3D Modelling of the atmosphere of Pluto and Triton

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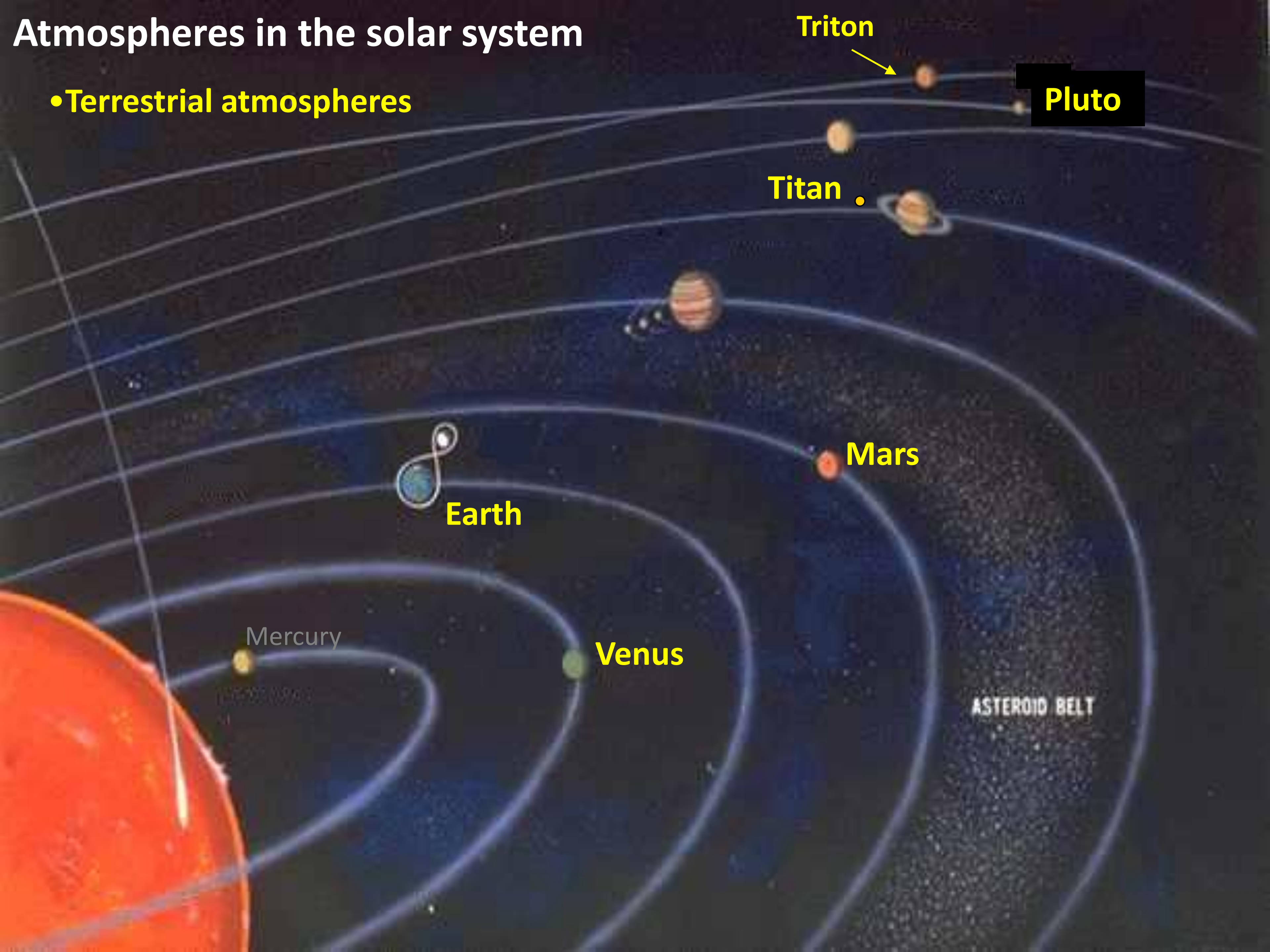
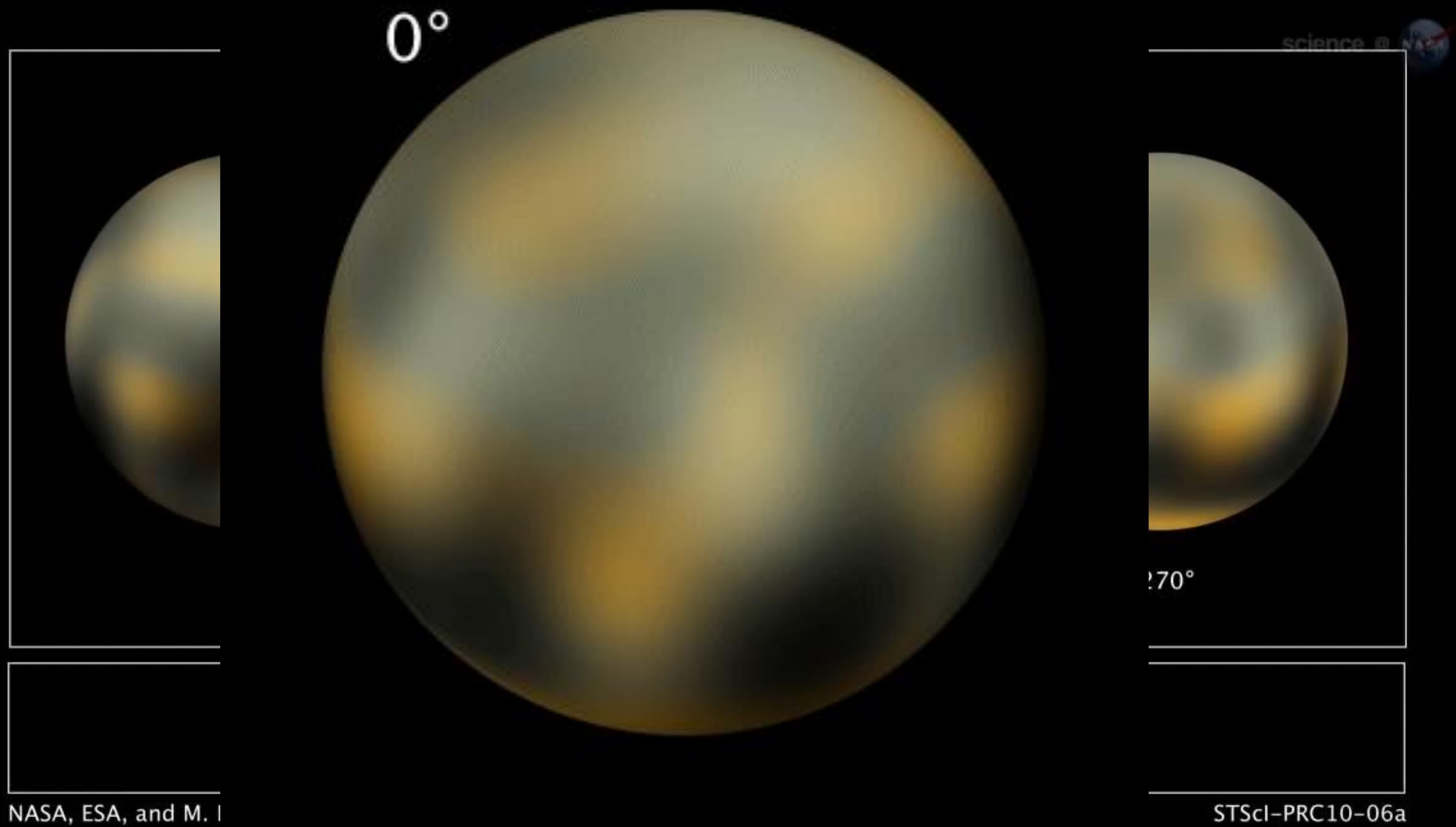
Atmospheres in the solar system

- Terrestrial atmospheres



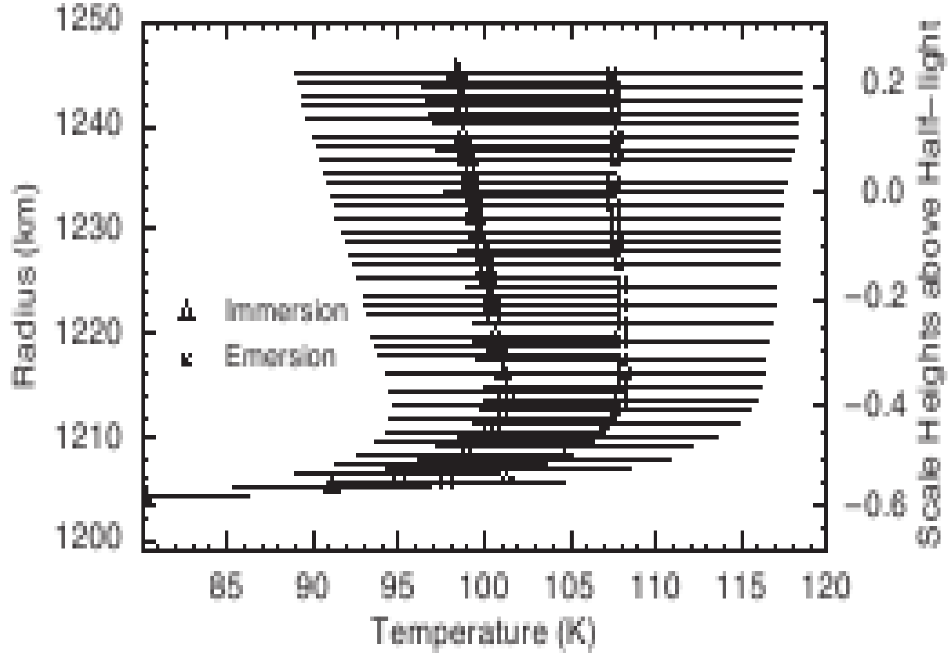
PLUTO



Pluto

- A surface covered by N
  ices + "Tholins"
- A strong seasonal cycle
  - 1 year pluto = 247.7 Eart
  - Obliquity = 122°
  - Perihelion = 29.6 AU/Aph
- A thin Nitrogen atmosphere.
  Currently :
  - Ps ~2 – 5 Pa (TBC)
  - [CH4] ~0.5% *(Lellouch et al. 2009)*

Stellar Ocultation (



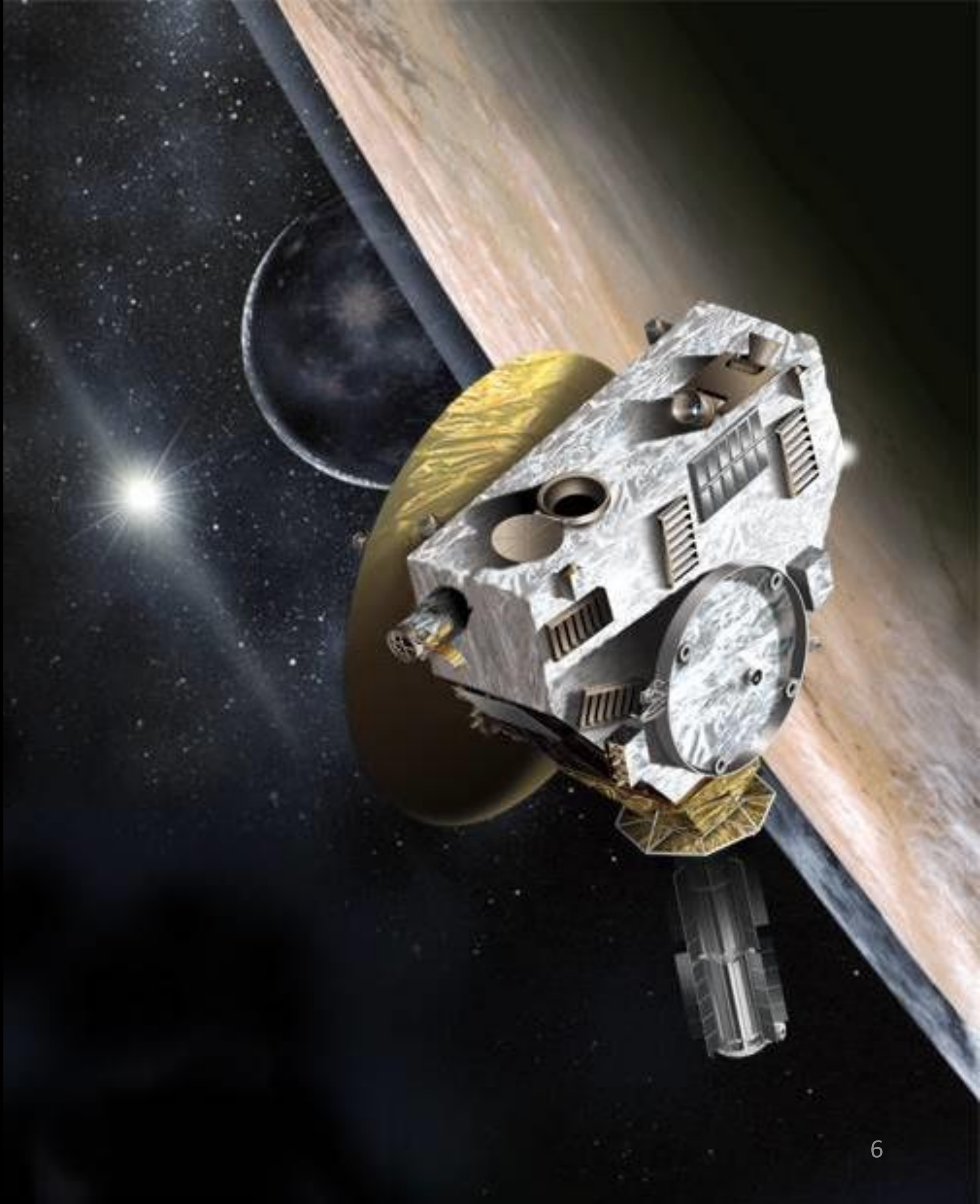
New Horizons

478 kg

Decembre 2005

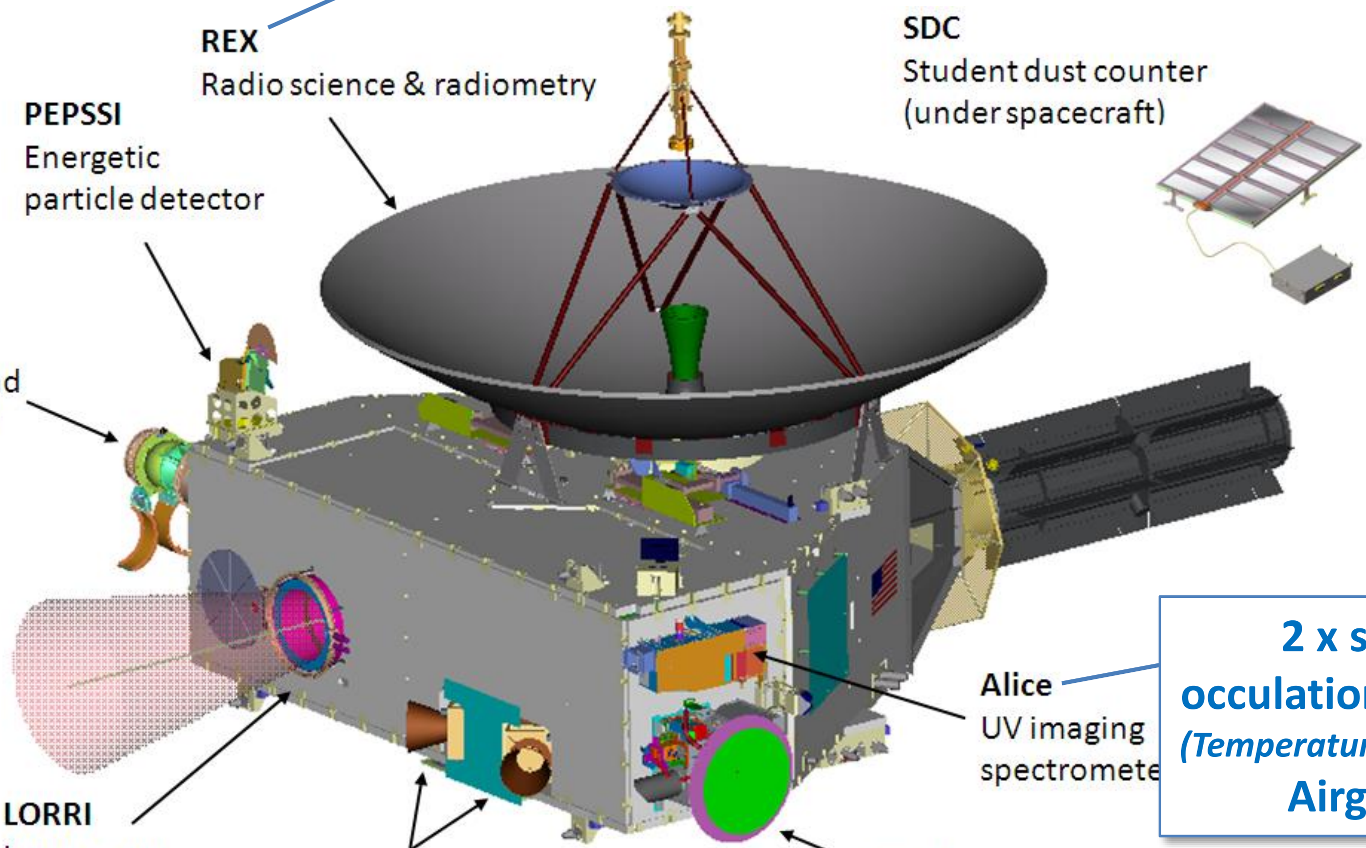
New Horizons
Flyby

July 14, 2015



New Horizon Payload (atm. Observations)

2 x atmospheric temperature profiles

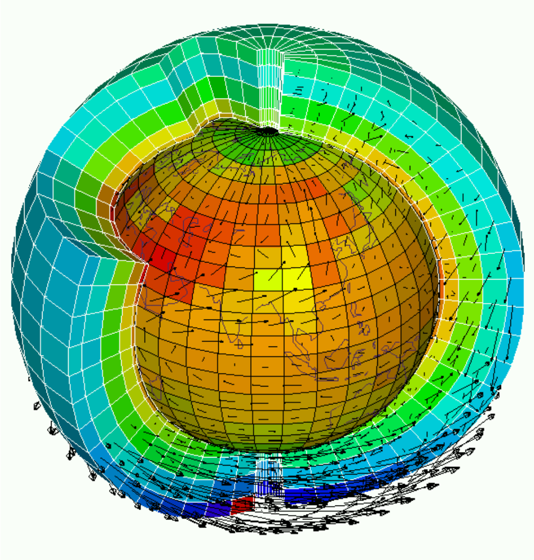


2 x solar occulation profiles
(Temperature, aerosols)
Airglow

Haze & surface imaging

Map surface ice & surface temperatures + hazes

The LMD Pluto Global climate model



1) 3D Hydrodynamical core

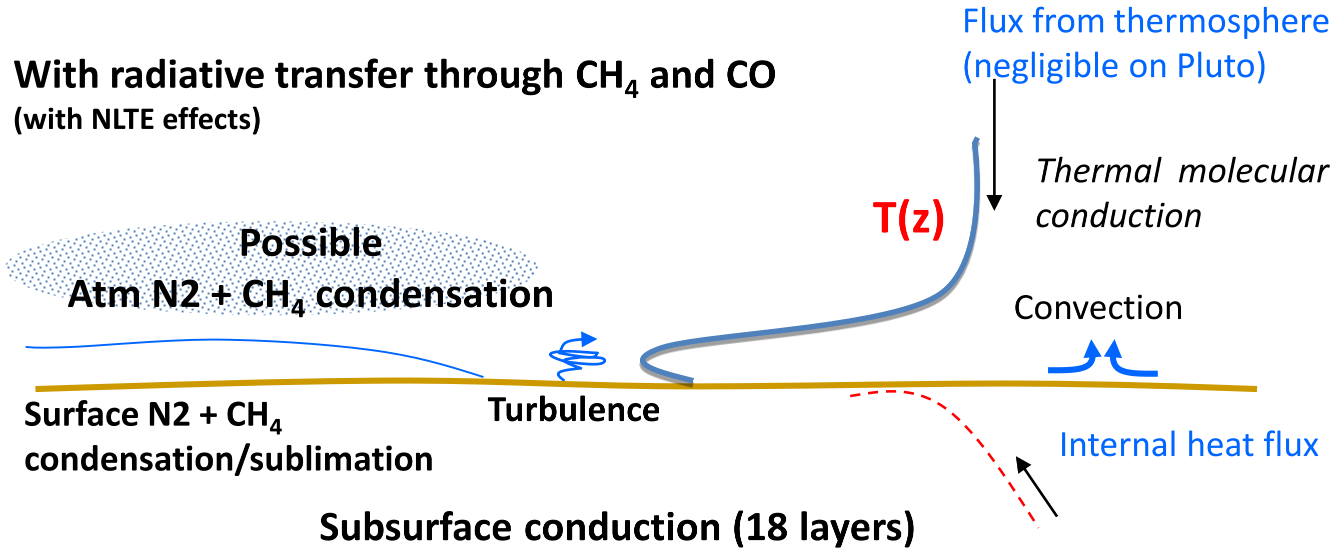
-> to compute large scale atmosphere motions and transport

- Grid point model ⇨ Typical resolution of 170 km
- 25 vertical layers (10m, 20m, 40m,...160km)

2) Physical parametrizations

-> to force the dynamic

-> to compute the details of the local climate



"Classical" parametrizations

- **Thermal conduction in the high atmosphere :**

$$\frac{\partial T}{\partial t}=\frac{1}{C}\frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right) avec\, C=C_p\rho(z)=\frac{C_p P}{RT}\, et\; K=AT^s, A=2{,}6.10^s-5\, W.m.K^{-(1+s)}\, et\; s=1.3$$

  – Semi-implicite scheme

  – Flux assumed to negligible at the top

- **Subsurface conduction**

$$C\frac{\partial T}{\partial t}=\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)$$

  – Semi-implicite scheme

  – 22 layers to account for Pluto timescales heat waves

- **Turbulent mixing in the Boundary layer :**

  – Turbulent closure scheme based on Mellor and Yamada 2.5 parameterisation :

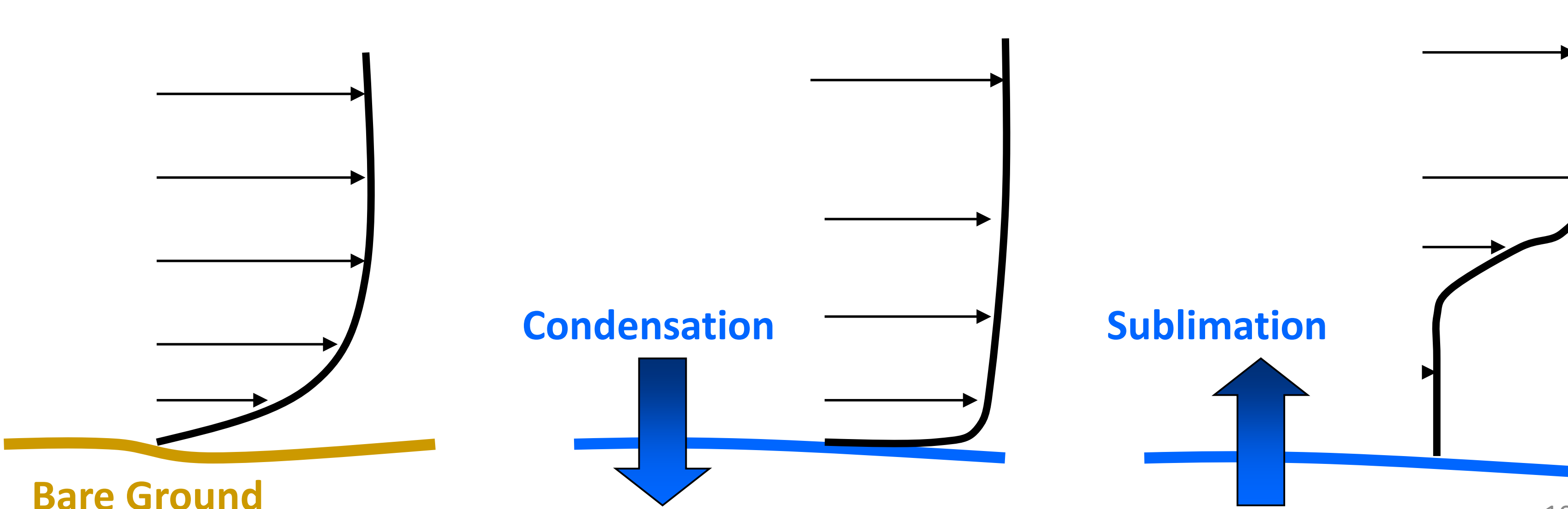
Condensation/sublimation of Nitrogen

- **Surface condensation & sublimation**

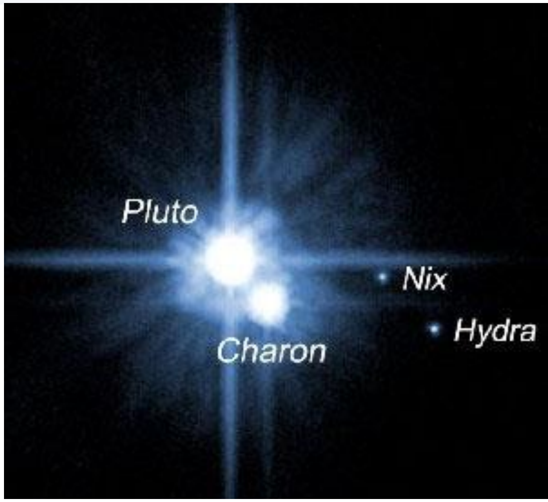
- N_2 condenses or sublime to conserve energy at N_2 frost point…
- **special parameterization in sigma coordinates :** *(Forget et al, 1998)*

→ Condensation:
  – the entire atmosphere is “pumped” into the ground.
  – “warm” air must be cooled

→ Sublimation : Cold and still air injected in the atmosphere



Gravitational tides from Charon



Navier-Stokes equation :

$$\frac{D\vec{v}}{Dt} = \vec{Coriolis} + \vec{Diffusion} - \frac{\vec{\nabla}P}{\rho} - \vec{\nabla}V_{tide}$$

V_{tide} : gravitational potential caused by Charon's tides

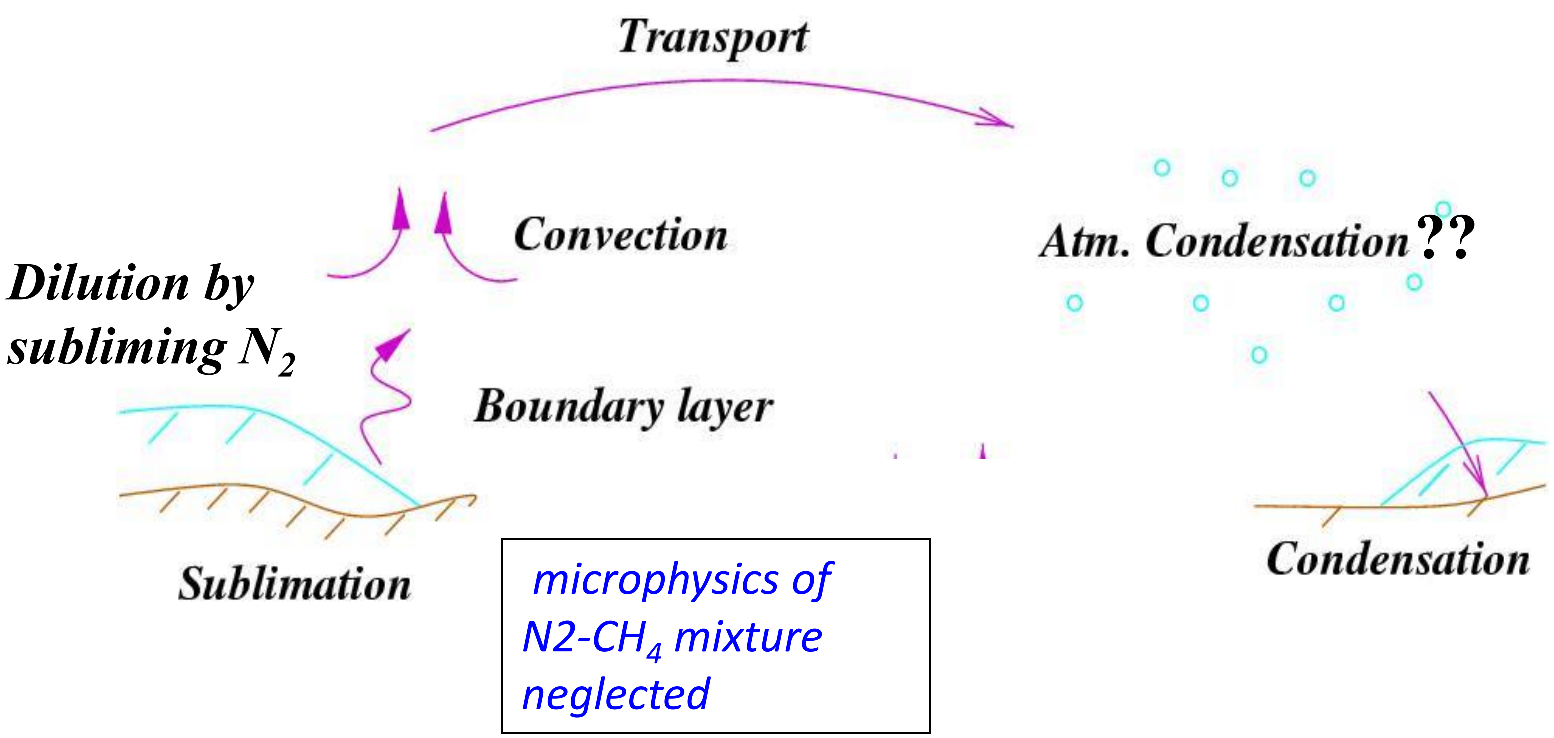
$$V_{tide} = V_0\left[\frac{7}{8}\cos^2\lambda\cos(2\phi - nt) - \frac{1}{8}\cos^2\lambda\cos(2\phi + nt) + \left(\frac{3}{4}\cos^2\lambda - \frac{1}{2}\right)\cos nt\right]$$

$$V_0 = -\frac{GM_{Charon}}{a}\left(\frac{R_{Pluto}}{a}\right)^2 3e$$

a =distance Charon-Pluto,
n = orbital angular velocity
e = excentricity
λ = latitude
ϕ = longitude

V_{wind} < $1E^{-5}$ m/s
dp_s=$2E^{-2}$Pa
-> Gravitational tides are assumed to be <u>Negligible</u>

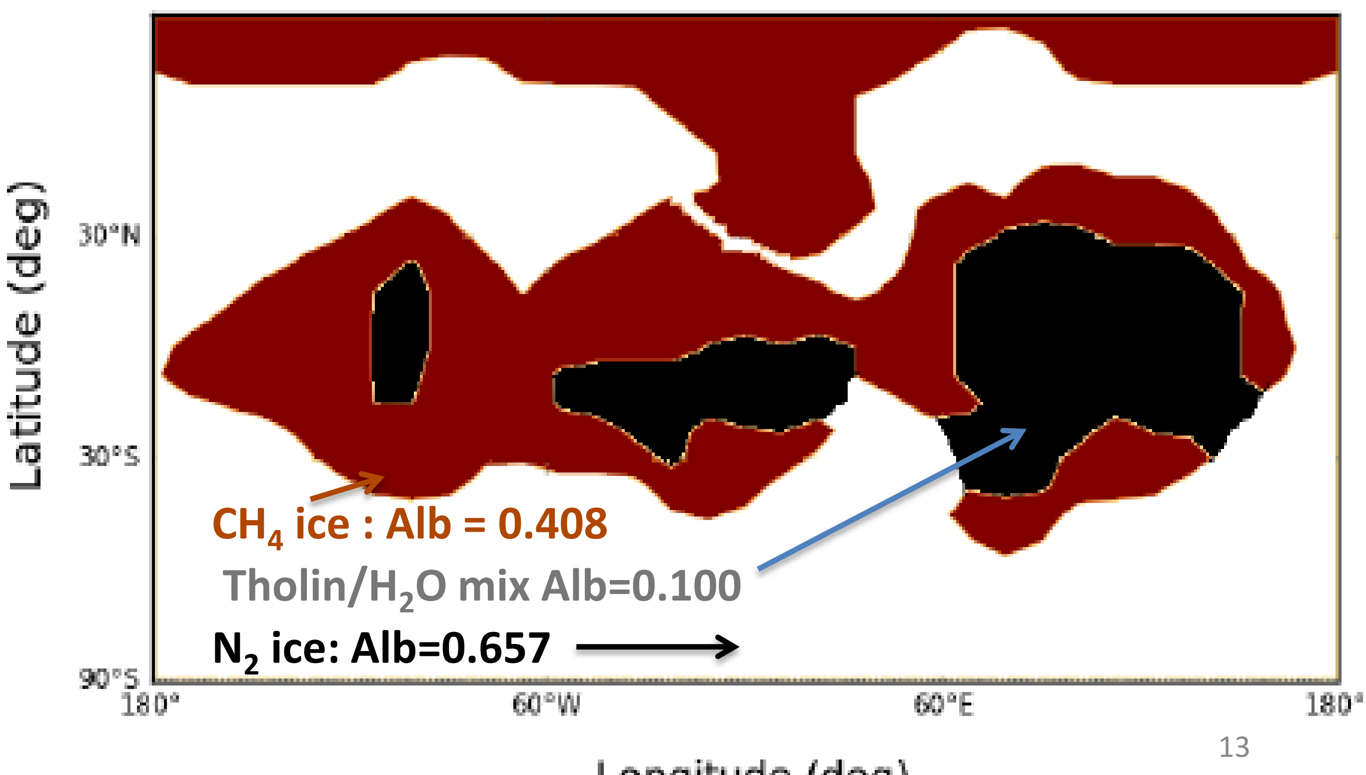
Modelling the Methane cycle



The key assumption: Initial map of surface deposits

We mostly assume the multi-terrain description of Pluto surface from Lellouch et al. 2000 (consistent with visible imaging, lightcurves, and visible and near-infrared spectroscopy).

- **Diurnal Thermal inertia set to 20 SI.**
- **Seasonal thermal inertia set to 500 USI**
- **Emissivity = 0.9 for all the three units**
- *Map with Buie et al, (1997) convention (Summer in the northern hemisphere in the 21st century).*

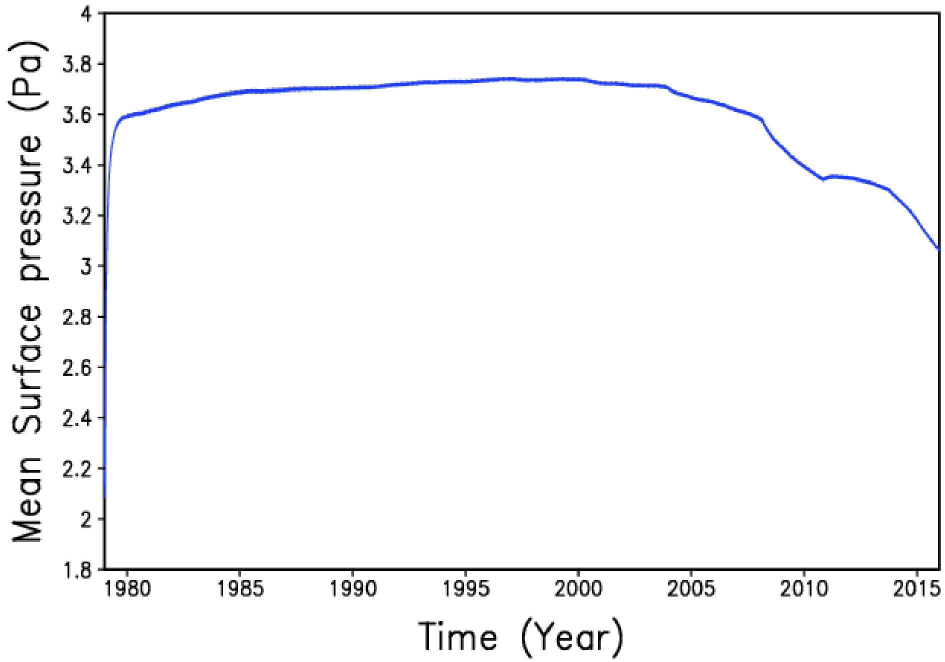


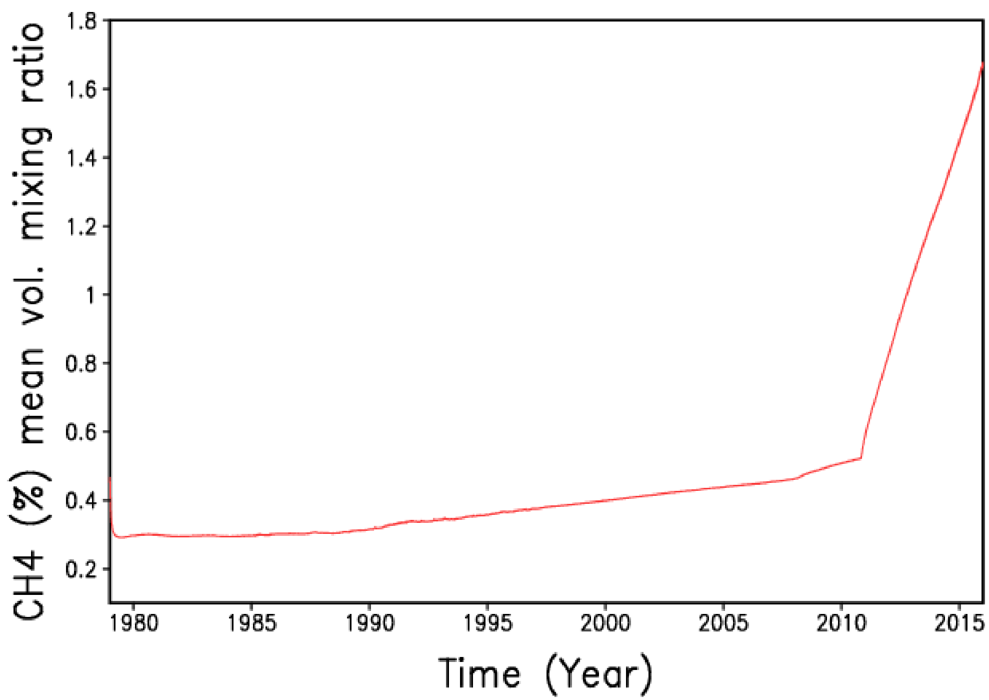
A challenge : long timescales

- Atm. Radiative timescale (10-20 years)
- seasonal heat storage in the subsurface

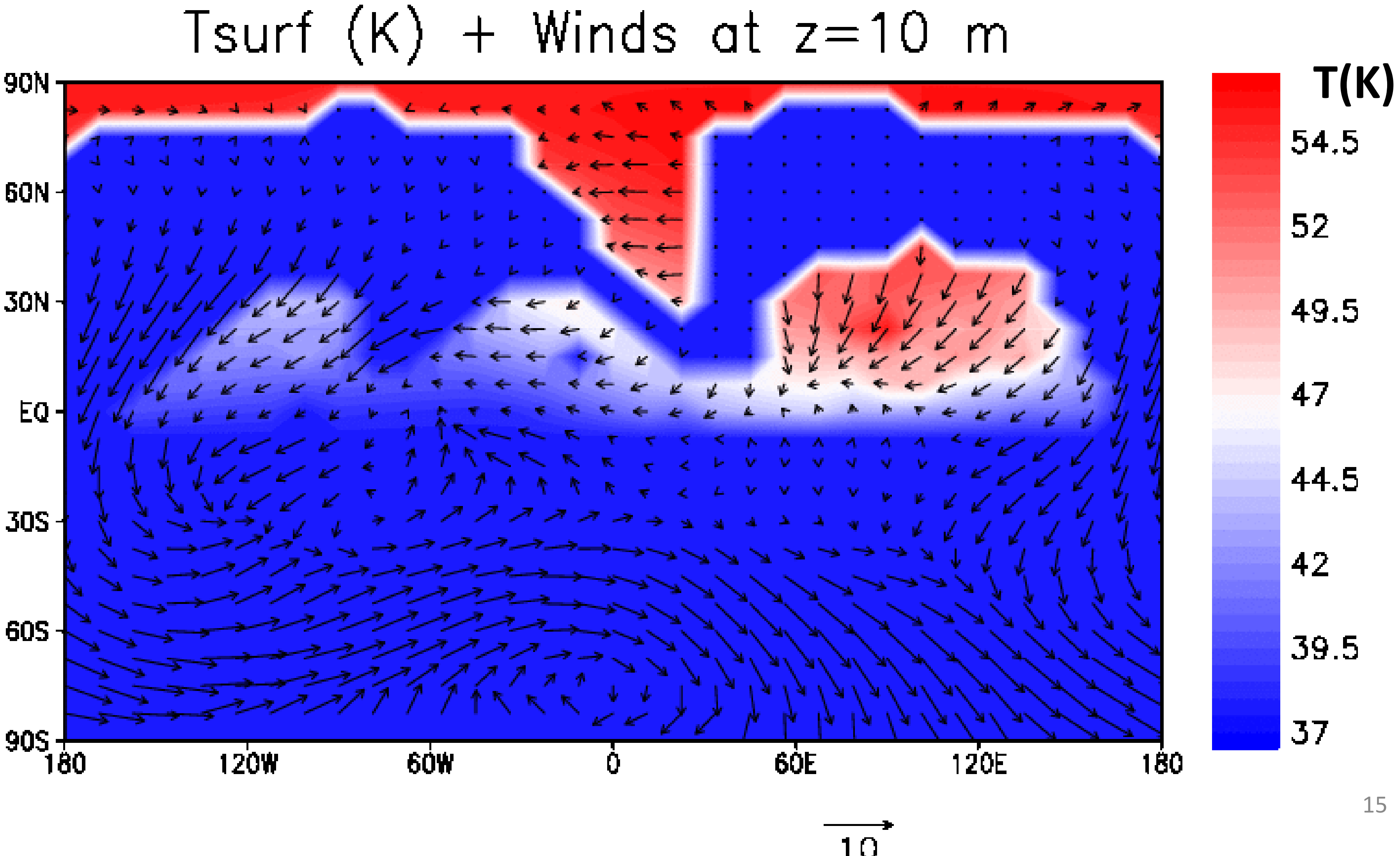
⇨ We start our simulation in 1980 with a “realistic” atmospheres, surface and subsurface temperatures, until 2015

⇨ Converged results after ~20 years (2008-2015) .

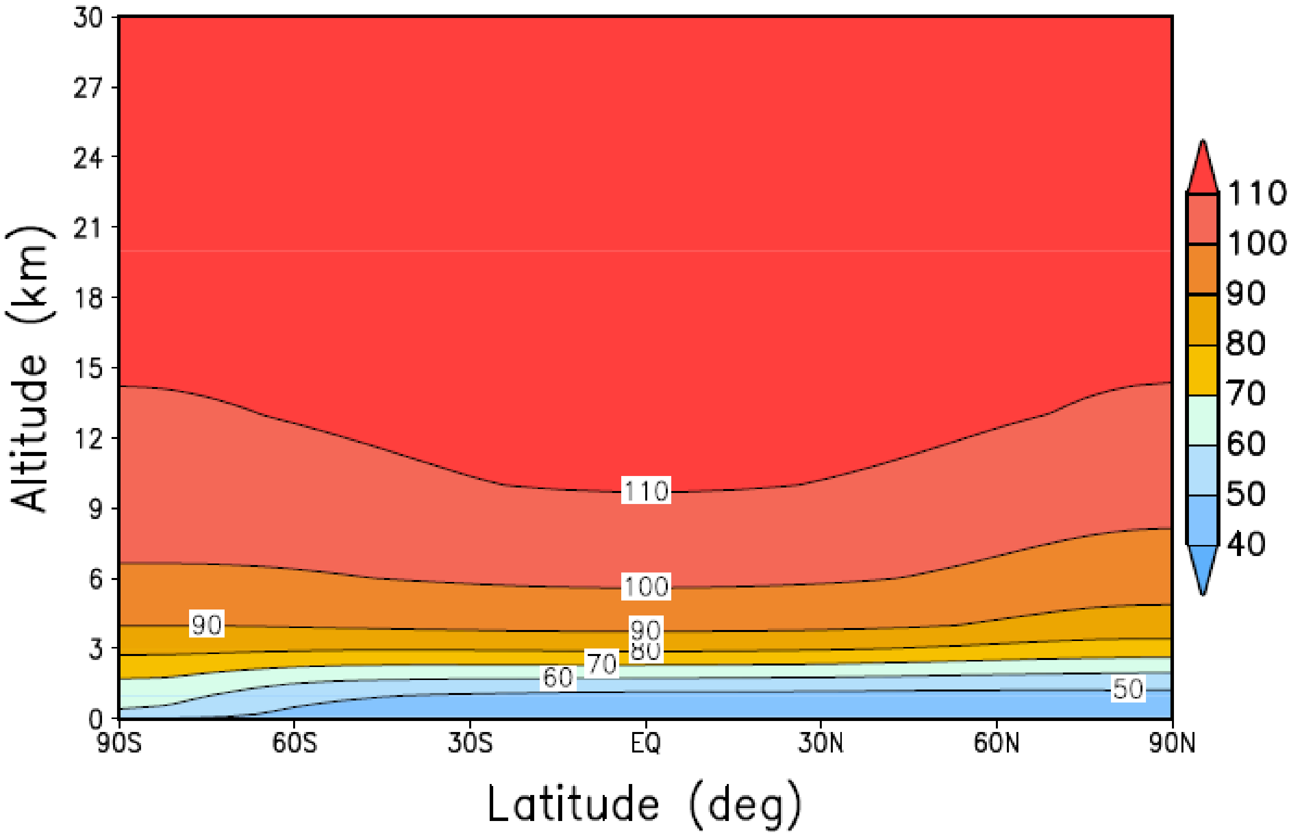




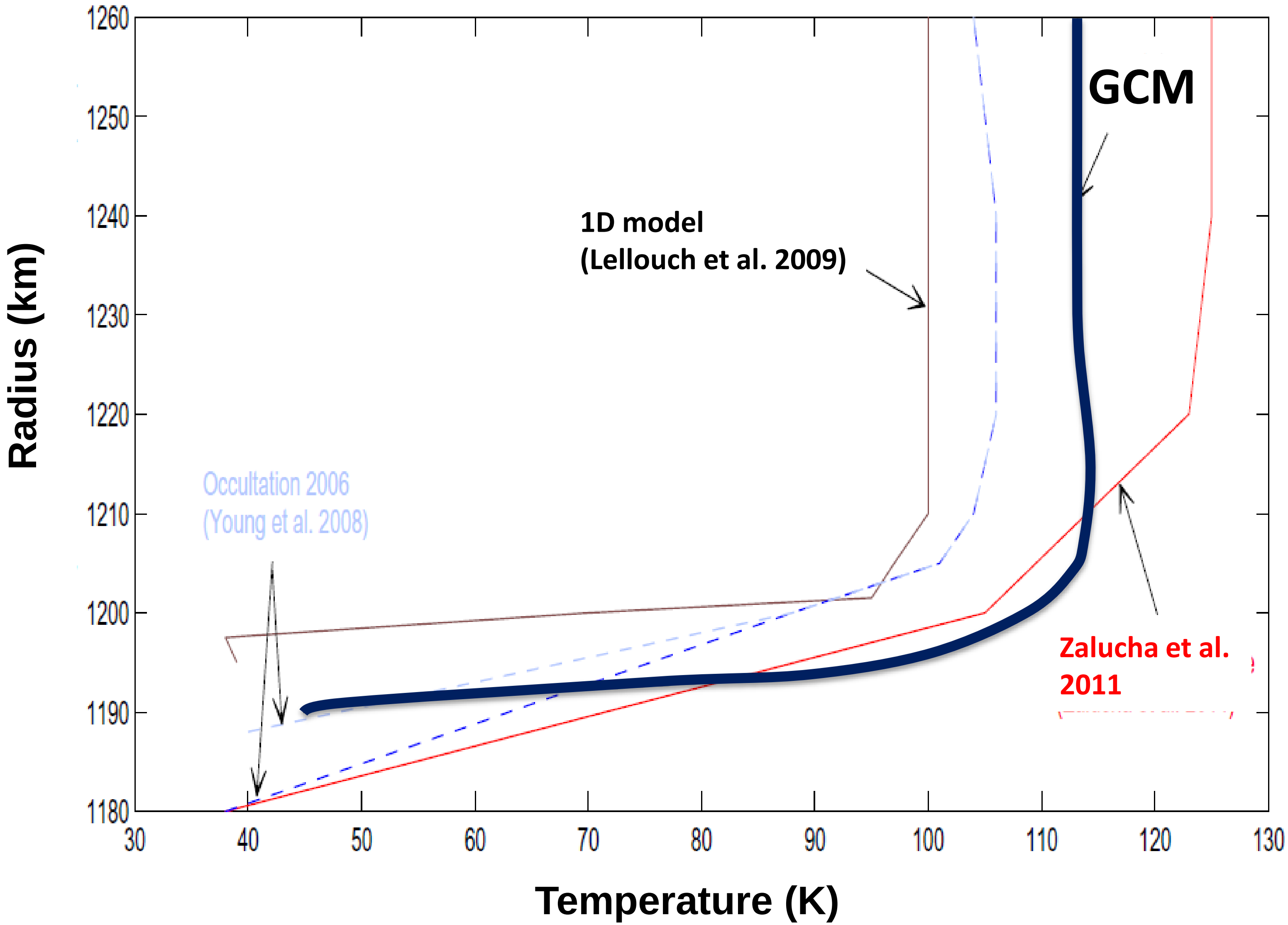
Pluto's Diurnal cycle in 2015



Thermal structure

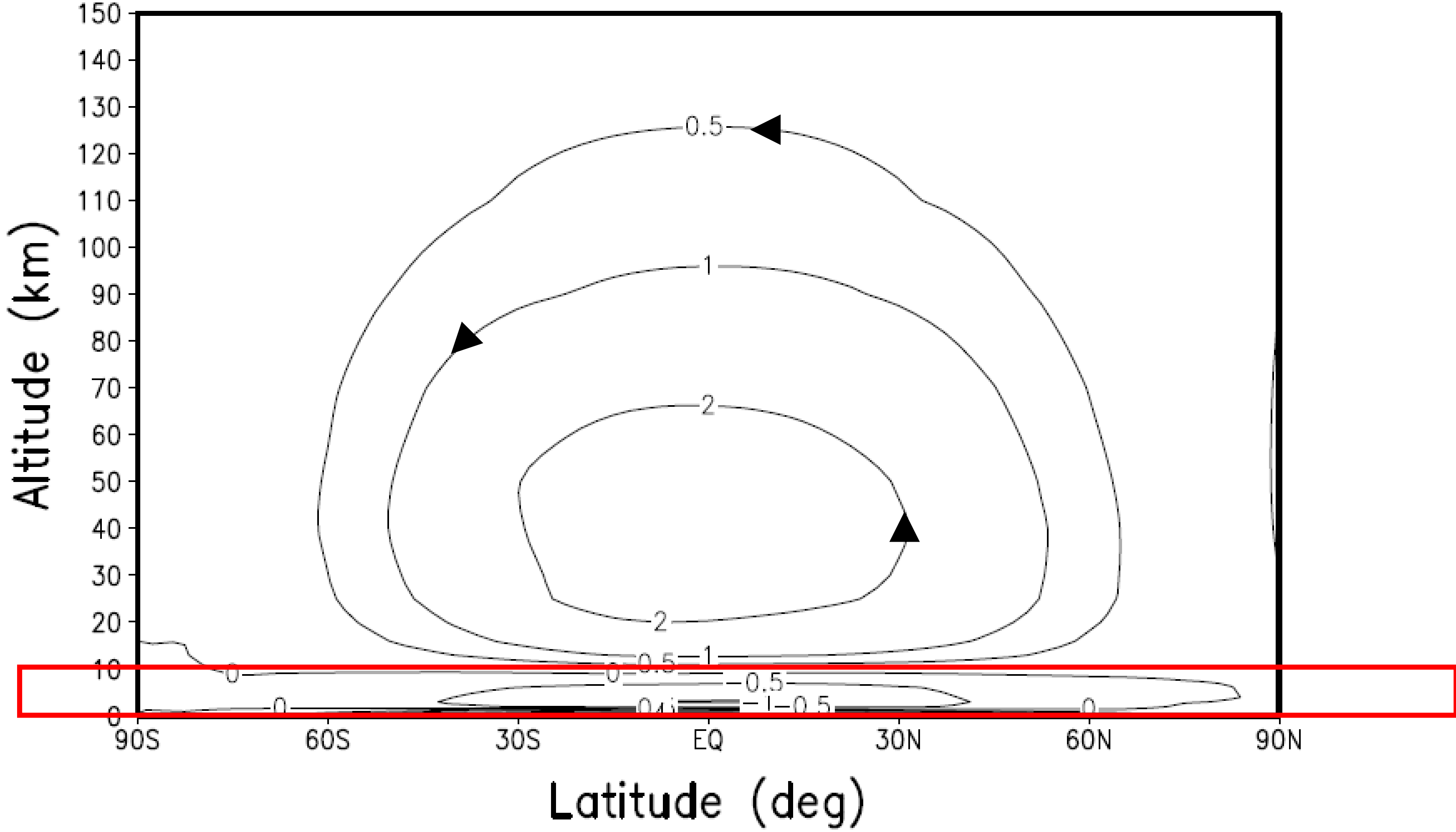


Mean Temperature profile: Comparison with observations and other models



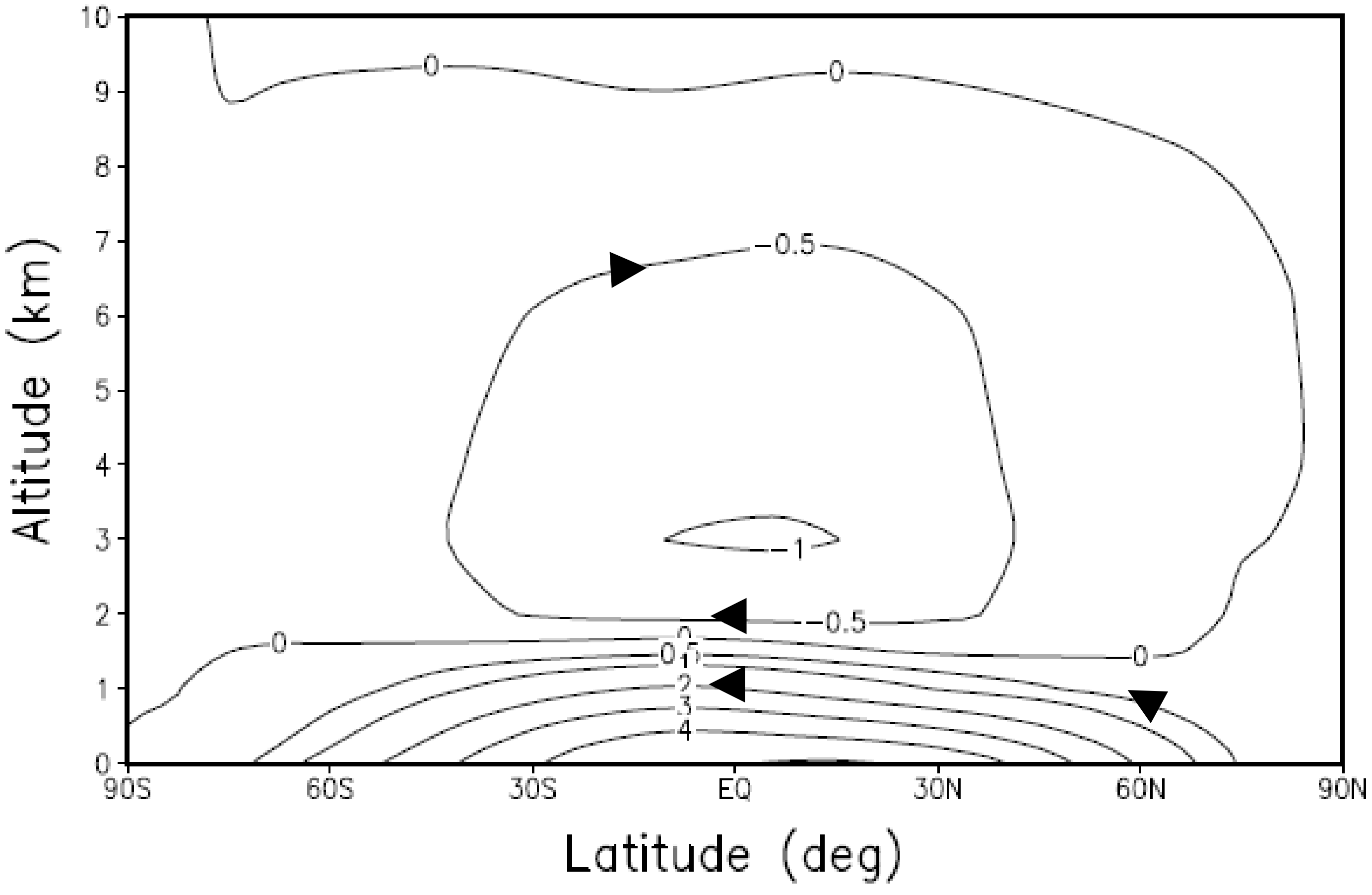
Mean Meridional Circulation

Mass streamfunction (10^7 kg m^{-2} s^{-1})



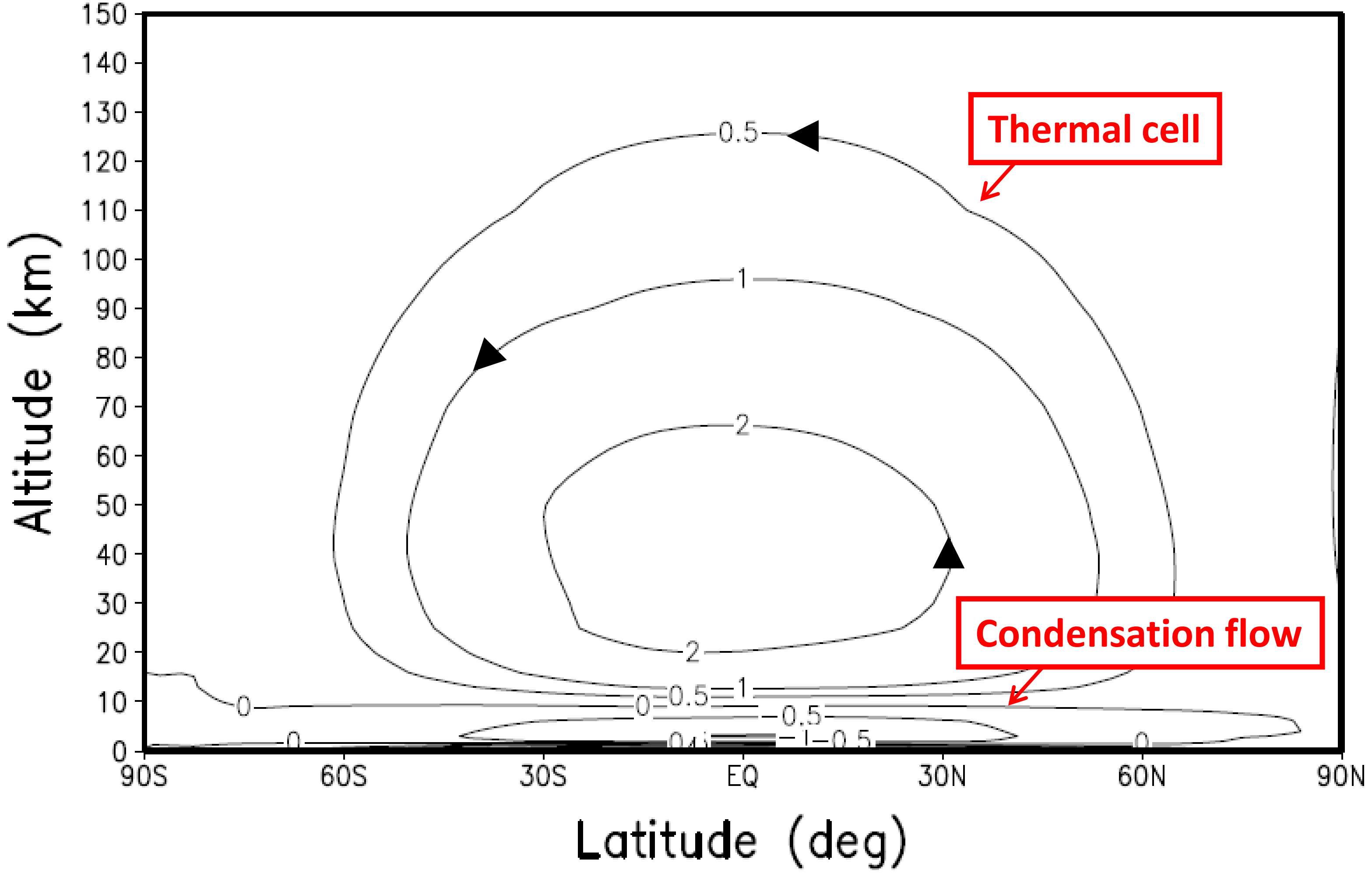
Mean Meridional Circulation IN THE LOWER ATMOSPHERE

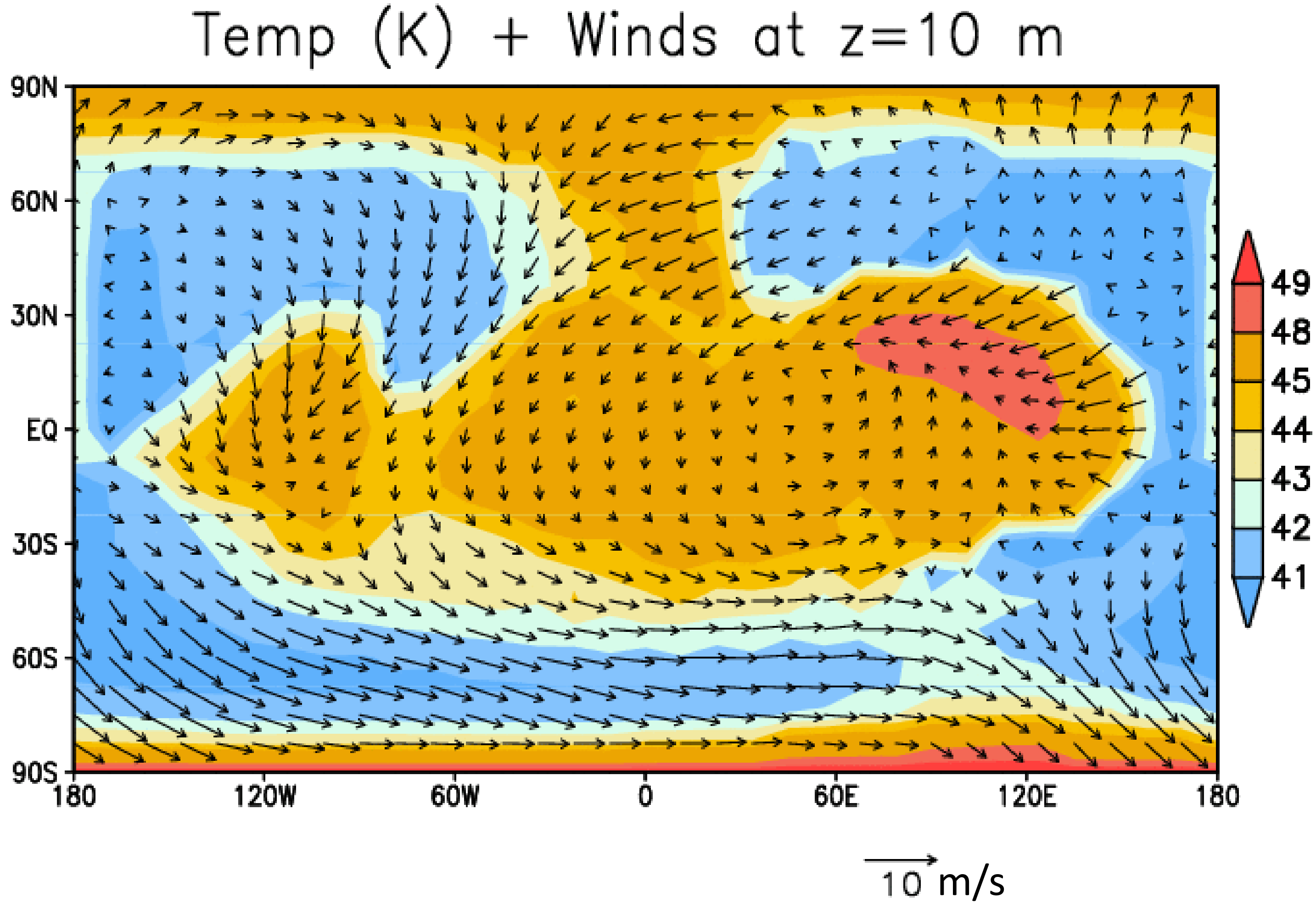
Mass streamfunction (10^7 kg m^{-2} s^{-1})



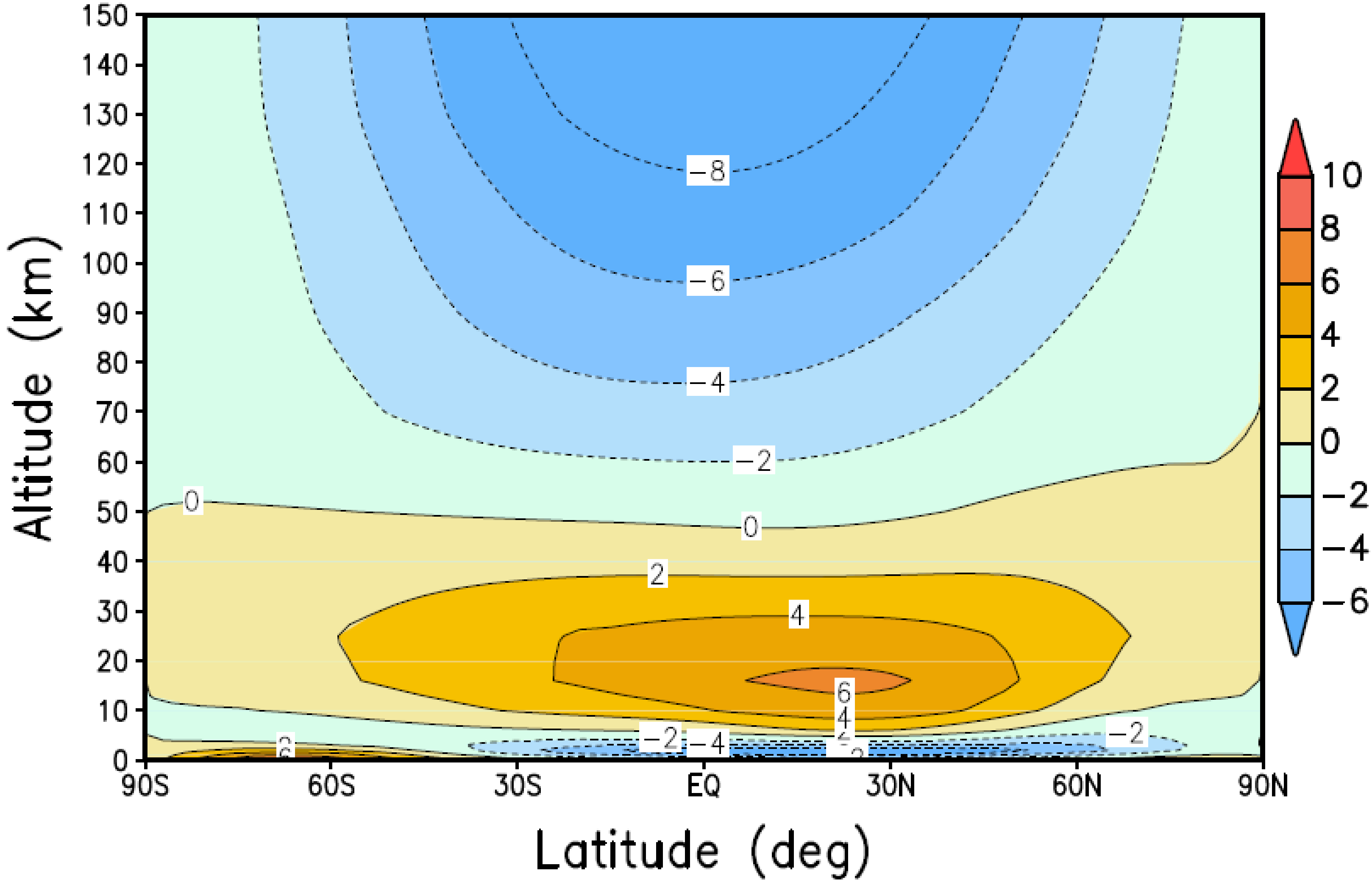
Mean Meridional Circulation

Mass streamfunction (10^7 kg m^{-2} s^{-1})



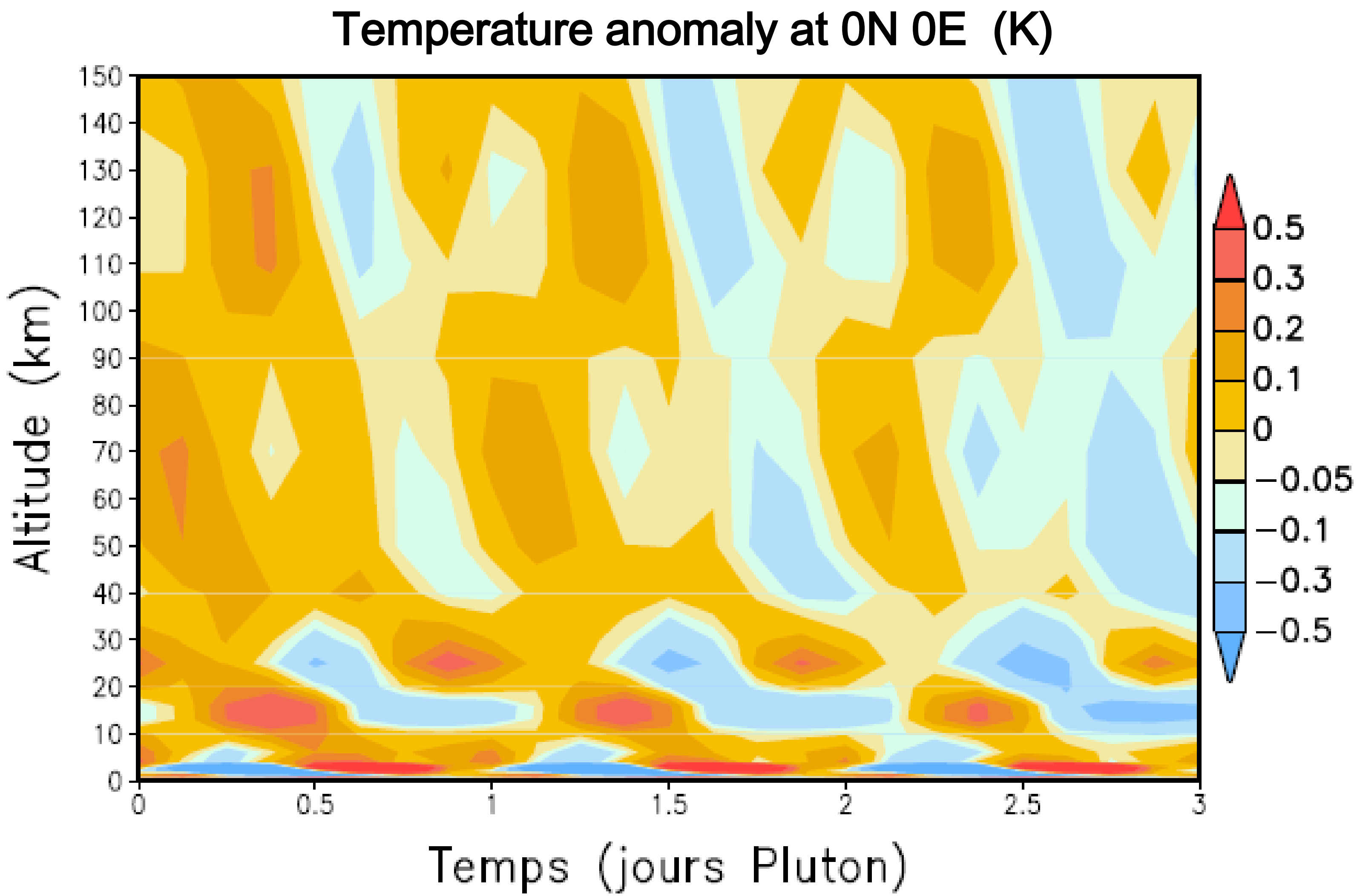

Temp (K) + Winds at z=10 m
90N
60N
30N
EQ
30S
60S
90S
180
120W
60W
0
60E
120E
180
49
48
45
44
43
42
41
10 m/s

Mean zonal wind in 2015



Propagation of Thermal tides to the upper atmosphere

(Signature detetected by stellar occulations (Toigo et al. 2010)



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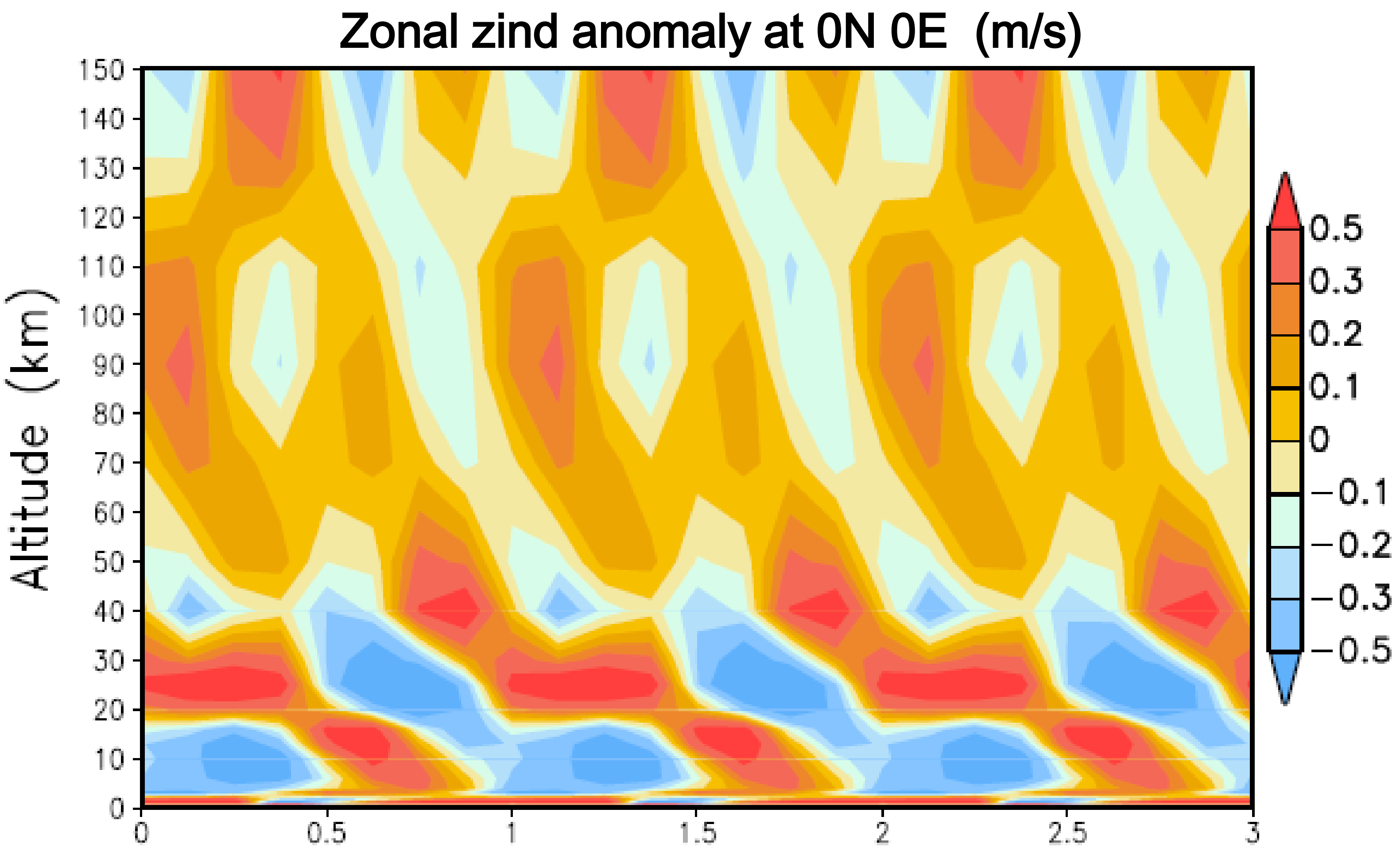
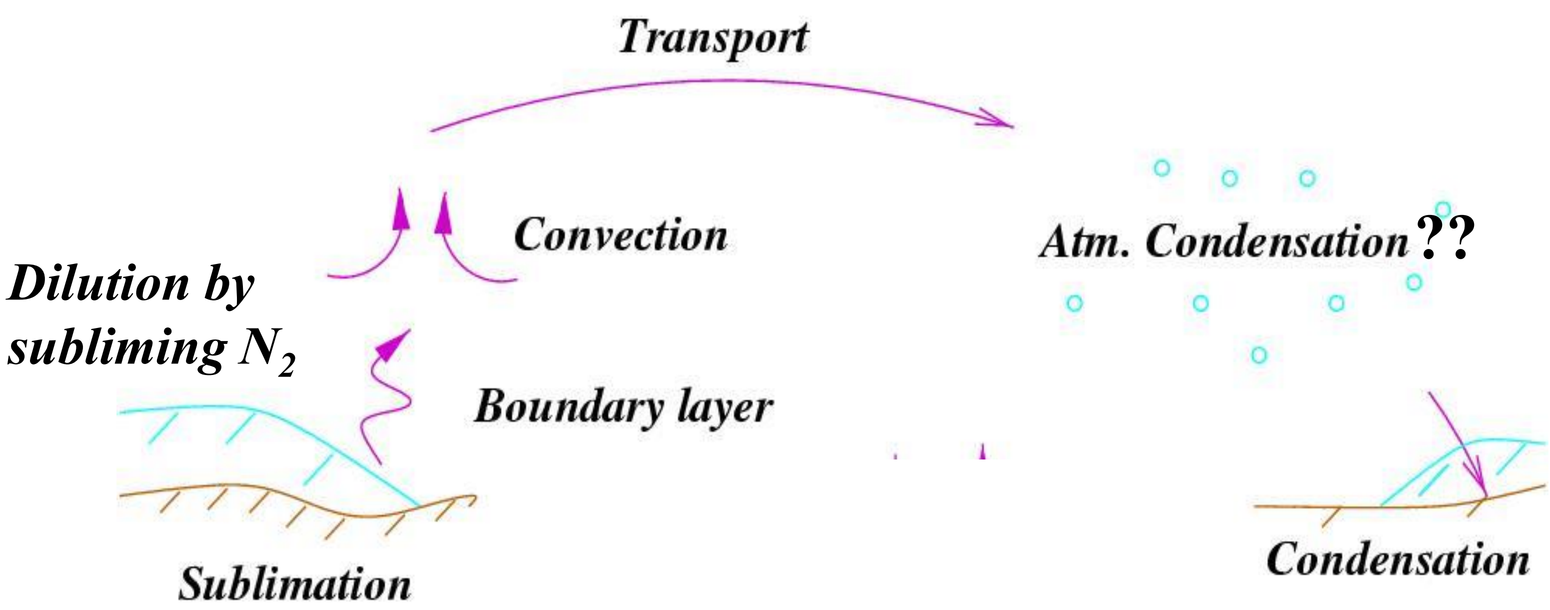


Time (Pluto days)

Will New Horizons see Hazes and clouds ?

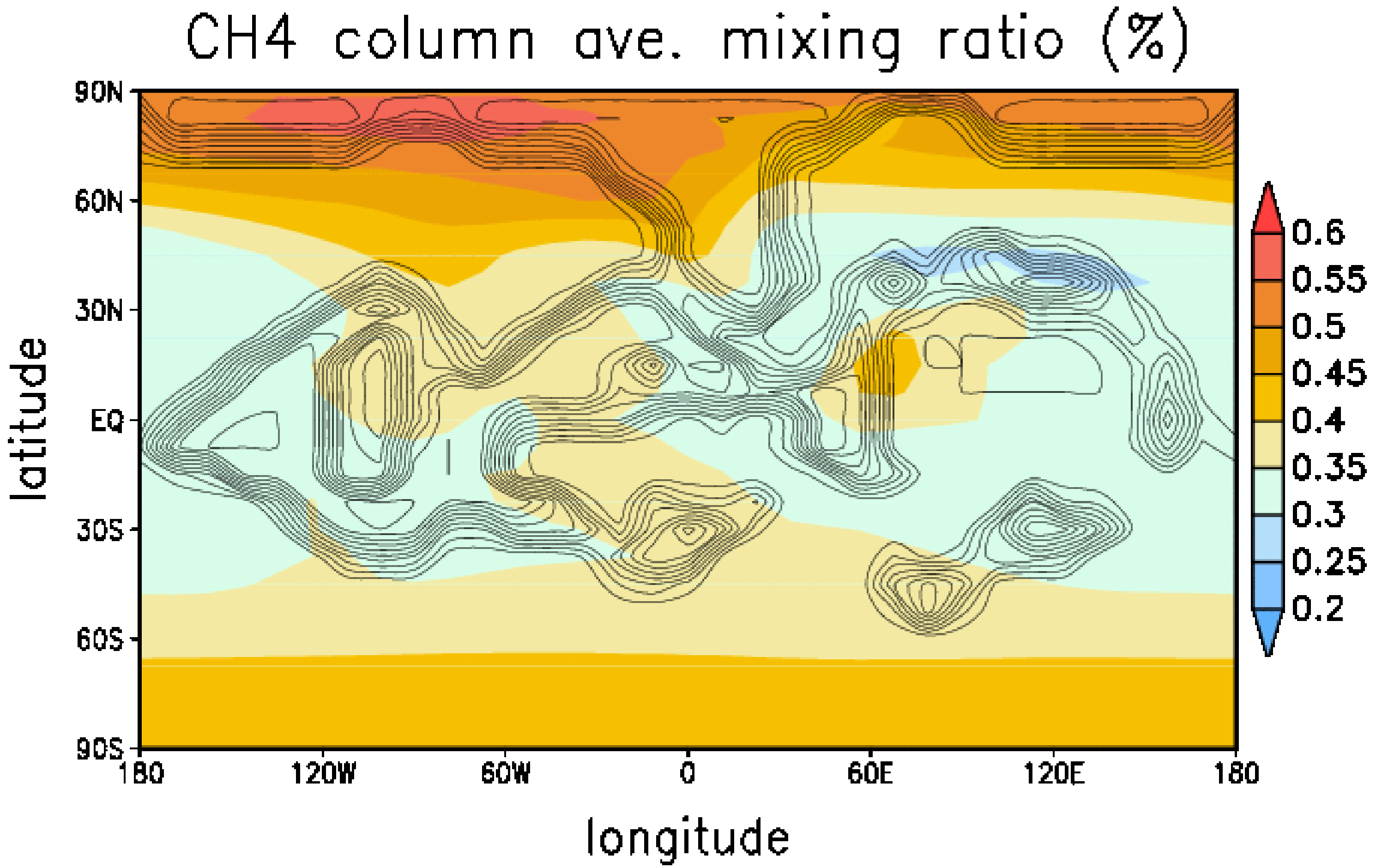
- Nitrogen Ice clouds? Probably not
- Methane ice clouds ?
- Photochemical organic Hazes ?

Modelling the Methane cycle

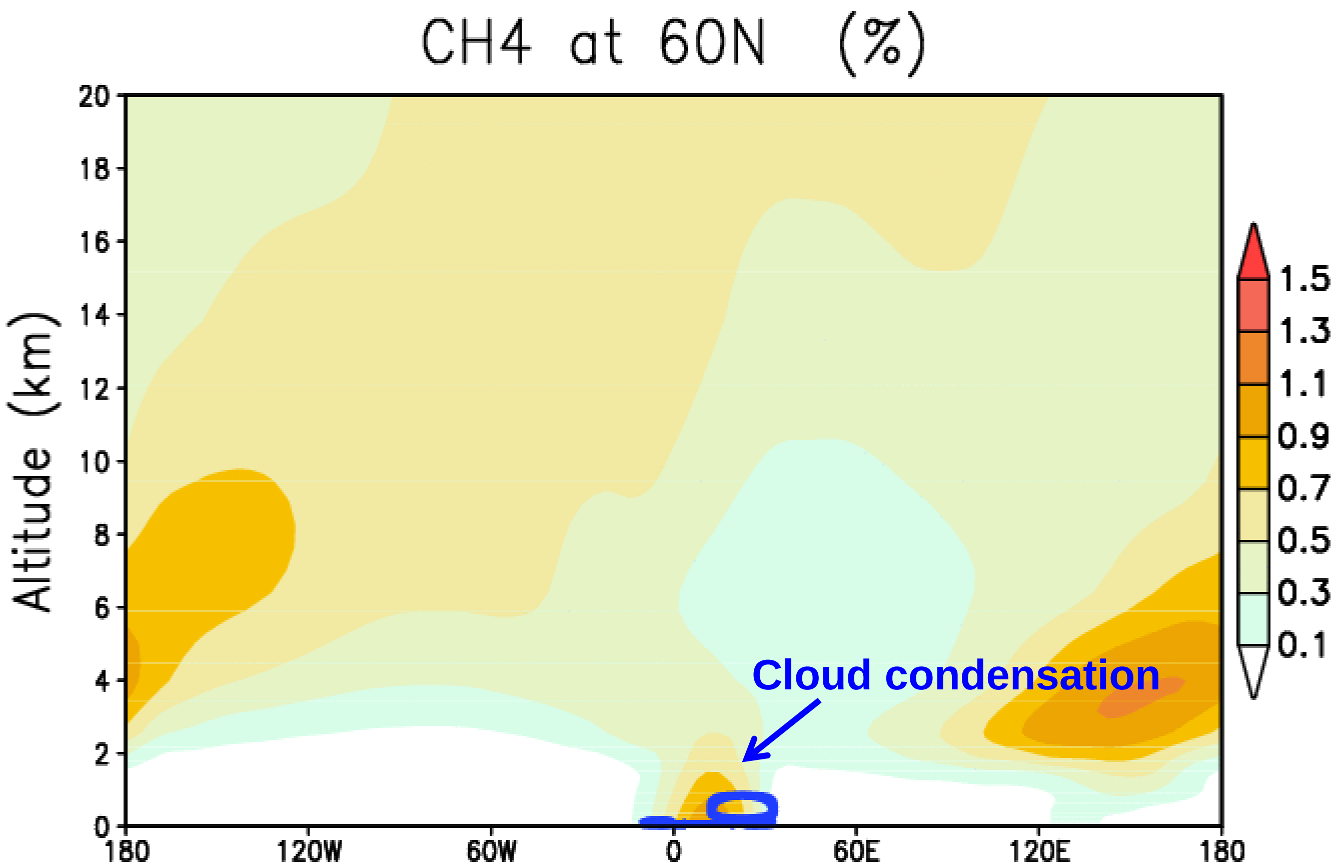


microphysics of N2-CH_4
mixture neglected

CH4 Column averaged volume mixing ratio



2015

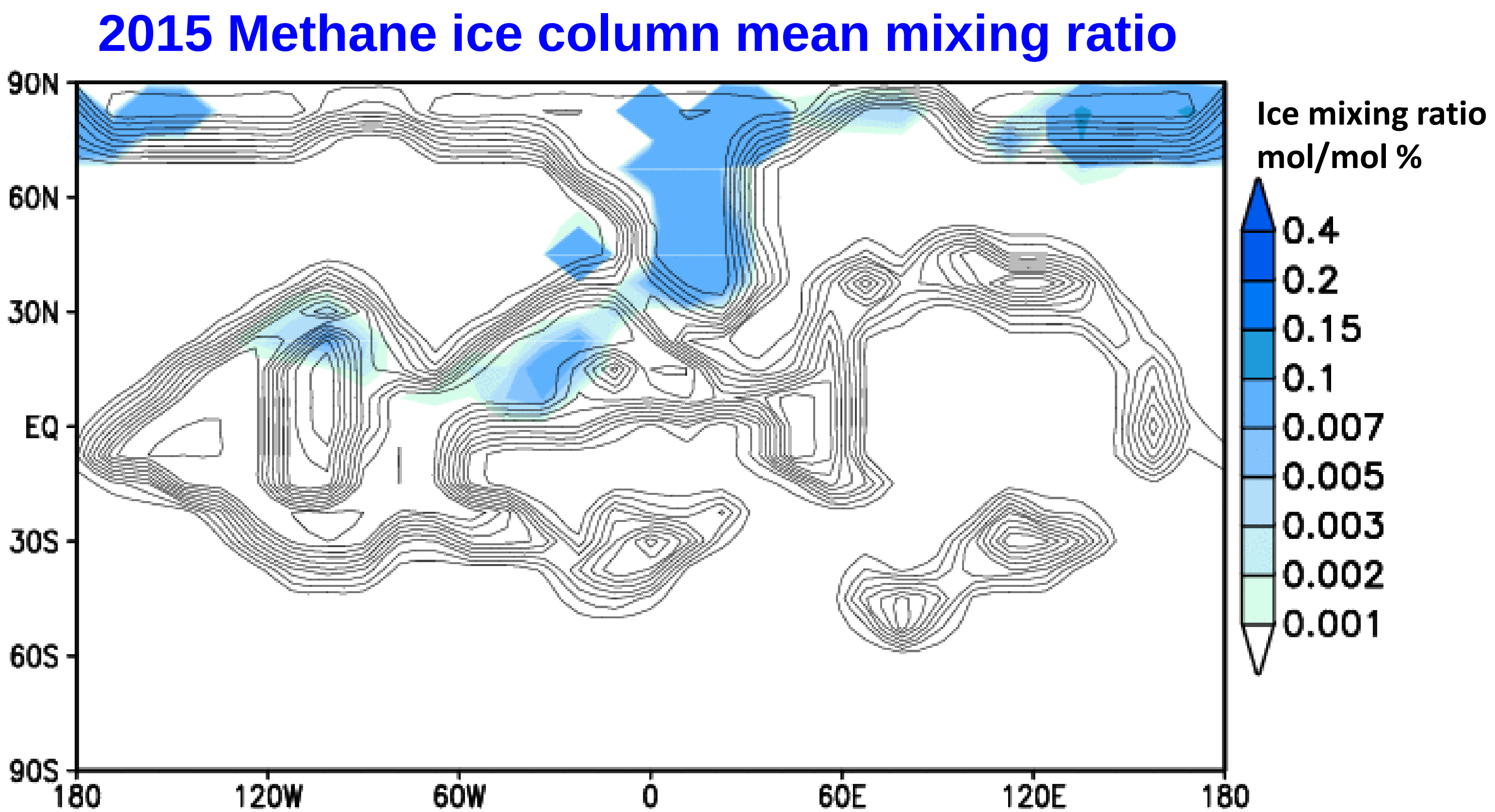


CH4 at 60N (%)
Altitude (km)
20
18
16
14
12
10
8
6
4
2
0
180
120W
60W
0
60E
120E
180
1.5
1.3
1.1
0.9
0.7
0.5
0.3
0.1
Cloud condensation

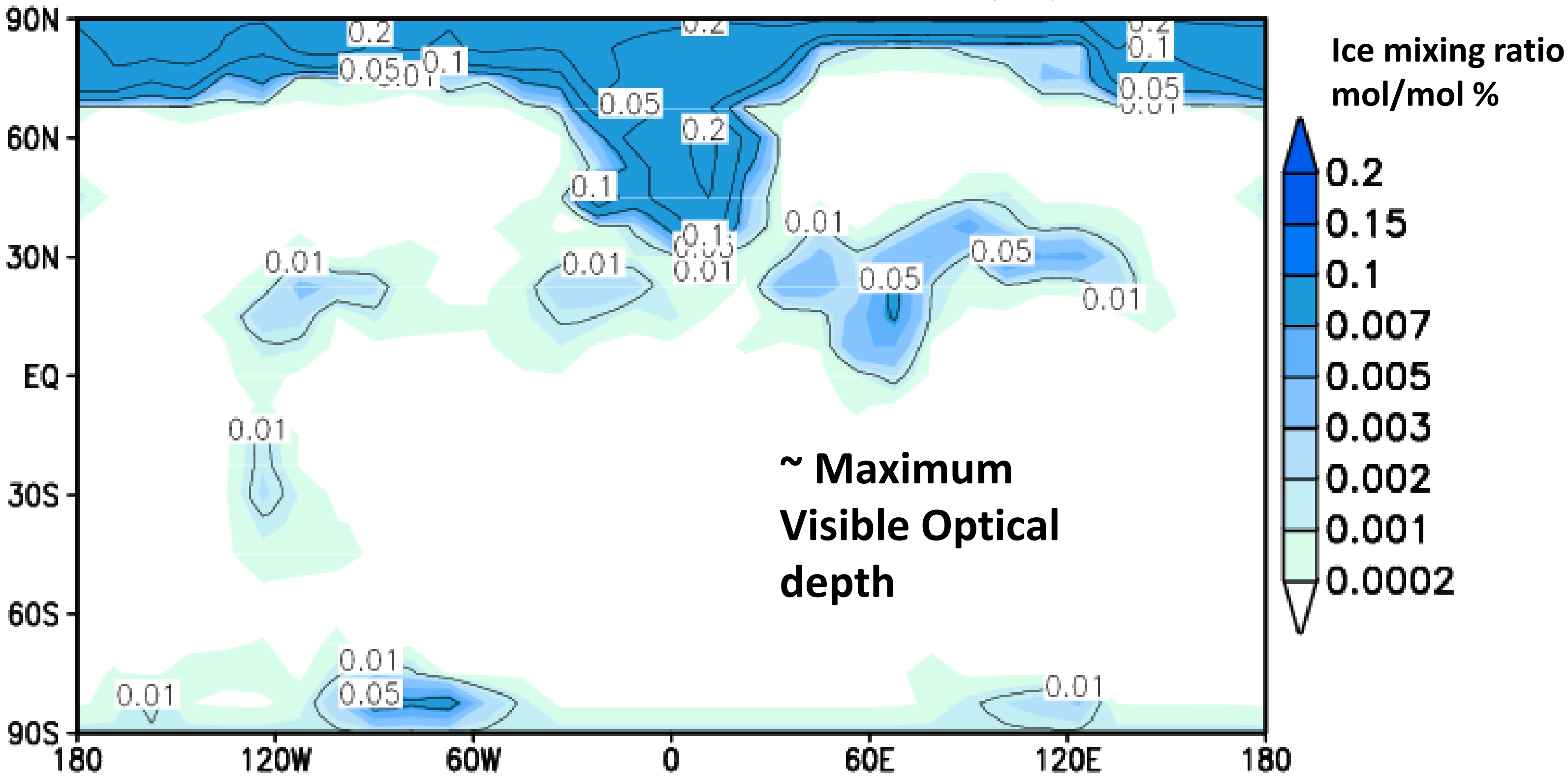
If one assume that CH4 ice clouds can nuclei on Pluto…

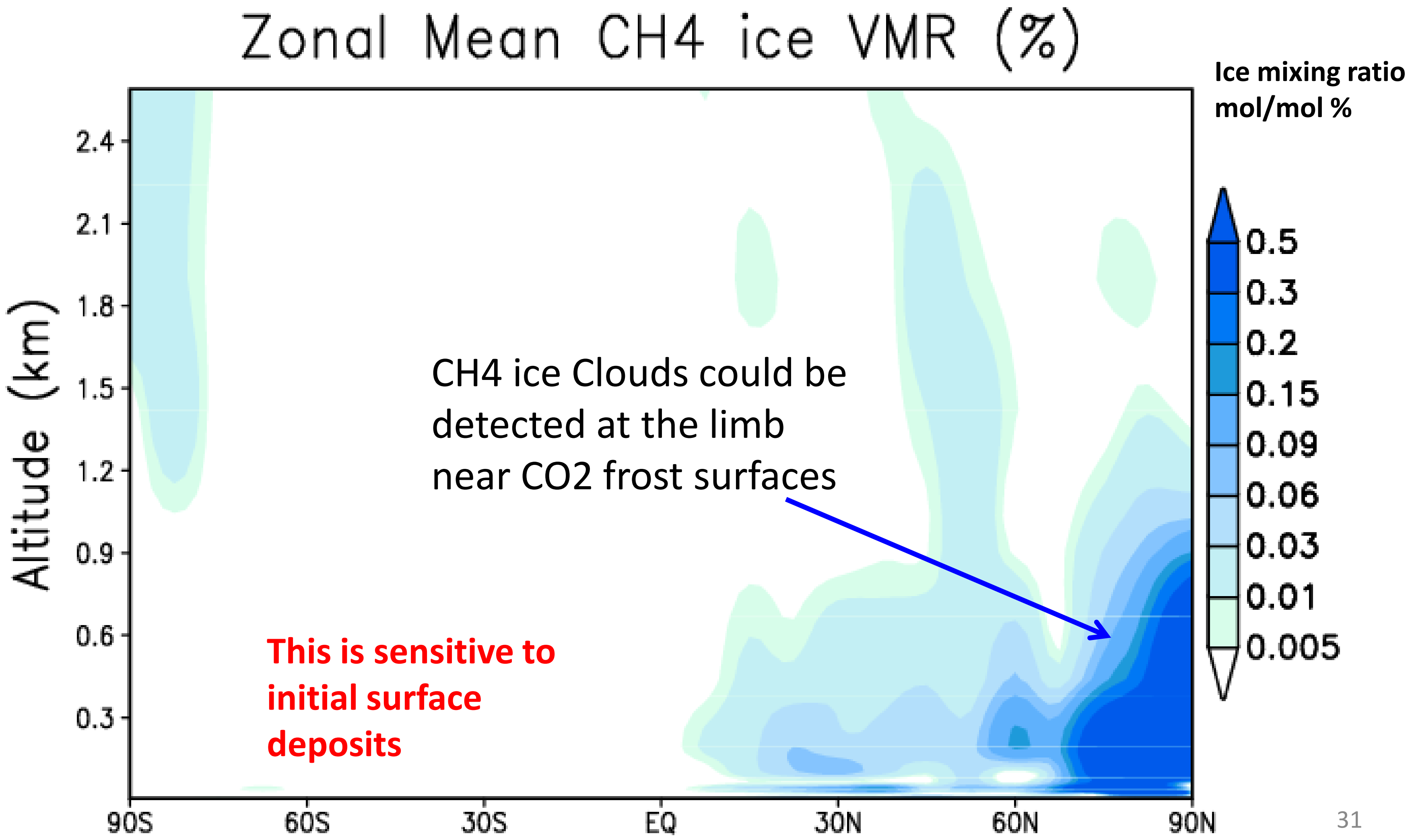
(Assuming 100 Cloud condensation nuclei per kg of air)

Map of clouds (mostly in the low, cold atmosphere)



2010 Mean Methane ice column mean mixing ratio



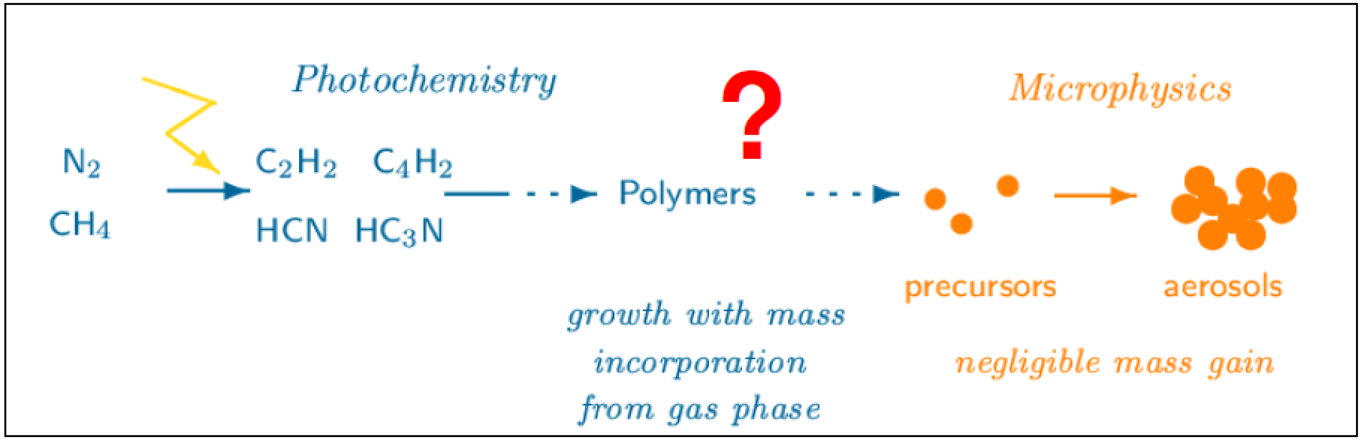


Zonal Mean CH4 ice VMR (%)
Ice mixing ratio
mol/mol %
Altitude (km)
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
90S
60S
30S
EQ
30N
60N
90N
0.5
0.3
0.2
0.15
0.09
0.06
0.03
0.01
0.005
CH4 ice Clouds could be detected at the limb near CO2 frost surfaces
This is sensitive to initial surface deposits

Organic Hazes, like on Titan

See Rannou and Durry, 2009

Titan-like aerosols formations

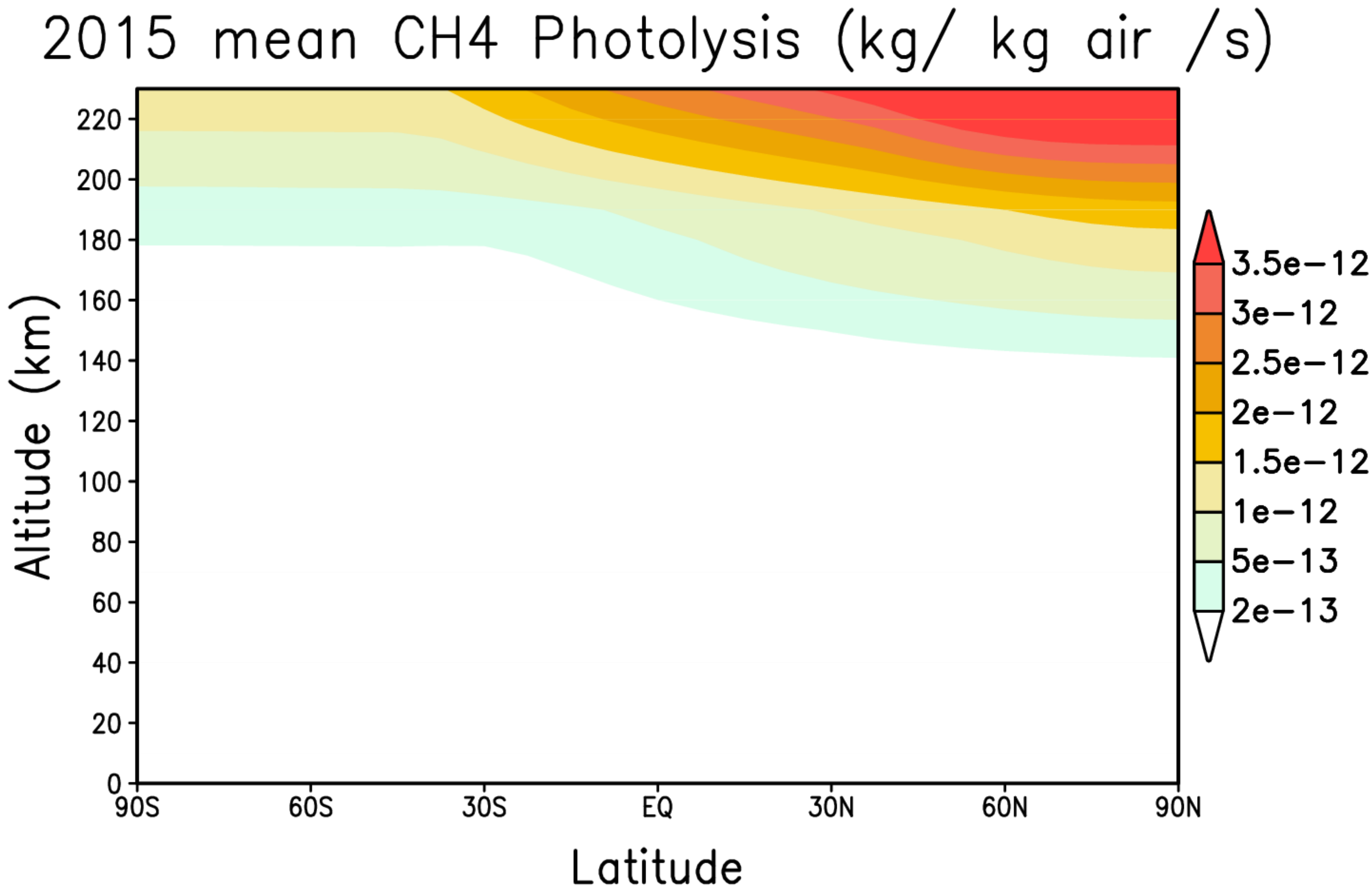


- **Pathway to aerosols not very well known:** [Lebonnois et al. (2002), Wilson and Atreya (2003) and Lavvas et al (2008)]
- **Hypothesis for Pluto**: Aerosols generated by Lyman-α photolysis of methane (CH3, CH2 , CH ⇨ + N …)

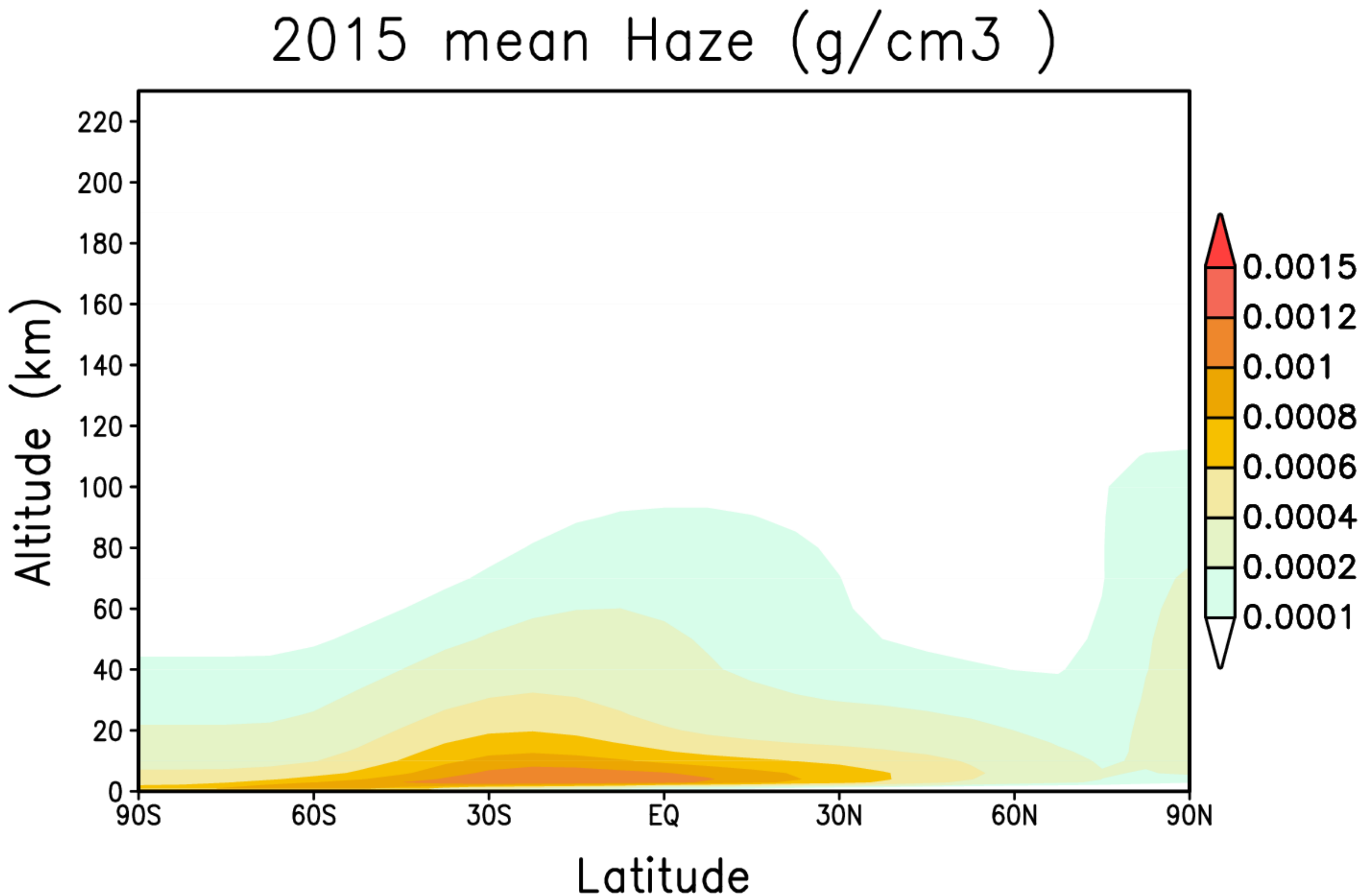
  ⇨ ***This provide an excellent estimation of Titan's total aerosol production (but not Triton?)***

- **Scheme for Pluto GCM**
  1) Radiative transfer of Ly-α *(Solar + Interplanetary: Gladstone et ql. 2015)* ⇨ precursor molecules in the upper atmosphere ⇨ Transport
  2) Precursor convert to aerosols with characteristic decay time scale τ (a fraction of C and N is added with C/N = 2).

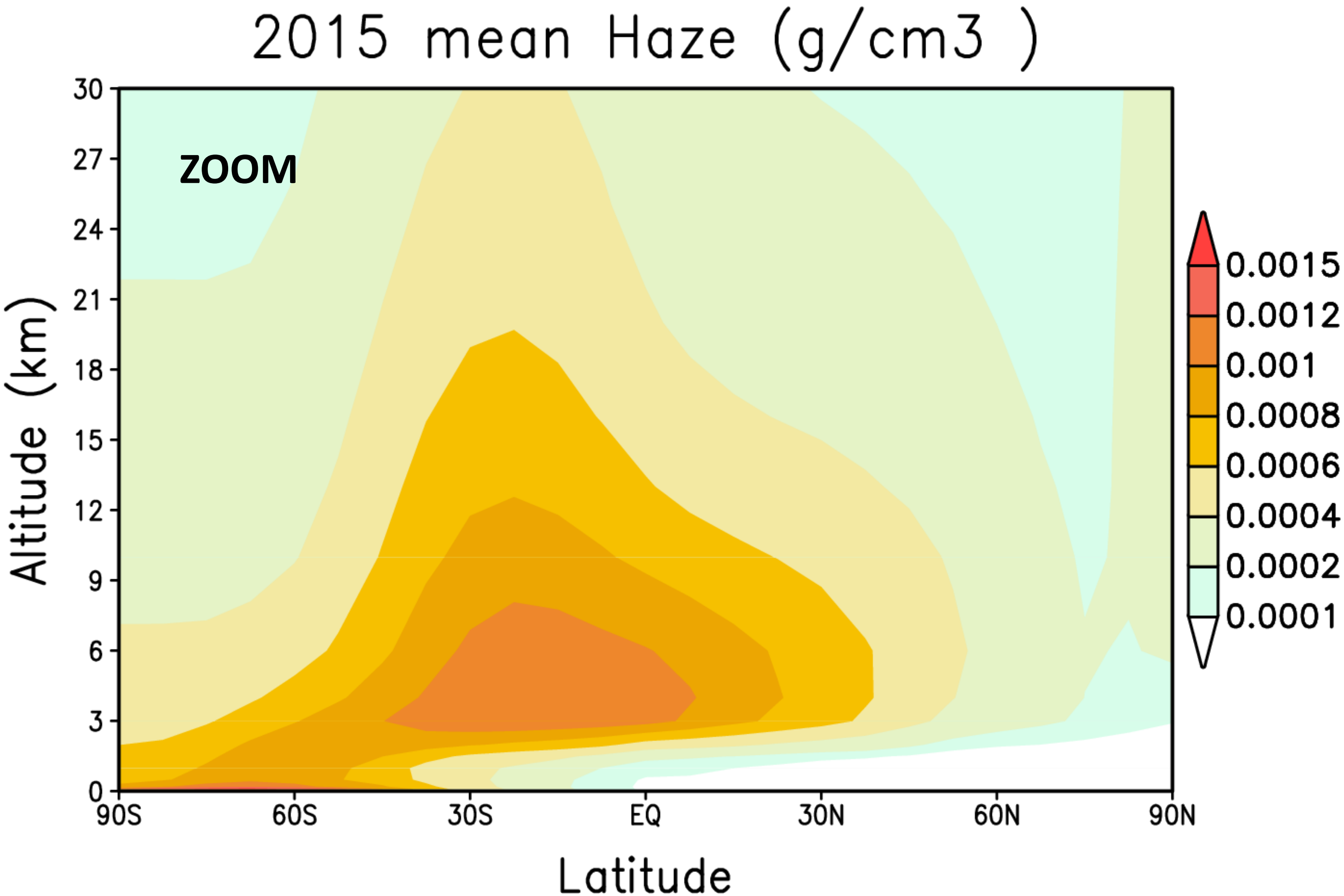
     ⇨ Transport & Sedimentation (monomers ~40 nm, ρ = 800 kg m^{-3})


2015 mean CH4 Photolysis (kg/ kg air /s)
Altitude (km)
220
200
180
160
140
120
100
80
60
40
20
0
90S
60S
30S
EQ
30N
60N
90N
Latitude
3.5e−12
3e−12
2.5e−12
2e−12
1.5e−12
1e−12
5e−13
2e−13

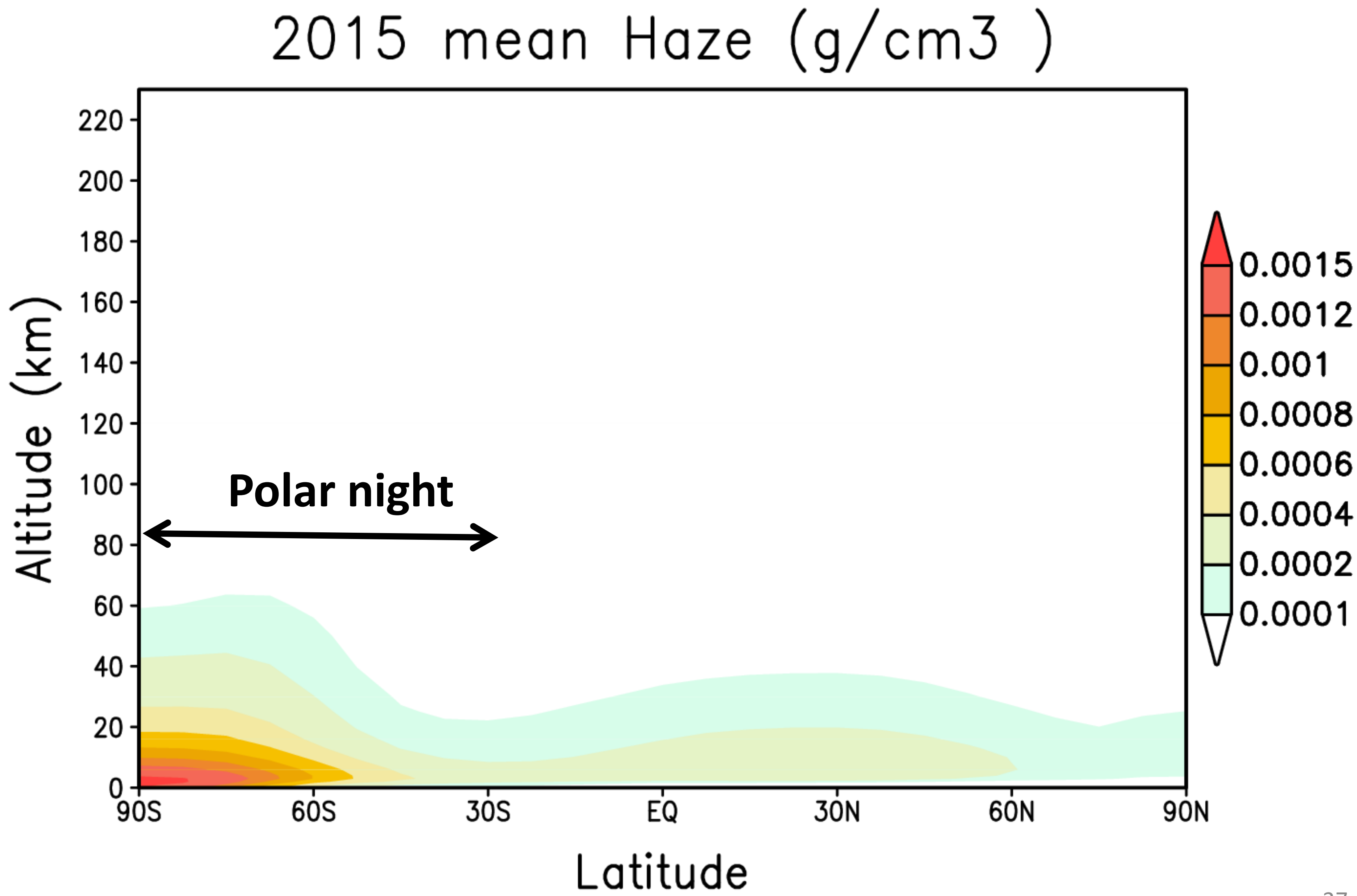
Direct conversion CH4+ hv → aerosols



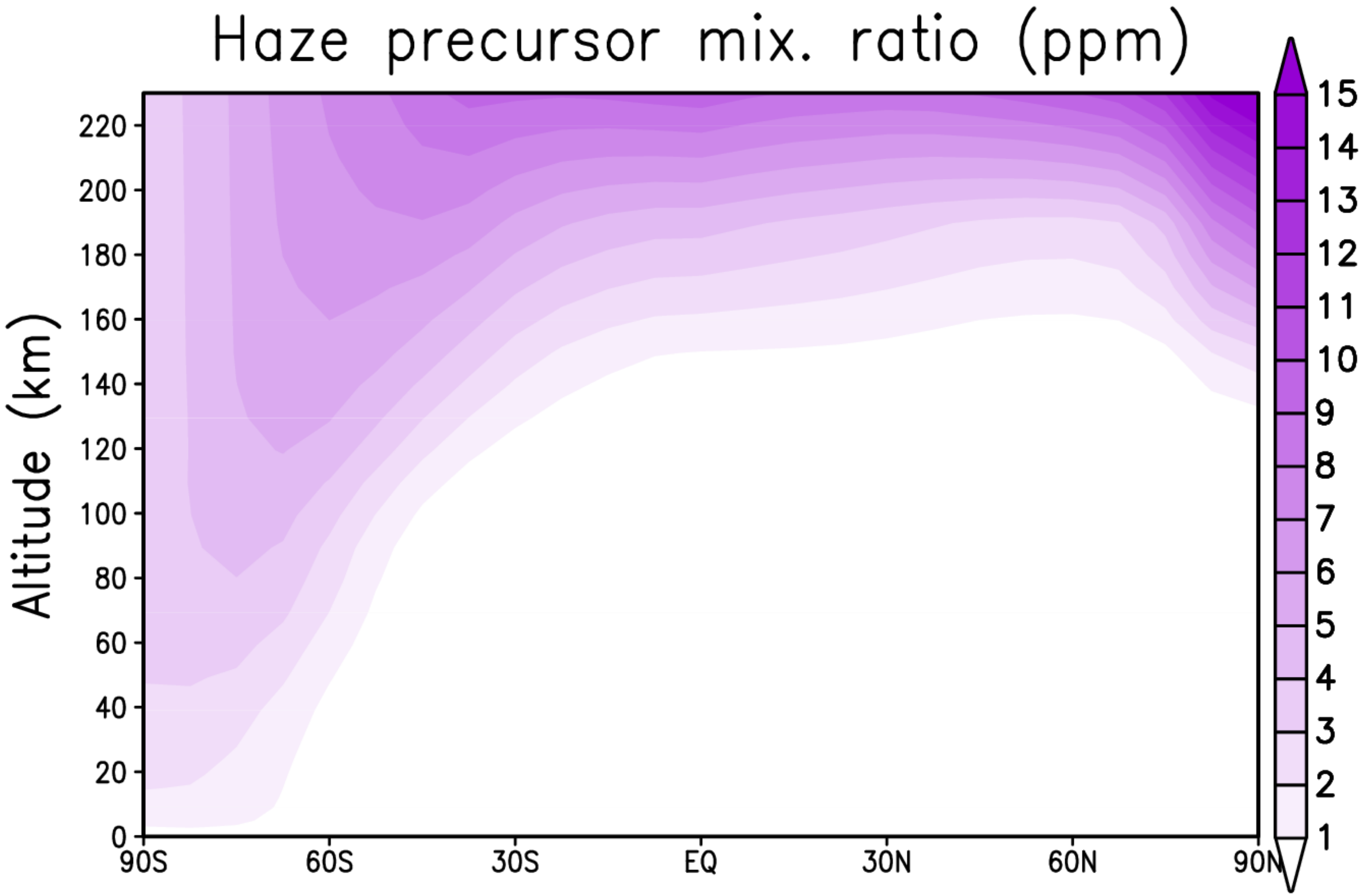
Direct conversion CH4+ hv → aerosols



CH_4+ hν → precursors (τ=1.E7s) → aerosols



$CH_4 + h\nu \rightarrow$ precursors (τ=1.E7s) $\rightarrow$ aerosols



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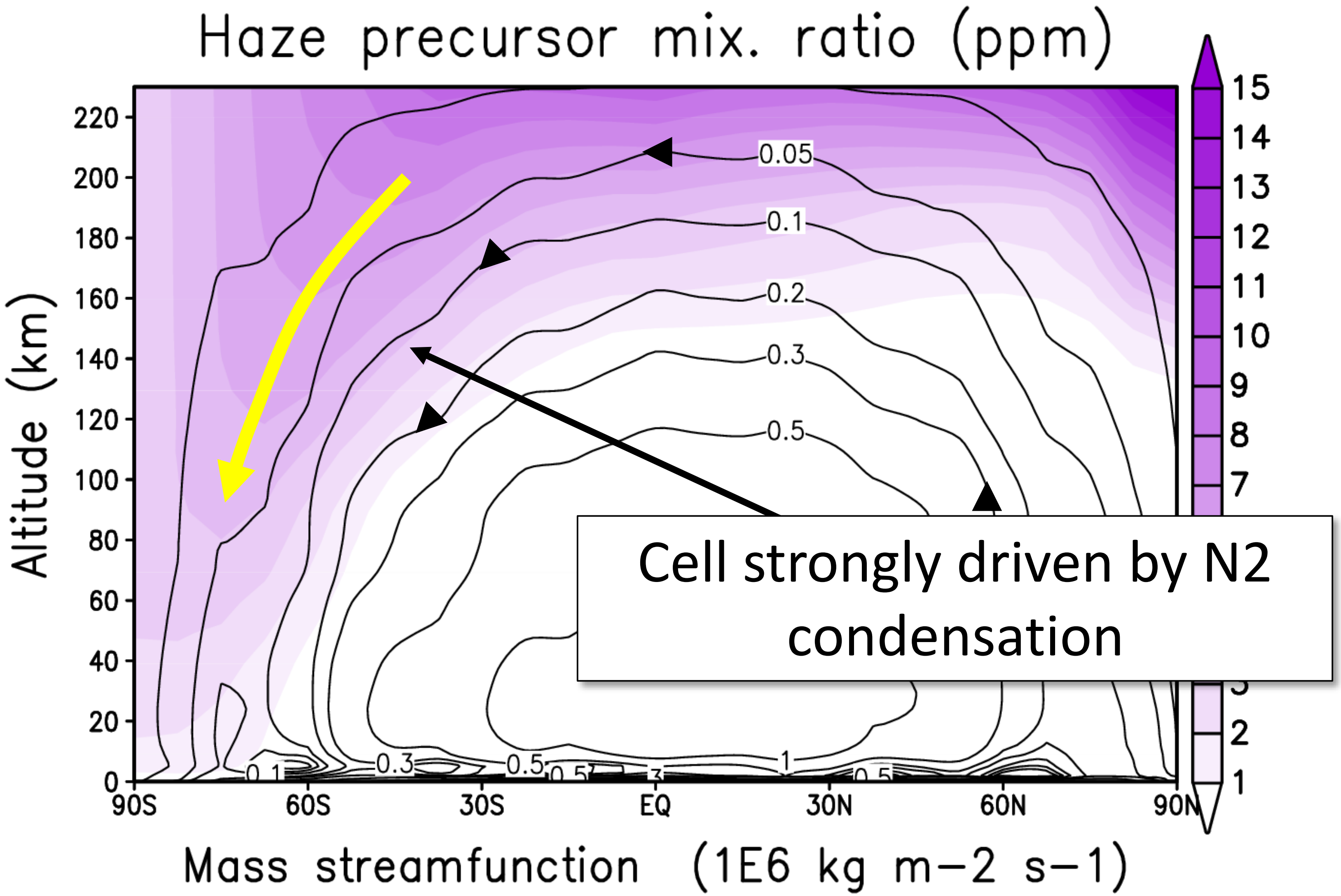
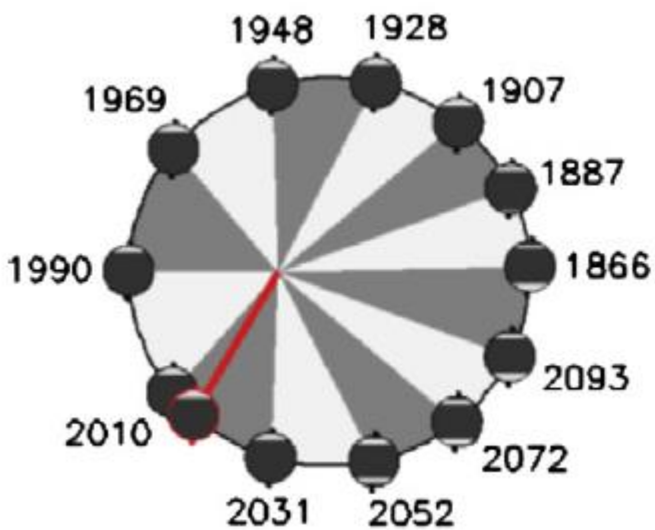
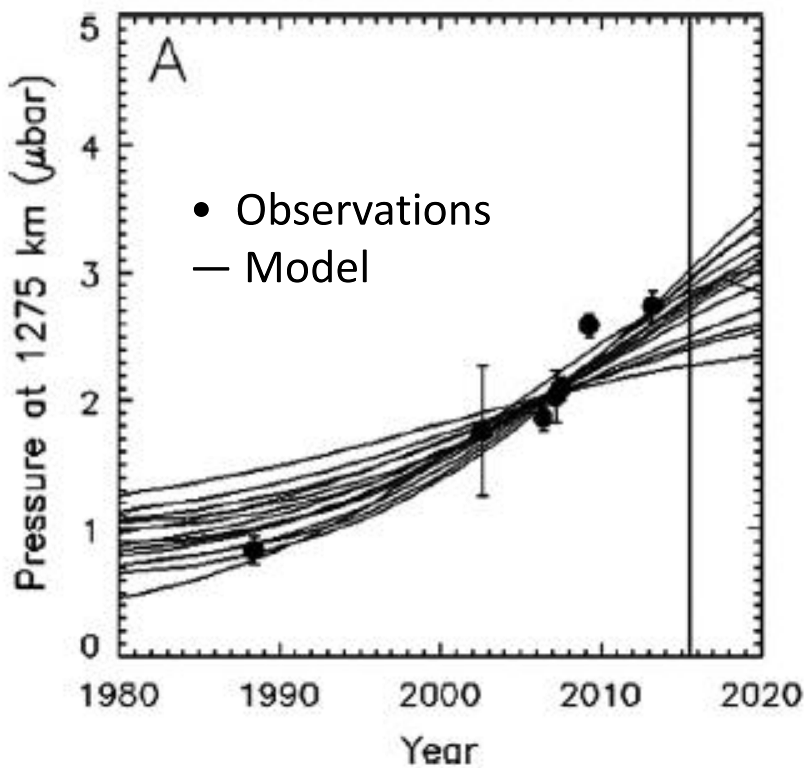


However: the winter polar cap may not yet be condensing (Olkin et al. 2014, Young 2013)

L. Young's model



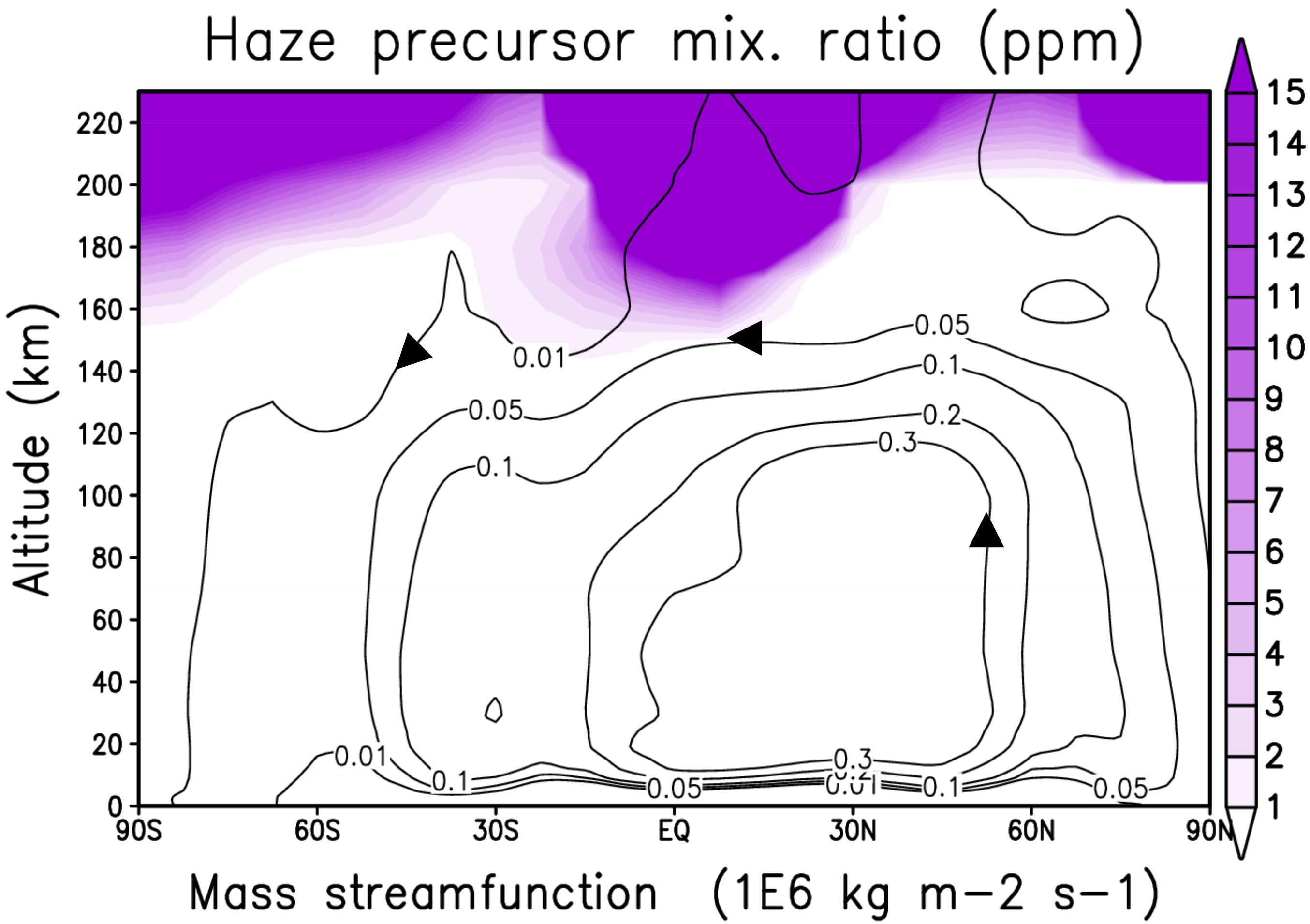


To explain the surface pressure increase detected by stellar occultations, it is necessary to account for a high seasonal thermal inertia, which prevent nitrogen to condense around the rotational south pole before 2050

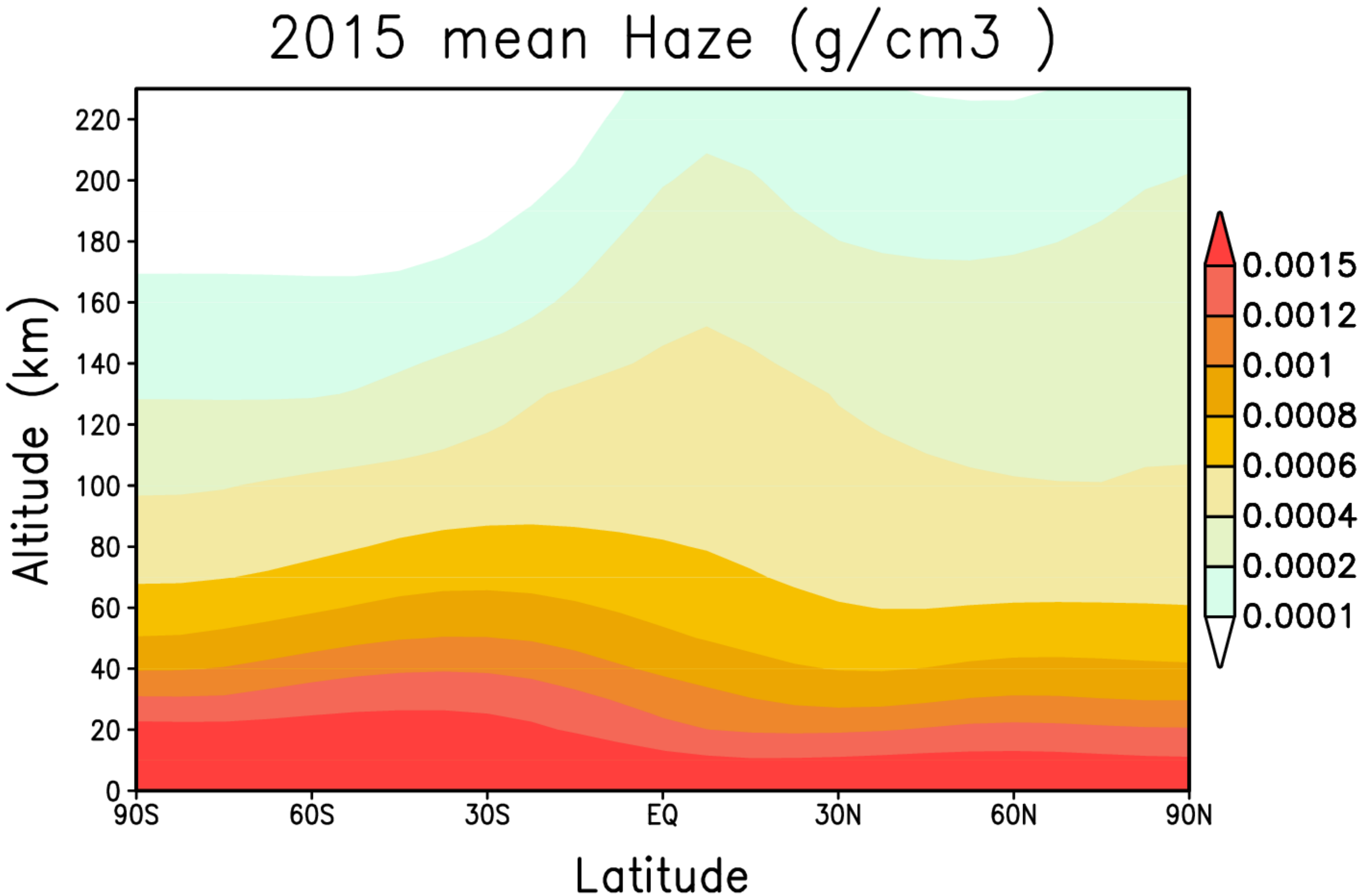
Haze on a Young & Olkin high thermal inertia Pluto

- High seasonal thermal inertia (2000 SI below 3 cm, 20 SI above)
- Low initial subsurface temperature (37K)
- no condensation in the rotational south

⇨ Pressure (strongly) increases ain the recent years expected

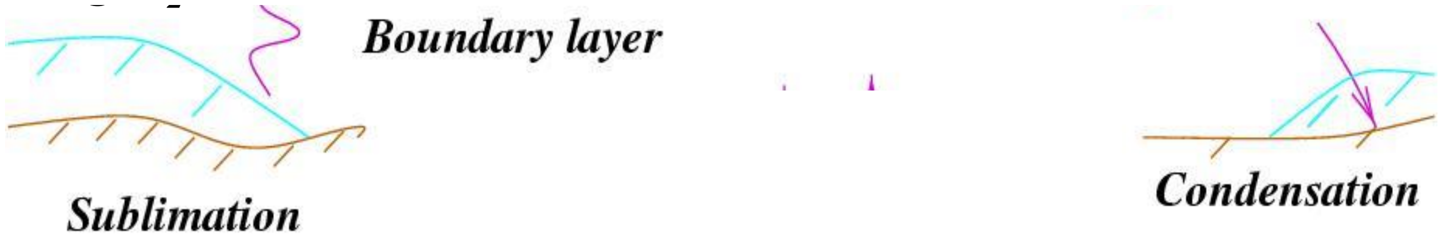


Organic Haze on a Young & Olkin high thermal inertia Pluto



A fast volatile surface model derived from the Global Climate Model

The atmospheric dynamics is replaced by an instantaneous mixing



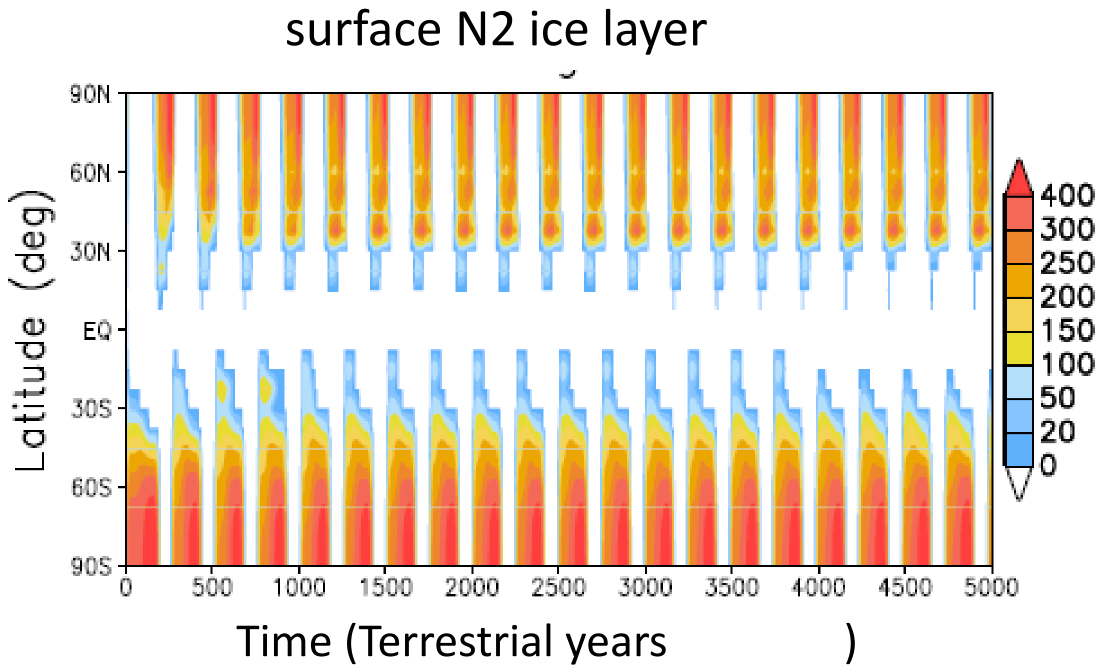
"Volatile Surface Model simulation" (Example)

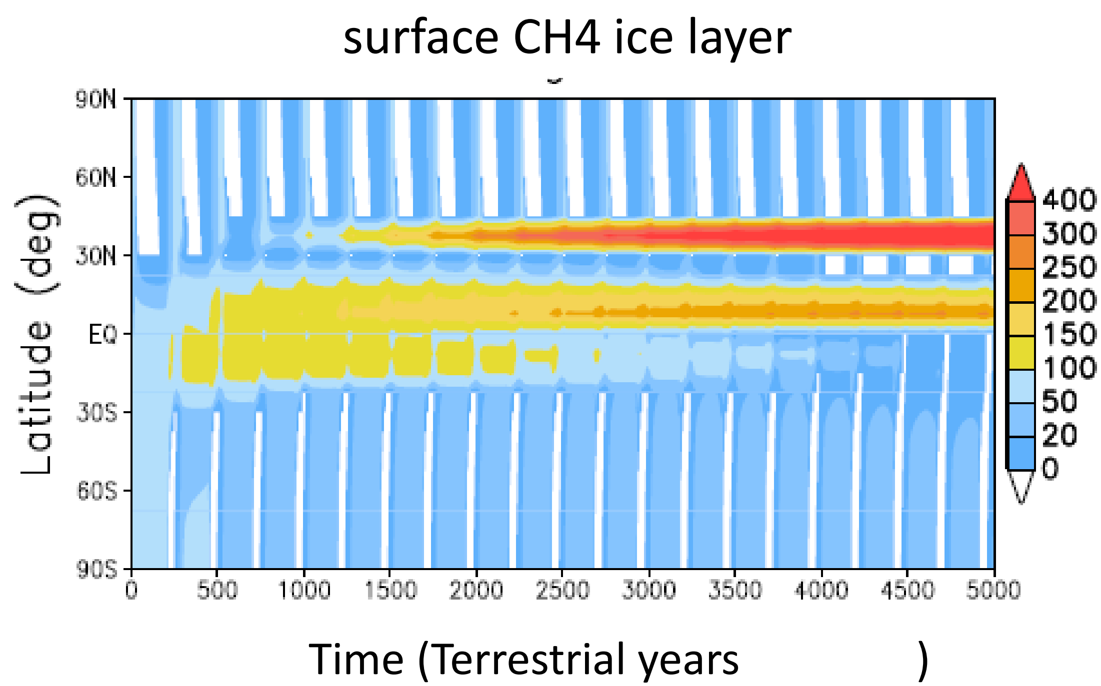
MEDIUM thermal inertia:

I =400 SI

A_{N2} = 0.65
A_{CH4} = 0.45
ε = 0.9

Initially 50 kg m^{-2} of both ices everywhere

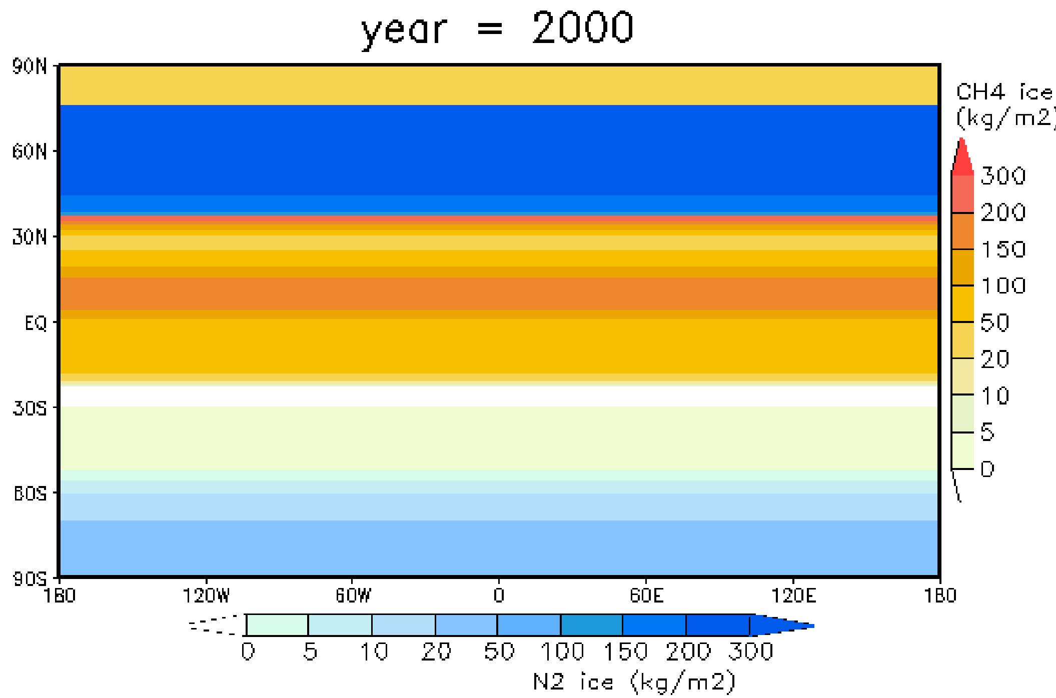


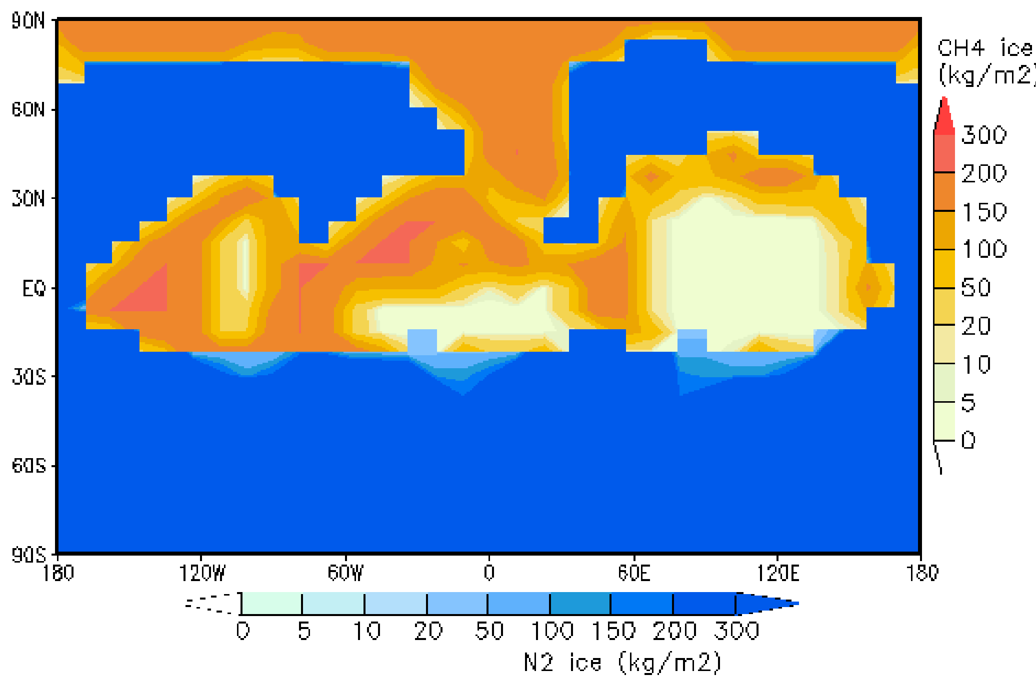


"Volatile Surface Model simulation" (Example)

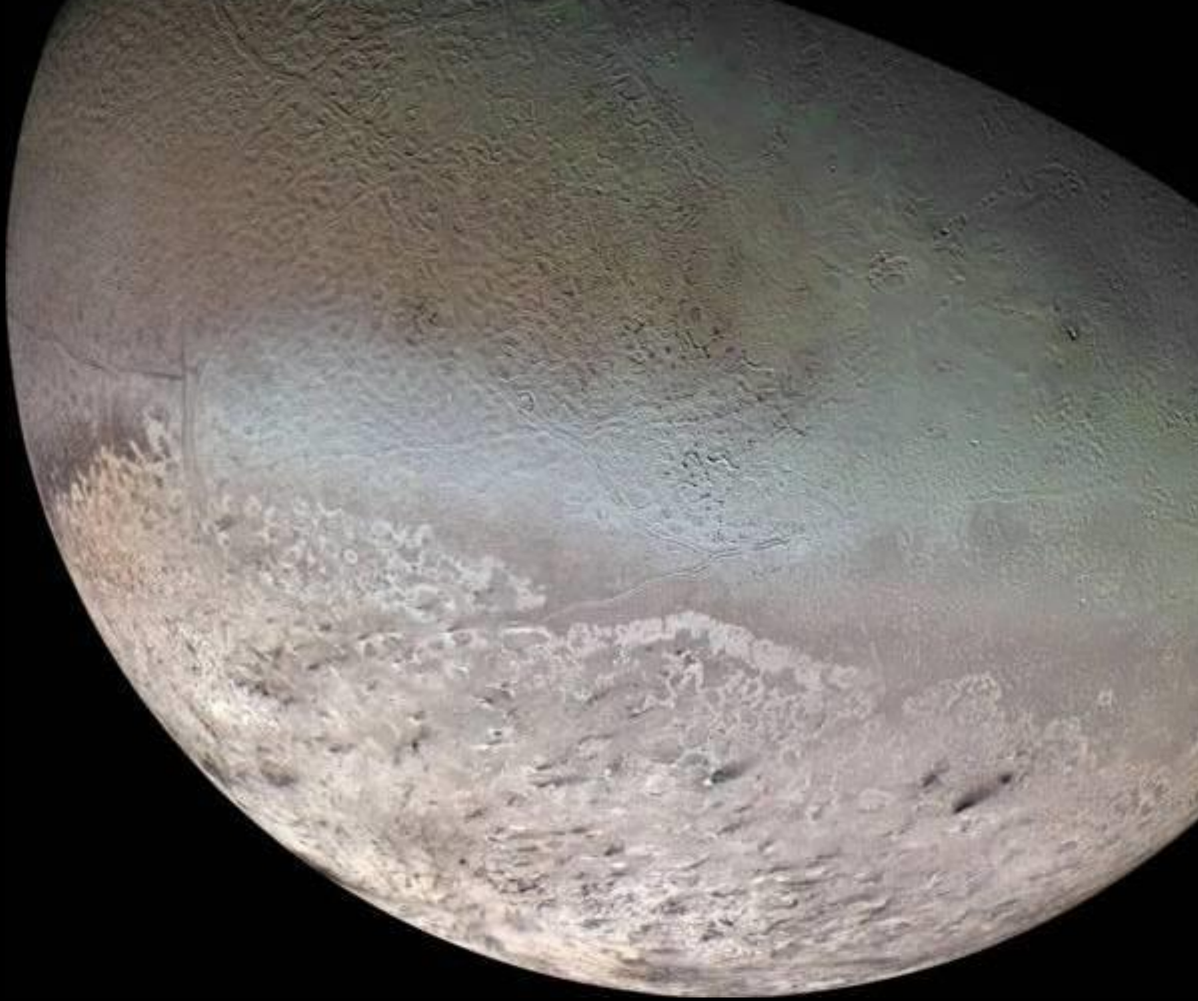
Evolution of modeled surface ices (CH4 ice , N2 ice)

~**Observations** in ~2000 using the same plotting system





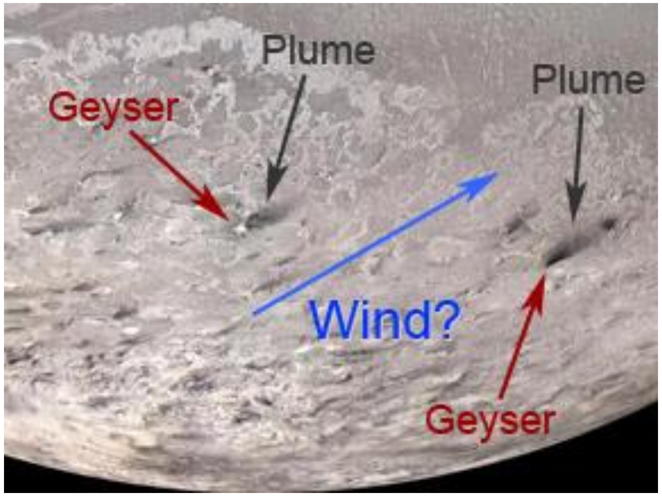
Some results with Triton’ GCM



Triton seen by Voyager 2, 1989

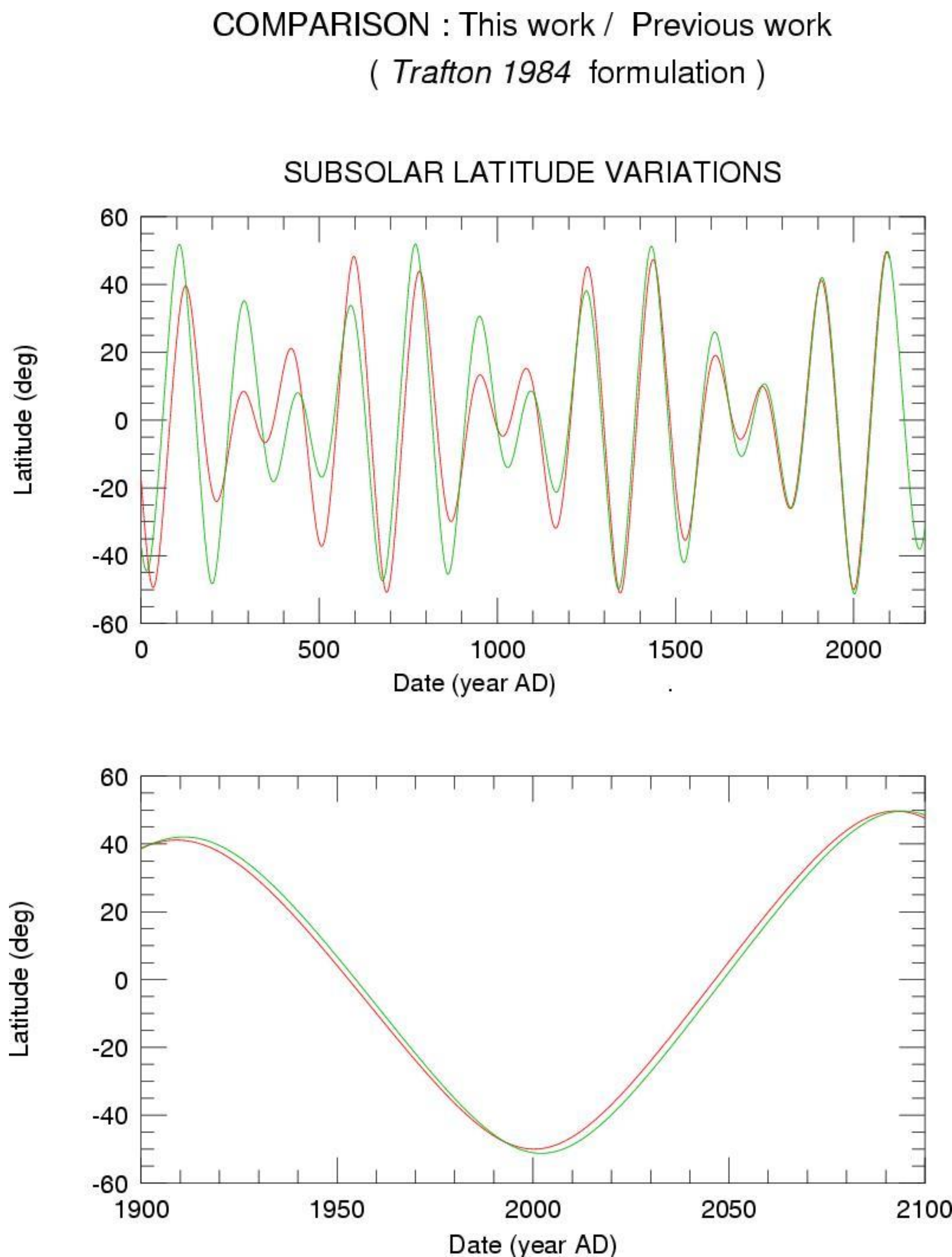
TRITON ATMOSPHERE

- Atmosphere: N_2 + 0.02 % CH_4
- Surface pressure (1989) ~1.4 Pa, rising
- Some things we know about Triton in 1989
  - Surface dark streaks direction : eastward surface wind in the southern hemisphere
  - Geyser like Plumes
    - Westward wing ad ~8 km in the southern hemisphere
    - Tropopause around ~8 km
- What we don't know well:
  - Surface frost distribution (N2, CO, CH4, …)



New calculation of Triton seasonal variations required to compute cap evolution…

(Forget et al. 2000)

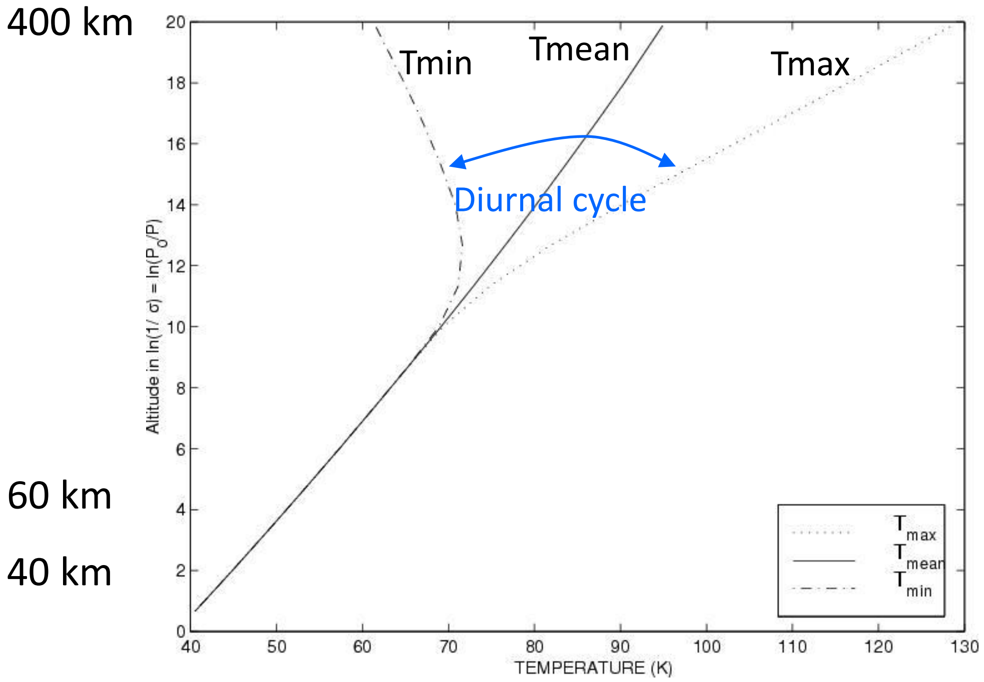


Triton free atmosphere processes : hypothesis

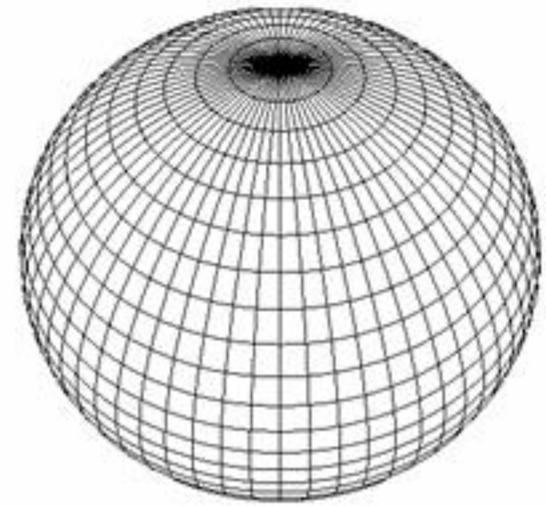
• No radiative transfer below 40 km (Yelle et al.
• Conduction : Temperature below 40 km insensitive to thermosphere variations (400 km)

⇨Constant flux from thermosphere

Example of temperature profiles



Triton General Circulation Model



1) Hydrodynamical code

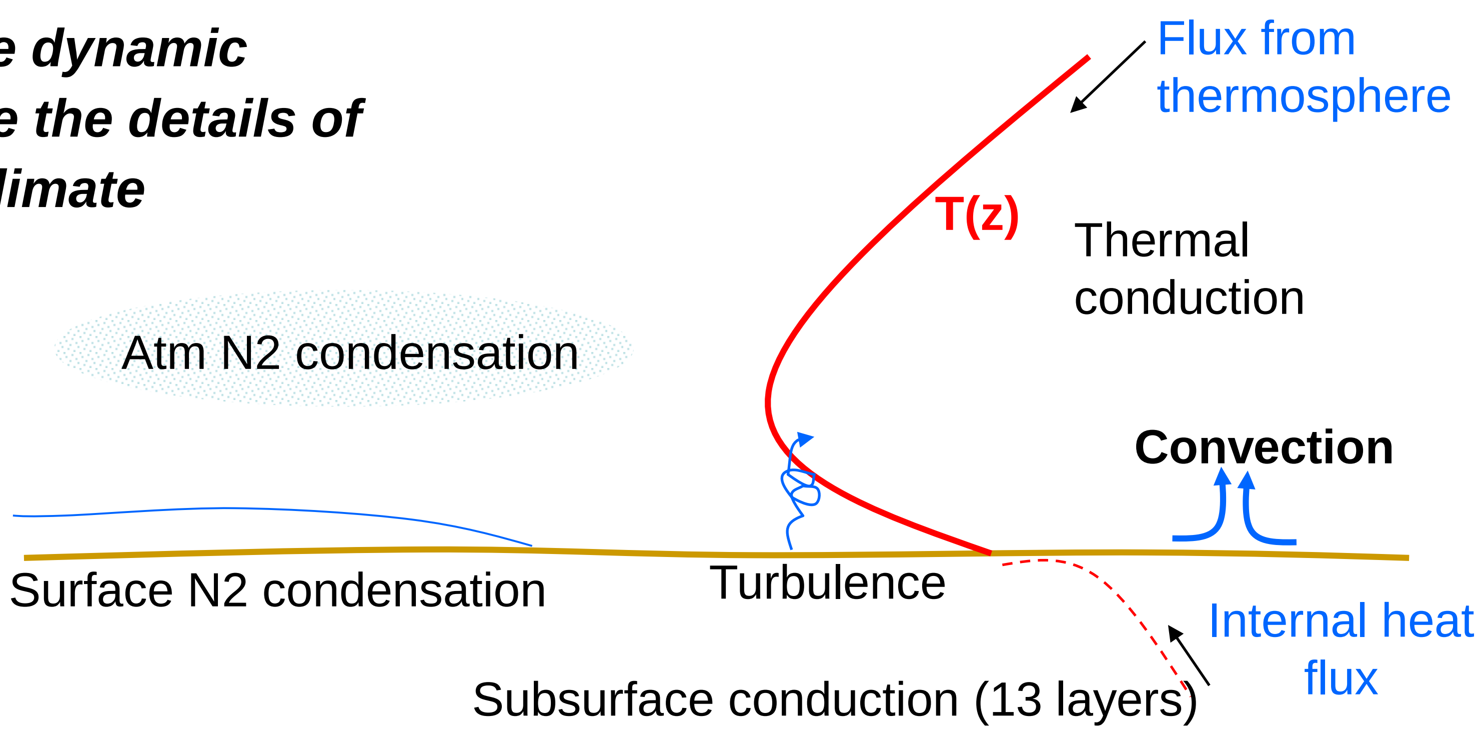
⇒ ***to compute large scale atmospheric motions and transport***

- Grid point model
- Horizontal resolution : ~200 km (32x24)
- 15 vertical layers (5m, 20m, … 50 km)

2) Physical parameterizations

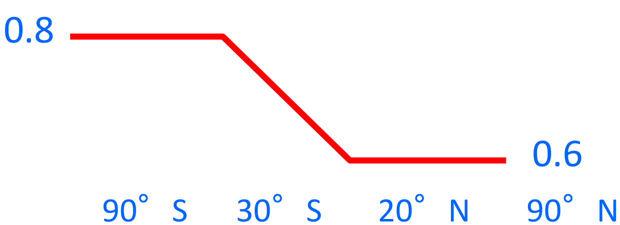
⇒ ***to force the dynamic***

⇒ ***to compute the details of the local climate***



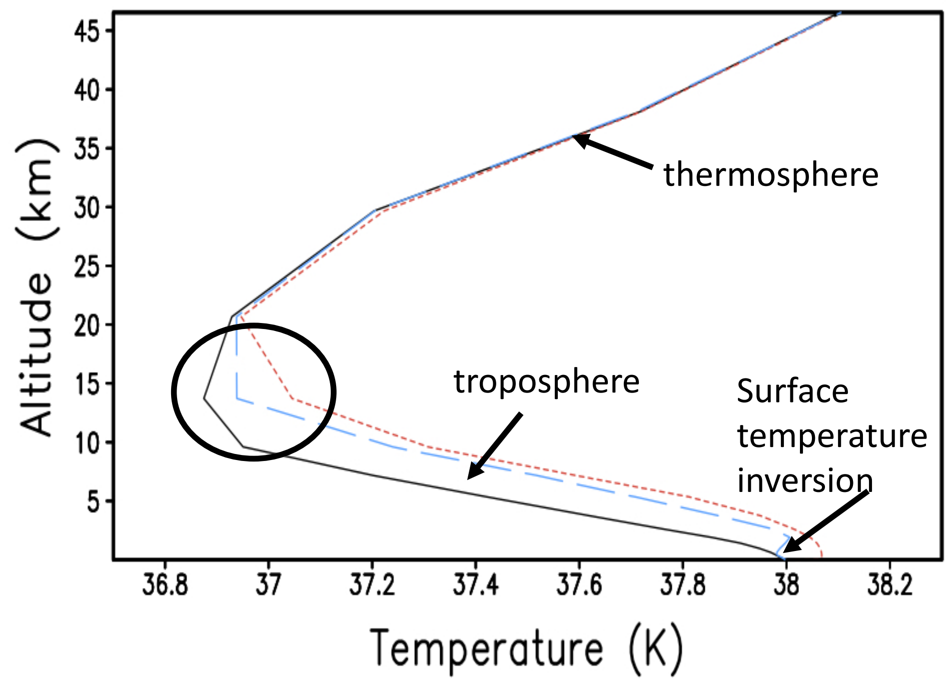
Case 1 : Triton totally covered by N_2 ice

- Bolometric albedo :



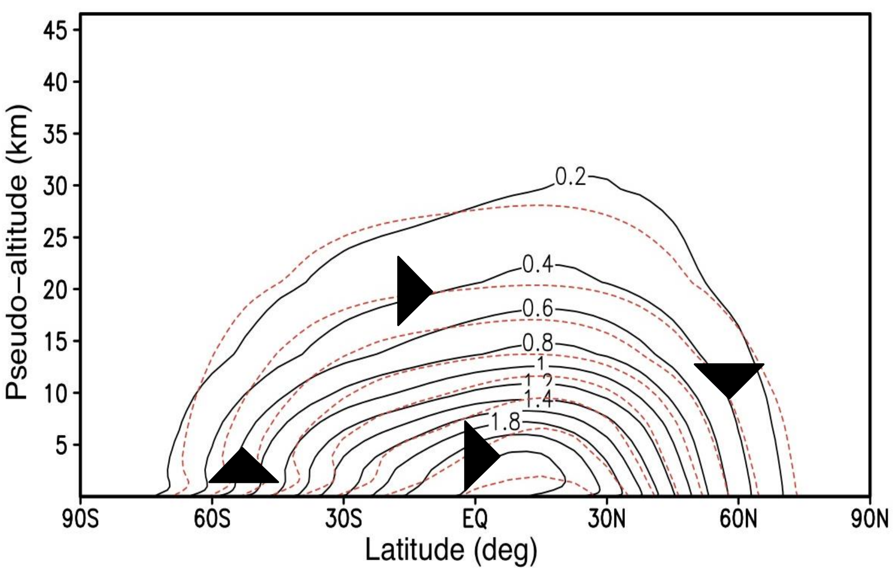
- Emissivity = 0.74
- Thermal inertia =50 J m^{-2} $s^{-1/2}$ K^{-1}
- Flux géothermique nul
- Ice Surface temperature = 38K
- Initial temperature profile = isotherm

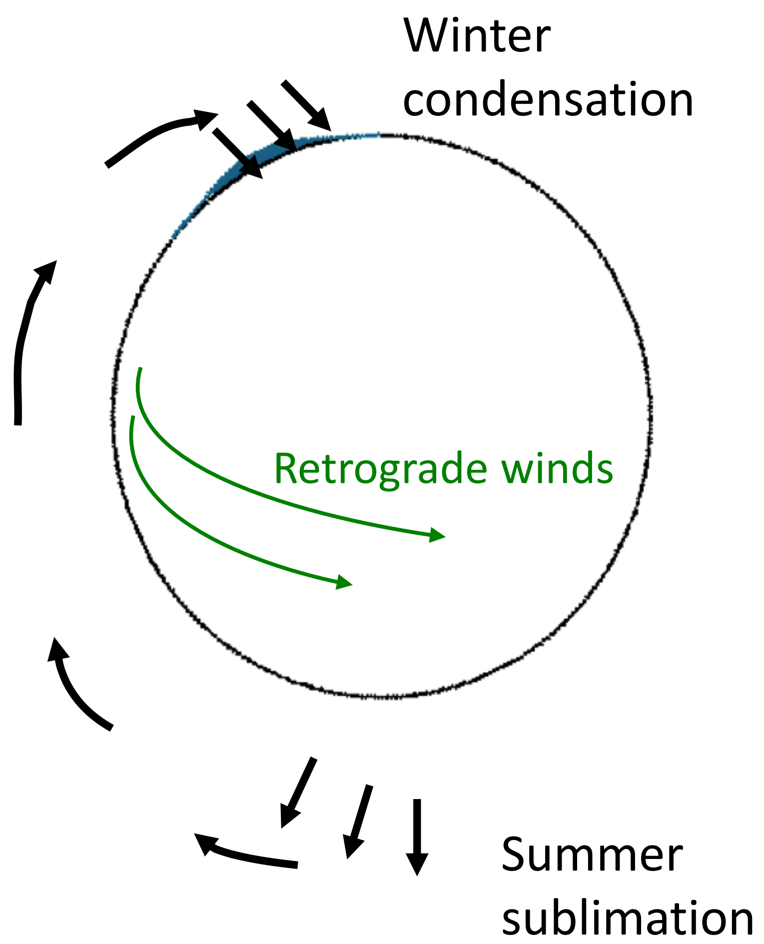
Mean temperature profiles for three different latitudes :
0° ; 45° N and 45° S.



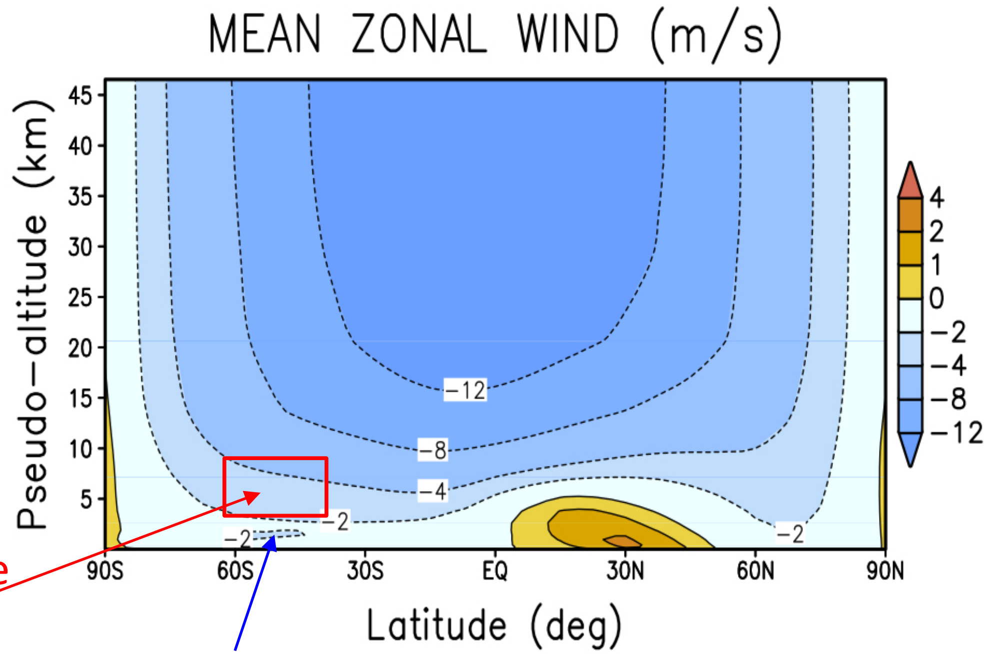
Case 1 : Triton totally covered by N_2 ice

Angular momentum +
Streamfunction (10^7 kg m^{-2} s^{-1})

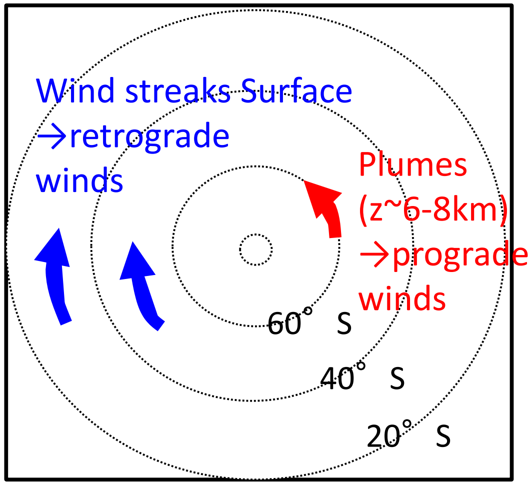




Case 1 : Triton totally covered by N_2 ice



Observations

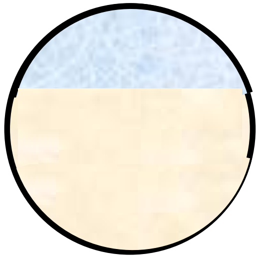


No prograde winds (contrary to observations)

Retrograde surface winds

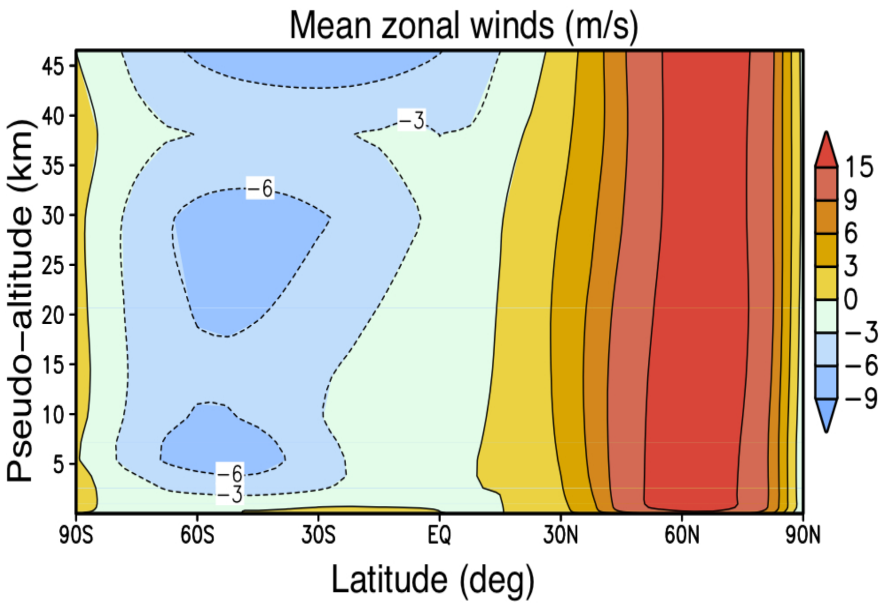
<u>**Not consistent with Voyager 2 winds observations**</u>

Case 2 : Frost free southern hemisphere



Frost free southern hemisphere (Spencer et al. 1990) ("Dark cap model", Hansen and Paige 1992)

- Ice bolometric albedo : 0.6 (dark ice)
- Ground bolometric albedo = 0.8
- Emissivity = 0.5
- Thermal inertia =50 J m^{-2} $s^{-1/2}$ K^{-1}
- Flux géothermique nul
- Ice Surface temperature = 38K
- Initial temperature profile = isotherm

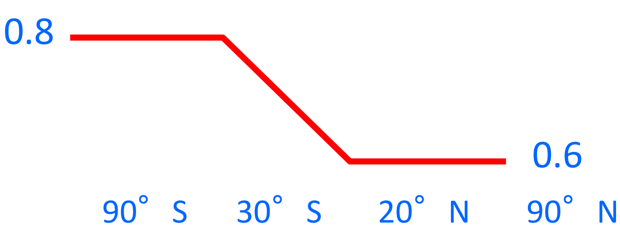


Not consistent with Voyager 2 winds observations

Case 3 : Triton with an unfrosted equatorial band

Ingersoll et al. 1990

- Bolometric albedo :



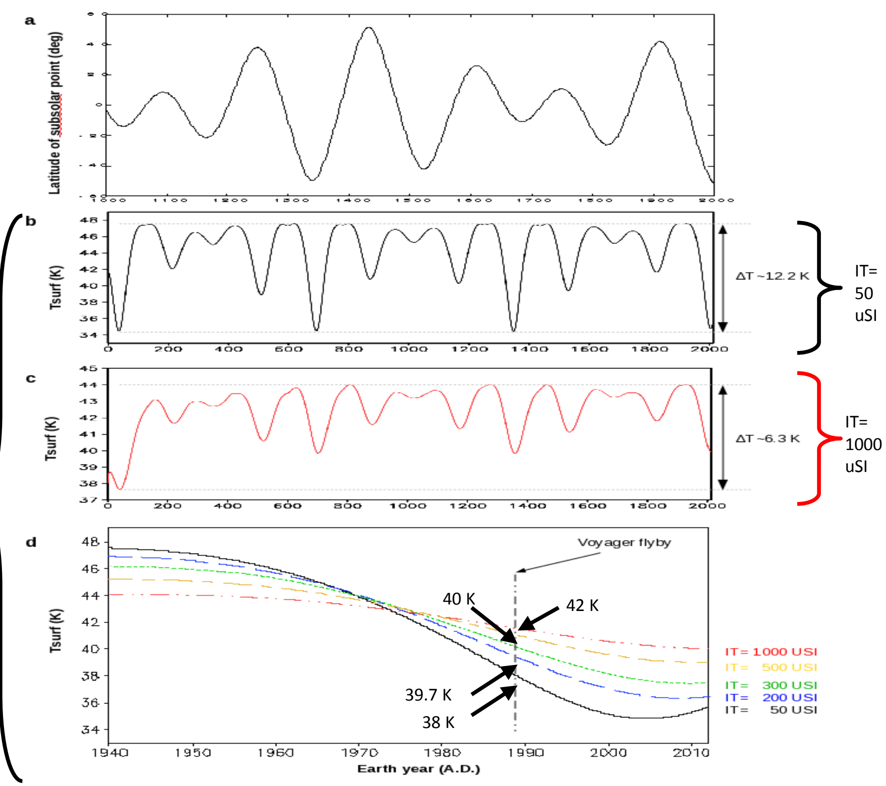
- Emissivity = 0.74
- Flux géothermique nul
- Ice Surface temperature = 38K
- Initial temperature profile = isotherm

- Initialisation of the band's temperature ?

Initialisation of the band's temperature :

®a serie of 1D simulations over more than 2000 terrestrial years for different values of thermal inertia

SURFACE TEMPERATURE AT 15° N



IT (uSI)	50	200	500	1000
T in 1989 (K)	38	39.7	40	42

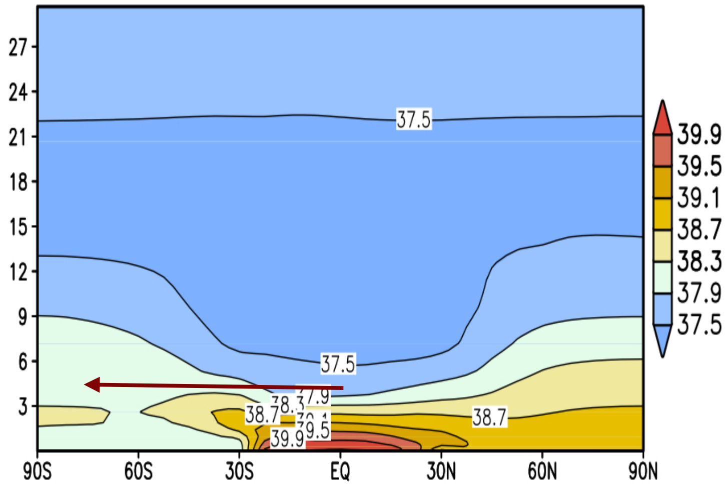
Case 3 : Triton with an unfrosted equatorial band

Case with IT=1000 uSI

Origin of prograde winds

Section of temperature in 1989

Mean zonal winds at 7 km (centered at 40° S)



Temperature gradient between the equator and southern latitudes

Prograde winds

- Thank you !