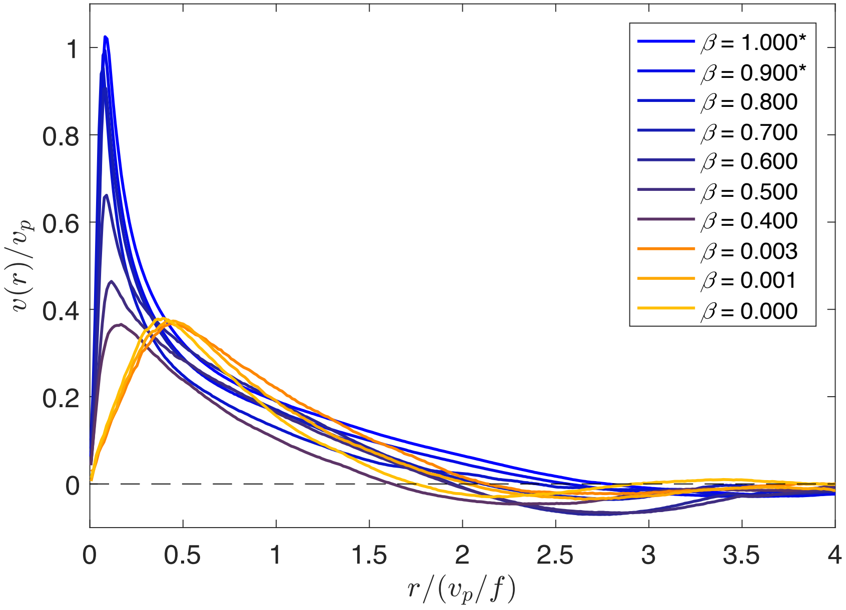
Contours show:

$$T_b' = \overline{T_b}\left(\frac{T'}{\overline{T}} + 0.608 q_v' - q_n - q_p - \frac{p'}{\overline{p}}\right)$$

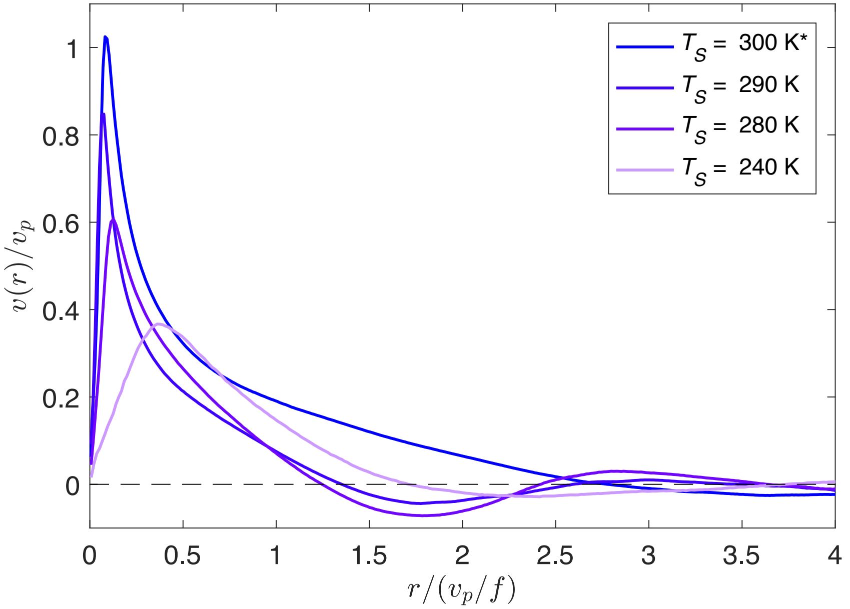
An attempt at a nondimensional plot of “no-storms-land”



Radial structure composites of intense cyclones



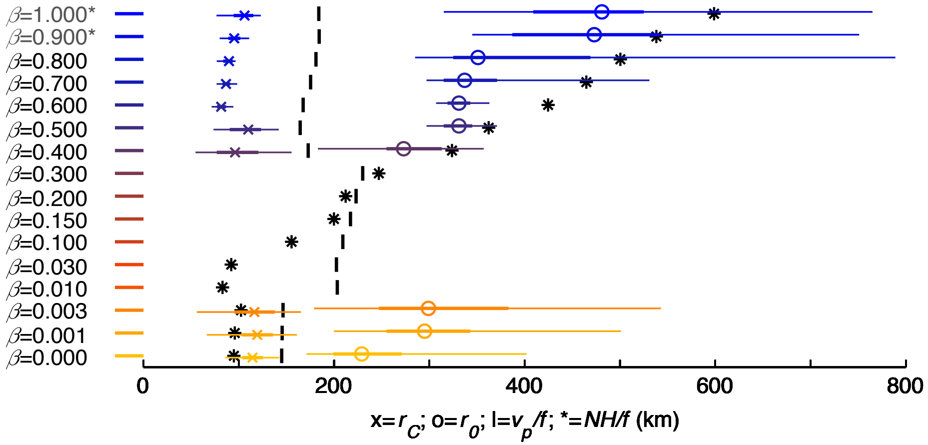
a) Composite structure for high-intensity cyclones over β



b) Composite structure for high-intensity cyclones over T_S

Outer size does not scale with deformation radius

a) Outer size distributions, varied β



b) Outer size distributions, varied T_S