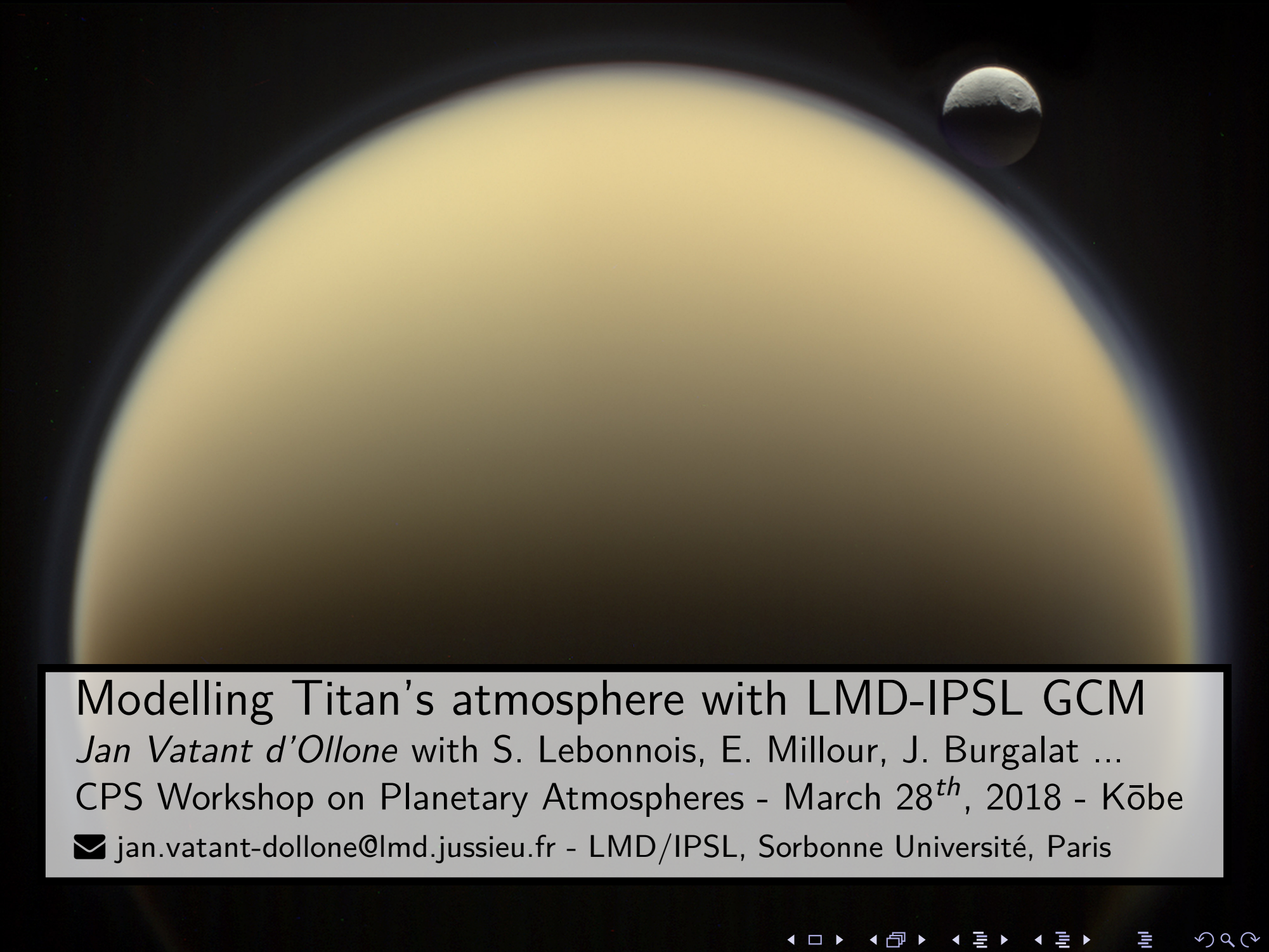

Modelling Titan's atmosphere with LMD-IPSL GCM

Jan Vatant d'Ollone with S. Lebonnois, E. Millour, J. Burgalat ...

CPS Workshop on Planetary Atmospheres - March 28^{th}, 2018 - Kōbe

jan.vatant-dollone@lmd.jussieu.fr - LMD/IPSL, Sorbonne Université, Paris

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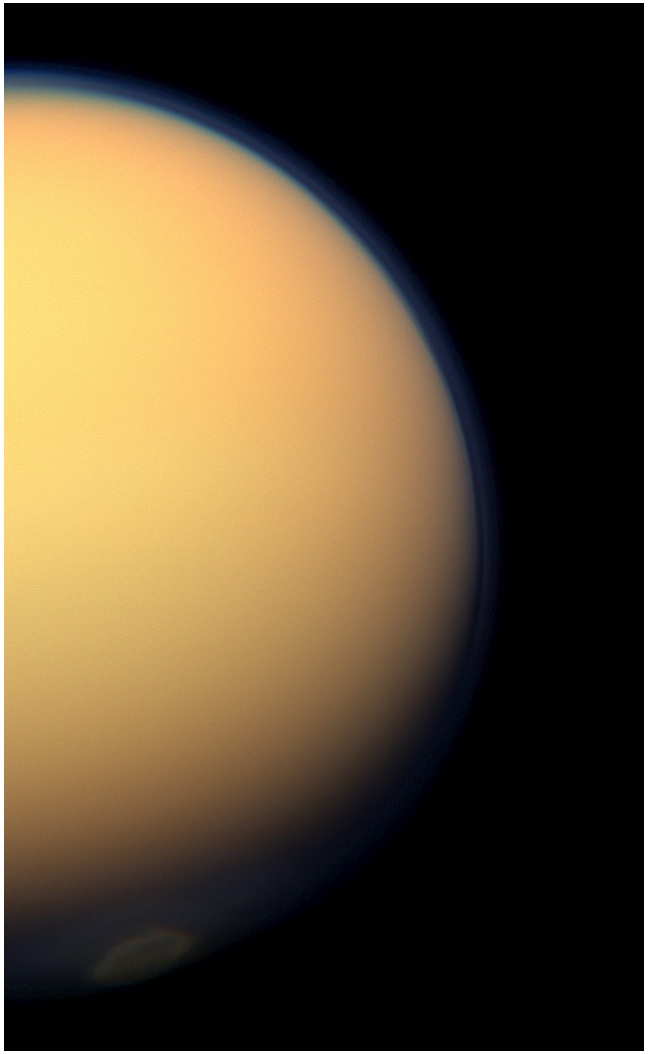
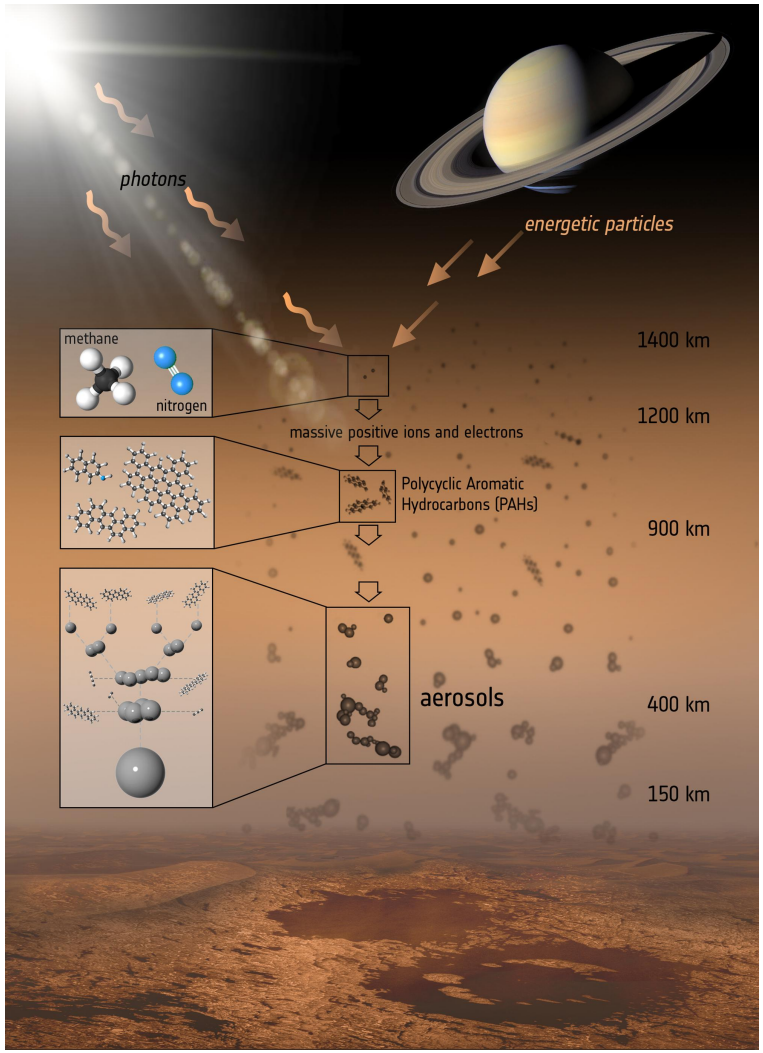
Context - Titan's atmosphere



- Largest Saturne's satellite, slow rotator, synchronous
- Dense N_2 (95-98%) and CH_4 (1.5-5%) superrotating atmoshere
- "Water-like" methane cycle
- Photochemistry + kronian magnetospheric particles
  $\Rightarrow$ Enrichment of upper atmosphere in hydrocarbons and nitrils
  $\Rightarrow$ Growth of organic haze (aerosols)

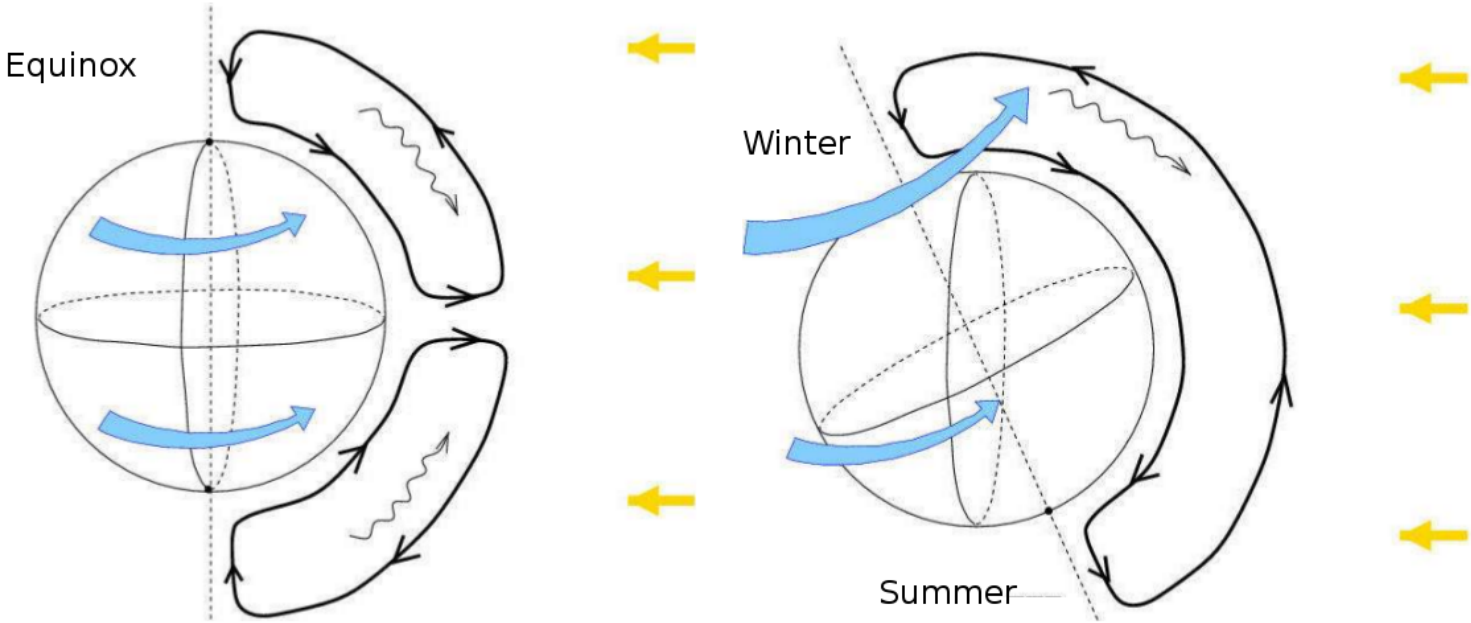
Titan's haze



- Very good solar UV absorber
- Main layer (150-300 km), responsible for stratospheric warming along with methane
- Detached layer ($\sim$ 500 km), subject to seasonal variations

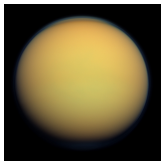
Titan's super-rotation (Gierasch mechanism)

First Titan GCM (*Hourdin et al. 1995*) predicted super-rotation !



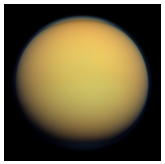
Transport of angular momentum by circulation $\Rightarrow$ high-latitude jet
Redistribution by waves (transient barotropic and inertial instability)
$\Rightarrow$ equatorial super-rotation

Titan vs Earth

	Earth 	Titan 
Radius (km)	6371	2575
Year lenght (♃ yr)	1	29.75
Obliquity (°)	23.5	26.7
P_{surf} (bar)	1	1.5
T_{surf} (K)	290	94
Composition (vmr)	N_2 (0.78) O_2 (0.20) Ar (0.01) ...	N_2 (0.95) CH_4 (0.05) C_2H_4,C_2H_6, HCN, ... (ppm)

Titan vs Earth

Seasonal cycle !

	Earth 	Titan 
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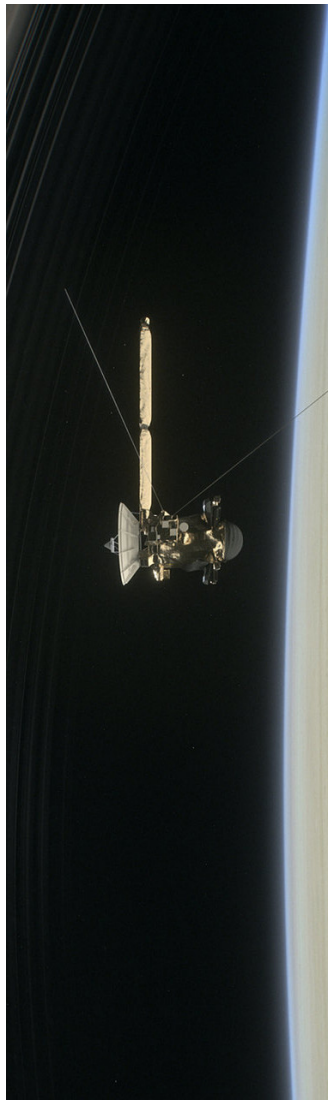
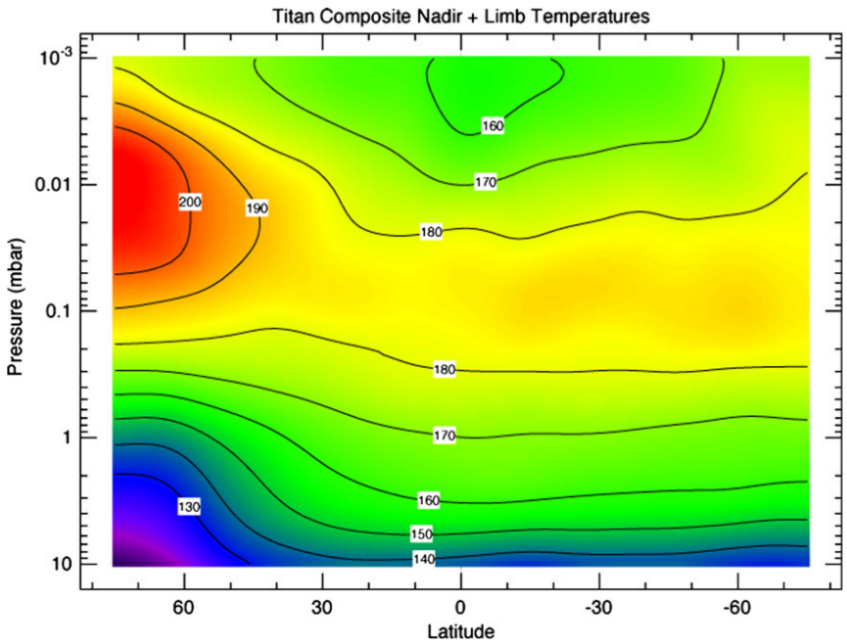
NASA-ESA Cassini/Huygens Mission

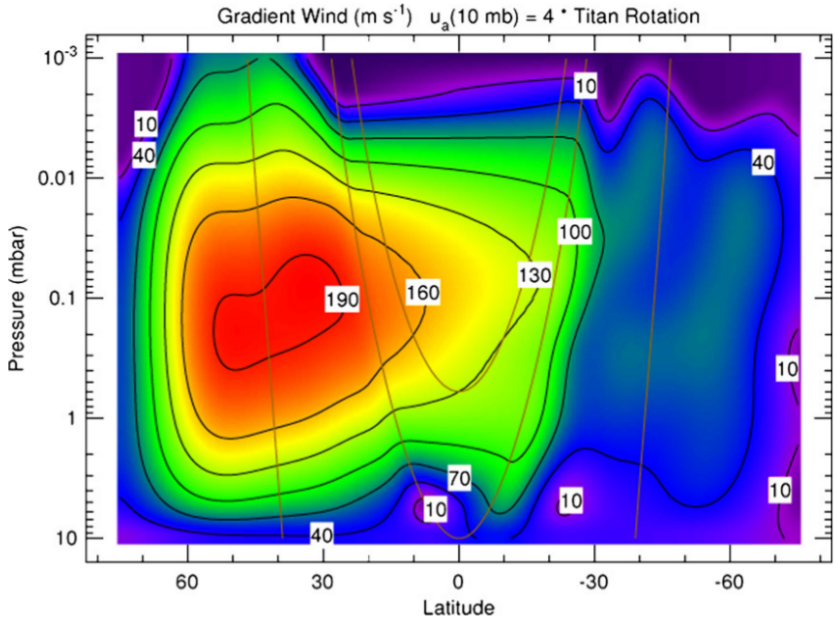
- Orbiting Saturn and moons from 2004 to 2017
- 126 Titan fly-bys
- Huygens lander (January 2005) : *in situ* measurements
  - Composition, wind, temperature, density and pressure profiles
- CIRS : Composite InfraRed Spectrometer (InfraRed Spectrometer (600 - 1500 cm^{-1})) :
  - Spectral resolution 15.5 cm^{-1} $\Rightarrow$ Emission spectra :
    - CH_4 $\Rightarrow$ Temperature field retrieval $\Rightarrow$ Thermal wind field
    - Trace compounds (C_2H2, C_2H_6, HCN...)
    - Aerosols $\Rightarrow$ Properties in the main layer

Farewell Cassini ! !



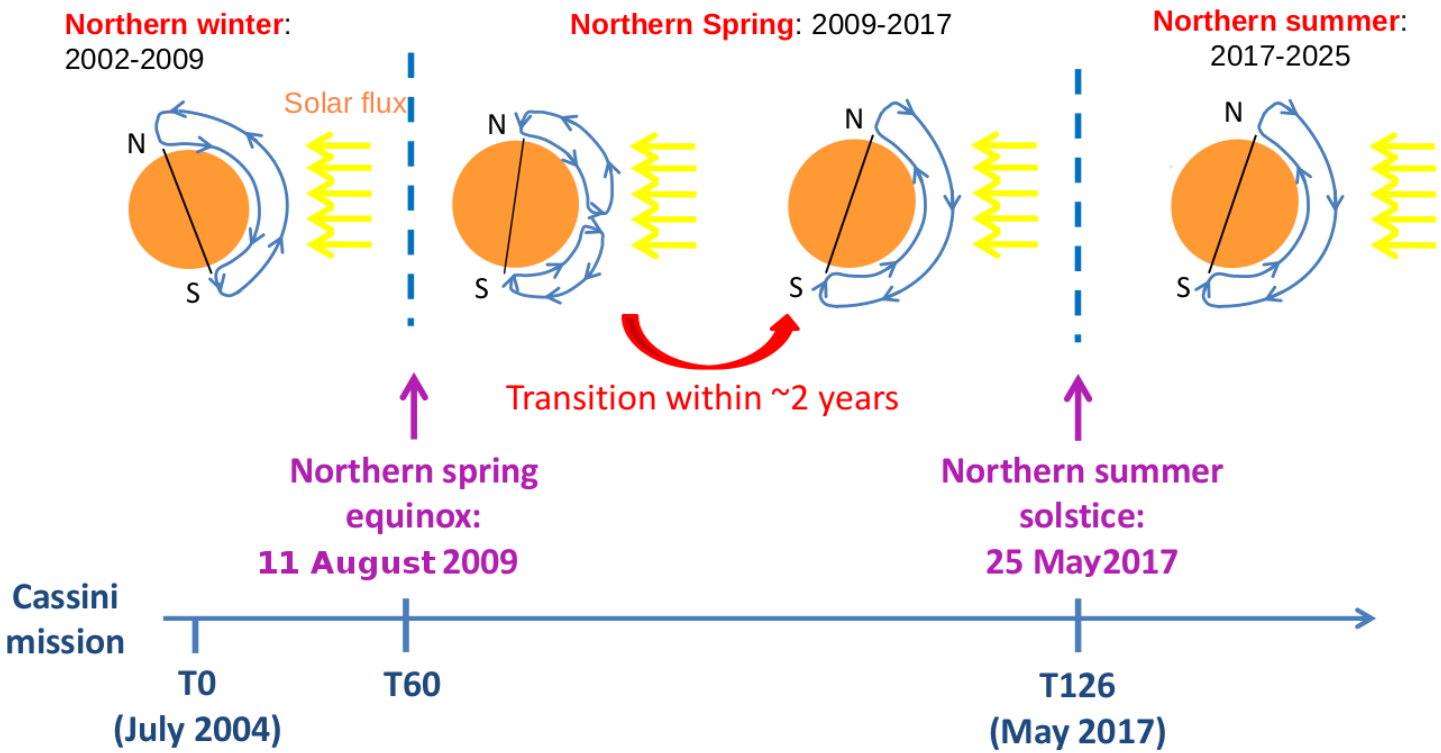
Cassini witnessed the super-rotation !





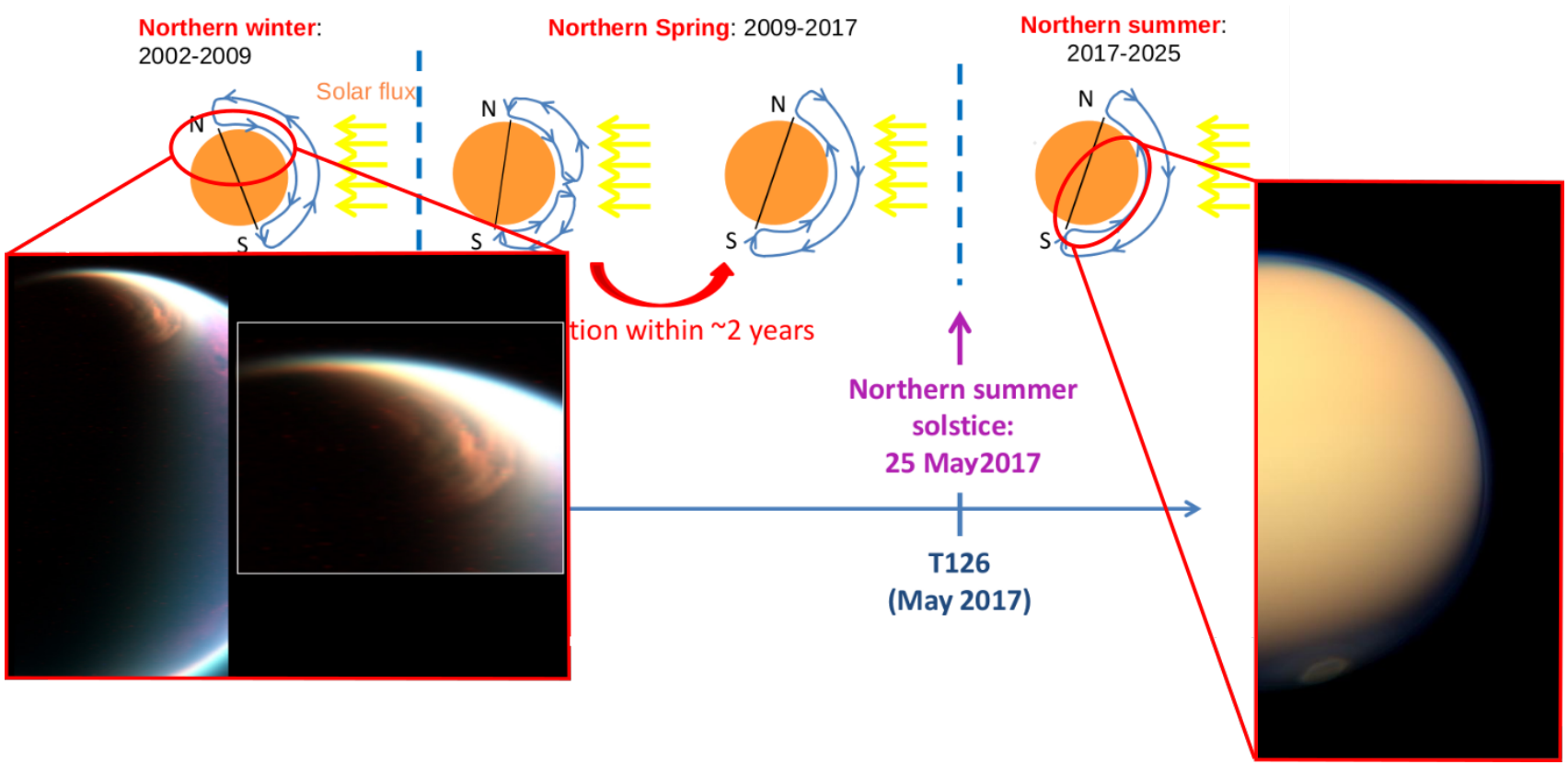
Retrieved stratospheric temperature and zonal wind maps with Casssini/CIRS (*Achterberg et al. 2008*)

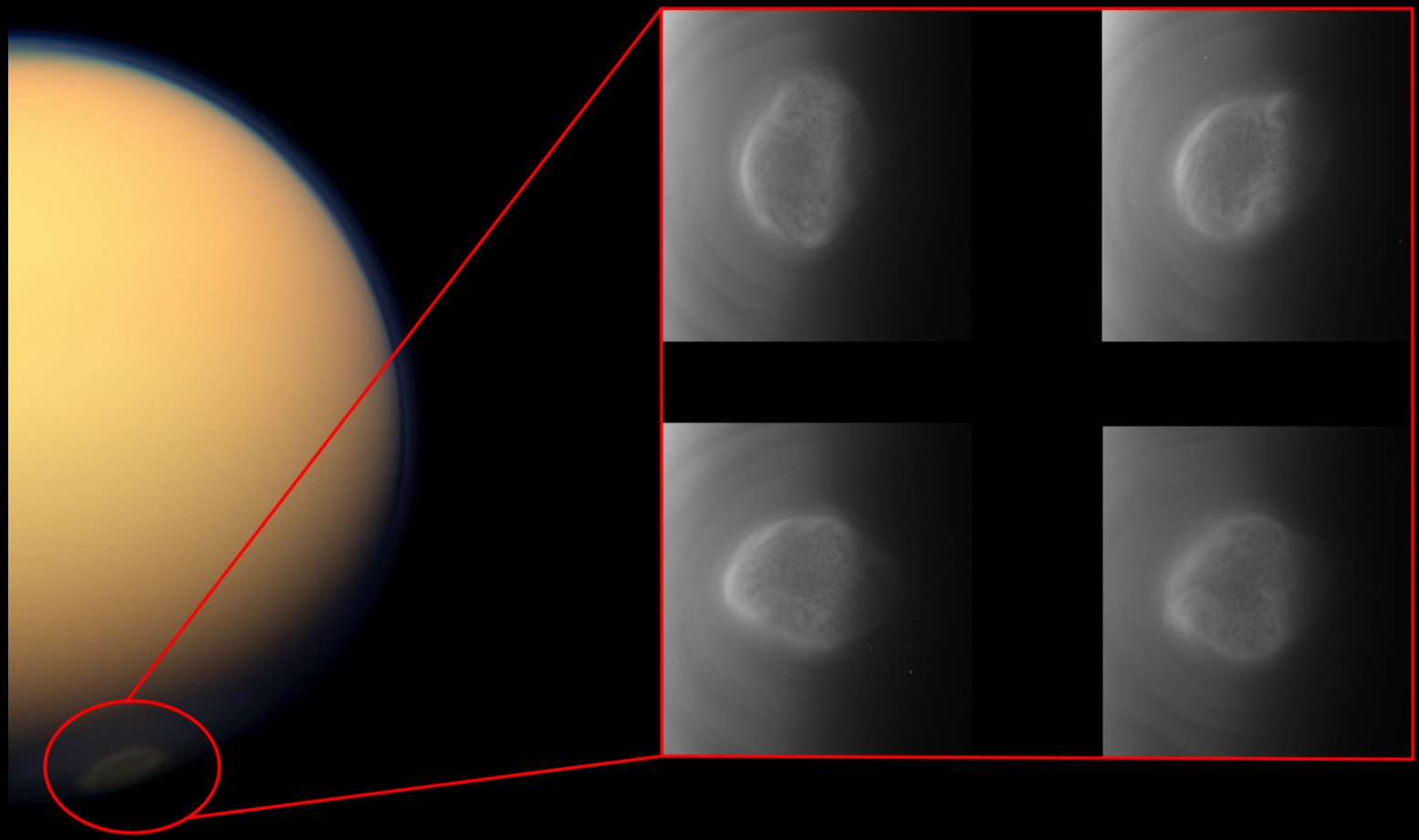
Titan seasonal evolution



Courtesy : S. Vinatier

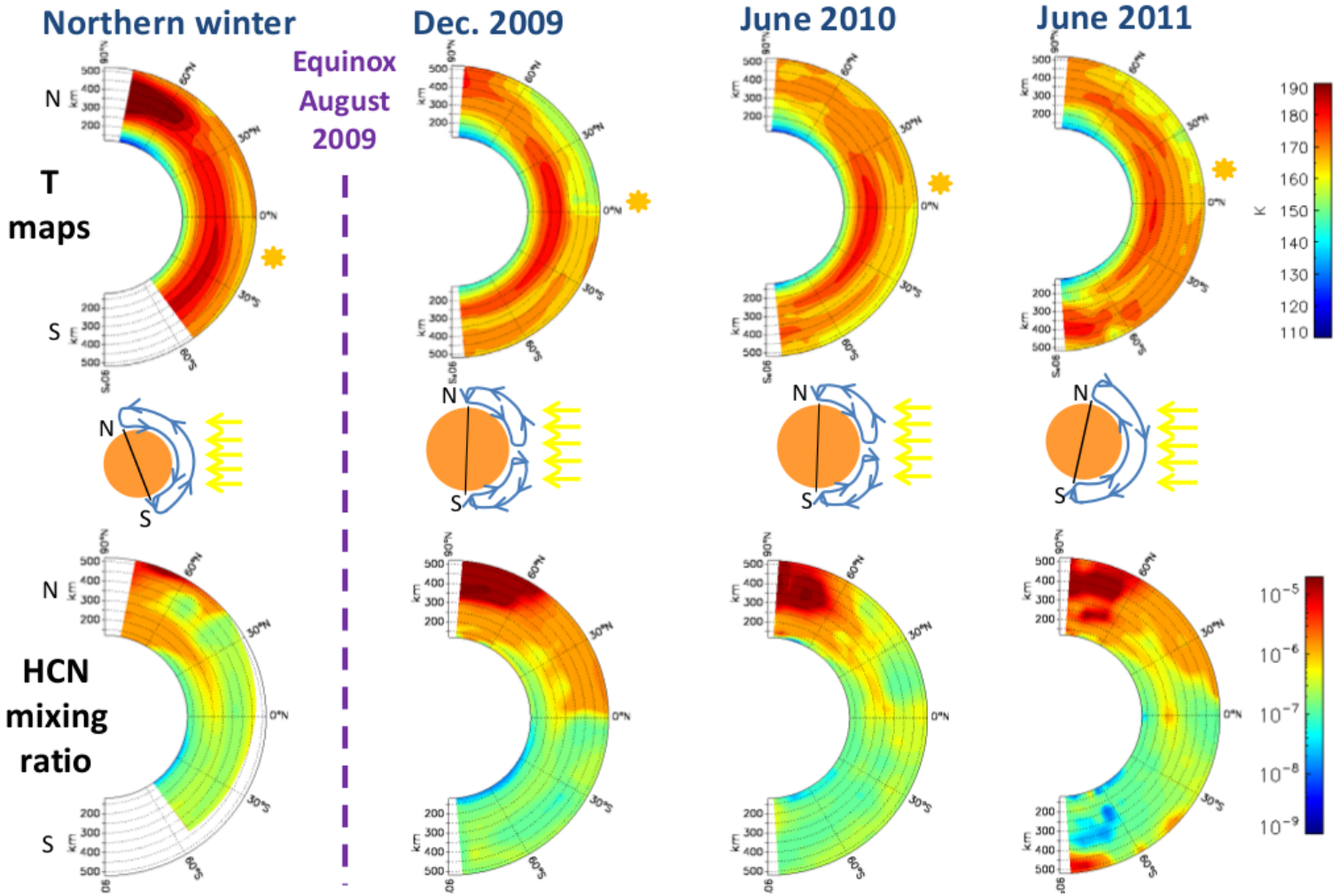
Seasonal evolution - winter polar vortex



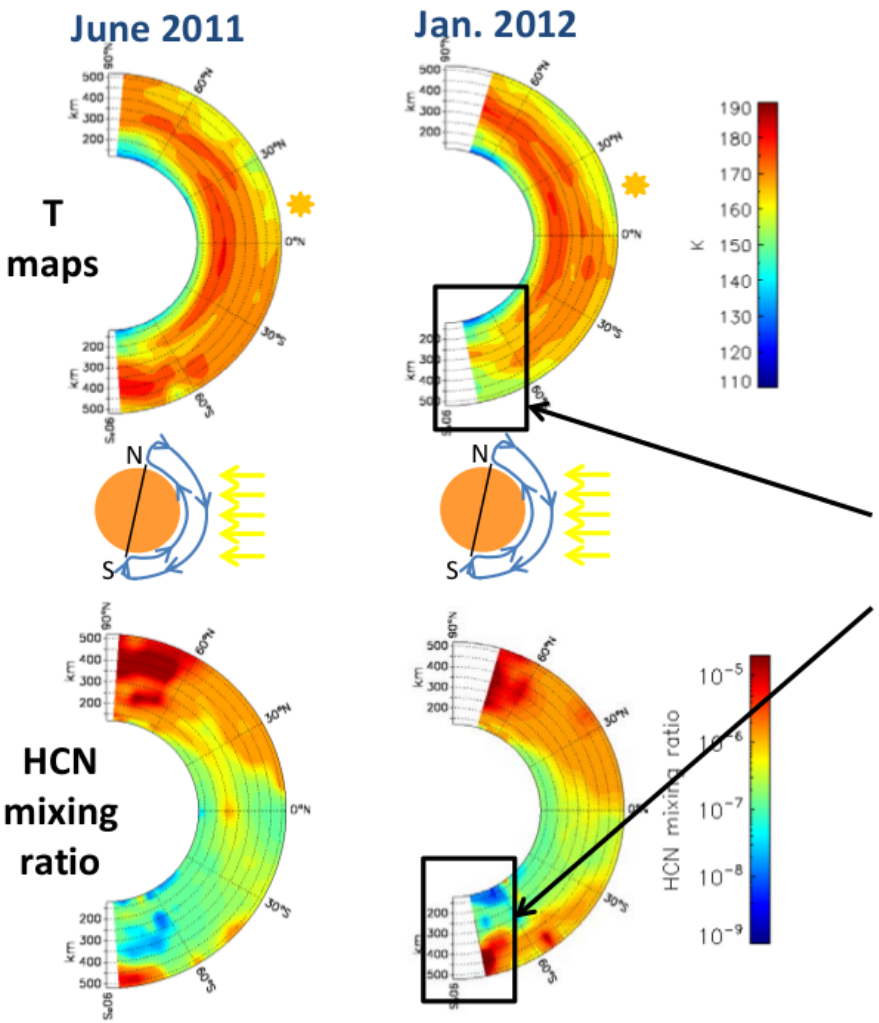


South polar vortex seen by Cassini (snapshots within $\Delta t \simeq$ some hours)

Reversal of the dynamics seen by CIRS



Reversal of the dynamics seen by CIRS



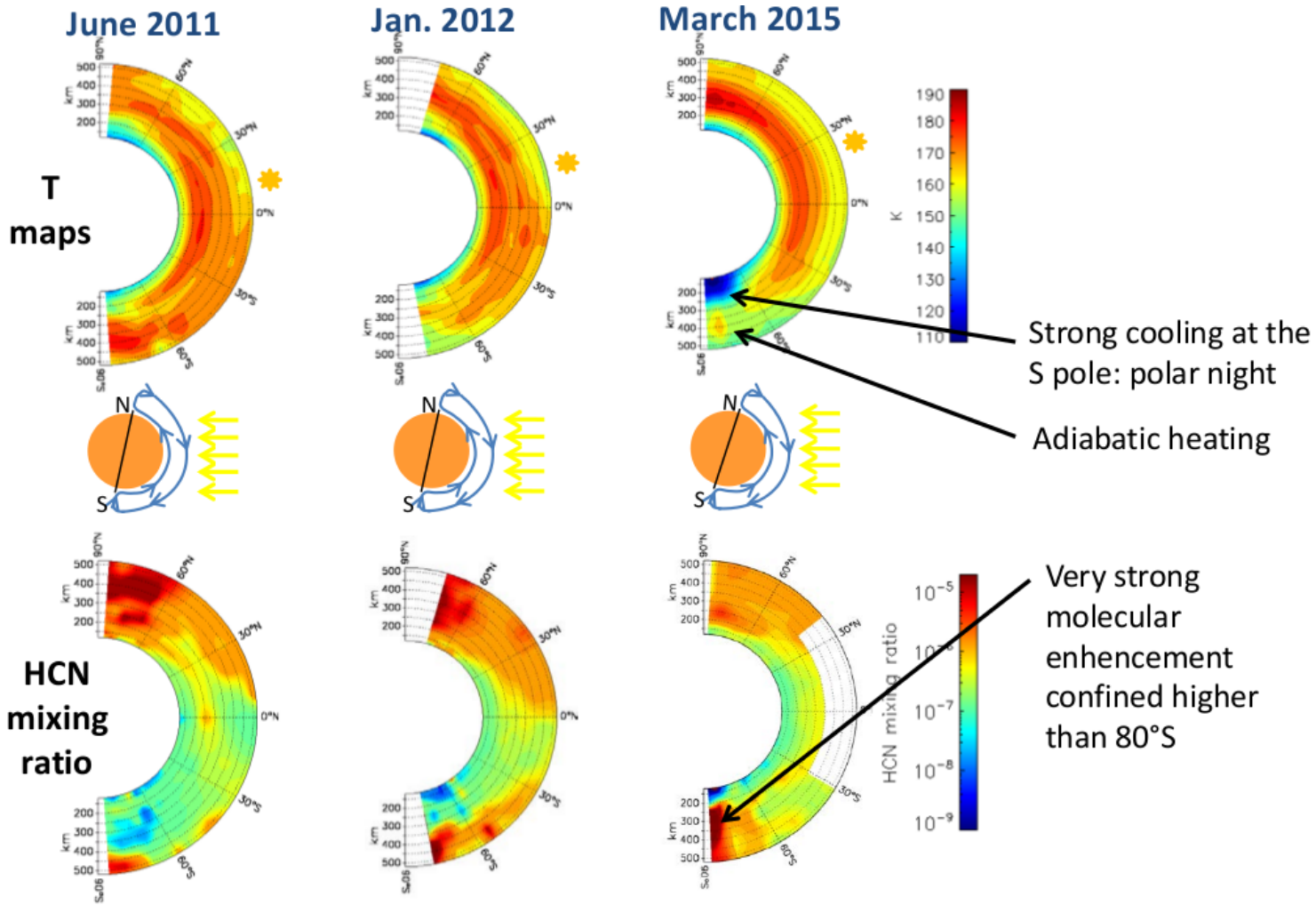
Vinatier et al., 2015, Icarus 250

Unexpected cooling at the S pole

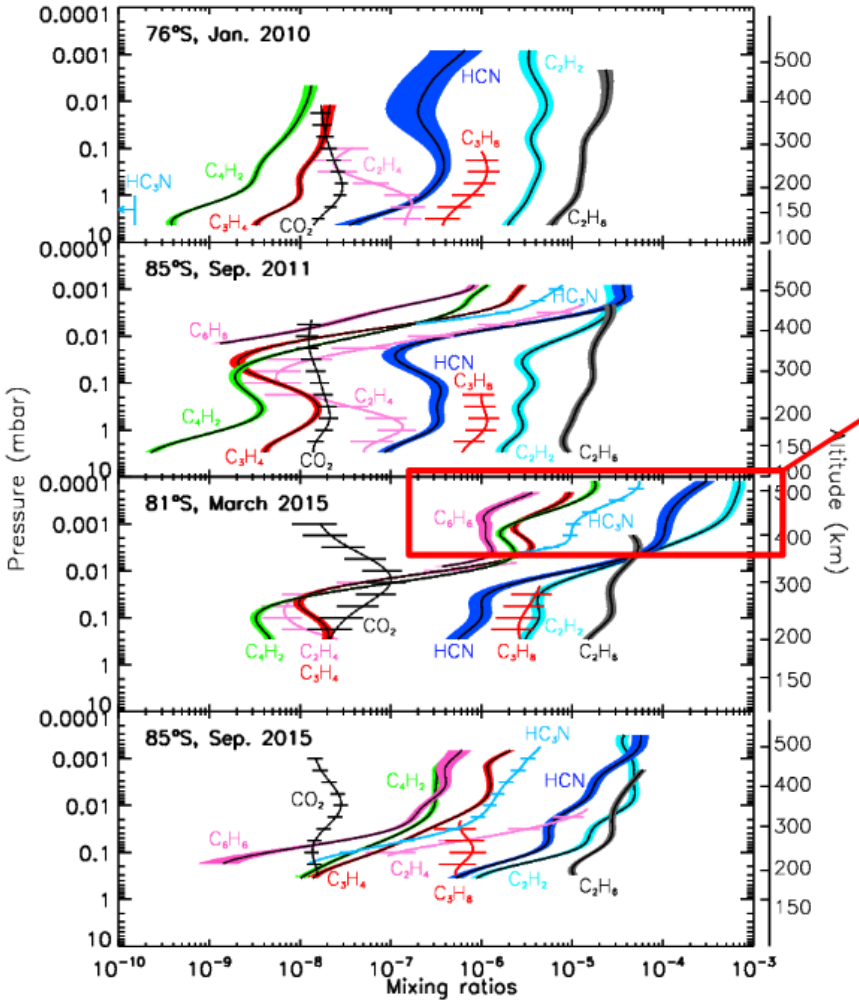
Strong enrichment at the S pole

→ Radiative cooling by molecules and aerosols compensate the adiabatic heating of descending branch

Reversal of the dynamics seen by CIRS



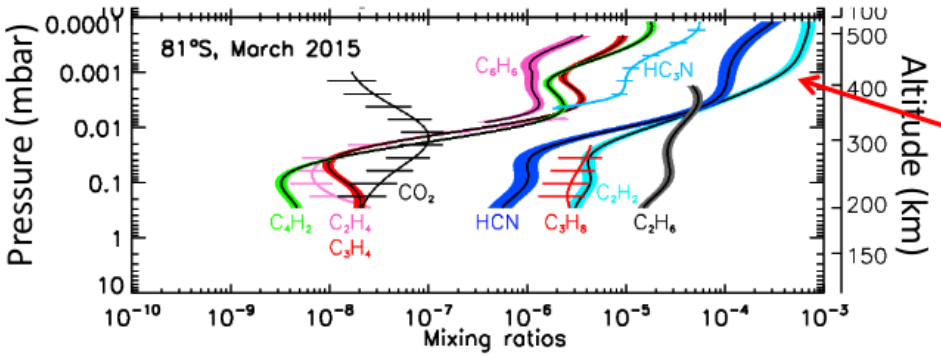
Enrichment at the S pole after equinox

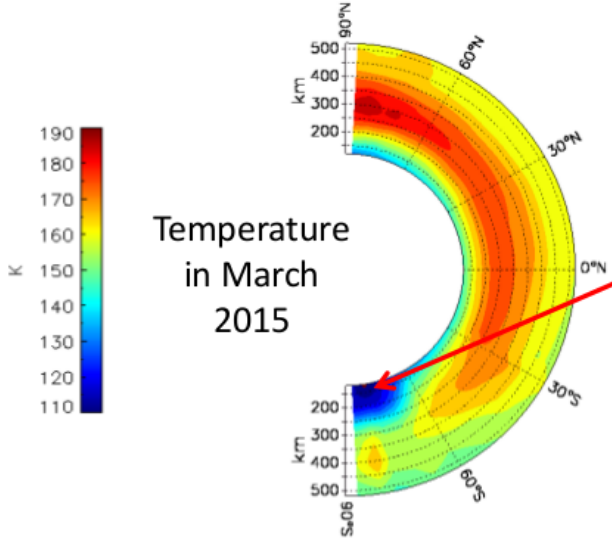


Very strong enrichment of many molecules above the south pole, not predicted by models.

In March 2015, at 500 km, molecular mixing ratios are similar to the values measured insitu at 1000 km by Cassini/INMS.

Condensates at the South pole in autumn





Very strong molecular enrichments

+

Very cold stratospheric temperature

⇓

Condensation of molecules at very high altitude

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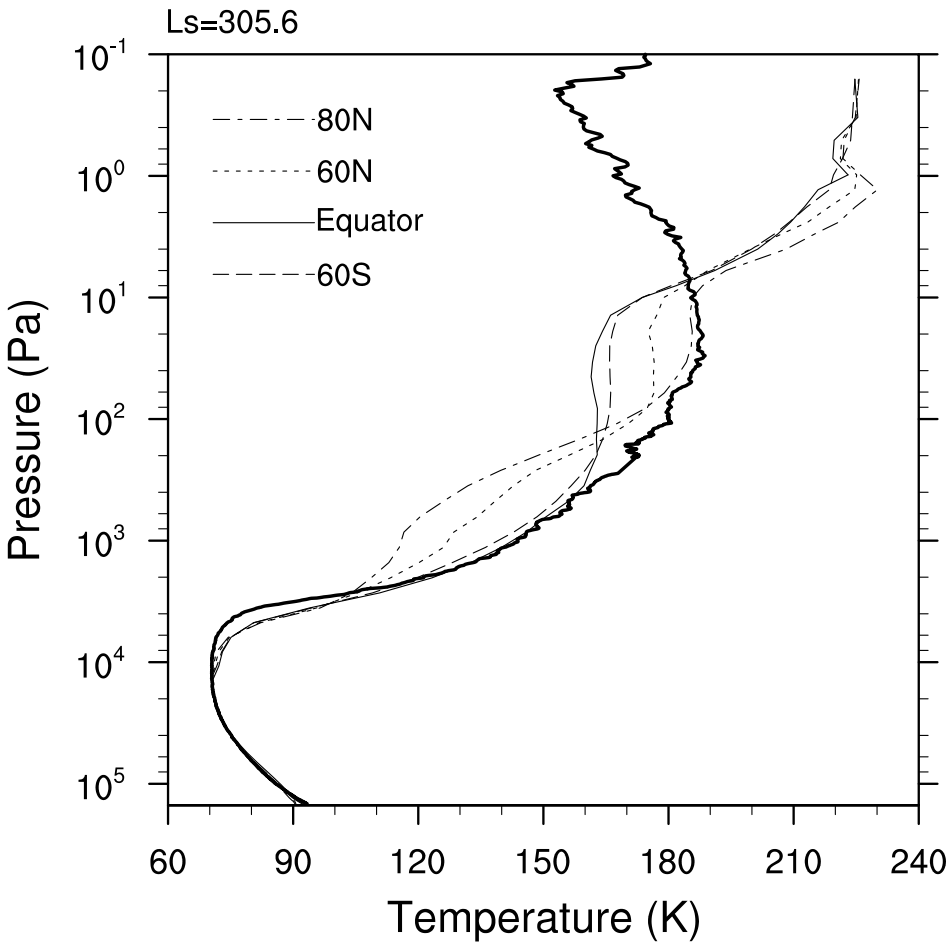
LMD Titan's GCM suffered from limitations



(Lebonnois et al., 2012)

- Temperature profiles diverge at the ceiling of the model
- Long-term runs lead to a strong stability zone, "stucking" the Hadley cell
- Stratospheric vertical mixing of tracer limited

Underlying radiative transfer problems ?

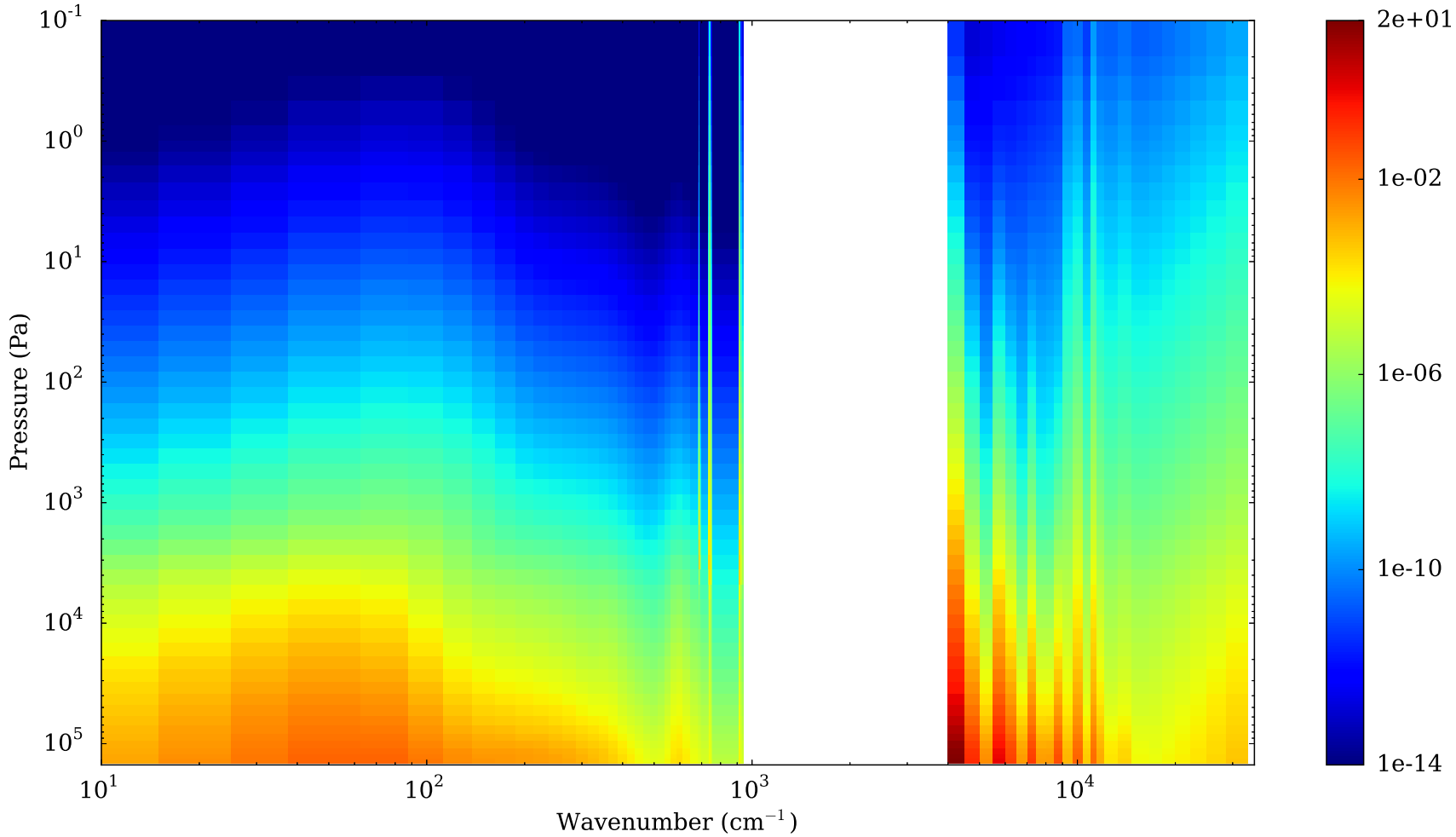
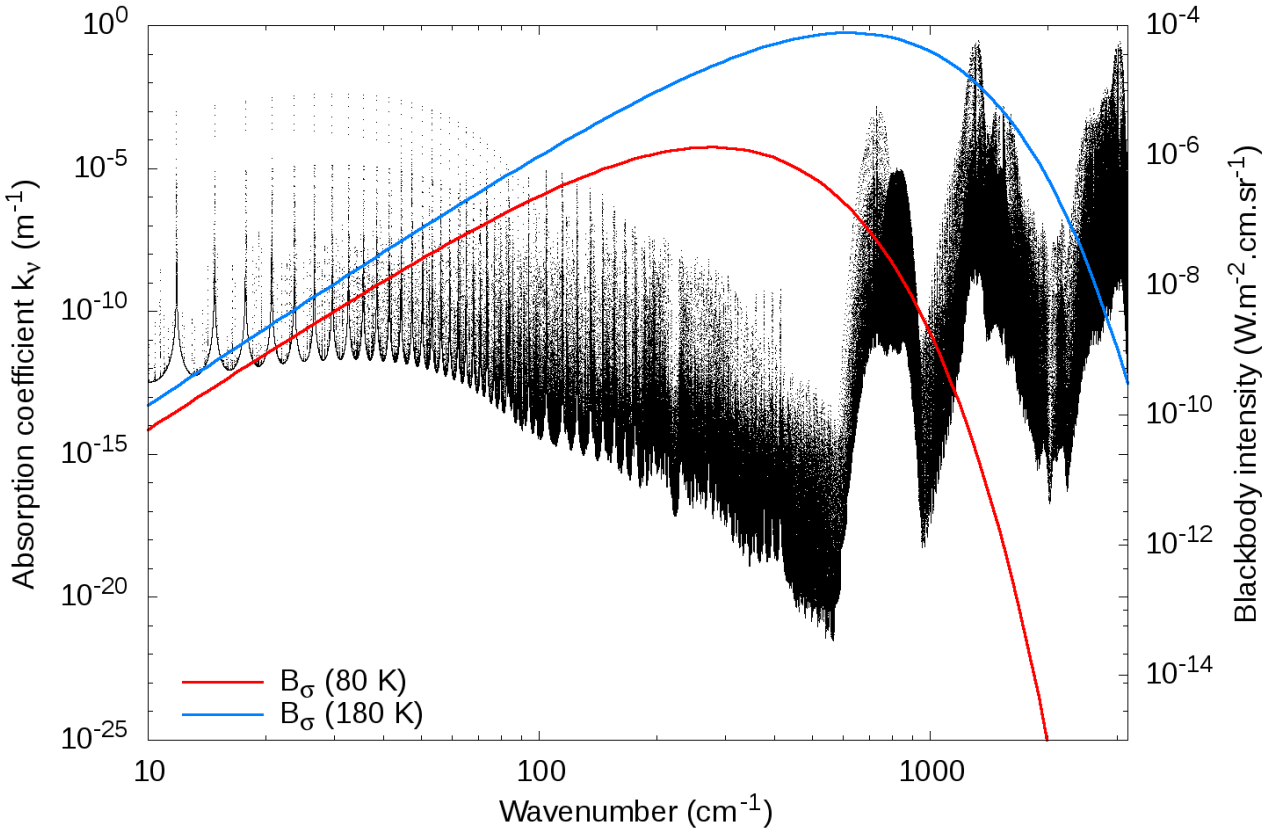


Figure – Extinction coefficients (m^{-1}), based on *McKay et al. 1989*

Yes indeed !



Warm stratosphere : you shall not neglect CH_4 ν_4 (7.7 μm) band !

A new radiative transfer scheme for Titan

- Correlated-k scheme with CH_4, C_2H_6, C_2H_2 and HCN from HITRAN 2012 (+ methane lines from Rey et al., 2016 in 7900-12000 cm^{-1} range)
- Collision-induced absorption (N_2, H_2 and CH_4)
- No time nor latitudinal variation of vertical abundances
- Aerosol mean opacity profile based on constraints retrieved from DISR data [Lavvas et al., 2010]

So far it implied to decouple radiative transfer from chemistry and haze ...

Updated opacity table

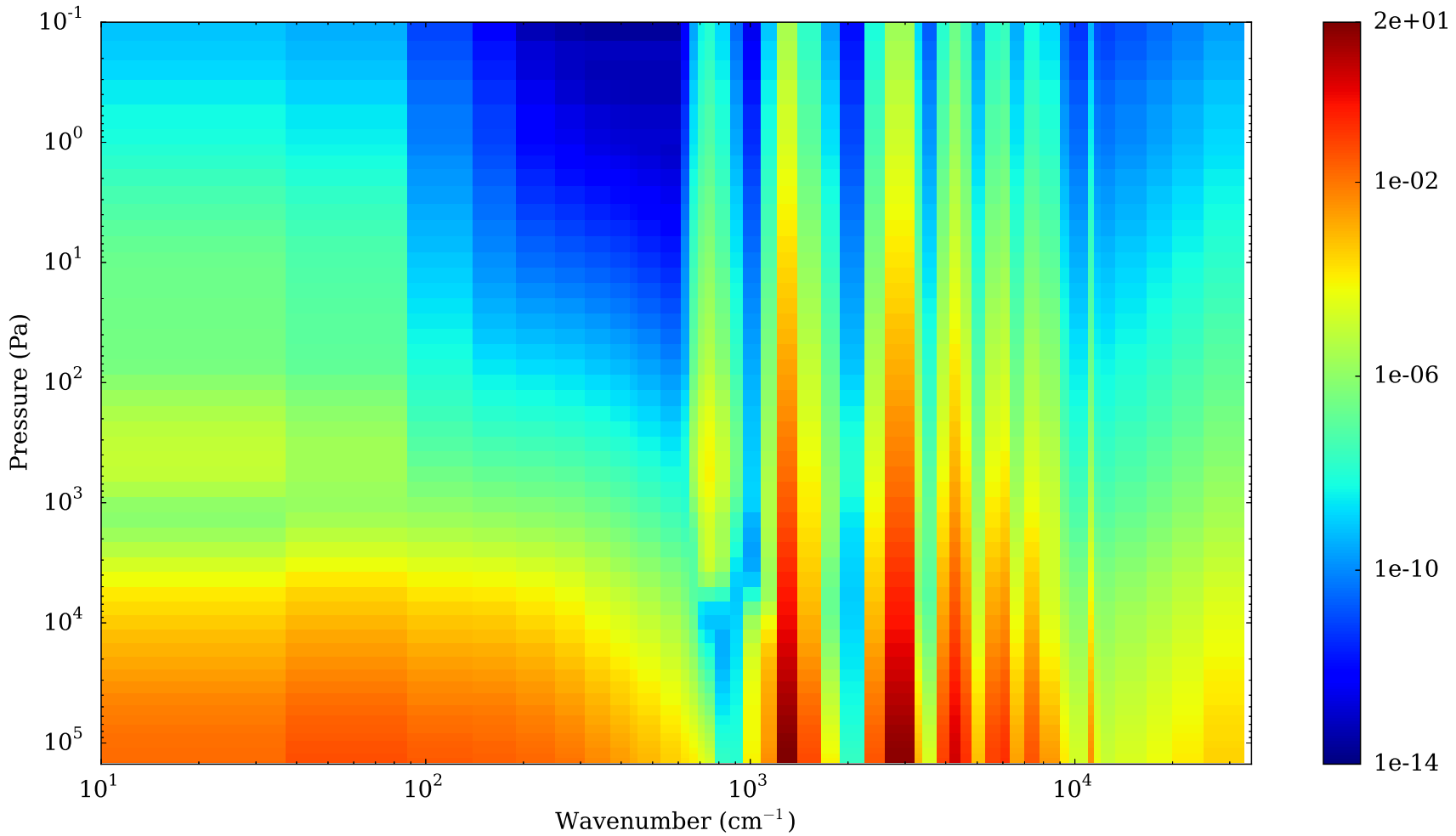
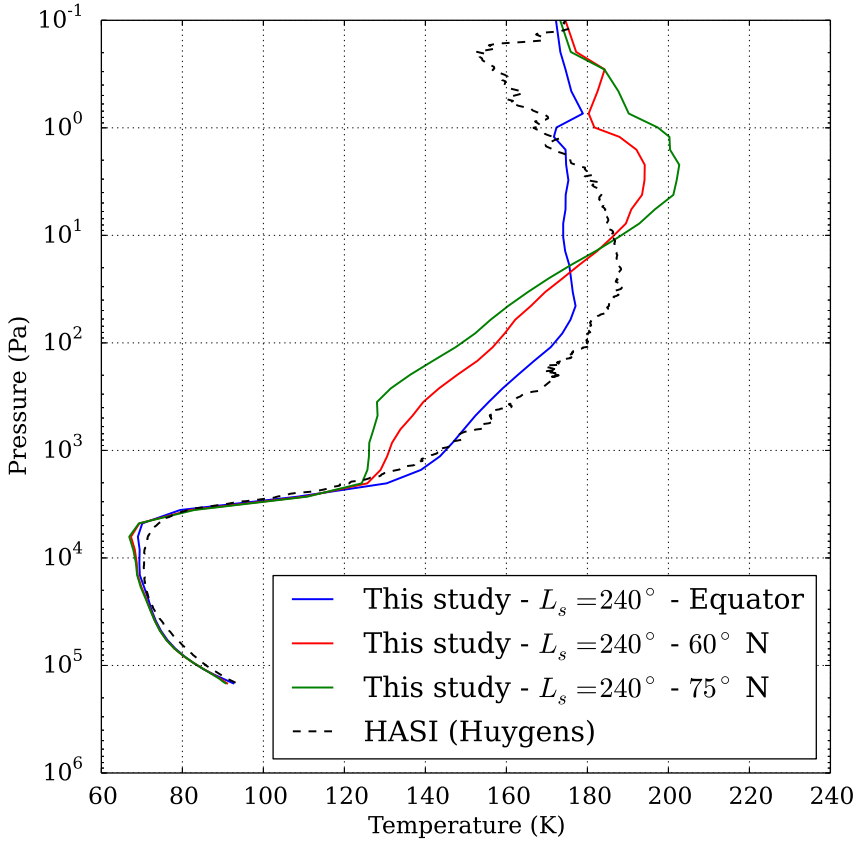
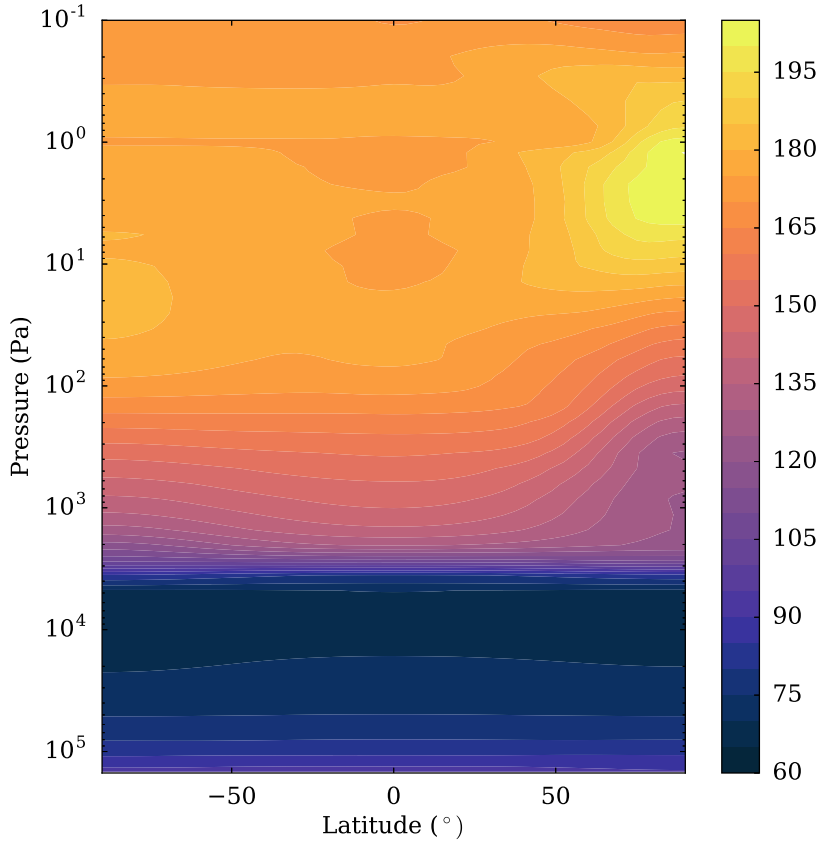


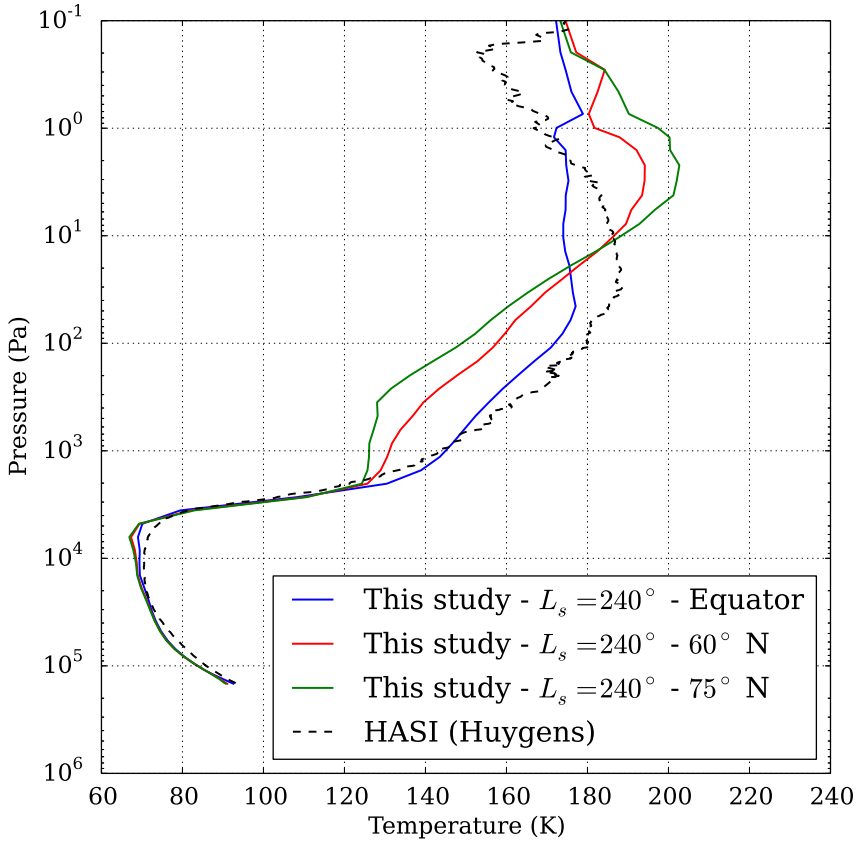
Figure – Updated extinction coefficients (m^{-1})

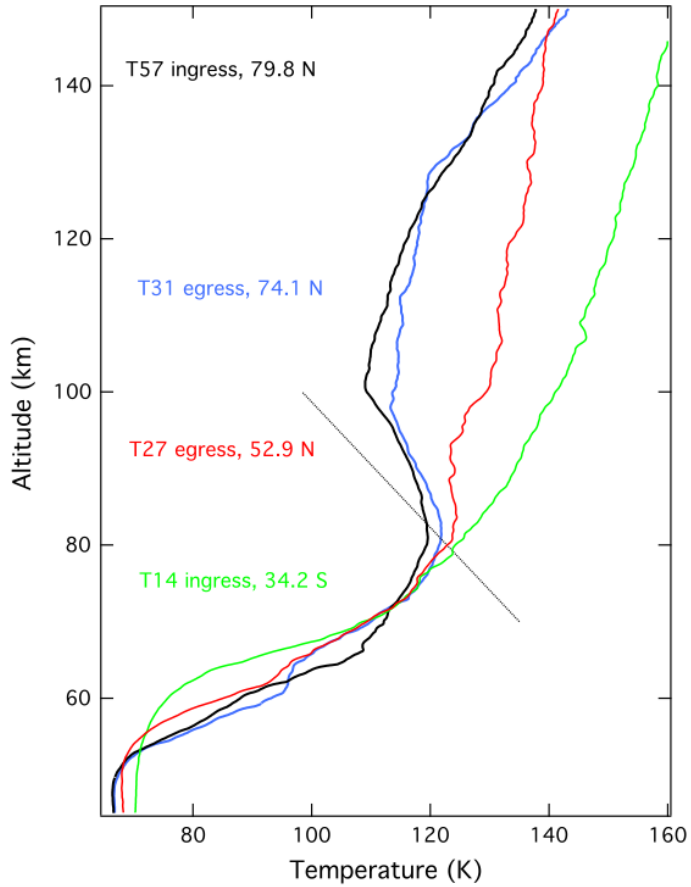
Main consequence : Simulated stratopause





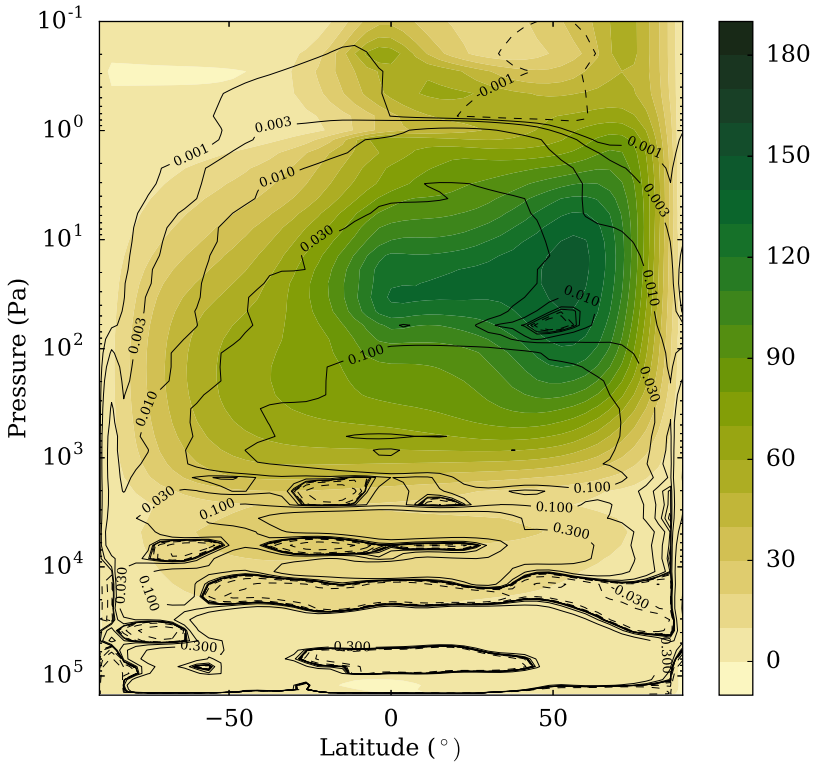
Better behaviour of the "polar shoulder"





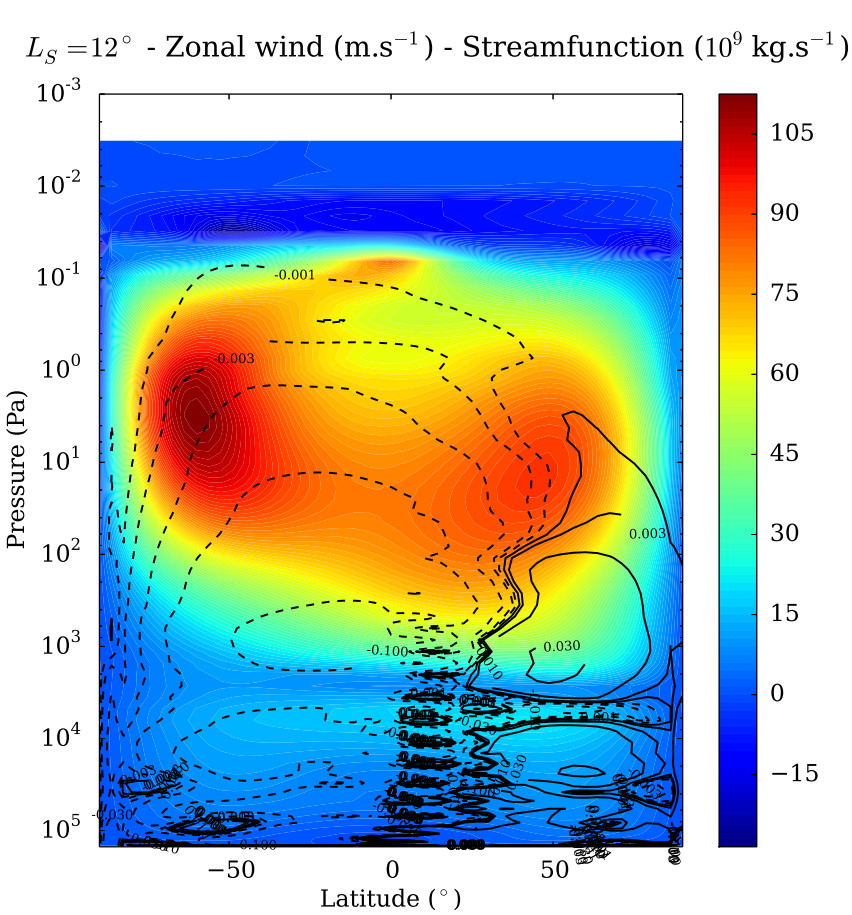
In polar winter stratosphere Cassini radio-occultations (*Schinder et al. 2012*) show a "shoulder".

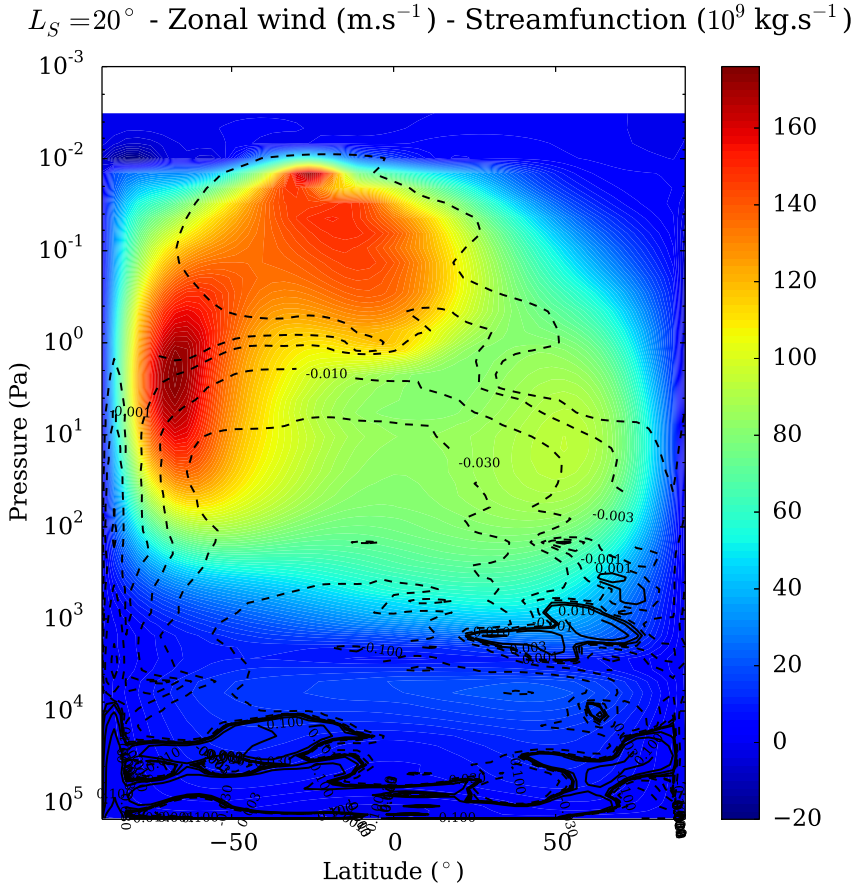
Yet, no haze coupling ⇒ no correct circulation



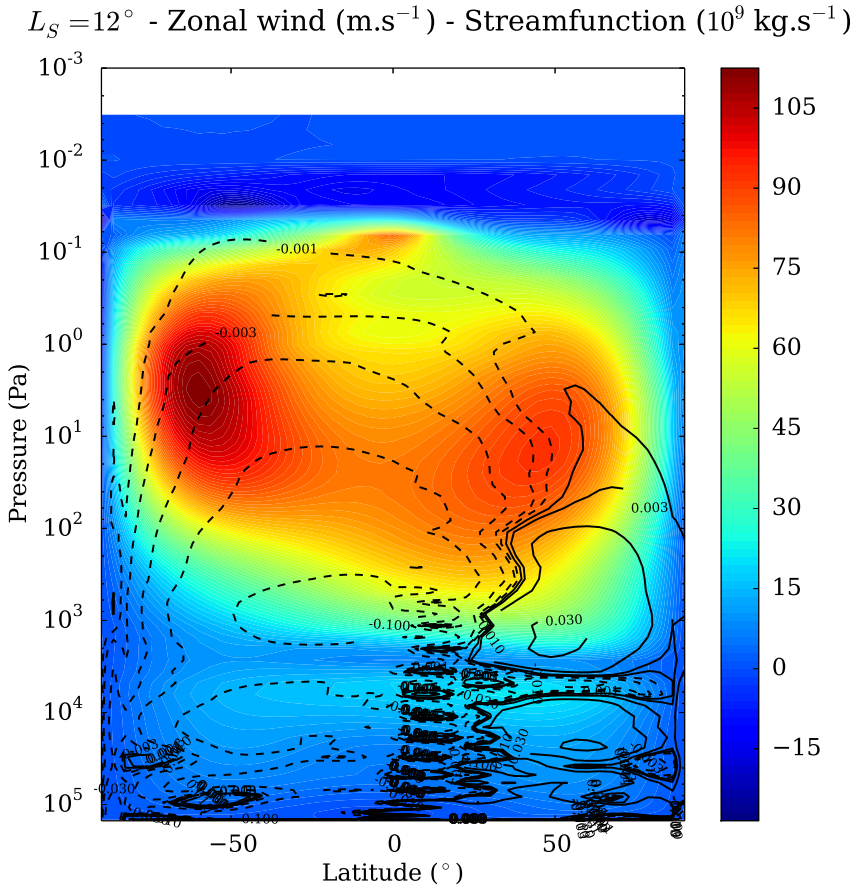
- Without haze retroaction, temperature latitudinal contrast is fainter than in the observations (*Lebonnois et al, 2009*)
- In the polar night aerosols should accumulate and cool the atmosphere (*Rannou et al. 2004*) but here haze is not interactive.

Towards an increased vertical extension ?





Towards an increased vertical extension ?



- Motivations
  - With improved temperature profiles, Hadley cell can now vertically extent
- But ...
  - **Thin layer approximation !** We need to use a deep atmosphere core (at 500 km $\frac{g}{g_0} \simeq 0.6$) !
  - Non-LTE processes
  - Illuminance over the poles

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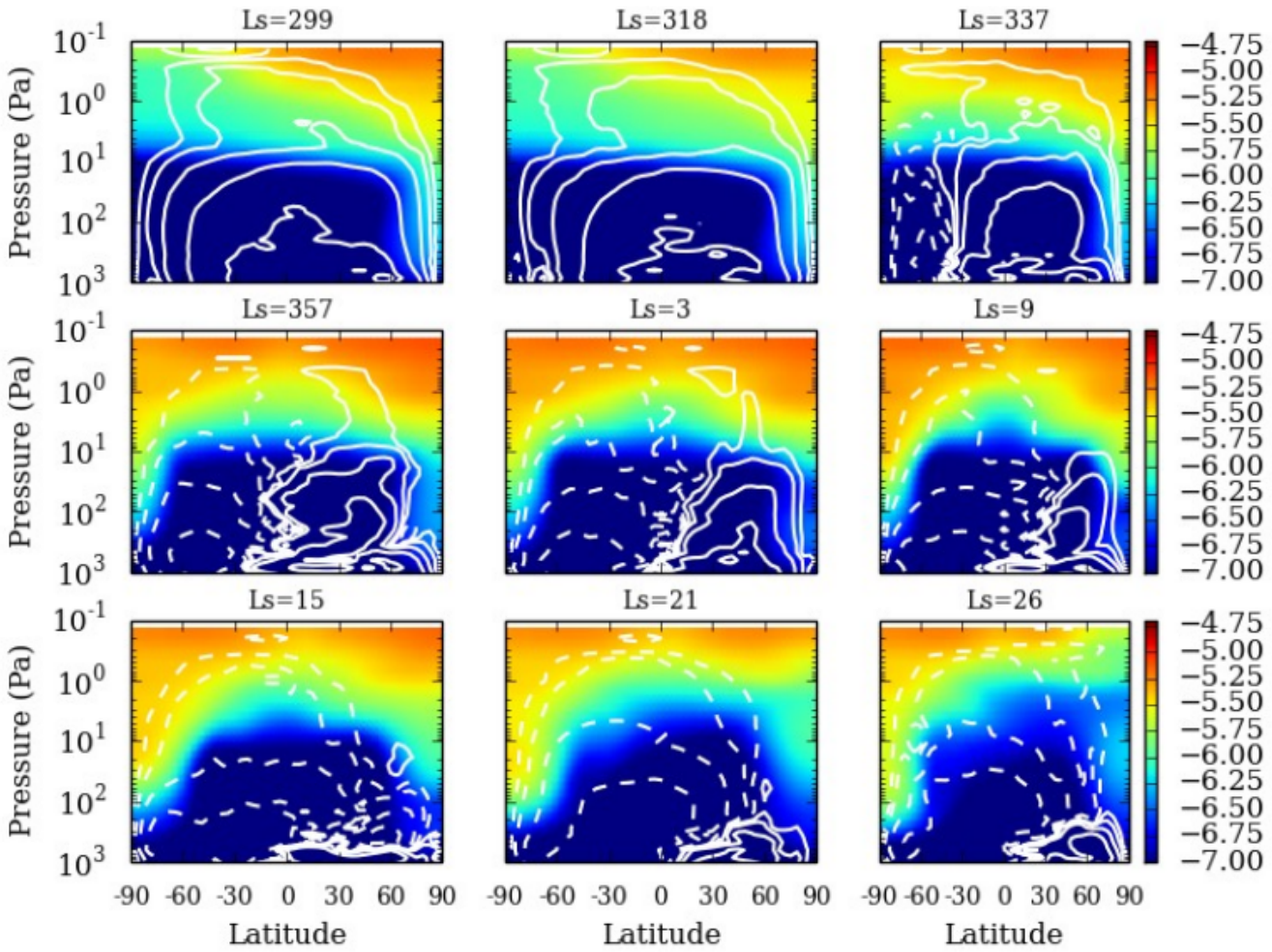
Chemistry - Overview

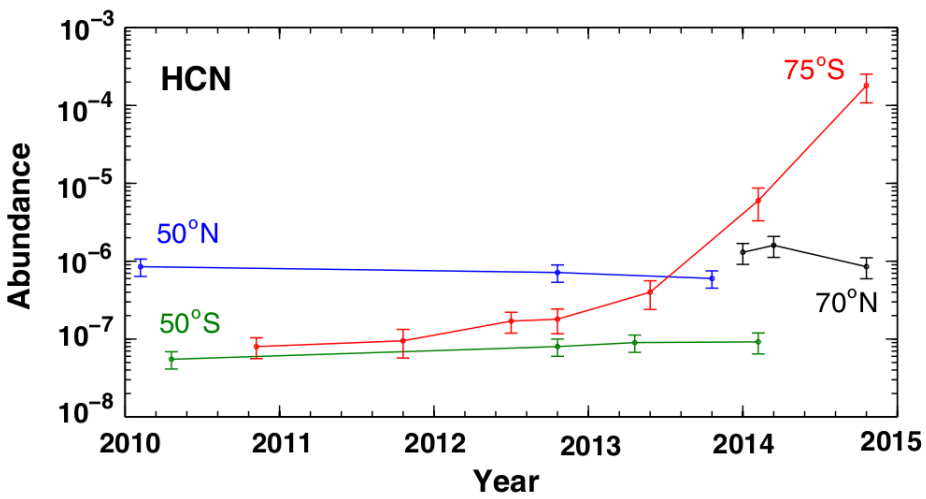
- State-of-the art in the LMD-IPSL GCM :
  - Chemical solver up to 1300 km (*Lebonnois et al. 2001*, *Crespin et al. 2008*)
  - 44 species and 377 photochemical reactions
- Limitations :
  - Due to weak circulation, stratospheric seasonal variations don't match observations
  - No radiative coupling
  - Mostly neutral chemistry. Latest works on the field have shown the importance of ion chemistry (*Lavvas et al. 2011*)
- What I'm trying to bring in :
  - Radiative coupling for C2H2, C2H6 and HCN (at least !)
  - Go on to a *correlated-k* radiative transfer that enables variable composition

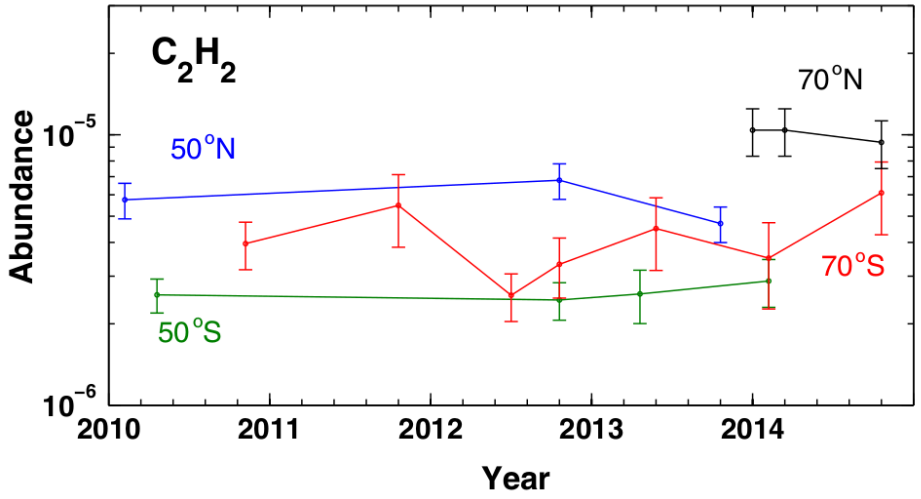
Chemistry evolution poorly represented ...



Enrichment too weak and reversal too early (starting at $L_s \sim 0$ instead of $L_s \sim 15$)

.. COMPARED TO OBSERVATIONS





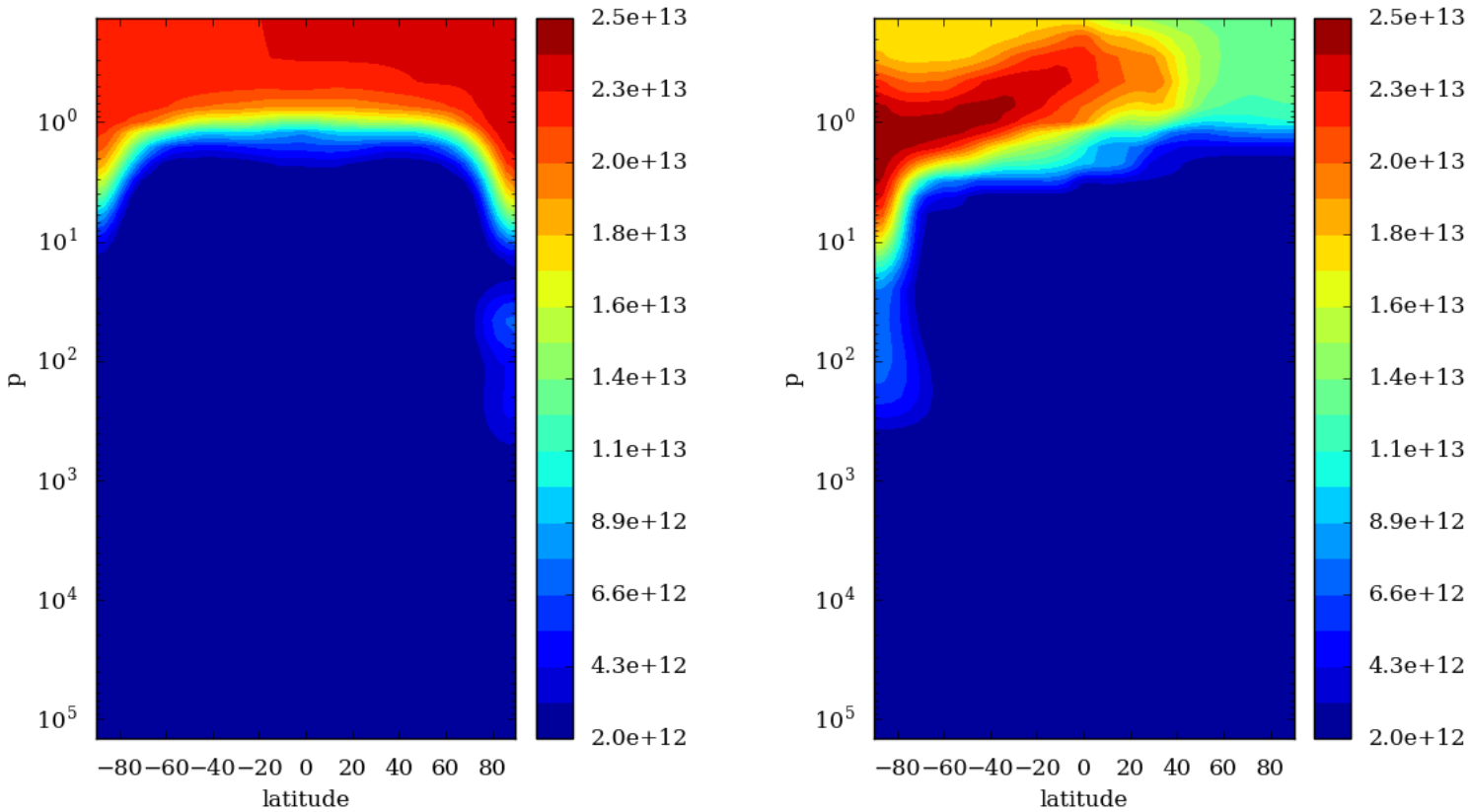
For long-lifetime species such as C_2H_2 enrichment in South Pole is dephased with circulation.

In 2015 there is still almost no depletion at North Pole.

Microphysics - Overview

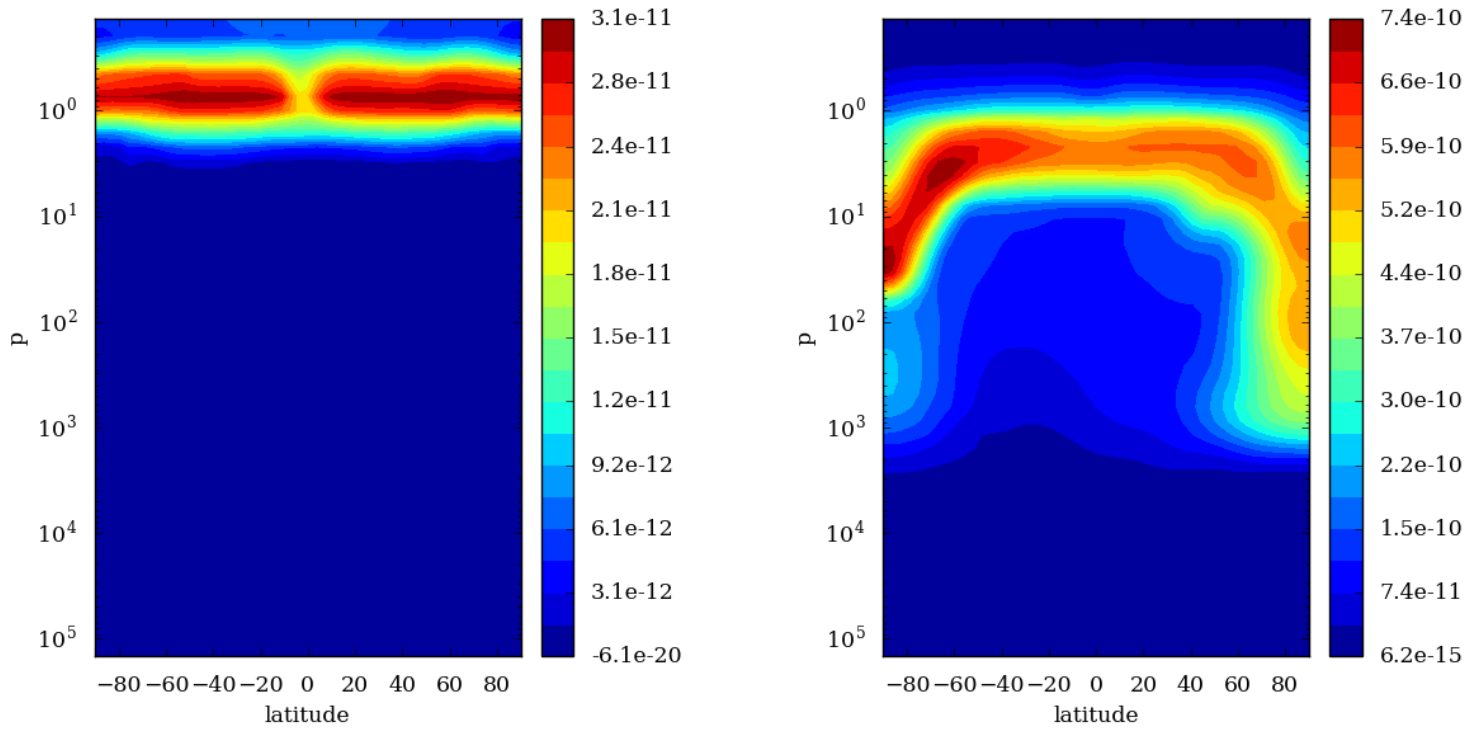
- State-of-the art in the LMD-IPSL GCM :
  - Radius bin microphysical aerosols model (*Rannou et al. 2004*, *Lebonnois et al. 2012*)
  - 10 bin-size (spherical and fractals)
  - Radiative coupling
- Limitations :
  - Long-term coupled simulations loss their momentum in the troposphere
  - Haze production is too low (1 Pa)
- What I'm trying to bring in :
  - A new microphysical model developped at URCA, Reims, France
  - Moment model instead of bin-model (*Burgalat et al. 2014*, *Burgalat et al. 2016*)
  - Computional-time-friendly (4 moments instead of 10 bins)
  - Bi-modal distribution of aerosols size (spherical and fractals), each M_0 and M_3
  - Radiative coupling
  - With highered ceiling, we could higher the production zone

Some results : seasonal variation



Left : northern spring equinox spherical M_0 - Right : northern summer solstice fractals M_0 ($M_0 \sim$ proxy for number of particles)

Some results : spherical vs fractals



Left : northern spring equinox spherical M_3 - Right : northern spring equinox fractals M_3 ($M_3 \sim$ proxy for volume)

Key take-home messages

- If you want to simulate Titan's stratopause don't forget the 7.7 μm CH_4 line !
- Gaz radiative transfer scheme is now correct, giving an improved temperature profile
- Vertical extension of the Hadley cell $\Rightarrow$ on the way to full view of seasonal transport and enrichment of gazes and aerosols !
- We still miss the aerosols radiative feedback for now (being solved), stratospheric circulation still too weak

Perspectives

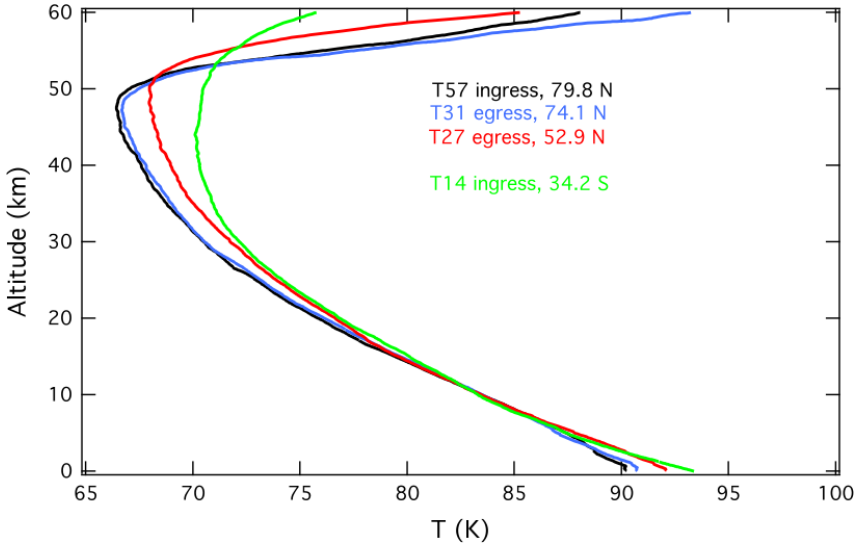
- ✓ Re-activate the photochemistry module
- Radiative impact of trace compounds variations (work in progress)
- ✓ Plug-in the new microphysical moment model
- Re-couple haze radiative effects and dynamics (work in progress)
- Study clouds formation, especially in polar winter stratosphere.
- Adapt the deep atmosphere core to run accurate simulations with vertical increased extension
- Study the formation and evolution of polar vortex, with good resolution (new icosahedral dynamical core Dynamico)

Thanks for your attention !
どうもありがとうございます

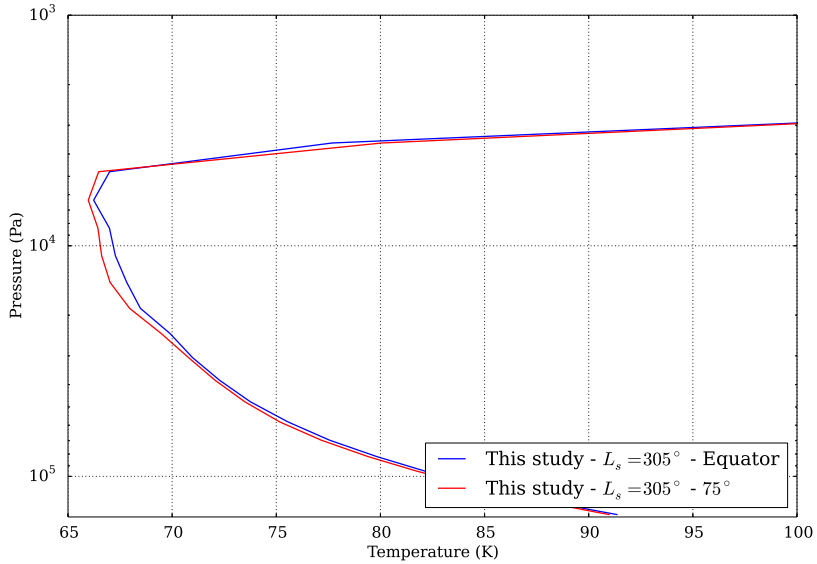
Any questions ?

Images courtesy : NASA/JPL processed by B. Seignovert.

Temperature latitudinal contrast



(Schinder et al., 2012)



This study

- Without haze retroaction, temperature latitudinal contrast is fainter than in the observations (*Lebonnois et al, 2009*)
- Too weak wind shear according to thermal wind equation in the troposphere.