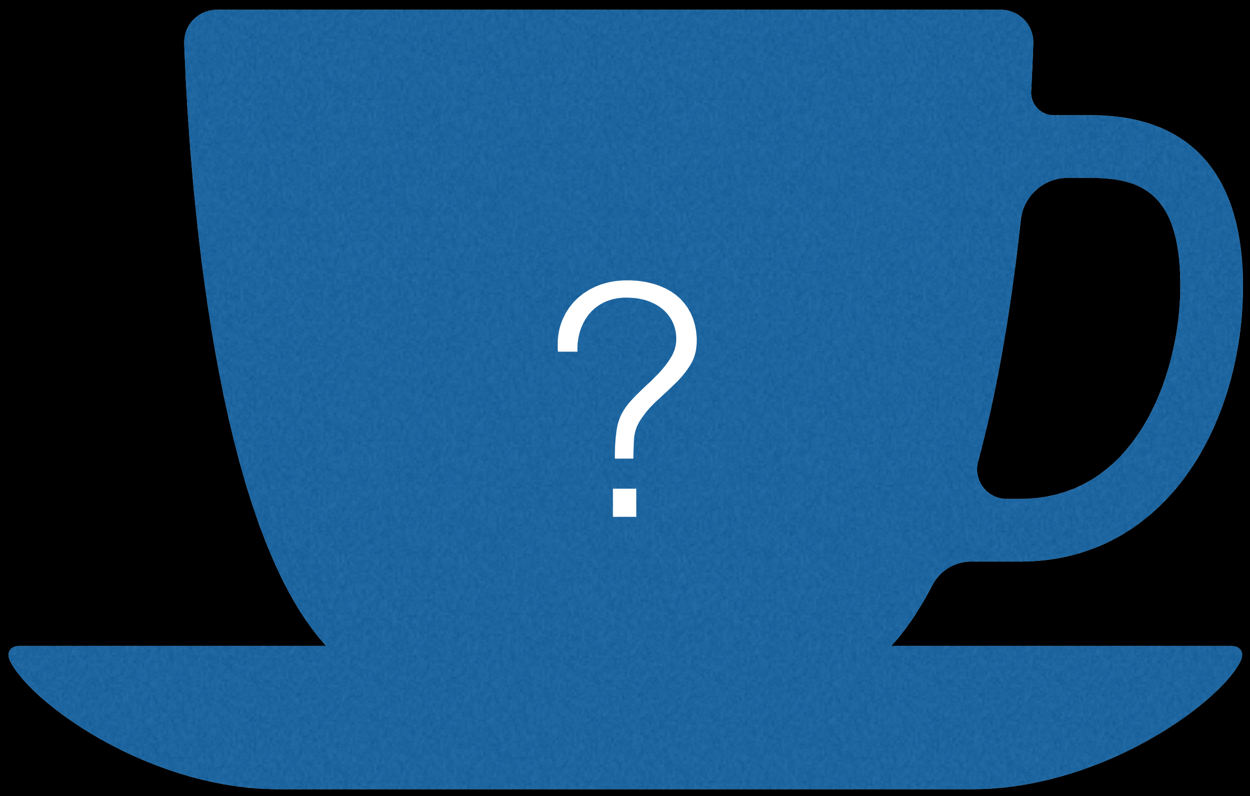
Beyond 1D atmospheres

Jérémy Leconte

Whiplash

This project has received funding from the European Research Council (ERC)
under the European Union's Horizon 2020 research and innovation program
(grant agreement No. 679030/WHIPLASH).



Equations of motion

★ Mass conservation

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

★ Momentum conservation

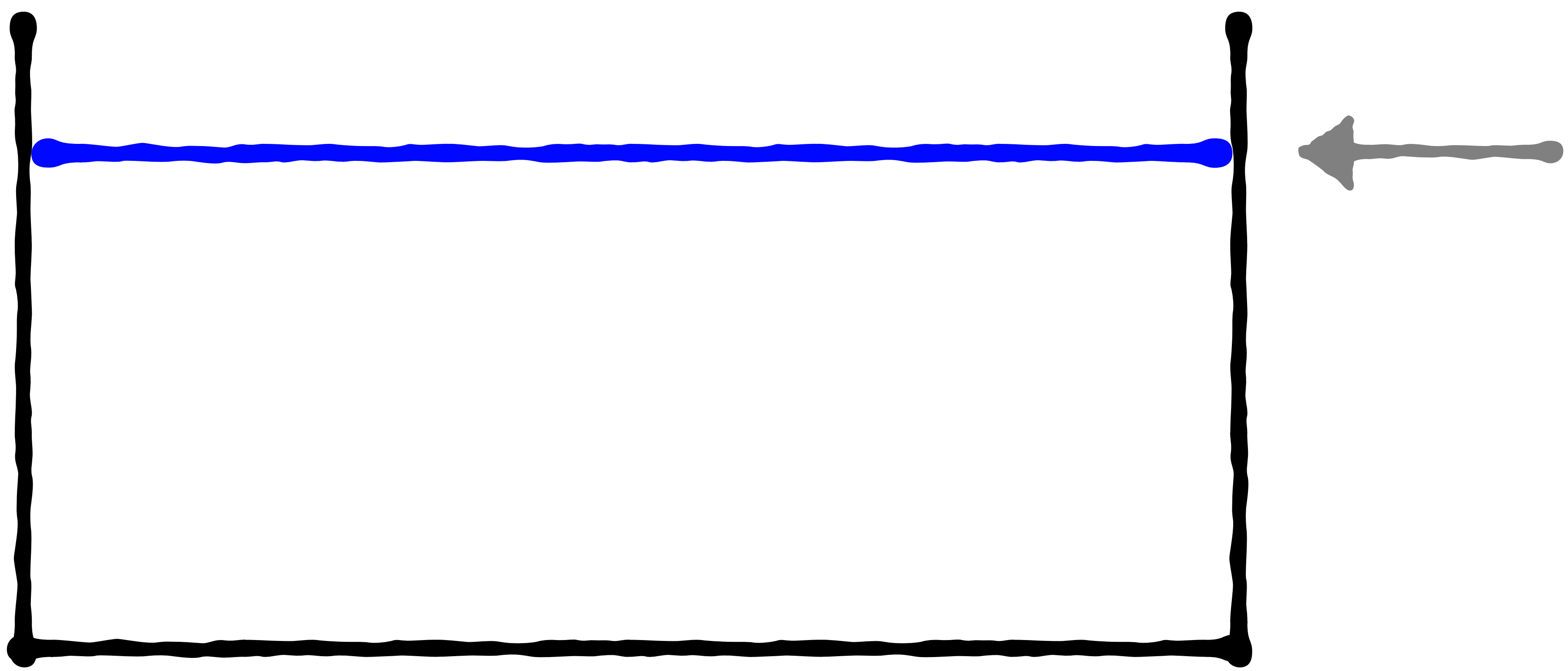
$$\frac{\mathrm{D}\boldsymbol{v}}{\mathrm{D}t} + 2\boldsymbol{\Omega} \times \boldsymbol{v} = -\frac{1}{\rho}\nabla p - \nabla \Phi$$

★ Equation of state

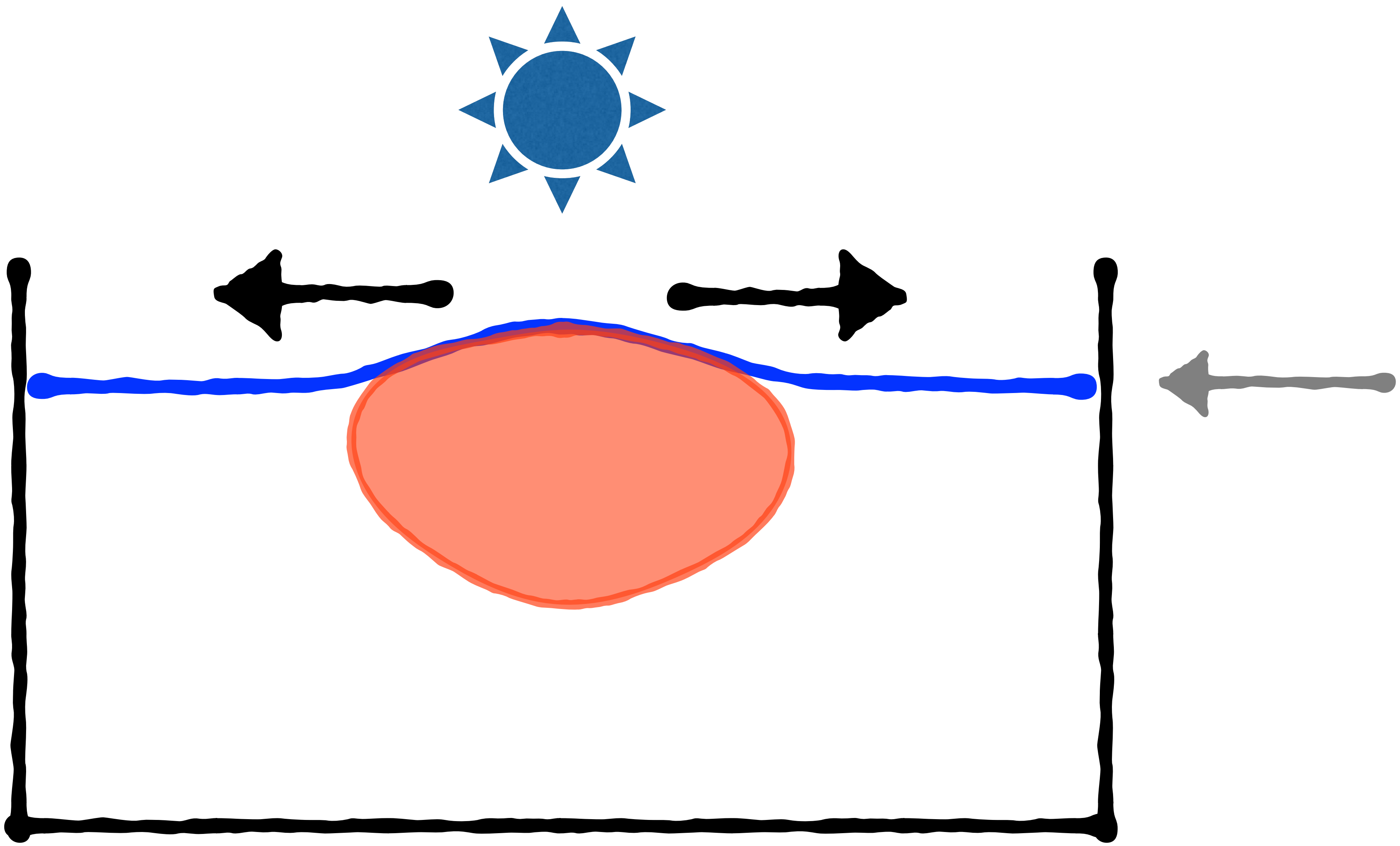
$$p = \rho R T$$

★ Conservation of energy

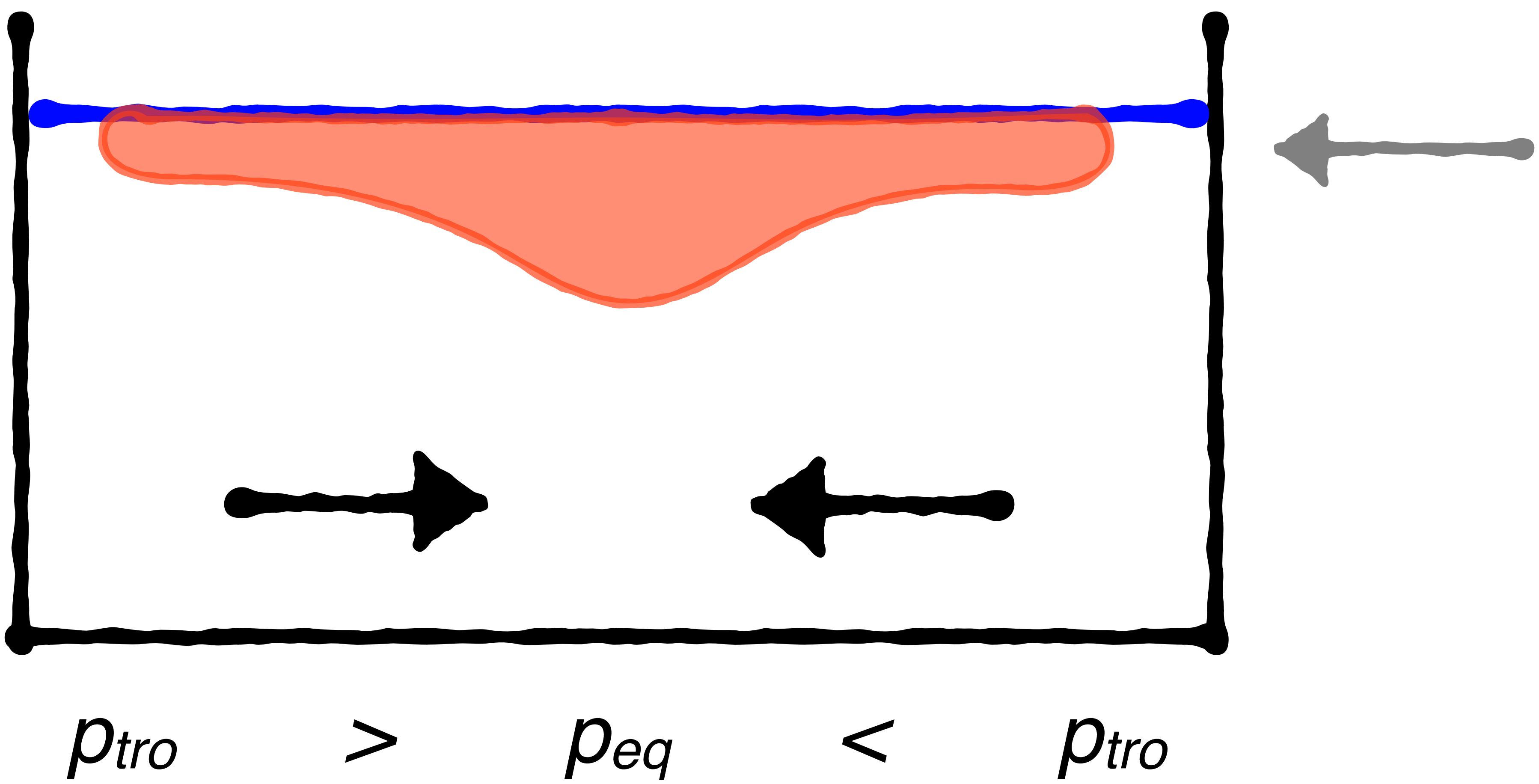
$$\frac{DS}{Dt} = H - Q$$

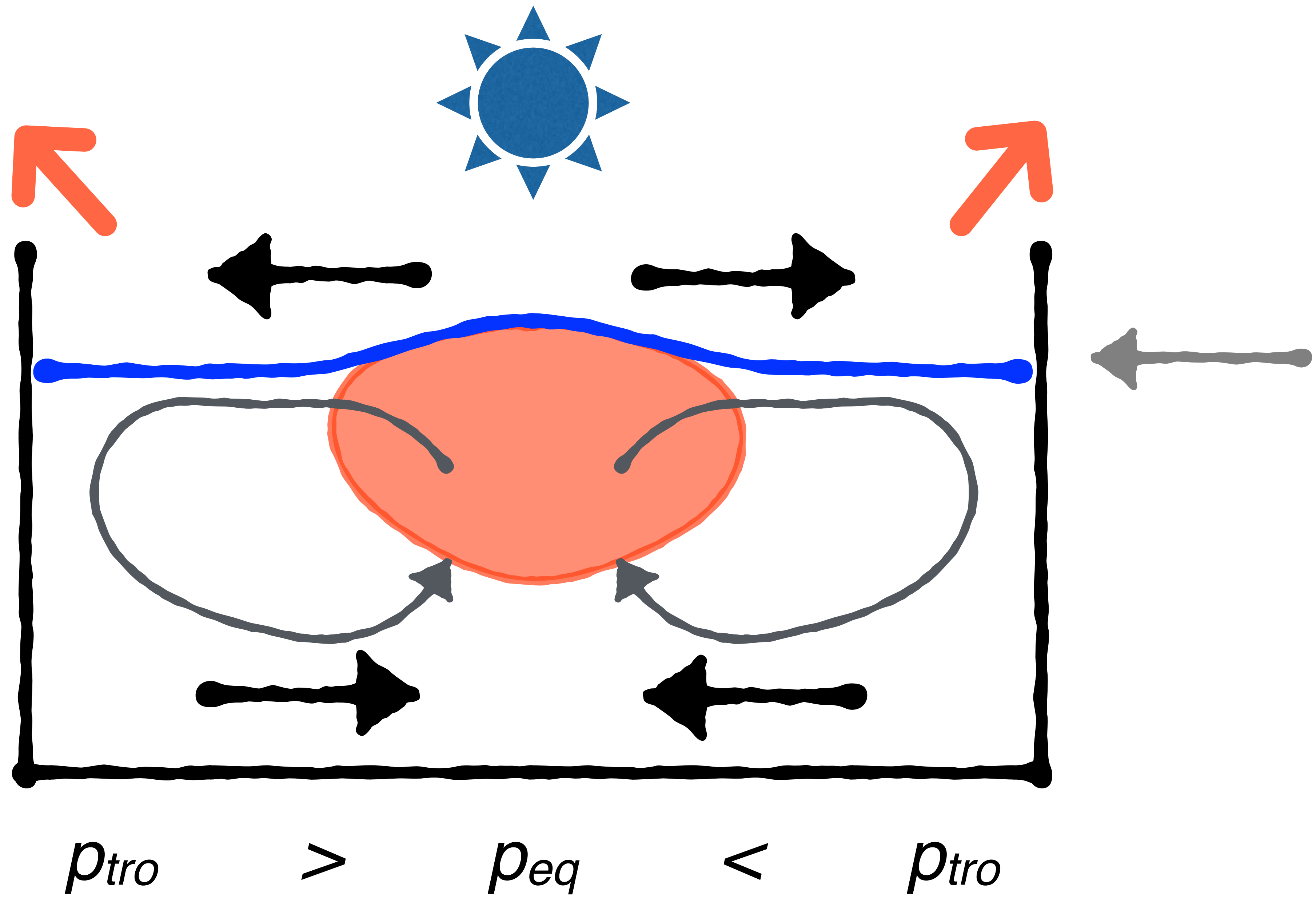


$$p_{tro} = p_{eq} = p_{tro}$$

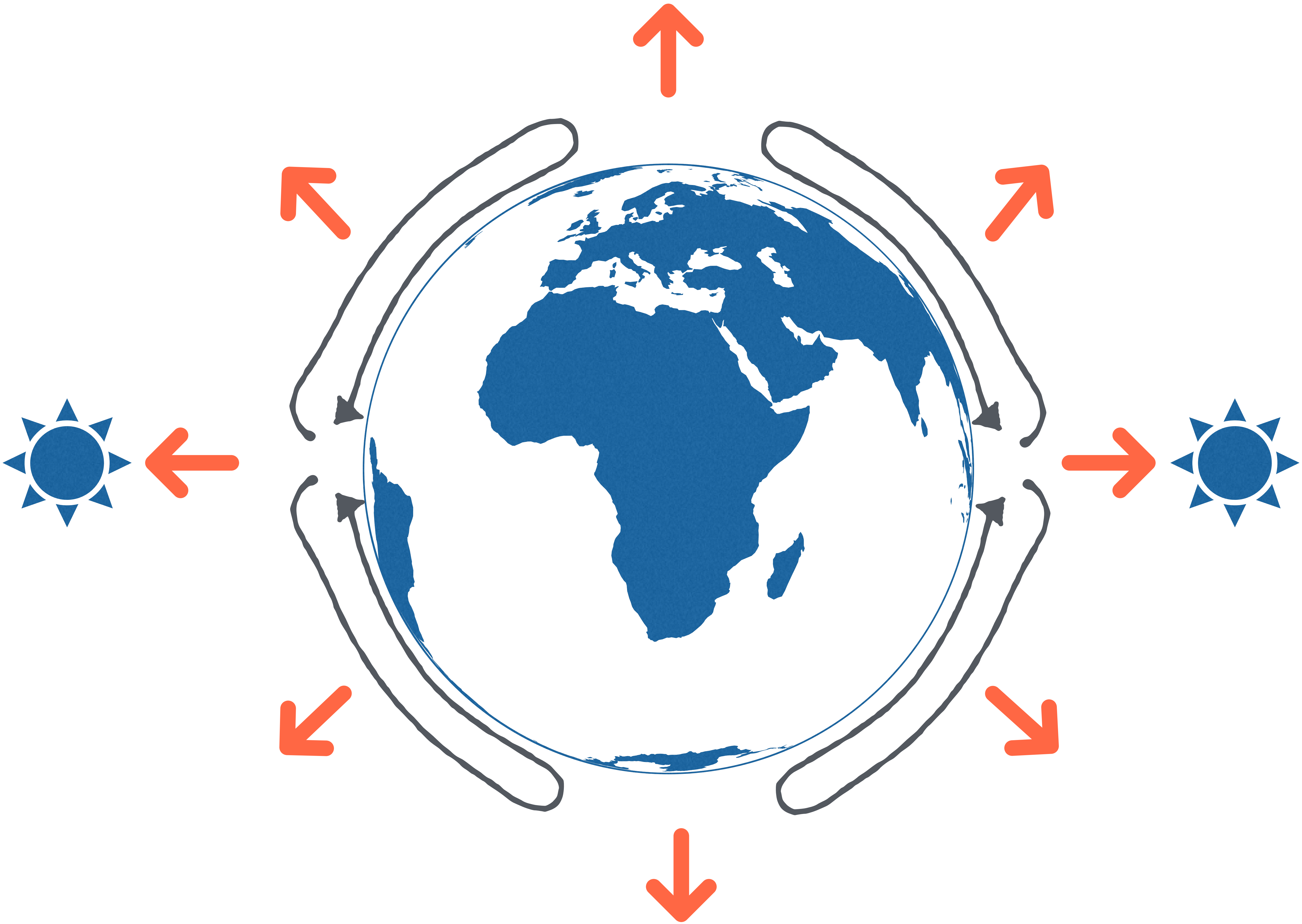


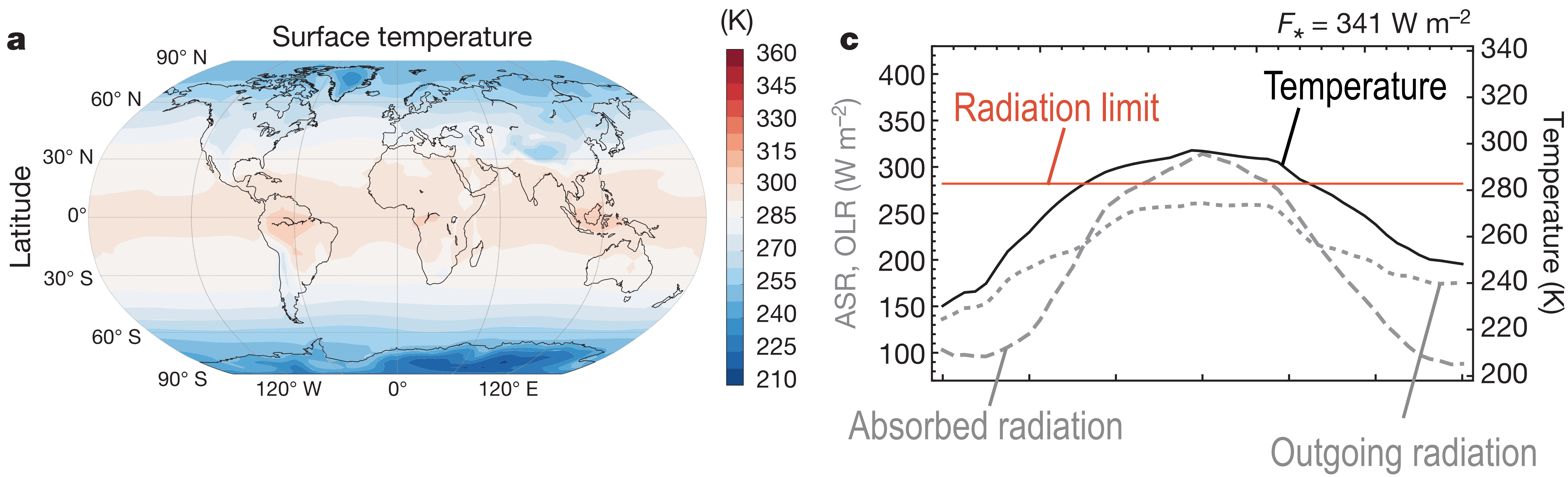
$$p_{tro} = p_{eq} = p_{tro}$$


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

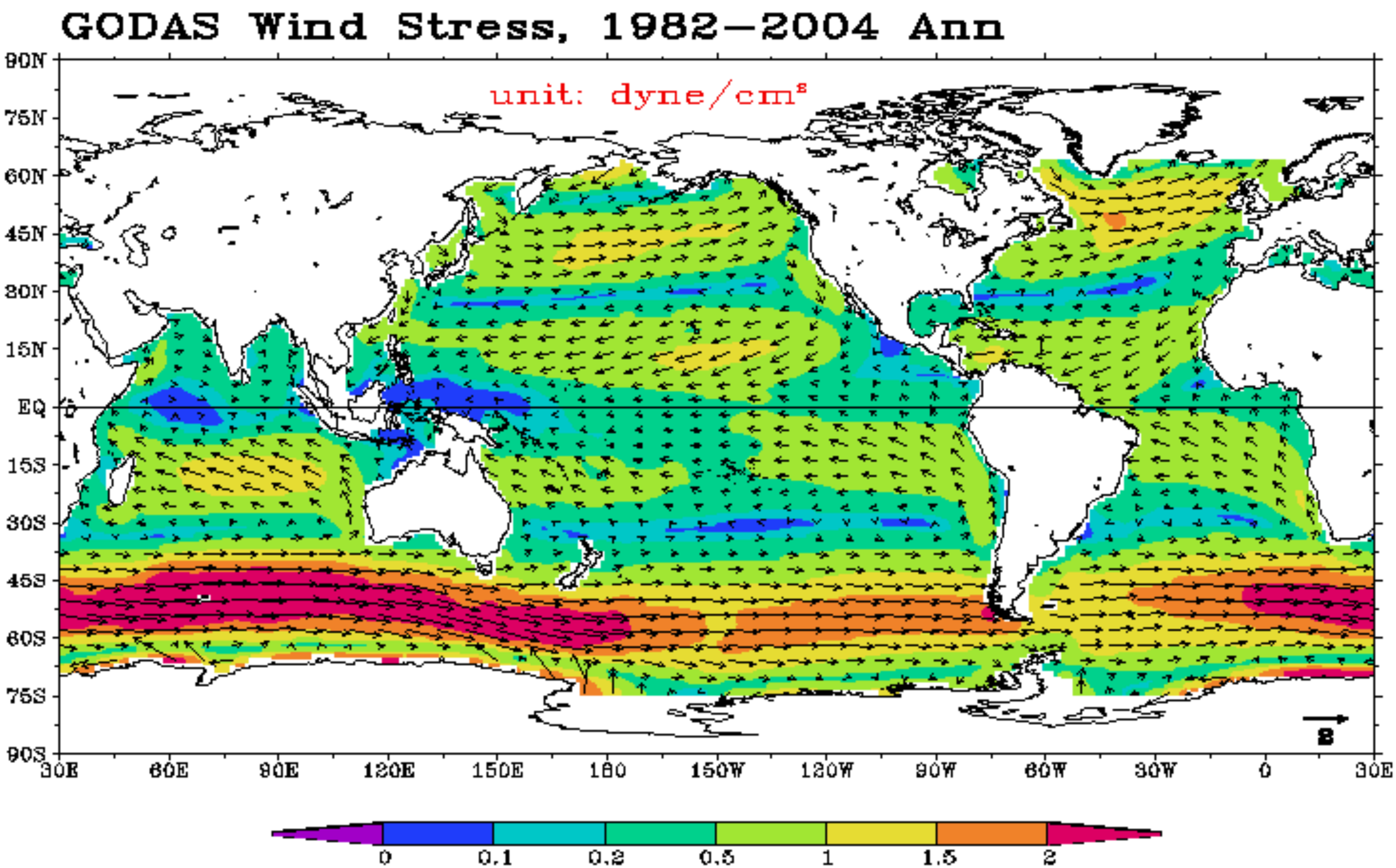


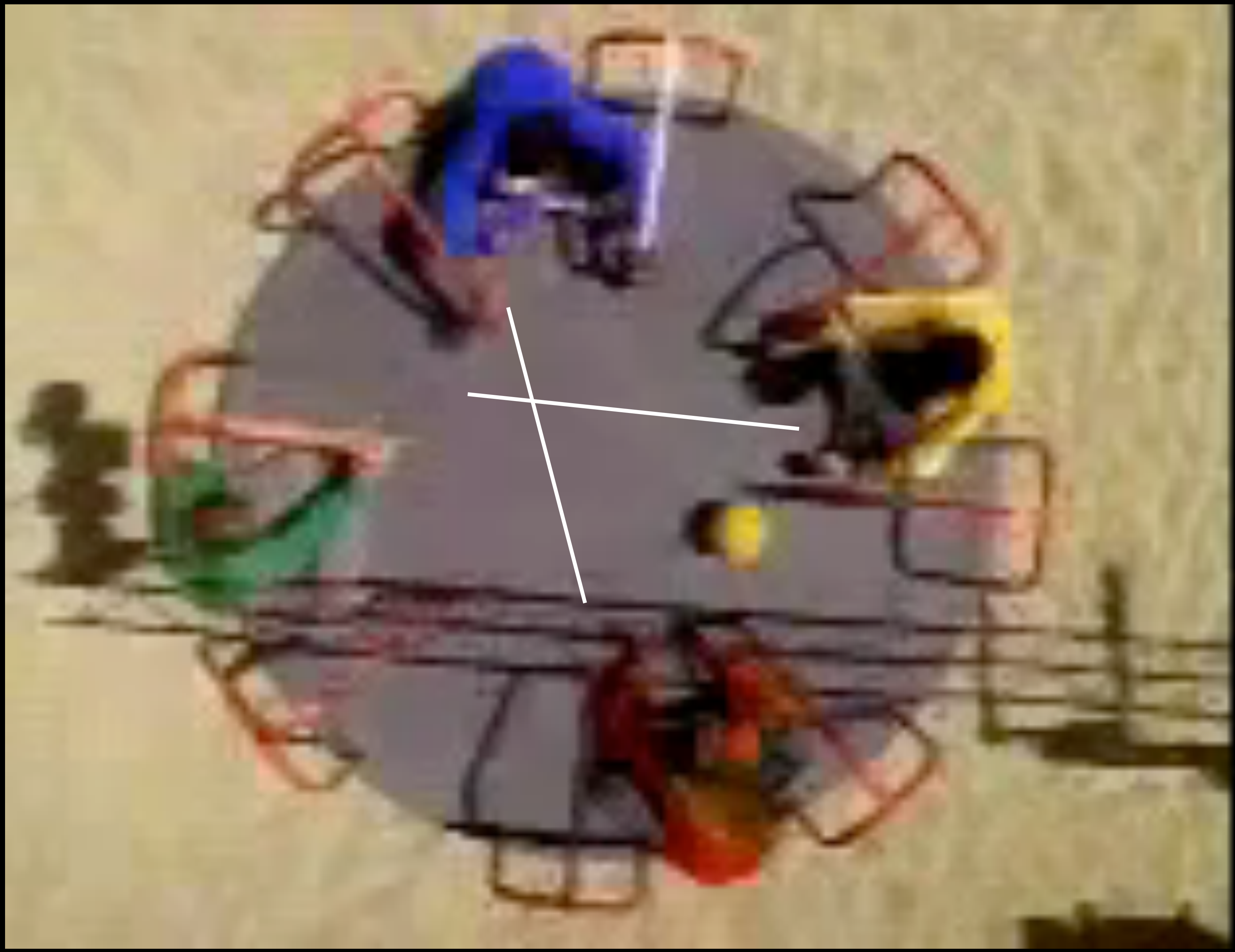
p_{tro} > p_{eq} < p_{tro}

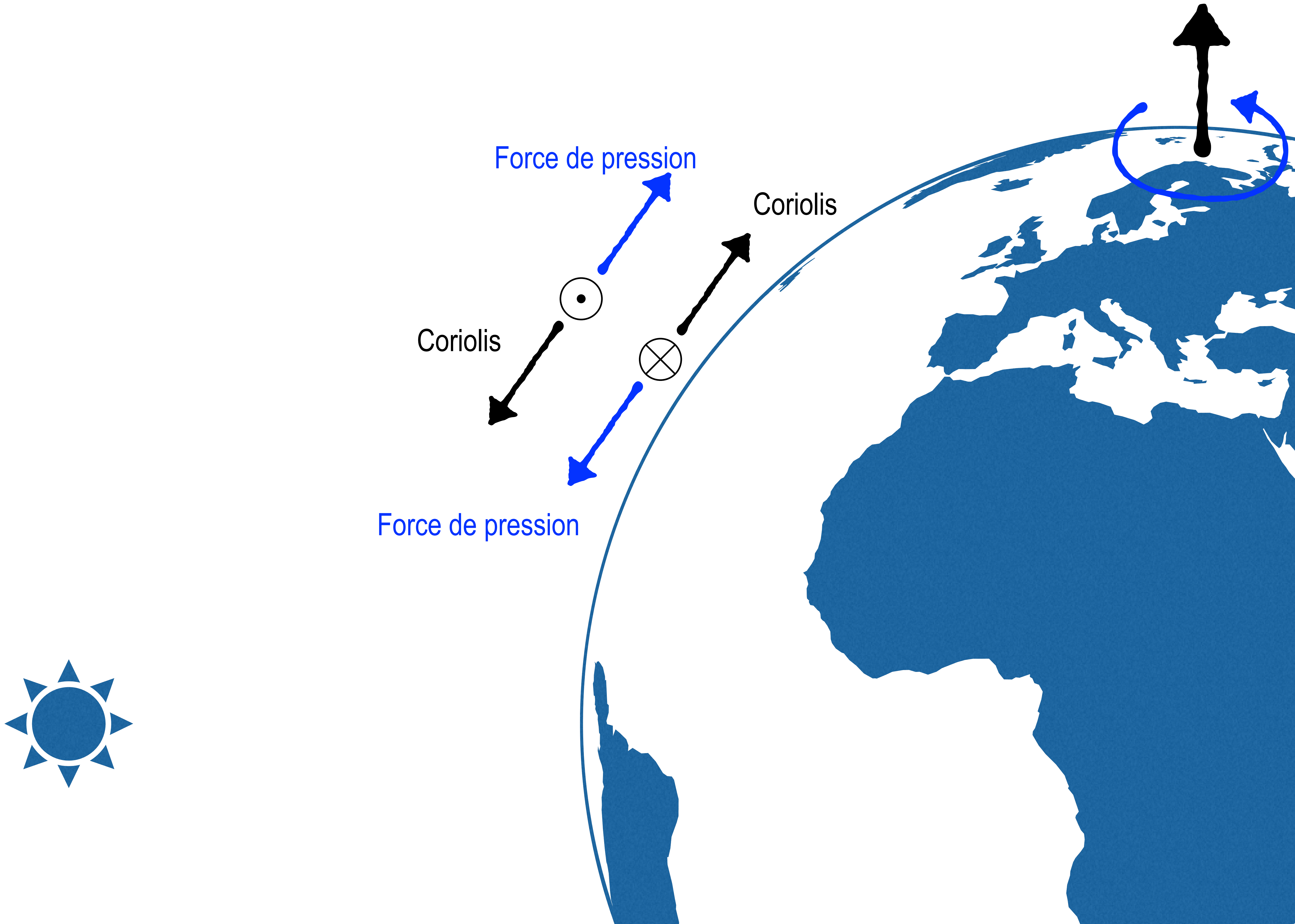


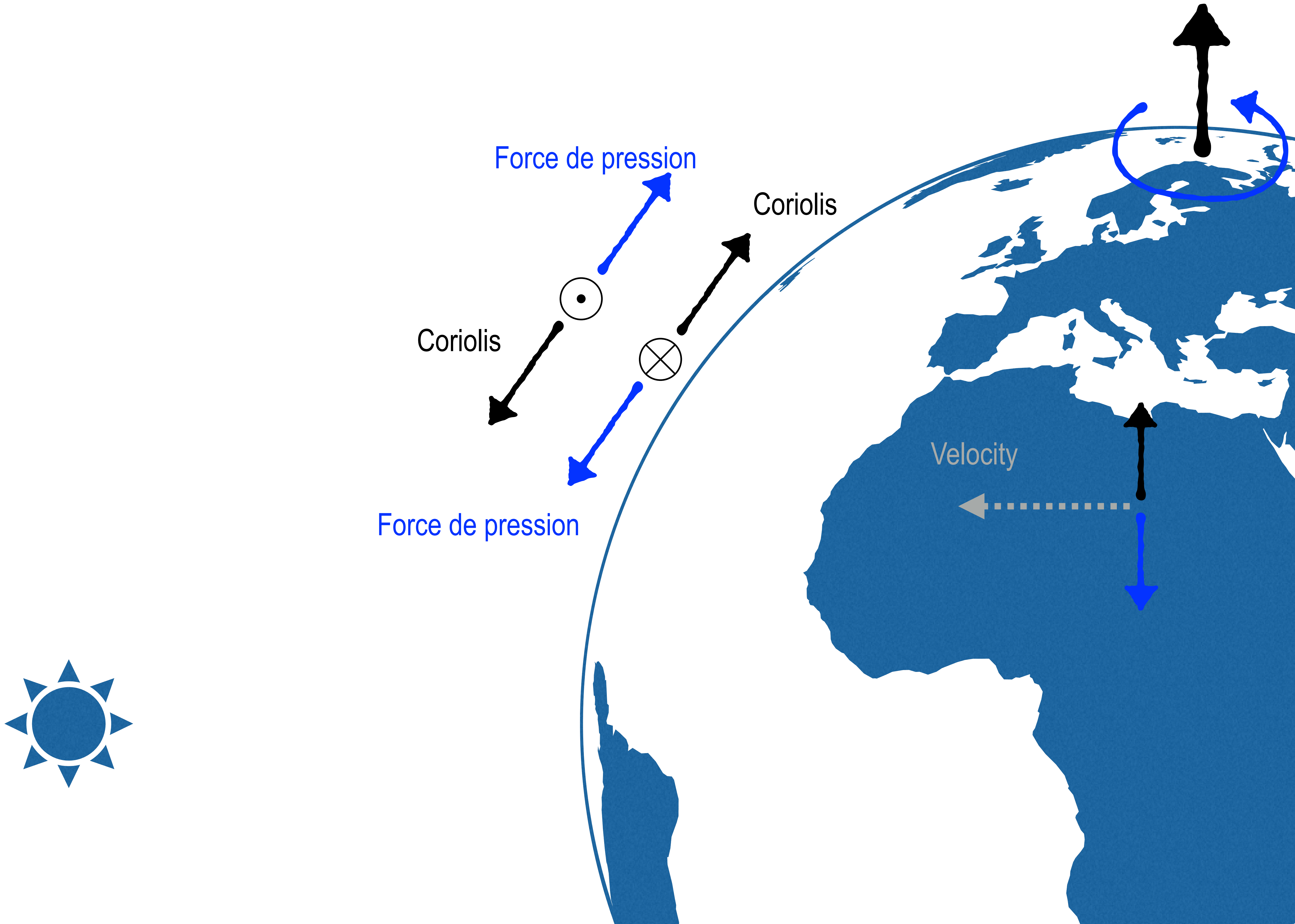


Leconte et al. (Nature, 2013)

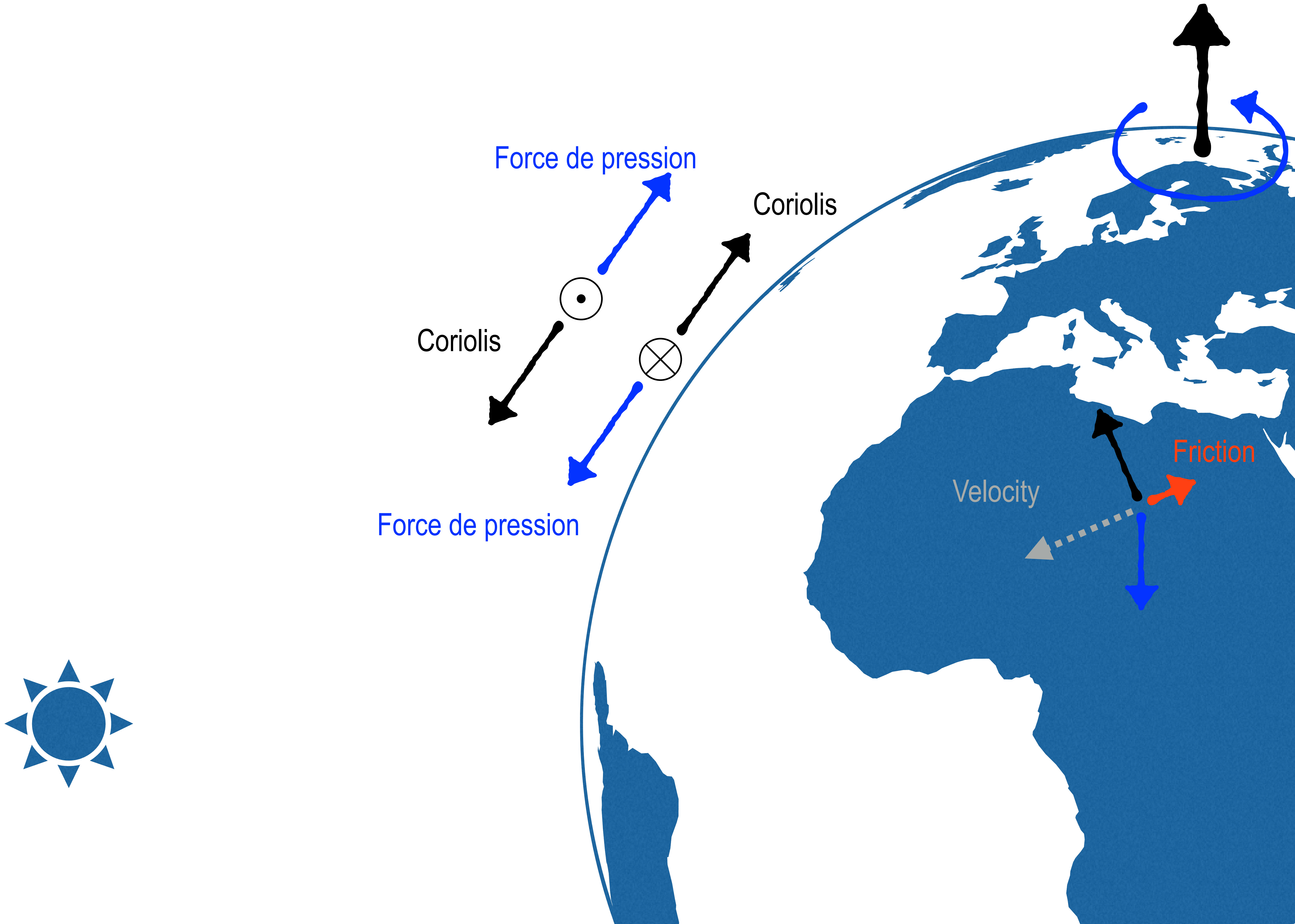

GODAS Wind Stress, 1982-2004 Ann
unit: dyne/cm²
90N
75N
60N
45N
30N
15N
EQ
15S
30S
45S
60S
75S
90S
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
30E
2
0
0.1
0.2
0.5
1
1.5
2

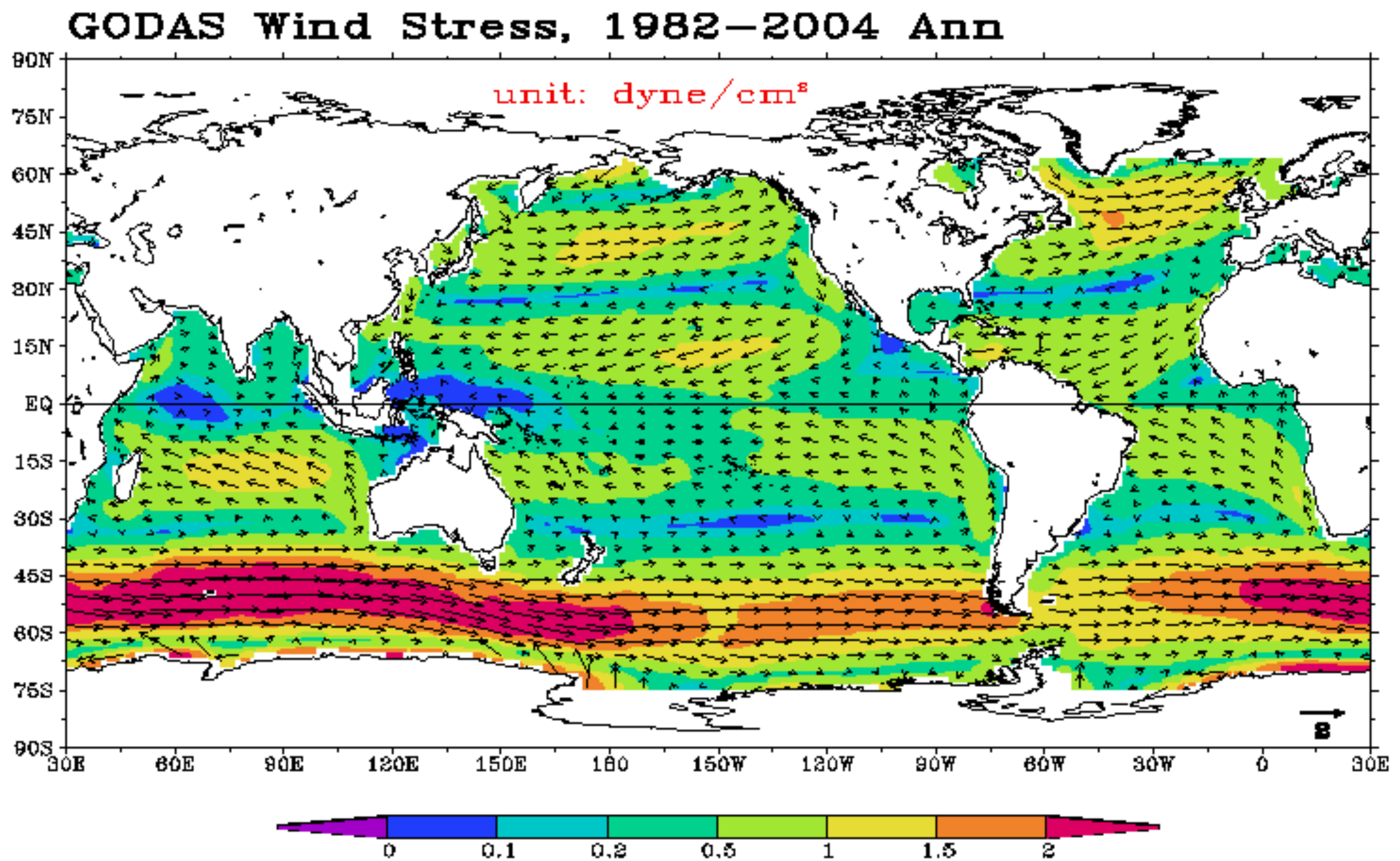



Force de pression
Coriolis
Coriolis
Force de pression

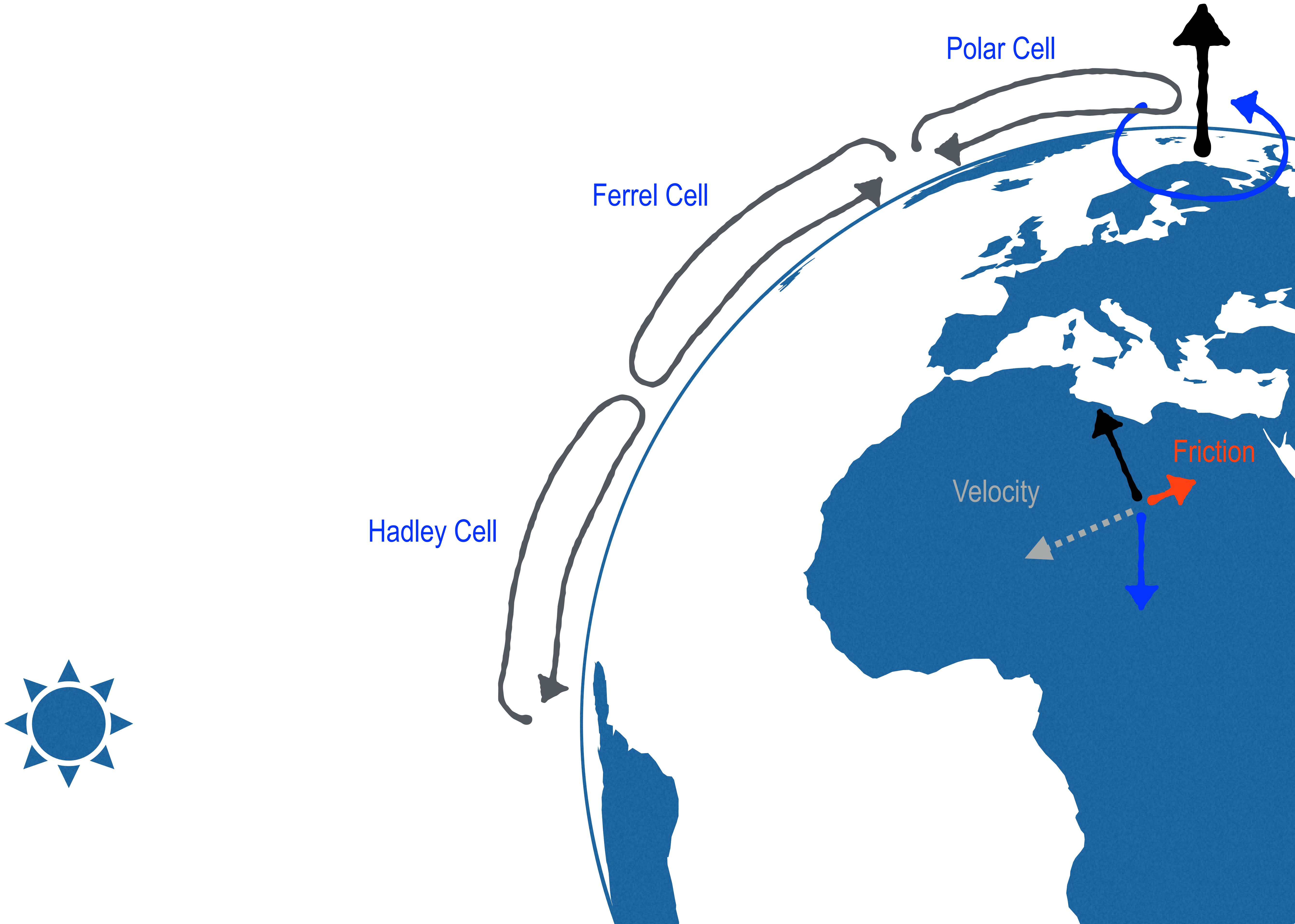


Force de pression
Coriolis
Coriolis
Force de pression
Velocity

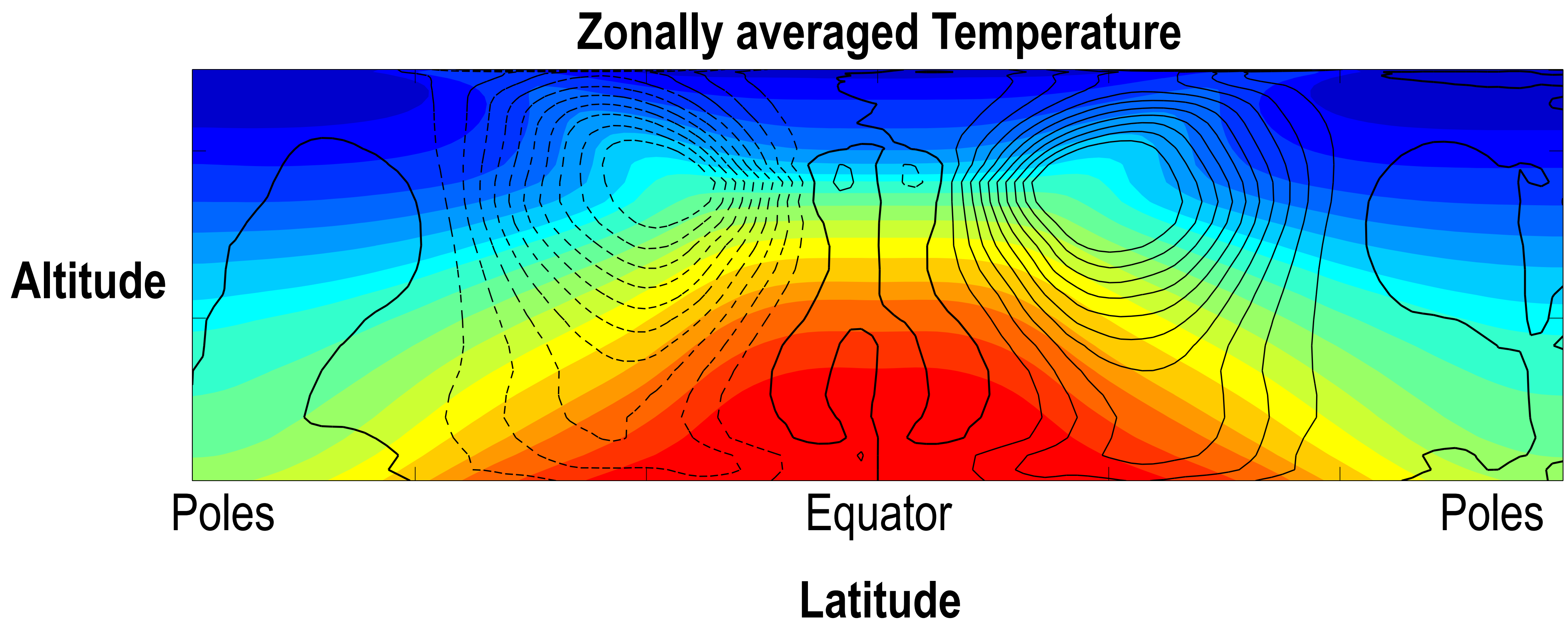

Force de pression
Coriolis
Coriolis
Force de pression
Friction
Velocity

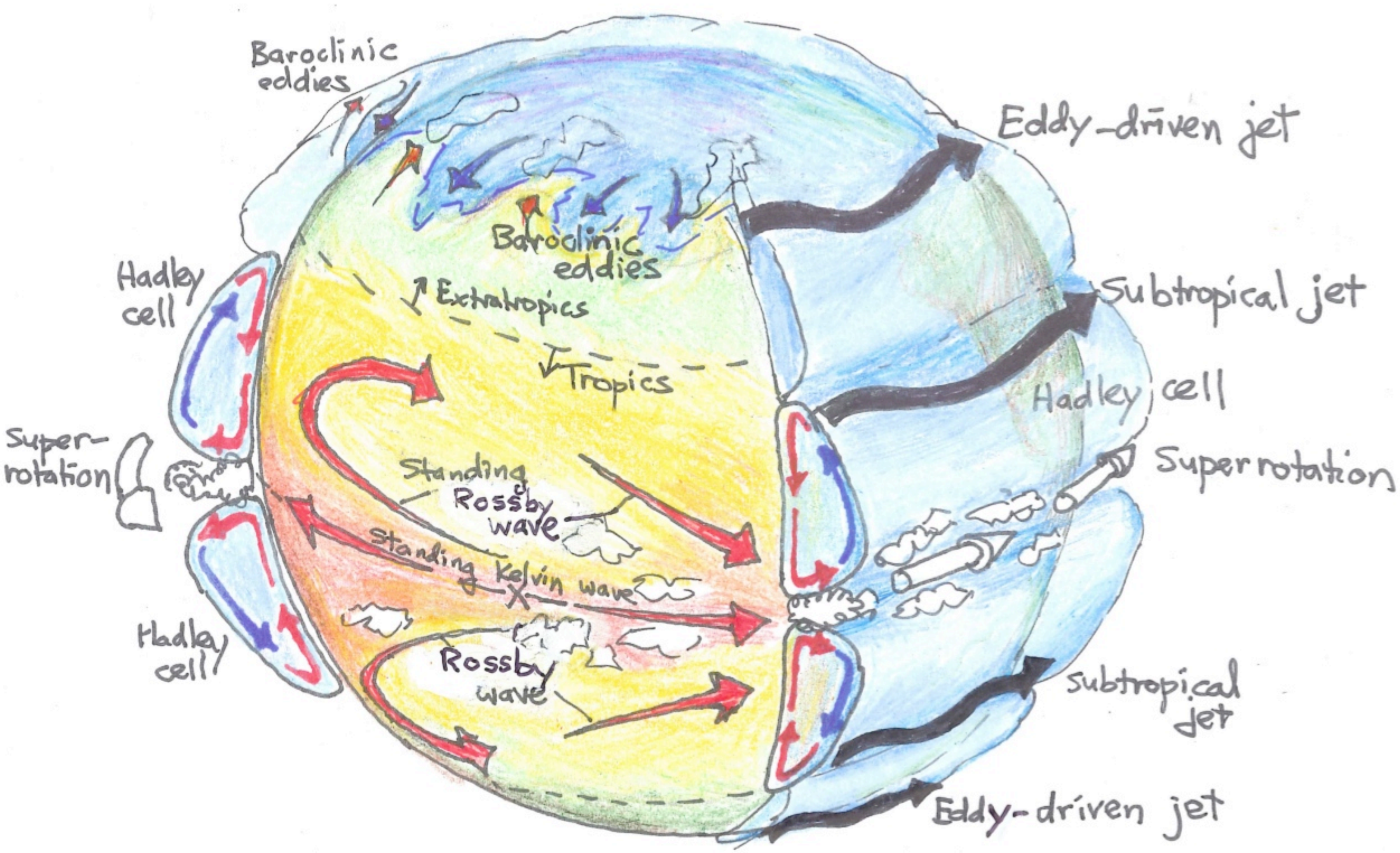


GODAS Wind Stress, 1982–2004 Ann
unit: dyne/cm²
90N
75N
60N
45N
30N
15N
EQ
15S
30S
45S
60S
75S
90S
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
30E
2
0
0.1
0.2
0.5
1
1.5
2



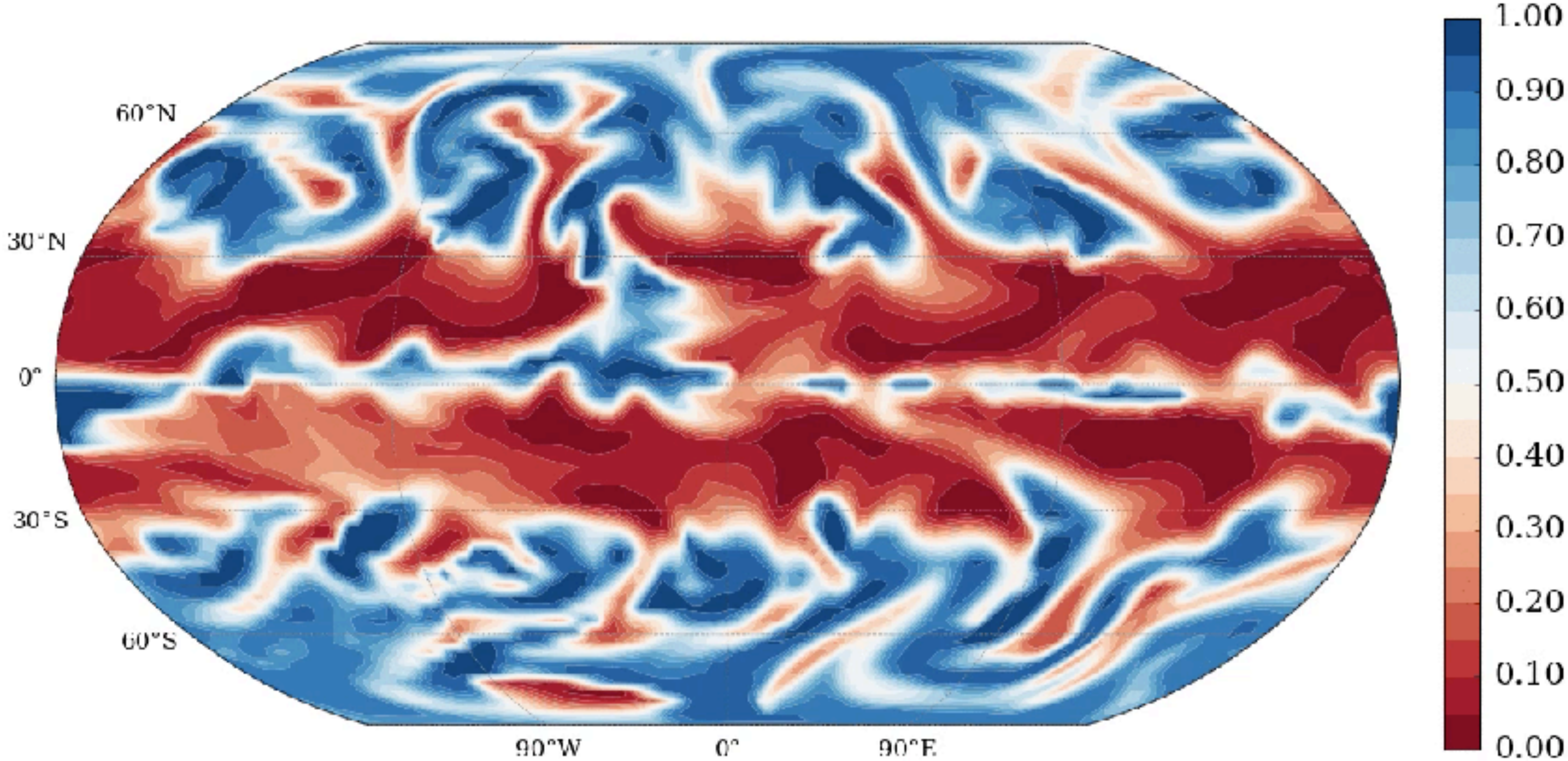
Polar Cell
Ferrel Cell
Hadley Cell
Friction
Velocity

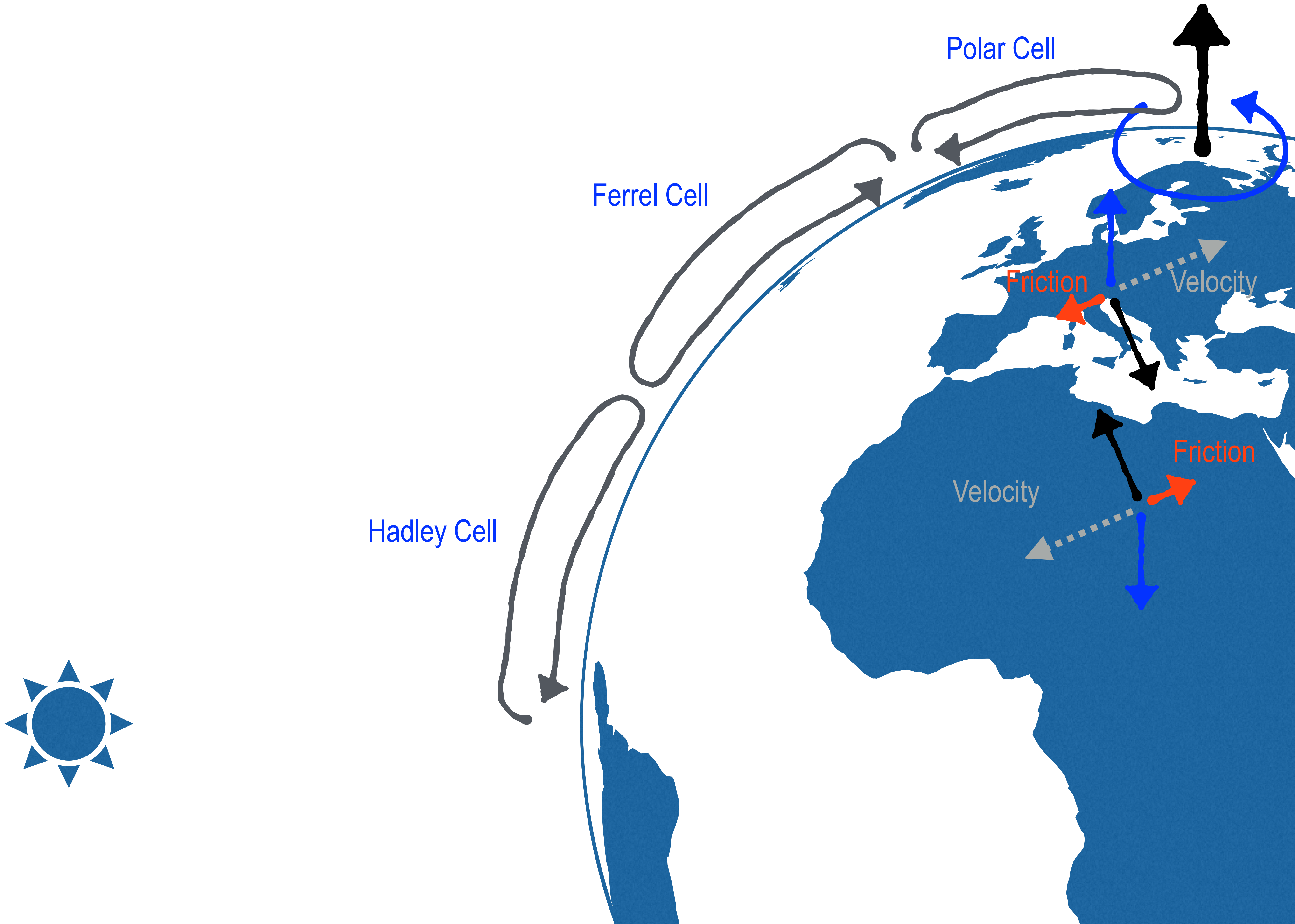


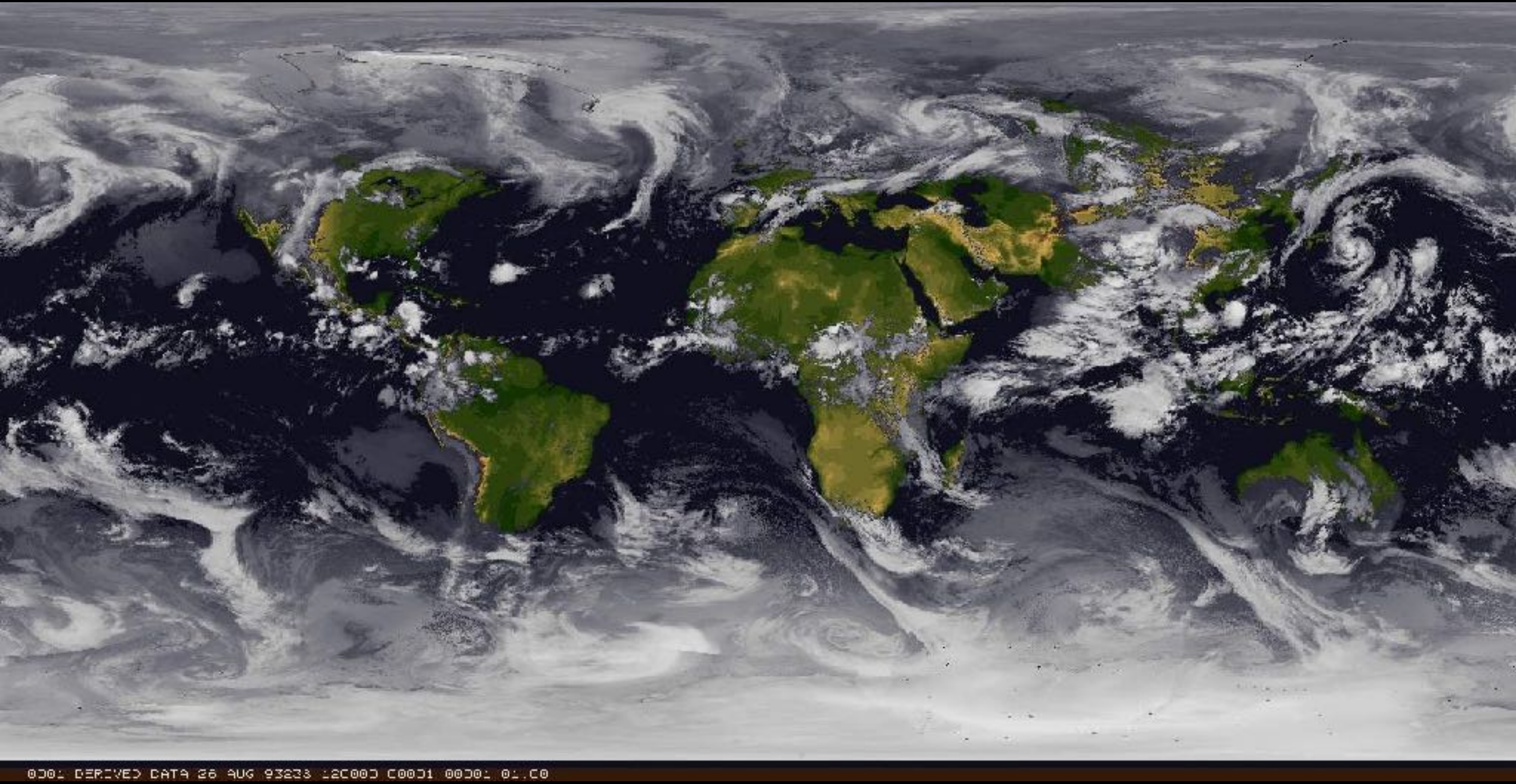


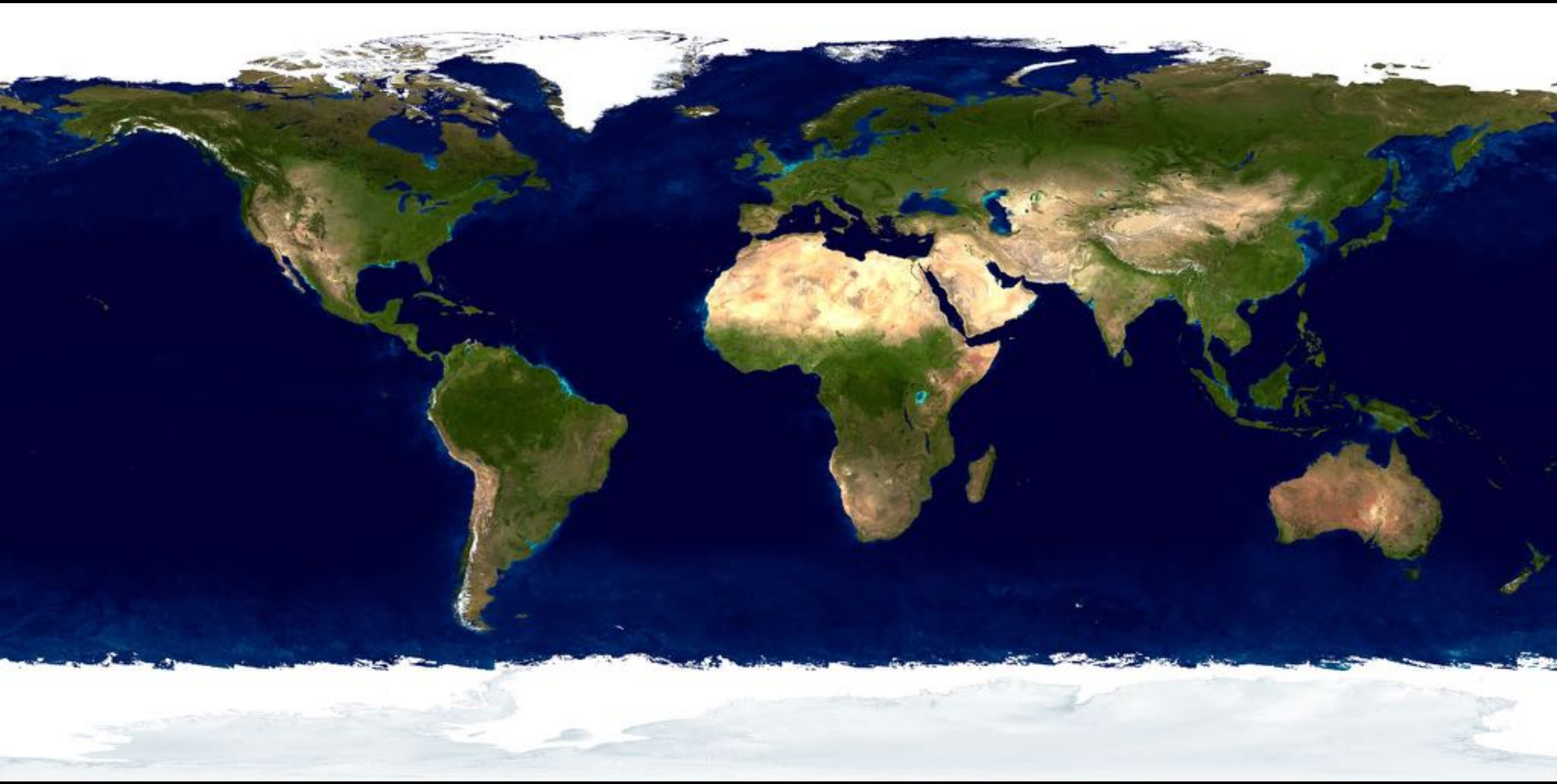
In memory of Adam Showman

Relative Humidity

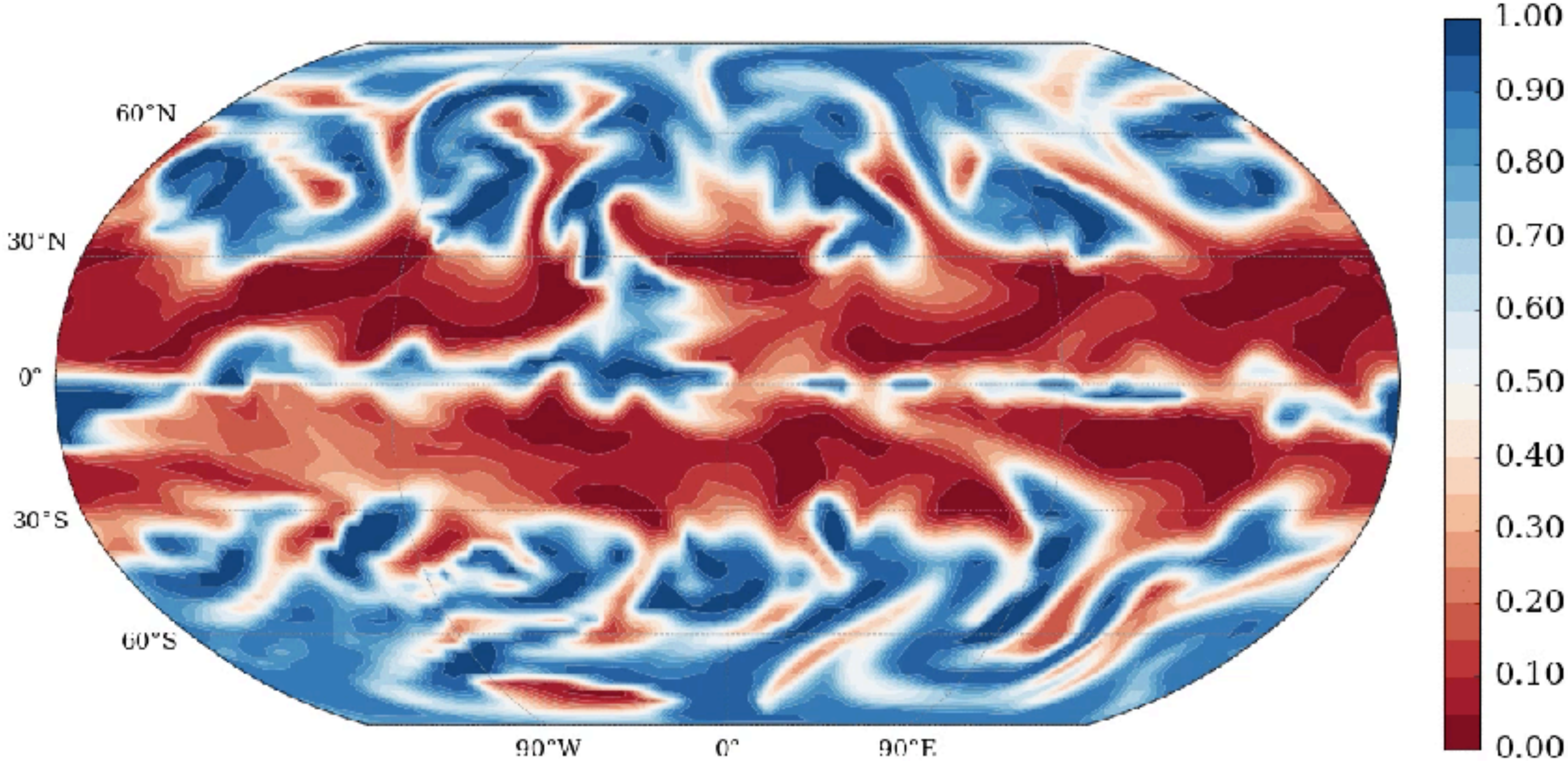



Polar Cell
Ferrel Cell
Hadley Cell
Friction
Velocity
Friction
Velocity

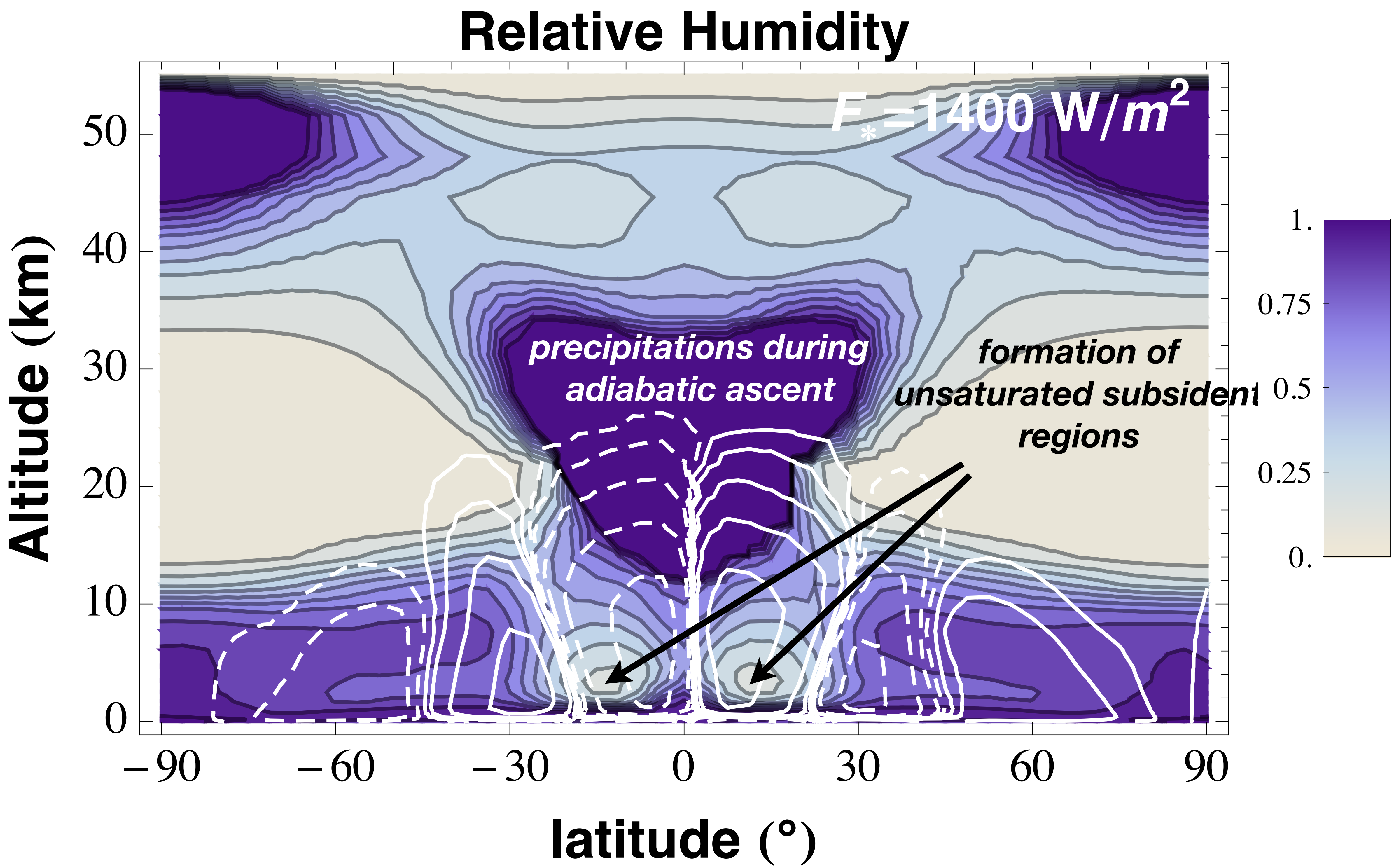

0001 DERIVED DATA 26 AUG 93238 120000 C0001 00001 01.C0



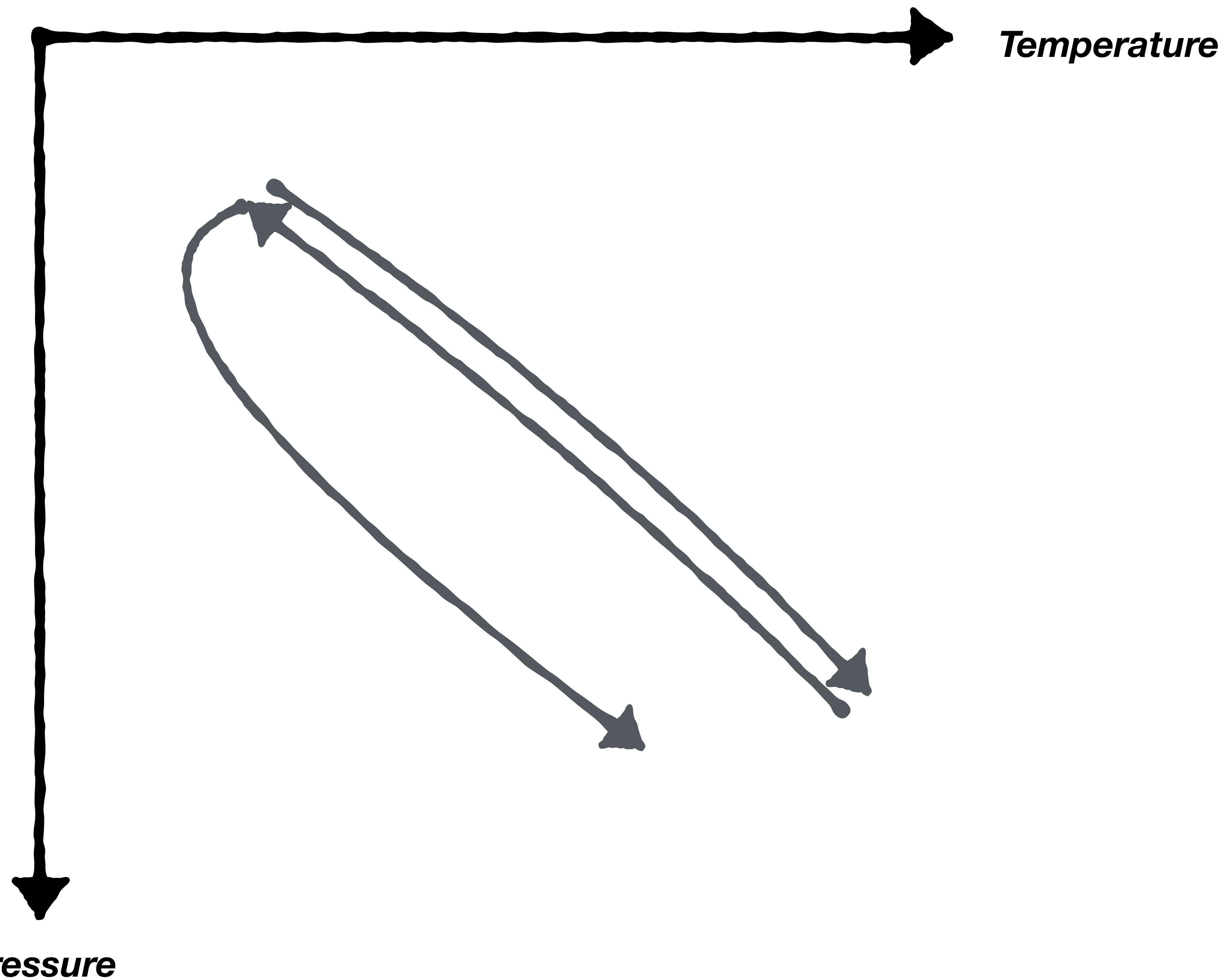
Relative Humidity



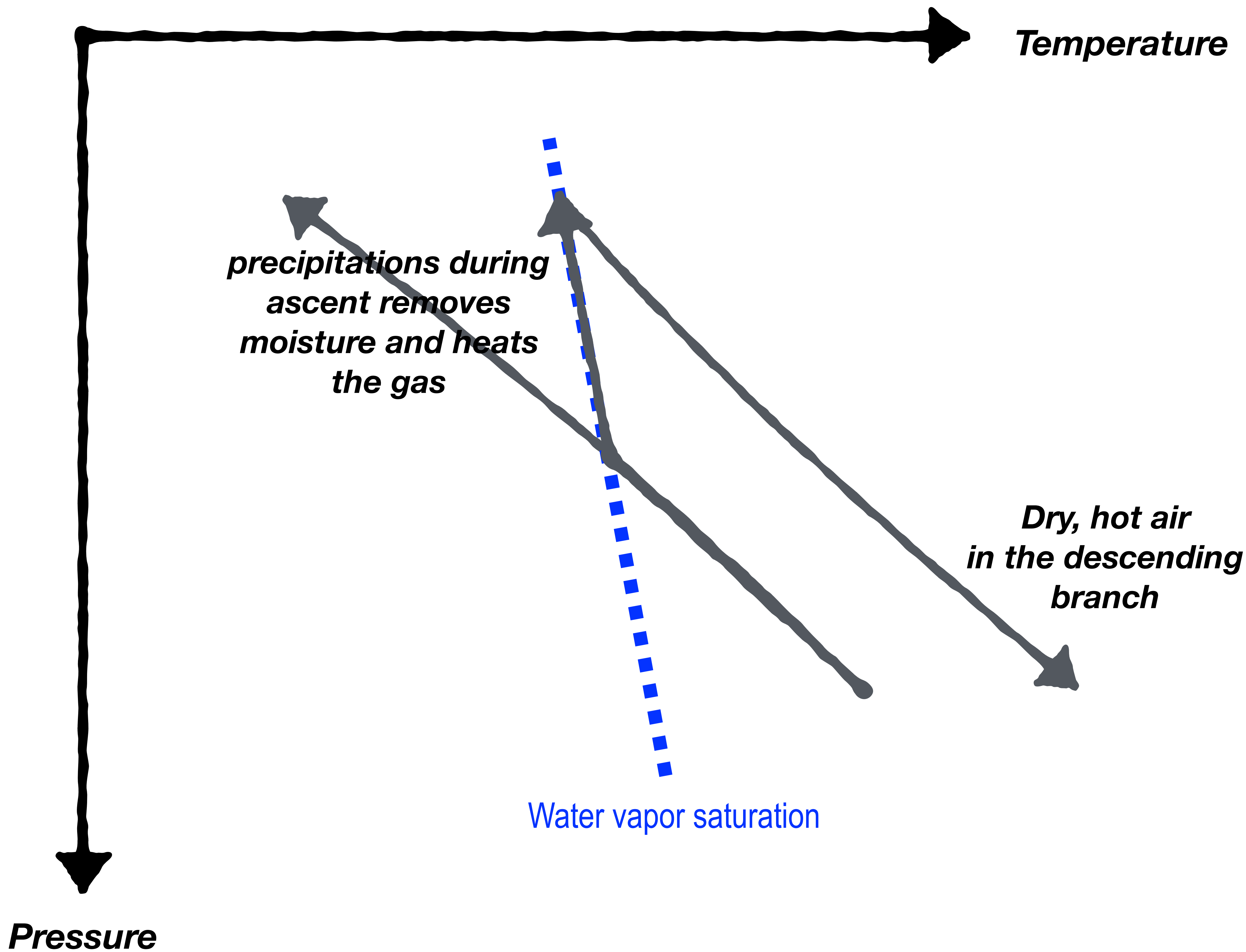
The impact of the Hadley cell

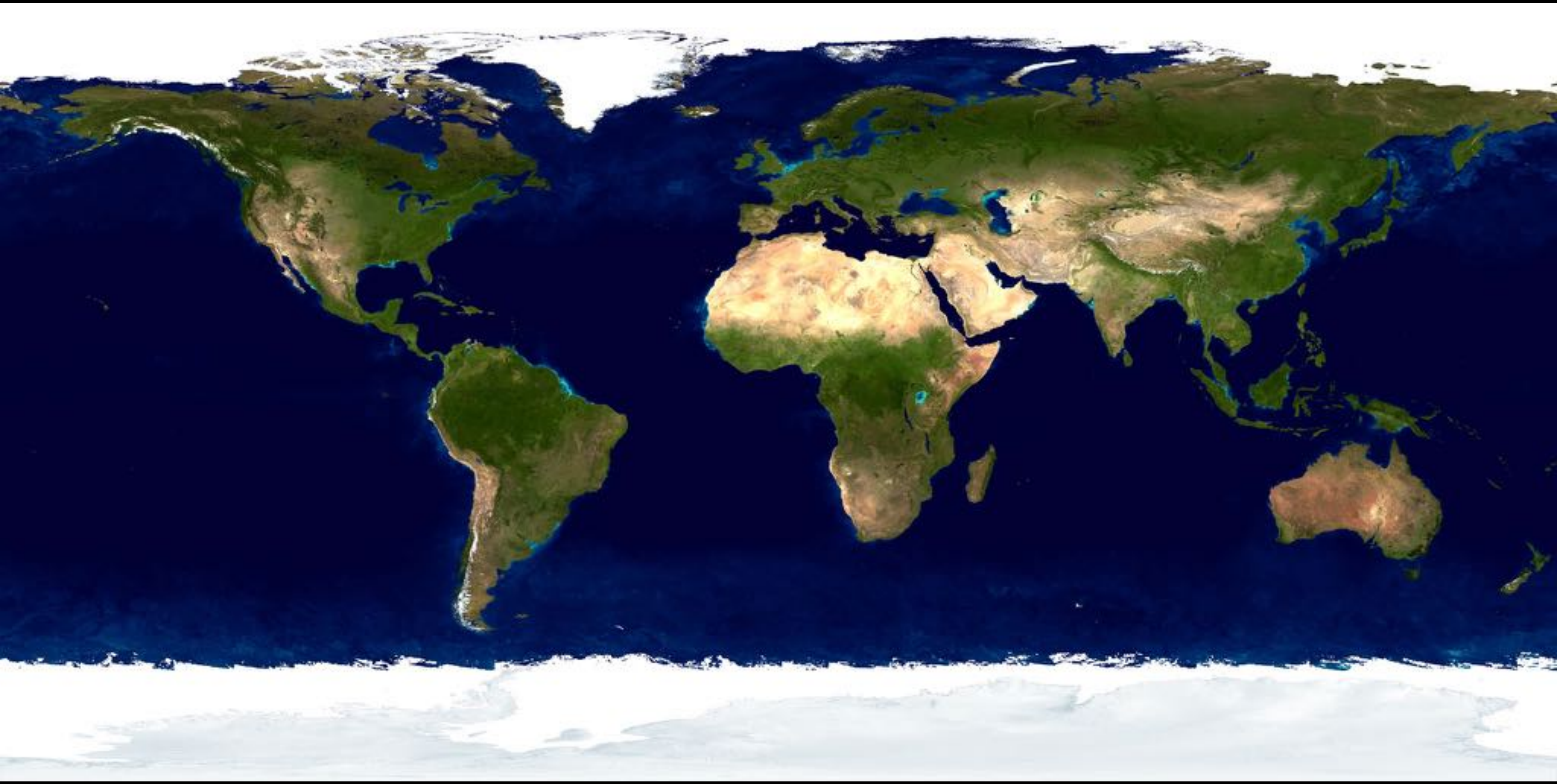


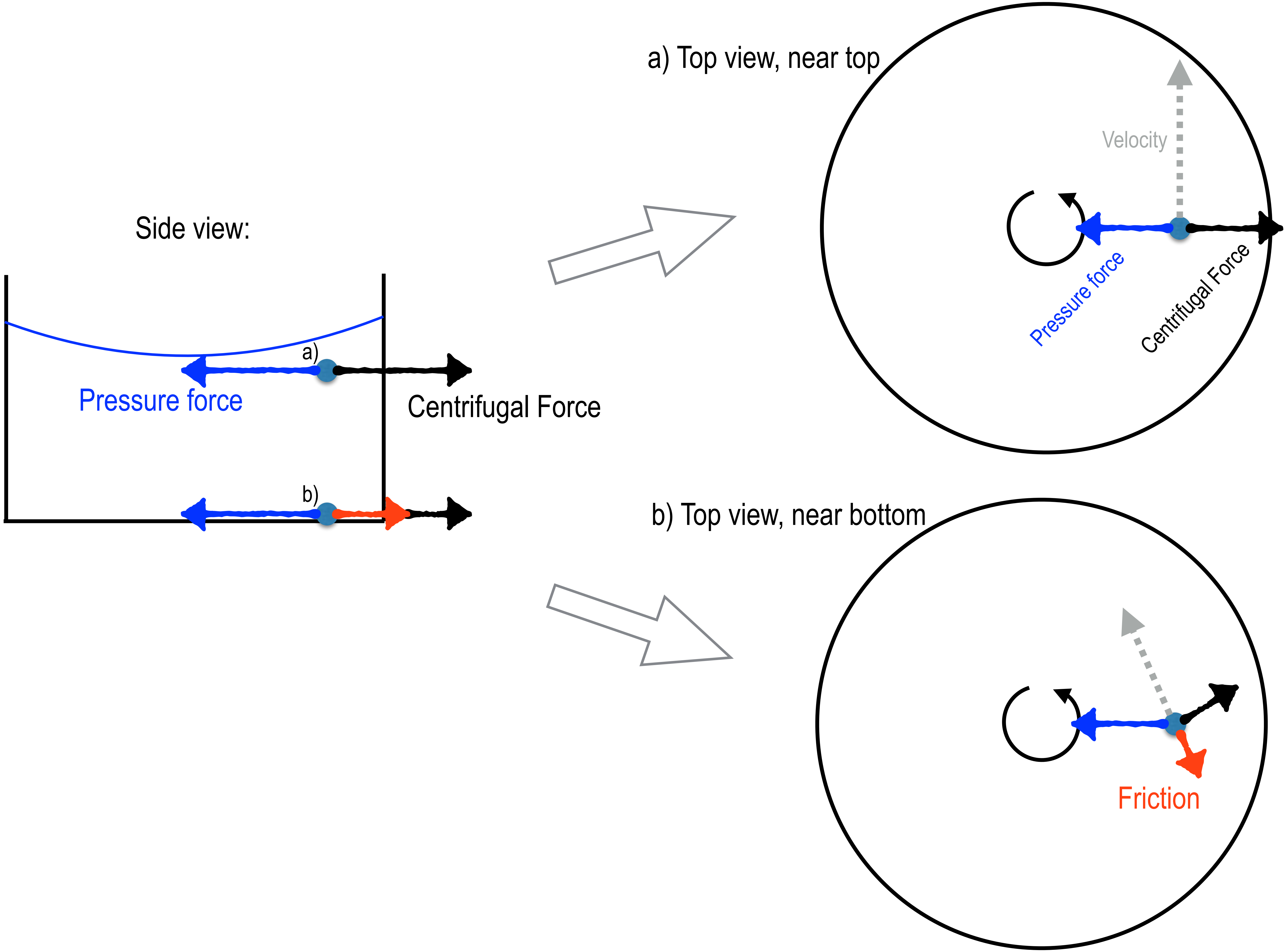
Thermodynamics of the Hadley Cell



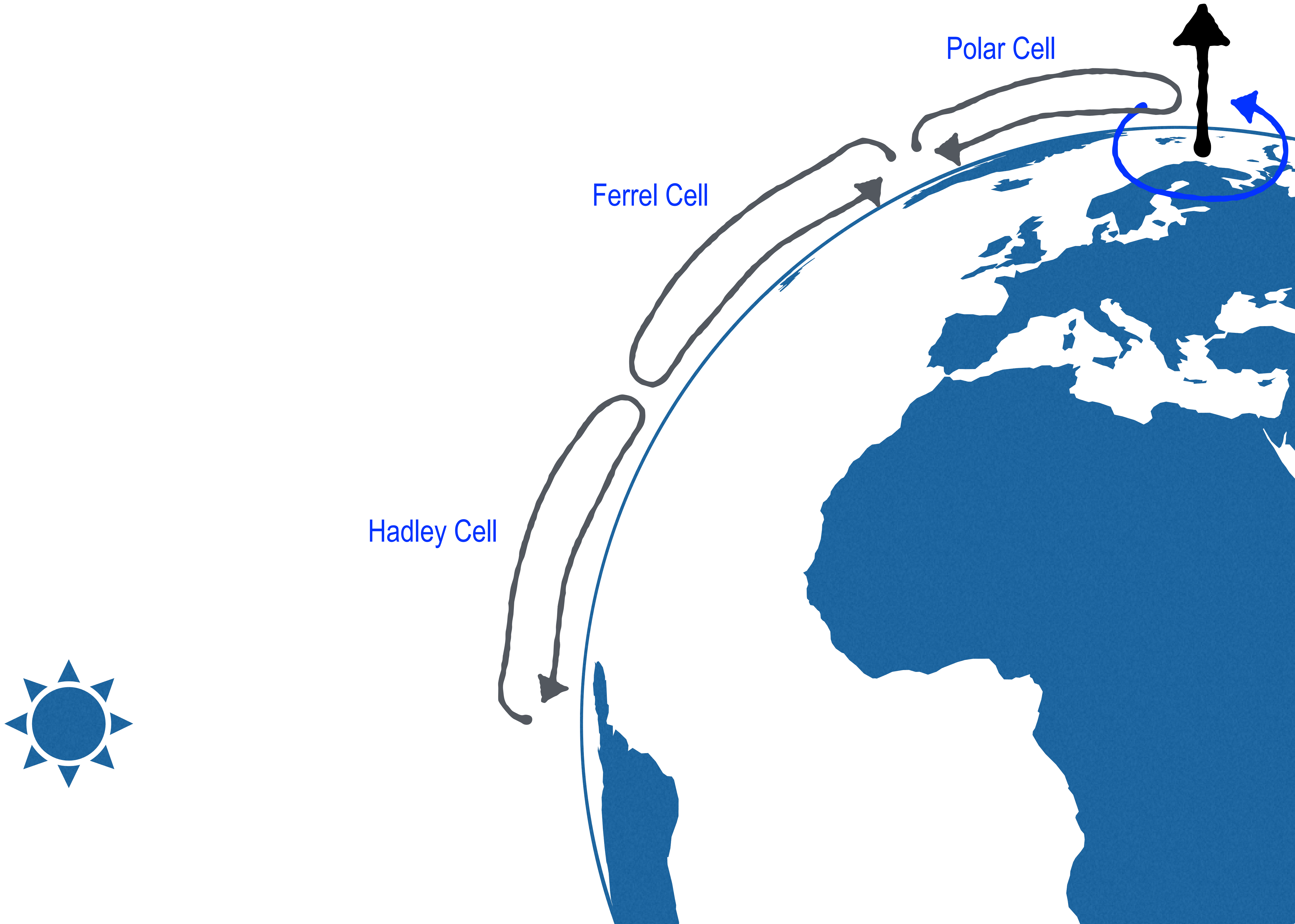
Thermodynamics of the Hadley Cell







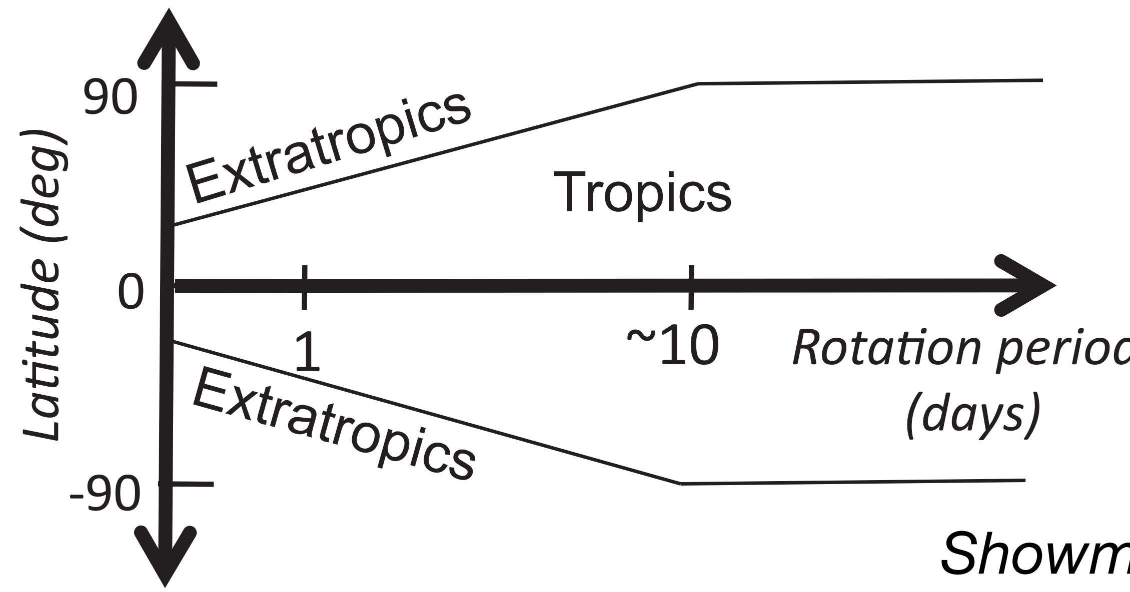
Side view:
a)
Pressure force
Centrifugal Force
b)
a) Top view, near top
Velocity
Pressure force
Centrifugal Force
b) Top view, near bottom
Friction



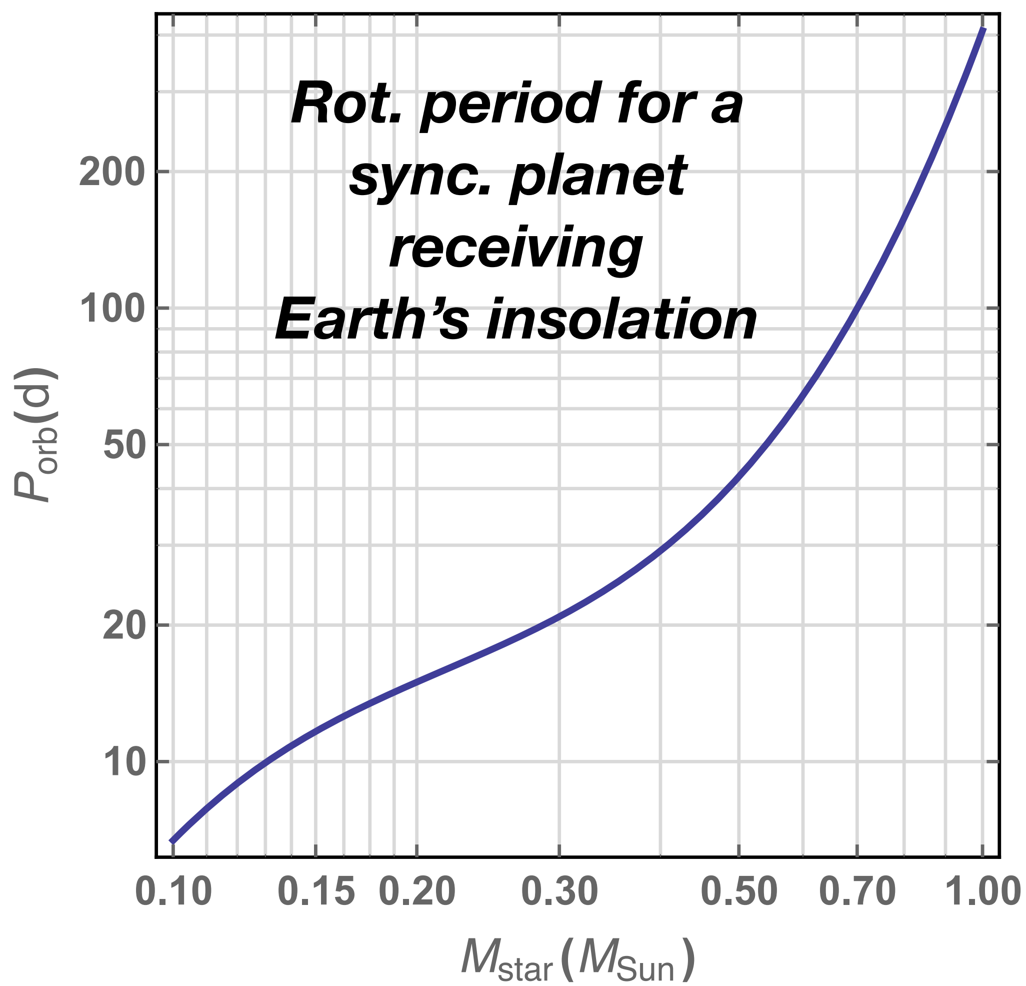
Polar Cell
Ferrel Cell
Hadley Cell

What about
synchronously rotating planets?

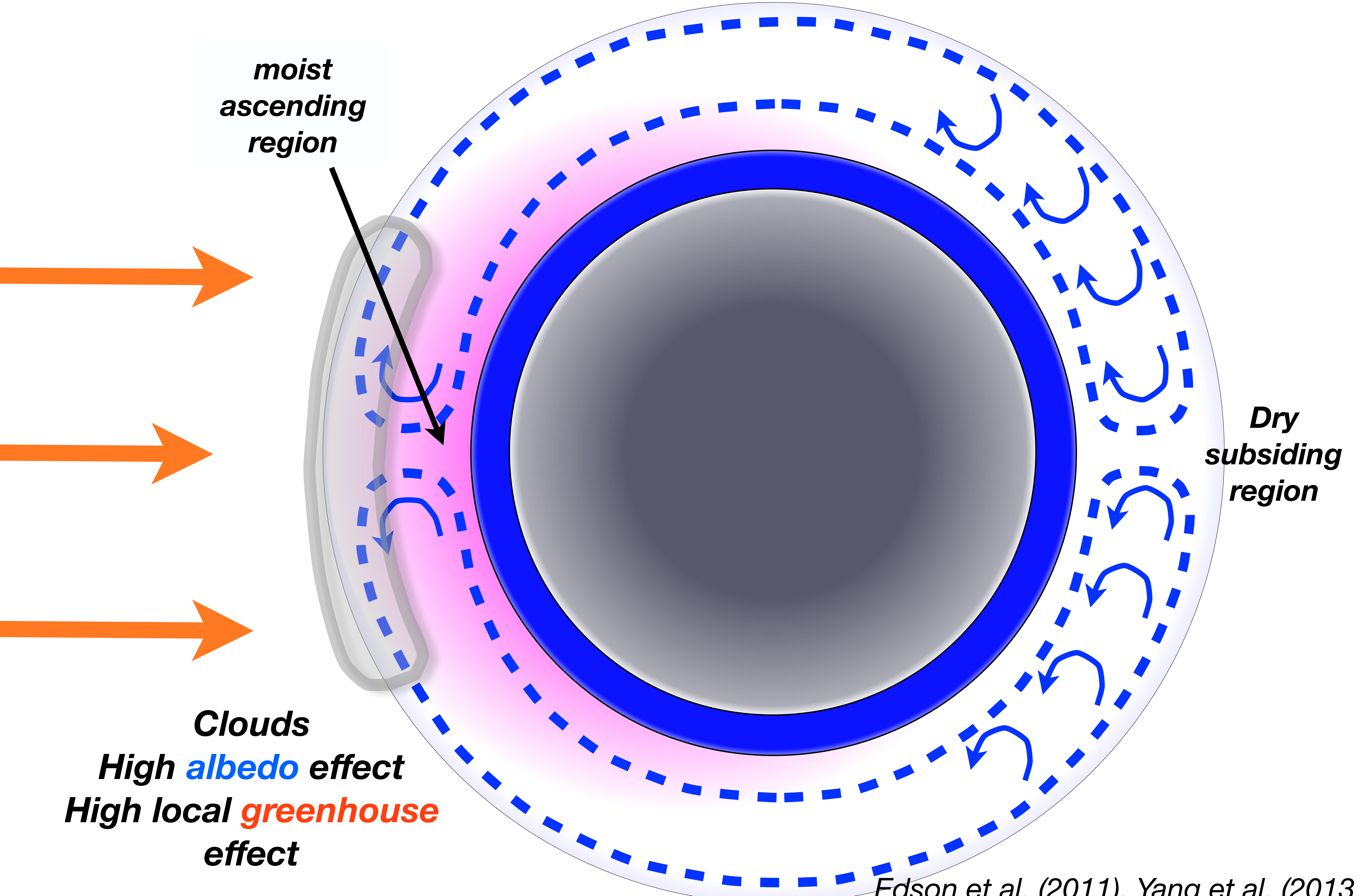
What about synchronously rotating planets?



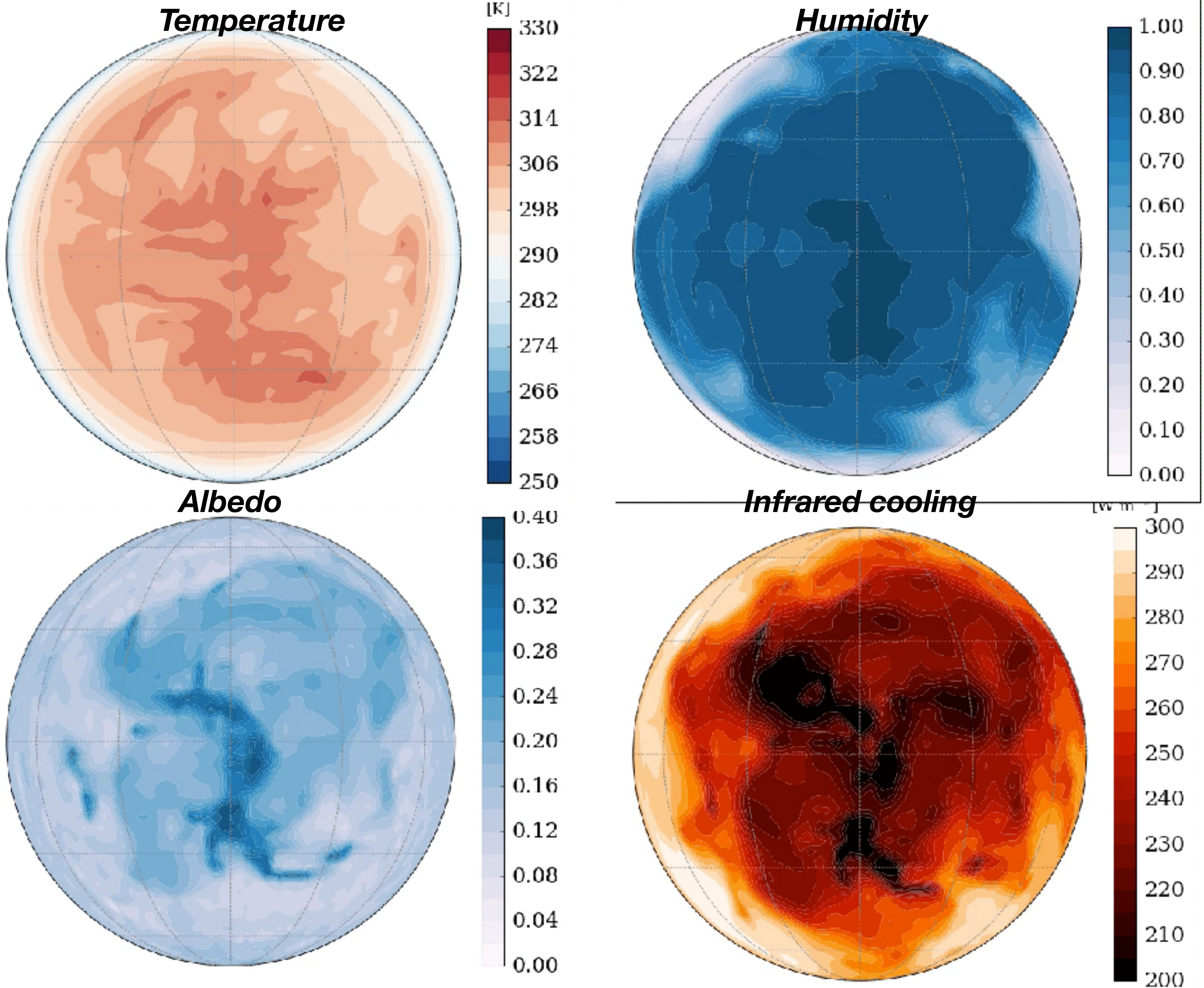
Showman et al. (2013)



Expected dynamics on tidally locked planets



Edson et al. (2011), Yang et al. (2013)


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

Two prototypes of synchronous planets

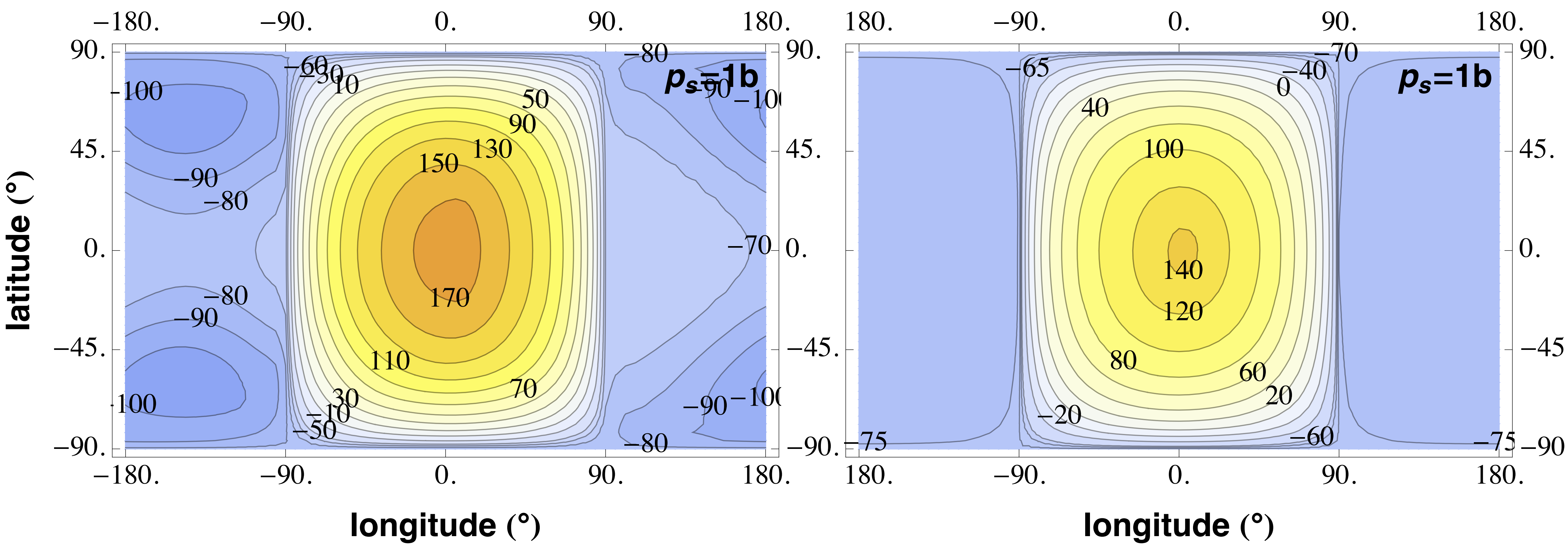
Planet name		Gl 581 c	HD 85512 b	
Stellar luminosity	$L_\star$ [$L_\odot$]	0.0135	0.126	
Stellar mass	$M_\star$ [$M_\odot$]	0.31	0.69	
Orbital semi-major axis	a [AU]	0.073	0.26	
Orbital period	$P_{\rm orb}$ [d]	13	58	
Orbital eccentricity	e	0-0.05	0-0.11	
Mass	$M_{\rm p}$ [$M_\oplus$]	6.25	4.15	
Radius	$R_{\rm p}$ [$R_\oplus$]	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)

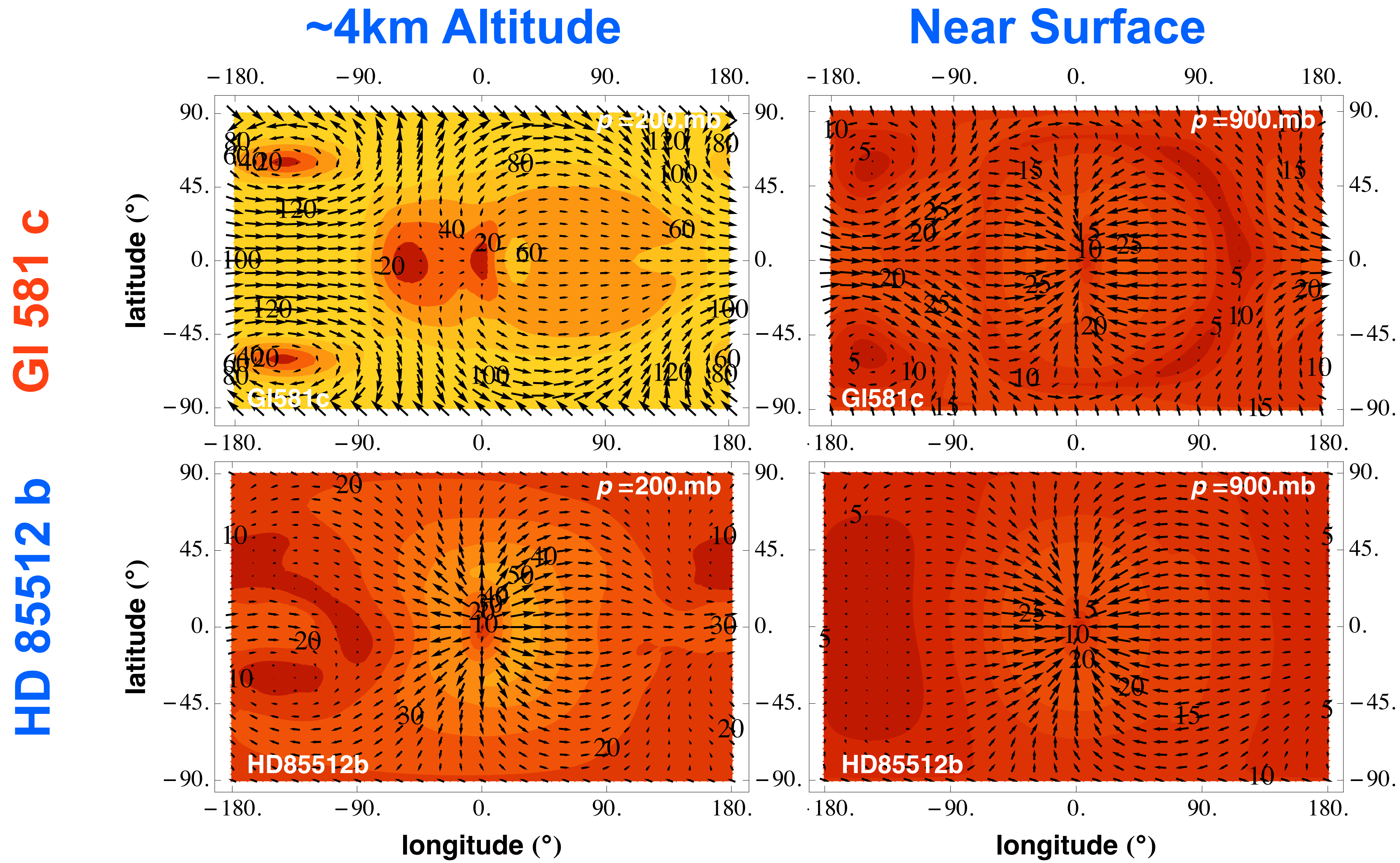
Gl 581 c **HD 85512 b**



(dry earthlike atmosphere)

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

wind maps (m/s)



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»

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

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

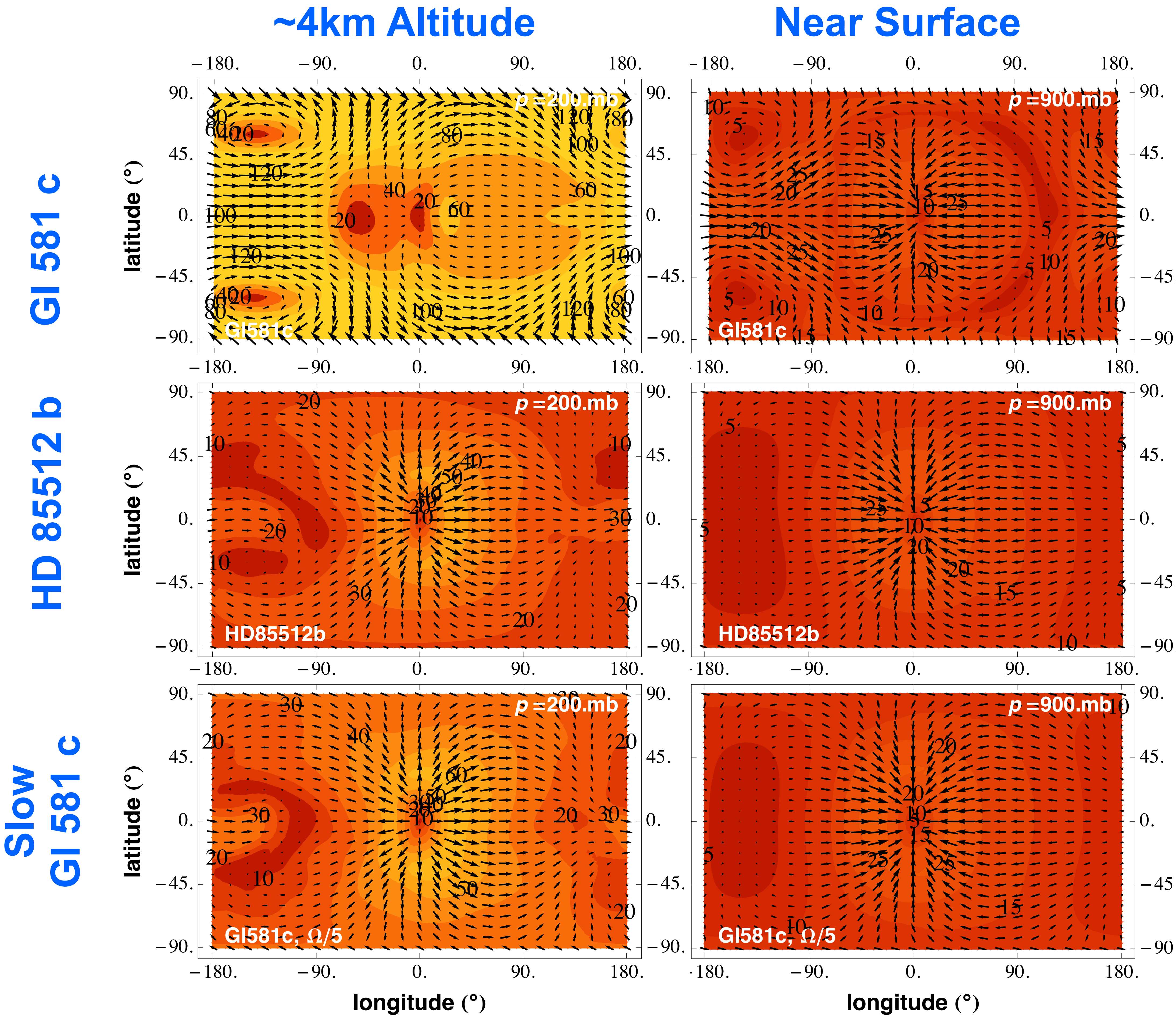
$$\mathcal{L} = \sqrt{\frac{k_{\mathrm{B}}}{m_{\mathrm{a}} c_{\mathrm{p}}^{1/2}} \frac{T^{1/2}}{2\,\Omega\,R_{\mathrm{p}}}}$$

Mechanism too weak

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

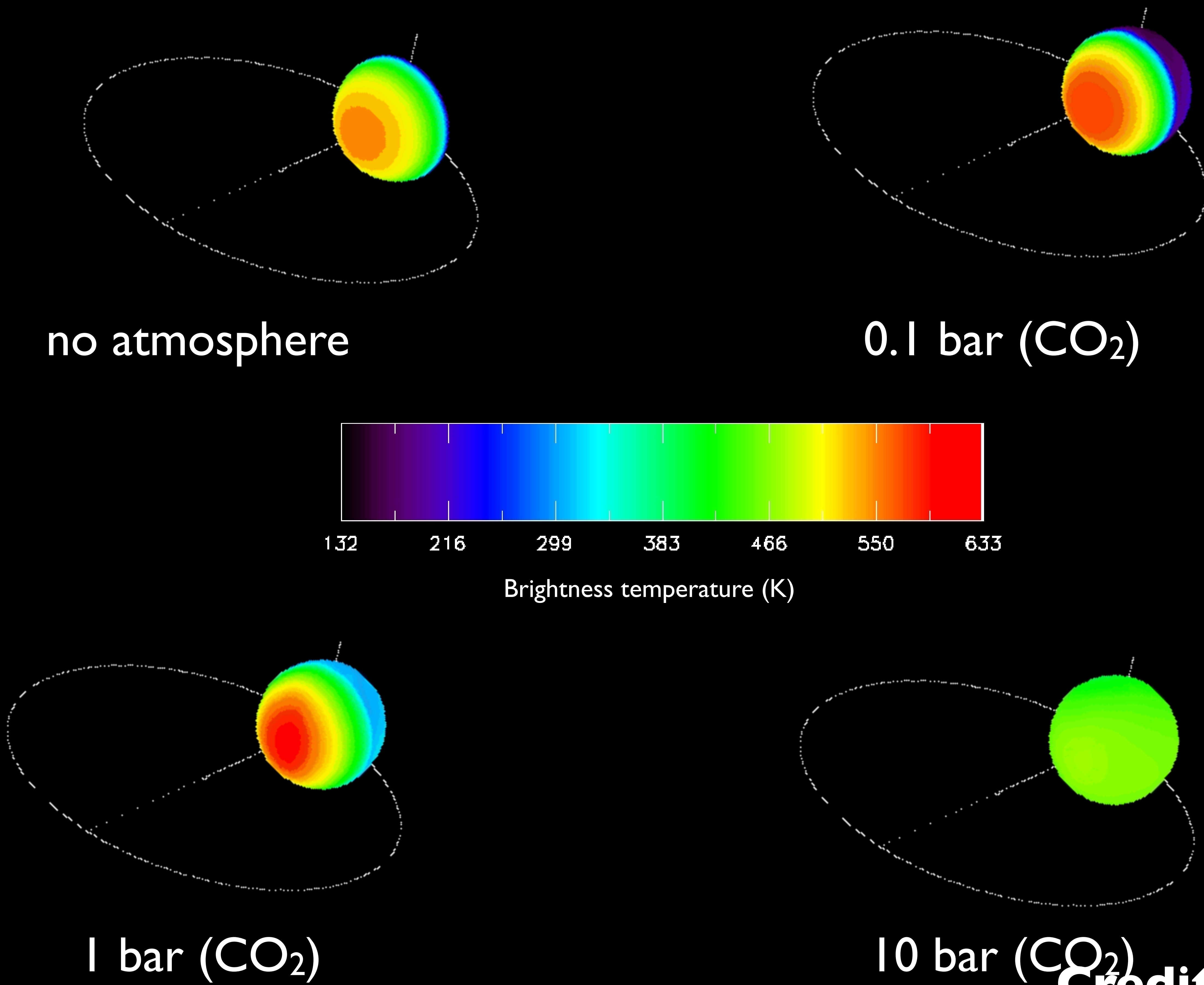
Leconte et al. (A&A, 2013a)

wind maps (m/s)

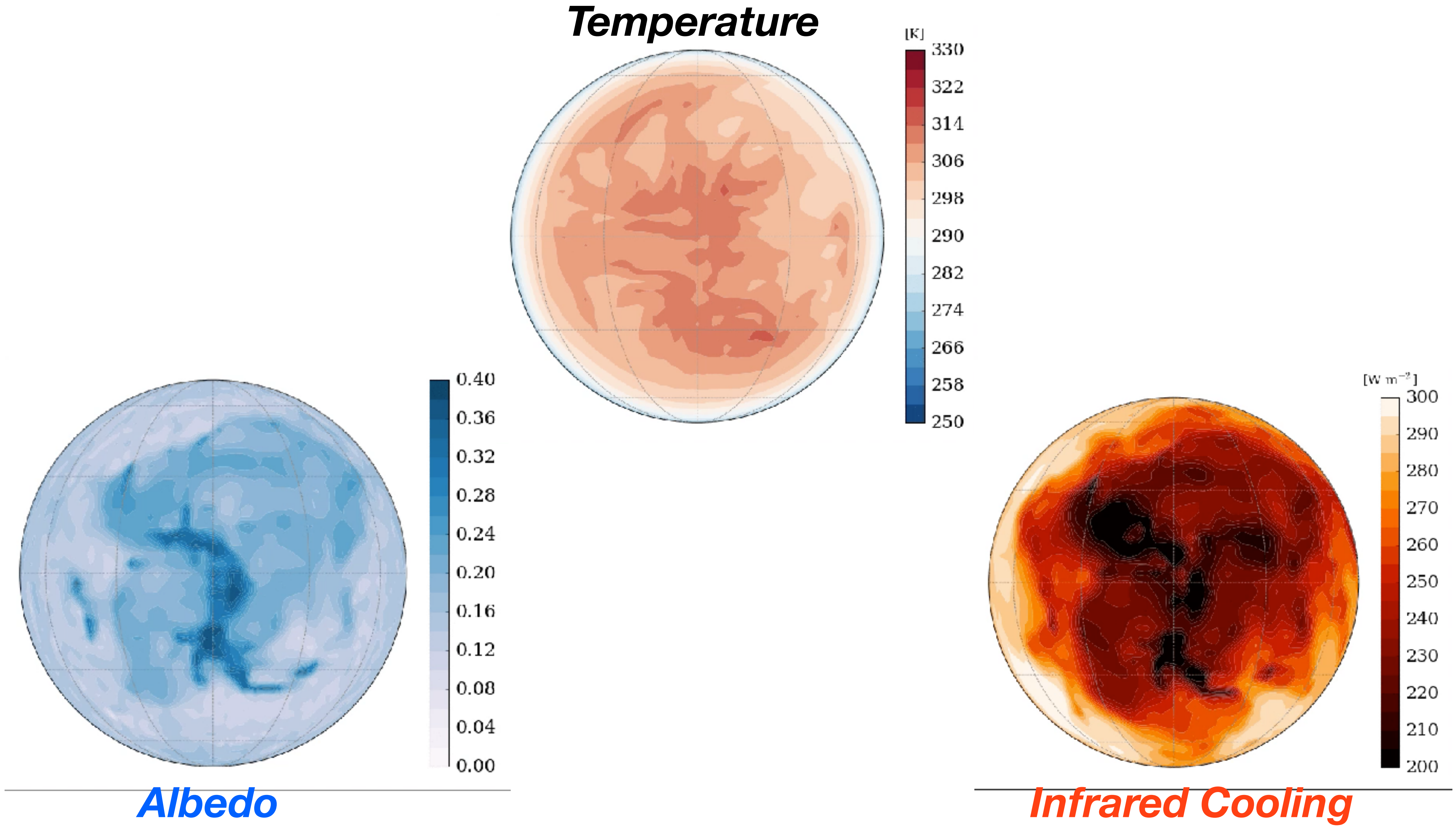

~4km Altitude
Near Surface
Gl 581 c
HD 85512 b
Slow
Gl 581 c
p =200.mb
p =900.mb
Gl581c
HD85512b
Gl581c, Ω/5
latitude (°)
longitude (°)

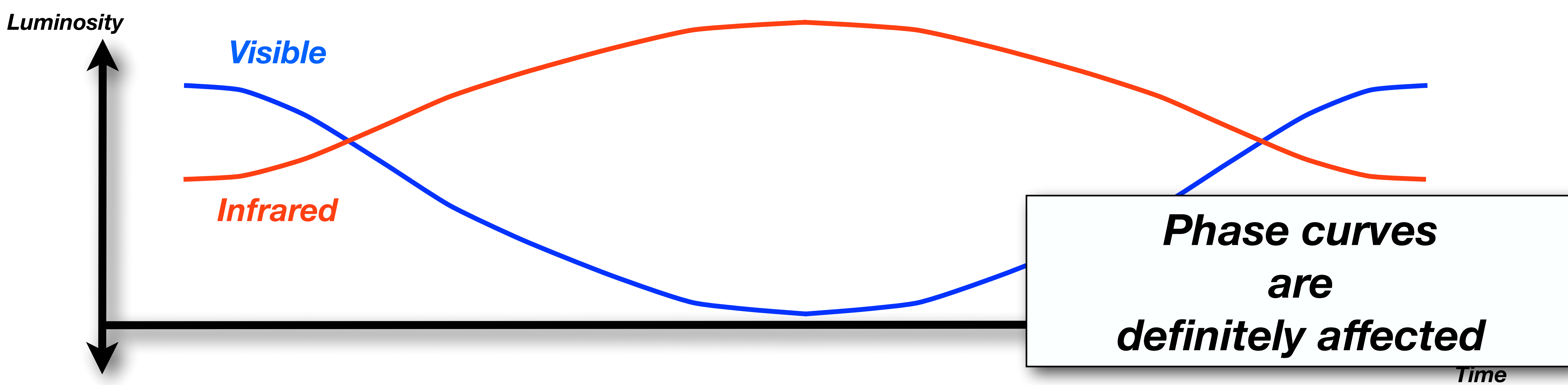
Does atmospheric dynamics affect observables?

8.7 μm



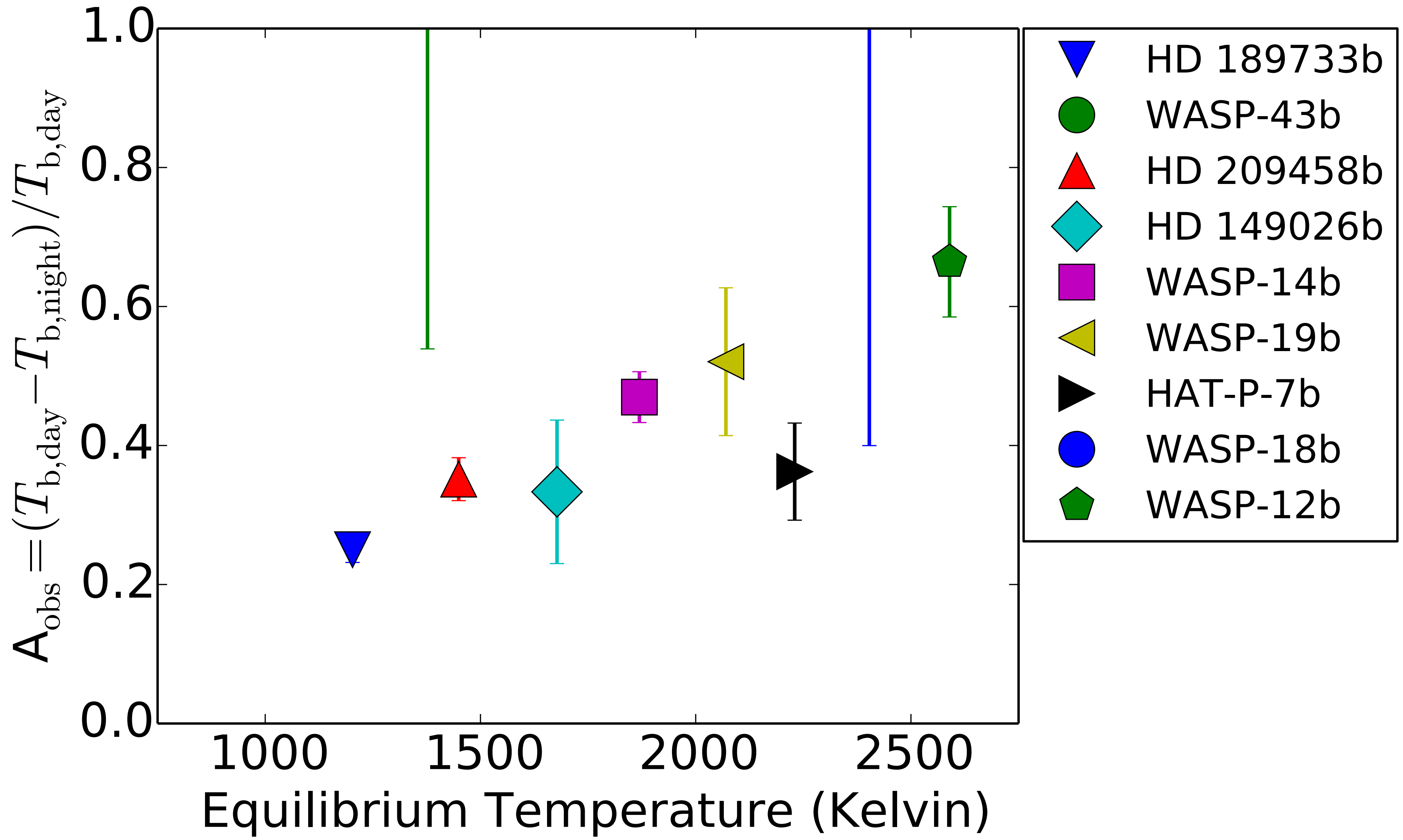
Credit F. Selsis





Phase curves are definitely affected

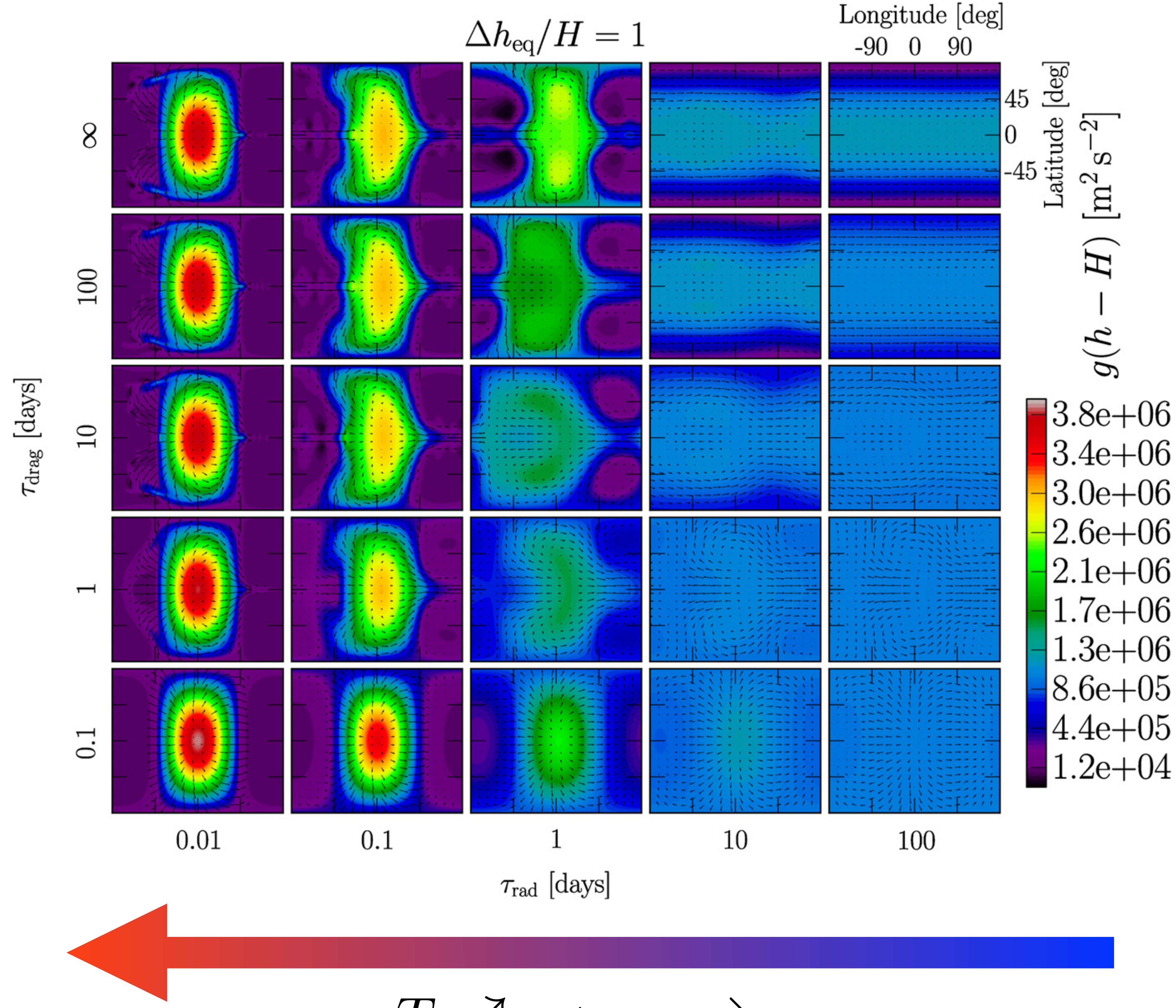
Observed trends in emission temperature…



Hotter planets have bigger day/night temperature contrasts

Komacek & Showman (2016)

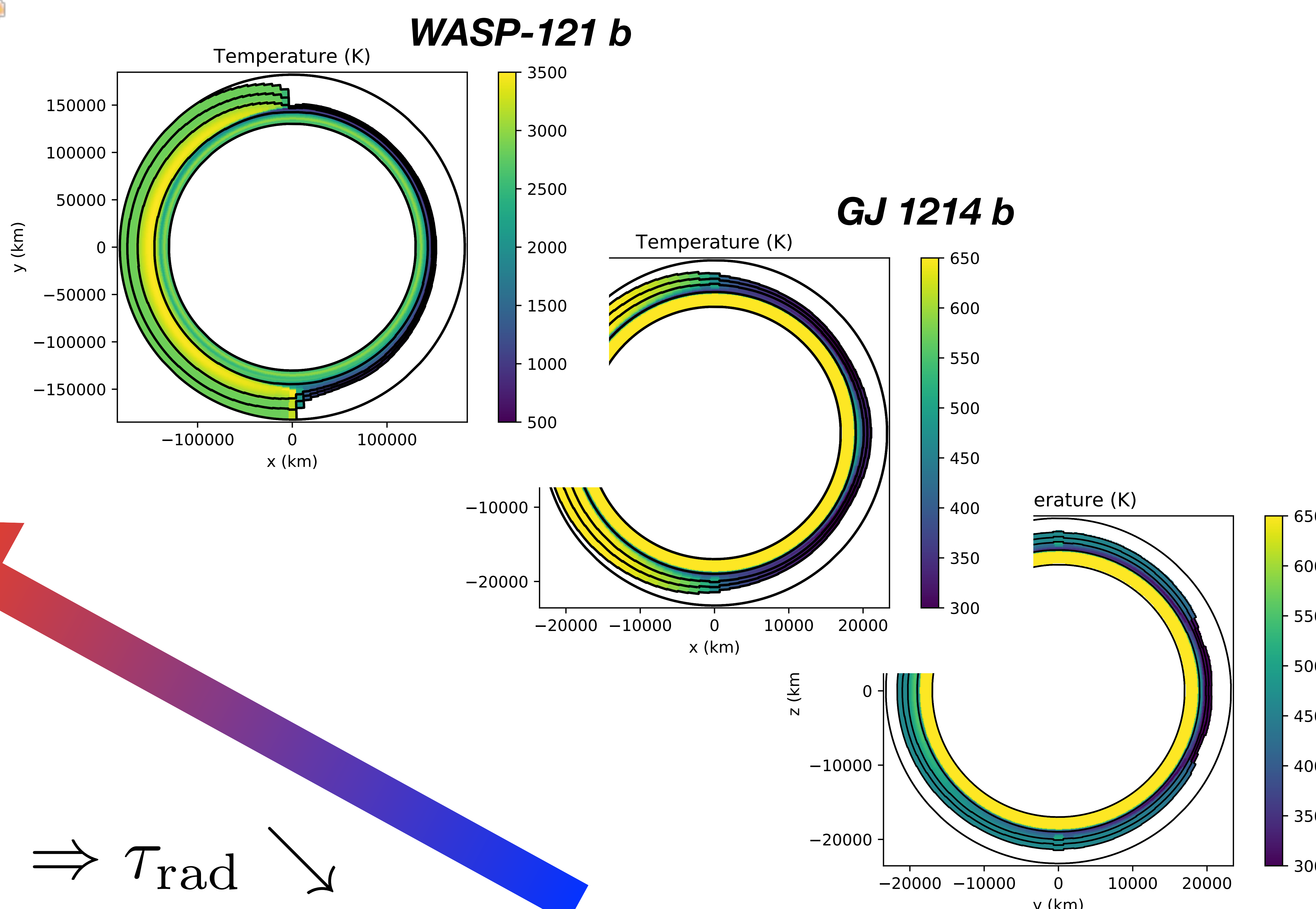
…Explained by atmospheric dynamics



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

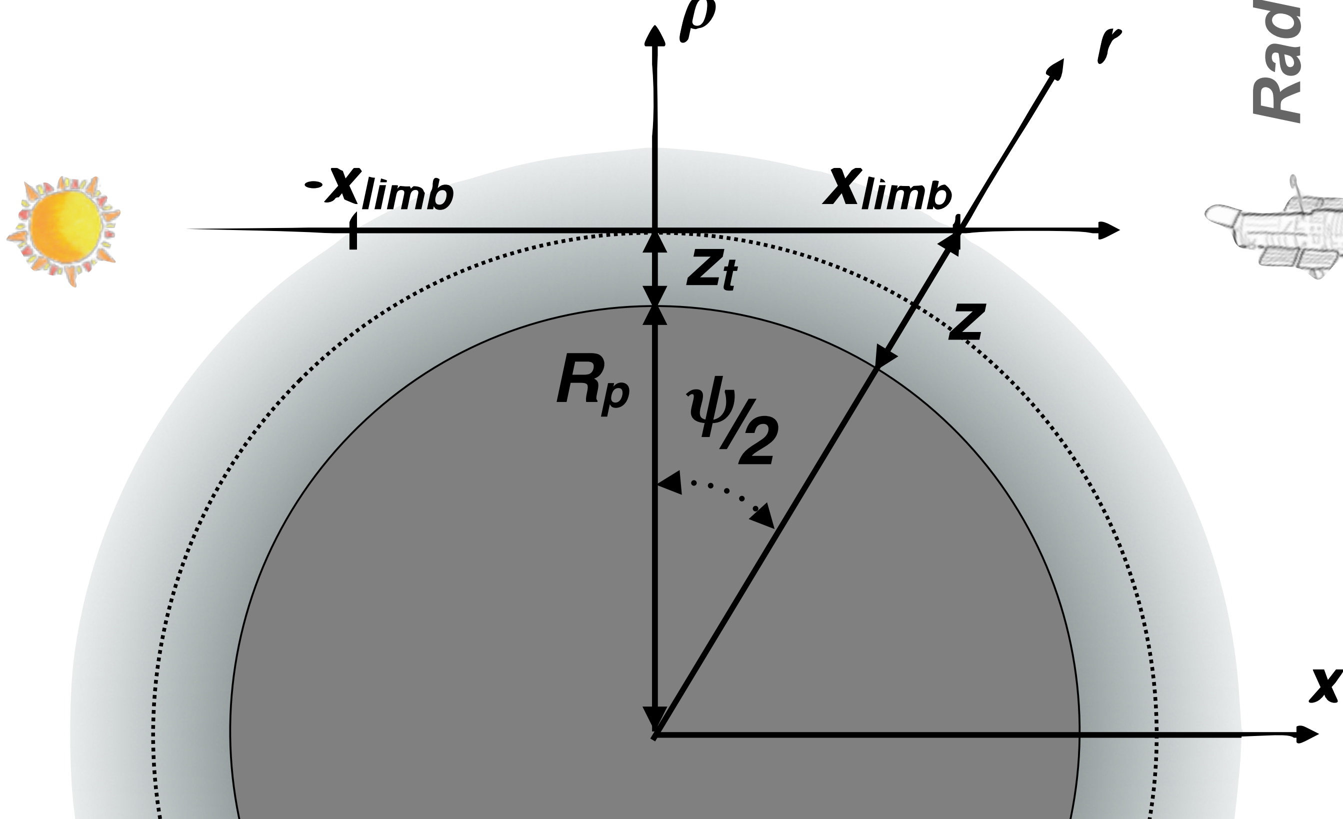
Perez Becker & Showman (2016)

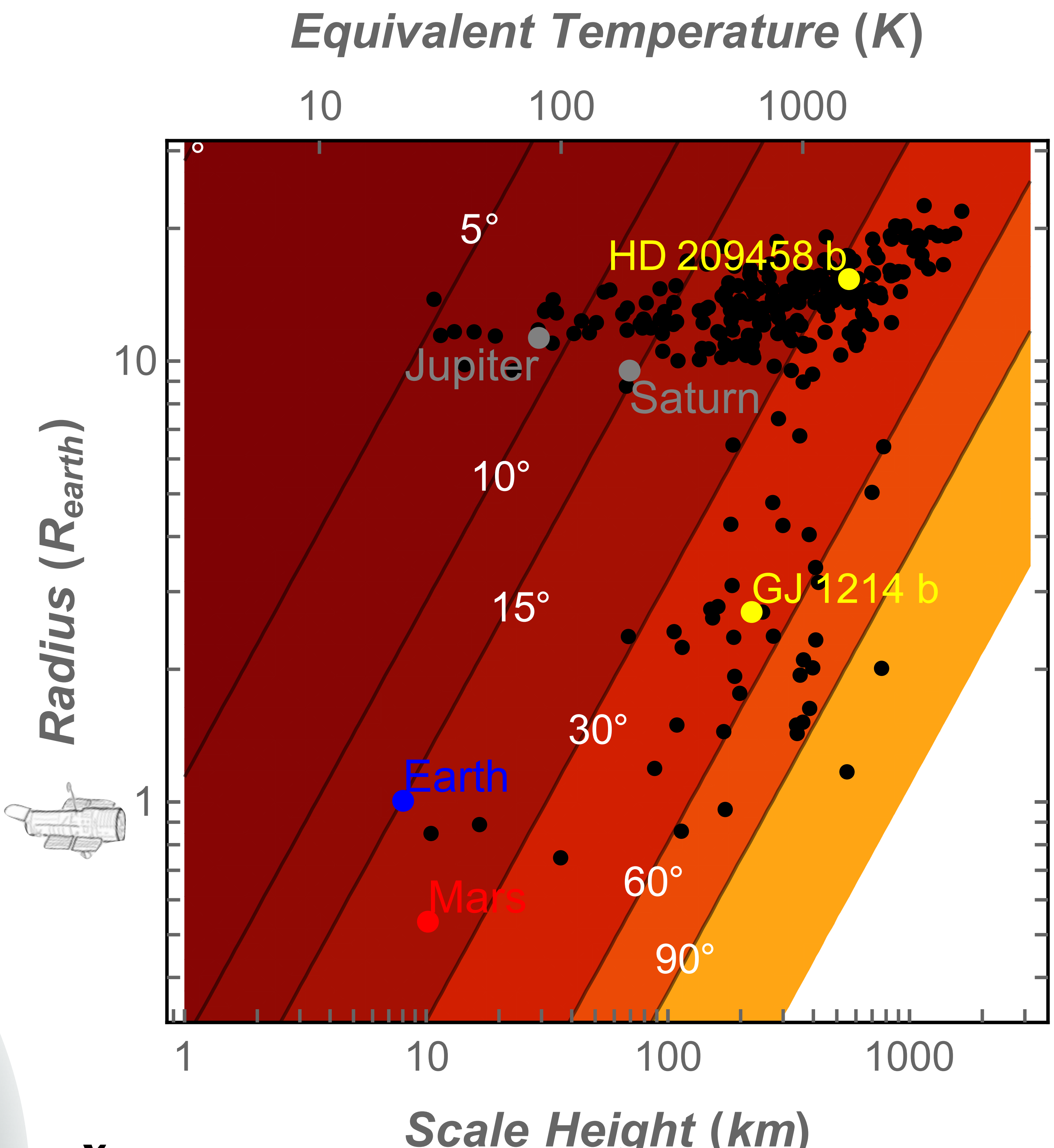
What implications for transit spectroscopy?



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

Opening angle of the transmission region (limb)

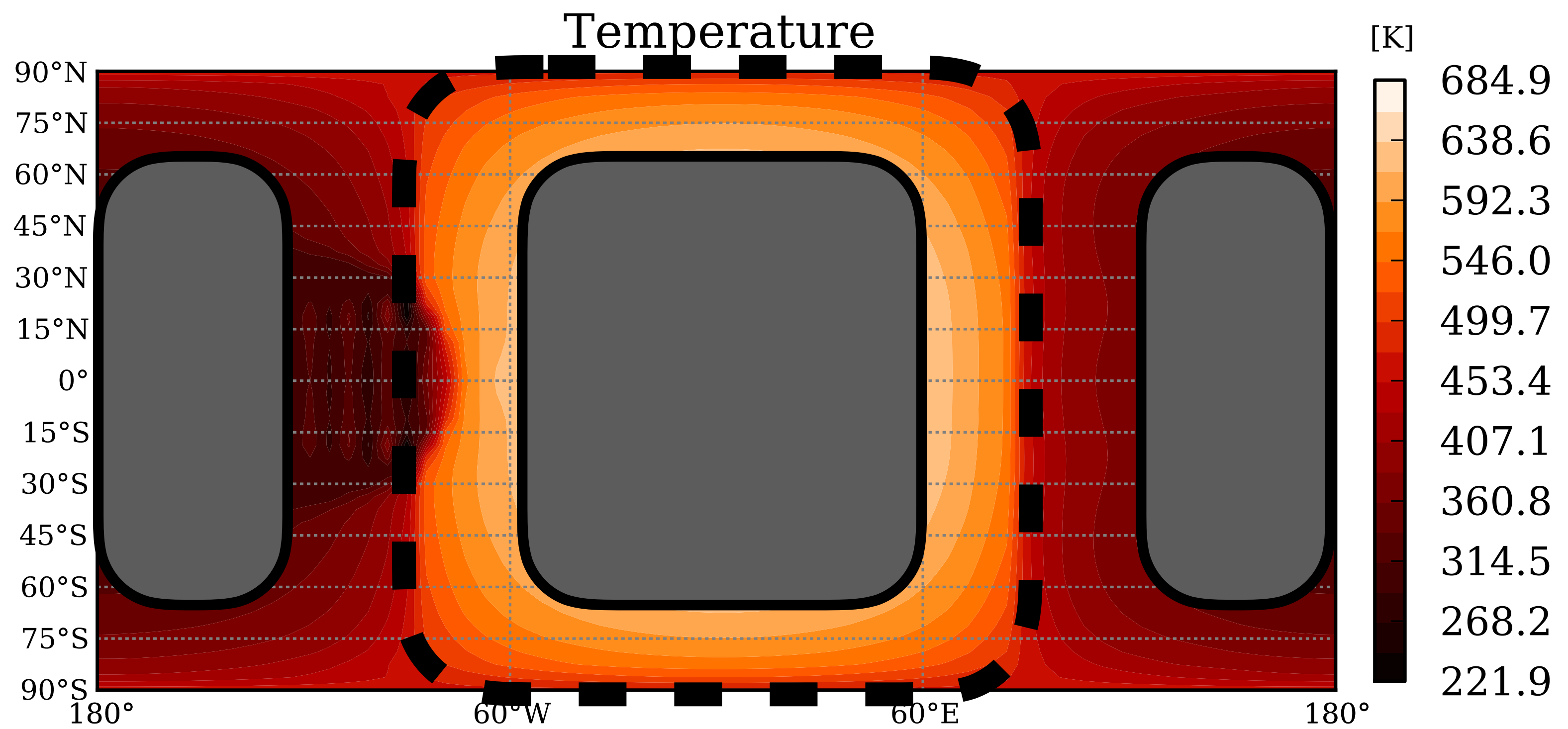




Caldas, Leconte, et al. (A&A, 2019)

Opening angle of the transmission region (limb)

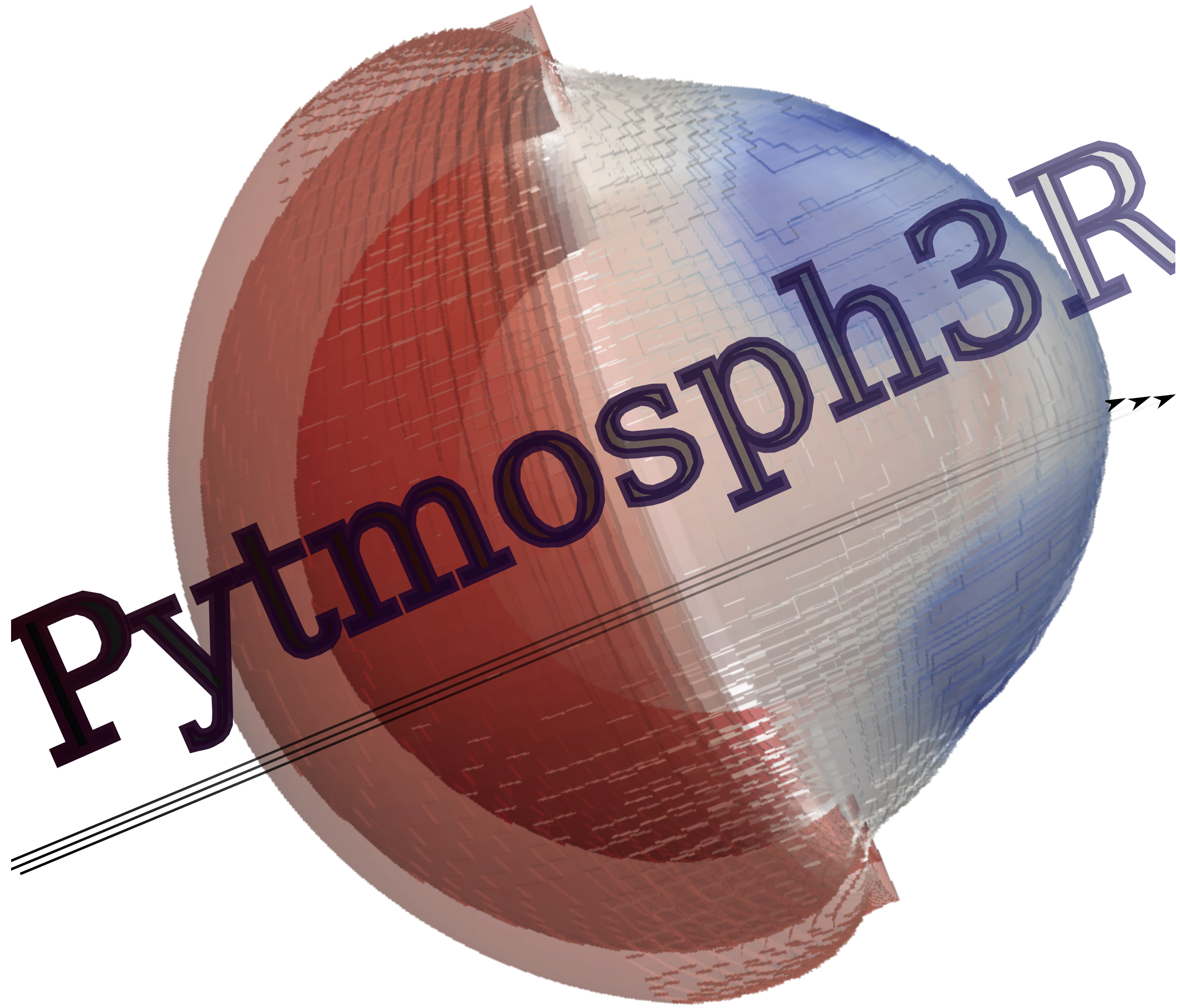
Temperature maps for GJ1214b (transit photosphere)



3D approach

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

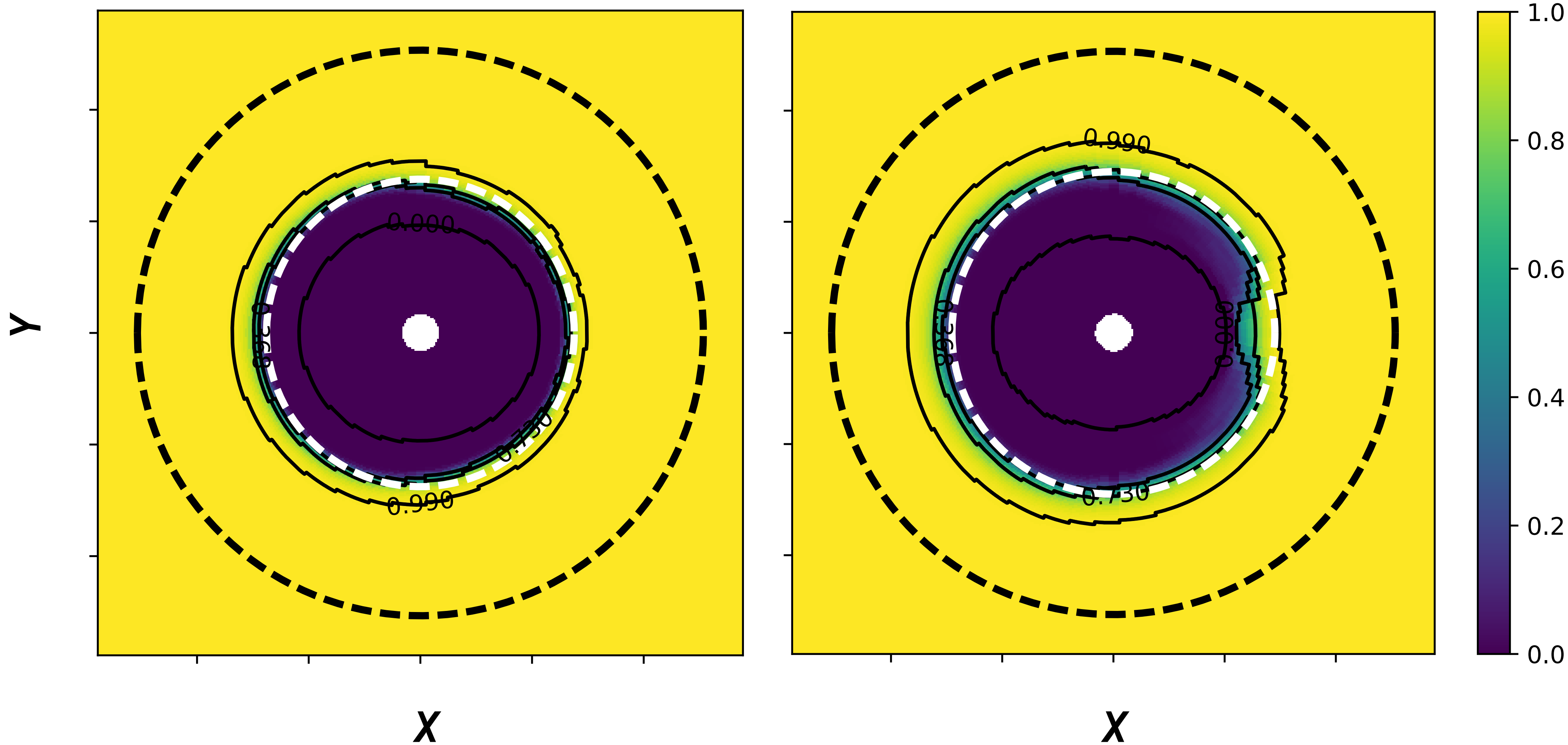
Need a 3D radiative transfer tool



Caldas, Leconte, et al. (A&A, 2019)
Falco et al. (A&A, 2021)

Computing transit spectra… in 3D

Transmittance maps (at every wavelengths)

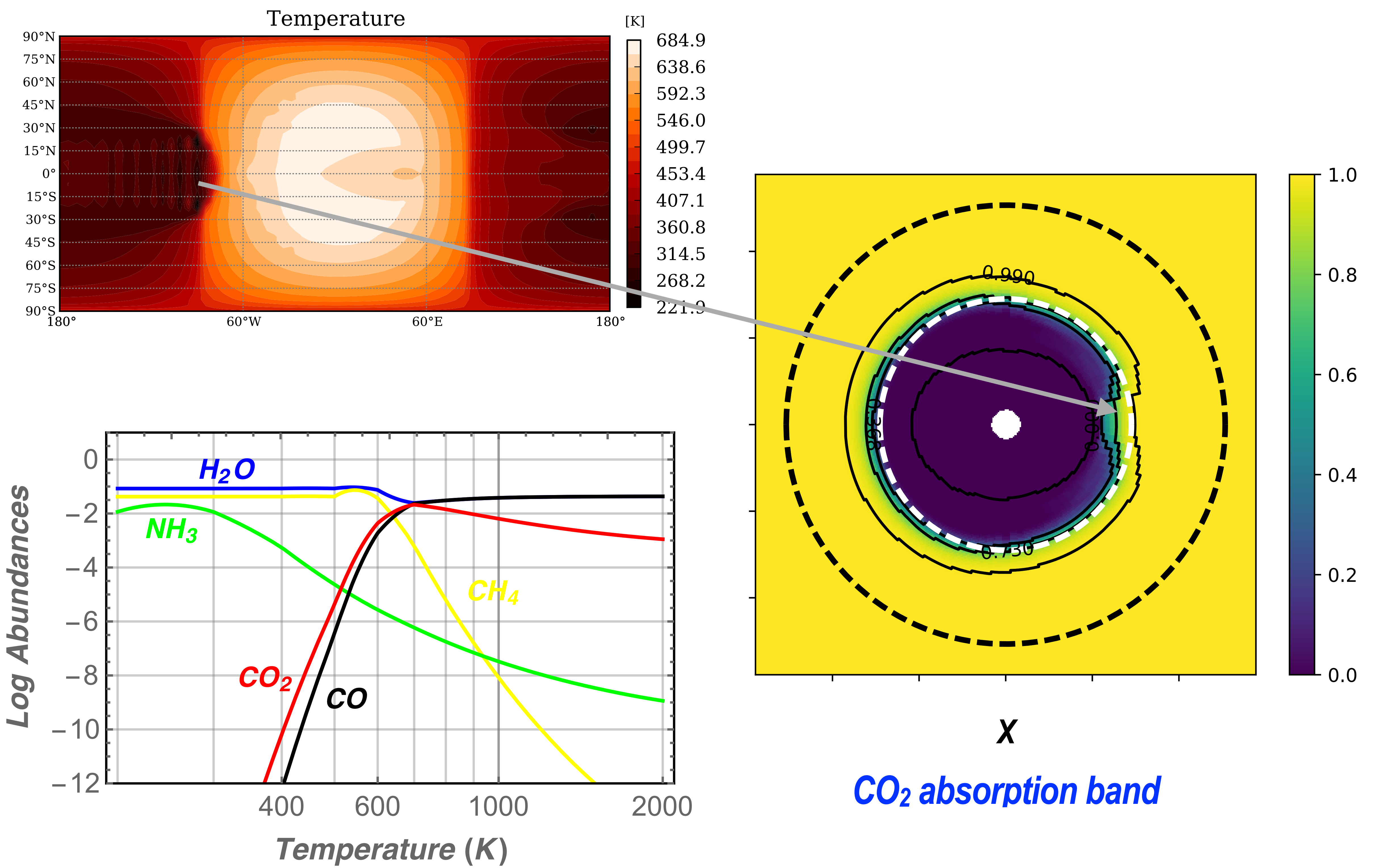


CO_2 window

CO_2 absorption band

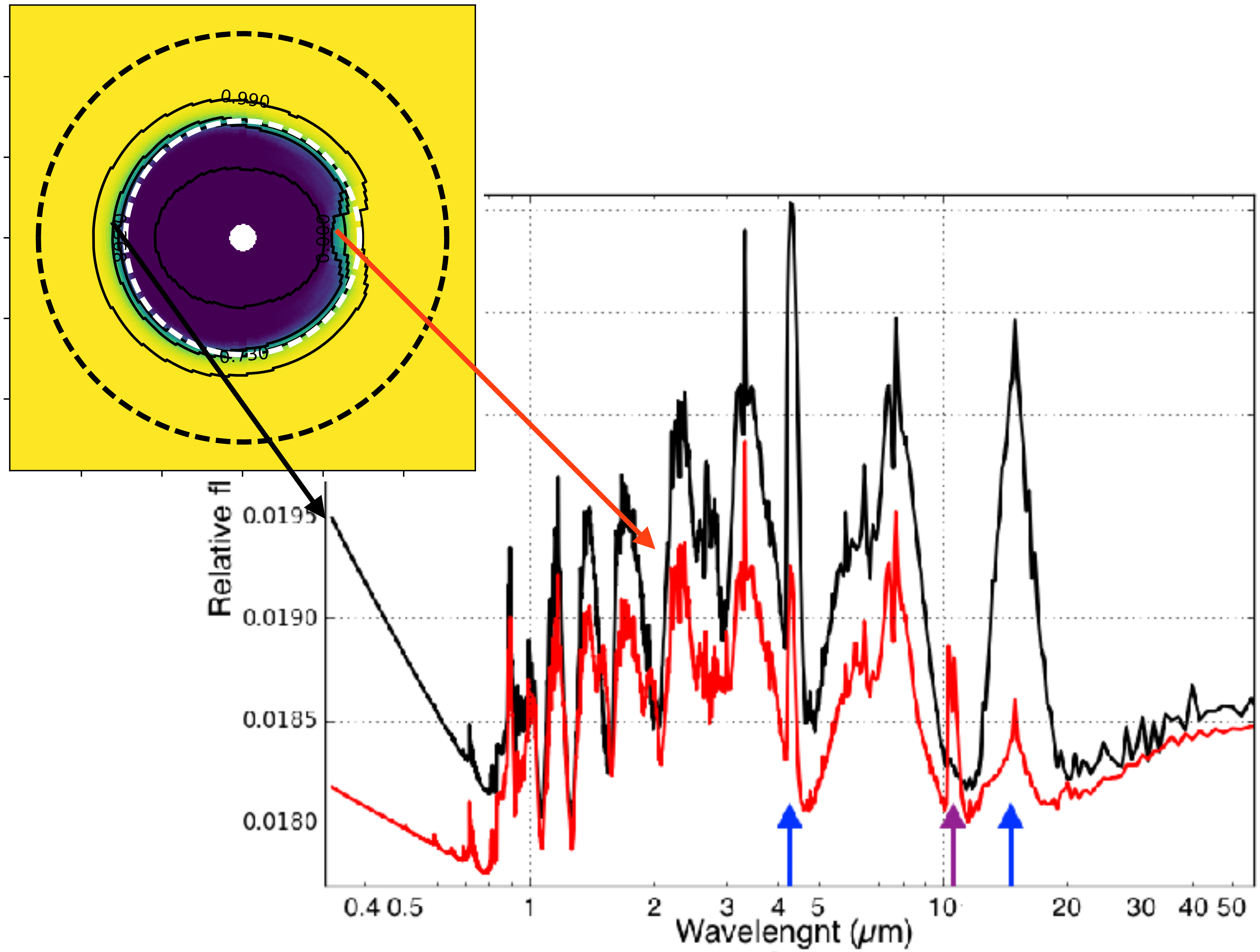
Caldas, Leconte, et al. (A&A, 2019)

Possibility to test chemical(dis)equilibrium



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

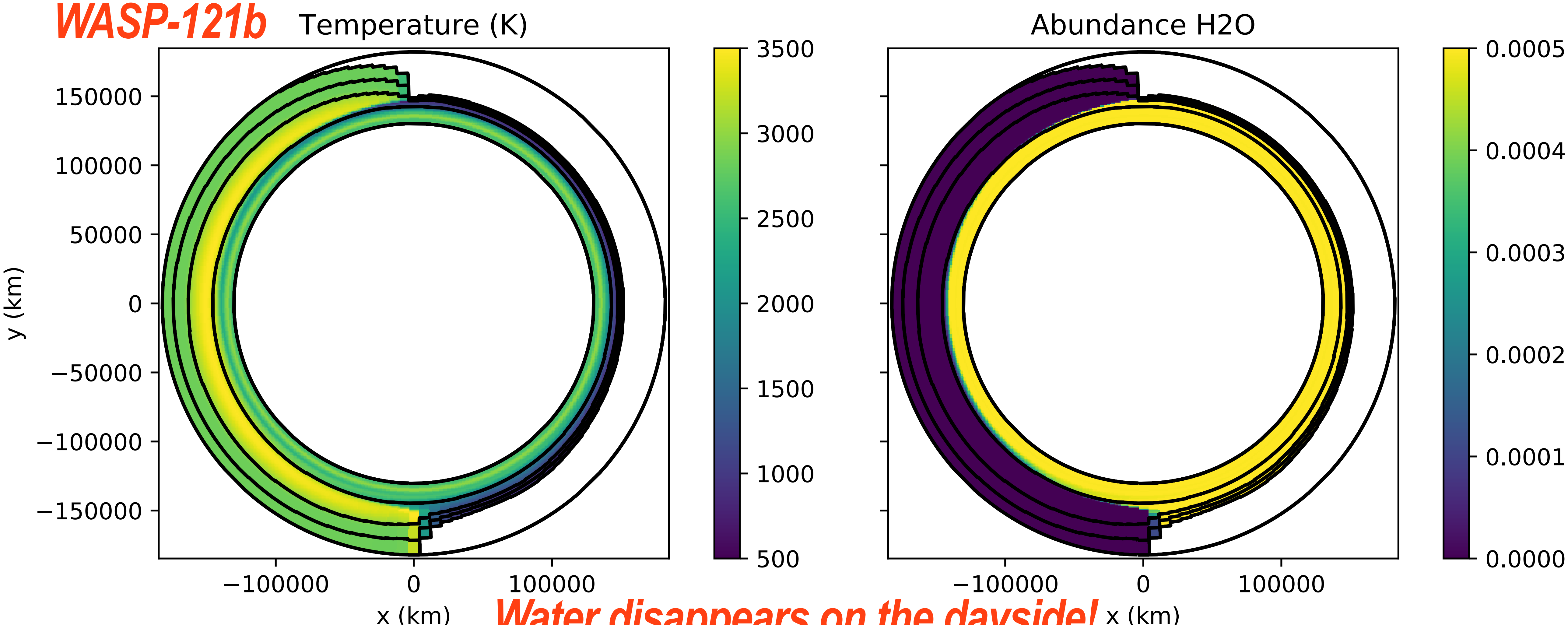
Possibility to test chemical(dis)equilibrium



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

What if there is also a chemical day-night contrast

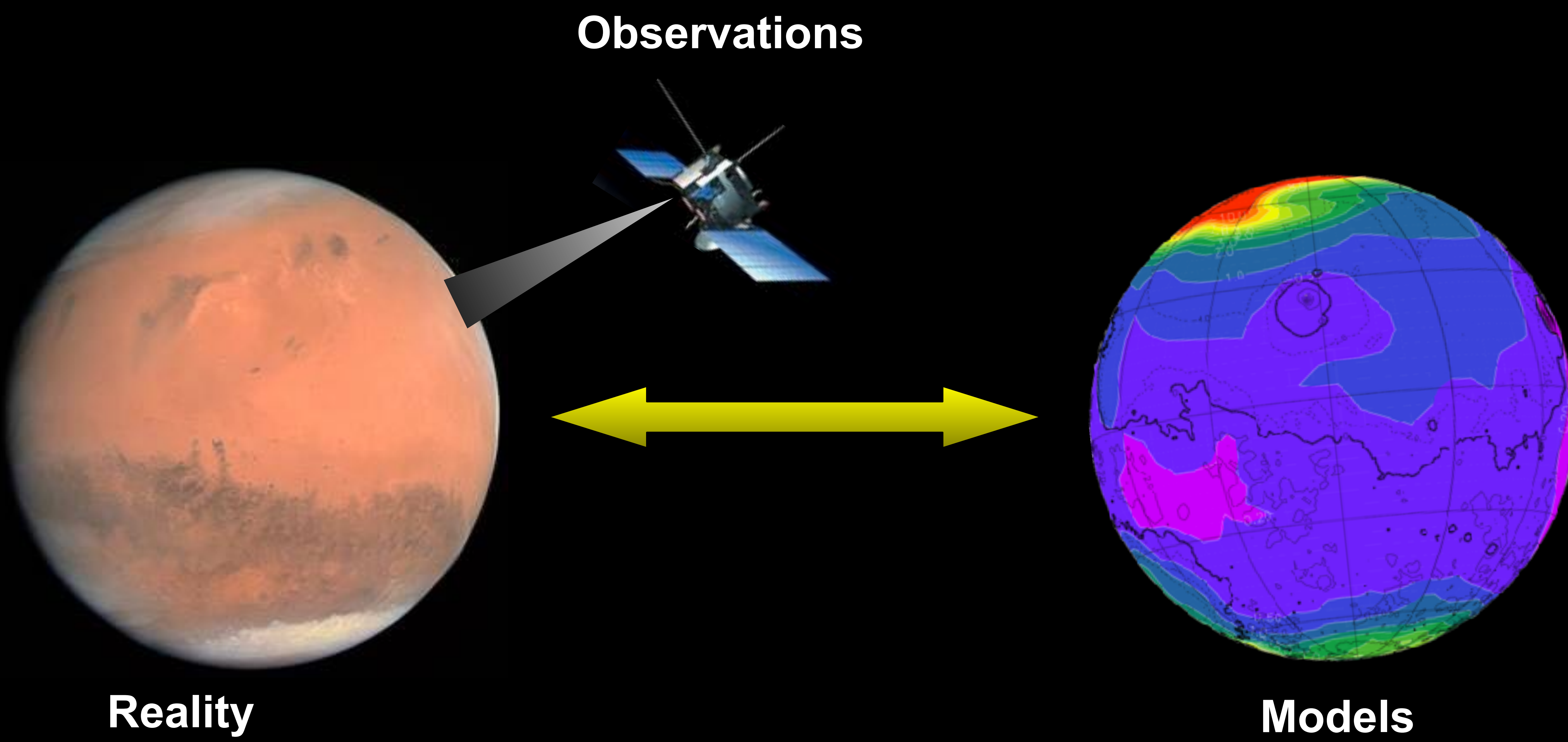
WASP-121b



Water disappears on the dayside!

Global Climate Models

"Global Climate Models" : an ambitious goal : Building "virtual" planets behaving like the real ones, on the basis of universal equations



Equations of motion

★ Mass conservation

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

★ Momentum conservation

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

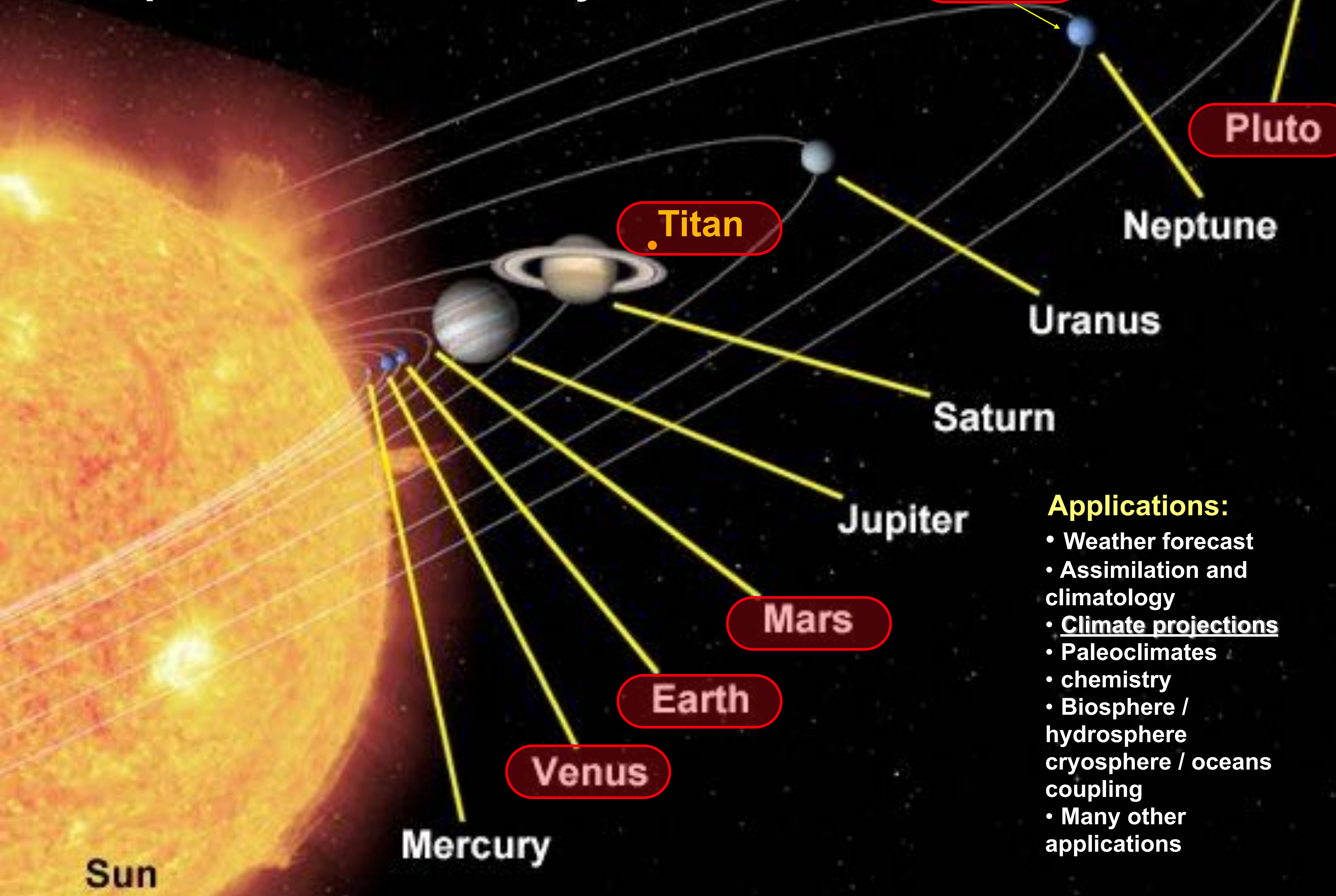
★ Equation of state

$$p = \rho R T$$

★ Conservation of energy

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

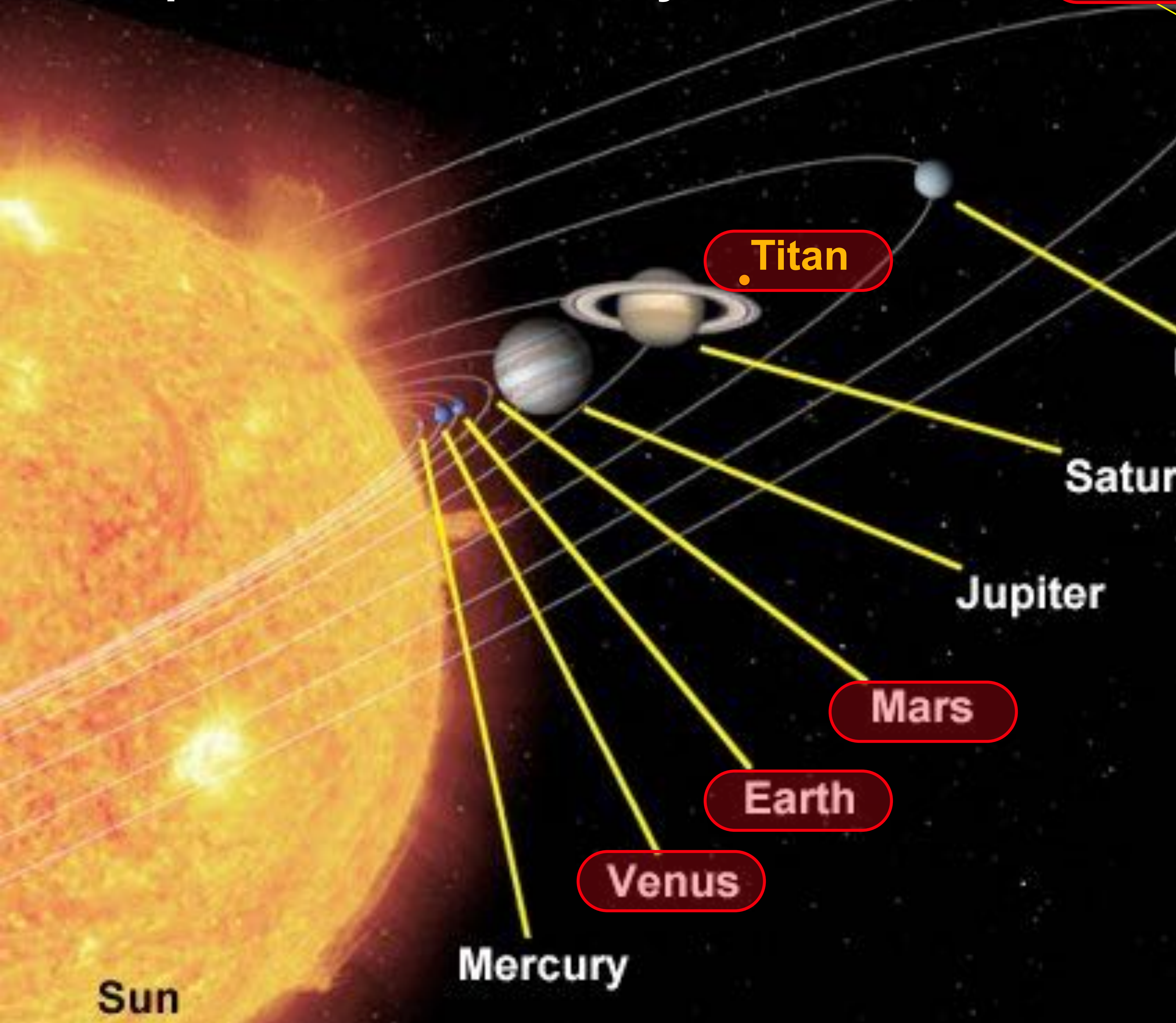
Dedicated GCM's for atmospheres in the solar system



Applications:

- Weather forecast
- Assimilation and climatology
- <u>Climate projections</u>
- Paleoclimates
- chemistry
- Biosphere / hydrosphere cryosphere / oceans coupling
- Many other applications

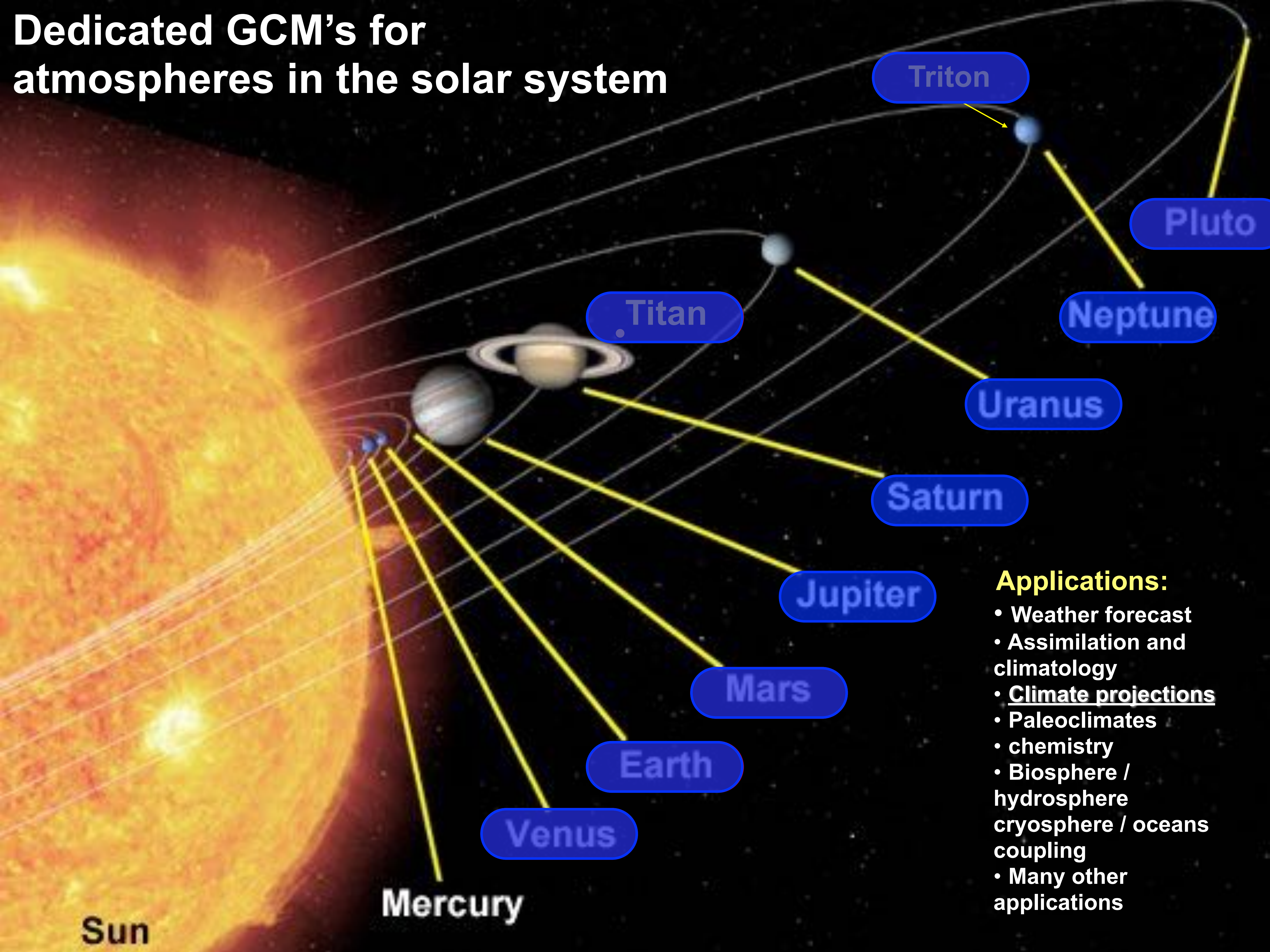
Dedicated GCM's for atmospheres in the solar system



Applications:

- Weather forecast
- Assimilation and climatology
- <u>Climate projections</u>
- Paleoclimates
- chemistry
- Biosphere / hydrosphere cryosphere / oceans coupling
- Many other applications

Dedicated GCM's for atmospheres in the solar system



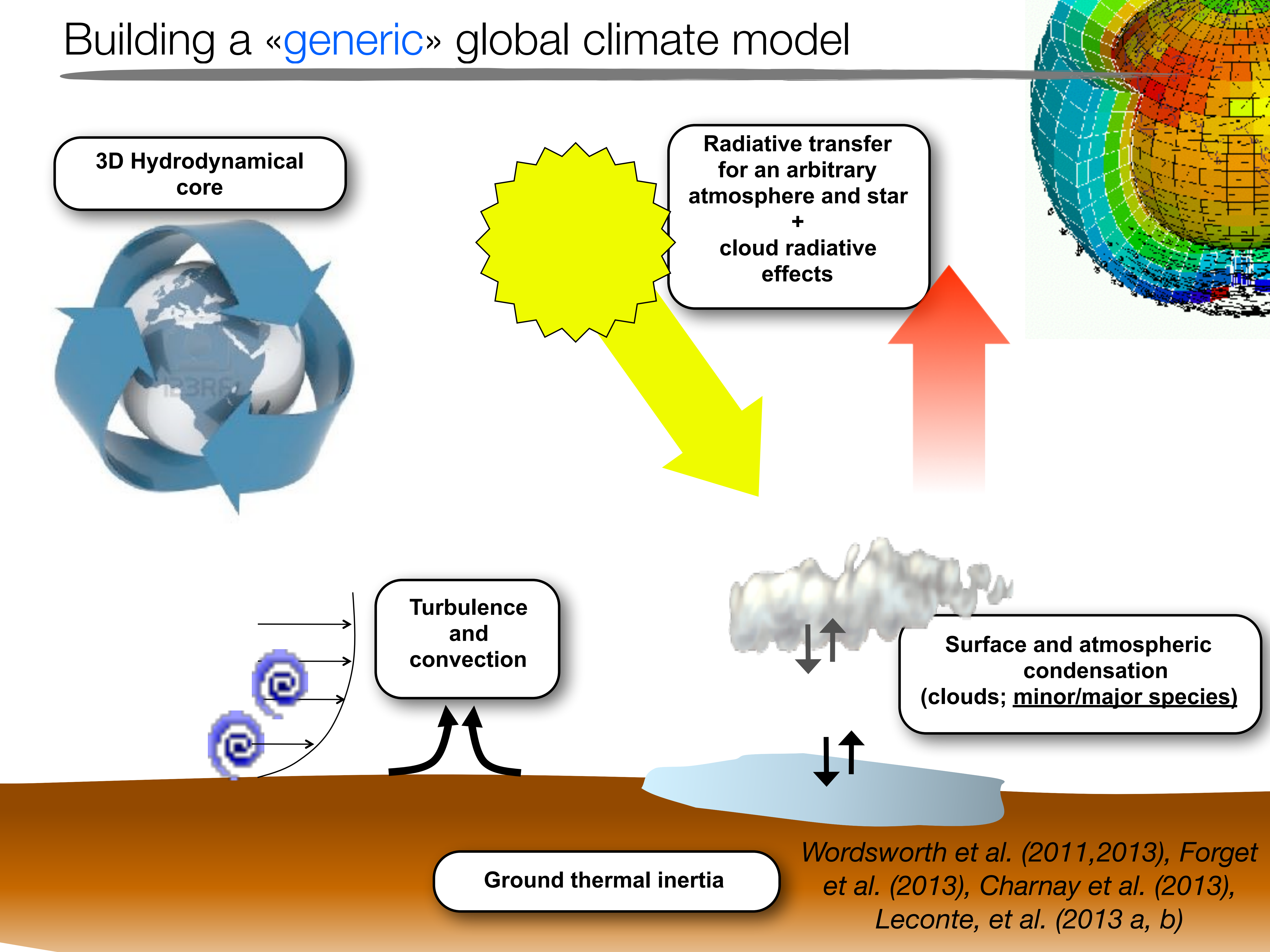
Applications:

- Weather forecast
- Assimilation and climatology
- Climate projections
- Paleoclimates
- chemistry
- Biosphere / hydrosphere cryosphere / oceans coupling
- Many other applications

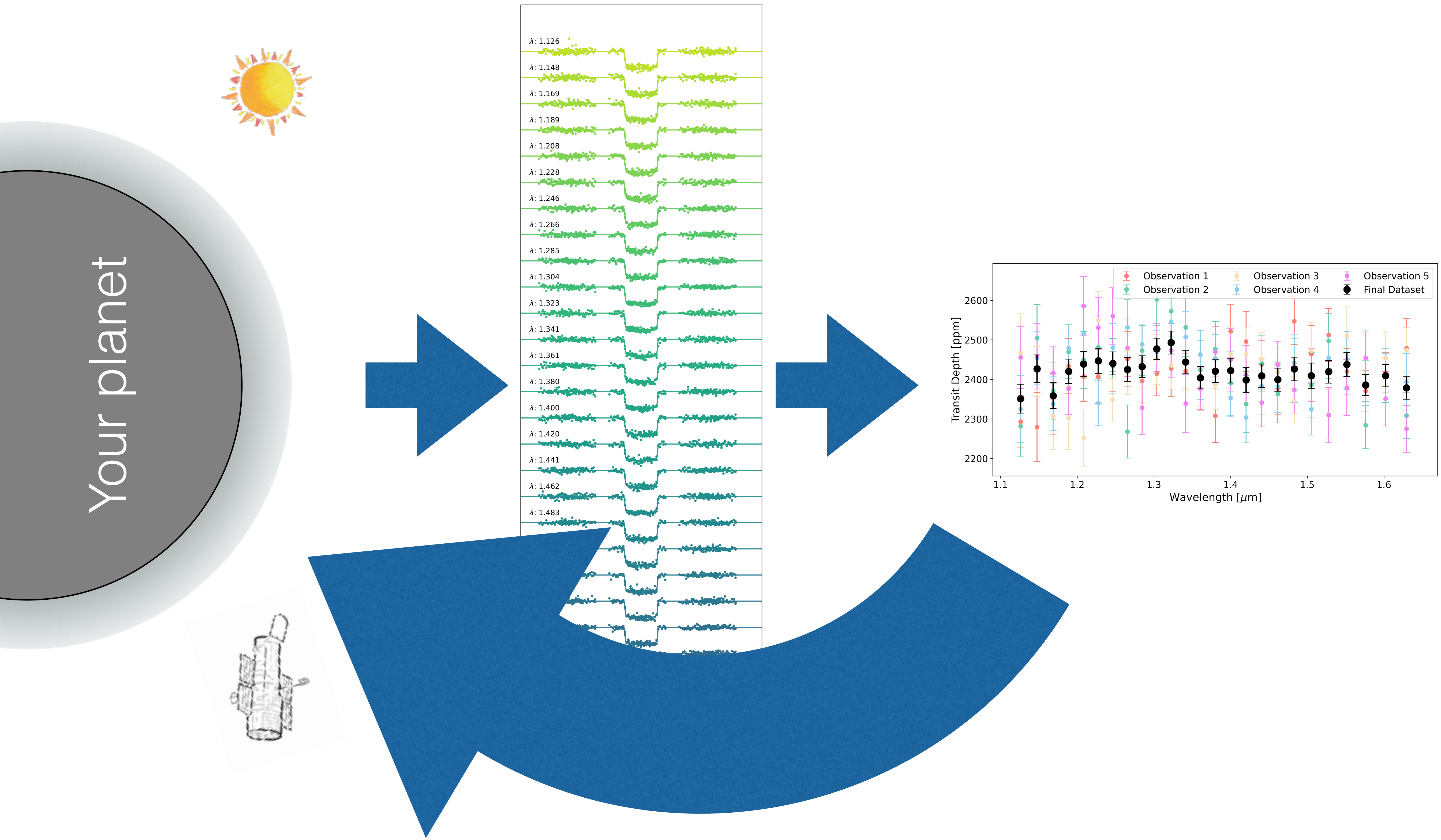
Building a «generic» global climate model

Building a «generic» global climate model

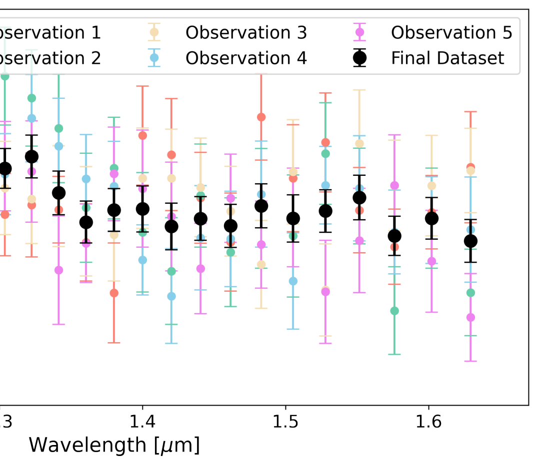
Building a «generic» global climate model

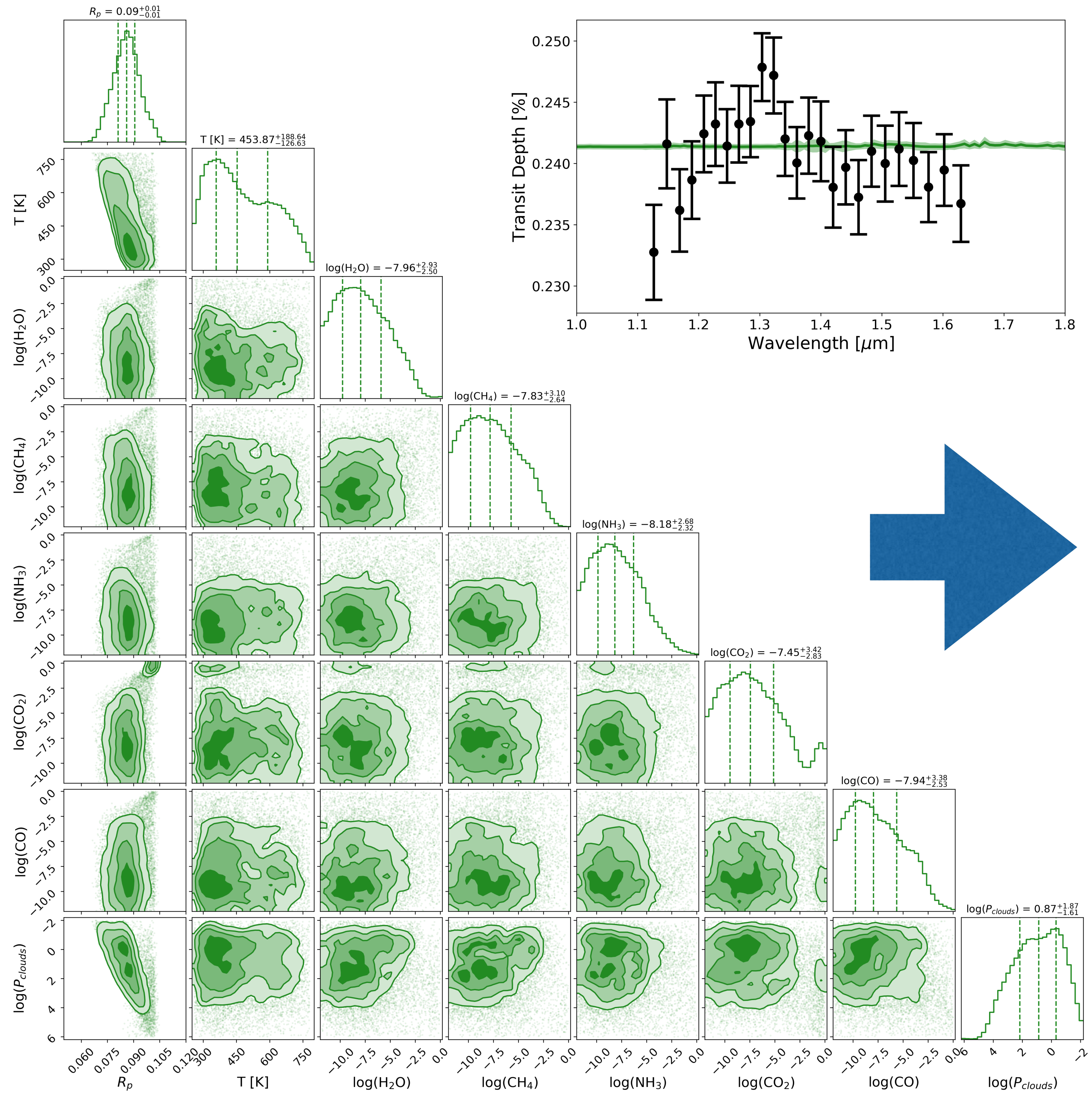


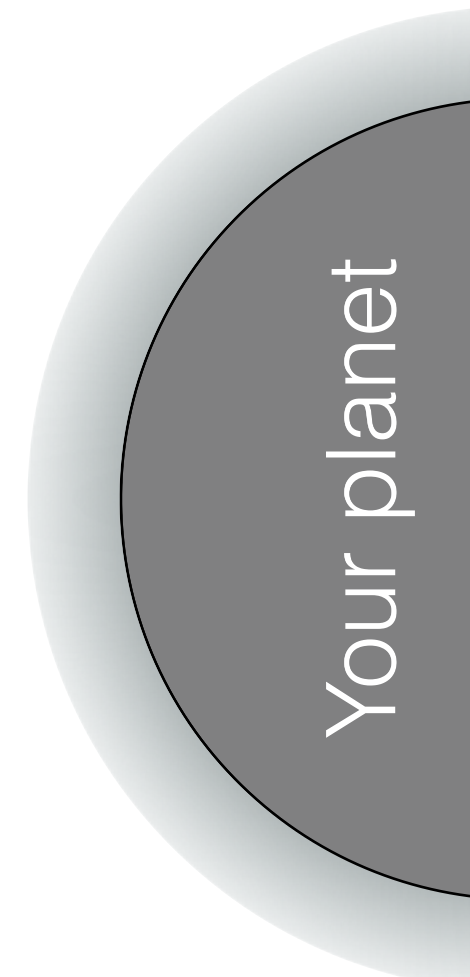
Goals of the Hand's on Training session



Your planet
λ: 1.126
λ: 1.148
λ: 1.169
λ: 1.189
λ: 1.208
λ: 1.228
λ: 1.246
λ: 1.266
λ: 1.285
λ: 1.304
λ: 1.323
λ: 1.341
λ: 1.361
λ: 1.380
λ: 1.400
λ: 1.420
λ: 1.441
λ: 1.462
λ: 1.483
Observation 1
Observation 2
Observation 3
Observation 4
Observation 5
Final Dataset
Transit Depth [ppm]
2200
2300
2400
2500
2600
1.1
1.2
1.3
1.4
1.5
1.6
Wavelength [μm]

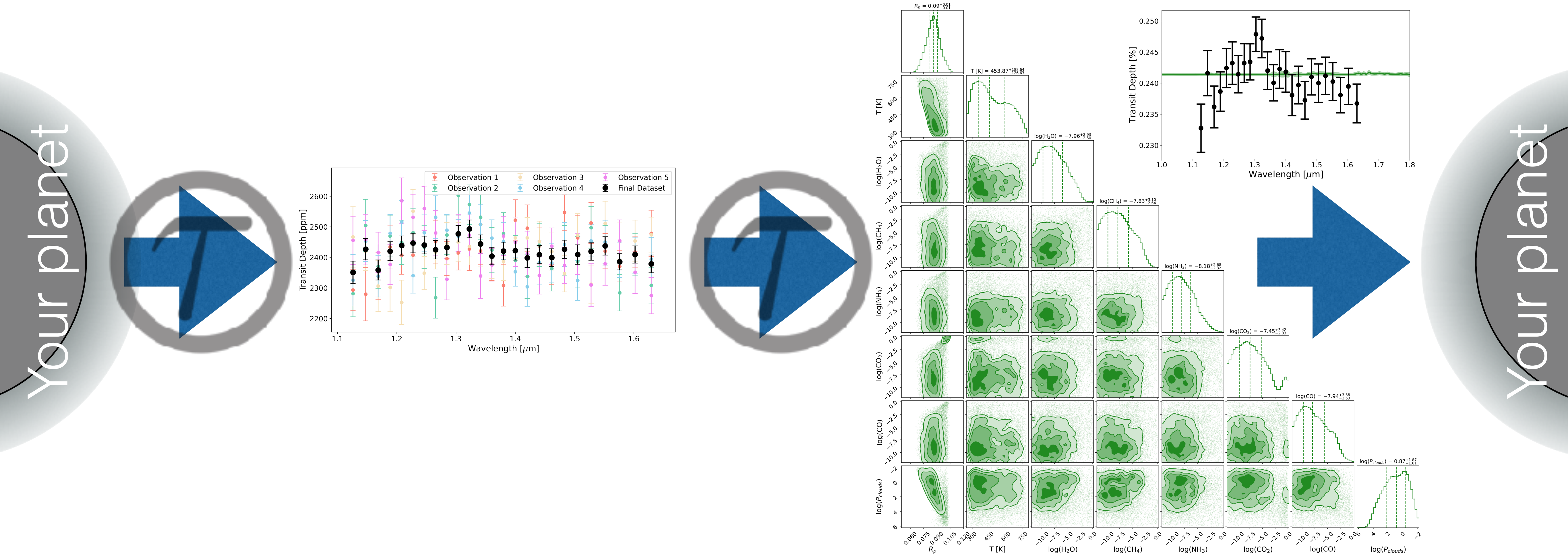






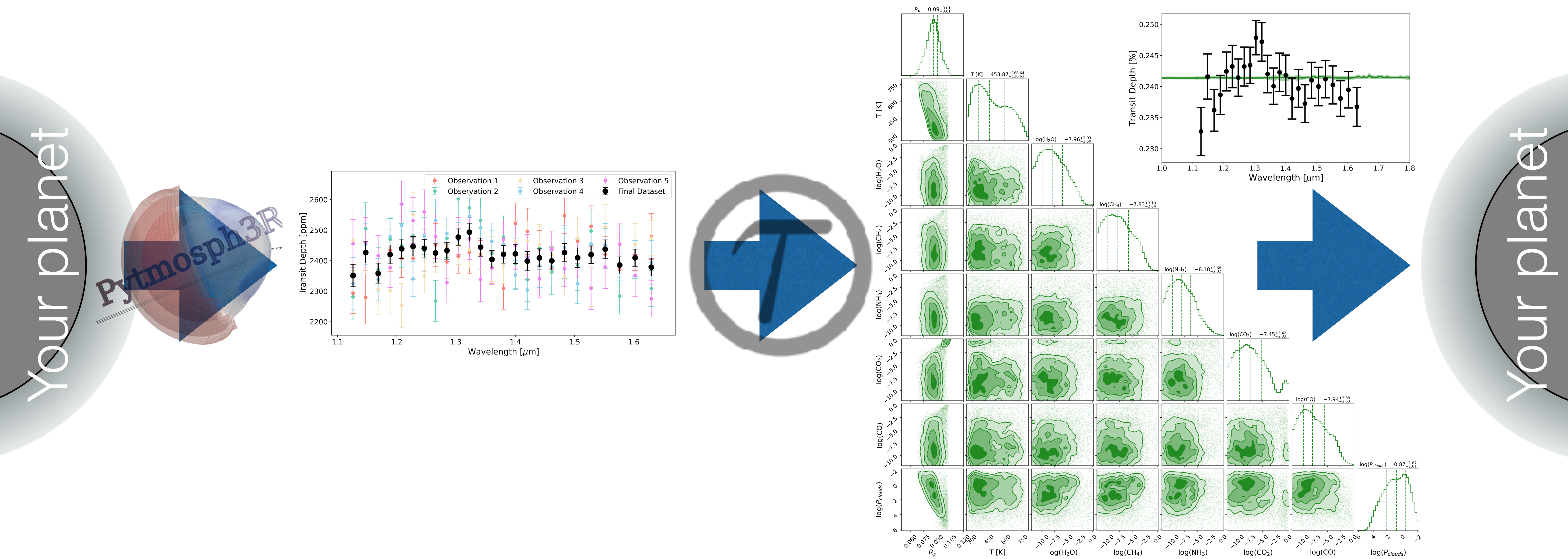
But is it the right composition/physics?

What people do: sanity check



But generally you are looking for (and you know) what you put in!!!

What we are gonna do



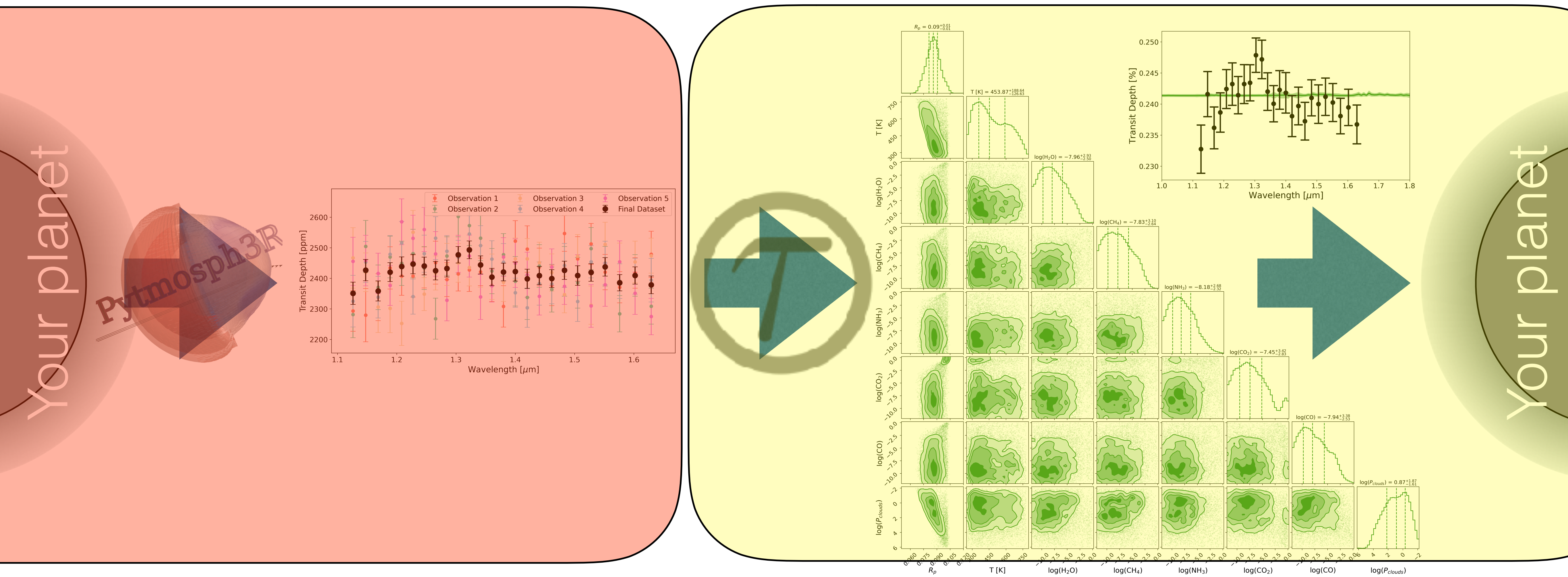
A real blind analysis like in real life

But let's make it interesting


Jean reno
William3D
Sombrero Malgache
Aurelien Falco

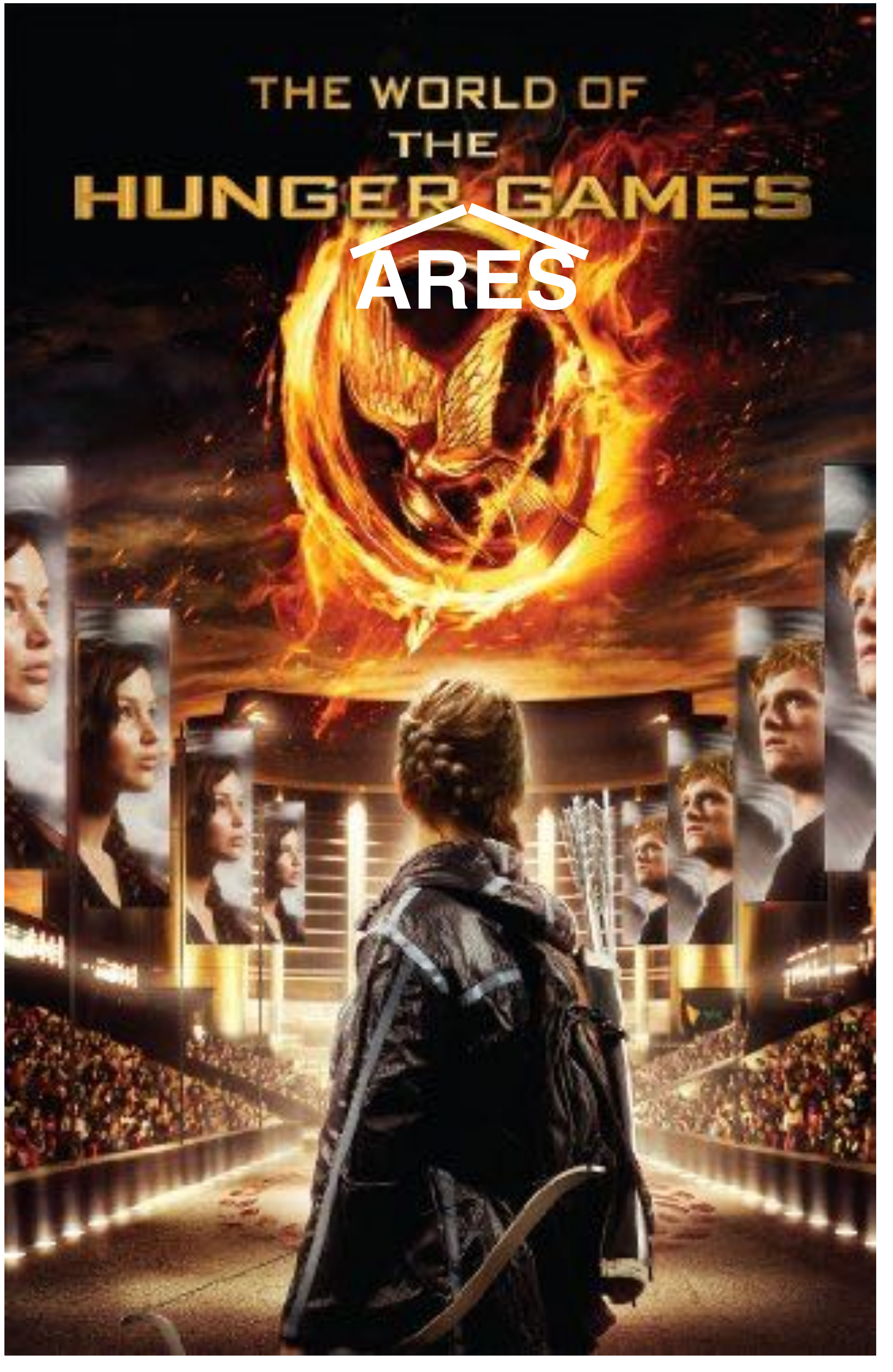
But let’s make it interesting

What we are gonna do



A real blind analysis like in real life

But it was not intense enough



Teams

- ★ *District 1: William Pluriel - Achrene Dyrek - Natalia Rektsini*
- ★ *District 3: Tiziano Zingales - Maria Chiara Maimone*
- ★ *District 5: Amelie Gressier - Christian Wilkinson*
- ★ *District 7: Arianna Saba - Gianluca Cracchiolo*
- ★ *District 2: Lucas Teinturier - Monika Stangret*
- ★ *District 4: Michelle Bieger - Bocchieri Andrea*
- ★ *District 6: Billy Edwards - Anastasia Ivanova - Jaume Orell-Miquel*
- ★ *District 8: Jack Skinner - Emilie Panek*

Teams (2)

- ★ *District 1: William Pluriel - Achrene Dyrek*
- ★ *District 3: Tiziano Zingales - Maria Chiara Maimone*
- ★ *District 5: Amelie Gressier - Christian Wilkinson*
- ★ *District 7: Arianna Saba - Gianluca Cracchiolo*
- ★ *District 2: Lucas Teinturier - Monika Stangret*
- ★ *District 4: Michelle Bieger Bocchieri Andrea - Natalia Rektsini*
- ★ *District 6: Billy Edwards - Anastasia Ivanova - Jaume Orell-Miquel*
- ★ *District 8: Jack Skinner - Emilie Panek*

Installing and running the GCM

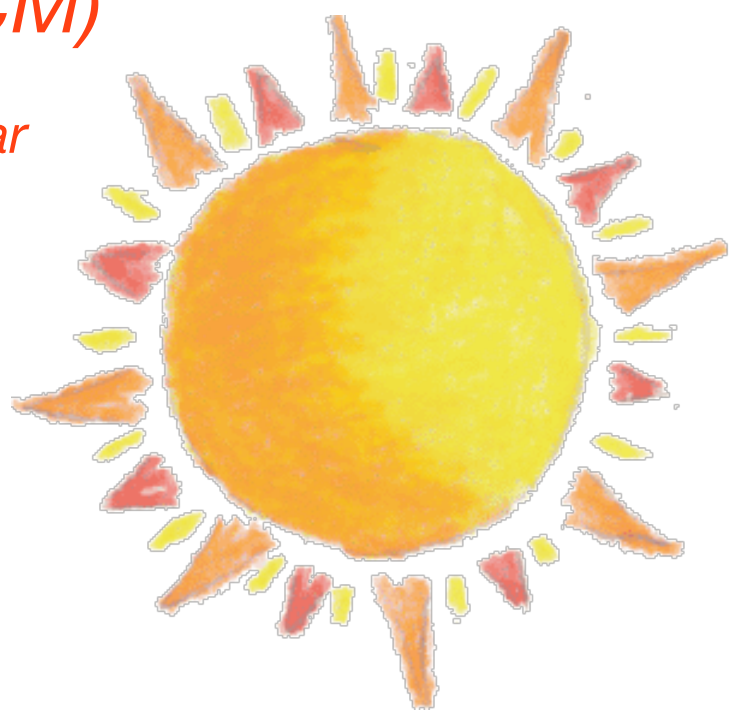
Installing the GCM

- ★ *Go to: https://forge.oasu.u-bordeaux.fr/jleconte/ares_tutorial*
- ★ *Follow the README in the base directory to setup your environment*
    - ★ *cloning the repository*
    - ★ *setting up python*
- ★ *Go to the GCM directory and follow the README there*

Choosing your planet

- P_{surf}
- Composition
  - ➡ Mugas, R/cp
  - ➡ Radiative properties (k-coefficients)

- R_{star} (not important for the GCM)
- T_{star}



- R_p (rad)
- Gravity
- Omega
  - ➡ Rossby number
- Surface (Albedo, Inertia)
- Resonance ratio (nres)
- Flux at Substellar point (Fat1AU)
- Orbital parameters

- daysec
- year_day
- Semi_major_axis
- peri_day
- obliquity

Compiling for the right resolution

- ❖ *copy firstcase to simu1 and go there.*
- ❖ *setup_compiler*
  - ★ *arch file (depends on your cluster)*
  - ★ *number of longitudes (32)*
  - ★ *number of latitudes (32)*
  - ★ *number of vertical levels (20)*
  - ★ *number of radiative bands (3 and 3)*
- ❖ *./compile.sh*

Initializing the planet

- *Planet start*
  - ★ P_{surf}
  - ★ R_p *(rad)*
  - ★ *Gravity*
  - ➡ *Mugas*
  - ➡ *R/cp*
  - ★ *daysec*
  - ★ *Omega*
  - ★ *year_day*
  - ★ *Semi_major_axis*
  - ★ *peri_day*
  - ★ *obliquity*
  - ★ *Surface (Albedo, Inertia)*
  - ★ *Initial temperature*
- *./init.sh*

Initializing the run

- *callphys.def*
  - *nres*
  - *iradia*
  - *stelTbb*
  - *corrkdir*
  - *Fat1AU*
- *run.def*
  - *nday*
  - *iphysiq*
  - *ecriphy*

day_step dynamical time steps per day
day_step/iphysiq physical time steps per day
day_step/iphysiq/iradia radiative time steps per day
day_step/ecritphy outputs per day
(but ecritphy must be a multiple of iradia*iphysiq)