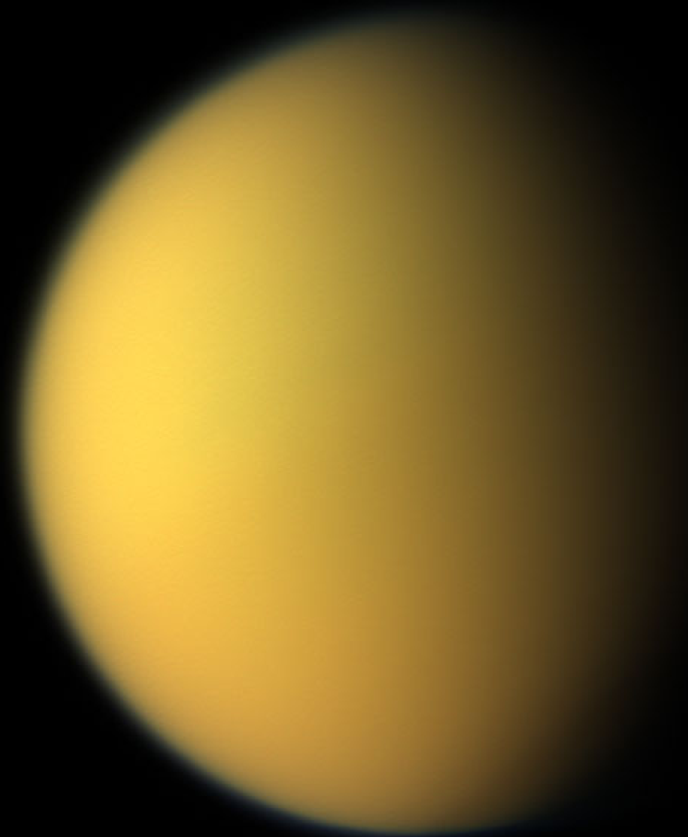
Idealized models for planetary climate & circulation: From Earth to Titan



Jonathan Mitchell
Earth & Space Sciences
Atmospheric & Oceanic Sciences
UCLA

Image credit: NASA/JPL/UovArizona

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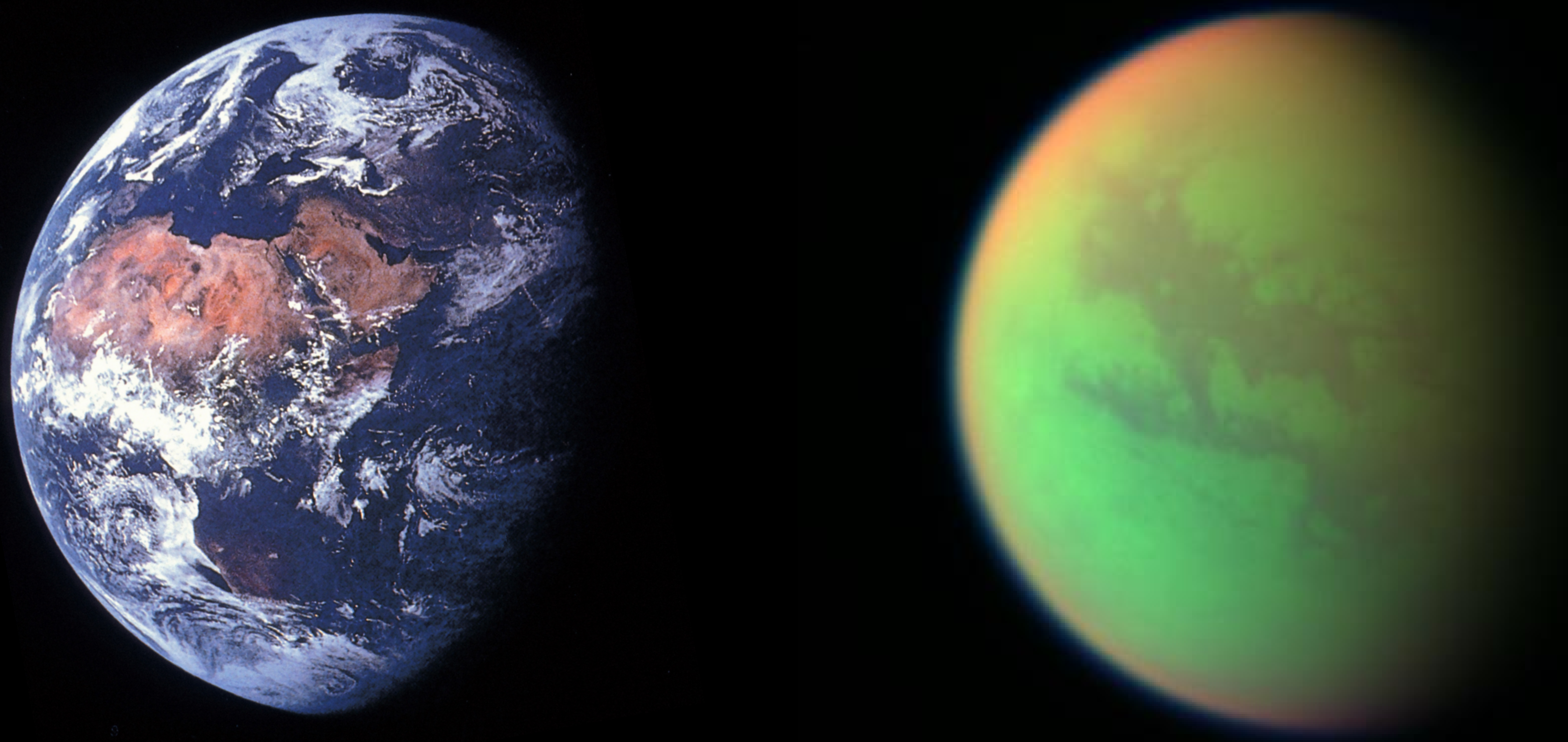

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Image credit: NASA/JPL/UovArizona

Part I:
Titan’s tropical weather and climate

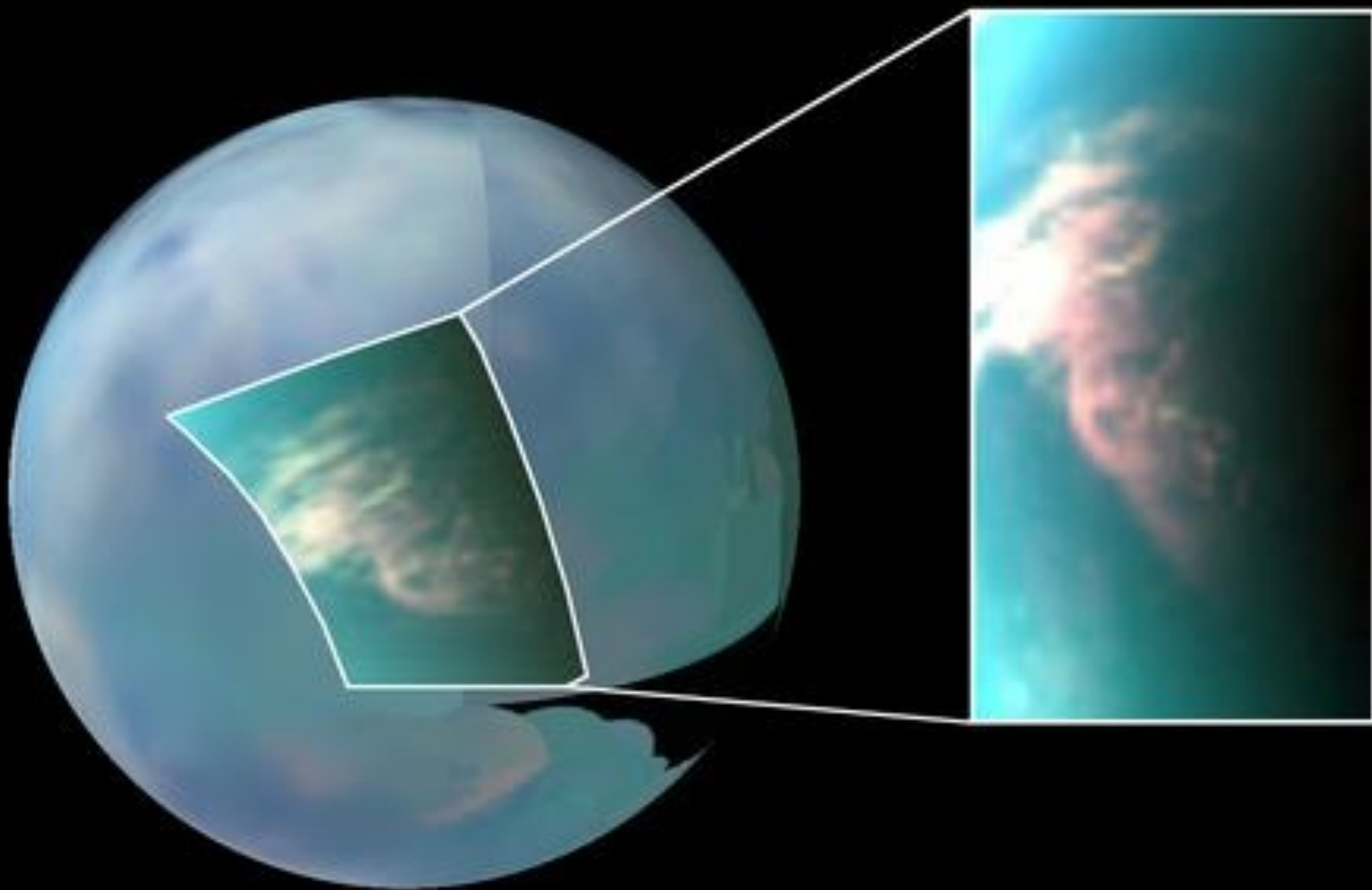
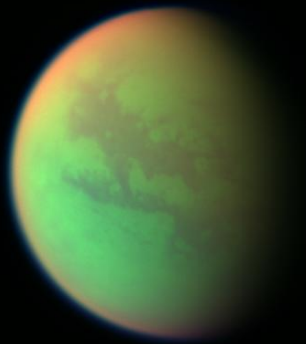
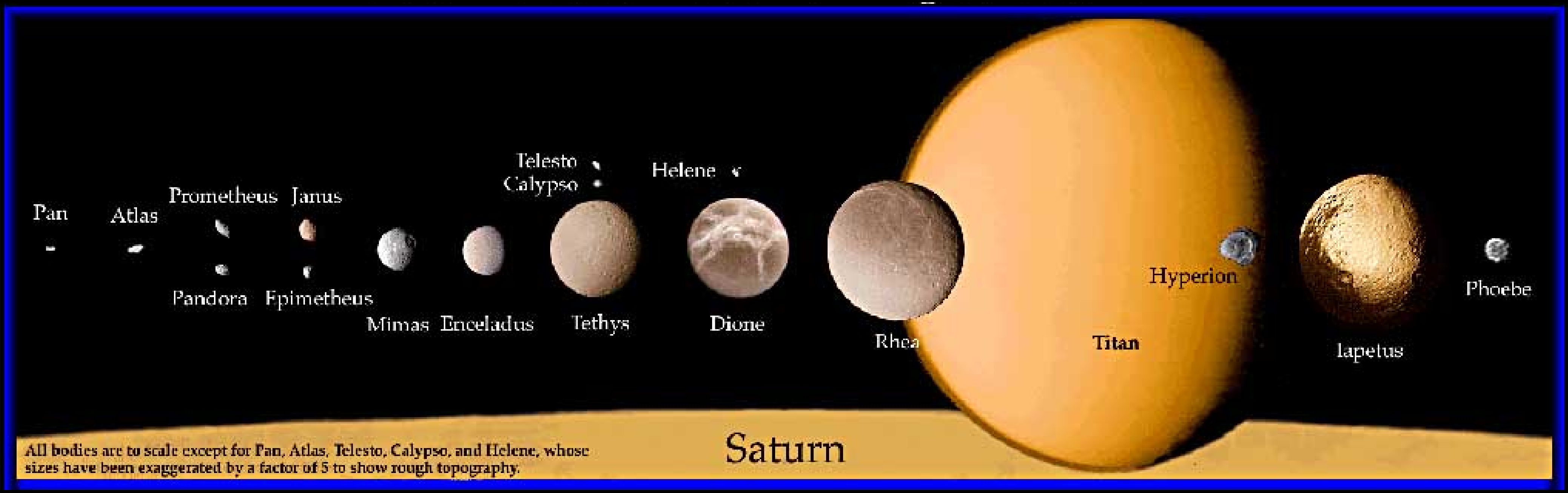
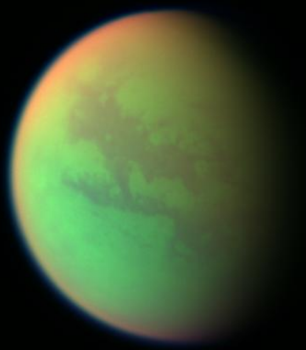


Image credit: NASA/JPL/UovArizona



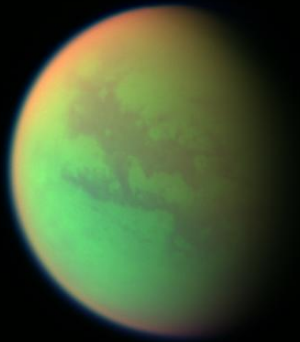
Titan: Saturn's largest moon





Titan: Saturn's largest moon

- *Larger than Mercury*



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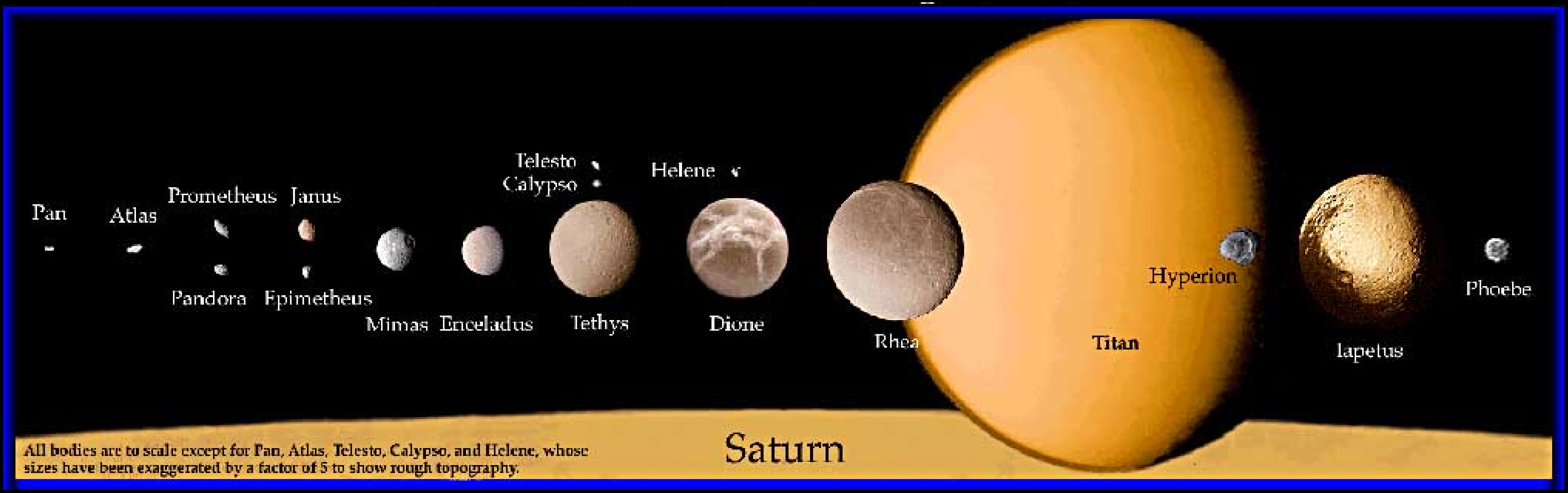
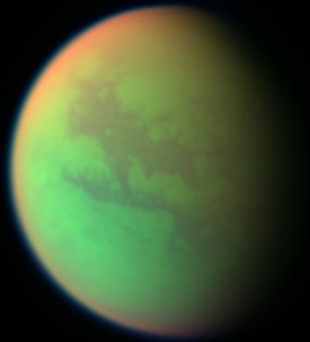


- *Larger than Mercury*
- *50% water (ice)*



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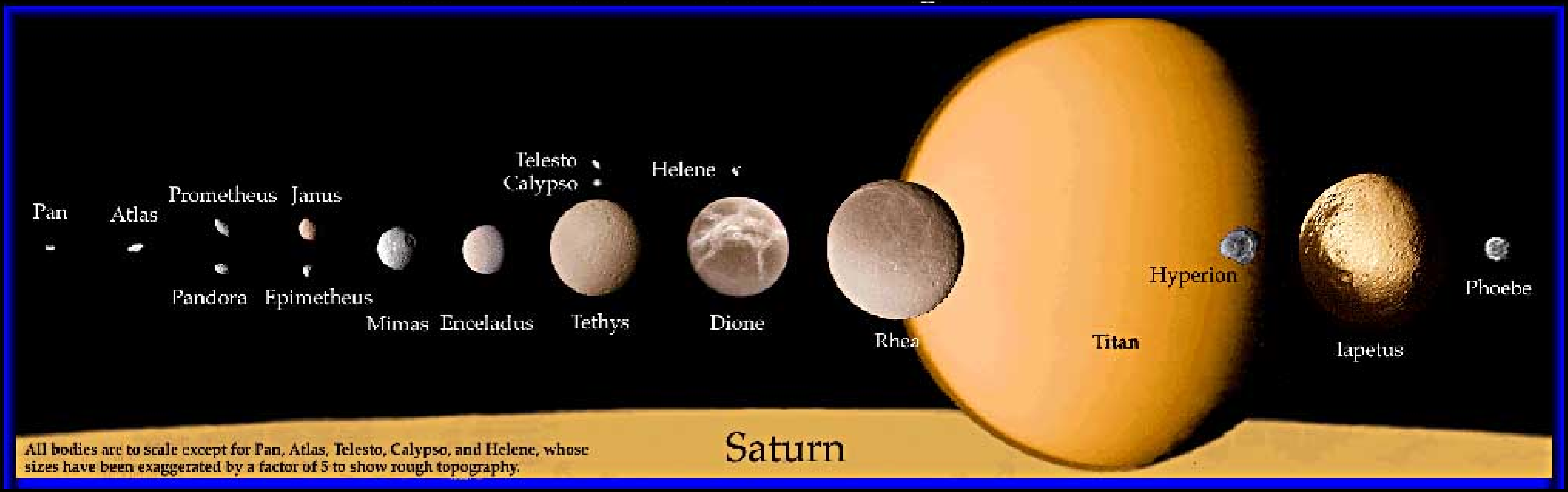
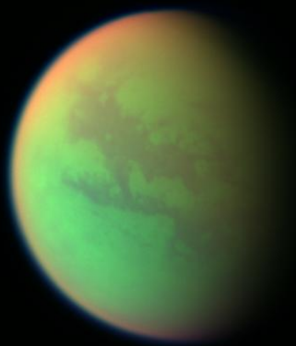
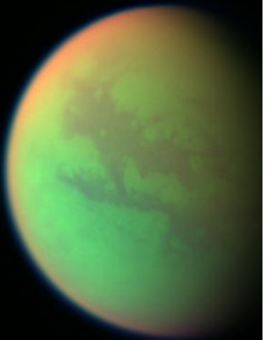


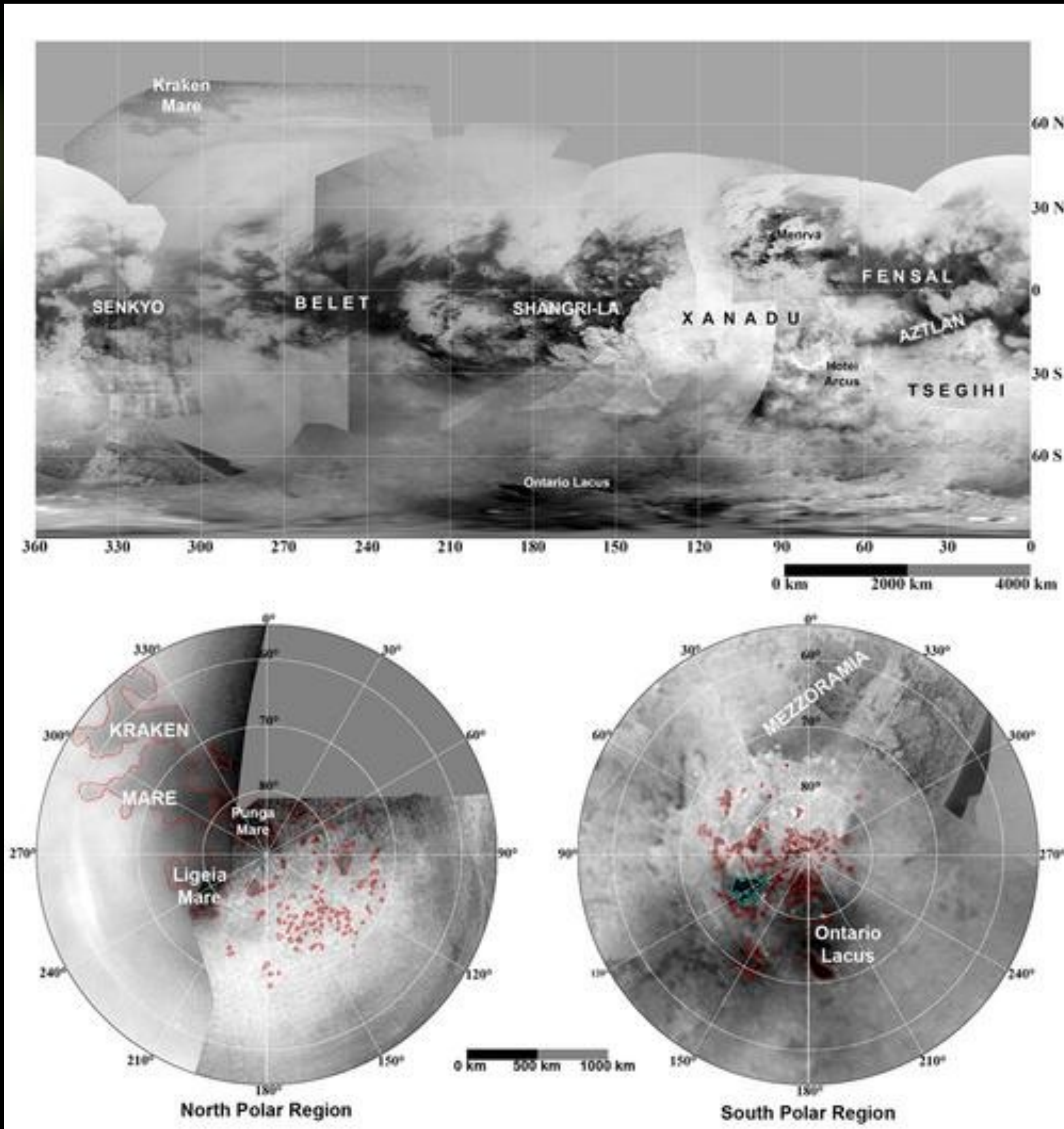
- *Larger than Mercury*
- *50% water (ice)*
- *1.5 bar N_2 atmosphere*

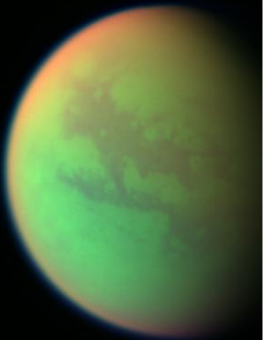


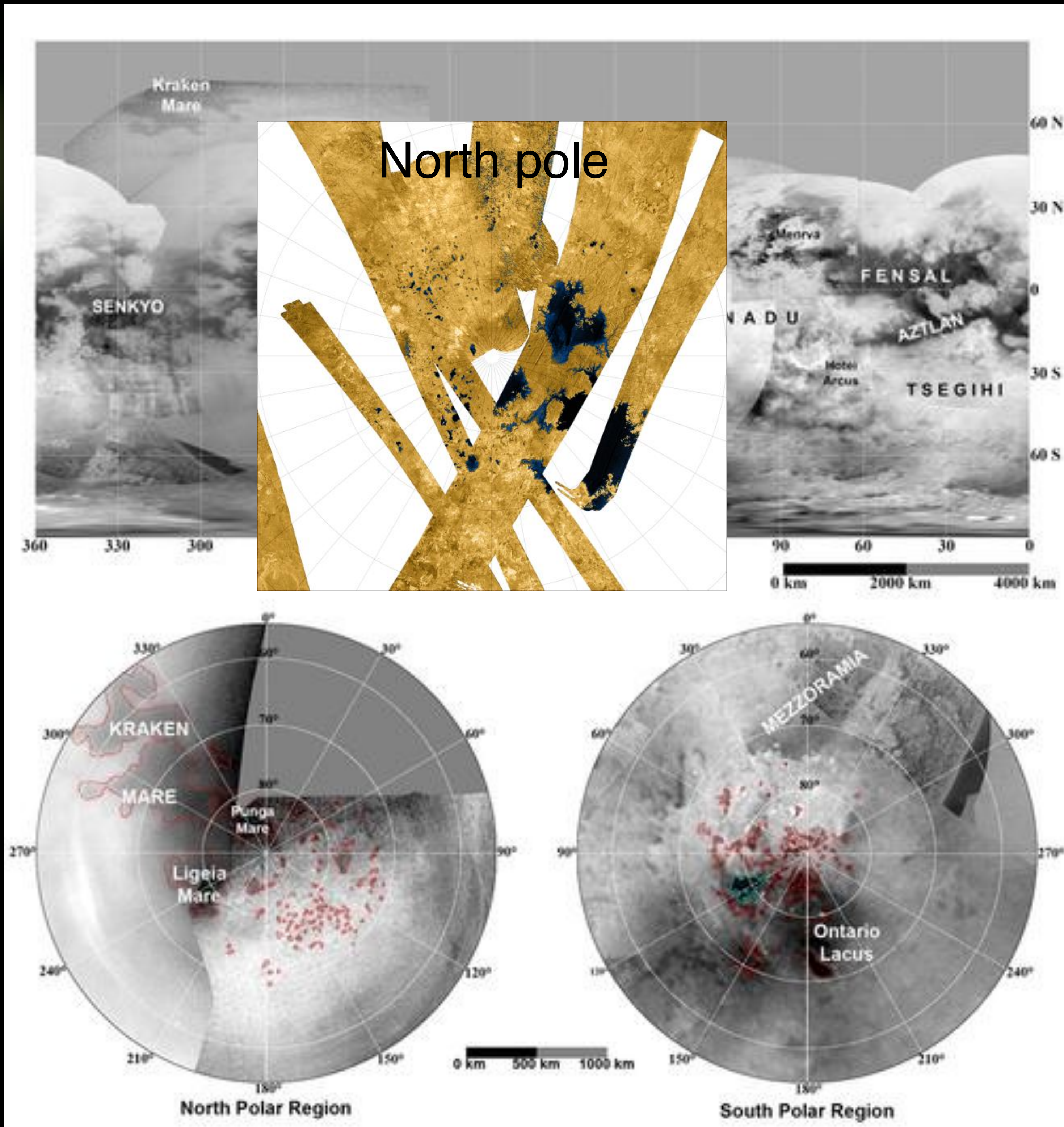
Titan: Saturn’s largest moon

- *Larger than Mercury*
- *50% water (ice)*
- *1.5 bar N_2 atmosphere*
- *5 m LMP!!*




Kraken Mare
60 N
30 N
0
30 S
60 S
Menrva
FENSAL
SENKYO
BELET
SHANGRI-LA
XANADU
AZTLAN
Hotei Arcus
TSEGIHI
Ontario Lacus
360
330
300
270
240
210
180
150
120
90
60
30
0
0 km
2000 km
4000 km
KRAKEN
MARE
Punga Mare
Ligeia Mare
MEZZORAMIA
Ontario Lacus
0 km
500 km
1000 km
North Polar Region
South Polar Region




North pole
Kraken
Mare
SENKYO
Menrva
FENSAL
N A D U
AZTLAN
Hotei
Arcus
TSEGIHI
60 N
30 N
0
30 S
60 S
360
330
300
90
60
30
0
0 km
2000 km
4000 km
KRAKEN
MARE
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MEZZORAMIA
Ontario
Lacus
0 km
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North Polar Region
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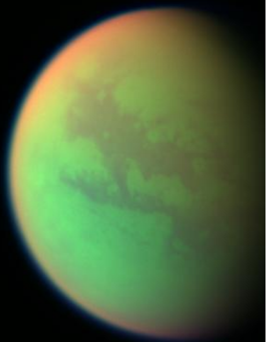

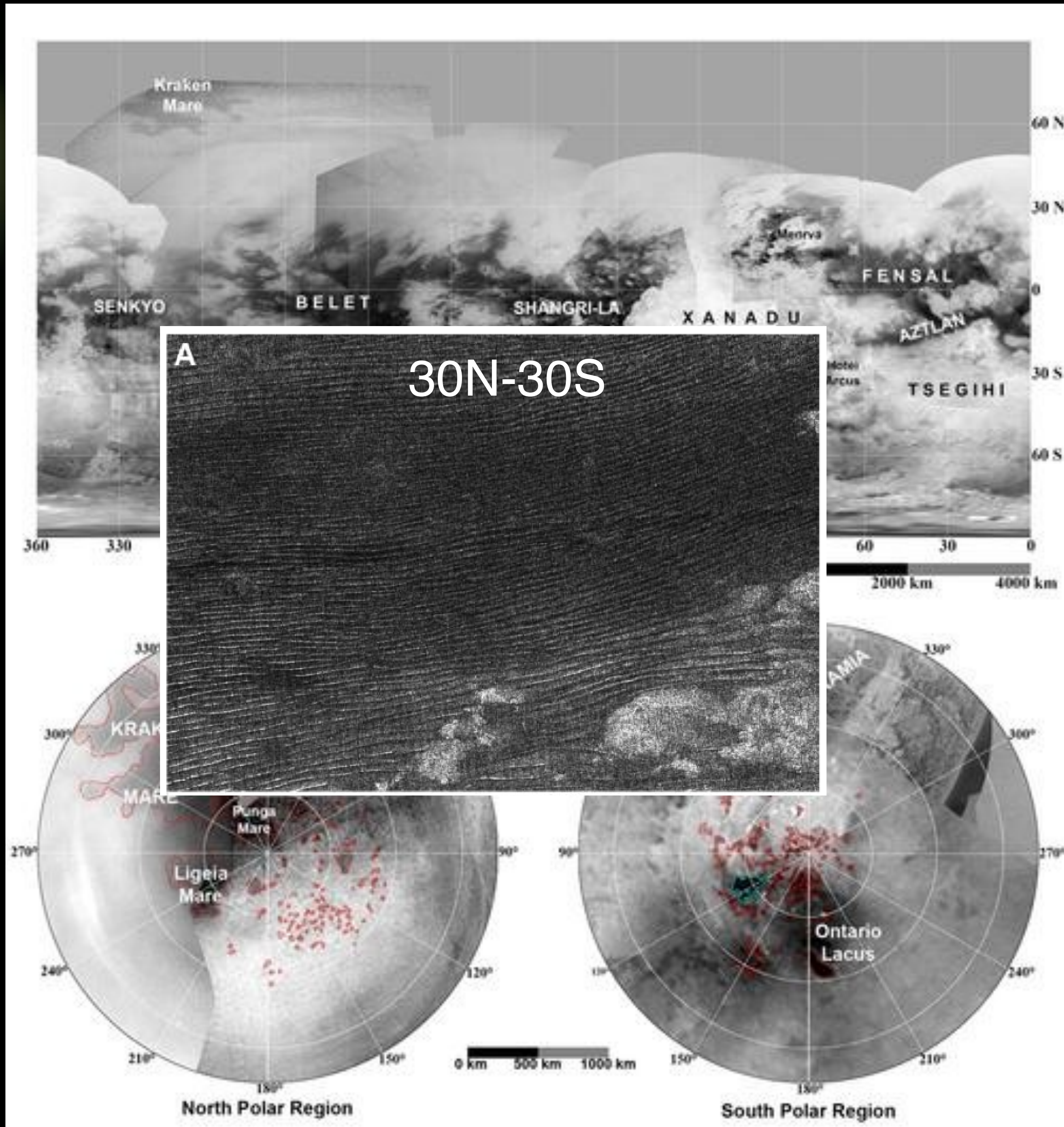

Kraken Mare
60 N
30 N
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FENSAL
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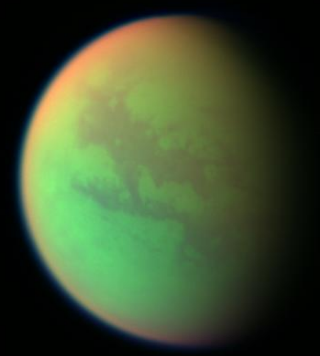
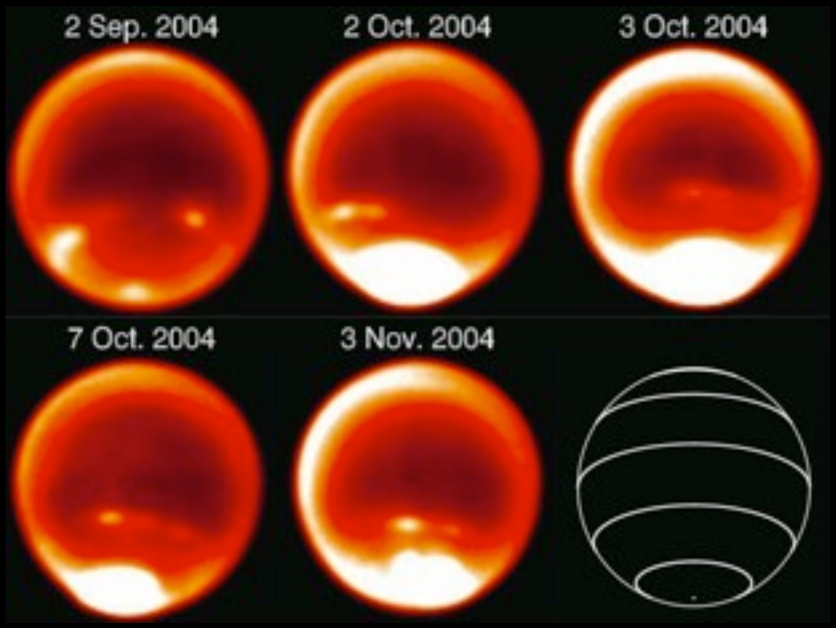
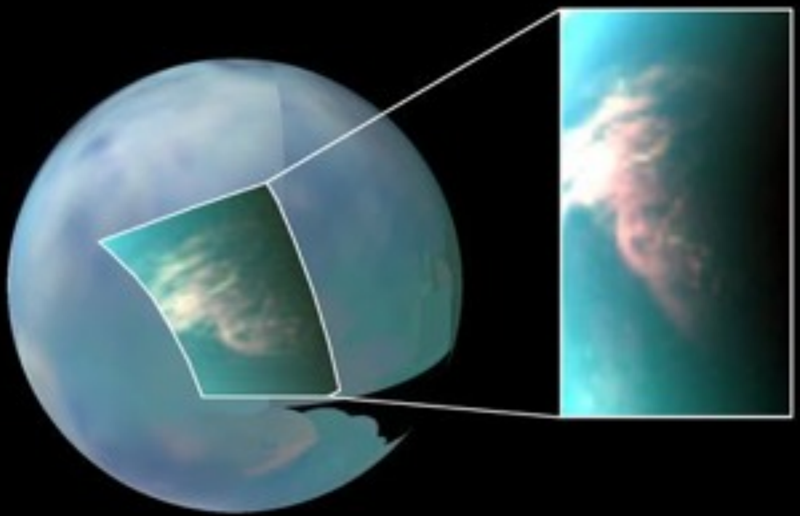


Titan's methane clouds



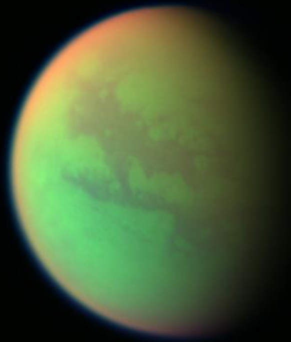
Roe et al. 2005



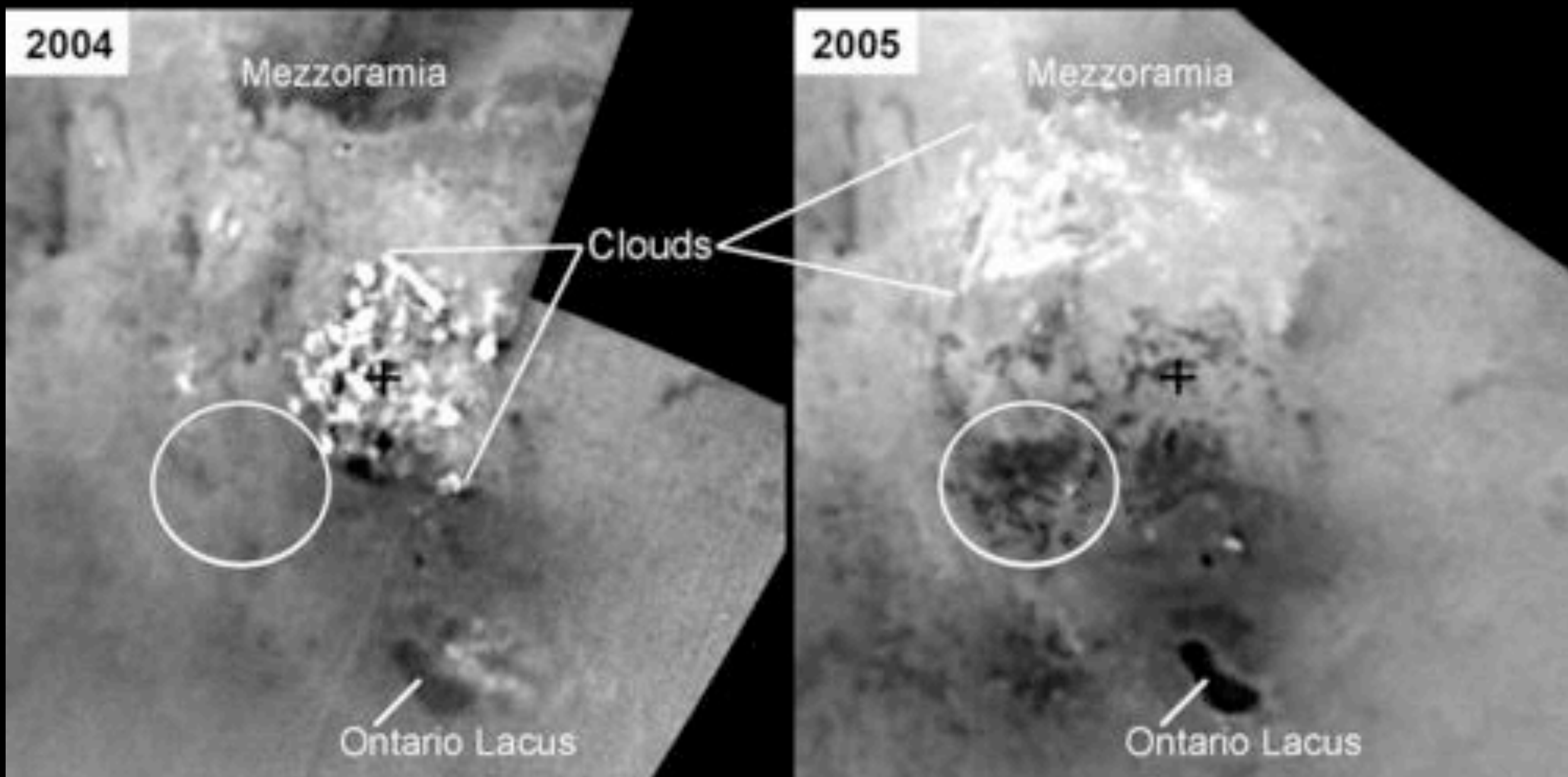
NASA/JPL/Univ. of Arizona

Keck Telescope

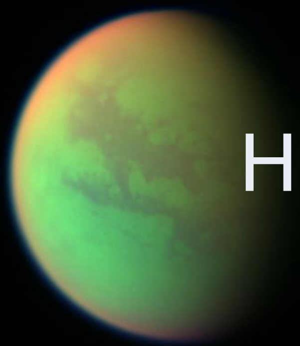
Cassini



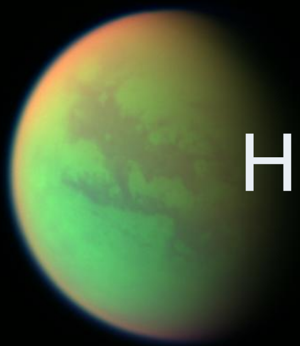
Titanian floods



Turtle et al. 09



Hadley cells and tropical climate



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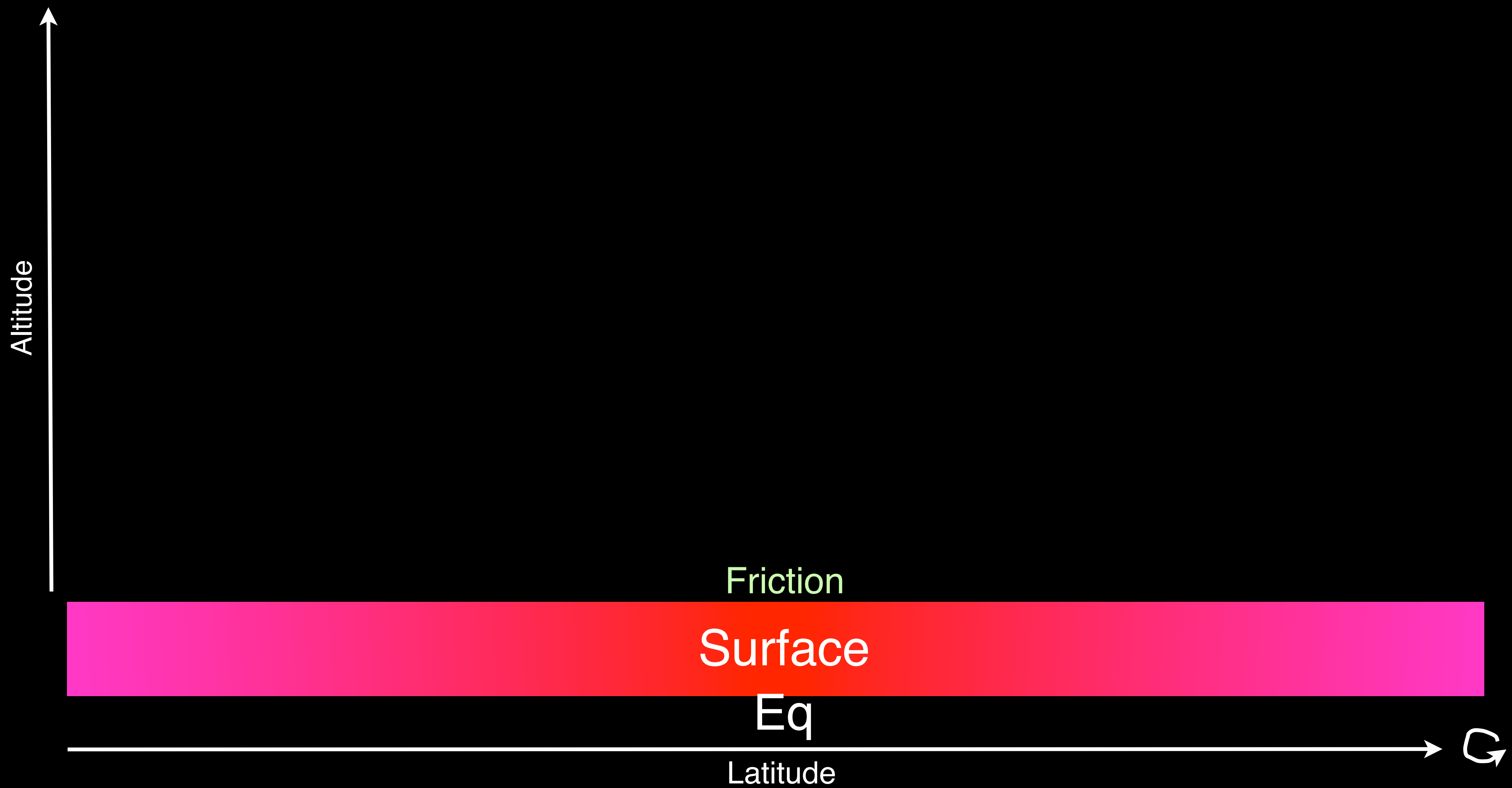

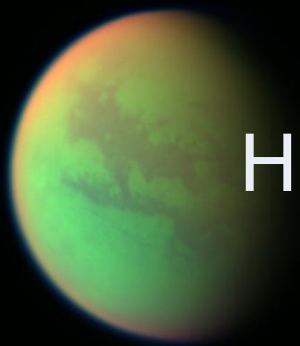

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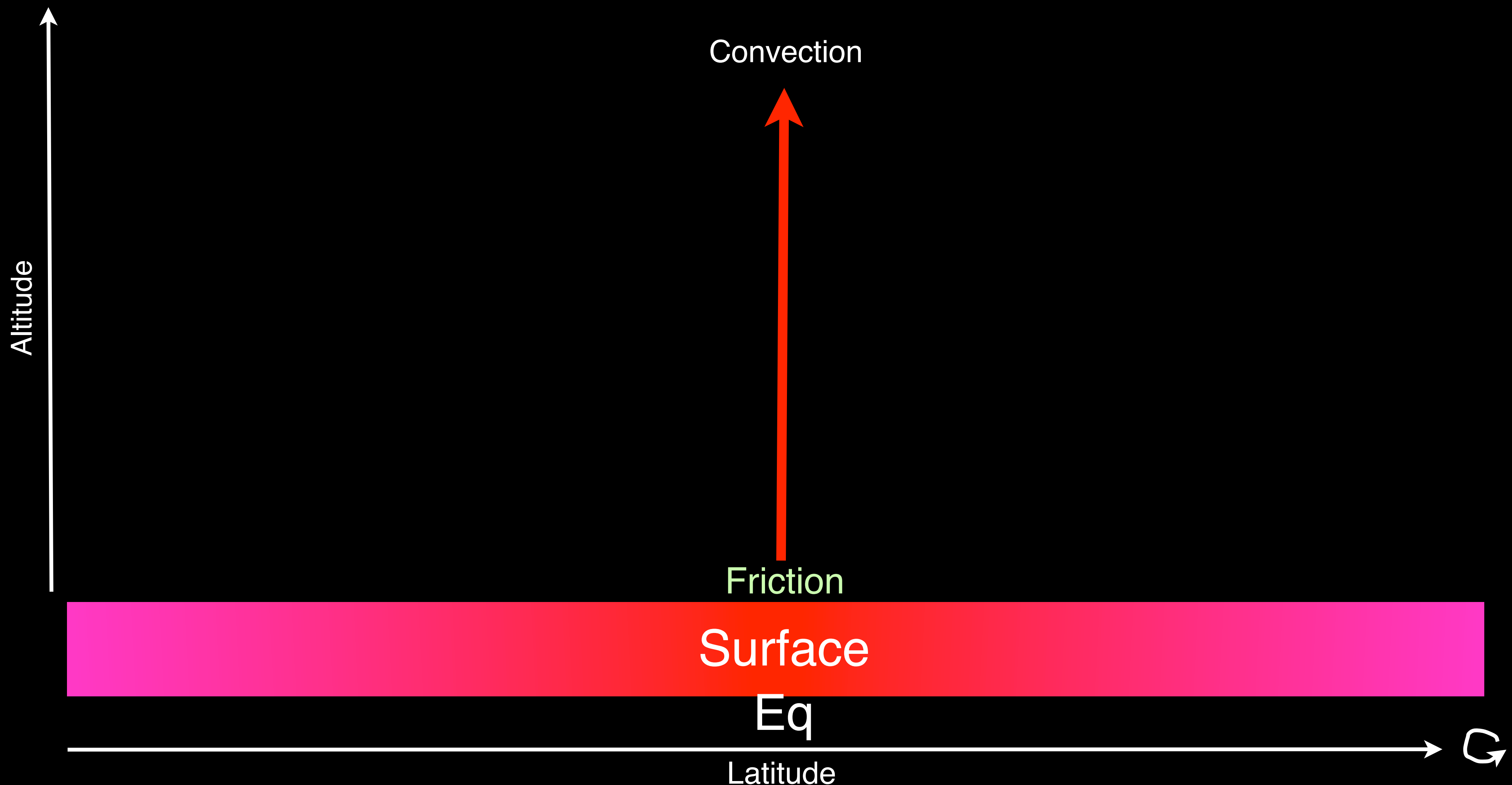
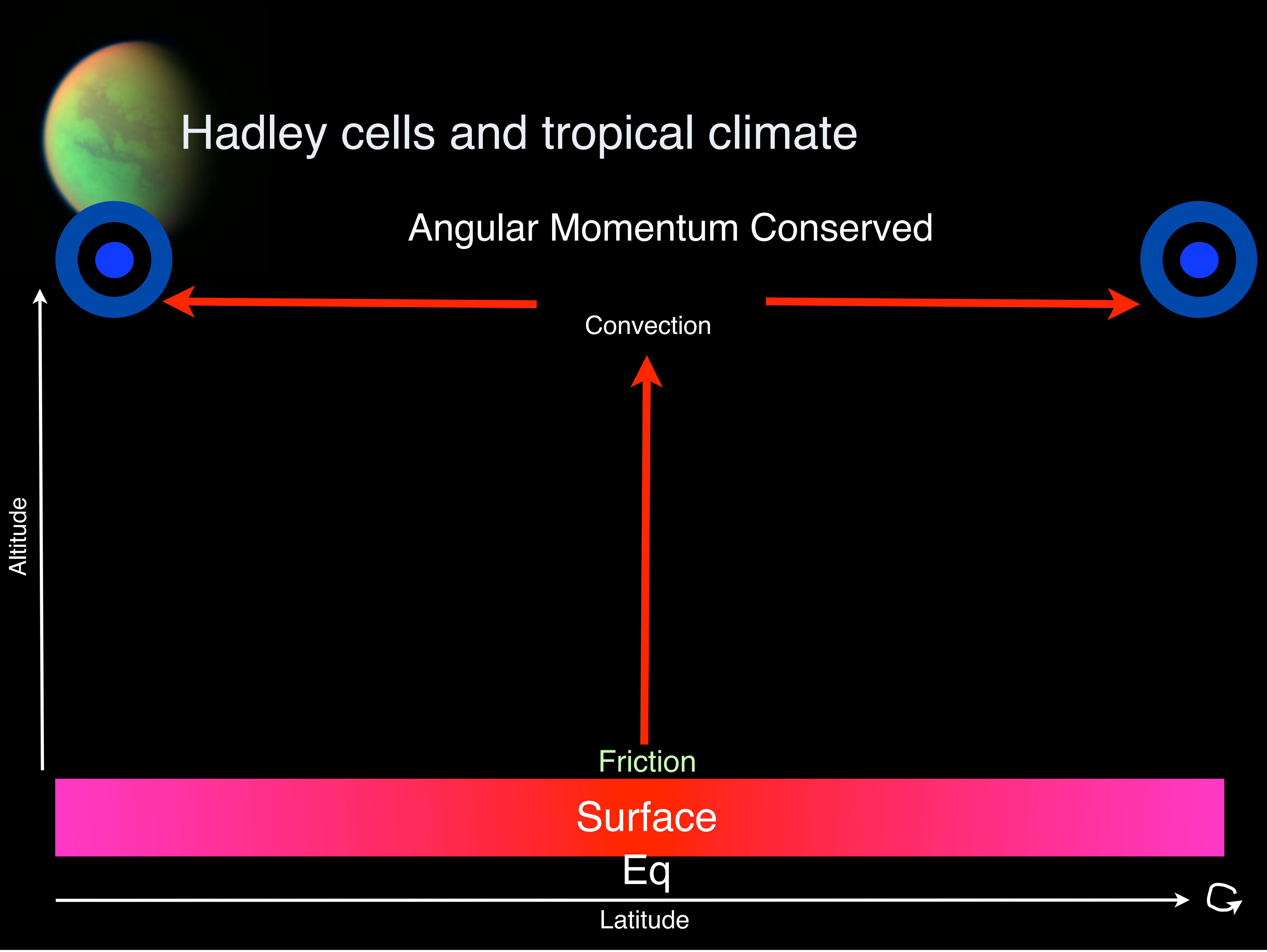
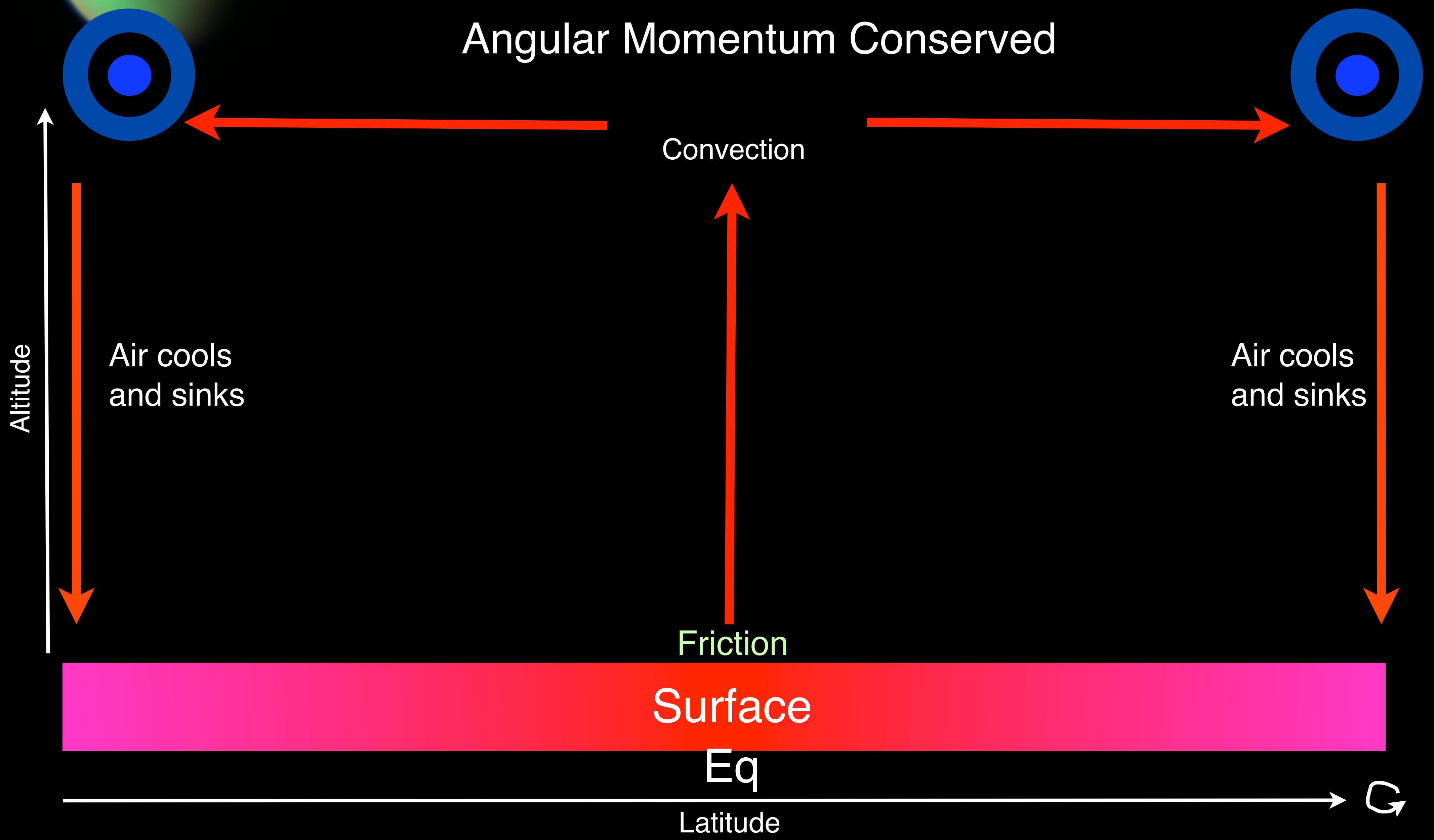
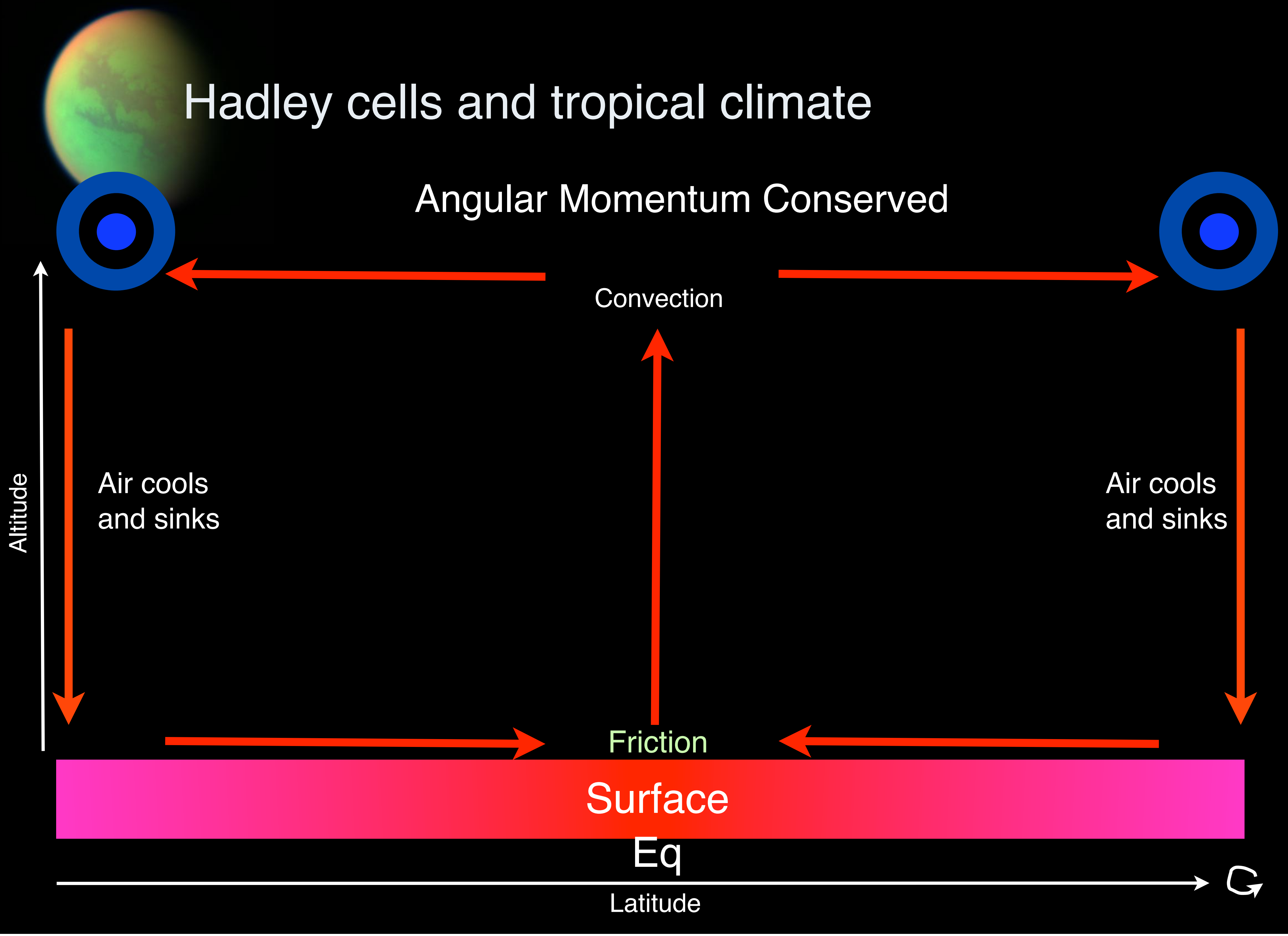



Hadley cells and tropical climate
Angular Momentum Conserved
Convection
Altitude
Friction
Surface
Eq
Latitude

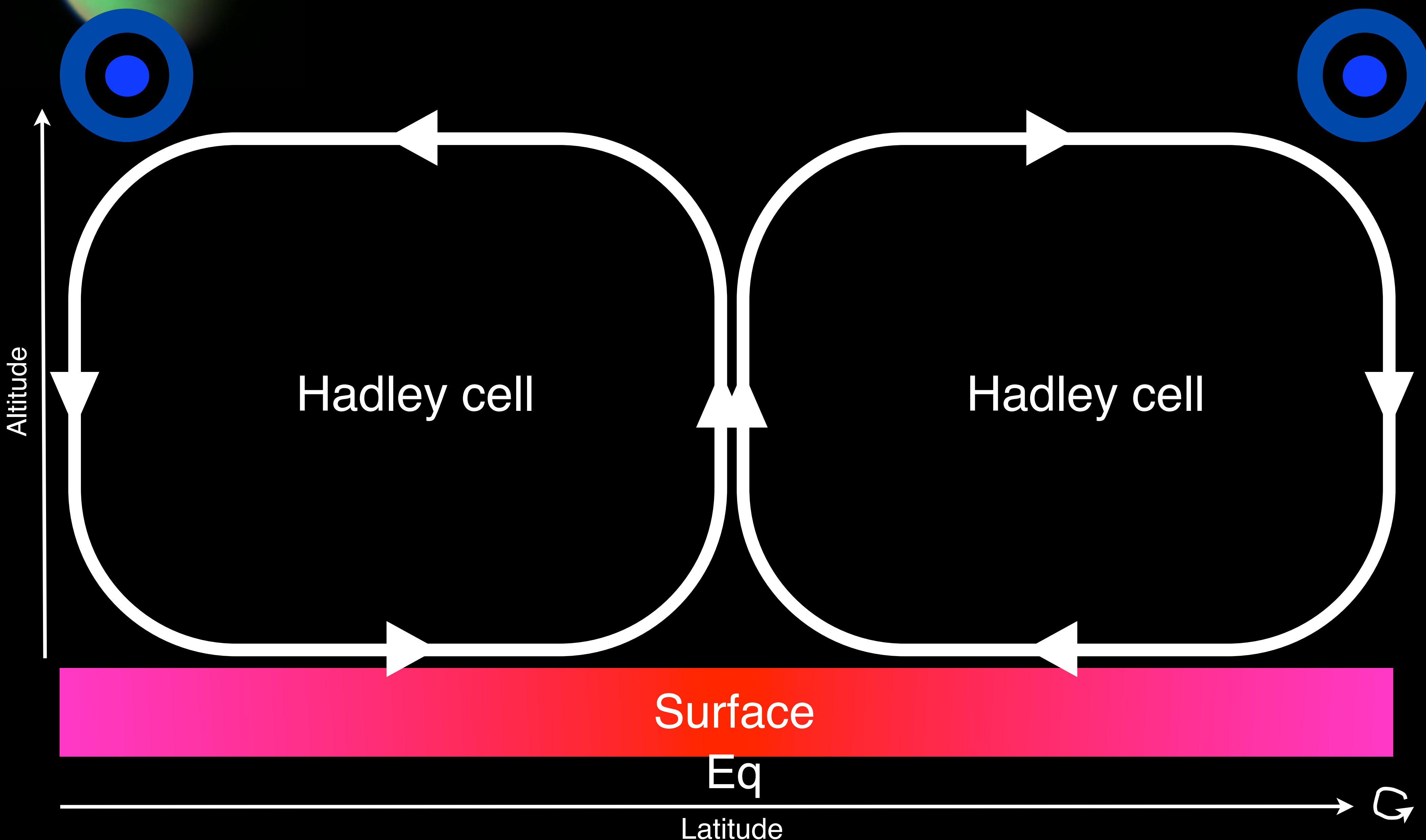
Hadley cells and tropical climate



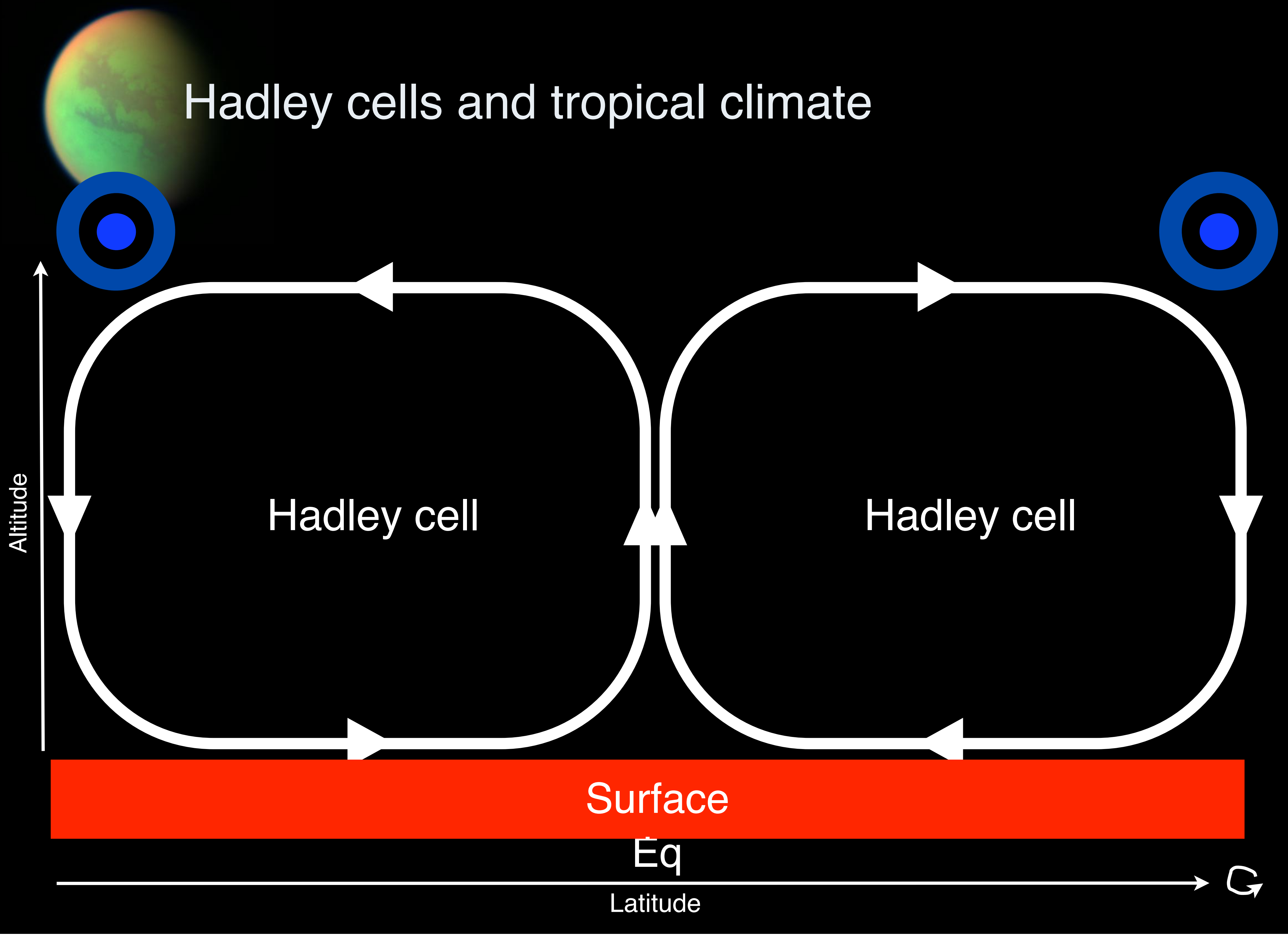
Hadley cells and tropical climate



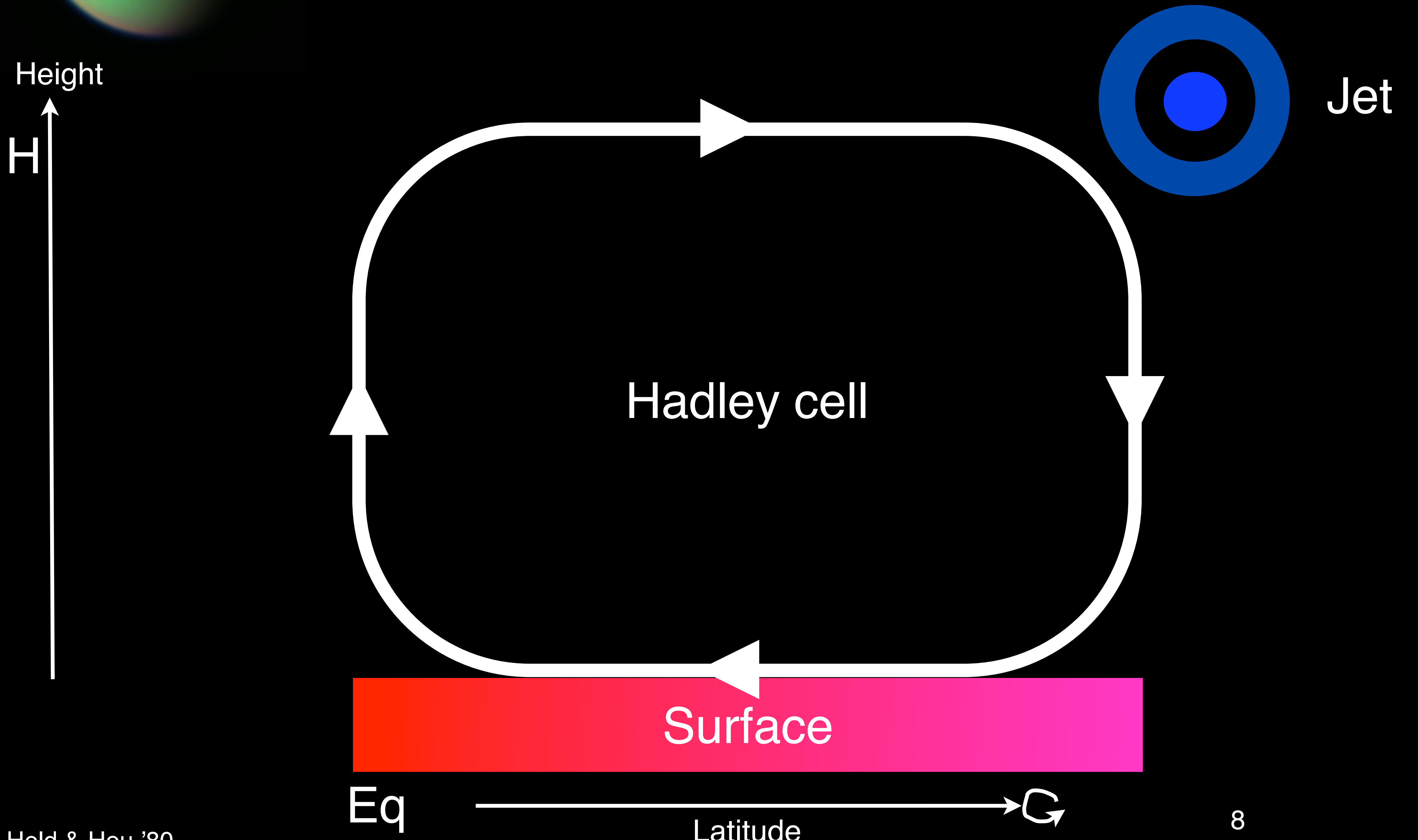
Hadley cells and tropical climate



Hadley cells and tropical climate



Steady Hadley cell theory: Momentum and energy transport by Hadley cells



Held & Hou ’80
Caballero, Pierrehumbert, **Mitchell** ’08

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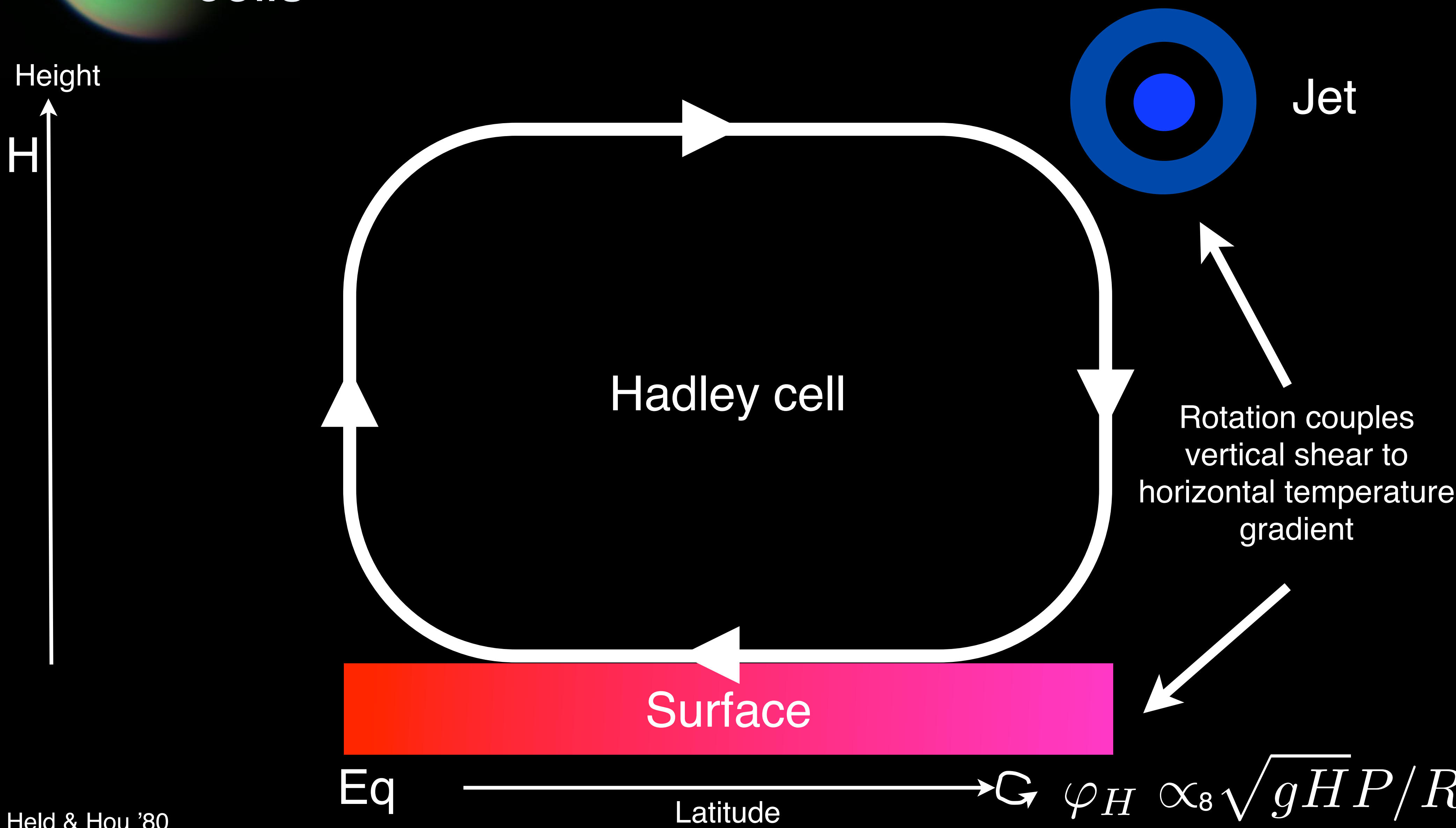
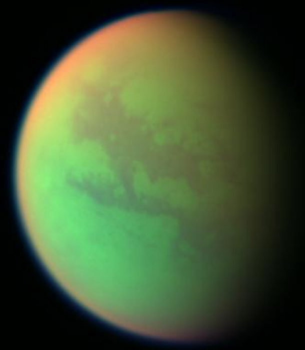


$$\varphi_H \propto_8 \sqrt{gHP/R}$$

Held & Hou '80
Caballero, Pierrehumbert, **Mitchell** '08

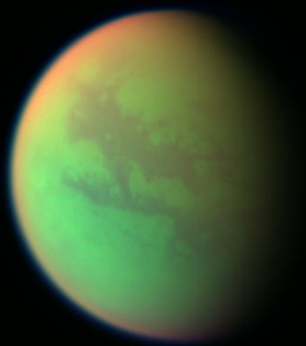


Tropics on Earth and Titan

$$\varphi_H \propto c_g P/R$$

Held & Hou '80
Caballero et al. '08

Held & Hou '80
Caballero, Pierrehumbert, Mitchell '08



Tropics on Earth and Titan

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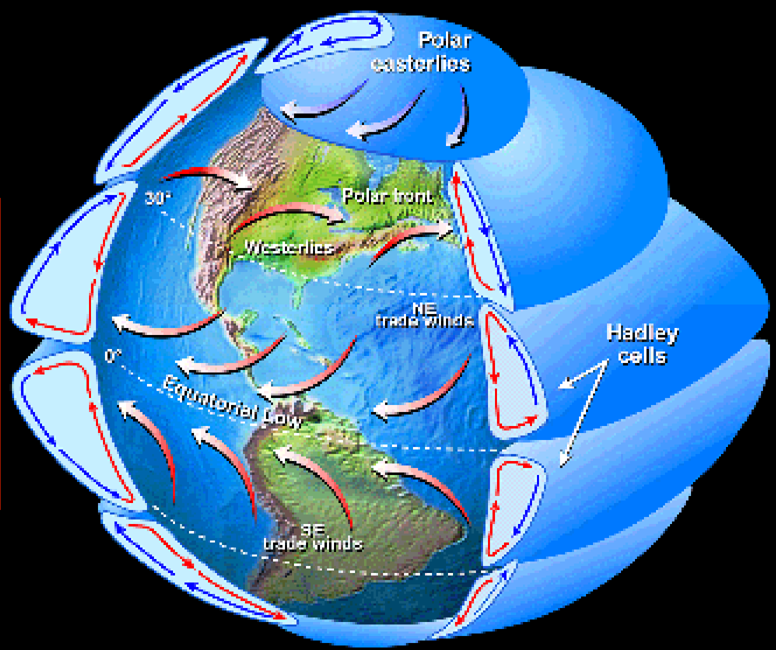
Earth

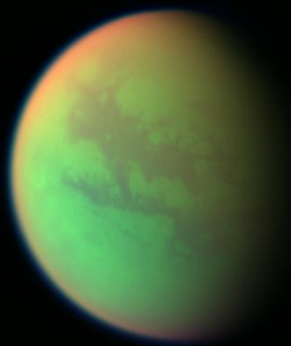
Tropics



P=1 day
R=6400 km
g=9.8 m/s^2
H=10 km

$$c_g = \sqrt{gH}$$

Held & Hou ’80
Caballero, Pierrehumbert, Mitchell ’08



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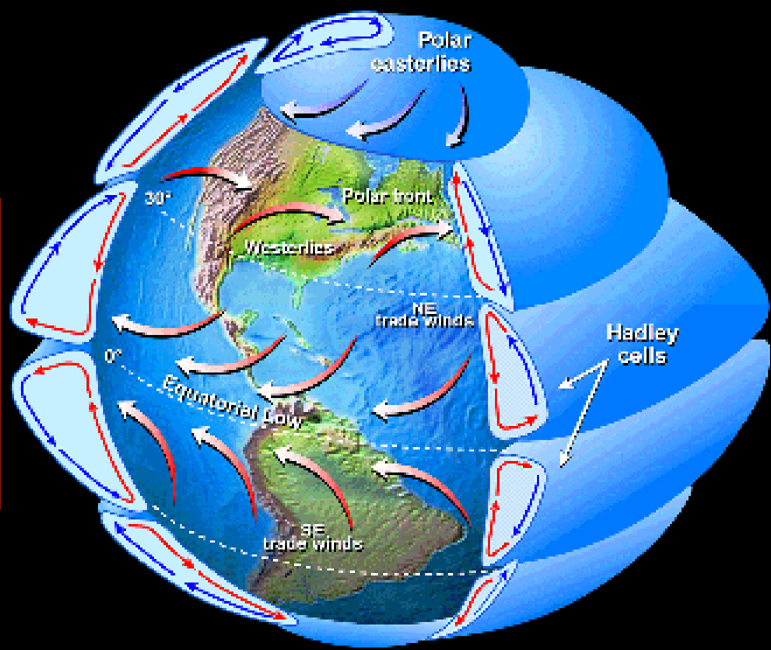
Tropics

Earth



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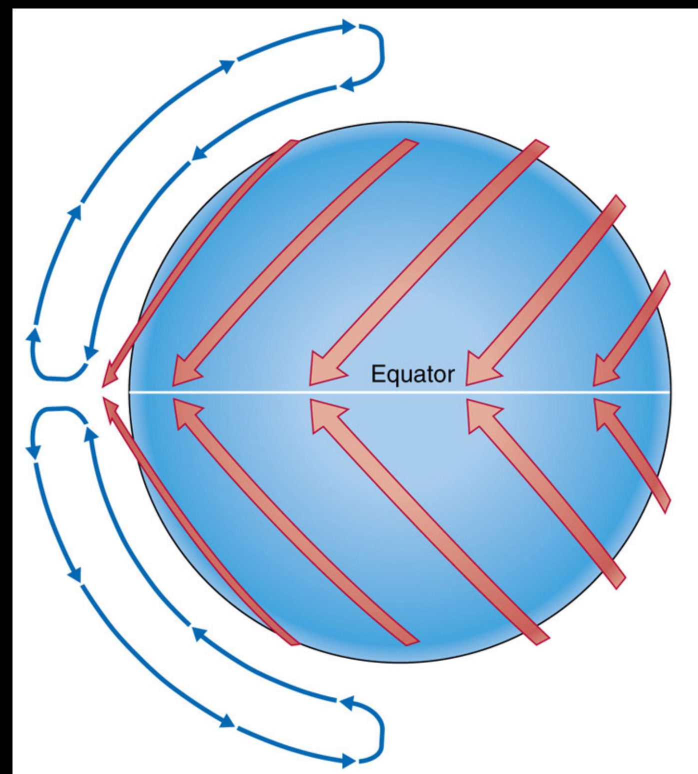
Titan



Tropics

P=16 days
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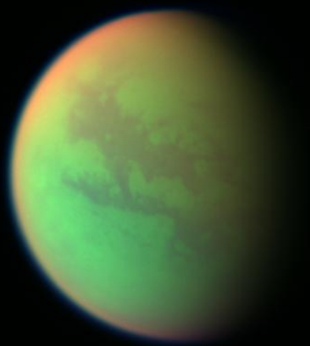
g=1.3 m/s^2
H=20 km

$$c_g = \sqrt{gH}$$

Held & Hou ’80
Caballero, Pierrehumbert, Mitchell ’08



Tropics on Earth and Titan

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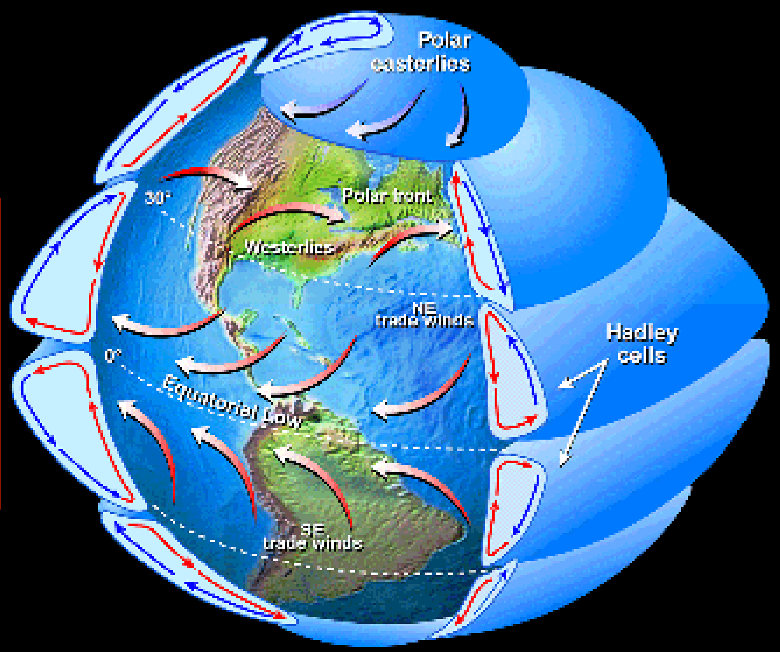
Held & Hou '80
Caballero et al. '08

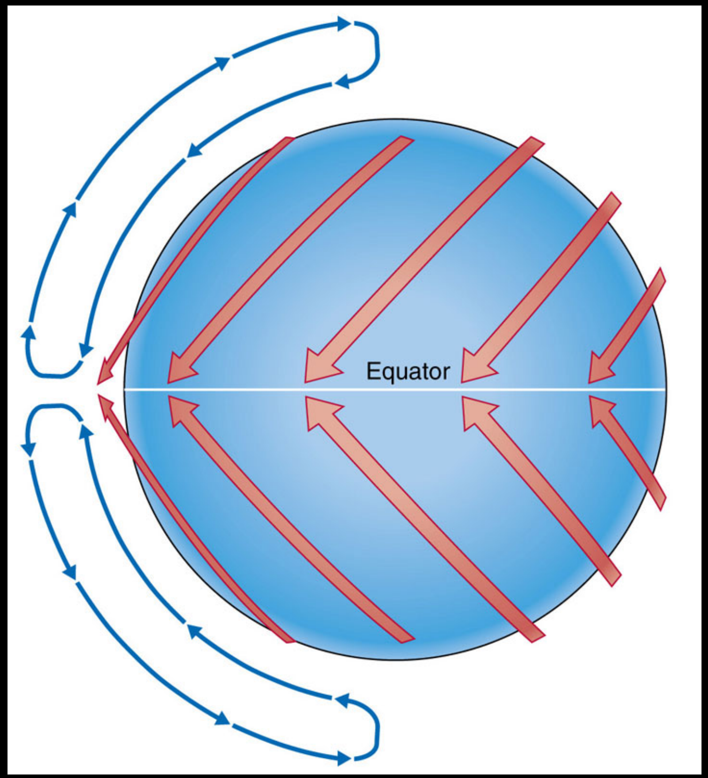
Earth



Tropics

ITCZ

Titan



Tropics

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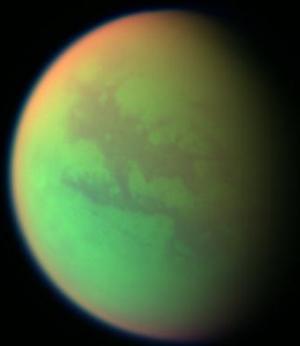

Tropics on Earth and Titan

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Held & Hou '80
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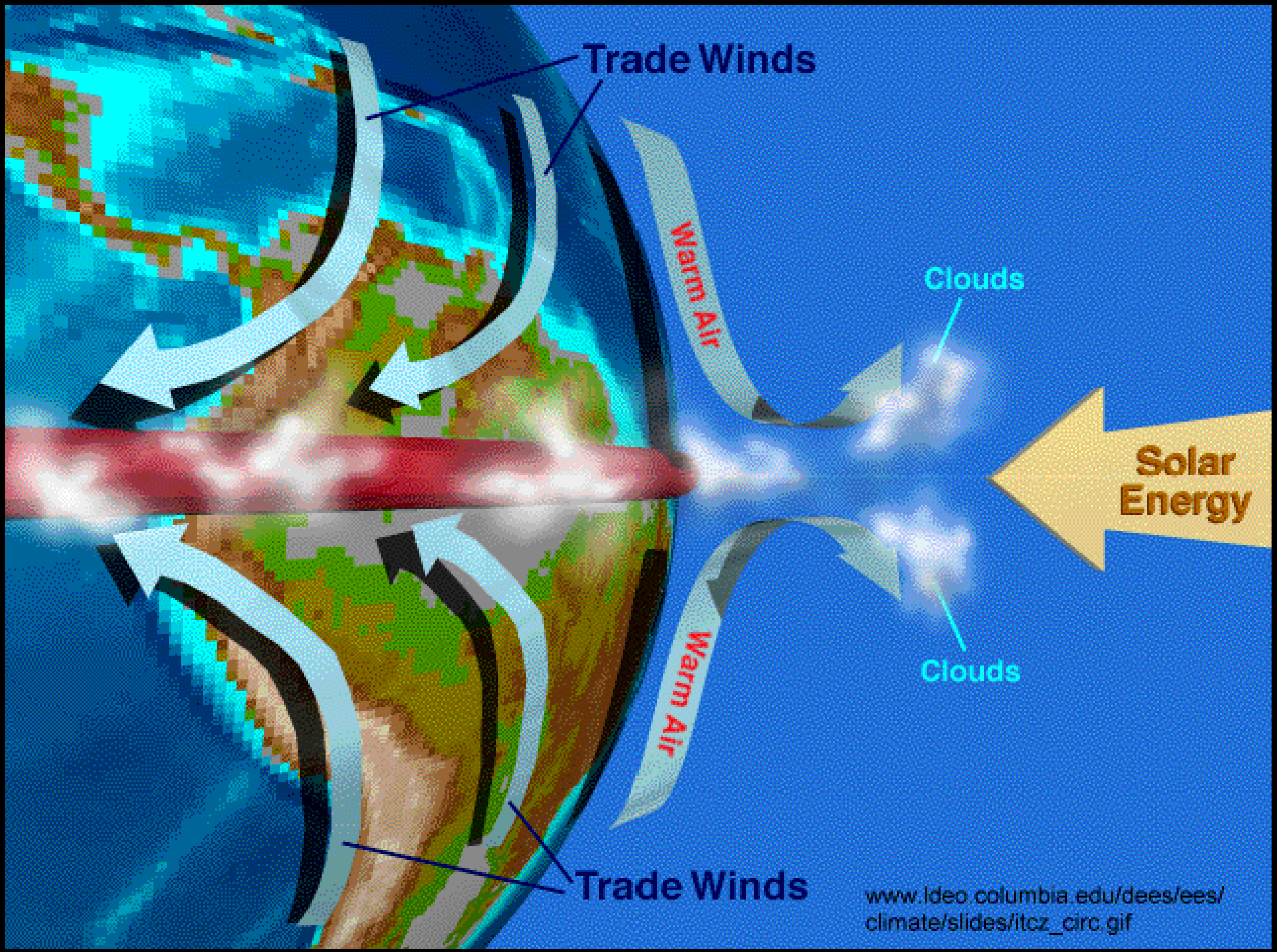

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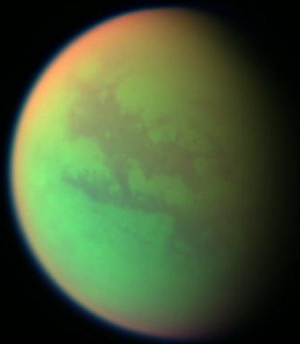

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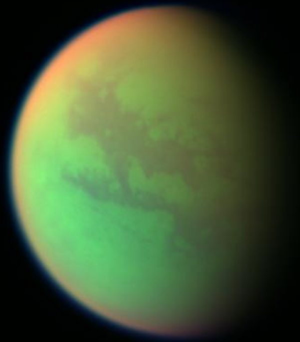
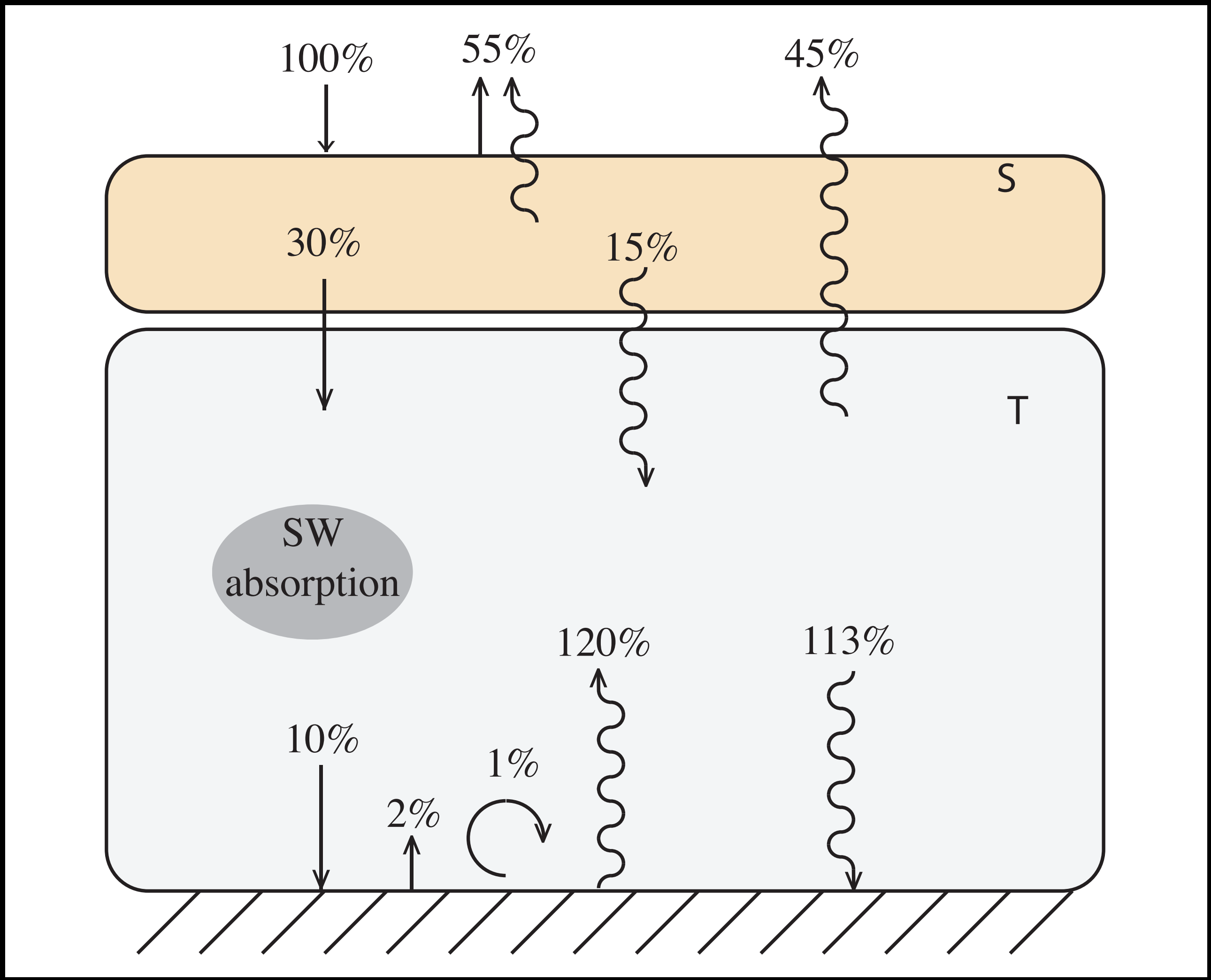
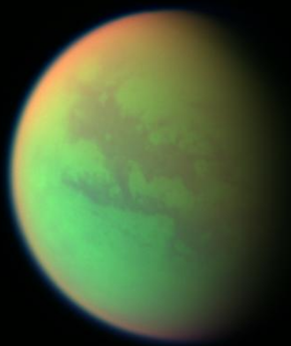


Titan's Greenhouse & Antigreenhouse



100% =
3.6 W/m²

McKay et al. '89, '91



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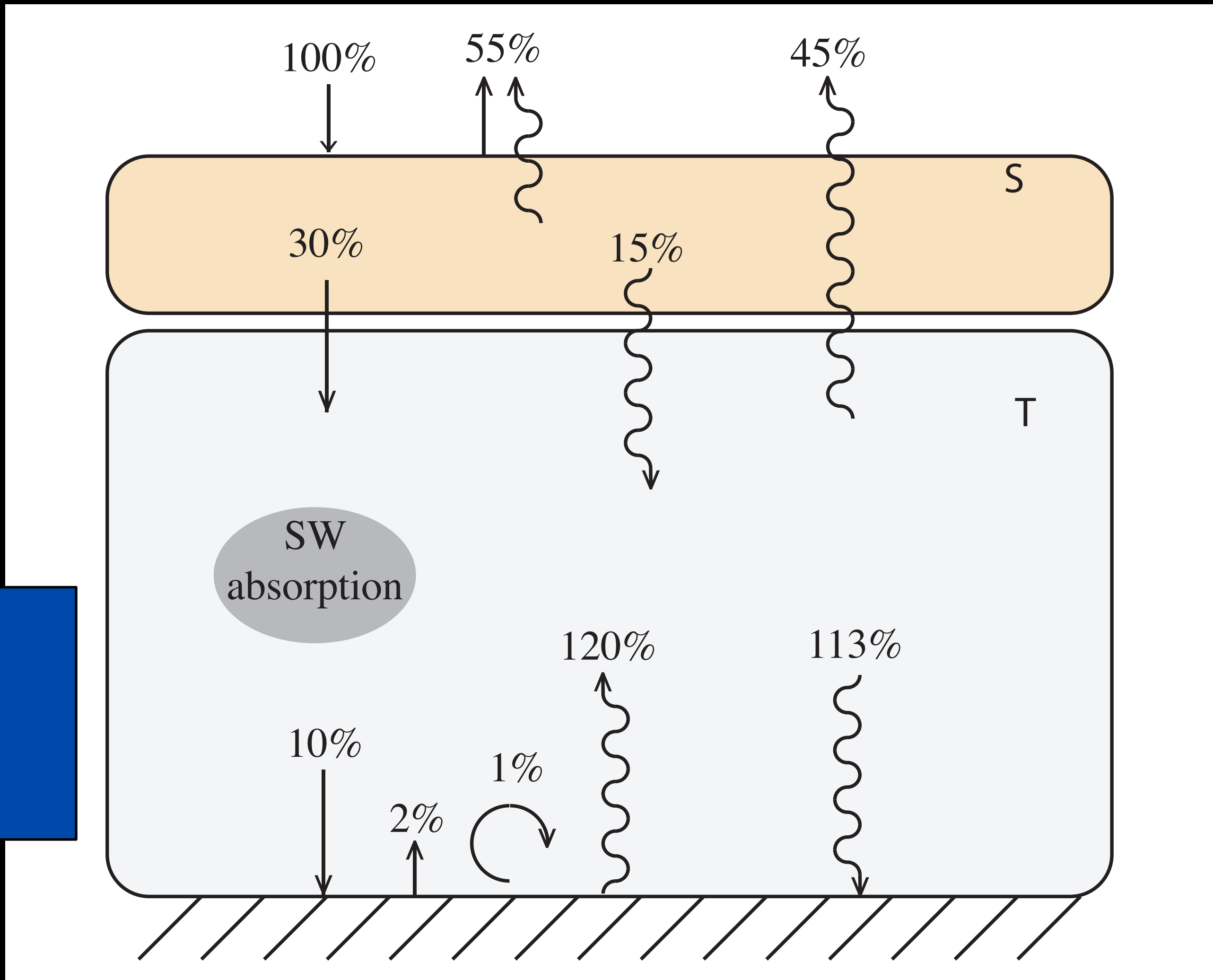

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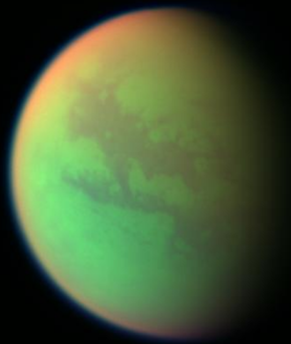
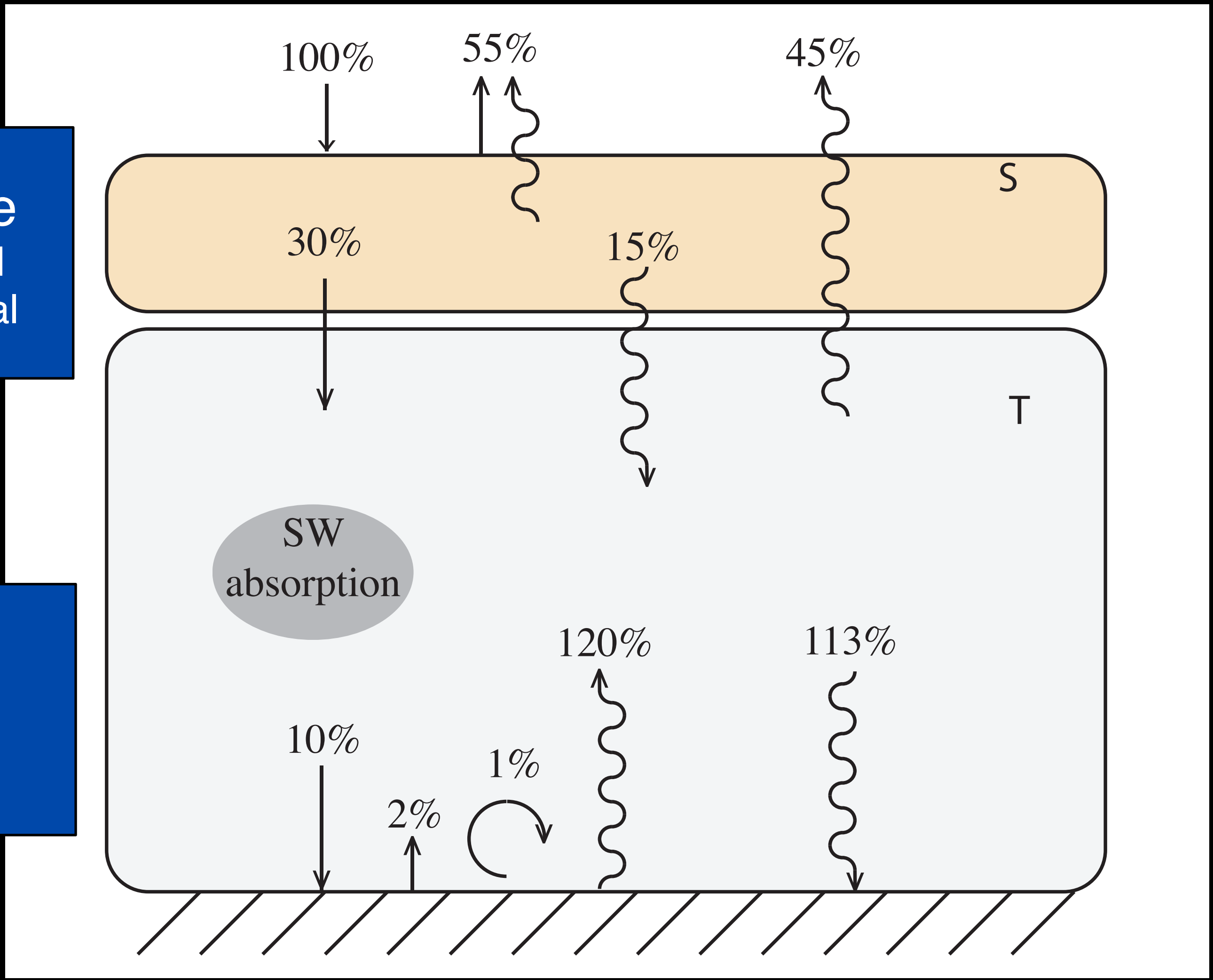
Greenhouse
-lapse rate
-absorption in IR

McKay et al. '89, '91

Titan's Greenhouse & Antigreenhouse



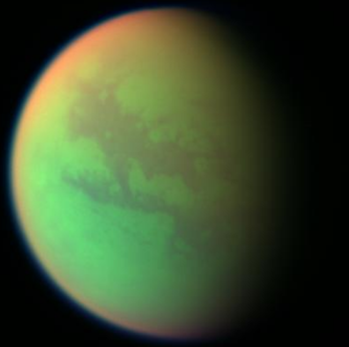


Antigreenhouse
-scattering in optical
-absorption in optical

Greenhouse
-lapse rate
-absorption in IR

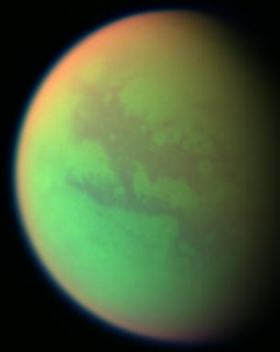
100% = 3.6 W/m²

McKay et al. '89, '91



A simplified climate model for Titan

- Axisymmetric primitive equations
- Gray radiative transfer (greenhouse)
- Parameterized shortwave absorption (antigreenhouse)
- Slab surface assumed to be saturated with methane
- Simplified Betts-Miller convection scheme *for a general condensate*



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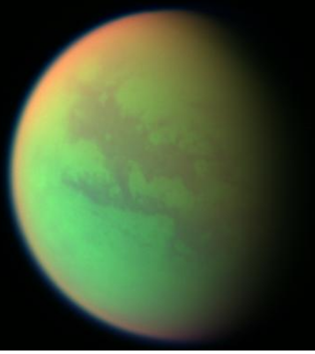
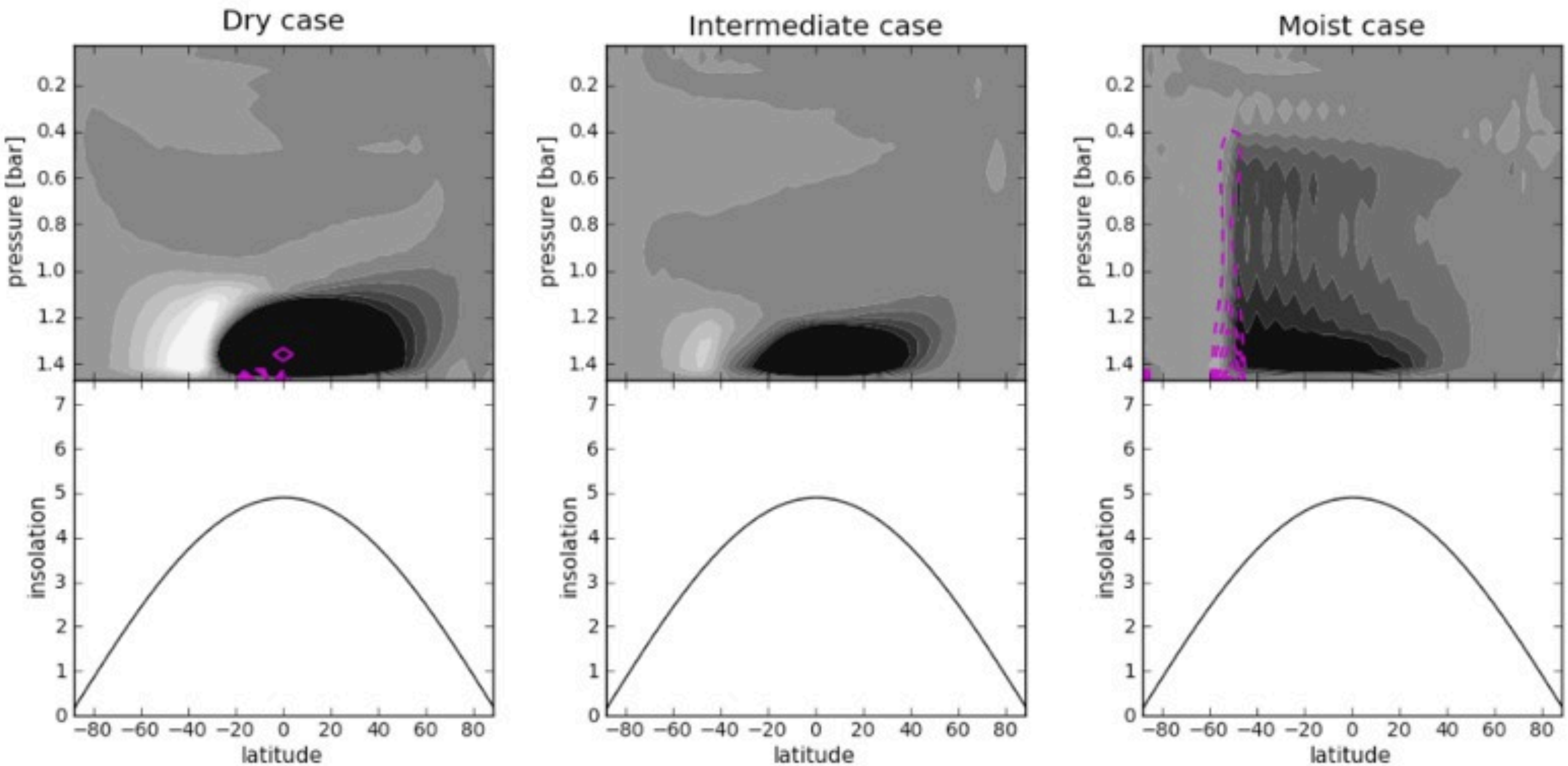
- **Approach**: Vary parameters controlling methane to pass from a dry to moist climate



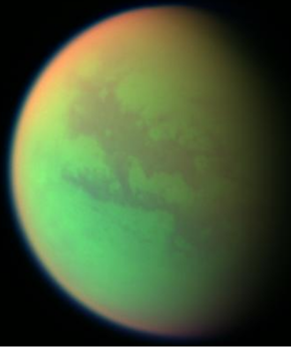
The range of Titanian climate from dry to moist

1 Titan year = 29.5 Earth years



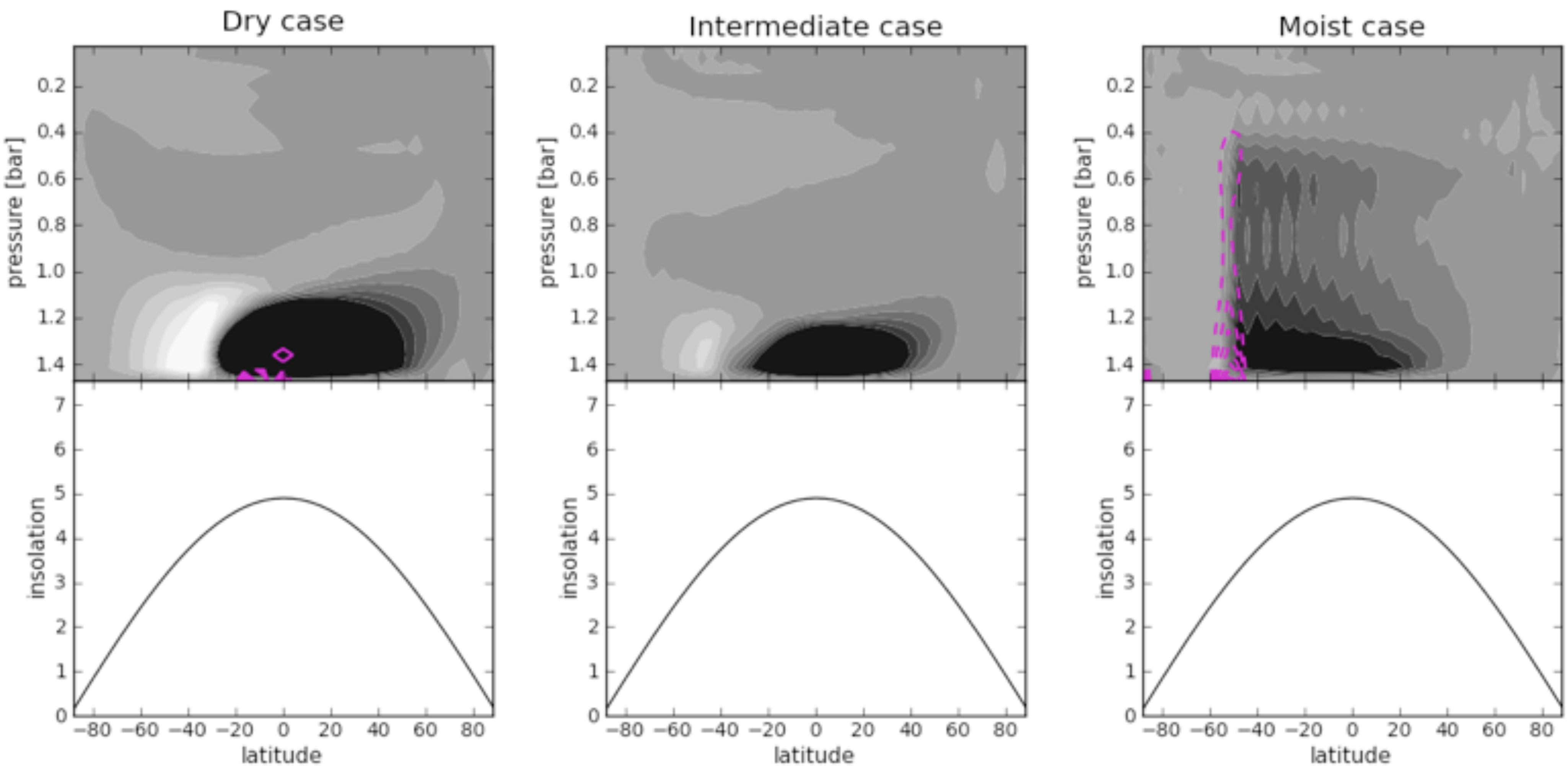
Mitchell et al. ’06 (*PNAS*)
Mitchell et al. ’09 (*Icarus*)

Friday, 10 September 2010



The range of Titanian climate

1 Titan year = 29.5 Earth years



Mitchell et al. ’06 (*PNAS*)
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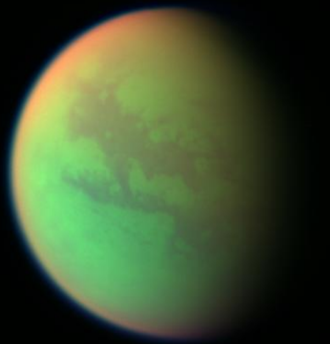
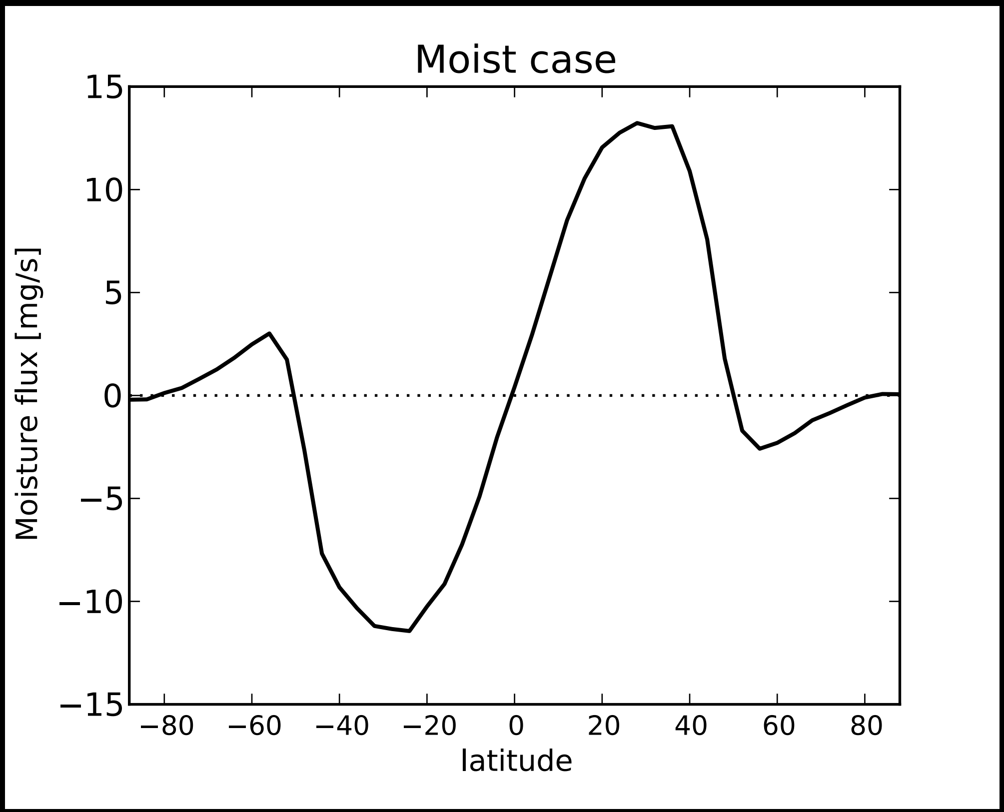
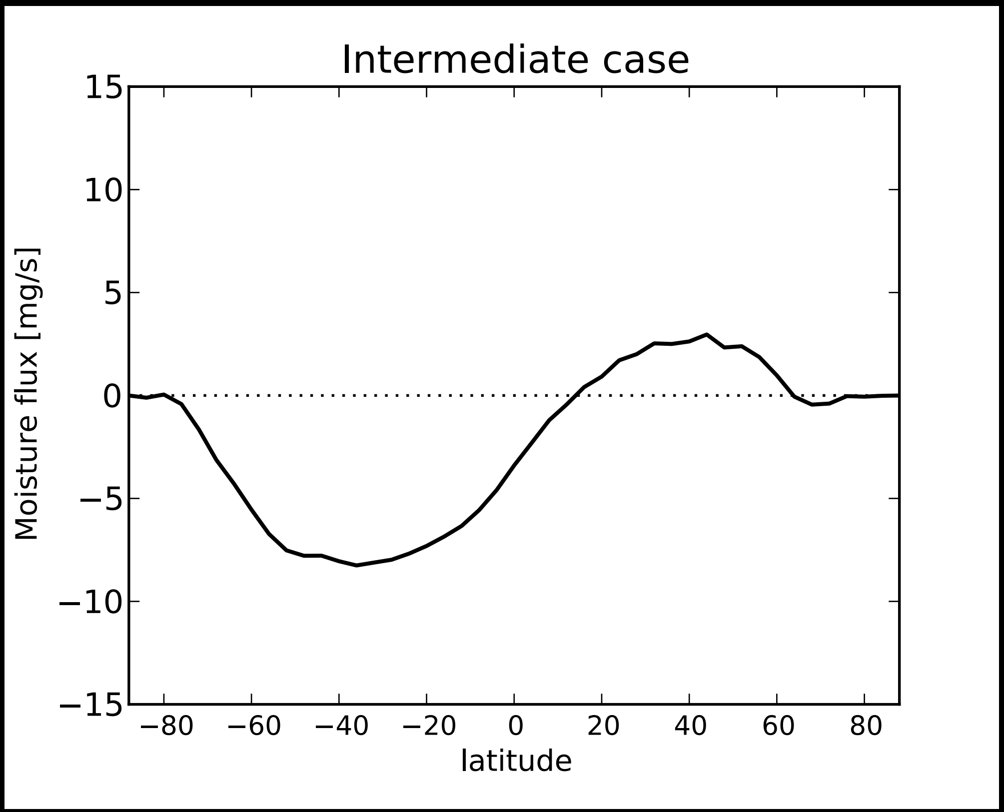
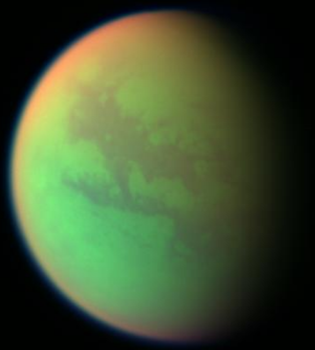


Climate implications of the oscillating Hadley cell





Mitchell ’08 (*JGR-Planets)*



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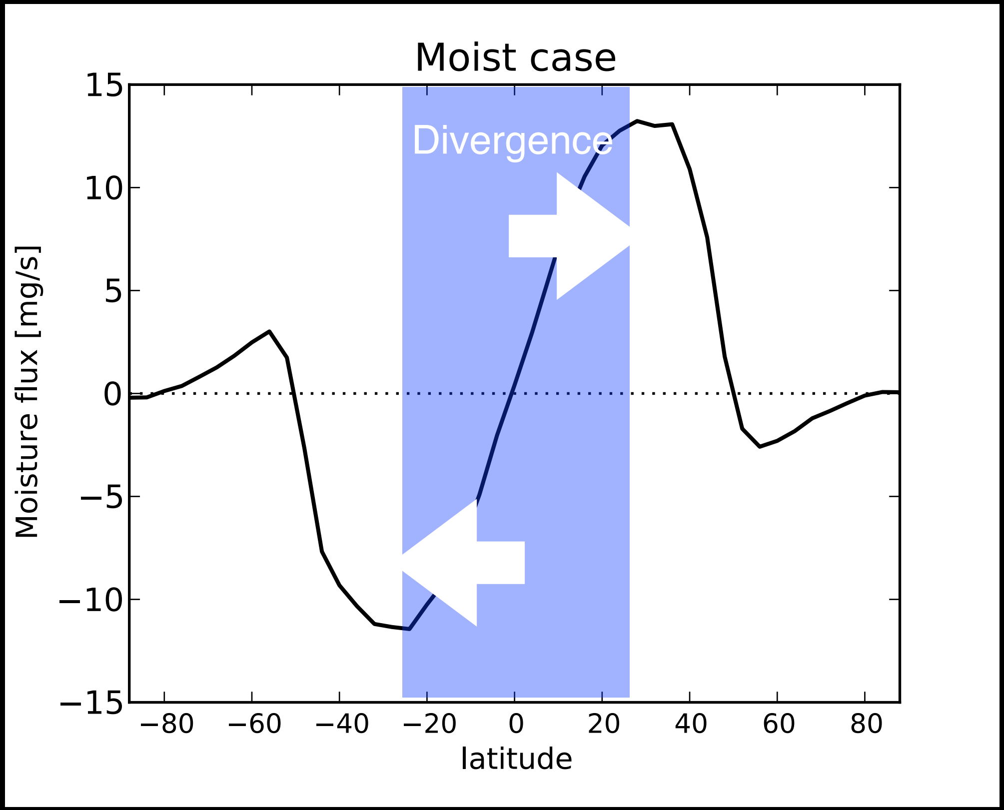
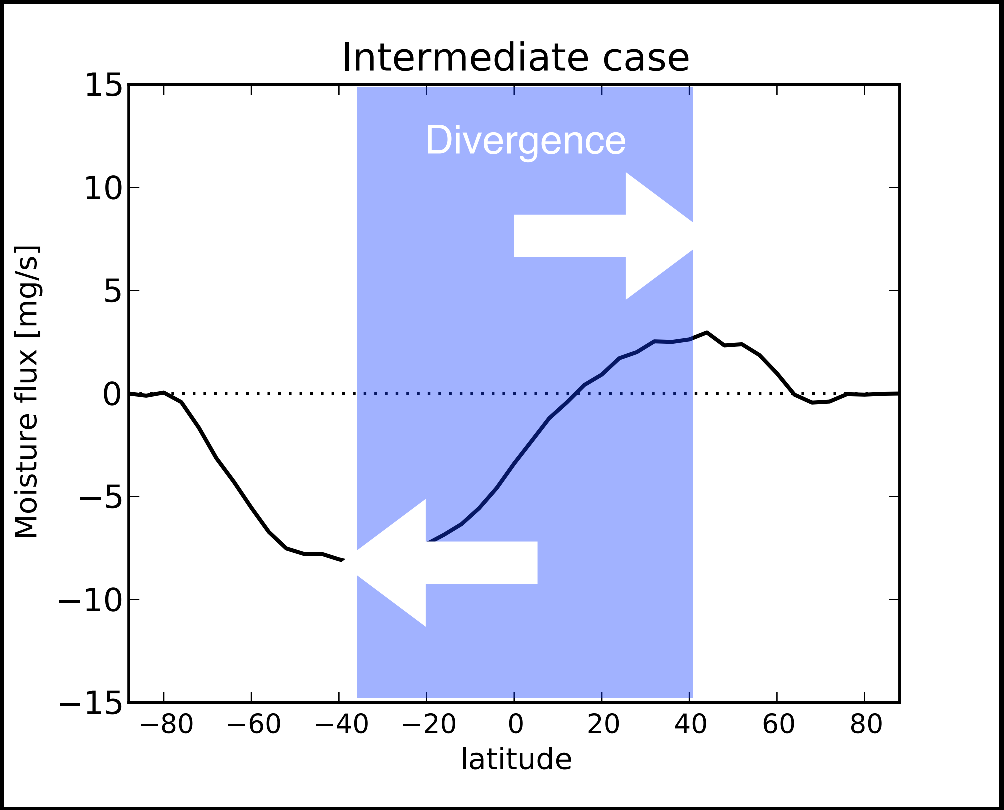
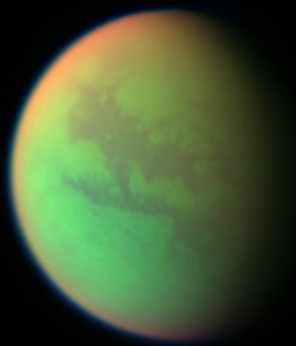




Moisture fluxed away from low-latitudes

Mitchell ’08 (*JGR-Planets)*



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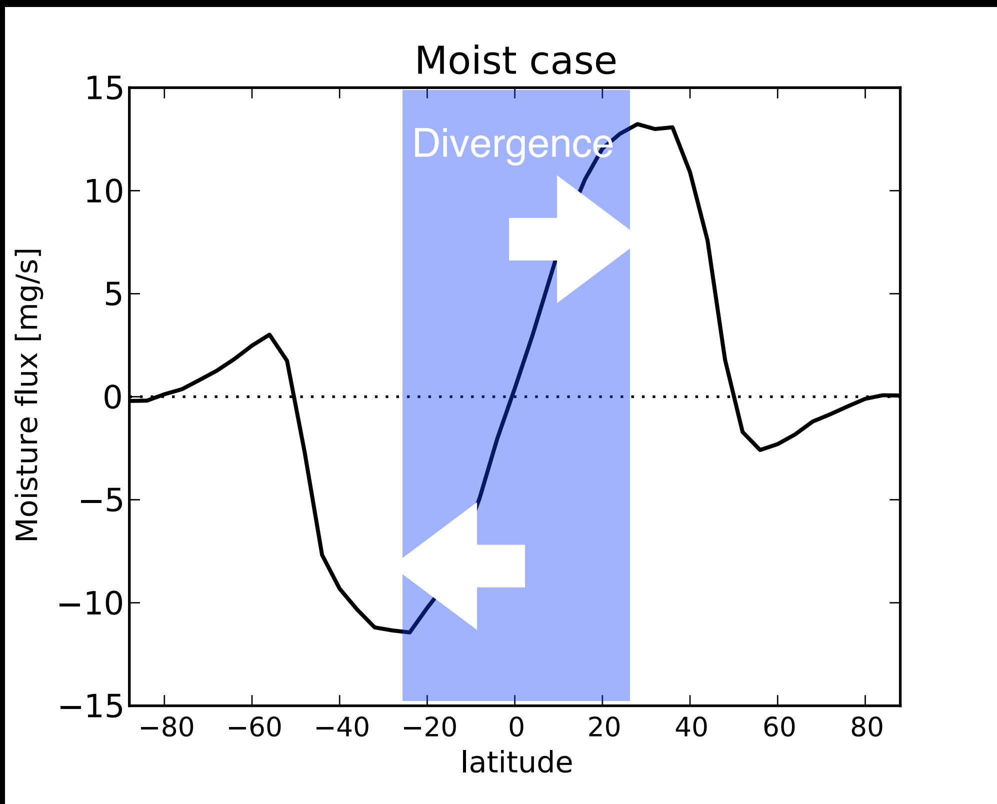
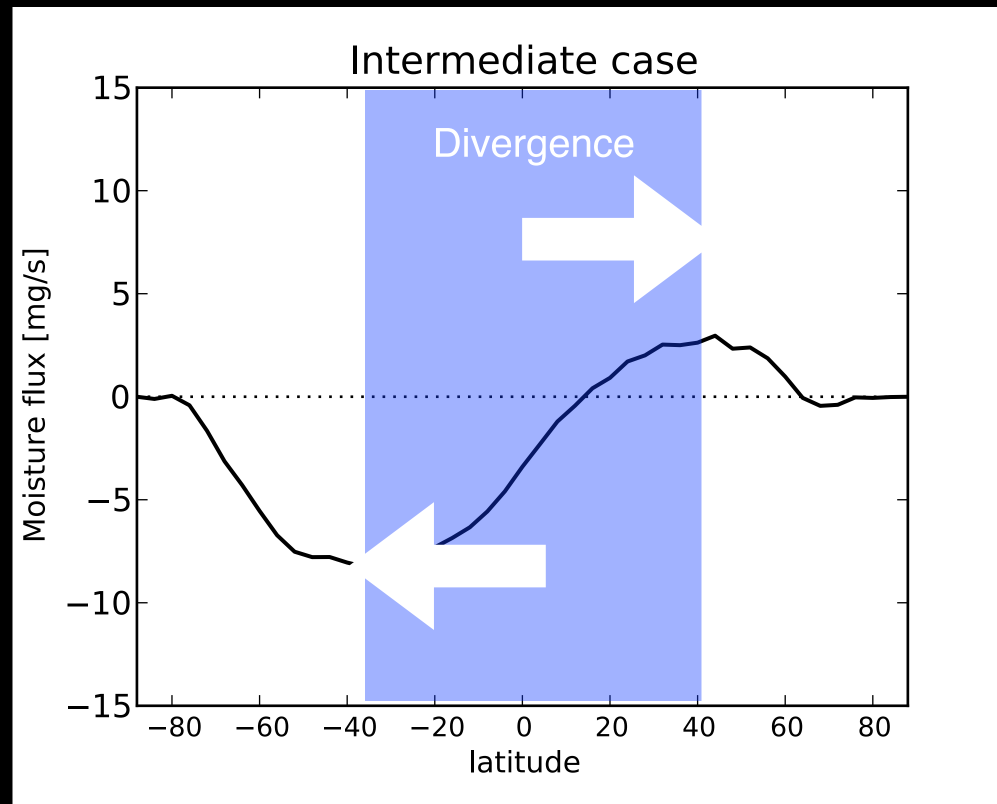


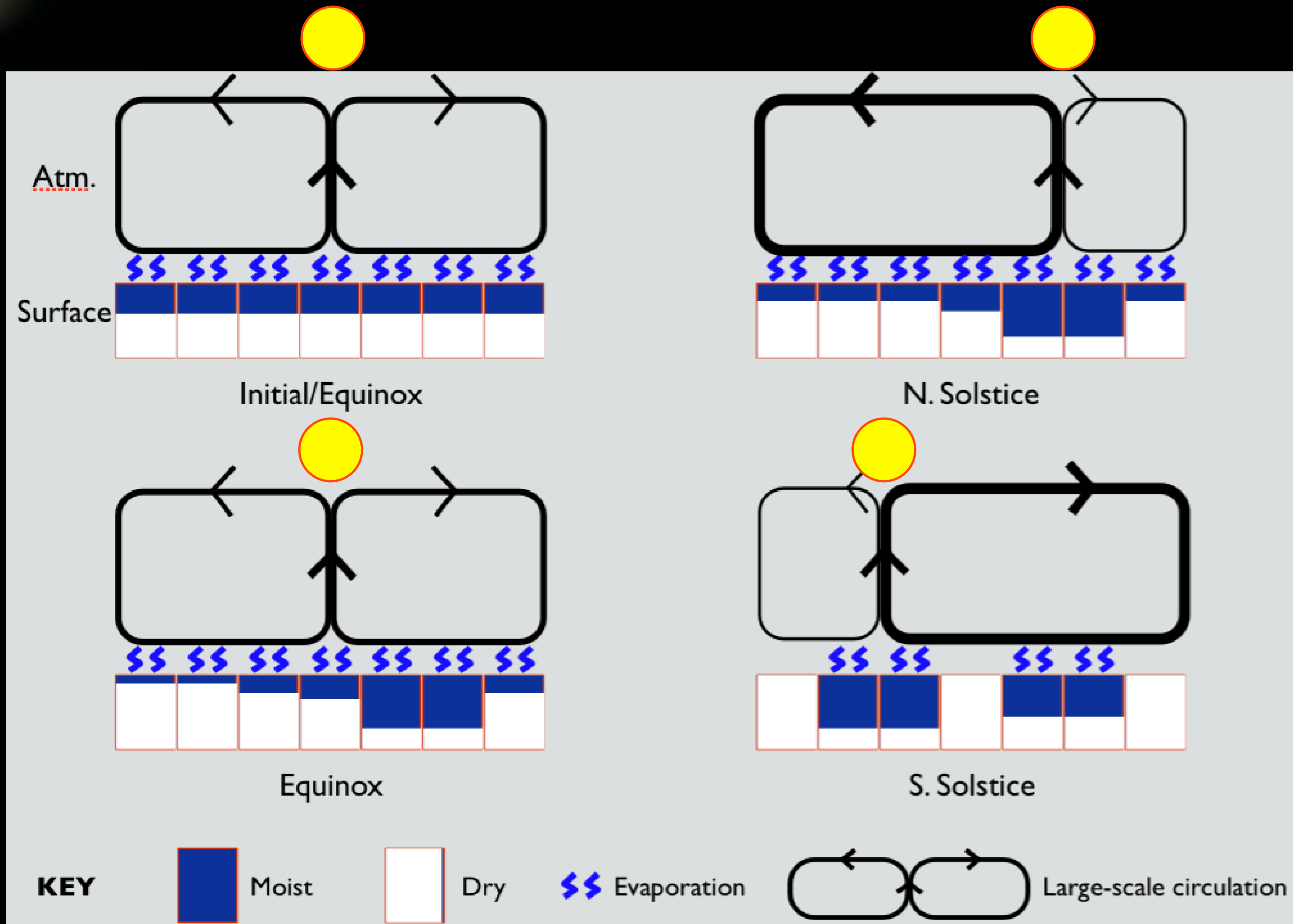


Moisture fluxed away from low-latitudes

Hydrology is needed

Mitchell ’08 (*JGR-Planets)*

Terraplanet experiment design



Mitchell '08 (*JGR-Planets)*

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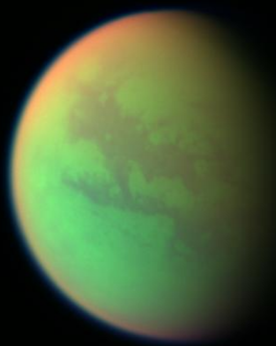
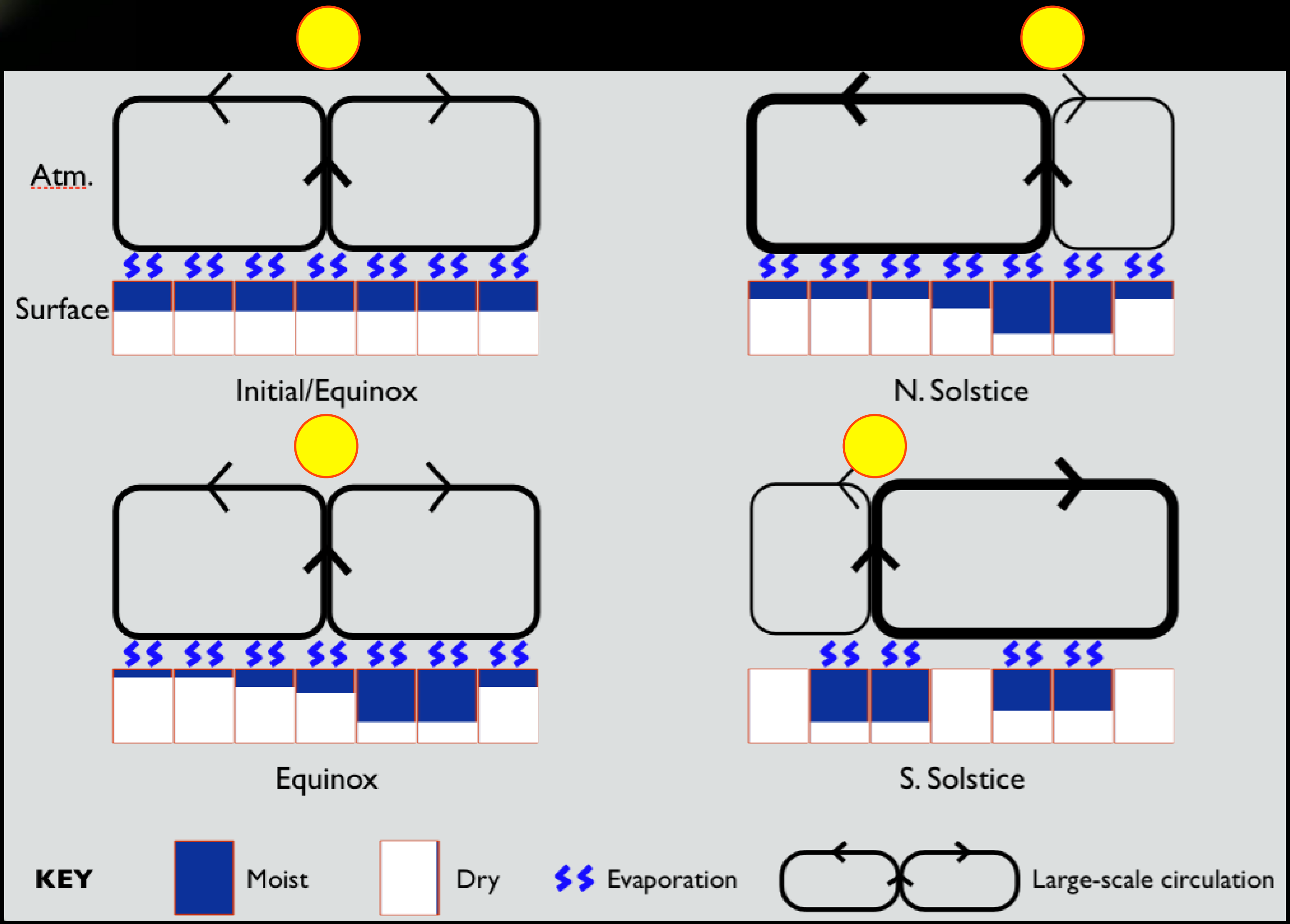
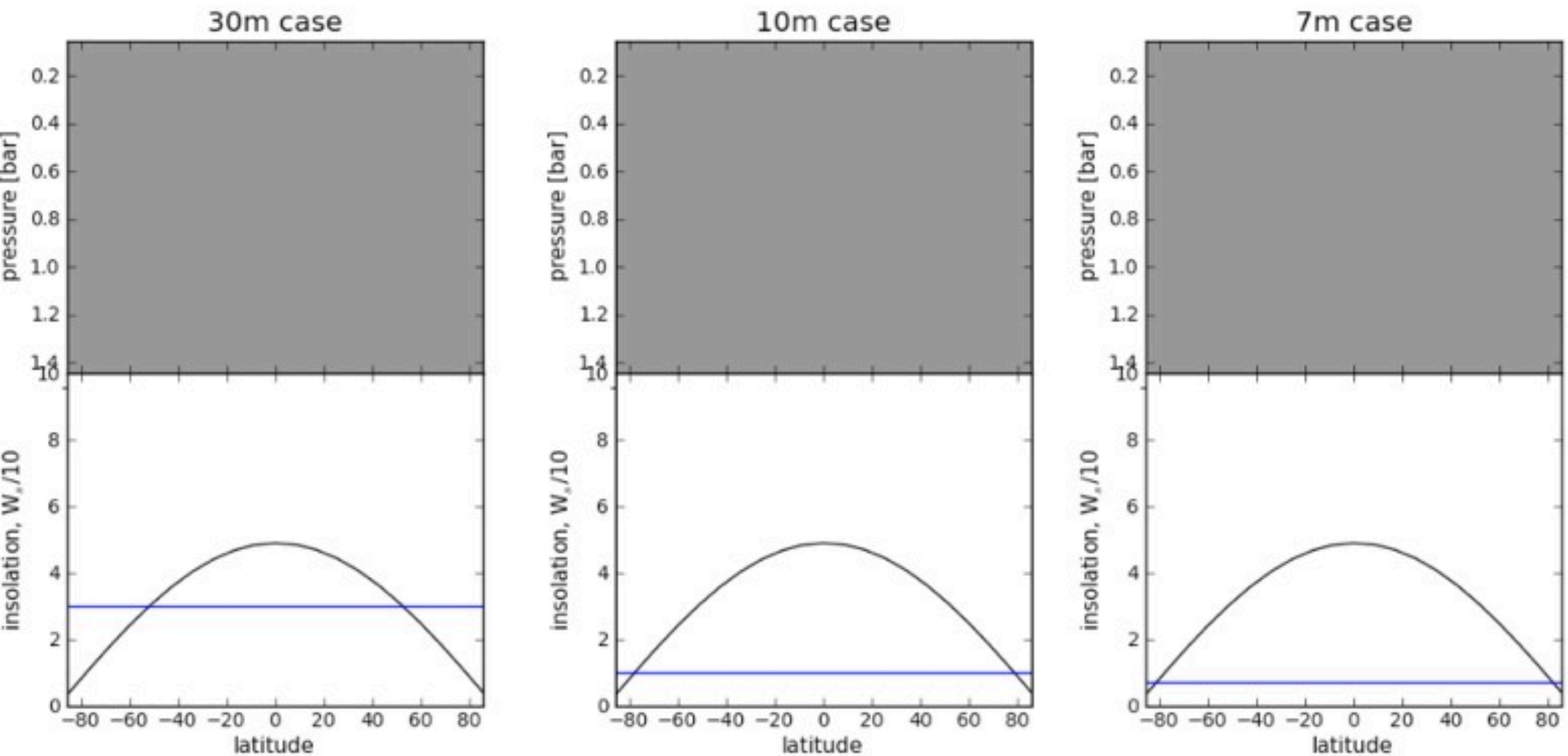




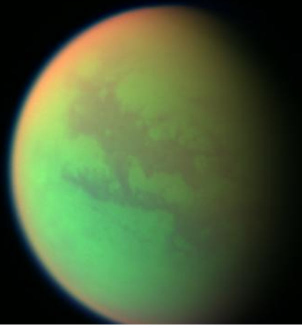
Approach: Vary the initial methane inventory

Mitchell '08 (*JGR-Planets*)

Variation of reservoir depth



Mitchell '08 (*JGR-Planets)*



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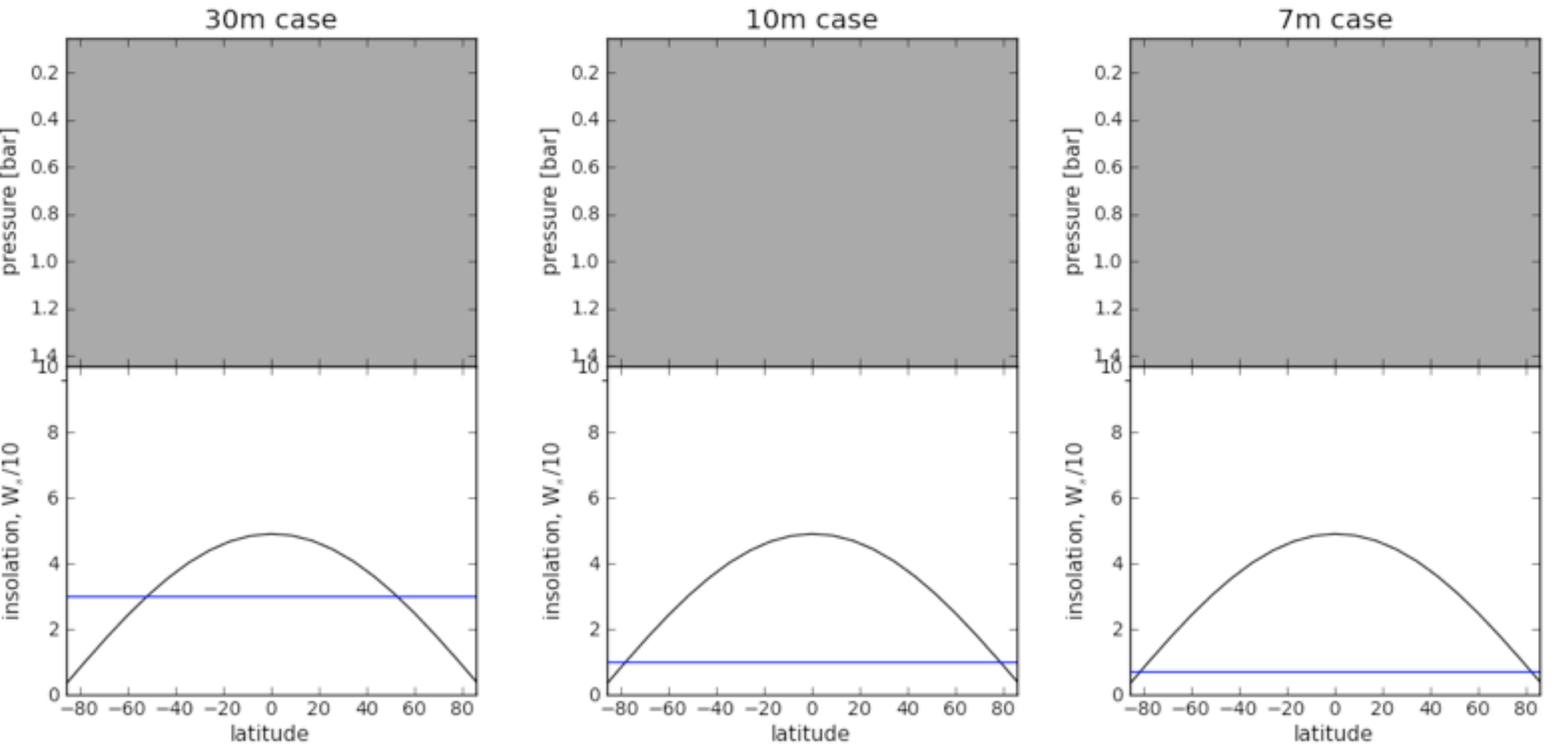

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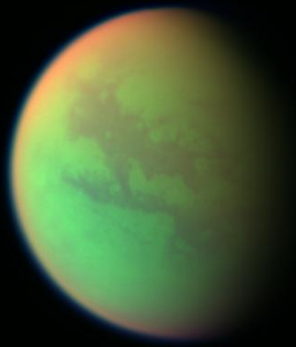
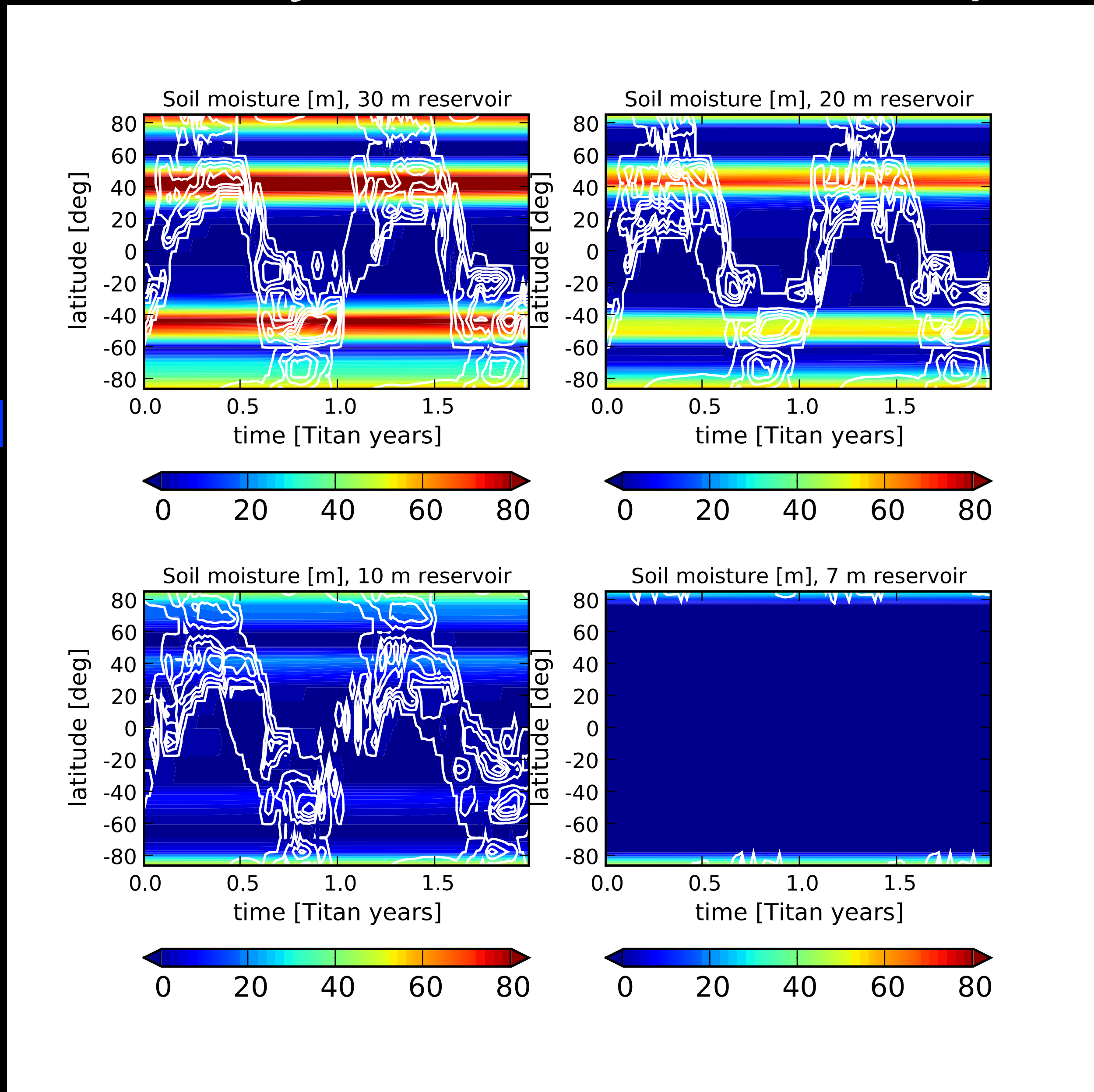


Terraplanet GCM simulations: sensitivity to initial reservoir depth

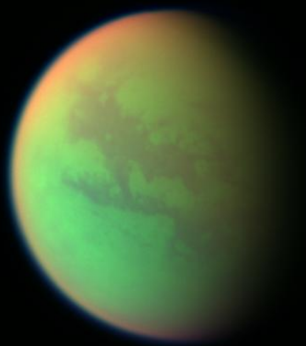


Final 2 years of 45 Titan years

Colors: Reservoir depth

Lines: Precipitation

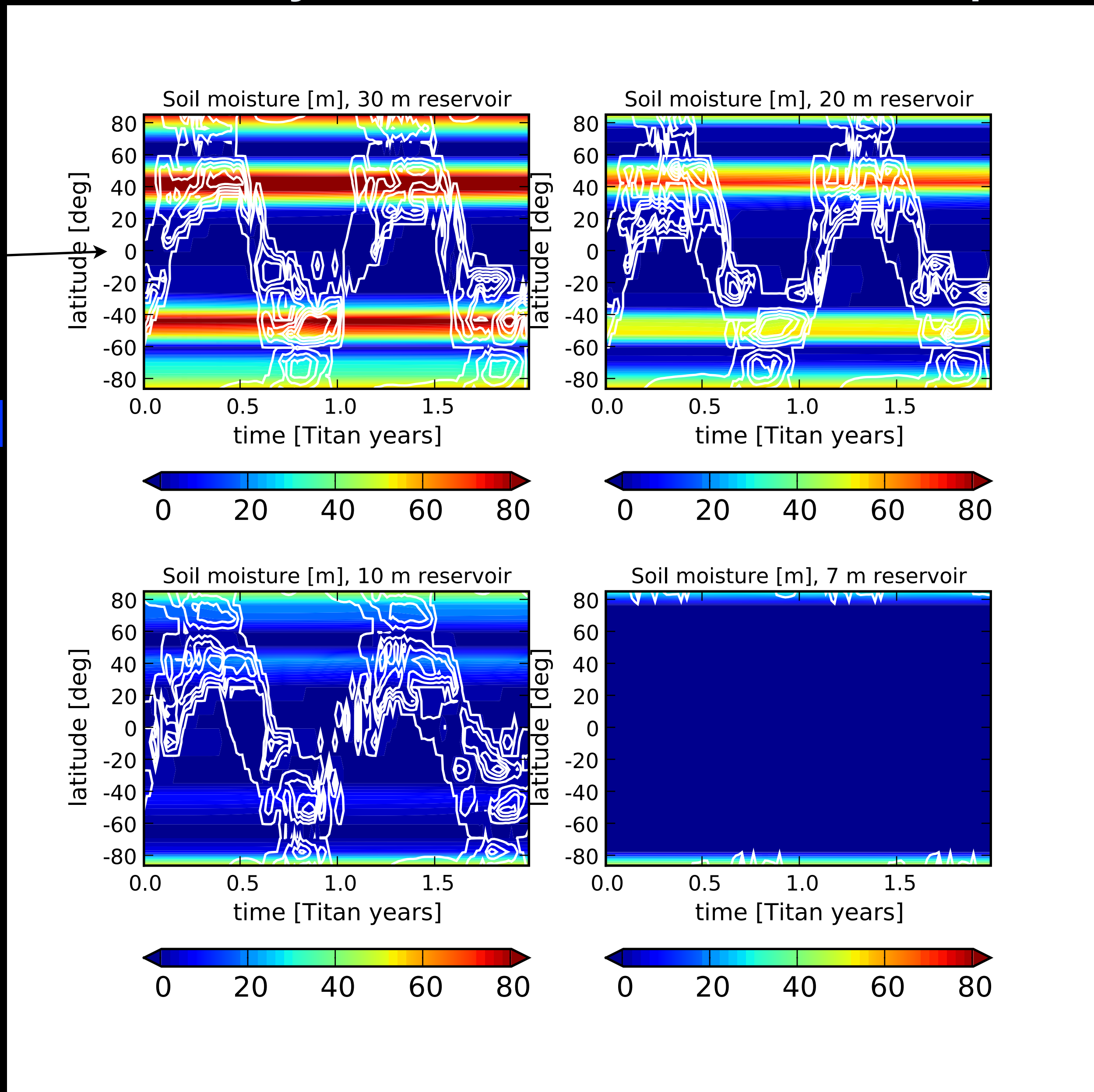
Mitchell ’08 (*JGR-Planets)*



Terraplanet GCM simulations: sensitivity to initial reservoir depth

Final 2 years of 45 Titan years

Climatologically dry



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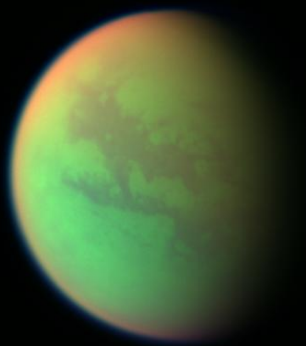
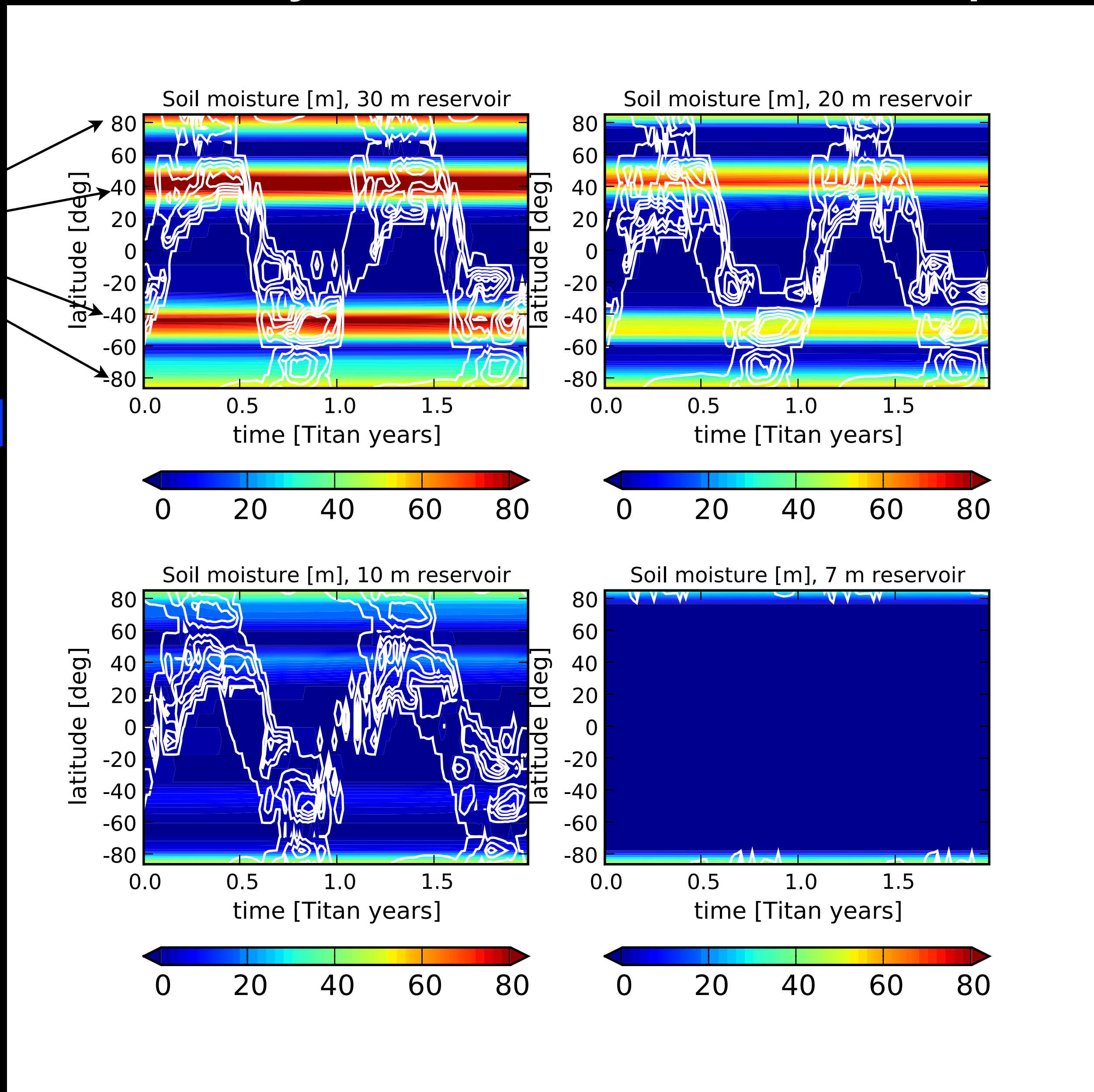


Terraplanet GCM simulations: sensitivity to initial reservoir depth

Final 2 years of 45 Titan years

Accumulation zones



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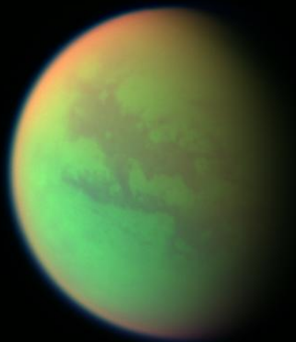

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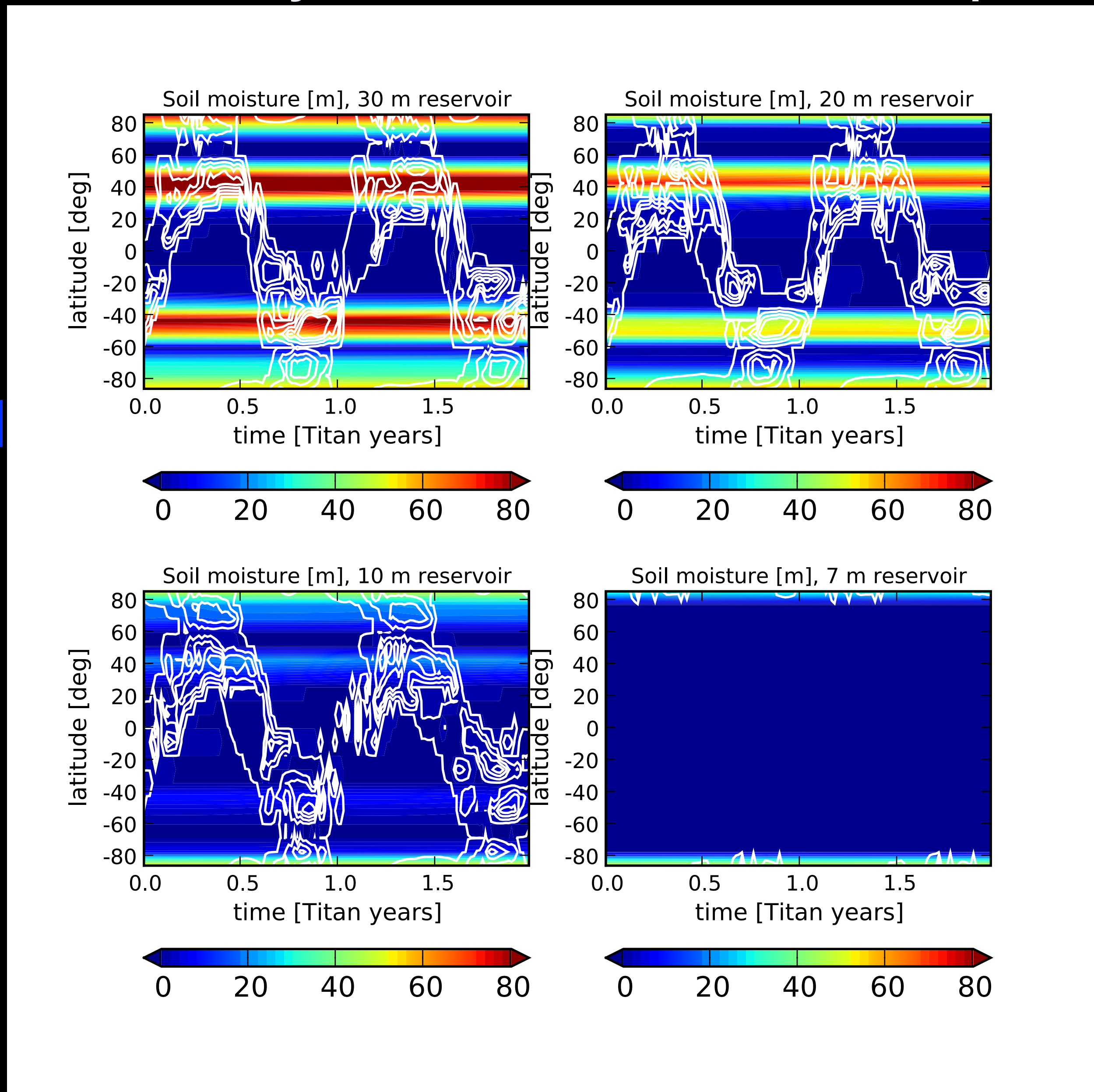

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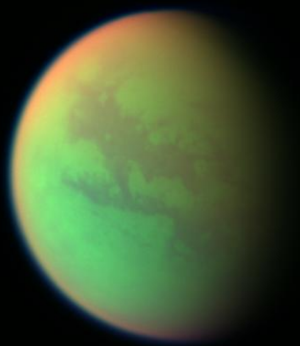

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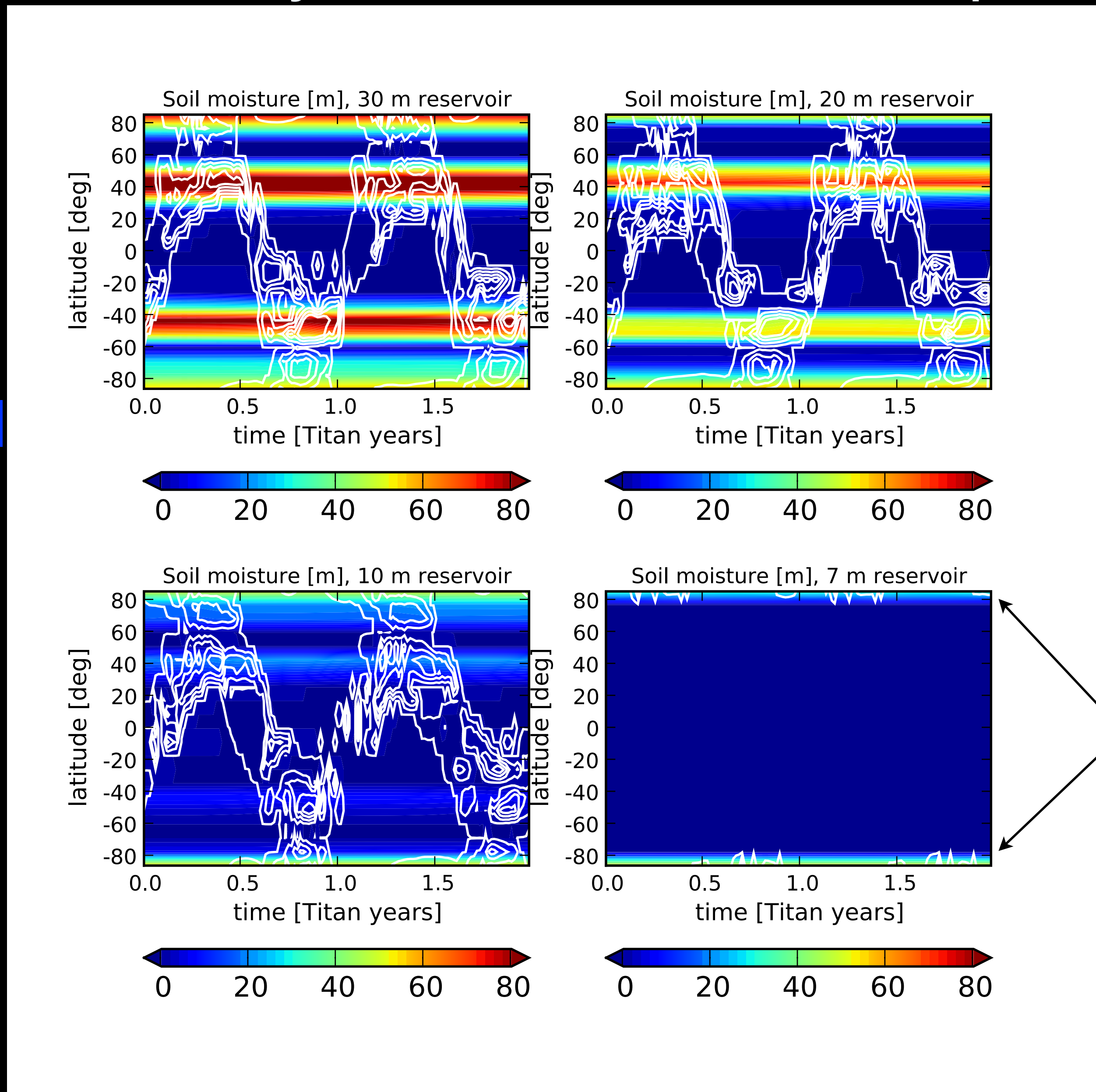

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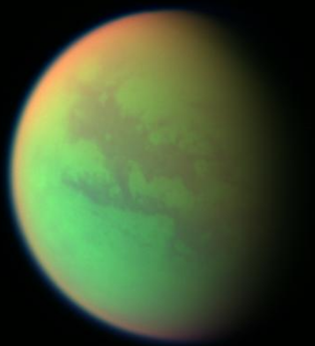
Only polar accumulation

Mitchell '08 (*JGR-Planets)*



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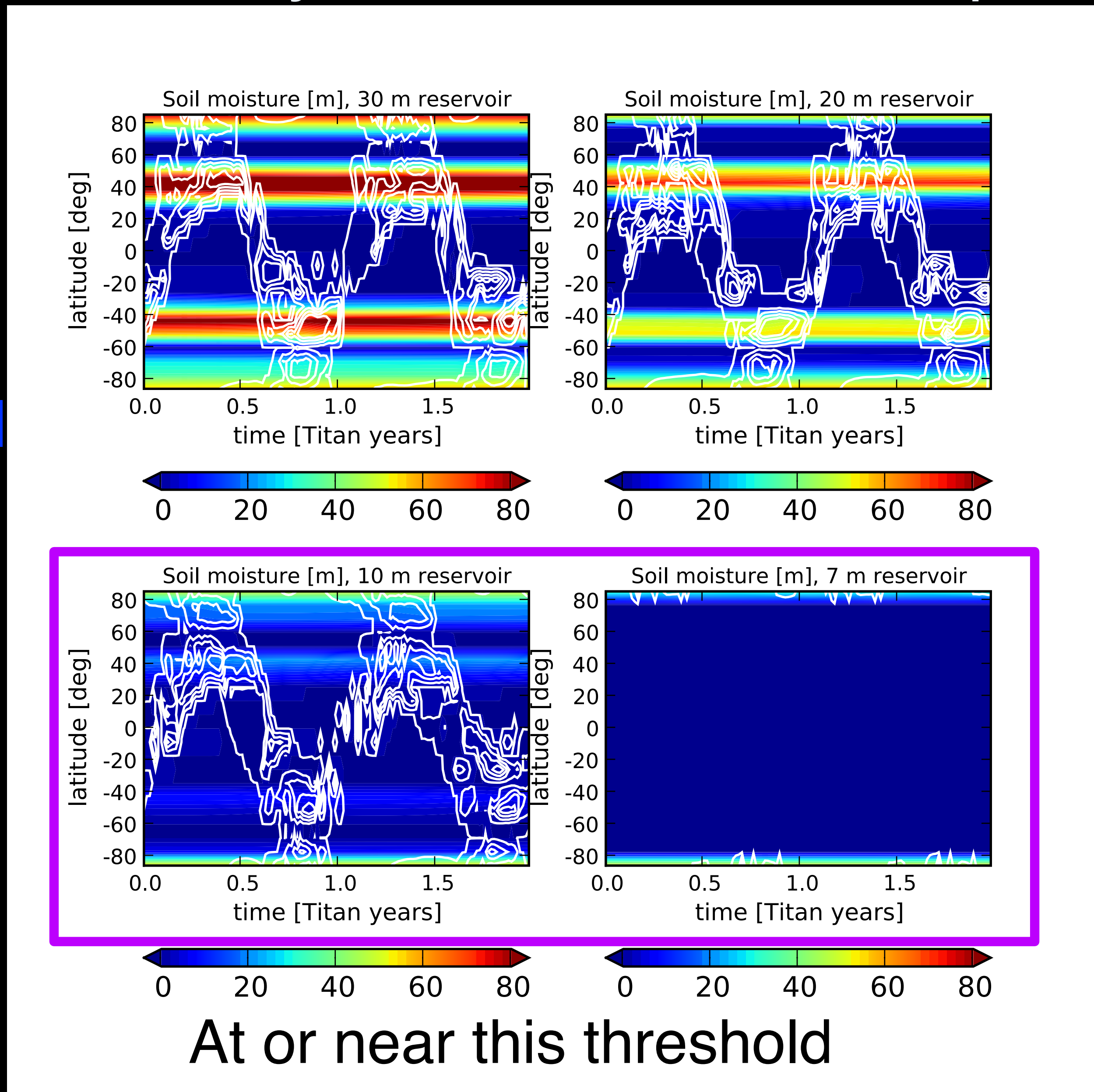

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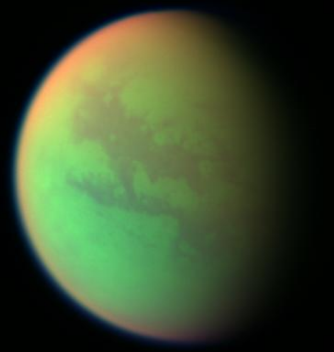


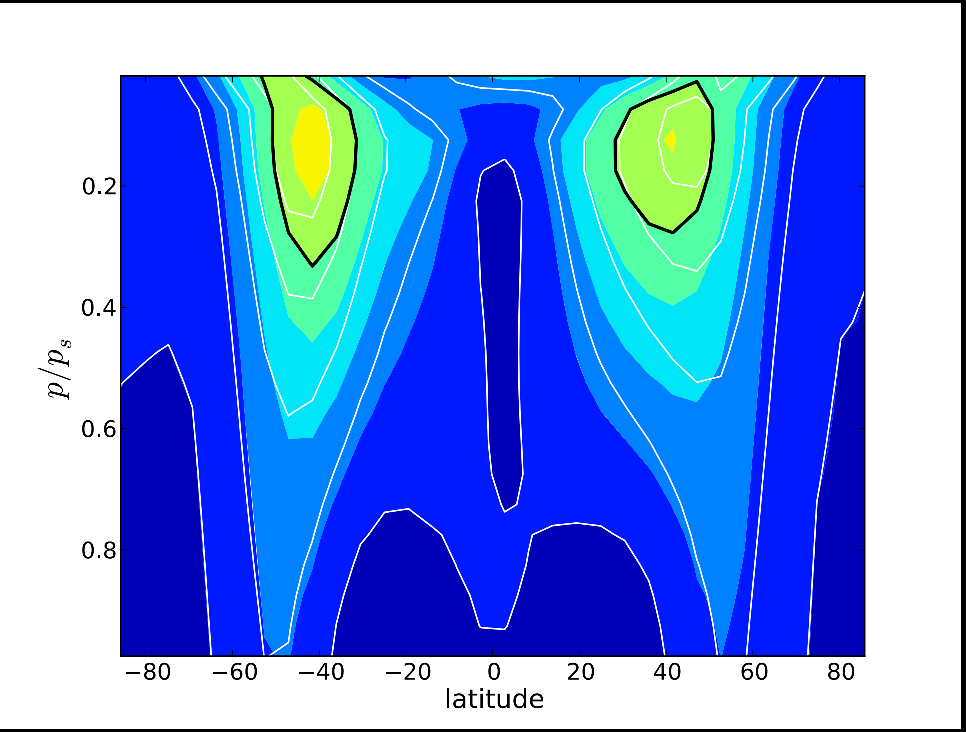
Summary

- Thermodynamic-dynamic coupling controls the positions and seasonality of methane clouds.
- The oscillating Hadley cell produces climatologically dry conditions near the equator and accumulation zones at the poles, as observed.

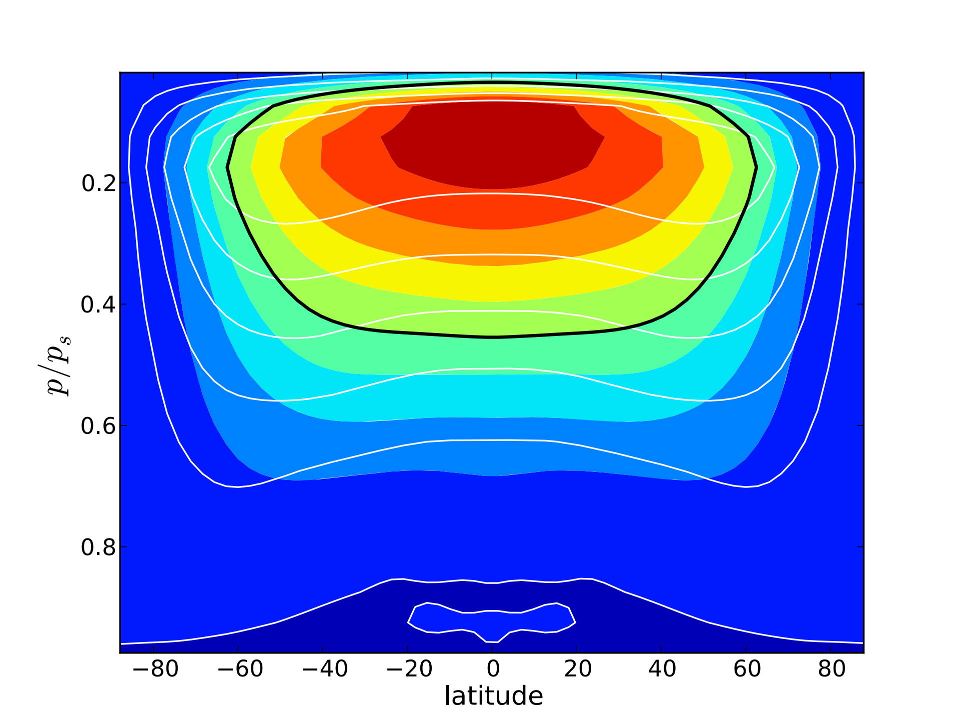
Mitchell et al. ’06 (*PNAS*)
Mitchell ’08 (*JGR-Planets)*
Mitchell et al. ’09 (*Icarus*)

Part II:
The transition to superrotation

Earth-like



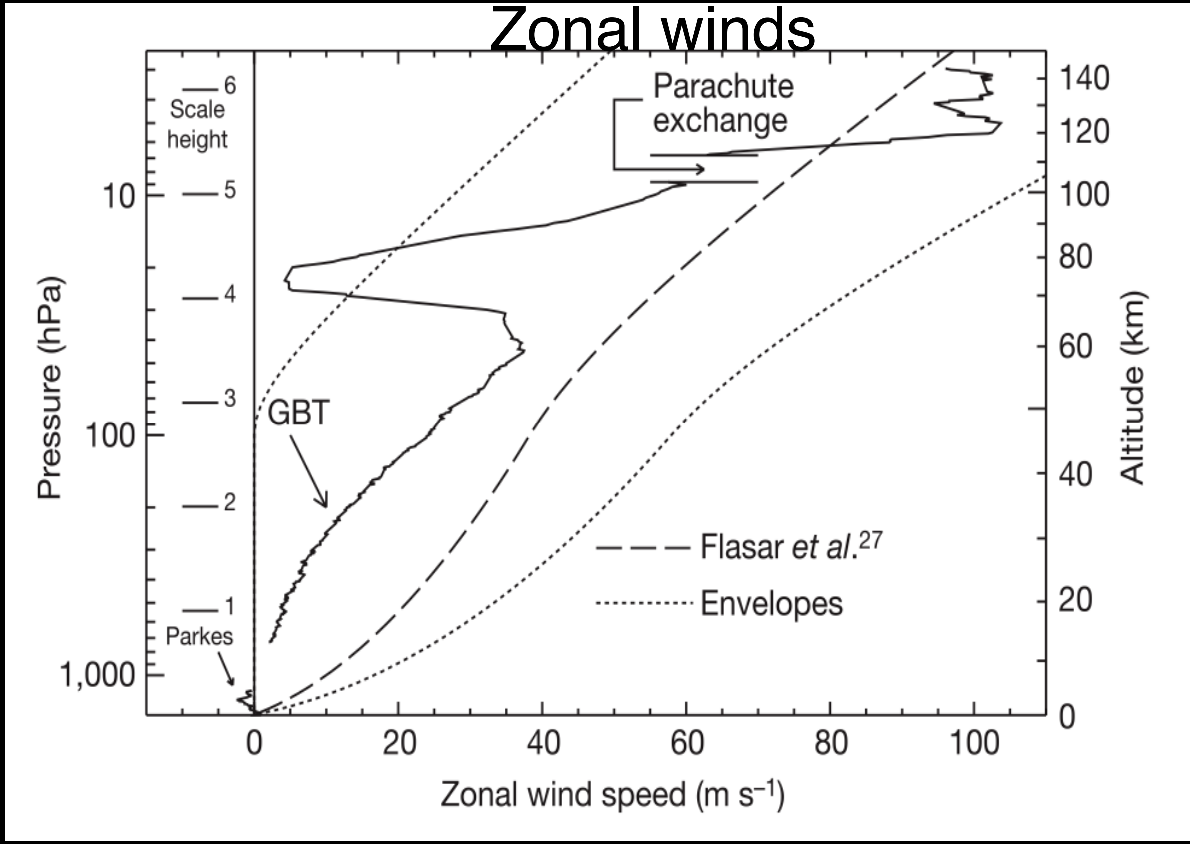
Titan-like



Jonathan Mitchell
AOS/ESS/IGPP
UCLA

Geoff Vallis
Princeton/GFDL

Evidence for superrotation in Titan's atmosphere: Huygens winds at 10° S latitude



Bird et al. 05

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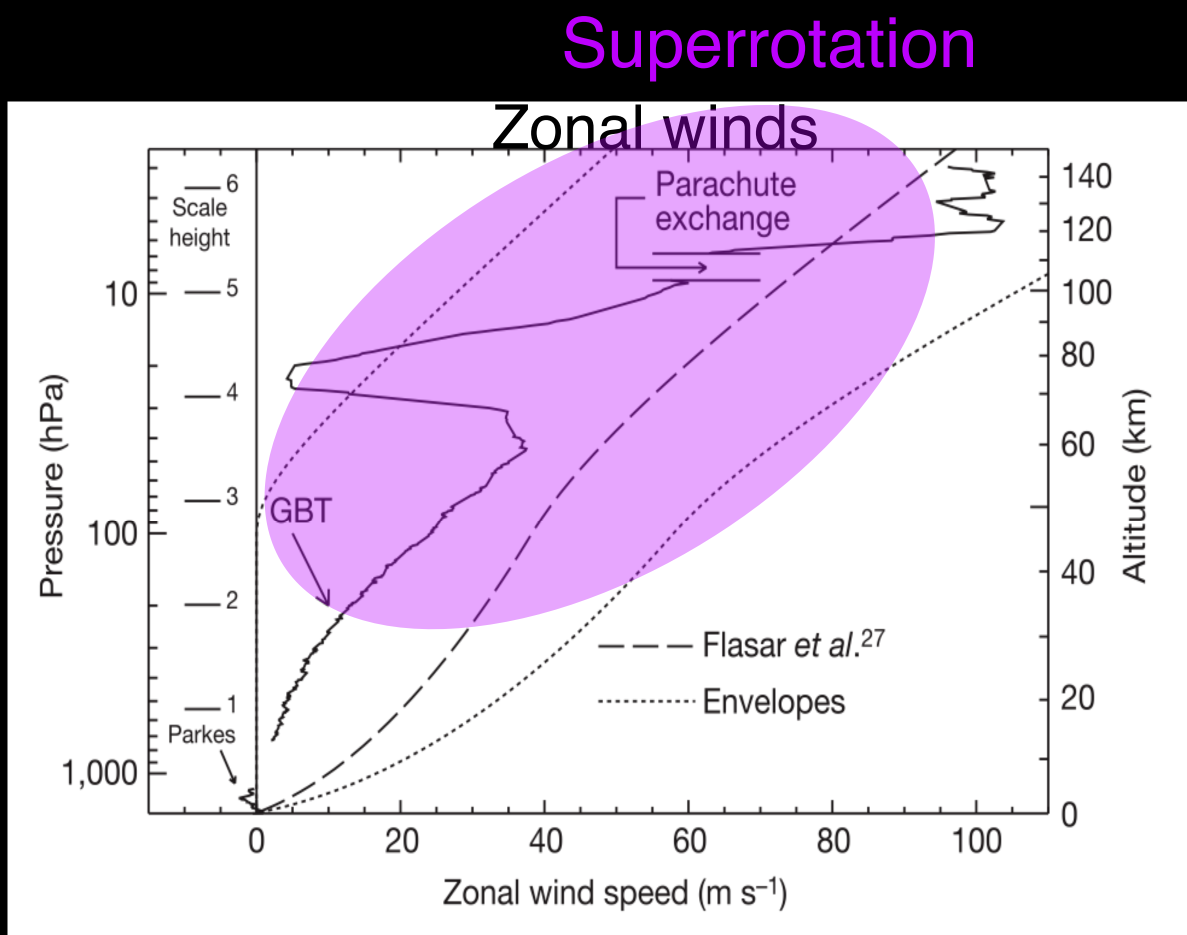
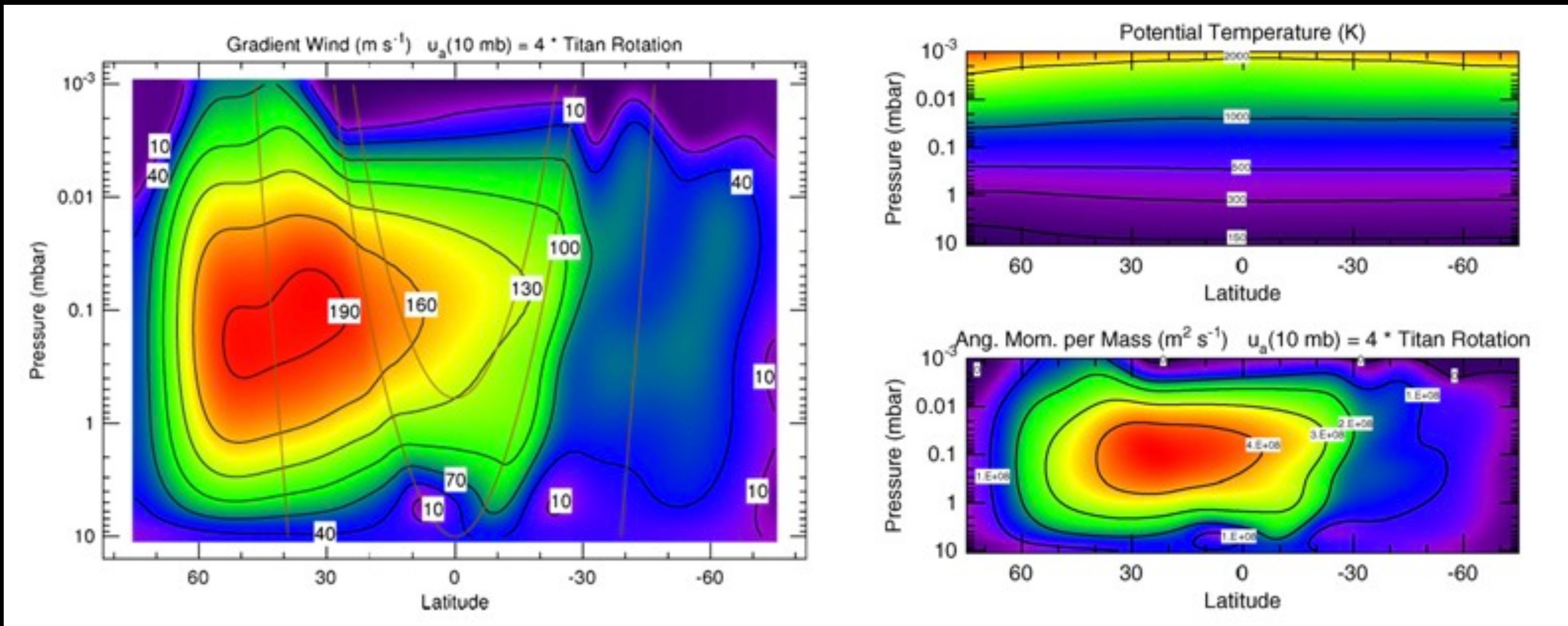


Bird et al. 05

Superrotation in Titan's upper atmosphere



Achterberg et al. 08

Superrotation mechanisms:
Non-axisymmetric forcing

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Superrotation mechanisms: Non-axisymmetric forcing

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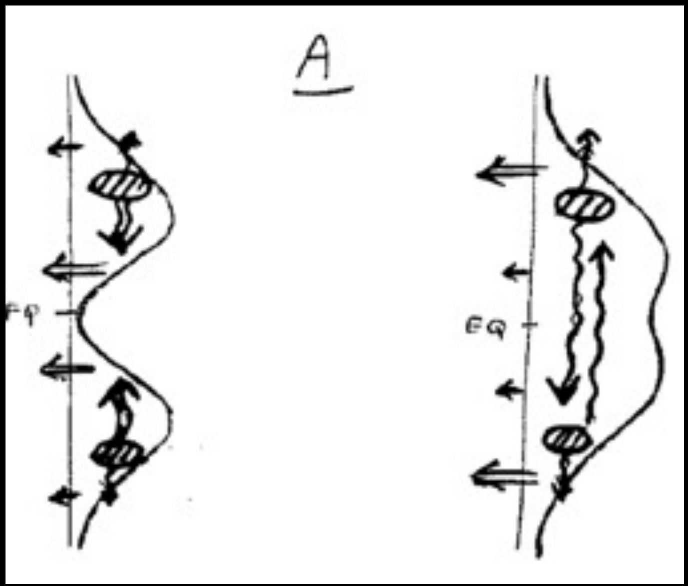
- Two-layer models of Earth bifurcate if driven by sufficiently non-axisymmetric heating
  - standard climatology -- superrotating climatology
- Equatorial region becomes "transparent" to transient eddies



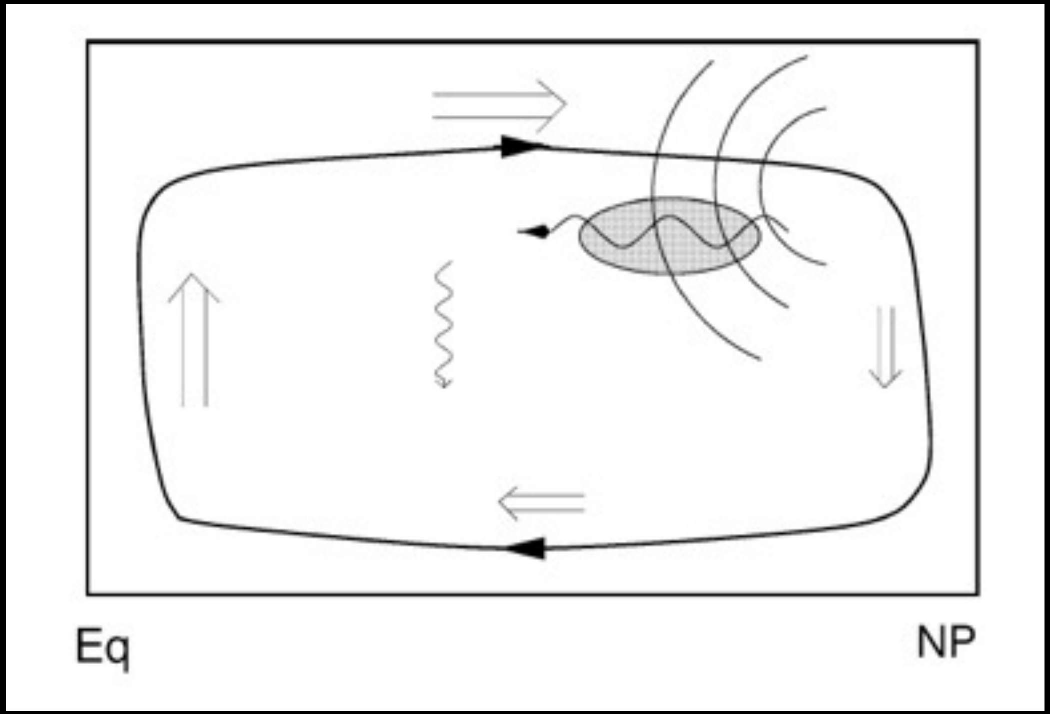
Held '00

Superrotation mechanisms:
Axisymmetric forcing

c.f. Lebonnois talk

Superrotation mechanisms: Axisymmetric forcing

- High-latitude barotropic instability
  - Geirasch, Rossow, Williams (also Yamamoto & Takahashi, Hourdin, Luz)



Luz & Hourdin ’03

c.f. Lebonnois talk

Modeling Framework

Mitchell & Vallis ’10 (*submitted to JGR*)

Modeling Framework

- GFDL FMS spectral dynamical core
- Newtonian cooling to a stable state
- Rayleigh friction
- Advantage: Allows non-dimensionalization

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- **Approach**: Vary a single parameter over a large range

Mitchell & Vallis ’10 (*submitted to JGR*)

Experiment design

- Vary the thermal Rossby number

Mitchell & Vallis ’10 (*submitted to JGR*)

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$$Ro = \frac{R\Delta T}{(2\Omega a)^2}$$

R	gas constant
ΔT	temperature gradient
Ω	rotation rate
a	radius

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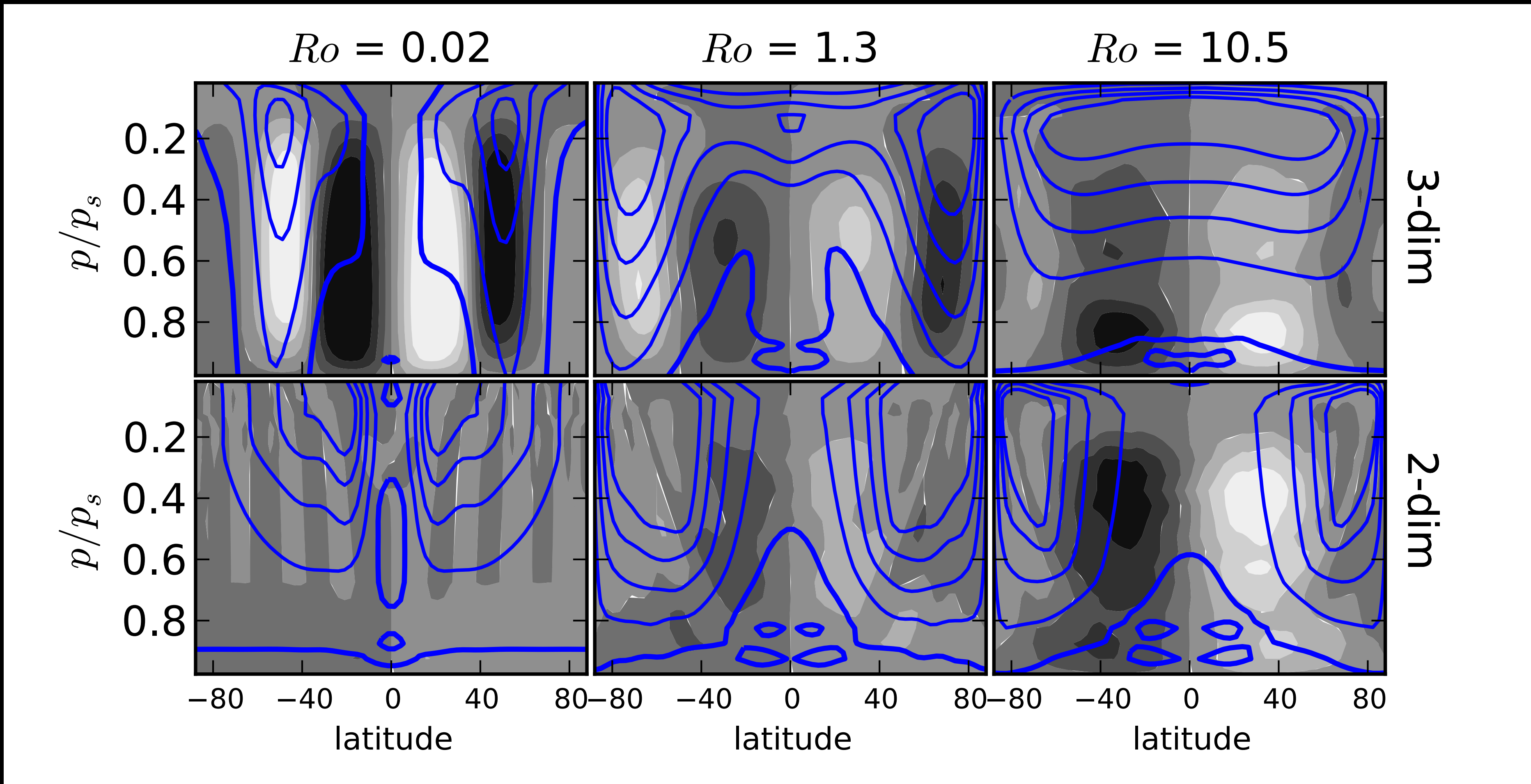
Transition to Superrotation?

Mitchell & Vallis '10 (*submitted to JGR*)

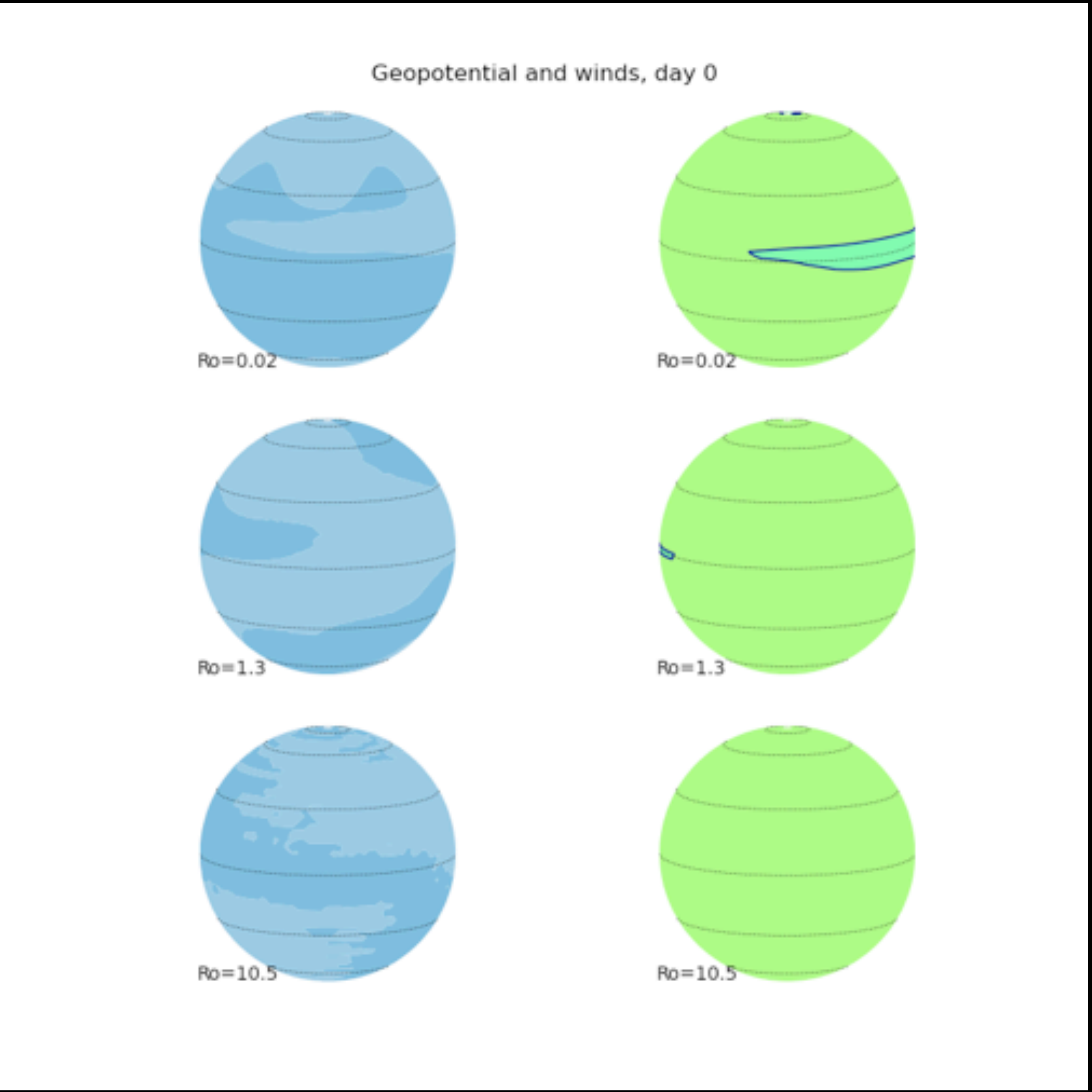
Results:
Hadley cell and zonal winds



Mitchell & Vallis ’10 (*submitted to JGR*)

Geopotential Anomaly
&
Zonal Winds

Mitchell & Vallis ’10 (*submitted to JGR*)



Earth

Intermediate

Titan

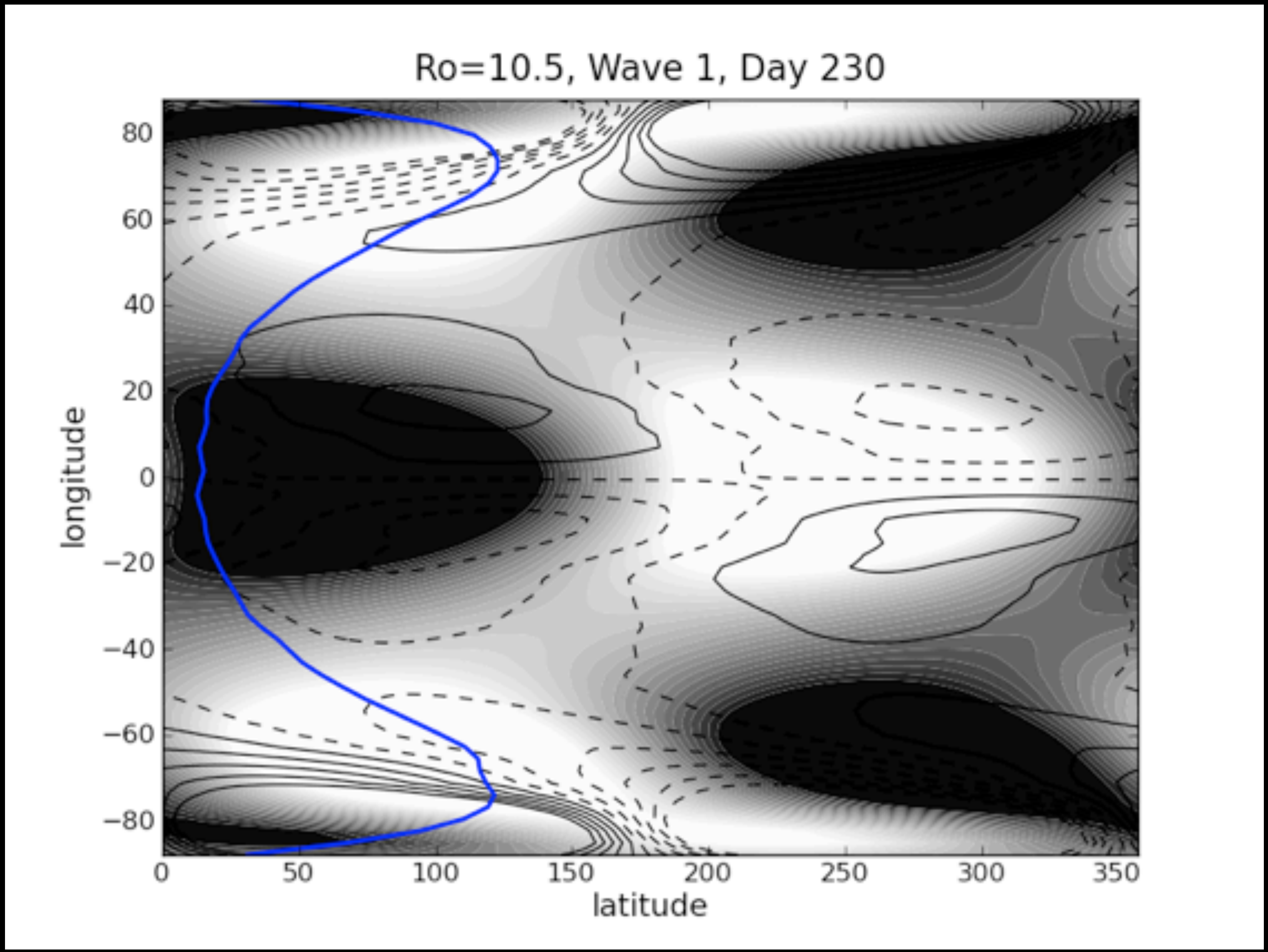
Mitchell & Vallis '10 (*submitted to JGR*)

Global wave structure: Field anomalies

Shaded:
Geopotential

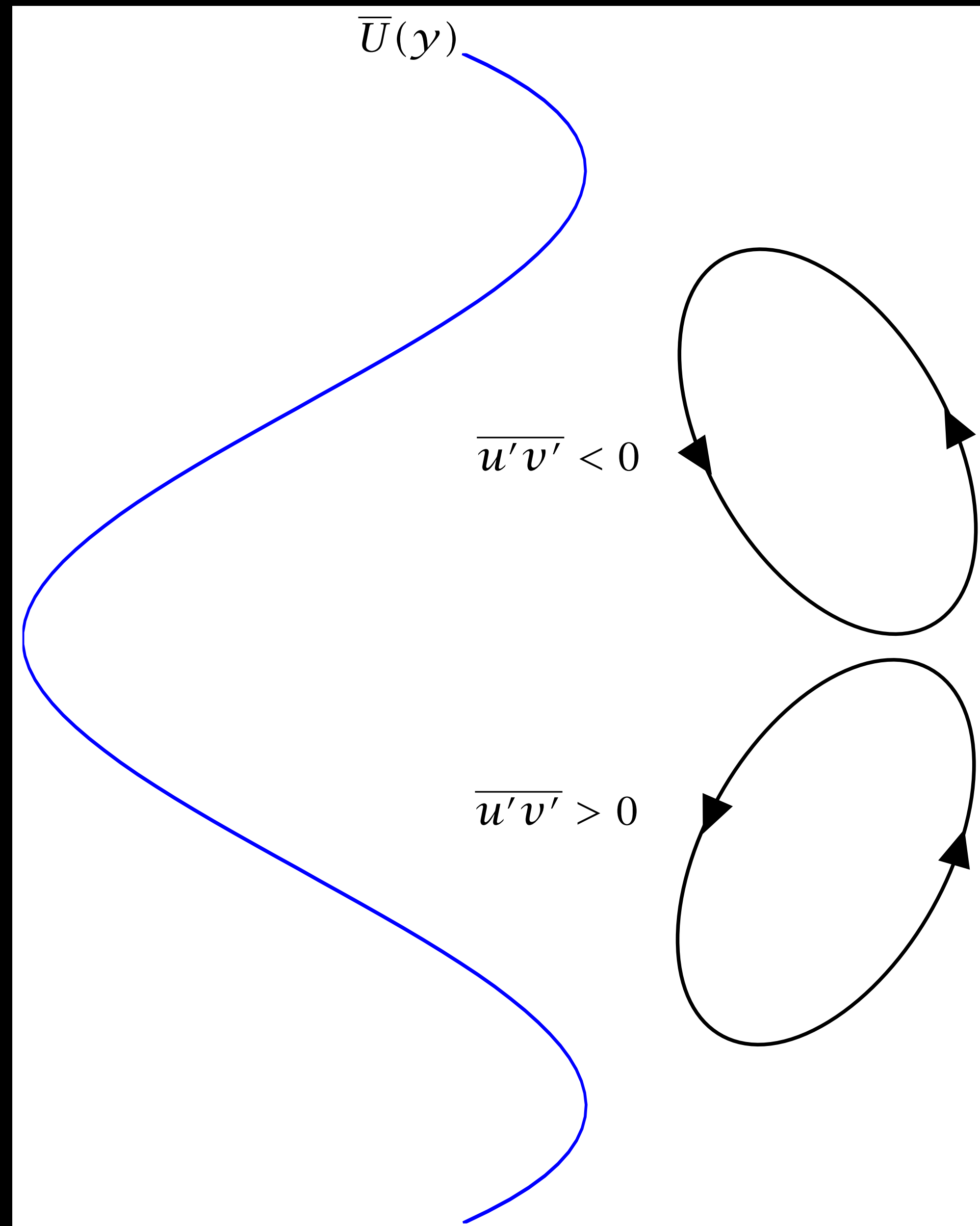
Contours:
Pot. Vorticity

Blue:
Zonal wind



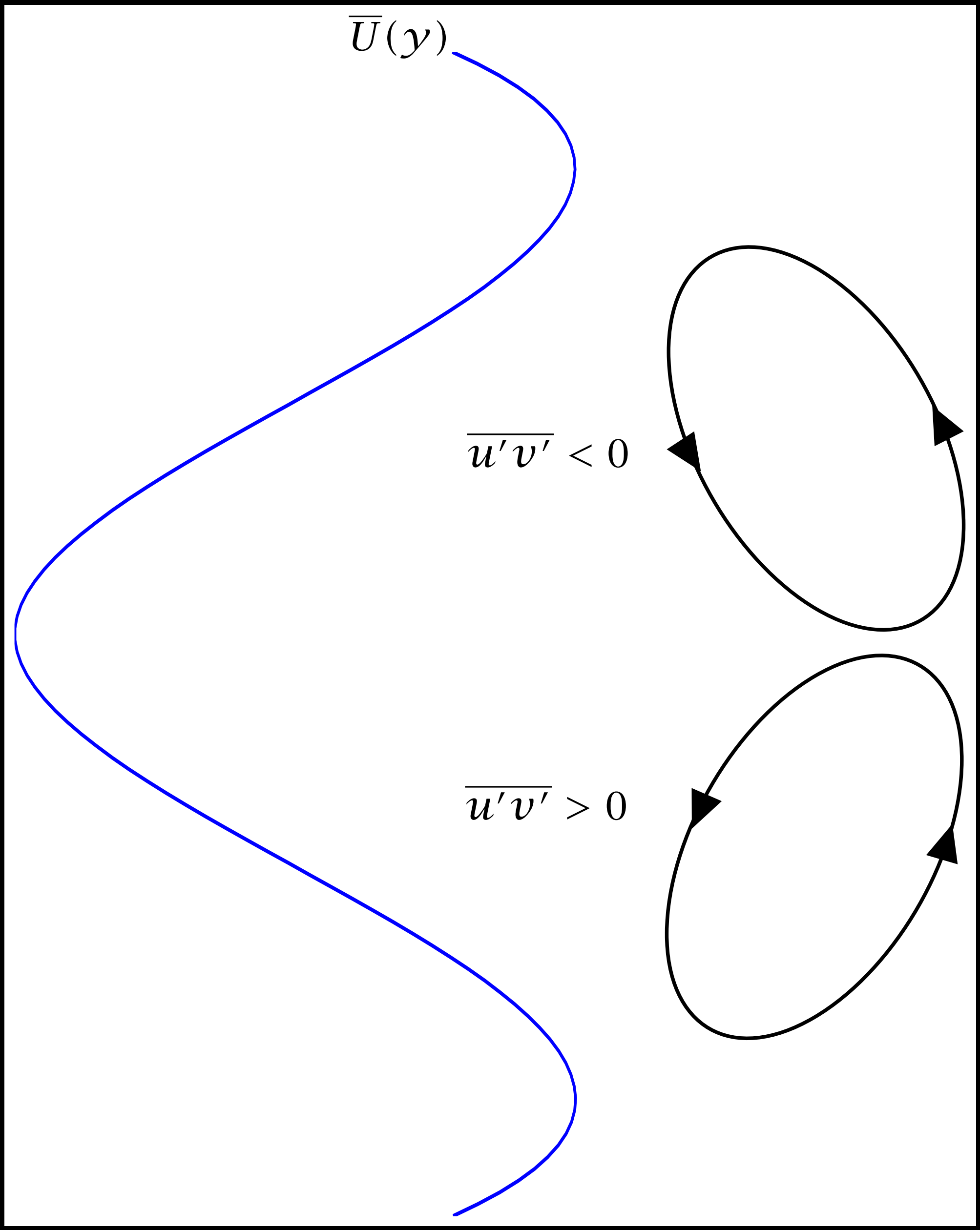
Mitchell & Vallis '10 (*submitted to JGR*)

Barotropic instability



Barotropic instability

- Interacting edge waves in mean shear



Barotropic instability

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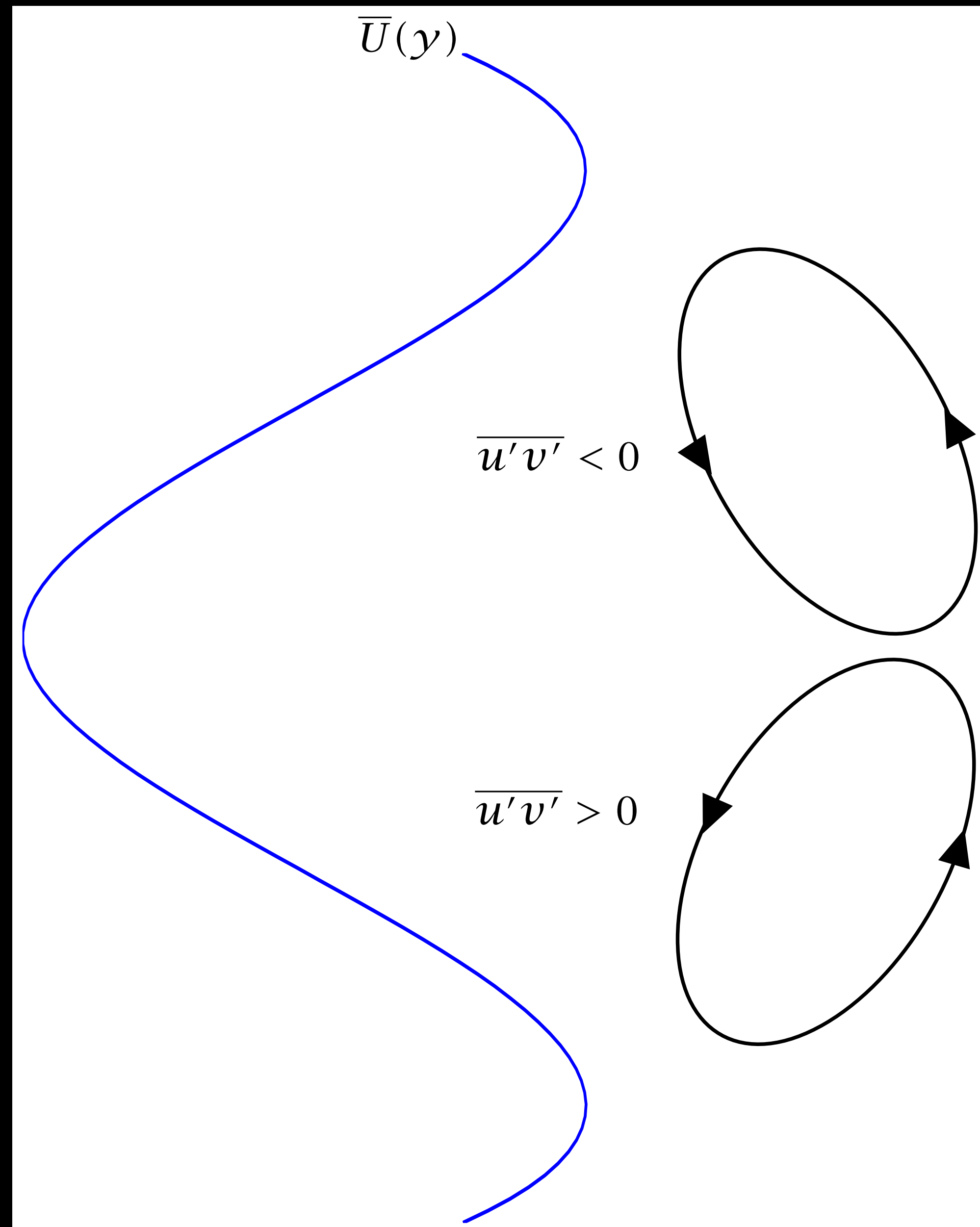

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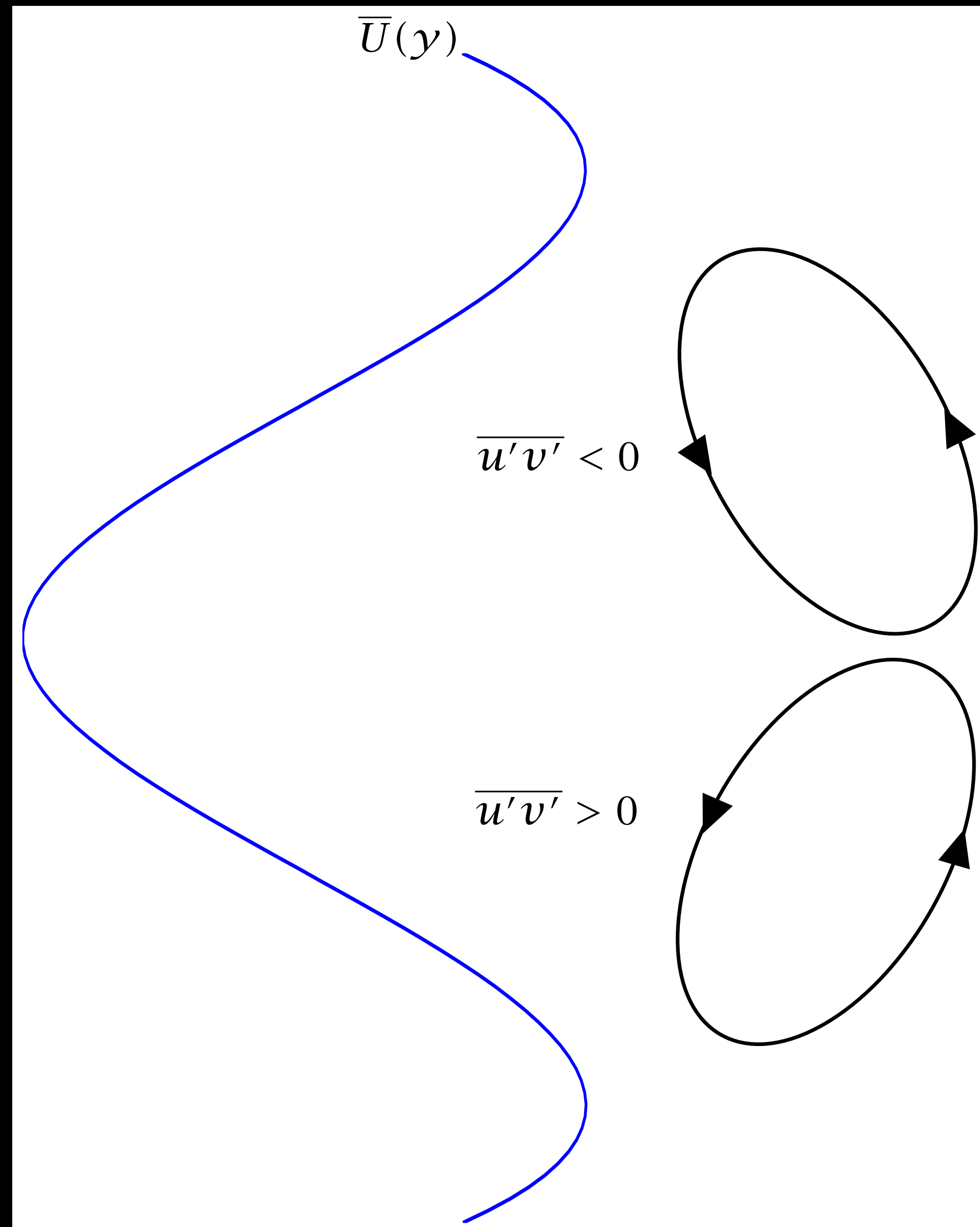

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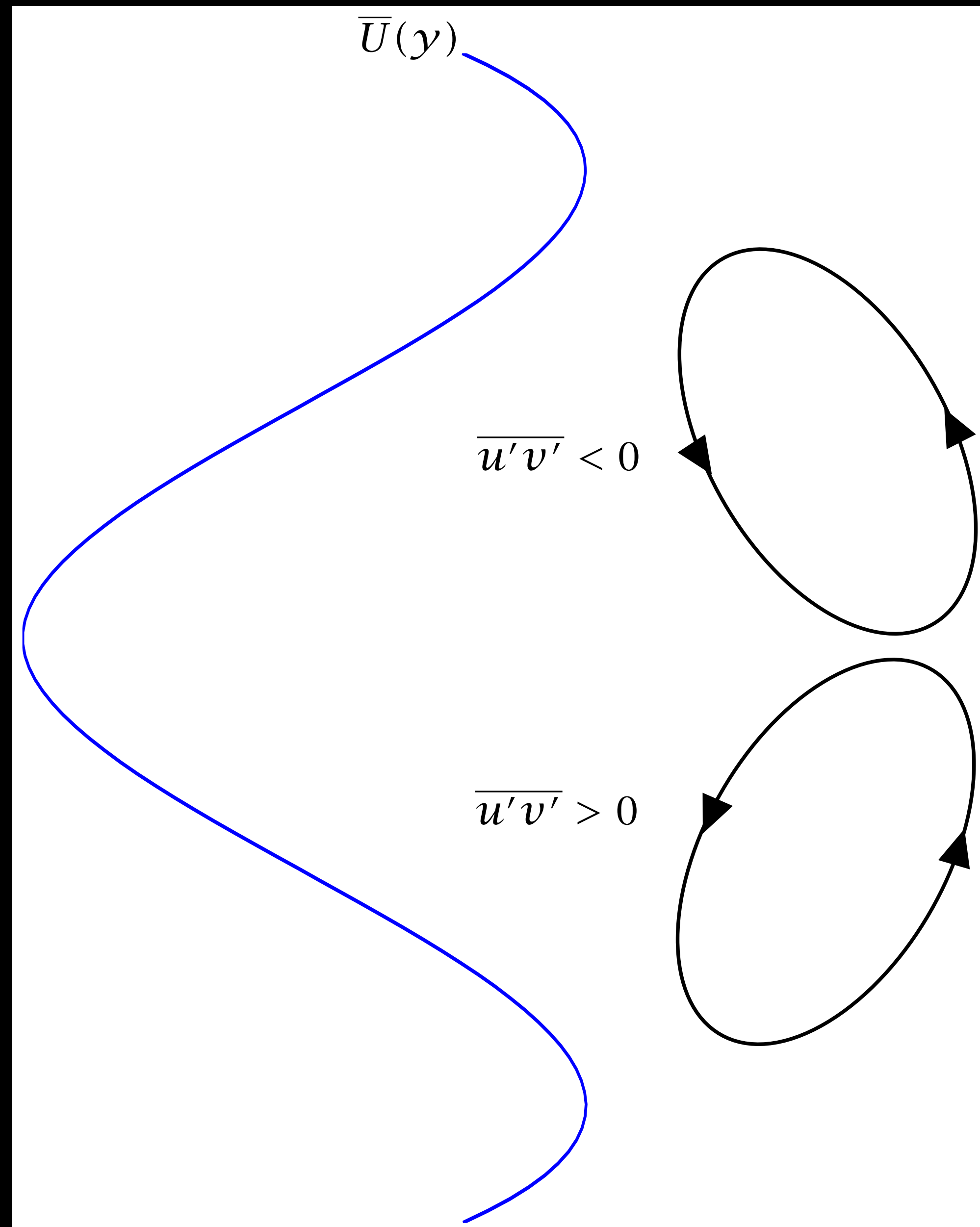

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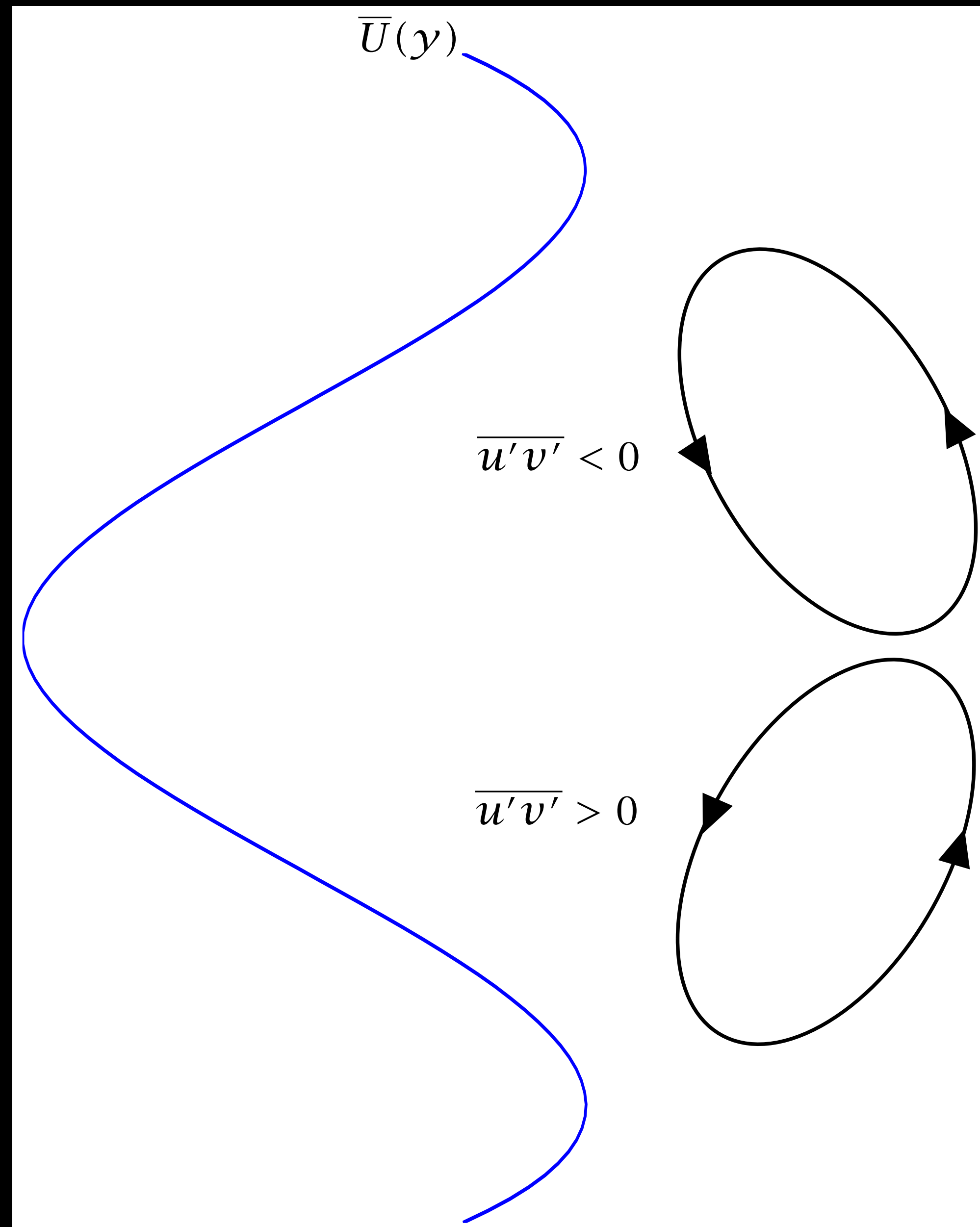
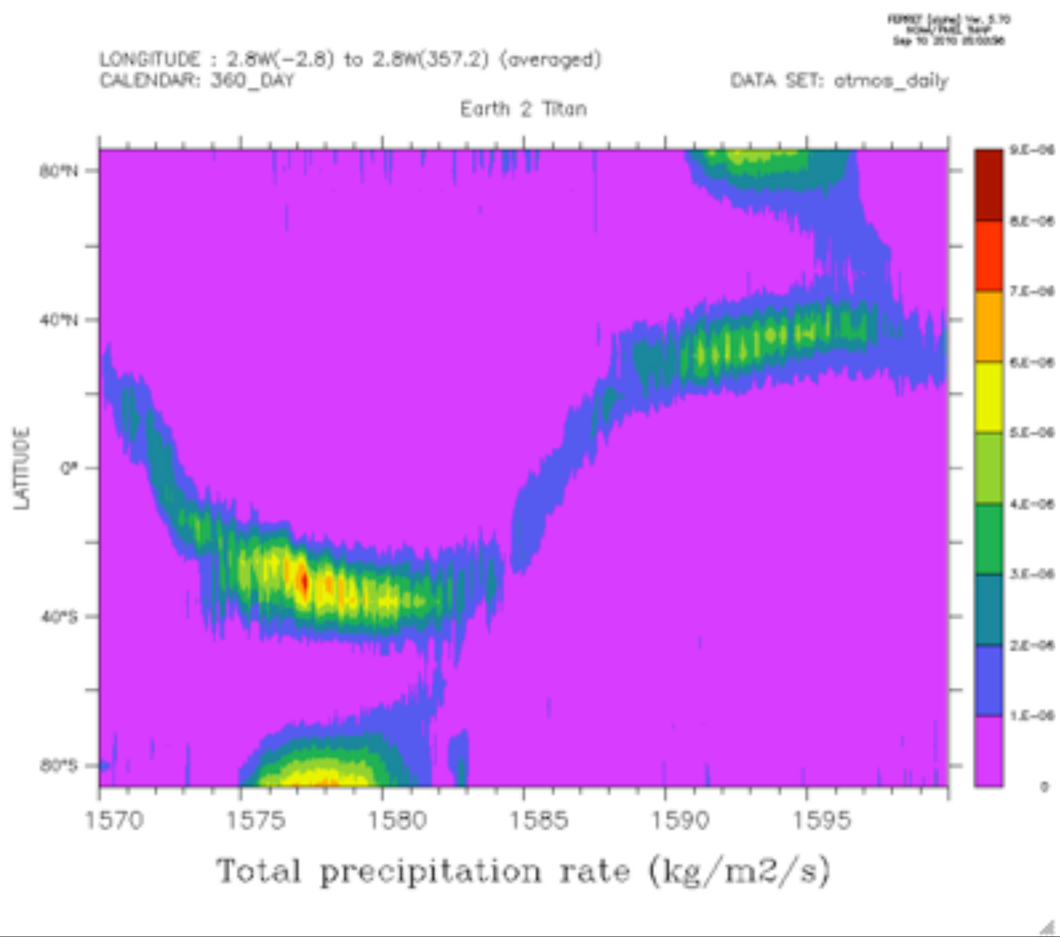
- *Up-gradient angular momentum transport*

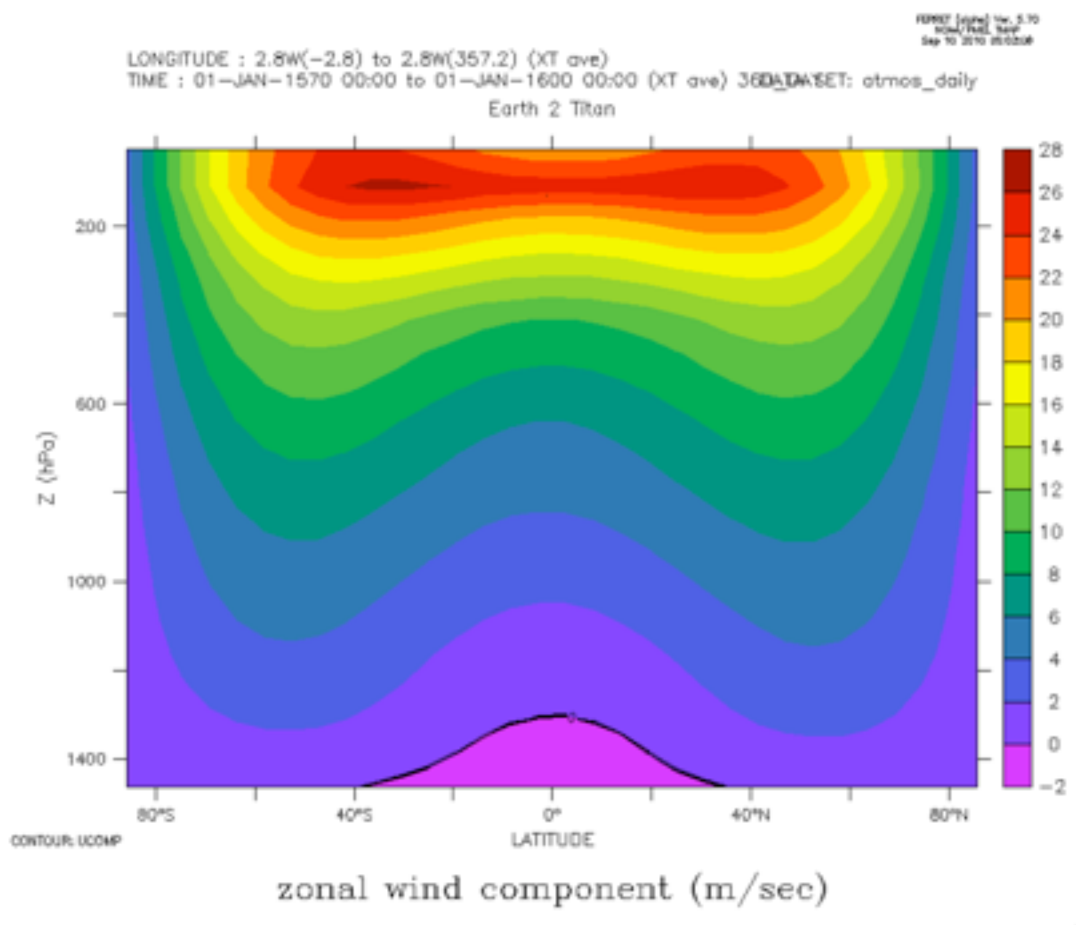


Putting it all together

Pricipitation



Zonal Winds



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- As such, they form the base of a model hierarchy
  - "using models to understand models"
  - parameter exploration in data-poor fields
- They do not replace more comprehensive models -- there is a synergy between them

Extra Slides

Summary

Mitchell & Vallis '10 (*submitted to JGR*)

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- A terrestrial atmosphere transitions to superrotation at Ro>1.

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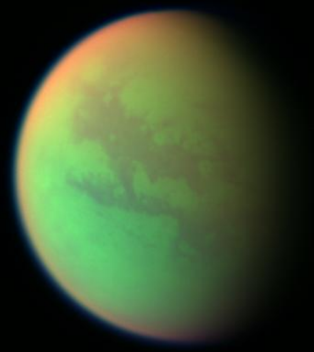
Summary

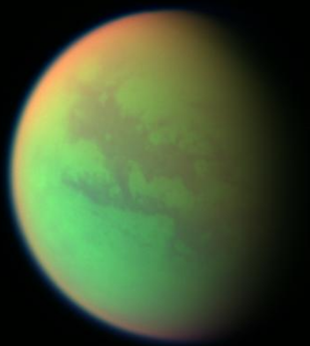
- A terrestrial atmosphere transitions to superrotation at Ro>1.
- A new, global wave dominates eddy momentum convergence at the equator.
  - travels *both* westward *and* eastward relative to mean flow
  - mixed baroclinic-barotropic instability
- Once established, superrotation is very stable
  - weak frictional and advective torques
  - a mix of high- and low-latitude barotropic instability

Mitchell & Vallis ’10 (*submitted to JGR*)



Experiment Design

Mitchell et al. ’06 (*PNAS*)
Mitchell et al. ’09 (*Icarus*)



Experiment Design

- ***Dry and moist cases***
  - Dry: Lv = 0, so that cond/evap do not heat/cool
  - Moist: Lv = $L_{v,CH4}$

$$e_s(T) = e_{so}e^{(L_v/R_v)(1/T_o - 1/T)}$$

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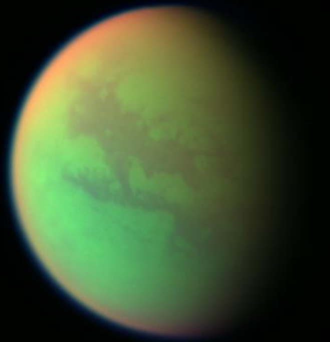

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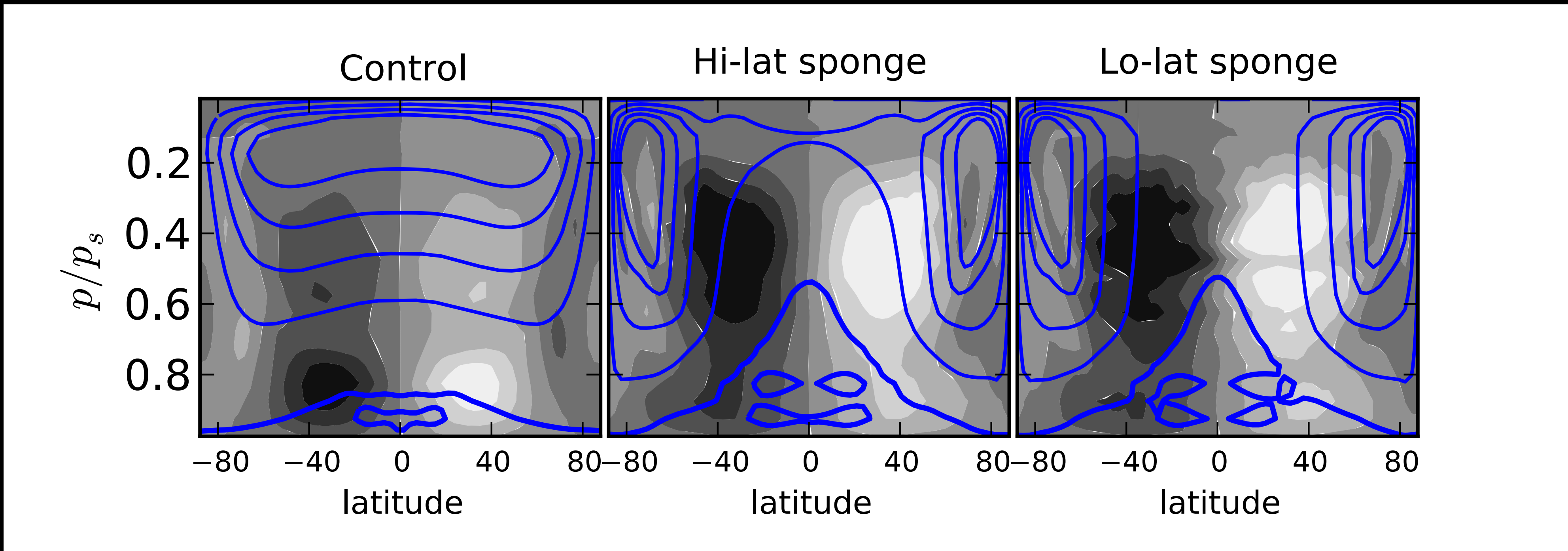
- ***Intermediate case***
- Limit latent surface fluxes by reducing the “target” relative humidity

$$F_{\text{lat}} \propto \rho U L_v (\text{rh}_s q_s - q_o)$$
$$\text{rh}_s = 0.5$$

Mitchell et al. ’06 (*PNAS*)
Mitchell et al. ’09 (*Icarus*)

Test cases:
Evidence for equatorial control



Mitchell & Vallis '10 (*submitted to JGR*)

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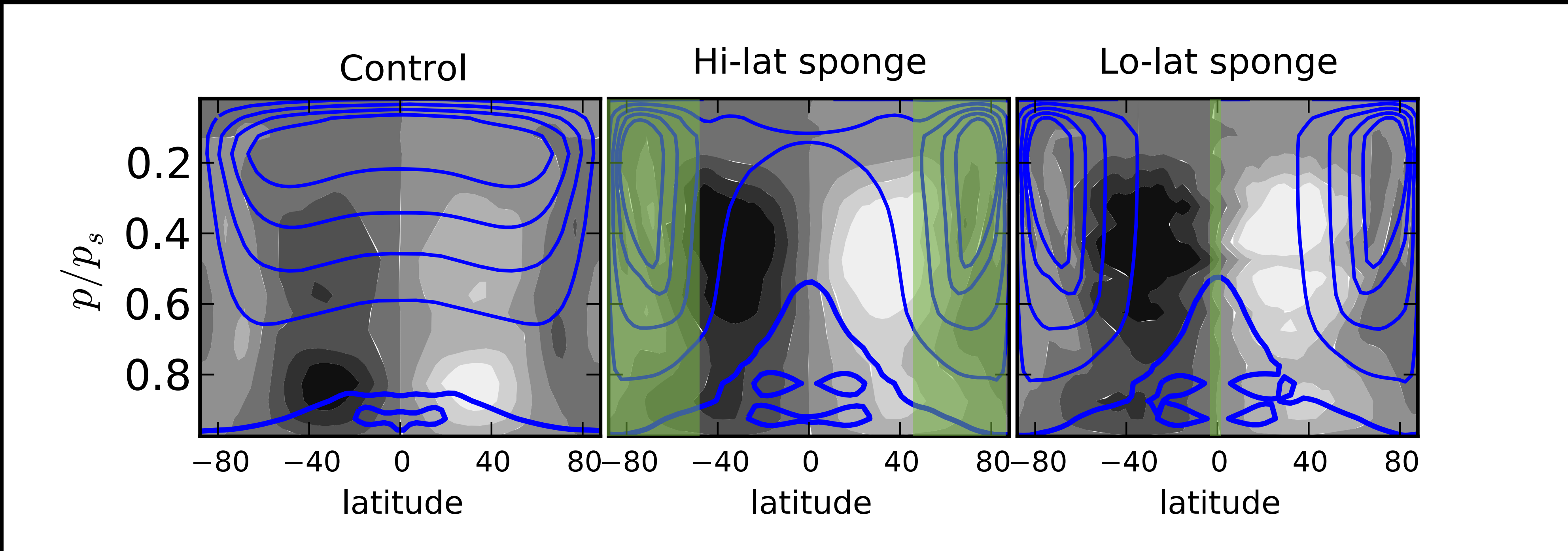
Evidence for equatorial control



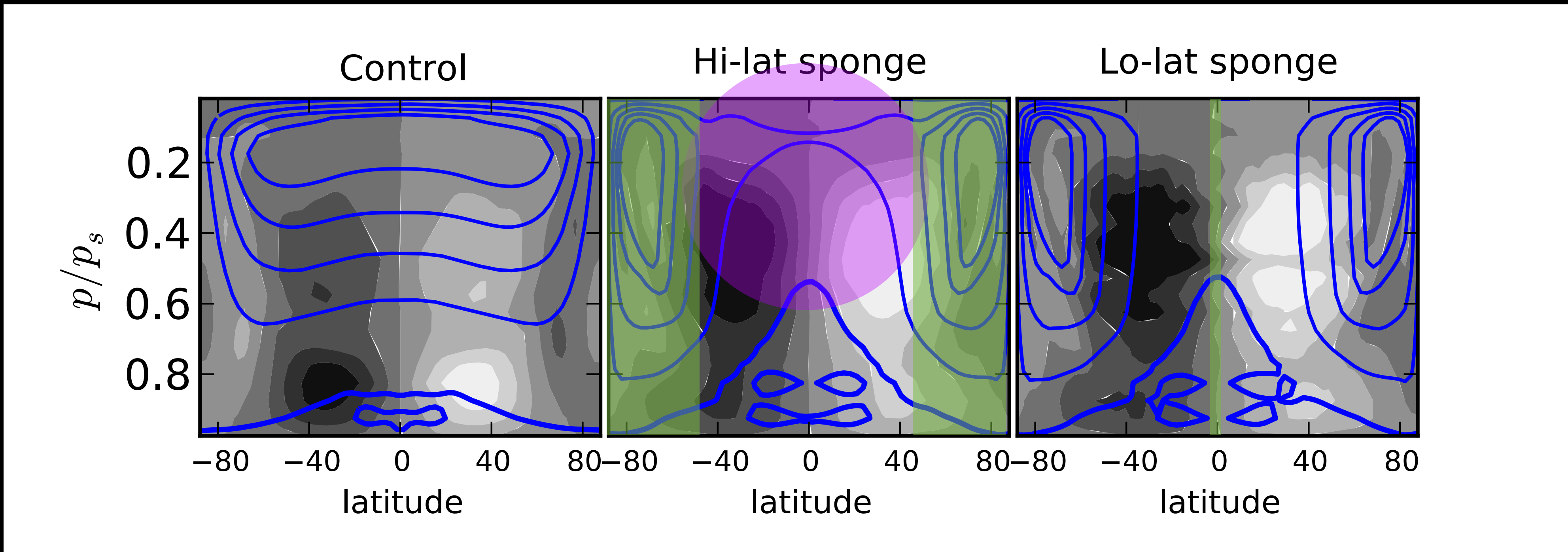
45-90N/S

3N-3S

Mitchell & Vallis ’10 (*submitted to JGR*)

Test cases:
Evidence for equatorial control

Weak Superrotation



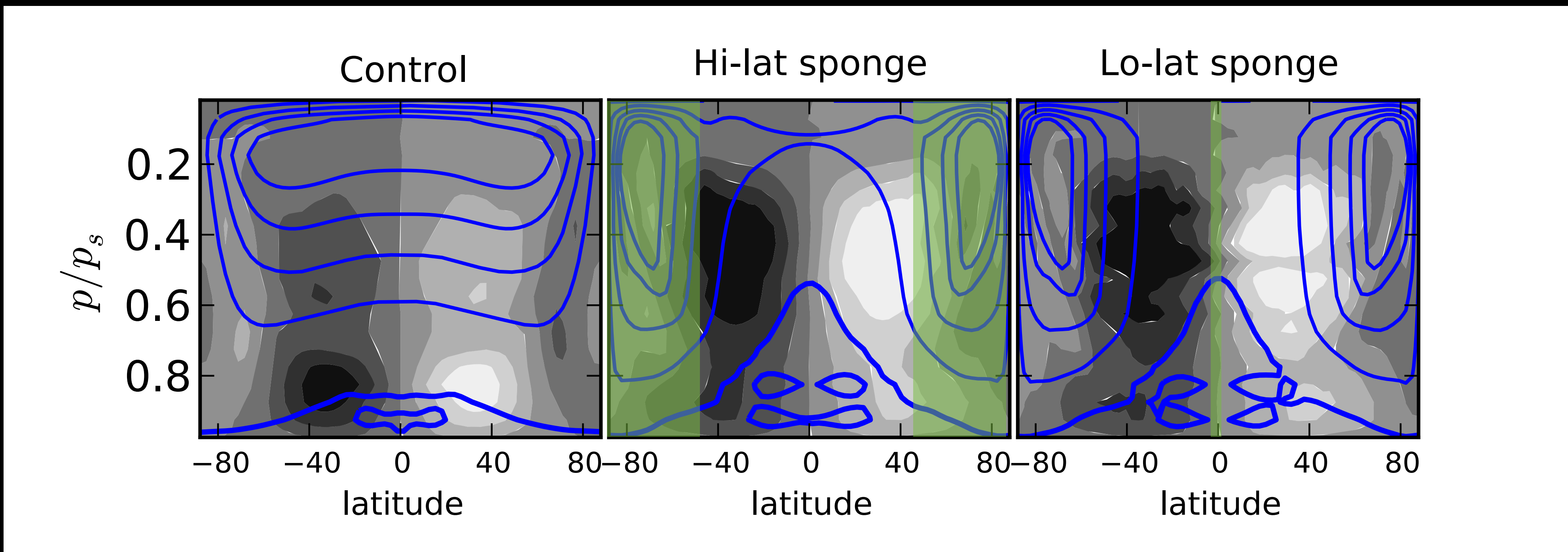
45-90N/S

3N-3S

Mitchell & Vallis ’10 (*submitted to JGR*)

Test cases:
Evidence for equatorial control

Axisymmetric!!



45-90N/S

3N-3S

Mitchell & Vallis '10 (*submitted to JGR*)

Fourier cospectra of eddy momentum fluxes

$$K_{n,\omega}(u, v) = 2\langle \mathrm{Re}(U'V'^*)\rangle$$

Randel & Held '90 (*JAS*)
Mitchell & Vallis '10 (*submitted to JGR*)

Fourier cospectra of eddy momentum fluxes

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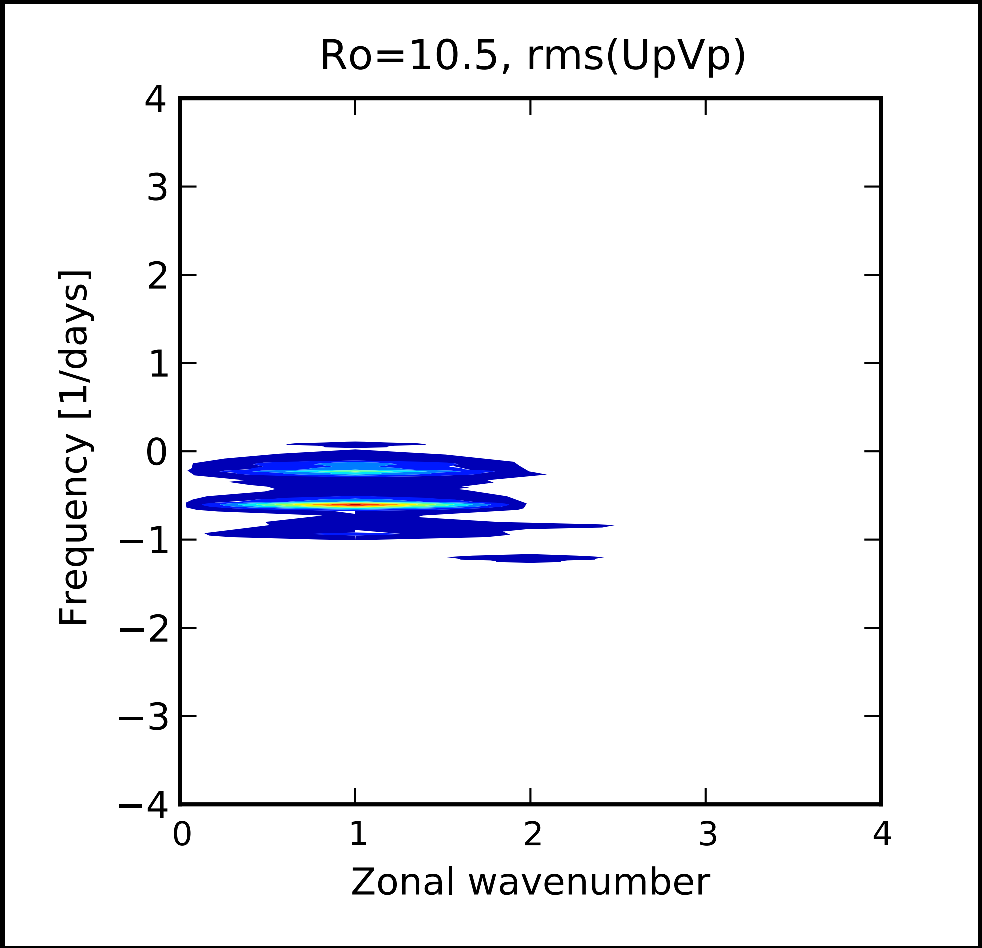
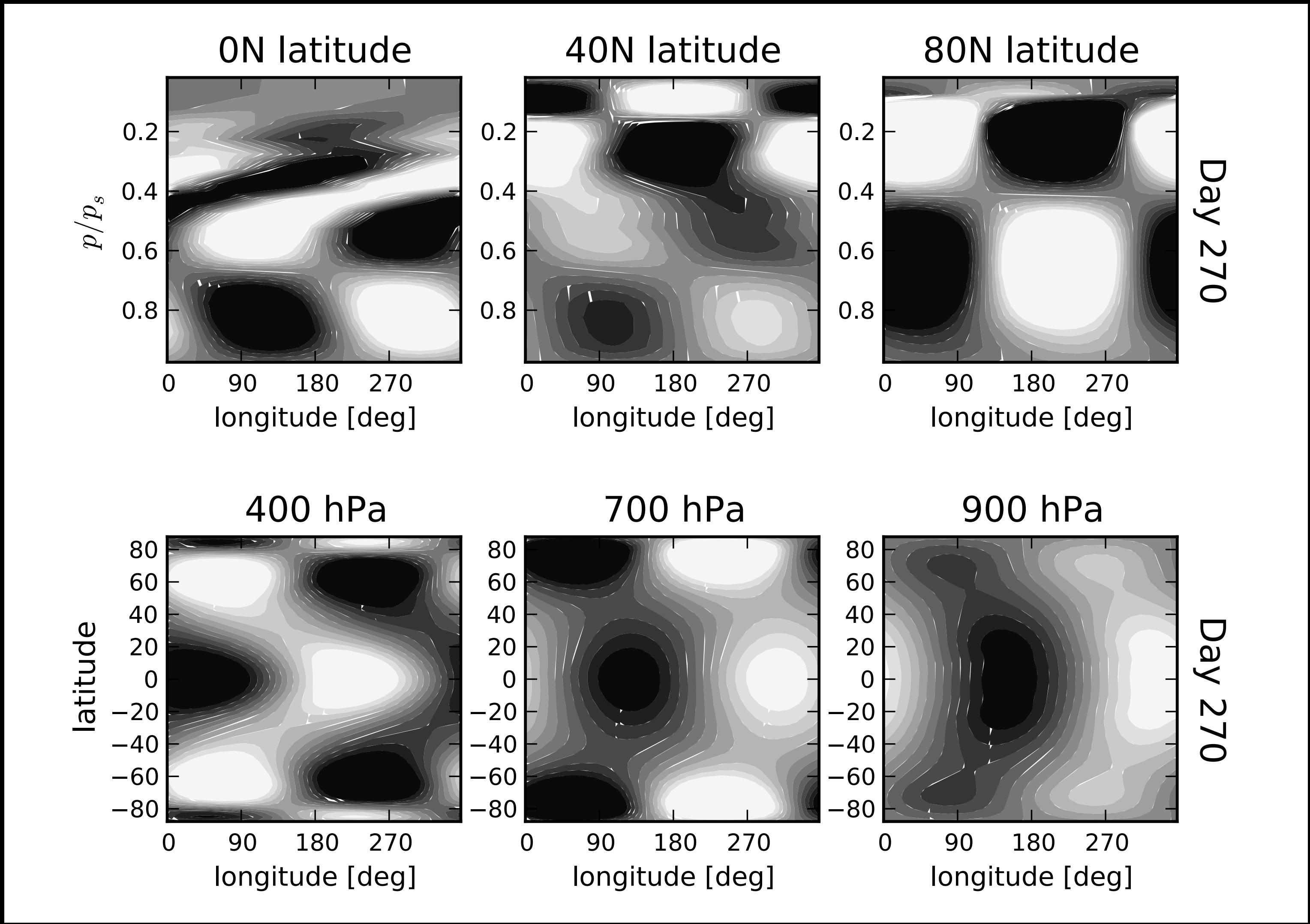
- Wavenumber 1 dominates the Ro=10.5 case.



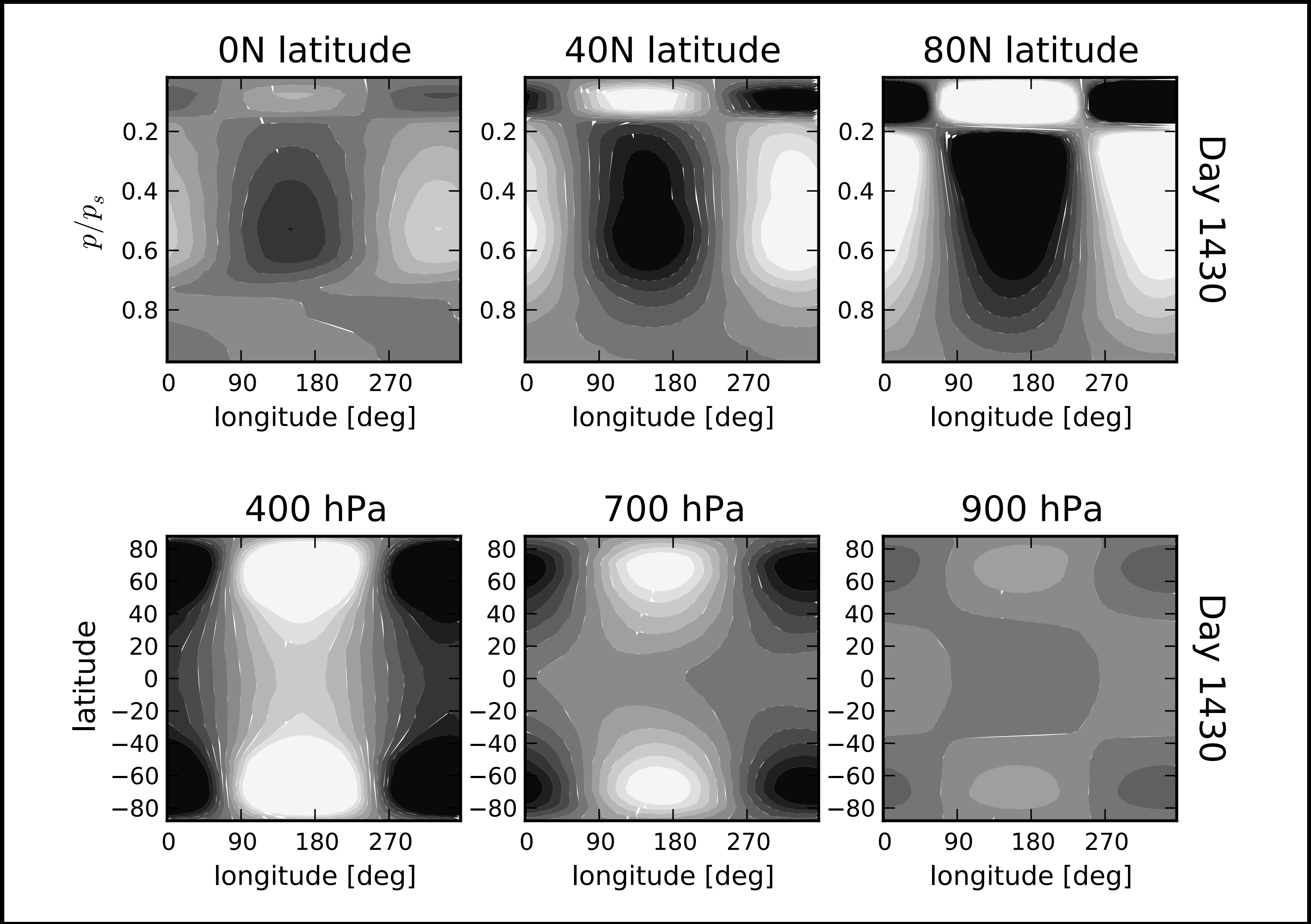
Randel & Held ’90 (*JAS)*
Mitchell & Vallis ’10 (*submitted to JGR*)

Geopotential anomaly of the global wave: *Spinup*



Mitchell & Vallis ’10 (*submitted to JGR*)

Geopotential anomaly of the global wave: *Steady state*



Mitchell & Vallis '10 (*submitted to JGR*)