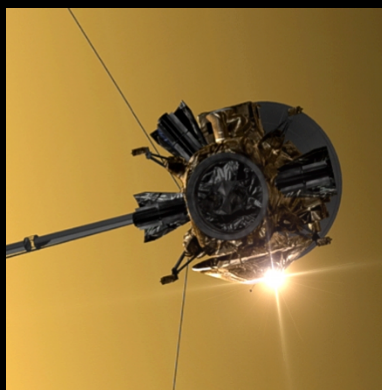
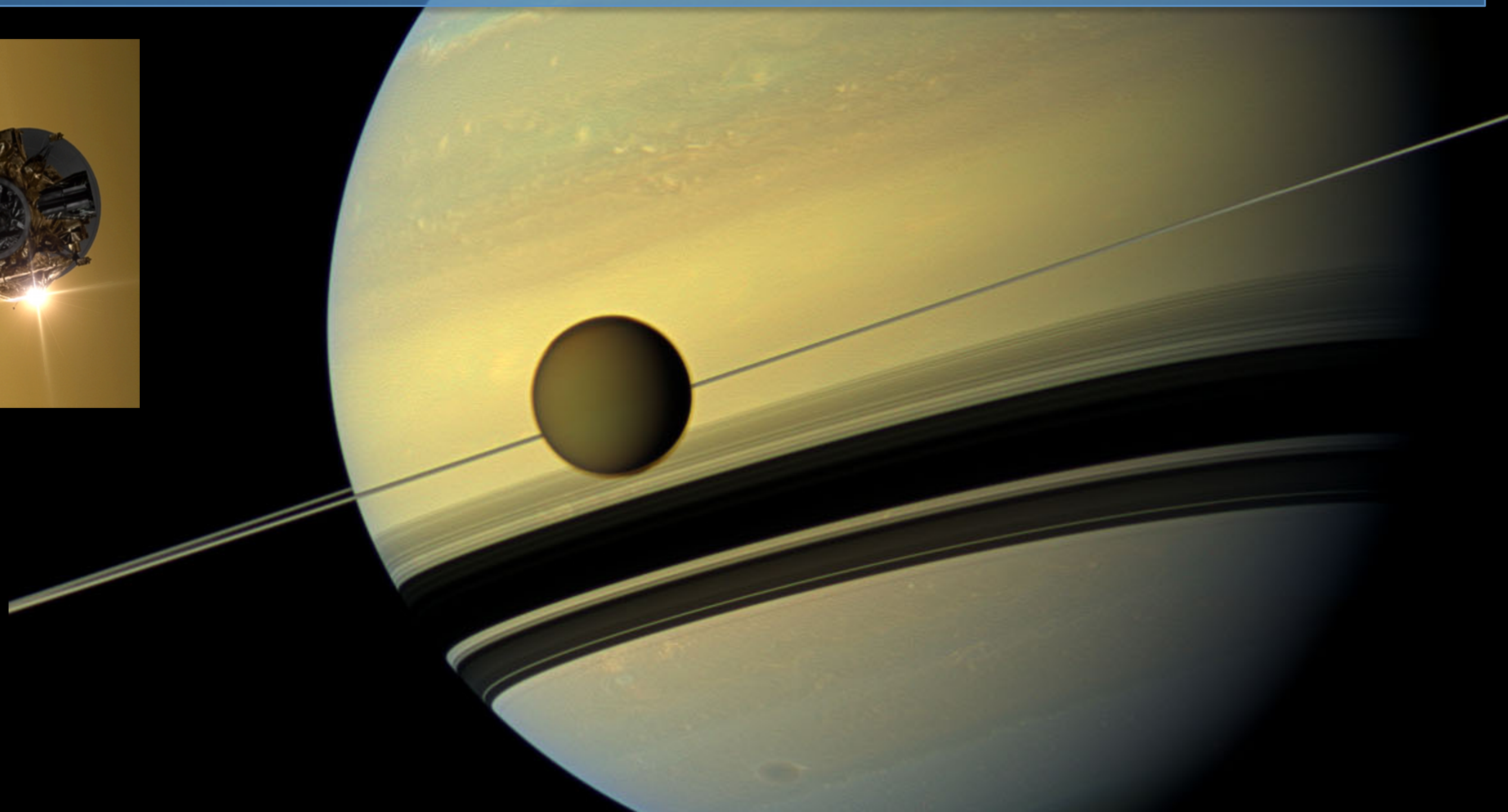
Saturn's Seasonally Changing Atmosphere: Thermal structure, composition, and chemistry [Chapter Ten]



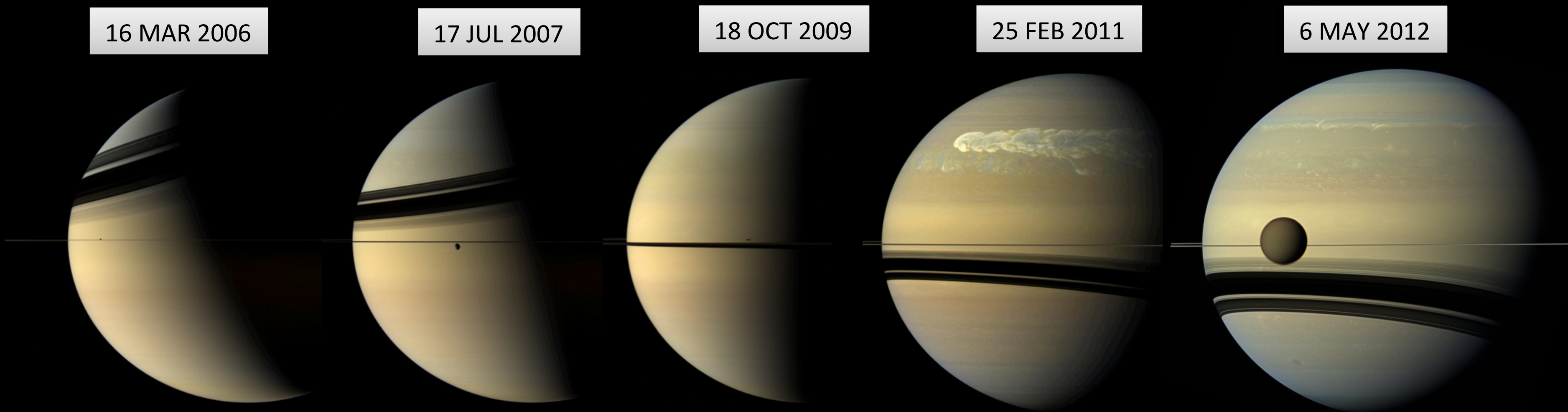


UNIVERSITY OF OXFORD

Leigh N. Fletcher, J. Moses, T.K. Greathouse, S. Guerlet, R. West

THE ROYAL SOCIETY

Seasonal Saturn



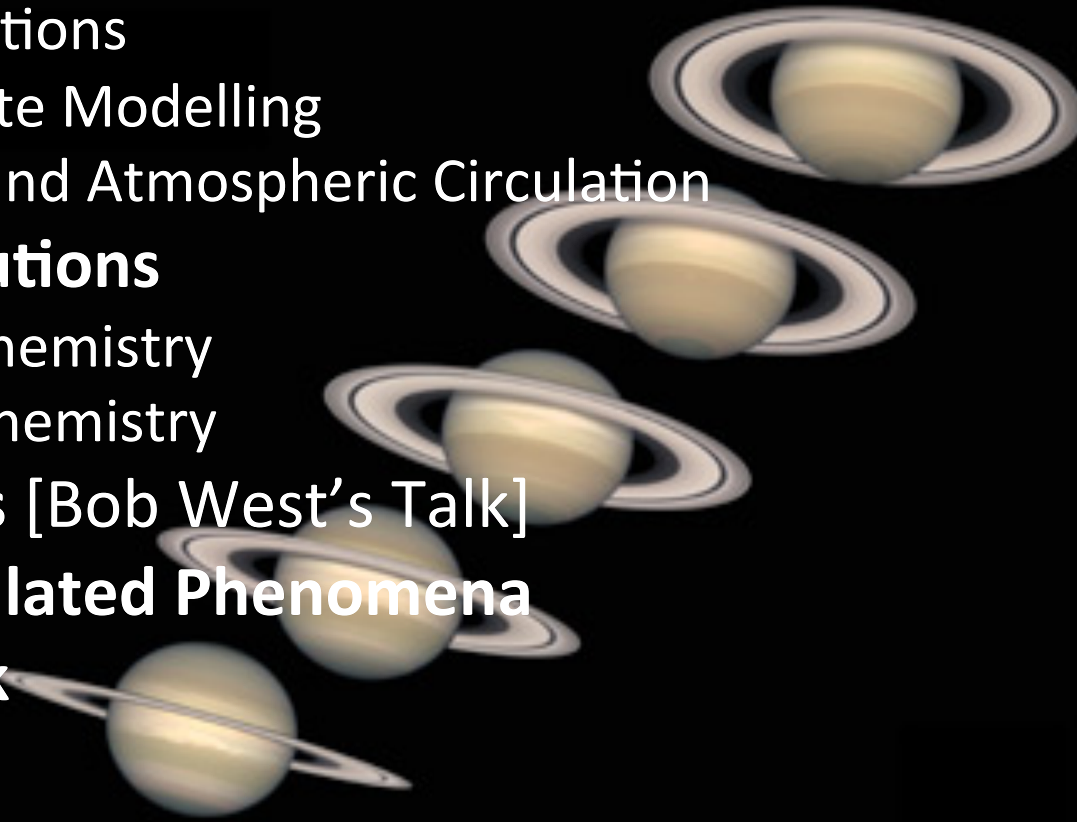
- Saturn has orbited the Sun 13.5 times since Galileo's first observations of the 'strange appendages'.
- Only for the last 1.5 have we been able to study seasonal thermal changes.
- …and only for the last 0.33 have we been studying from Saturn orbit.

Chapter Ten Outline

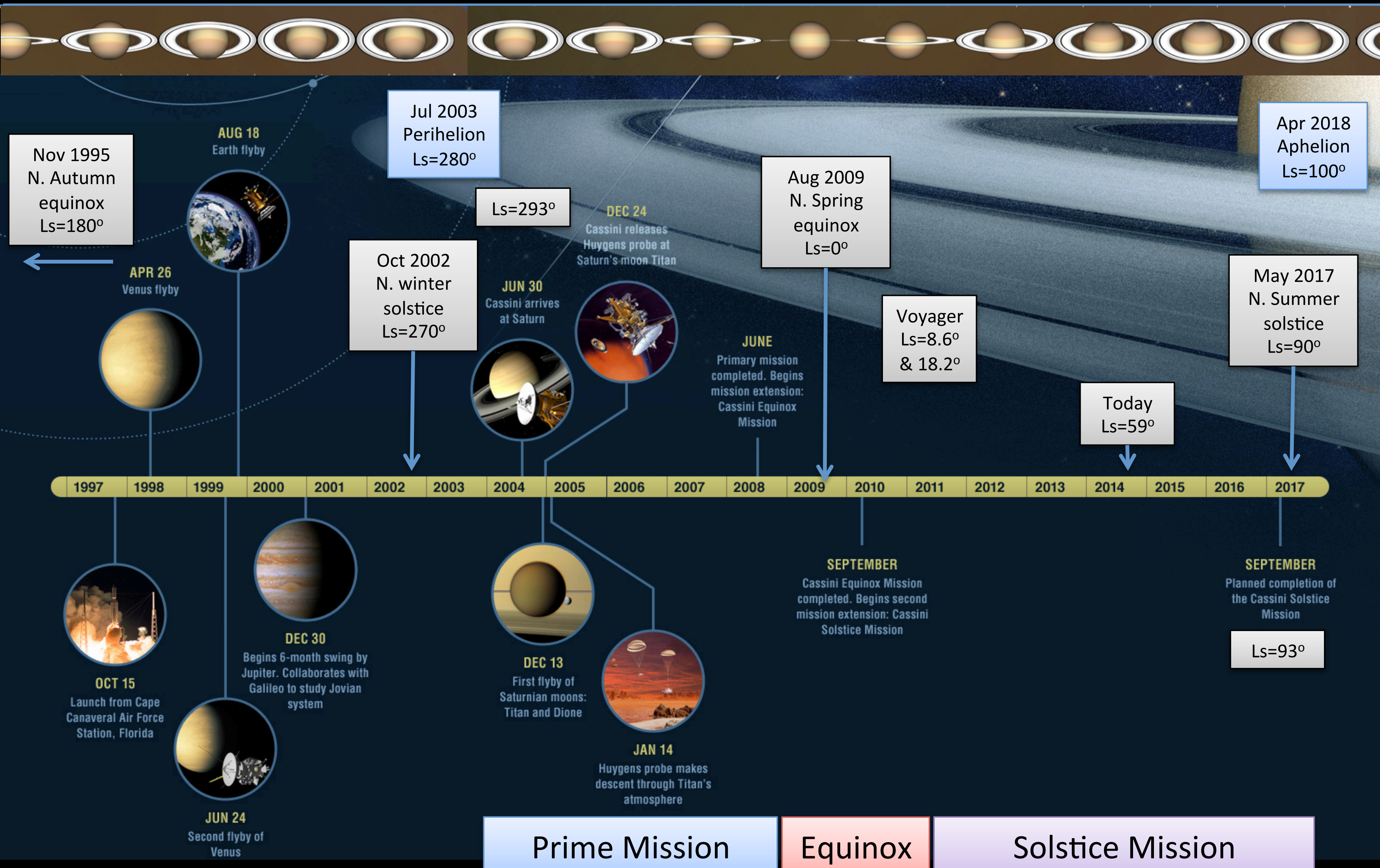
PART ONE

PART TWO

1. **Introduction**
2. **Seasonally-Evolving Temperature Structure**
   a) Cassini Observations
   b) Radiative Climate Modelling
   c) Temperatures and Atmospheric Circulation
3. **Chemical Distributions**
   a) Tropospheric Chemistry
   b) Stratospheric Chemistry
4. **Clouds and Hazes** [Bob West's Talk]
5. **Seasonally-Modulated Phenomena**
6. **Seasonal Outlook**



Cassini’s Exploration of Seasons

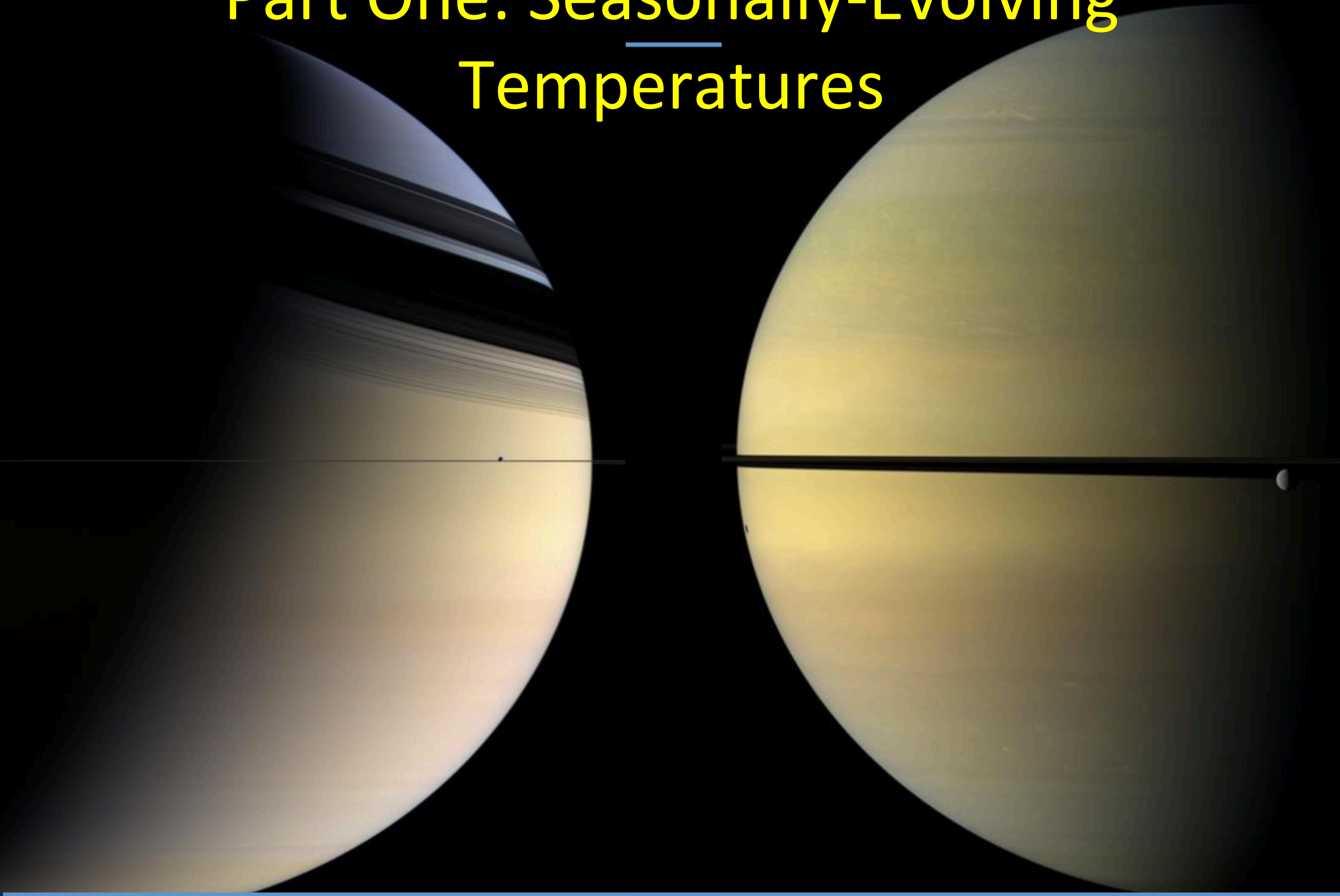


What do we Expect?

- **Warm summers and cold winters** with phase lags that increase with depth
  - Temperature asymmetries, variable windshears.
  - Warmer summers in the south (nearer perihelion) than the north.
- **Atmospheric circulation** to redistribute energy.
  - Localized dynamics perturbing hemispheric asymmetries; large-scale overturning.
- **Variable ionization/photochemistry rates** influencing population of stratospheric & tropospheric species/hazes.
  - Chemical and aerosol hemispheric asymmetries.
- **Varying stratification & wave transmissivity**
  - Altering propagation of dynamic activity (e.g., storm plumes, waves).

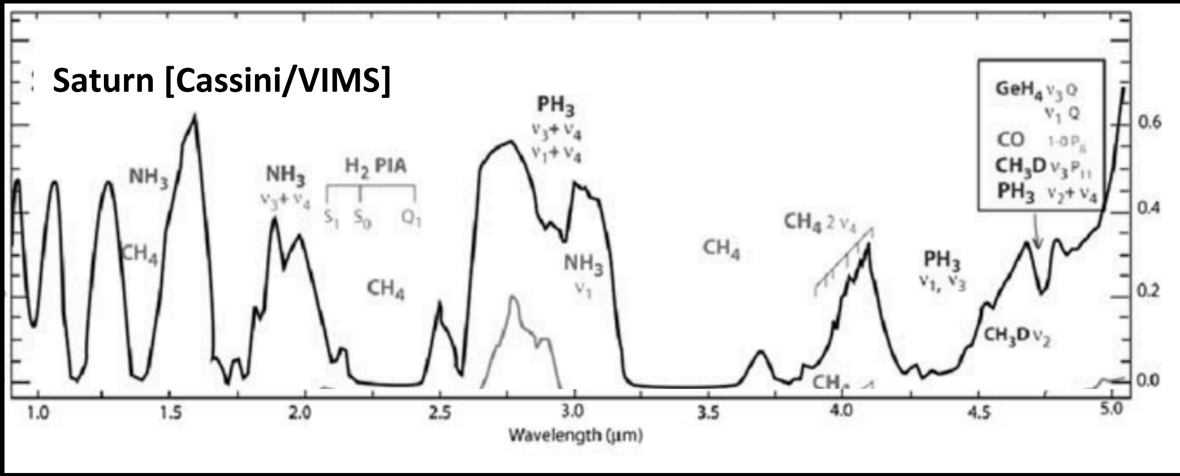
Long term remote sensing record allows us to compare hypotheses to observations

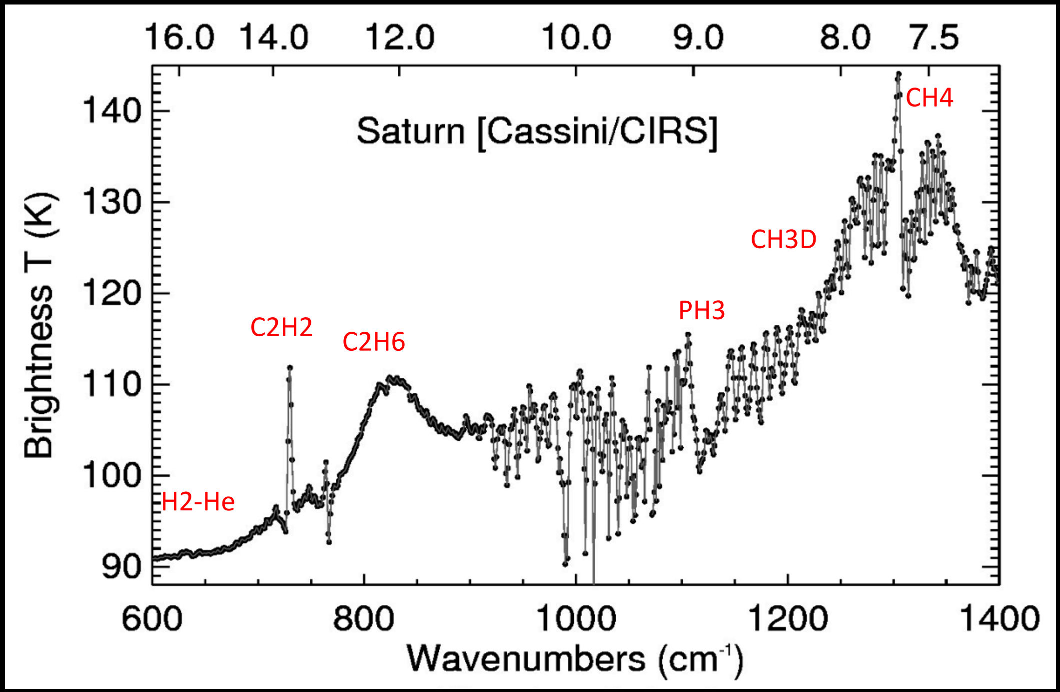
Part One: Seasonally-Evolving Temperatures



Saturn's Infrared Spectrum

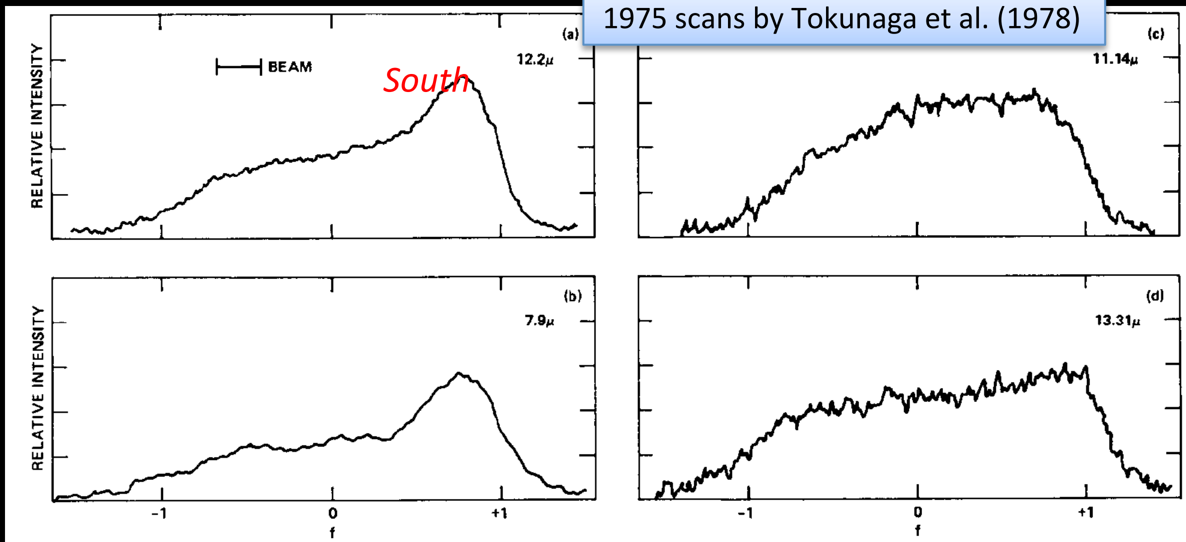
- **Remote sensing toolkit for seasonal studies**:
  - Reflected sunlight for clouds/hazes/ composition.
  - Thermal emission for T(p) and composition.
- Reflectivity changes (UV-Vis) to be discussed in Bob West's talk.
- Temperature/ composition variations covered here.



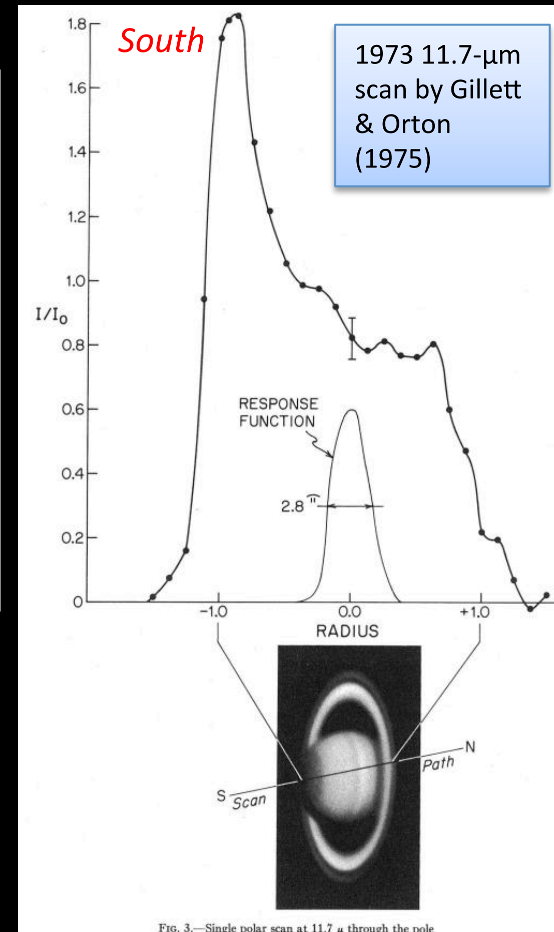


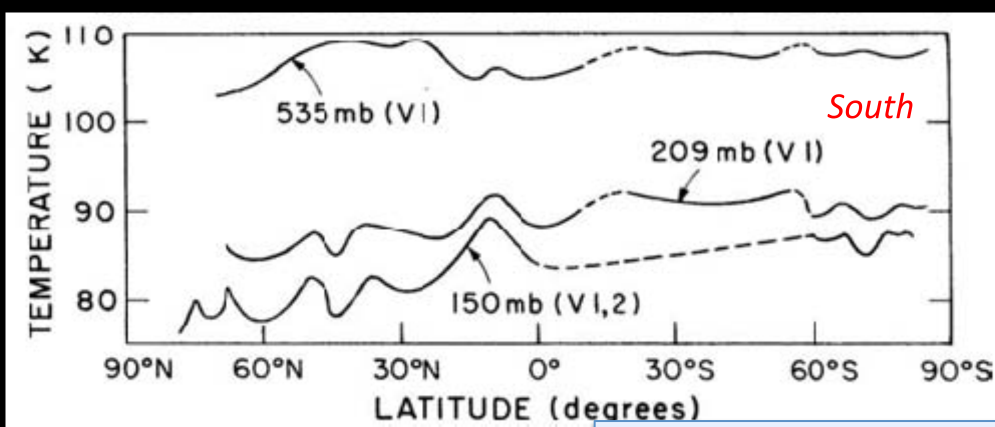
Detection of Asymmetries: 1970s & Voyager

1975 scans by Tokunaga et al. (1978)



1973 11.7-μm scan by Gillett & Orton (1975)





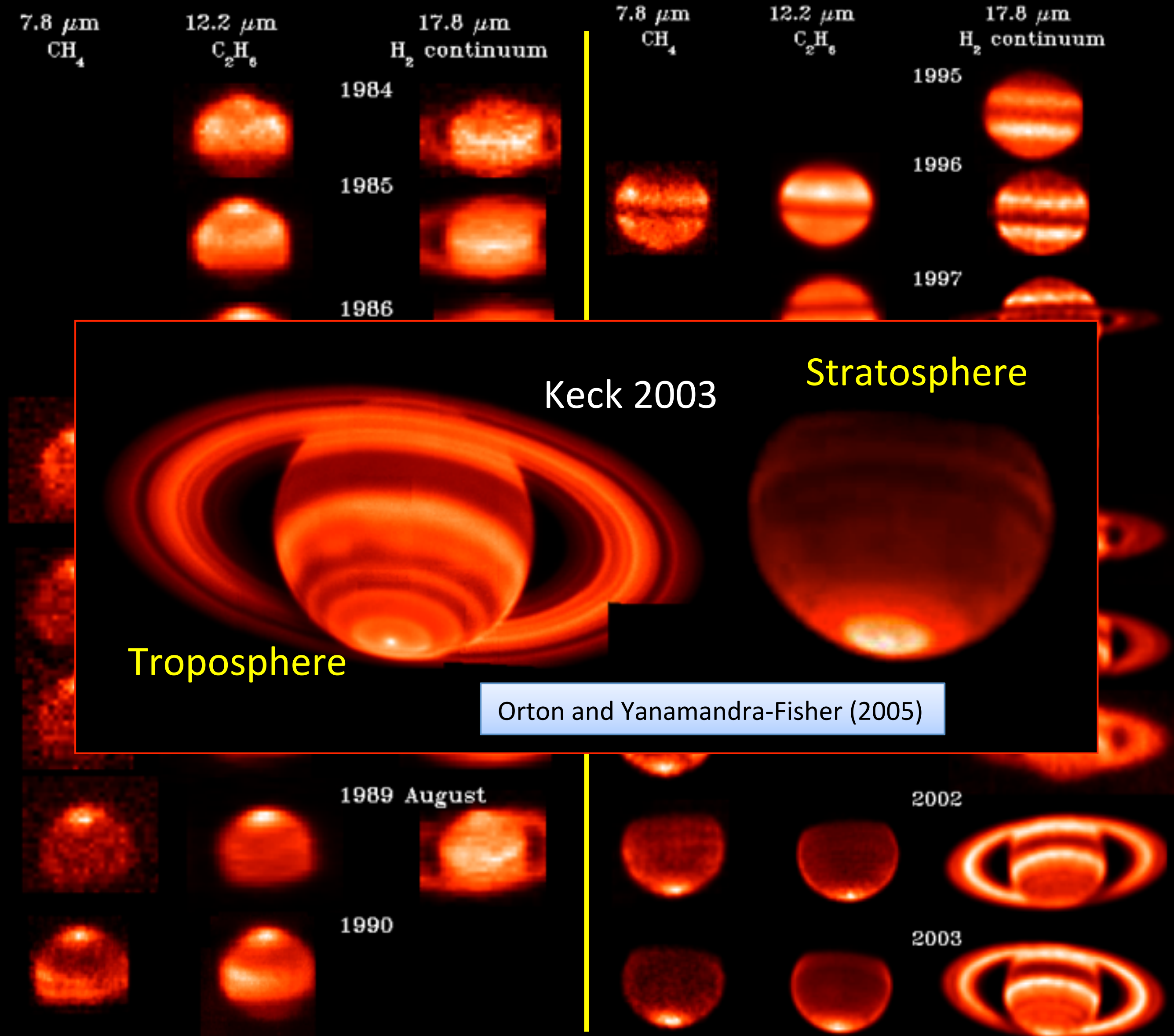
1980/81 Voyager/IRIS observations (Hanel et al., 1981; Conrath & Pirraglia (1983)

- *Detection of asymmetries in troposphere and stratosphere in southern summer/autumn.*

2D Thermal Imaging: From Voyager to Cassini

Northern spring equinox, March 1980 Ls=0

Northern summer solstice, Dec 1987 Ls=90

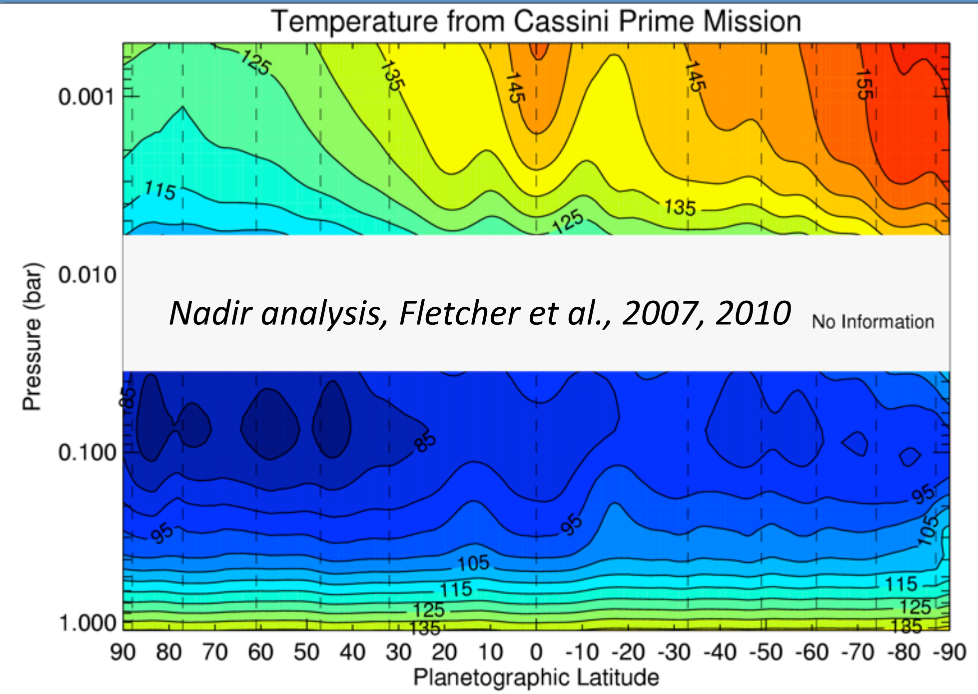


Orton and Yanamandra-Fisher (2005)

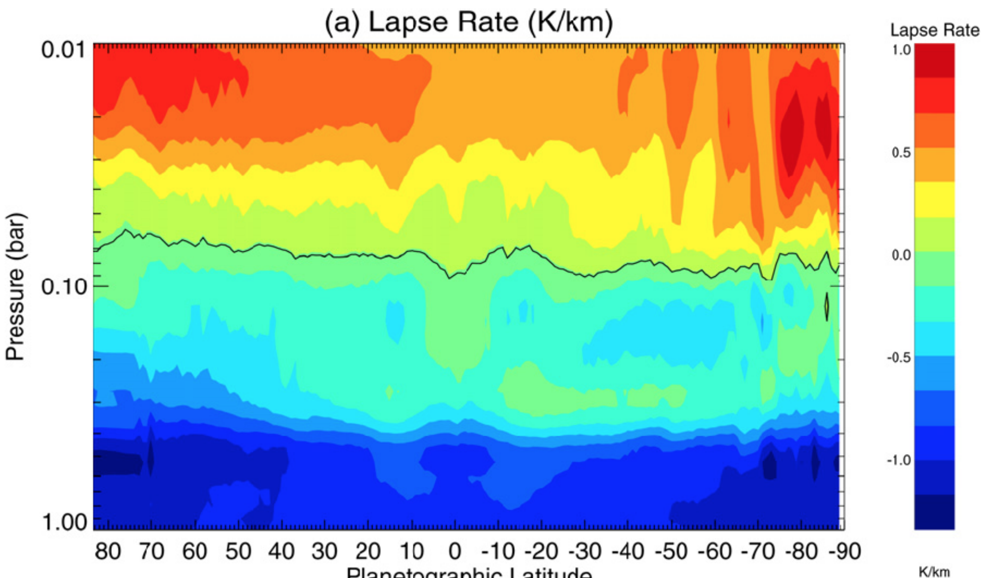
Northern autumnal equinox, Nov 1995 Ls=180

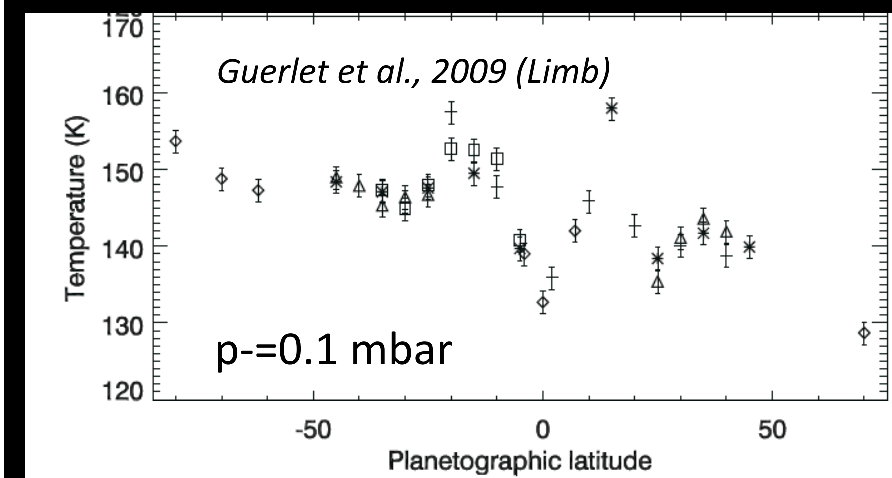
Northern winter solstice, Oct 2002 Ls=270

Summertime Asymmetries



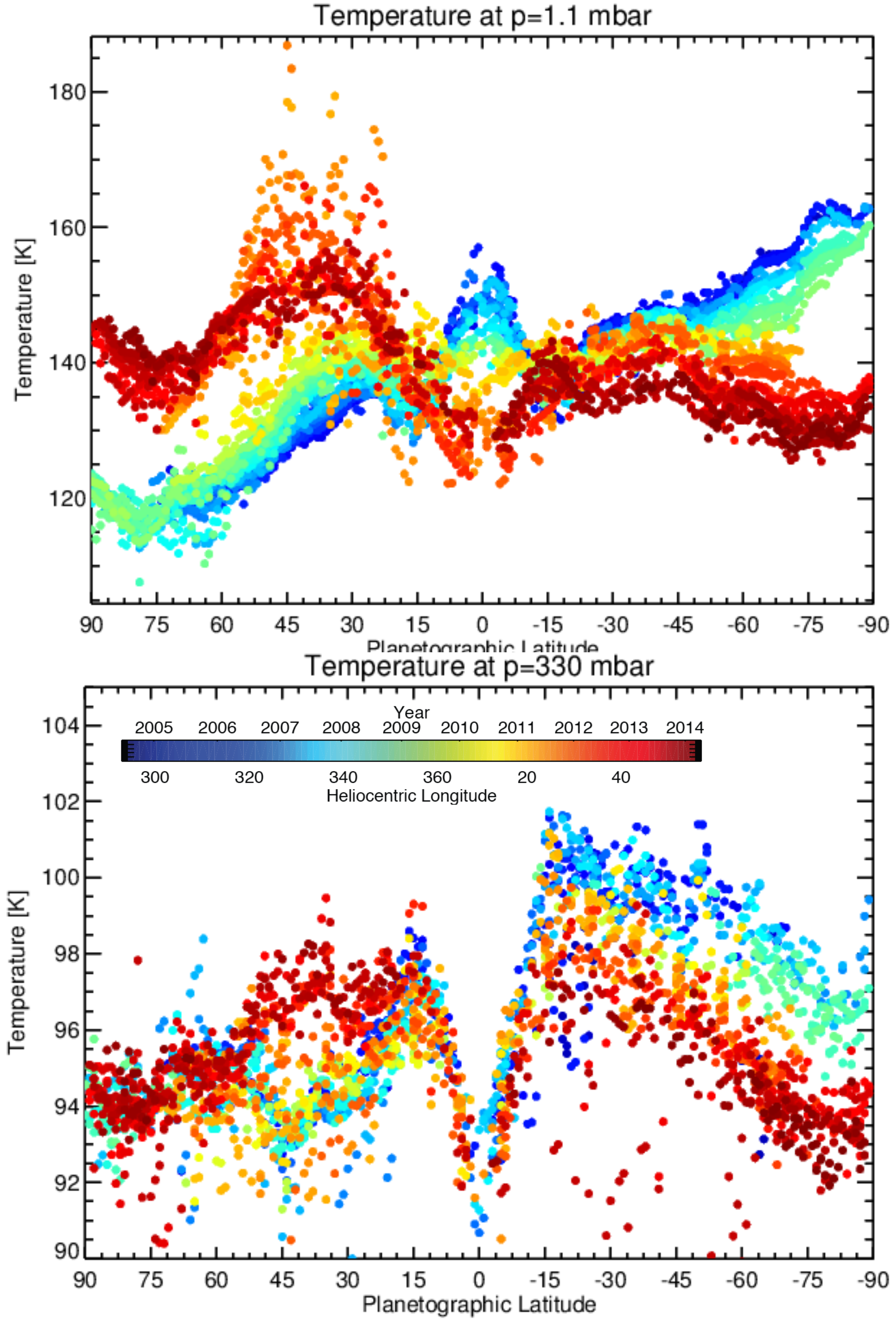
- Stratospheric 40 K asymmetry; 10 K tropopause asymmetry; no asymmetry p>500 mbar.
- Belt/zone contrasts superimposed onto hemispheric asymmetries.
- 80-mbar tropopause and 350-500 mbar RC boundary both slightly deeper in summer hemisphere.





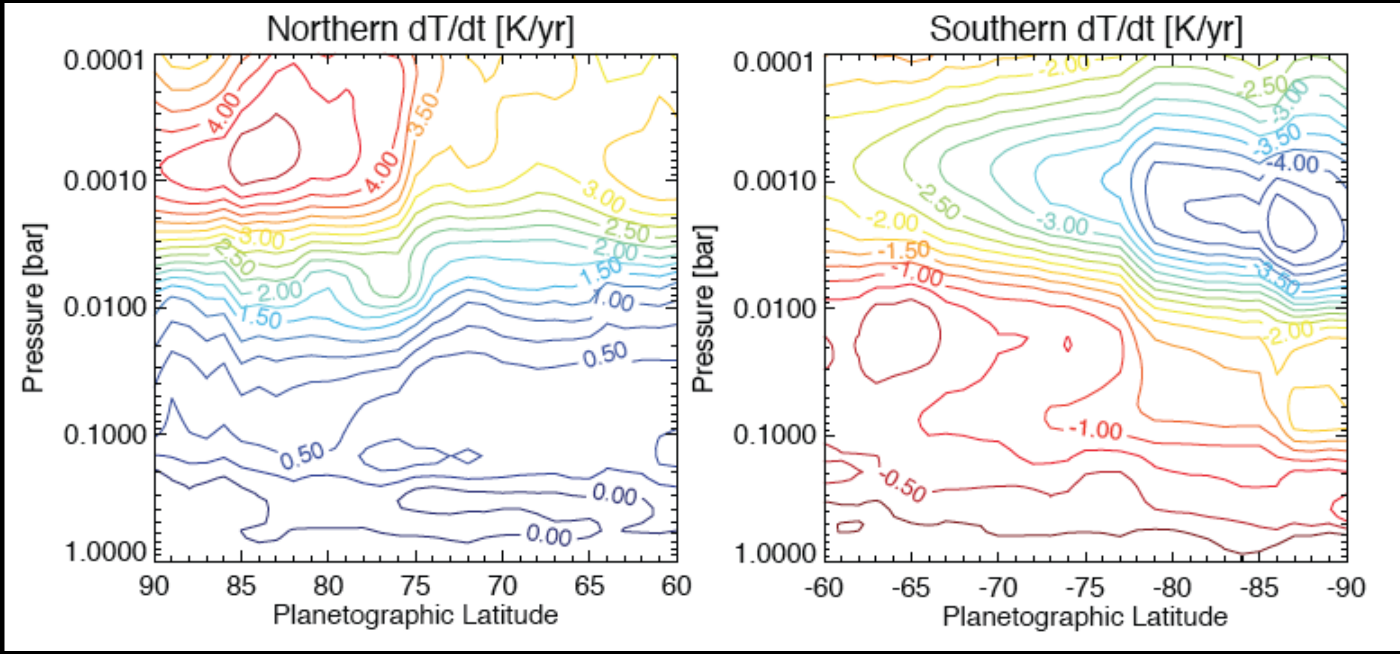
Temperature Evolution

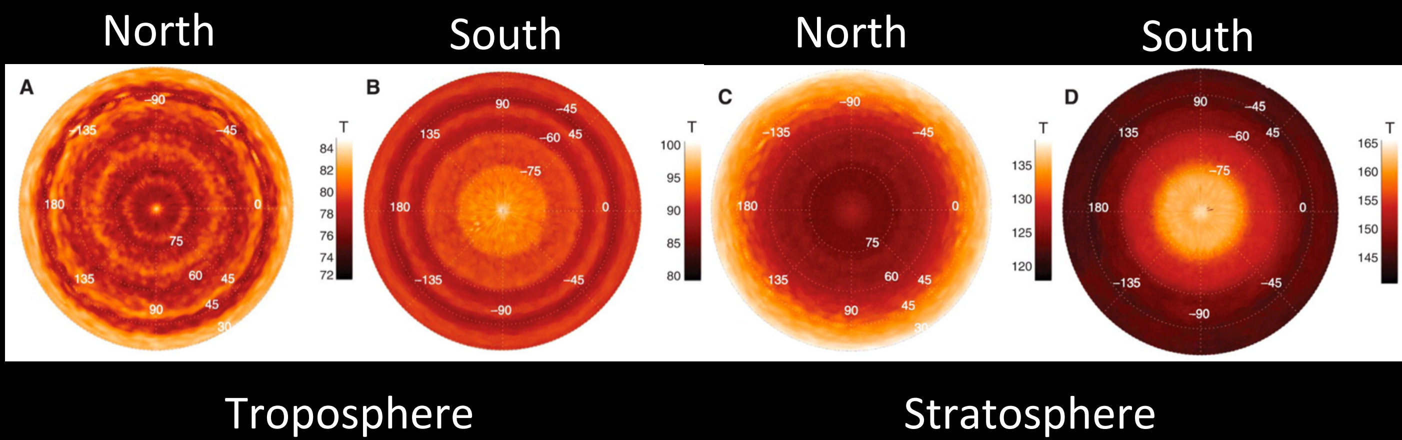
- Nadir temperature sounding for a 1/3 Saturn year
  - Updated from Fletcher et al. (2010) pre-equinox observations.
- **Thermal asymmetries reversing**.
  - Northern mid-latitudes and poles are changing the fastest.
  - Equatorial oscillation associated with SSAO.
- Trends governed by radiative heating/cooling & adiabatic compression/expansion.
- Implications for:
  - Thermal wind balance.
  - Saturn emitted power (Li et al., 2010).



Polar Seasonal Change

- Polar vortices – most dramatic manifestation of seasonal effects.
- Closer inspection reveals most rapid dT/dt (and dq/dt) within the polar vortices.
- Either:
  - vigorous vertical motion and adiabatic heating/cooling, or
  - aerosol contribution to radiative budget.



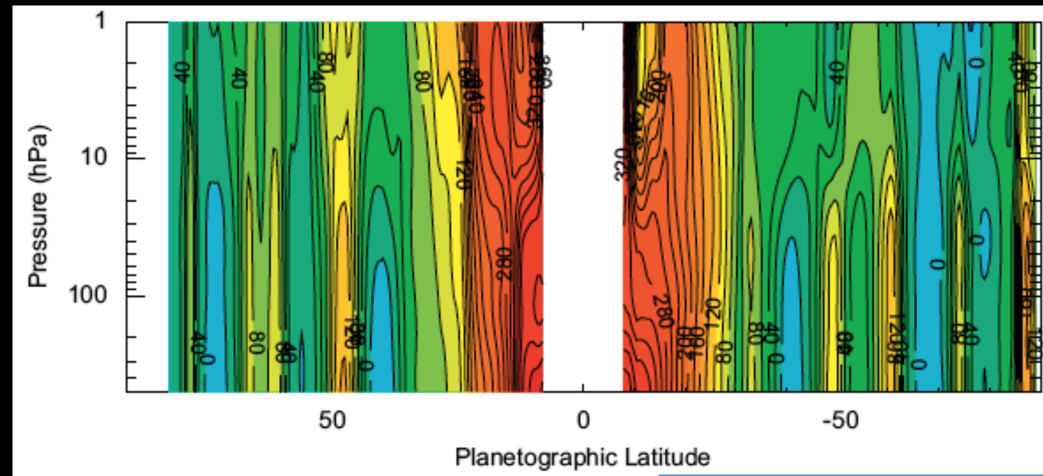


Implications for Wind Shear

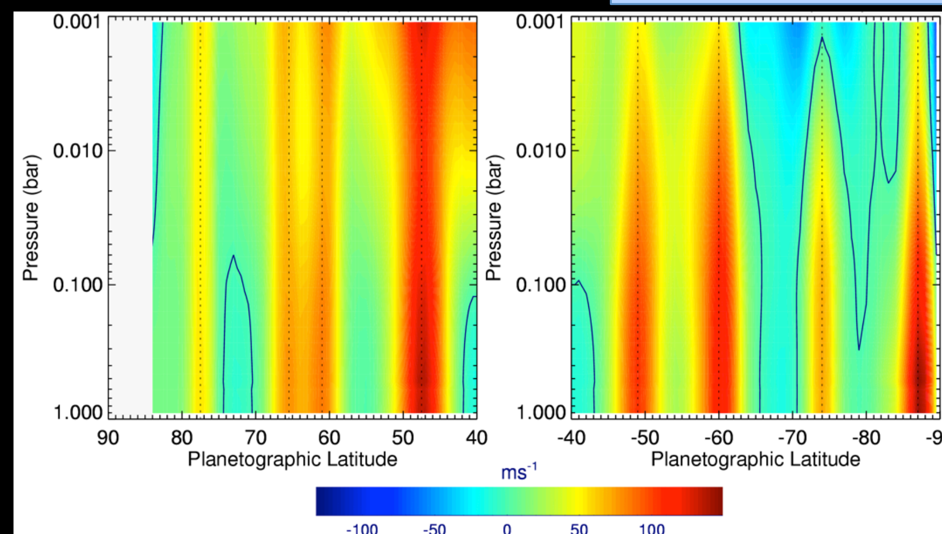
$$f\frac{\partial u}{\partial \ln(p)} = \frac{R}{a}\frac{\partial T}{\partial \psi} = R\frac{\partial T}{\partial y}$$

$$f\frac{\partial v}{\partial \ln(p)} = -\frac{R}{a\cos\psi}\frac{\partial T}{\partial \phi} = -R\frac{\partial T}{\partial x}$$

- Seasonal dT/dy strongly affects vertical shear.
- Decay with altitude stronger in the summer hemisphere; increasingly barotropic (height-independent) zonal jet structure in the winter hemisphere.
- Influences stratification/ trapping vertically-propagating waves.

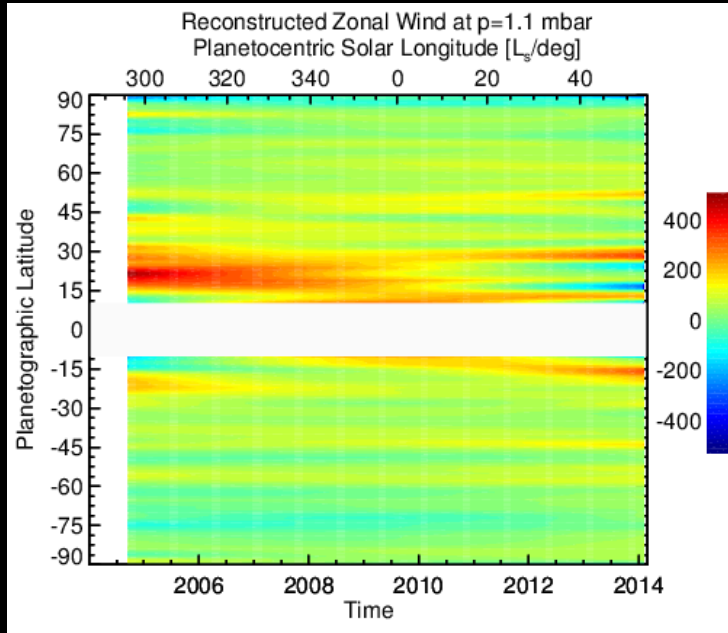


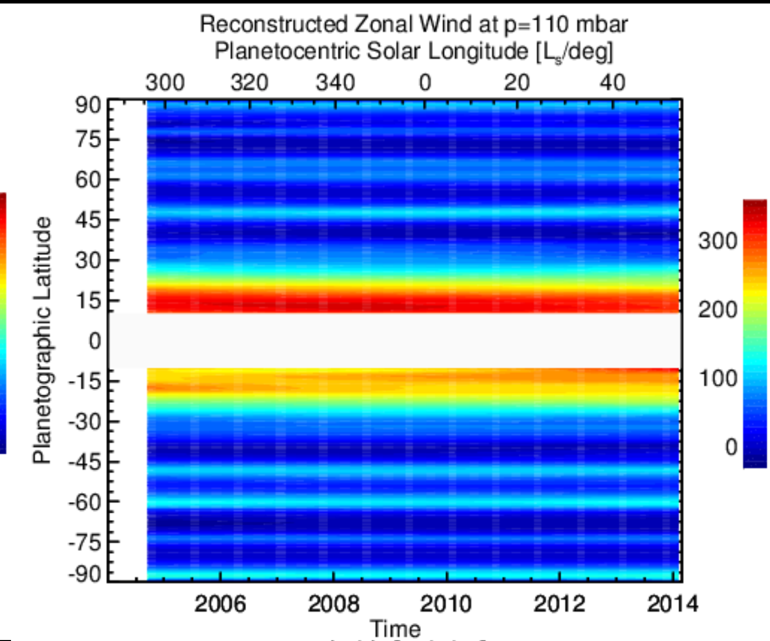
Read et al. (2009)

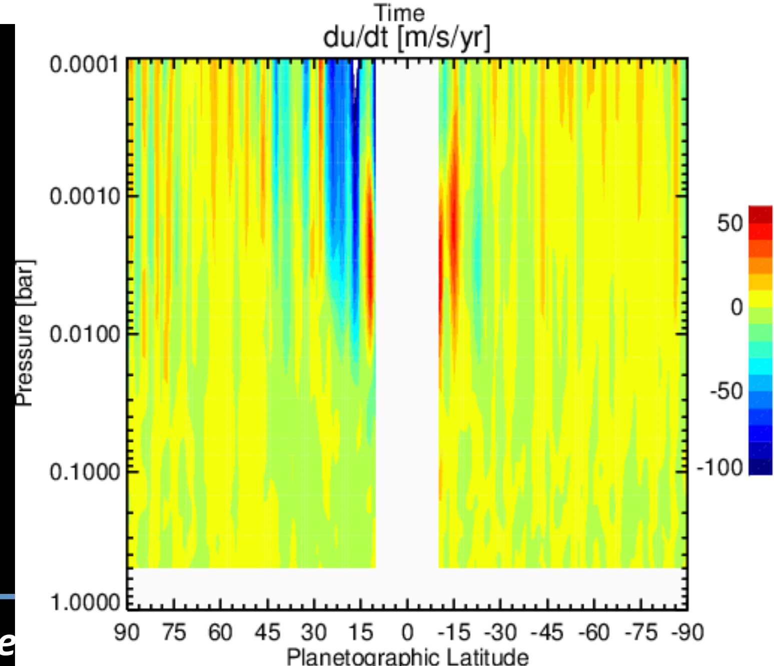


Fletcher et al., (2008)

Evolving Stratospheric Winds



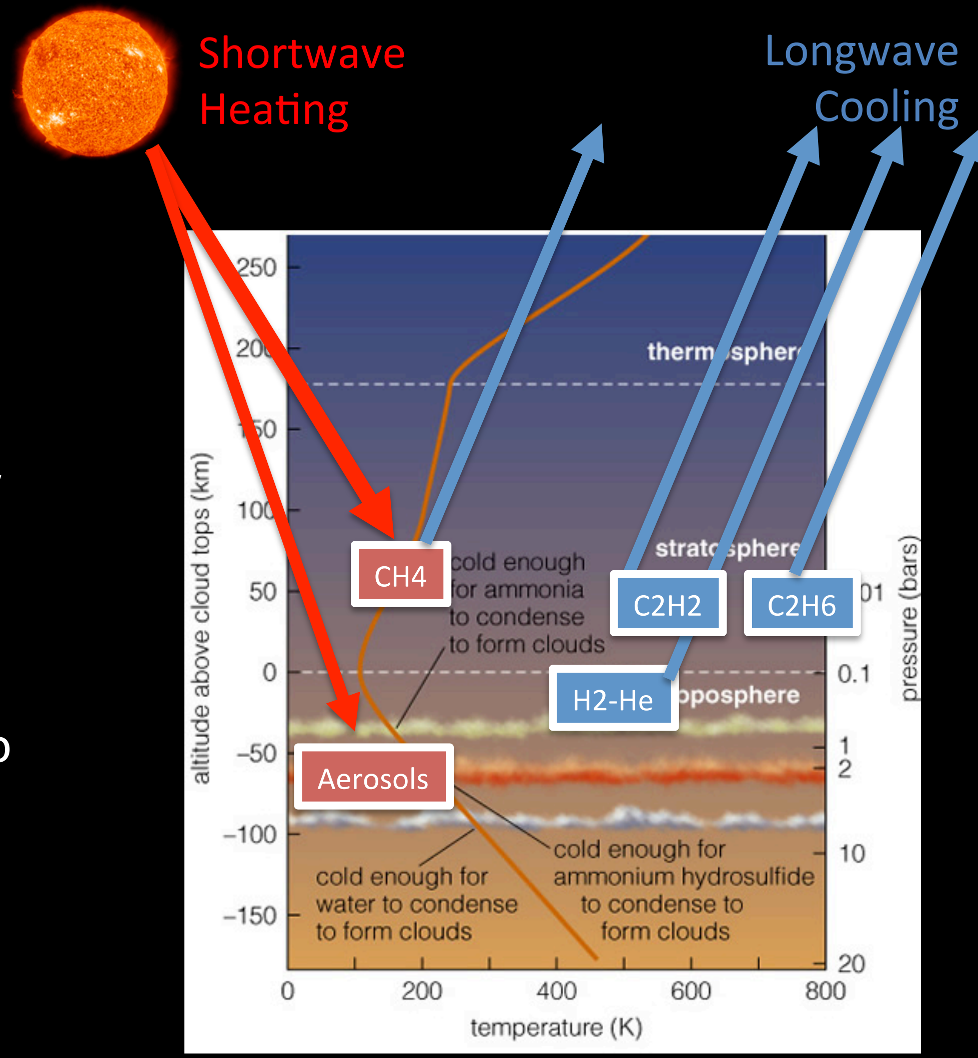




- Zonal winds reconstructed from 10-years of T(p).
- Seasonal dT/dy promotes positive vertical shear in the winter hemisphere and negative vertical shear in the summer hemisphere (e.g., Friedson and Moses, 2012).
- Stratosphere: Should see **northern prograde winds weakening**, **southern prograde winds strengthening** – partial confirmation by CIRS (unpublished).

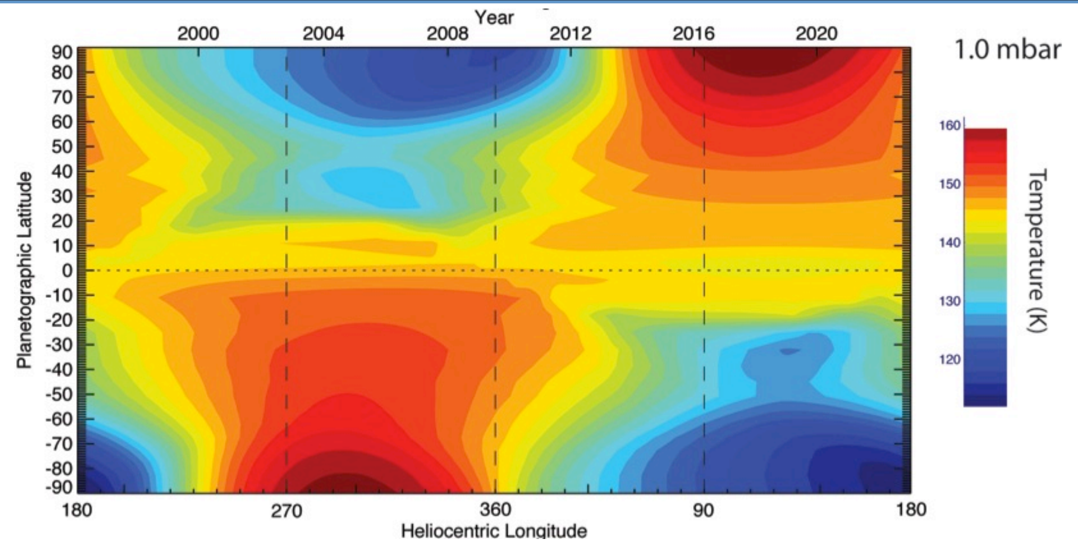
Radiative Climate Models

- Balance atmospheric heating (methane and aerosols) with key coolants (strat. ethane/acetylene; trop H2-He).
- Earliest 1D radiative convective models (1970s) explained temperature inversion
  - Methane VNIR absorption and UV aerosol absorption (Caldwell, 1977; Tokunaga & Cess, 1977).
- 2D (zonal and seasonal) models started in the stratosphere (Cess and Caldwell, 1979), extended into troposphere (Bezard 1984; Bezard & Gautier, 1985; Conrath et al., 1990, Barnet et al., 1992).
- Next generation of models developed for Cassini analysis.



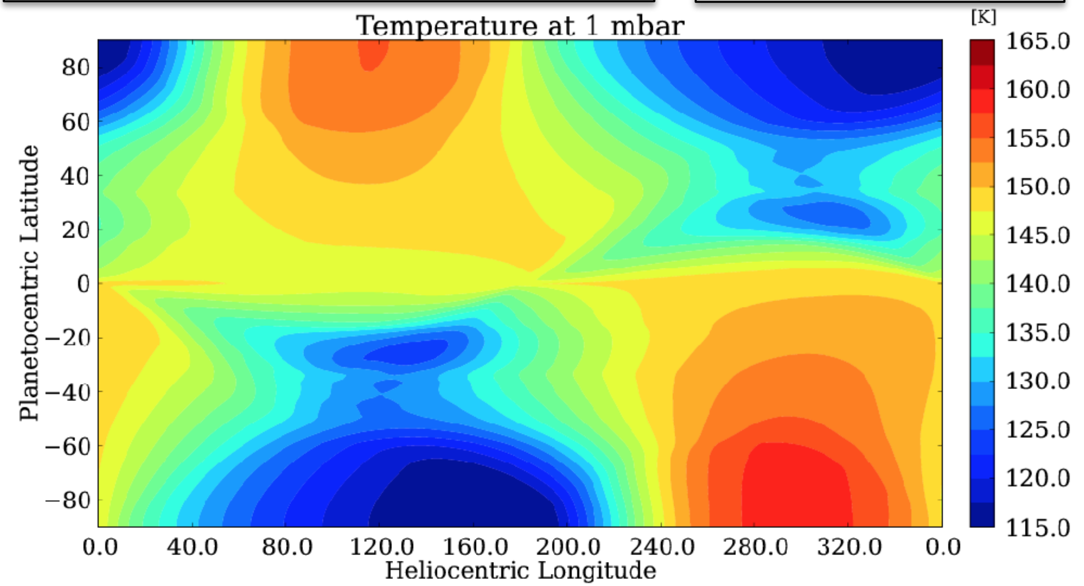
Radiative Climate Models II

- **Greathouse et al. (2008); Friedson and Moses (2012); Guerlet et al. (2014)** most current:
  - Oblateness, ring shadowing, eccentricity all accounted for.
  - Guerlet & Friedson extend into troposphere with aerosols.
  - Friedson includes eddy transport/advective circulation.
- Reproduce large-scale stratospheric trends.
  - reproduce lag timescales and equator-to-pole contrast amplitudes.
- Greathouse uses spatially-variable CxHy; Guerlet/Friedson fix at average values.

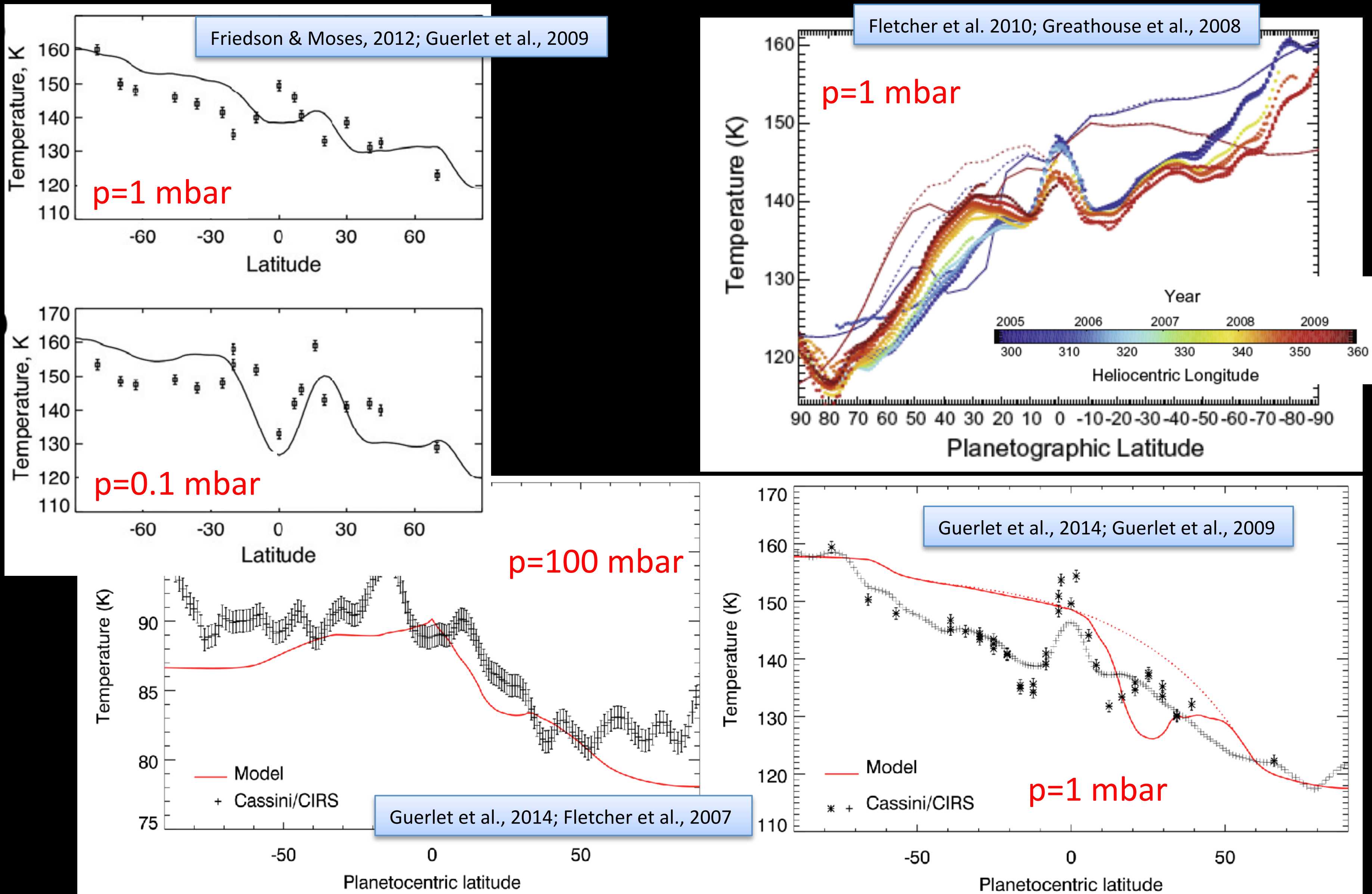


Fletcher et al., 2010; Greathouse et al., 2008

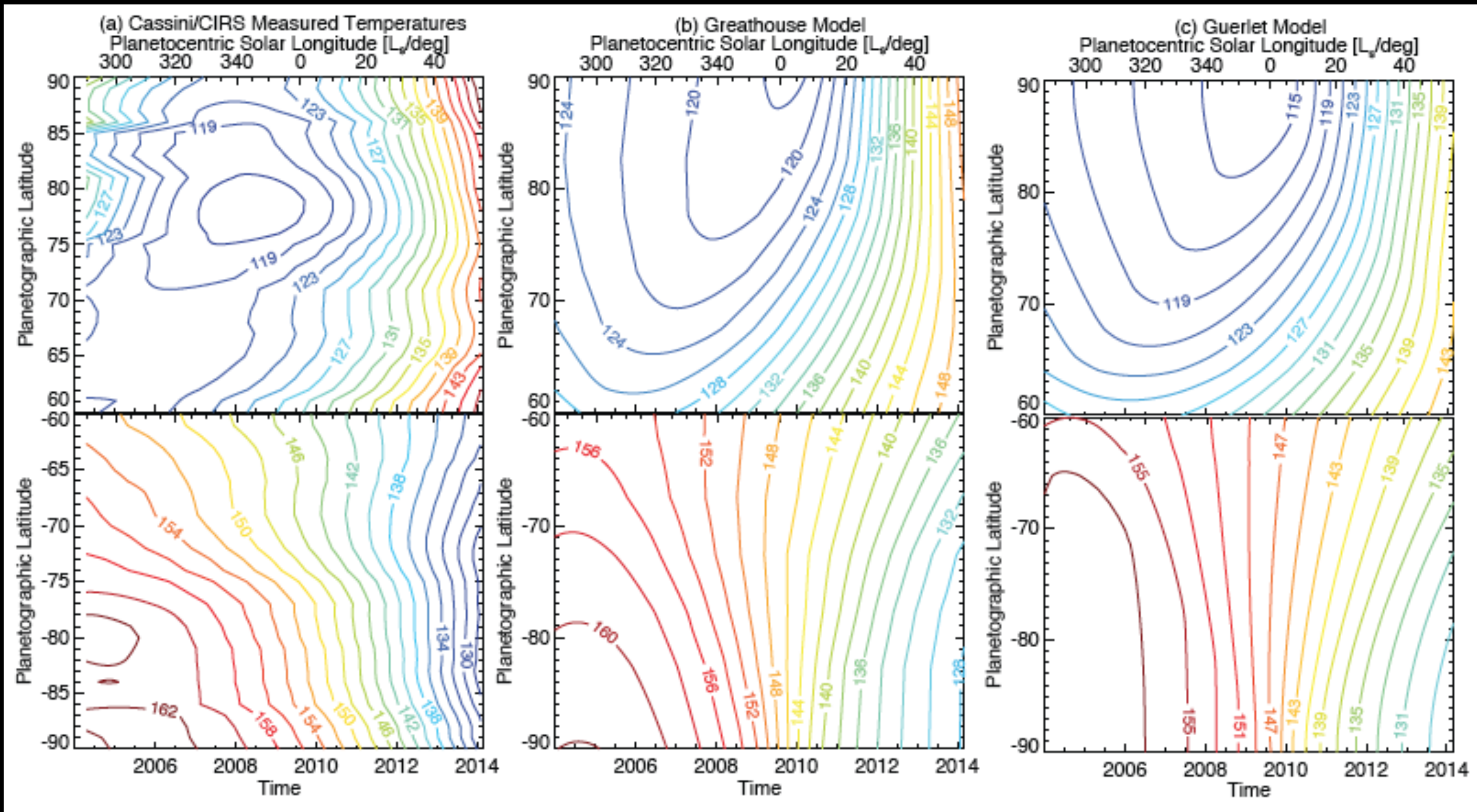
Guerlet et al. (2014)



Model – Data Comparisons



Comparison in the Polar Stratosphere

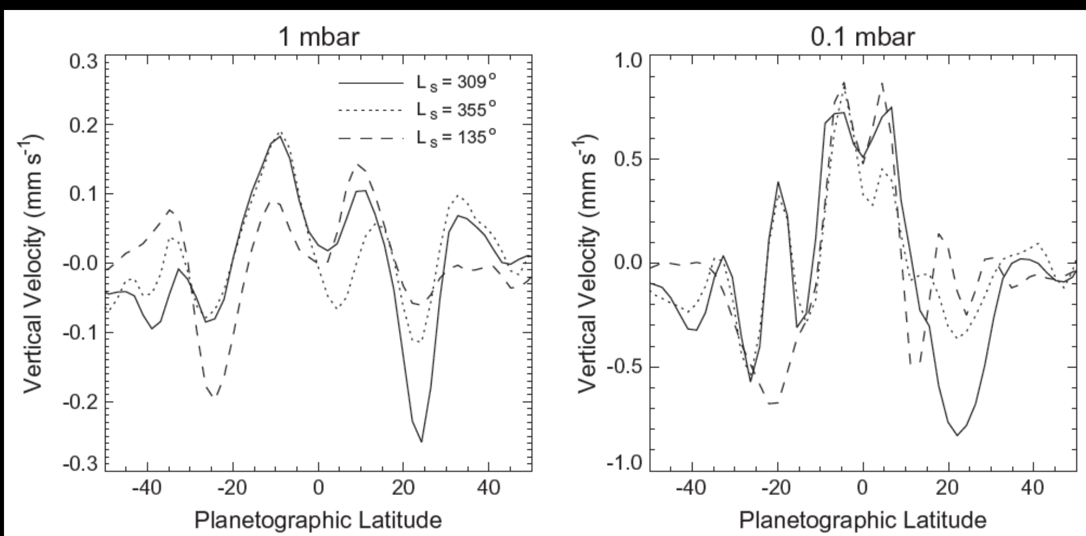


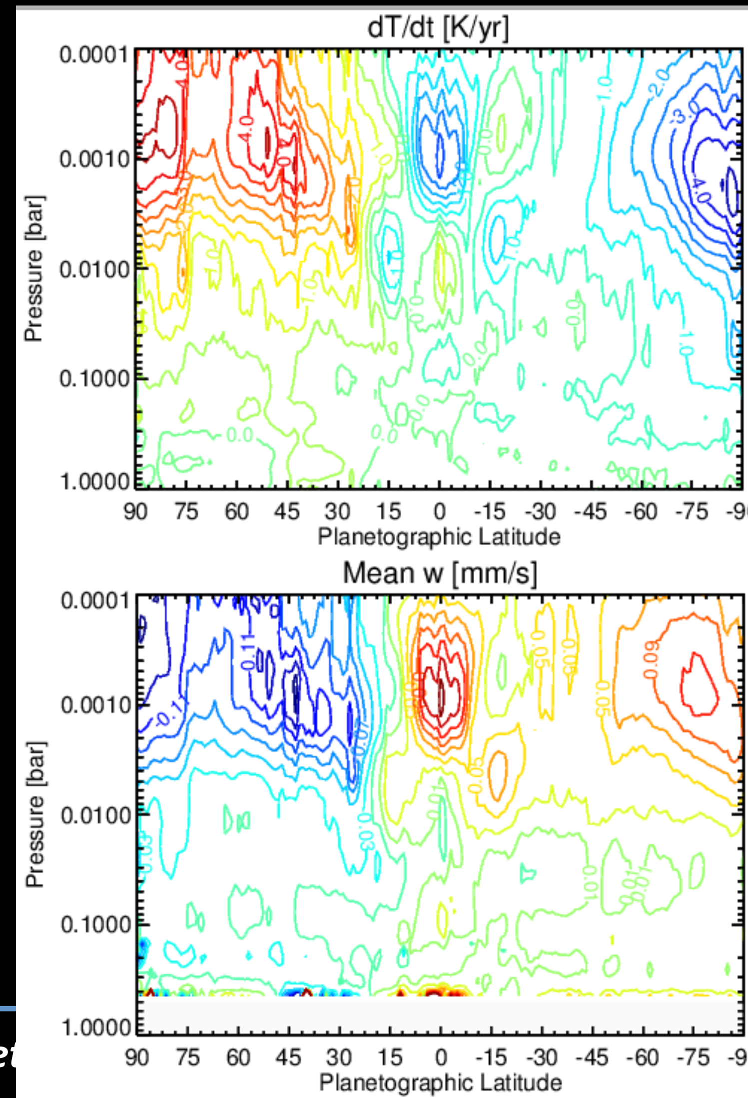
Fletcher et al., in prep.

Need for Atmospheric Circulation

- **Thermodynamic relation** of the primitive equations (e.g., Andrews, 1987).
  - Balances temporal evolution of temperature, advective heat transport and radiative relaxation to equilibrium.
- **Allows crude estimation of vertical velocities**, dominated by dT/dt term,
  - |w|~0.1 mm/s.
- Velocities will vary seasonally –
  - Reversing Hadley circulation?
  - Doesn't capture SSAO?

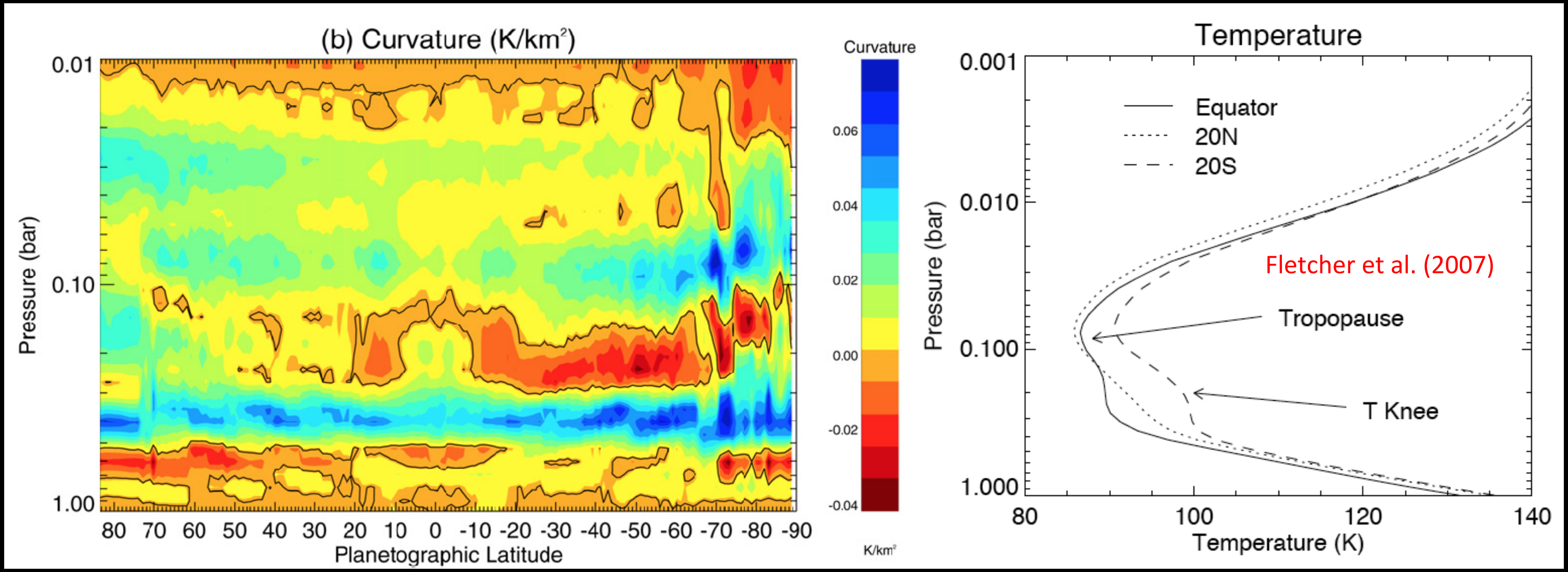
$$\left(\frac{\partial T}{\partial t} + w\left[\frac{\partial T}{\partial z} + \frac{RT}{Hc_p}\right]\right) = \frac{Q}{\rho c_p} \approx \frac{T_E - T}{\tau}$$



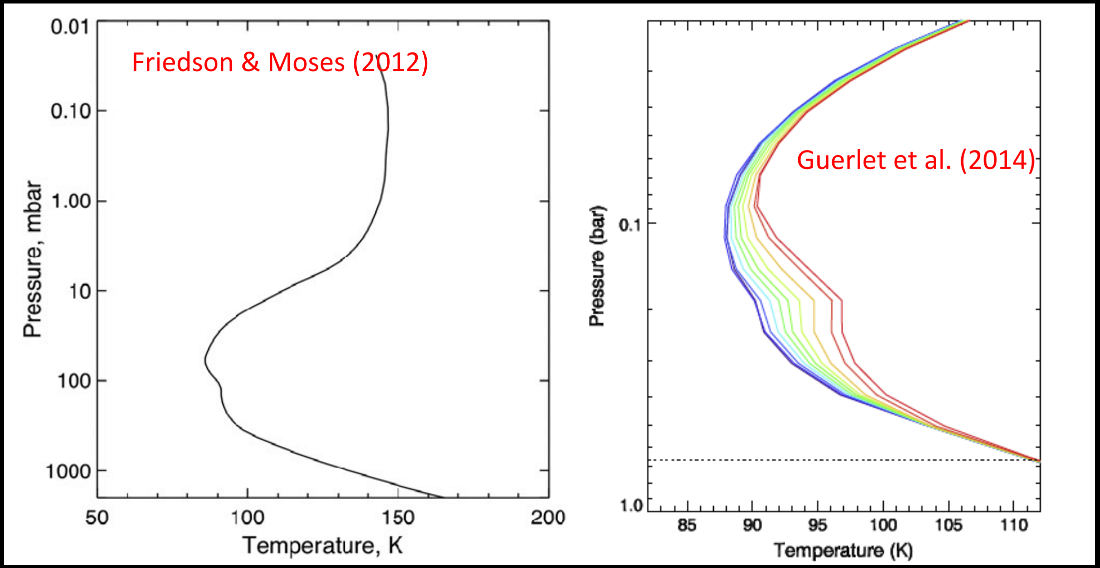


Friedson and Moses (2012)

Tropospheric Temperatures

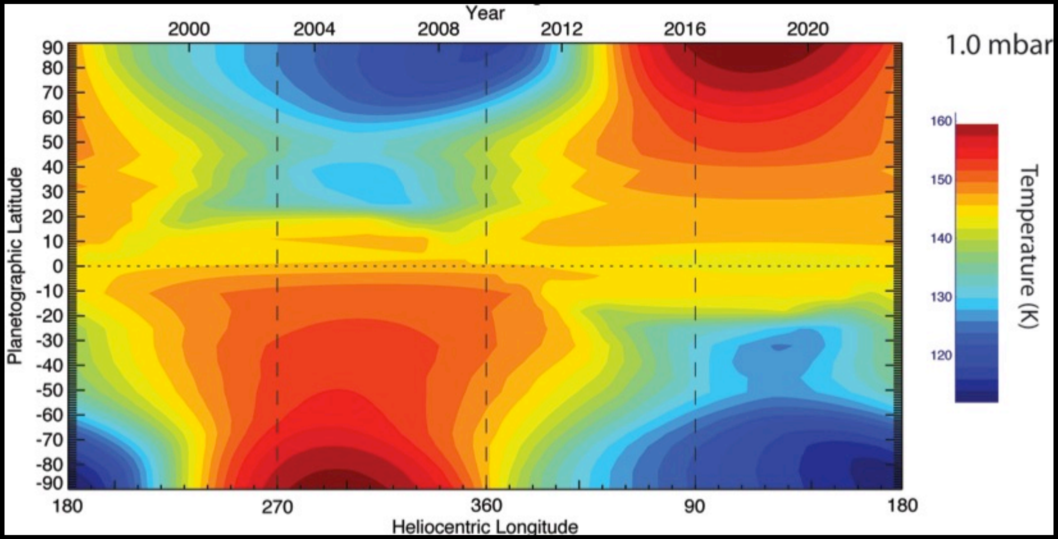


- Temperature 'knee' identified as radiative effect associated with haze (Fletcher et al., 2007).
- Hemispheric asymmetry matched VIMS 5-µm asymmetry.
- Friedson and Moses (2012) and Guerlet et al. (2014) reproduce the temperature knee
  - Don't require aerosol asymmetry to explain effect.



Summary of Part One: Temperatures

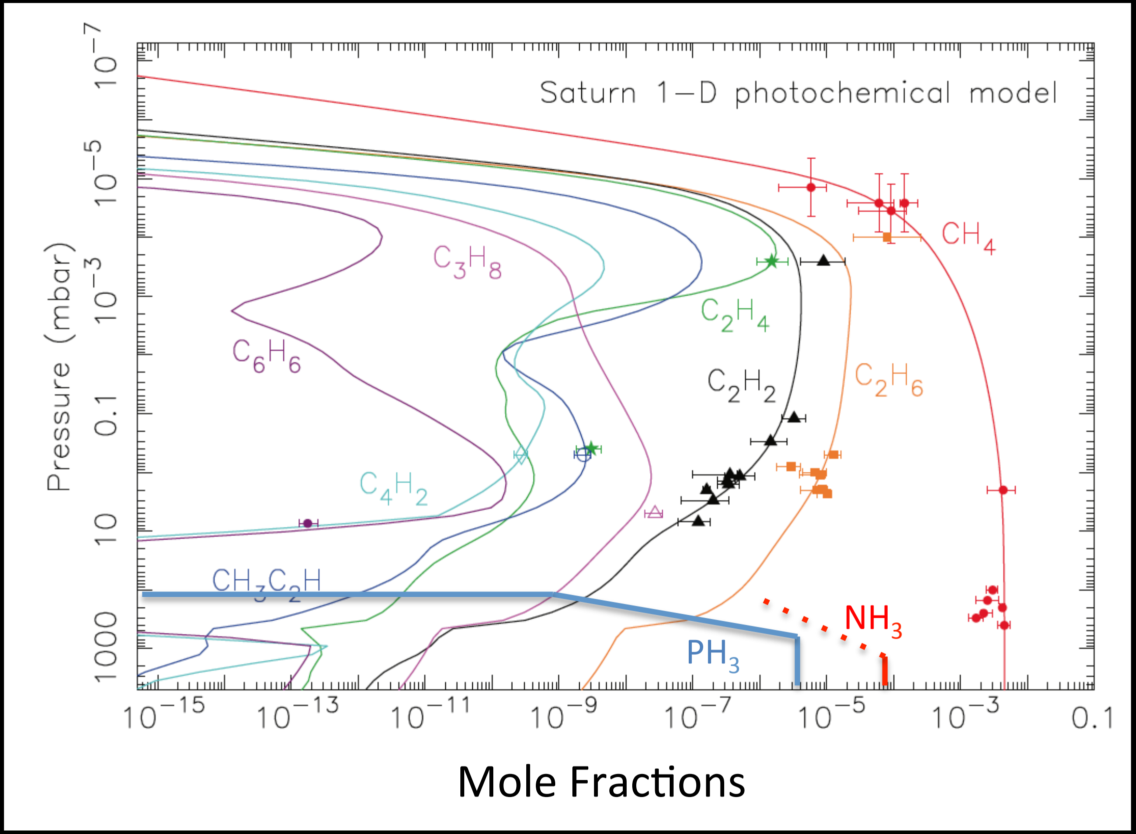
1. Ground-based and Cassini observations **reveal hemispheric thermal contrasts superimposed onto belt/zone contrasts**.
2. Seasonal amplitudes and increasing phase lag with depth **reproduced by radiative climate models**.
3. **Contributions from aerosols** suggested in tropospheric 'knee' and polar vortices.
4. Implications for Saturn's **energy balance**, stratospheric **circulation**, middle-atmospheric **zonal winds.**



Part Two: Seasonally-Evolving Composition

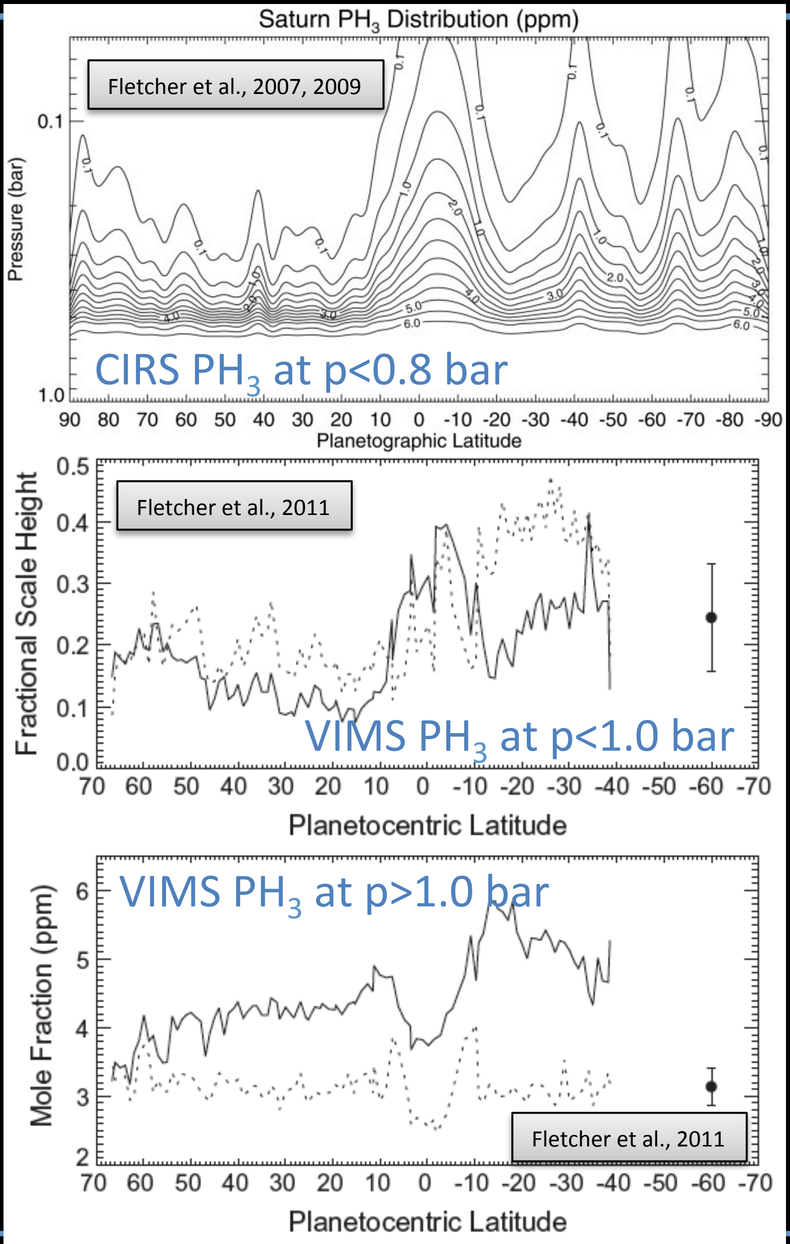
Introduction: Chemical Soup

- **Chemical distributions intricately tied to radiative budget.**
- Fouchet et al. (2009) review of all **pre-Cassini measurements**
  - Mostly disc-integrated from the ground and Voyager.
- Cassini **detected asymmetries in stratospheric and tropospheric composition** in southern summer, now hoping to trace reversals.
  - Related to tropospheric/stratospheric circulation and efficiency of photolytic destruction/production.



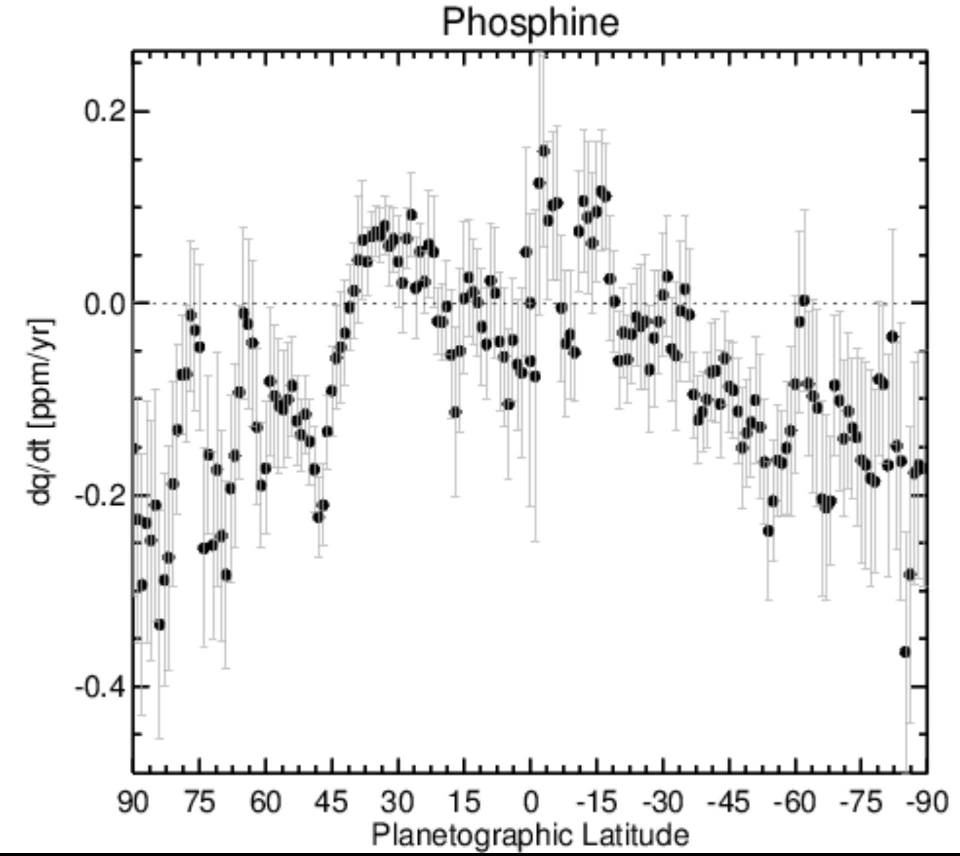
Phosphine in Southern Summer

- Tropospheric **disequilibrium species**.
  - Well mixed p>500-600 mbar.
  - Depleted at p<500 mbar by photolysis.
- CIRS and VIMS agree on upper tropospheric tropical peak; north-south asymmetry p<1 bar.
- **Inconsistencies in absolute mixing ratios** still to be resolved.
- More PH_3 where there's more sunlight?
  - Matches asymmetry in haze opacity, possible shielding effects?
  - More convective mixing in warmer conditions?



Evolution of Phosphine Distribution

- **PH_3 asymmetry could trace reversal of tropospheric aerosol opacity asymmetry**.
  - Fletcher et al. (2010) reported no significant changes in PH3 from 2004-2009.
- Latest [preliminary!] results suggest declining abundances in both hemispheres poleward of ±45° – but extremely noisy and hard to explain!
- No changes to equatorial upwelling.

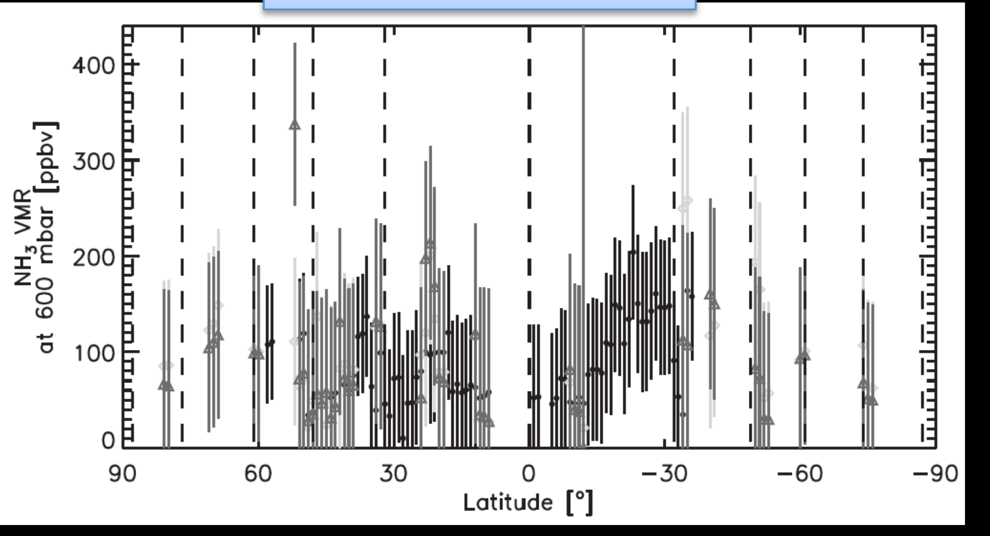


dq/dt at 0.5 bar from ten years of CIRS

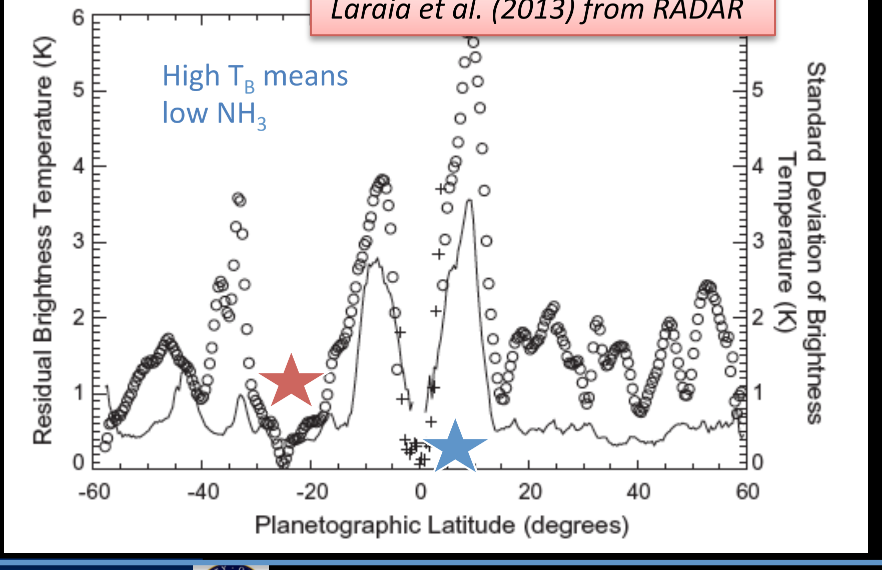
Unchanging Ammonia?

- Expect NH_3 photolysis to follow similar trends to PH_3
- Also expect **more NH_3 where it's warmer** (saturated abundances increase).
- CIRS observes hints of a north-south asymmetry p< 1 bar.
- VIMS & RADAR see an equatorial maximum between ±10° p>1 bar.

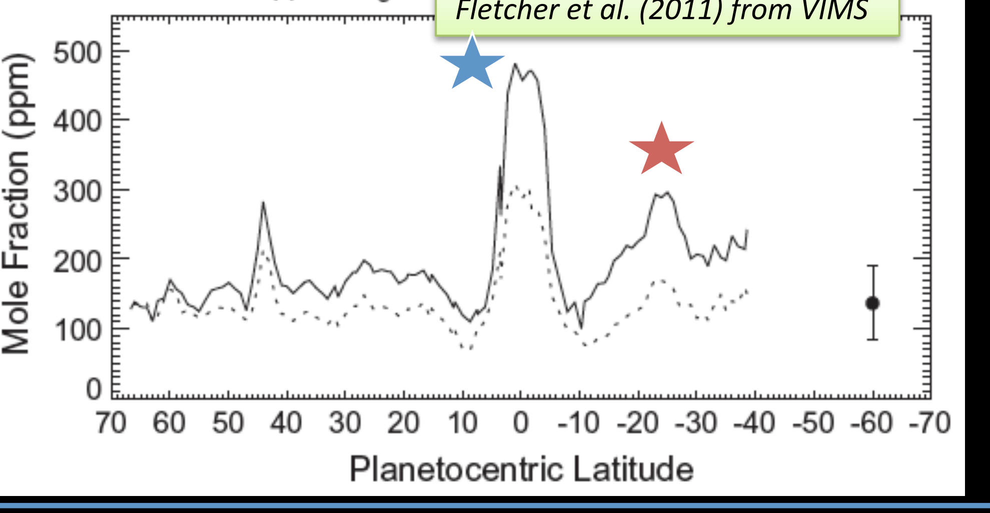
Hurley et al. (2012) from CIRS



Laraia et al. (2013) from RADAR

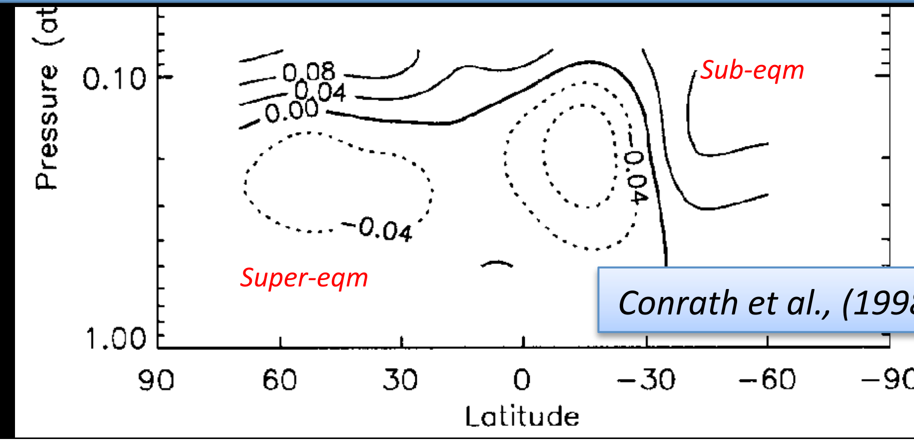


Fletcher et al. (2011) from VIMS

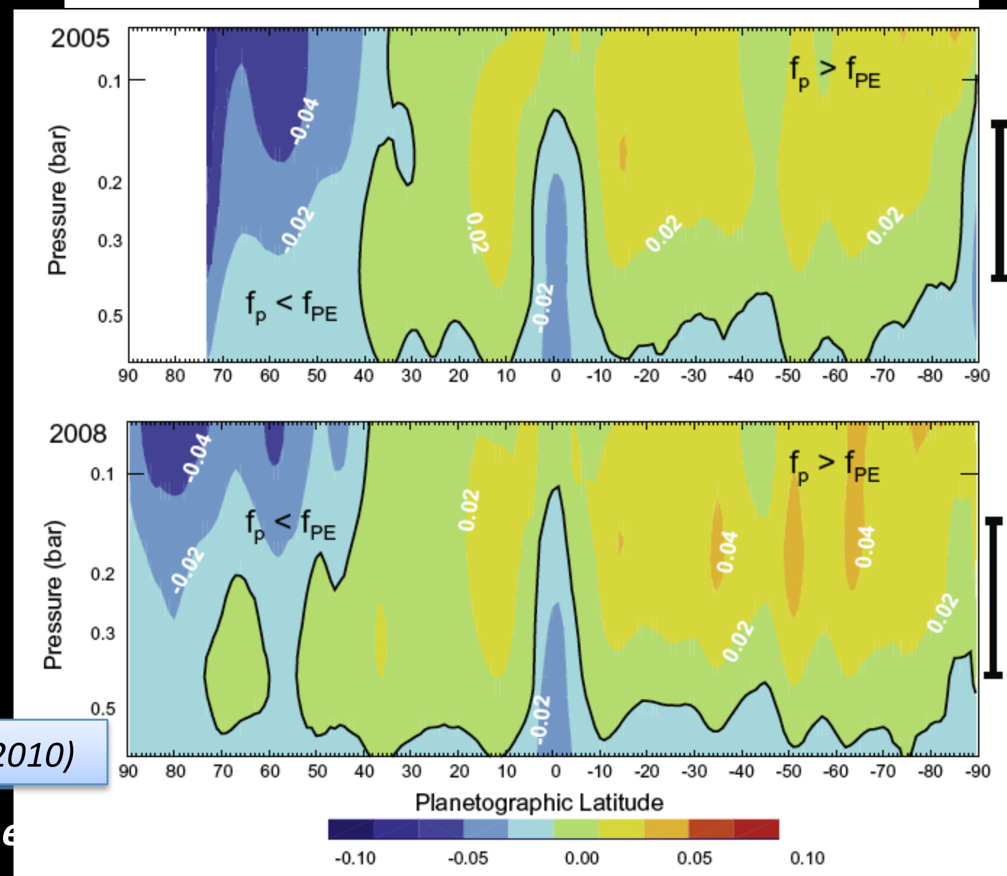


Para-H_2 Asymmetry

- **Tracer of tropospheric mixing**/catalytic efficiency.
  - Rising air parcels retain low para fraction (fp) of deeper, warmer levels (sub-eqm, fp<feqm).
  - Sinking parcels have fp>feqm (super-eqm)
- Voyager: Subsidence in the northern spring hemisphere; upwelling in autumn hemisphere.
- Cassini shows different asymmetry to Voyager; equatorial upwelling.

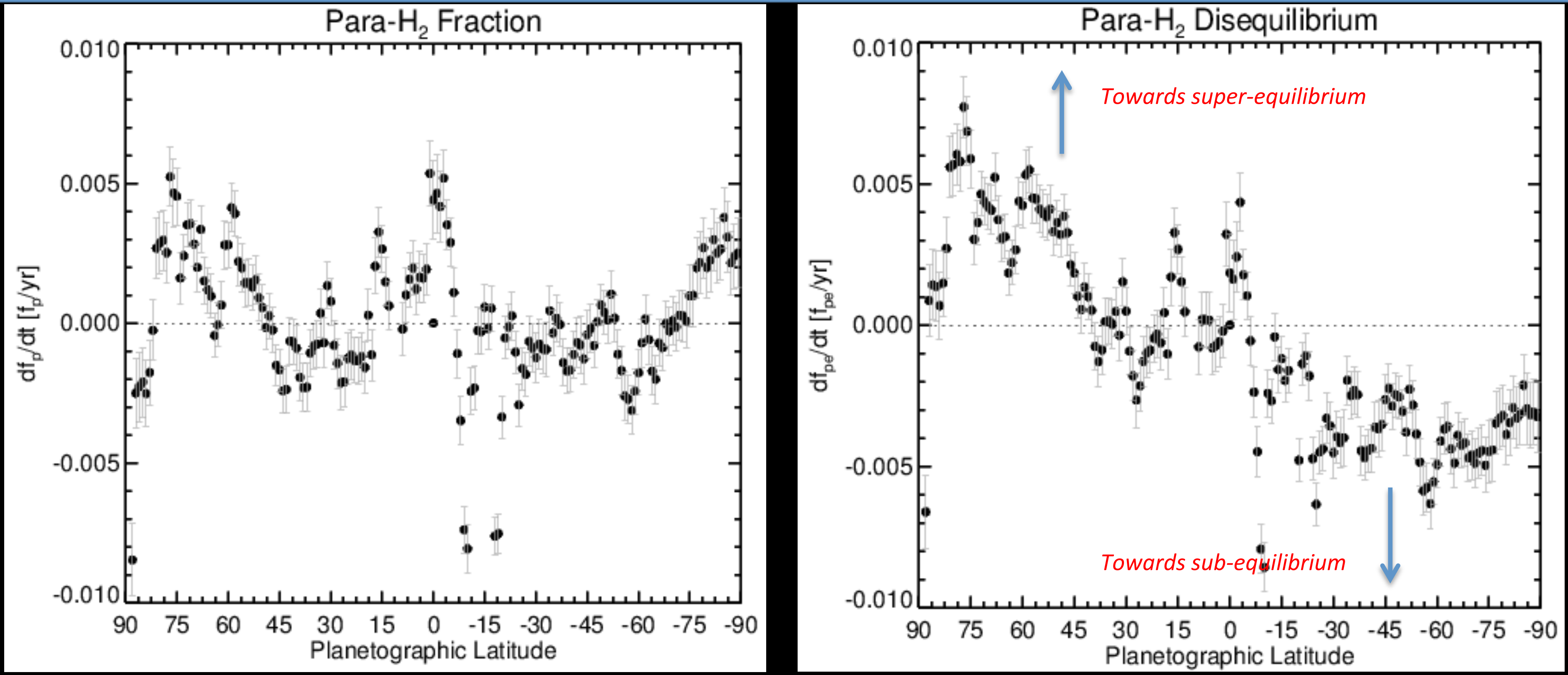


Conrath et al., (1998)



Fletcher et al. (2007,2010)

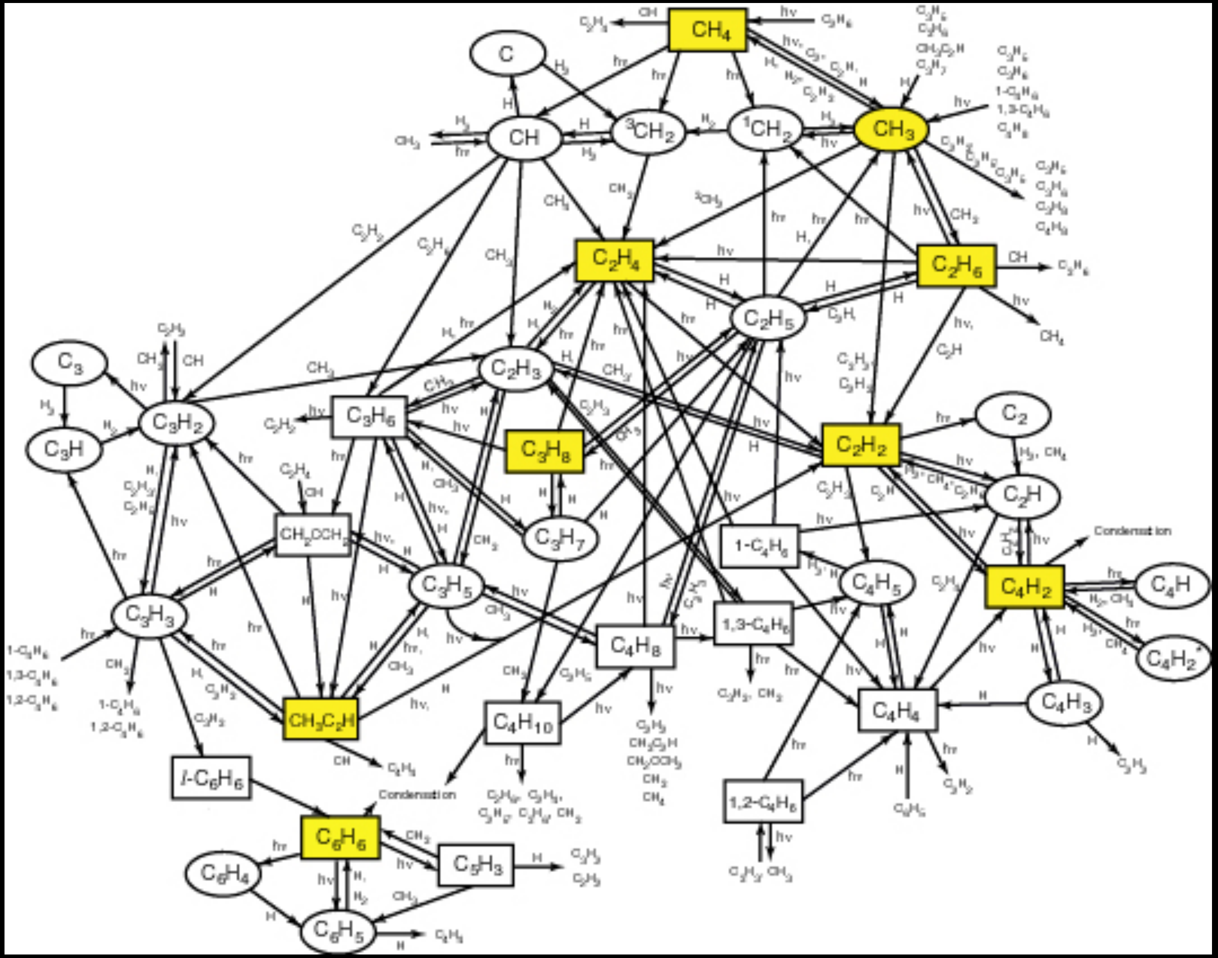
Latest Para-H_2 Results [Preliminary!]



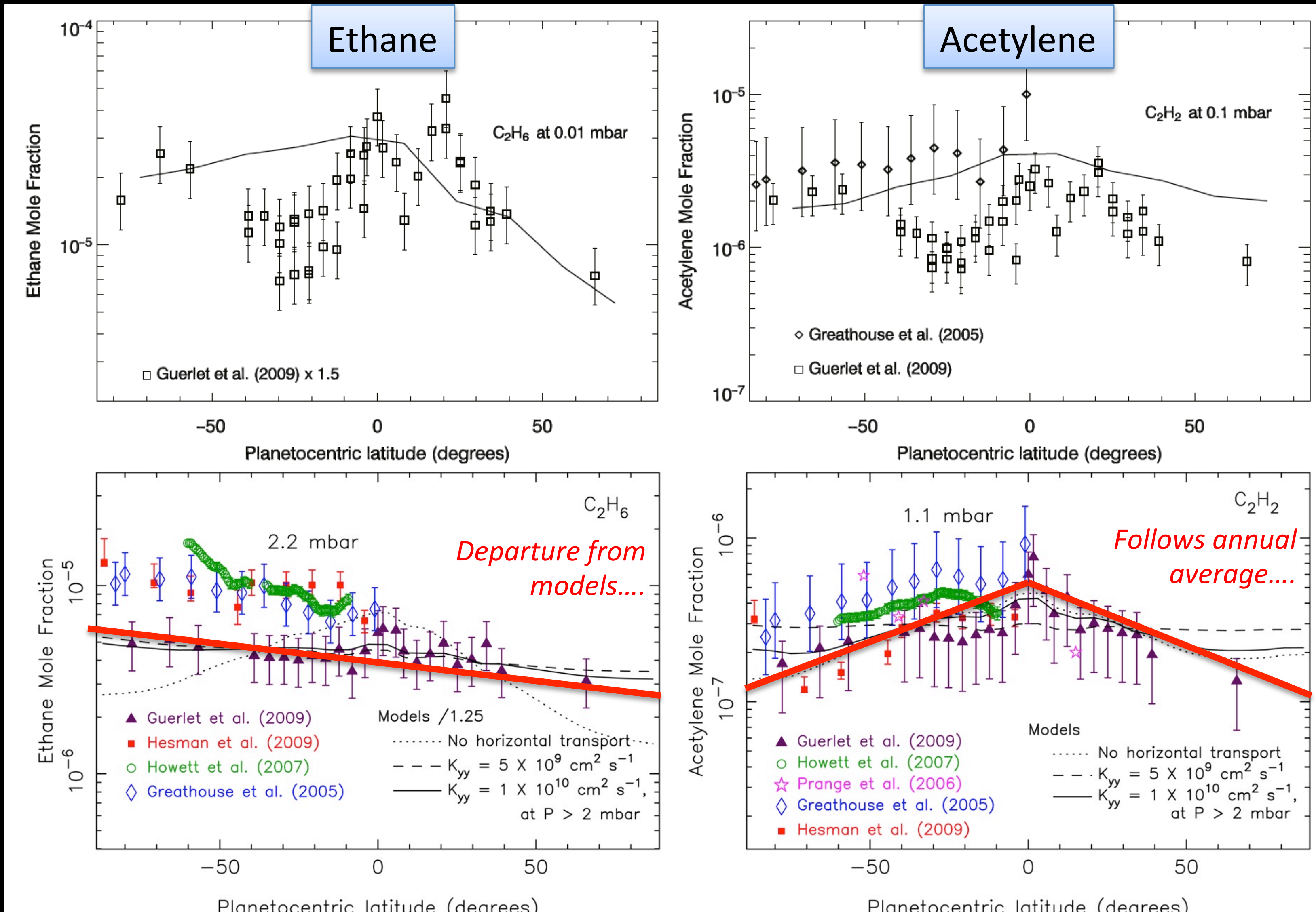
- Para-H_2 has not changed significantly, **disequilibrium asymmetry has started to reverse** (slowly) due to equilibrium para-H_2 changes.
  - Equilibriation timescale ~ century @ 200 mbar, **don't expect big changes**.
- Northern latitudes have become super-equilibrium, southern latitudes tending to sub-equilibrium, tracking temperature/aerosol asymmetry reversal.

Stratospheric Hydrocarbons

- Before Cassini, 1D chemistry-diffusion models limited to fixed seasons & few latitudes.
- Full seasonal 1D (Kzz) diffusive photochemistry model (Moses and Greathouse, 2005) predict:
  - Long-lived CxHy more affected by transport and follow annual average insolation (C_2H_6 and C_3H_8).
  - Short-lived CxHy continue to show seasonal asymmetries at p>1 mbar (CH_3, C_2H_2, C_2H_4, CH_3C_2H, and C_4H_2)
  - Species should follow annual-average insolation at p>1 mbar
- No published 2D models (i.e., Kzz and Kyy mixing) to date.
  - *Work in progress….*

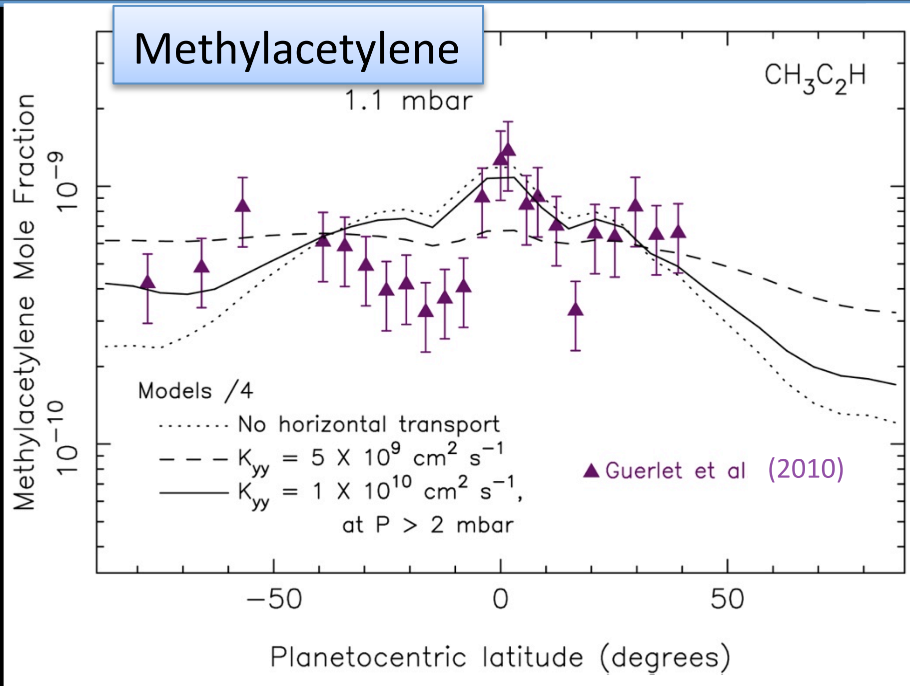


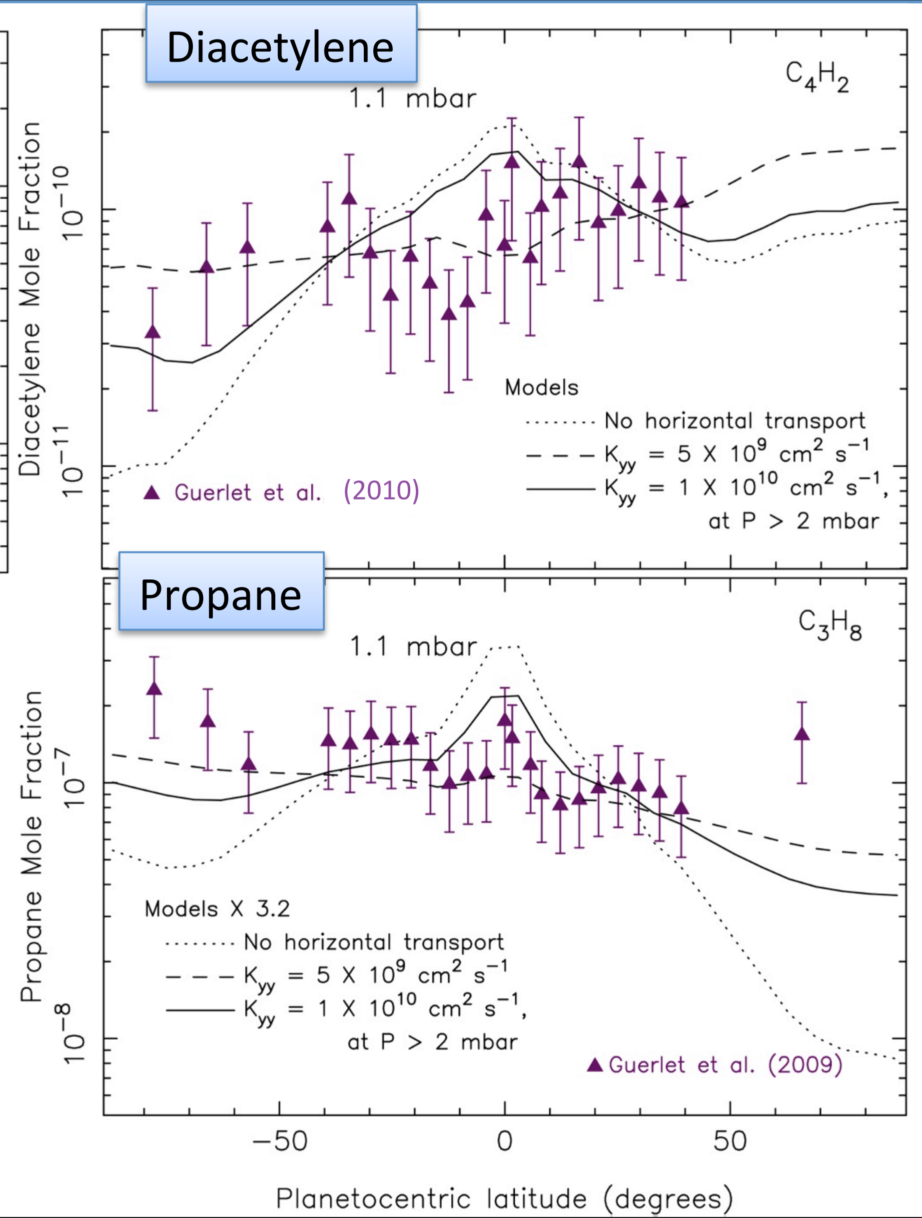
C_2H_2 & C_2H_6 Summer Observations



Greathouse et al. (2005), Howett et al. (2007), Hesman et al. (2009), Guerlet et al. (2009), Sinclair et al. (2013)

C_3H_x and C_4H_x Summer Observations

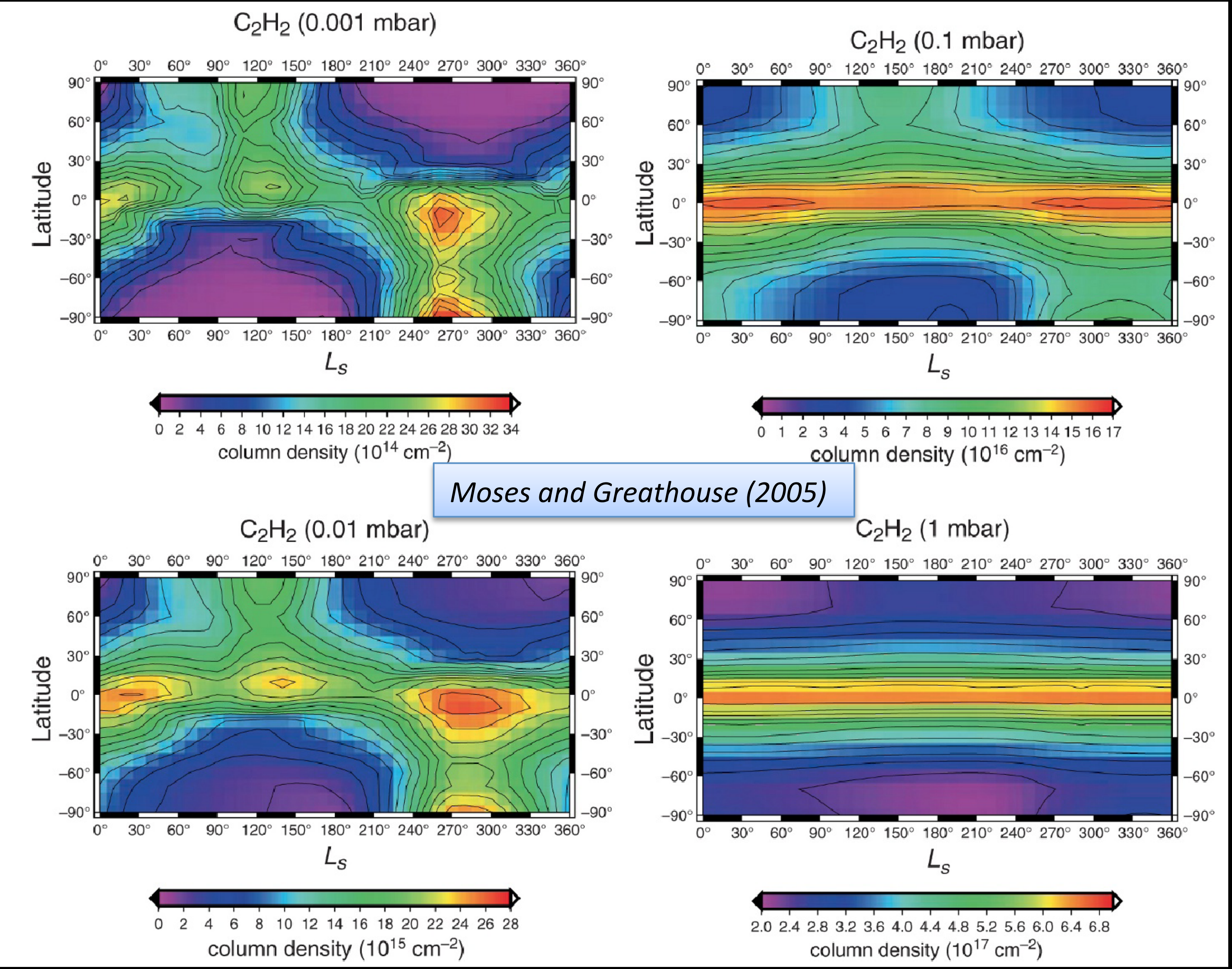




- Asymmetries in C3H4 and C4H2 not captured by models, higher in mid-northern latitudes.
- C3H8 relatively flat, hints of elevation in south.
- Departures may be caused by transport.

Temporal CxHy I: Predictions

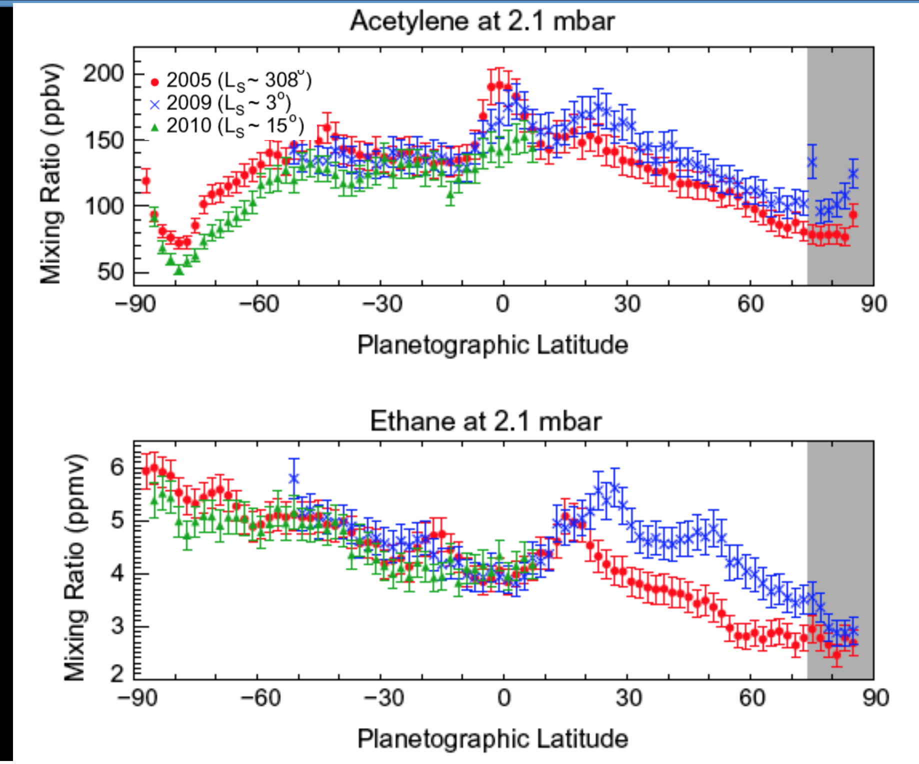
- Summertime pulse moves downwards with phase lag.
- Strong asymmetries expected at microbar pressures.
- Negligible asymmetries at millibar pressures.
- Introduction of Kyy may improve reproduction of data.

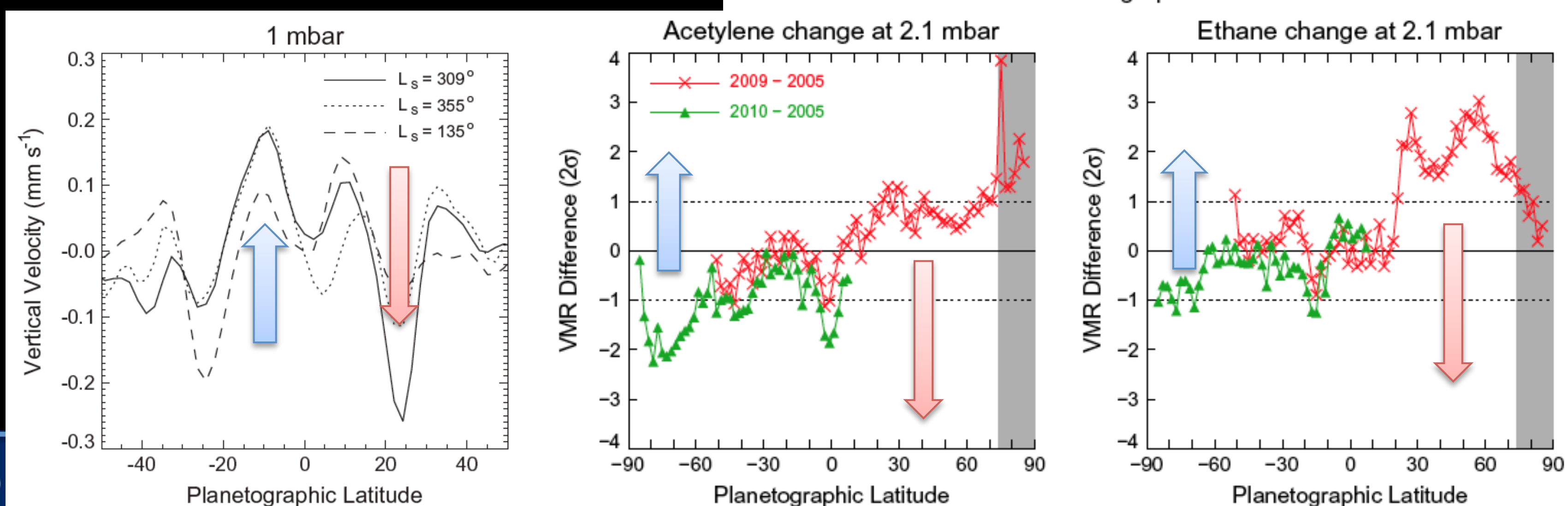


Moses and Greathouse (2005)

Temporal CxHy II: Global Trends

- Sinclair et al. (2013) first seasonal study of C_2H_2 and C_2H_6.
  - Increasing abundances in northern spring; decreasing in southern autumn.
- Low-latitude changes consistent with simulation of Friedson and Moses (2012).
- Correspondence at high latitudes unclear.





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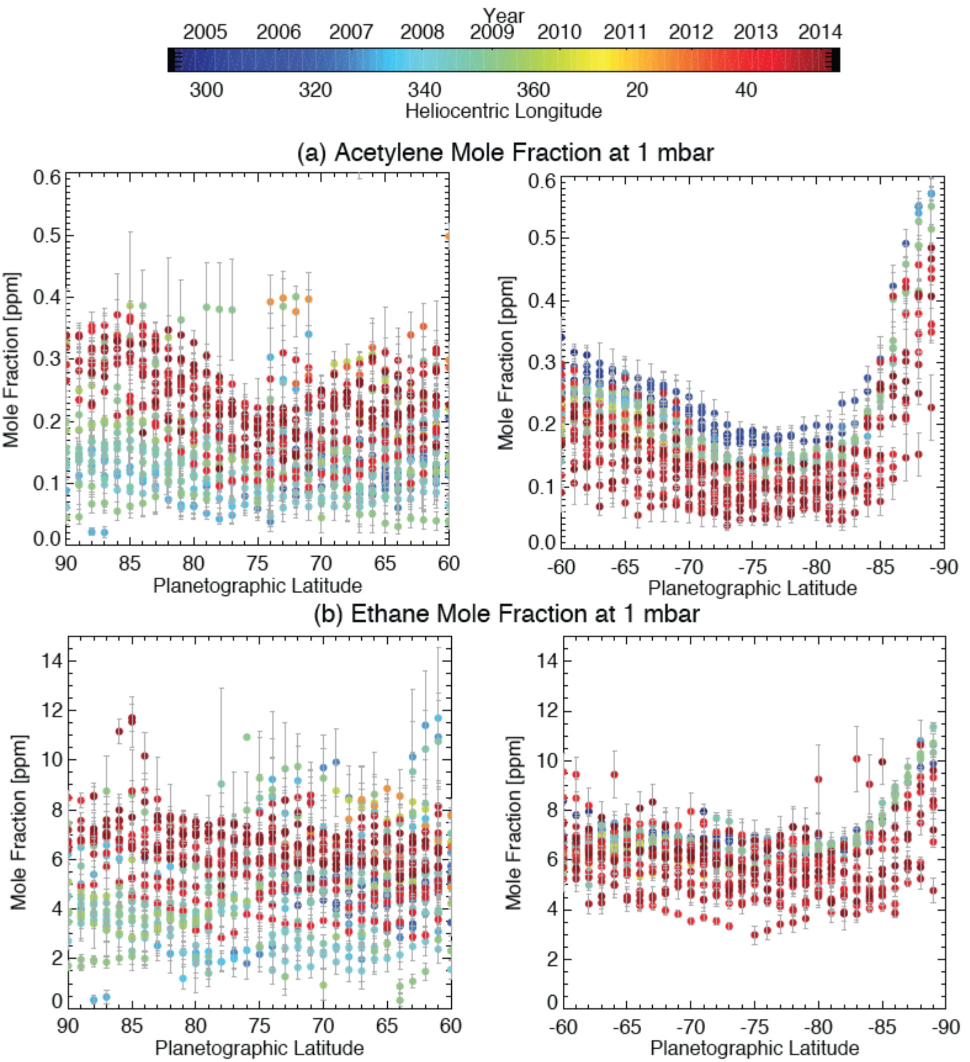
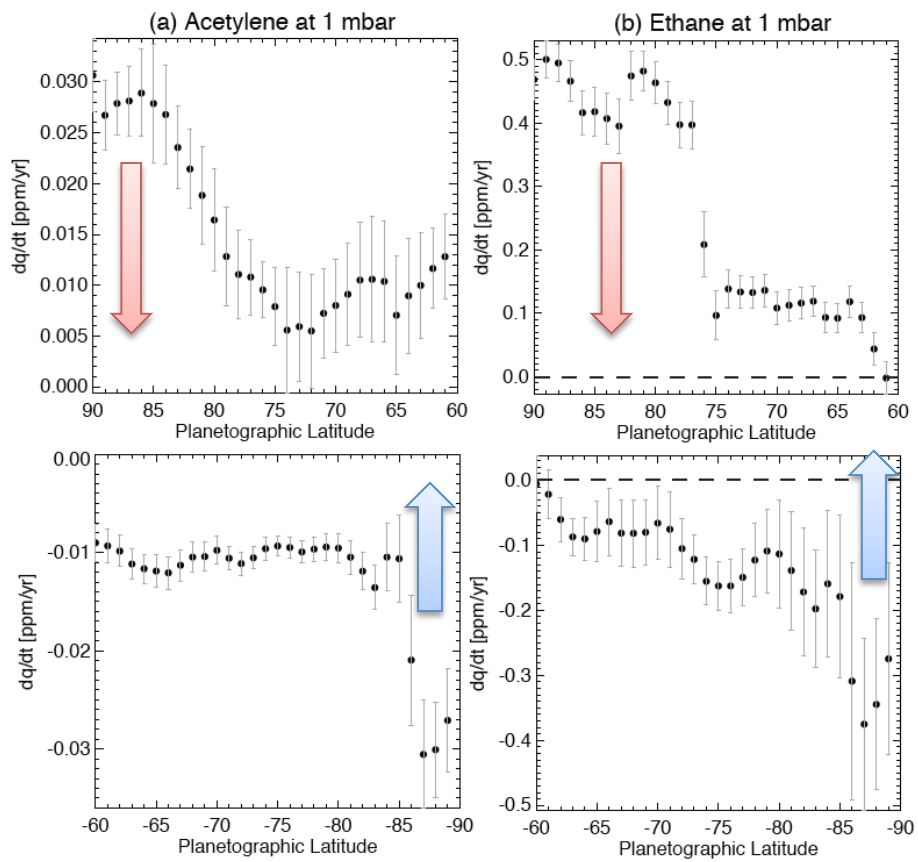
Temporal CxHy III: Polar Variability

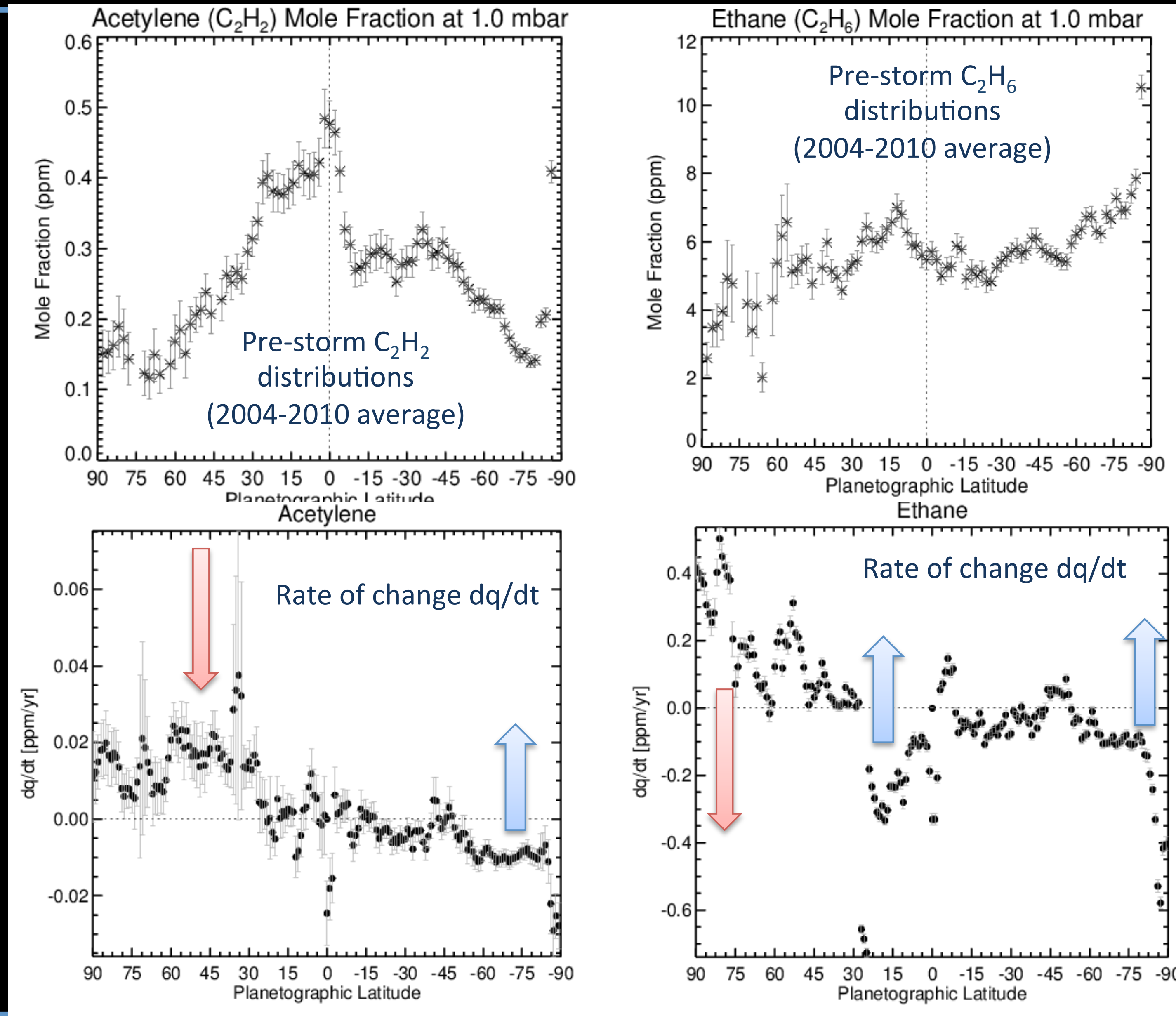
- C_2H_2 and C_2H_6 changes most dramatic within polar vortices:
  - dq/dt measured over ten years.
  - Continuity implies |w|~0.1 mm/s





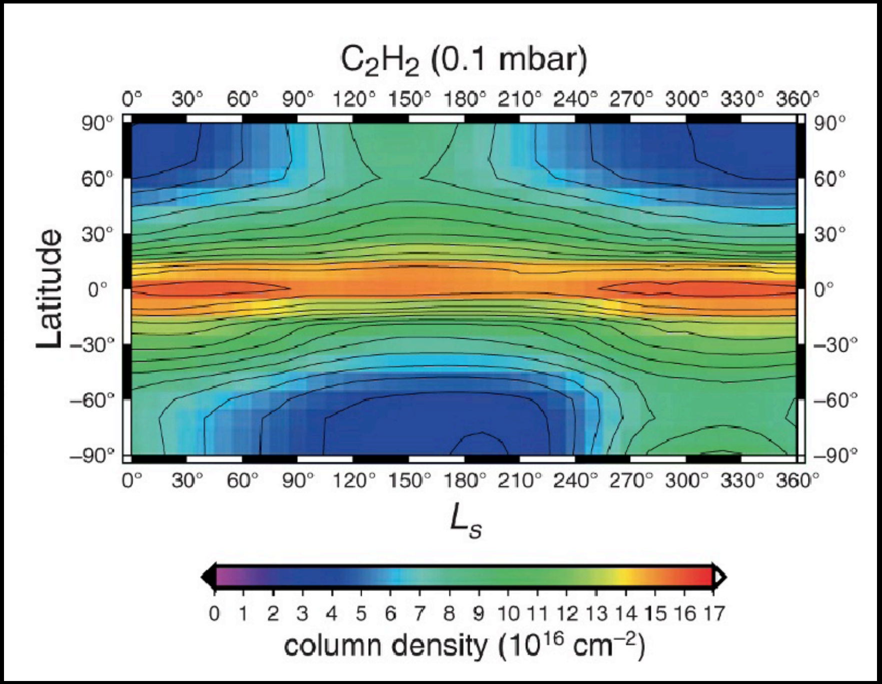
Temporal CxHy IV: Latest Results

- Preliminary investigation of CIRS data suggest ethane and acetylene asymmetries are starting to reverse at 1 mbar.
- Hemispheric trends perturbed by tropical and polar circulation cells.

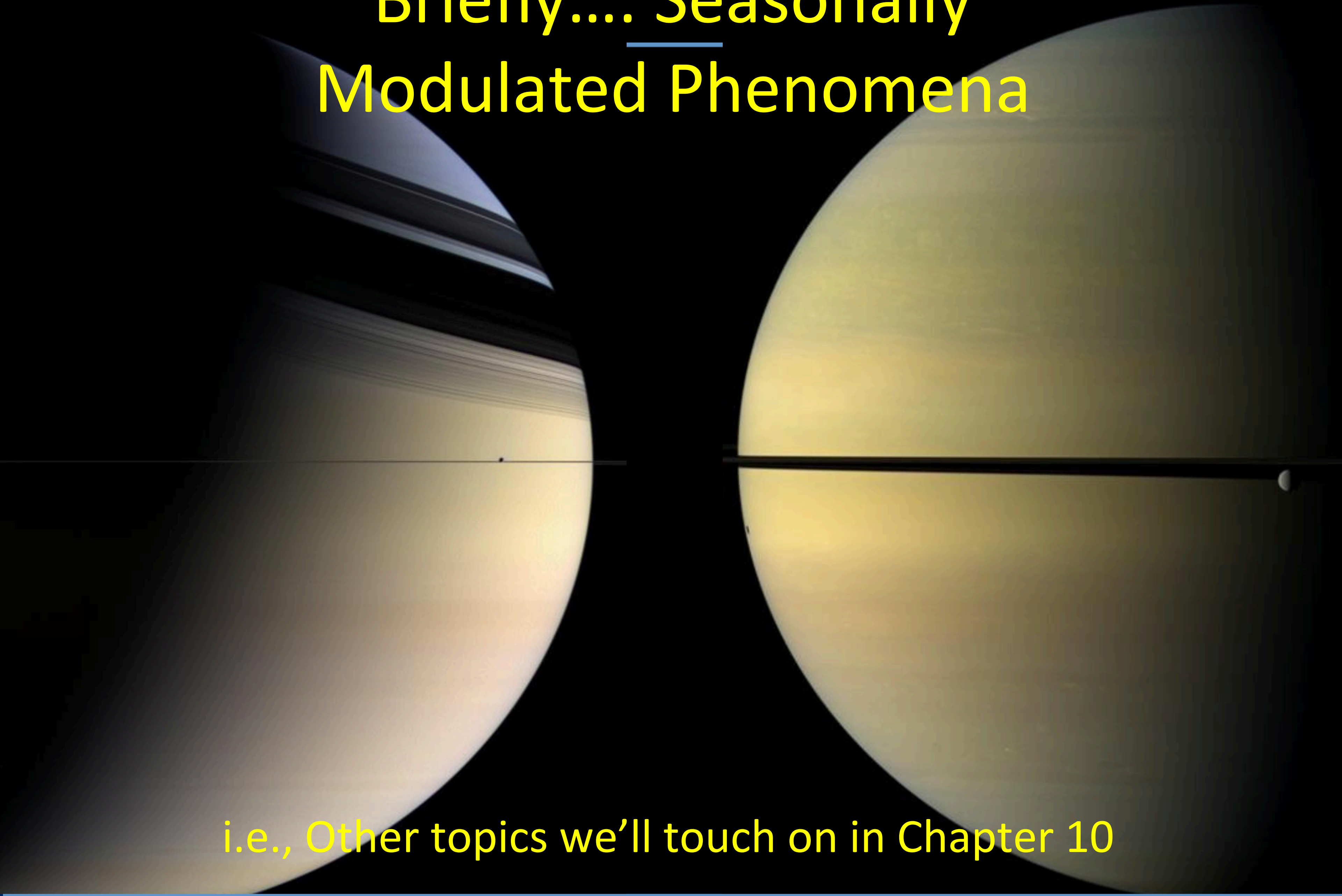


Summary of Part Two: Composition

1. Tropospheric and stratospheric species influenced by photochemistry/circulation all show **summertime asymmetries**.
2. Diffusive **photochemistry models can reproduce some** (but not all) observed trends.
3. Latest Cassini results show **asymmetries reversing post-equinox**.
4. Disentangling chemical and transport effects means use of species as tracers isn't always clear-cut.

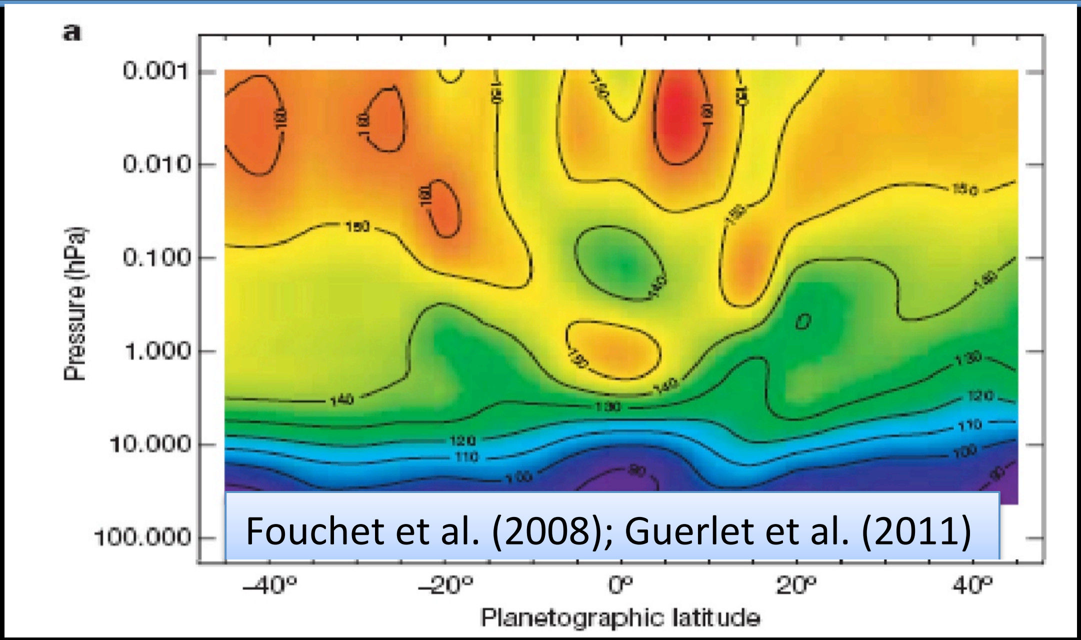


Briefly…. Seasonally Modulated Phenomena

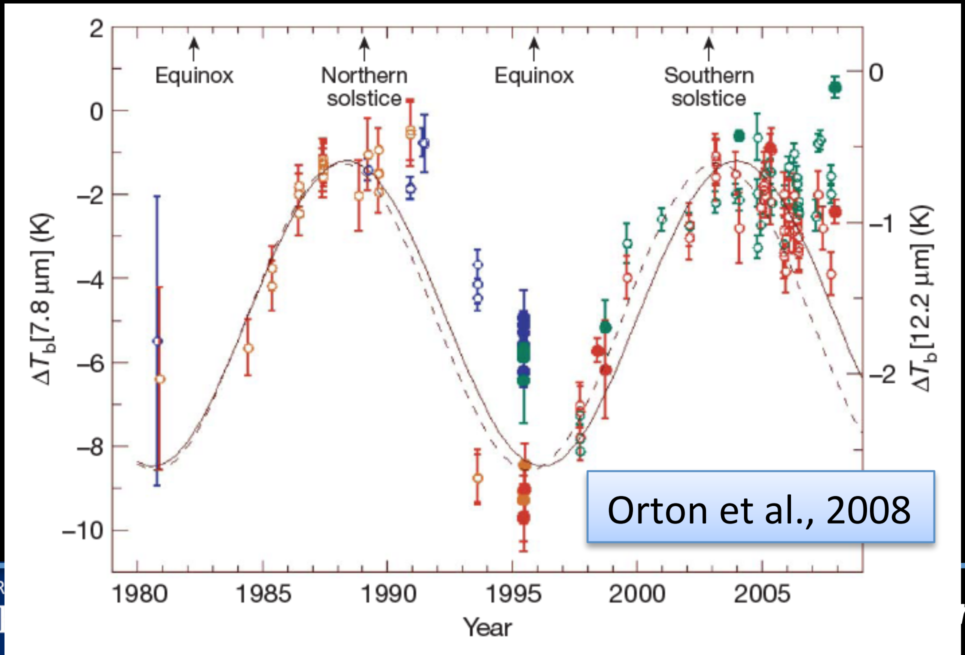


i.e., Other topics we'll touch on in Chapter 10

Wave Phenomena



Fouchet et al. (2008); Guerlet et al. (2011)



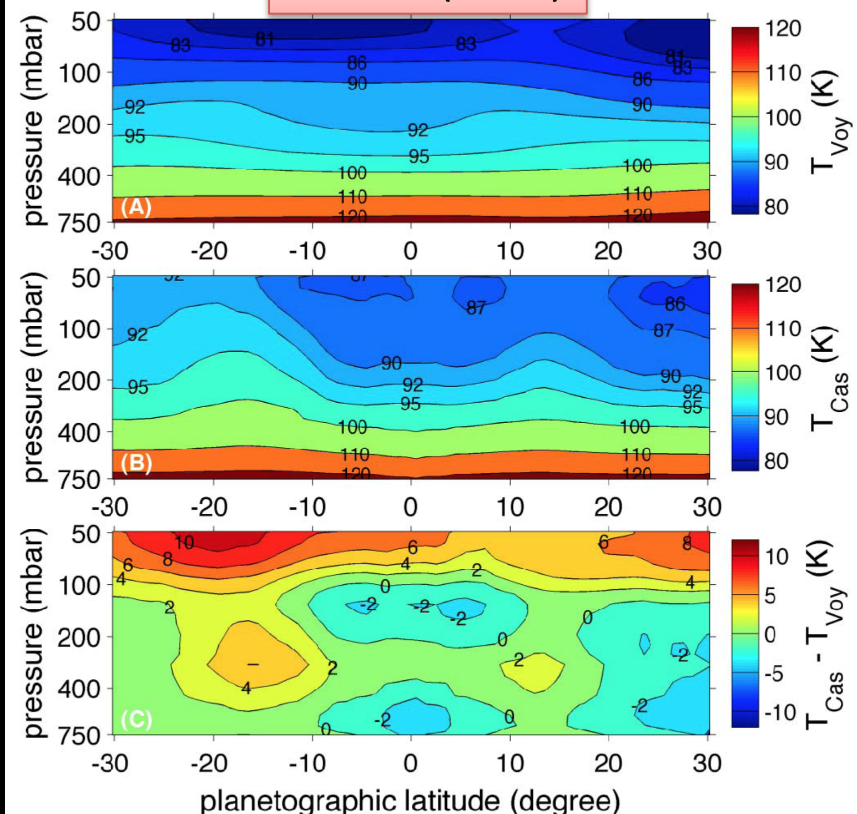
Orton et al., 2008

- **Tropical stratosphere dominated by effects of quasi-periodic oscillation**
  - (Fouchet et al. 2008; Orton et al., 2008; Fletcher et al., 2010; Schinder et al., 2011; Guerlet et al., 2011).
- Downward motion of a chain of warm/cool airmasses.
- Upward-propagating planetary waves interacting with the mean zonal flow.
- Phase of SSAO connected to seasonally-reversing Hadley circulation? [Friedson & Moses, 2012]
- **Recent disruption of SSAO due to storm beacon**?

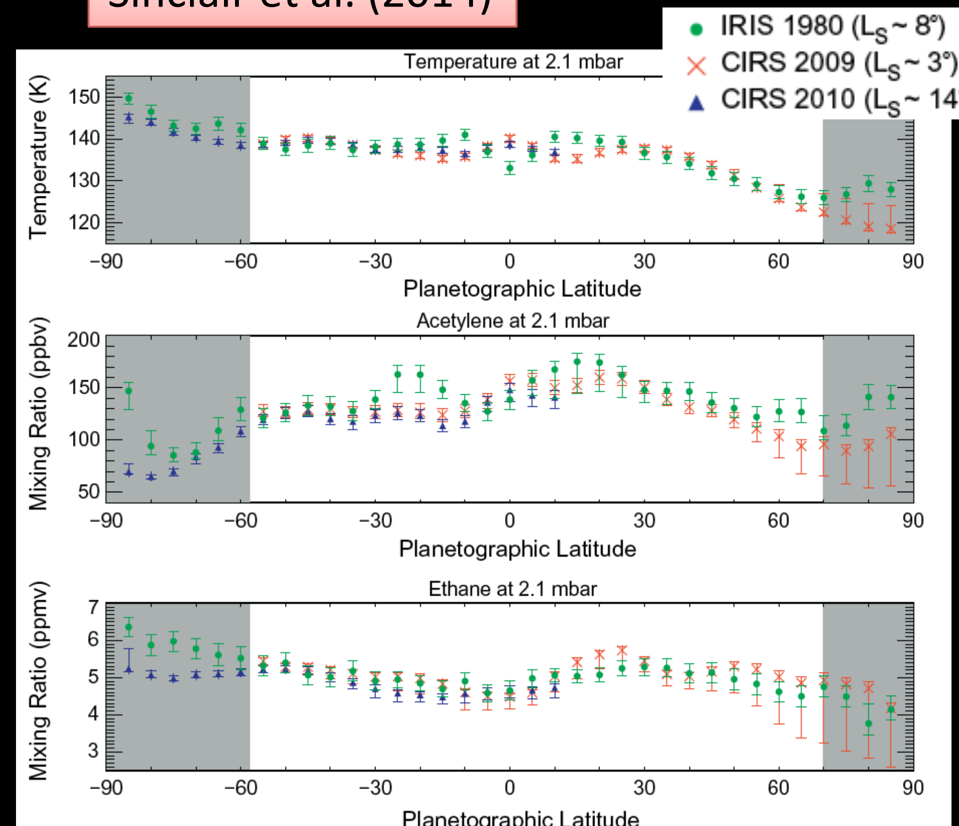
Interannual Variability?

- Tropospheric [Li et al., 2013] and stratospheric [Sinclair et al., 2014] conditions different in Voyager/Cassini epochs despite same Ls.
- Viewing **a different phase of SSAO**, not quite semi-annual?

Li et al. (2013)



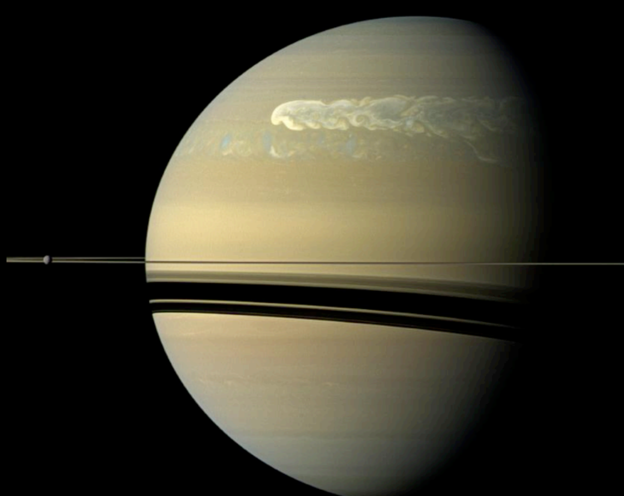
Sinclair et al. (2014)

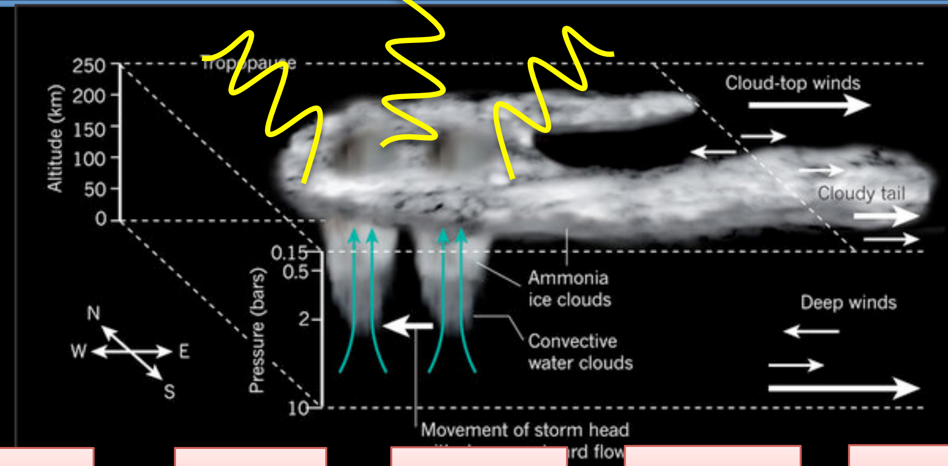


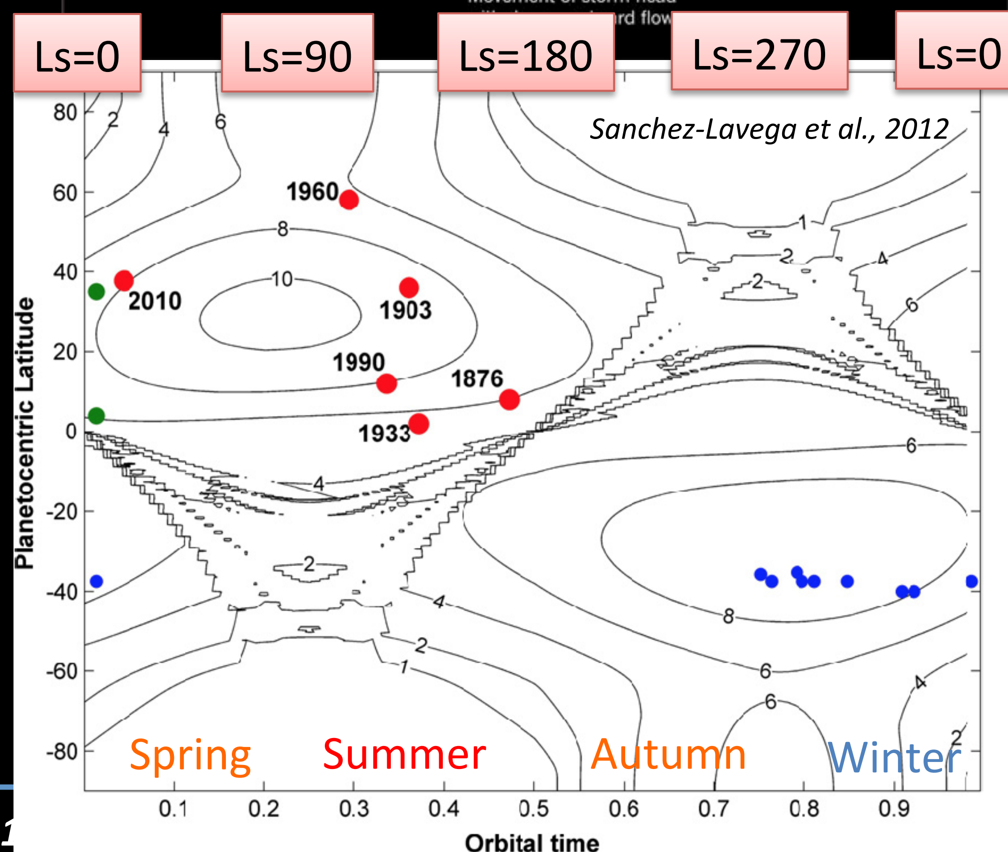
Annual Storm Activity

- Convective storms and vortices localised in ‘storm alleys’.
  - Intensity/frequency decreasing in southern autumn, increasing in northern spring?
- Seasonal modulation of GWS phenomenon despite eruption from great depth
  - Modification of stability of background troposphere.

Feb 25, 2011







Conclusions

- Saturn's seasons have been **tracked for more than 30 years**, including 10 years of continuous orbital reconnaissance.
- **Temperature asymmetries** discovered in the 1970s; tracked globally by Cassini:
  - Follows seasonal radiative predictions except in regions of strong dynamic activity (equator, poles).
  - Implications for seasonally reversing mid-atmosphere winds and circulation.
- **Compositional asymmetries** discovered by Cassini
  - Tropospheric PH_3 and para-H_2
  - Stratospheric hydrocarbons.
  - Only partially explained by photochemical models lacking comprehensive transport schemes.
  - Reversing asymmetries post-equinox.

- **By northern summer:**
  - Stratosphere temperature asymmetry reversed, but not as warm as southern summer.
  - PH_3, para-H_2 and CxHy asymmetries reversed or reversing.
  - South polar vortex dissipated; strong methane and hydrocarbon emission from new north polar vortex.
- ***Watch this space…***