AMS Tropical Conference

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The Small-amplitude Dynamics of Spontaneous Tropical Cyclogenesis

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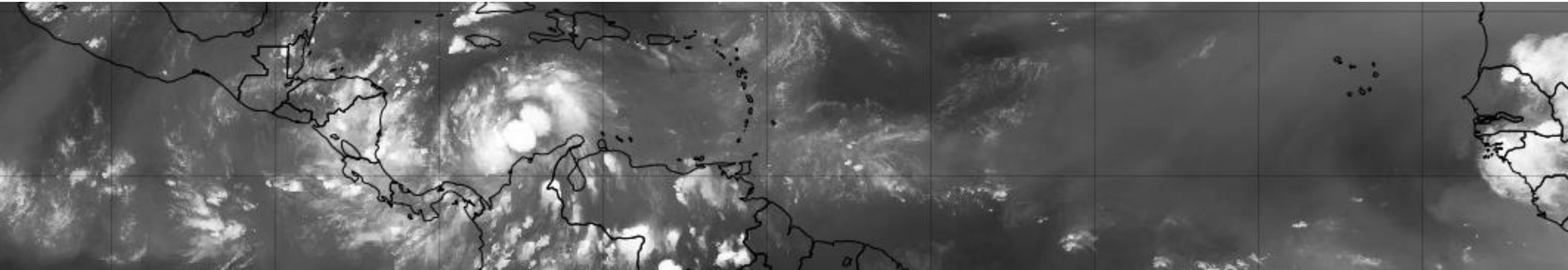
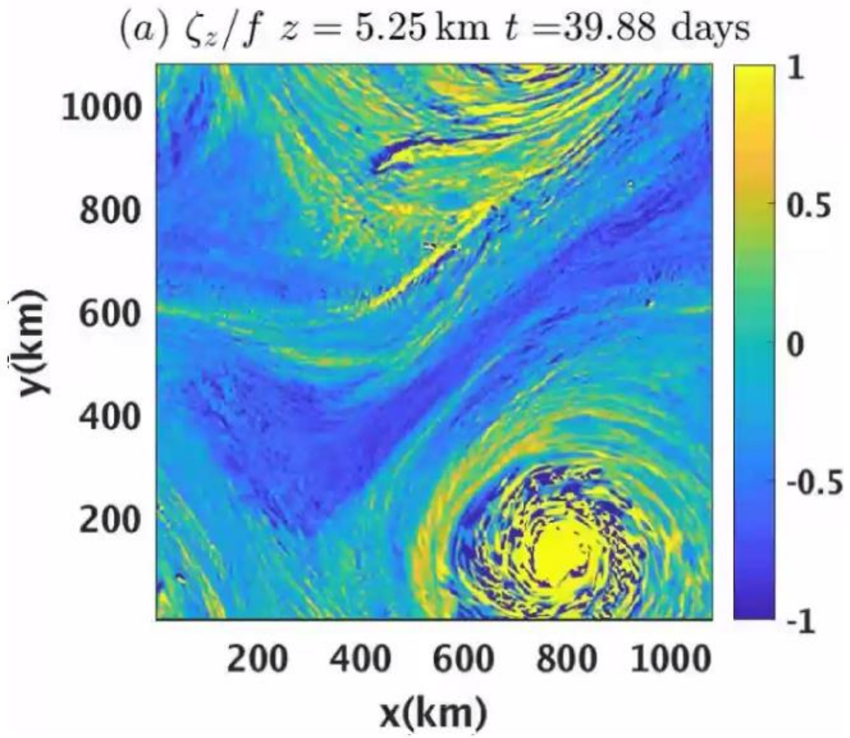
Fu H, O'Neill M. The Small-Amplitude Dynamics of Spontaneous Tropical Cyclogenesis. Part I. *J. Atmos. Sci., 2024*



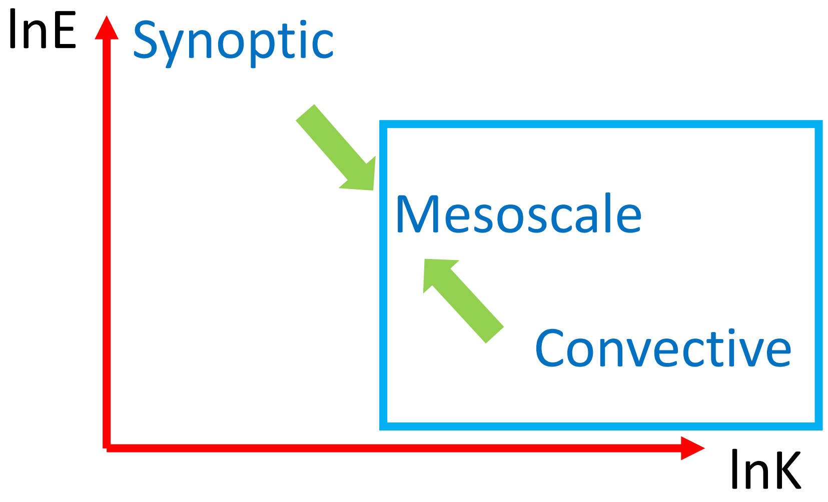
An idealized setup:
Spontaneous tropical cyclogenesis

Bretherton et al. 2005
Nolan 2007
Davis 2015
Wing et al. 2016
Carstens and Wing 2020, 2022
Yang and Tan 2020
Ruppert et al. 2020
...

Midlevel vorticity



SST=300 K, $f = 10^{-4}\ \mathrm{s}^{-1}$

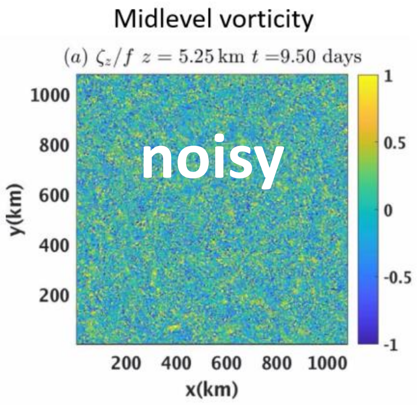


Modified from Montgomery 2016

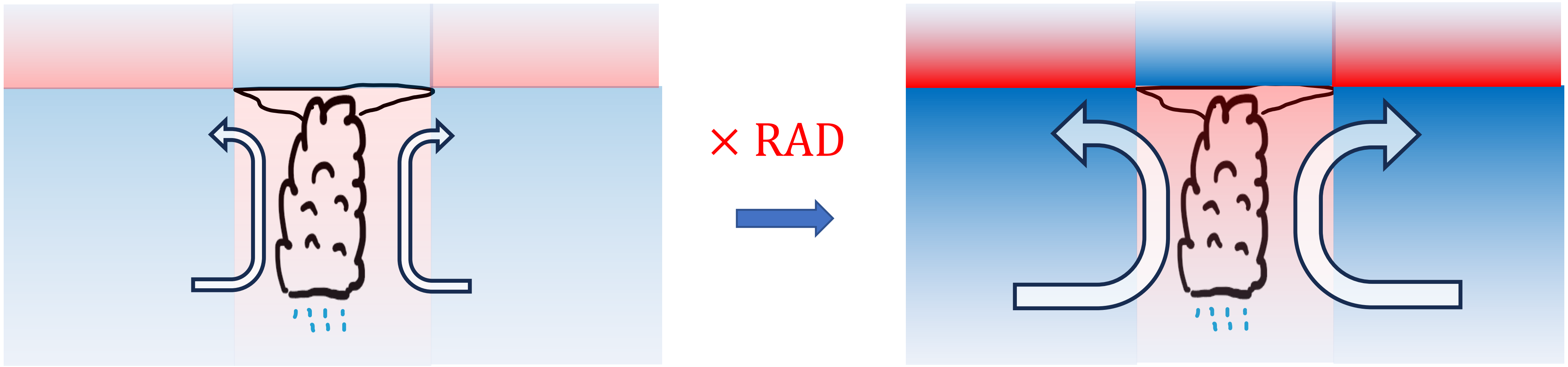
- f-plane, uniform SST
- No background shear
- Initialized with noise in the boundary layer

Cloud Model 1 (developed by **George Bryan**)
$\Delta x = 2$ km, $L = 1080$ km, model top at 27 km
Morrison double moment microphysics + RRTMG radiation

What is going on within the first 30 days?

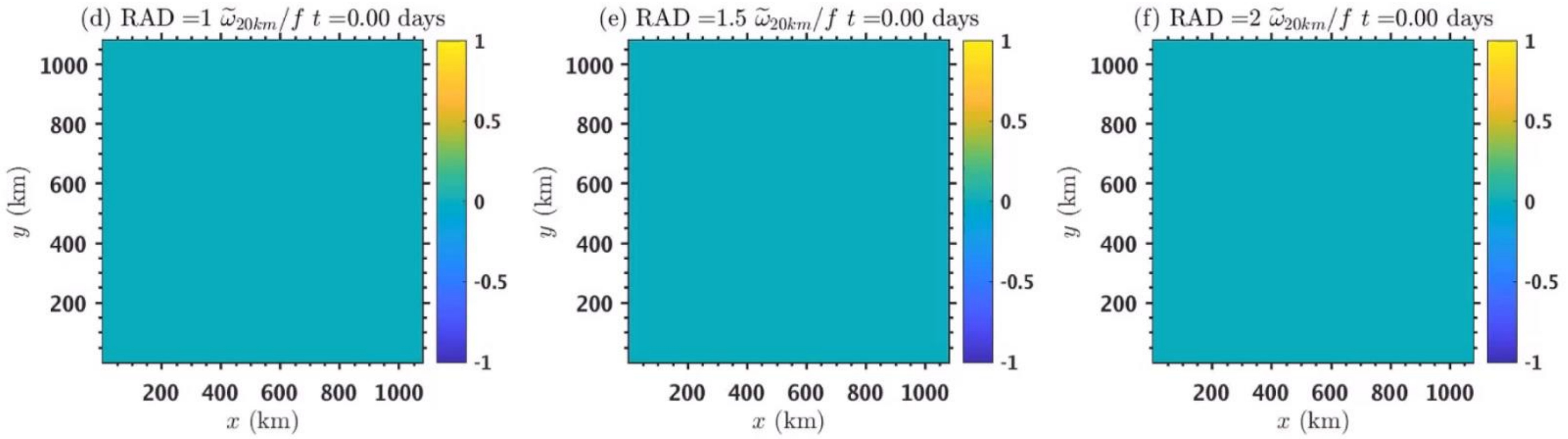


- Enhance the signal-to-noise ratio
- **Amplify the horizontal anomaly of the longwave heating tendency: LW**
- $\mathrm{LW} = \overline{\mathrm{LW}} + \mathrm{LW'}$ ➡ $\mathrm{LW}(new) = \overline{\mathrm{LW}} + \mathrm{RAD} \times \mathrm{LW'}$



Spontaneous TC genesis with amplified radiative feedback

20 km –Gaussian filtered vertical vorticity at z=5.25 km



$f = 10^{-4}\ s^{-1}$

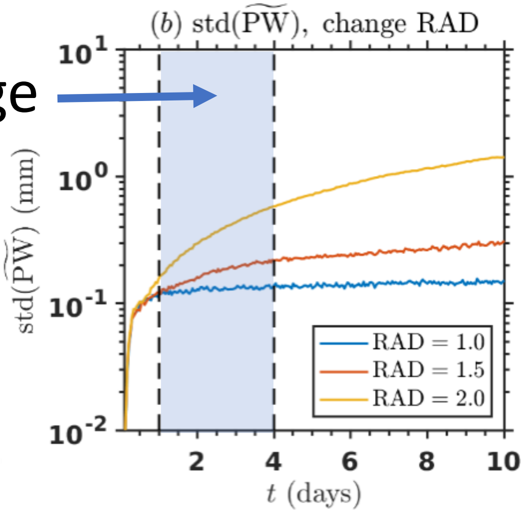
RAD=1

RAD=1.5

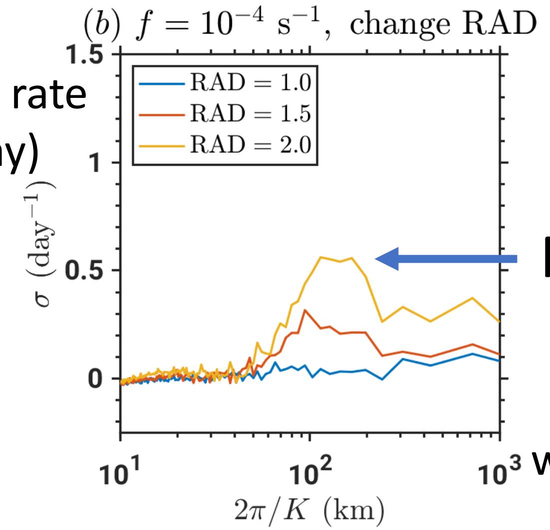
RAD=2

Small-amplitude stage

std of column precipitable water



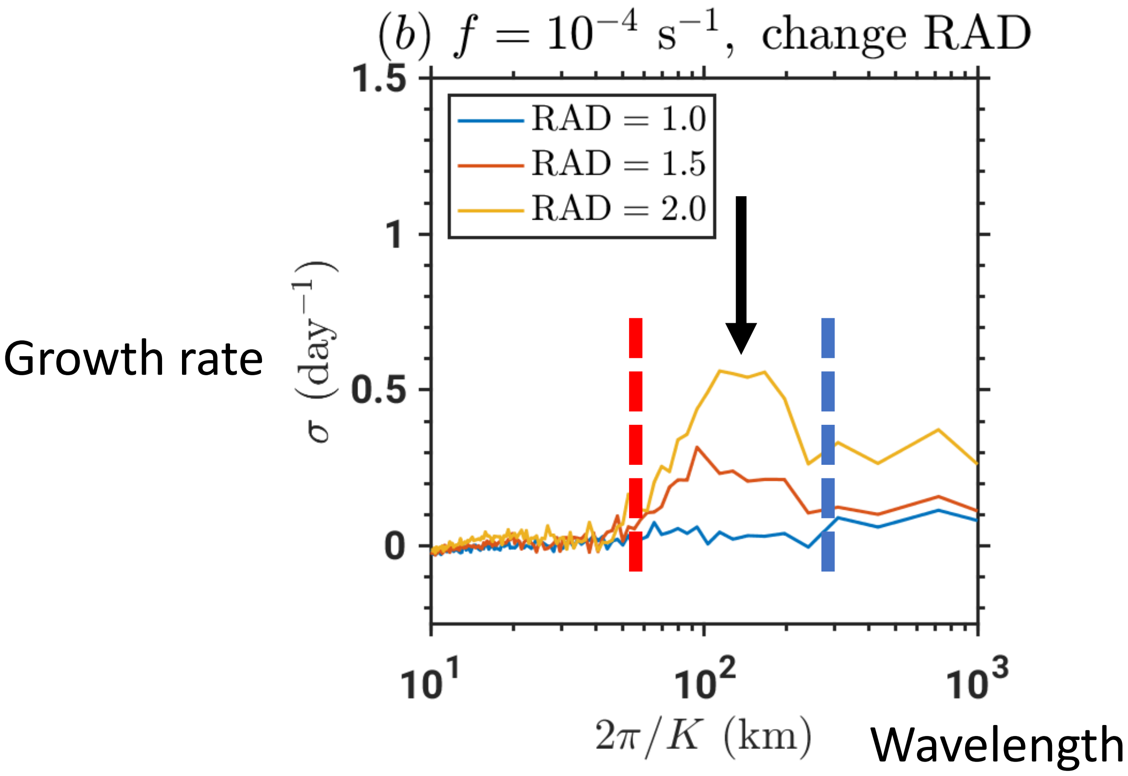
Growth rate (1/day)



Most unstable wavelength ~150 km

wavelength (km)

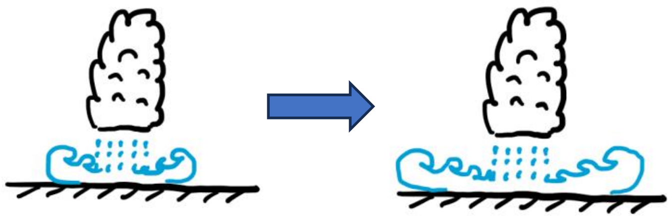
Questions



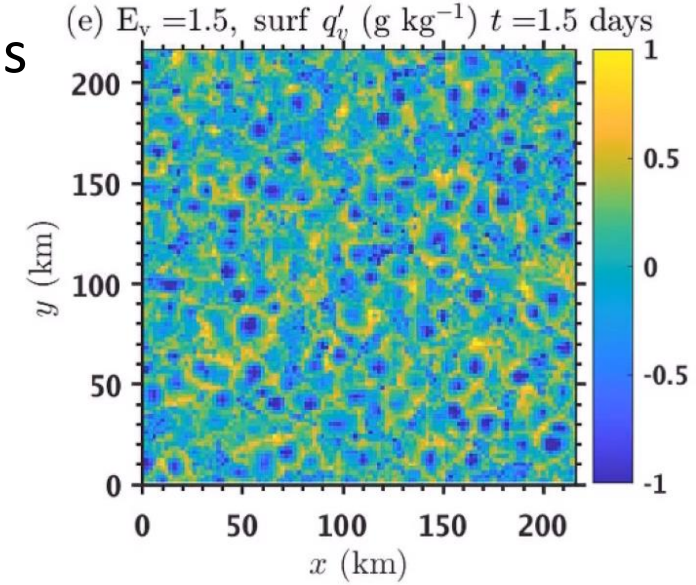
- What sets the short-wavelength cutoff?
- What sets the long-wavelength cutoff?
- How do the two cutoffs set the **most unstable wavelength** (~150 km)?

The short-wavelength cutoff (~10 km)

One of the important factors: Stronger cold pools

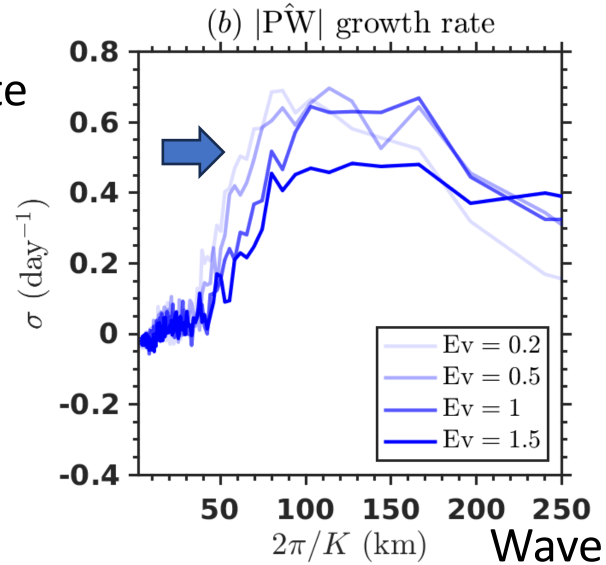


Near-surface vapor mixing ratio



Experiments: higher sub-cloud evaporation

Growth rate



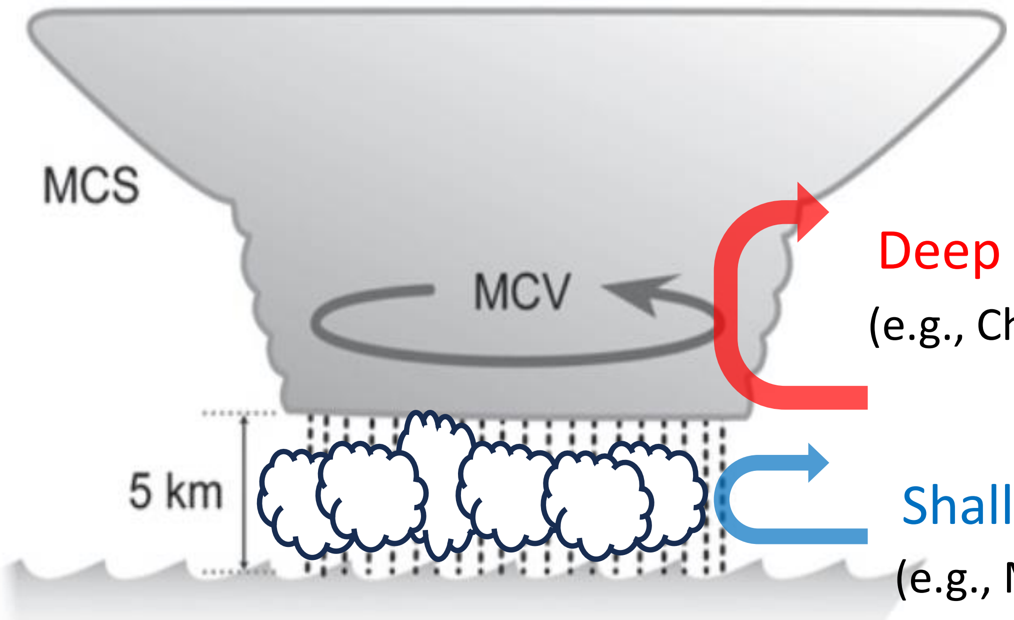
Wavelength

Project in progress:

The chain triggering of convection as wave packet diffusion

The long-wavelength cutoff: vertical structure

- How do deep and shallow cells cooperatively converge water vapor?



From Houze et al. 2009

Deep cell: deep + stratiform

(e.g., Chen and Frank 1993)

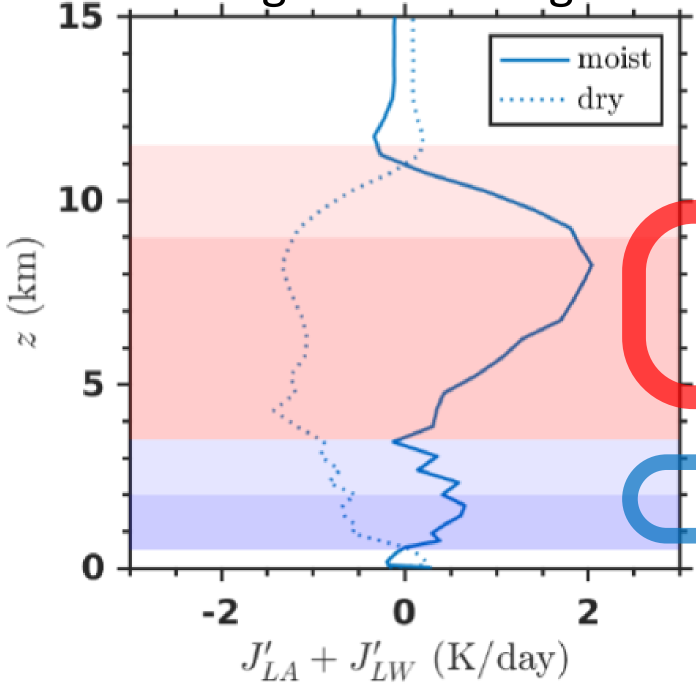
Shallow cell: congestus

(e.g., Muller and Romps 2018)

The long-wavelength cutoff

- How do deep and shallow cells cooperatively converge water vapor?
- The effective Rossby deformation radius?

Latent + longwave heating anomaly



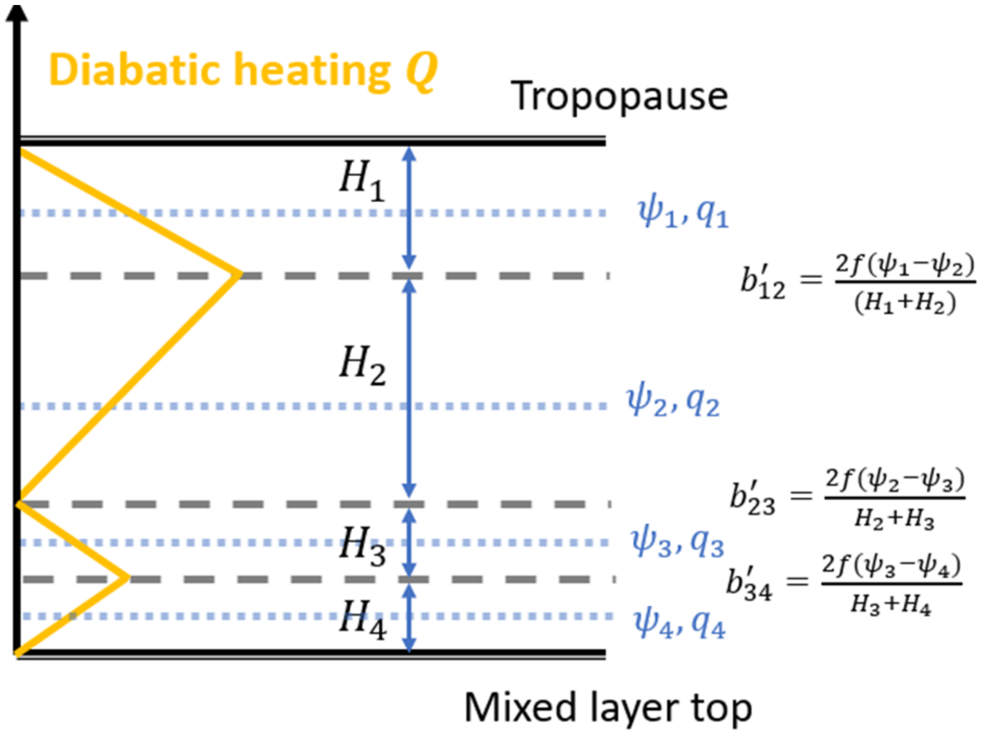
Deep cell: deep + stratiform

(e.g., Chen and Frank 1993)

Shallow cell: congestus

(e.g., Muller and Romps 2018)

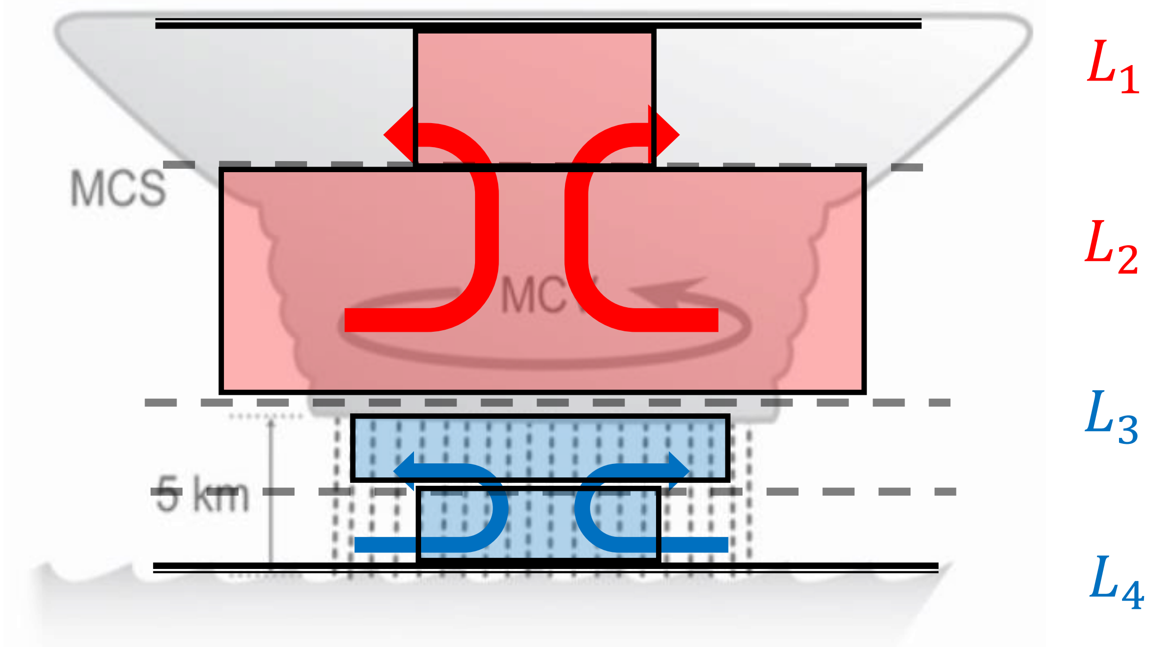
A four-layer quasi-geostrophic model



The long-wavelength cutoff

Rossby radius of each inflow/outflow branch

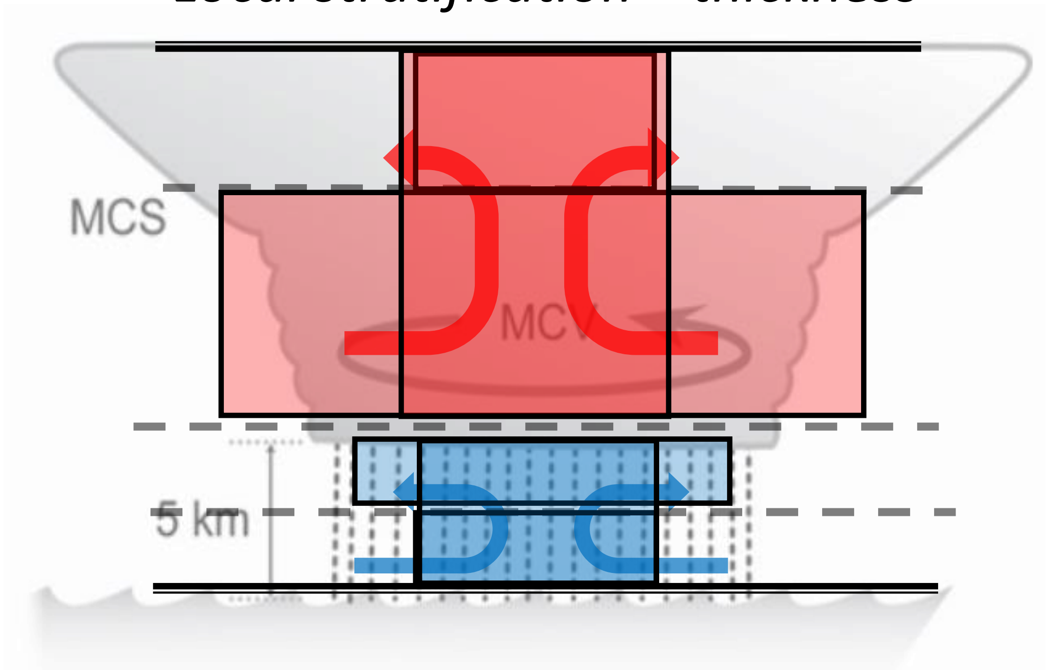
Local stratification + thickness



The long-wavelength cutoff

Rossby radius of each inflow/outflow branch → Rossby radius of each cell

Local stratification + thickness



L_1, L_2 →

$$L_{12} = \frac{N_{12}}{f}\left(\frac{H_1 H_2}{2}\right)^{1/2}$$

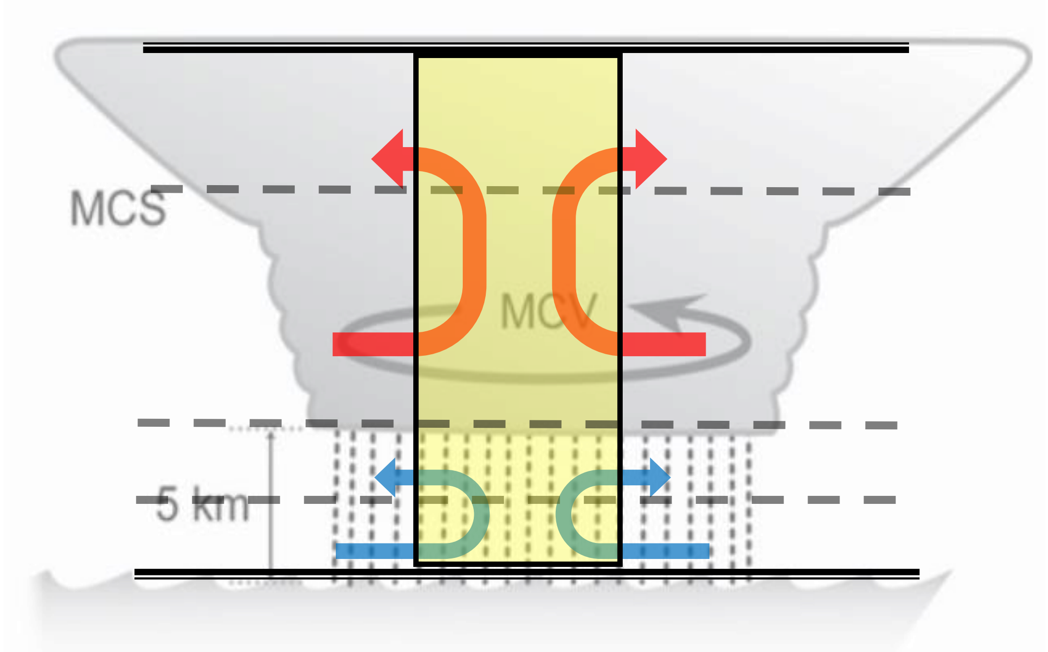
L_3, L_4 →

$$L_{34} = \frac{N_{34}}{f}\left(\frac{H_3 H_4}{2}\right)^{1/2}$$

The long-wavelength cutoff

Rossby radius of each inflow/outflow branch → Rossby radius of each cell → Rossby radius of the system

Local stratification + thickness



L_1, L_2 →

$$L_{12} = \frac{N_{12}}{f}\left(\frac{H_1 H_2}{2}\right)^{1/2}$$

L_3, L_4 →

$$L_{34} = \frac{N_{34}}{f}\left(\frac{H_3 H_4}{2}\right)^{1/2}$$

Weighted average

$$L_e^2 = \alpha L_{12}^2 + (1-\alpha) L_{34}^2$$

α: fractional contribution of moistening from the deep cell

Combining the short- and long-wavelength cutoff

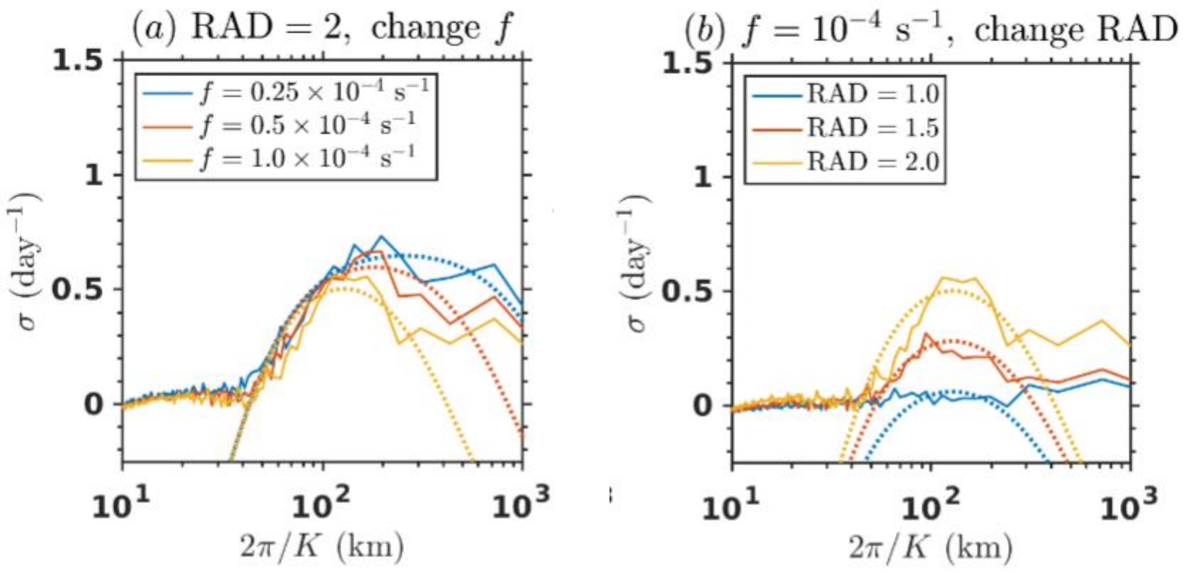
Growth rate $\sigma \approx \sigma_0 \frac{K^2}{K^2+L_e^{-2}} \exp\left(-\frac{K^2 l_{cp+av}^2}{4}\right) - \frac{1}{\tau}$

Long-wavelength cutoff L_e: effective Rossby radius ($\sim$80 km for $f = 10^{-4}\ \mathrm{s}^{-1}$)

Short-wavelength cutoff l_{cp+av}: cold pools + others ($\sim$10 km)

➡ **Most unstable wavelength** $\propto$ (short cutoff $\times$ long cutoff)$^{1/2}$

Change f

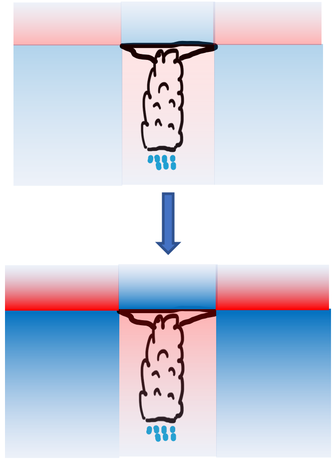


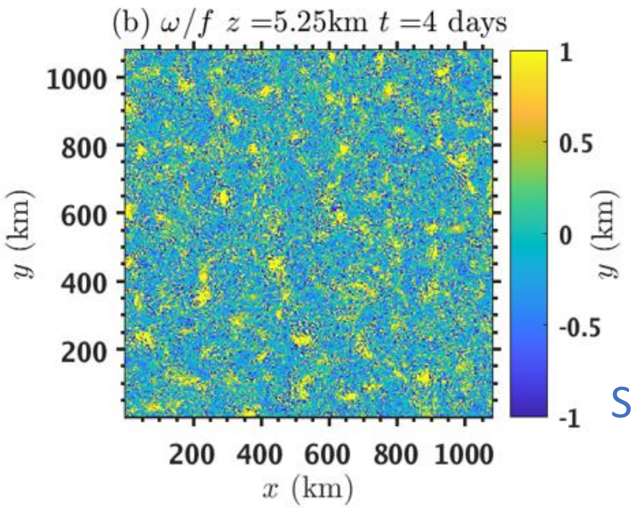
Change radiative feedback strength

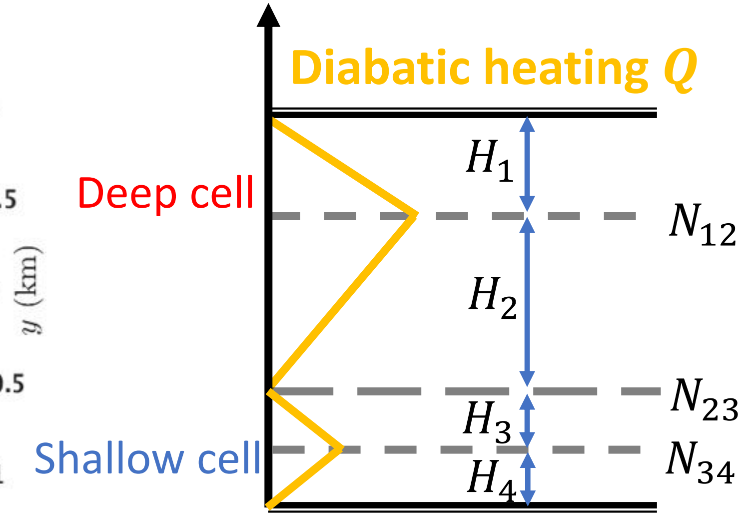
Summary

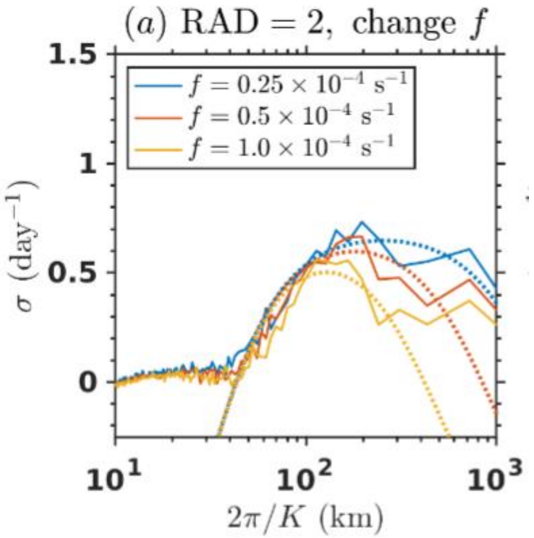
Thanks for watching!
haofu@uchicago.edu

- Amplifying longwave radiative feedback → diagnose the spectral growth rate
- Short-wavelength cutoff: convective triggering by **cold pools** + others
- Long-wavelength cutoff: the effective Rossby radius of the shallow-deep cell system
- Vortex size ~ most unstable wavelength ~ $(\text{short cutoff} \times \text{long cutoff})^{1/2}$







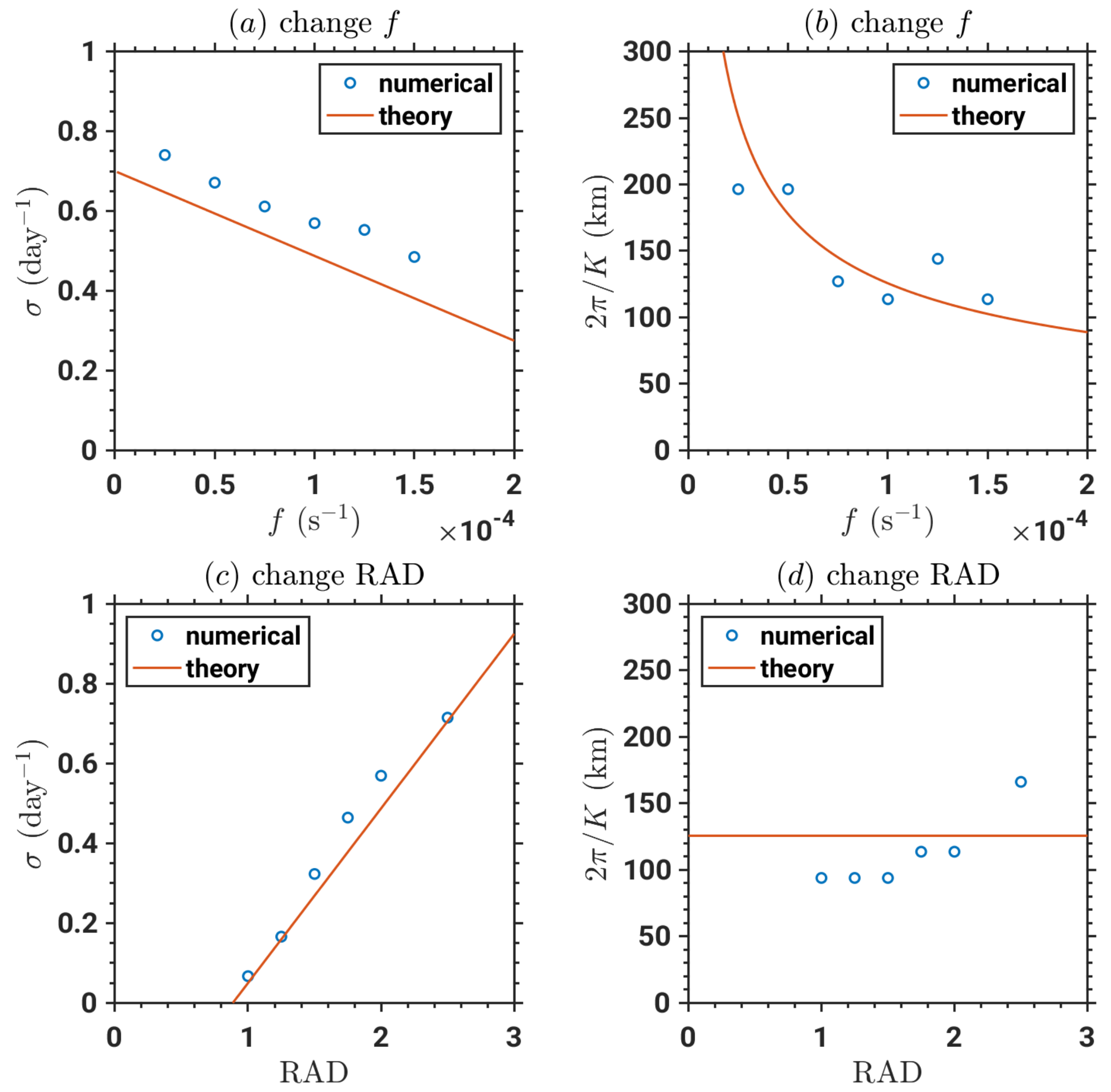


Backup slides

Maximum growth rate　　Most unstable wavelength

Change f

Change radiative feedback strength



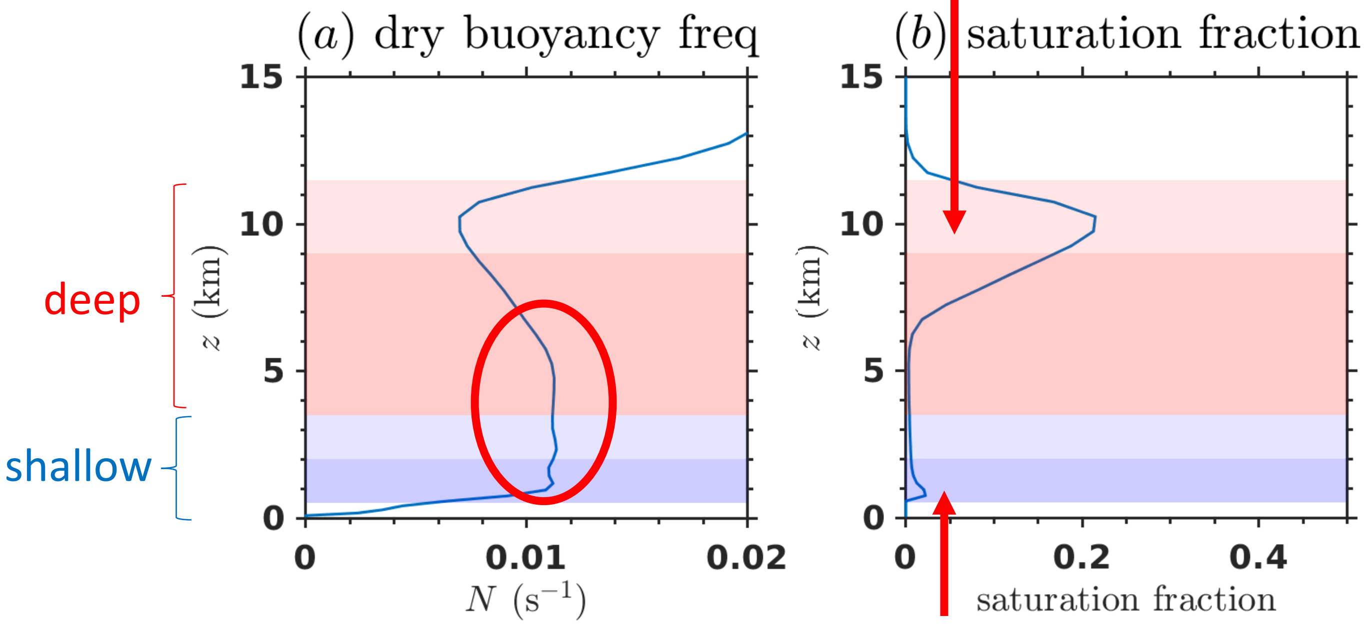
A midlevel waveguide → weak buoyancy gradient

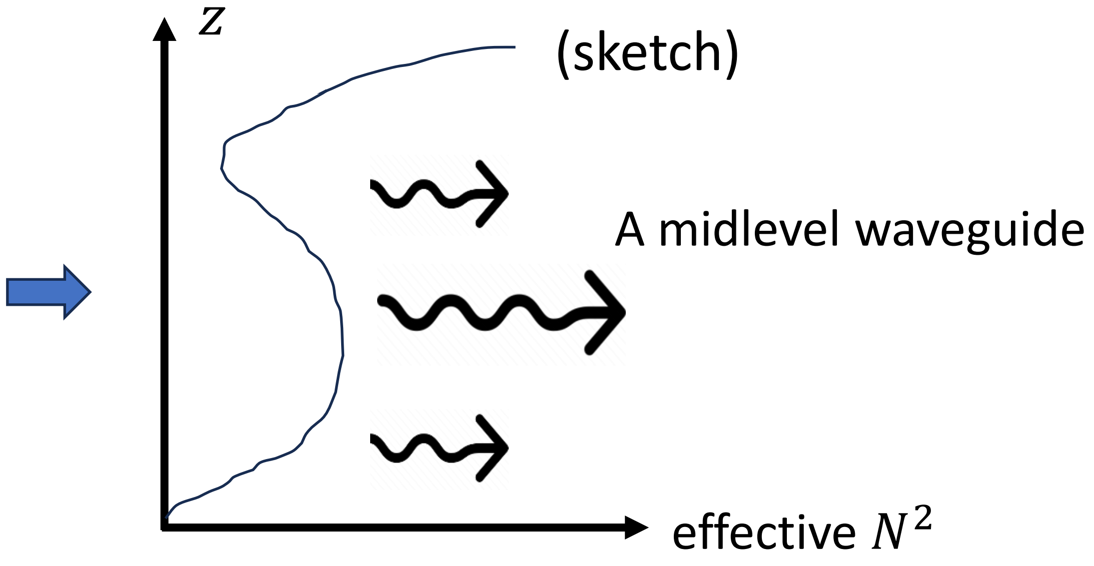
e.g. Sobel et al. 2001

- The gravity wave speed is lower in a **saturated environment** (diabatic heating compensates for adiabatic)

Durran and Klemp 1982

Stratiform cloud (Chen and Frank 1993; Houze 2004)



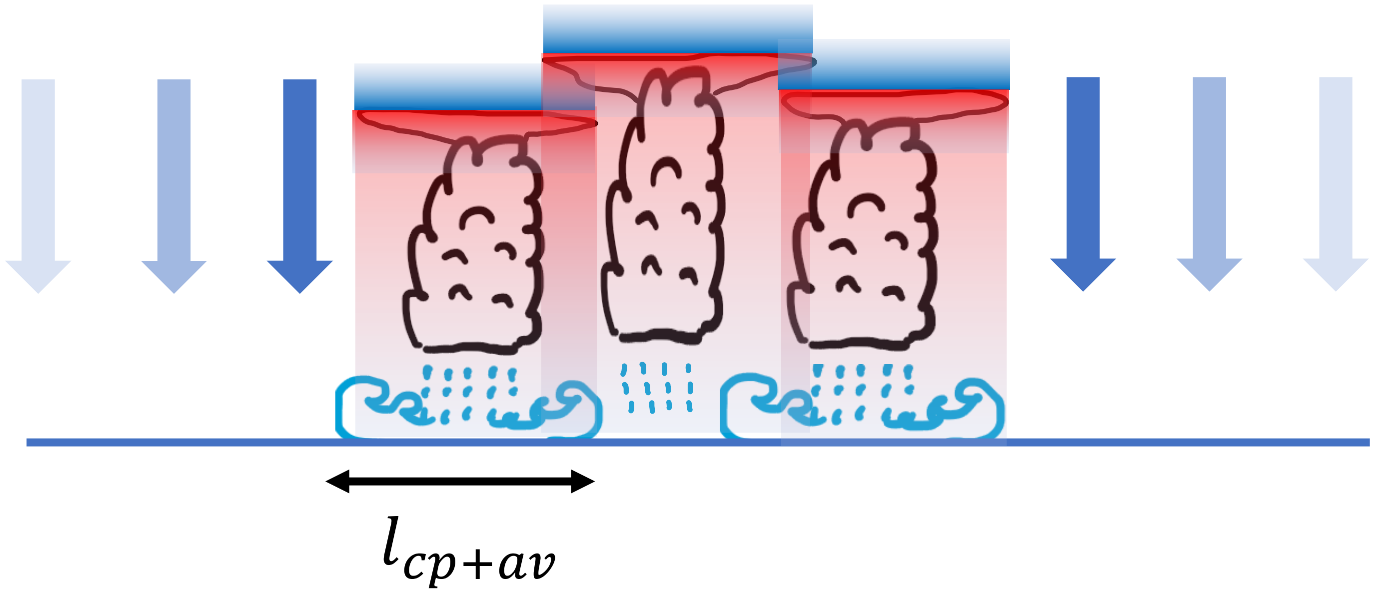


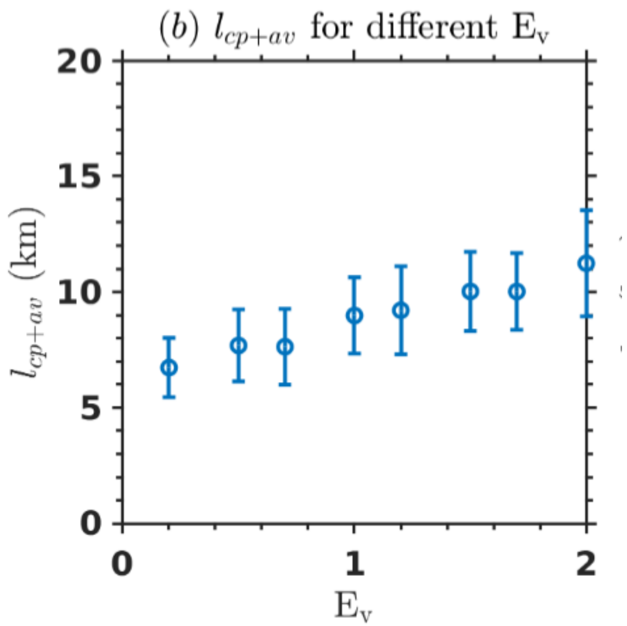
Shallow convection (Wu 2003; Liu et al. 2019, 2022)

The short-wavelength cutoff (~10 km)

- The nonlocal convective triggering by **cold pools**
- The nonlocal longwave radiative effect of **anvil clouds**

convective scale processes sensitive to microphysics

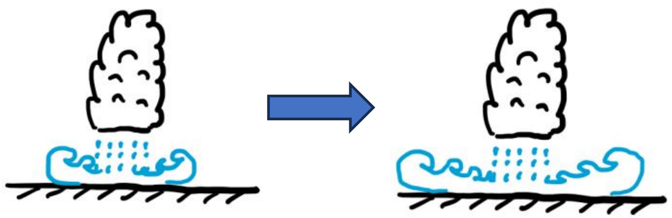




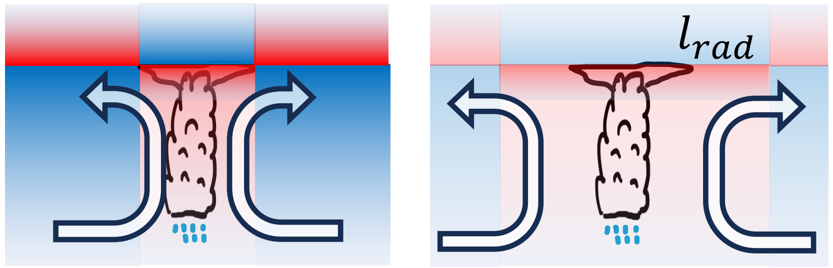
higher sub-cloud evaporation

The short-wavelength cutoff (~10 km)

Stronger cold pools

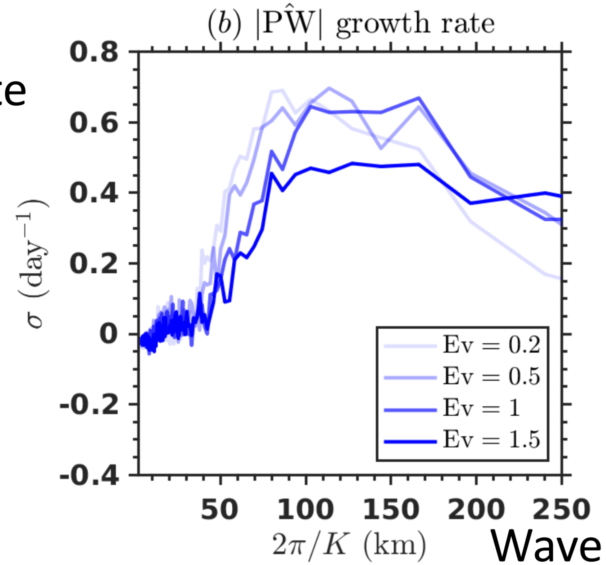


A canopy of LW heating by anvil clouds



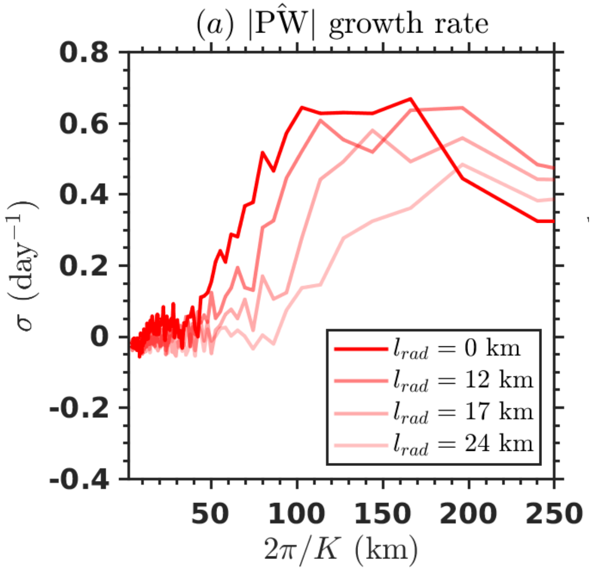
Experiments: higher sub-cloud evaporation

Growth rate



Wavelength

Smoothing the longwave heating tendency



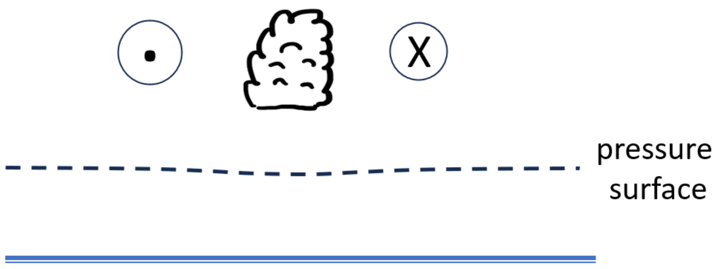
Open question: early-stage vortex size & growth rate?

On the Growth of the Hurricane Depression[1]

JULE G. CHARNEY
Massachusetts Institute of Technology

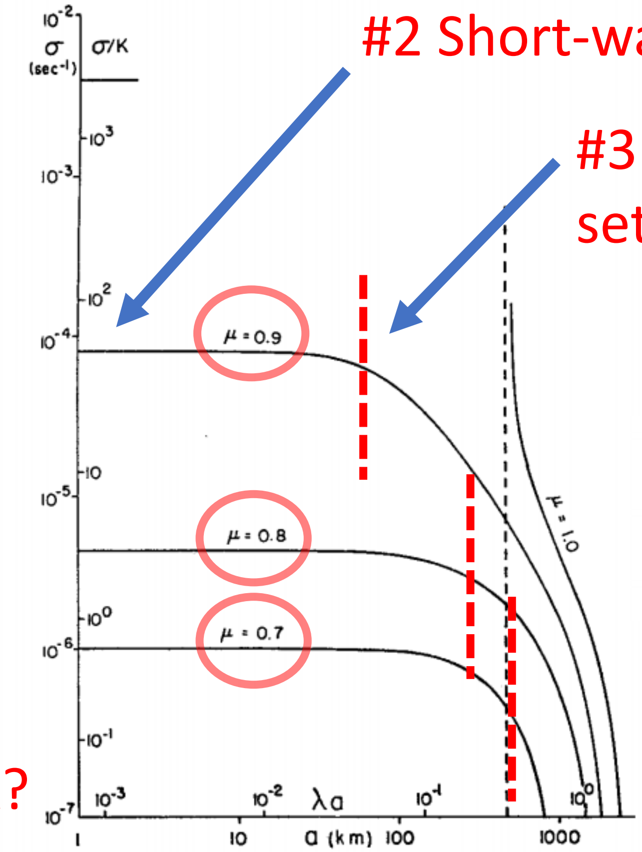
AND ARNT ELIASSEN
University of Oslo

(Manuscript received 16 August 1963, in revised form 24 October 1963)



#1 Ekman pumping or moisture-radiation feedback?

growth rate



vortex radius

#2 Short-wavelength cutoff ?

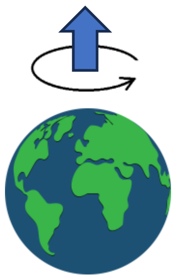
#3 Long-wavelength cutoff set by Rossby radius?

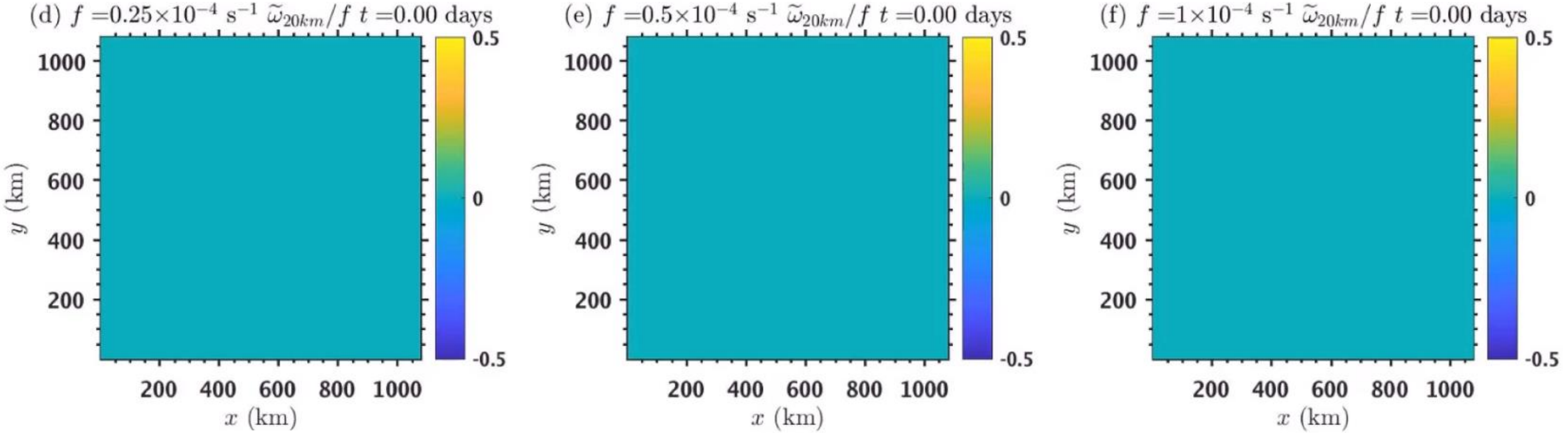
$$I = -\int_0^\infty \bar{\rho}\bar{w}\frac{\partial(\mu\bar{q}_s)}{\partial z}dz.$$

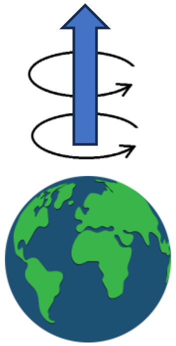
Sensitive to saturation fraction μ

Spontaneous TC genesis:
doubly periodic domain + uniform SST

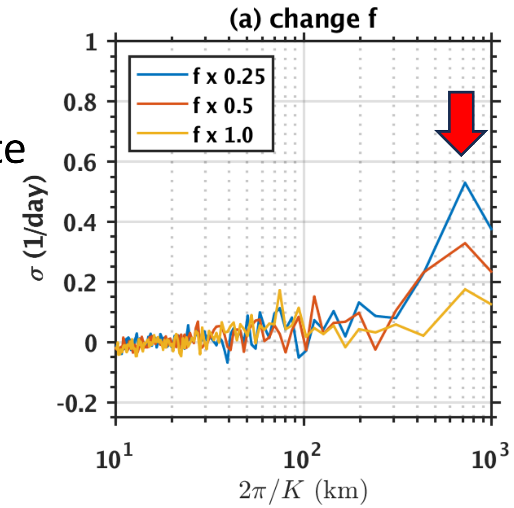
20 km –Gaussian filtered vertical vorticity at z=5.25 km







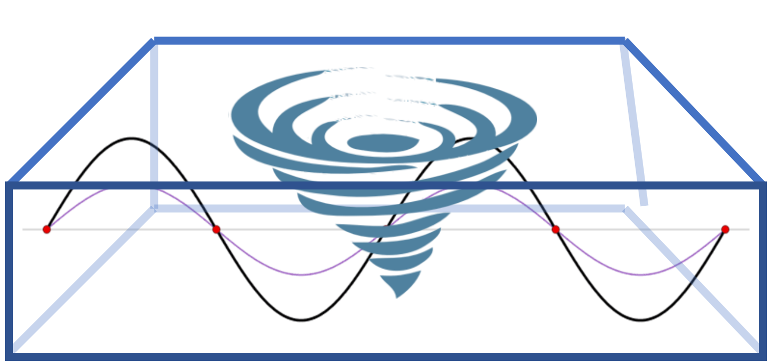
Growth rate (1/day)

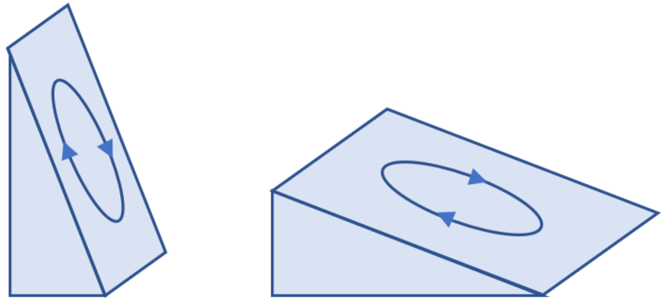


wavelength (km)

- A growth rate peak at ~500 km scale
- Lower f, faster growth

Challenge: the coexistence of waves and vortices





- Standing gravity waves trigger TC genesis at $f = 2.5 \times 10^{-5}\ \mathrm{s}^{-1}$ (~10°N)
- **How to make the vortices stand out?**

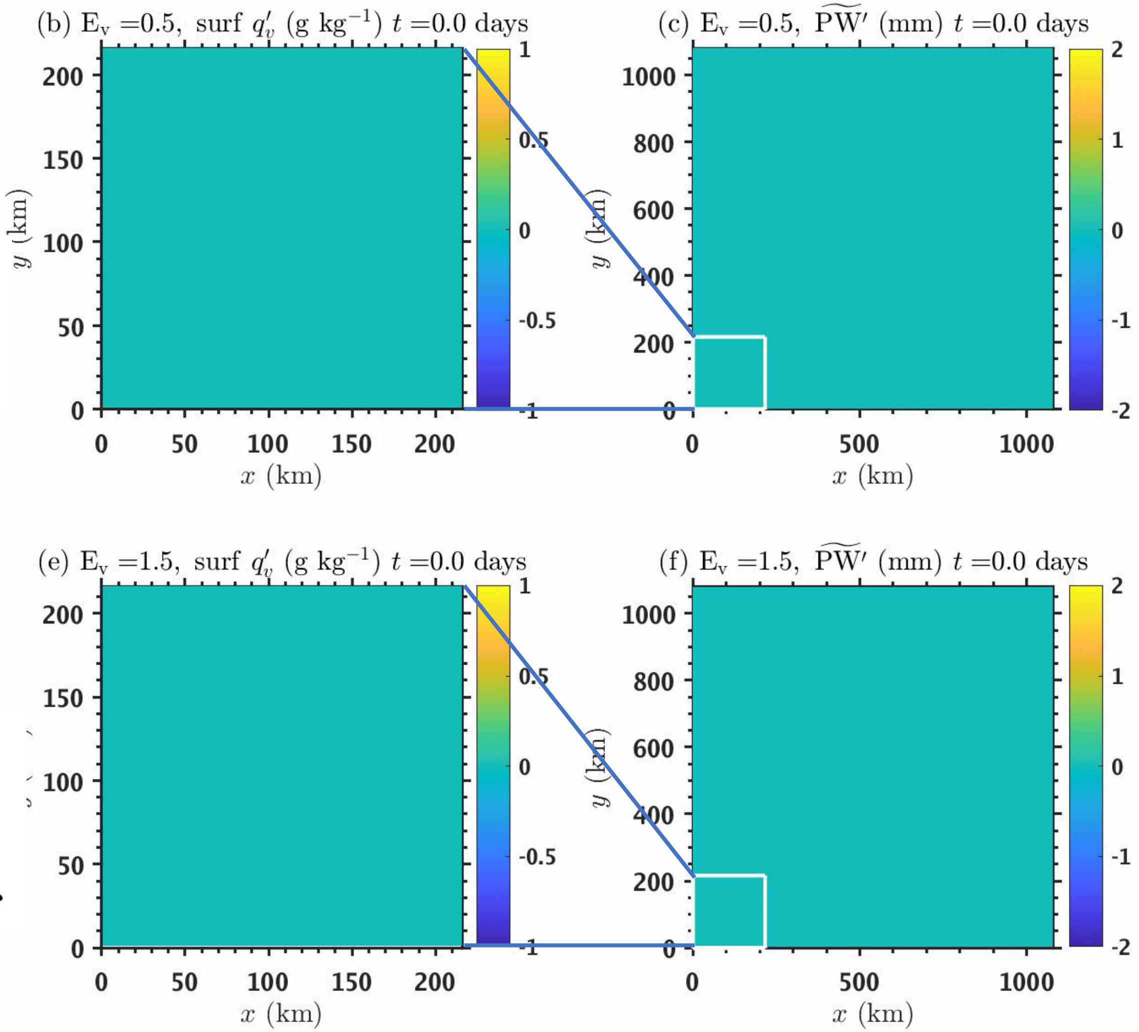
  i) Suppress the wave by increasing f: lift the wave's cutoff frequency

  ii) Amplify the horizontal anomaly of longwave radiative heating

Cold pools: change sub-cloud evaporation rate

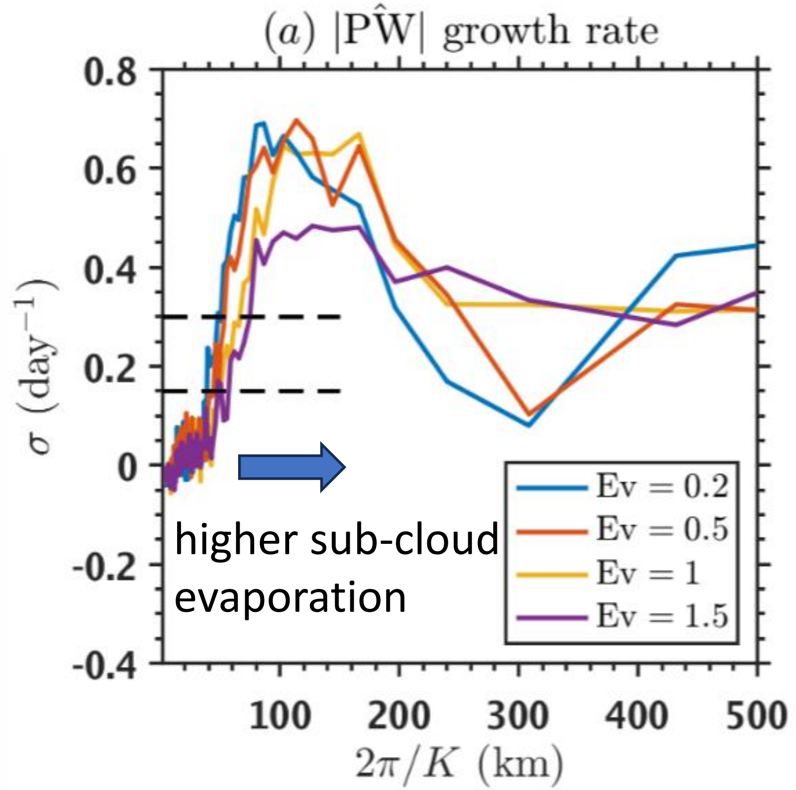
Surface vapor mixing ratio

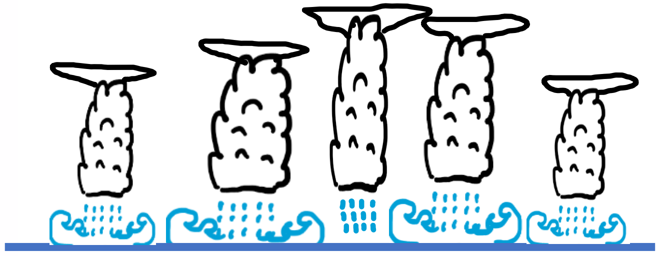
Column precipitable water



Weak
Rain evap

Strong
Rain evap





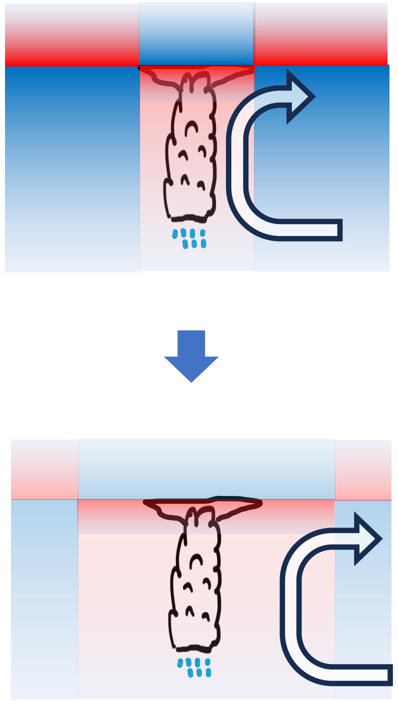
Physics: a wavepacket diffusion process

Anvil clouds

Novel experimental technique:

generate “ghost” anvil clouds by smoothing the longwave heating

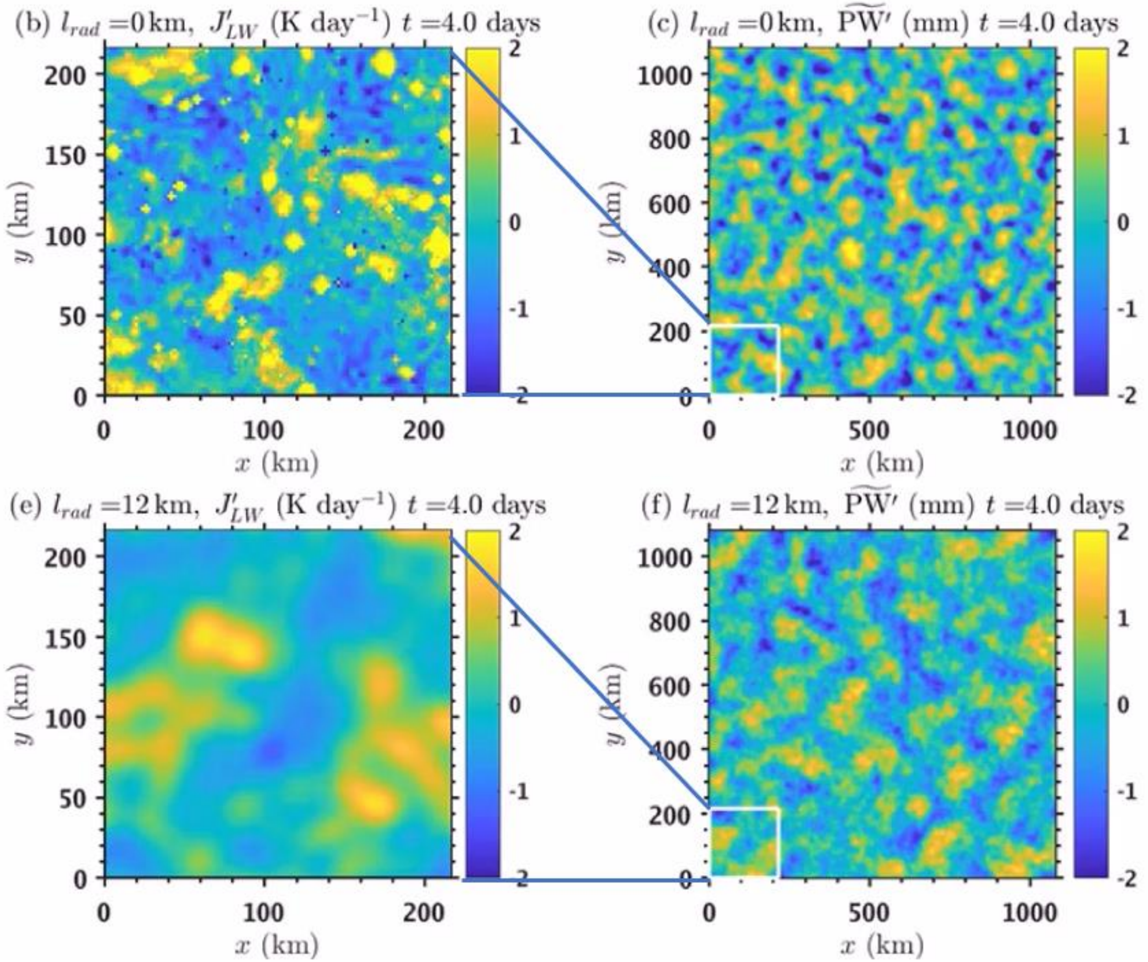
Nonlocal “greenhouse”

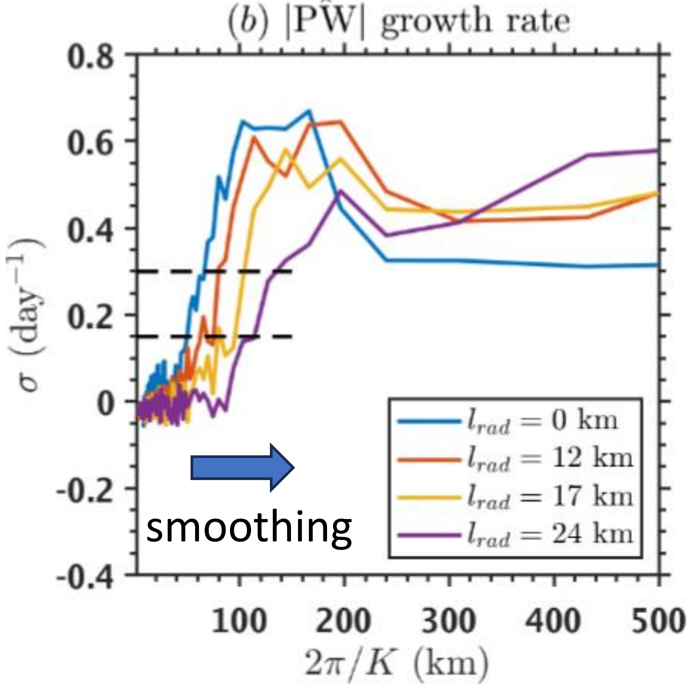


12 km Gaussian filter

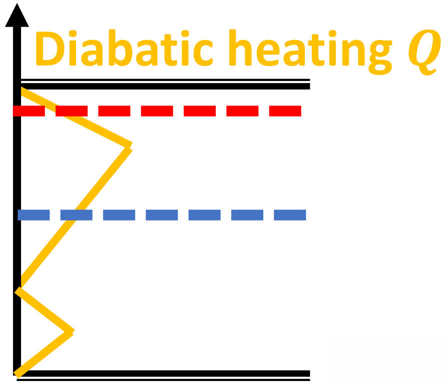
z=5.25 km Longwave heating

Column precipitable water

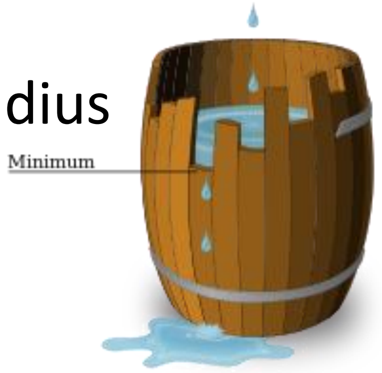




Why does the thin outflow control the vortex size?



- The upper-level eddies are limited to ∼100 km → Rossby radius
- The outflow and inflow couplet is an entity
- A top-down control of the vortex size



Midlevel vorticity

Upper-level vorticity