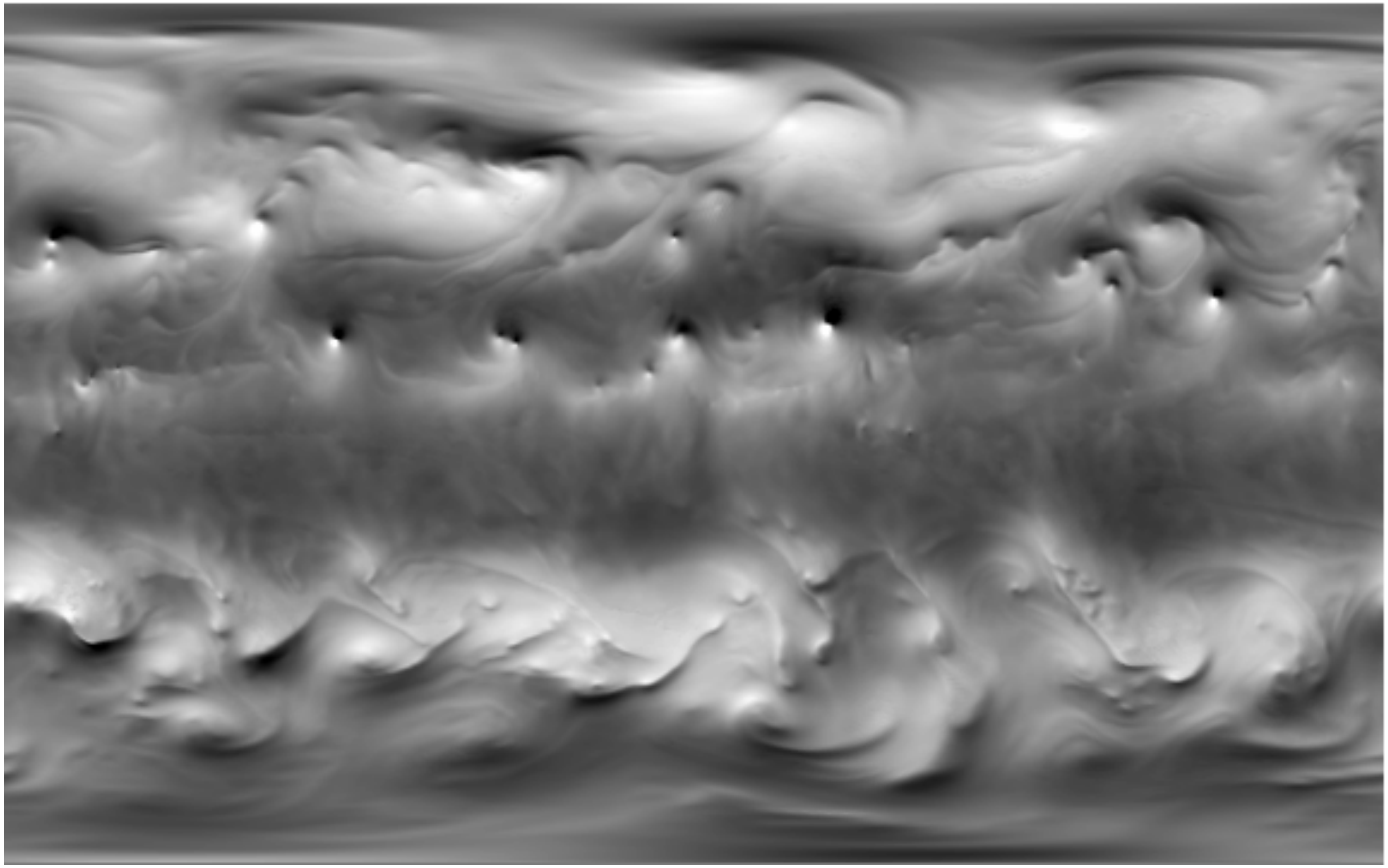
Studying tropical cyclone climatology with a hierarchy of models

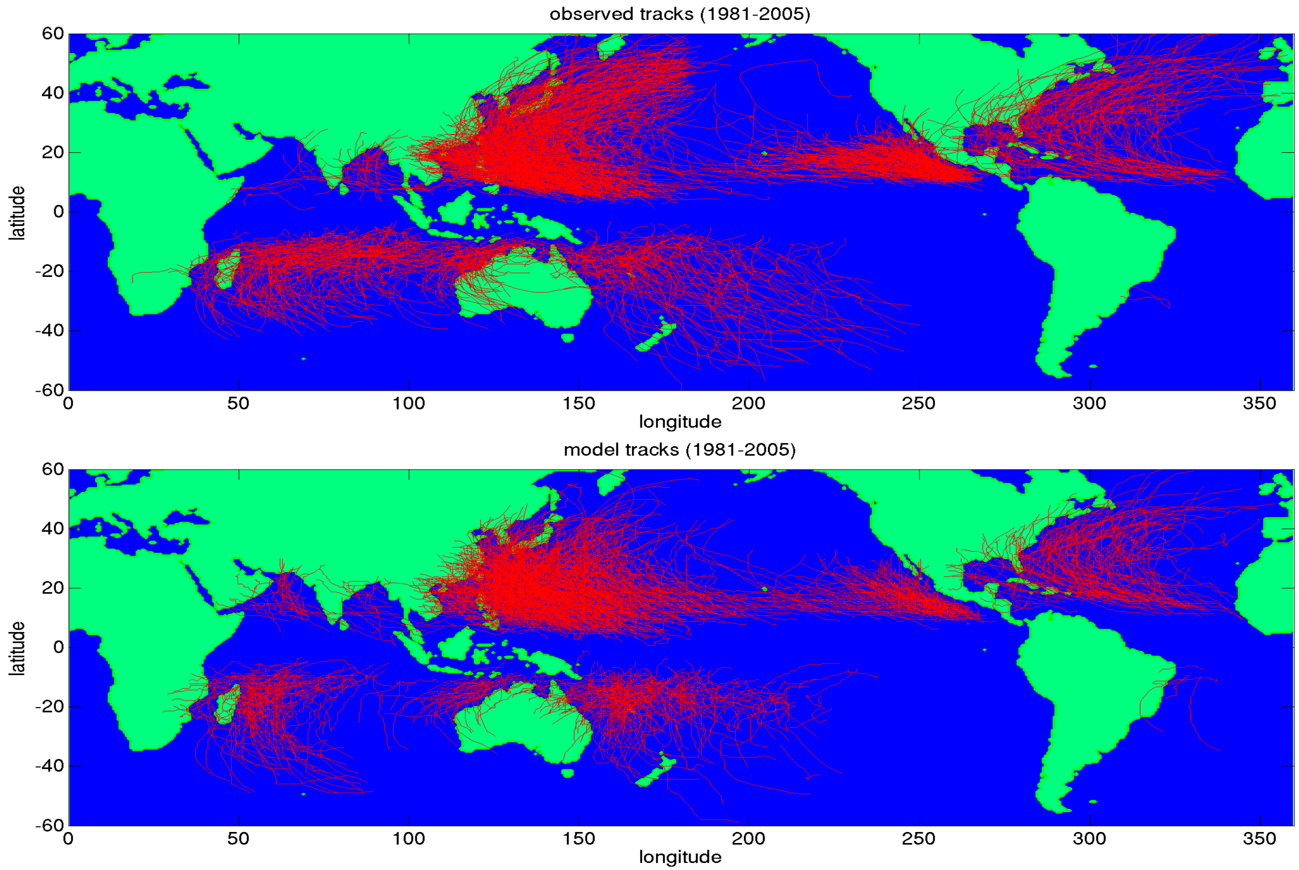
Isaac Held

DCMIP, Boulder, June 2016



Tropical Cyclones and Global Models: Entering a Golden Age?

HiRAM (50km & 25km): Zhao, Held, Lin, Vecchi, JAS, 2009



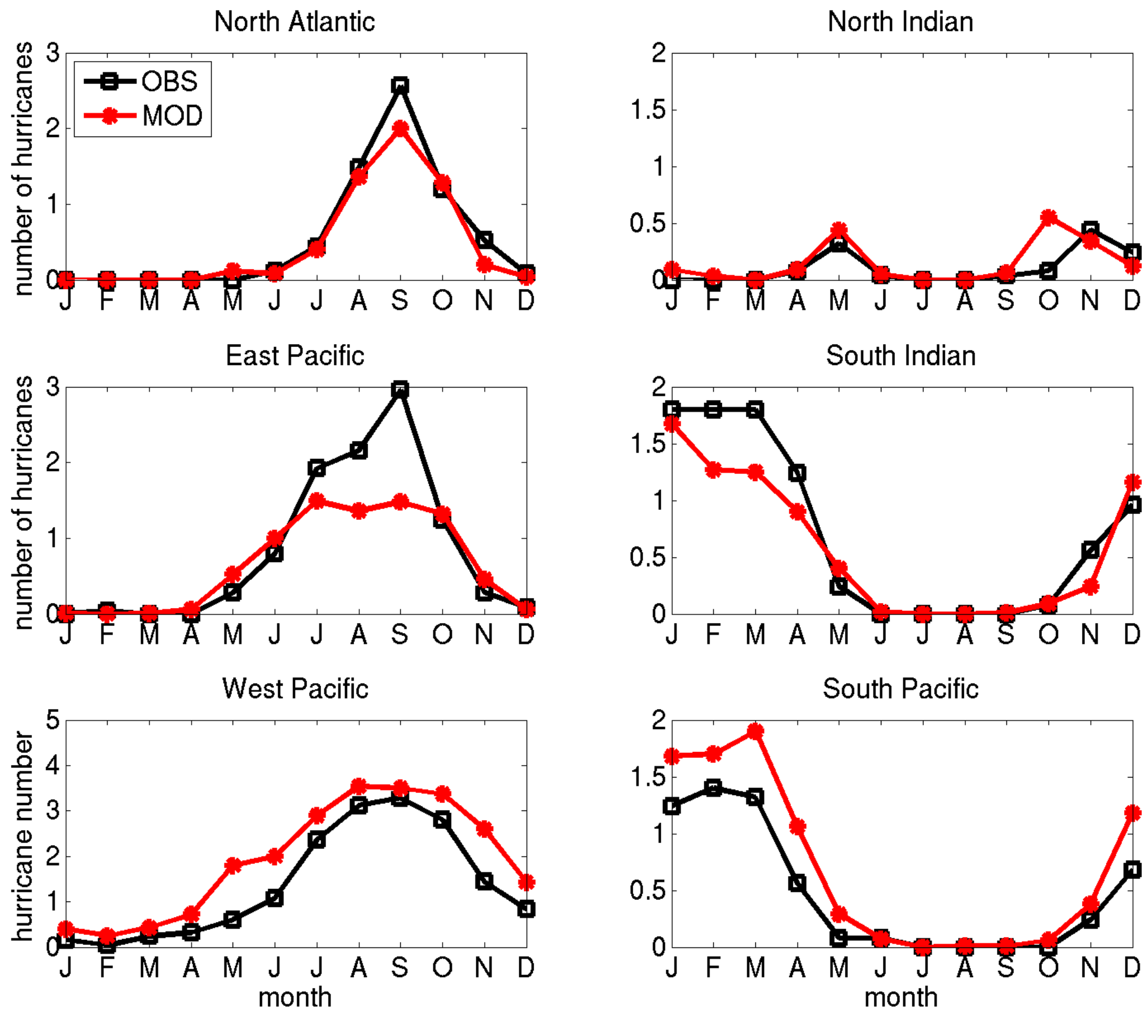
hurricane tracks (1981-2005) upper: obs, lower: model

Claim:

we are poised for rapid progress in our understanding the tropical cyclone climate based on simulation of tropical cyclones in global models

analogous to the transition in 1970-80's in simulations of midlatitude baroclinic eddies in global models (models are not perfect but good enough that we feel justified in manipulating them to better understand the factors that control TCs)

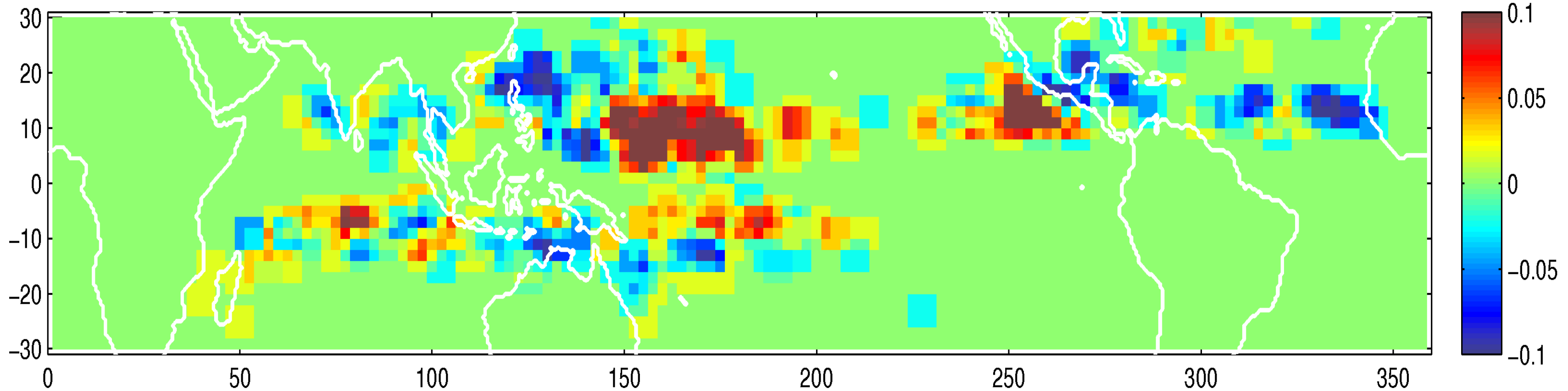
Model captures the seasonal cycle of hurricane frequency over various ocean basins



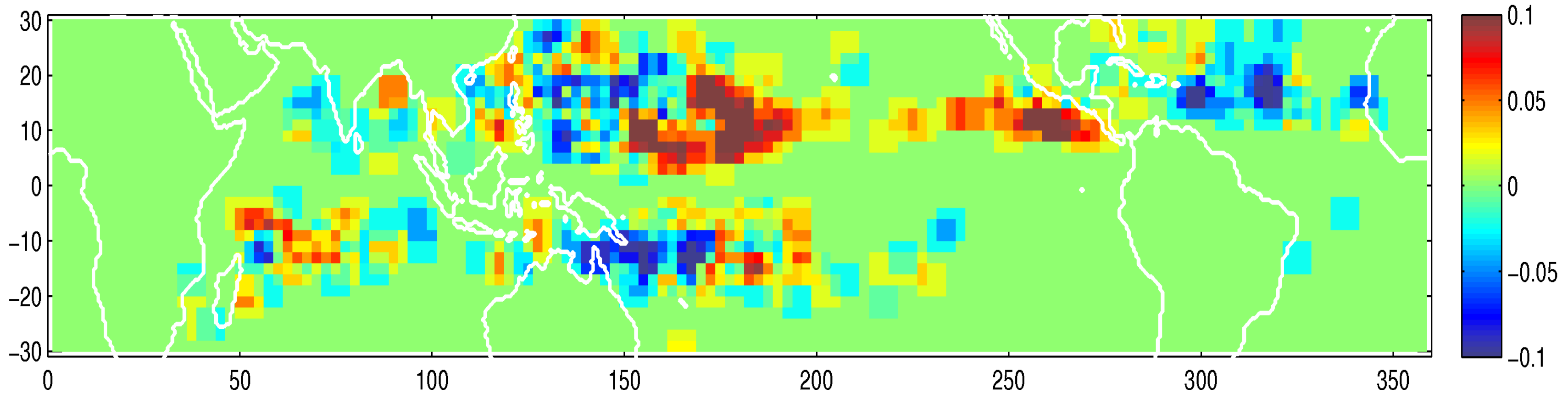
Zhao et al, JAS, 2009

Model captures ENSO effect on hurricane genesis frequency

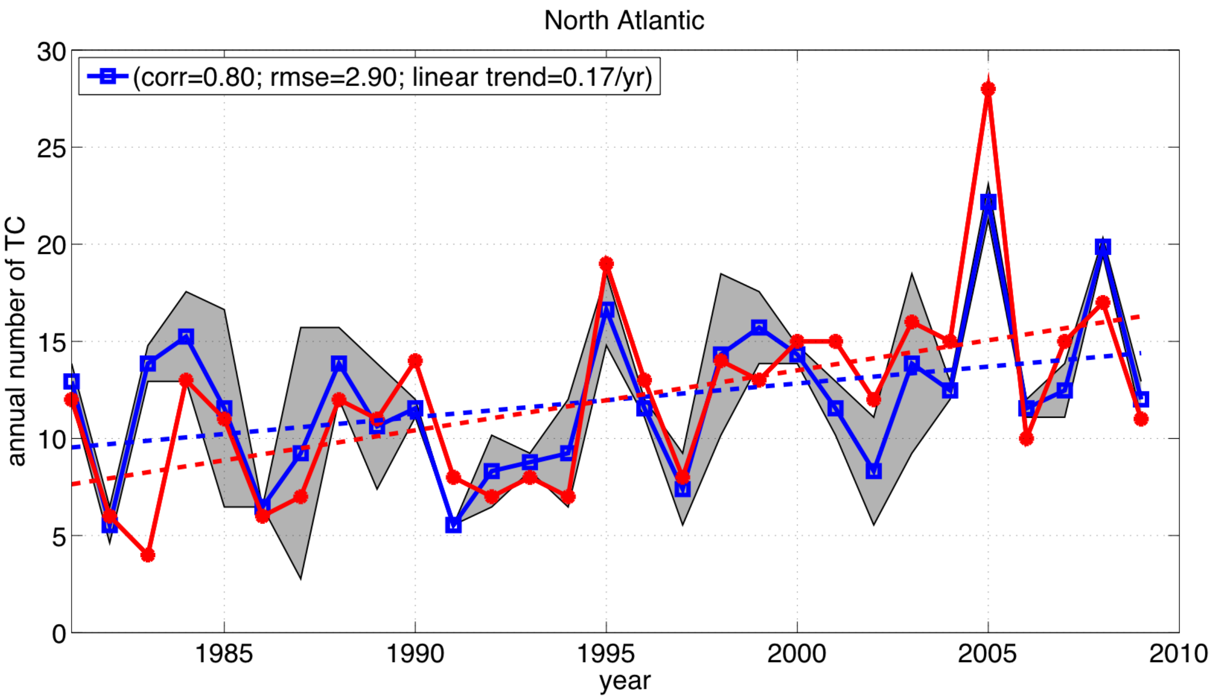
El-Nino years minus La-Nina years (observation)



El-Nino years minus La-Nina years (C180HiRAM)

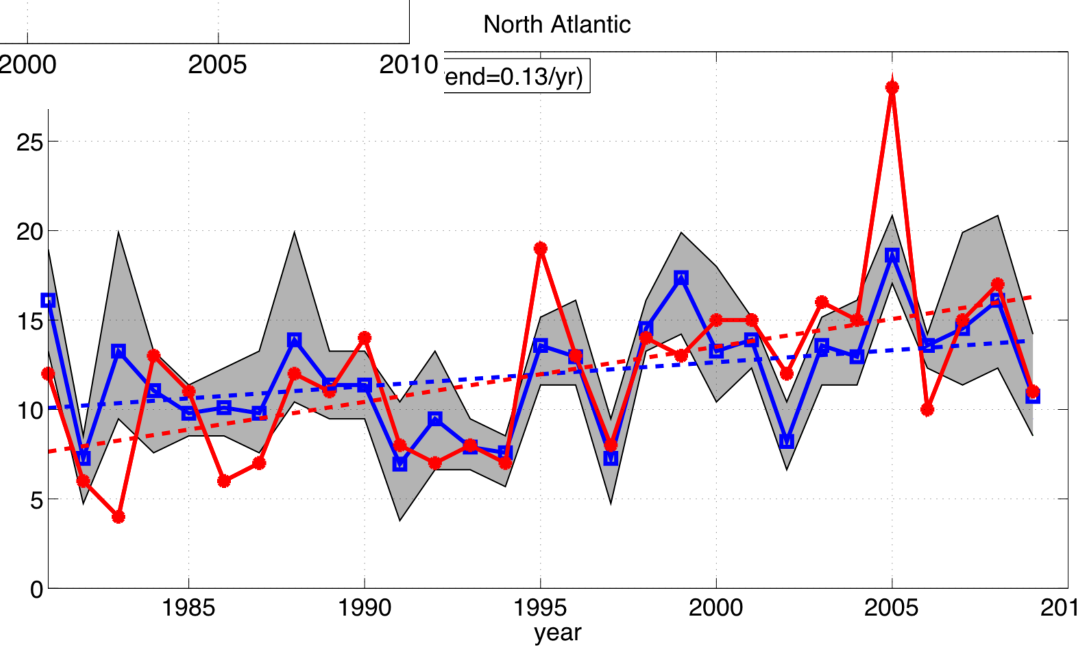


Zhao et al, JAS, 2009



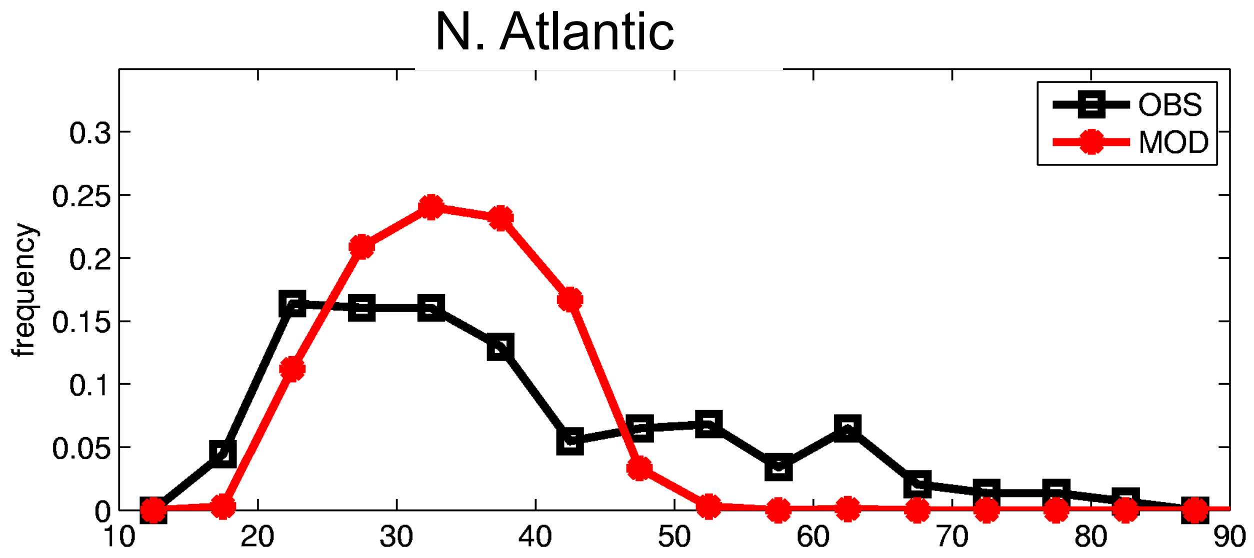
2-member ensemble
CMIP5 25km model

3-member ensemble
CMIP5 50km model



Red: observations
Blue: model ensemble mean
Shading: model spread

Raw model output cannot be used to study intensity (but intensity pdf varies substantially from model to model)



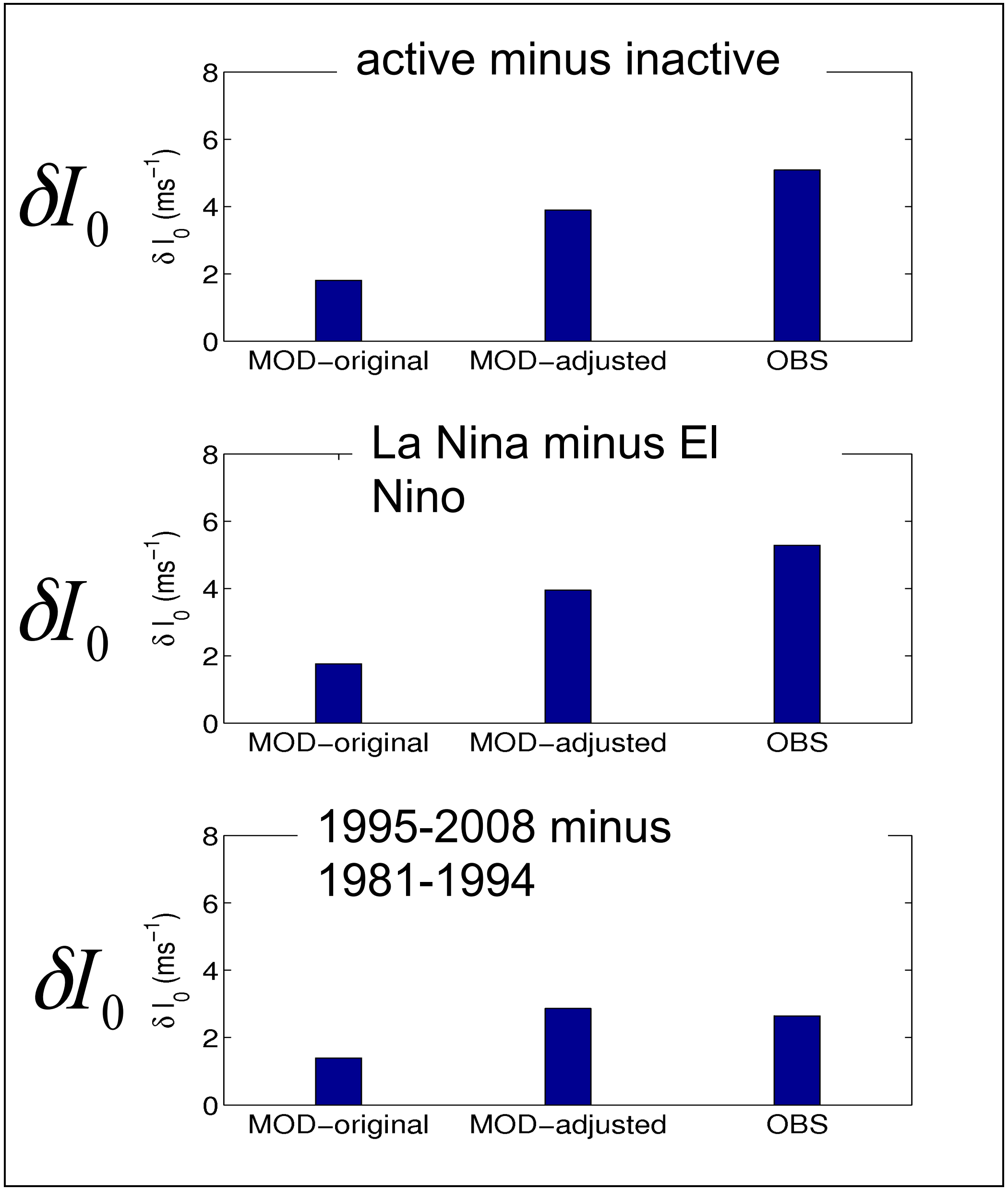
pdf of max lifetime wind speed

HIRAM (50km grid)
Observation

raw global model output cannot be used for quantitative info on intensity
but
a statistical adjustment captures observed variability of storm mean intensity

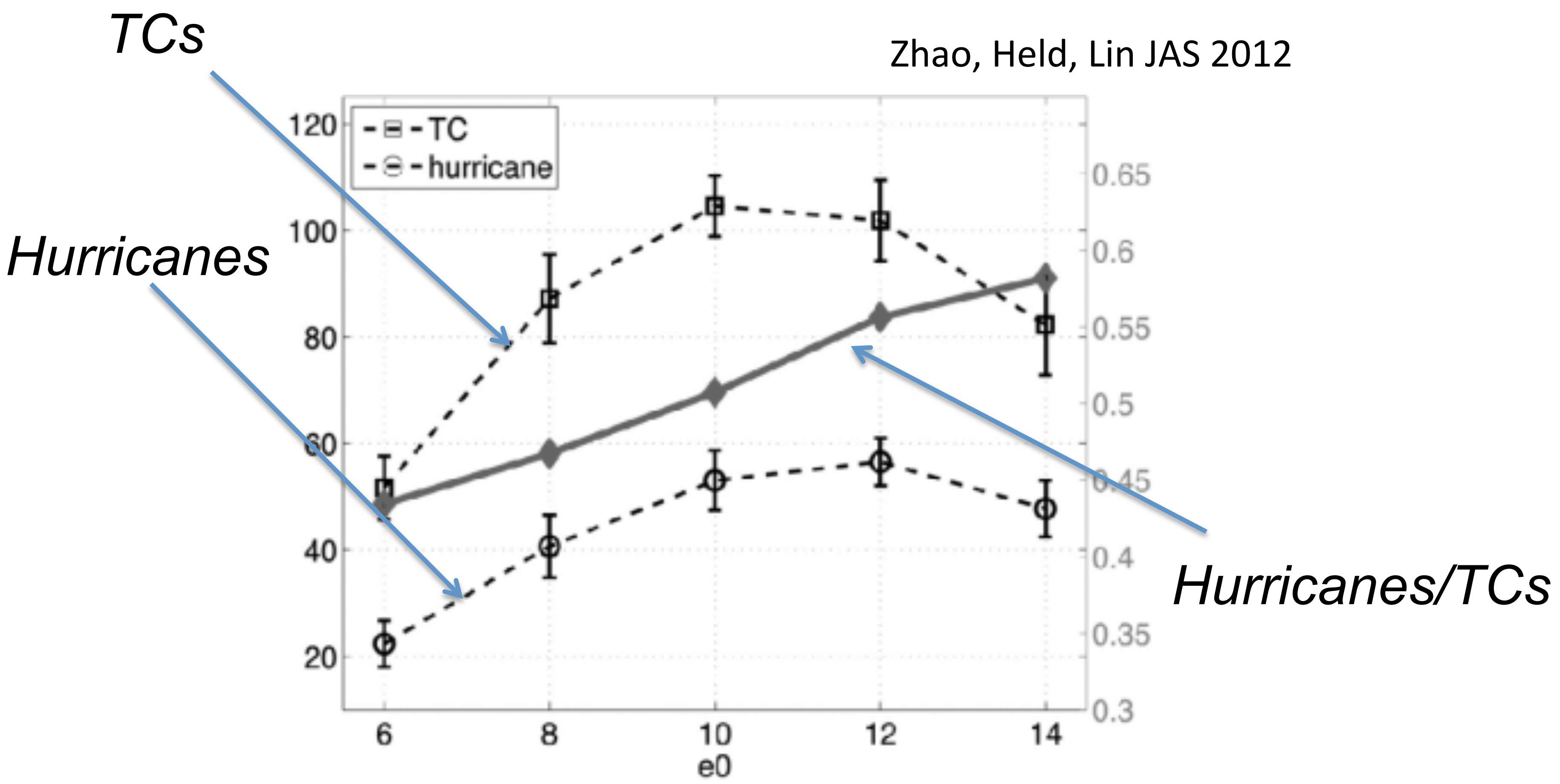
Mean intensity is obtained by averaging the maximum intensity of each storm over all TCs in given years

Zhao and Held, 2010, J. Clim



North Atlantic storms

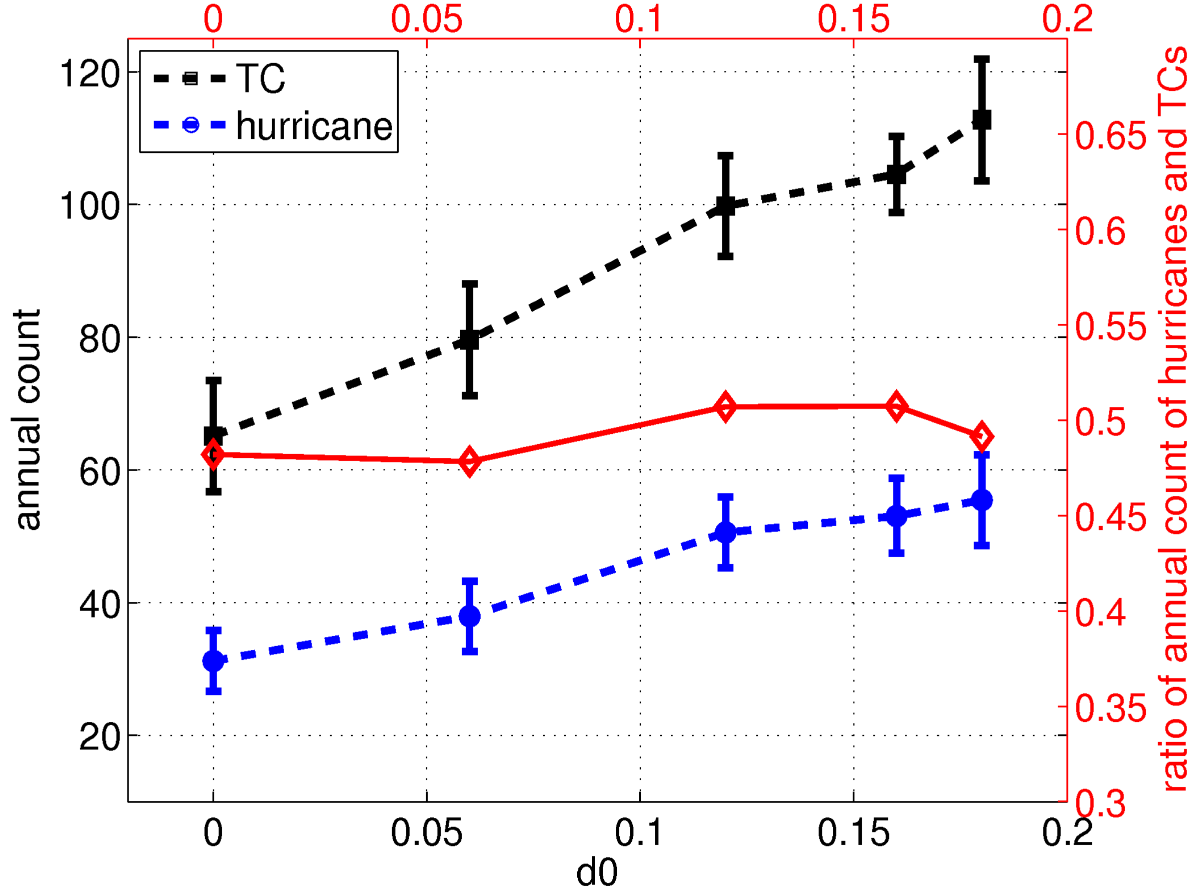
Effect of change in convection scheme on TCs in HiRAM



Inhibiting parameterized convection =>

Sensitivity of global mean frequency to
”divergence damping” in dynamical core

Zhao, Held, Lin JAS 2012



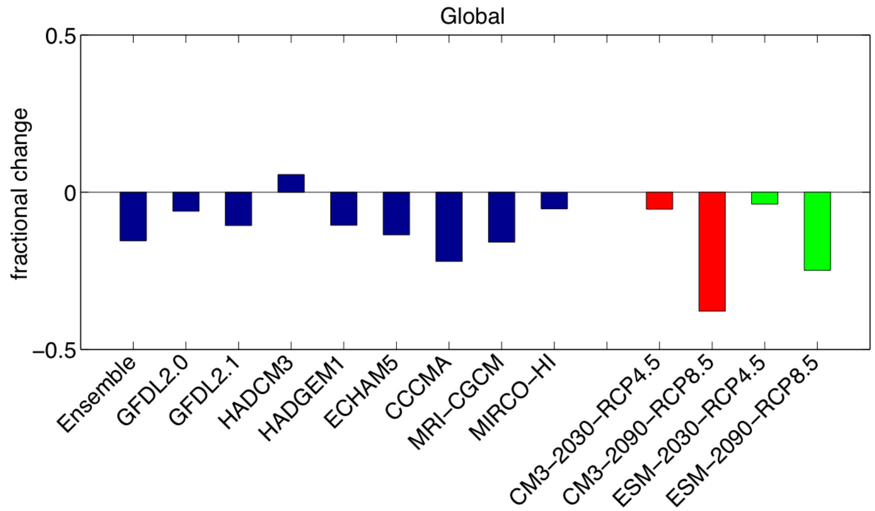
Global GCMs typically predict global mean decrease in TC frequency

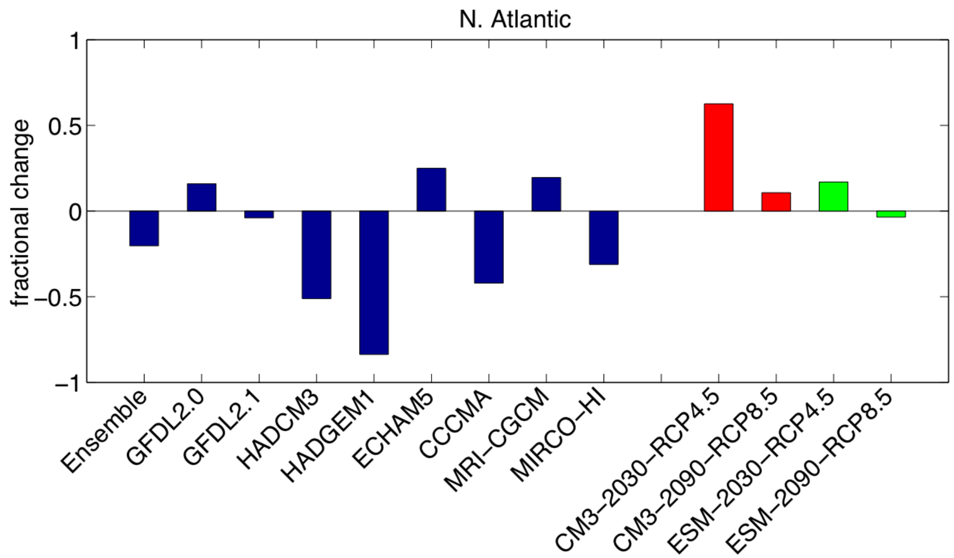
Taking SSTs from coupled model projections for A1B scenario for end of 21st century – also doubling CO2

Zhao and Held J. Climate 2012

Global mean
reduction

North Atlantic
mixed



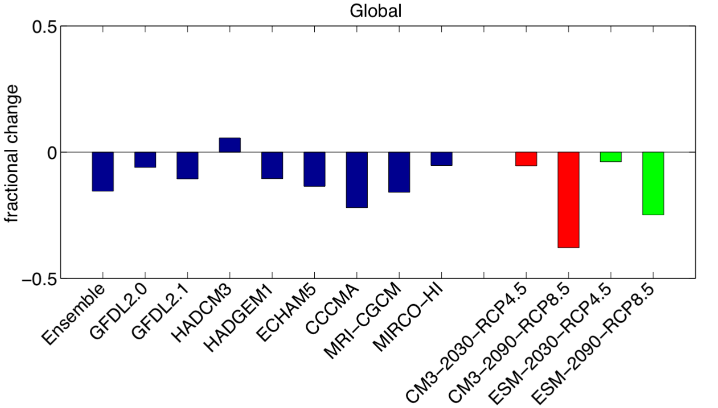


Global GCMs predict global mean decrease in TC frequency -- Why??

My perspective (not a consensus view)

Reduction in convective mass flux:
less convection overall => fewer TC's

TCs just the tail of the distribution of disorganized and organized convection



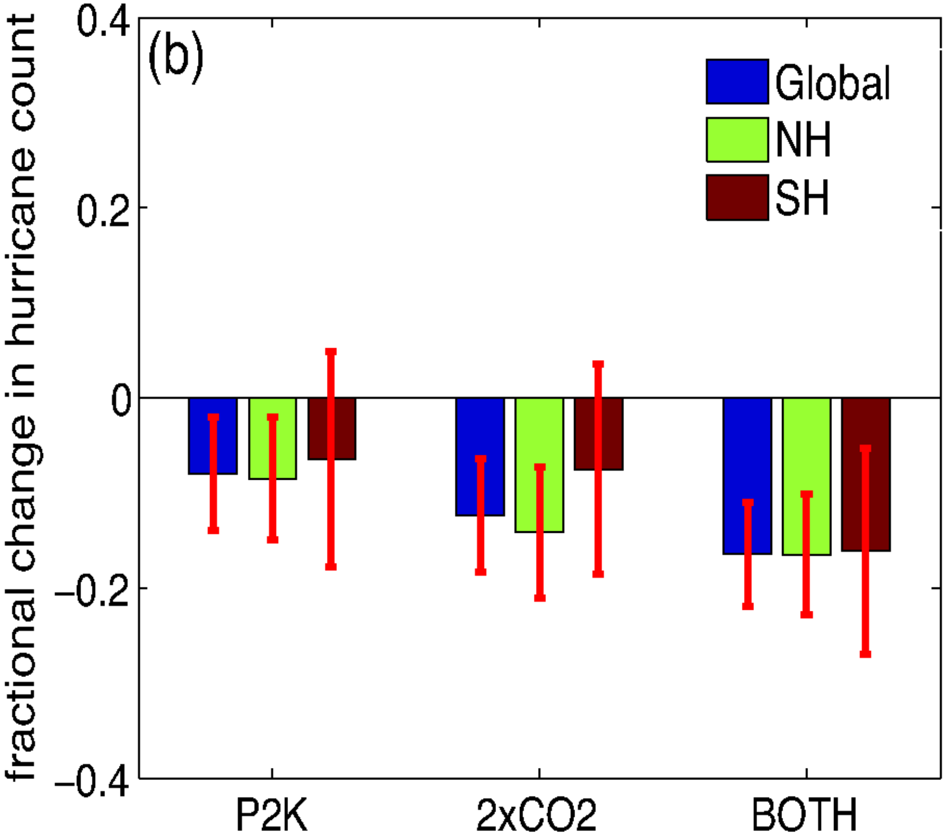
Global mean reduction is due in part to CO_2 increase with fixed SSTs

P2K: uniform SST increase of 2K
no change in CO2

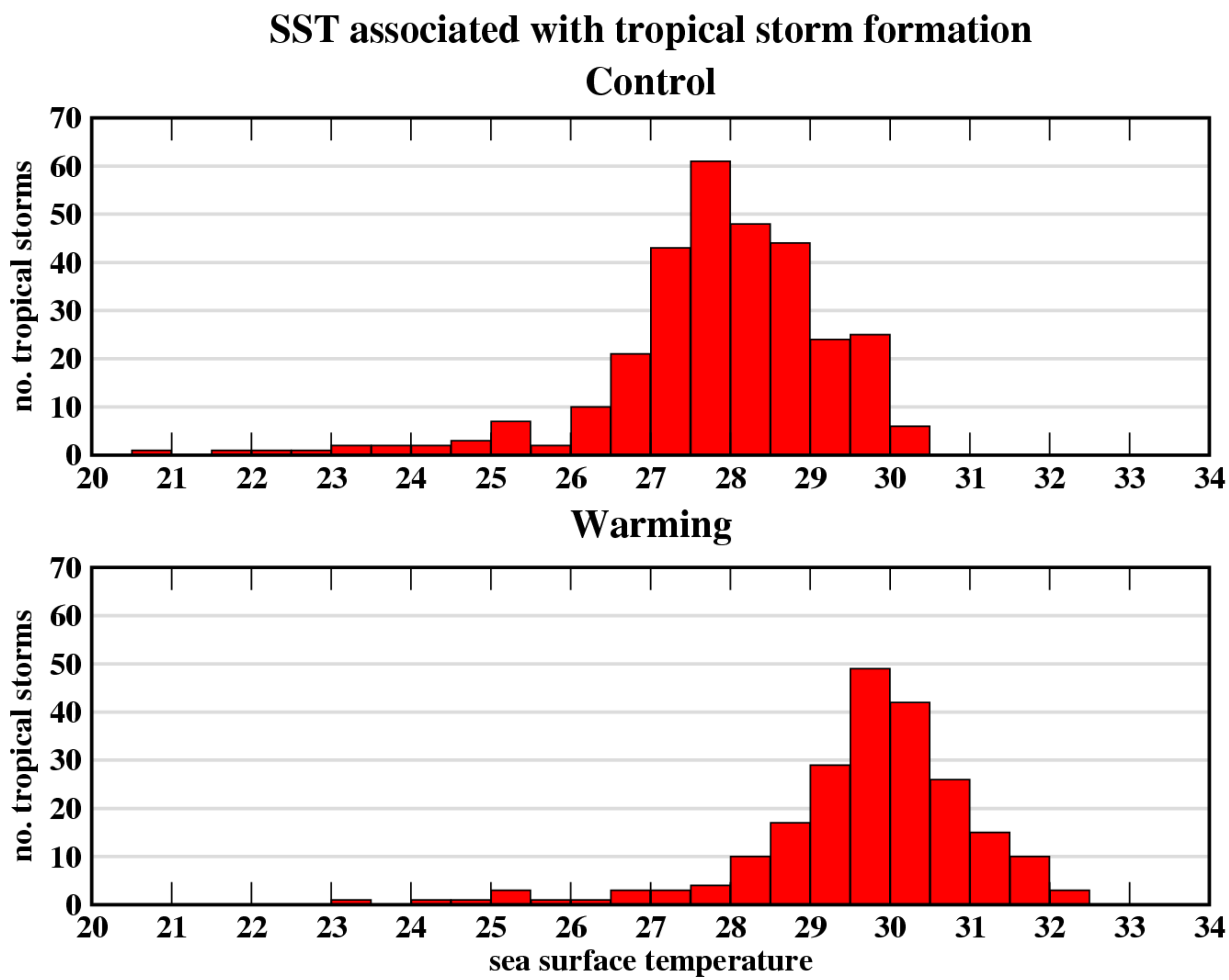
2xCO2: double CO2
no change in SST

Contribute about equally to global mean reduction in frequency

Held and Zhao, J. Climate, 2011

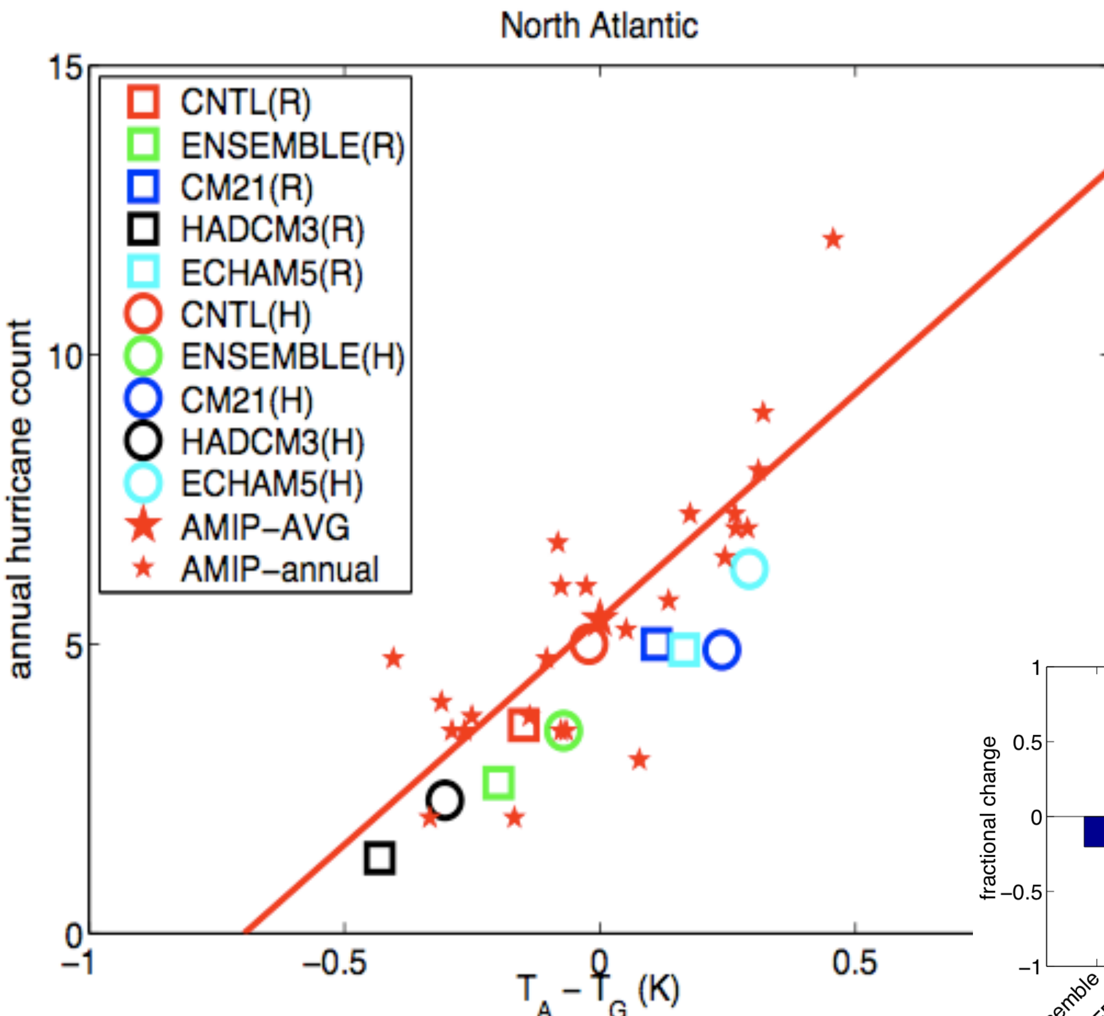


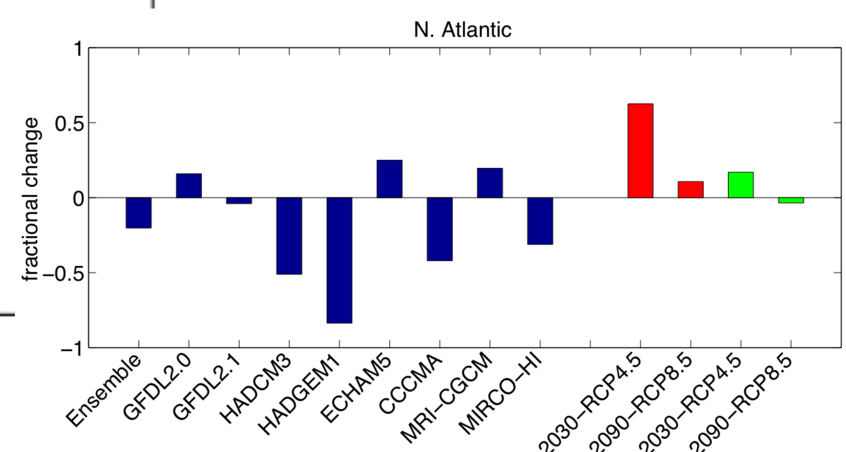
The 26.5^{o}C "threshhold temperature" for tropical storm formation:
a *climate dependent* threshhold…



Source: Knutson et al., *2008*, *Nature Geoscience*.

Change in Atlantic hurricane frequency over 21st century
Downscaling SST projections from many models,
is predicted by difference between
tropical N.Atlantic and tropical mean ocean temperatures



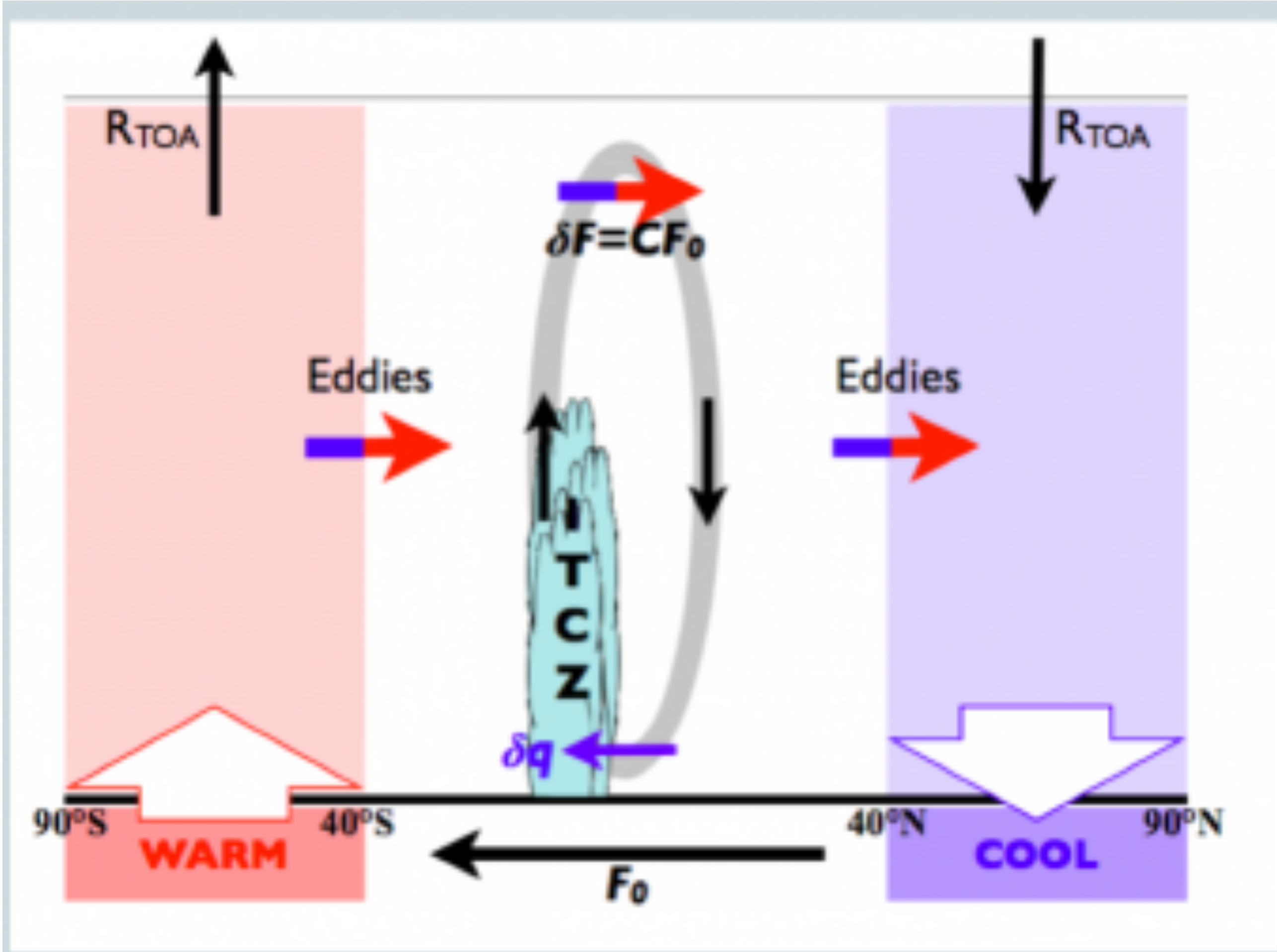


Plausibly realistic TC statistics in global models just the starting point

Idealized models retaining GCM physics/numerics but with simplified boundary conditions/geometry are valuable for

1) developing an understanding of tropical storm statistics, and

2) understanding differences between global models

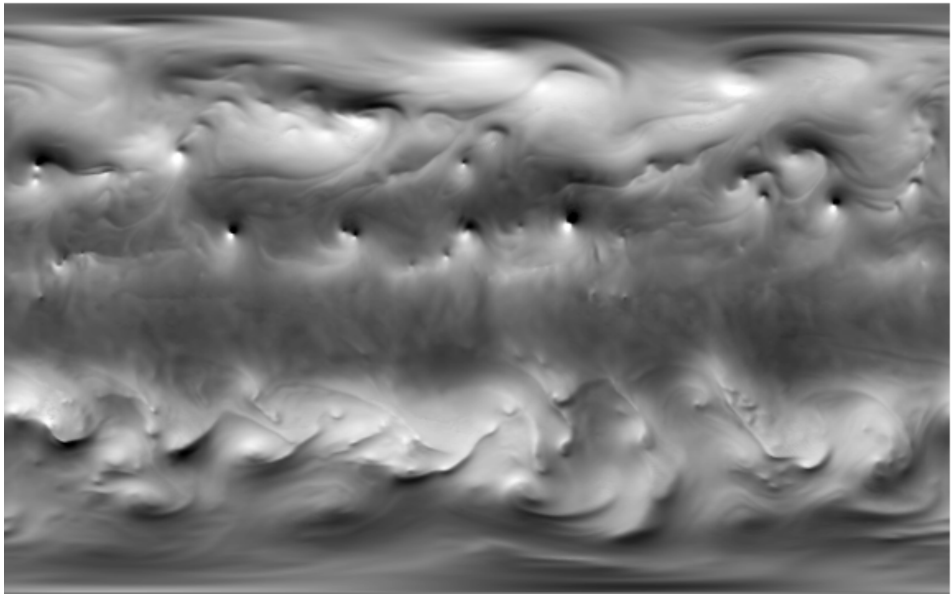


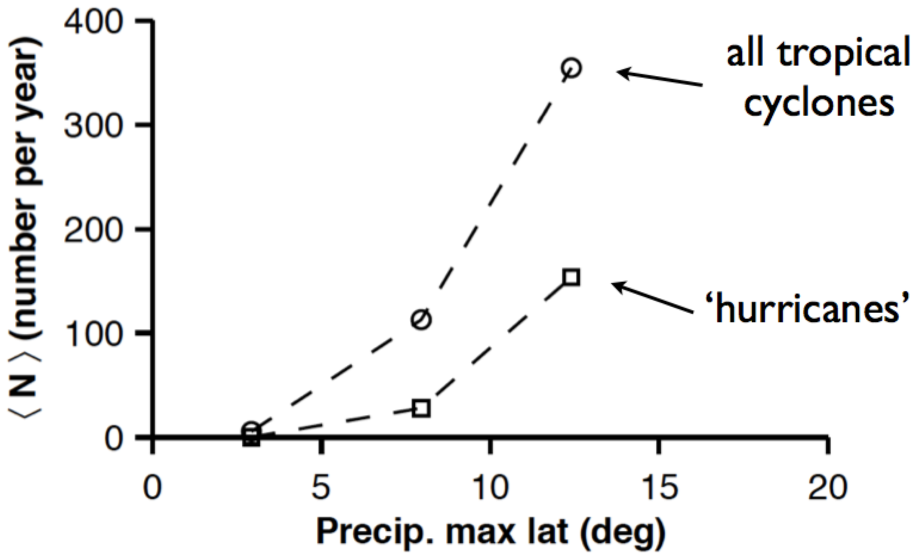
Aquaplanet with zonally symmetric climate over "slab" ocean with no seasonal cycle

Merlis, et al, GRL, 2013

Typically, number of TCs decreases with global warming with realistic boundary conditions

But in the aqua-planet configuration, the number increases because ITCZ moves poleward

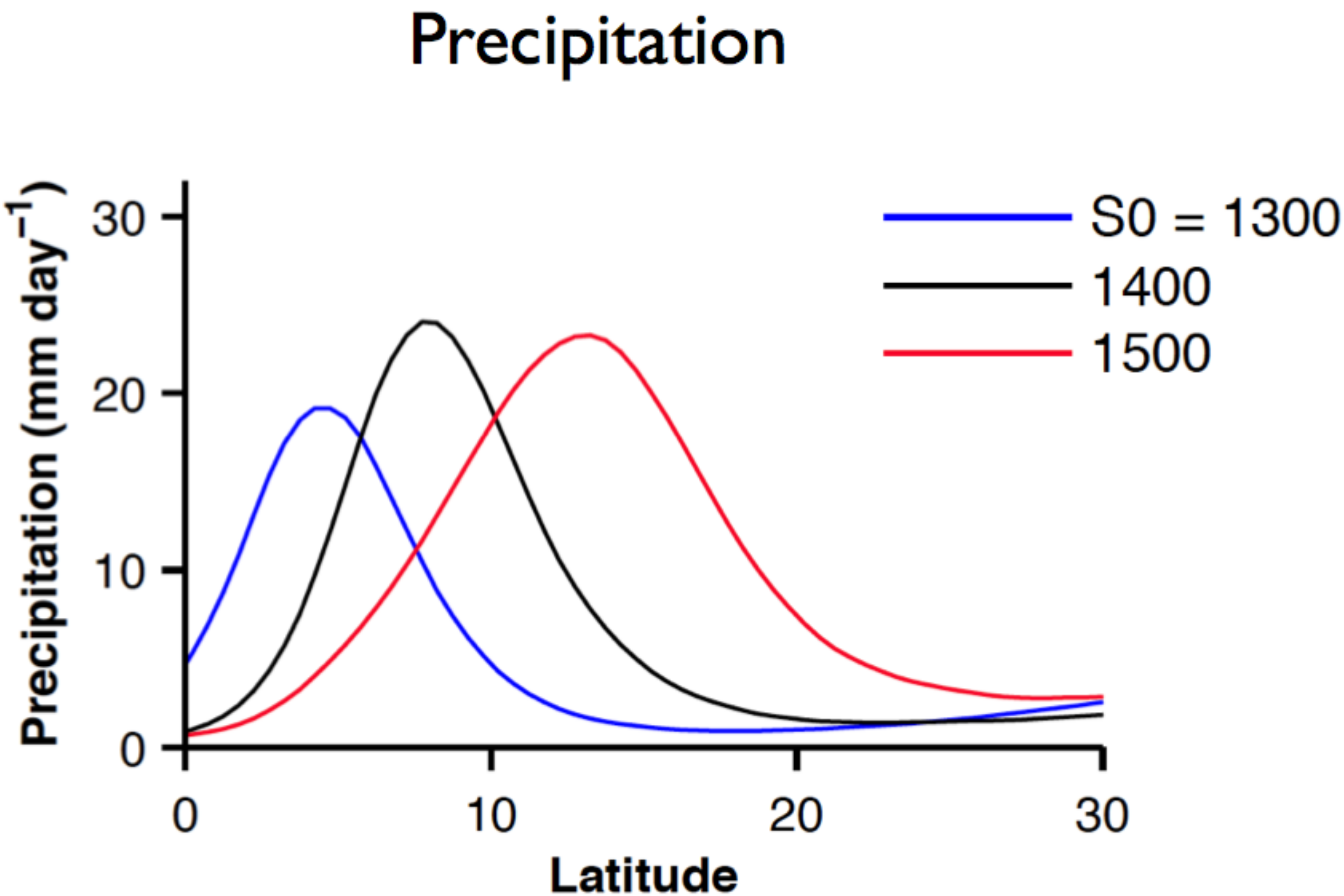




Poleward ITCZ more favorable for cyclogenesis.

Moving ITCZ by changing prescribed cross-equatorial "oceanic" energy flux

Tim Merlis, et al – GRL 2013



ITCZ shifts northward as NH is warmed

Tim Merlis, et al – GRL 2013

Typically, number of TCs decreases with global warming with realistic boundary conditions

But in the aqua-planet configuration, the number increases because ITCZ moves poleward

Understanding this result has at least 3 distinct parts
-- how does the ITCZ move with warming
-- how does the TC number change with ITCZ latitude
-- how does the TC number change with warming with fixed ITCZ latitude

$$N = f(\ Q, T) = g(\ ITCZ(Q, T), T)$$

$$\frac{\partial f}{\partial T} > 0; \quad \frac{\partial g}{\partial T} < 0$$

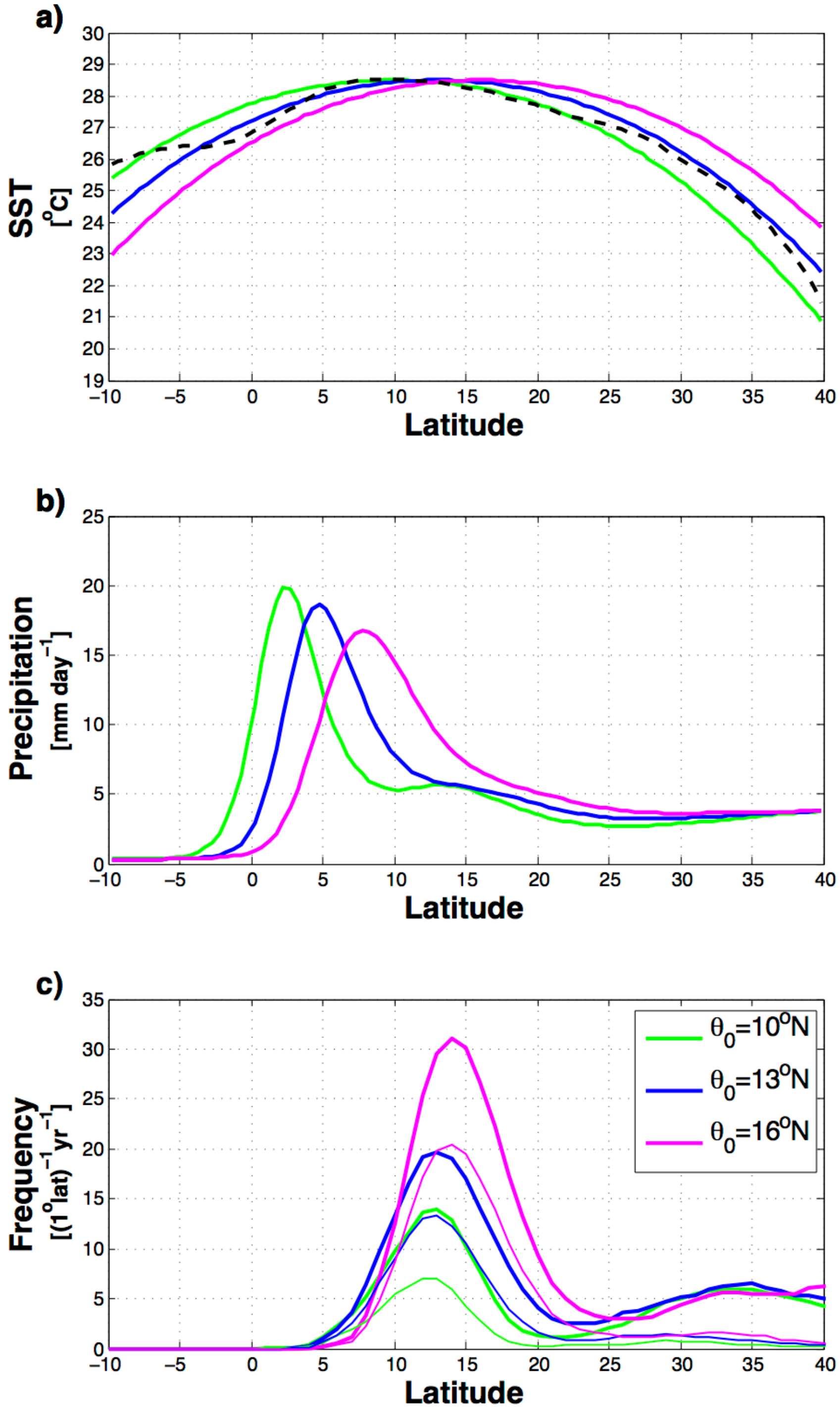
Ballinger et al, JAS 2015

Aqua planet HiRAM with prescribed
Zonally symmetric SSTs

Varying

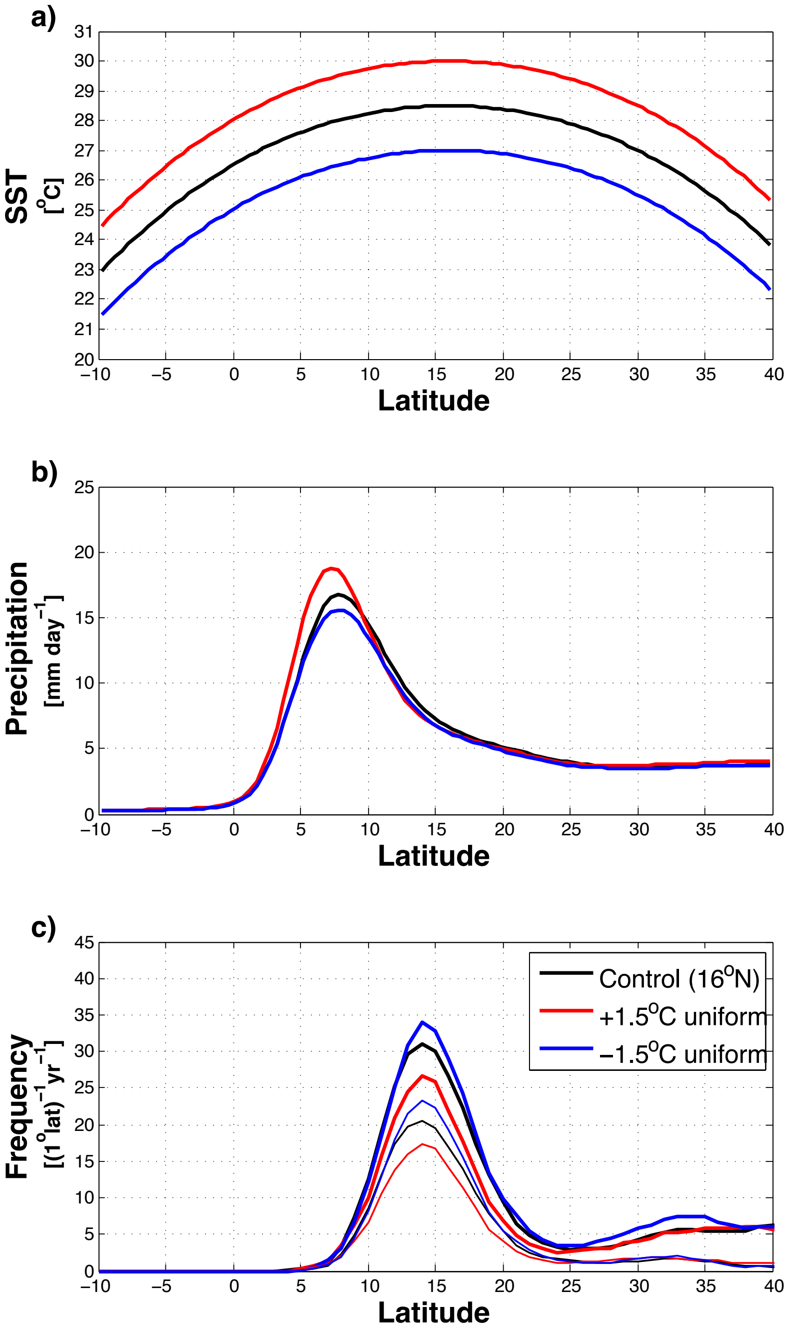
- Mean SST
- Flatness/sharpness of SST profile
- Latitude of Max SST

Ballinger et al, (in prep.)
Zonally asymmetric SSTs



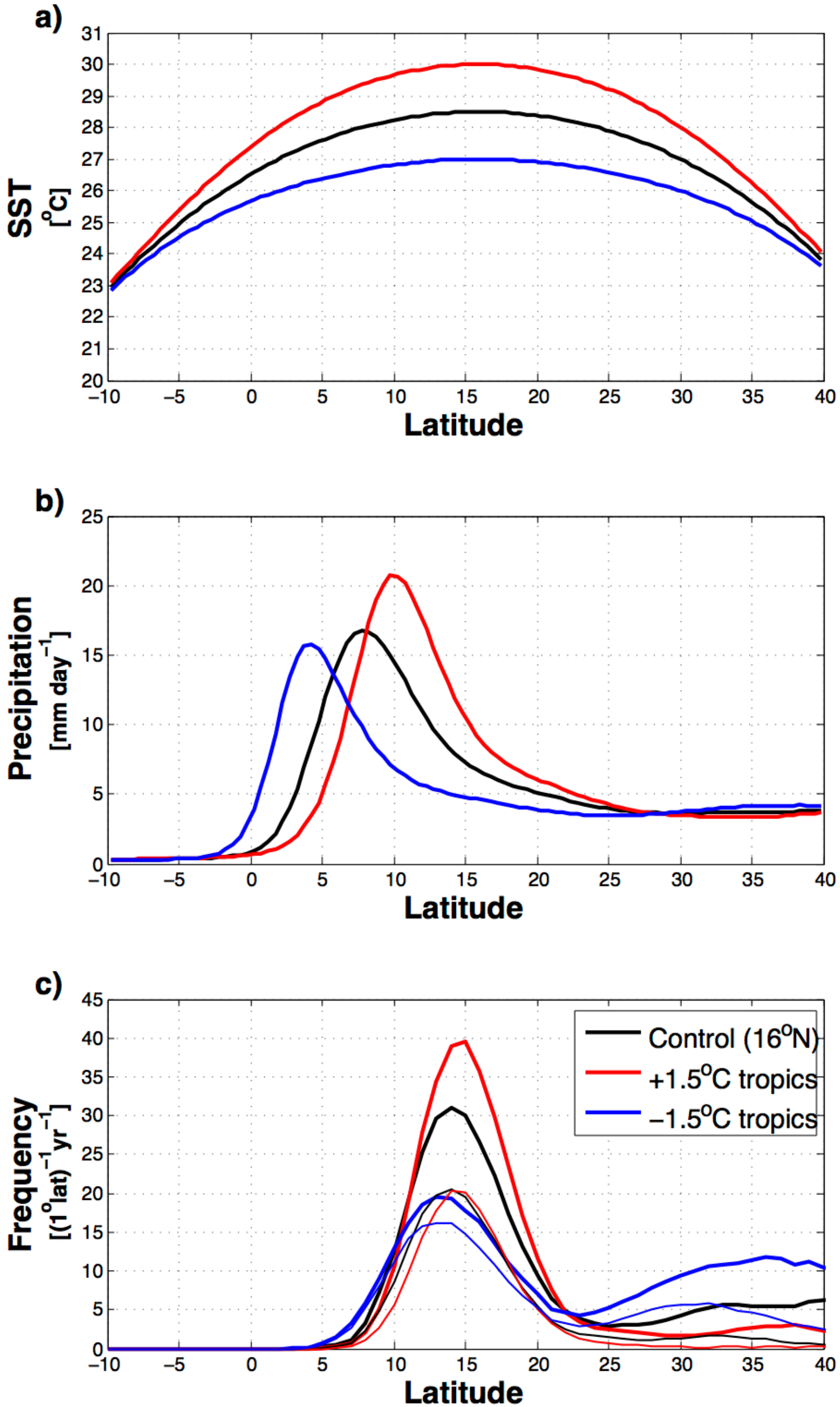
Ballinger et al, JAS 2015

Varying
Latitude of Max SST



Ballinger et al, JAS 2015

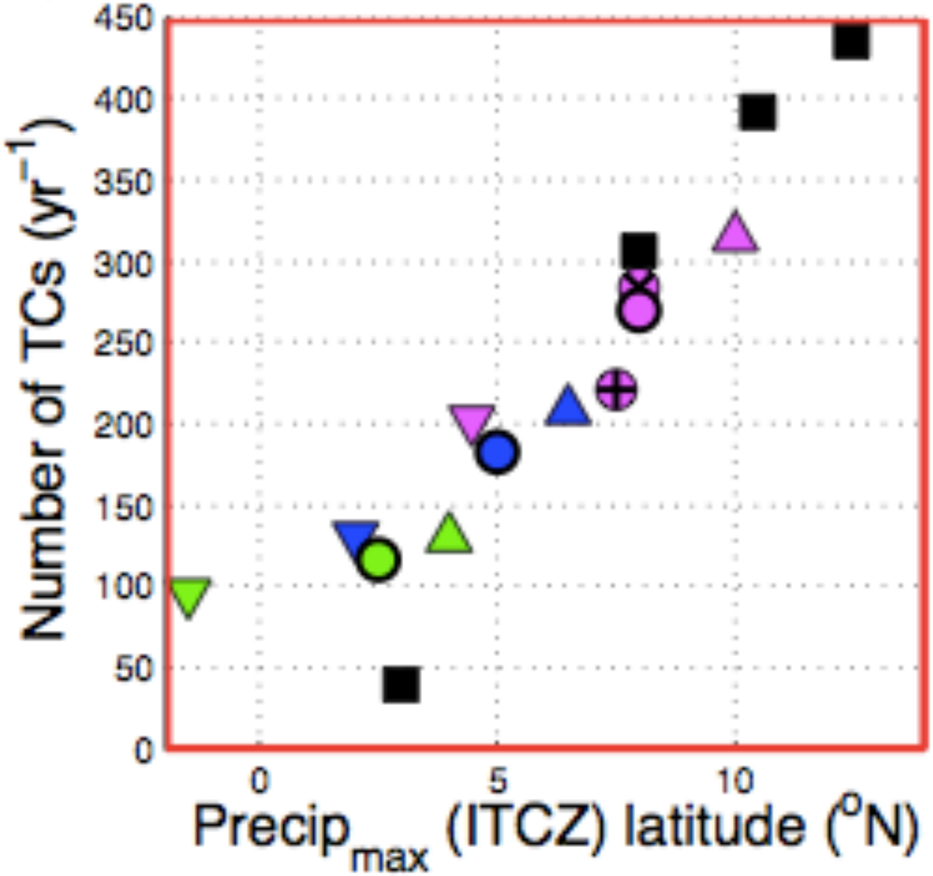
Varying Mean SST



Ballinger et al, JAS 2015

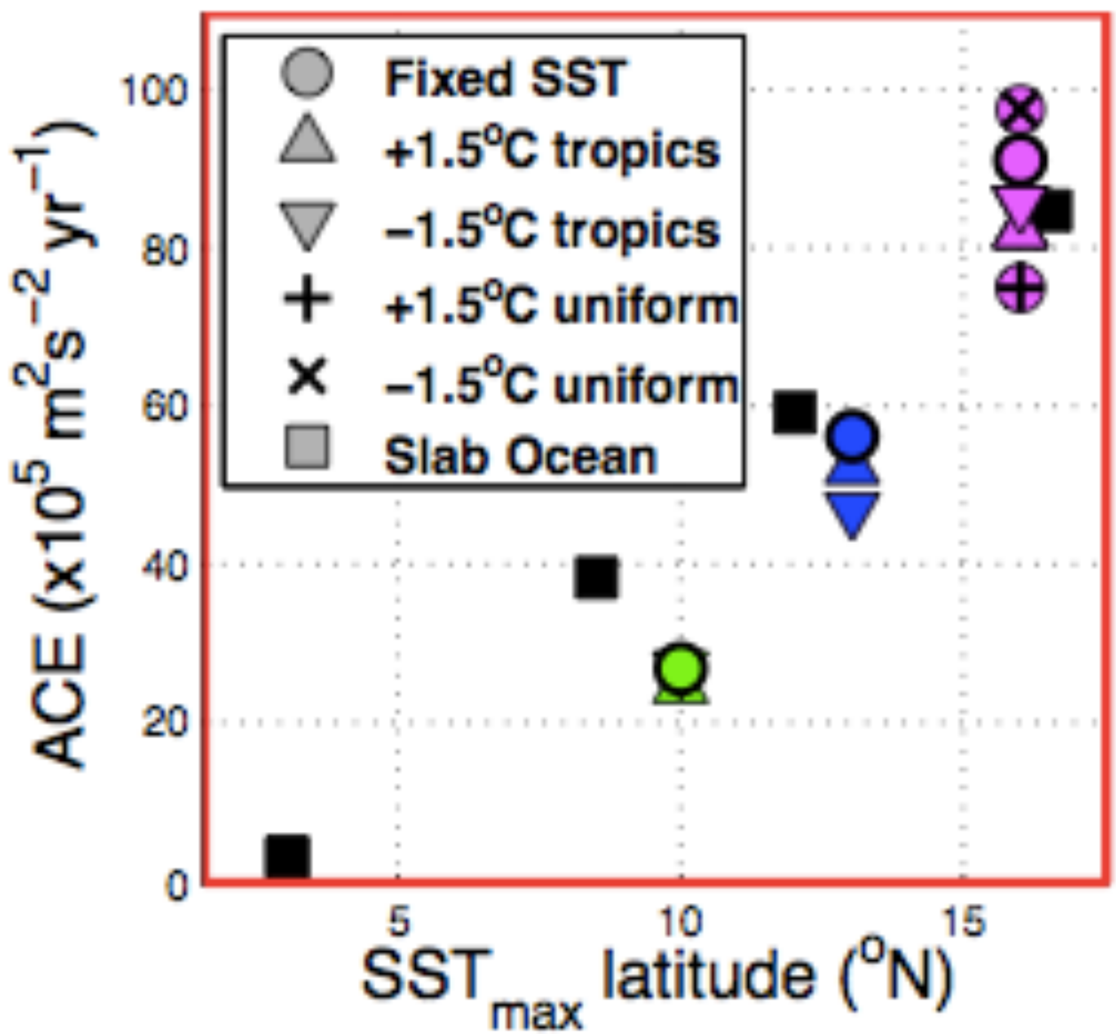
Varying Flatness/Sharpness of SSTs

e)

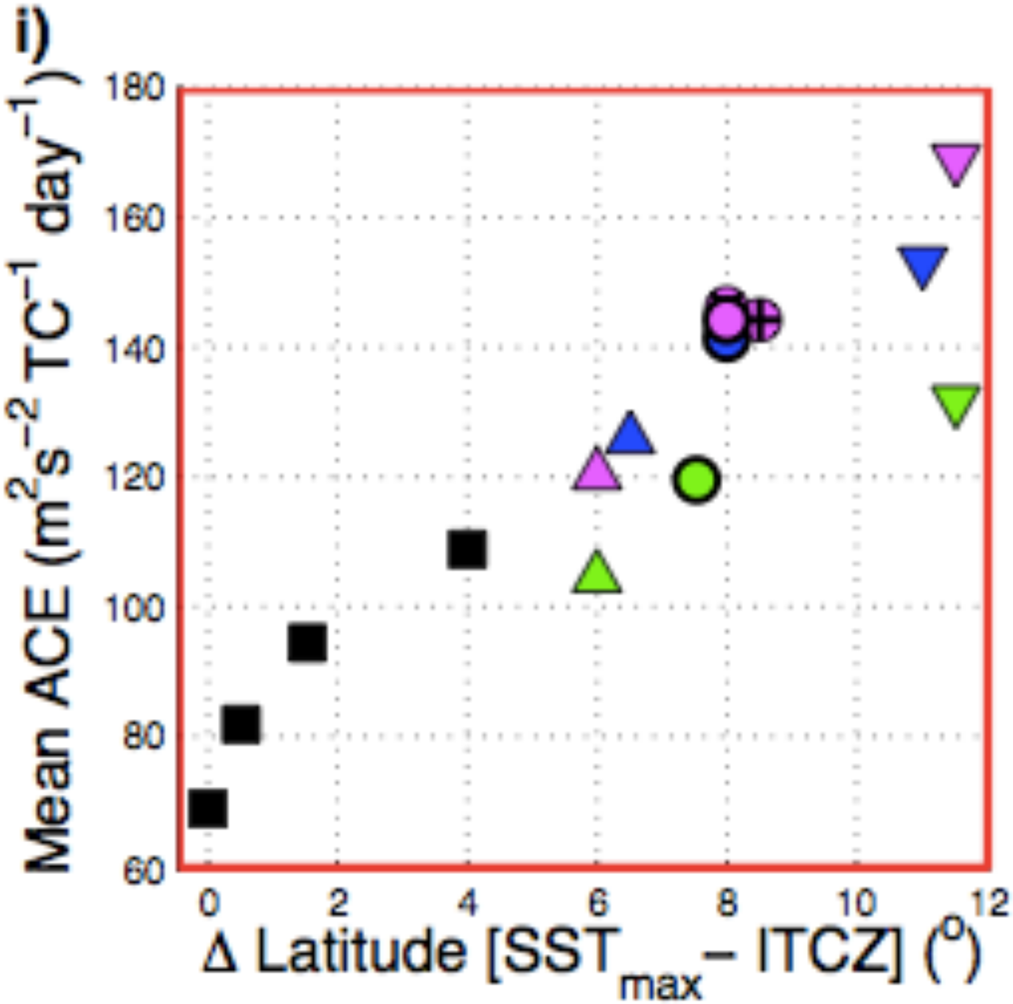


Number of TCs (yr^{-1})
Precip$_{max}$ (ITCZ) latitude (^oN)
0
50
100
150
200
250
300
350
400
450
0
5
10

a)



Fixed SST
+1.5°C tropics
−1.5°C tropics
+1.5°C uniform
−1.5°C uniform
Slab Ocean
ACE (x10^5 m^2 s^-2 yr^-1)
0
20
40
60
80
100
5
10
15
SST_max latitude (°N)

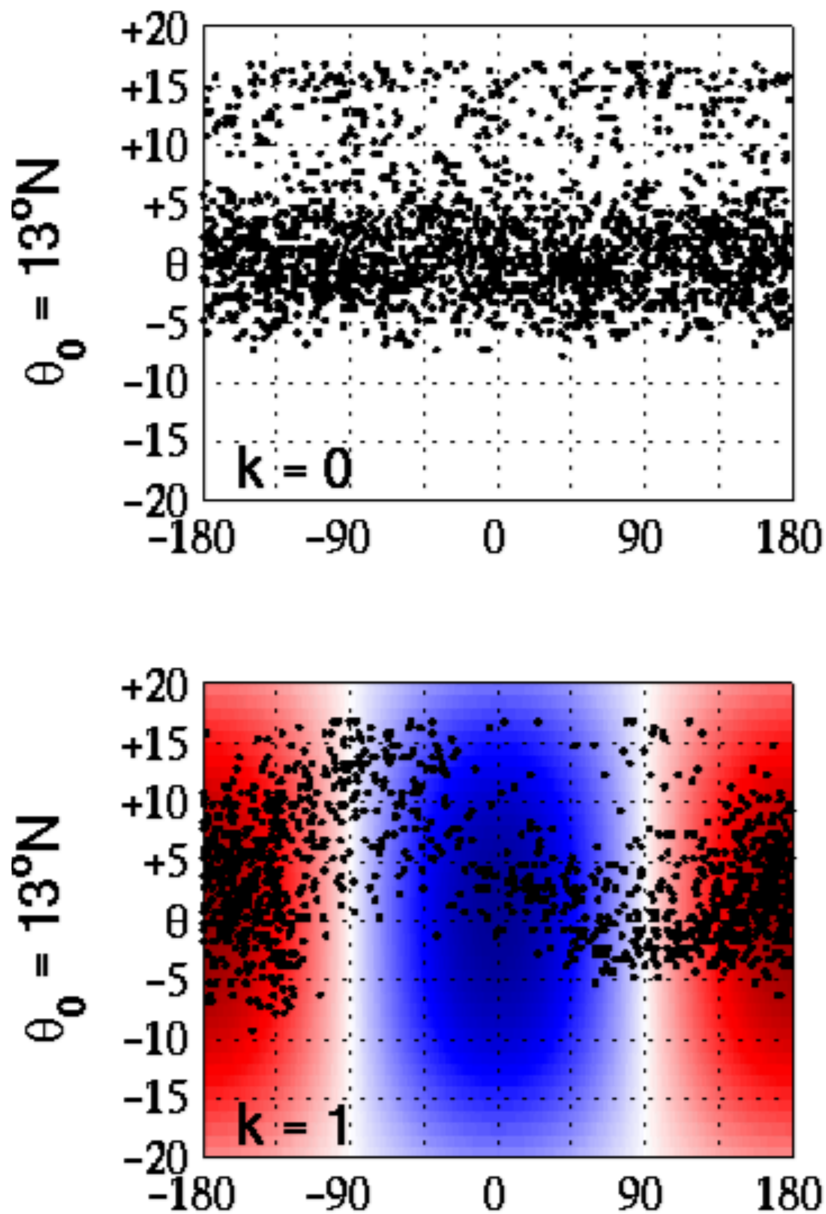


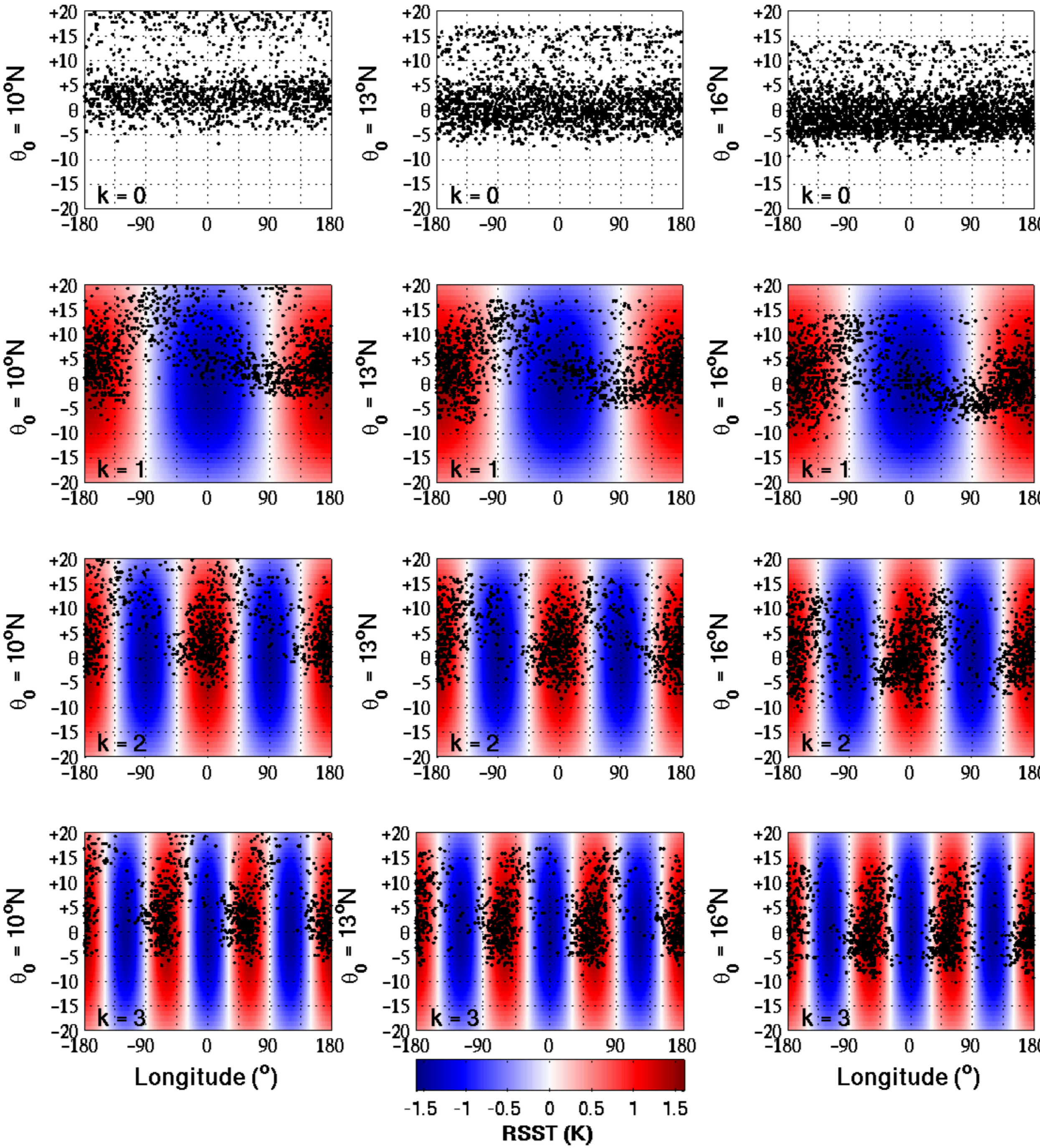
i)
Mean ACE (m^{2}s^{-2} TC^{-1} day^{-1})
180
160
140
120
100
80
60
0
2
4
6
8
10
12
Δ Latitude [SST$_{max}$ – ITCZ] (^{o})

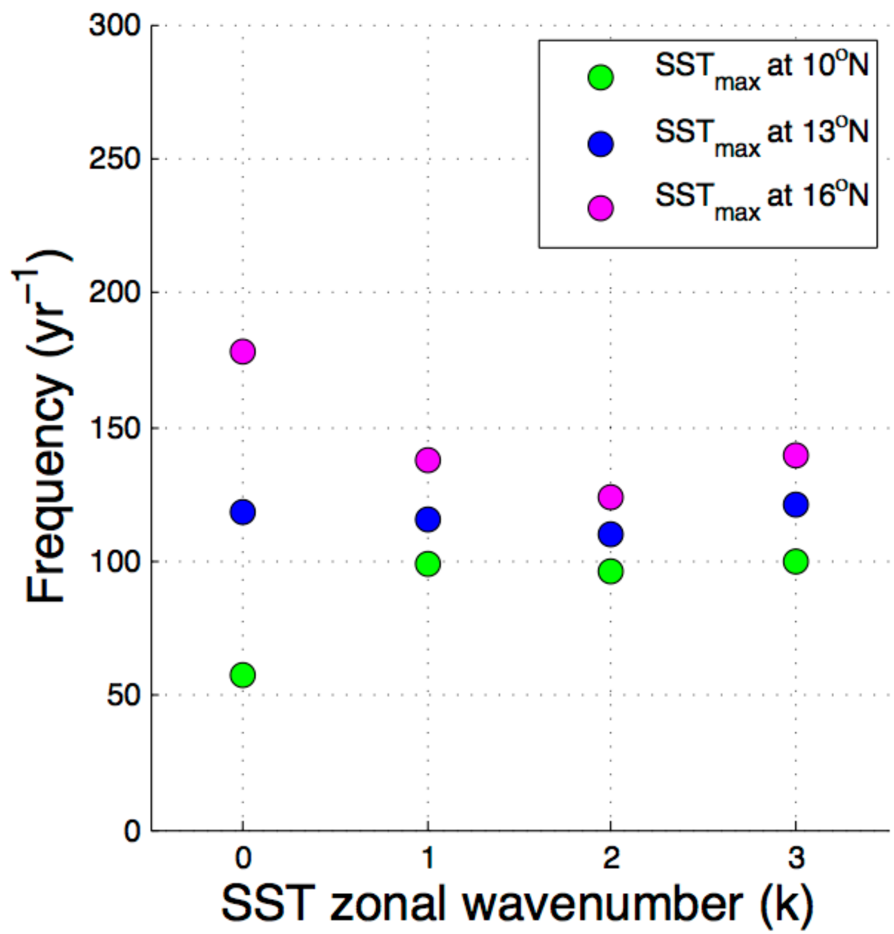
adding zonal variations

$SST = SST_0(y) + (1.5K)*\sin(kx)$

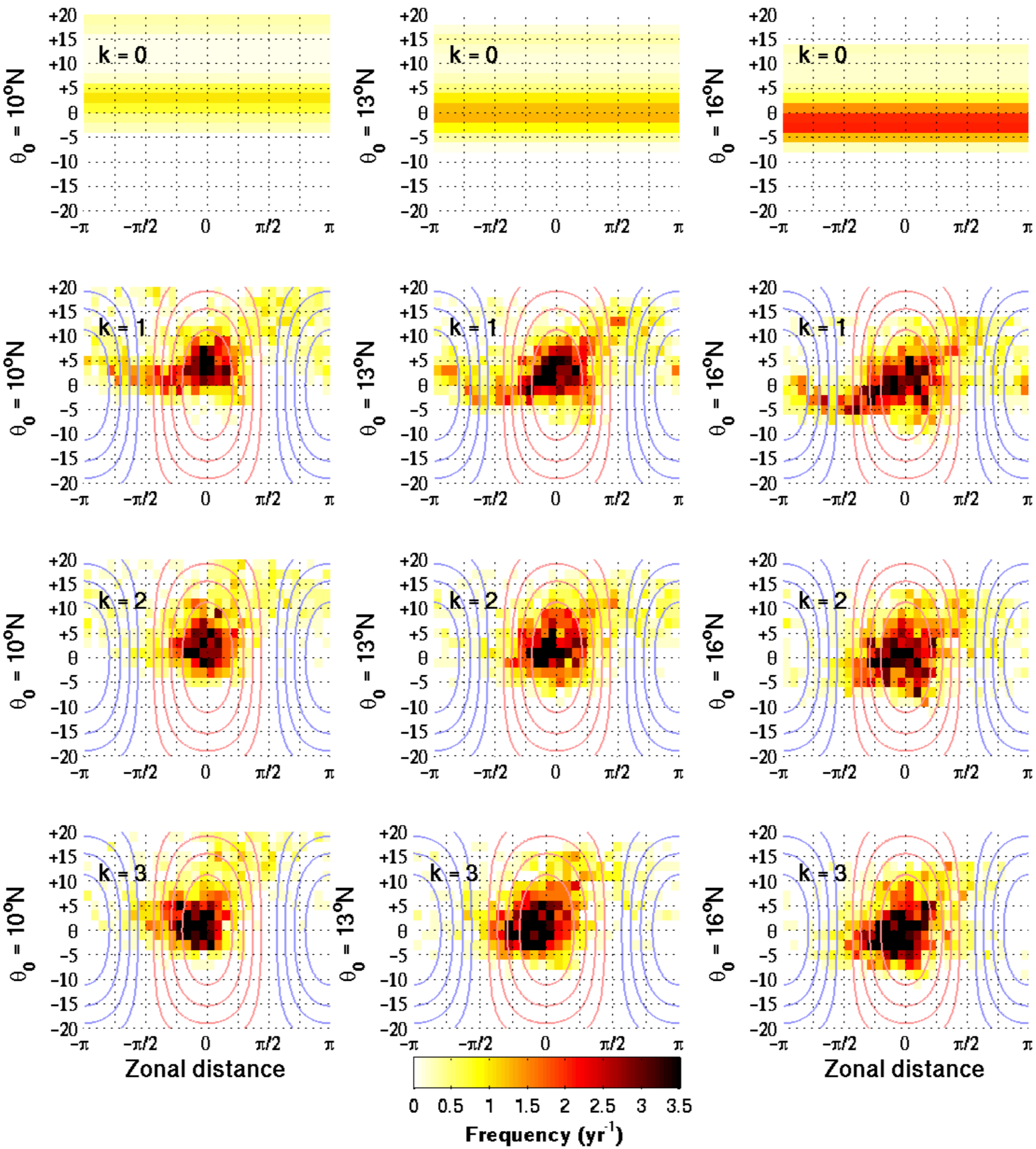
Ballinger, in prep




θ0 = 10°N
θ0 = 13°N
θ0 = 16°N
k = 0
k = 1
k = 2
k = 3
Longitude (°)
RSST (K)
-1.5 -1 -0.5 0 0.5 1 1.5

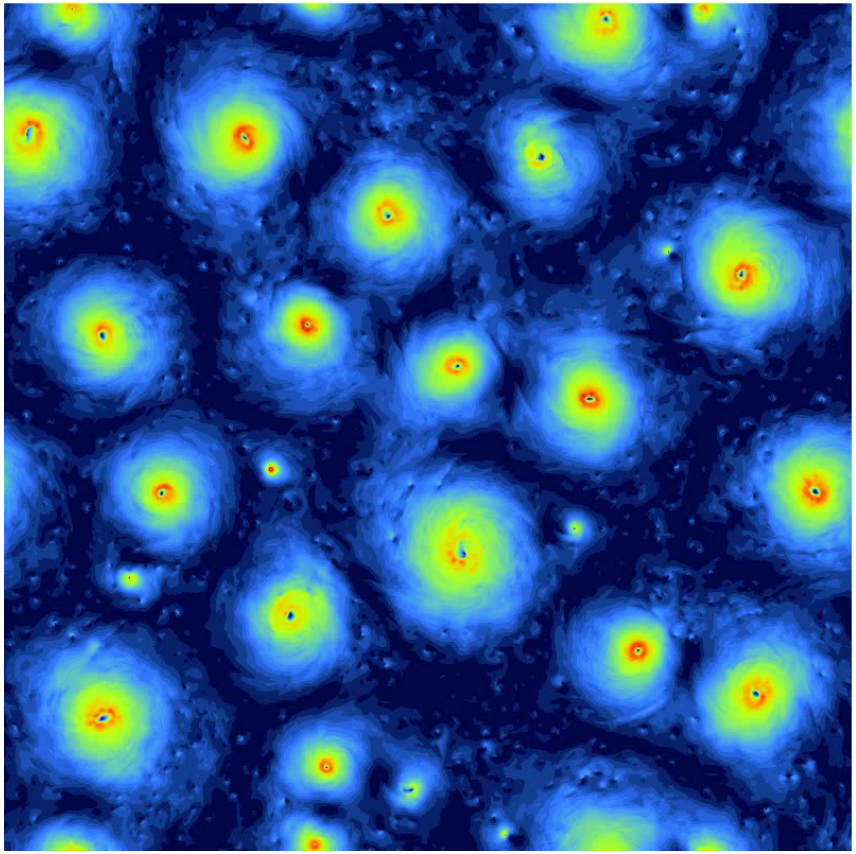


300
250
200
150
100
50
0
Frequency (yr^{-1})
0
1
2
3
SST zonal wavenumber (k)
SST$_{max}$ at 10^{o}N
SST$_{max}$ at 13^{o}N
SST$_{max}$ at 16^{o}N


k = 0
k = 1
k = 2
k = 3
θ0 = 10ºN
θ0 = 13ºN
θ0 = 16ºN
+20
+15
+10
+5
0
-5
-10
-15
-20
−π
−π/2
0
π/2
π
Zonal distance
0
0.5
1
1.5
2
2.5
3
3.5
Frequency (yr-1)

Rotating Radiative Convective Equilibrium

Identical model except for f-plane doubly-periodic geometry and homogeneous forcing and SSTs

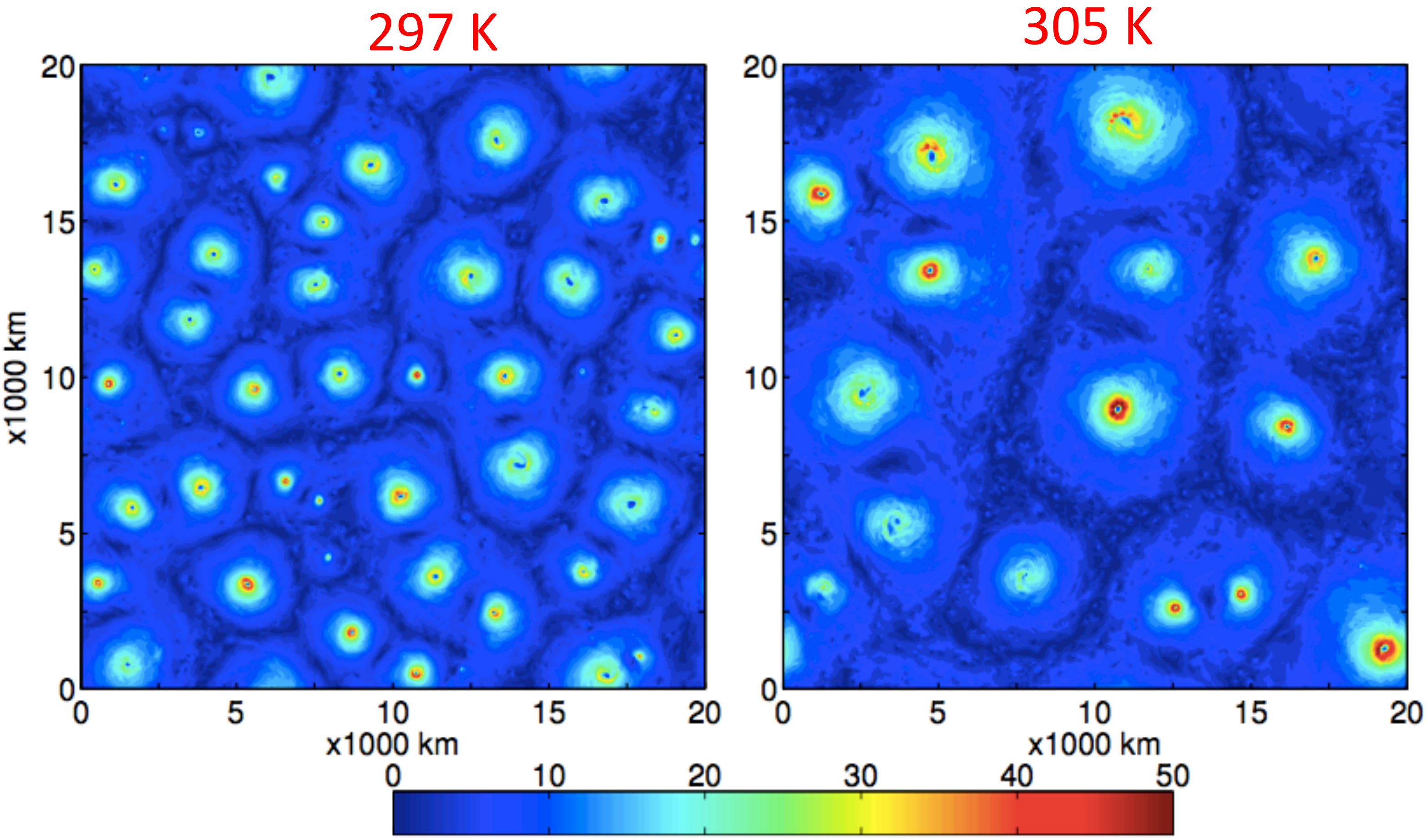


Surface wind speed

Zhou et al, 2014, JAS

Lots of interesting parameter dependencies:

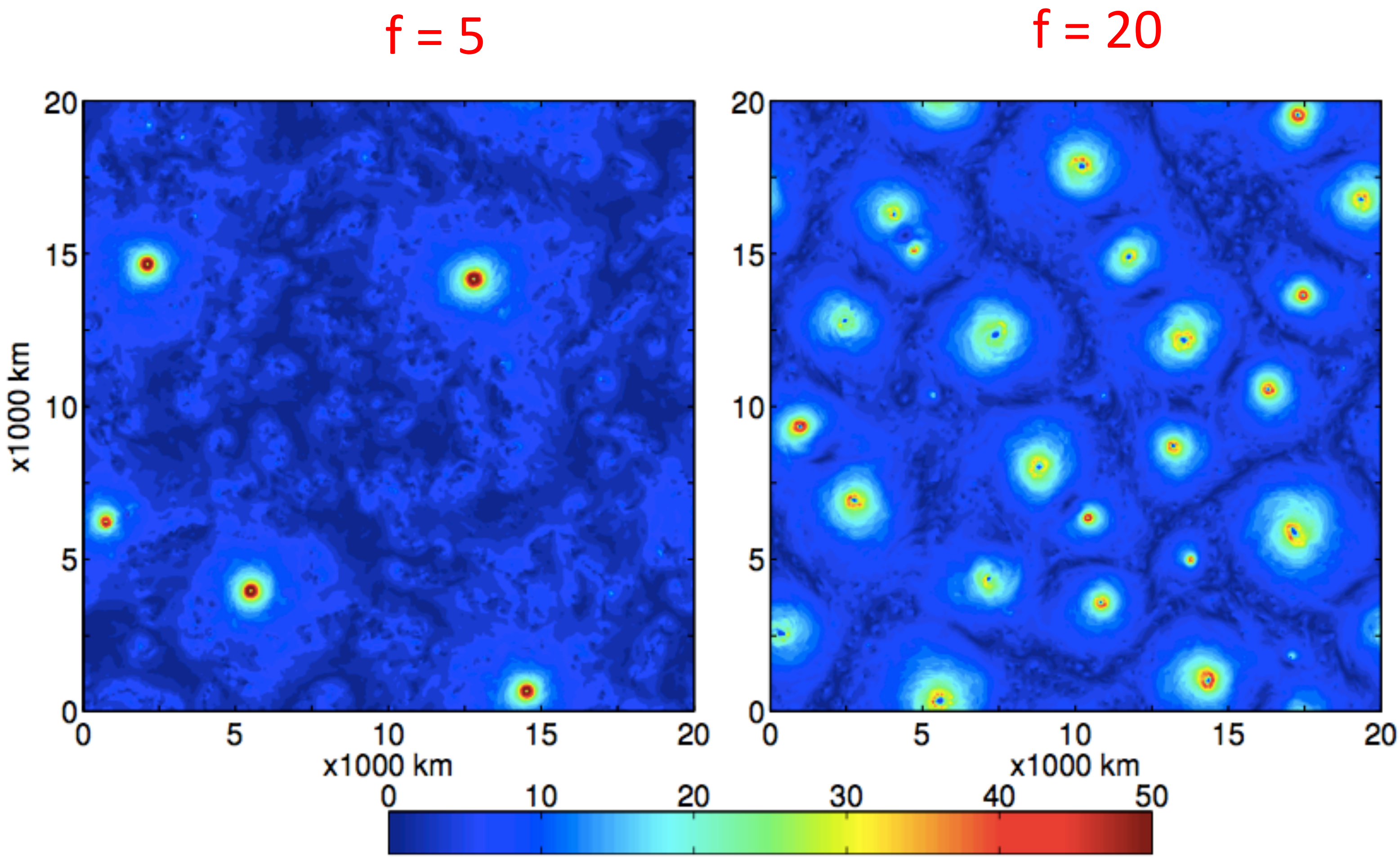
distance between storms increases with SST: NH/f ?, u/f ?*



Zhou et al, J. Atmos. Sci 2014

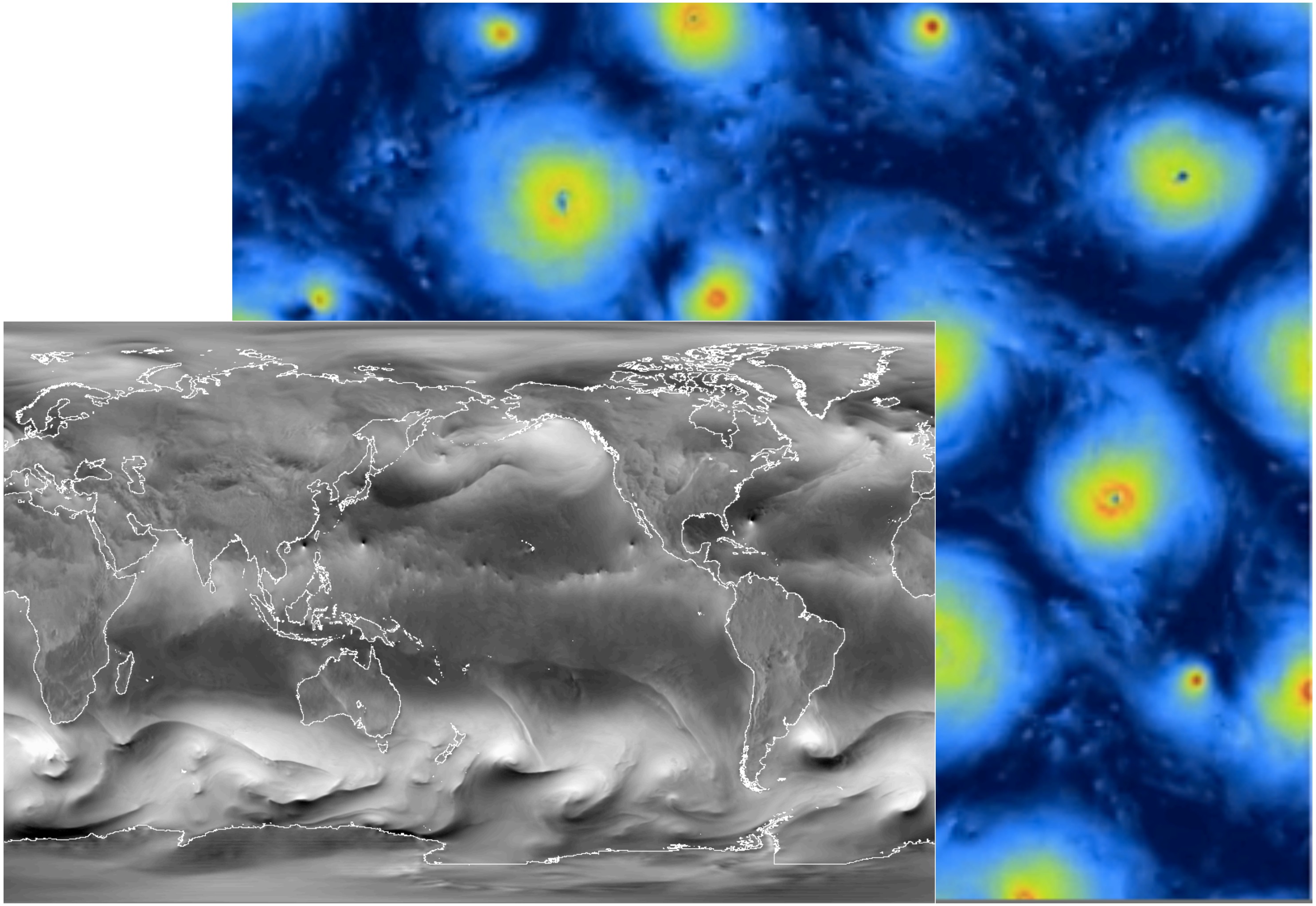
Lots of interesting parameter dependencies:

distance between storms decreases with rotation rate: NH/f ?, u/f ?*



Wenyu Zhou et al, J. Atmos. Sci 2014

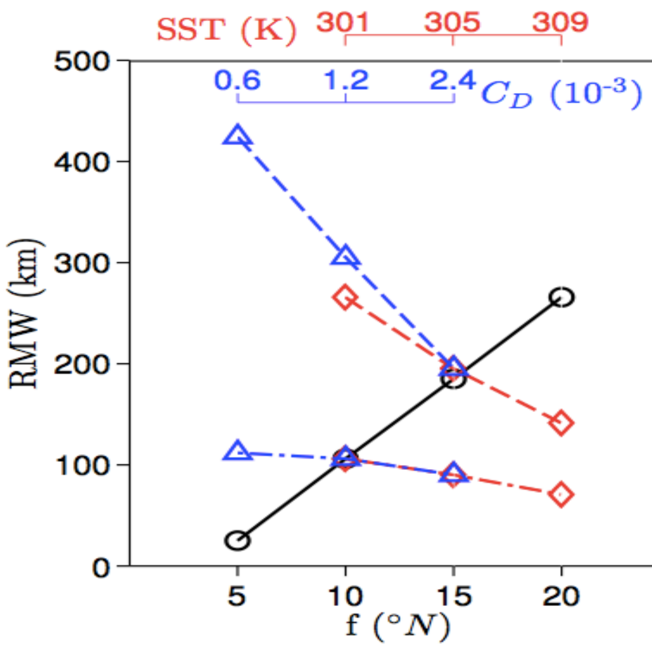
Rotating radiative convective equilibrium on doubly-periodic f-plane with GCM column physics and dynamics



Wenyu Zhou et al, J. Atmos. Sci 2014

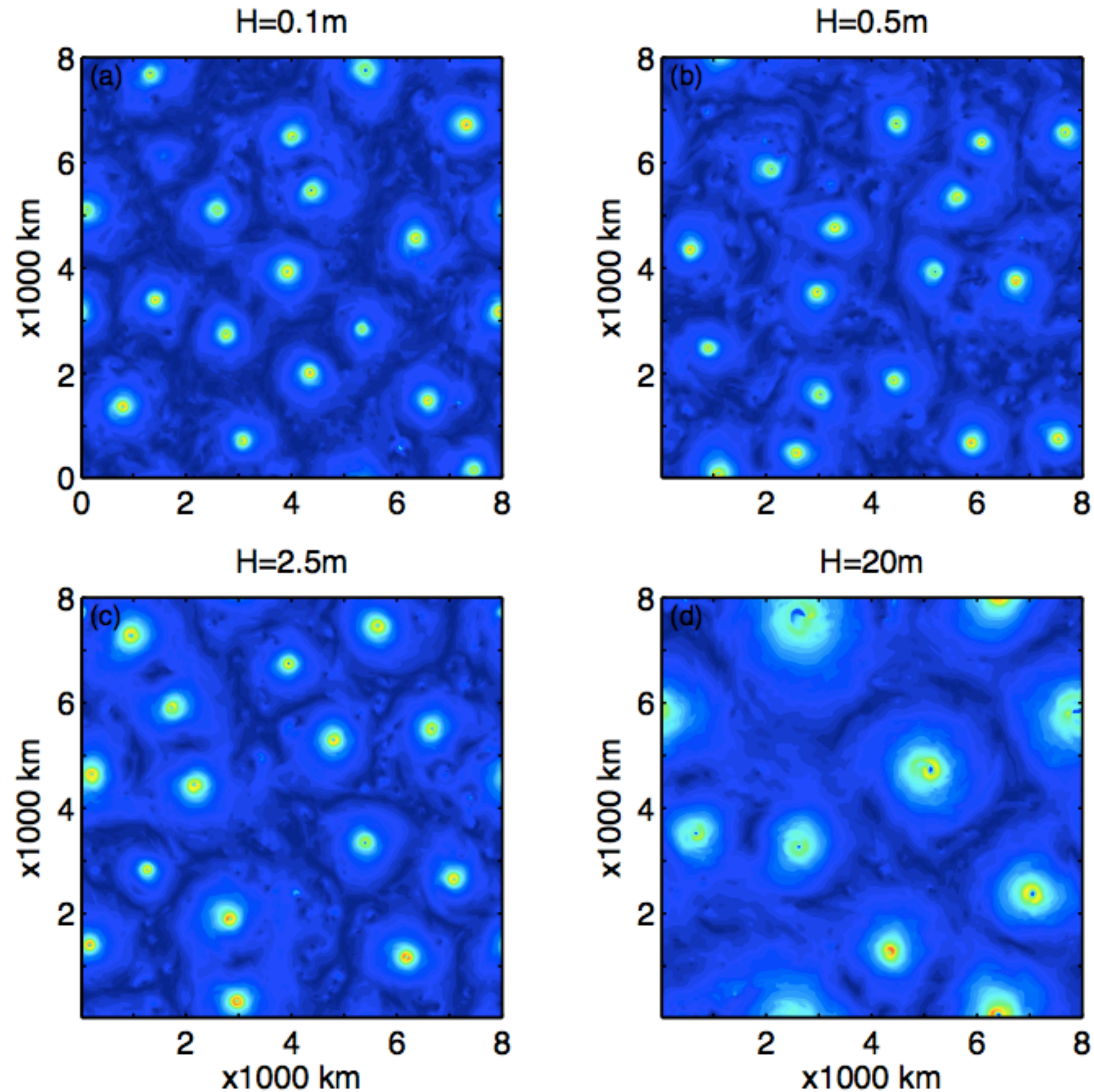
Lots of interesting parameter dependencies:

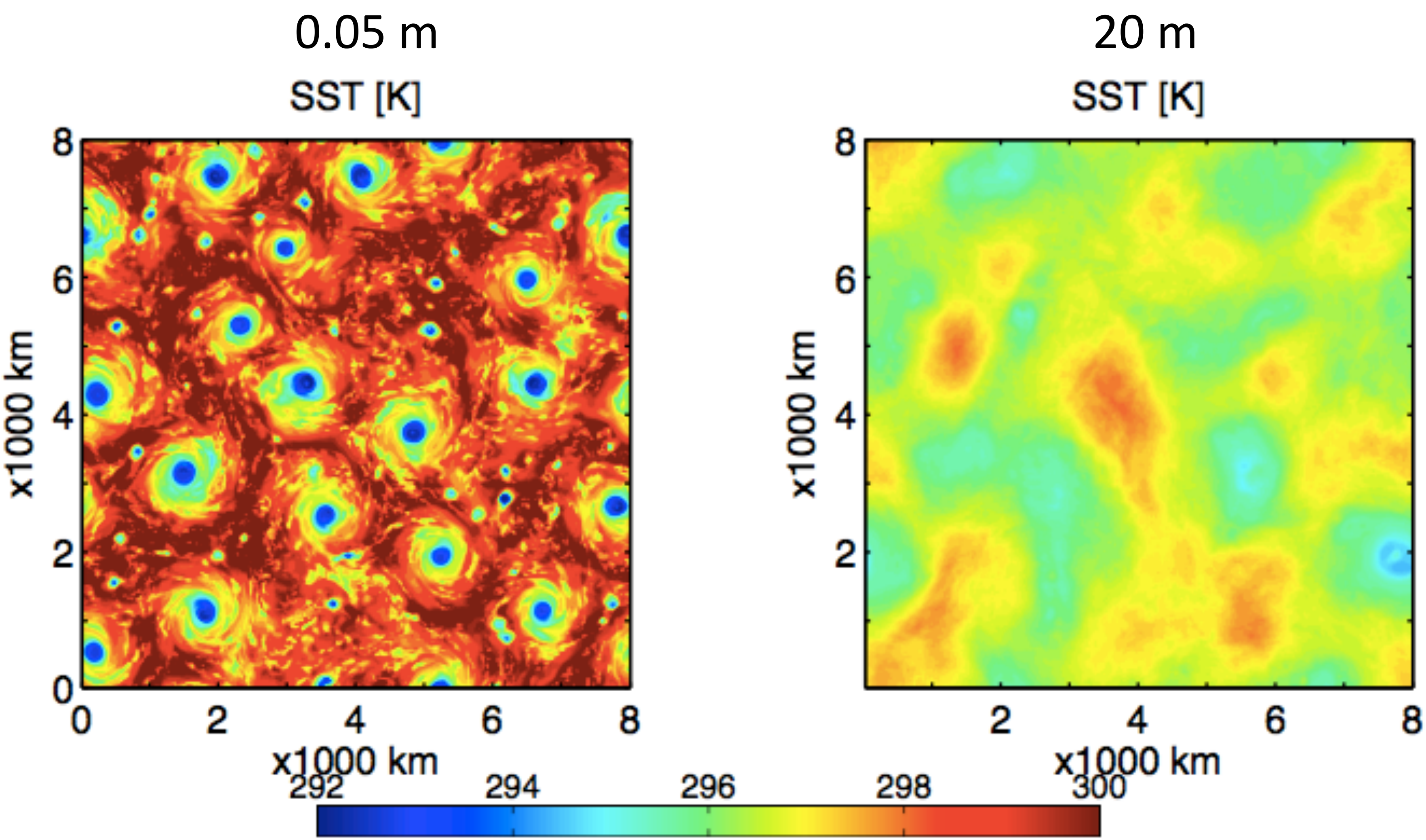
distance between storms decreases with rotation rate and increases with SST,
but
radius of maximum winds increases with rotation rate and decreases with SST



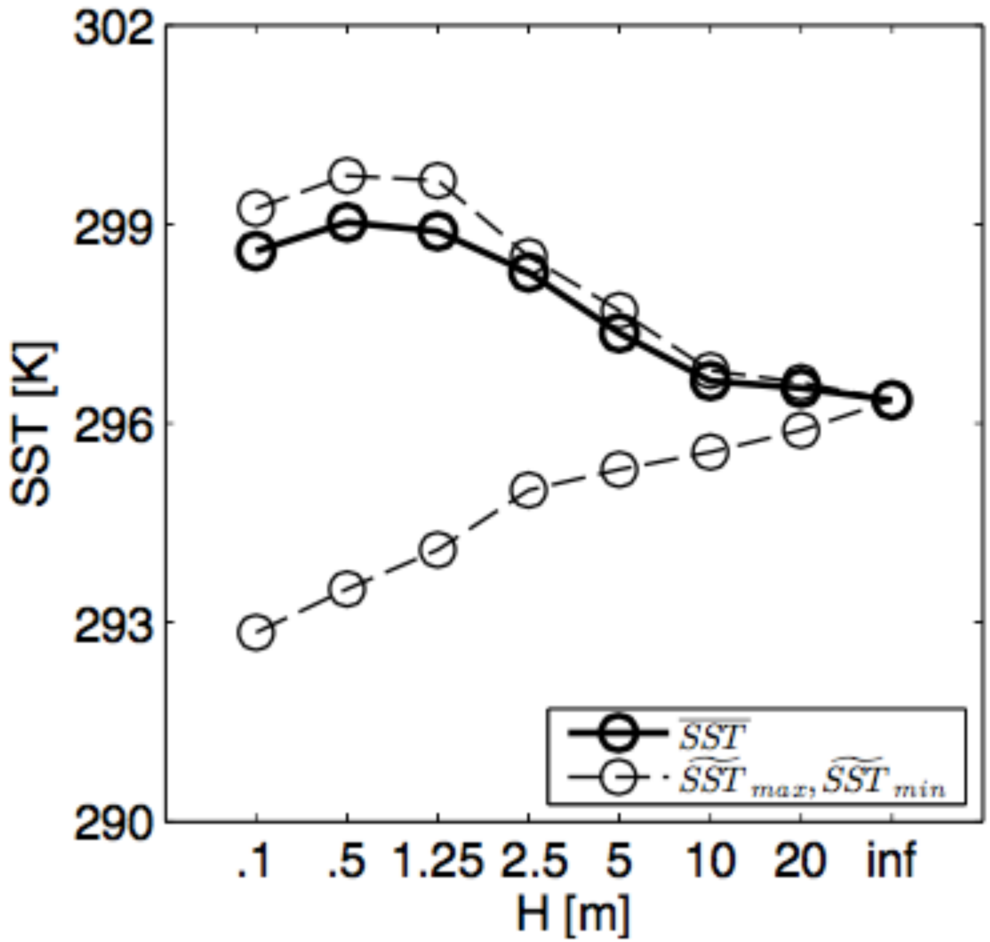
Wenyu Zhou et al, J. Atmos. Sci 2014

Rotating radiative-convective equilibrium coupled to slab ocean (interactive SSTs) -- Zhou et al, submitted to JAMES

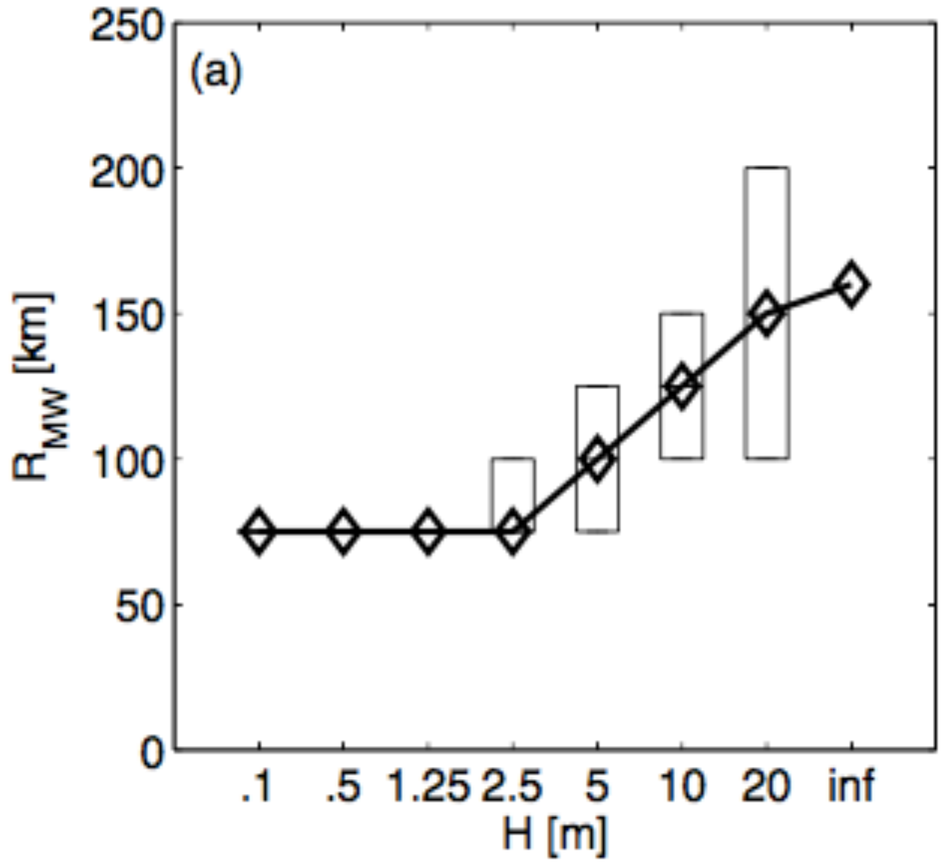




Zhou et al, 2016, submitted

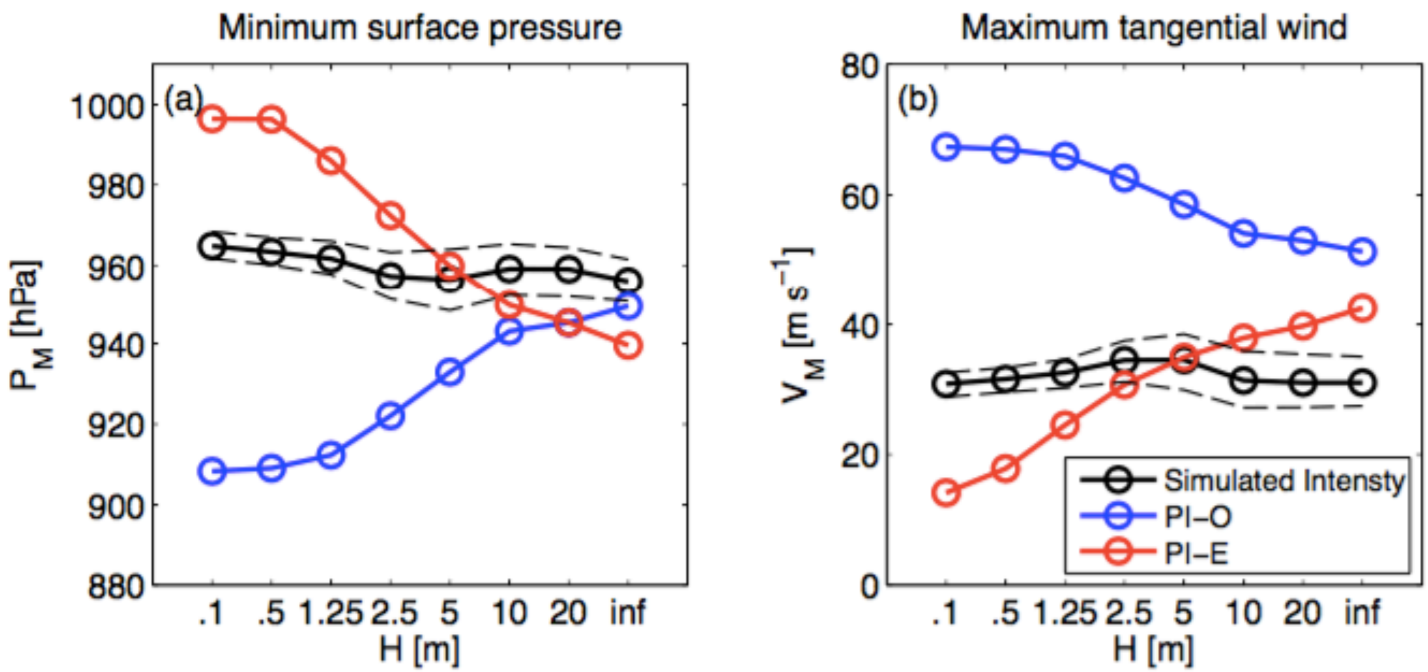


Zhou et al, 2016, submitted



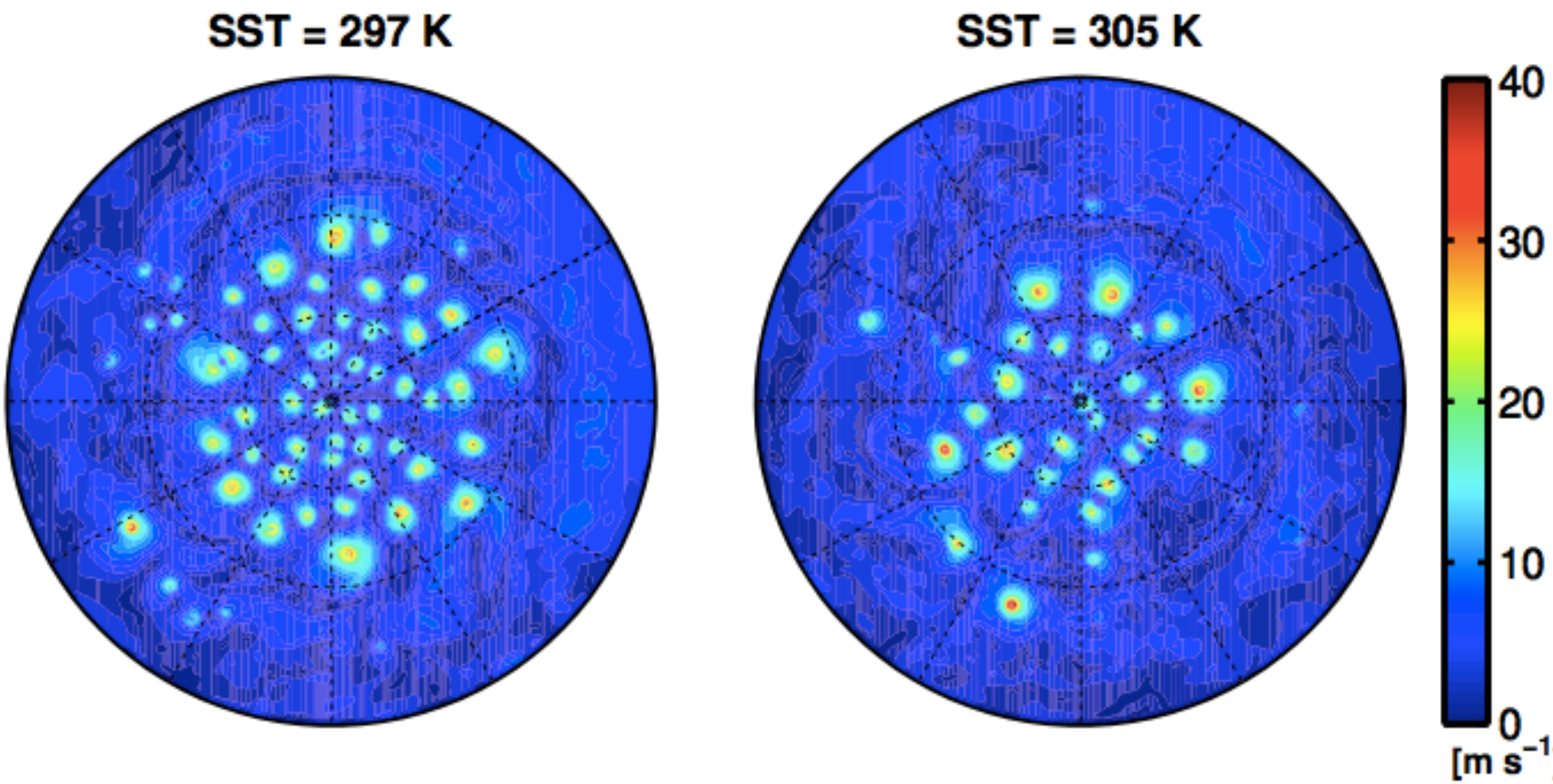
Zhou et al, 2016, submitted

Intensity nearly independent of depth of slab
(hard to reconcile with potential intensity theory)



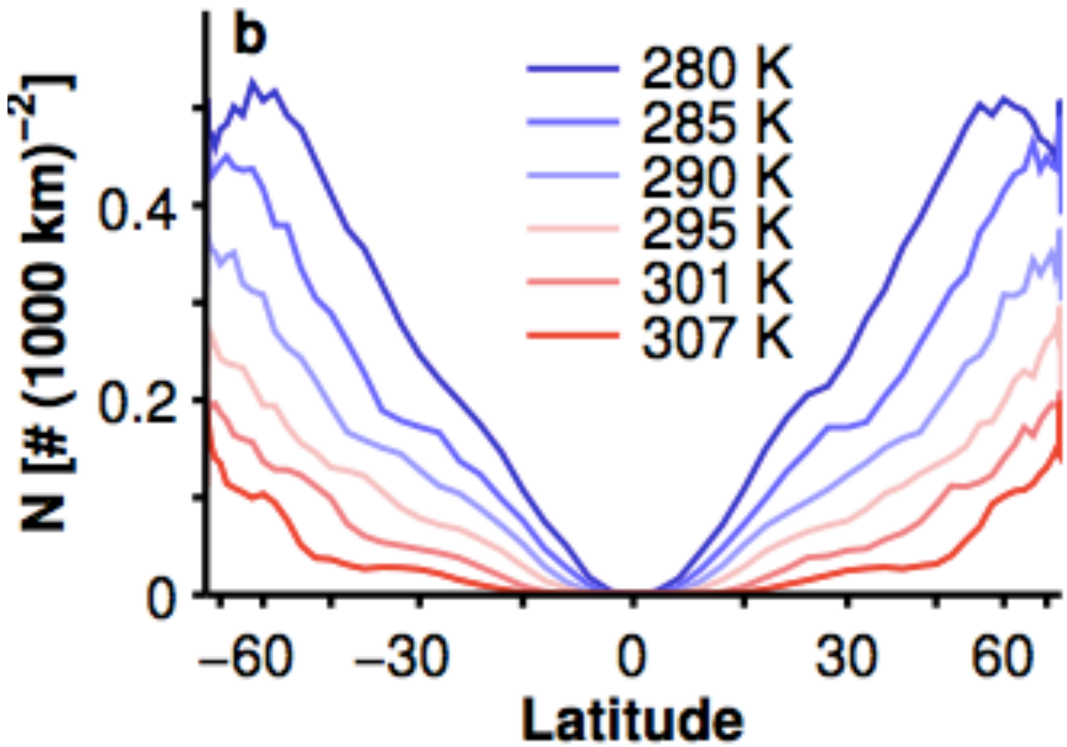
Zhou et al, 2016, submitted

Spherical rotating radiative-convective equilibrium
uniform prescribed SSTs and uniform insolation
Only inhomogeneity is spherical geometry
=> β-drift of TCs



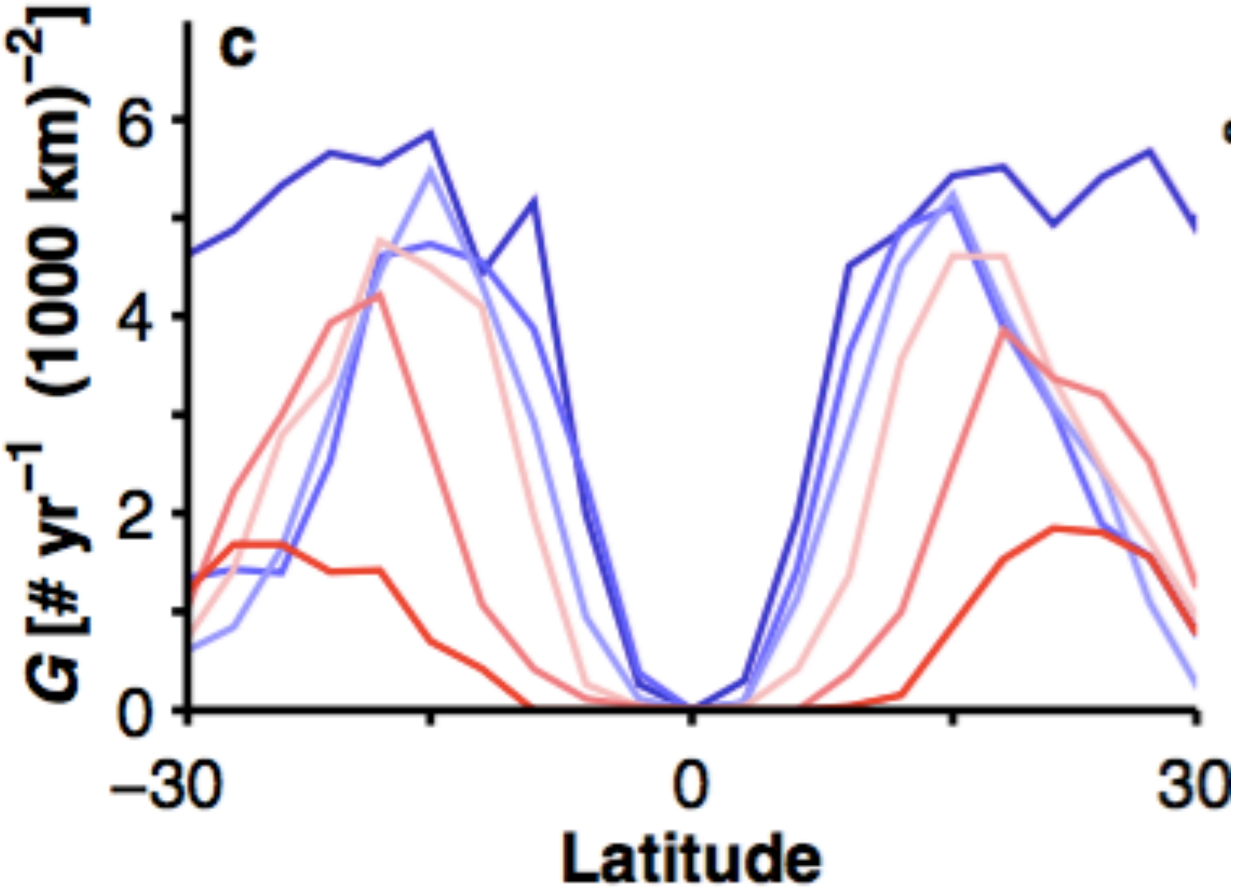
Merlis et al, GRL, 2016

TC density



Merlis et al, GRL, 2016

TC genesis rate

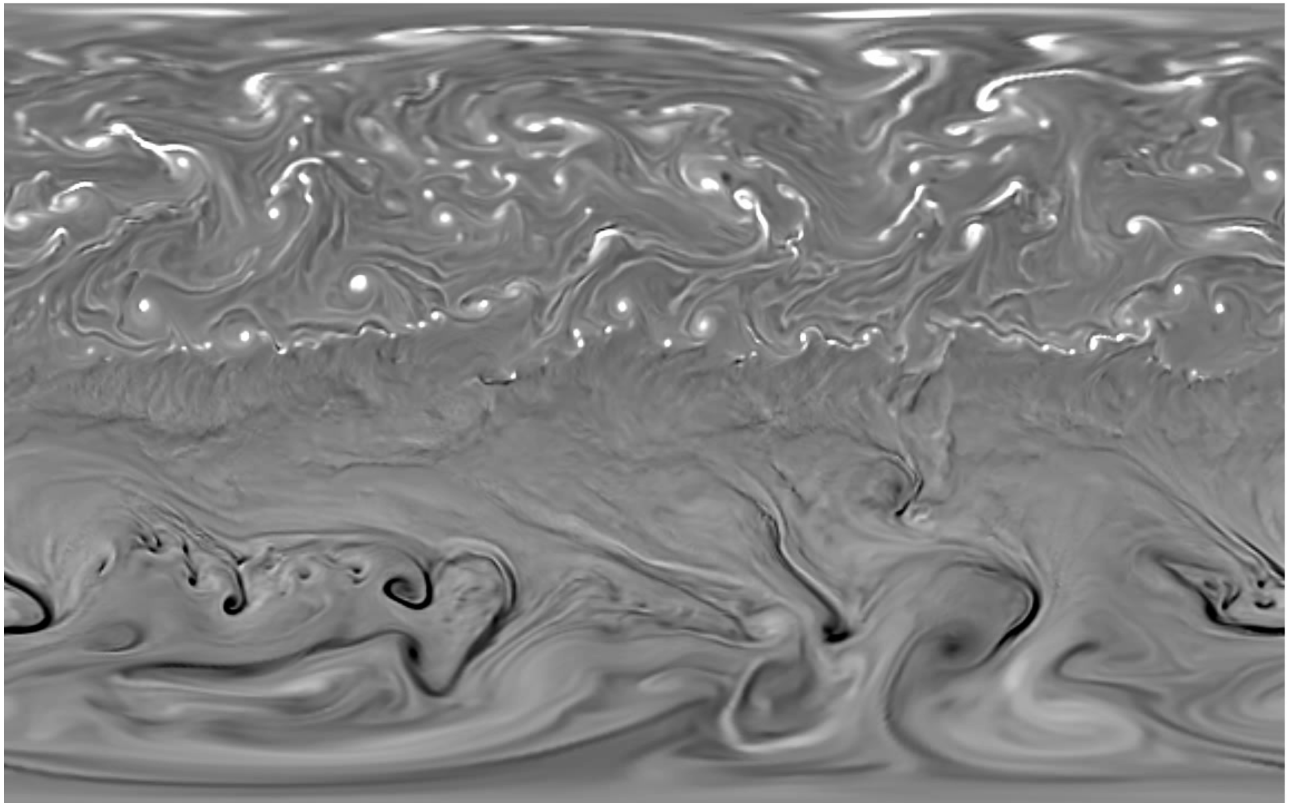


Merlis et al, GRL, 2016

Idealizing boundary conditions starting with
GCMs with sufficient realism

But also need further idealization to generate a new class of theories of tropical storm genesis

example: moist instability of an ITCZ ??



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2) understanding differences between global models