Introduction to tropical general circulation and the global monsoons

Spencer A. Hill

The City College of New York

Workshop on Global Monsoons: Theory, Models, and Observations

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First: a little about the City College of New York (CCNY)

Founded in 1847 as **The Free Academy** of the City of New York, the *first free, public university in the U.S.*, as an experiment:

"whether the children of the people, the children of the whole people, can be educated; and whether an institution of the highest grade, can be successfully controlled by the popular will, not by the privileged few.""

First: a little about the City College of New York (CCNY)

For much of 20th century, affectionately known as the "poor man's Harvard"

Today: an officially designated R-2, Minority Serving Institution, and Hispanic Serving Institution (but, alas, tuition no longer free)

One of 25 universities and colleges within the broader *City **University** of New York* (C**U**NY) system, founded 1968

The Five Demands

THE STUDENT PROTEST AND TAKEOVER OF 1969

1969: Student Protests at City College

“Support the Five Demands” served as the battle cry for City College students who seized the moment in the spring of 1969.
Photo courtesy of City College Archives

CCNY students, some of ther
Action (PRISA) demonstrate
faculty members. Student at
Photo courtesy of The Ne

National Autonomous University of Mexico

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History [edit]

The university was founded on 22 September 1910 by Justo Sierra,[2][3][4][5] then minister of education in the Porfirio Díaz regime, who sought to create a very different institution from its 19th-century precursor, the Royal and Pontifical University of Mexico, which had been founded on 21 September 1551 by a royal decree signed by Crown Prince Phillip II on behalf of Charles I of Spain[21] and brought to a definitive closure in 1865 by Maximilian I of Mexico.[22][23] Instead of reviving what he saw as an anachronistic institution with strong ties to the Roman Catholic Church,[24] he aimed to merge and expand Mexico City's decentralized colleges of higher education (including former faculties of the old university) and create a new university, secular in nature and national in scope, that could reorganize higher education within the country, serve as a model of positivism and encompass the ideas of the dominant Mexican liberalism.[3]

What is the *general circulation*?

Take 1 minute to discuss with somebody near you, and/or write it down for yourself.

Let's ask our ascendant AI overlord, ChatGPT:

In one sentence, what is the "general circulation" in climate science?

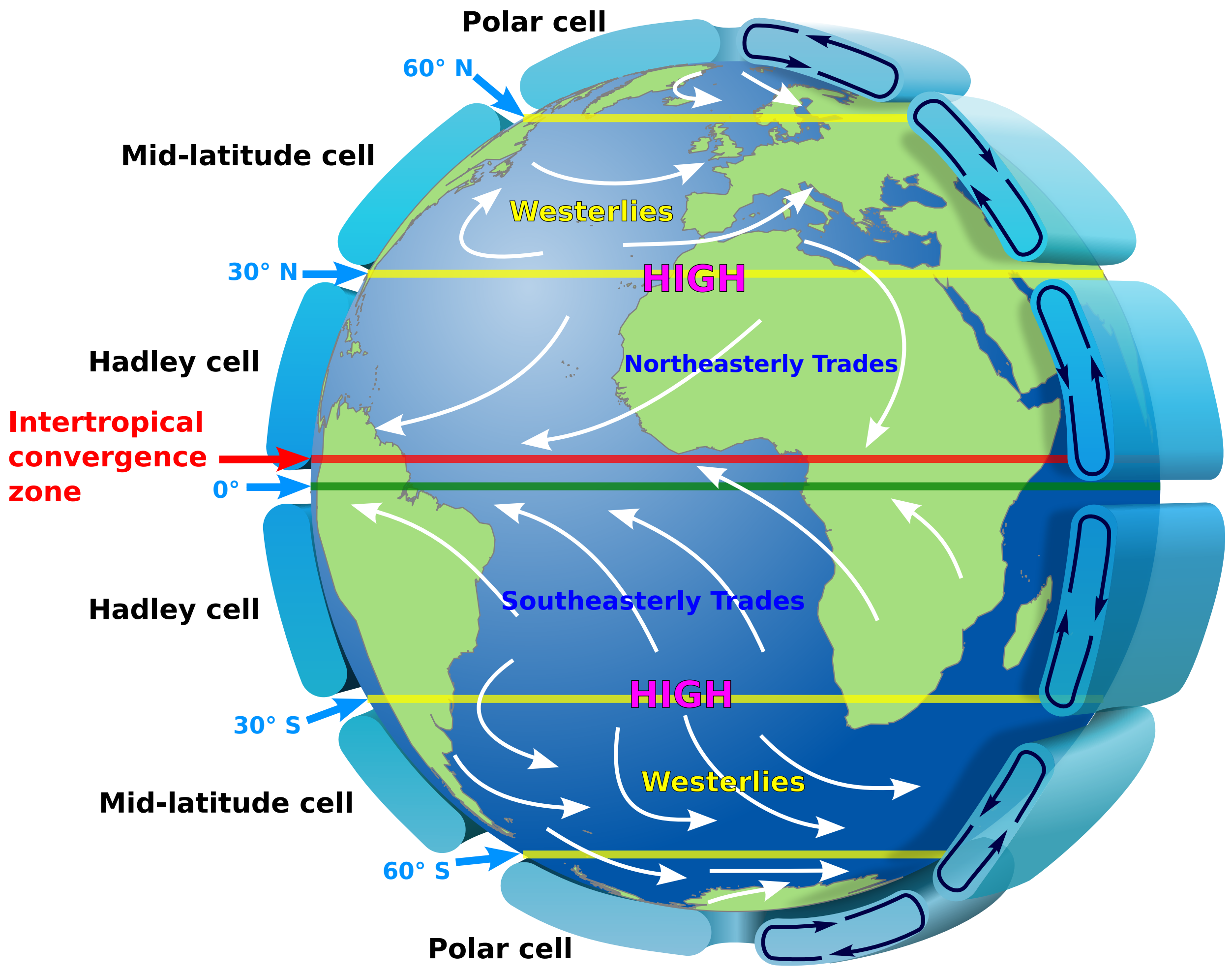
The **general circulation** in climate science is the large-scale, global pattern of atmospheric motion that redistributes heat, moisture, and momentum across the Earth, driven by differential solar heating and the planet's rotation.

Nailed it!

Time mean: long-term averages, "climatologies"

Zonal mean: individual monsoons → Hadley cells and the ITCZ

https://commons.wikimedia.org/w/index.php?curid=23902538



Time mean doesn't just mean annual-mean: it includes the **climatological seasonal cycle** (monsoons!)

But we'll start with the annual mean and then come back to the seasonal cycle

What, then is the tropical general circulation?

What, then is the tropical general circulation?

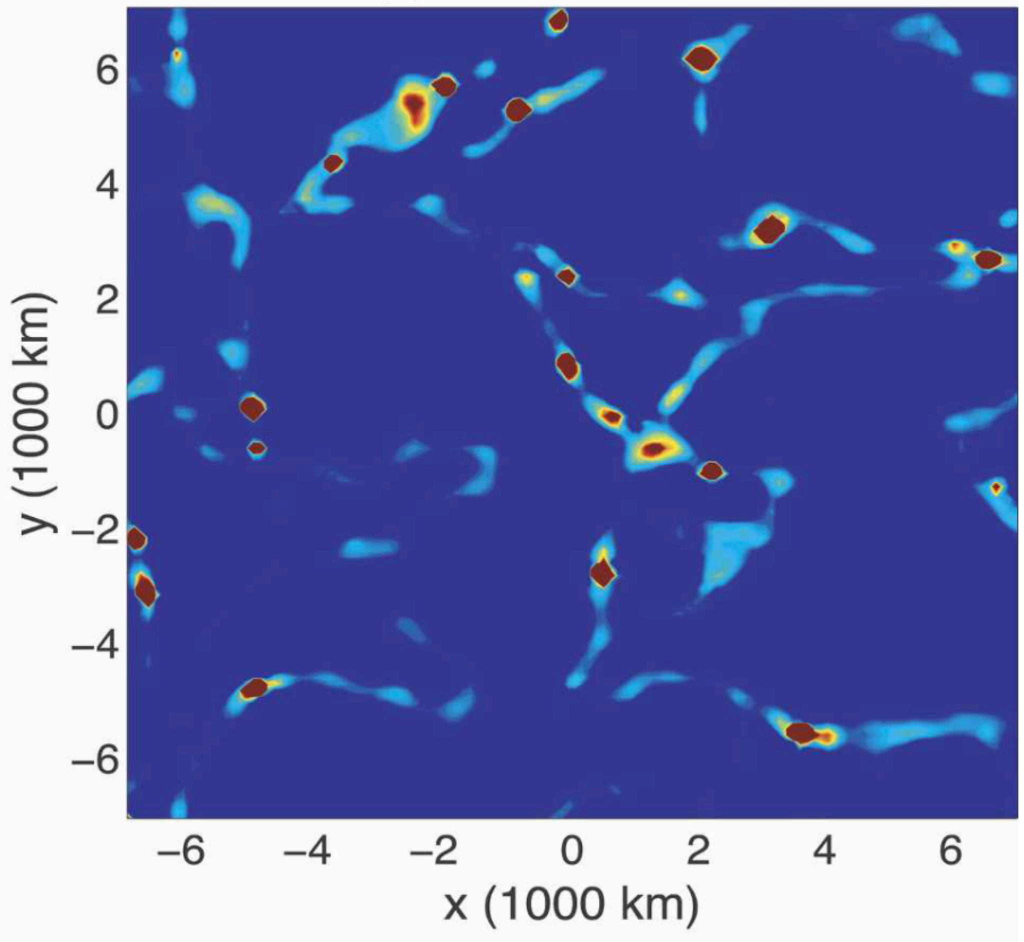
Trick question 😉: it's just the general circulation within the tropics

Recall radiative-convective equilibrium (RCE):

At sufficiently large horizontal scales ($\gtrsim 1000 \times 1000$ km), time-mean balance between forcing (insolation, OLR, surface fluxes) and convection

For example, this snapshot of precip (blue=none, red=lots) from a doubly periodic, non-rotating simulation in a climate model:

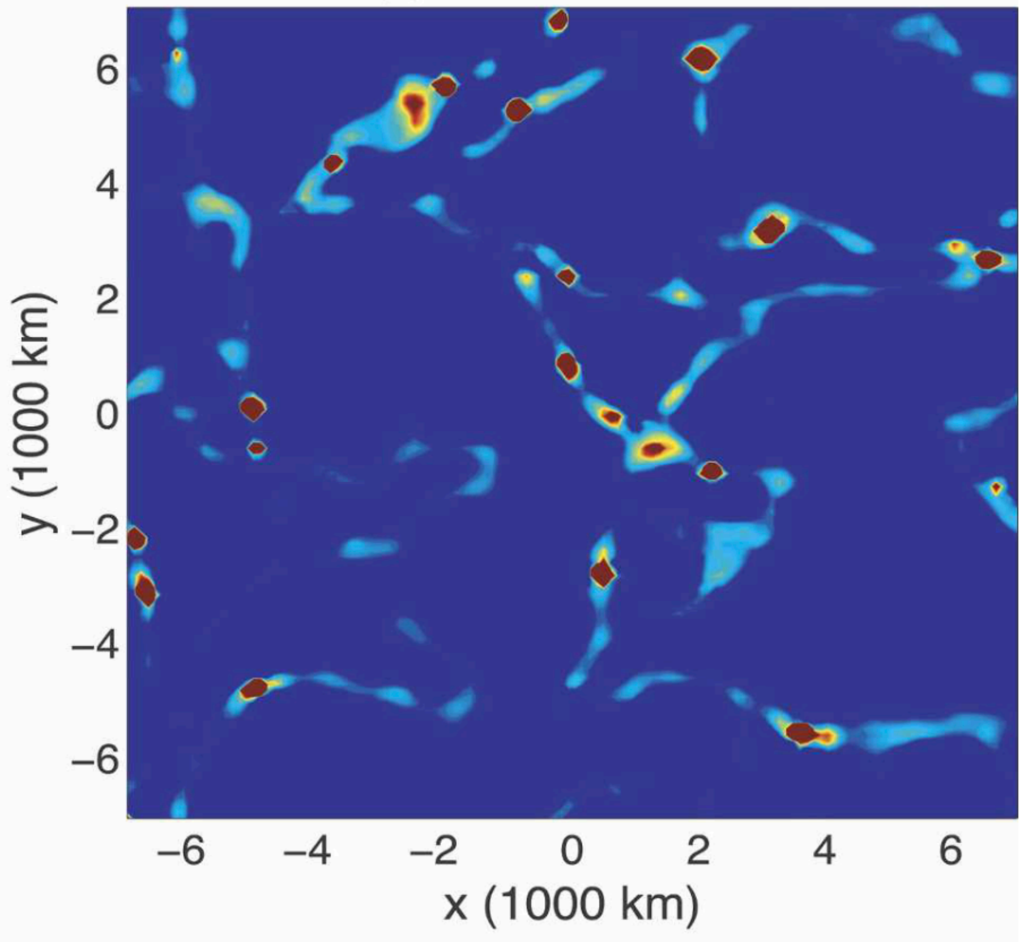
(Fig. 2d of *Held et al 2007*)



At any given time, some locations are convecting and raining heavily, others dry and subsiding

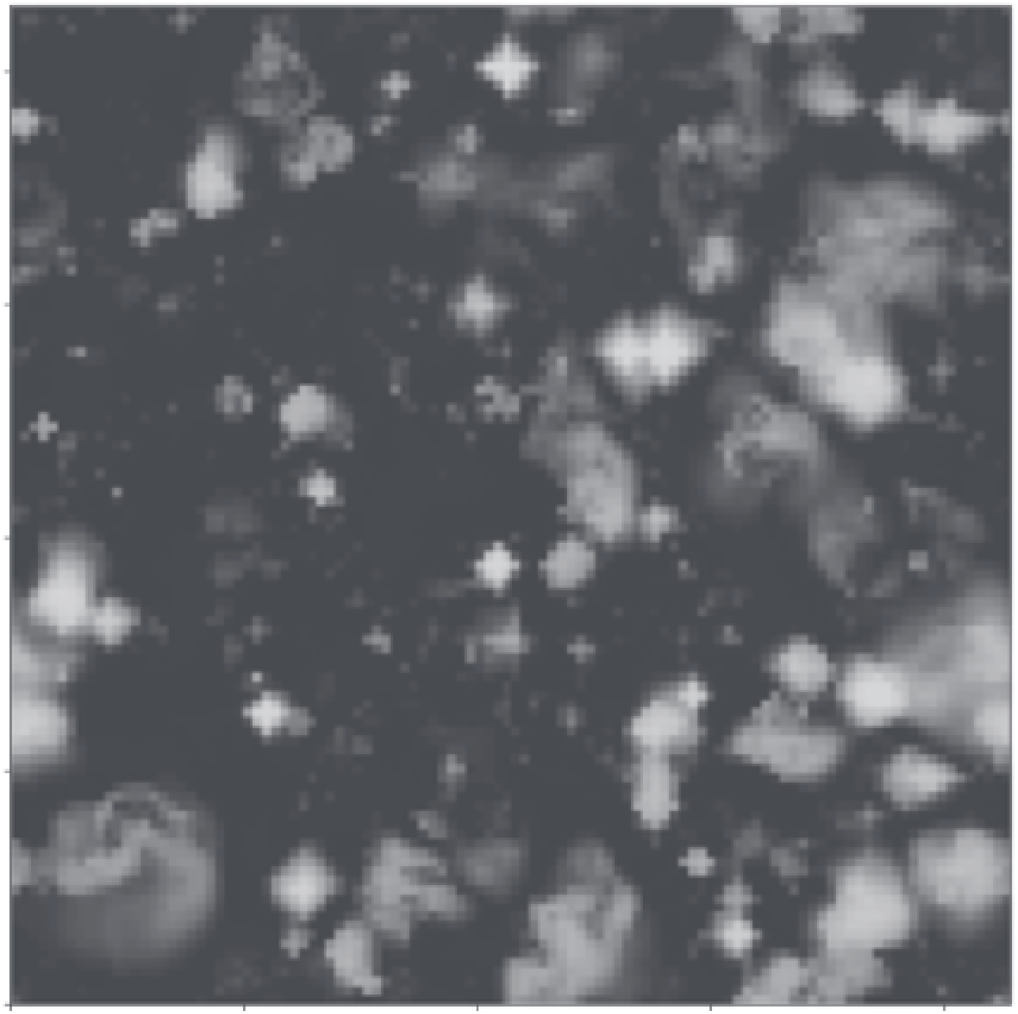
But **averaged over the domain and in time**, ascent within convection exactly balanced by descent elsewhere

(Fig. 2d of *Held et al 2007*)



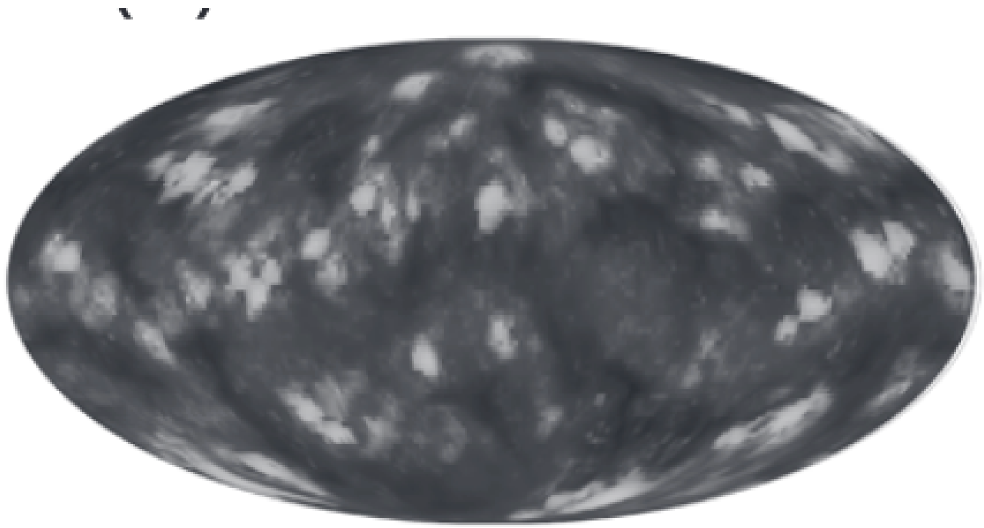
Or this, from a cloud-resolving model:

(Fig. 2d of *Wing et al 2018*, snapshot of OLR, white=low OLR=high cloud=convection)



You can even get it on the whole sphere, if the forcing and lower boundary are uniform and it's non-rotating:

(Fig. 5d of *Wing et al 2018*, again OLR)



In all these cases, *net result* is **upward transport of heat and moisture**: ~moist adiabatic lapse rate, warmer and moister upper troposphere, cooler, drier lower troposphere *compared to pure radiative equilibrium*

(Fig. 5 of *Manabe and Wetherald 1967*, the paper underlying Manabe's 2021 Nobel Prize)

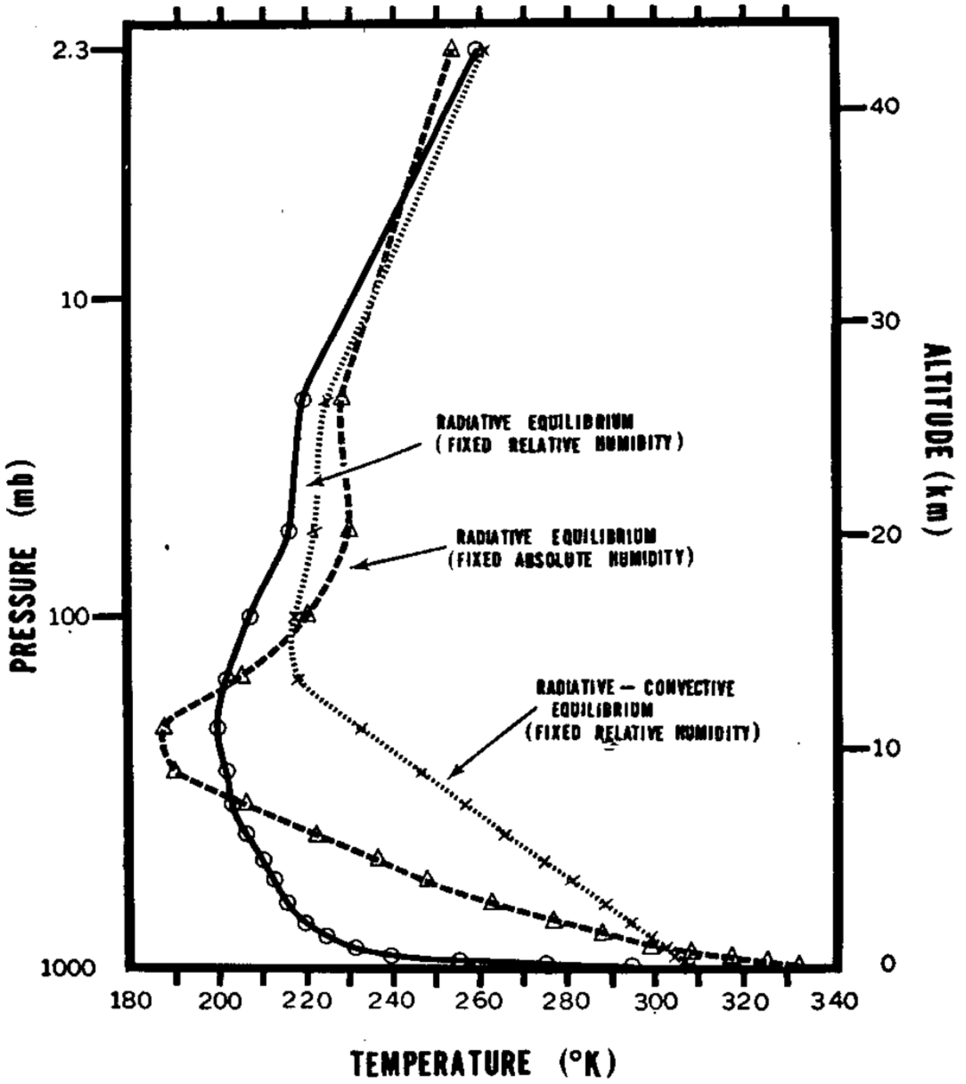


FIG. 5. Solid line, radiative equilibrium of the clear atmosphere with the given distribution of relative humidity; dashed line, radiative equilibrium of the clear atmosphere with the given distribution of absolute humidity; dotted line, radiative convective equilibrium of the atmosphere with the given distribution of relative humidity.

In these cases, convection generates lots of motion *at small scales*: $u \neq 0$, $v \neq 0, w \neq 0$

But there is **no large-scale flow**: $\overline{u} = \overline{v} = \overline{w} = 0$
where overbars denote temporal and spatial averages.

No large-scale flow = no monsoons = 😞

Even if Earth was an *aquaplanet*, with no zonal asymmetries at all, with no diurnal cycle and no seasonal cycle, there are **two key ways** it would still differ from these previous RCE scenarios. What are they?

Hint: recall ChatGPT's wisdom (usually a good idea):

In one sentence, what is the "general circulation" in climate science?

The **general circulation** in climate science is the large-scale, global pattern of atmospheric motion that redistributes heat, moisture, and momentum across the Earth, driven by differential solar heating and the planet's rotation.

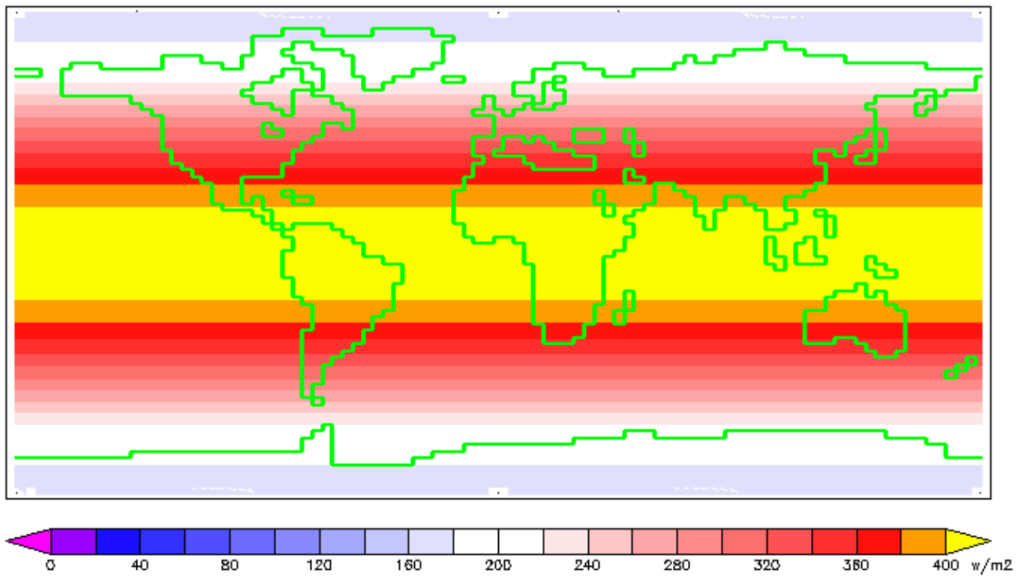
Earth's Tropics are not in local RCE because:

1. The **incoming solar radiation (insolation) is *not* uniform**
2. The **planet is *rotating***

1. Non-uniform insolation

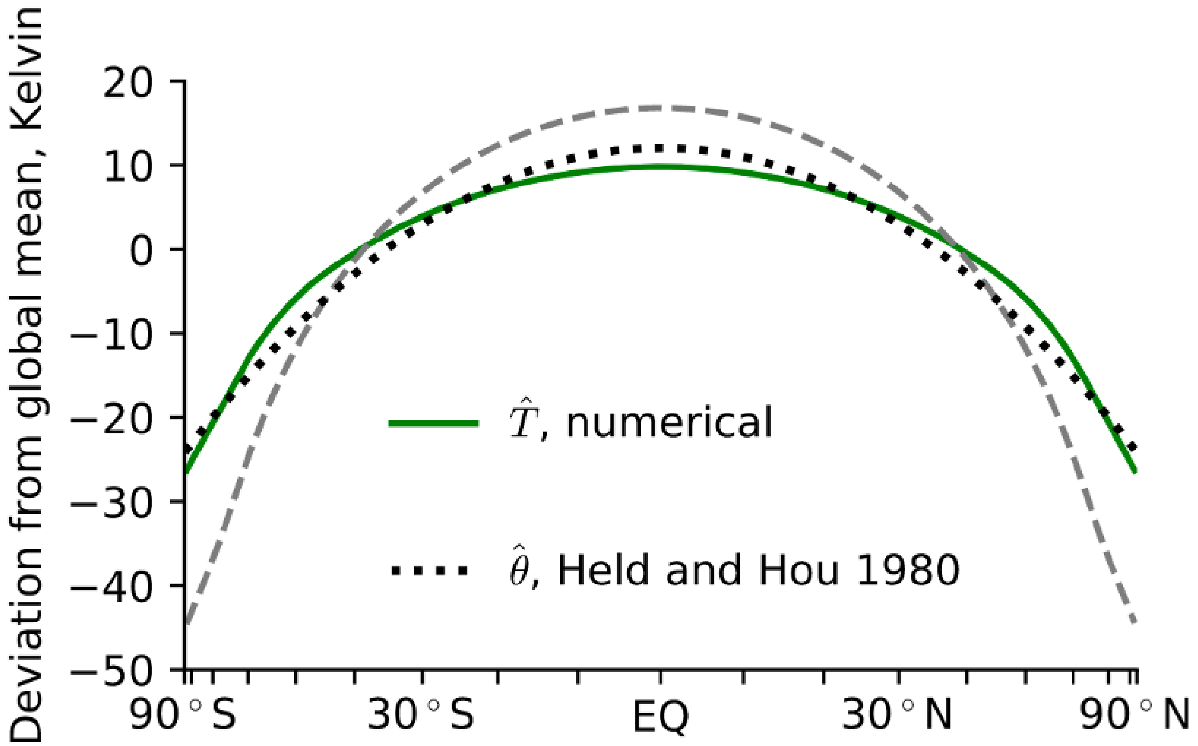
Because Earth is a sphere, there's **more sunlight per unit area at low latitudes than high latitudes**

https://en.wikipedia.org/wiki/Solar_irradiance#/media/File:Insolation.png



RCE therefore warmer at low latitudes

$$\rightarrow \frac{\partial \overline{T}}{\partial y} \neq 0$$



Hill et al 2020 Fig. 7

Numerical annual-mean lat-by-lat RCE depth-averaged temperature

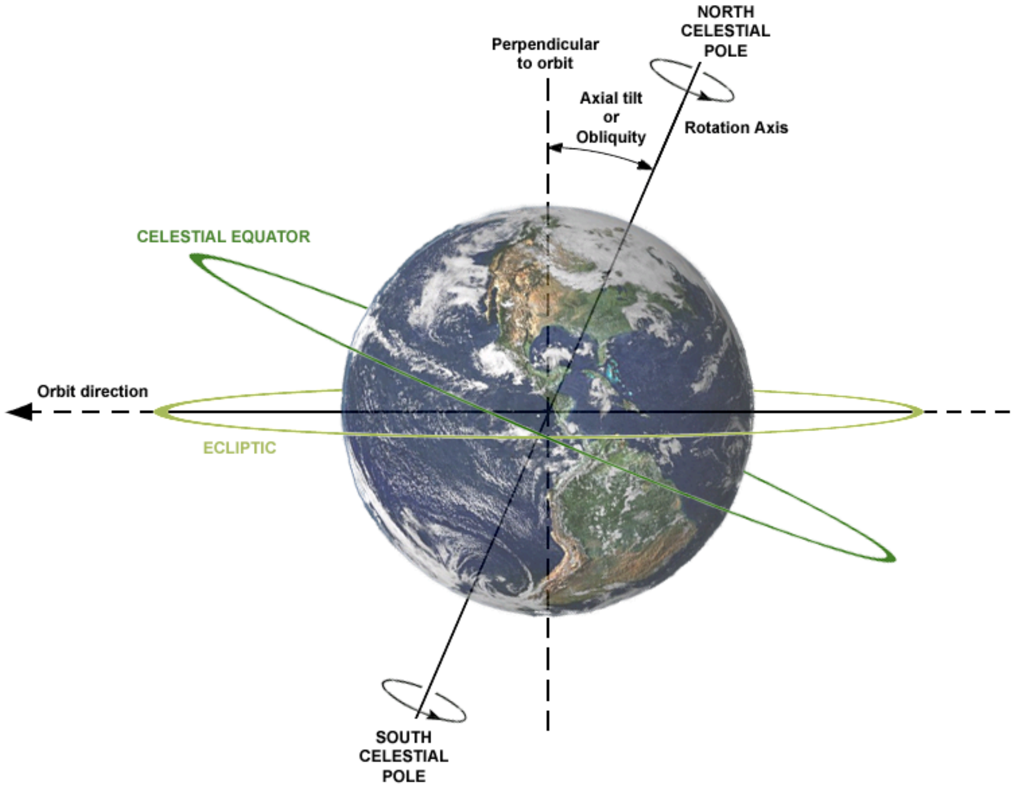
2. The planet is *rapidly rotating*

Planetary rotation rate:

$$\Omega = 2\pi/\text{day} \approx 7 \times 10^{-5}\ \text{s}^{-1}$$

What matters is *rotation in the horizontal plane*, as encapsulated in the **Coriolis parameter** f: $f \equiv 2\Omega \sin\varphi$, where φ is latitude

https://en.wikipedia.org/wiki/Earth's_rotation#/media/File:AxialTiltObliquity.png



The **planetary rotation fundamentally affects large-scale fluid motions**.

Rotating with the Earth (as we all are), we are in a *non-inertial reference frame*, resulting in an *apparent force* encapsulated into the Coriolis parameter f.

Horizontal momentum equation for a single layer, inviscid, *non-rotating* fluid, where $\mathbf{u} = (u, v)$:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla p$$

Now for the same system but rotating:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} + \mathbf{f} \times \mathbf{u} = -\frac{1}{\rho} \nabla p$$

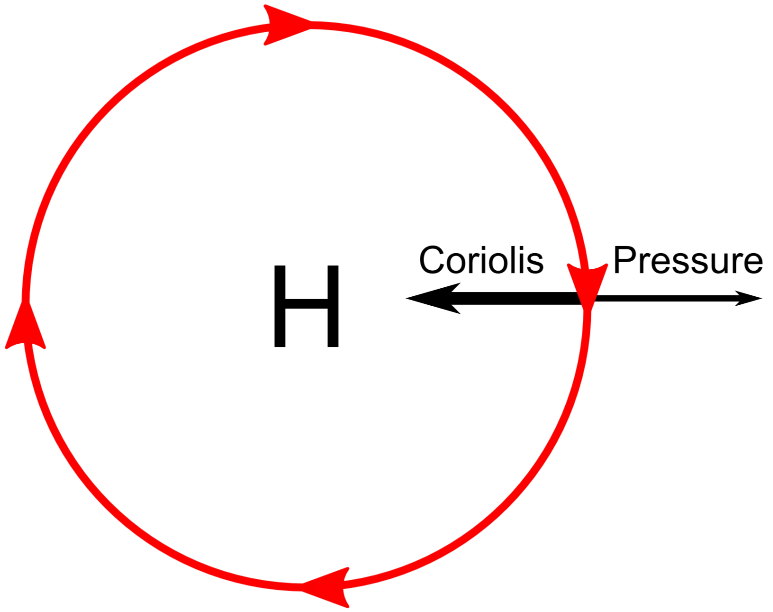
Recall from calculus: cross product $\mathbf{f} \times \mathbf{u}$ *is at a right angle to the flow itself,* $\mathbf{u}$!

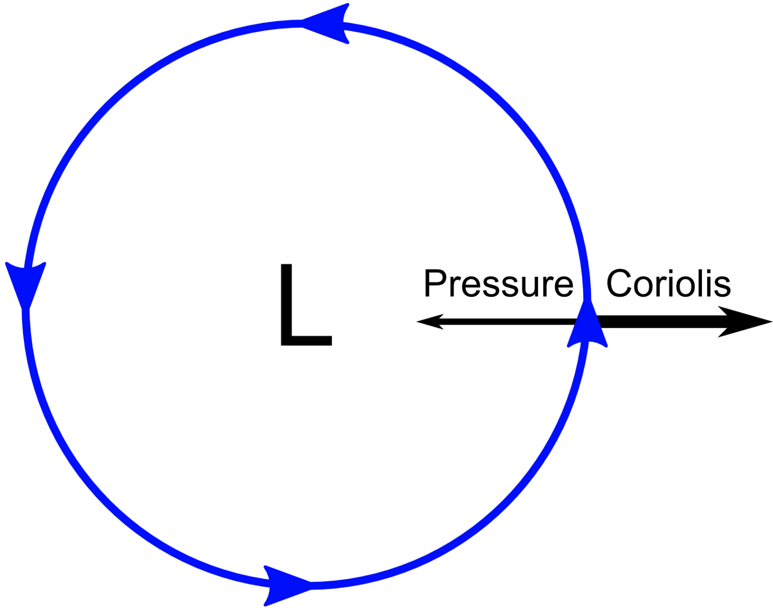
In particular, flow tends to be approximately **geostrophic**: *balance between the horizontal pressure gradient and the Coriolis force*:

$$\mathbf{f} \times \mathbf{u} \approx -\frac{1}{\rho}\nabla p$$

Instead of flow *down* the pressure gradient---in other words, *across isobars*---flow is *normal* to the pressure gradient: **along isobars**

https://sammorrell.co.uk/2015/02/16/the-fluid-mechanics-of-planetary-atmospheres/





Zonal thermal wind: *vertical shear* of zonal wind, $\partial u/\partial z$, proportional to meridional temperature gradient:

$$\frac{\partial u}{\partial z} \propto \frac{1}{f}\frac{\partial T}{\partial y} \neq 0$$

In Northern Hemisphere: $f > 0$, $\partial T/\partial y > 0$, so $\partial u/\partial z > 0$: *zonal wind becomes more positive (=more westerly) with height*

Southern Hemisphere: $f < 0$ and $\partial T/\partial y > 0$, so likewise $\partial u/\partial z > 0$

At the surface, friction forces zonal wind to go to zero (*no-slip boundary condition*): $u(z=0)=0$

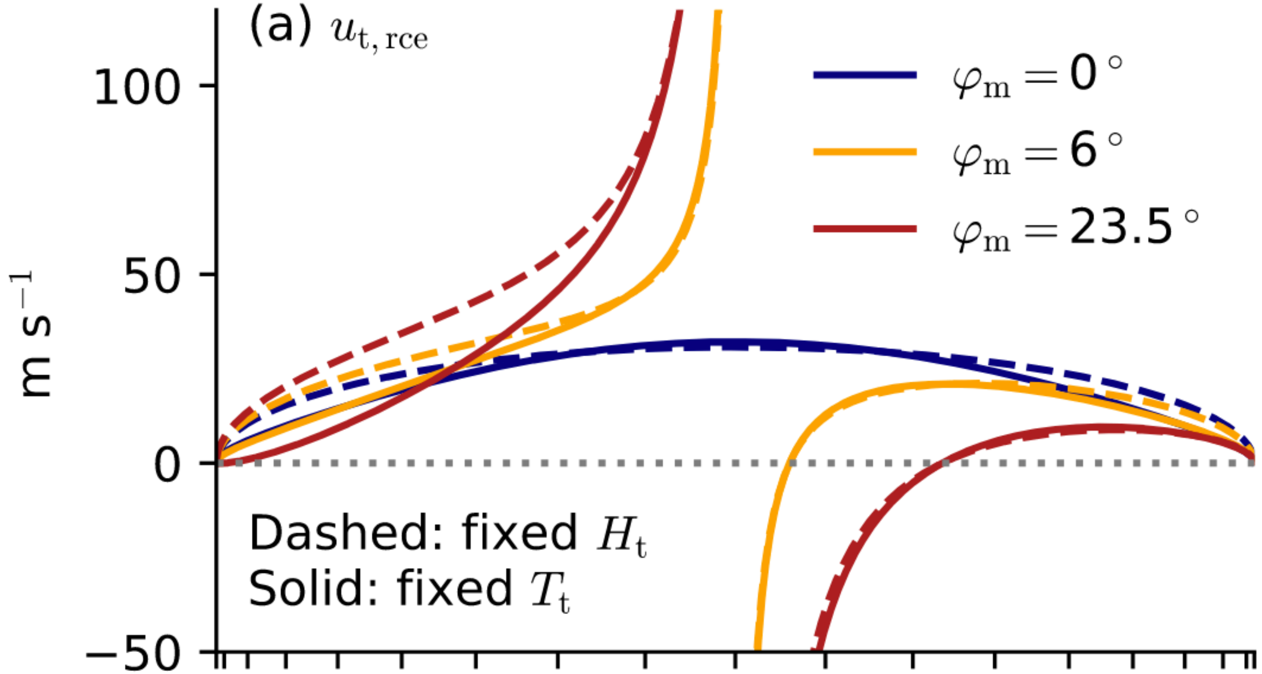
So, combined with the requirement that $\partial u/\partial z > 0$, it follows that **in the free troposphere $u_{\mathrm{rce}} > 0$ at all latitudes**!

(where u_{rce} notation reminds us: this is *hypothetical, lat-by-lat RCE state*)

E.g. this Fig. 1a from *Hill, Bordoni, and Mitchell 2020 J. Atmos Sci*.

Focus on blue solid curve; ignore all others. Horizontal axis is latitude, from 90S to 90N

$u_{\rm rce}$ at the tropopause positive everywhere, including at the equator



So what? Why care if $u > 0$ everywhere? Several reasons.

One reason: westerly wind at the surface pulls the solid Earth along with it. If $u > 0$ everywhere, then the atmosphere is accelerating Earth's spin!

Must have mix of easterly and westerly surface winds across latitudes, such that the total stress on solid Earth is zero: neither spun up nor down

$\rightarrow$A **general circulation must arise** that accomplishes this

So a general circulation must emerge...

but what controls the form it takes?

Recall two things:

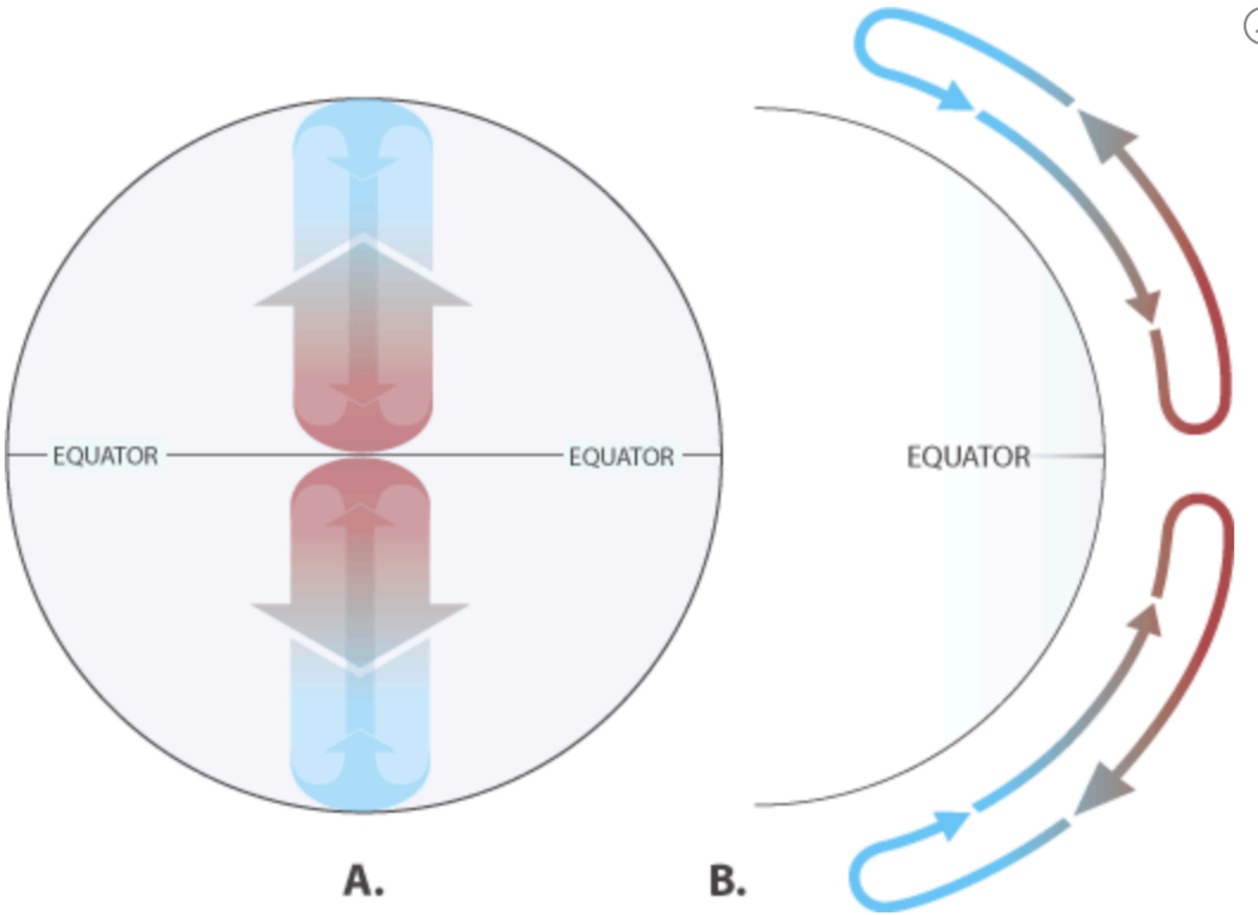
1. (from earlier slides) Annual-mean insolation highest at equator, lowest at poles.

2. (from earlier talks): convection in the atmosphere driven by heating.

Together: expect convection primarily at the equator.

As such, could it just be two global-scale Hadley cells: in each hemisphere, a single overturning cell rising at equator, sinking at pole?

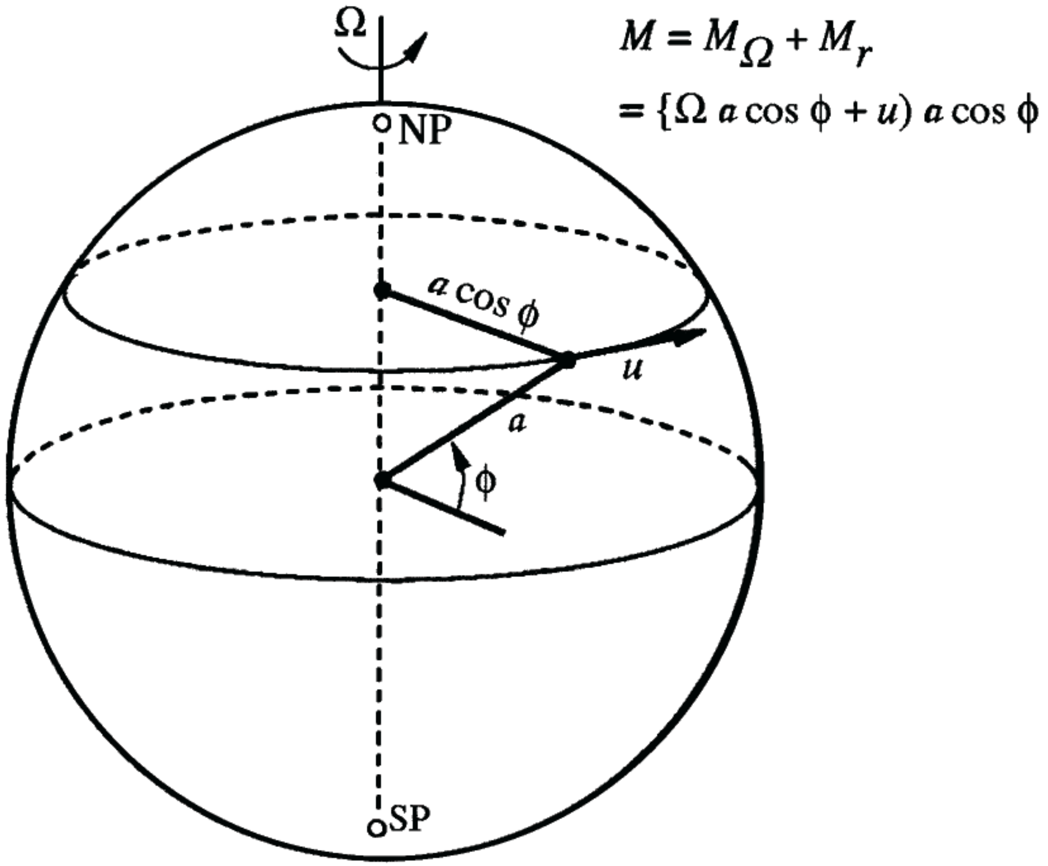
https://oceanservice.noaa.gov/education/tutorial_currents/media/supp_cur04a.html



To answer that, we'll turn to *angular momentum*, M

Recall from physics class: angular momentum = (distance from rotation axis) X (linear tangential velocity)

Distance from rotation axis = $a \cos \varphi$, where a is planetary radius



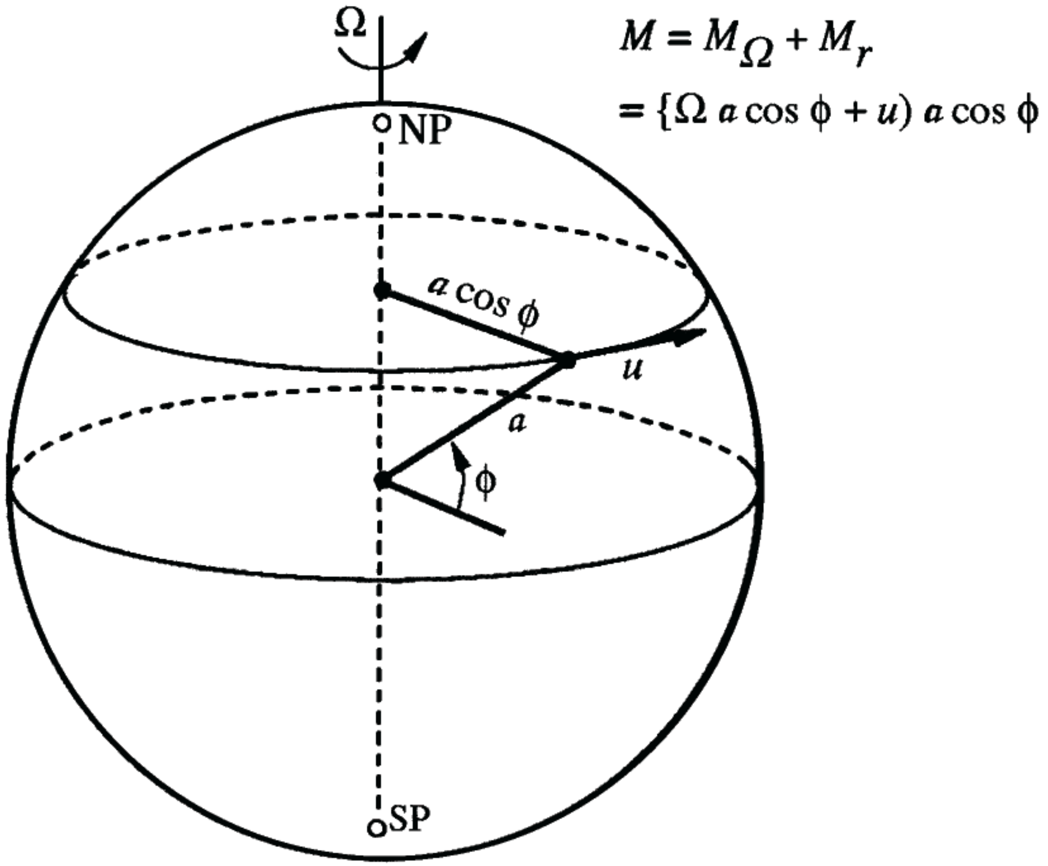
To answer that, we'll turn to *angular momentum*, M

On Earth, two contributions:

1. Planetary rotation: $\Omega(a\cos\varphi)$
2. The flow itself: u

All together:

$$M = a\cos\varphi(\Omega a\cos\varphi + u)$$



Once the parcels ascend out of the *boundary layer* near the equator, they reach the *free troposphere*

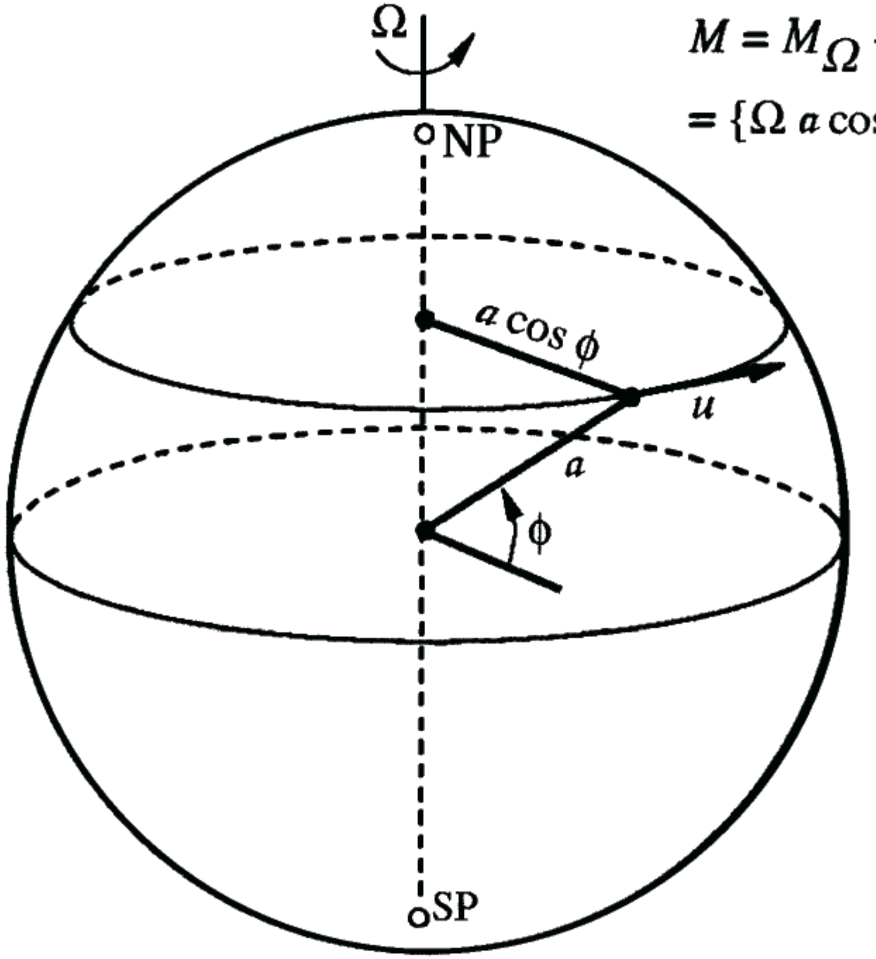
Crucially for us, the **free troposphere is nearly inviscid**: ~no friction and so angular momentum conserved

So parcel leaving boundary layer stuck with that value!

Now we follow that parcel as it moves poleward.

Its angular momentum is fixed, but it's getting closer to the rotation axis.

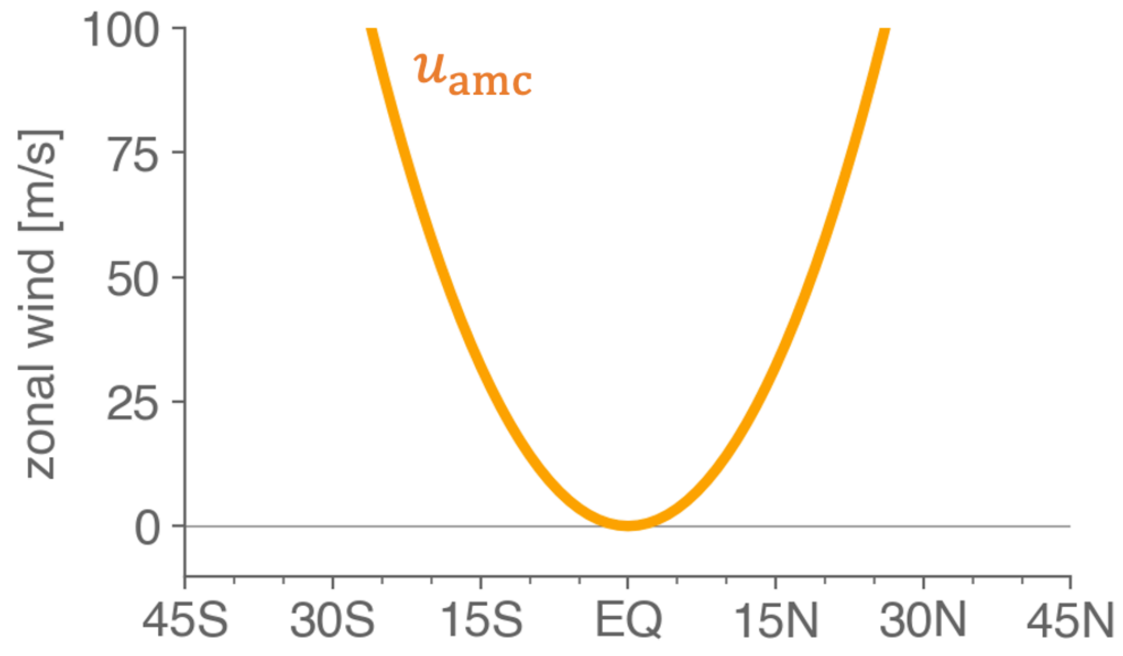
How is that possible?



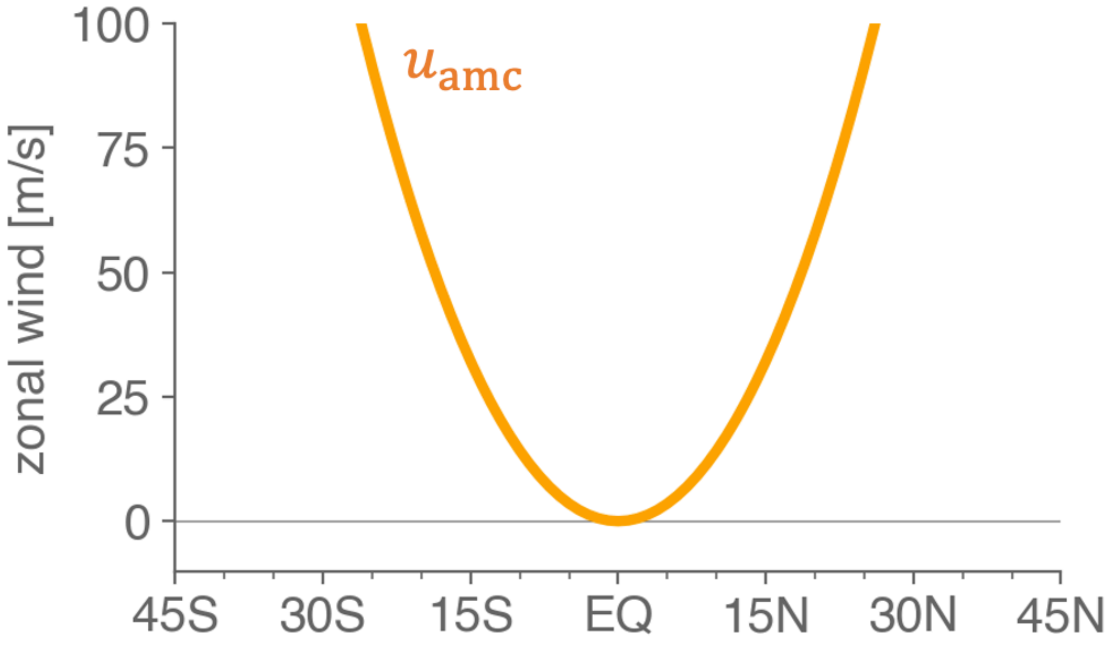
$$M = M_{\Omega} + M_r$$
$$= \{\Omega\, a \cos\phi + u)\, a \cos\phi$$

Its *relative* angular momentum *increases* to exactly compensate for its *planetary* angular momentum *decreasing*

Exercise: prove to yourself that the resulting **angular momentum conserving** (AMC) zonal wind field is: $u_{\mathrm{amc}} = \Omega a^2 \sin^2 \varphi / \cos \varphi$



This AMC zonal wind field cannot extend all the way to the pole: it would be infinite!



In fact, the AMC zonal wind u_{amc} cannot extend much beyond ~30S/N for Earth, from multiple lines of argument:

1. **Equal-area**: if *everything* was zonally symmetric and steady, the *heat* transport out of deep tropics to subtropics is the constraint (*Held and Hou 1980*)

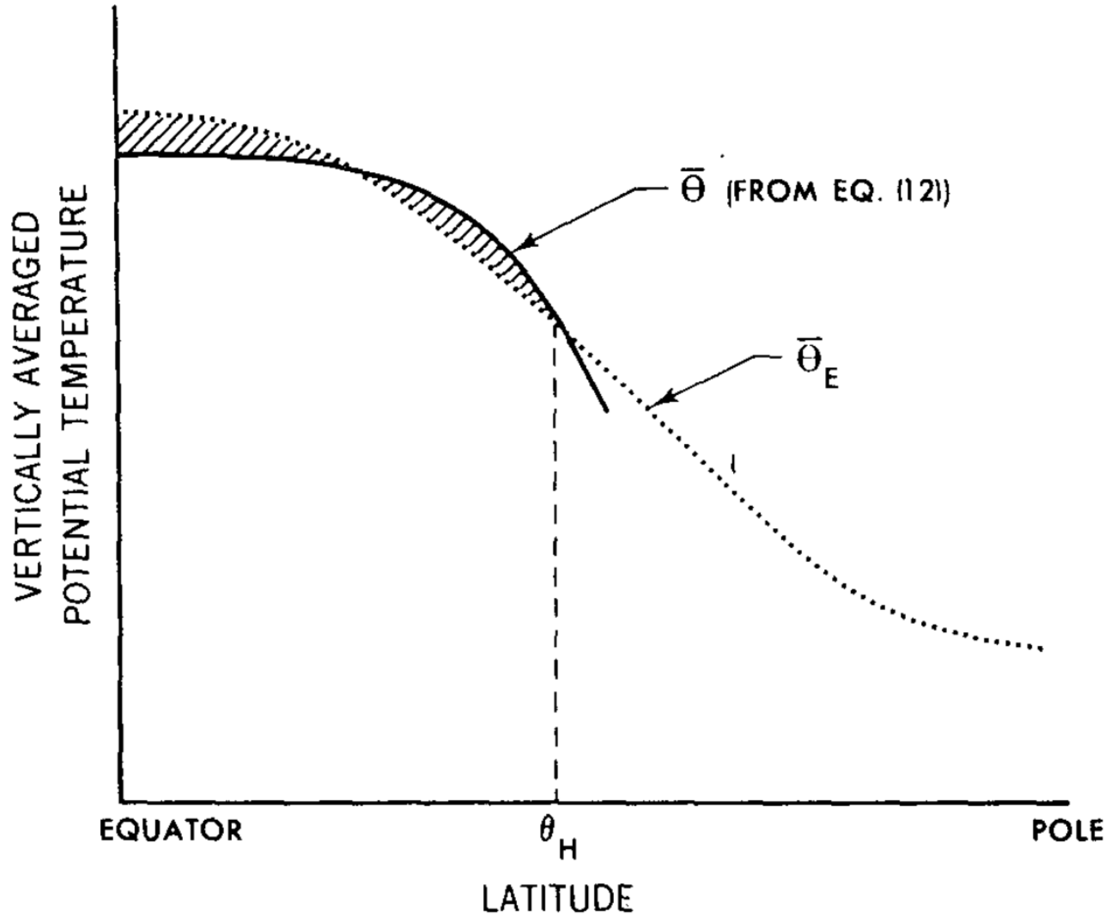
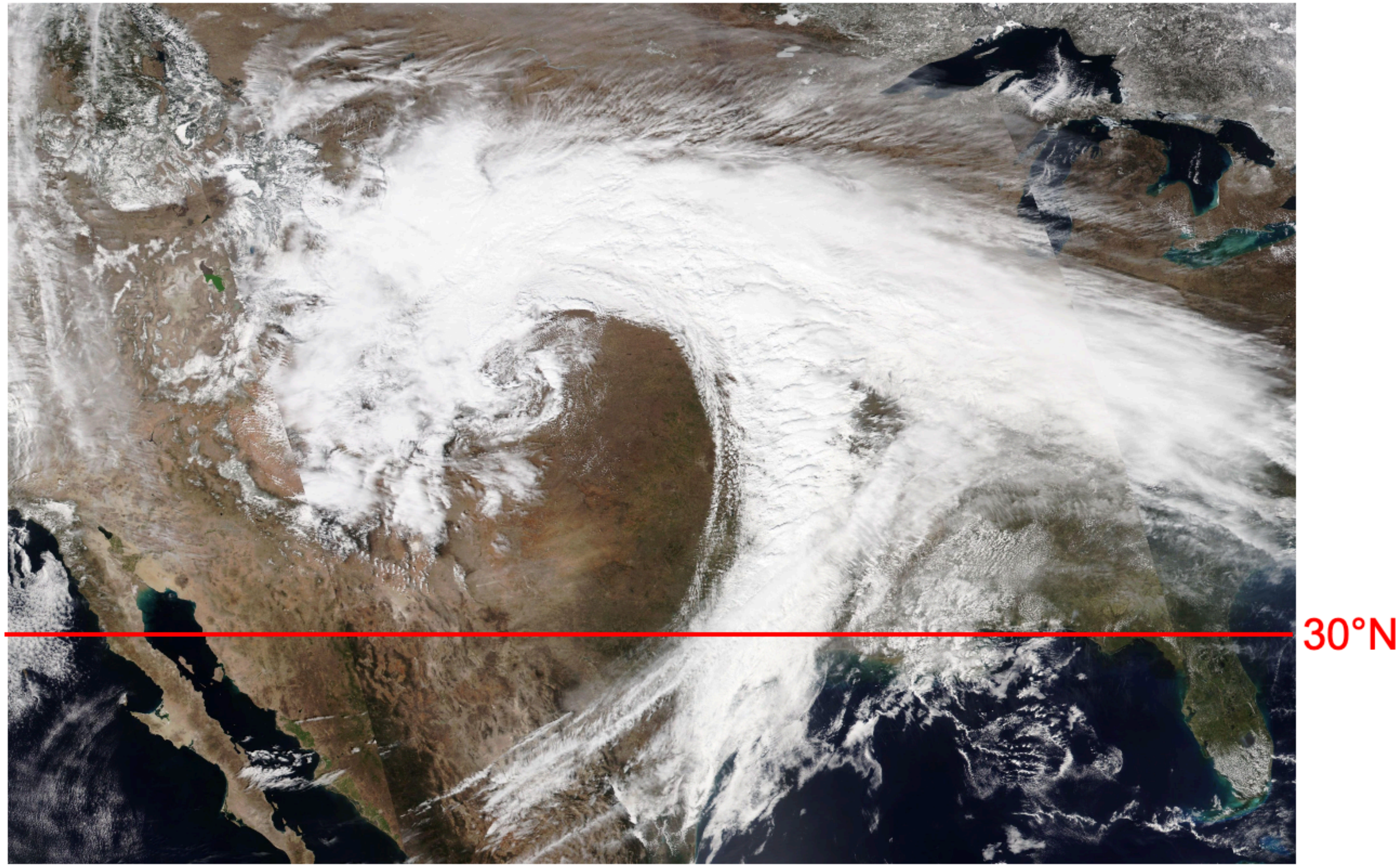


FIG. 1. The equal-area geometric construction equivalent to the argument of Section 4a. The two shaded areas are equal.

2. Baroclinic eddies: in reality, giant mid-latitude storms generate large stresses that decelerate u in the subtropics and force the zonal-mean Hadley cells to sink (*Held 2000*)



https://twitter.com/weatherdak/status/1371323519435411460

Recap:

zonal-mean insolation gradient + rapidly rotating spherical planet +
viscous boundary layer + inviscid free troposphere

equals

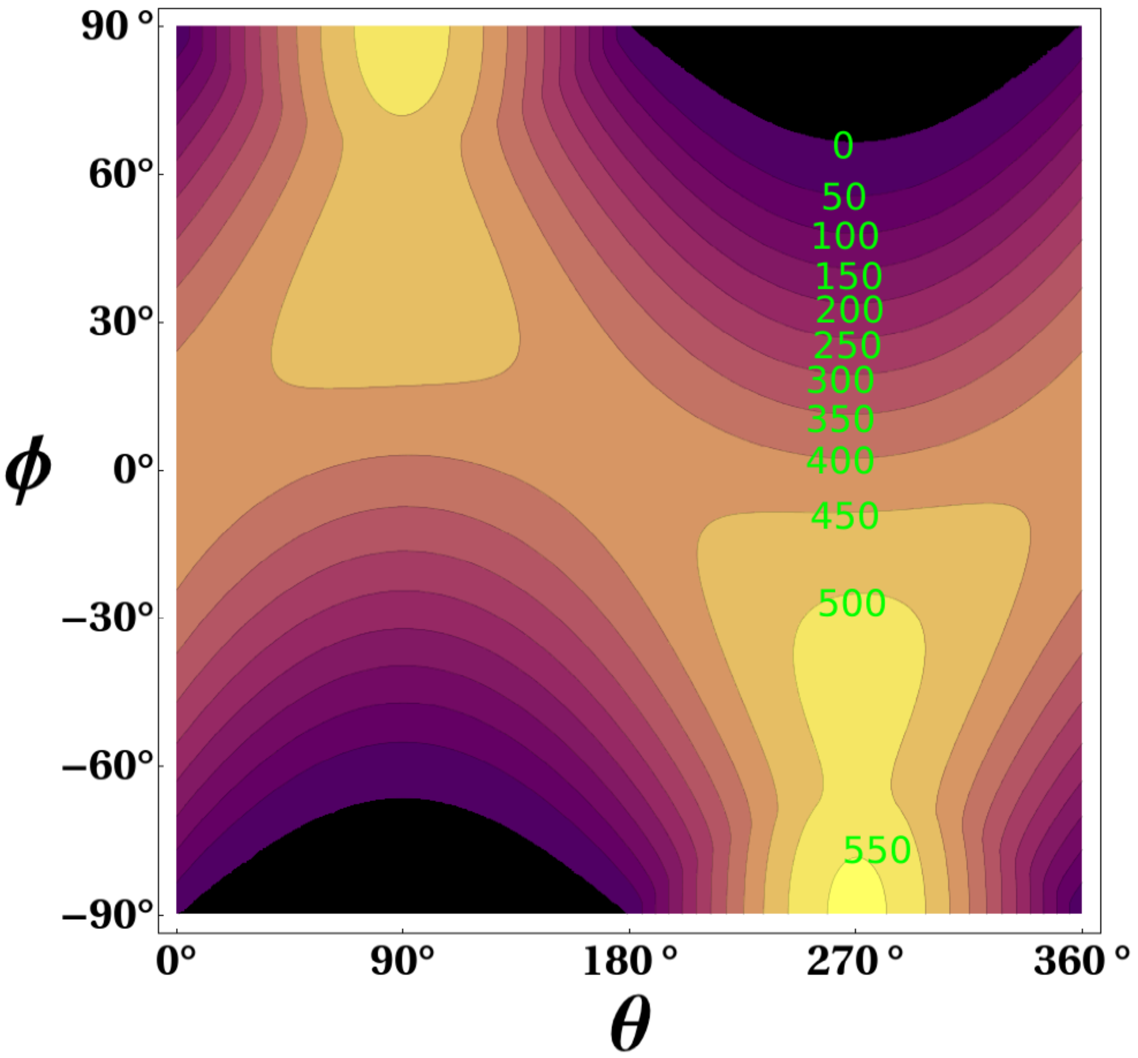
annual-mean ITCZ @ equator +
overturning Hadley cells descending ~30S/N +
westerly upper tropospheric winds

Now: let's (finally!) bring in the *seasons*

Insolation seasonal cycle. X axis is time of year, Y axis is latitude, units are W m^{-2}.

Insolation peaks *on the equator* only twice per year, the equinoxes. *All other times*, it's off equator, and at solstice it's at the summer pole!

https://en.wikipedia.org/wiki/Solar_irradiance#/media/File:InsolationTopOfAtmosphere.png

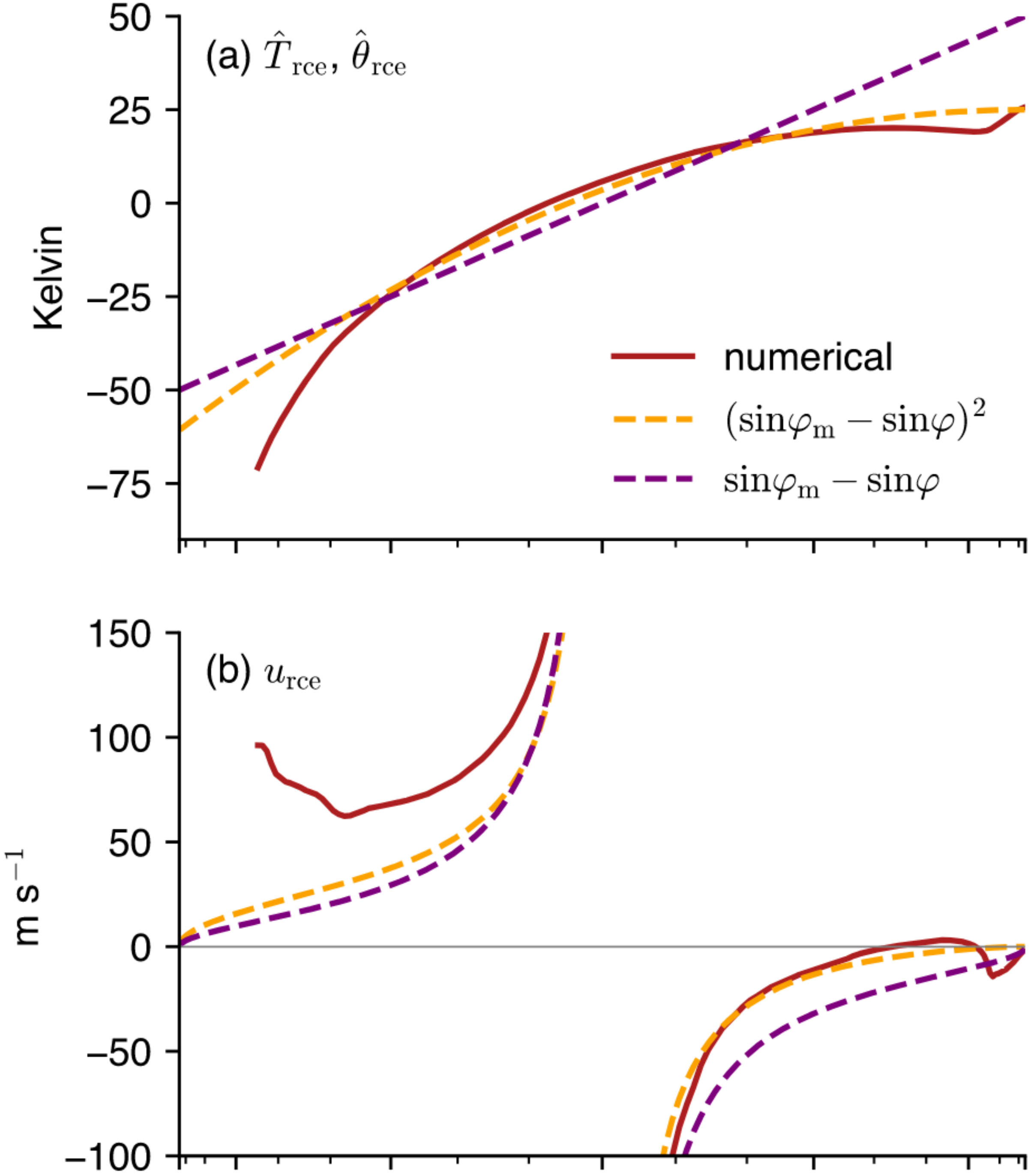


Let's return to the hypothetical latitude-by-latitude, radiative-convective equilibrium (RCE) state, i.e. what would happen if there was no general circulation, now for seasonal insolation.

From *Hill, Bordoni, and Mitchell 2021*: x axis is latitude from -90 to +90, numerical lat-by-lat RCE solutions

NH summer: T increases northward, and at the equator $\partial T/\partial y \neq 0$

By thermal wind balance, this causes $u \rightarrow \pm\infty$ approaching the equator from either side



Obviously, a solution with infinite wind speeds is not physically realizable!

So already, we know that a general circulation *must* emerge at least in the direct vicinity of the equator.

But how far beyond that? Possibly not much? On the other hand, insolation and RCE temperature max at summer pole…ascent at the summer pole too?

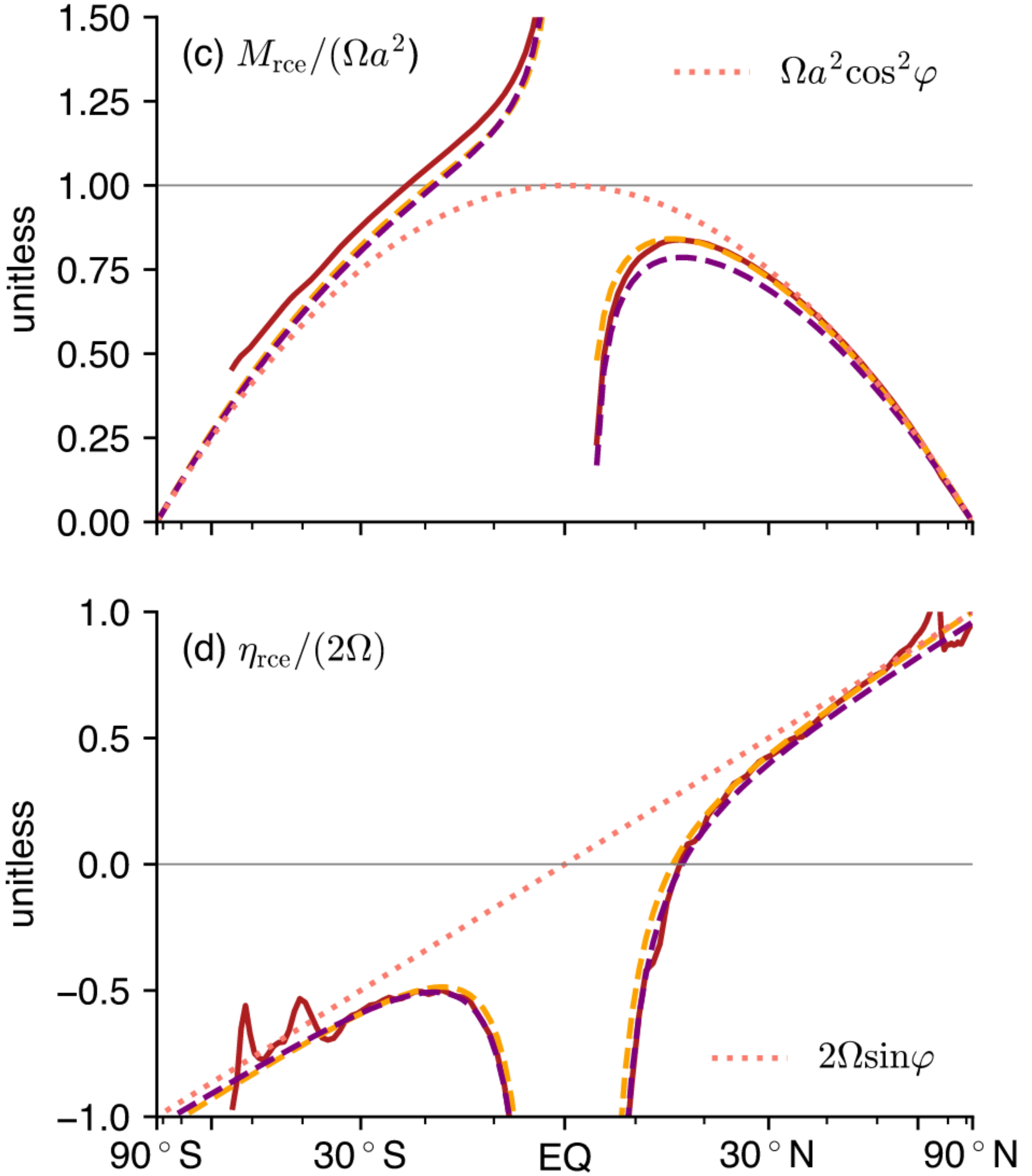
To answer this we'll look at the corresponding angular momentum M and a new, useful quantity, **absolute vorticity**: $\eta = f + \zeta$,

This is the sum of planetary vorticity (f) and relative vorticity $\zeta \sim -\partial u/\partial y$

Absolute vorticity scales with minus the meridional angular momentum gradient: $\eta \propto -\partial M/\partial y$

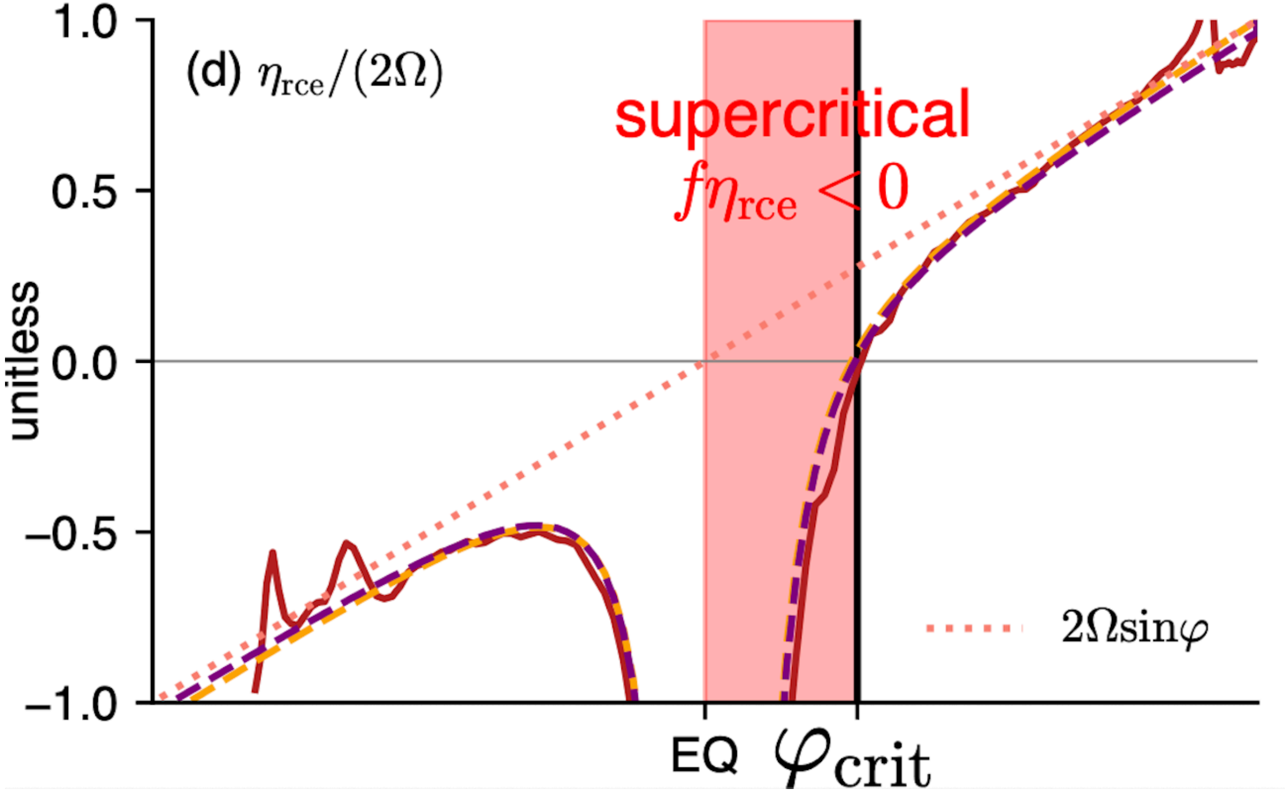
Top: since u blows up, M does too, pretty straightforward

Bottom: dashed pink shows just the planetary part, f. Notice in the NH that the full η is negative from equator to $\sim 15^{\circ}$N.



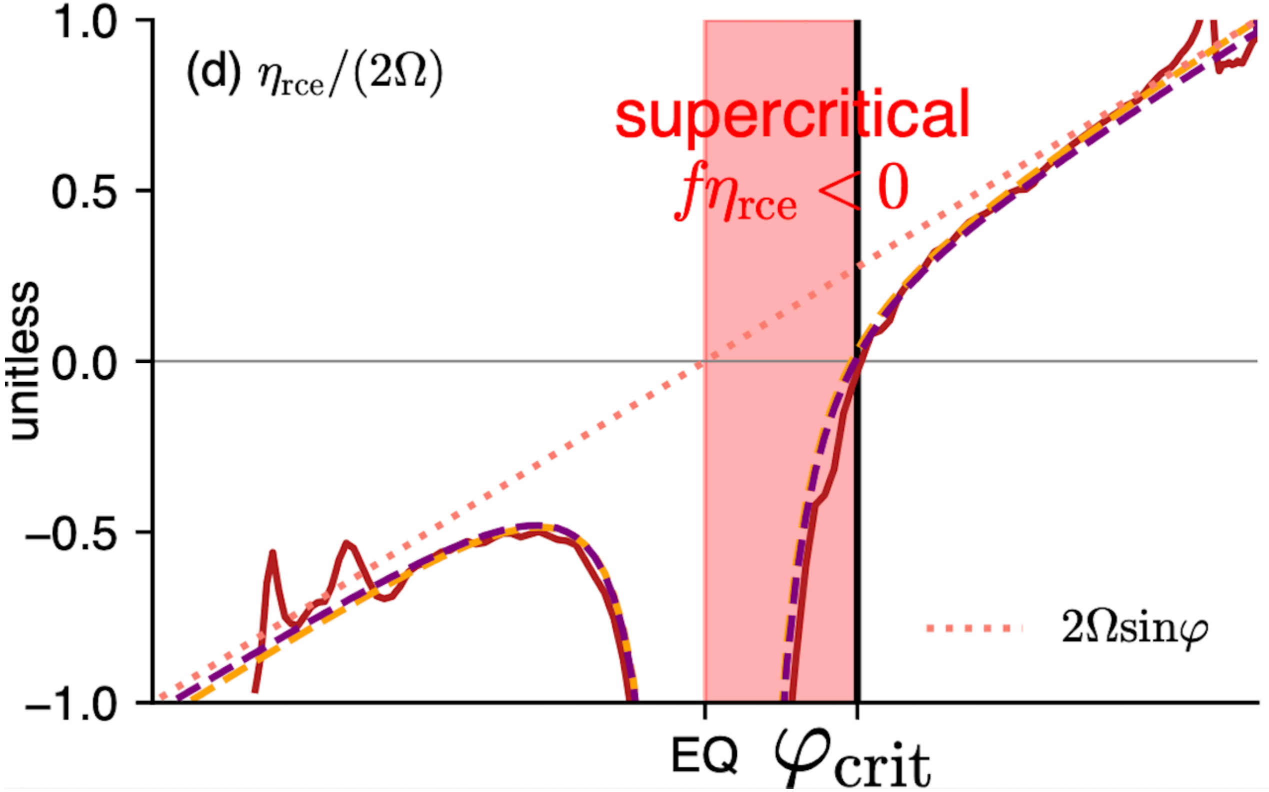
This region with $f\eta_{\mathrm{rce}} < 0$ is called **supercritical**, c.f. *Plumb and Hou 1992*, *Emanuel 1995*, and ends at φ_{crit}

From multiple lines of argument, the general circulation **must** span at least the entire supercritically forced region



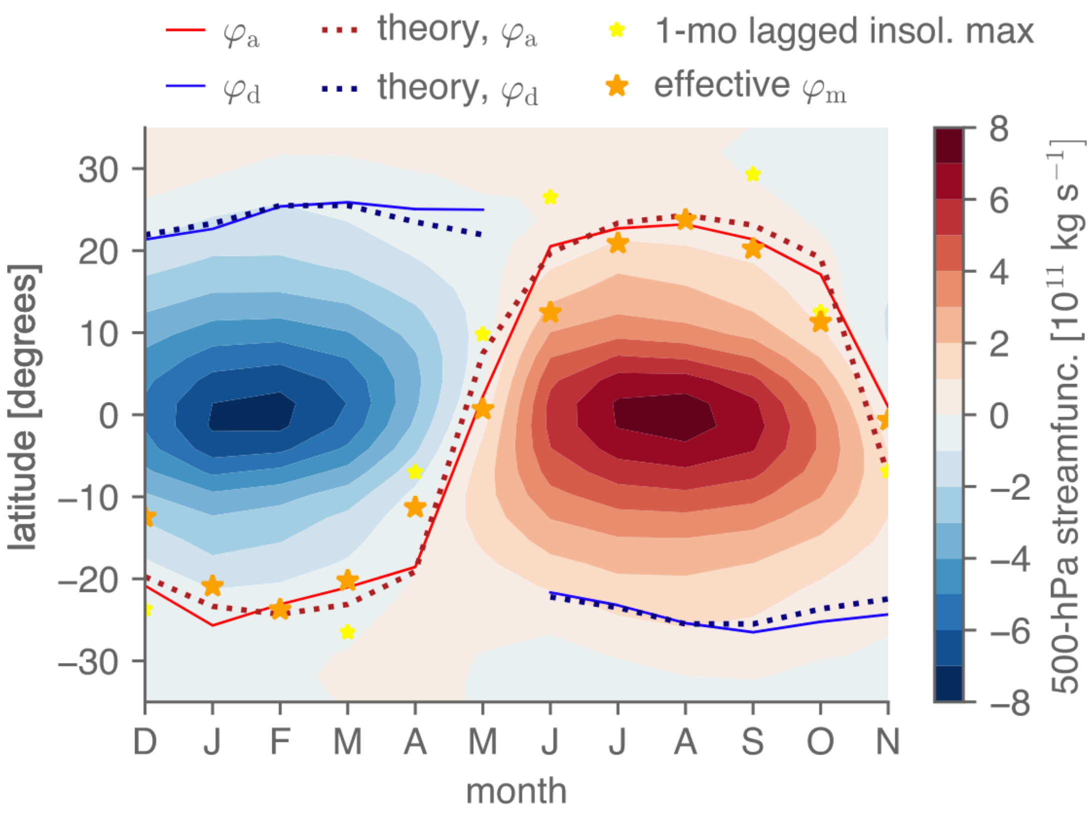
Just one, from *Emanuel 1995*: if you start from rest, then from the vorticity equation which governs $\partial\eta/\partial t$ at the tropopause, $\eta = 0$ is a *stationary point*: $\partial\eta/\partial t = 0$

So it's impossible to change η from its original sign, i.e. impossible for $f\eta < 0$...it gets *stuck* at $\eta = 0$.



In *Hill, Bordoni, and Mitchell 2022*, we used this seasonally varying supercritical forcing extent to predict the seasonal cycle of the ~ITCZ (φ_a) in an ~Earth-like aquaplanet model.

And combined it with the *Held 2000* theory based on baroclinic instability to predict the *descending edge* (φ_d) in the winter hemisphere



Limitation: tropical supercriticality is strictly speaking a *lower bound*, not a precise value, for the cross-equatorial, *monsoonal* Hadley cell ascent location (i.e. the ITCZ latitude).

How to get a more precise theory? I'll briefly note two research strands, which will be discussed in more detail in coming days: (1) **seasonal equal-area**, and (2) **ITCZ energetic framework**

Recap

Tropical general circulation, in part = **time-mean, zonal-mean, seasonally varying circulation**

On our **rotating, spherical, seasonally forced Earth**, this comprises **Hadley cells** with **descent in the subtropics year-round** and **ascent "following the sun" to the summer hemisphere**

The combination of **these influences plus the land-sea configuration** turn this zonal-mean circulation into the constellation of **Earth's monsoons, oceanic ITCZs, and regional subsidence zones**.

Limitations

There's a fascinating array of subseasonal and zonally confined large-scale circulations in Earth's tropics: convectively coupled equatorial waves, tropical cyclones, monsoon low pressure systems, ...

And these play a meaningful role in the time-mean zonal-mean transports that I've otherwise been equating solely with the Hadley cells

Annual mean: ITCZ is not on the equator! Energetic framework is best way to think about that.