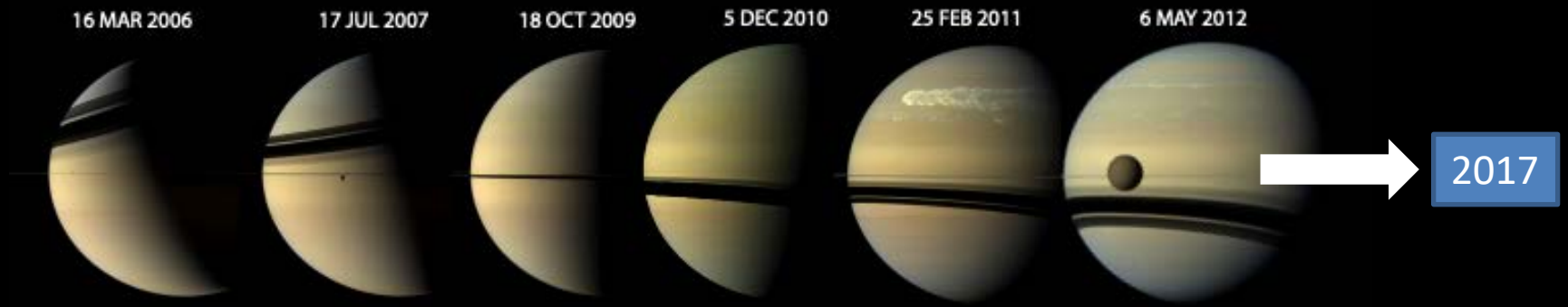
Saturn's Seasonal Atmosphere at Northern Summer Solstice

Proposed Chapter 12 for Cassini at Saturn: The Grand Finale



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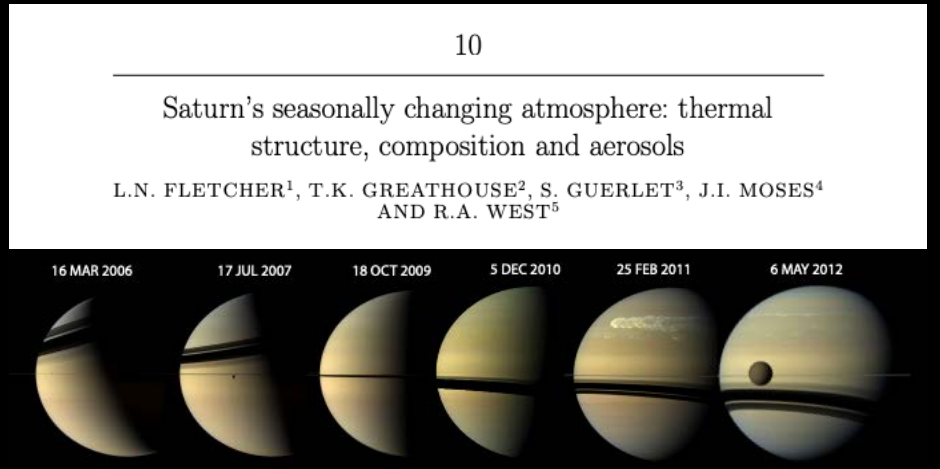
Premise of Old ”Seasonal Saturn” Chapter

- First edition completed in 2014, online in 2015, book published in 2018.
  - Covered Cassini observations 2004-2014, and comparison to ground-based observations 1980-2004.
  - Extensive section 10.2 on temperature evolution and comparison to models (Guerlet, Greathouse, Friedson – limited development since that time).
  - Extensive section 10.3 on chemical observations and comparison to models (mostly Moses, could now add Hue et al. studies).
  - Smaller section 10.4 on clouds and hazes, primarily summarizing pre-Cassini work and scope for updates based on Sromovsky et al.



https://arxiv.org/abs/1510.05690

Premise of "New" Chapter – Focus on 2015-2017

- **12.1 Intro/Background:**
  - A review of the 2015 seasonal book chapter, reminding the reader of the open questions.
- **12.2 Seasonal Variations approaching Summer Solstice:**
  - Update to temperature/hydrocarbon seasonal trends since 2014 (CIRS work, Leigh; UVIS work, Tommi).
  - Review UVIS/VIMS/ISS studies of aerosols since 2014 chapter (Bob, Larry)
  - Comparison of end-of-mission thermal field to ground-based TEXES (Sandrine, Tommy).
  - Connection to upper atmosphere (Sandrine, Tommi)
- **12.3 Dynamic events disrupting seasonal evolution:**
  - Disruption of the QQO (Leigh, Sandrine)
  - Hexagon presence in stratosphere (Leigh) - Fold in of polar stratospheric vortices (i.e., those from 75-90^{o}, not the small cyclones to be covered in polar chapter)
- **12.4 Stratospheric chemistry (don't think we need cover the troposphere again):**
  - Updates to chemical models since 2014 (Julie, Vincent)
  - Impact of exogenic inputs (Julie, Tommi)
- **12.5 Open Questions - Looking ahead:**
  - More unanswered questions. Emphasise need for modelling studies to interpret observations.
  - What we can do from the ground and JWST.

Chapter Parameters & Guidance

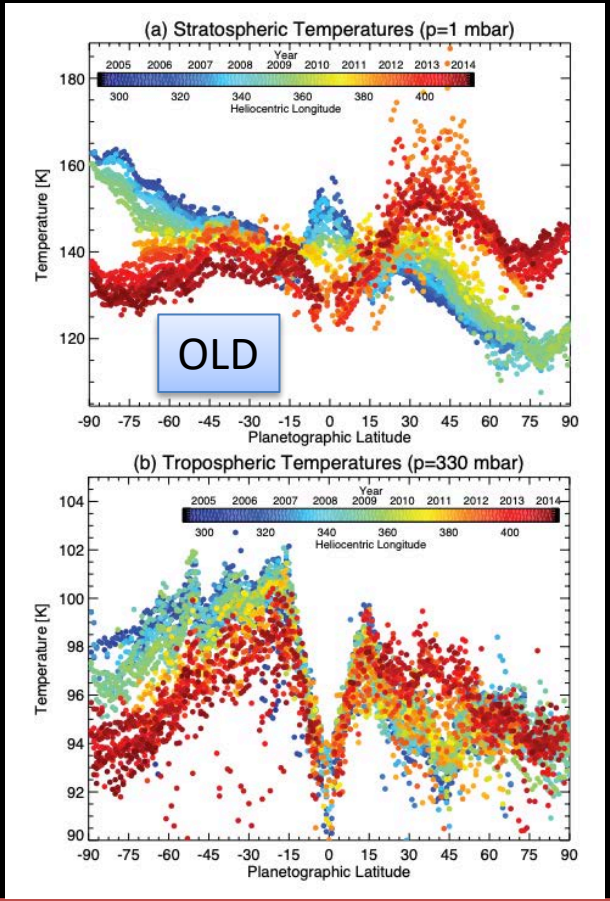
- Deadline: November 30, 2020
- Only include material that will be published by May 2021.
- Length: 10,000 words total, including figure captions
- Figures:
  - 3 color photos/figures to fit in 1.5 pages of color plates, where each page is 276x219 mm.
  - 15 black and white illustrations (graphs, figures, etc)
  - Nominally, 3 B+W photos/images.
- Minimise overlap with chapters on dynamics, upper atmosphere, and polar phenomena where possible.
  - Nothing on ring rain.
  - Limit discussion of circulation to seasonal variability.
  - Avoid discussion of polar cyclones (although larger-scale upper troposphere/stratosphere seasonal change is needed here).

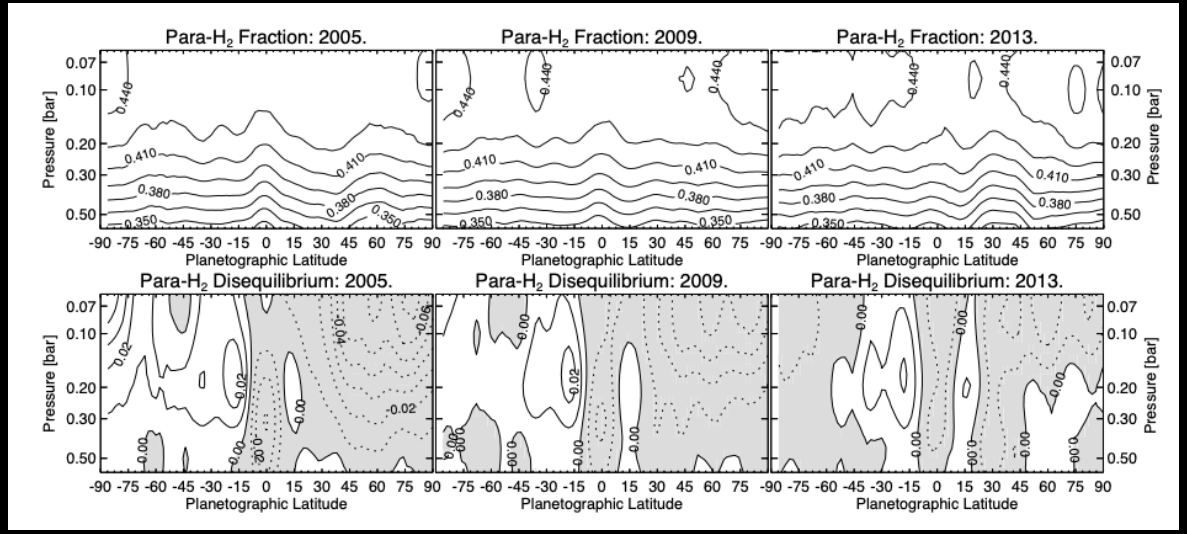
12.2 Seasonal Variations approaching Summer Solstice

This section collates ideas for inclusion in the "seasonal trends" section of Chapter 12, and should focus on things that have changed (or been published since) the end of the last book. This section primarily deals with observations (and radiative models), chemical models to be discussed in 12.4.

- Temperatures and para-H2 (CIRS limb and nadir)
- Chemicals (primarily stratosphere) – comparison to models in 12.4.
- Aerosols (ISS, VIMS).

Section 12.2: Seasonal Change

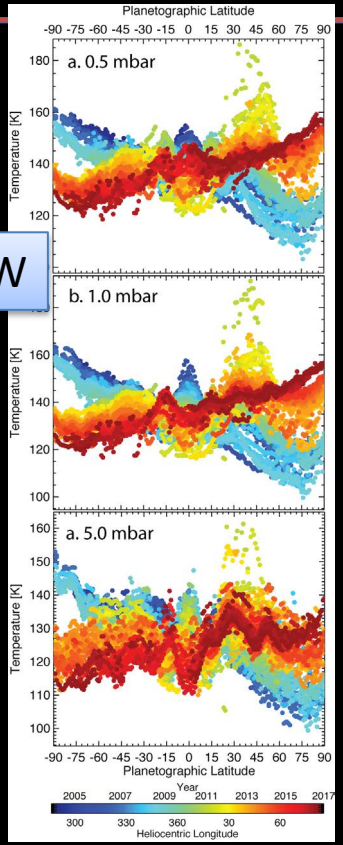


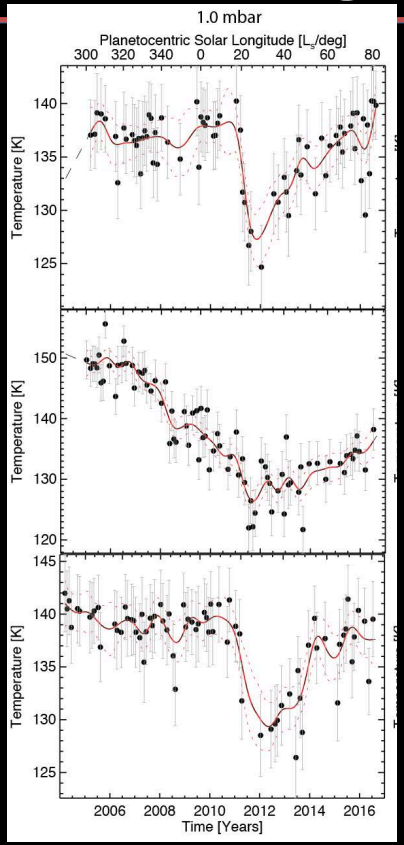


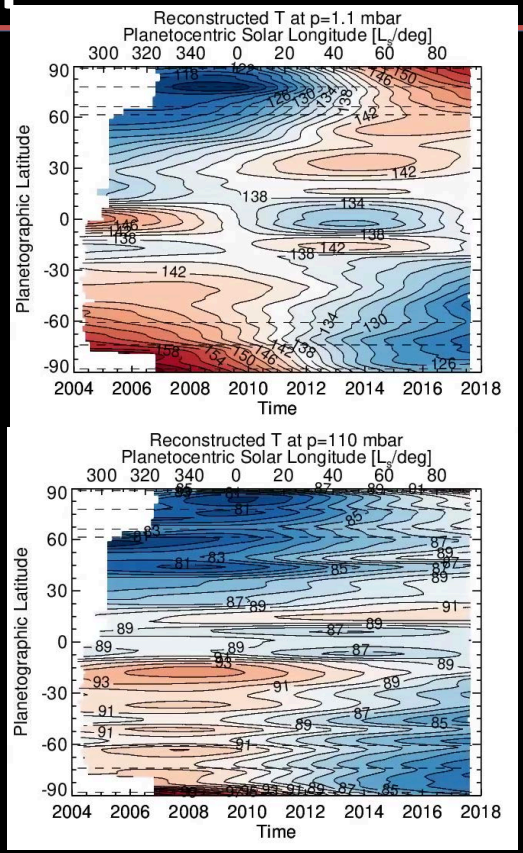
- Leigh to update nadir-T inversions to span 2004-2017 (temperatures from CIRS mid-IR; T and para-H2 from CIRS far-IR).
  - Work already published in Fletcher++2017,18 but will be refined as new figures (next slide)

Section 12.2: Seasonal Change Update

NEW





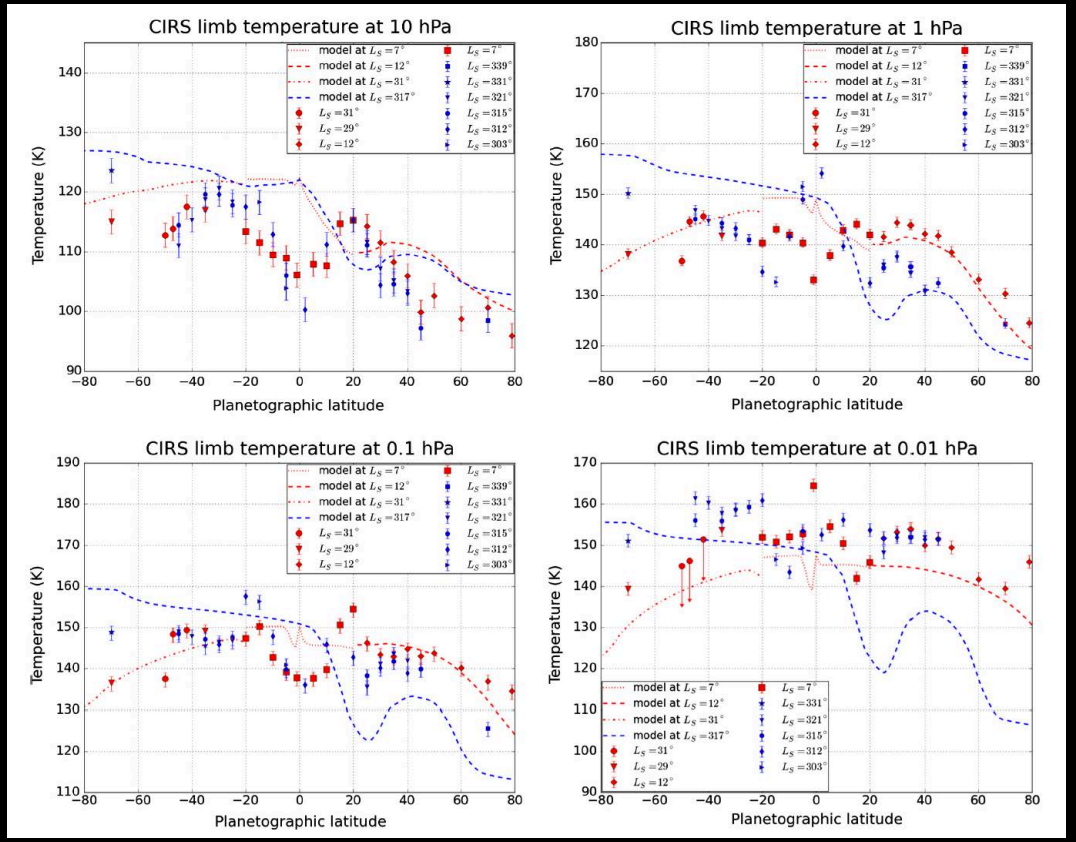


Temperature Measurements → Temperature Interpolation → Temperature Reconstruction

- 12.2 will emphasize availability of complete climate record 2004-2017.
- Discuss implications of cooling/warming trend at each latitude.
- Note largest stratospheric changes at poles, and dynamics of equator.
- Include comparison to Brown et al. (2020) thermosphere gradients.

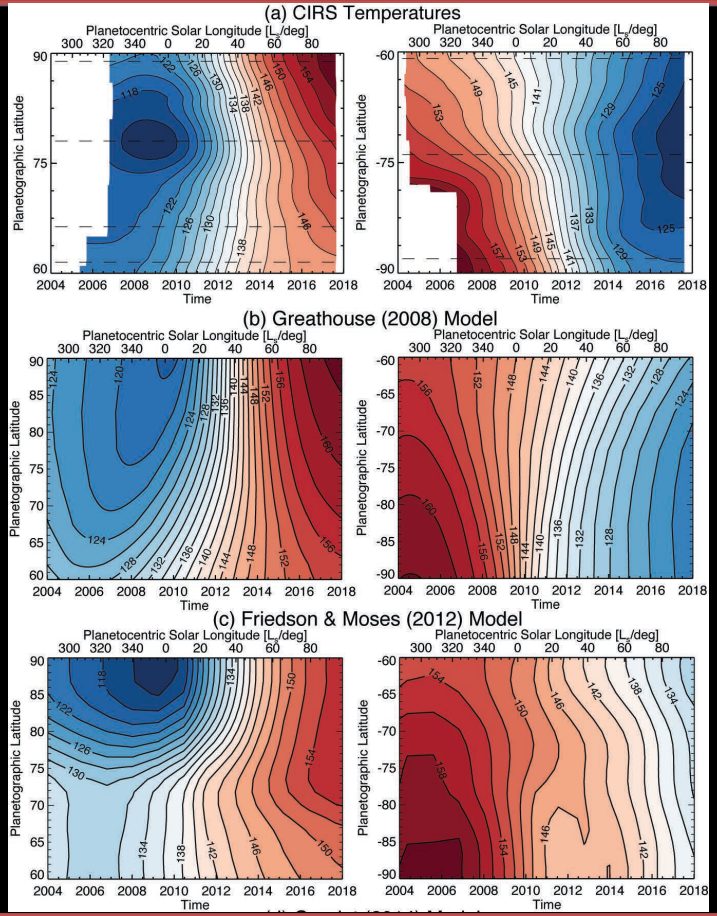
Section 12.2: Limb-Sounding Temperature Updates

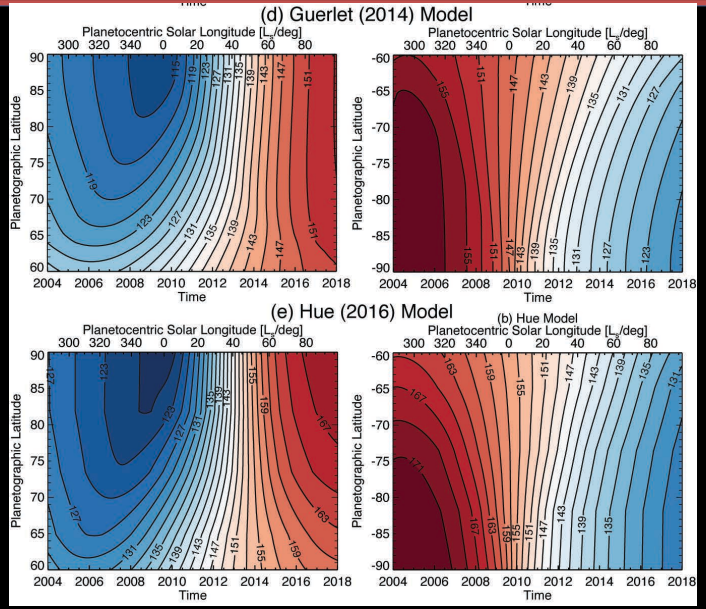
- Sylvestre et al. (2015) updated stratospheric temperature trends from CIRS limb-sounding.
- Aim to describe comparison to nadir-sounding results and new insights beyond 2014 Saturn Chapter.
- Still doesn't cover anything >2015 – *any updates?*



http://dx.doi.org/10.1016/j.icarus.2015.05.025

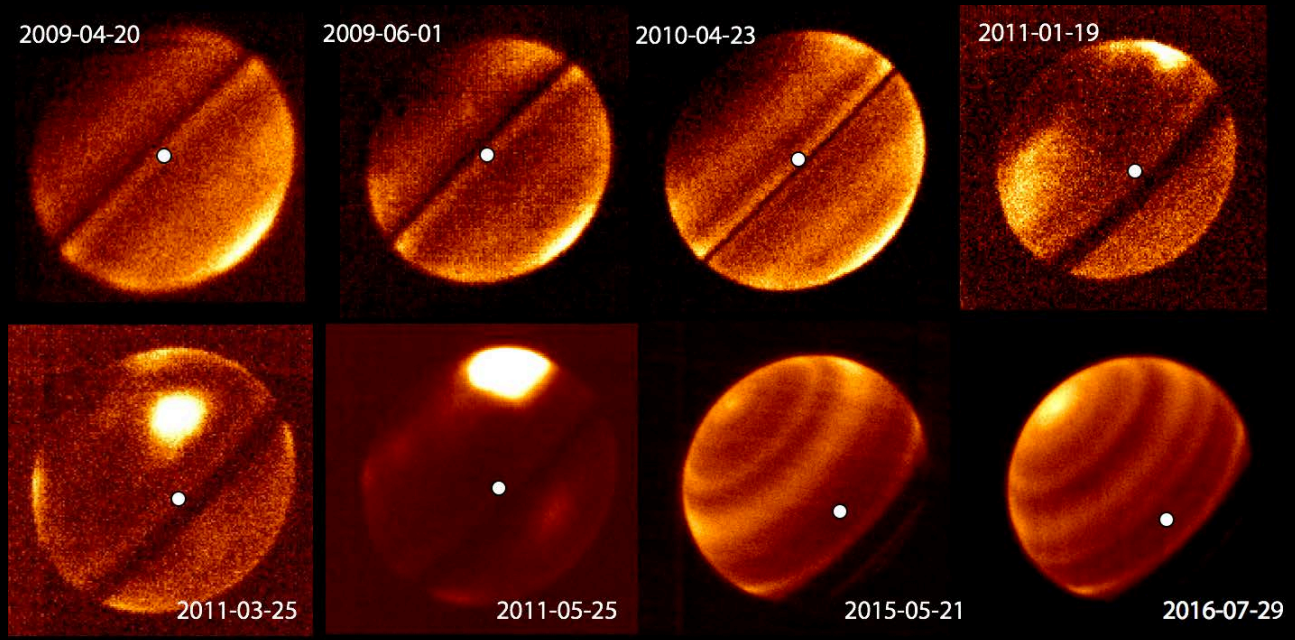
Section 12.2: Comparison to Models





Charts show 1-mbar temperature at the poles compared to four different Saturn models (one new since last book, Fig. from Fletcher+2018). Could extend to all latitudes to show model-data comparison, but not as extensive as last book.

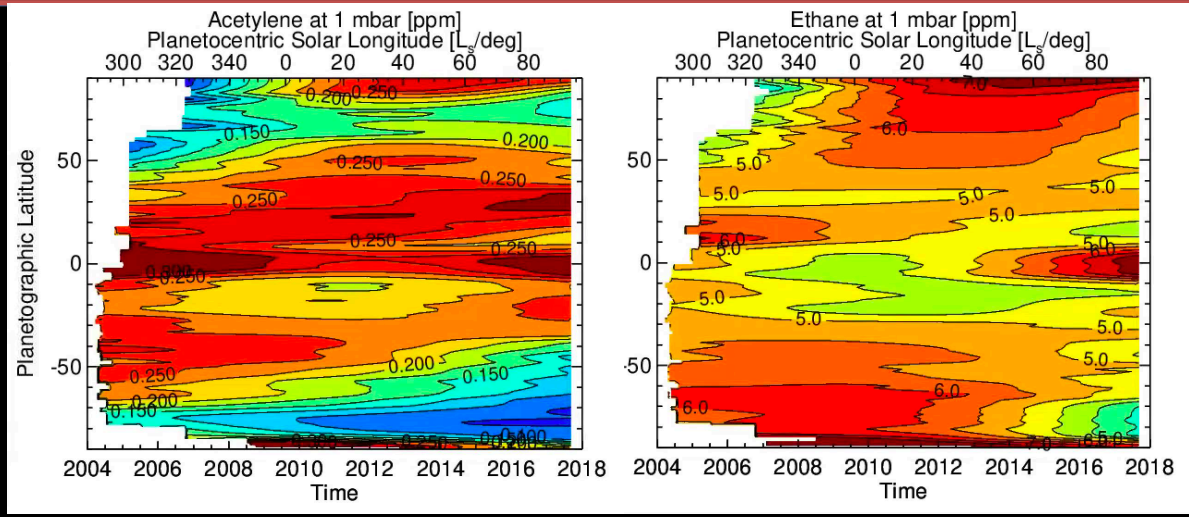
Section 12.2: Comparison to Ground-Based

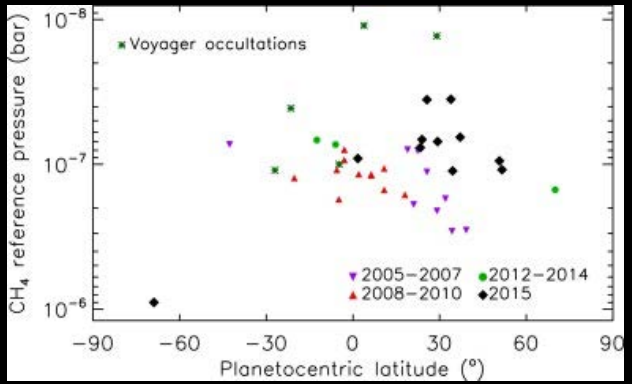


- Aim to include comparison of Cassini T(p) record to ground-based imaging (e.g., VLT, left) and spectroscopy (e.g., Gemini/TEXES).
- Demonstrates that seasonal studies can continue post-Cassini.

Section 12.2: Stratospheric Chemical Changes

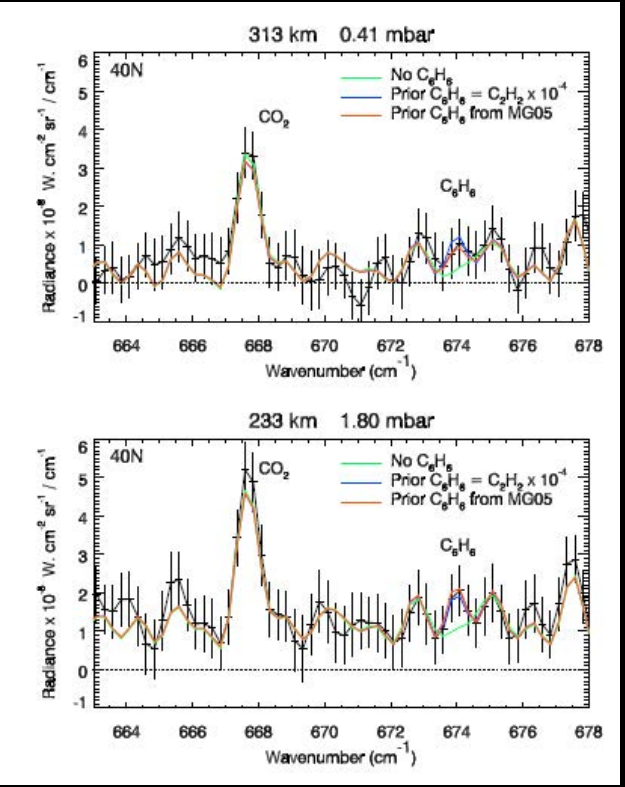
- Old Book presented CxHy profiles in comparison to Moses et al. models.
- New info to include:
  - Nadir analysis of ethane/acetylene (Fletcher+2018, right, only polar details published so far) extended to all latitudes.
- Updates from upper-atmos analysis:
  - CH4 homopause altitude from UVIS/CIRS is variable but has too much scatter to draw conclusions (Koskinen & Guerlet, 2018, right, cross-ref to thermosphere chapter.)



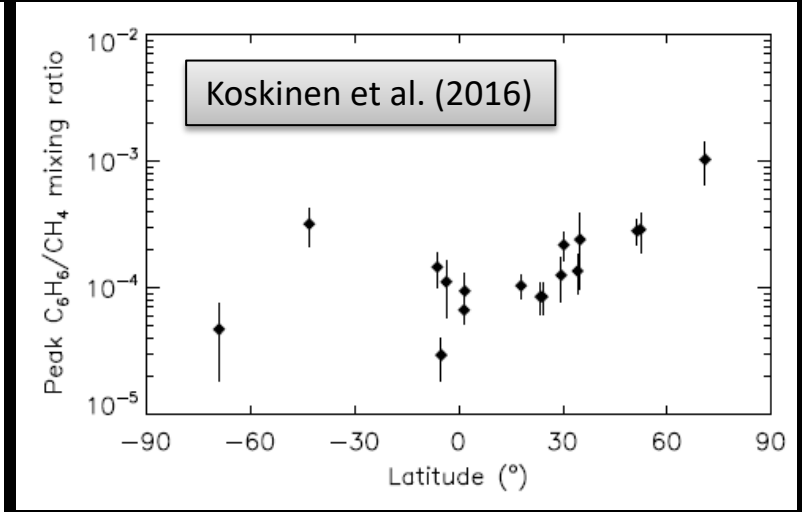


Plots are preliminary and need refining, comparison to Moses/Hue models.

Section 12.2: Seasonal Trends Dominate over Latitude?



Guerlet et al. (2015)



Maximum benzene/methane ratio at 0.1-10 μbar

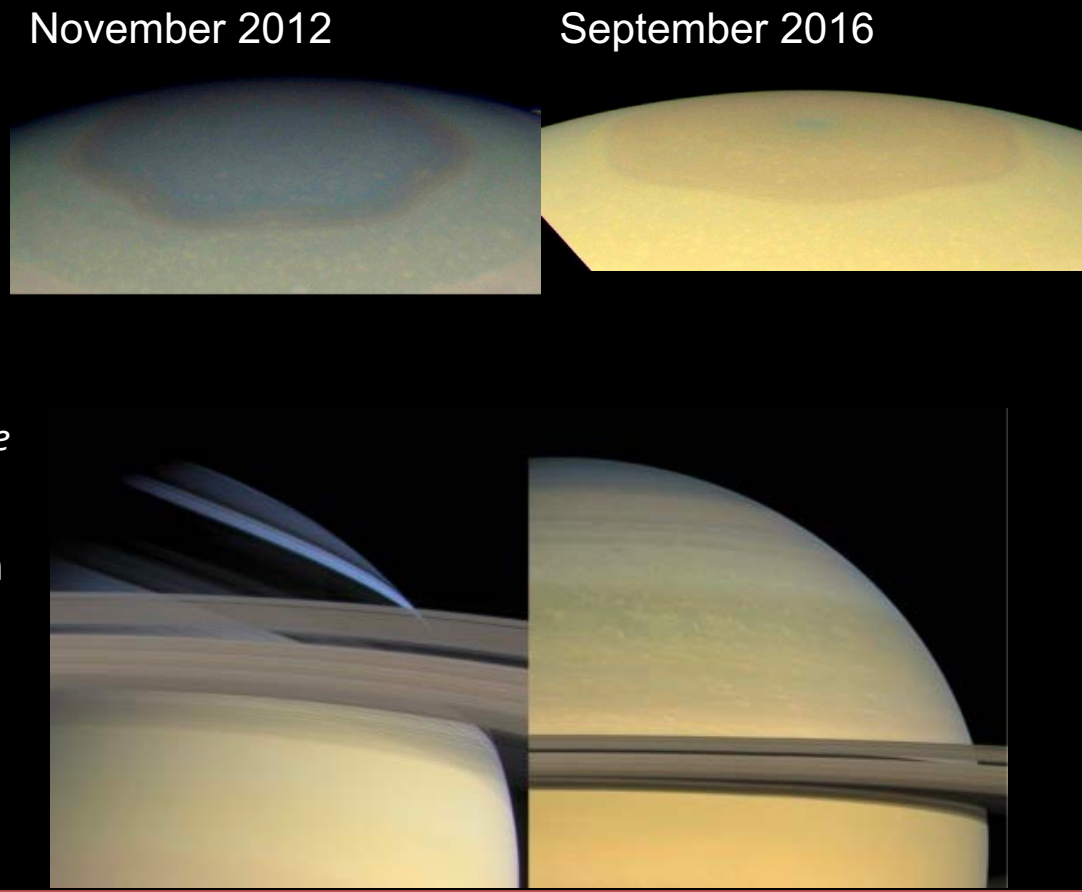
- Self-consistent story for chemistry section:
- Koskinen et al. (2016) study suggesting that seasonal trends might be more important than latitude for benzene – this is the only UVIS meridional CxHy trend available.
- Haze distribution (e.g., VIMS analysis of south pole, Kim et al. 2019) also contributes to this consistent story.

Section 12.2: Tropospheric Chemical Changes?

- No further papers (TBD) discussing changes to PH3 and NH3 as a function of latitude and time – likely to be omitted from new chapter.

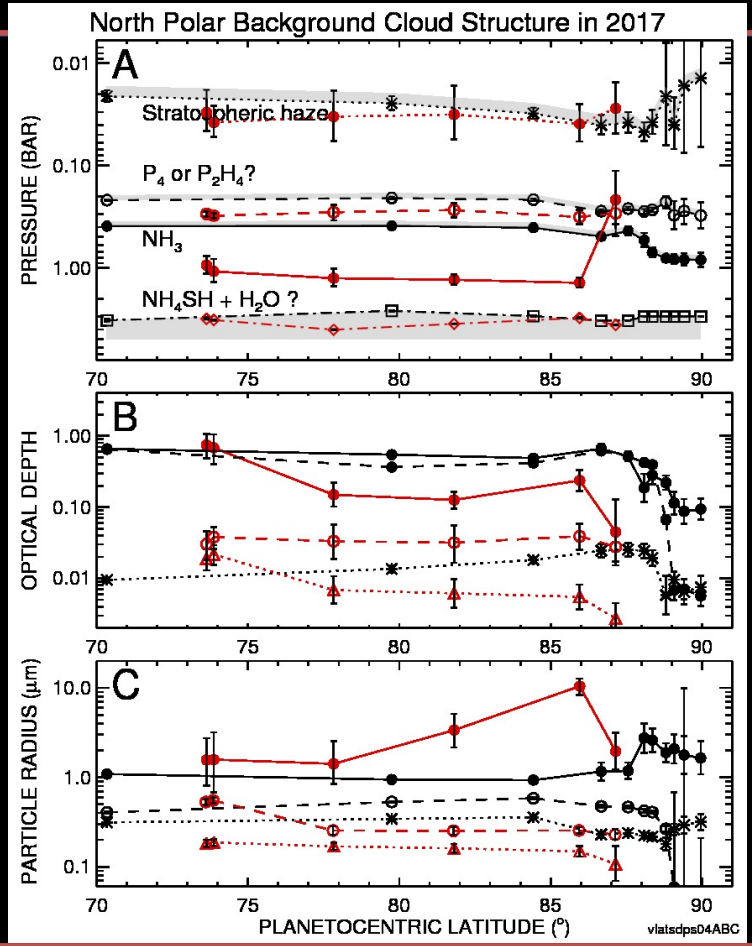
Section 12.2: Aerosol Changes

- Cassini aerosol studies have been rather thin.
- ISS imaging of changing colours (most notable at poles)
  - *Has this been published anywhere?*
- VIMS assessment of cloud structure from Sromovsky et al., Kim et al. (others?)
  - *Hasn't really dealt with seasonal change yet, but does start to show latitudinal trends.*
- Chapter 12 is the only one to deal with clouds, so there's scope for a "non-seasonal" short review of what we have to date.
  - E.g. Waldman & Griffith (2019) on VIMS spectroscopy (possibly for storm chapter).



Section 12.2: Aerosol Changes

- Initial steps in quantative constraint on seasonal changes in the clouds/hazes from Cassini/VIMS.
- **Sromovsky et al. (EPSC 2019):**
  - Comparison of 2013 (red) vs 2017 (black).
  - The cloud/haze layers in 2013 were of especially low optical depth inside the hexagon.
  - Between 2013 and 2017 the north polar cloudlayers all increased in optical deptj outside the eye region.
  - Most surprising was the factor of 10 increase in the putative P_2H_4 layer.
  - Photochemistry acting after polar illumination comes increases aerosol production.
  - The relatively clear eyes are plausibly results of downwelling.
- Comparison with results from ISS and Hubble from Perez-Hoyos++2016; Sanz-Requena++2018 and Sanchez-Lavega++2020
  - Latter on multi-layer hazes above the hexagon might be better for Sayanagi polar chapter.



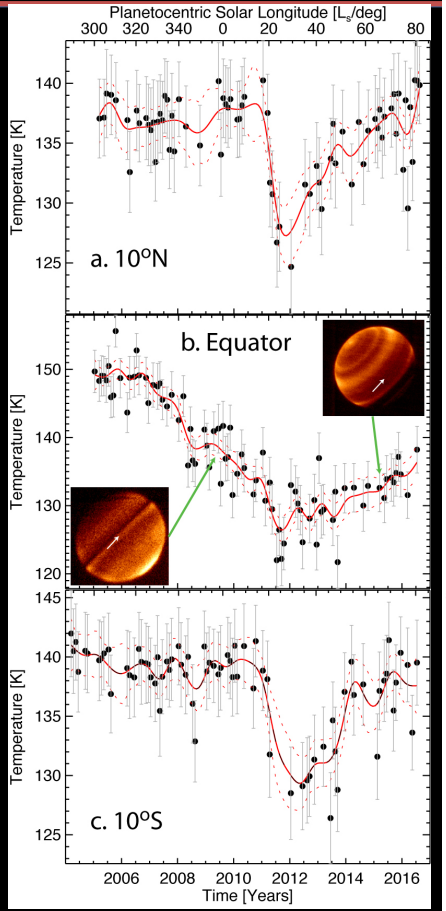
12.3 Dynamic events disrupting seasonal evolution

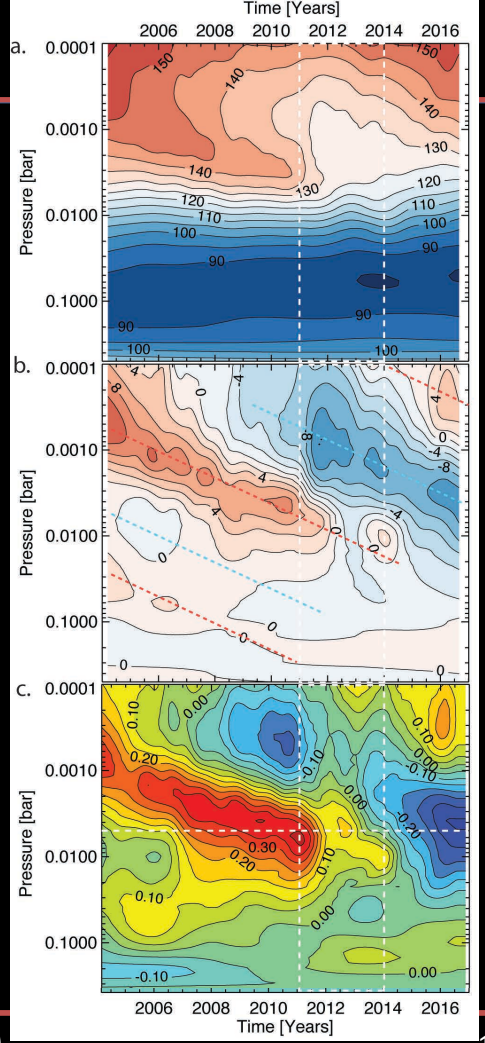
This section looks at dynamic phenomena that are perturbing the slow seasonal evolution. It will be brief and refer to other chapters where the dynamical theory is described in more depth.

- Polar vortices (e.g., 75-90 deg.)
- Equatorial Oscillation
- Storms (primarily a cross-reference to Sanchez-Lavega)
- Others?

12.3: Saturn Equatorial Oscillation

- Disruption of oscillation by northern storm 2011-2013 (Fletcher+2017, Guerlet+2017).
- Returned to pre-storm trends by Cassini EOM?
- Predictions for oscillation appearance beyond 2017 and comparison to more recent ground-based data.
- Discuss modelling work of Bardet+2020.

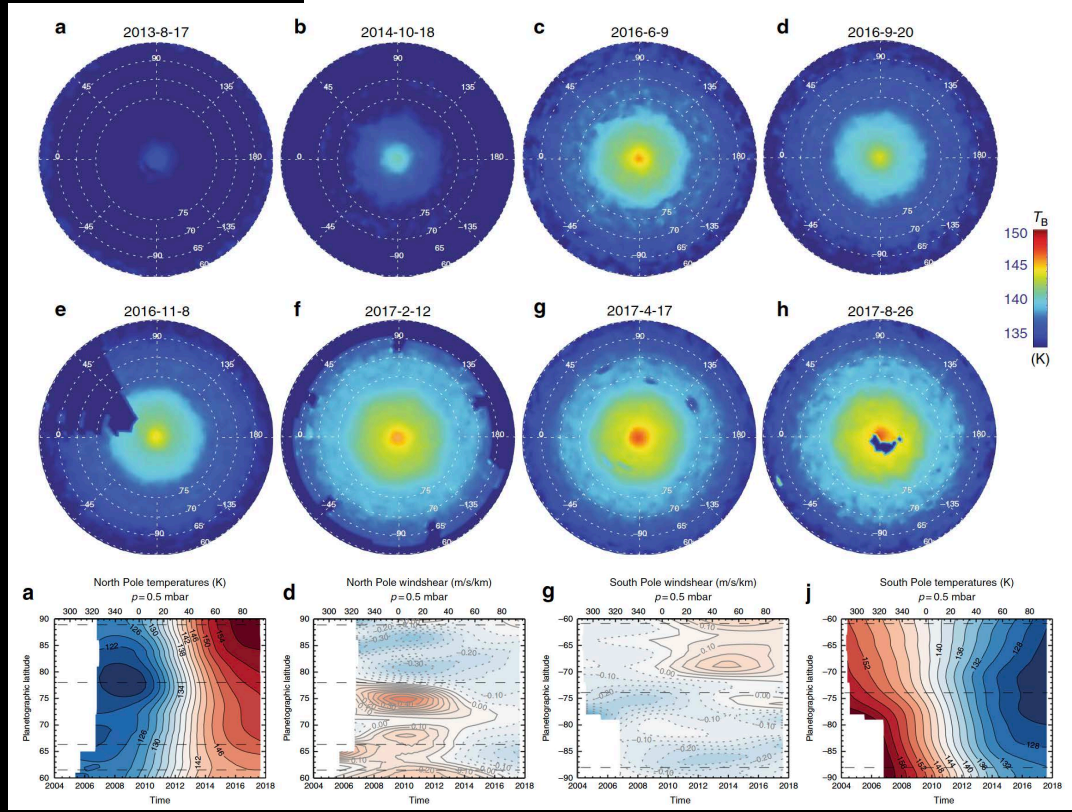




12.3: Saturn Polar Warming/Cooling

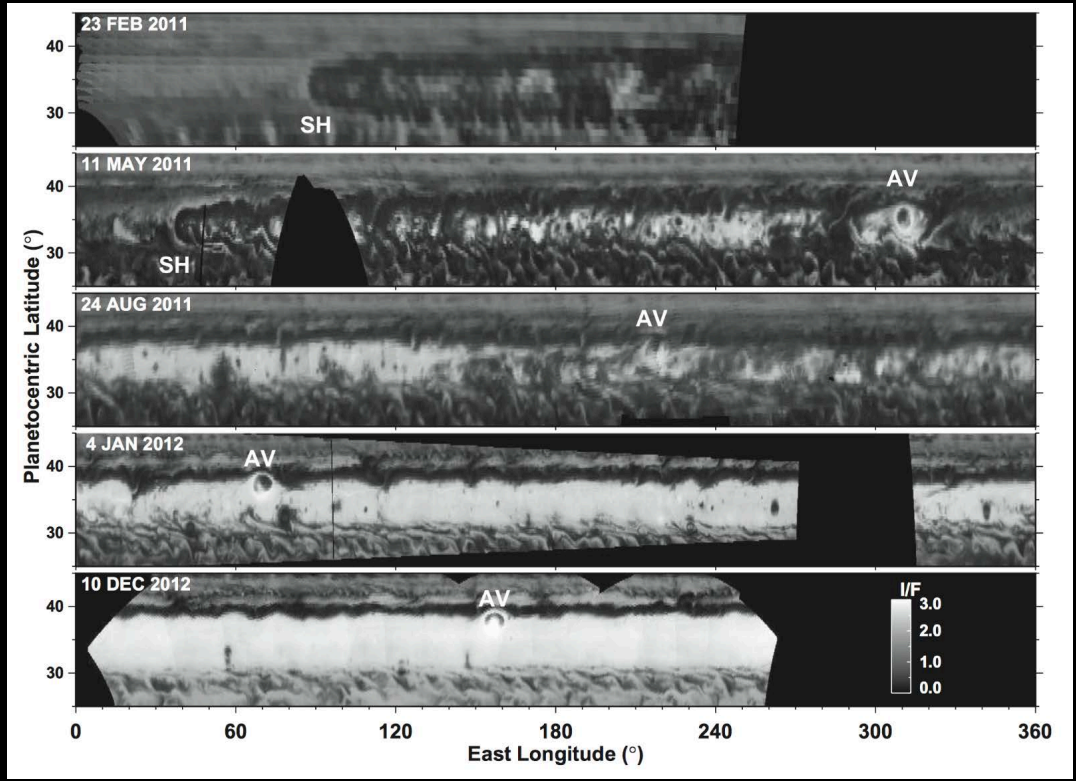
- **Clarify:** we mean the large, seasonal 75-90º vortices in the upper troposphere and stratosphere, not the 88-90º cyclones.
- Changes to temperatures & abundances are larger than expected from seasonal trends alone:
  - Complications over separating uncertain aerosol properties from residual-mean circulation.

NATURE COMMUNICATIONS | DOI: 10.1038/s41467-018-06017-3



12.3: Seasonal Storms

- Very short section that is primarily a cross-reference to Sanchez-Lavega chapter.
- Describe seasonal occurrence of previous storms, reference Li&Ingersoll (2015).
- Ref Sromovsky et al. (2013) for long-lasting cloud-clearing in the wake of the storm – affected northern hemisphere for long period.



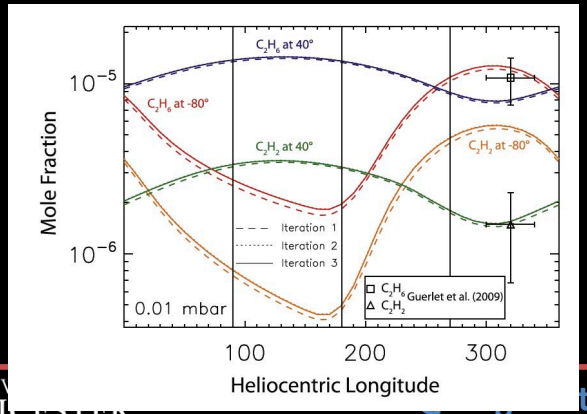
12.4 Advances in Chemical Modelling

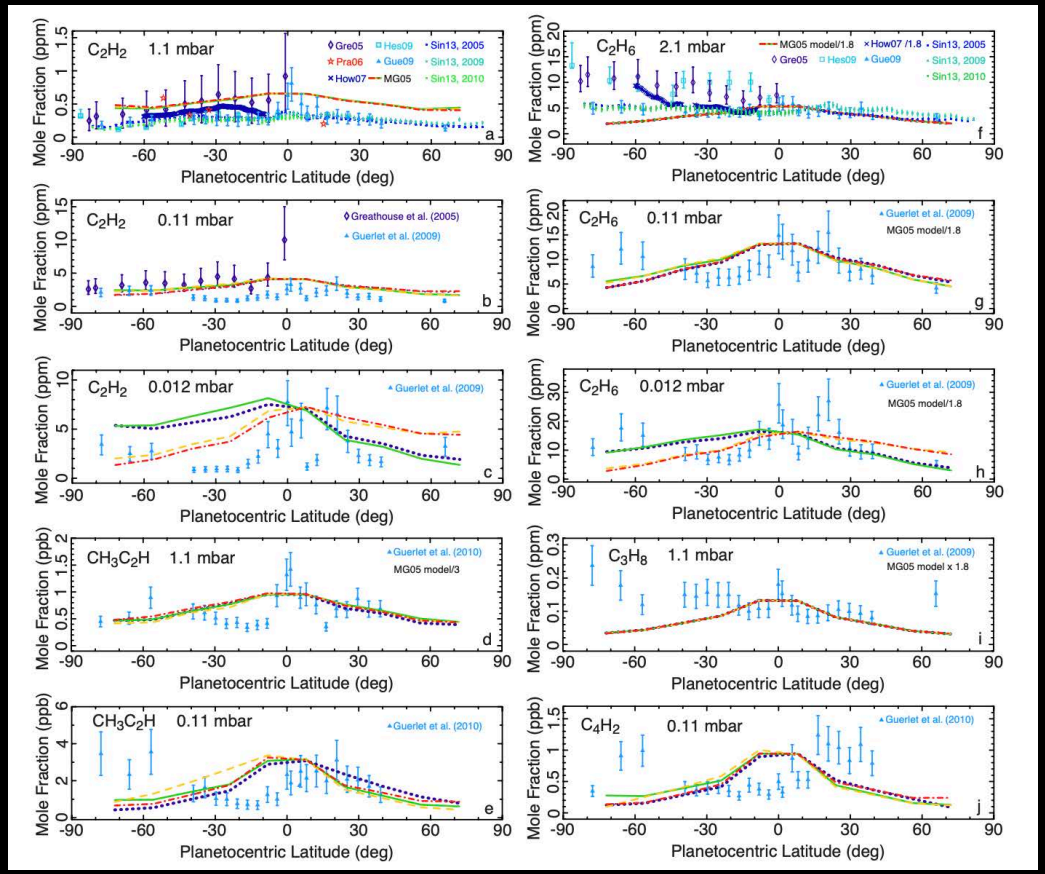
This section explores any recent advances in seasonal chemistry modelling. Last Book focused on Moses et al. work, new insights from Hue et al., Koskinen et al.

We could potentially move the chemical comparison part of 12.2 to this section to avoid too much repetition, and need to be mindful of chemistry in "upper atmosphere" chapter.

12.4 Stratospheric Neutral Chemistry

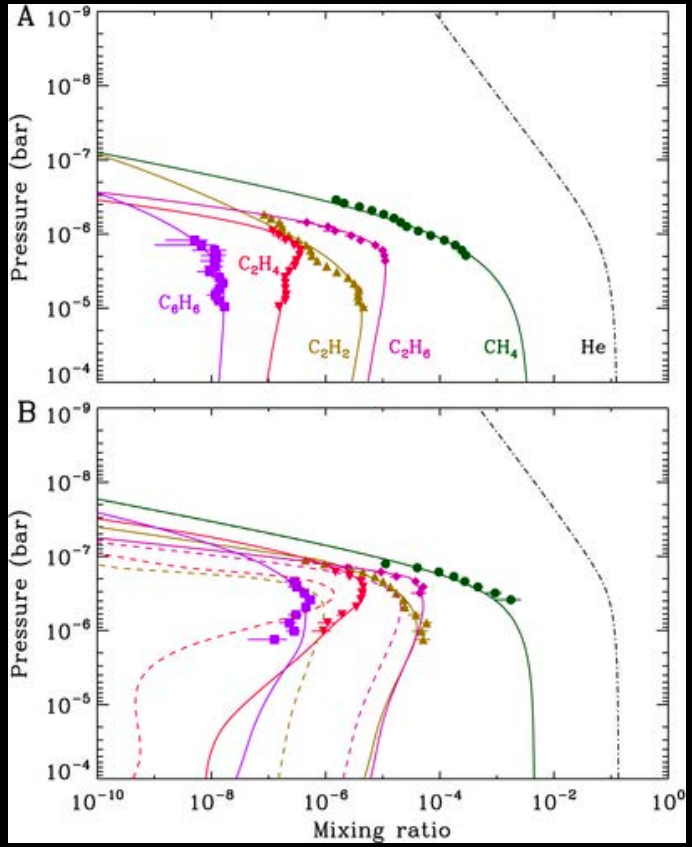
- Old Book:
  - Results from multiple authors (right) compared to Moses et al. models as a function of season.
  - No need to update? Add in Chang et al. (2020) ethane modelling.
- New Book:
  - Focus on advances since 2014, esp. feedback study of Hue et al. 2016 (below)?
  - Generate 2D (latitude/time) plots for comparison with data.





12.4 Stratospheric Ion-Neutral Chemistry

- Will not be covered in Koskinen chapter, but might feature in ionosphere chapter (TBD).
- Benzene detection (and other CxHy/haze) from UVIS/CIRS study.
- Chapter 12 won't include INMS and ring rain information.
- Comparison to photochemical models suggests need for ion-neutral chem.
  - *Any further updates?*



Research Letter

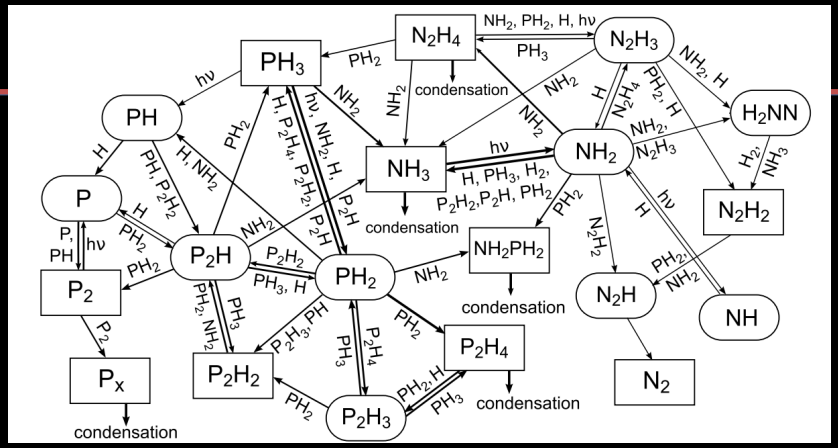
The detection of benzene in Saturn's upper atmosphere

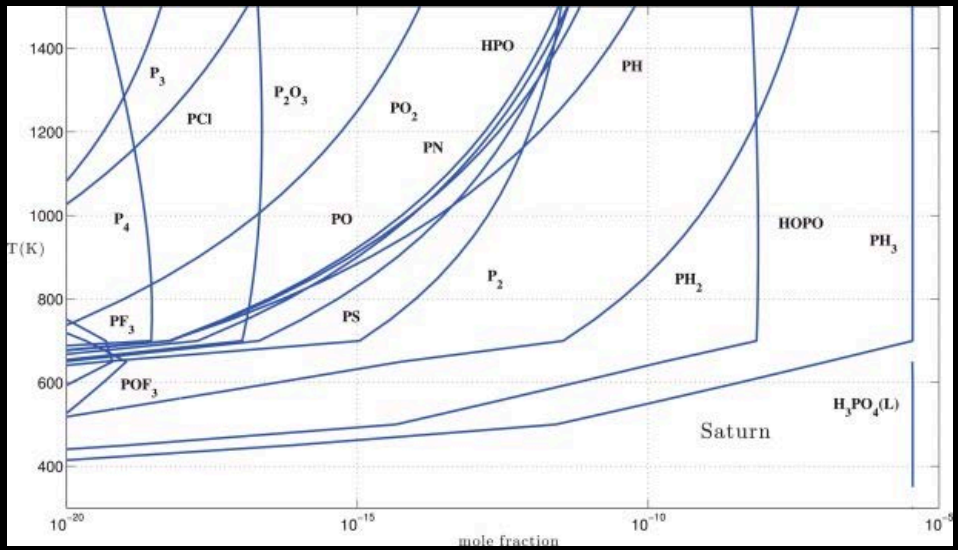
T. T. Koskinen, J. I. Moses, R. A. West, S. Guerlet, A. Jouchoux

First published:04 August 2016 | https://doi.org/10.1002/2016GL070000 | Citations: 15

12.4 Tropospheric Chemistry

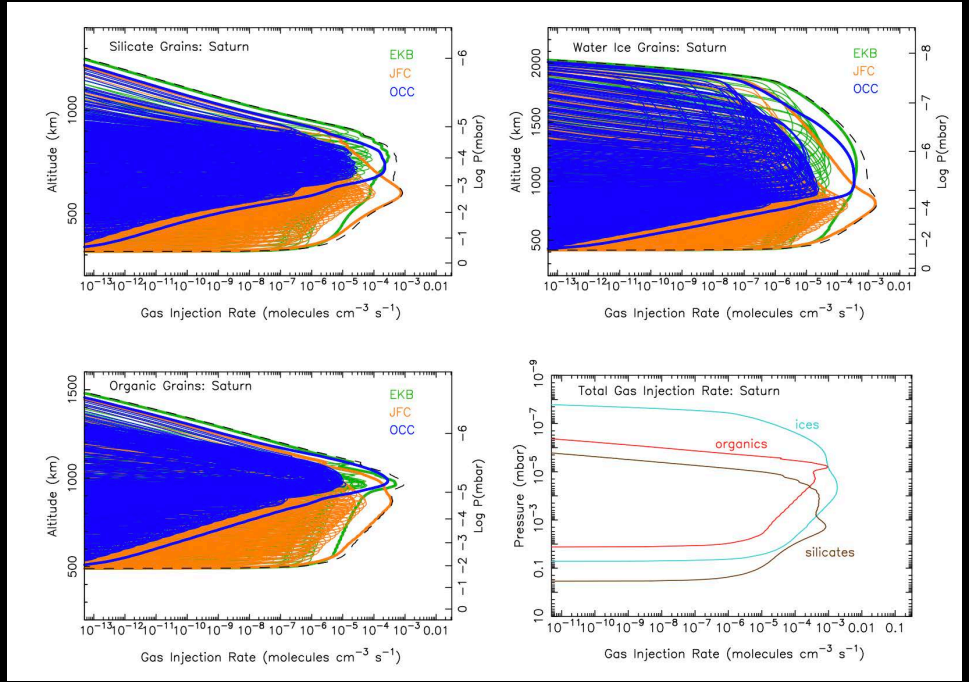
- Well-covered in 2014 chapter and no updates since then (unless Moses et al. PH3 work published by May ‘21).
- Wang et al. (2016) quench modelling of PH3 and other species (this is the only tropospheric modeling since the last book chapter, but not seasonal)





12.4 Exogenic Materials

- Some coverage in Old Book, and no observational evidence of seasonal change, but will it be covered elsewhere?
- Include some discussion of Moses & Poppe dust grain ablation modelling (2017, right), alongside Hamil et al. (2018)
  - *Or will this be covered elsewhere?*
- Discuss connection between water and Enceladus plume (Cavalie++2019).

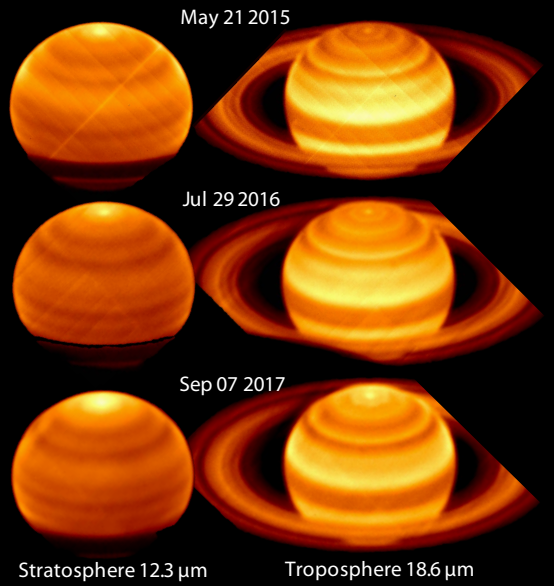


12.5 Open Questions and Looking Ahead

Final section deals with look beyond summer solstice – continued observations 2017-2021 with observatories (VLT, Gemini, Hubble); proposed plans with JWST; and opportunities with future missions/observatories.

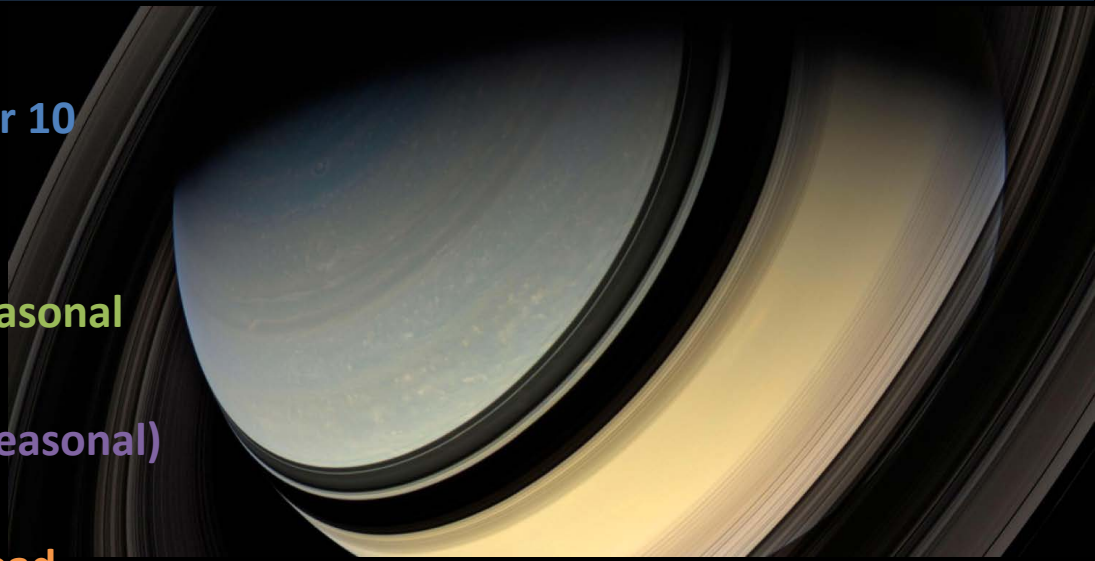
Can be relatively short, as many of the open questions are similar to the Old Chapter.

Emphasise need for modelling work to go hand-in-hamd with the observations.



Summary – Chapter 12

- 12.1 Overview of Old Book Chapter 10
- 12.2 Observed Seasonal Variations approaching Summer Solstice
- 12.3 Dynamic events disrupting seasonal evolution
- 12.4 Advances in (Seasonal/Non-Seasonal) Chemical Modelling
- 12.5 Open Questions - Looking ahead beyond Solstice



Aim to write a chapter that focuses on seasonal phenomena up to summer solstice, alongside advances in troposphere/stratosphere modelling.

Library of references: https://ui.adsabs.harvard.edu/public-libraries/QTuyjBTXS8aYEy9mNDlbsg