12.307 Guest Lecture

Tropical Cyclones

Martin Velez-Pardo

02/23/2023

Recap: Balance of forces and Rossby number

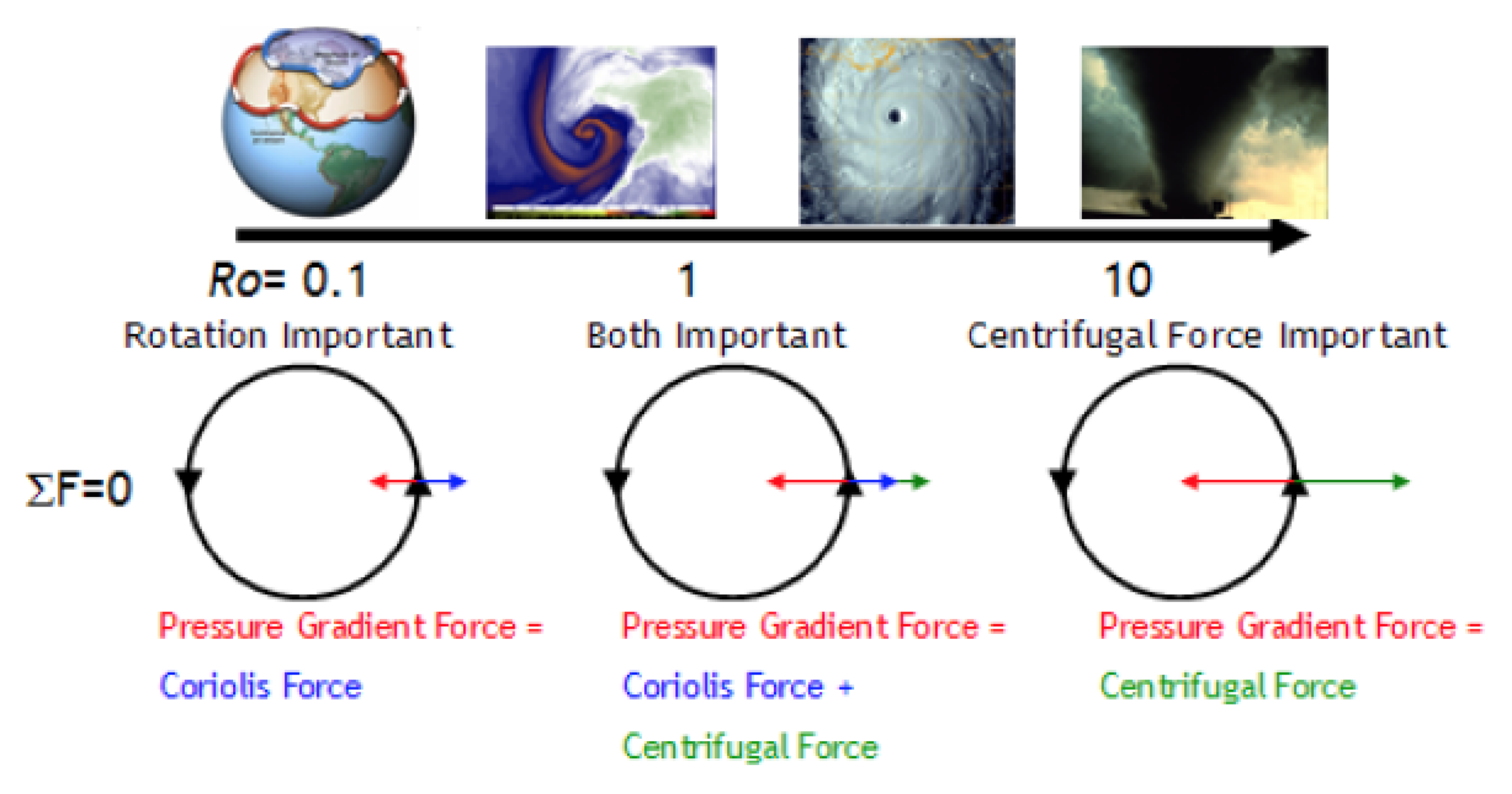
Gradient wind balance

$$\frac{v_\theta^2}{r} = g\,\frac{\partial h}{\partial r} - 2\Omega v_\theta$$

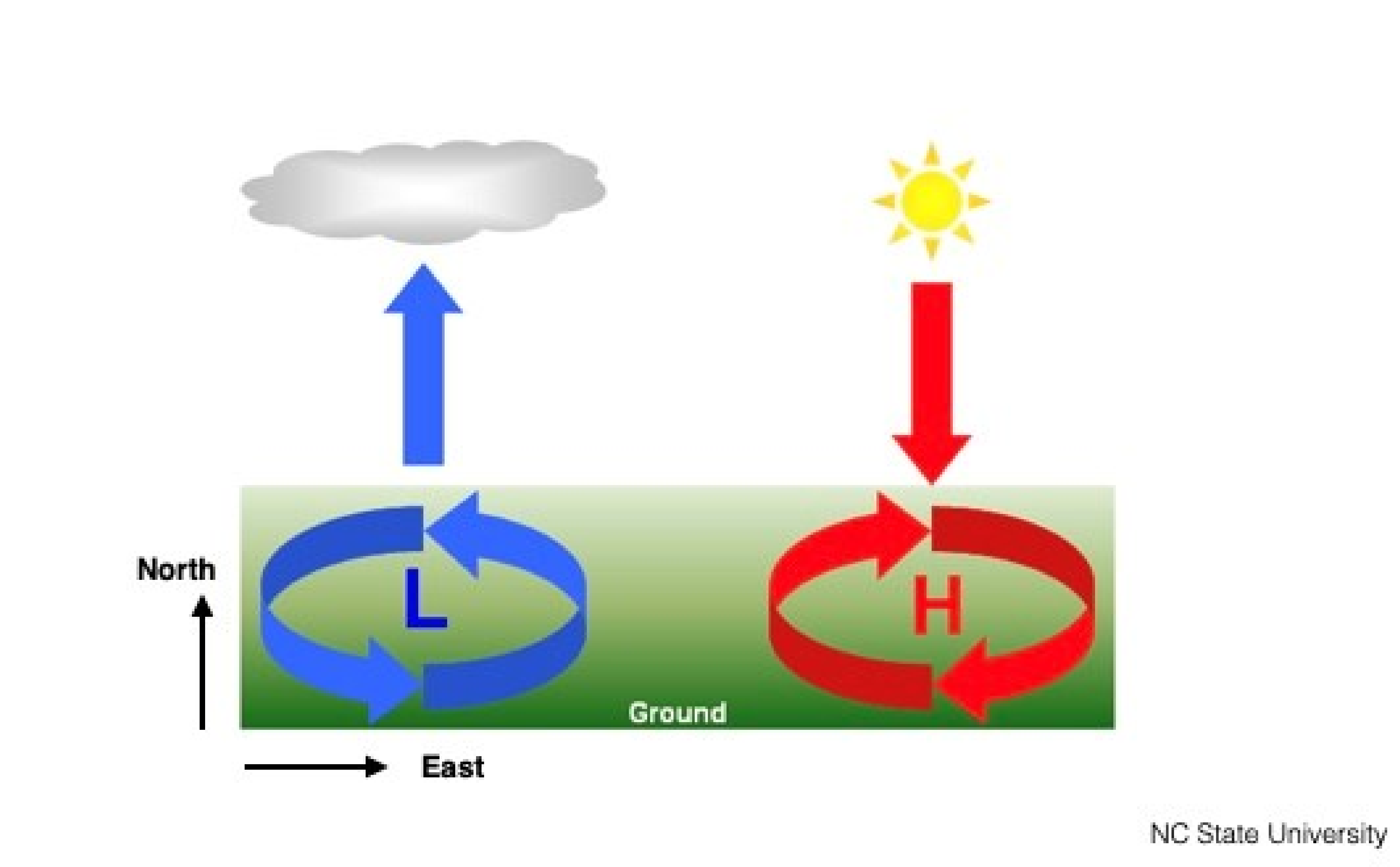
Rossby number

$$R_o = \frac{v_\theta^2/r}{2\Omega v_\theta} = \frac{v_\theta}{2\Omega r} \quad \left(= 2 \cdot \frac{T_{rot}}{T_{circ}}\right)$$

Recap: Balance of forces and Rossby number



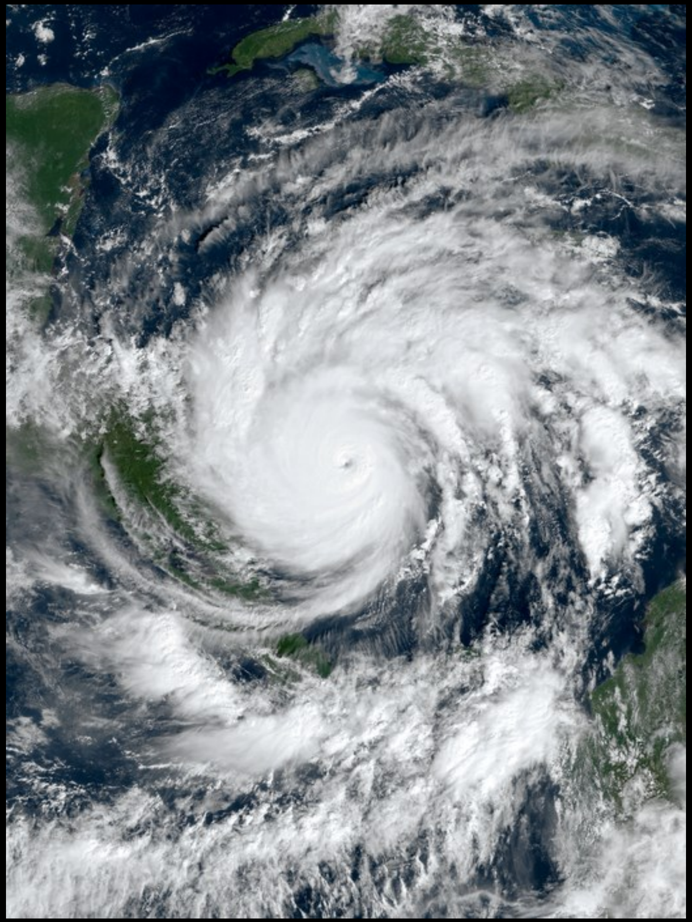
Recap: High and Low Pressure Systems



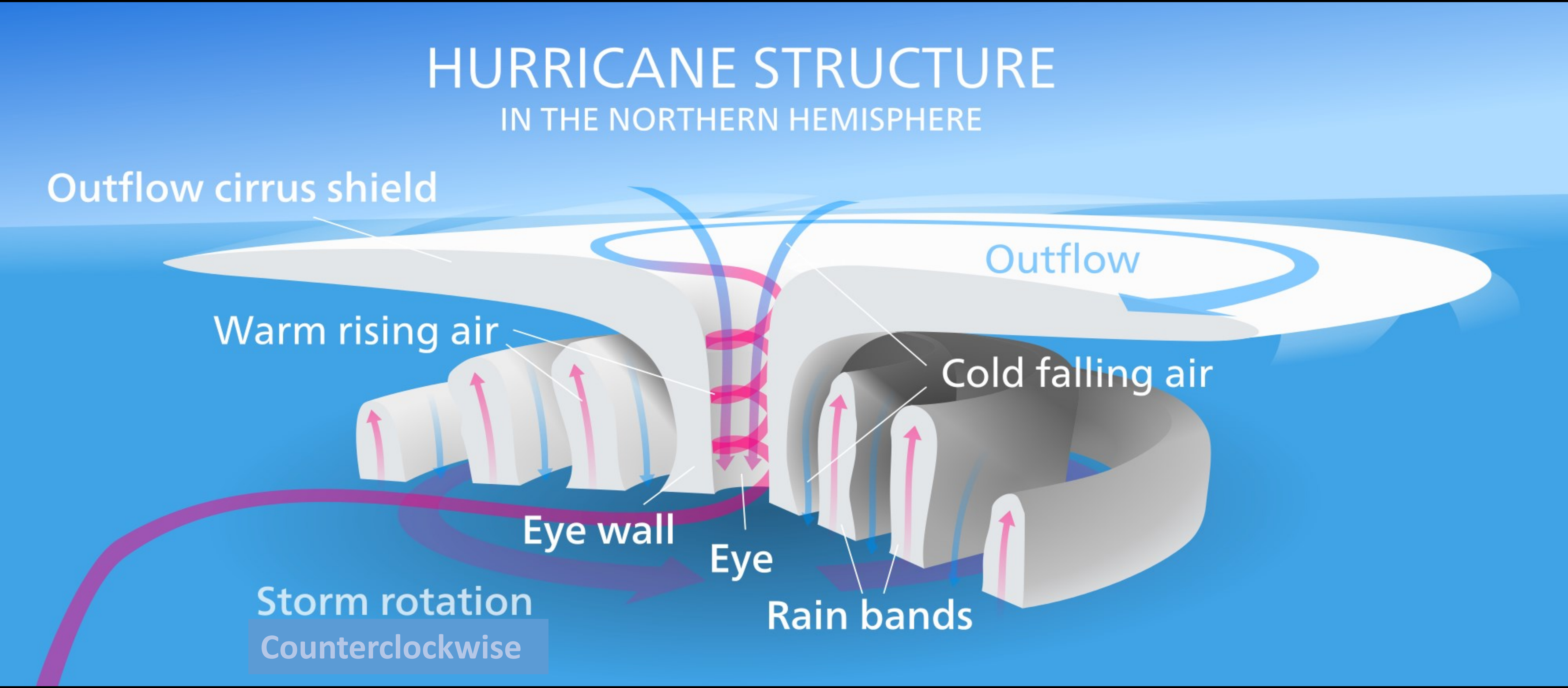
What is a Tropical Cyclone?

- Cyclonically rotating storm system.
- Gradient wind balance.*
- Low-pressure center.
- Warm core of ascending air (convection).
- Very strong winds near the surface.
- Heavy rain (+ storm surges).
- A.k.a. Hurricanes or Typhoons

*Covering the range from geostrophic to cyclostrophic, depending on the region of the flow.



Hurricane Iota (2020)
Photo credit: NOAA


HURRICANE STRUCTURE
IN THE NORTHERN HEMISPHERE
Outflow cirrus shield
Outflow
Warm rising air
Cold falling air
Eye wall
Eye
Storm rotation
Counterclockwise
Rain bands

In the eye of hurricane Katrina (2005)

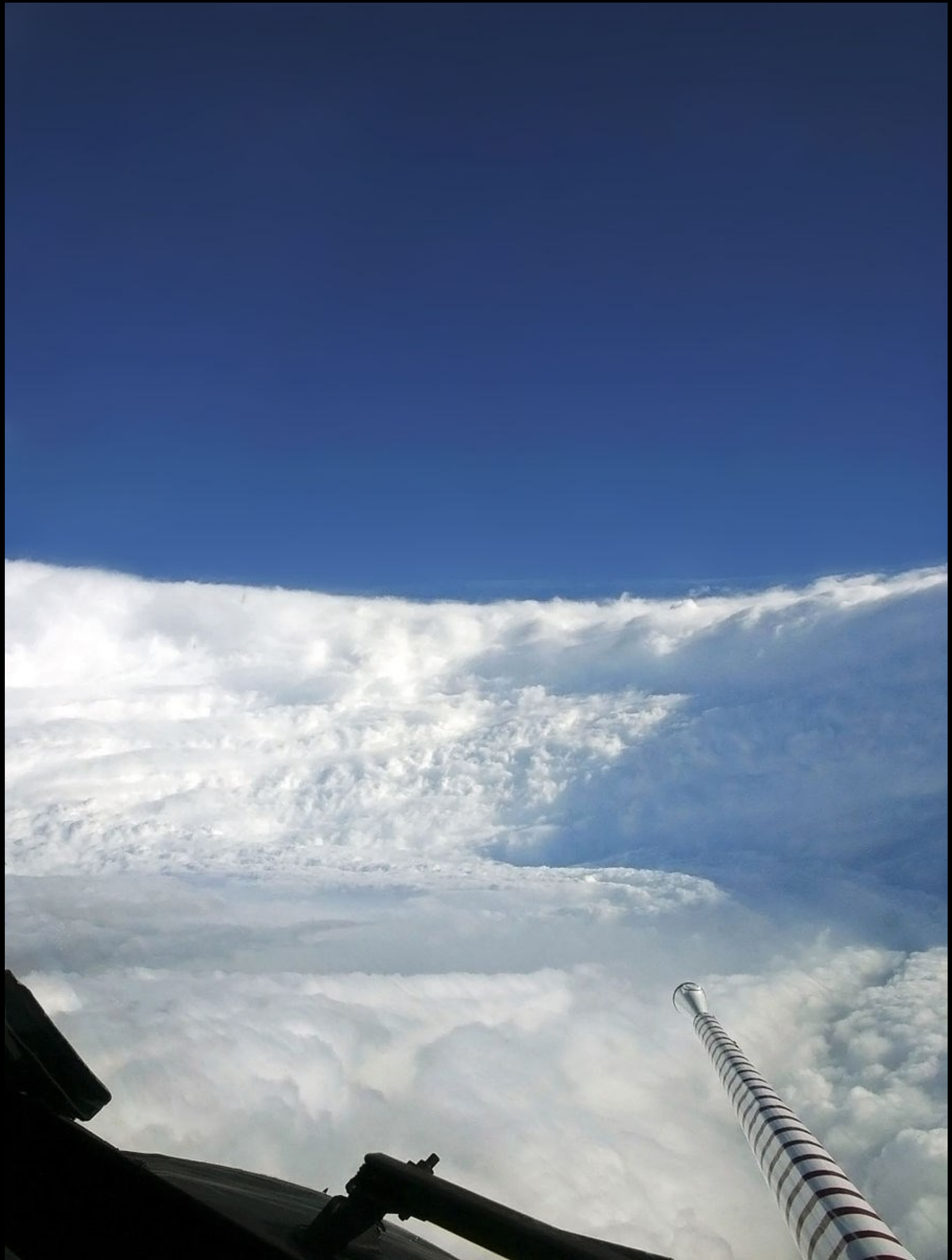
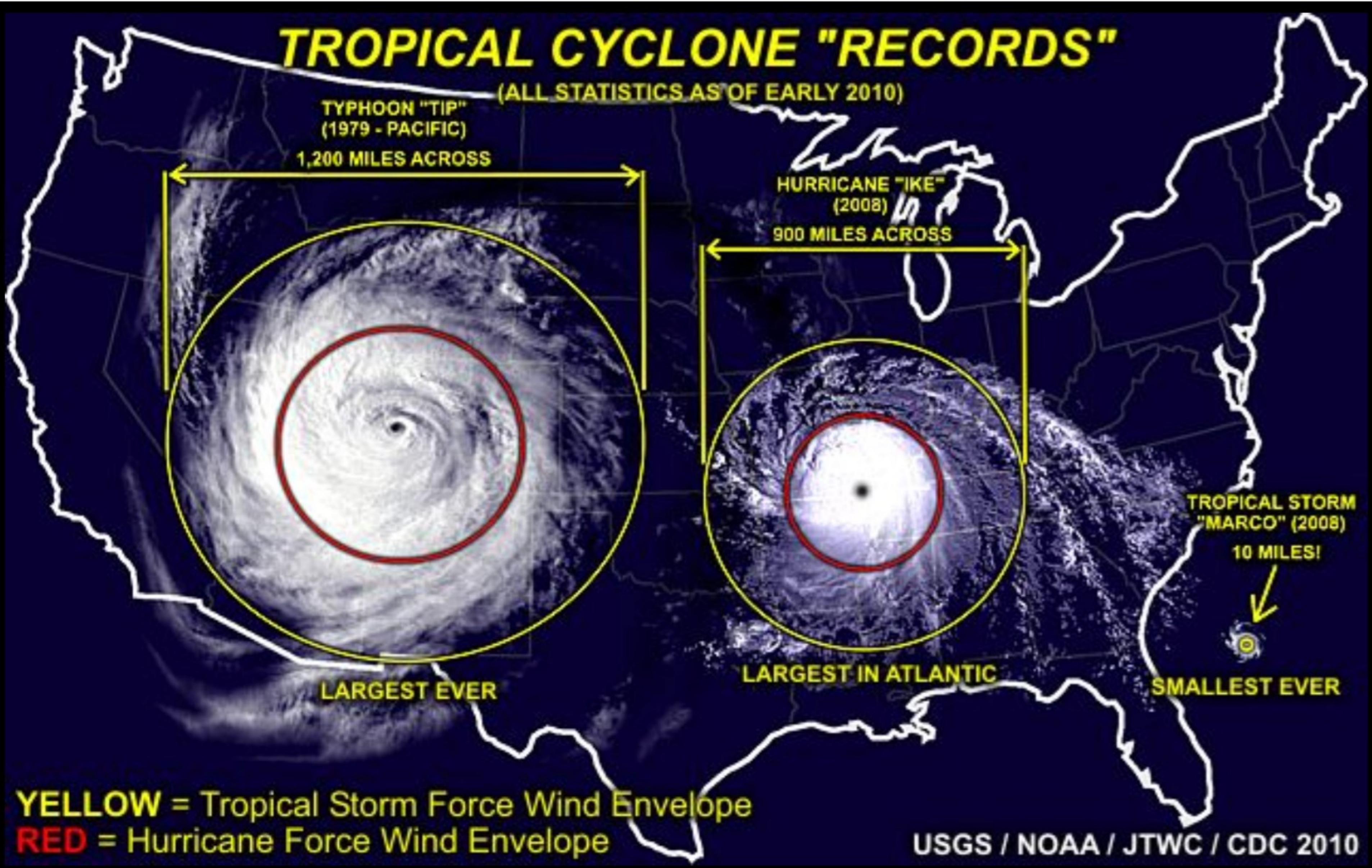
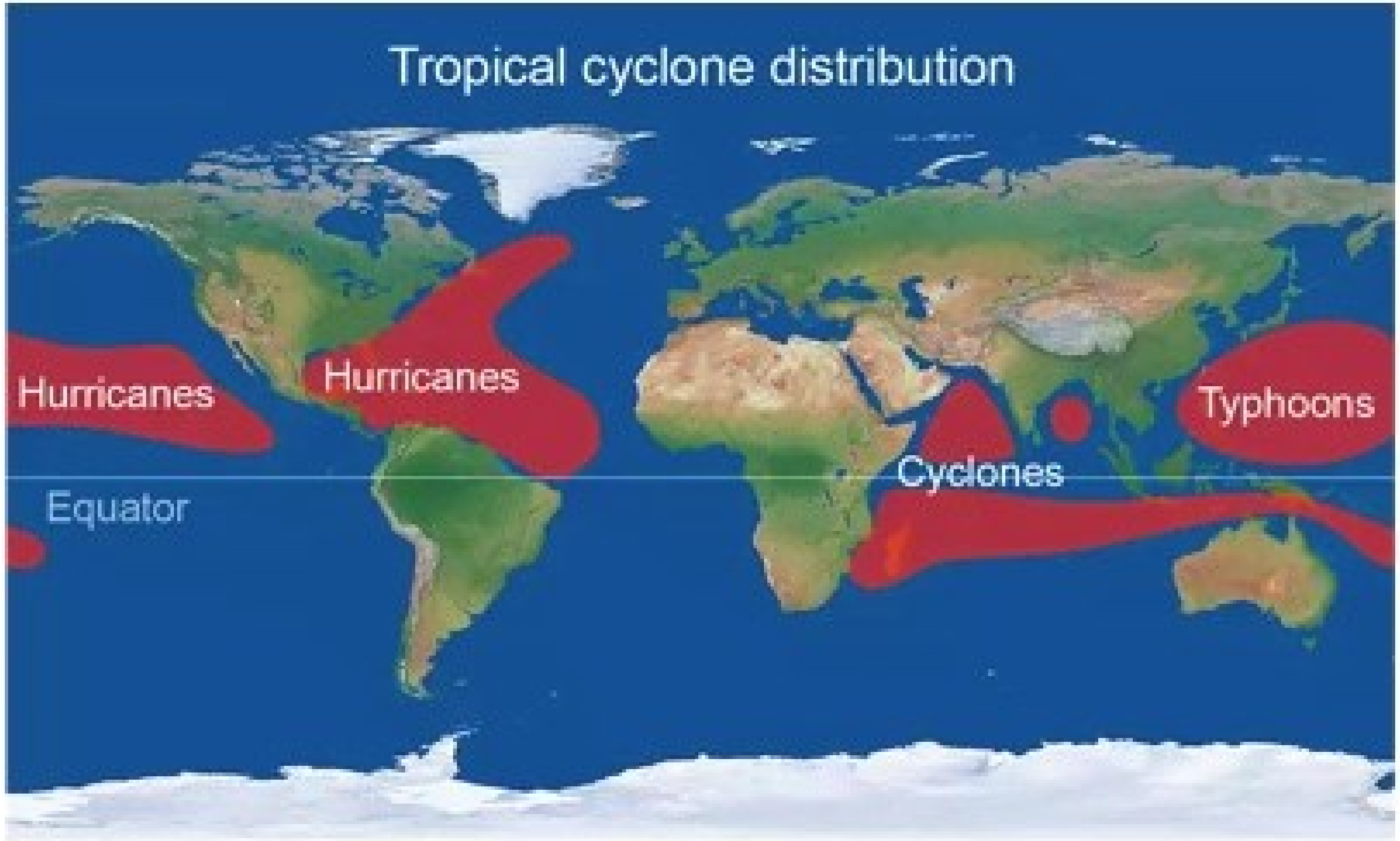


Image credit: NOAA



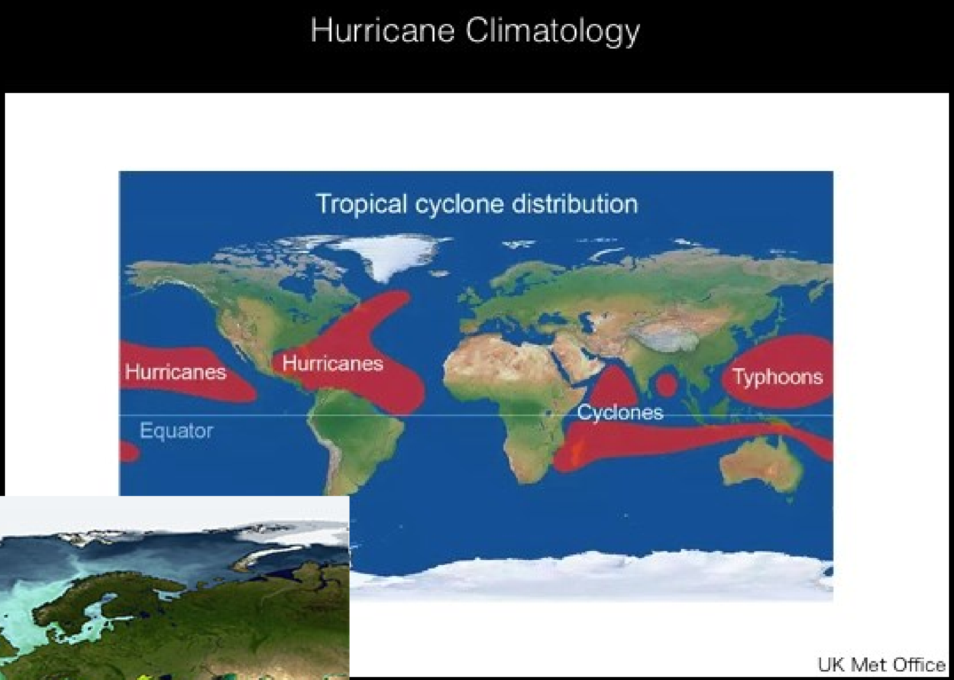
Note: Ike's record was broken by Hurricane Sandy of 2012

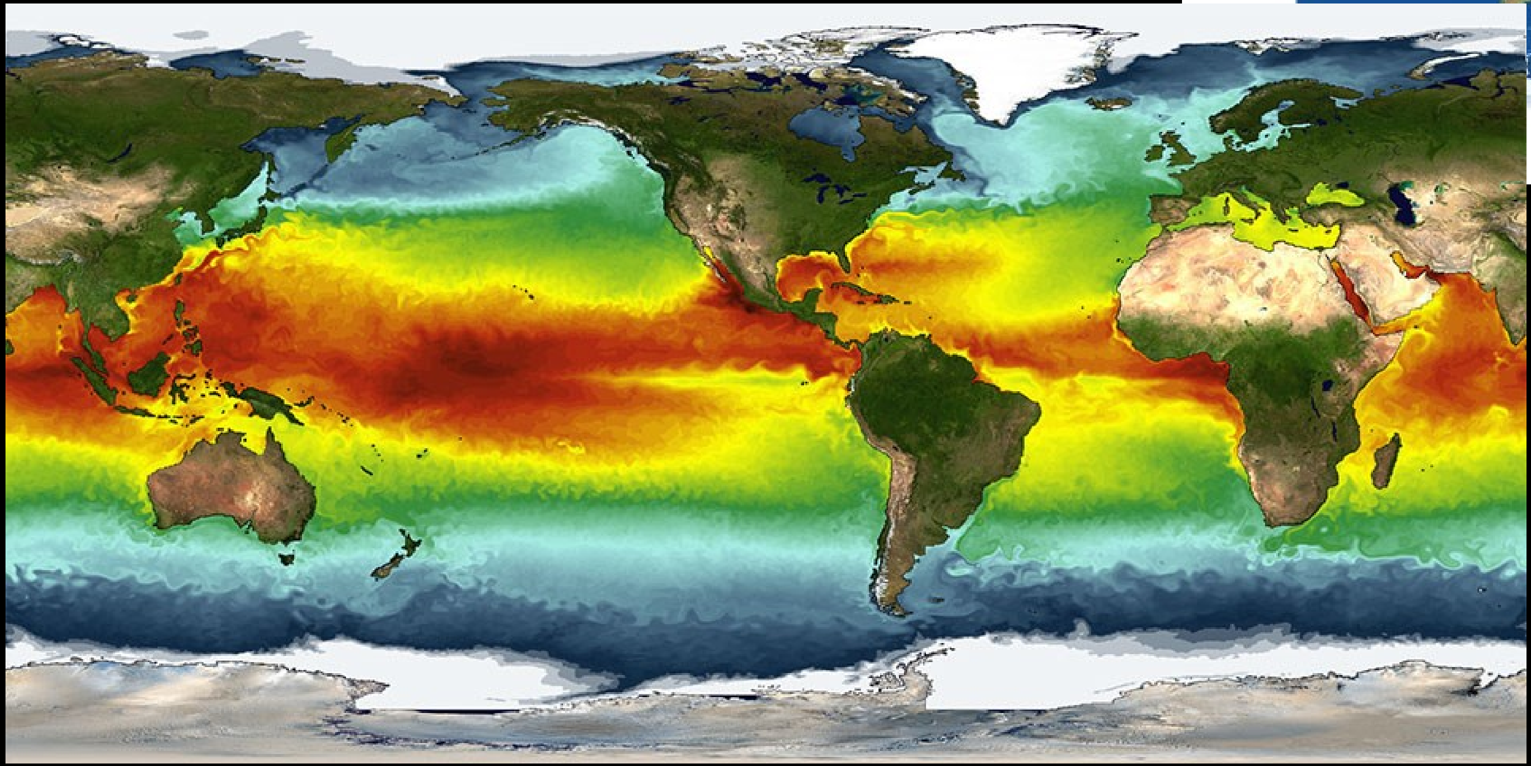
Hurricane Climatology



UK Met Office

Where do Tropical Cyclones form?
High sea-surface temperature





Credit: NOAA-GFDL

Where do Tropical Cyclones form? Earth's Rotation (Coriolis Parameter)

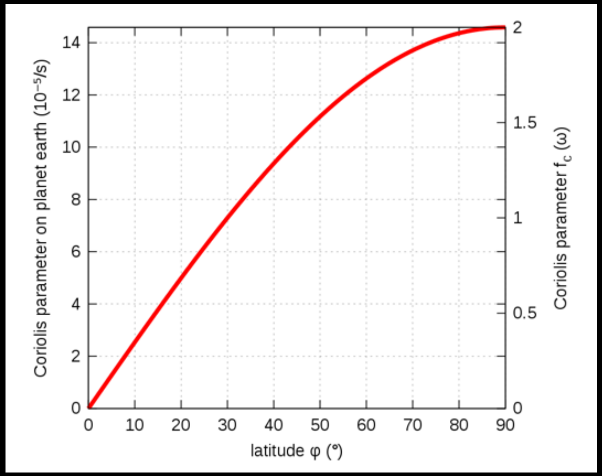
Gradient wind balance

$$\frac{v_\theta^2}{r} = g\frac{\partial h}{\partial r} - \boxed{2\Omega v_\theta}$$

For a sphere, a better approximation is:

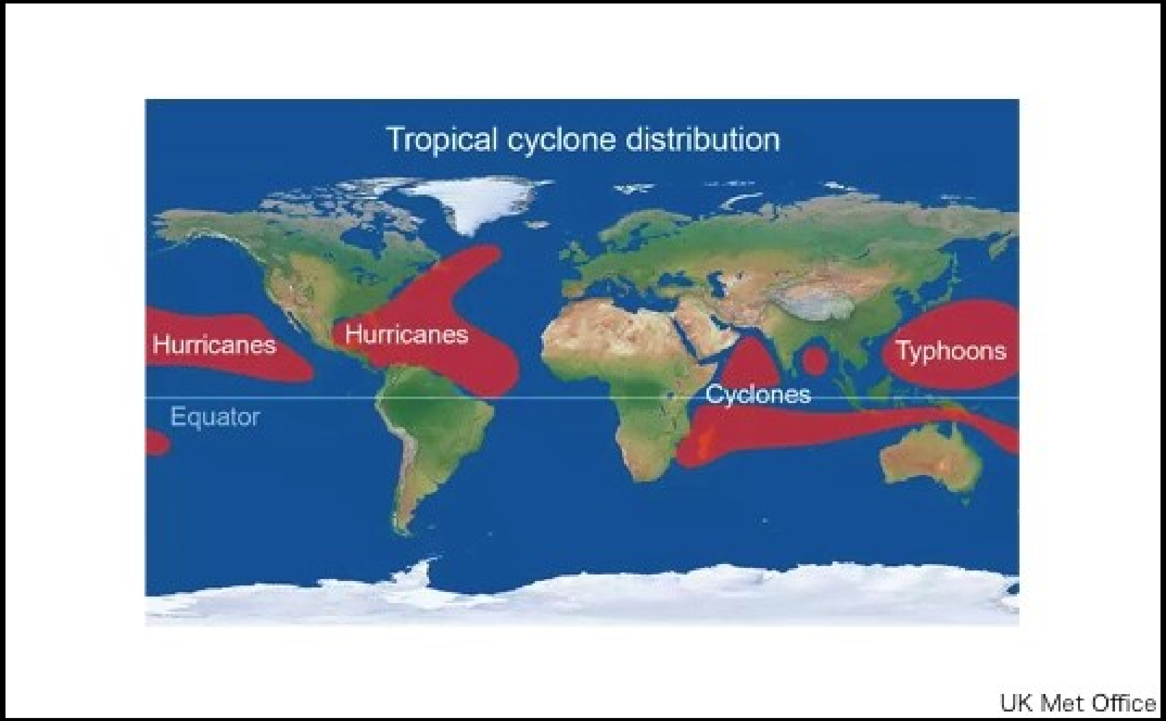
$$\boxed{2\Omega \sin(lat) v_\theta}$$

(This is still a simplification of what happens on Earth)



Credit: Wikimedia Commons

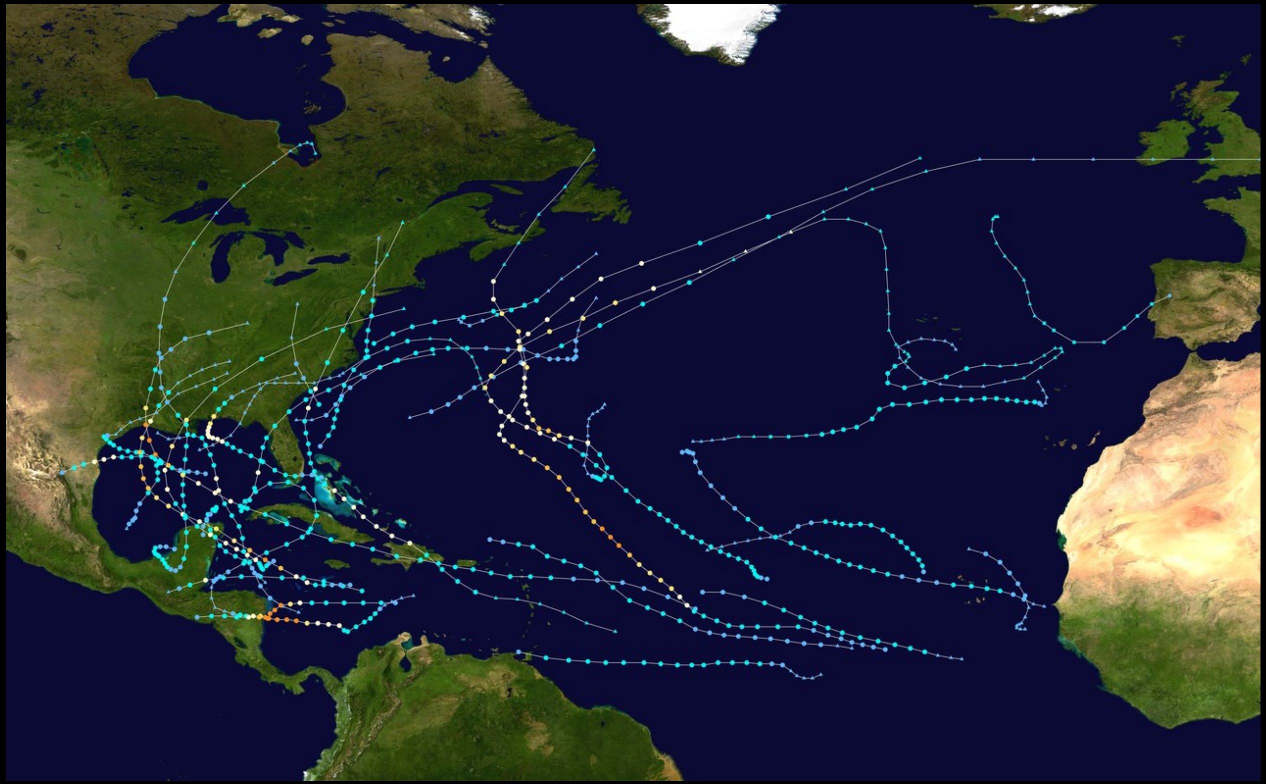
Hurricane Climatology



What sets the track of a Tropical cyclone?

Tropical storm Henri:

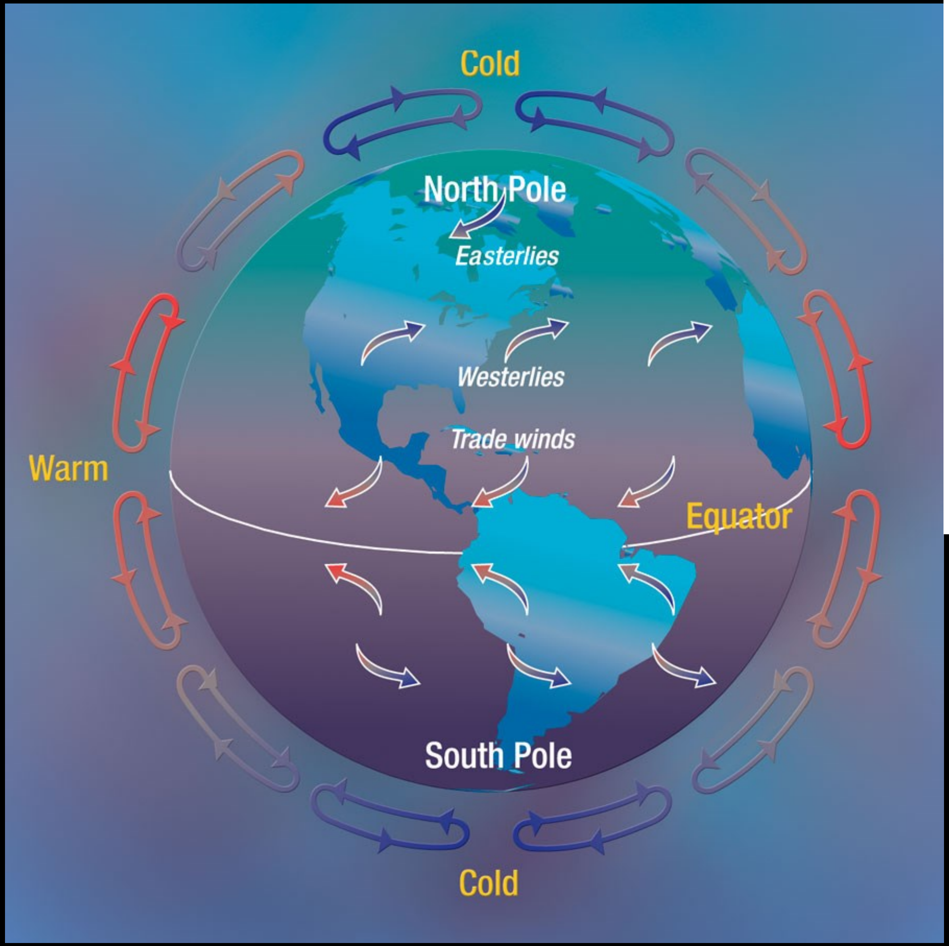
https://www.nhc.noaa.gov/archive/2021/HENRI_graphics.php?product=5day_cone_no_line

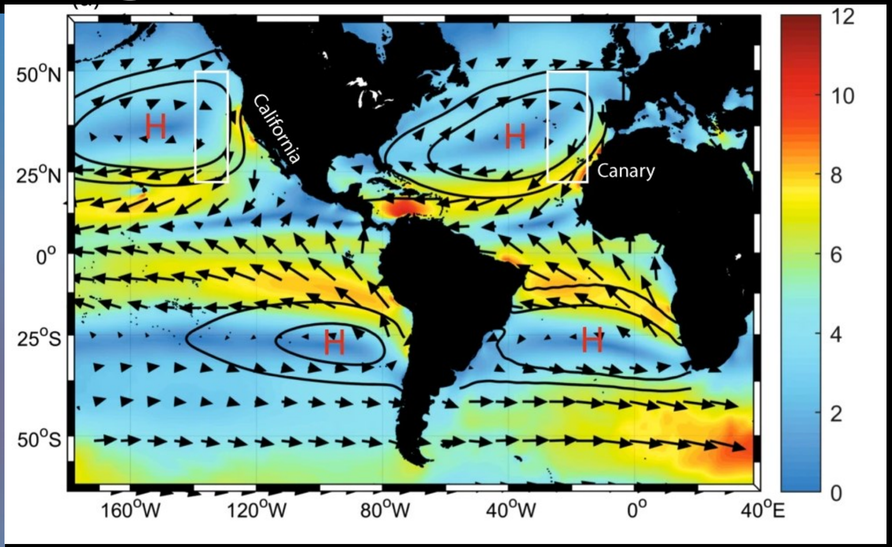


2020 Atlantic Hurricane season
Credit: Master0Garfield/WikiProject/NHC

What sets the track of a Tropical cyclone? Steering (+other things)

TCs are transported by the background atmospheric flow. This is called "steering".





Credit: Aguirre et al., Nature, 2019.

Credit: UCAR. Warning: Just a cartoon of the annually-averaged circulation

What is needed to form a tropical cyclone?

Necessary conditions for tropical cyclone formation (on Earth):

- Warm ocean surface (T above $\sim 26.5°C$). (Latent and sensible heat fluxes from the surface are the energy sources of TCs!)
- Large-scale convective organization.
- Rotation (latitudes of at least $5°$).
- Humidity in the mid-troposphere.
- Little or no wind shear.
- Often a pre-existing disturbance (low pressure system/wave).

However, even if we include all of this, a tropical cyclone may not form.
Tropical cyclone formation (tropical cyclogenesis) is mostly an open problem in atmospheric physics.
The relation between convection and genesis is part of the puzzle.

Takeaways

- Tropical cyclones are affected at different scales by the Coriolis and centrifugal accelerations, which act to balance the pressure gradient force. Most of the region of high winds is close to gradient wind balance.
- Characterized by low pressure at the center, a core of ascending warm air, strong winds at and near the surface that spiral towards the core, and a lot(!) of rain.
- Their tracks are set mainly by the background winds (steering), but are modulated by their interaction with the surrounding environment (beta drift).
- On Earth, they are mainly powered by latent heat fluxes from the surface (water evaporating at the surface and condensing as it ascends), with some contribution from sensible heating (temperature difference between the ocean surface and the air above).
- Their formation requires high sea-surface temperature, rotation, midlevel humidity, and low wind shear. A better understanding of formation is still an open problem.

Questions?

Necessary conditions for tropical cyclone formation (on Earth):

- Warm ocean surface (T above ~$26.5°C$). (Latent and sensible heat fluxes from the surface are the energy sources of TCs!)
- Large-scale convective organization.
- Rotation (latitudes of at least 5°).
- Humidity in the mid-troposphere.
- Little or no wind shear.
- Often a pre-existing disturbance (low pressure system/wave).

Image credit: NASA

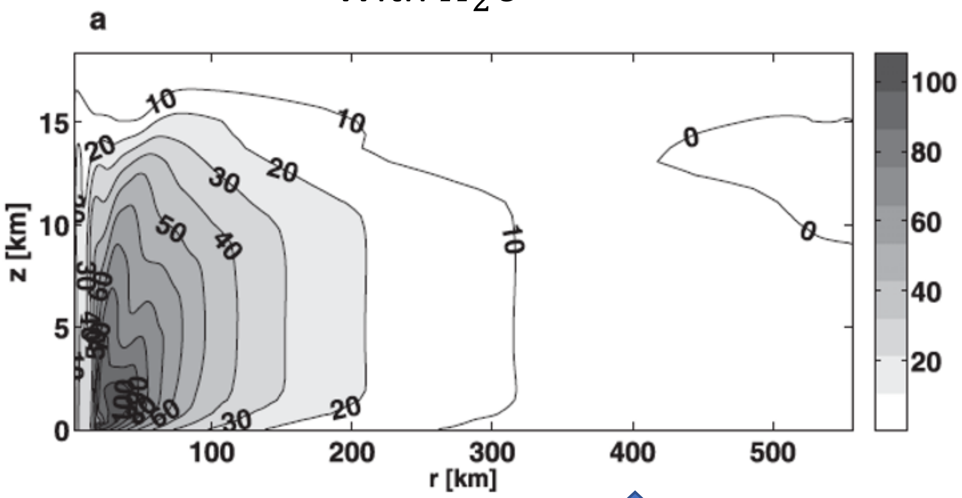
$- H_2O$?

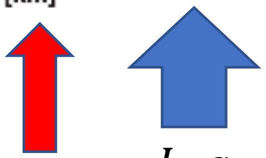
A bit about my work…(with Tim Cronin)

Tropical cyclones can form in the absence of moisture(!)

Mrowiec et al. (2011), inspired by Emanuel (1986)

With H_2O

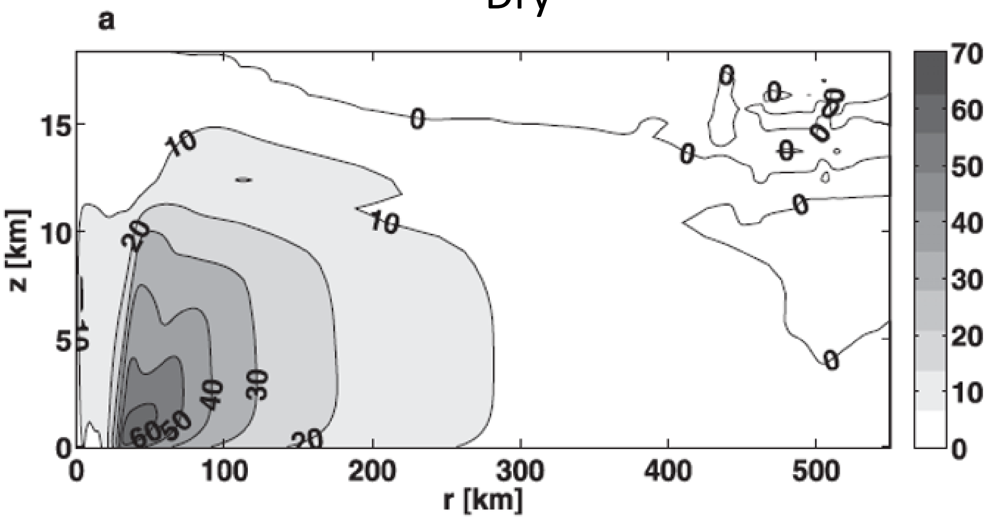


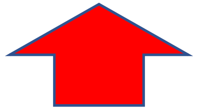


$$S_m \approx c_p \ln\theta + \frac{L_v q}{T}$$

Sensible and latent heat fluxes

Dry





$$S_d = c_p \ln\theta$$

Sensible heat flux only

Dry convection is easier to analyze than moist convection

Moist convection

$$\frac{D\vec{u}}{Dt} + 2\Omega \times \vec{u} = -\nabla\phi + (b_u H_u + b_s H_s)\hat{z}$$

$$\frac{Db_u}{Dt} + N_u^2 w = 0$$

$$\frac{Db_s}{Dt} + N_s^2 w = 0$$

$$\nabla \cdot \vec{u} = 0.$$

Dry convection

$$\frac{D\vec{u}}{Dt} + 2\Omega \times \vec{u} = -\nabla\phi + b\hat{z}$$

$$\frac{Db}{Dt} + N^2 w = 0$$

$$\nabla \cdot \vec{u} = 0.$$

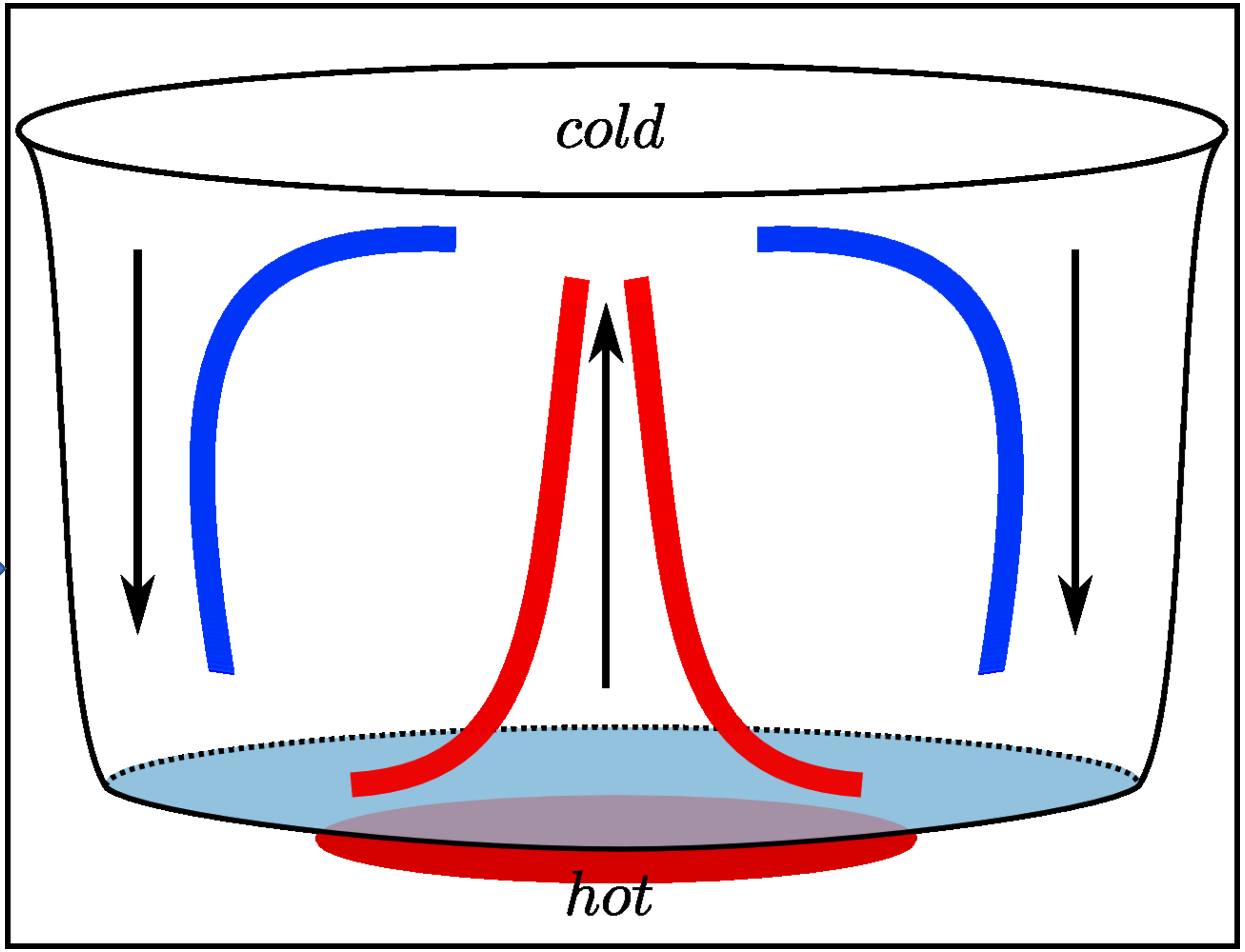
This is the Boussinesq system, which is a simplified form of the full equations we use for the atmosphere

We know a lot* about dry convection

*not nearly everything!

Henri Bénard & Lord Rayleigh, early 20th century

Rayleigh-Bénard model of convection



Credit: Max Planck Institute

Momentum, mass and energy conservation

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} + \boxed{\frac{1}{Ro_c} \vec{\Omega} \times \vec{u}} = -\vec{\nabla} p + \widehat{T'} \hat{e}_3 + \left(\frac{Pr^{\frac{2}{3}}}{Ra_F^{\frac{1}{3}}} \right) \vec{\nabla}^2 \vec{u}$$

$$\vec{\nabla} \cdot \vec{u} = 0$$

$$\frac{\partial \hat{T}'}{\partial \hat{t}} + \vec{u} \cdot \vec{\hat{\nabla}} \hat{T}' = \frac{1}{(Ra_F Pr)^{\frac{1}{3}}} \vec{\hat{\nabla}}^2 \hat{T}$$

- Ro_c is the convective Rossby number. Think of it as the ratio of the time of the earth's rotation to the time of convective overturning.

We solve the equations on a grid in a 3-D, doubly periodic domain

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \frac{\partial \vec{u}}{\partial (x,y,z)} + \boxed{\frac{1}{Ro_c} \vec{\Omega} \times \vec{u}} = -\vec{\nabla} p + \widehat{T}' \hat{e}_3 + \left(\frac{Pr^{\frac{2}{3}}}{Ra_F^{\frac{1}{3}}} \right) \vec{\nabla}^2 \vec{u}$$

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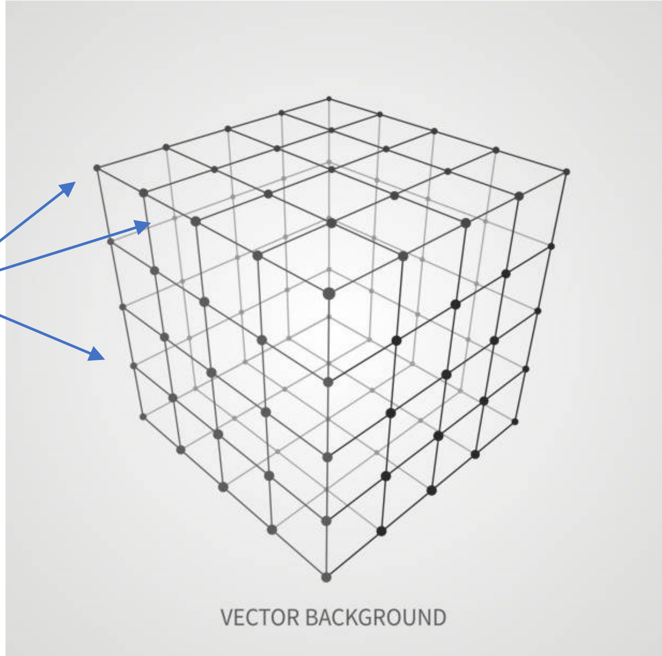
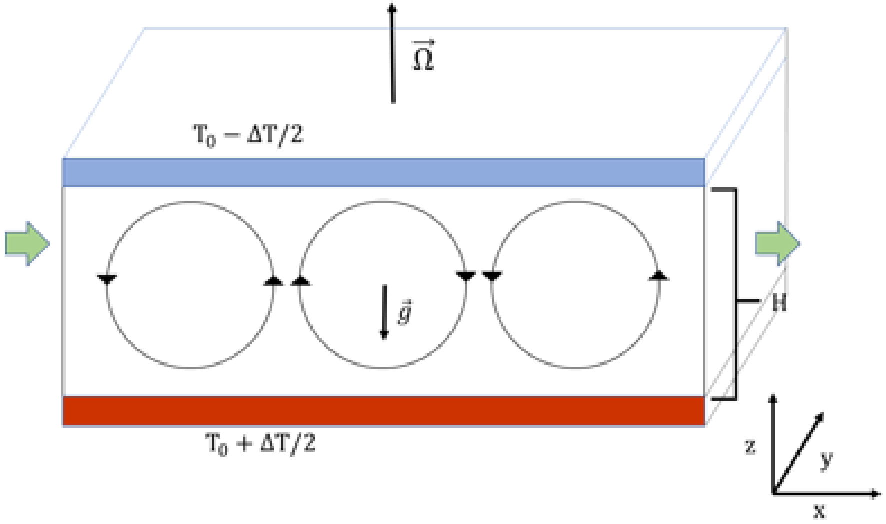
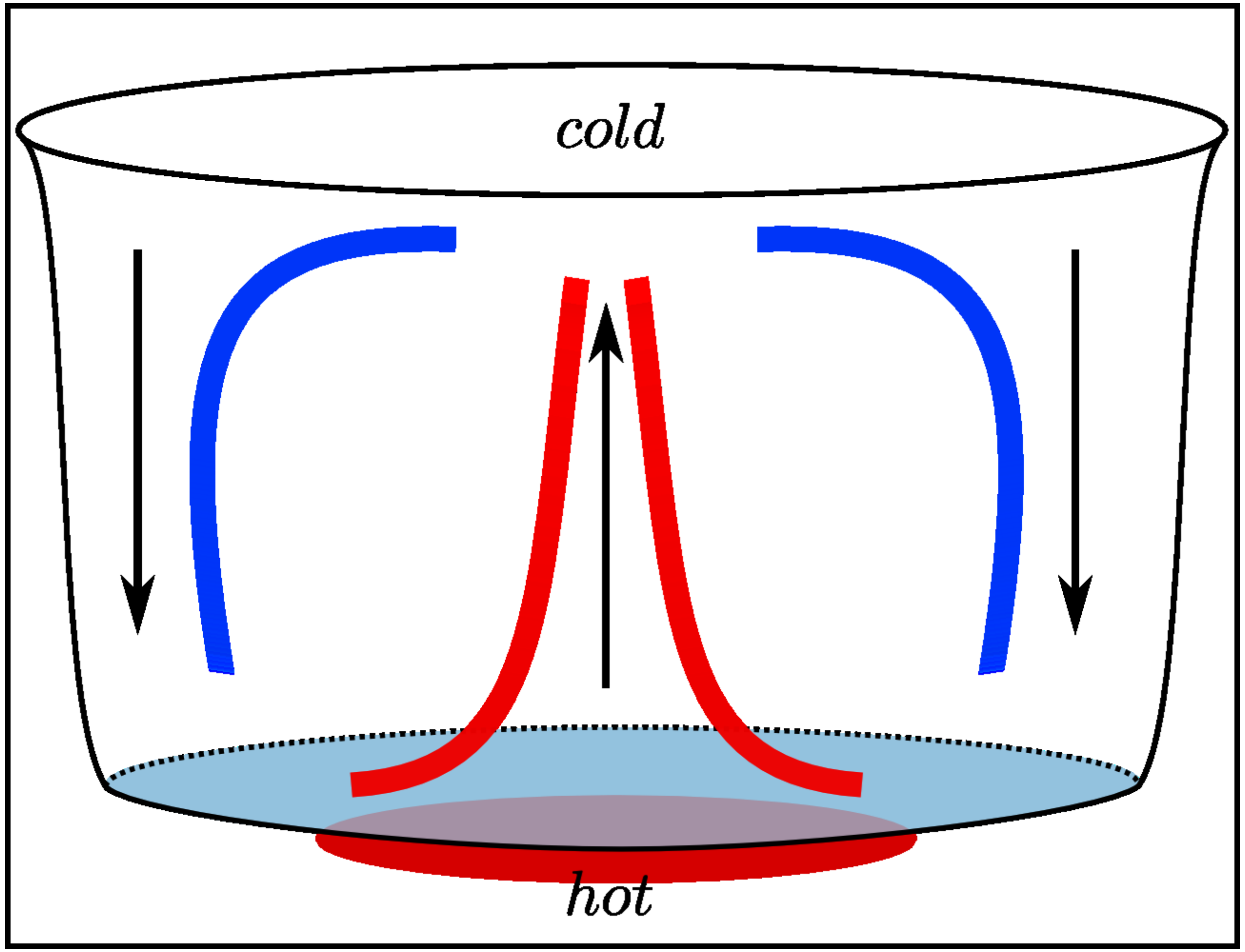
$$\frac{\partial \widehat{T}'}{\partial \hat{t}} + \vec{u} \cdot \vec{\nabla} \widehat{T}' = \frac{1}{(Ra_F Pr)^{\frac{1}{3}}} \vec{\nabla}^2 \widehat{T}$$





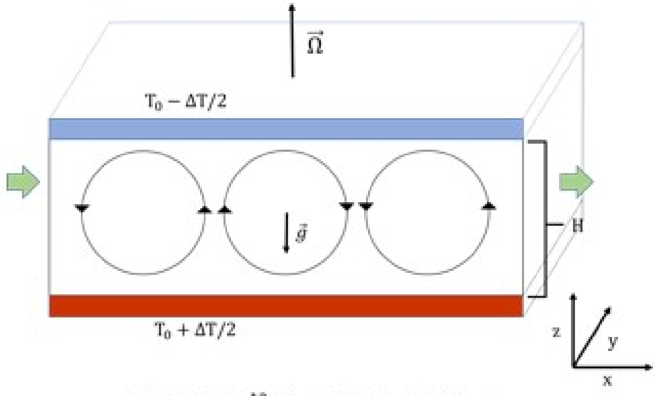
We use the pseudo-spectral numerical solver **Dedalus** (Burns et al., 2020) to solve the governing equations on a 3-D domain (doubly periodic in the horizontal. No-slip boundary conditions at top and bottom. 32 Tchebyshev basis functions in z, 512 Fourier basis functions in x and y). The resolution is such that we are running direct numerical simulations (no parameterizations).

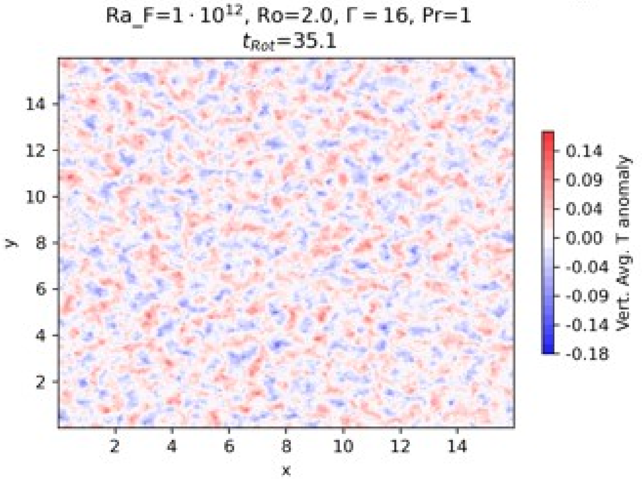
Dry Convection

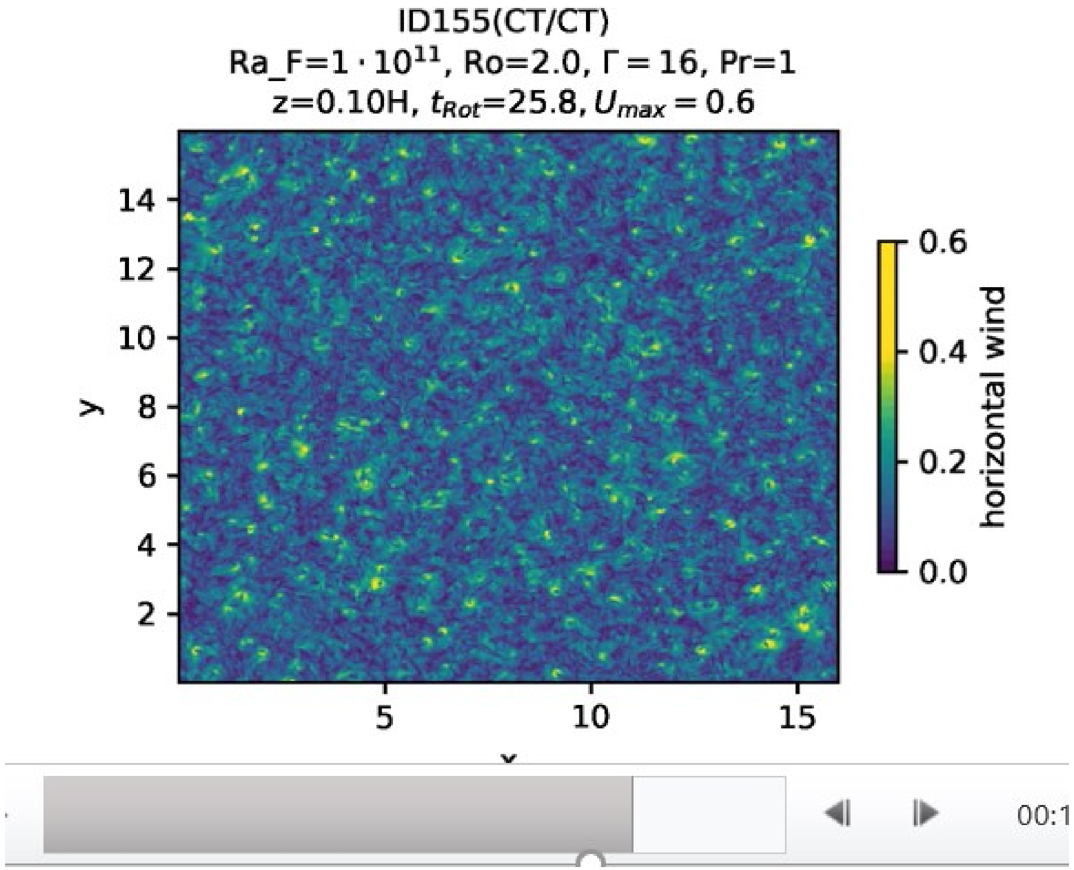


Credit: Max Planck Institute

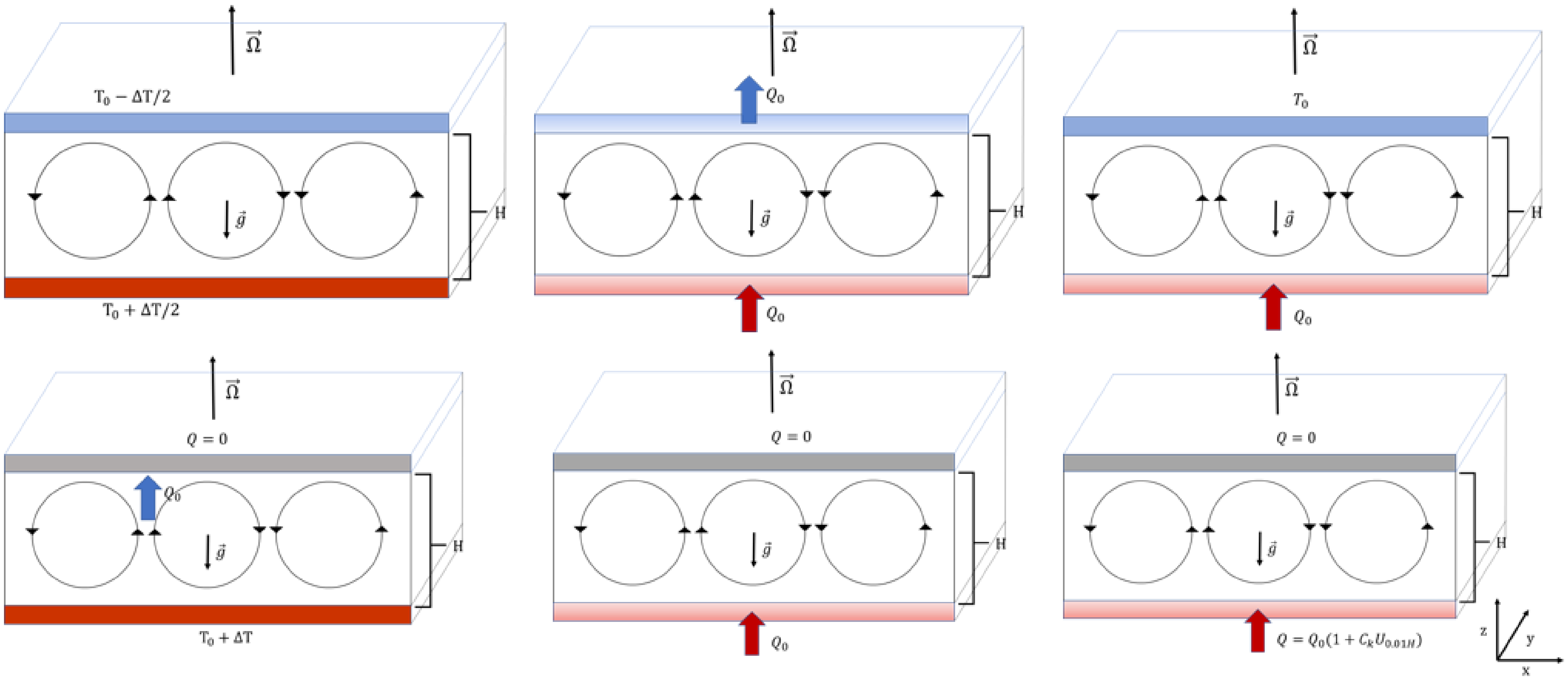
When the bottom temperature is constant - only small-scale organization; no TC-like vortices



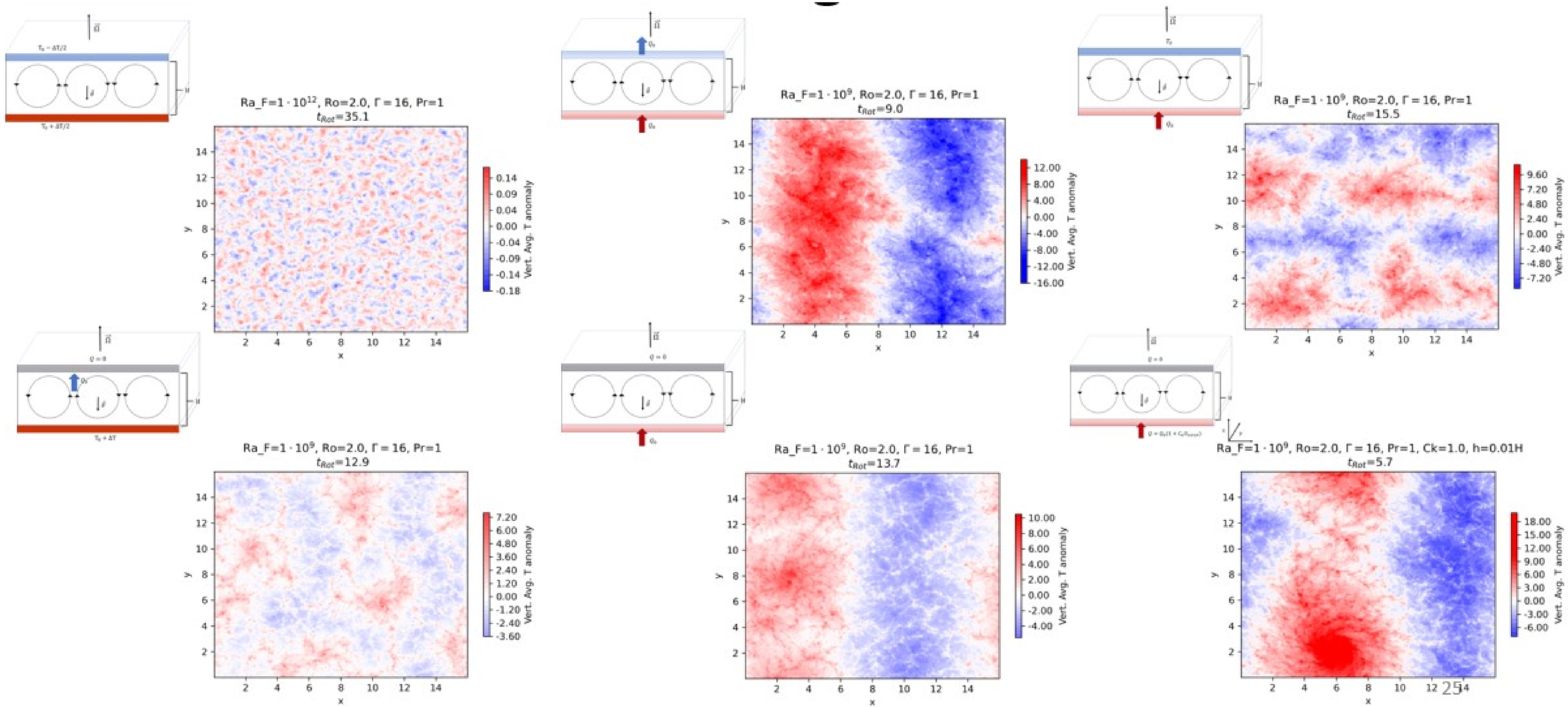




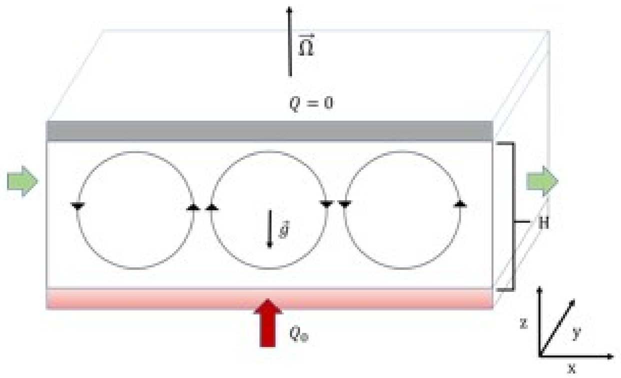
Setups—Thermal Boundary Conditions

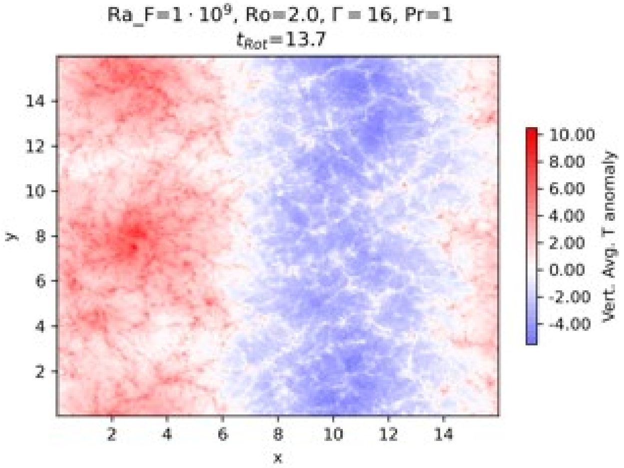


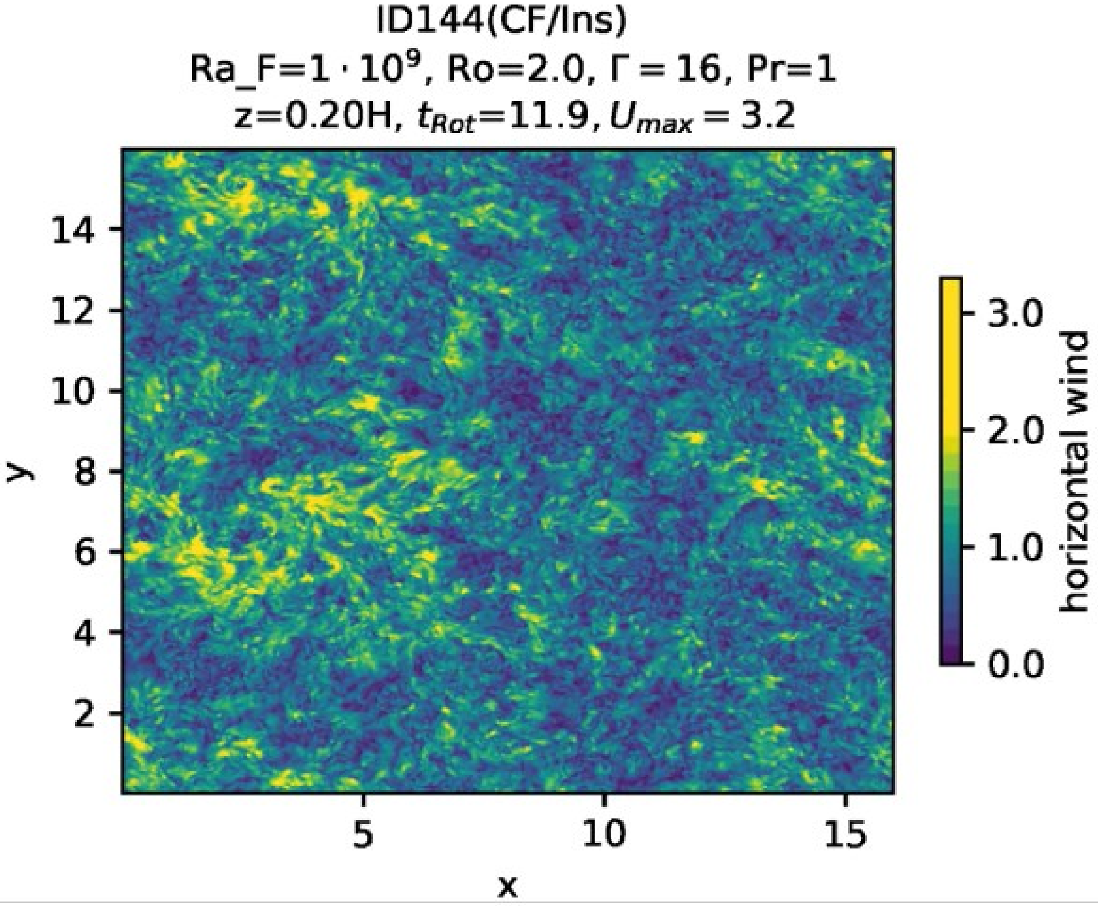
Different BCs—Different degrees of convective organization



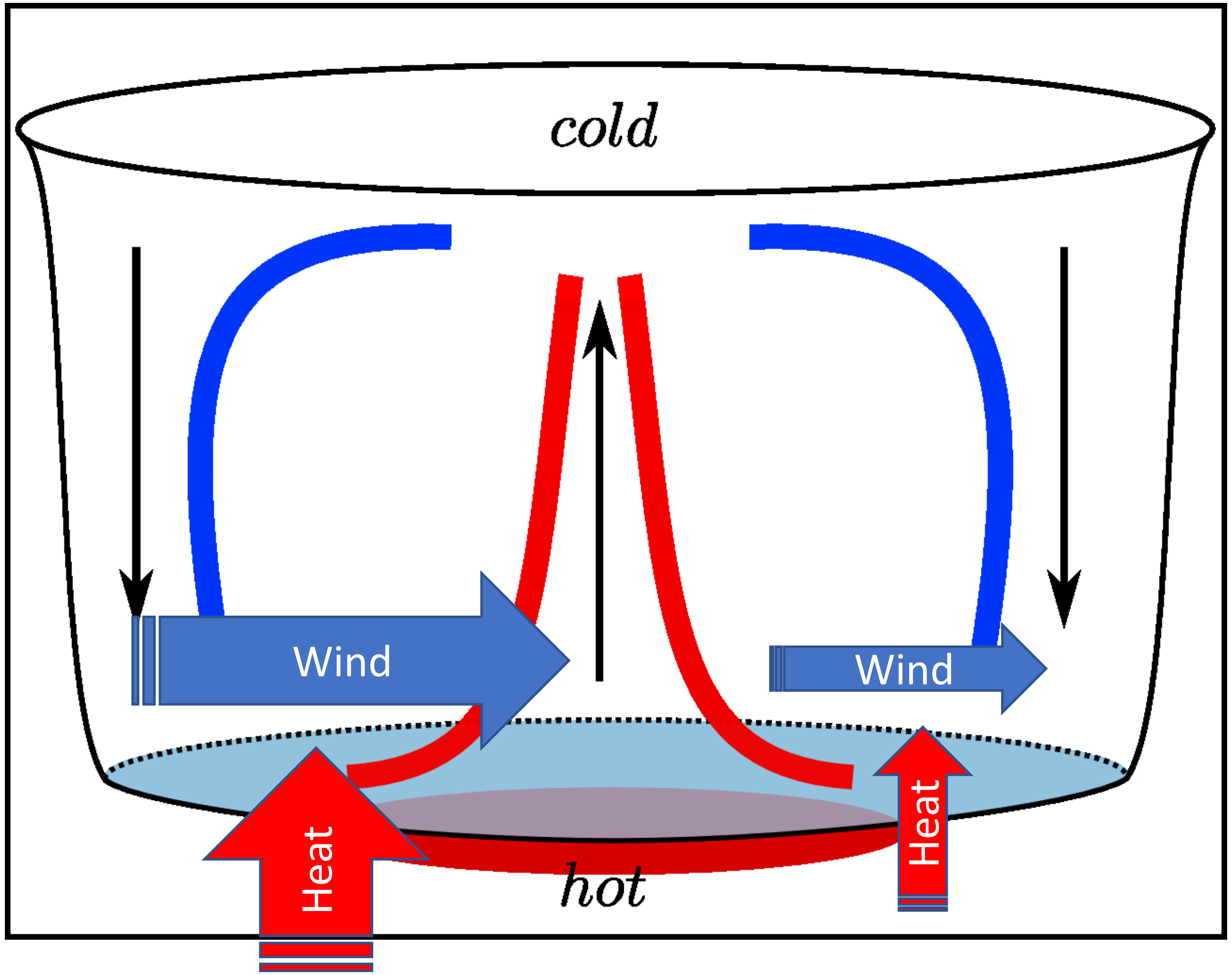
Constant heat flux at the bottom, insulating top– large-scale organization; TC-like vortices form





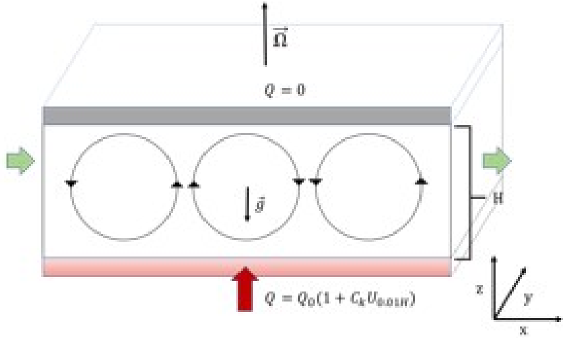


Dry Convection

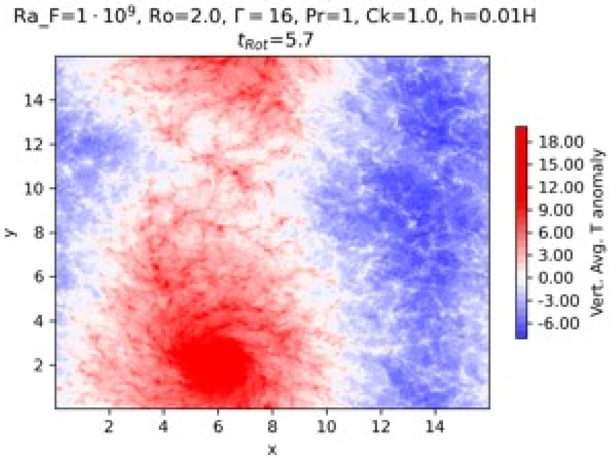


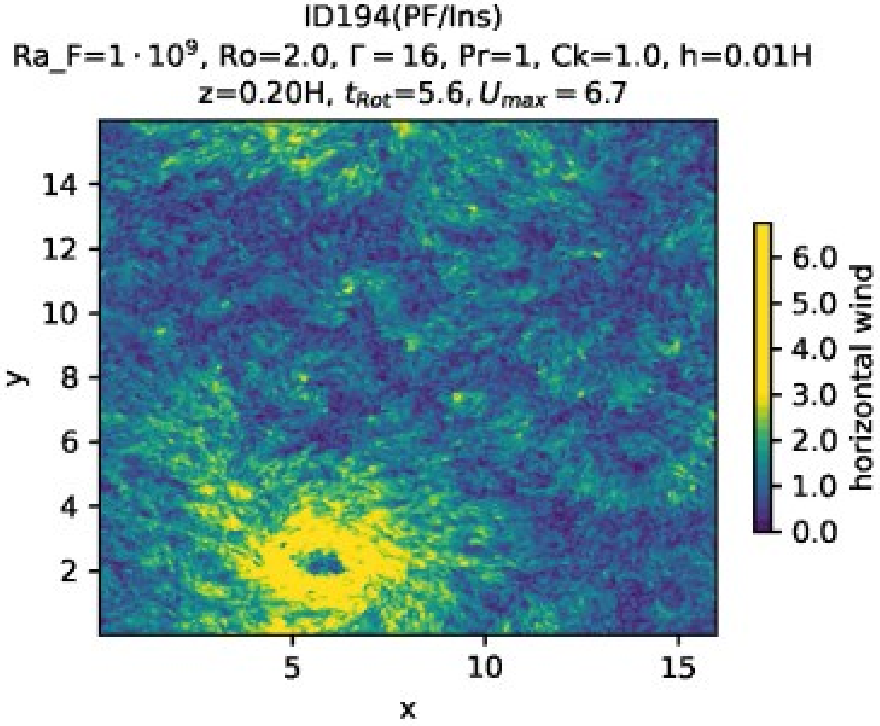
Credit: Max Planck Institute

When the bottom heating depends on the strength of the winds…

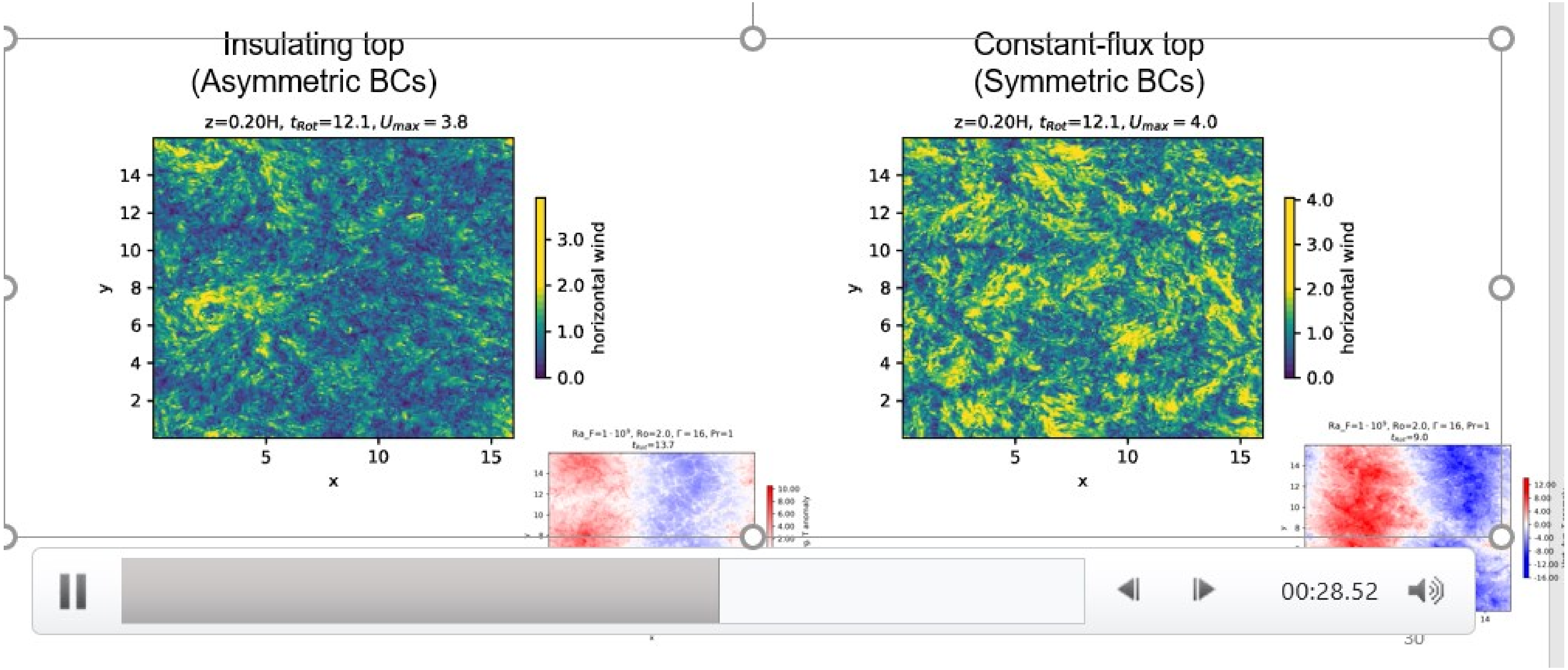


$$\frac{\partial T}{\partial z} = -(Ra_F Pr)^{\frac{1}{3}} \cdot (1 + C_k U_h)$$





Symmetric Thermal Boundary Conditions– TCs are Destroyed



Scan the QR code below for videos of simulated dry hurricanes!