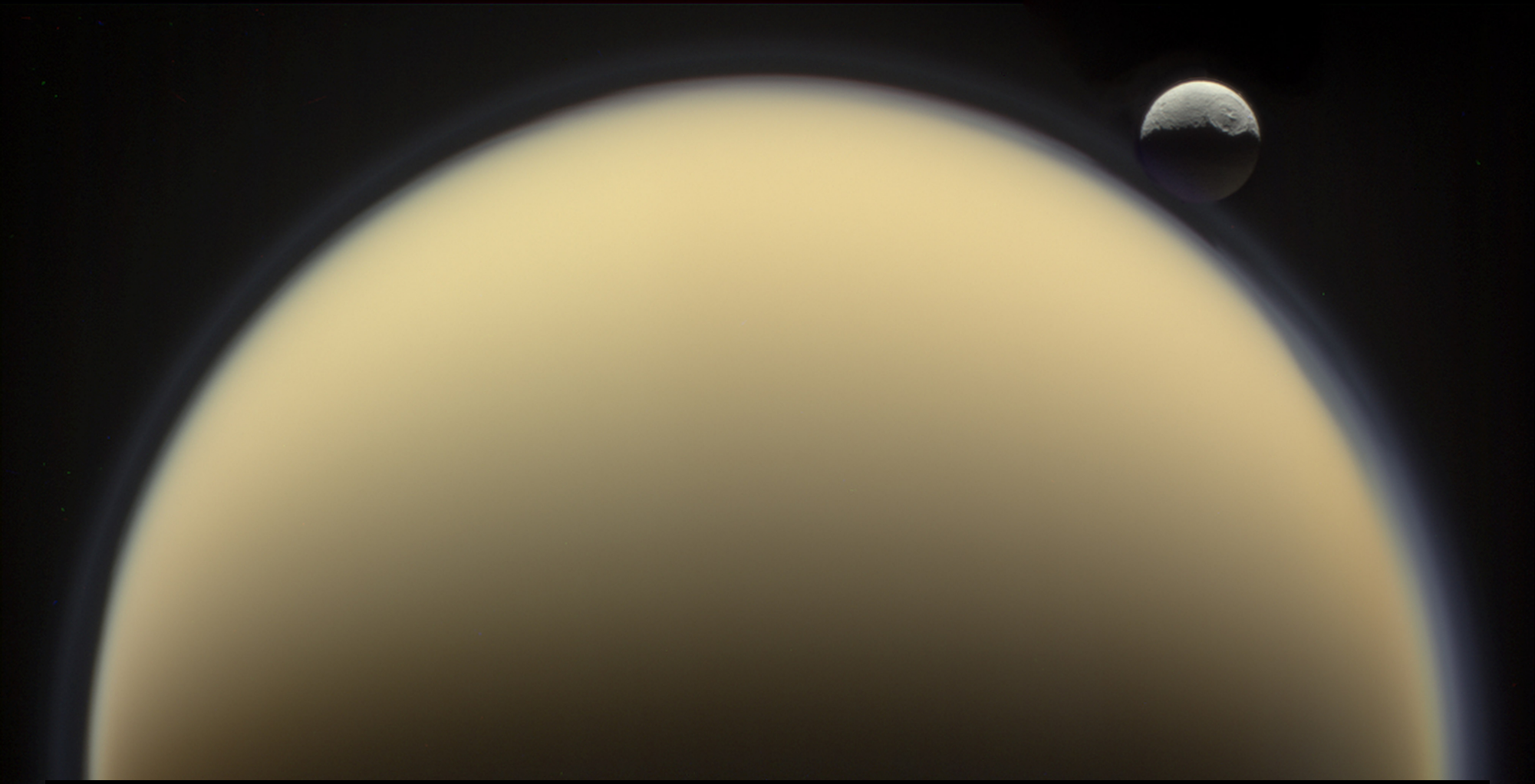

Seasonal effects in Titan's stratosphere analyzed through Global Climate Modelling

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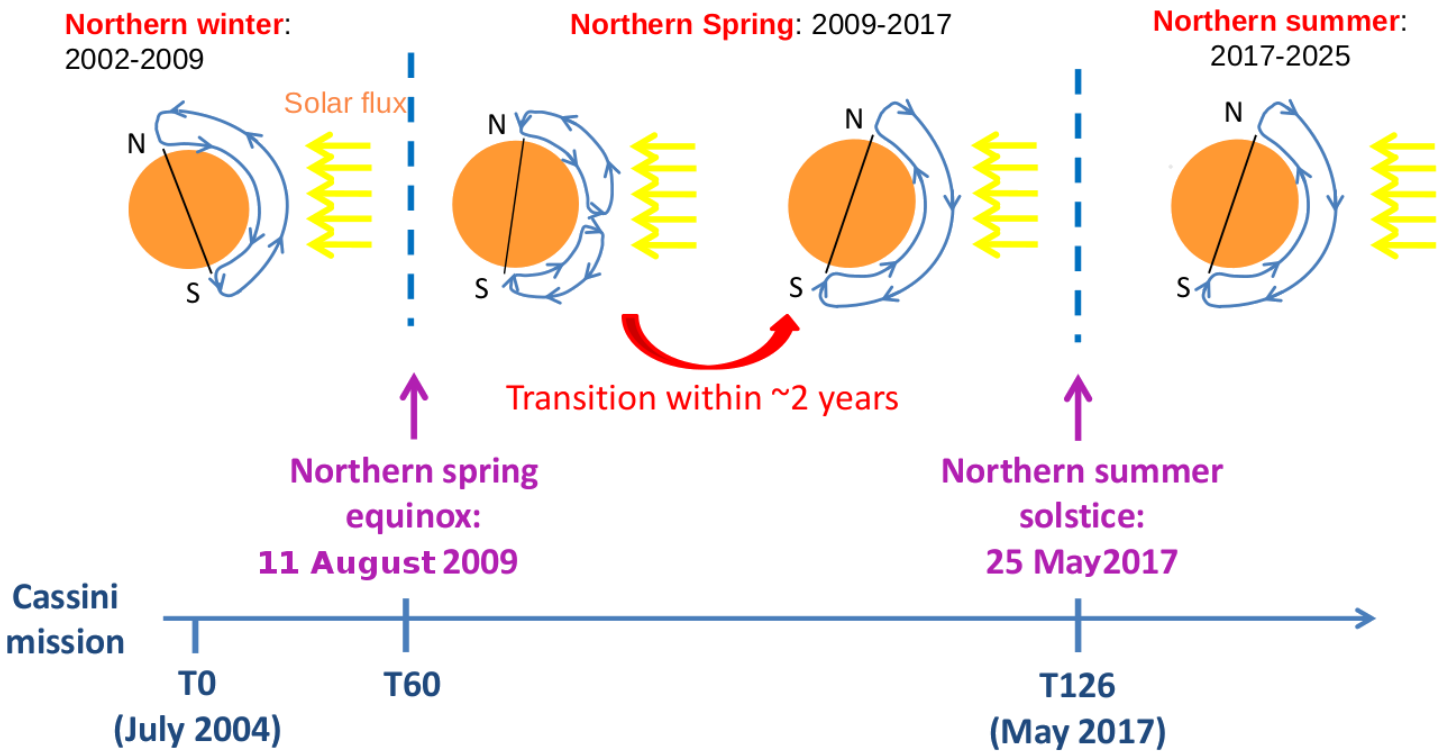
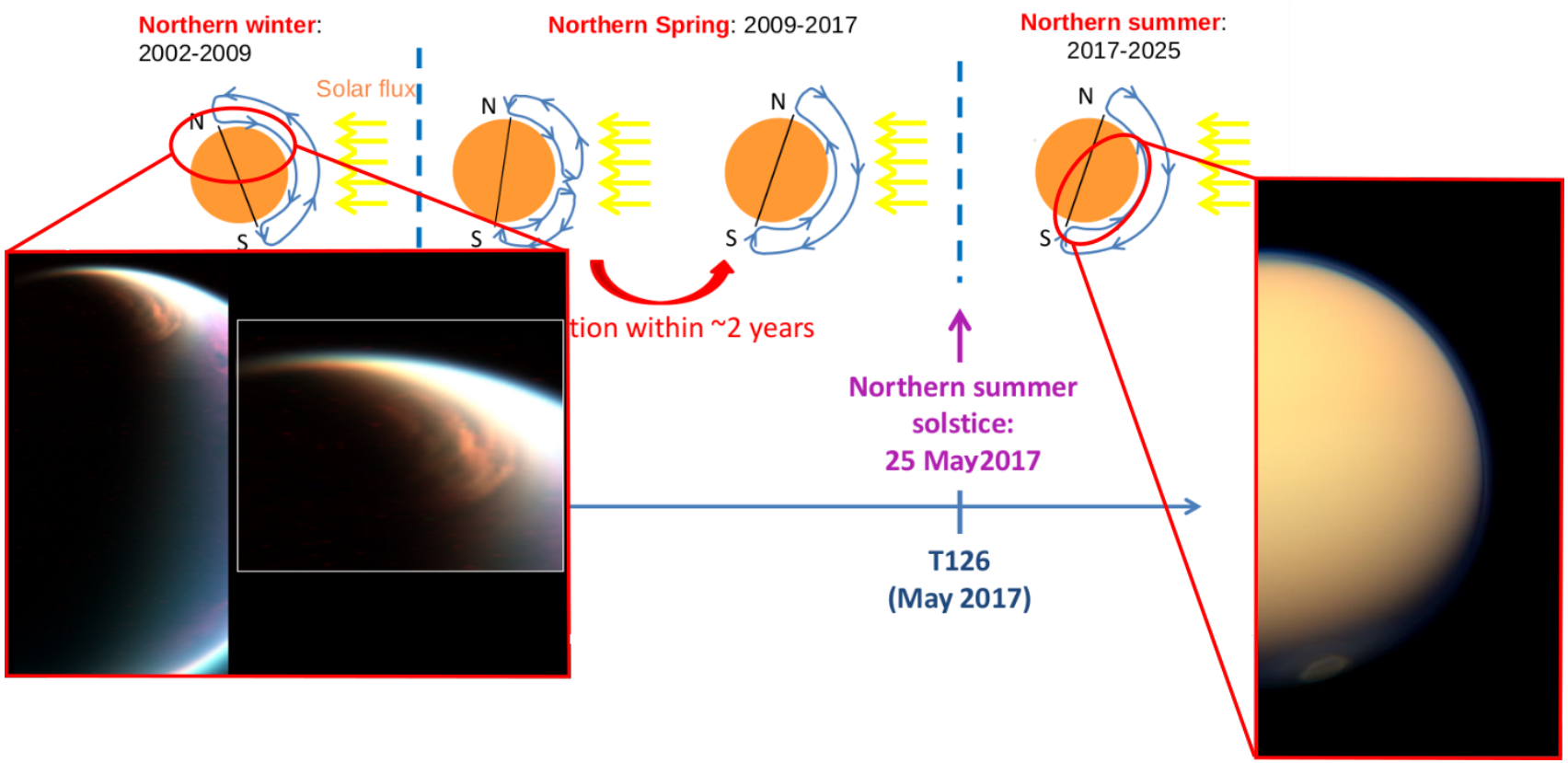
Seasonal evolution

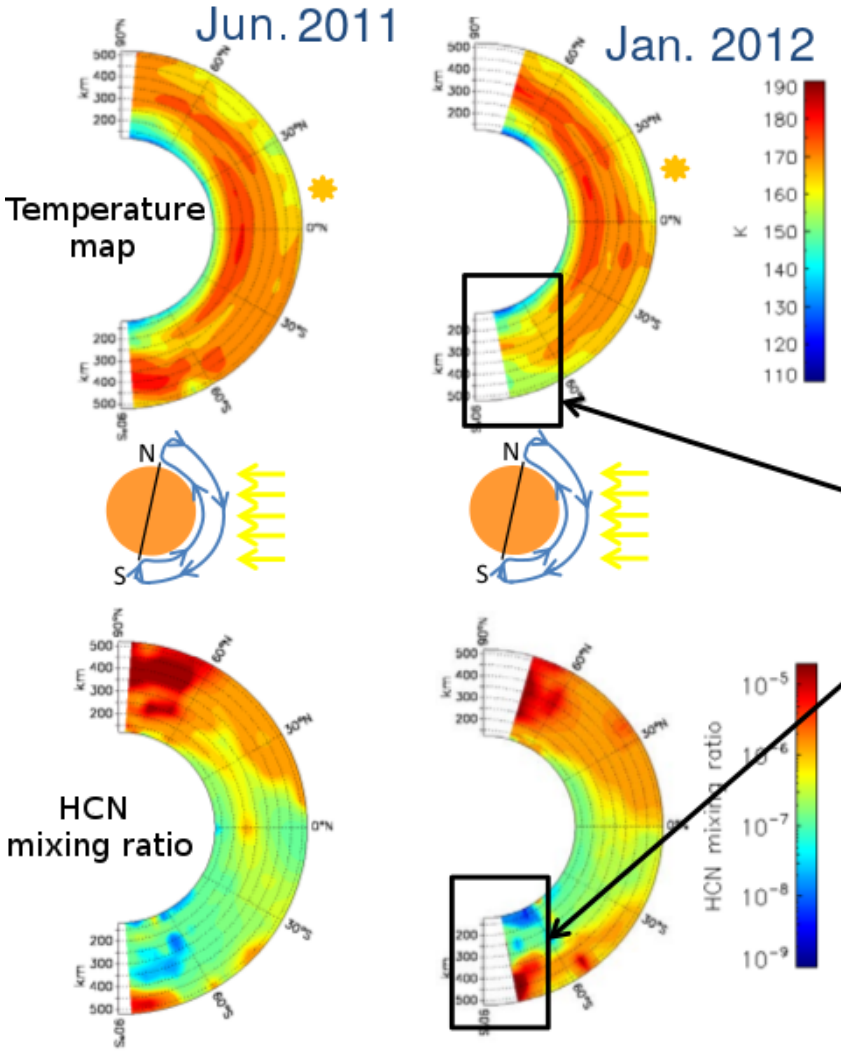


Courtesy : S. Vinatier

Seasonal evolution - winter polar vortex



Recent works - South polar vortex



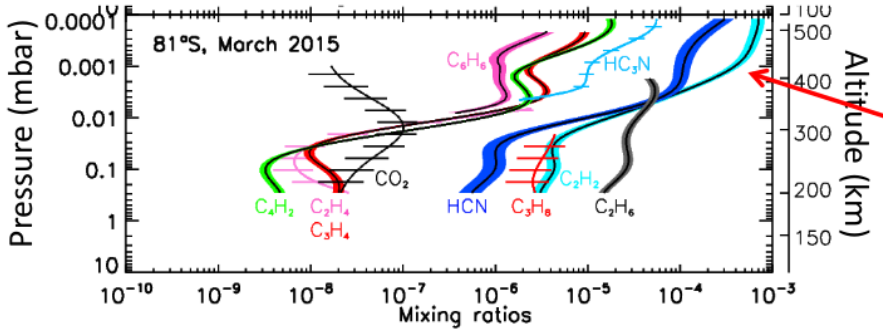
Vinatier et al., 2015, Icarus

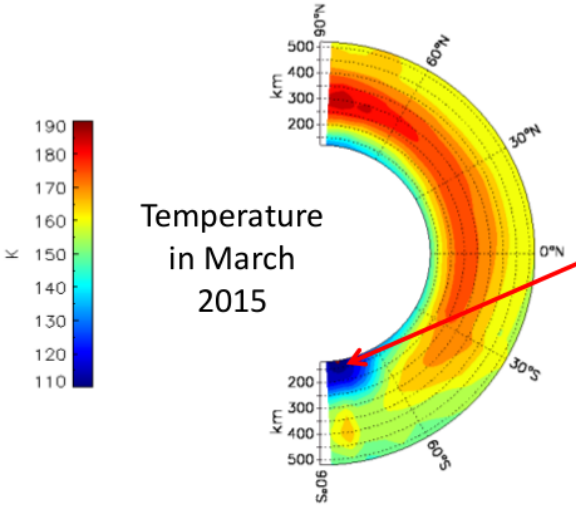
Unexpected cooling at the South pole

Strong enrichment at the South pole

Radiative cooling by trace species and aerosols compensates the adiabating heating from descending branch ?

Recent works - Condensates at South Pole





Very strong molecular enrichments

+

Very cold stratospheric temperature

Condensation of molecules at very high altitude

Courtesy : S. Vinatier

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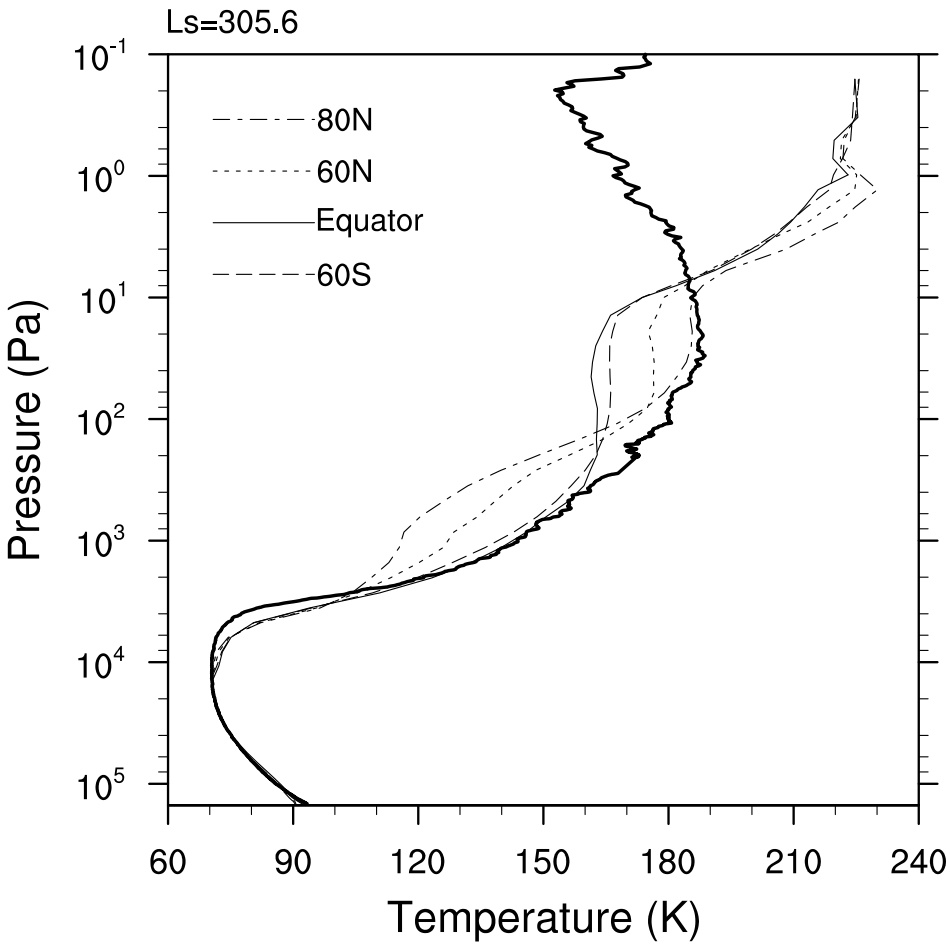
LMD Titan's GCM suffered from limitations



(Lebonnois et al., 2012)

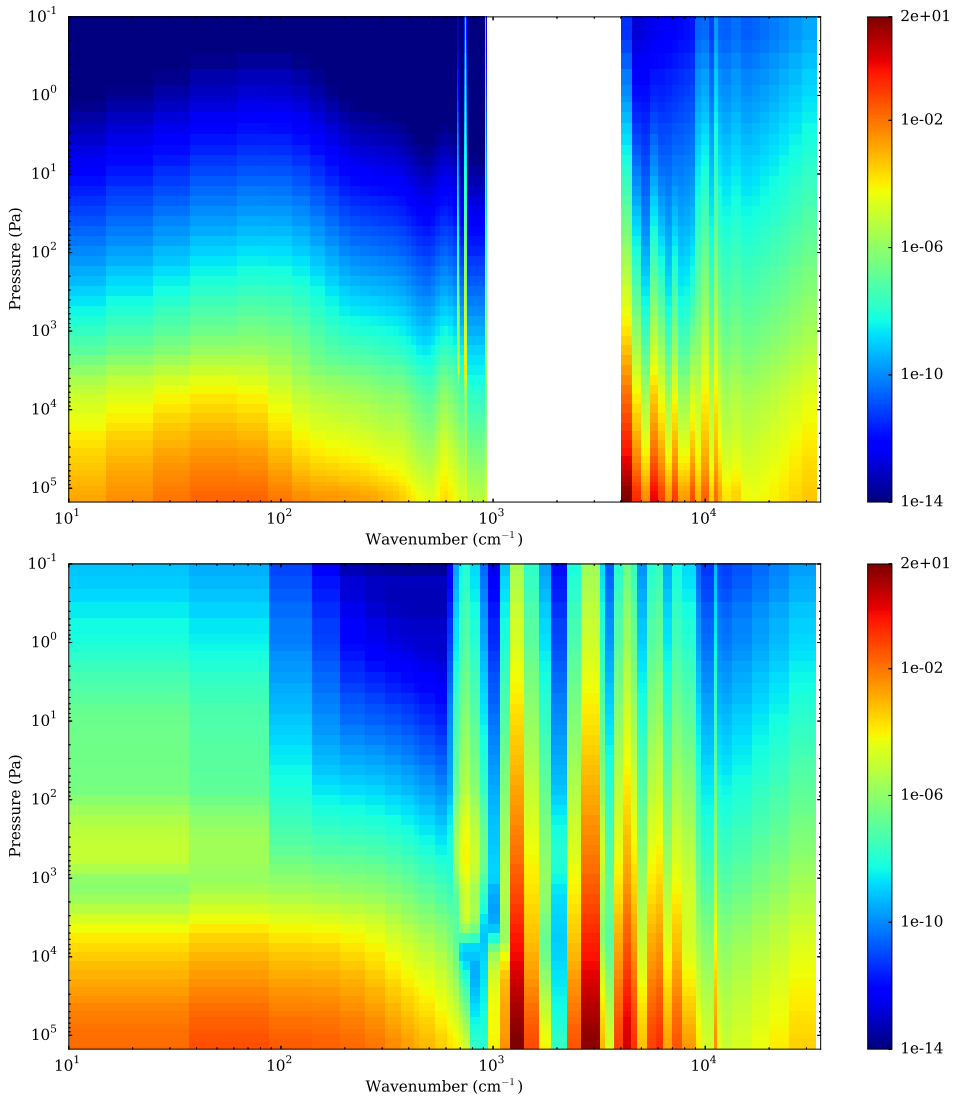
- Temperature profiles diverged at the ceiling of the model
- Long-term runs lead to a strong stability zone, "stucking" the Hadley cell
- Limited vertical mixing of stratospheric compounds

New set-up for Titan GCM

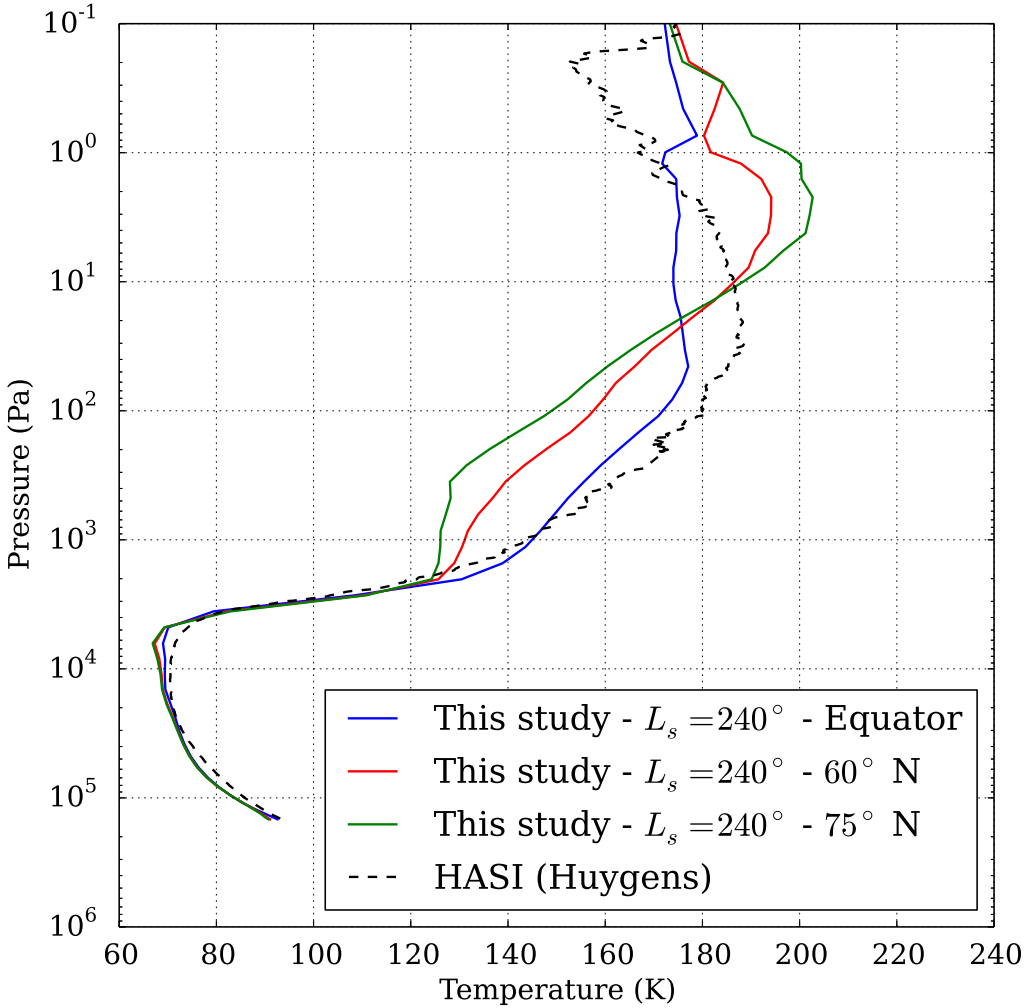
- Correlated-k scheme with CH_4, C_2H_6, C_2H_2 and HCN from HITRAN 2012 (+ Reims GSMA methane line database in 7900-12000 cm^{-1} range) + Collision-induced absorption (N_2, H_2 and CH_4)
- Aerosol mean opacity profile based on constraints retrieved from DISR data [Lavvas et al., 2010]
- Photochemical solver (Lebonnois et al. 2001, Crespin et al. 2008) up to 1300 km, 44 species (H,C,N) and 344 photochemical reactions

So far it implied to decouple radiative transfer from microphysics (no latitudinal or temporal variations) ...

Radiative transfer extinctions (m^{-1}) update



Main consequence - Simulated stratopause



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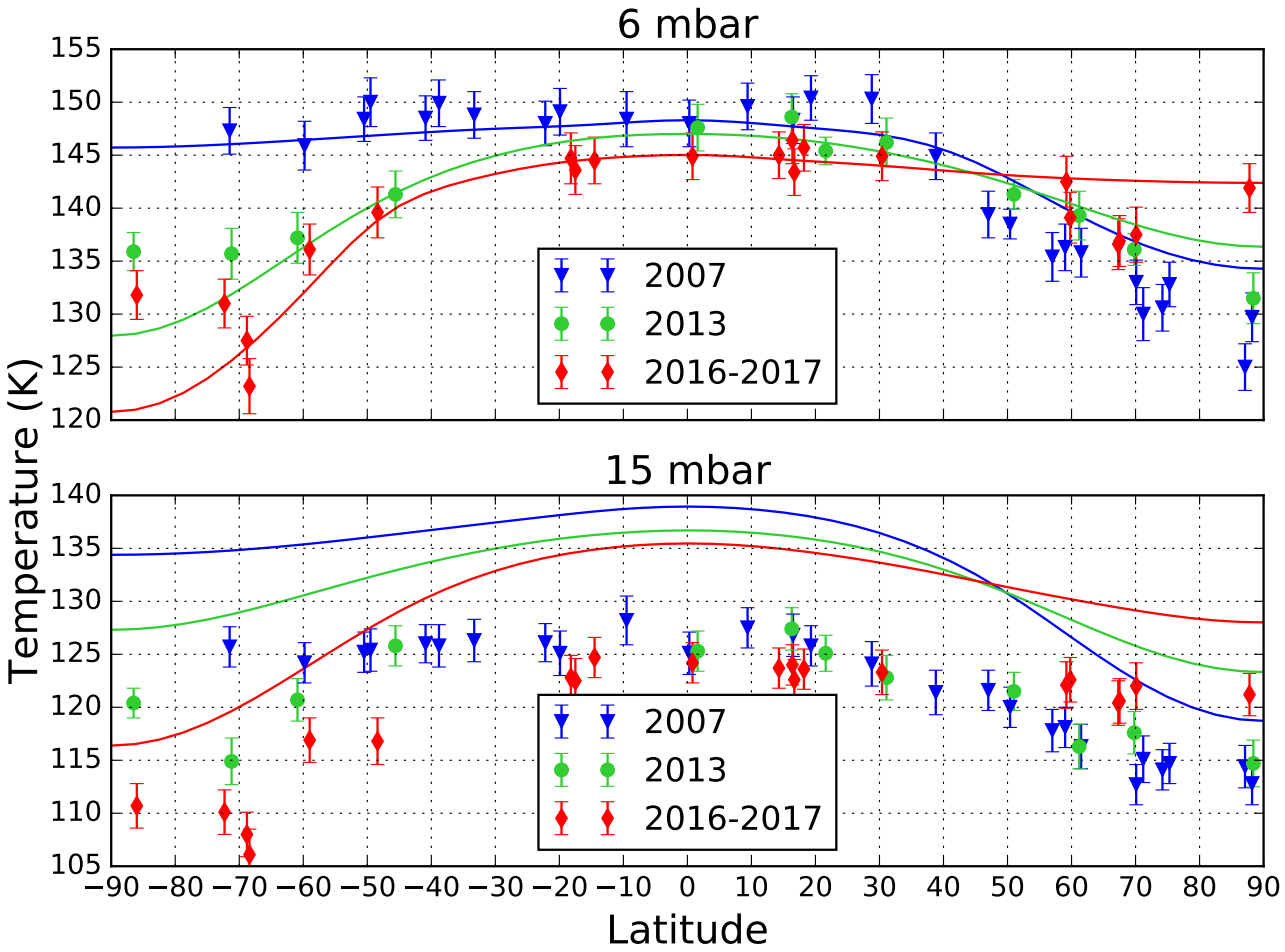
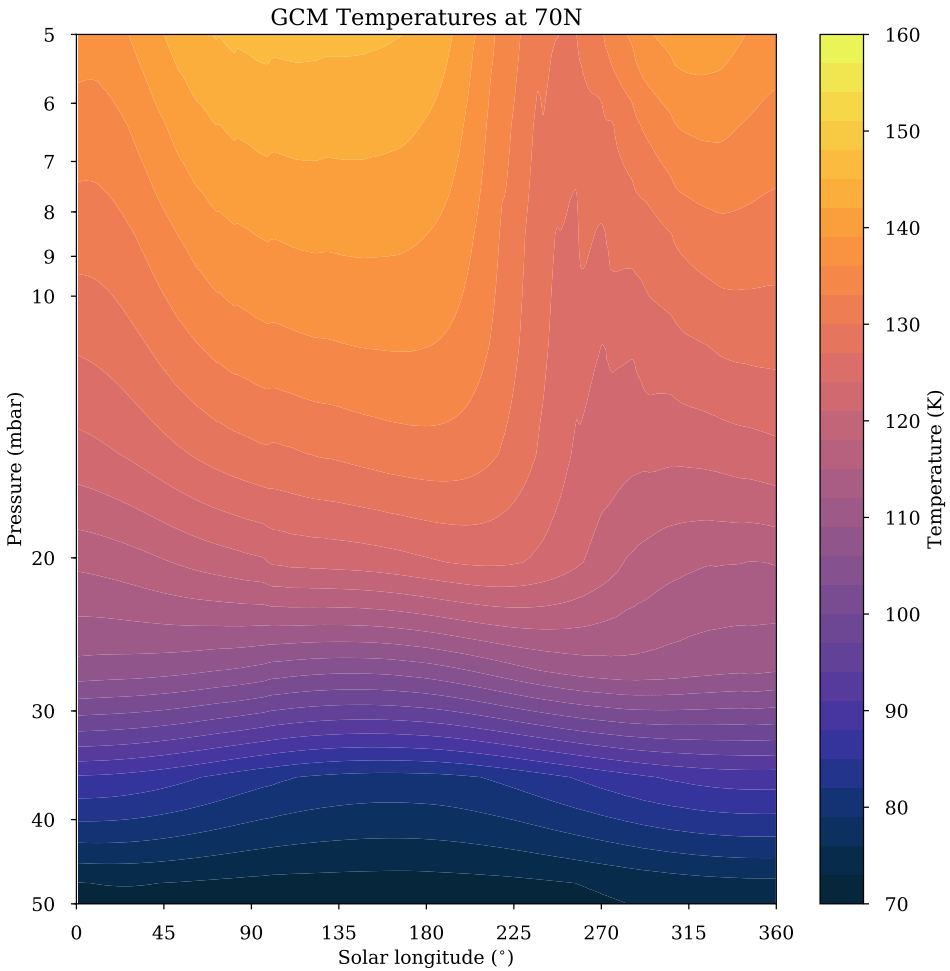
Low stratosphere



Sylvestre et al., Submitted to Icarus

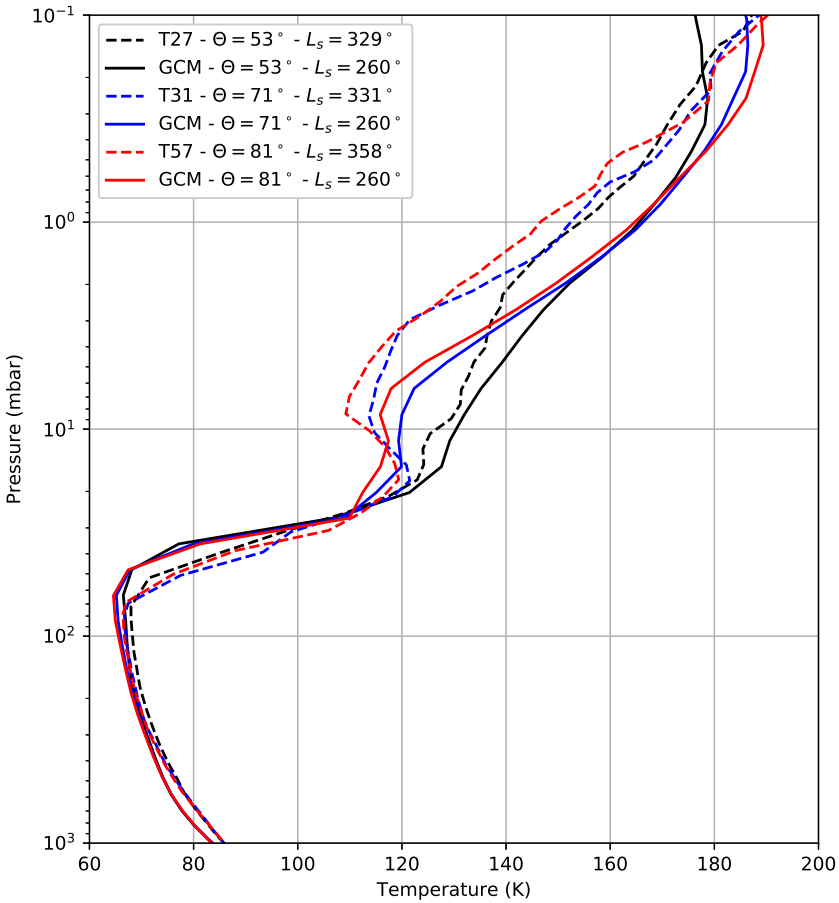
Low stratosphere seasonal evolution



Sylvestre et al., Submitted to Icarus

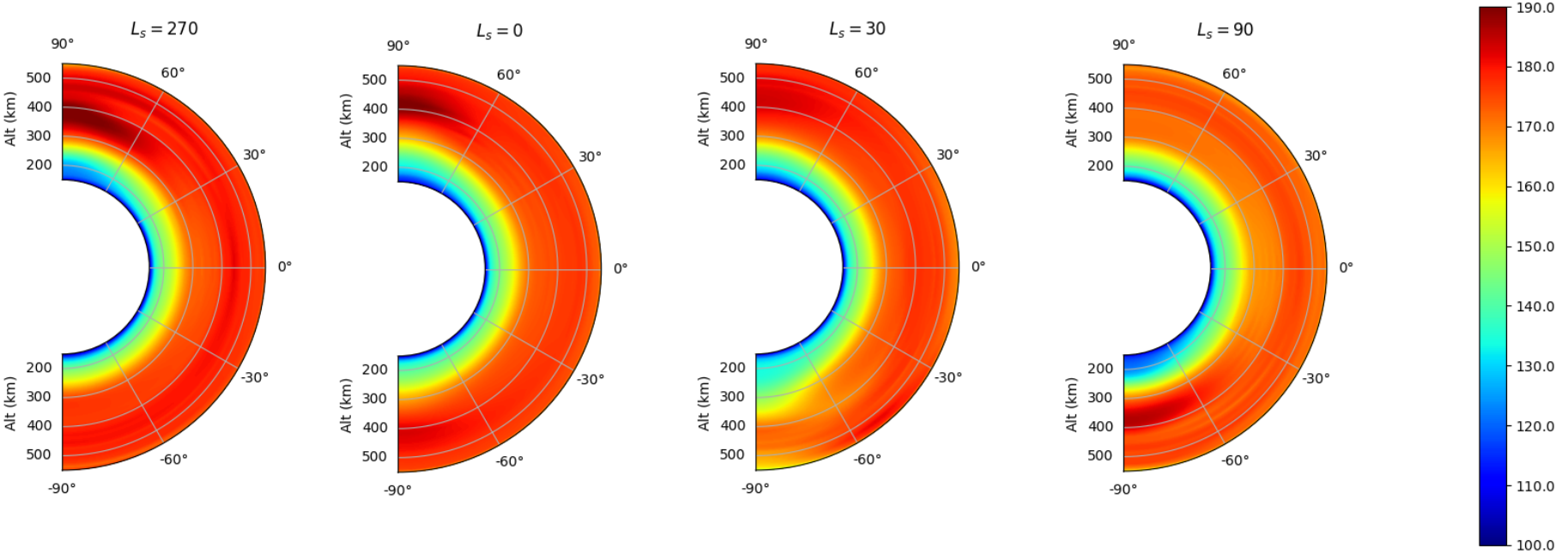
- Pronounced asymetry between ingress and egress of polar winter consistent with CIRS observations : It's a (cold) trap !
- Under $\simeq$ 25 mbar the seasonal cycle is damped due to radiative timescales reachin 1 Titan year (cf *Bézard et al. 2018*).

Winter "polar shoulder"



- Observed in radio-occultations (*Schinder et al. 2012*)
- Quite reproduced in simulations without latitudinal or temporal variations of composition !
- Drived by polar night lack of insolation (symmetric wrt solstice) and radiative timescale transition zone.
- Presence of clouds would certainly sharpen this destabilization and enhance the "trap" in cold state.
- Are other Cassini radio-science profiles available ?

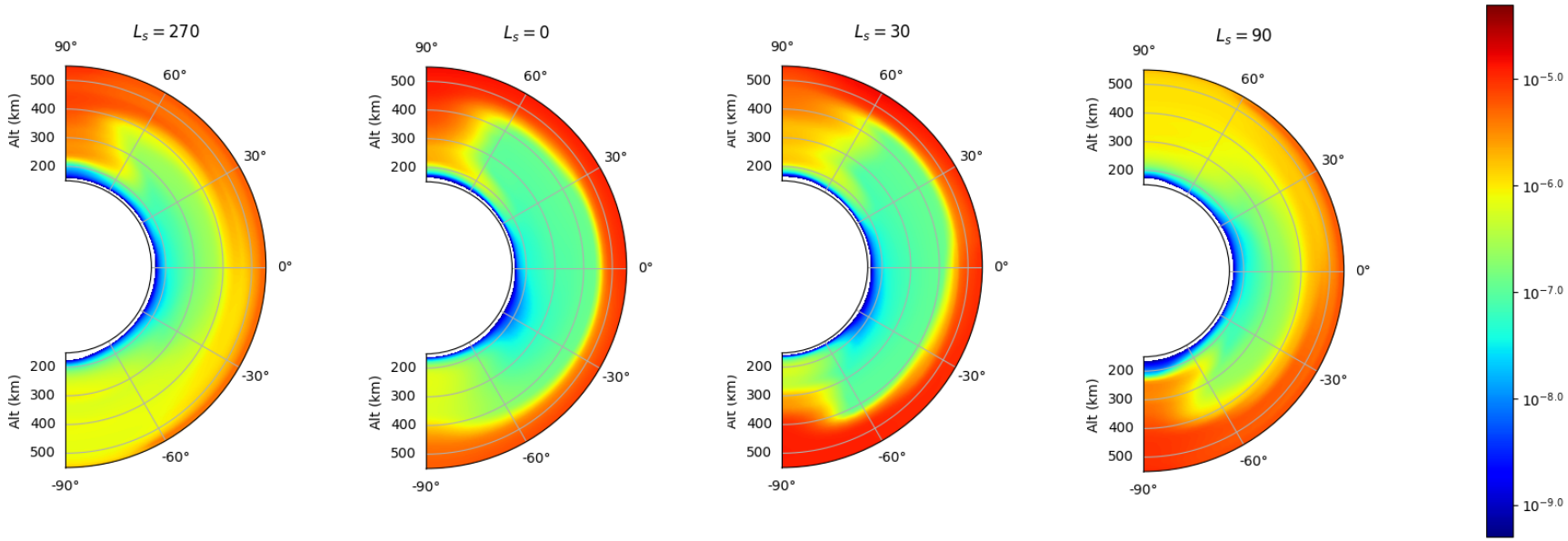
Seasonal behaviour of the thermal structure



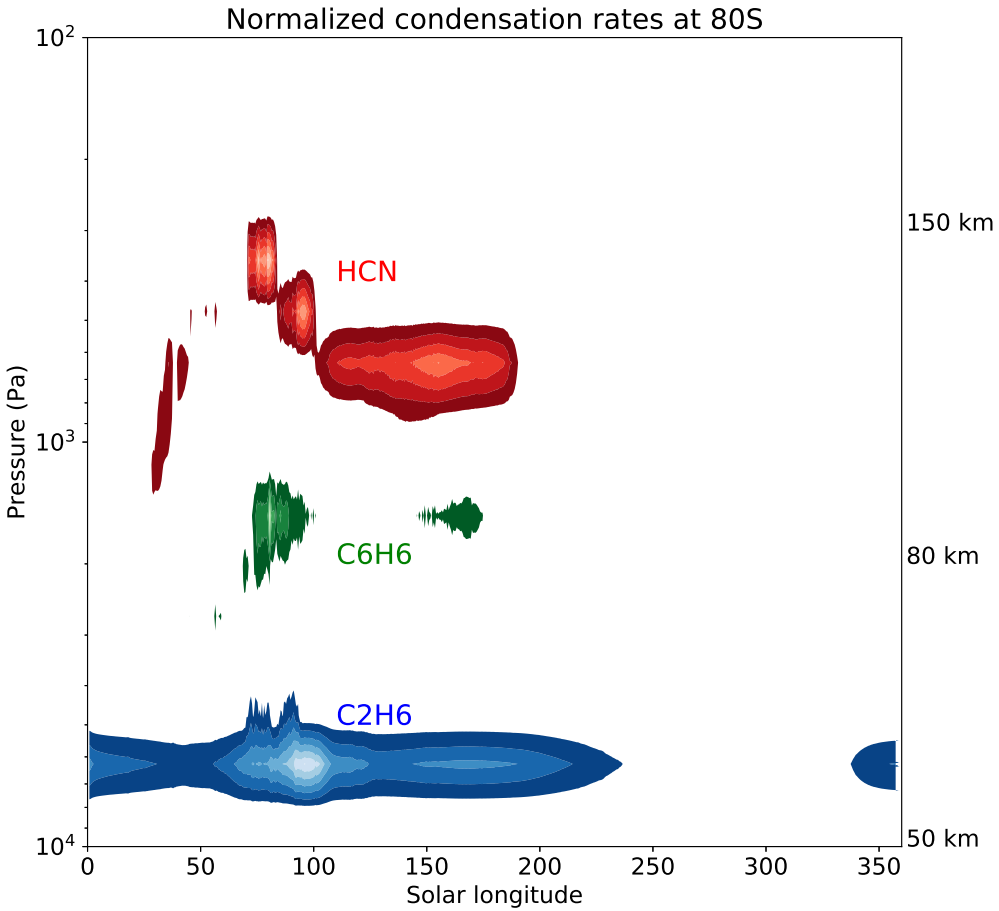
Thermal structure sum-up

- :-) Low-latitudes thermal profiles quite correct (with stratopause !)
- :-(Lack of winter polar cooling since no retroaction of haze accumulation
- :-(Too warm and too low polar winter stratopause compared to CIRS data
- :-(Induced circulation weaker than expected and limited in vertical extension during the heart of winter
- :-) Low stratosphere destabilization ("polar shoulder") quite well reproduced

Seasonal behaviour of HCN

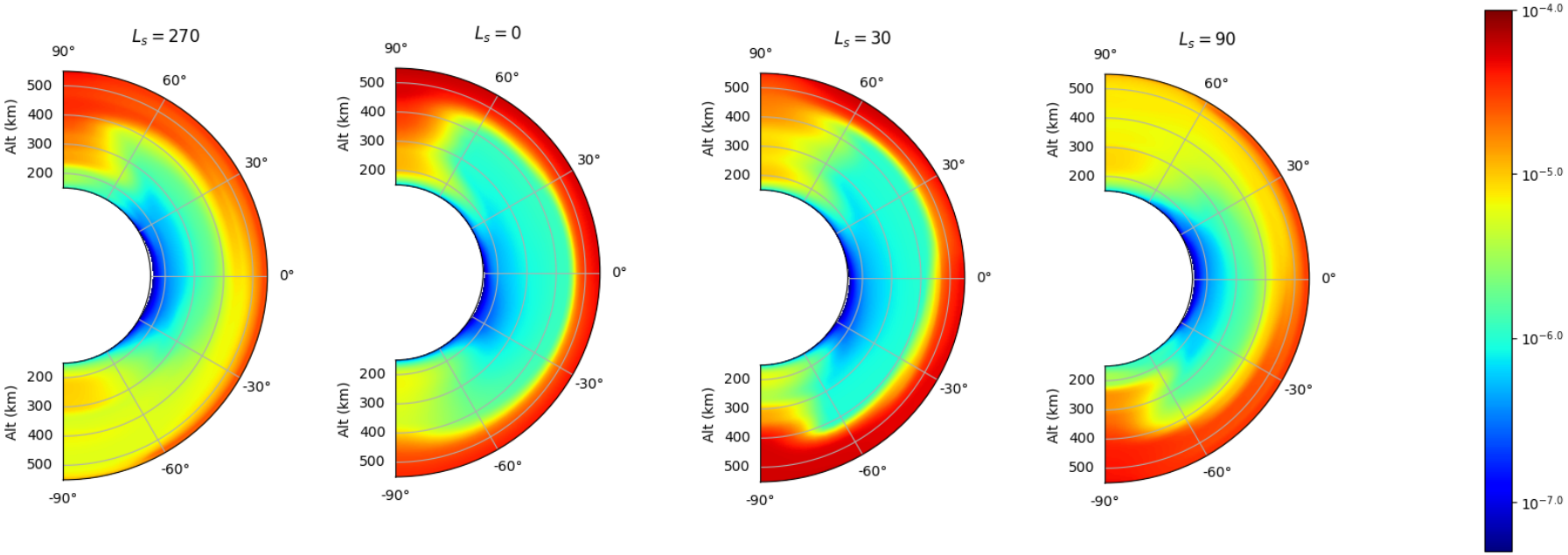


Towards a high-altitude cloud ?

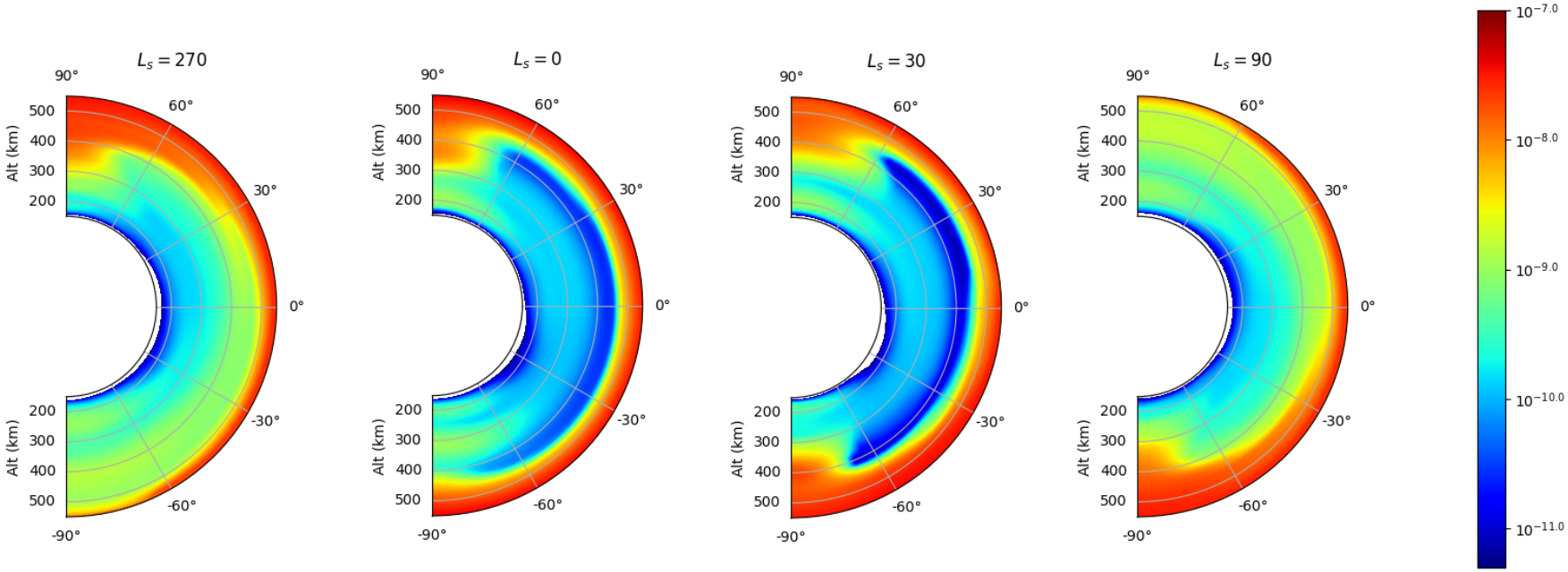


- Unlike *Hourdin et al. 2004* variations of temperature now impact condensation.
- *De Kok et al. 2014* : HCN ice at 300 km
- *Vinatier et al. 2018* : C6H6 ice at 250 km
- With further cooling (polar night haze, cloud condensates) and better trace compounds enrichment, we could maybe reach 300 km !
- $\rightarrow$ We need a coupled microphysical model !

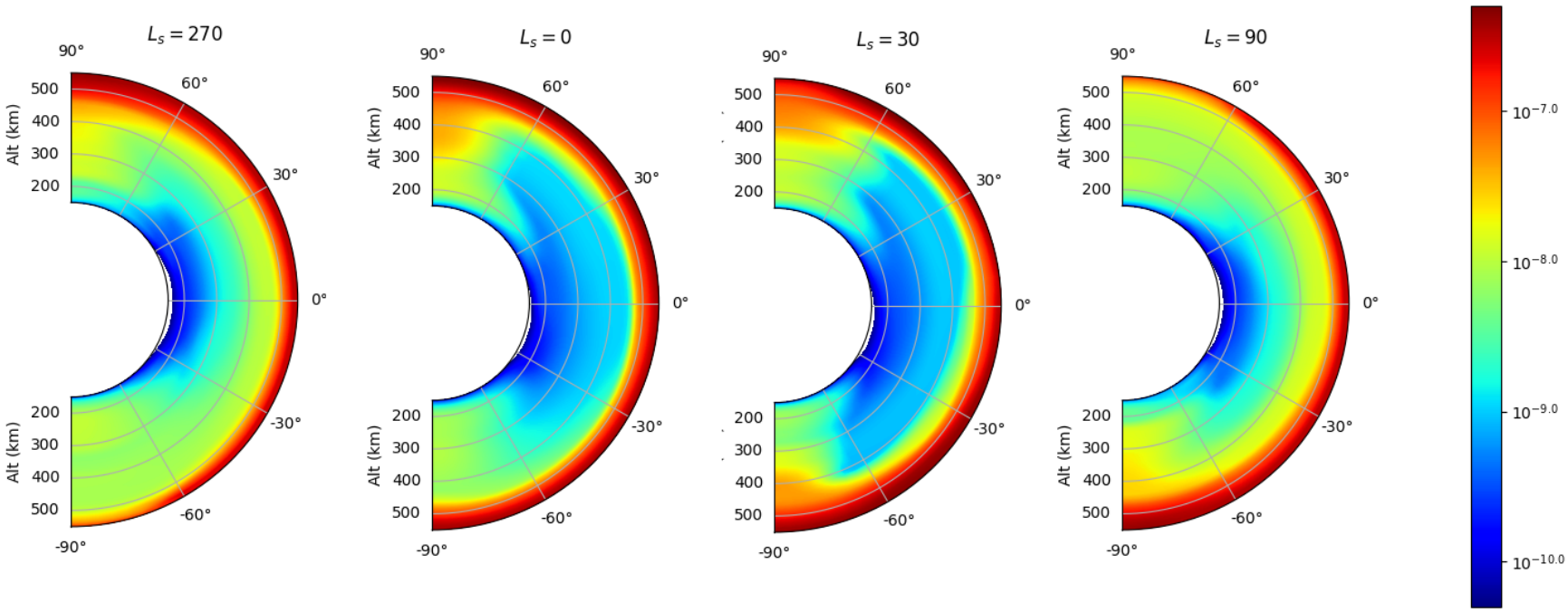
Seasonal behaviour of C2H2



Seasonal behaviour of C6H6



Seasonal behaviour of HC3N

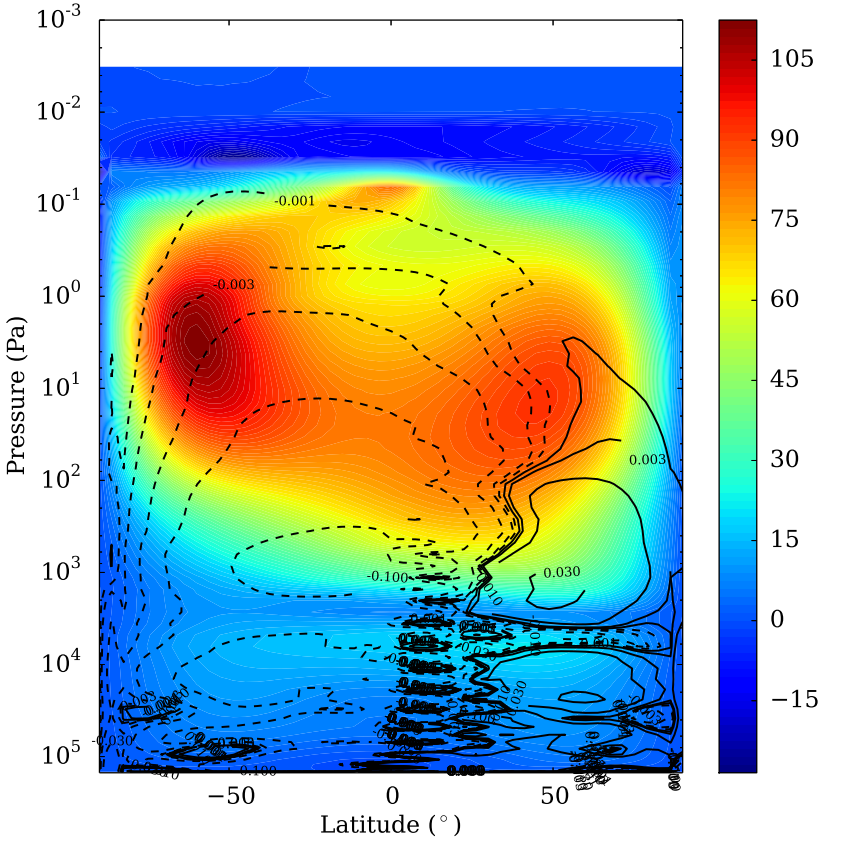


Seasonal enrichment variations

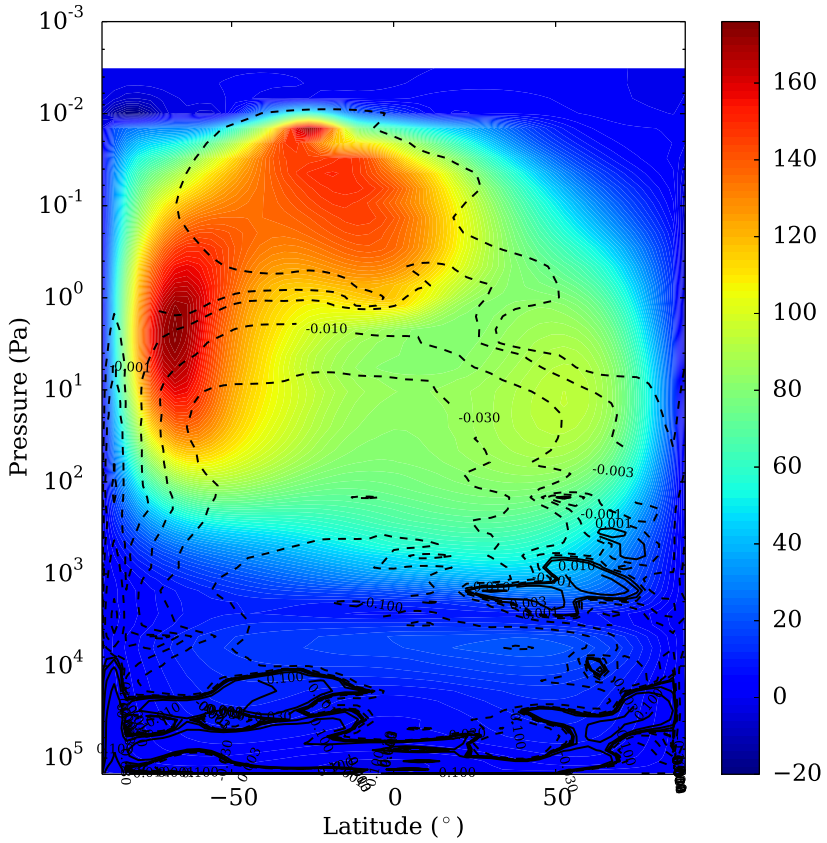
- :-) Amplitude of variations in good agreement with CIRS data.
- :-) Hints of high-altitude condensation.
- :-(Reversal of polar enrichment occuring too early compared to the observation because of the limited vertical extension of the circulation due to lack of polar night haze cooling.
- :-) Small return cell above summer pole trapping some compounds.
- ?? High altitude equatorial depleted C6H6.
- ?? No real enrichment of HC3N above pole ? Linked to very short lifetime ?
- :-) High-altitude variations indicate that above winter pole, abundances of photochemical products increase after spring equinox around 600-800 km altitude. With circulation more extended above 350 km, this could be related to the increase observed in the polar enrichment after the equinox.

Hadley cell vertical extension ?

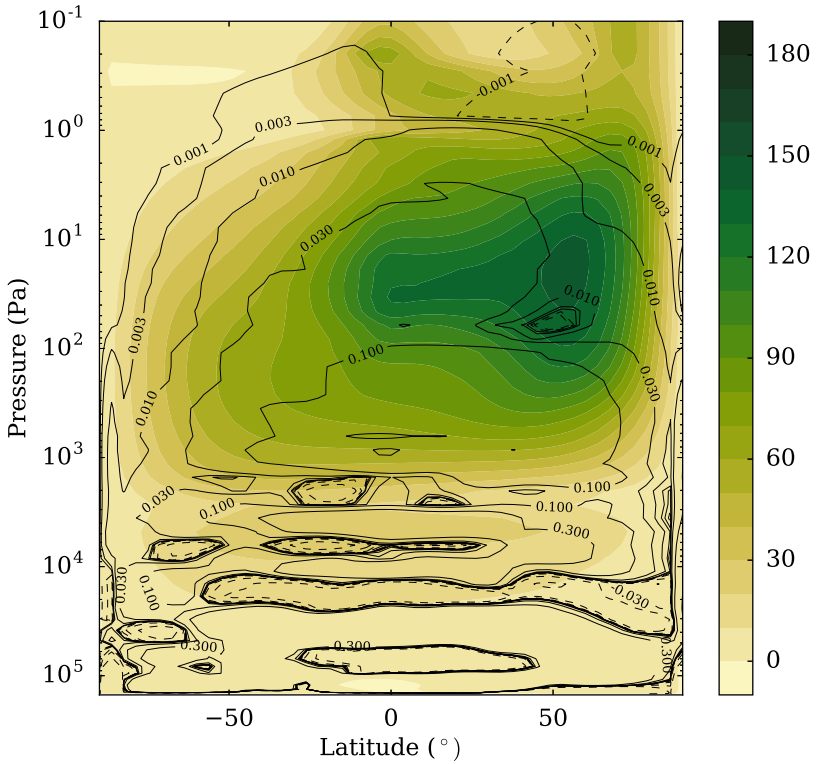
$L_S = 12^\circ$ - Zonal wind (m.s^{-1}) - Streamfunction (10^9 kg.s^{-1})



$L_S = 20^\circ$ - Zonal wind (m.s^{-1}) - Streamfunction (10^9 kg.s^{-1})



Towards an increased vertical extension



- Motivations
  - With the improved temperature profiles, Hadley cell could now vertically extent
- But ...
  - As long as we lack polar cooling vertical circulation in winter will be limited
  - Thin layer approximation ! We need to use the deep atmosphere core (at 500 km $\frac{g}{g_0} \simeq 0.6$) !
  - And also, non-LTE processes, illuminance over the poles ...

What's next ?

- A new bulk microphysical model for the haze (work in progress with Reims team)
  - ✓ Transport of the microphysical moments
  - Radiative coupling
  - Activate clouds formation
- Radiative impact of trace compounds variations (work in progress)
- Run simulations with vertical increased extension (implementation of a deep atmosphere core for more accuracy)

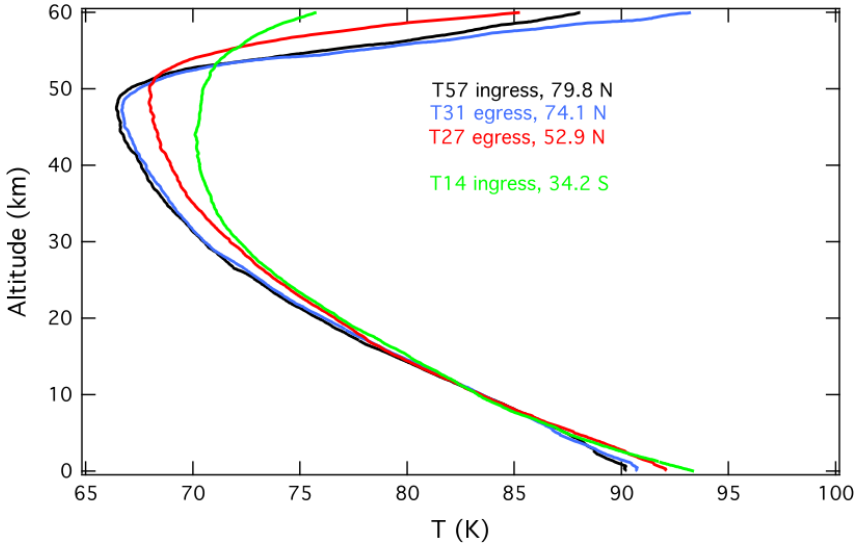
Key take-home messages

- Radiative transfer scheme is now correct, giving an improved thermal structure
- Lack of cooling above winter poles as long as no retroaction of haze accumulation $\Rightarrow$ still limited vertical extension of circulation
- Once we have vertical extension of the Hadley cell $\Rightarrow$ full view of seasonal transport and enrichment of gazes and aerosols !
- "Polar shoulder" destabilization reproduced in the low stratosphere without radiative feedback of haze or trace compounds !
- Enrichment in trace compounds (HCN,C2H2,C2H6 ...) in good agreement with CIRS data except for the delay at circulation reversal.
- High altitude condensation of HCN and C6H6 in the winter pole yet not as much as in the observations.

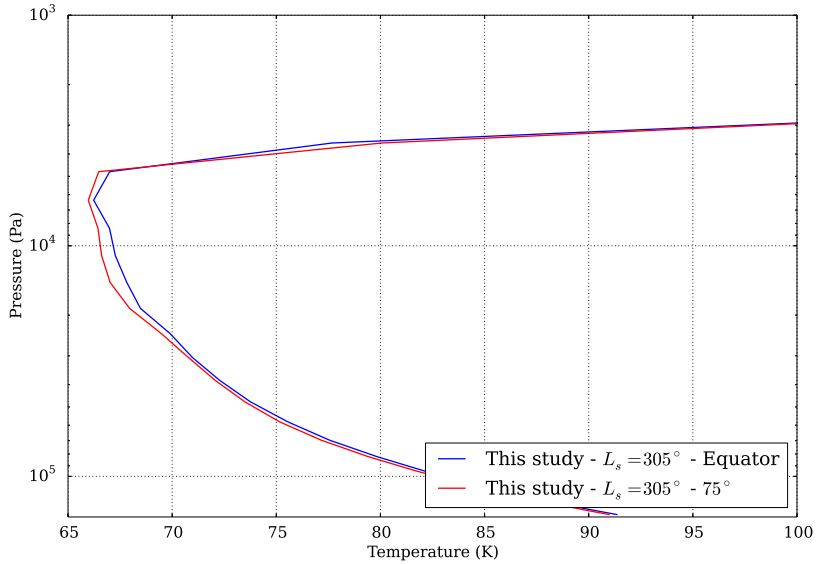
Thanks for your attention !

Images courtesy : NASA/JPL

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.