Beyond 1D atmospheres

Jérémy Leconte

Whiplash

Equations of motion

★ Mass conservation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

★ Momentum conservation

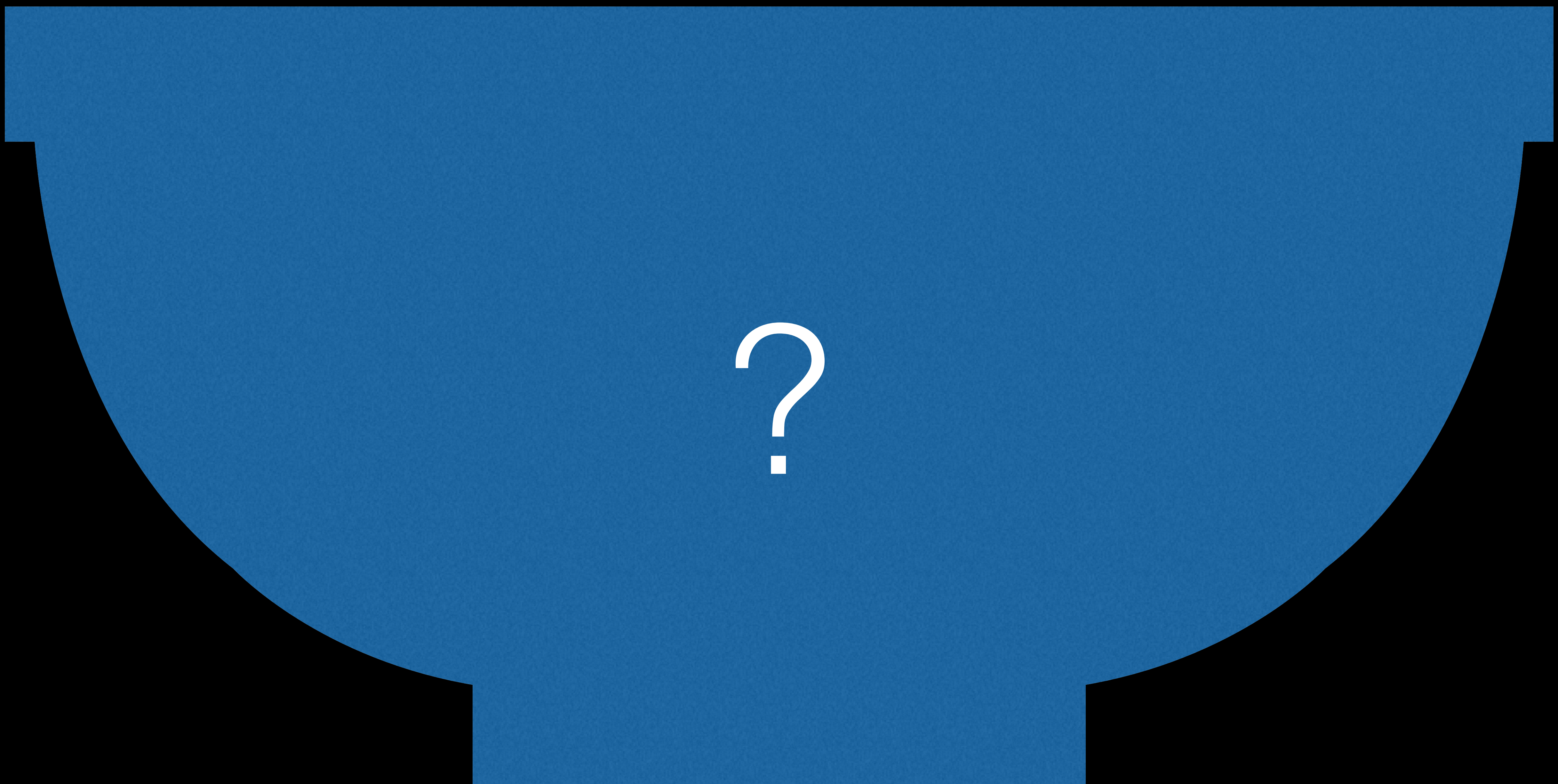
$$\frac{\mathrm{D}\boldsymbol{v}}{\mathrm{D}t} + 2\boldsymbol{\Omega} \times \boldsymbol{v} = -\frac{1}{\rho}\nabla p - \nabla \Phi$$

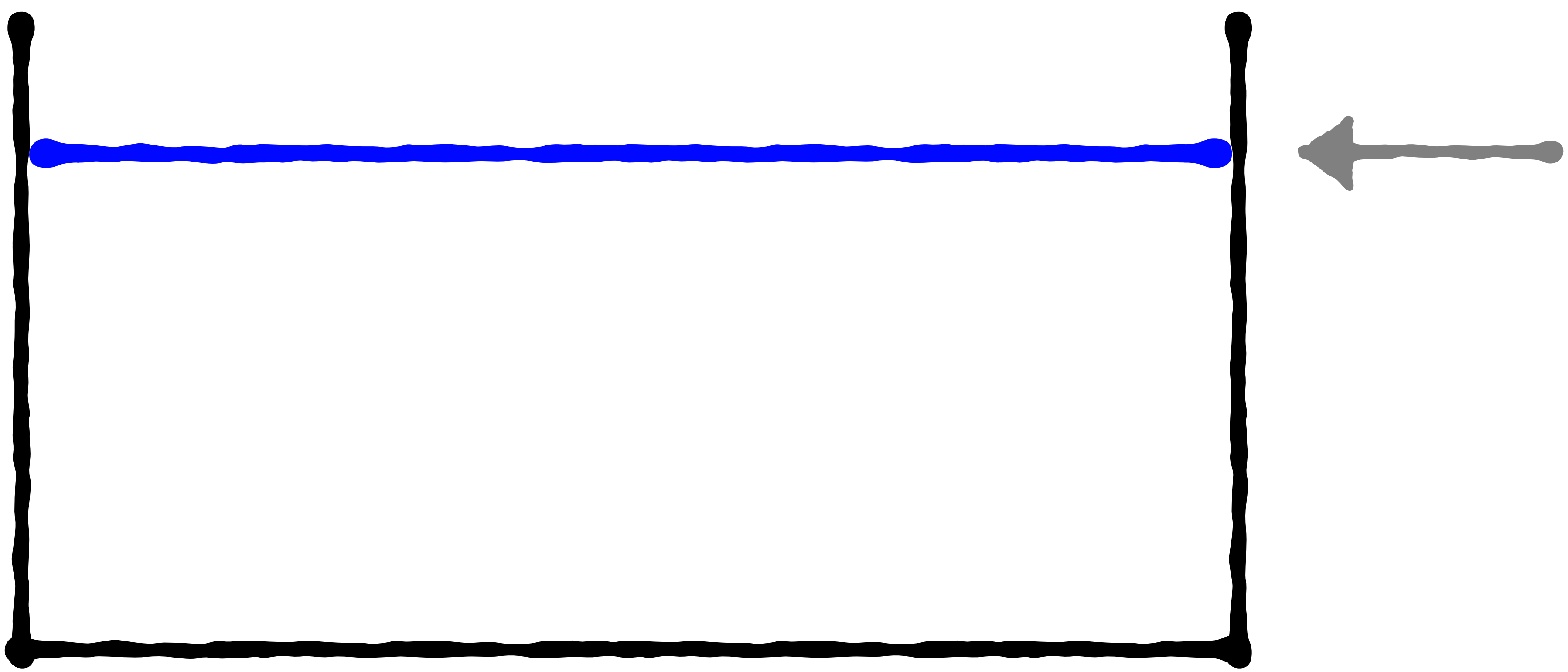
★ Equation of state

$$p = \rho R T$$

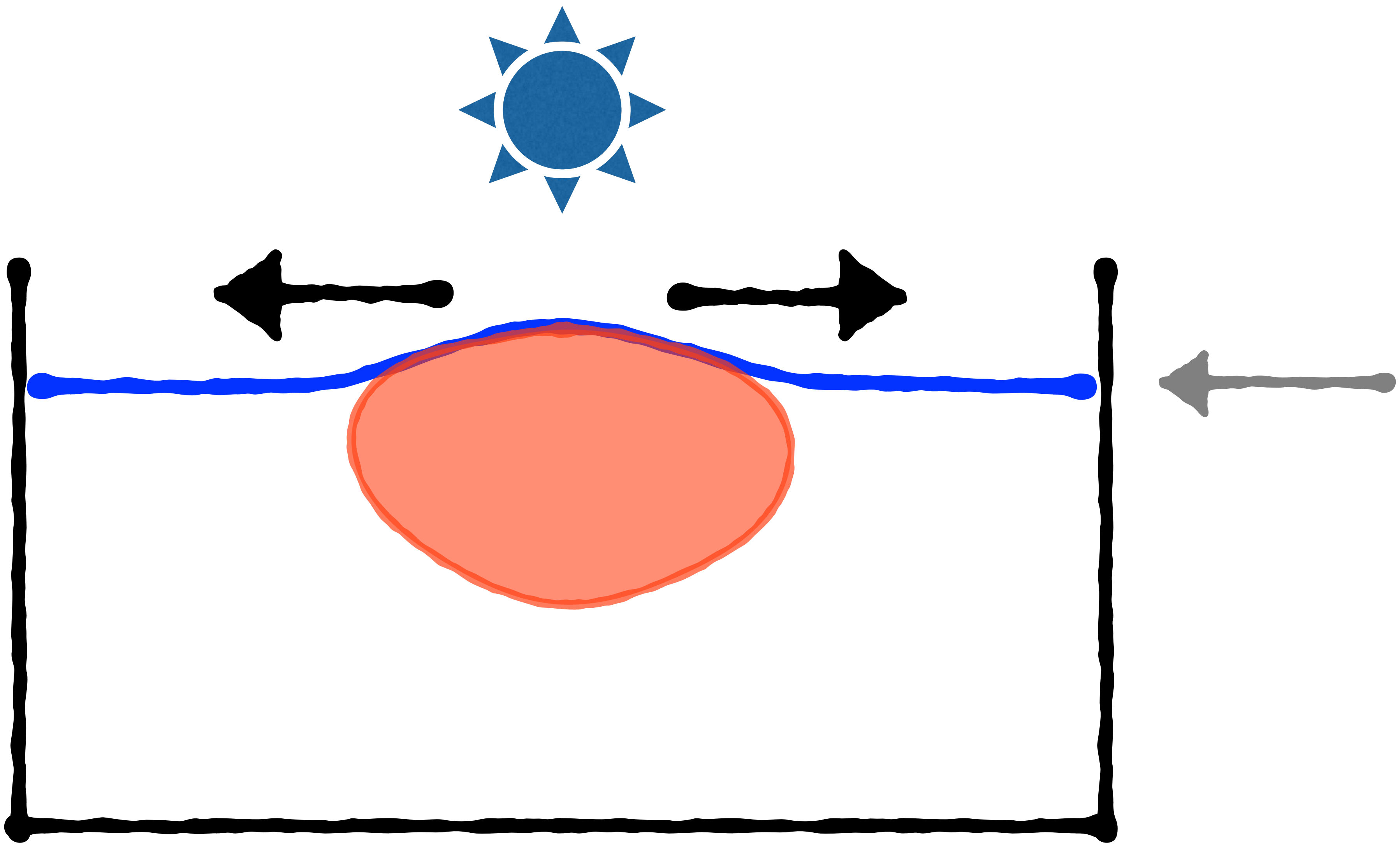
★ Conservation of energy

$$\frac{DS}{Dt} = H - Q$$

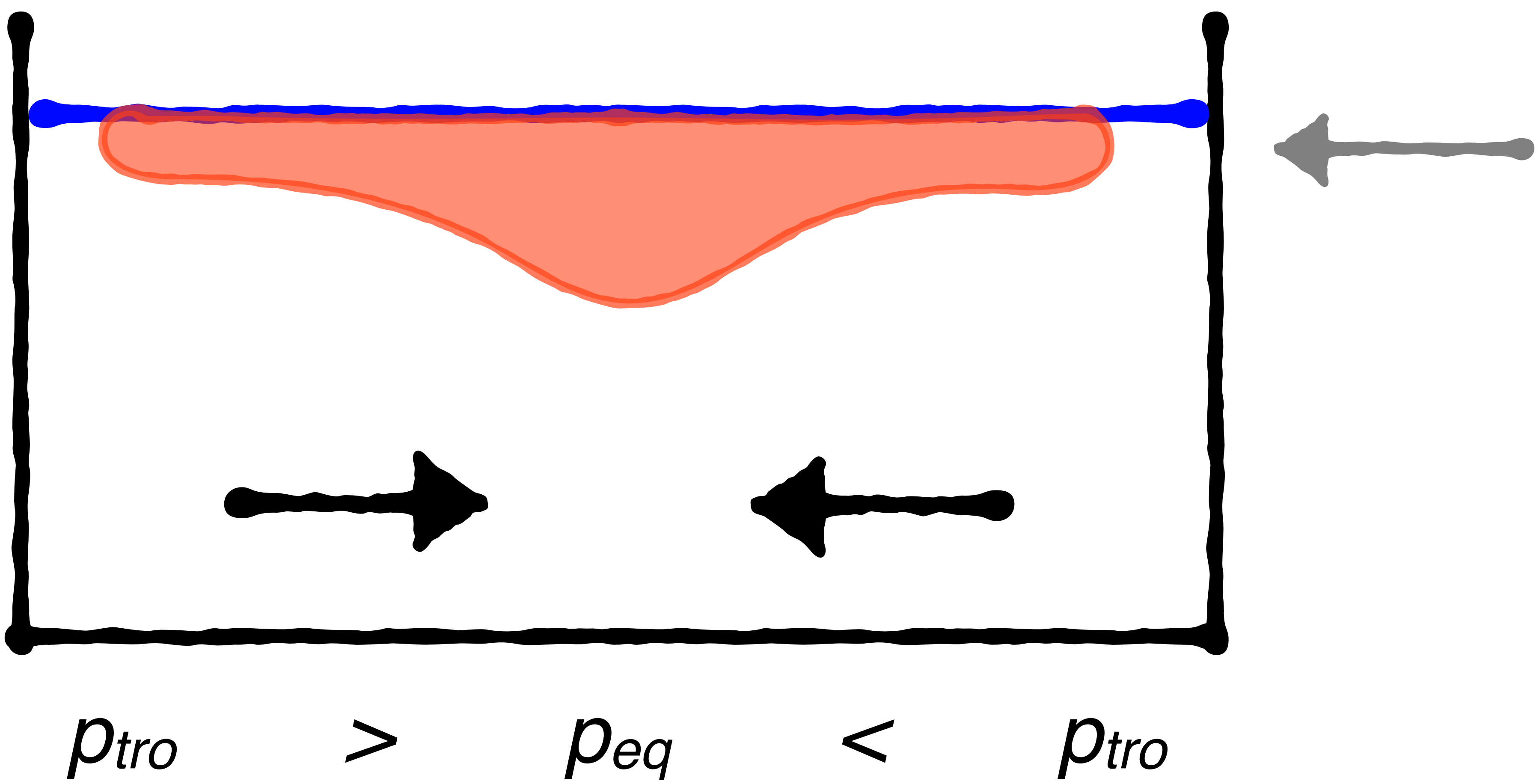


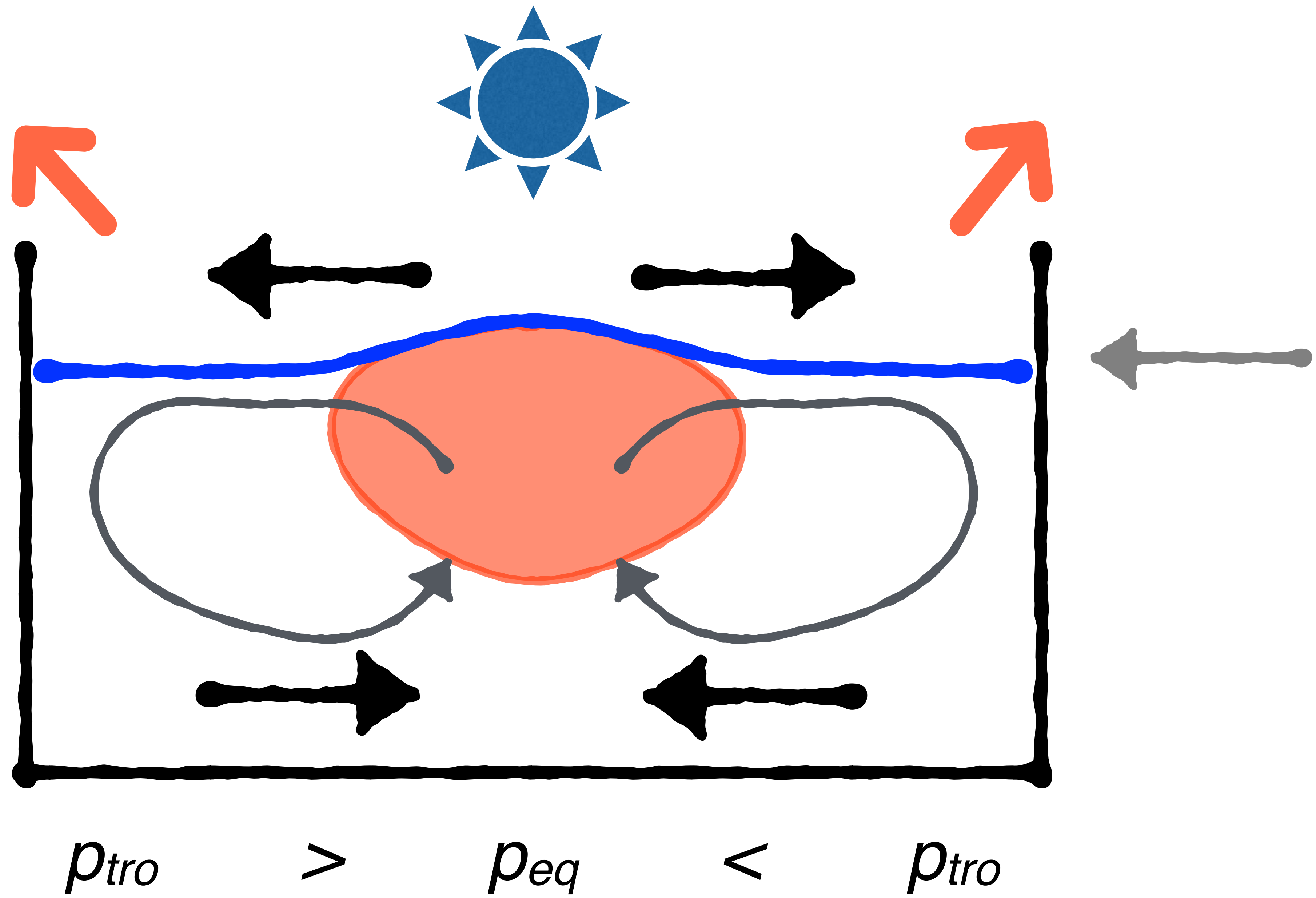


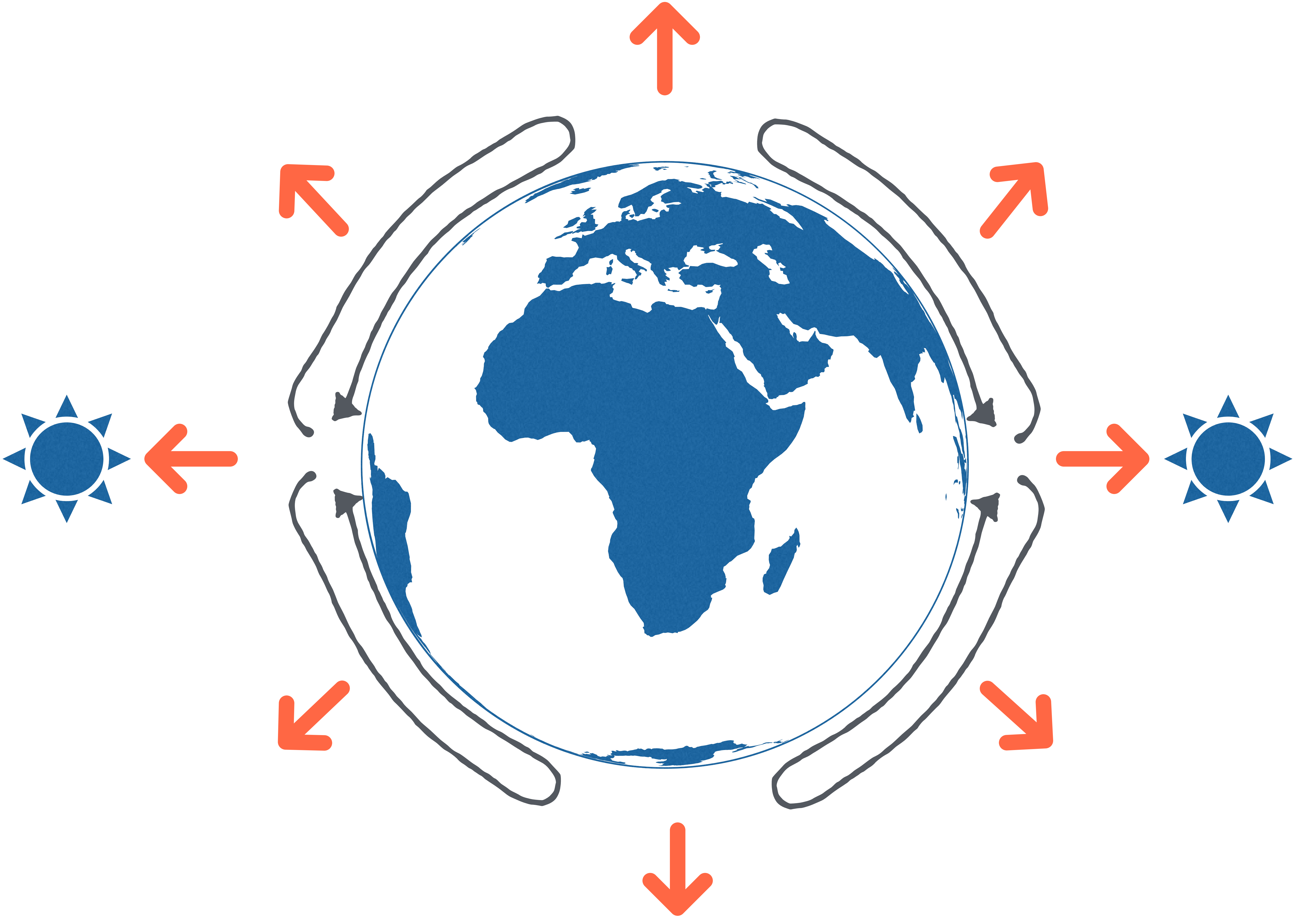
$p_{tro} \quad = \quad p_{eq} \quad = \quad p_{tro}$

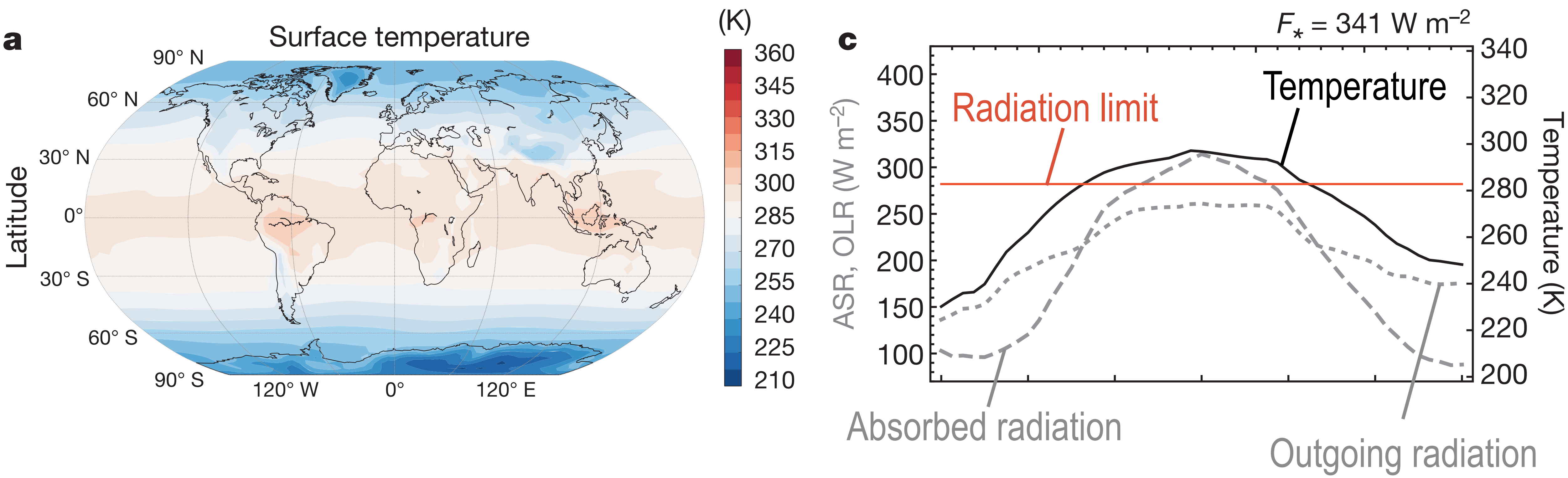


$$p_{tro} = p_{eq} = p_{tro}$$

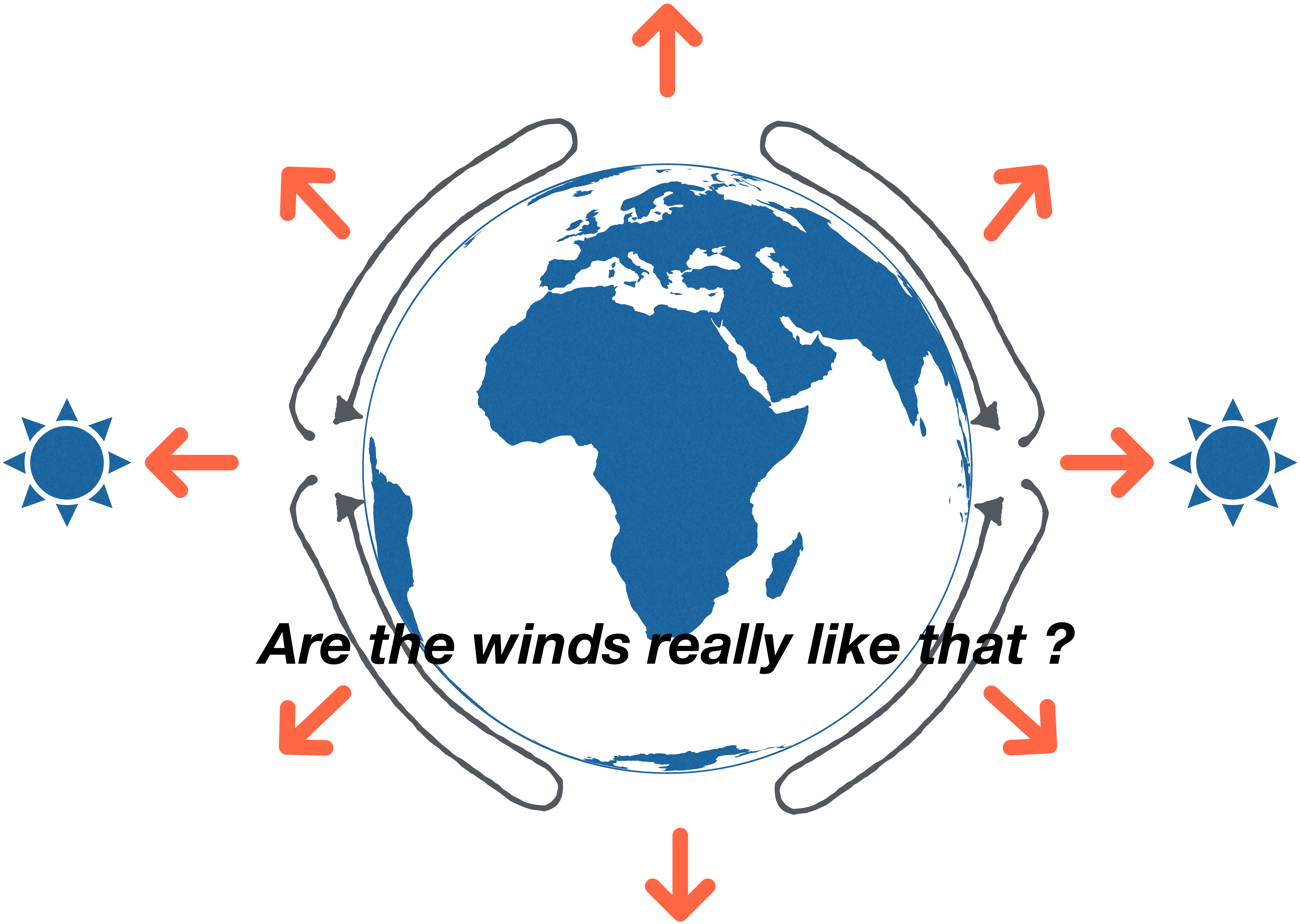

p_{tro} > p_{eq} < p_{tro}


p_{tro} > p_{eq} < p_{tro}

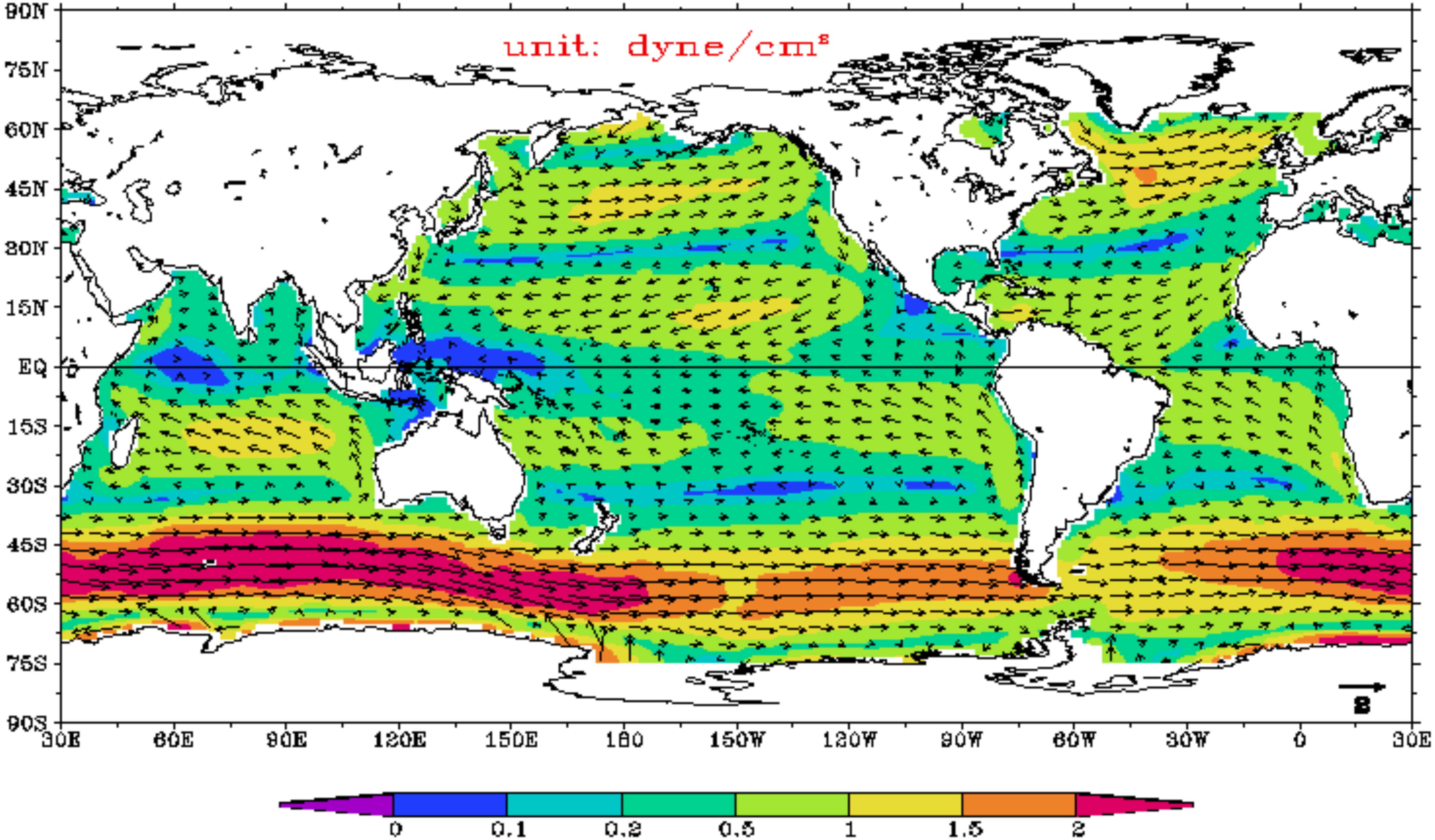


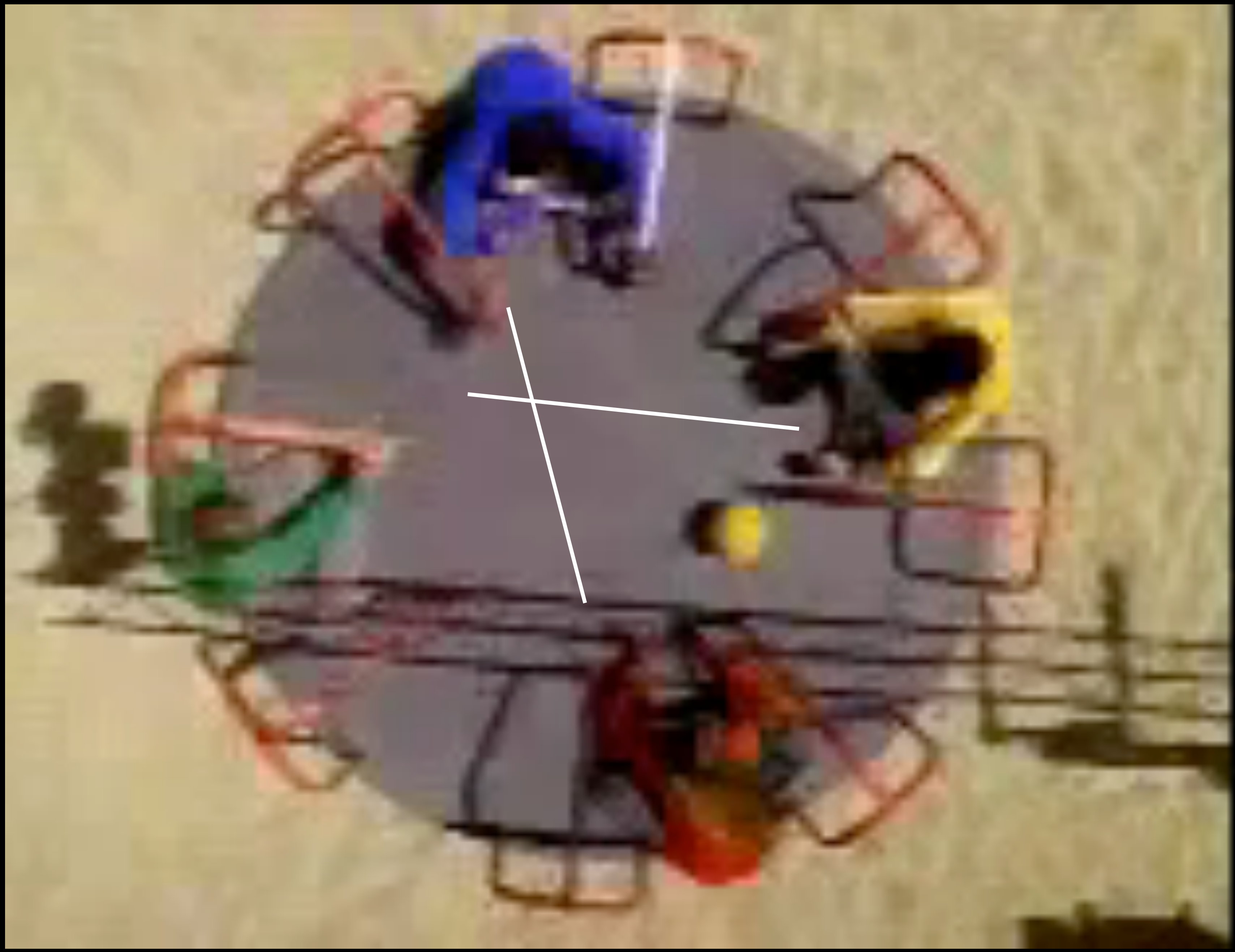


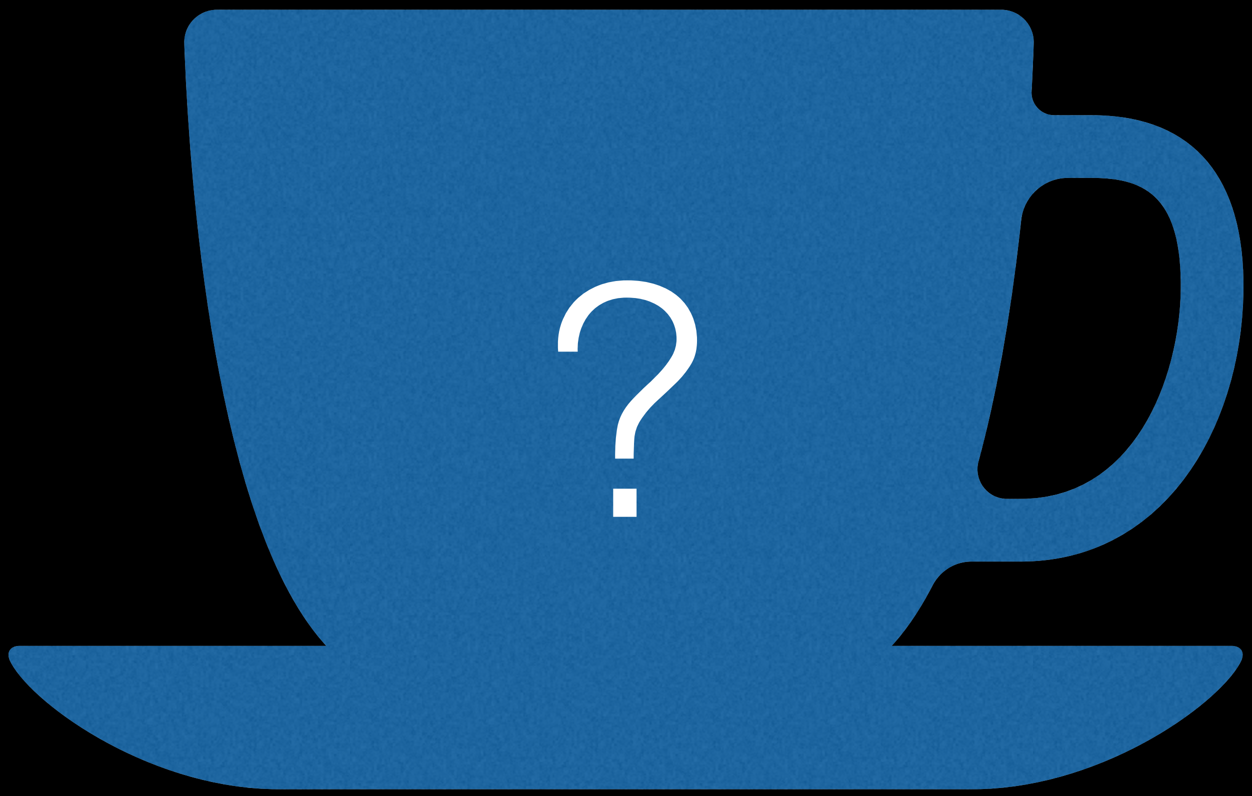
Leconte et al. (Nature, 2013)

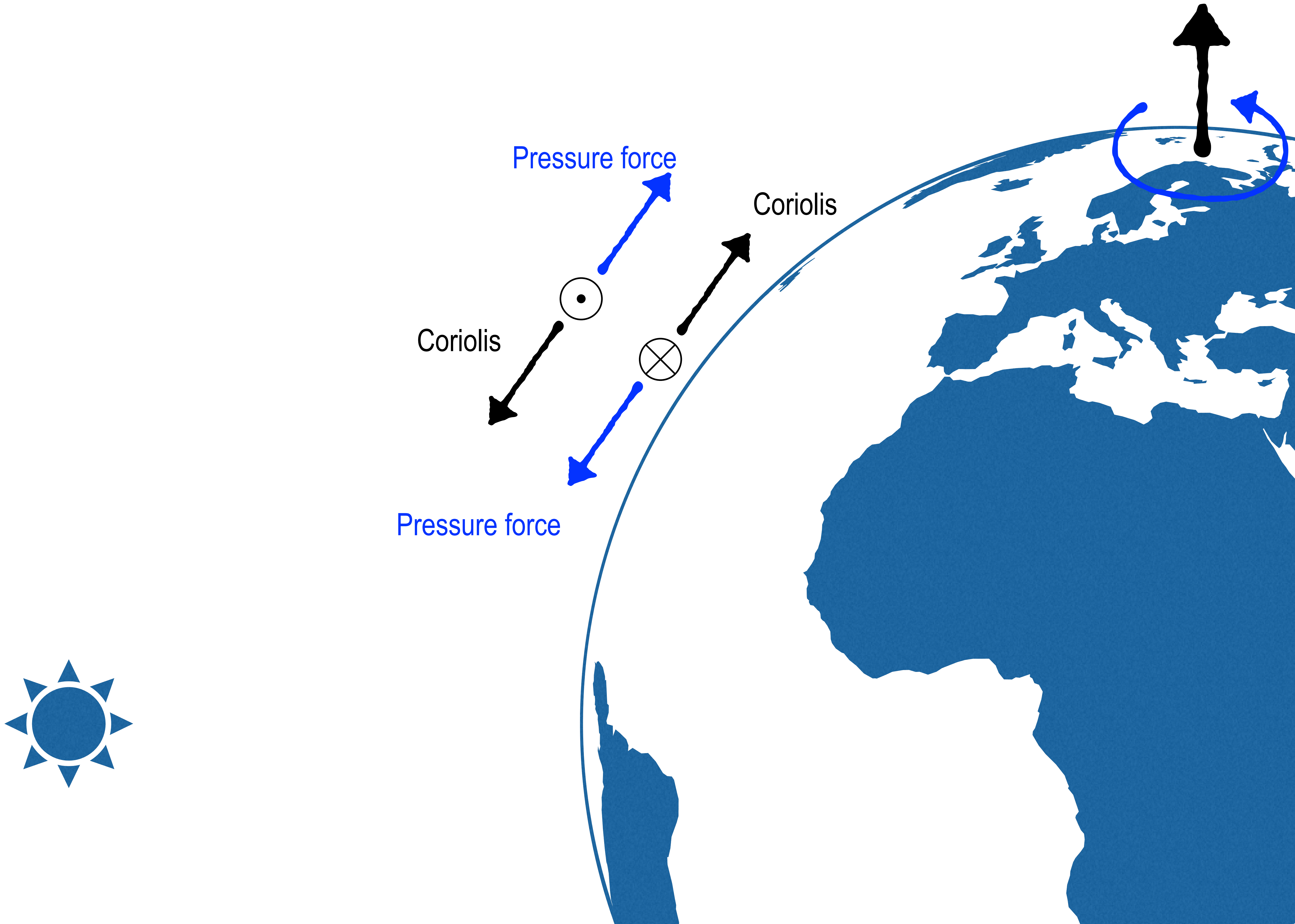

Are the winds really like that ?

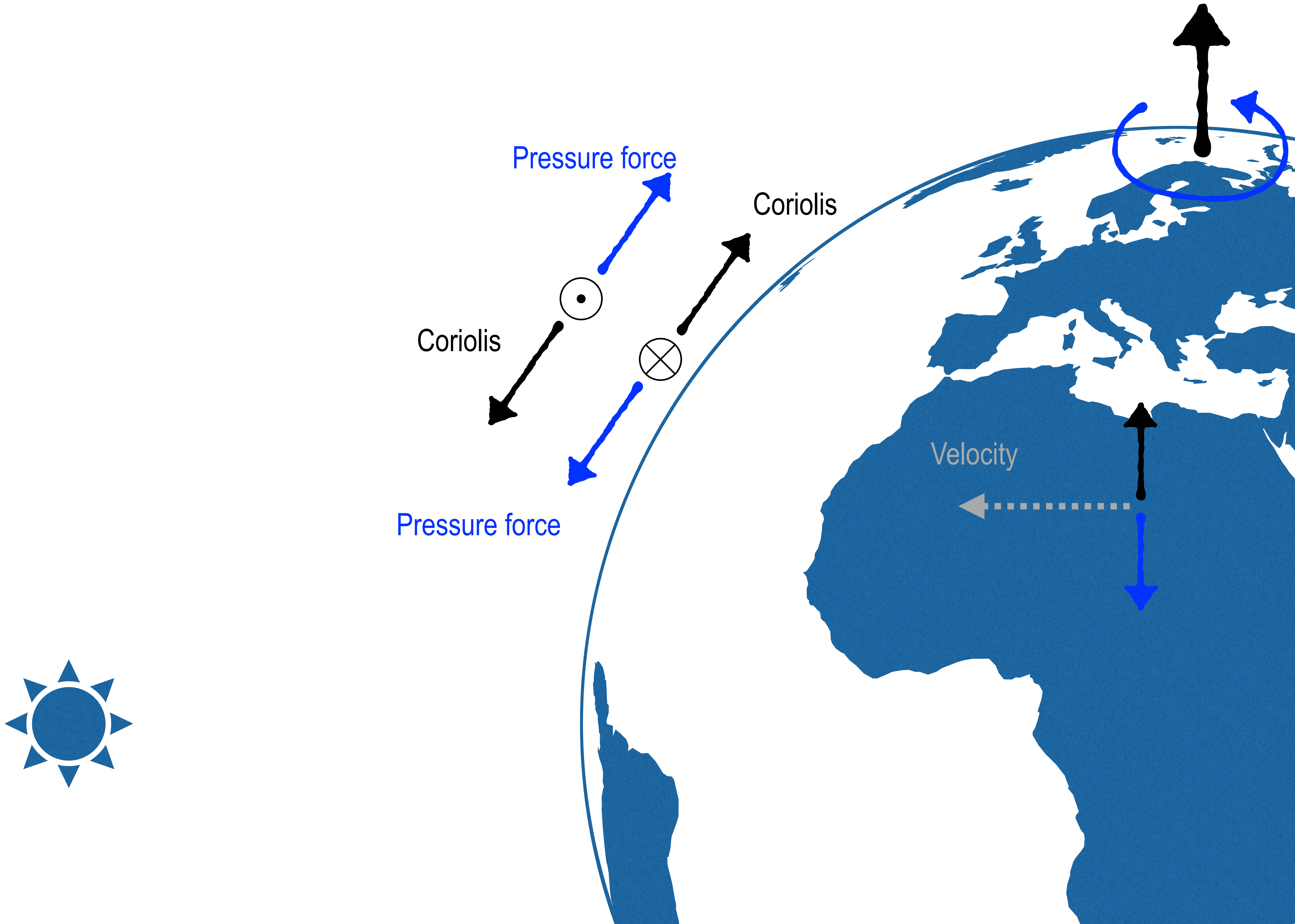
GODAS Wind Stress, 1982–2004 Ann

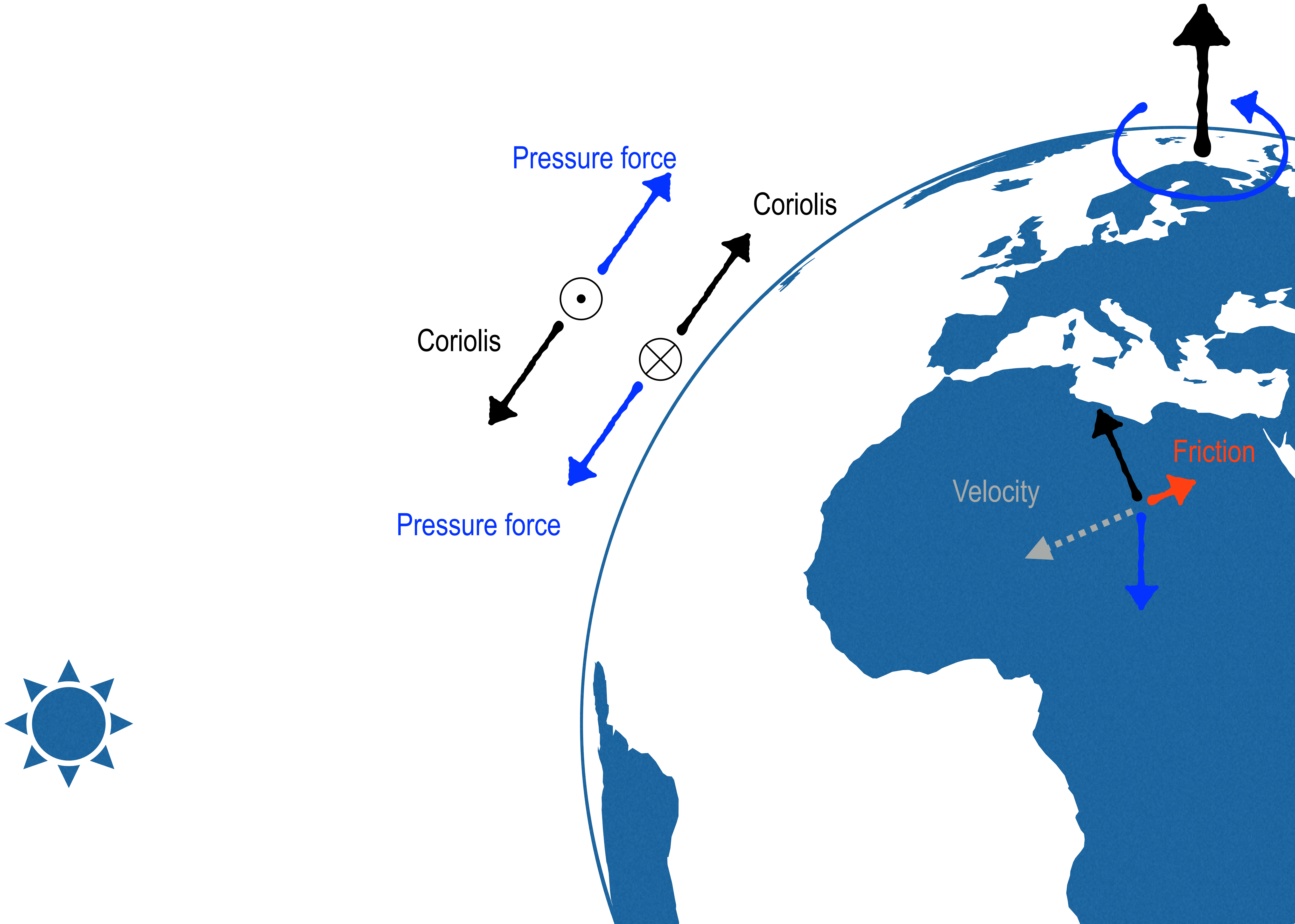


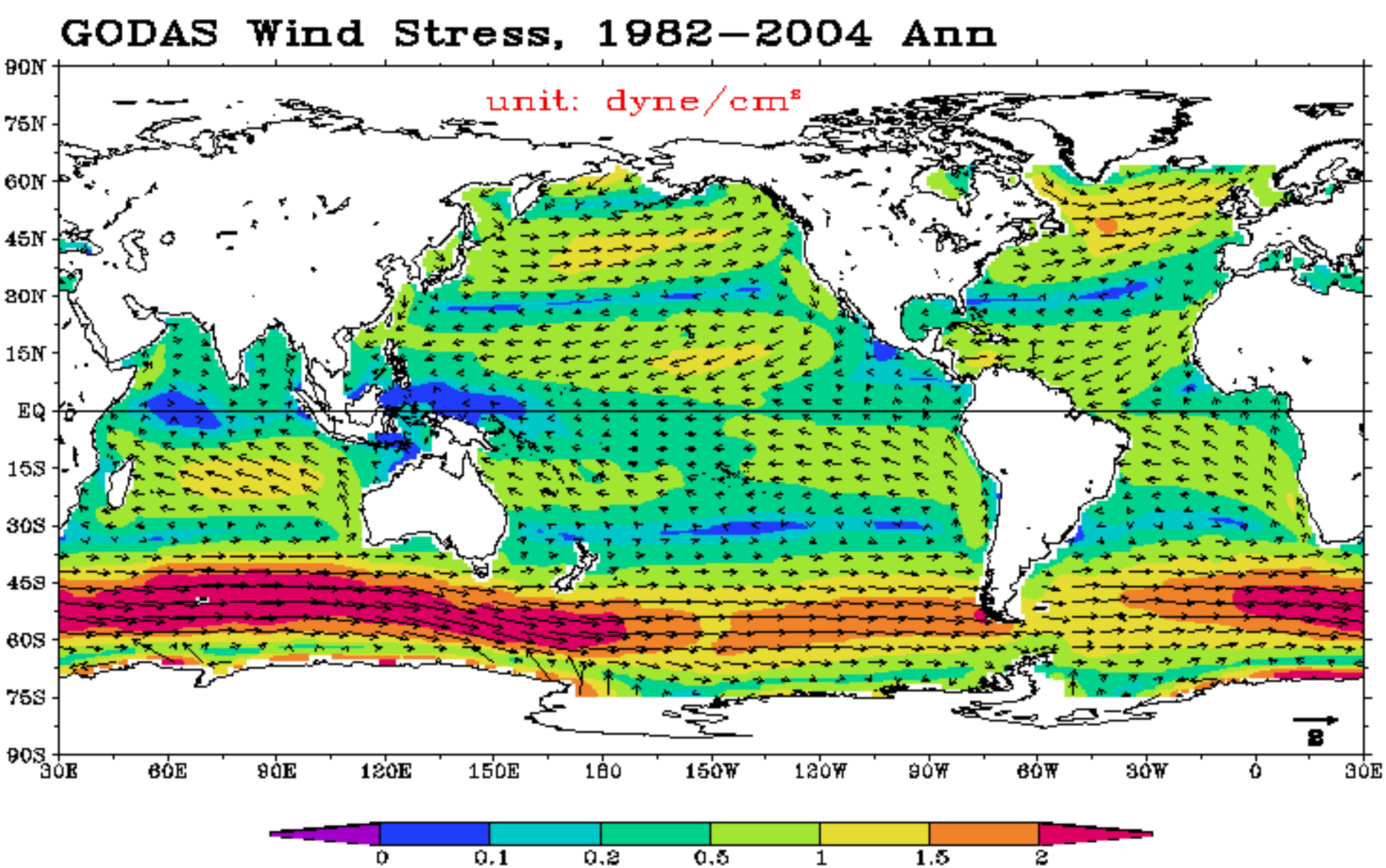


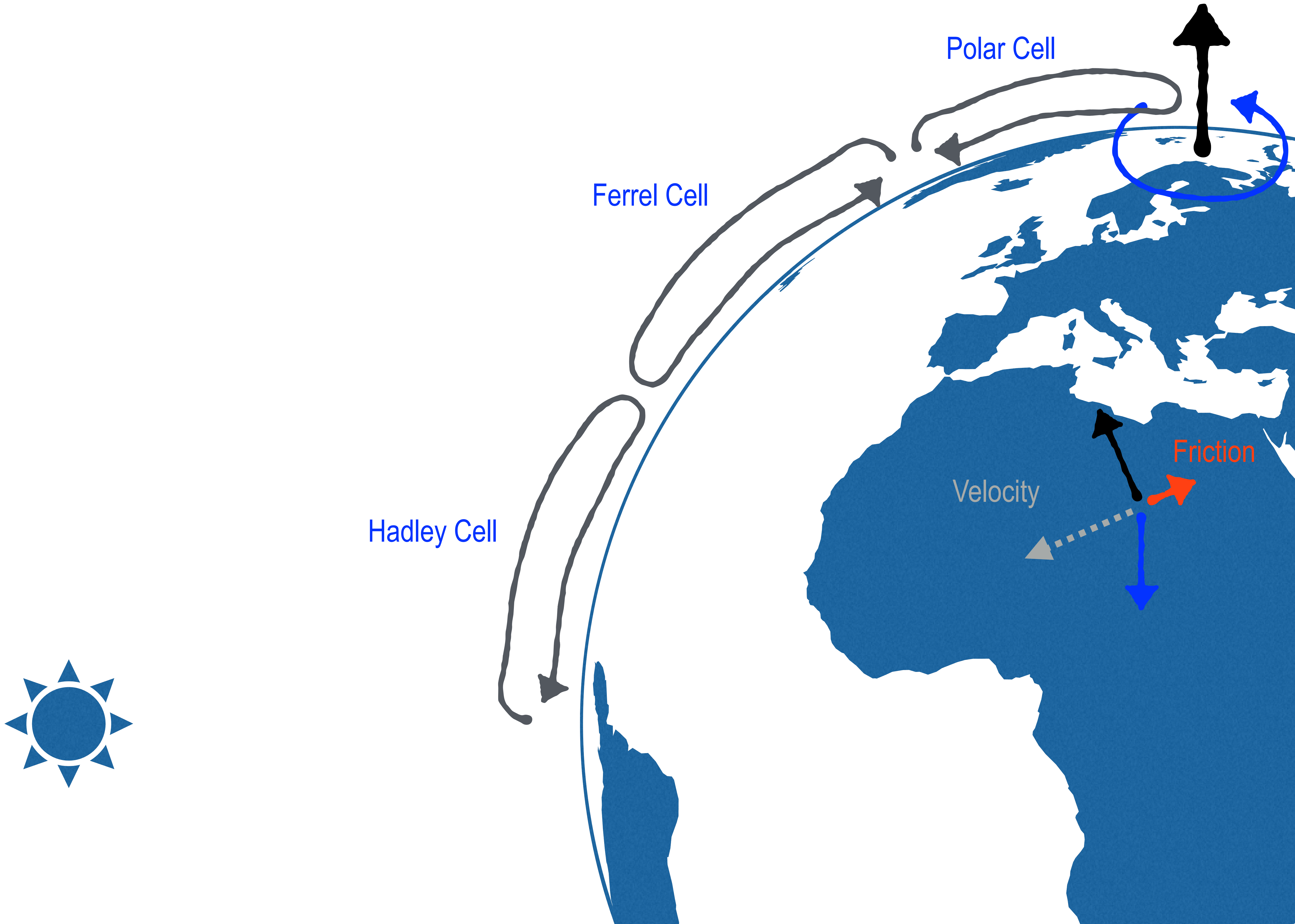


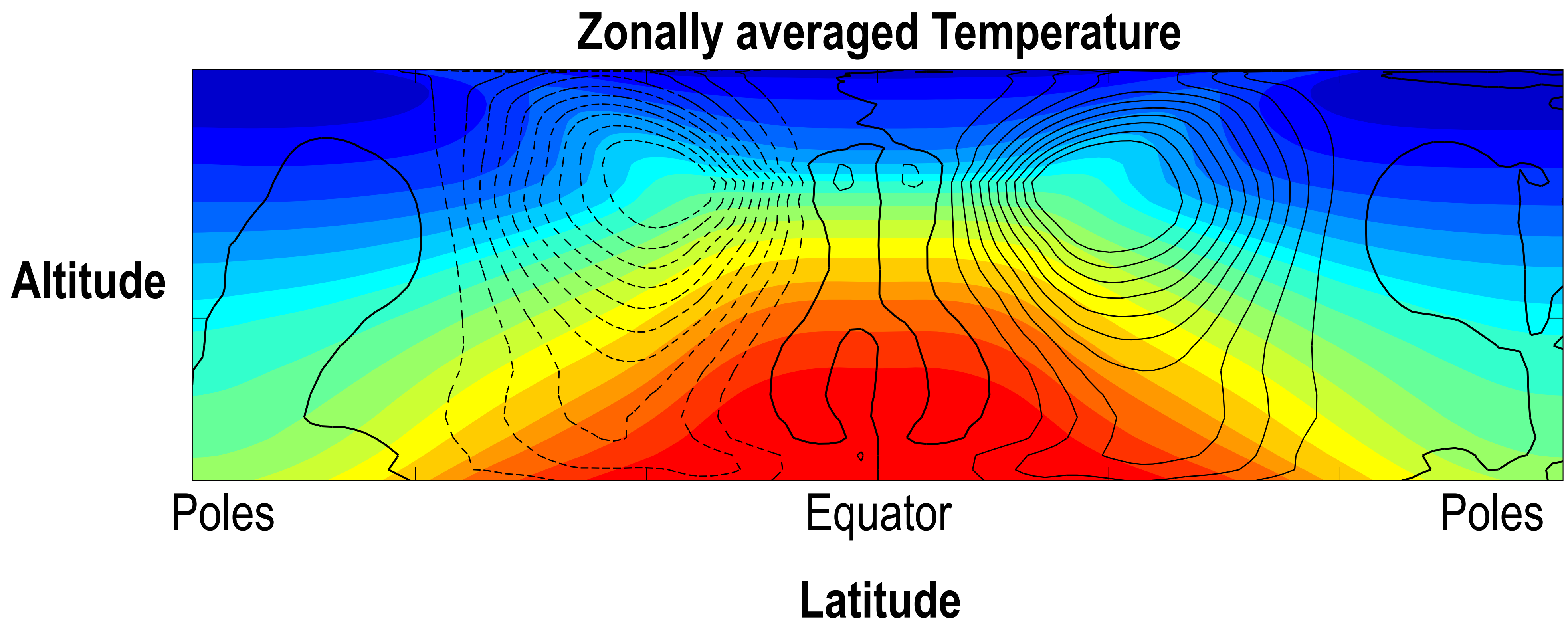

Pressure force
Coriolis
Coriolis
Pressure force

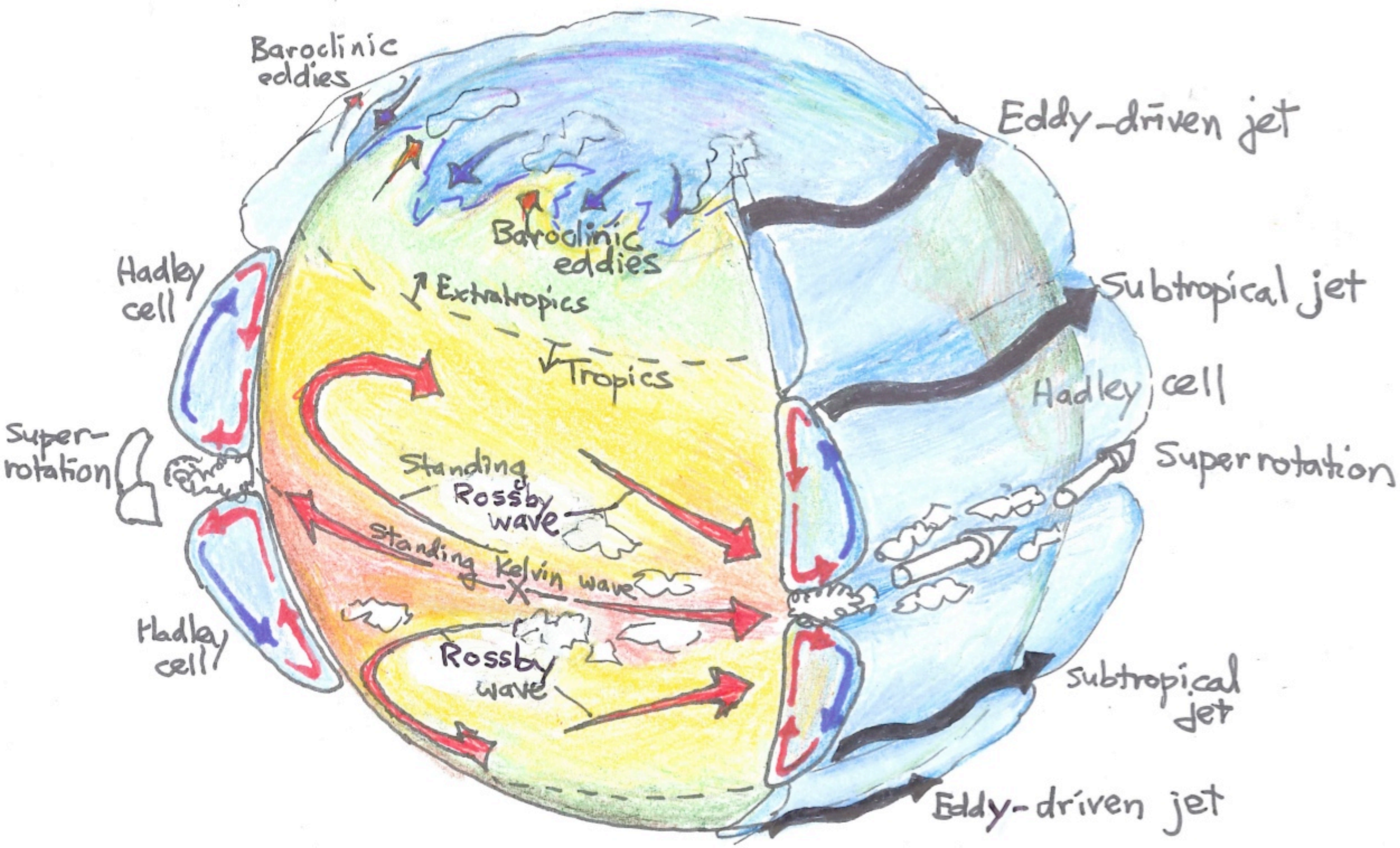

Pressure force
Coriolis
Coriolis
Pressure force
Velocity


Pressure force
Coriolis
Coriolis
Pressure force
Friction
Velocity


GODAS Wind Stress, 1982–2004 Ann
unit: dyne/cm²
90N
75N
60N
45N
30N
15N
EQ
15S
30S
45S
60S
75S
90S
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
30E
2
0
0.1
0.2
0.5
1
1.5
2

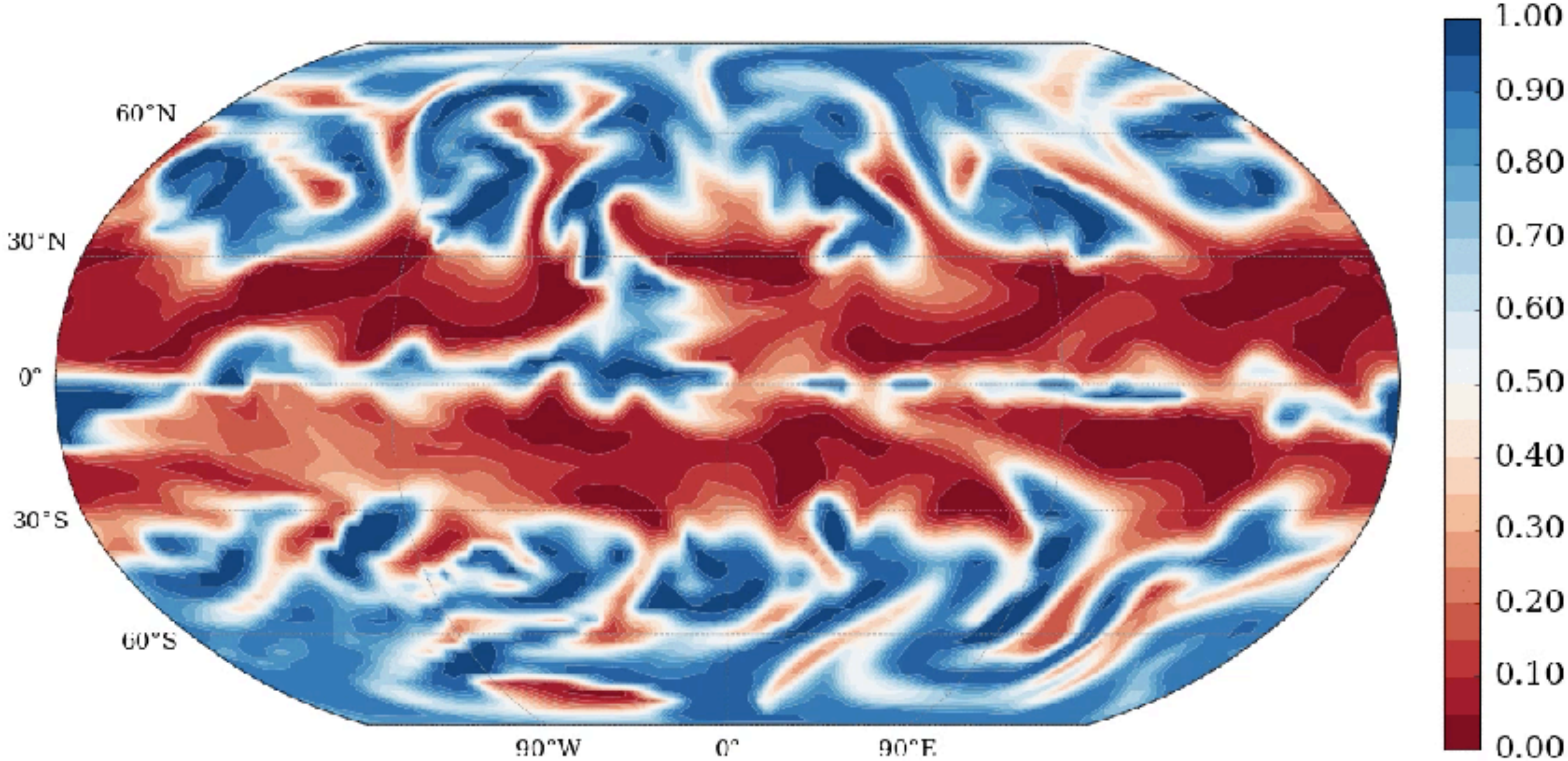

Polar Cell
Ferrel Cell
Hadley Cell
Friction
Velocity

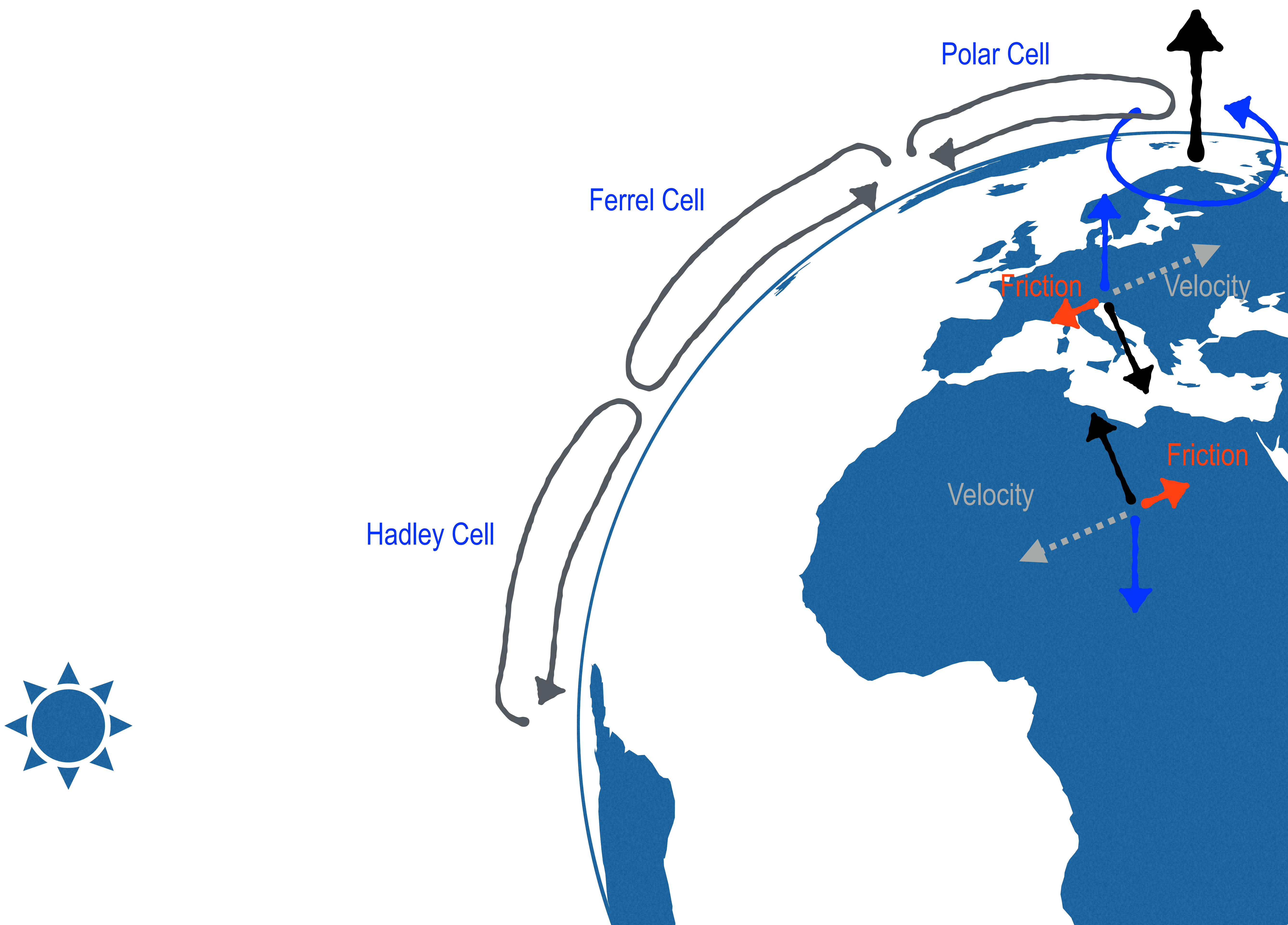




In memory of Adam Showman

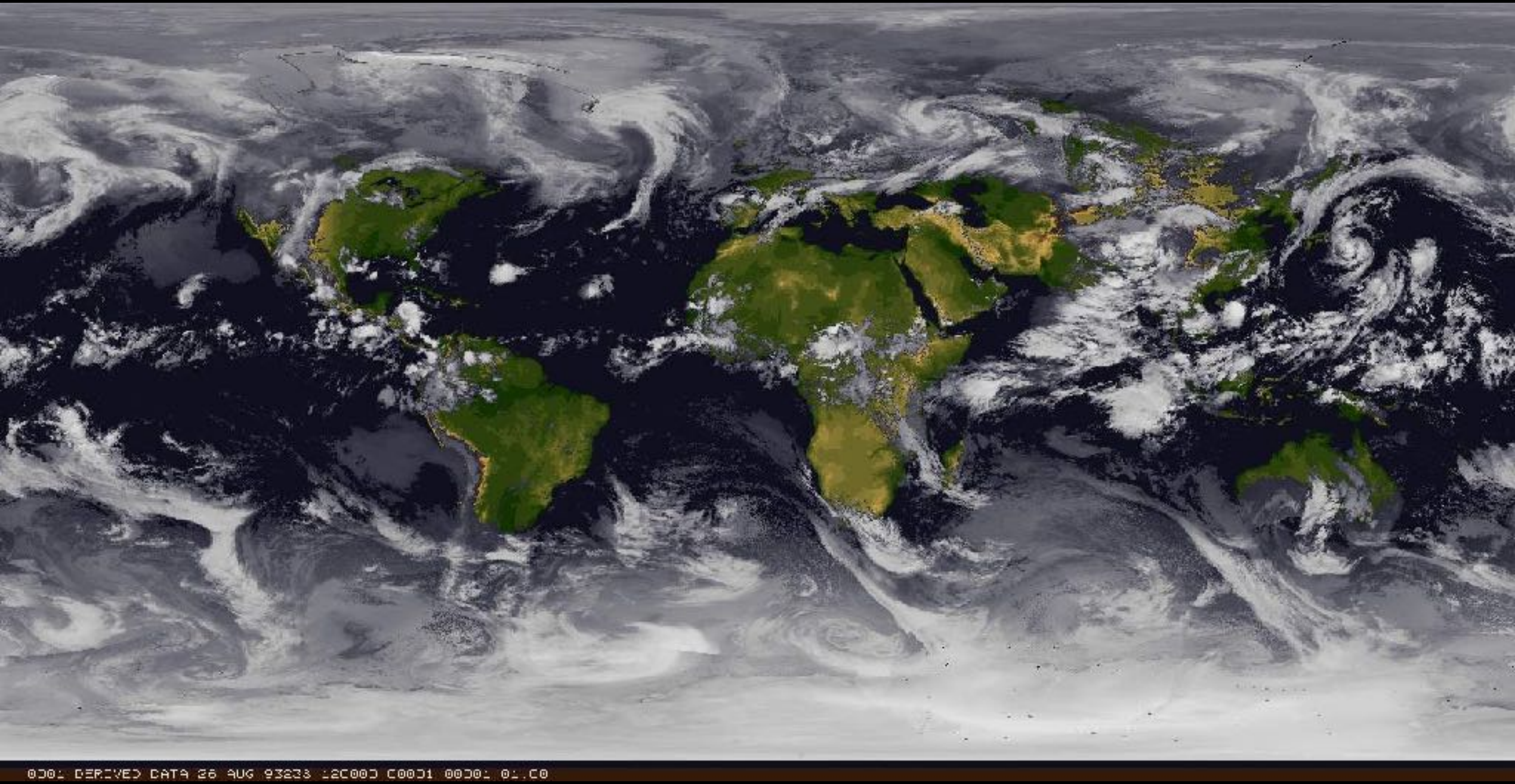
Relative Humidity

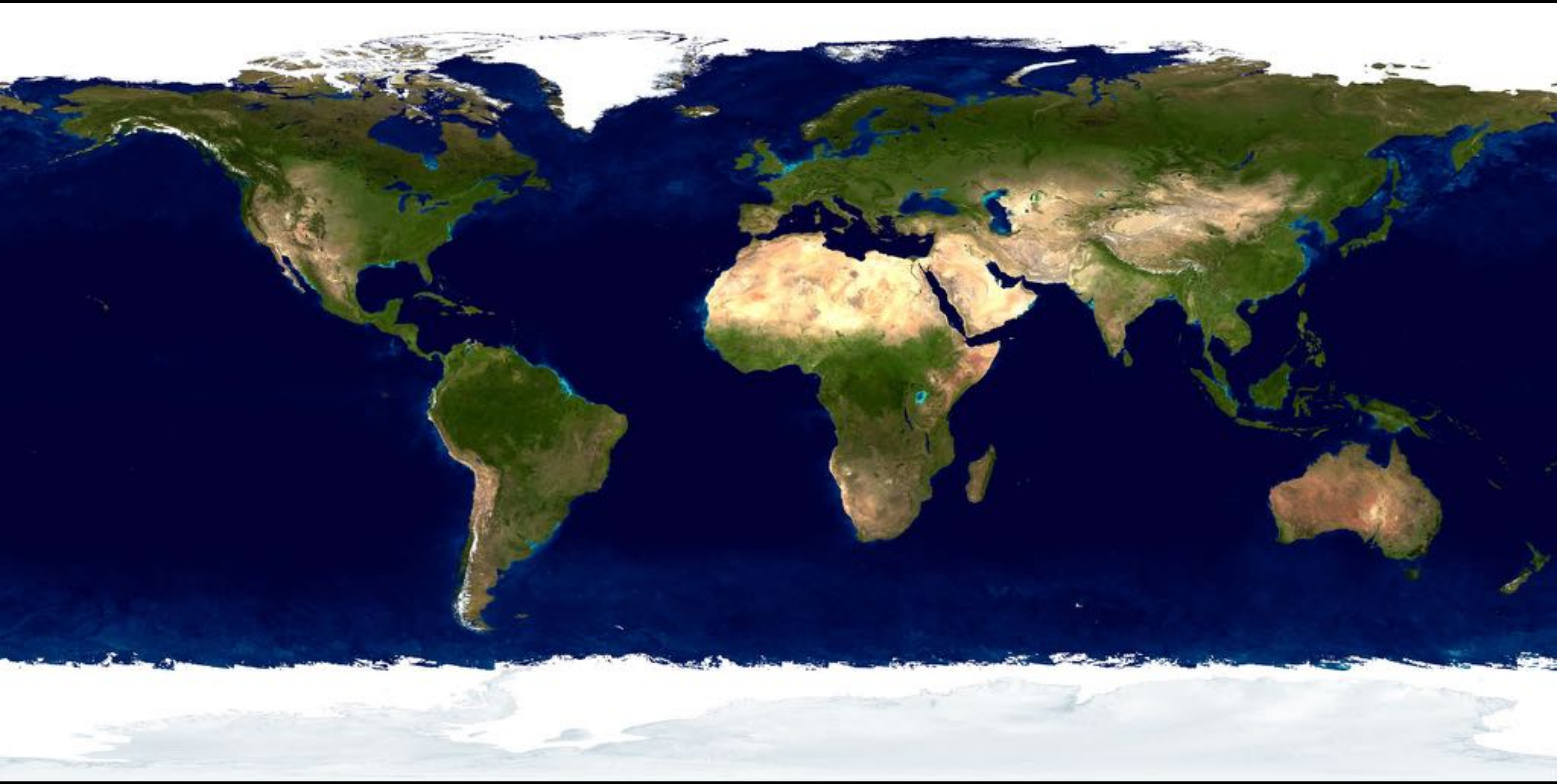




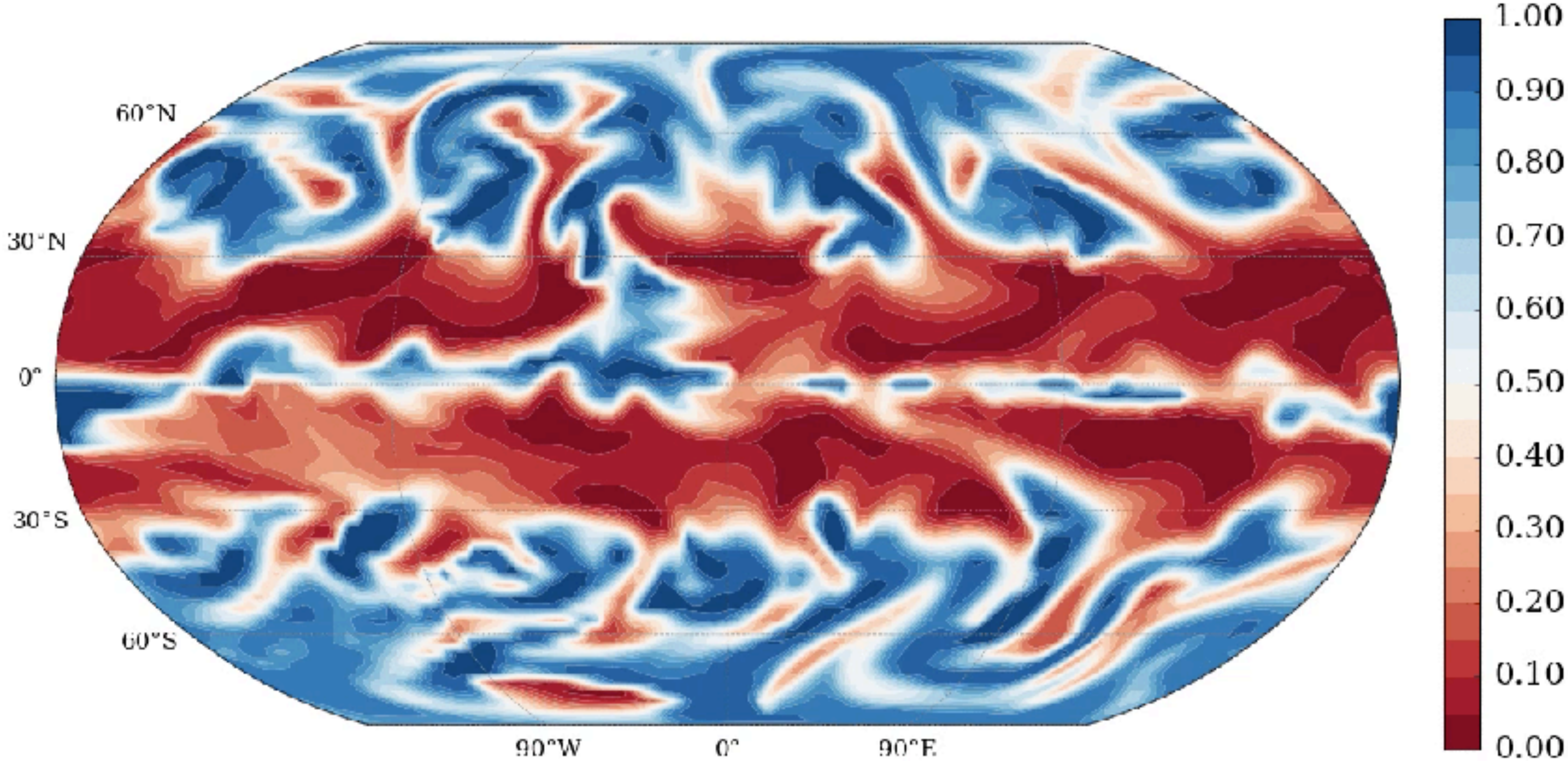
Polar Cell
Ferrel Cell
Hadley Cell
Friction
Velocity
Friction
Velocity

Can we actually see it ?

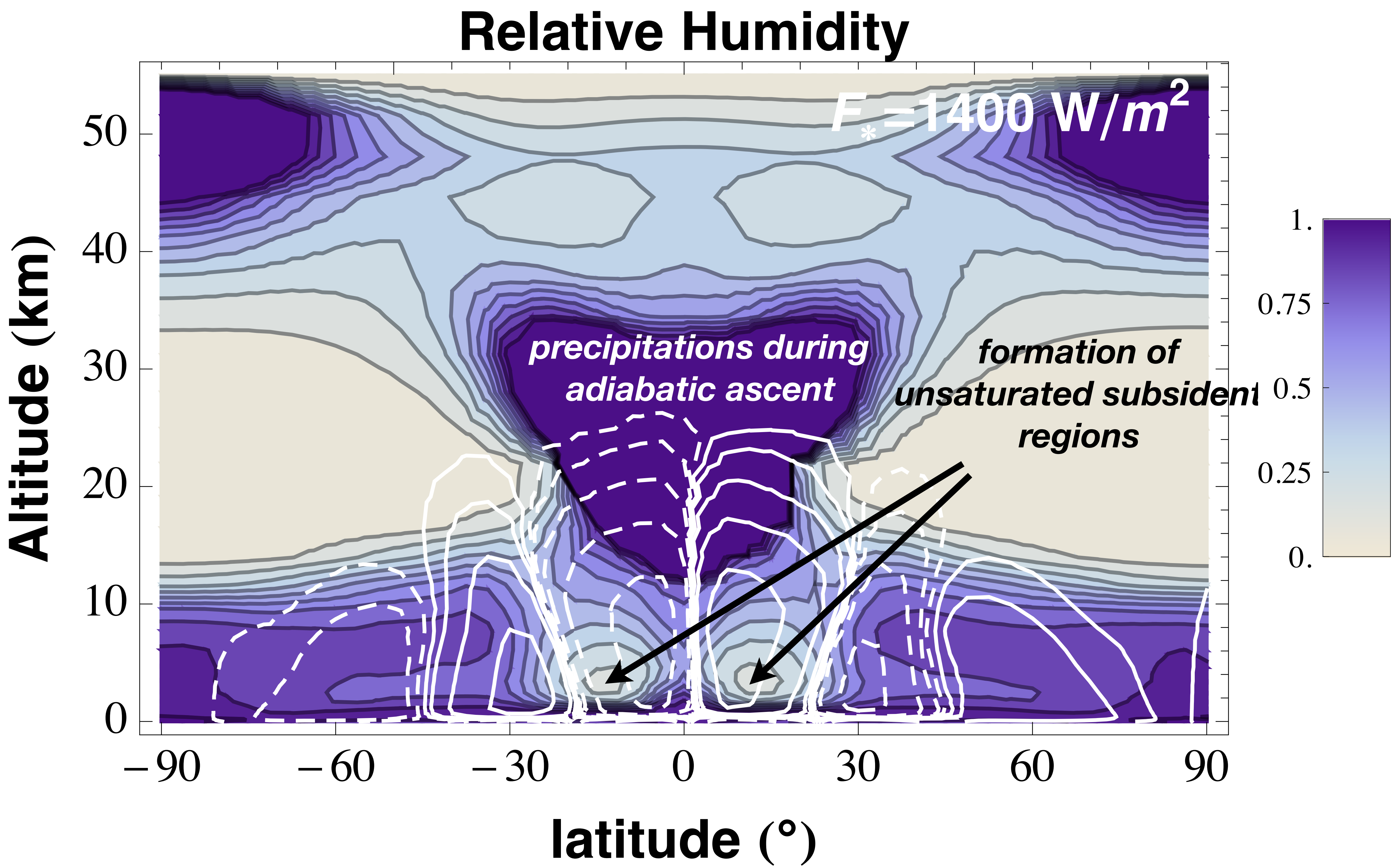

0001 DERIVED DATA 26 AUG 93238 120000 00001 00001 01.00



Relative Humidity

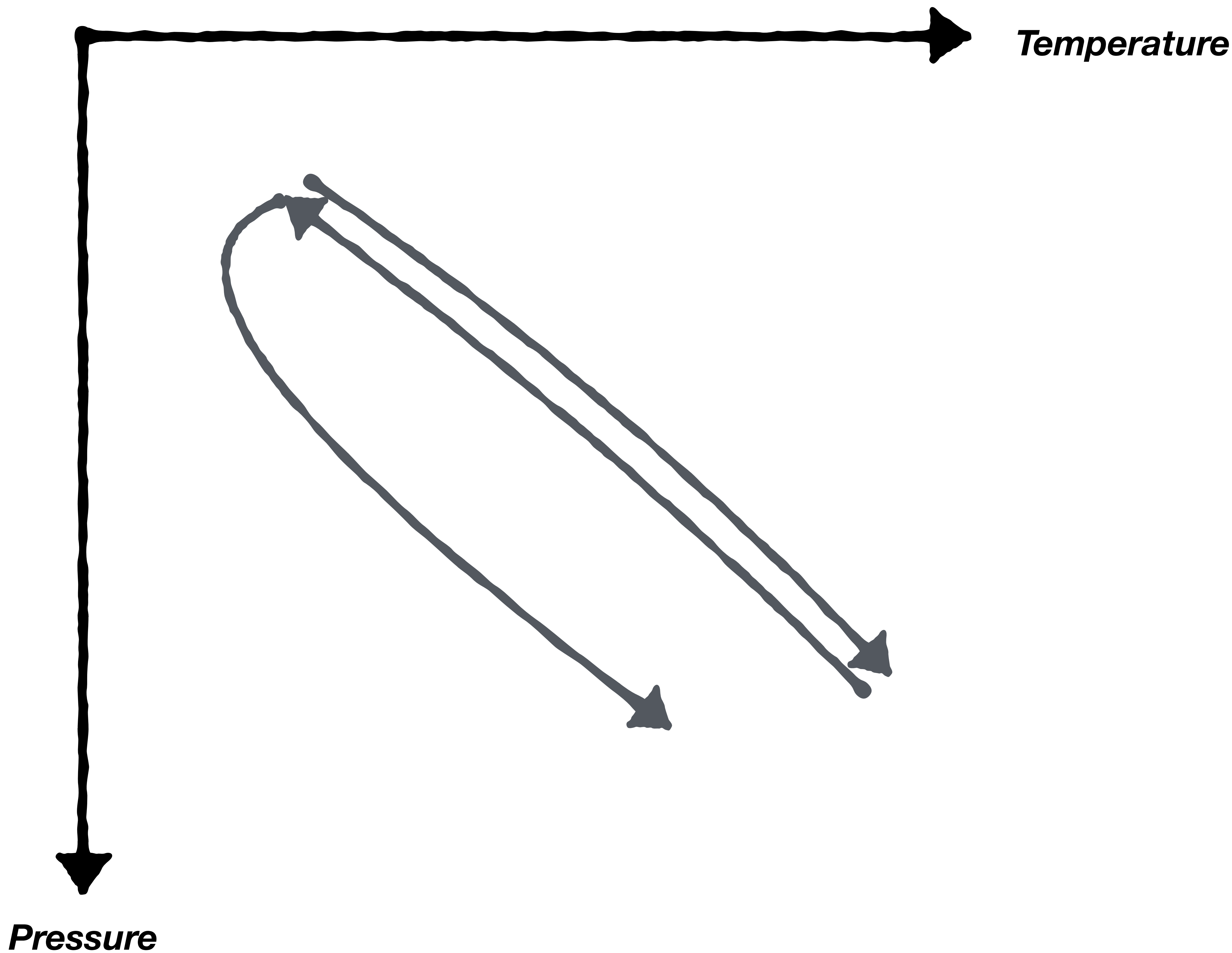


The impact of the Hadley cell

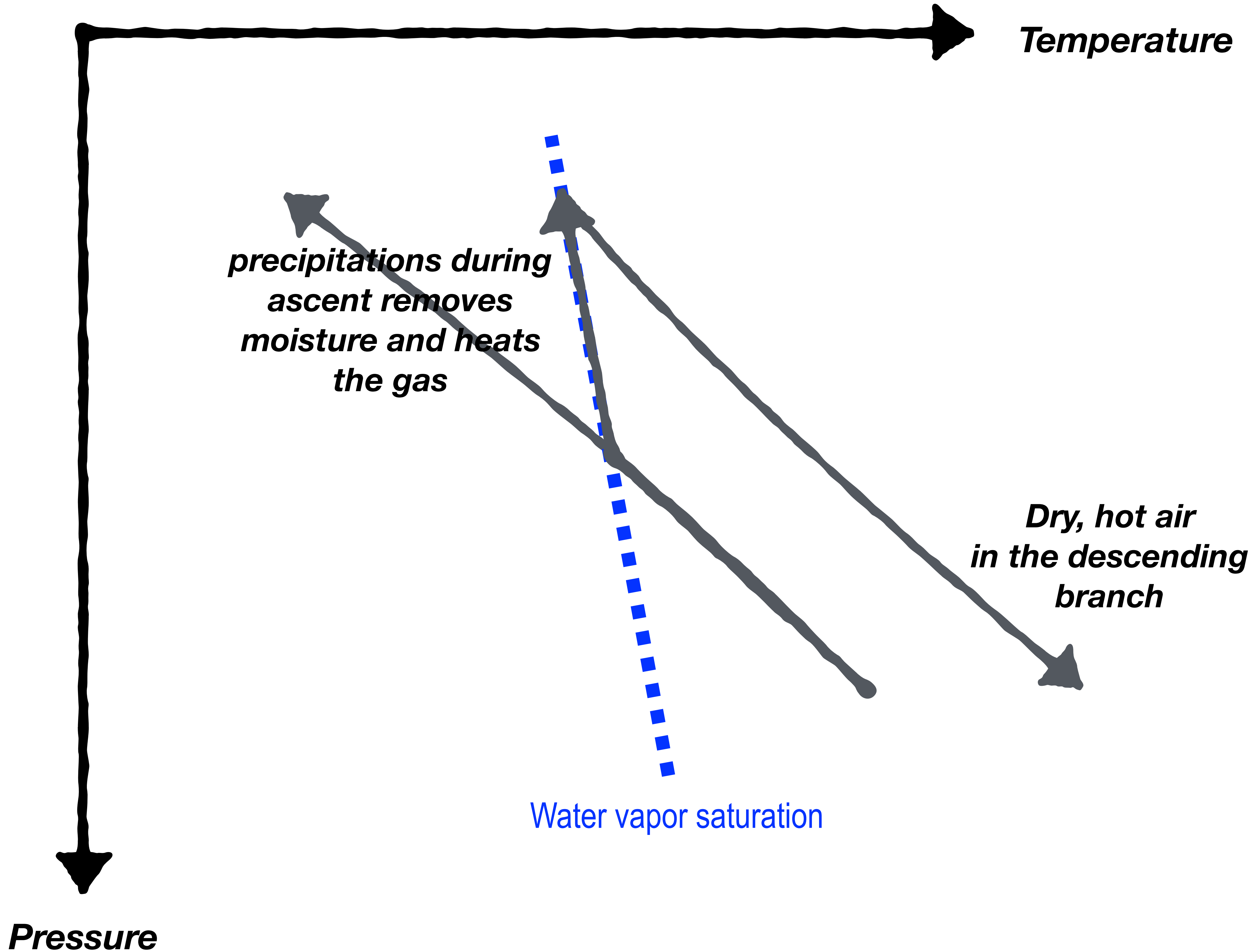


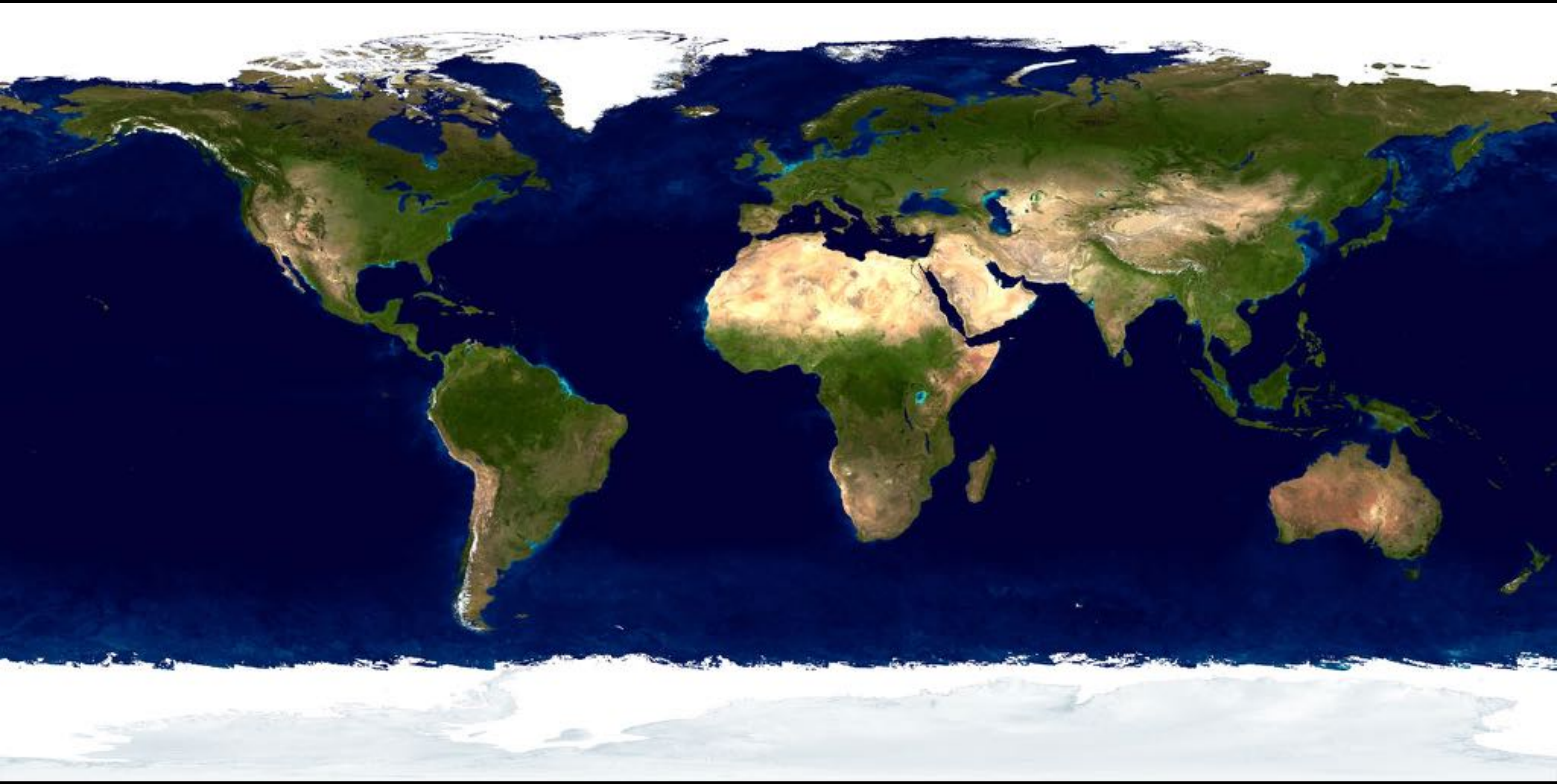
Leconte et al. (Nature, 2013)

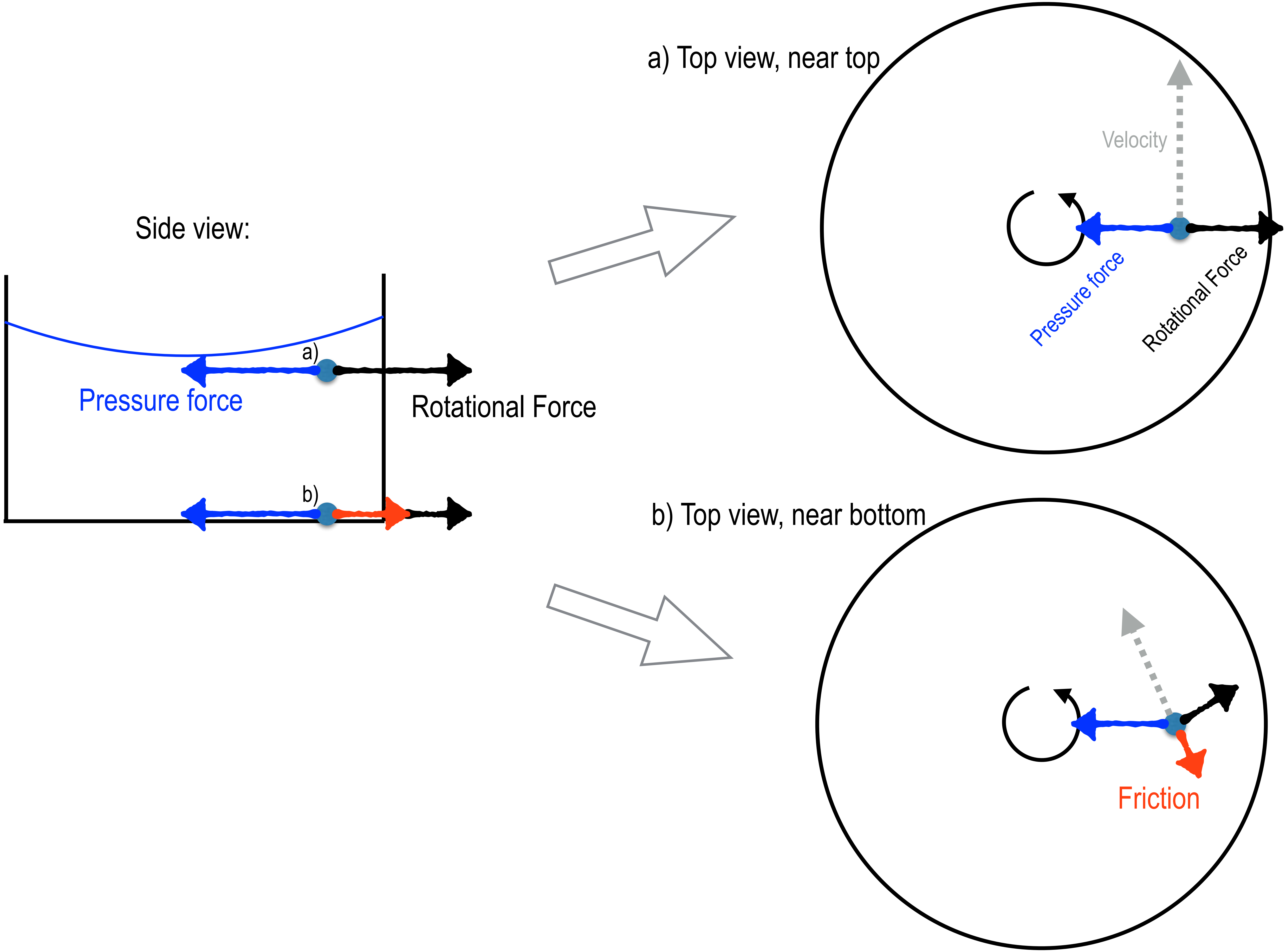
Thermodynamics of the Hadley Cell

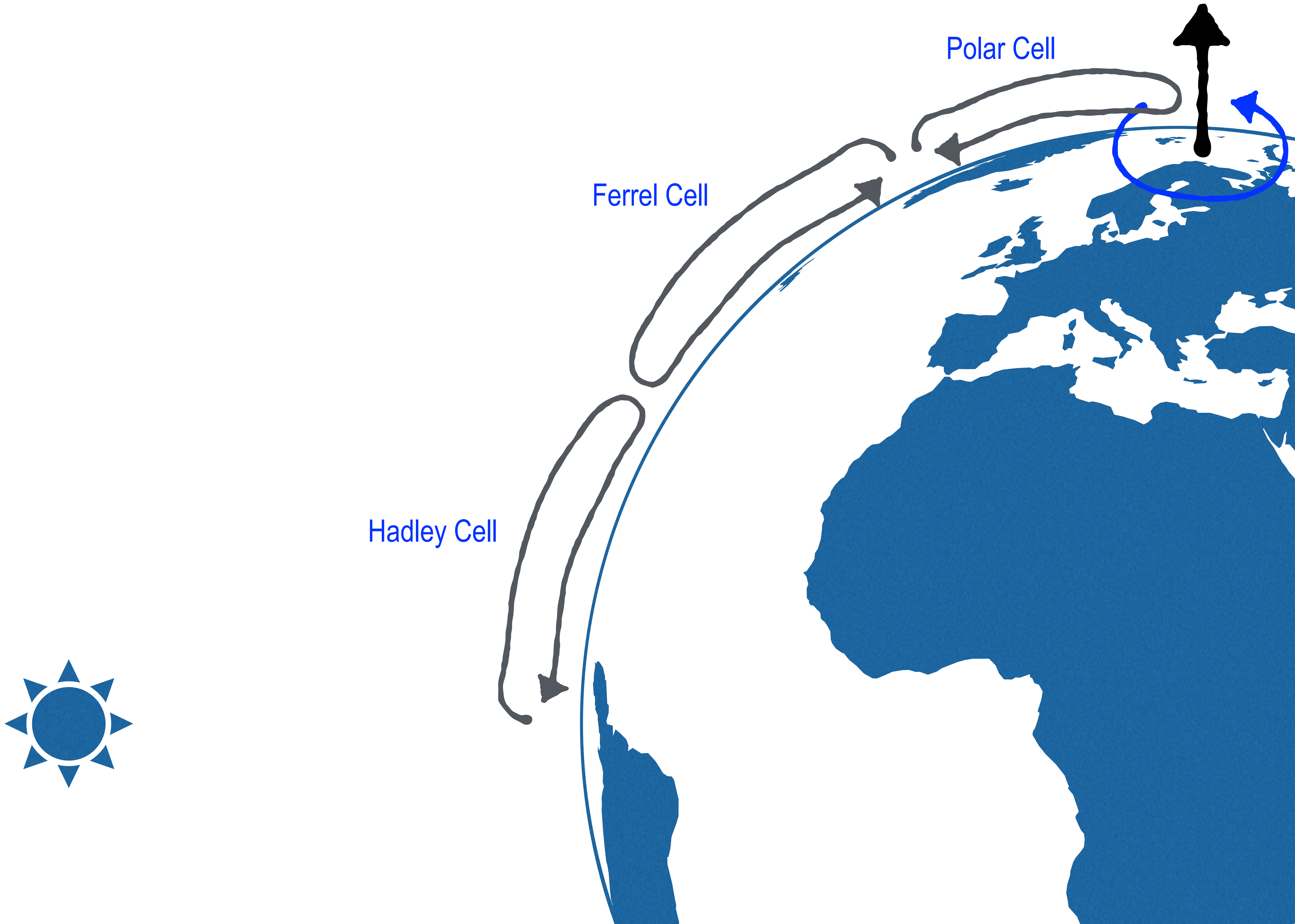


Thermodynamics of the Hadley Cell



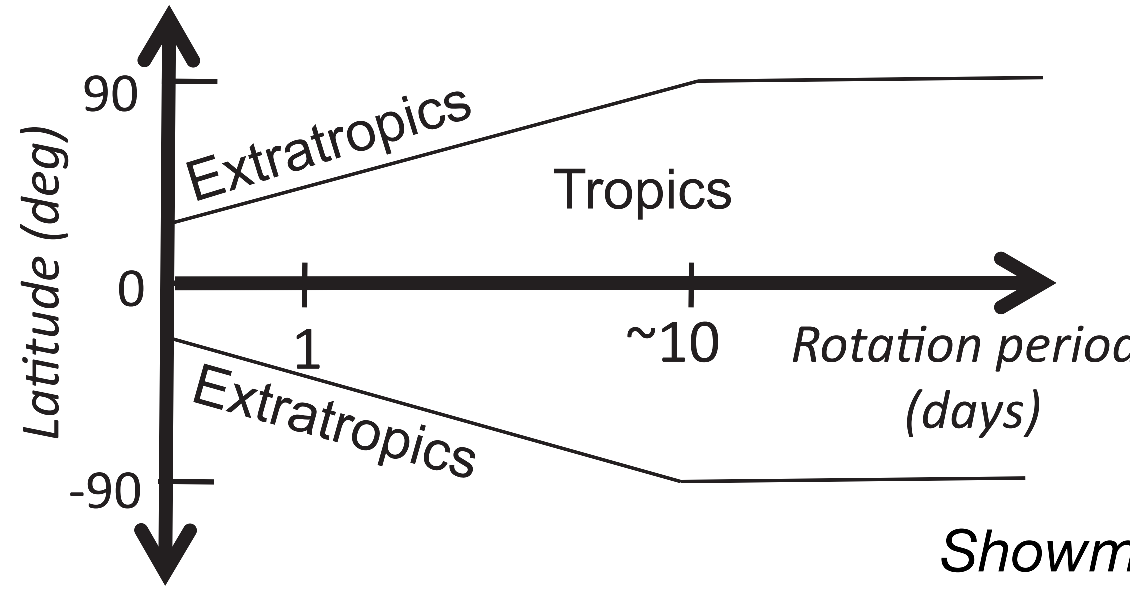



Side view:
a)
b)
Pressure force
Rotational Force
a) Top view, near top
Velocity
Pressure force
Rotational Force
b) Top view, near bottom
Friction

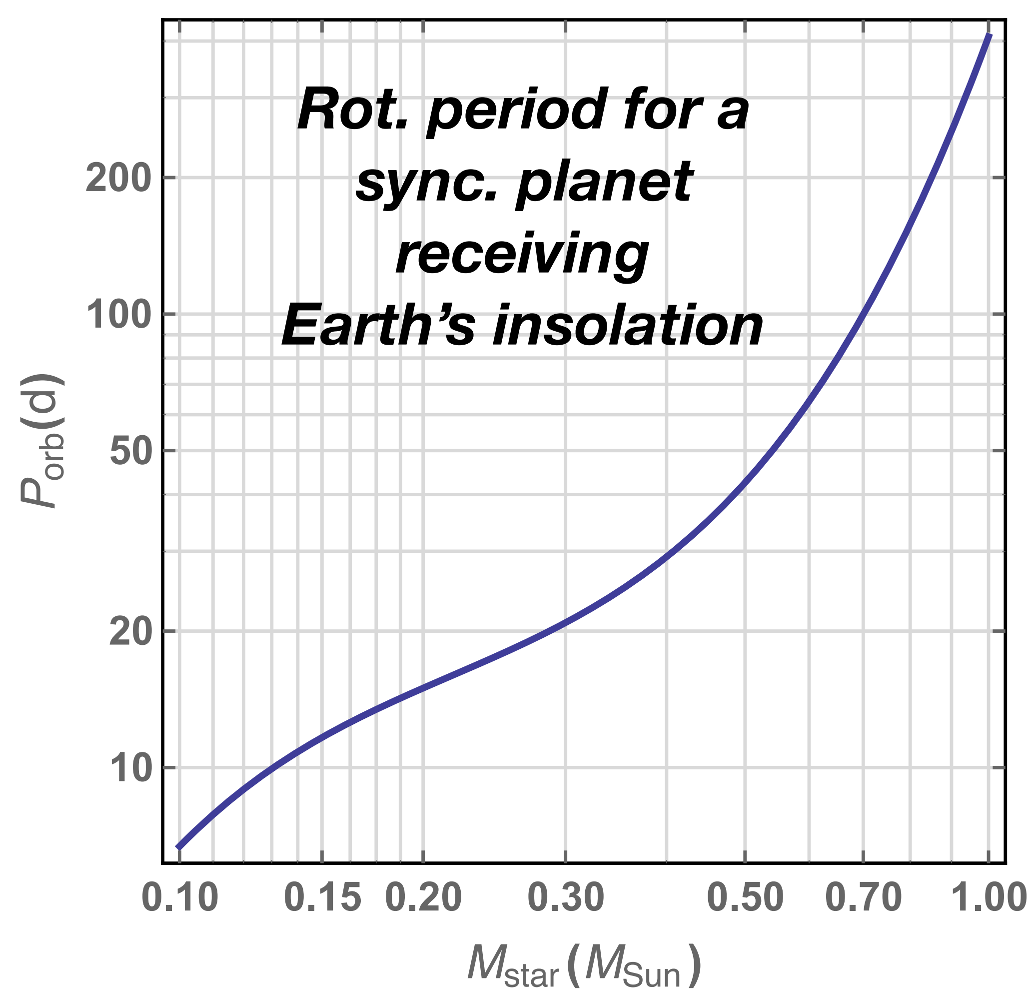

Polar Cell
Ferrel Cell
Hadley Cell

What about
synchronously rotating planets?

What about synchronously rotating planets?



Showman et al. (2013)



Two prototypes of synchronous planets

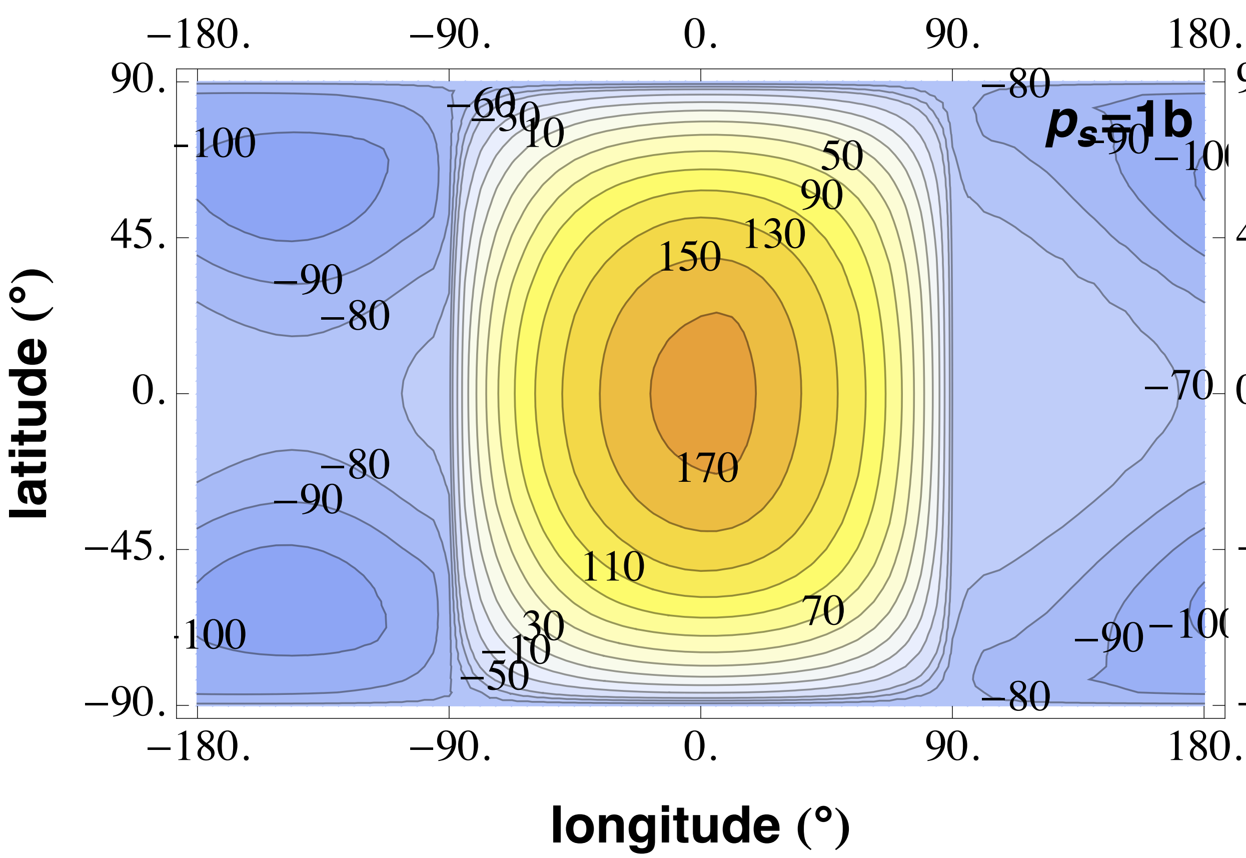
Planet name		Gl 581 c	HD 85512 b	
Stellar luminosity	$L_\star$ [$L_\odot$]	0.0135	0.126	
Stellar mass	$M_\star$ [$M_\odot$]	0.31	0.69	
Orbital semi-major axis	a [AU]	0.073	0.26	
Orbital period	$P_{\rm orb}$ [d]	13	58	
Orbital eccentricity	e	0-0.05	0-0.11	
Mass	$M_{\rm p}$ [$M_\oplus$]	6.25	4.15	
Radius	$R_{\rm p}$ [$R_\oplus$]	1.85	1.60	
Surface gravity	g [m s^{-2}]	18.4	15.8	
				Earth
Stellar Flux	$F_\star$ [W/m^2]	3300	2500	**1366**
Equilibrium temperature	$\bar{T}_{\rm equ}$ [K]	317	296	**255**

$$\bar{T}_{\rm equ} = \left(\frac{(1-\bar{A})\,F_\star}{4\,\sigma_{\rm SB}} \right)^{1/4}$$

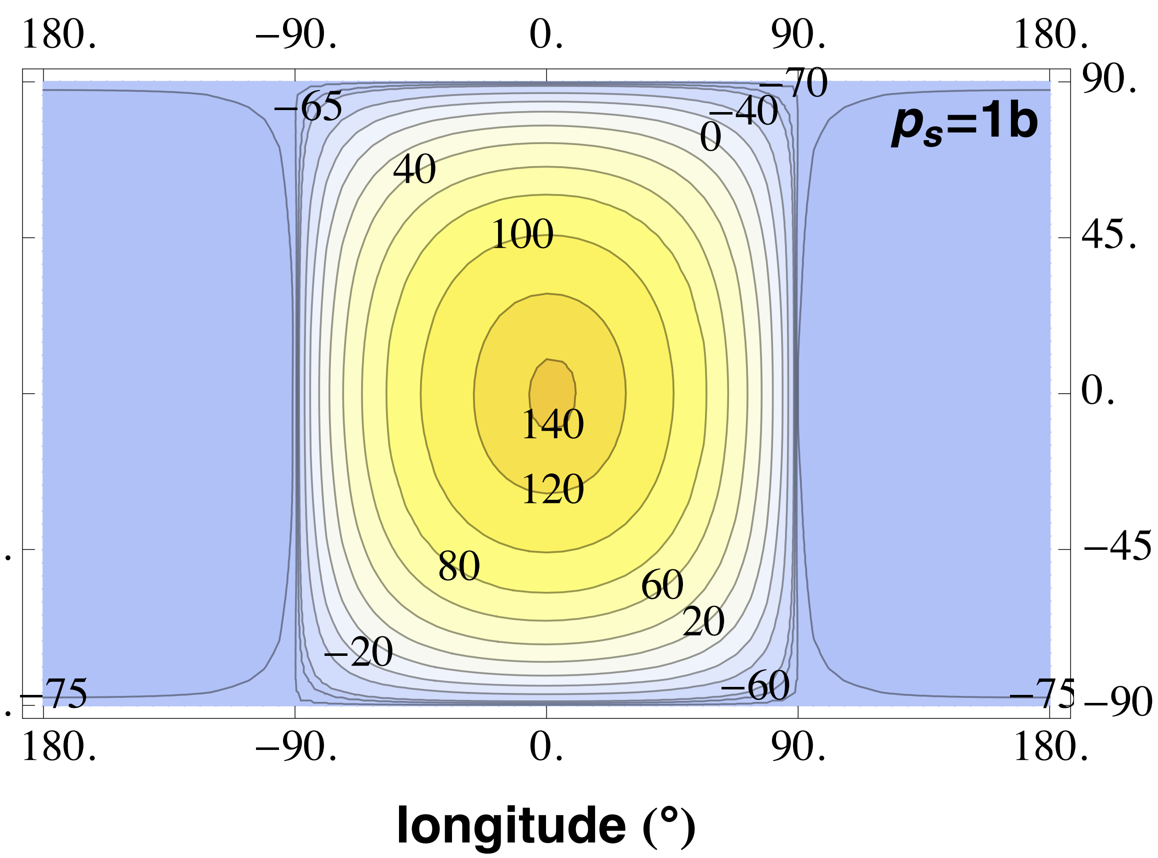
Two prototypes of synchronous planets

Temperature maps (°C)

Gl 581 c



HD 85512 b



(dry earthlike atmosphere)

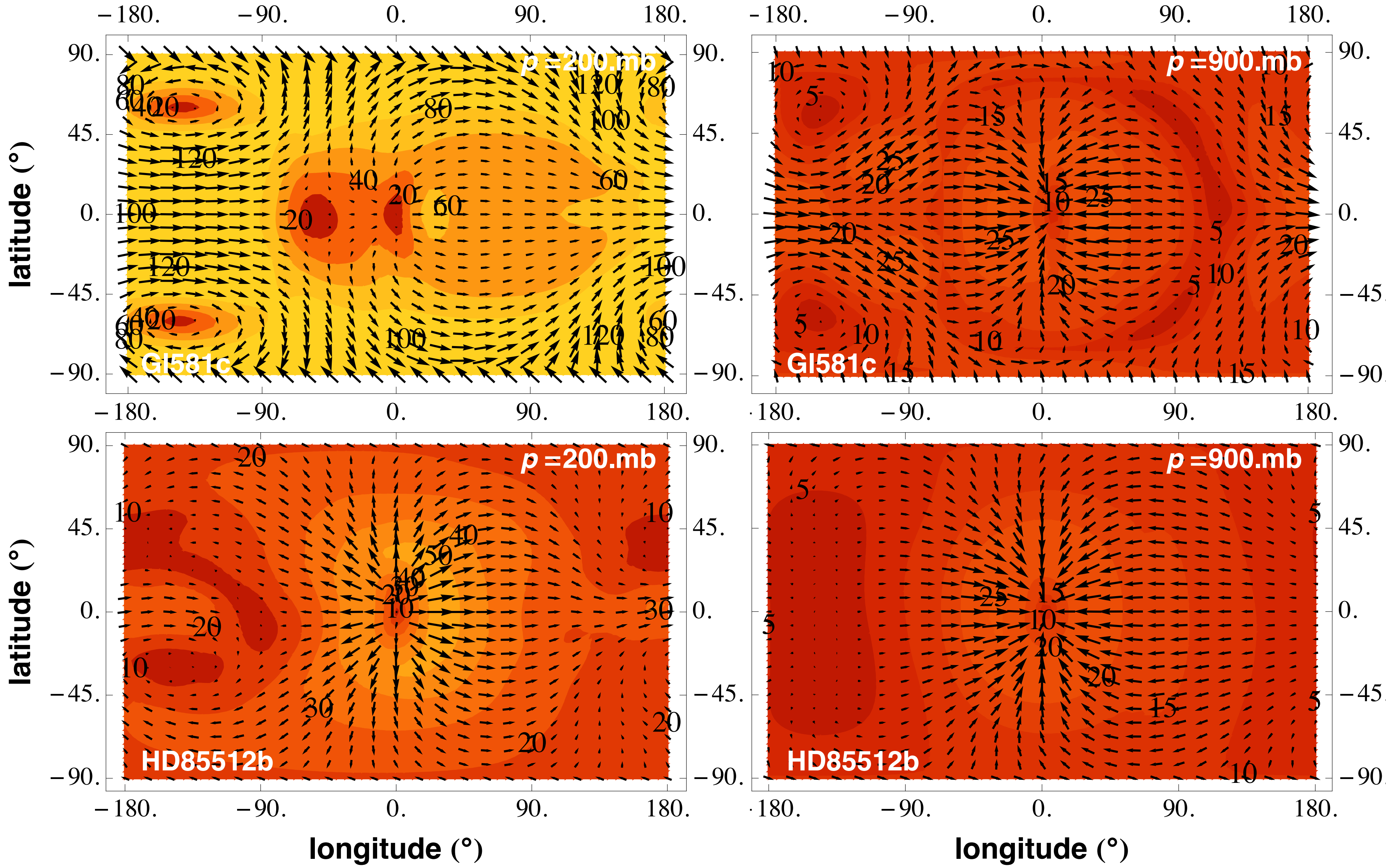
Leconte et al. (A&A, 2013a)

wind maps (m/s)

~4km Altitude　　　　Near Surface

Gl 581 c

HD 85512 b



Super-rotation vs Stellar/Antistellar circulation!

Jets impede redistribution!

Leconte et al. (A&A, 2013a)

Circulation regime on synchronous exoplanets

Showman & Polvani (2011)

«Eastward Jets pumped by the interaction of the mean flow with planetary Rossby and Kelvin waves»

$$L_{\mathrm{Ro}} = \sqrt{\frac{N\,H\,R_{\mathrm{p}}}{2\,\Omega}} \Rightarrow \mathcal{L} = \sqrt{\frac{N\,H}{2\,\Omega\,R_{\mathrm{p}}}}$$

$$H = \frac{k_{\mathrm{B}}\,T}{m_{\mathrm{a}}\,g} \qquad N^2 = \frac{g^2}{c_{\mathrm{p}}\,T}$$

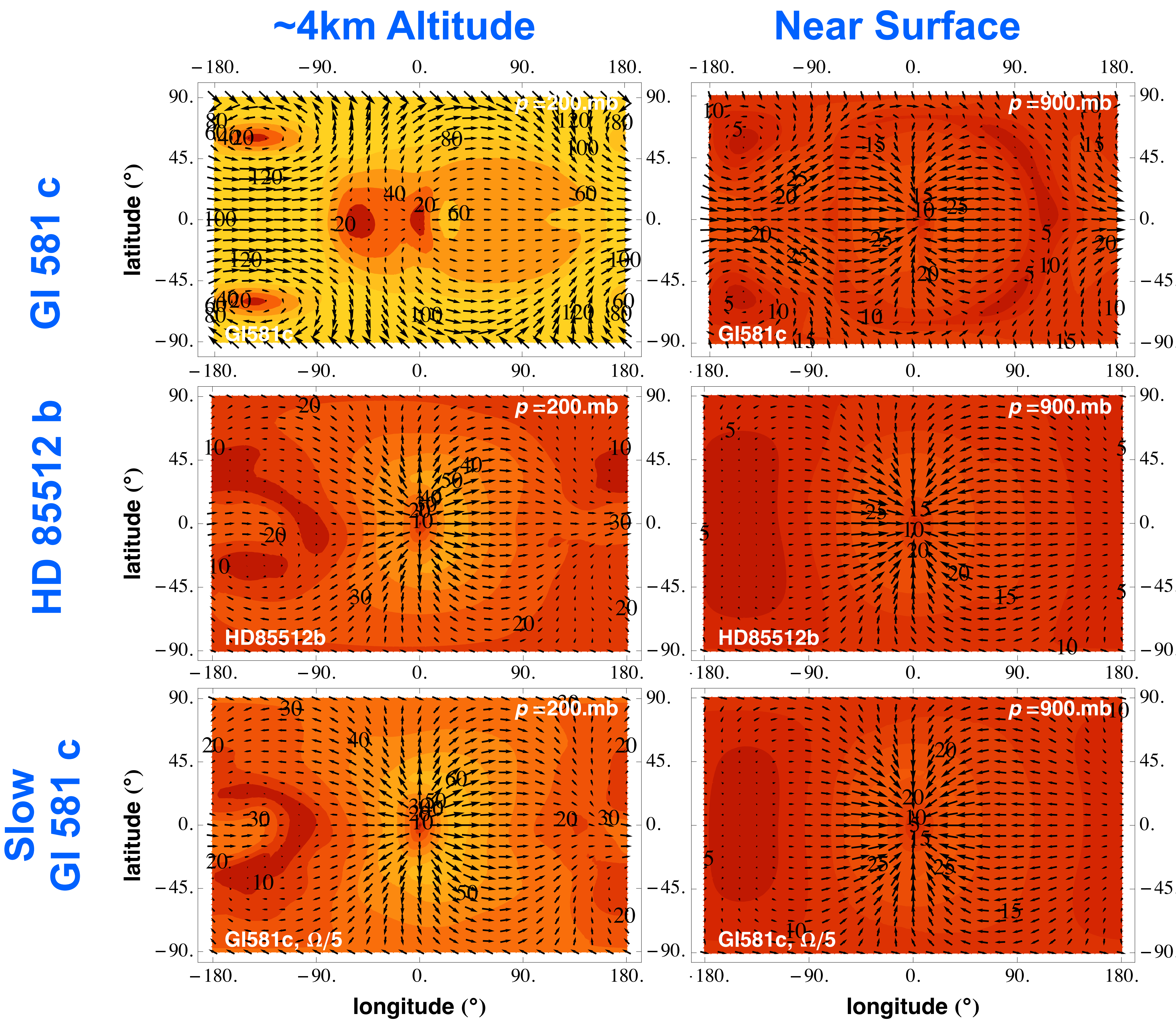
$$\mathcal{L} = \sqrt{\frac{k_{\mathrm{B}}}{m_{\mathrm{a}} c_{\mathrm{p}}^{1/2}} \frac{T^{1/2}}{2\,\Omega\,R_{\mathrm{p}}}}$$

Mechanism too weak

$$\mathcal{L} = \boxed{1.1\ (\mathrm{Gl\,581\,c}),} \quad \boxed{2.5\ (\mathrm{HD\,85512\,b})}$$

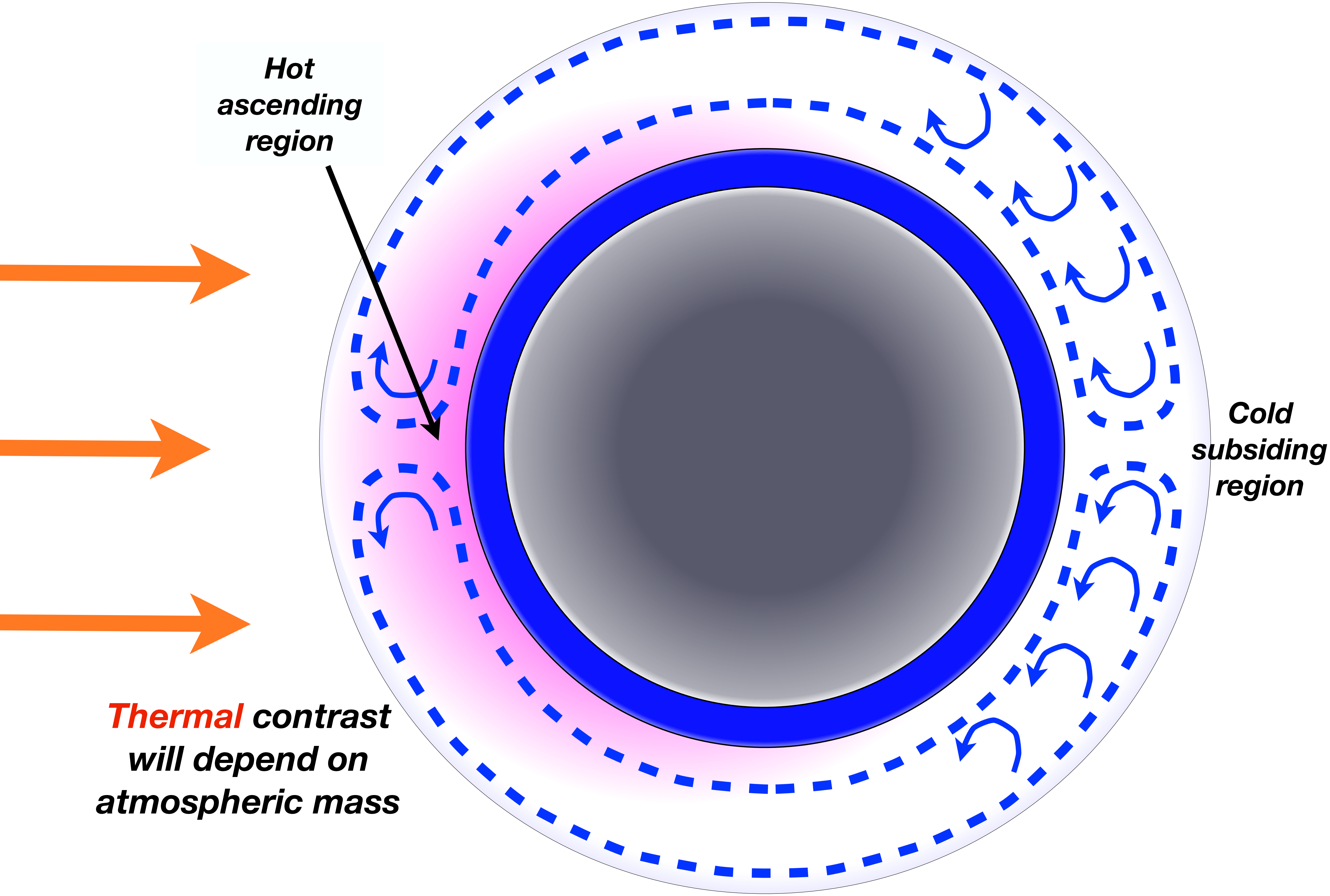
Leconte et al. (A&A, 2013a)

wind maps (m/s)

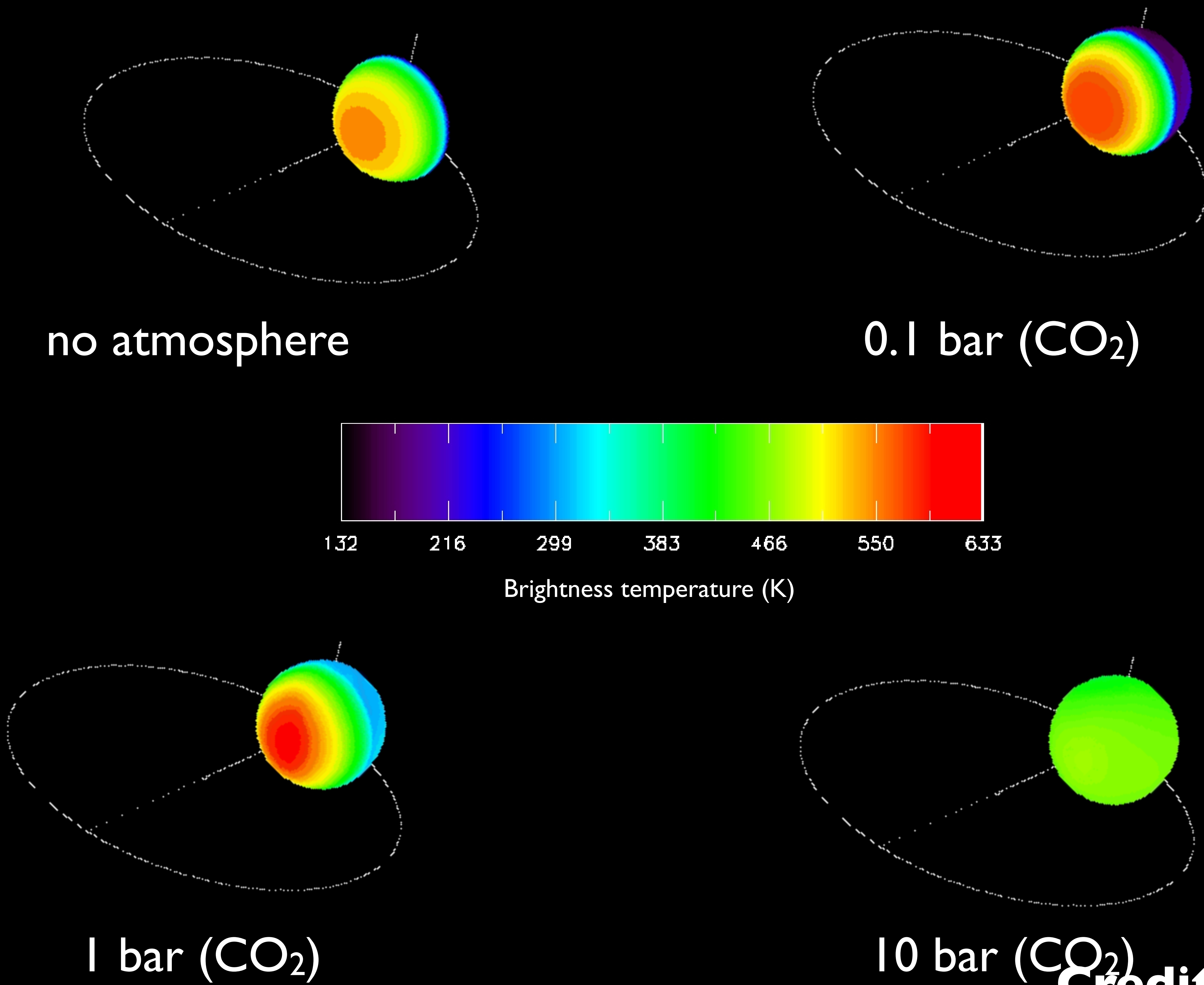

~4km Altitude
Near Surface
Gl 581 c
HD 85512 b
Slow
Gl 581 c
p =200.mb
p =900.mb
Gl581c
HD85512b
Gl581c, Ω/5
latitude (°)
longitude (°)

Does atmospheric dynamics affect observables?

Expected dynamics on tidally locked planets

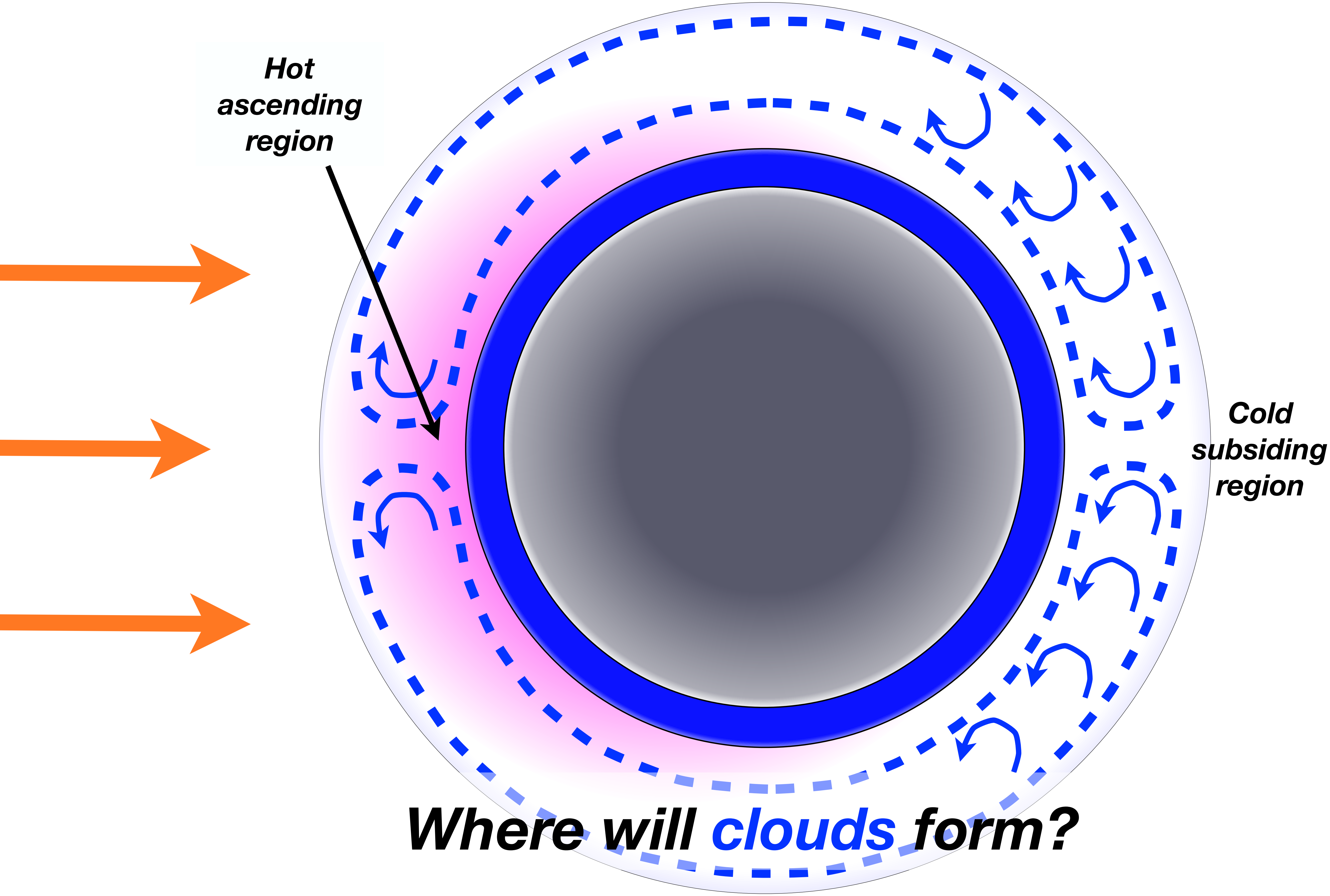


8.7 μm

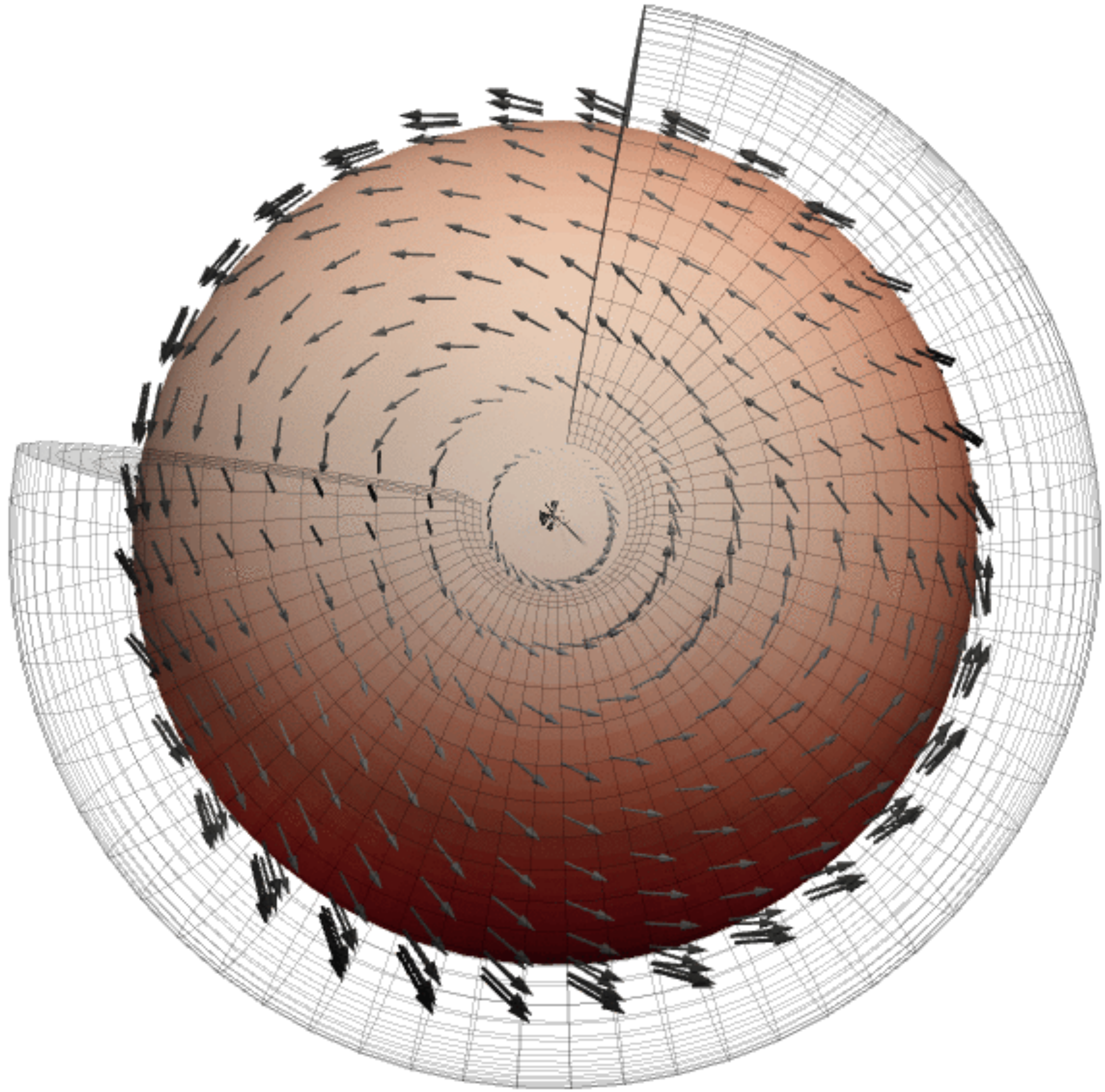


Credit F. Selsis

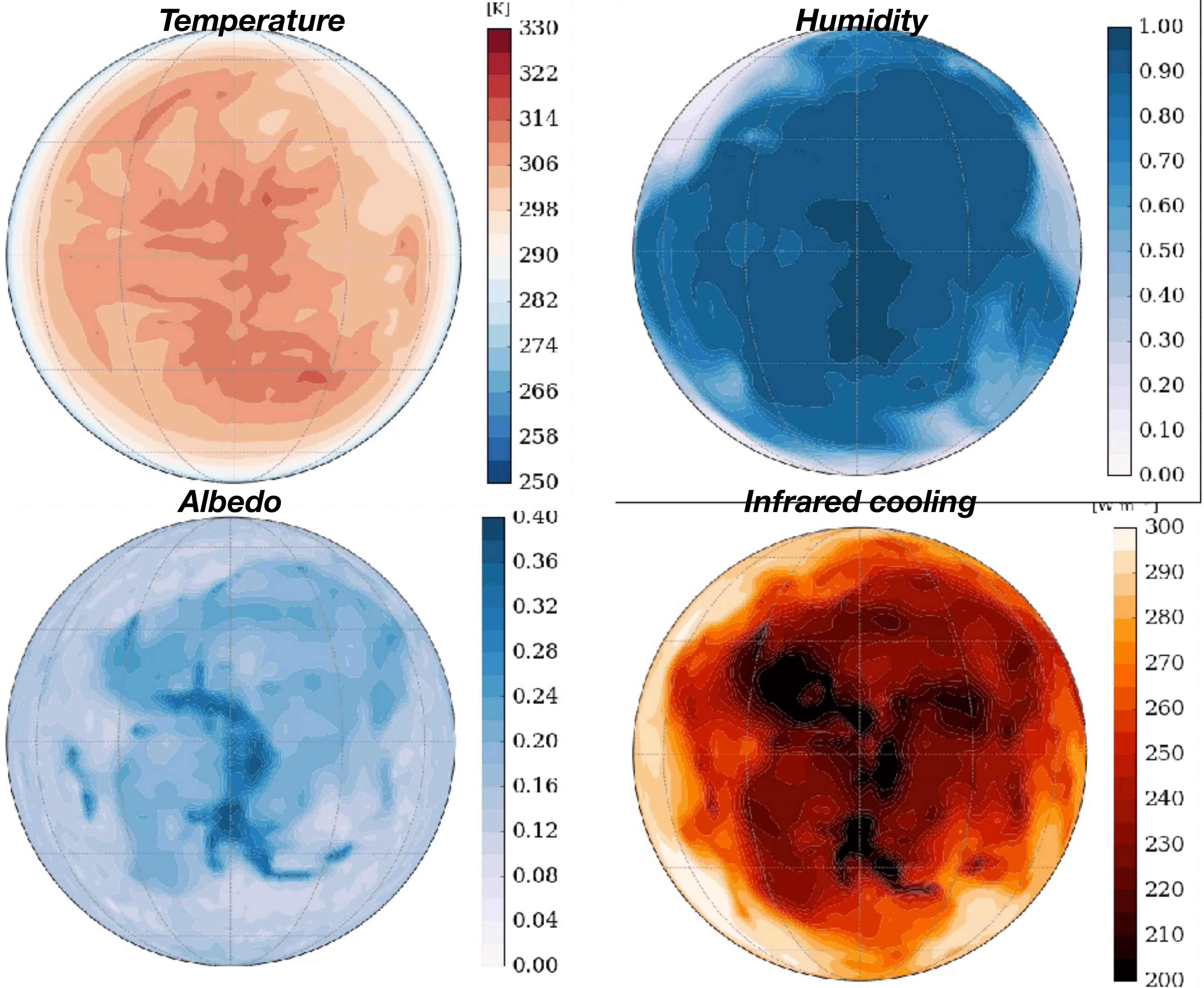
Expected dynamics on tidally locked planets

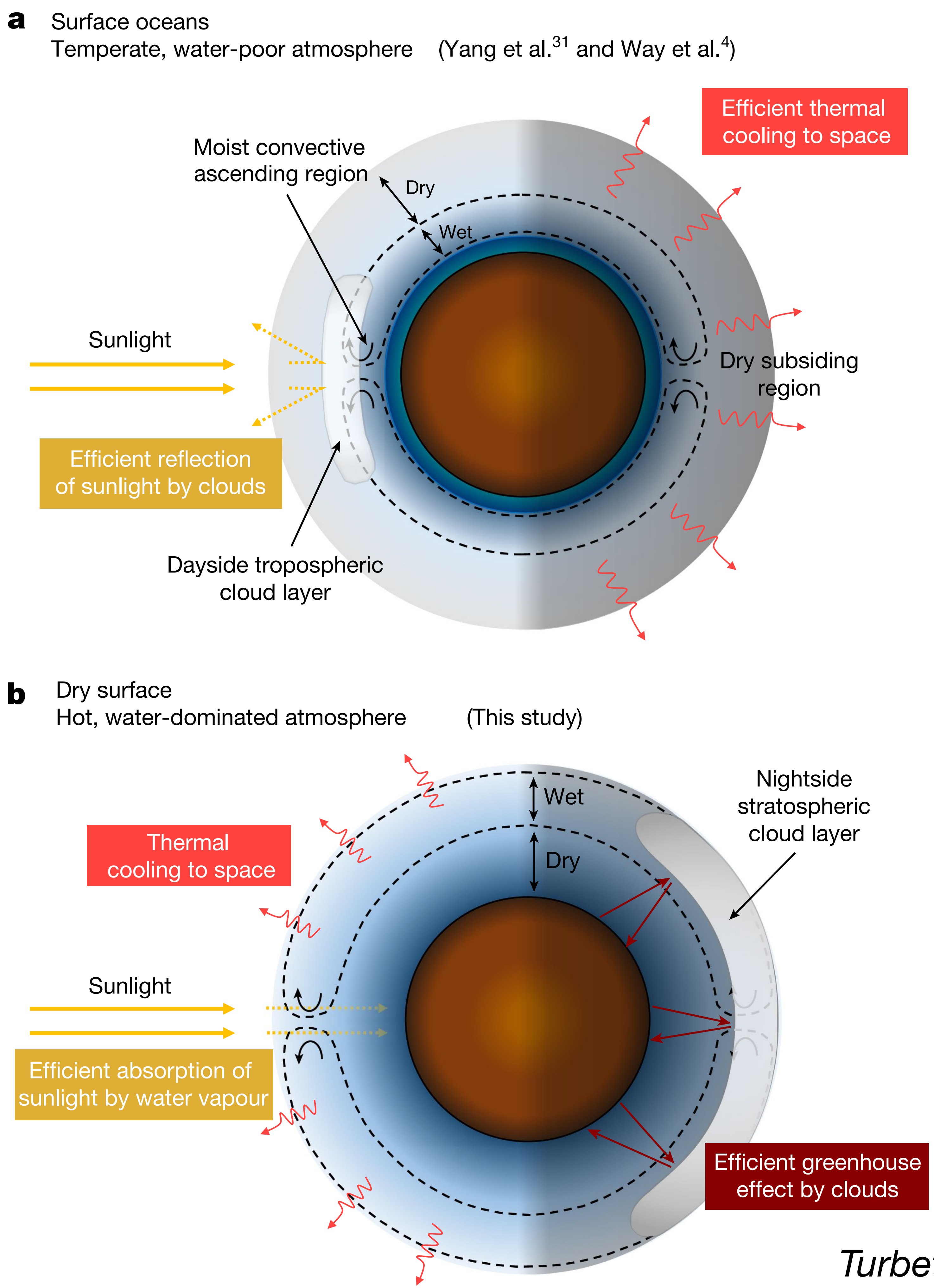


Where will clouds form?

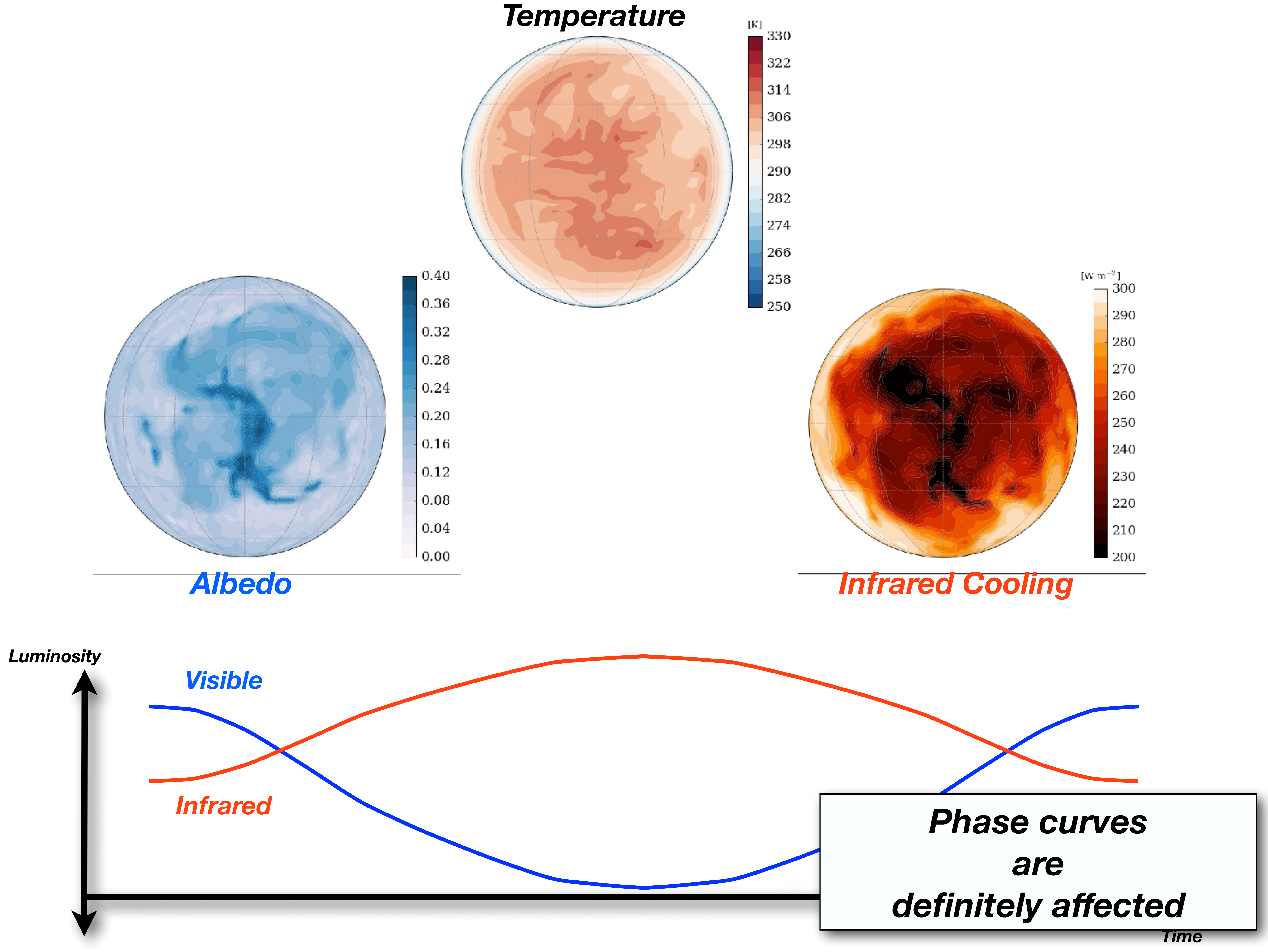


Turbet et al. (2021)


Temperature
[K]
330
322
314
306
298
290
282
274
266
258
250
Humidity
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Albedo
0.40
0.36
0.32
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0.00
Infrared cooling
300
290
280
270
260
250
240
230
220
210
200

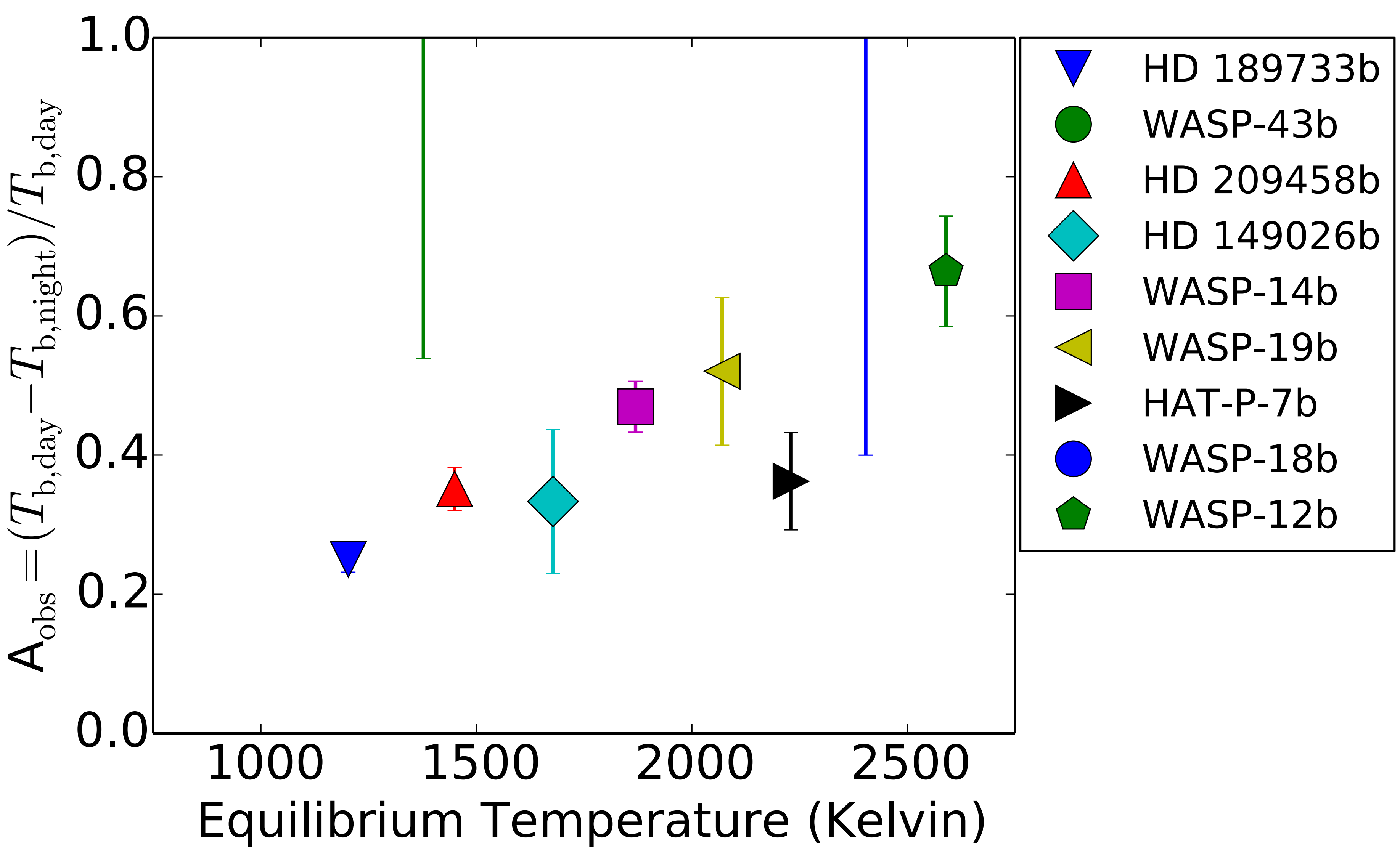


Turbet et al. (Nature, 2021)



Temperature
[K]
330
322
314
306
298
290
282
274
266
258
250
0.40
0.36
0.32
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0.00
Albedo
[W m⁻²]
300
290
280
270
260
250
240
230
220
210
200
Infrared Cooling
Luminosity
Visible
Infrared
Time
Phase curves
are
definitely affected

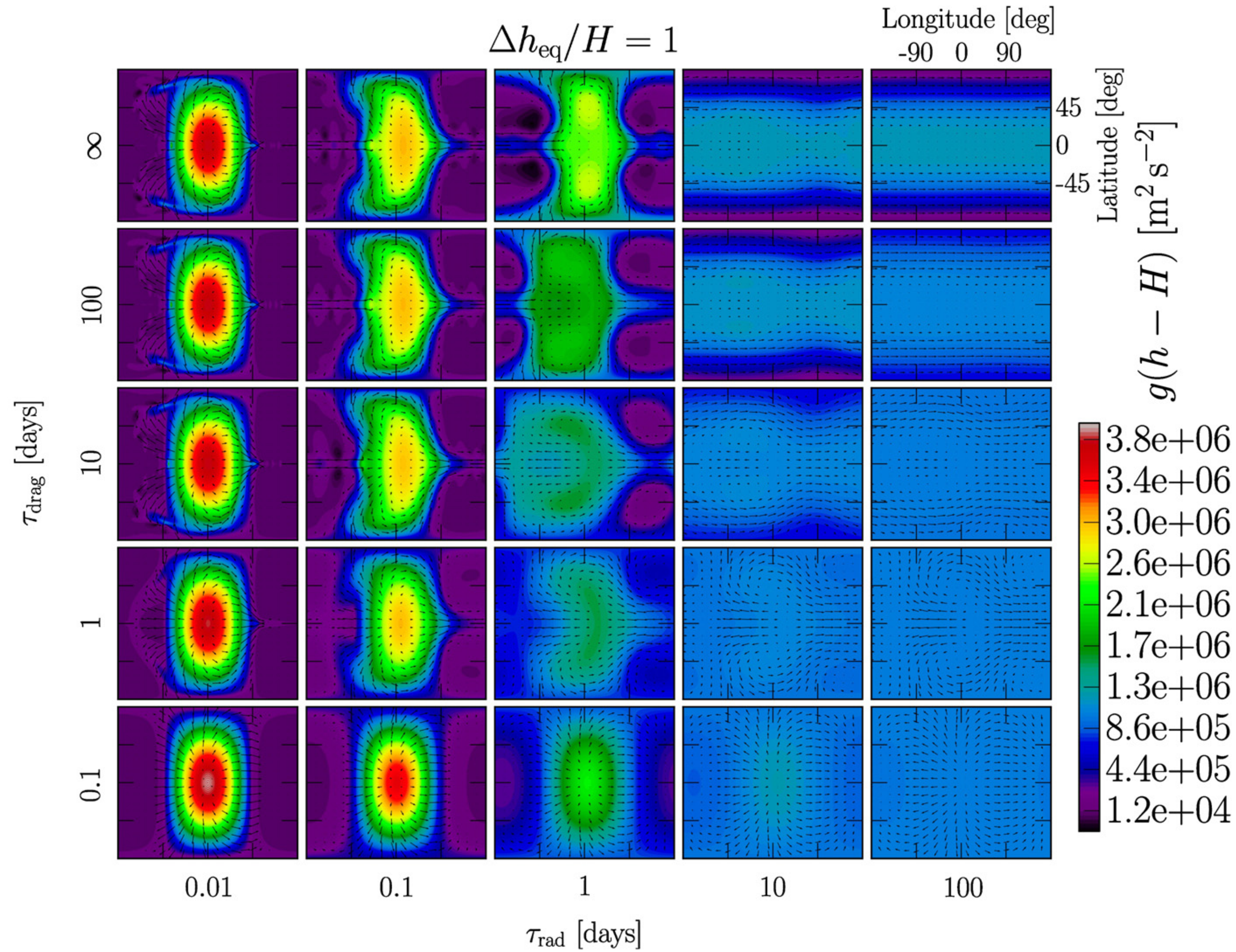
Observed trends in emission temperature…



Hotter planets have bigger day/night temperature contrasts

Komacek & Showman (2016)

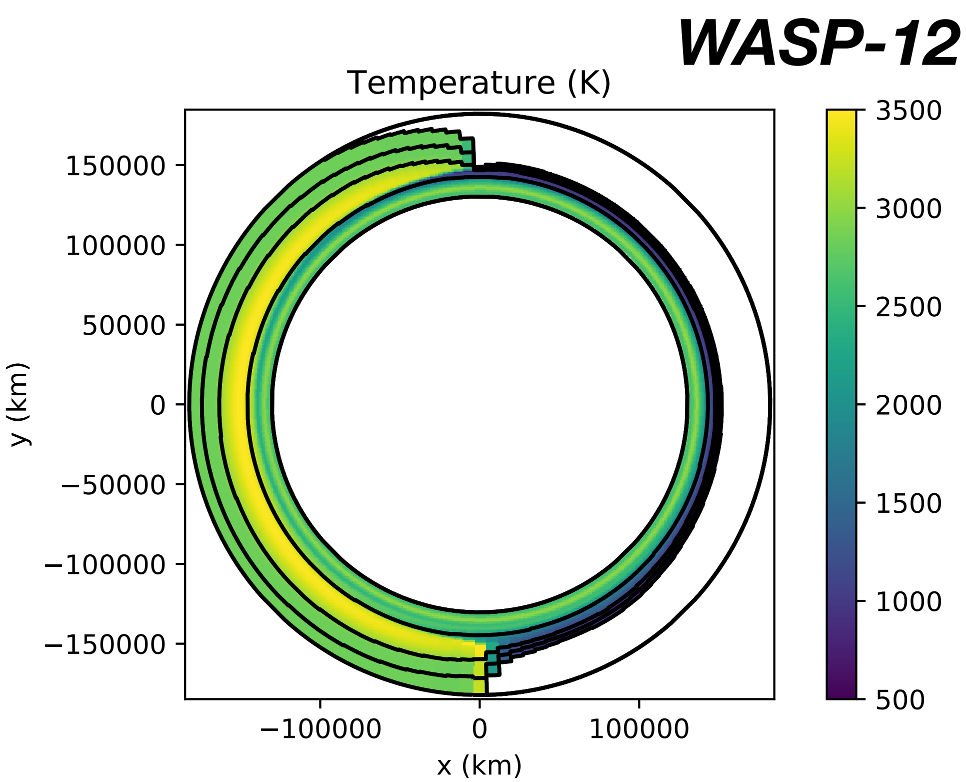
…Explained by atmospheric dynamics

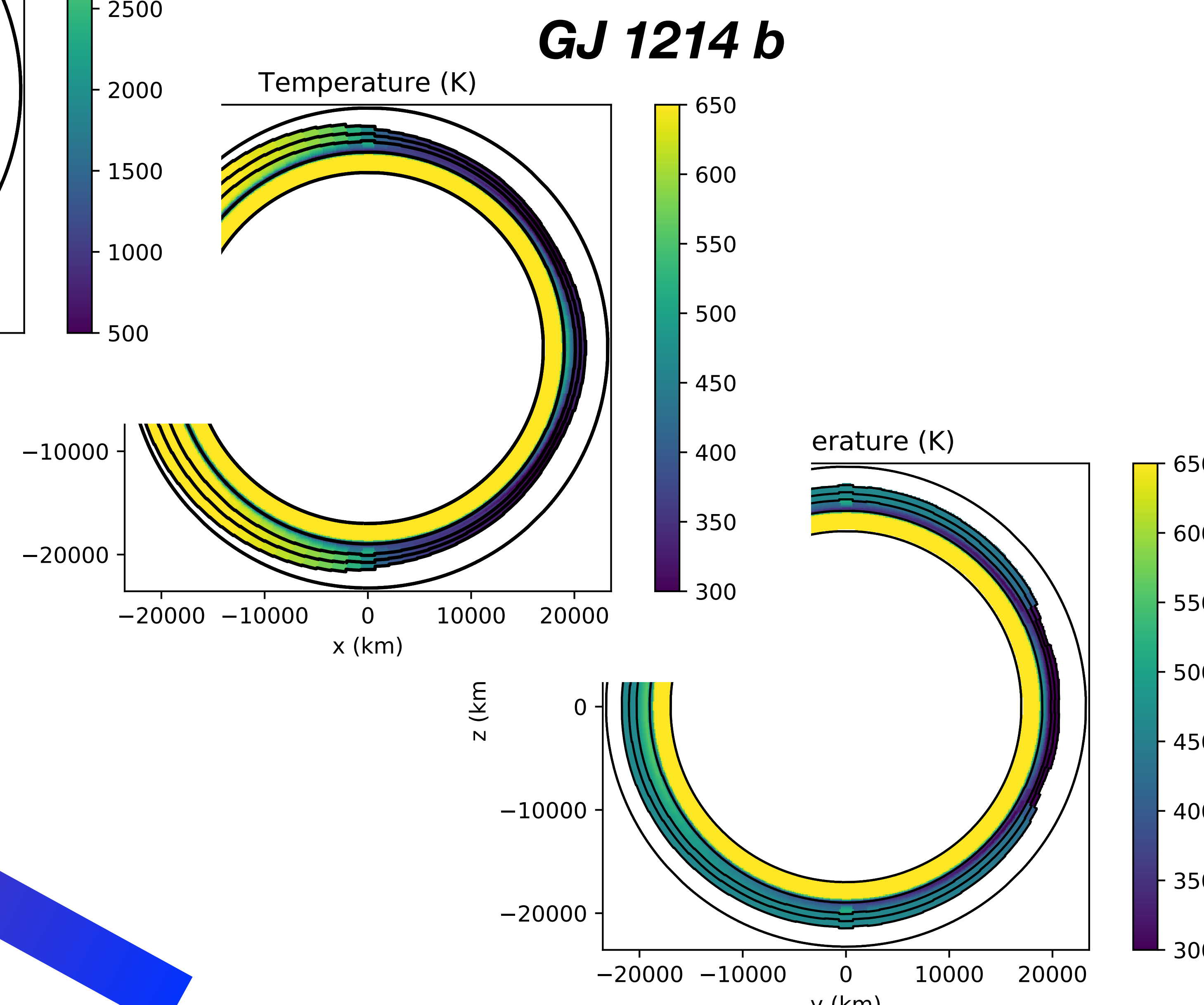


$T \nearrow \Rightarrow \tau_{rad} \searrow$

Perez Becker & Showman (2016)

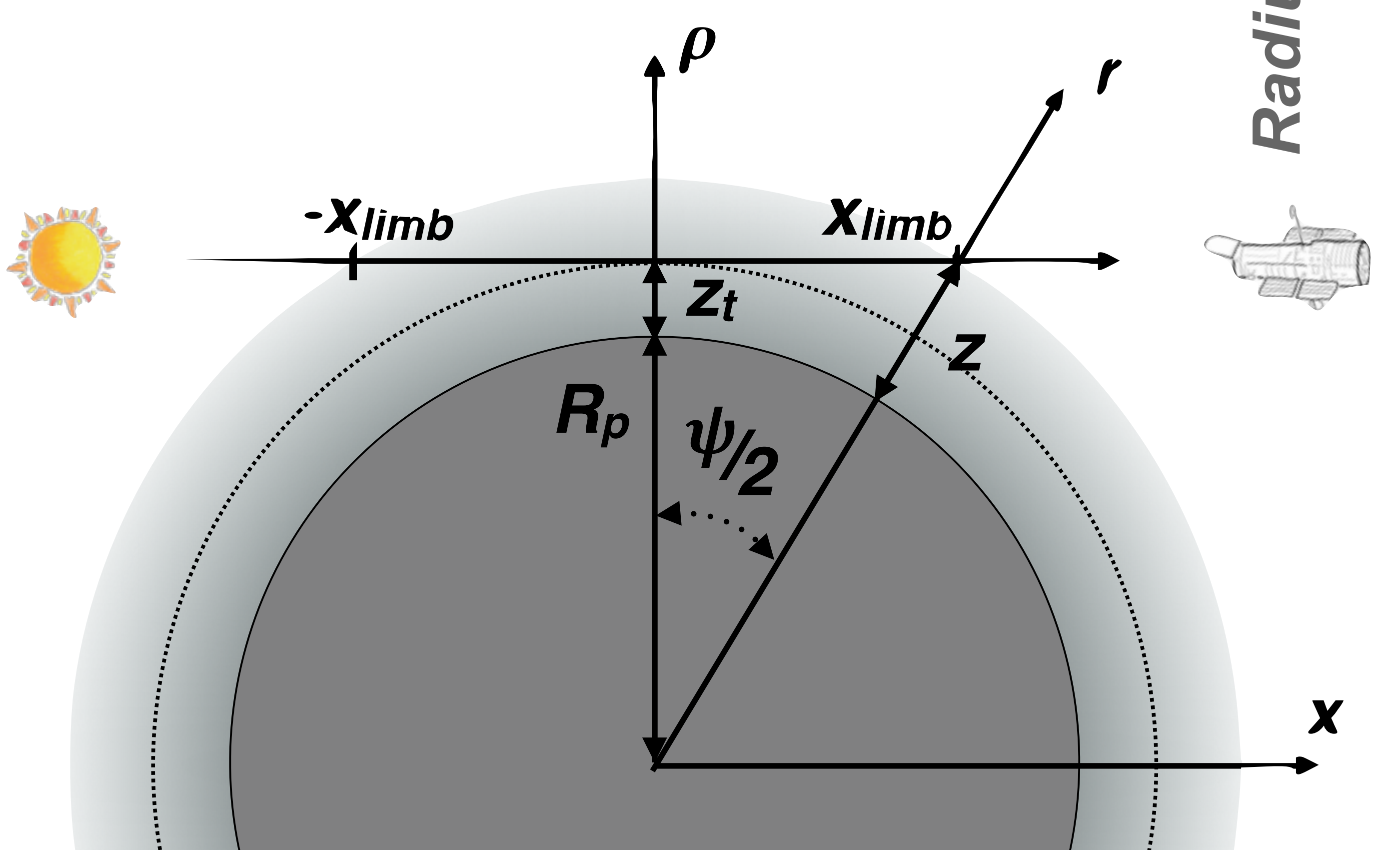
What implications for transit spectroscopy?

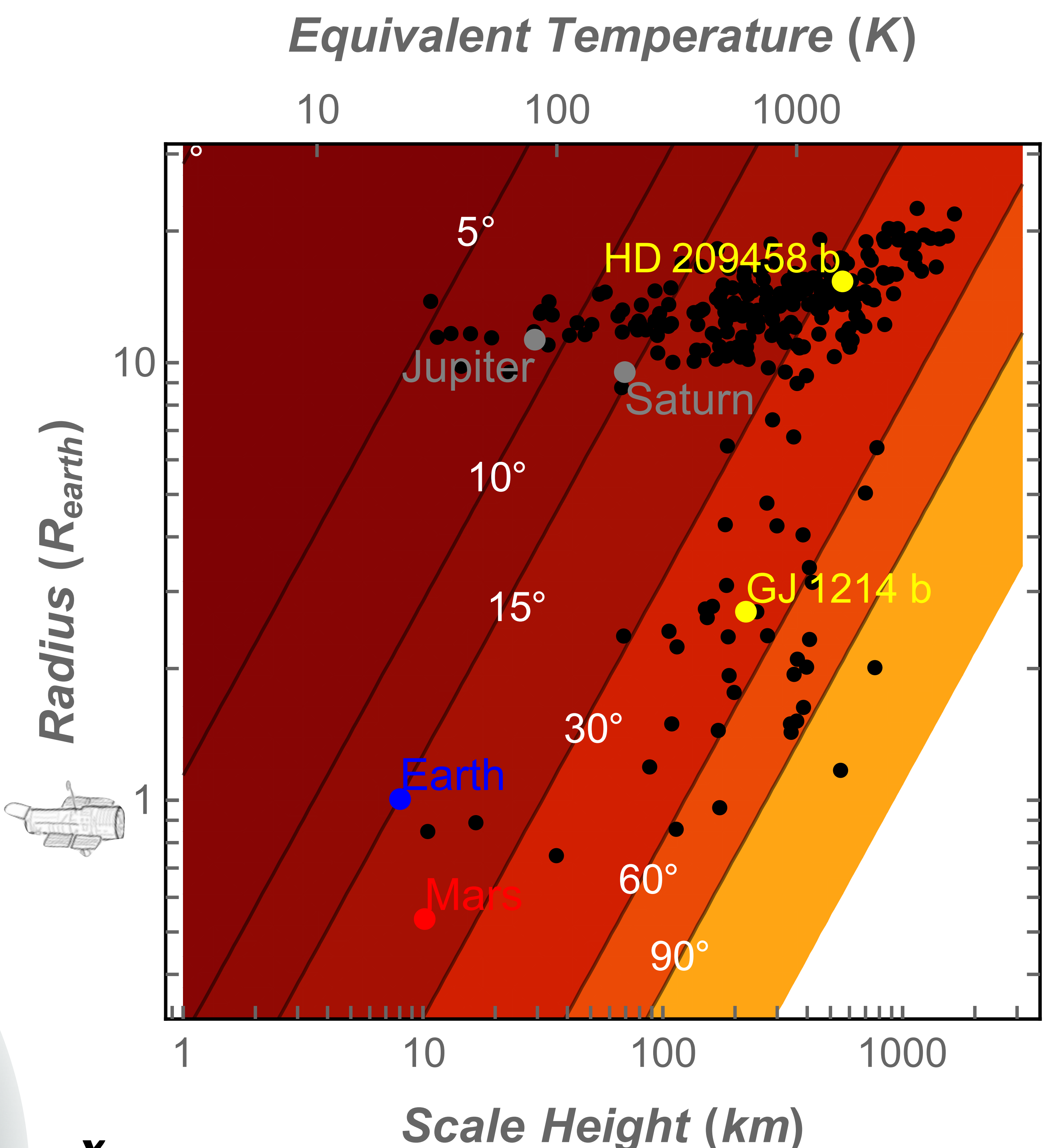




$$T \nearrow \;\Rightarrow\; \tau_{\mathrm{rad}} \searrow$$

Opening angle of the transmission region (limb)

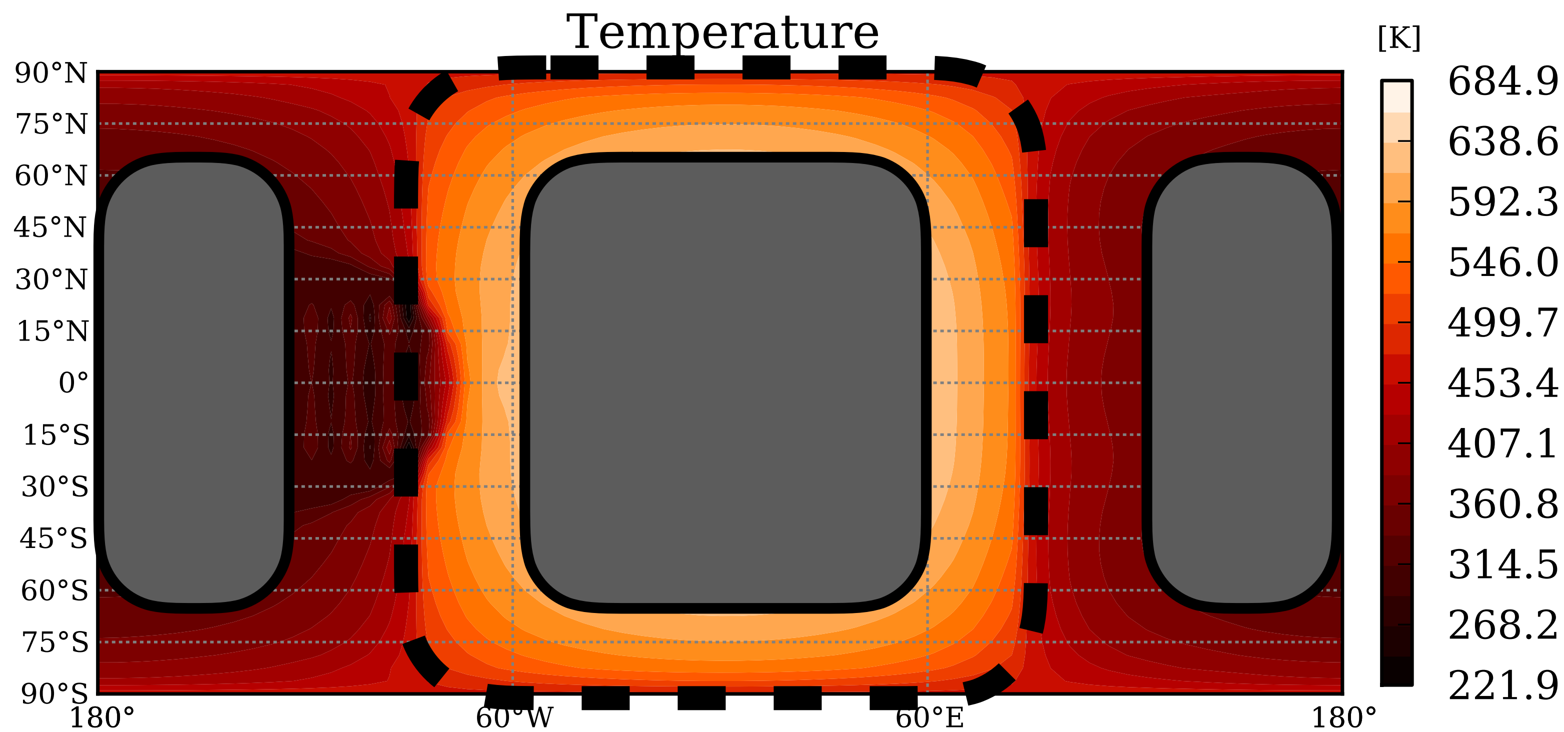




Caldas, Leconte, et al. (A&A, 2019)

Opening angle of the transmission region (limb)

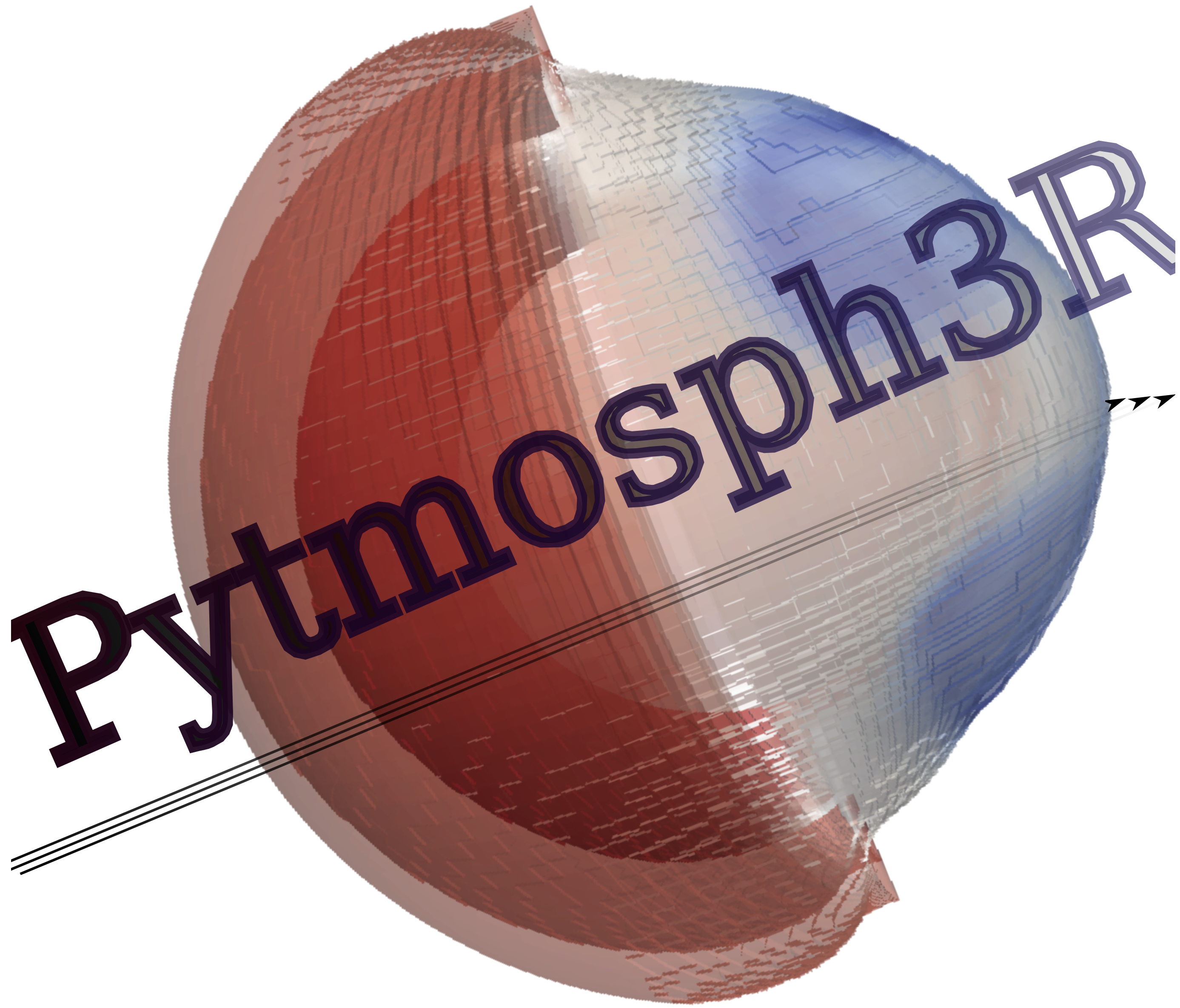
Temperature maps for GJ1214b (transit photosphere)



3D approach

Caldas, Leconte, et al. (A&A, 2019)

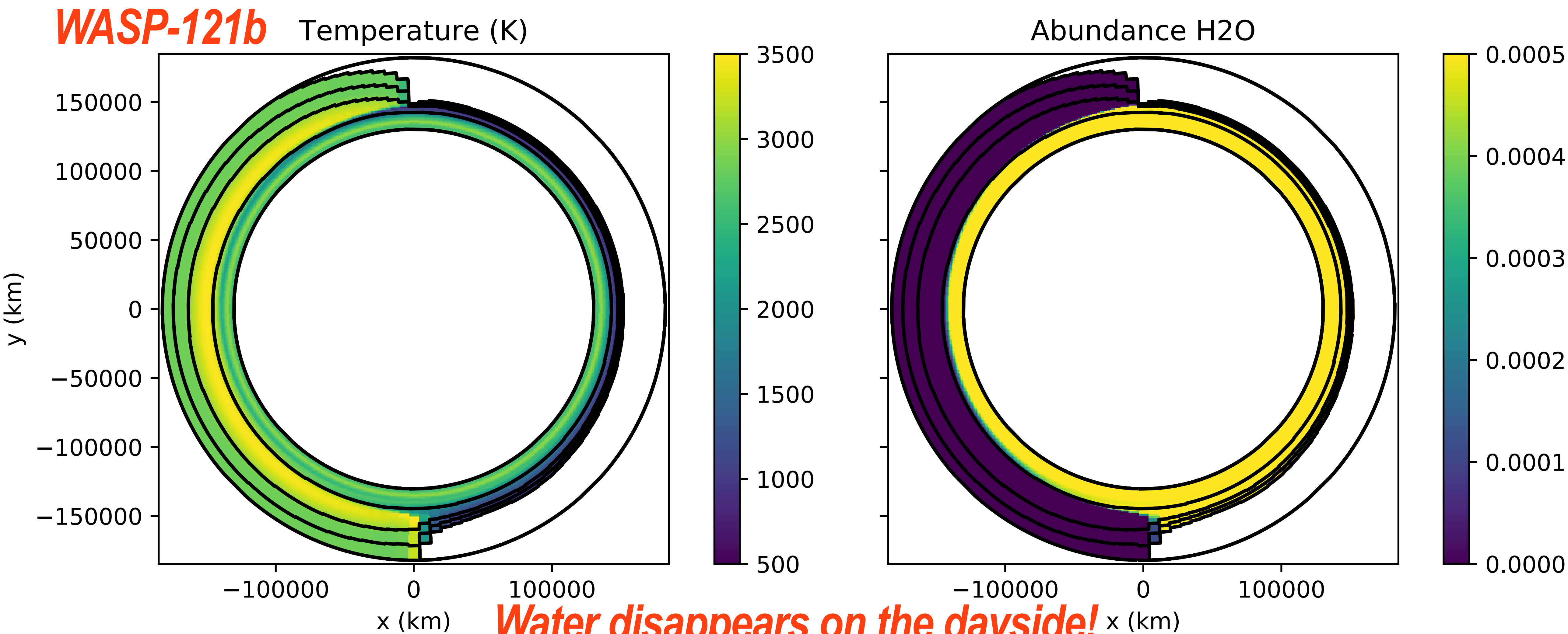
Need a 3D radiative transfer tool



Caldas, Leconte, et al. (A&A, 2019)

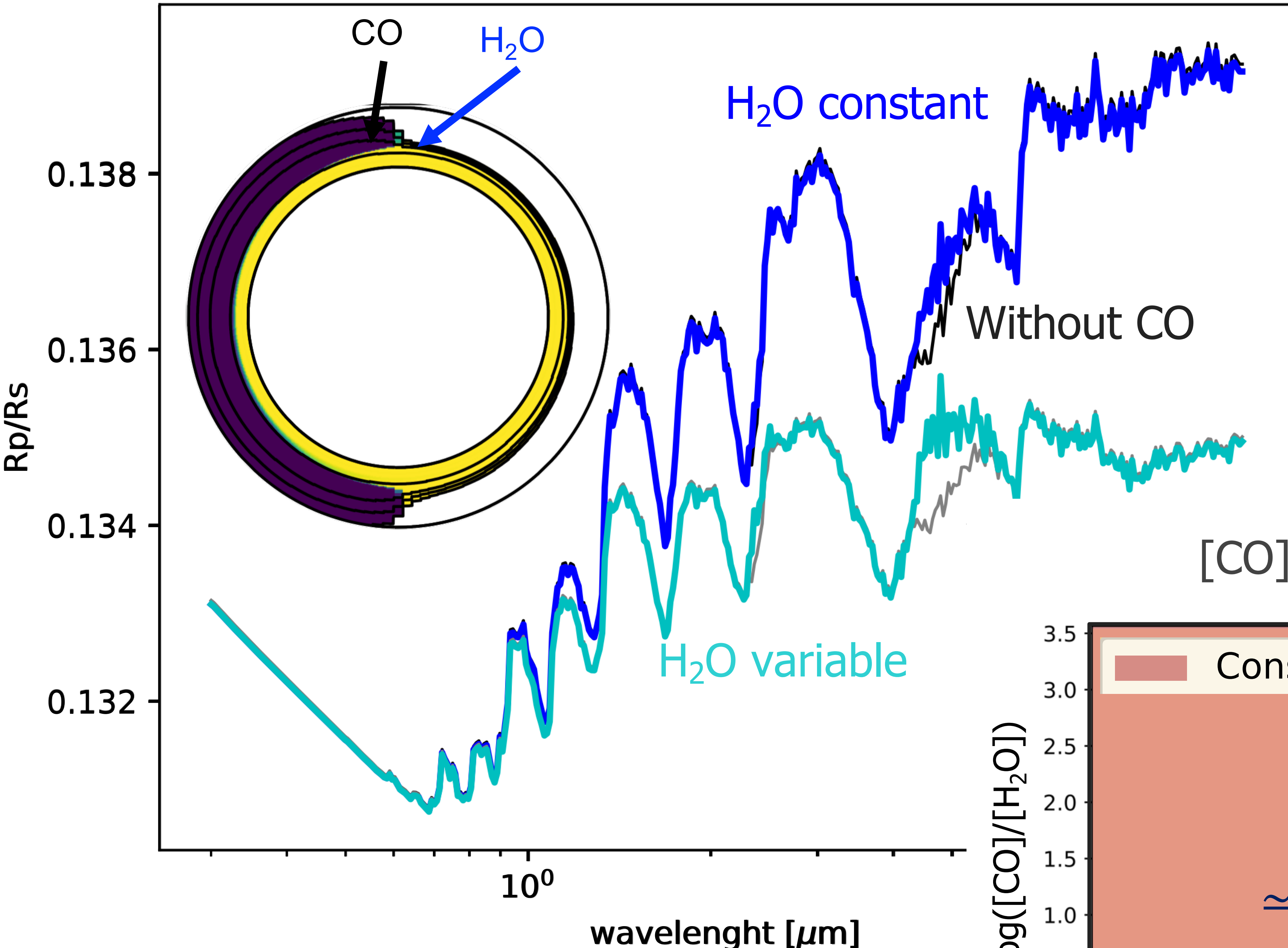
Falco et al. (A&A, 2021) alias COVID GUY

What if there is also a chemical day-night contrast

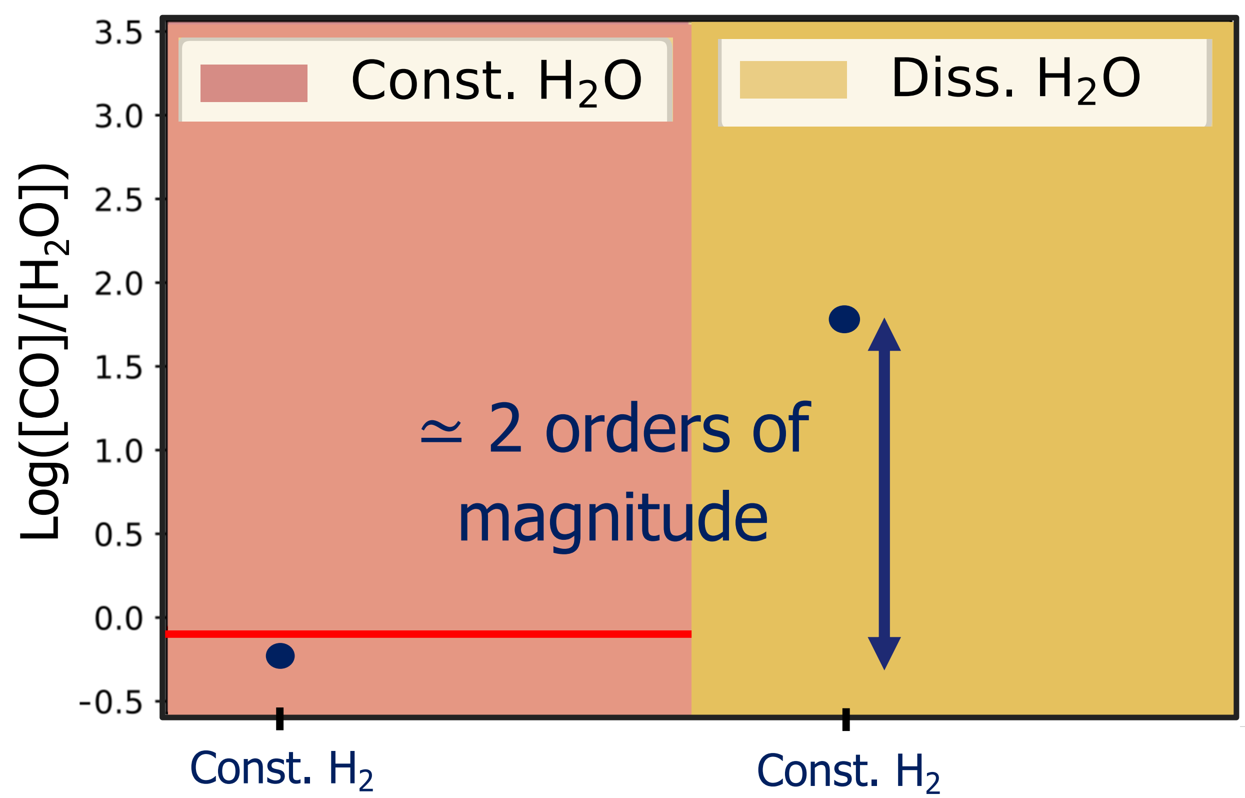


Water disappears on the dayside!

What if there is also a chemical day-night contrast



[CO]/[H_2O] ratio retrieved



Pluriel et al. (A&A, 2020)