WACCM-X studies of the thermospheric hydrogen response to solar activity and to impacts of greenhouse gases across atmospheric regions

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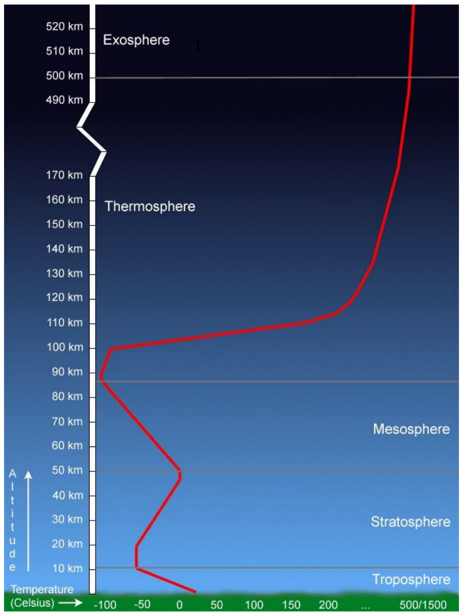
CESM Workshop 2025

Coupling of hydrogen-containing species

1



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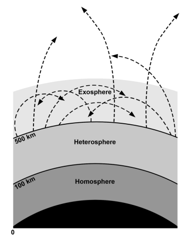
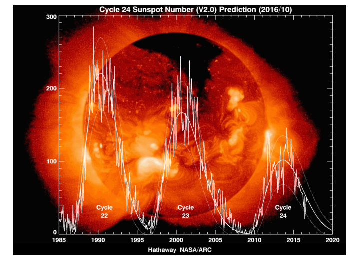
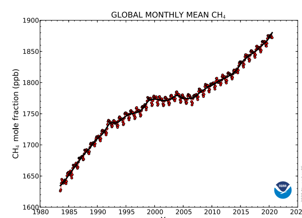


Atomic hydrogen becomes increasingly dominant with altitude



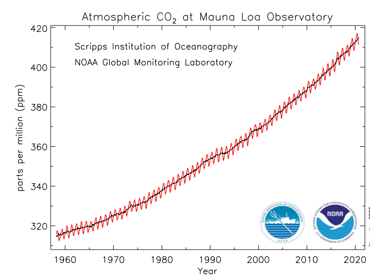
3

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/

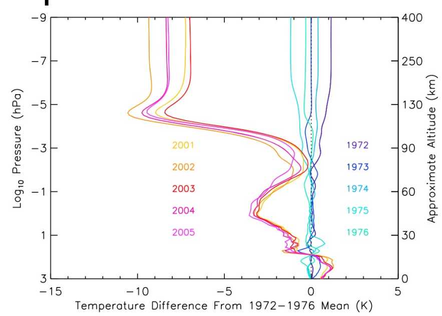
Online: http://www.britannica.com/ebc/art-95671

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

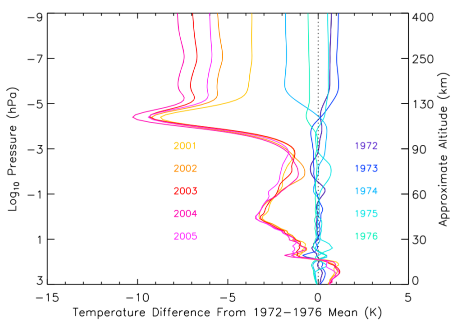
[4]Source: Carruthers, Page, and Meier, Apollo 16 Lyman alpha imagery of the hydrogen geocorona, J. Geophys. Res., 81, 1664, 1976. and . pluto.space.swri.edu/.../ apollo_geocorona2.gif

WACCM-X Global Average Hydrogen Profile Calculated on Altitude

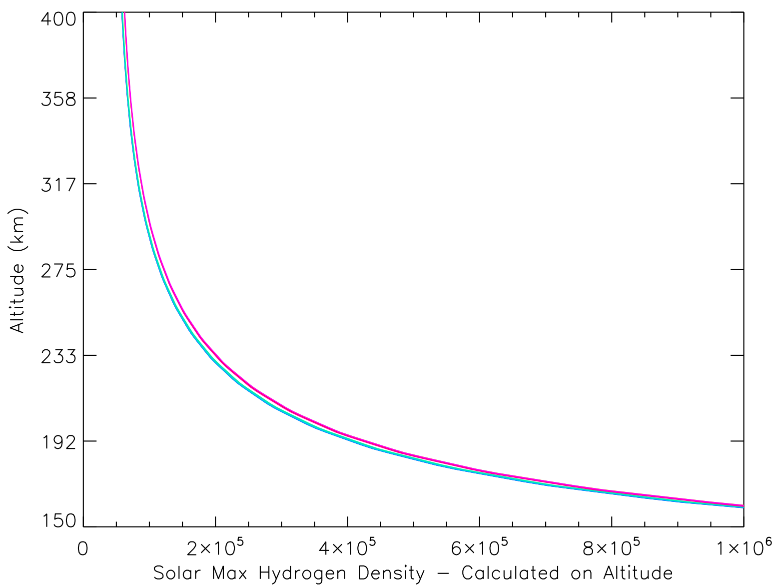
Temperature Difference



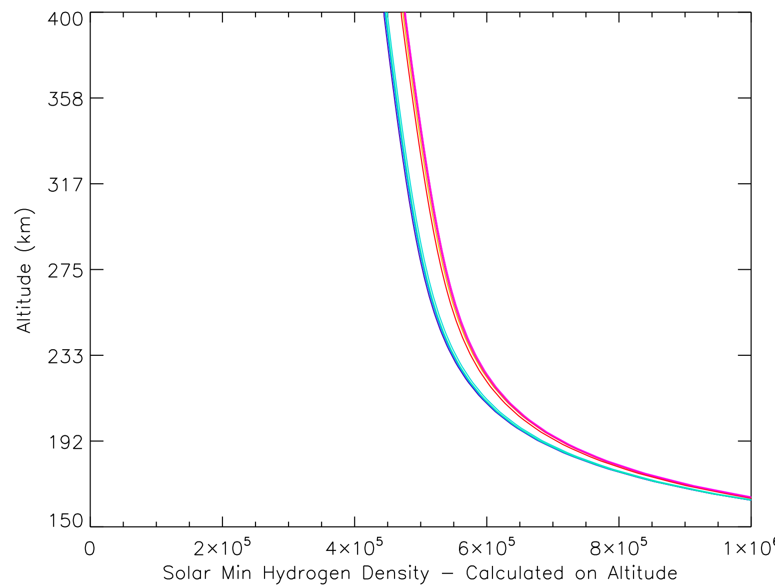
From *Solomon et al.* [2018] solar min



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



Solar Maximum

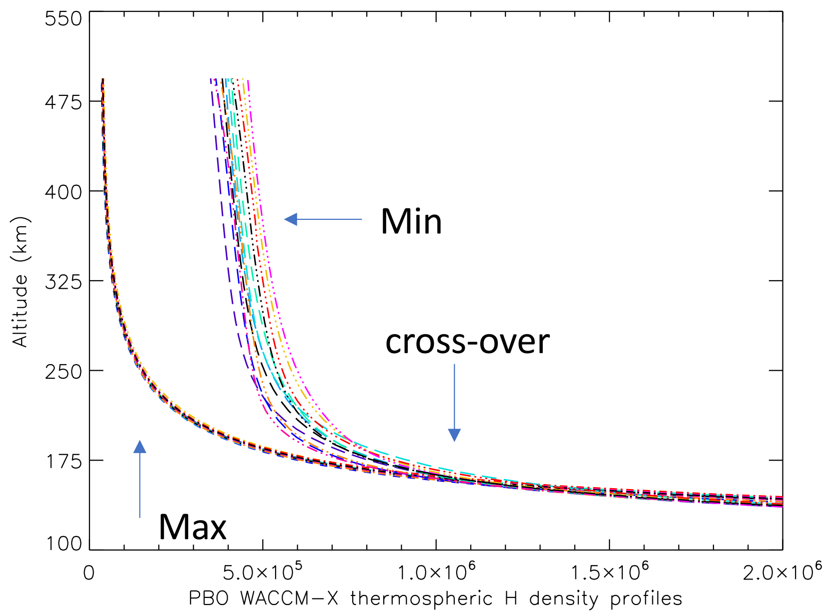


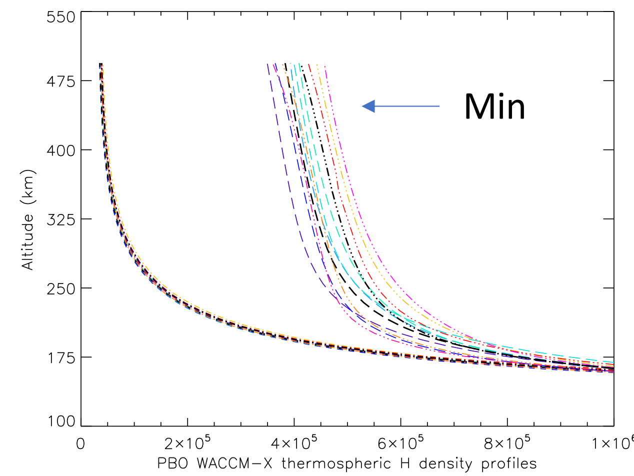
Solar Minimum

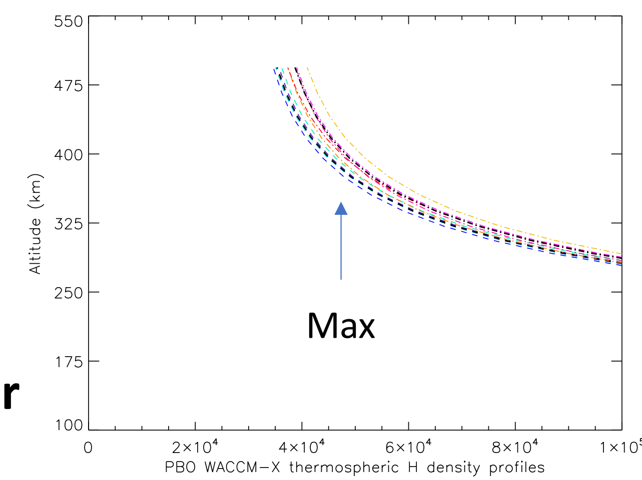
Using Output from WACCM-X model simulations for perpetual solar conditions run for *Solomon et al.* [2018, 2019]. Blue curves from early 1970s and red from early 2000s.

- 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.

WACCM-X Simulations of thermospheric hydrogen density profiles near the Pine Bluff, WI Observatory



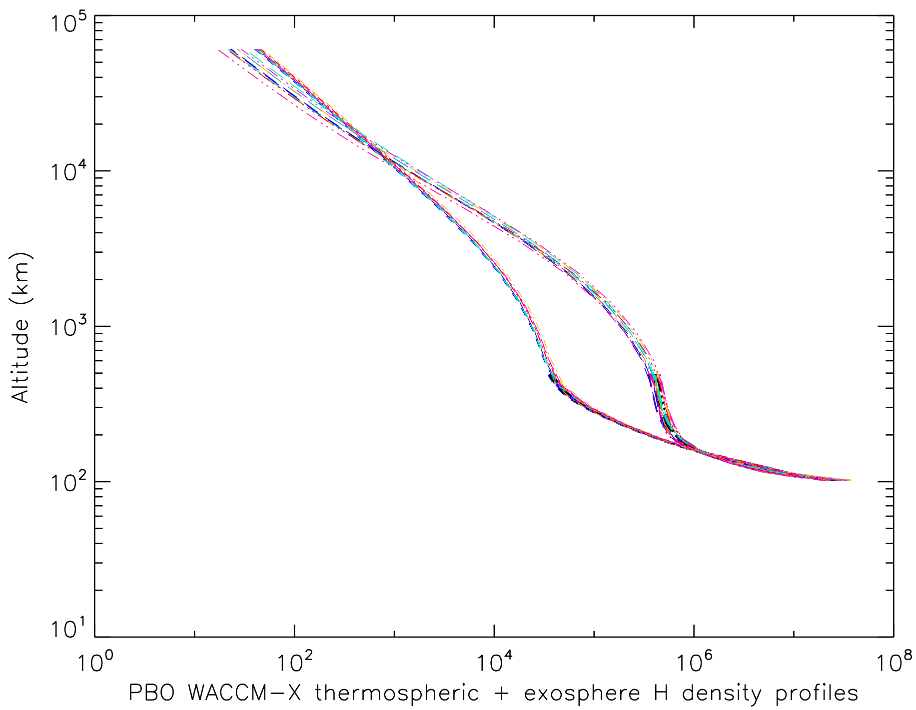


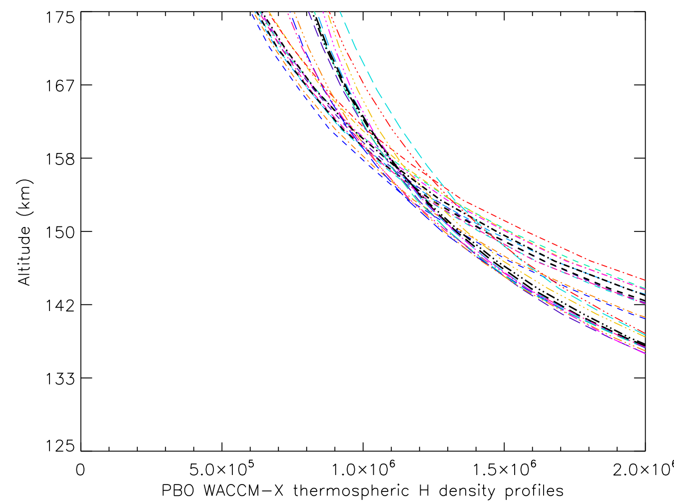


Thermospheric hydrogen density profiles simulated by WACCM-X: five runs for early 1970s (blue/green colors) and early 2000s (red/orange colors) during perpetual solar minimum and solar maximum conditions for UT 0 and near the Pine Bluff, WI Observatory location. Averages of each group of five years are in black.

Larger H density in the upper thermosphere during solar min; larger increase in H due to GHGs during solar min.

WACCM-X Simulations of thermospheric hydrogen density profiles near the Pine Bluff, WI Observatory

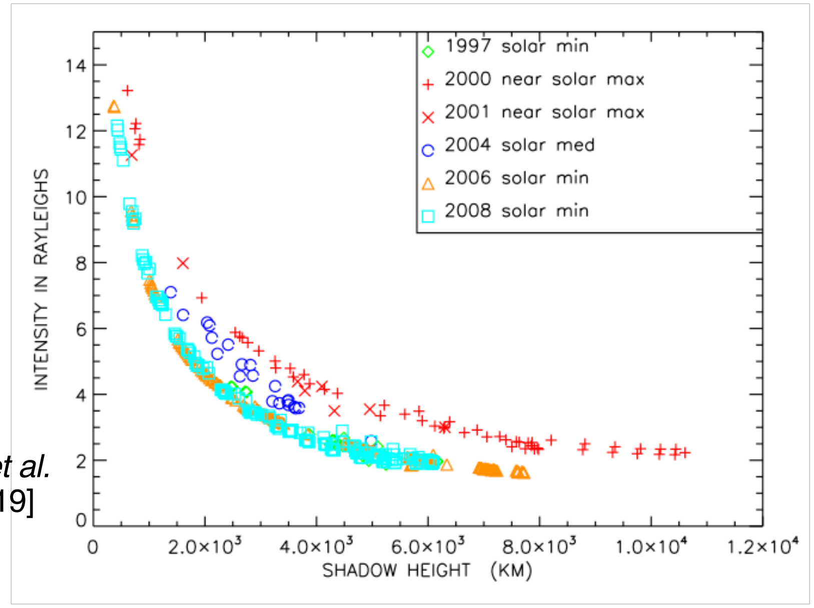




Thermospheric H density profiles simulated by WACCM-X: five ensemble runs for early 1970s (blue/green colors) and early 2000s (red/orange colors) during perpetual solar minimum and solar maximum conditions for UT 0 and near the Pine Bluff, WI Observatory location. The averages of the five-year runs are in black. H profiles extended with the Analytic Exosphere Model of *Bishop* [1991, 2001].

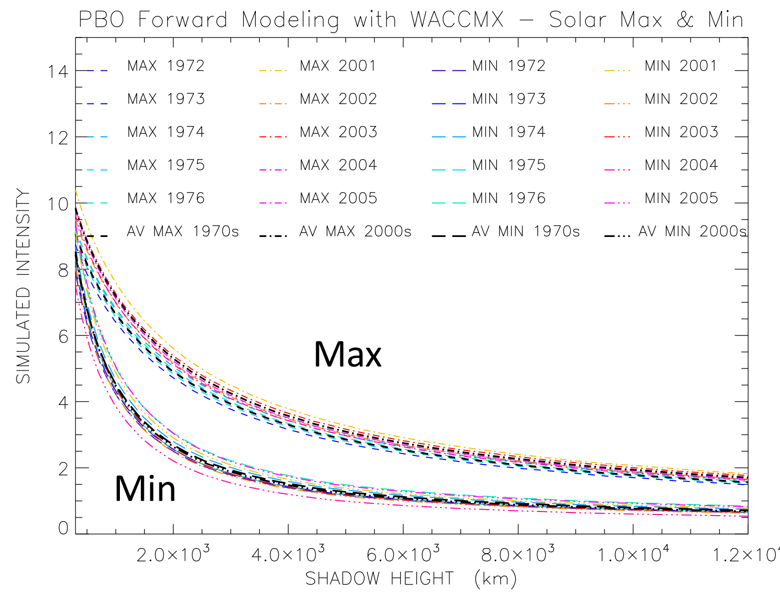
Two cross-over points with simulated H density higher at solar max above about 10,000 km & below about 155 km. H density higher at solar min at altitudes in between.

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



[*Nossal et al.* 2008, 2019]

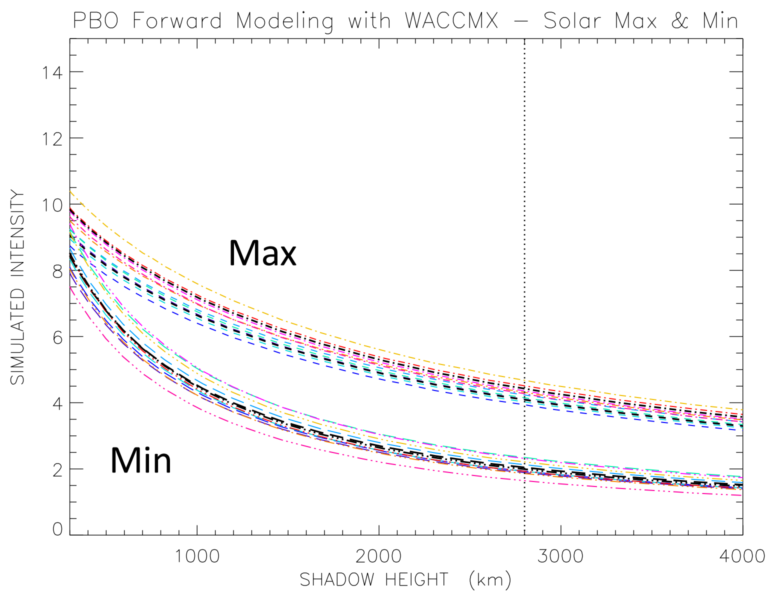
H column emission observations by the Wisconsin H-alpha Mapper Fabry-Perot taken from Kitt Peak, AZ during winter and in low Galactic emission directions



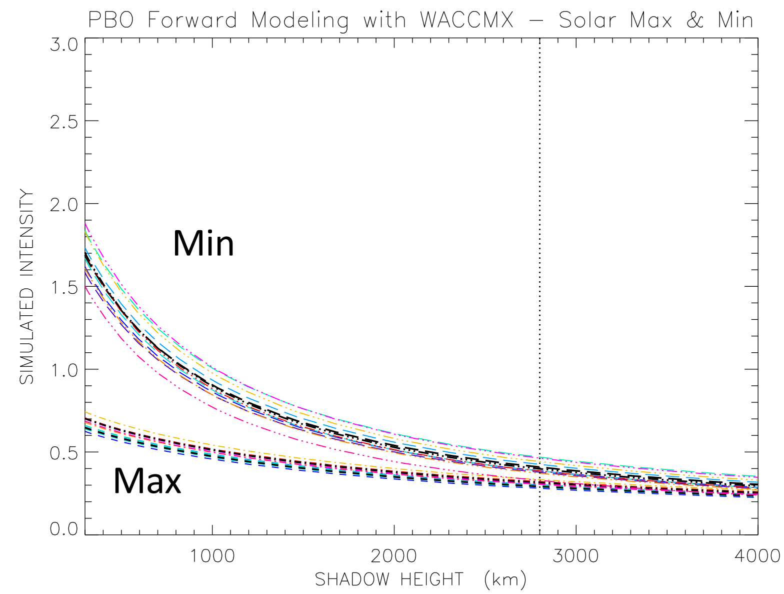
Forward modeling with lyao_rt [*Bishop, 1999,* 2001] of H emission using output from WACCM-X model simulations for perpetual solar conditions run for *Solomon et al.* [2018, 2019]. Solar Lyman-beta excitation flux estimated using high resolution line center measurements from SUMER instrument on SOHO at solar min [*Warren et al.*, 1998] and scaling from TIMED-SEE irradiance (lasp.colorado.edu/lisird).

Solar Maximum/Minimum Comparison shows qualitative agreement

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



H column emission intensity calculated using forward modeling for low shadow altitudes

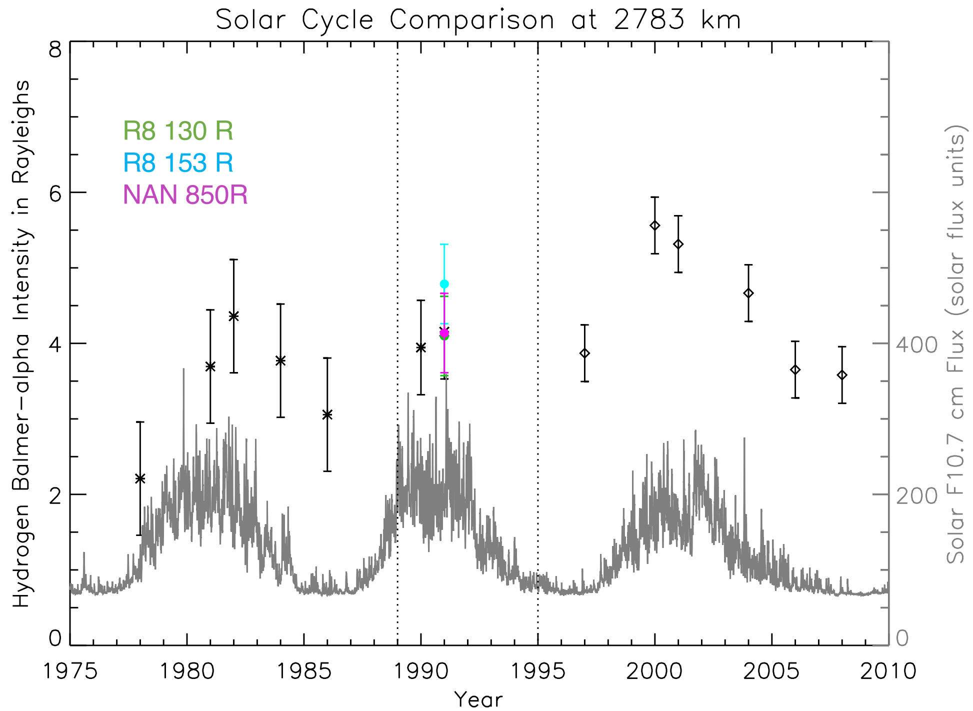


H column emission intensity calculated using forward modeling for low shadow altitudes: unit solar Lyman-beta excitation flux

H-alpha column emission intensities calculated using forward modeling are higher during solar max: contributing factors are the changing solar Lyman-beta excitation flux & that the emission is an integrated column emission.

Merged Northern Hemisphere Mid-latitude Balmer α Column 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; calibration w/ nebular sources
- half-year bins spanning winter conditions represent many spectra and, in most cases, multiple nights.
- Error bars indicate uncertainty in the *relative* column emission 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.

Conclusions

- Unlike the thermospheric total neutral density which decreases with CO_2 cooling, the **thermospheric atomic H density rises with increases in greenhouse gases**.
- **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 and extended with the Bishop Analytic Exosphere model [1991, 2001] **are greater for high solar activity conditions**, as is the case for ground-based observations, contributing to WACCM-X model validation.
- Forward modeling with WACCM-X thermospheric inputs suggests that **possible signatures of GHG increases** may be **more apparent in *in situ* measurements of H in the upper thermosphere during solar min** and **in ground-based remote sensing of H airglow column emissions during solar max conditions.**
- There is **qualitative consistency between calculated H column emissions intensities** and **the apparent observed increase** between two solar max periods. The **increase in** the **observed** column emission **intensity is likely of larger magnitude than predicted** by forward modeling with WACCM-X**. Additional observations and modeling studies are needed for attribution.**

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.

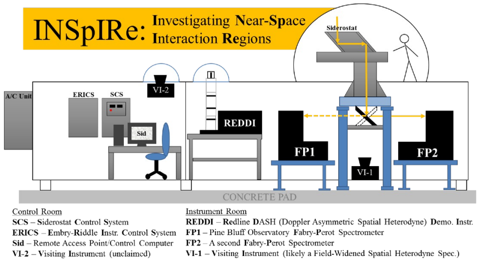


Figure 3.2: Five instrument ports are shown here, as well as the siderostat, electronics box locations, and control computer.

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.

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

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Thank you!