WACCM-X Simulations of the Response of Thermospheric Hydrogen to Increases in Greenhouse Gases and to Changes in Solar Activity

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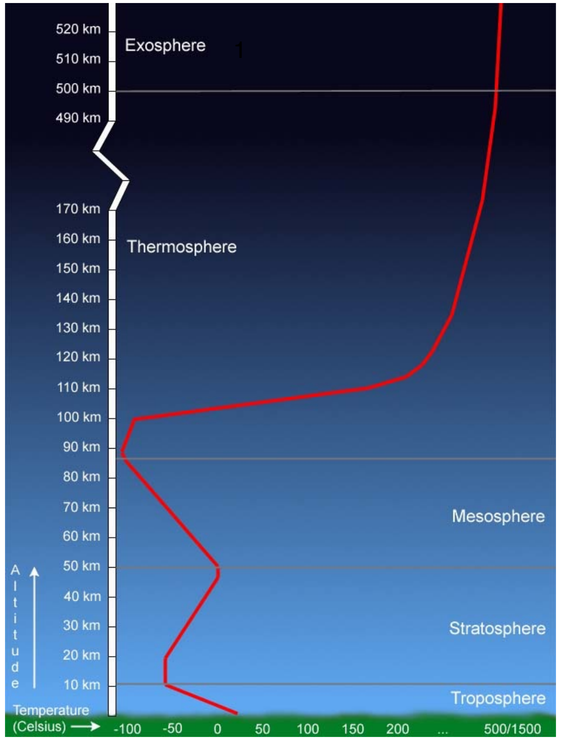
CESM Workshop 2024

Coupling of hydrogen-containing species

1



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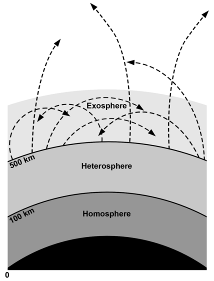
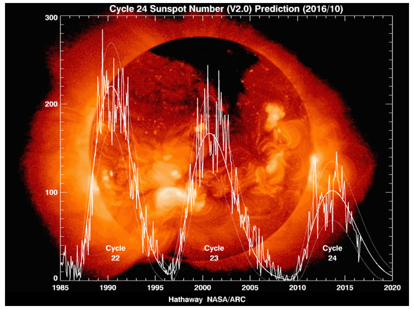
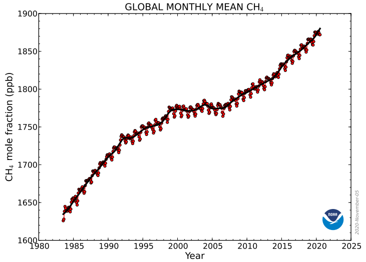


Atomic hydrogen becomes increasingly dominant with altitude



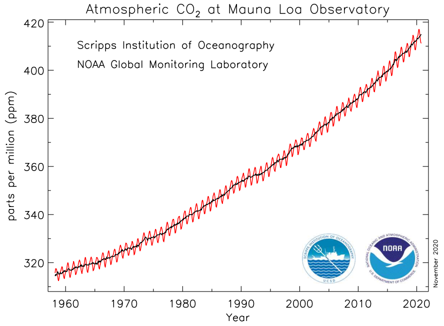
3

CH_4, H_2O, H_2 chemistry & photolysis reactions



Methane Concentrations

Sources of methane include: Agriculture, natural gas and petroleum systems, landfills, coal mining, wetlands, biomass burning



Carbon Dioxide Concentrations

[1]Courtesy of Windows to the Universe, http://www.windows.ucar.edu

[2]from: http://earthobservatory.nasa.gov/Features/BiomassBurning/

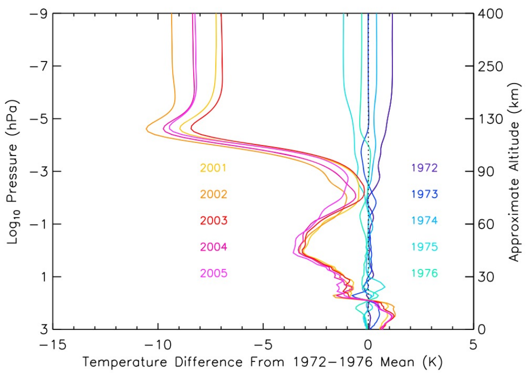
Online: http://www.britannica.com/ebc/art-95671

[3]© Pekka Parviainen From http://lasp.colorado.edu/noctilucent_clouds/

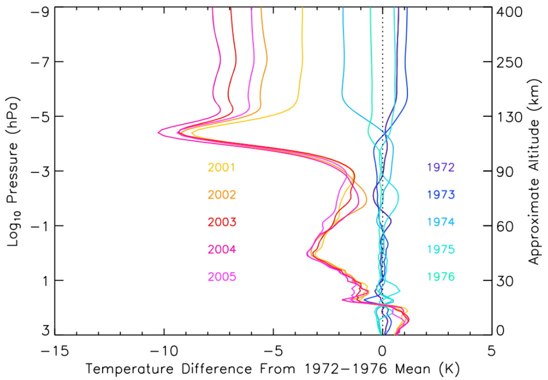
[4]Source: Carruthers, Page, and Meier, Apollo 16 Lyman alpha imagery of the hydrogen geocorona, J. Geophys. Res., 81, 1664, 1976. and . pluto.space.swri.edu/.../ apollo_geocorona2.gif

WACCM-X Hydrogen Profile Calculated on Altitude

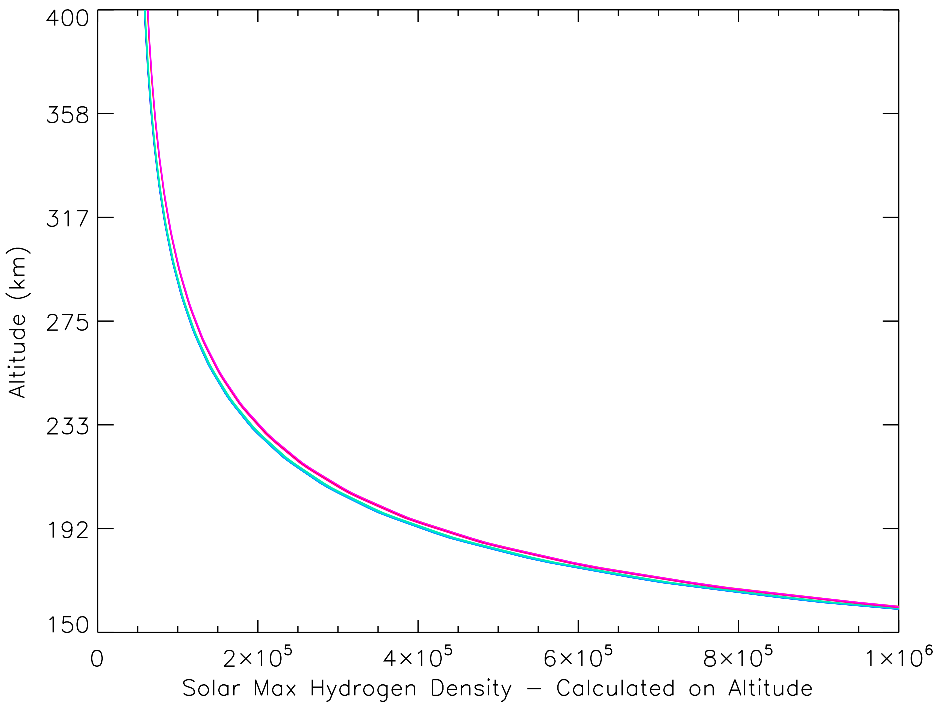
Temperature Difference



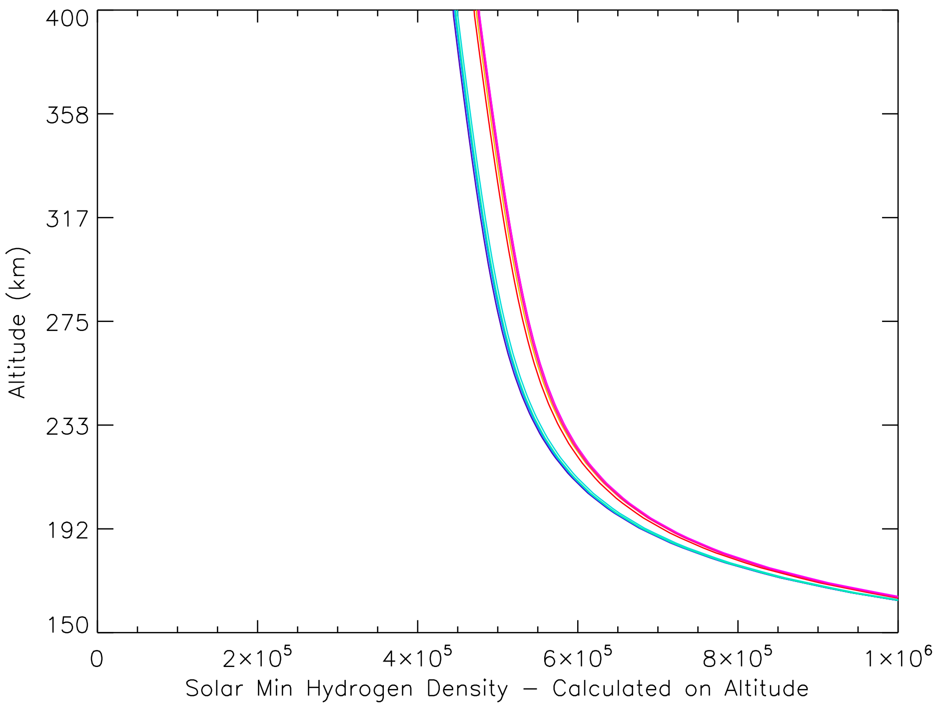
From *Solomon et al.* [2018] solar min



From *Solomon et al.* [2019] solar max



Solar Maximum

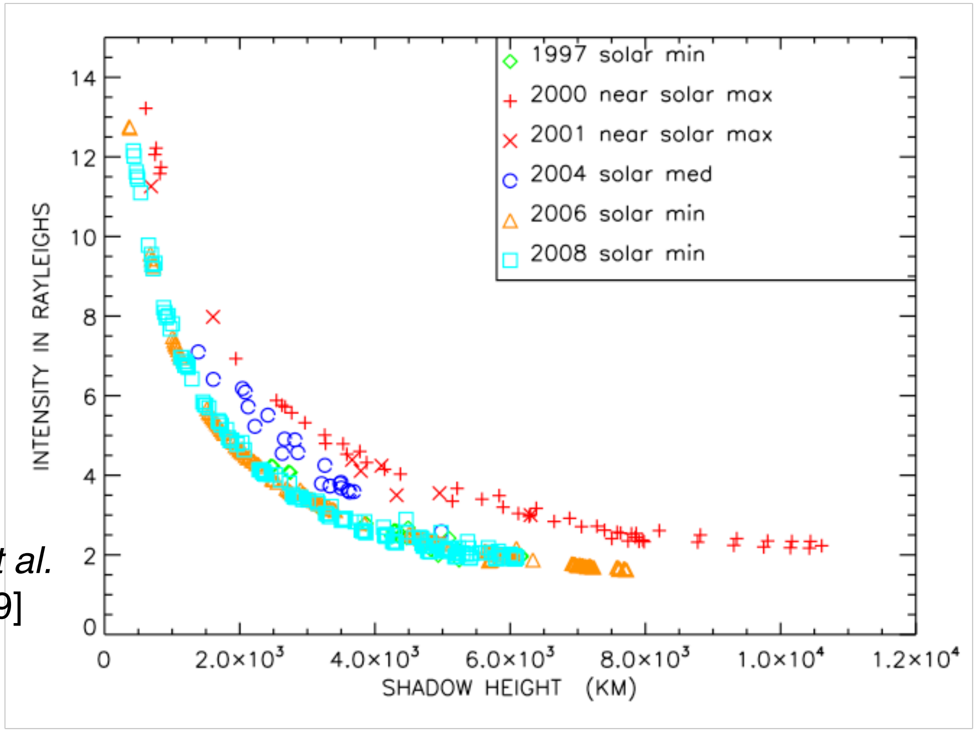


Solar Minimum

Using Output from WACCM-X model simulations for perpetual solar conditions run for *Solomon et al.* [2018, 2019]. Blue curves from early 1970s and red from early 2000s.

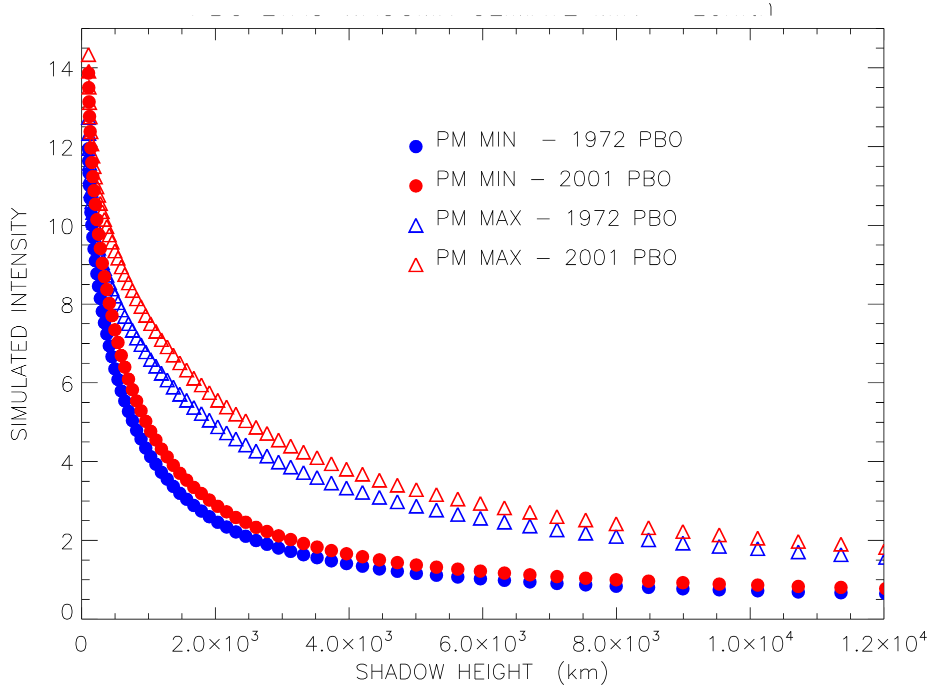
- WACCM-X Upper thermospheric **H increases during solar minimum & with increases in GHGs.**
- WACCM-X thermospheric H rises due to increases in source species for H from CH_4 and due to CO_2 cooling.
- **H response to GHGs is greater during solar min**, consistent with greater CO_2 cooling during min.
- WACCM-X H response to solar cycle is larger than due to increases in CO_2 and CH_4 over 30-year time period.

Forward Modeled Hydrogen Emission Intensity using WACCMX thermosphere inputs to the Lyao_rt code



[*Nossal et al.* 2008 2019]

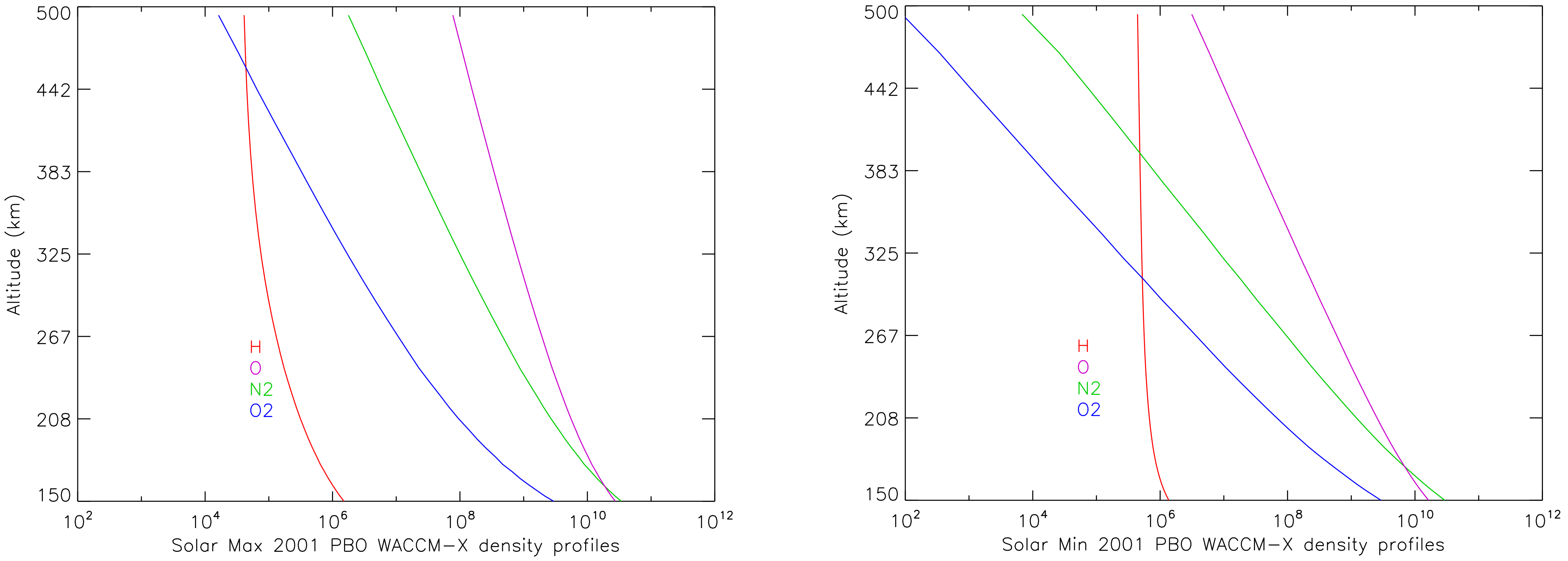
H column emission observations by the Wisconsin H-alpha Mapper Fabry-Perot taken from Kitt Peak, AZ during winter and in low Galactic emission directions



Forward modeling of H emission using output from WACCM-X model simulations for perpetual solar conditions run for *Solomon et al.* [2018, 2019]. Solar excitation flux estimated using high resolution line center measurements from SUMER instrument on SOHO at solar min [*Warren et al.*, 1998] and scaling from TIMED-SEE irradiance (lasp.colorado.edu/lisird).

Solar Maximum/Minimum Comparison shows qualitative agreement

WACCM-X 2001 atmospheric profiles used in the lyao_rt forward model

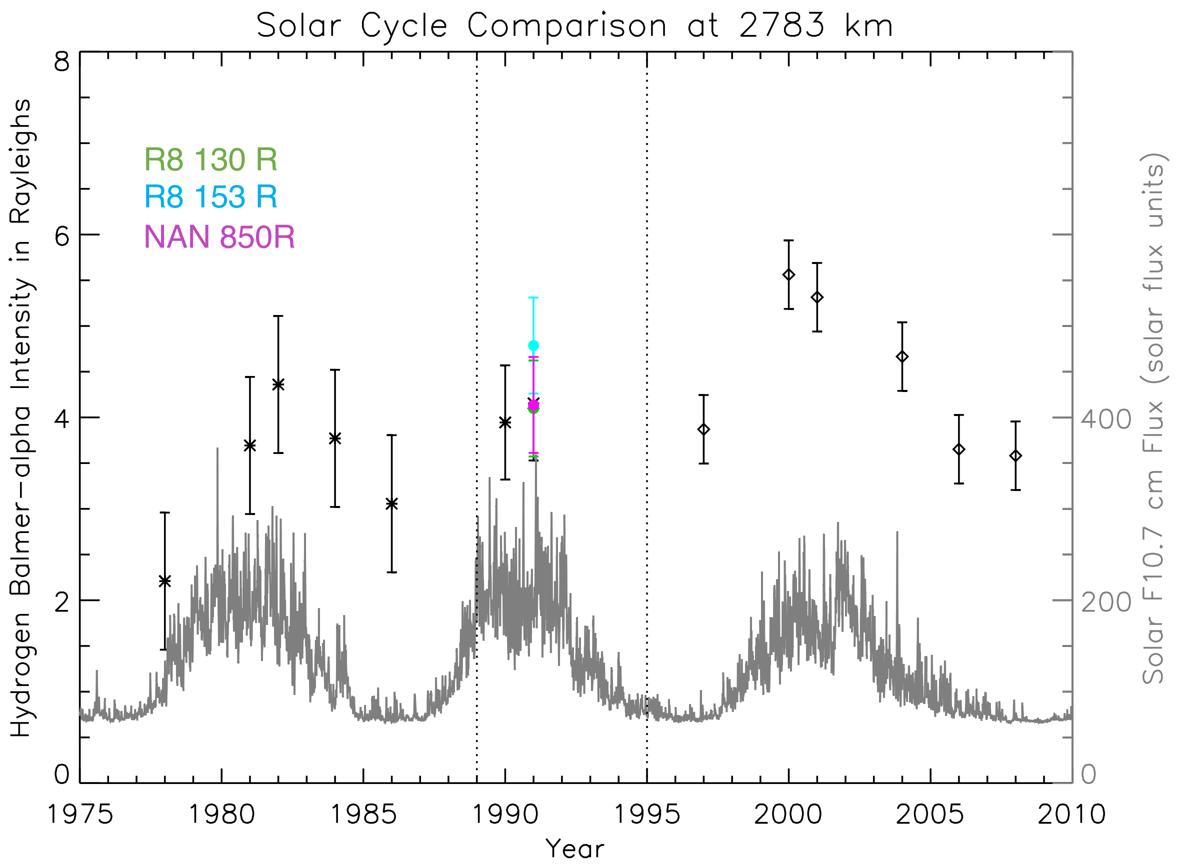


Solar Max — Solar Min

- During low solar activity, WACCM-X Upper thermospheric H density increases while other background species (O, N2, O2) decrease.
- *Qian et al.* [2018] discuss how complex dynamics, including diffusion, likely contribute to hydrogen variability with solar activity.

Merged Northern Hemisphere Mid-latitude Balmer α Emission Observations

b



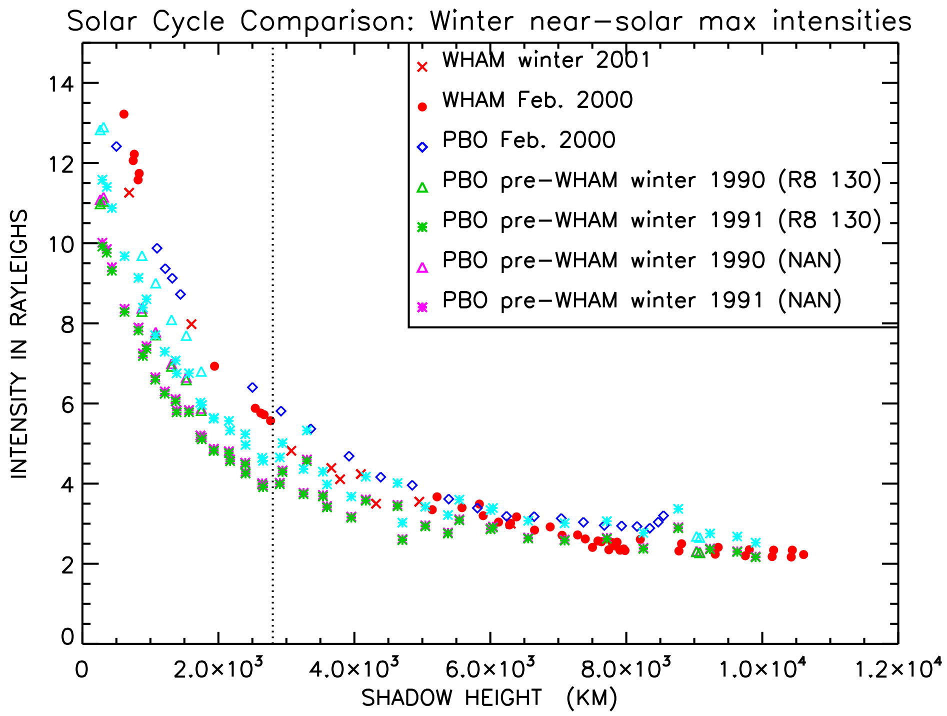
Daily Solar Radio F10.7 cm flux.

Data were downloaded from the LASP Interactive Solar Irradiance Data Center (http://lasp.colorado.edu/lisird/data/noaa_radio_flux/

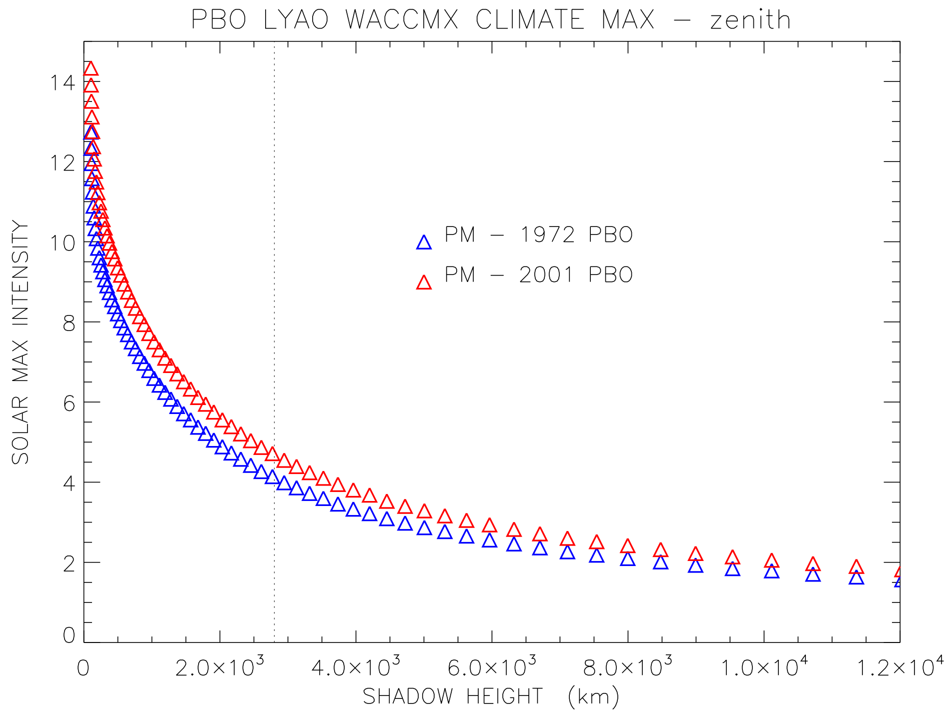
[*Nossal et al.*, JGR, 2019]

- column emission intensity for a midrange shadow altitude of ~2800 km
- half-year bins spanning winter conditions represent many spectra and, in most cases, multiple nights.
- Error bars indicate uncertainty in the *relative* intensity
- **The WI Northern hemisphere data suggest an increase that has not been accounted for by uncertainties due to experimental factors**, including calibration, tropospheric scattering, cascade fine structure excitation and Galactic emission, with the caveat that this is a limited data set.

Northern Hemisphere Mid-latitude Hydrogen Emission Observations over two solar maxima



H emission observations with different calibrations for 1990-91 observations



Forward modeling with WACCM-X perpetual solar max climate simulation & zenith look directions

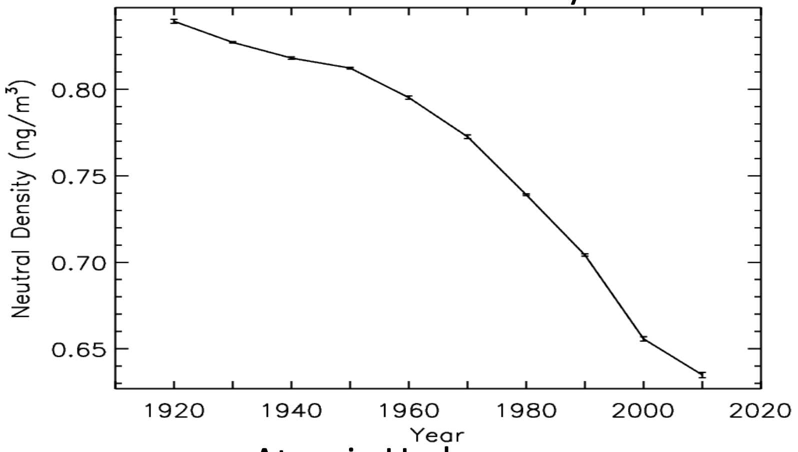
- The data suggest a likely increase in H emission intensity between the two solar maxima, with the caveat that this is a limited data set. [*Nossal et al., JGR,* 2019]
- Forward modeling likely does not account fully for the apparent increase in observed H emission
- Next steps include using WACCM-X simulations with times more closely matching the observations.

From McInerney et al. (2024)

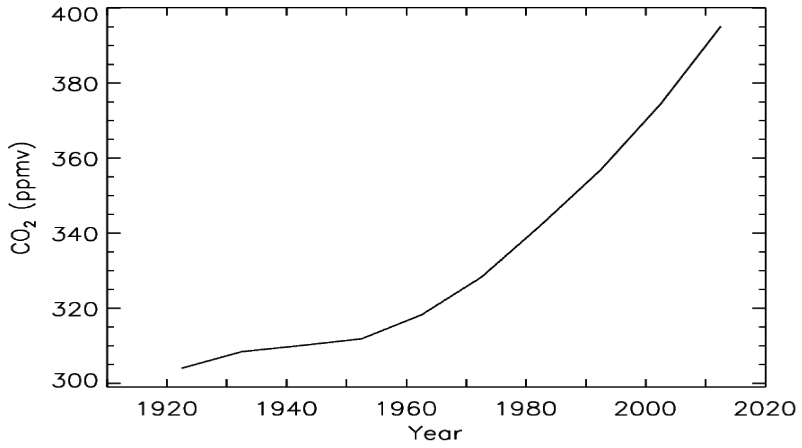
Past Century Hydrogen Changes in WACCM-X

Time Series ~400km Solar Min Decadal 5 Year Annual Global Means

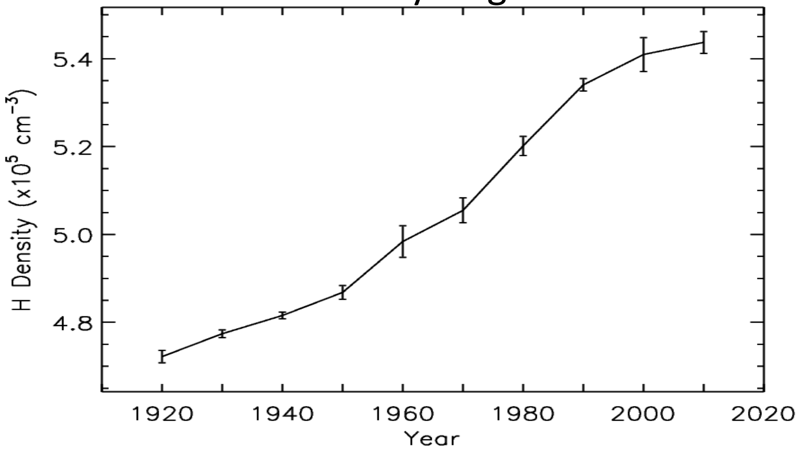
Neutral Mass Density



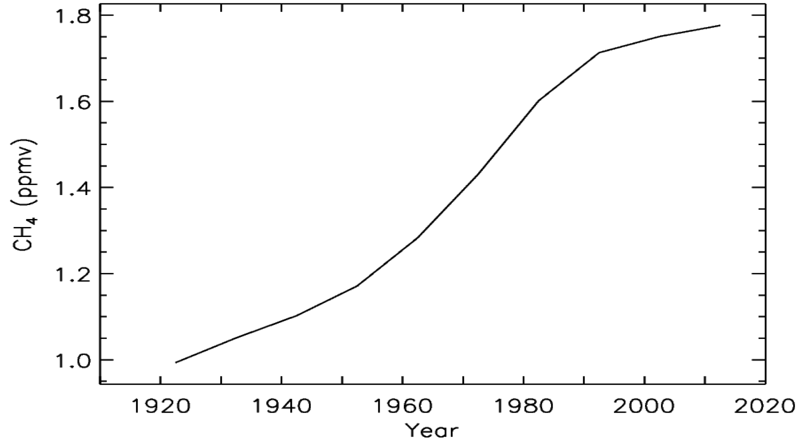
Carbon Dioxide



Atomic Hydrogen

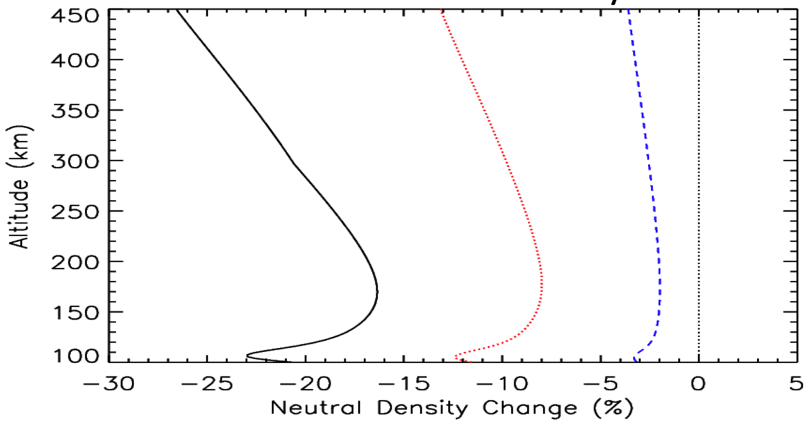


Methane

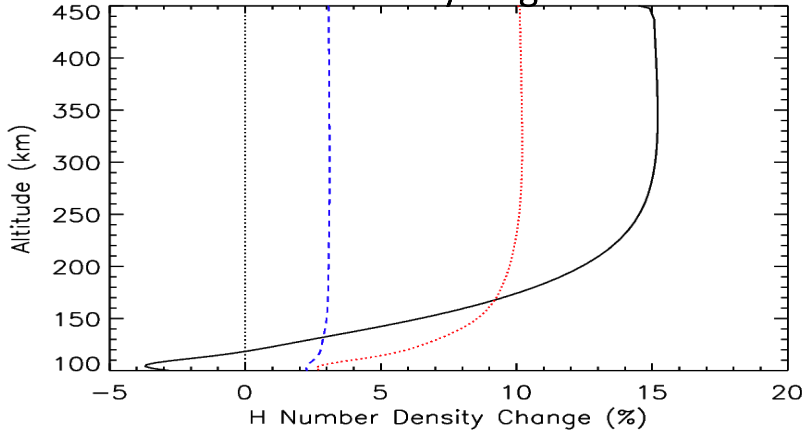


% Difference Altitude Profiles

Neutral Mass Density



Atomic Hydrogen



Blue – 1920s to 1950s
Red - 1920s to 1980s
Black – 1920s to 2010s

- Over past century, neutral mass density (NMD) decreases while H increases
- NMD has the largest % changes in the latter decades and H has largest % changes in the middle decades
- Clearly see the influence of both CO_2 and CH_4 increases on the upper atmosphere

Conclusions

- Upper thermospheric **H is a byproduct of hydrogen-containing molecules** at lower altitudes.

- **CH_4 increases the source species for H** and **CO_2 cooling also contributes to an increase in H** in the upper thermosphere.

- **WACCM-X H density is higher at solar min**. Over the three-decade WACCM-X simulation, the solar cycle has a larger impact on thermospheric H than do historical increases in GHGs.

- WACCM-X simulated **response of thermospheric H to GHGs depends on solar activity** with a greater H response to GHGs during low solar activity.

- **H column emission intensities calculated using forward modeling with WACCM-X thermosphere inputs show areas of agreement and difference with ground-based Fabry-Perot observations.** These calculated intensities are greater for high solar activity conditions, as is the case for observations.

- **Calculated H column emission intensities are higher with increases in GHGs**. WACCM-X climate simulations do not fully account for the apparent observed increase in H column emission intensity between two solar maxima periods.

- Higher WACCM-X thermospheric H densities for low solar activity and with increases in GHGs are consistent with other studies over multiple time scales that indicate **higher H densities and larger magnitude variations during cooler conditions.**

Ongoing and Future work

- Investigation of how middle and upper atmospheric studies may contribute to whole atmosphere pattern studies of hydrogen-containing species.
- Forward modeling comparisons with simulation time frame & viewing geometry closer to observations.
- Merging upcoming observations from the INSpIRe FPI at PBO Wisconsin [PI Mierkiewicz] with the Northern midlatitude H-alpha emission data set.
- Comparison of Northern hemisphere H-alpha observations with solar cycle variation in observations from Cerro Tololo, Chile.
- Investigation of H variability over multiple timescales using FPI observations, WACCM-X simulations and forward modeling.
- Long term ground-based observational comparisons require careful attention and documentation of calibration, observational viewing, and other observational methods.

We welcome collaborations with people studying hydrogen-containing constituents at different altitudes.

CHAPTER 3. OBSERVATORY SYSTEMS 40

Figure 3.1: The INSpIRe Observatory at Embry-Riddle Aeronautical University. Photo credit: Maggie Gallant, October 2016.

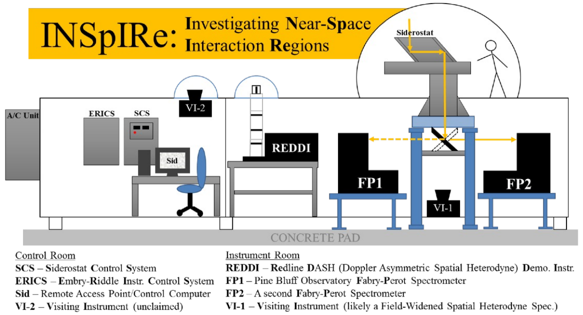


Figure 3.2: Five instrument ports are shown here, as well as the siderostat, electronics box locations, and control computer.

Future work: Collaboration across atmospheric regions

To what extent might thermospheric and exospheric hydrogen observations and model simulations contribute to a whole atmosphere understanding of hydrogen containing species and serve as diagnostics of climate change processes and mitigation efforts?

To what extent might H and other hydrogen-containing species provide vertical footprints for climate change processes?

- One of the goals of this work is to contribute towards whole atmosphere pattern studies of climate change impacts on hydrogen-containing species across atmospheric regions.

- Hydrogen-containing constituents are likely more uniformly distributed in the middle and upper atmosphere than in the lower atmosphere.

We welcome collaborations with people studying methane and other hydrogen-containing constituents at different altitudes.

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Thank you!