Role Of the Sun and the Middle atmosphere/thermosphere/ionosphere In Climate (ROSMIC): A Retrospective and Prospective View

William Ward, Franz-Josef Lübken, Annika Seppälä,

Bernd Funke, Alexei Krivolutsky, Tom Woods,

Takuji Nakamura Claudia Stolle , Erdal Yigit,

Jan Lastovicka, Dan Marsh,

Duggirala Pallamraju, and Stan Solomon

Role Of the Sun and the Middle atmosphere/thermosphere/ionosphere In Climate (ROSMIC)

Goals & Objectives: To understand the impact of the Sun on the terrestrial middle atmosphere/ lower thermosphere/ionosphere (MALTI) and Earth‘s climate and its importance relative to anthropogenic forcing over various time scales from minutes to centuries.

Anticipated Outcome: The development of a better understanding of the impact of solar activity on the entire atmosphere, relative to anthropogenic forcing and natural long term variability.

ROSMIC Co-chairs:

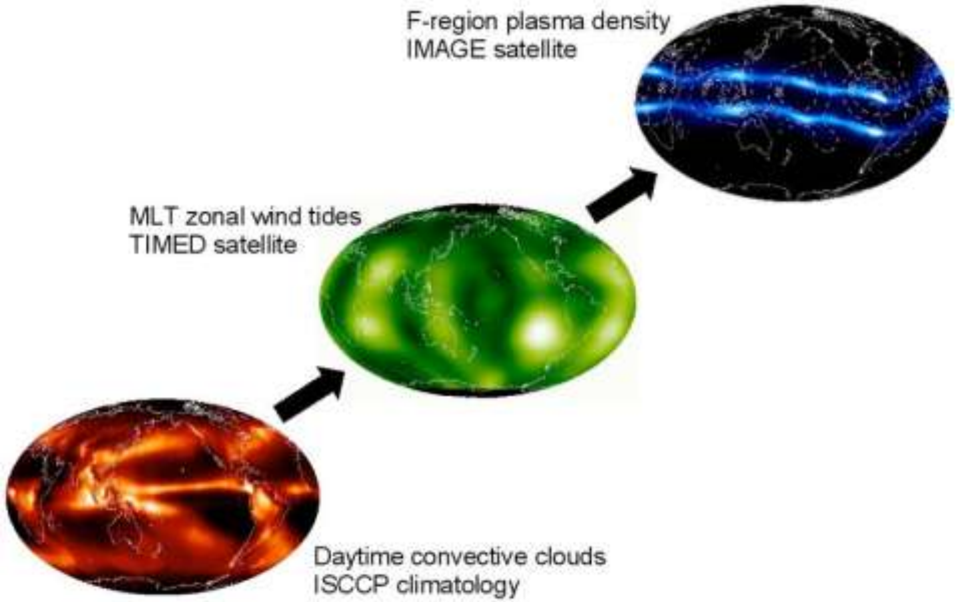
- Prof. Dr. Franz-Josef Lübken, Leibniz Institute of Atmospheric Physics, Germany
- Dr. Annika Seppälä, Finnish Meteorological Institute, Finland.
- Prof. William E. Ward, University of New Brunswick, Canada

ROSMIC is organized into four working groups to address these questions. These groups and their leaders are:

- **Solar Influence on Climate**: Bernd Funke (Instituto de Astrofisica de Andalucia, Spain), Alexei Krivolutsky (Central Aero-logical Observatory, Russia), Tom Woods (LASP, USA).
- **Coupling by Dynamics**: Takuji Nakamura (National Institute of Polar Research,Japan), Claudia Stolle (GFZ German Research Centre for Geosciences, Germany), Erdal Yigit (George Mason University, USA).
- **Trends in the MLT**: Jan Lastovicka (Institute of Atmospheric Physics, AS CR, Czech Republic), Dan Marsh (NCAR, USA)
- **Trends and Solar Influence in the Thermosphere**: Duggirala Pallamraju (Physical Research Laboratory, India), Stan Solomon (NCAR, USA)


not present:
Krivolutsky, Marsh, Funke, Stolle.
First ROSMIC meeting, Nagoya, 22 Nov. 2013

Courtesy of Oberheide - CAWSES



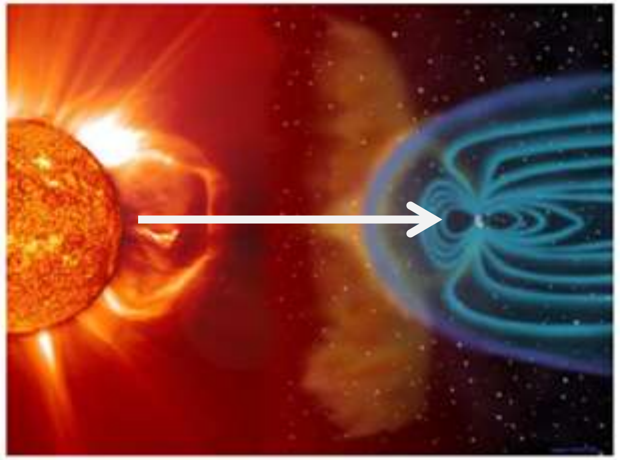
Solar-Terrestrial System

What are the solar drivers which influence the Earth system?

What are the processes (nonlinear and non-local) through which the Earth system responds to these drivers?

The **system** is influenced by changes in the solar drivers **and** changes in the manner in which the Earth system accommodates the solar input.

We do not yet fully understand the mechanisms through which the Earth responds to solar variability.



ISEST Overview

Global Energetics of the Atmosphere

TABLE 1. Traditional energetics of two standard atmospheres of different depths. Values for the equilibrium atmosphere are in parentheses. The total energy is the sum of the internal and potential energies (TE = IE + PE).

Depth (km)	TE (GJ m^{-2})	IE (GJ m^{-2})	PE (GJ m^{-2})
25	2.4733	1.8111	0.6622
	(2.4619)	(1.8195)	(0.6423)
50	2.5896	1.8521	0.7375
	(2.5772)	(1.8443)	(0.7329)

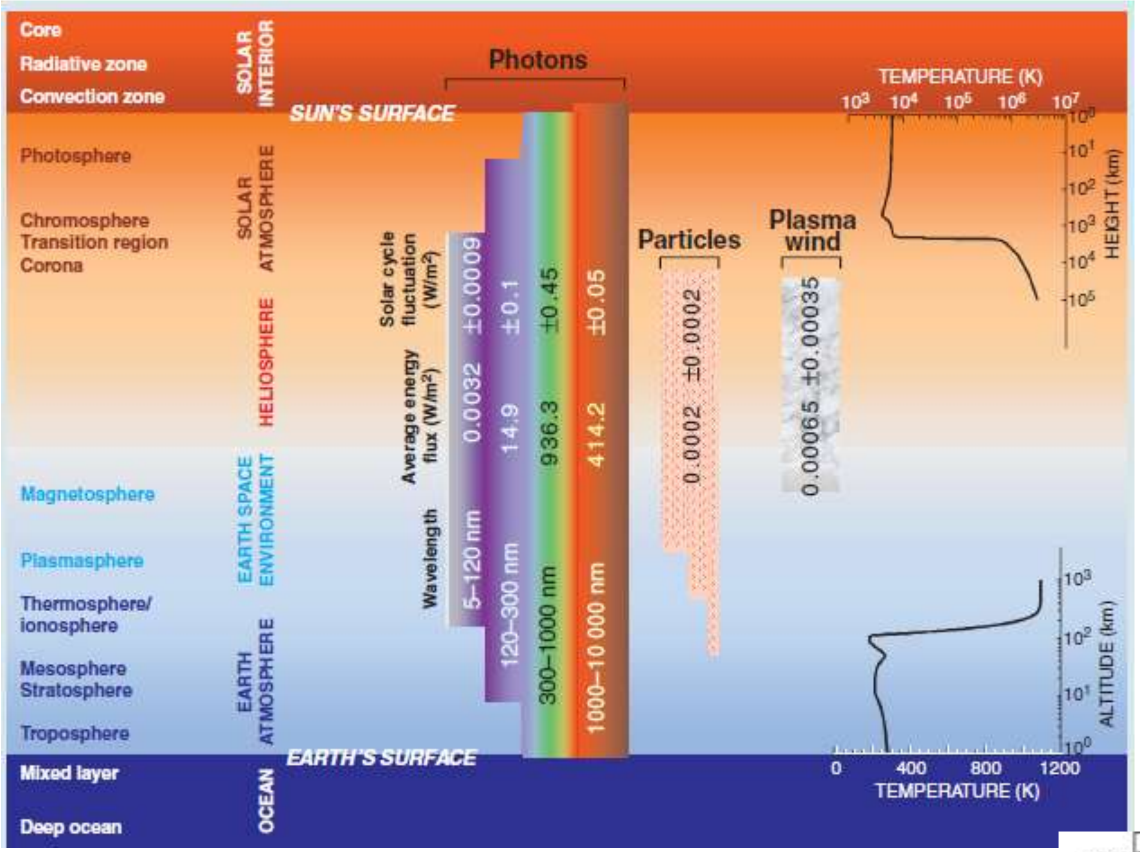
TABLE 2. Available energetics of the two standard atmospheres. δTE is the difference of the total energies of the atmosphere and its equilibrium atmosphere.

Depth (km)	T_0 (K)	δTE (MJ m^{-2})	AE (MJ m^{-2})	APE (MJ m^{-2})	AEE (MJ m^{-2})
25	251.95	11.40	11.45	10.29	1.16
50	249.25	12.38	12.55	10.74	1.81

TABLE 10. Dissipation of kinetic energy. In a steady state the total dissipation rate equals the rate of conversion of available energy to kinetic energy.

Process	Rate (W m^{-2})
Large-scale dissipation	2
Mesoscale dissipation	1
Hydrometeor dissipation	1–3
Wind stress	1
Precipitation	10^{-5}
Total	5–7

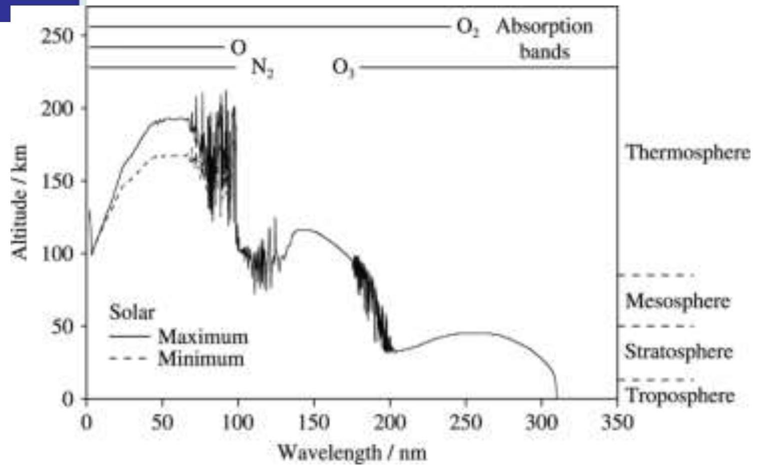
Bannon, JAS, 2012



Lean, 2005,
Physics Today

Solar Constant: ~1361 W/m^2

Andrews, 2000



There is an interesting connection between where various parts of the solar spectrum is emitted and where they are absorbed in the Earth's atmosphere. These figures summarize this relationship.

Earth's Energy Budget

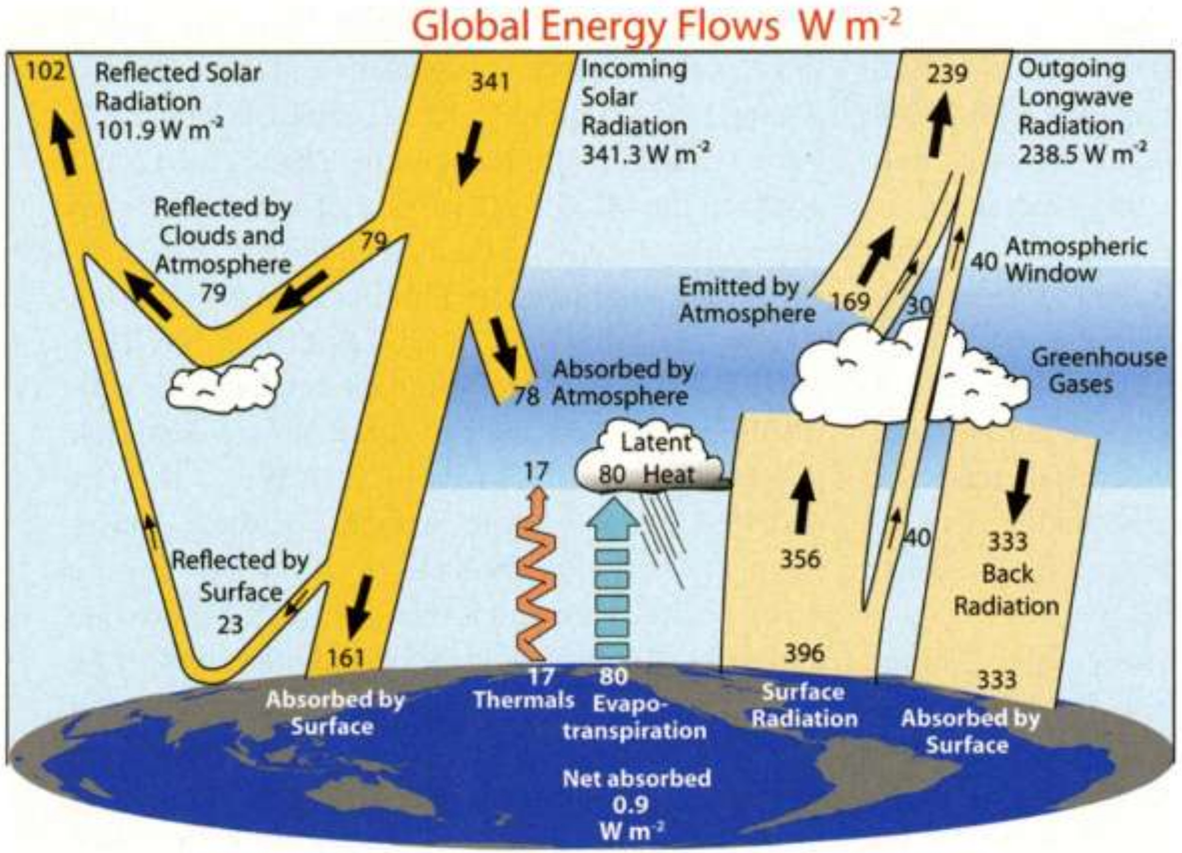


FIG. 1. The global annual mean Earth's energy budget for the Mar 2000 to May 2004 period (W m⁻²). The broad arrows indicate the schematic flow of energy in proportion to their importance.

Trenbreth et al., BAMS, 2009

The incoming energy from the sun is balanced by the outgoing radiation

Thermal Wind Shear

Shepherd, 2003

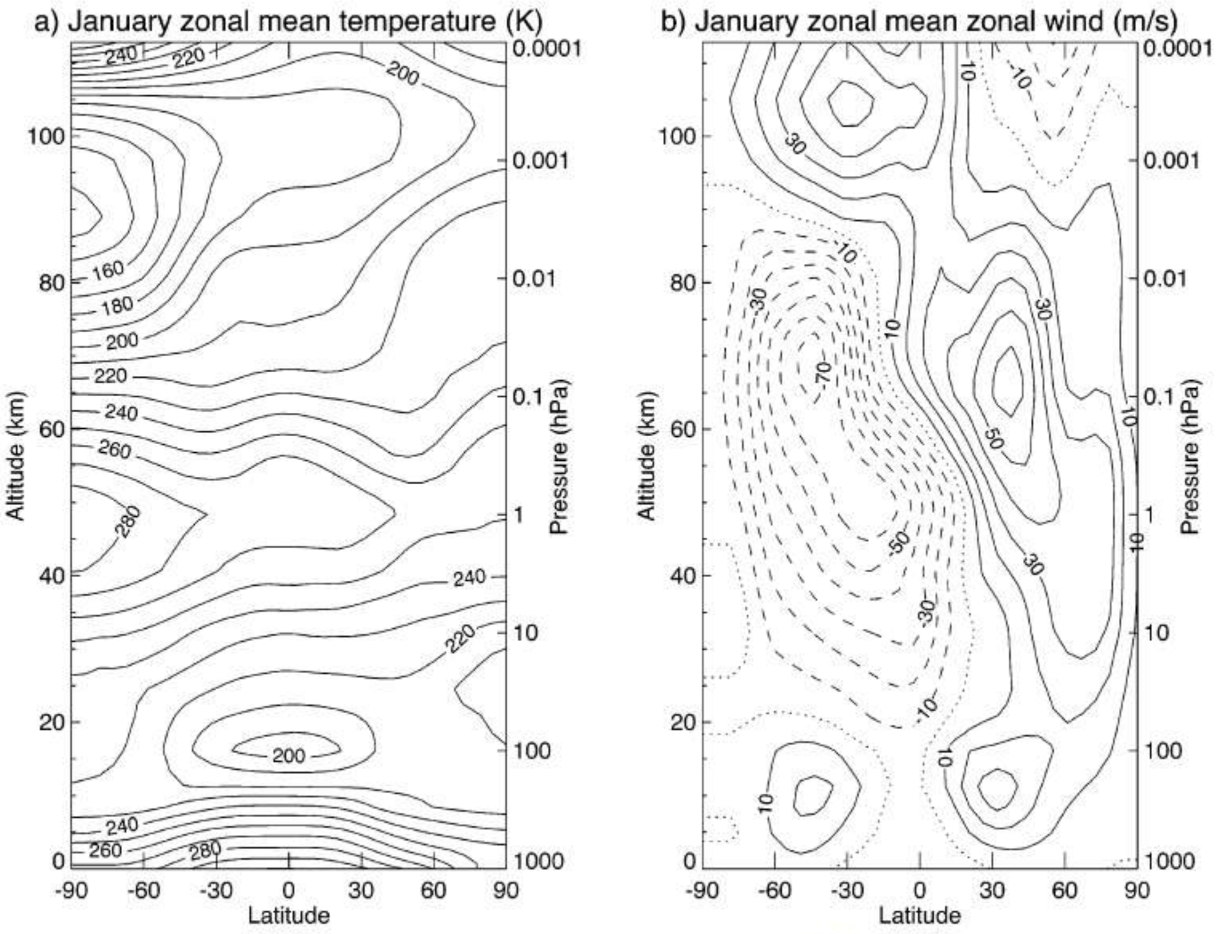
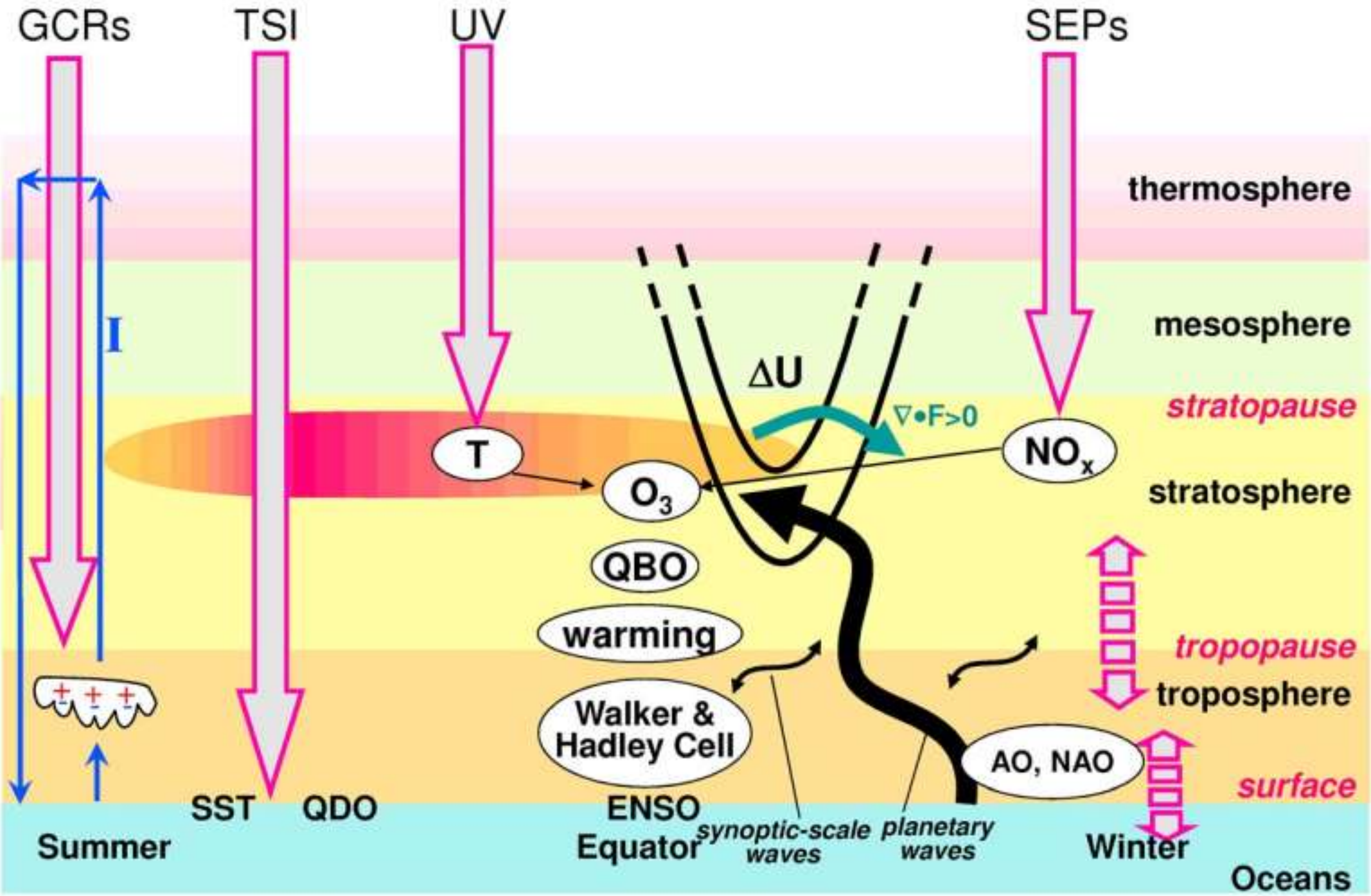


Figure 5. Zonal mean (a) temperature and (b) zonal wind as a function of latitude and height, for January, from the COSPAR International Reference Atmosphere (CIRA) data set.[3] July conditions are, to a first approximation, a mirror image of these.

In response to the variation in radiative heating as a function of latitude, large scale jets develop as a result of a balance between the pressure gradient force and the Coriolis force.
The vertical is structure through hydrostatic equilibrium.
Stresses exerted by dissipating waves close the jets.

Solar forcing of the climate system



Gray et al., Rev. Geophys., 2010

Atmospheric Modelling
(Maher et al., Rev. Geophys., 2019)

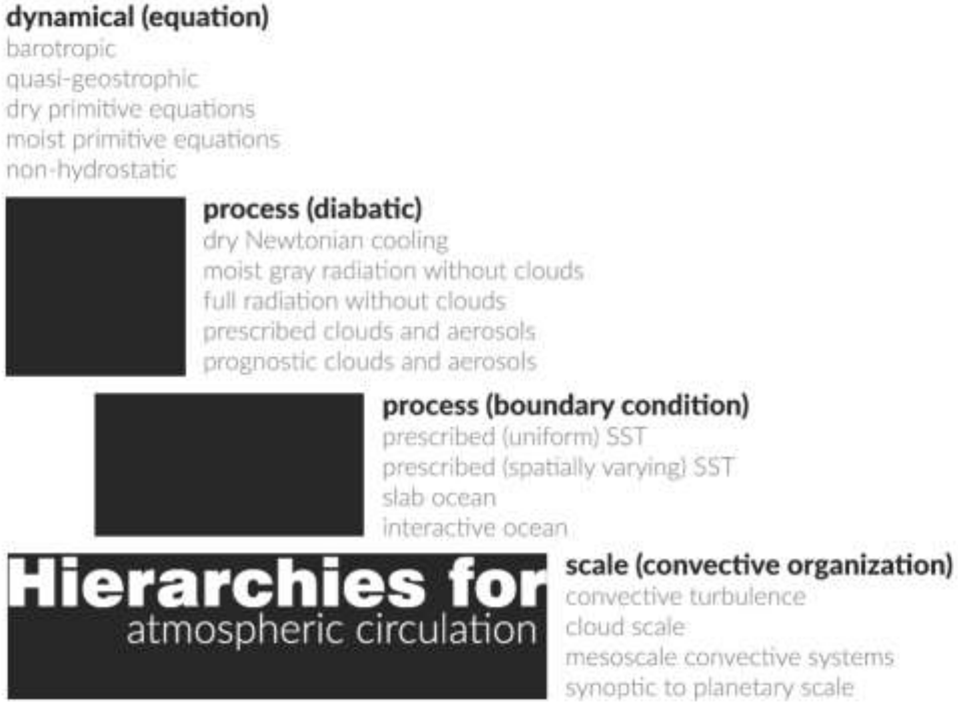


Figure 2. The three-principles view of model hierarchies used for understanding the large-scale circulation. A dynamical hierarchy can be constructed by systematically varying the governing equations of the fluid flow. Two sample process hierarchies capture systematic variations in the representation of the thermodynamic processes and the boundary conditions. Convective organization at different scales is used as an example to illustrate the scale hierarchy. For each list, the first element is the simplest or smallest scale and builds down to the most complex or largest scale.

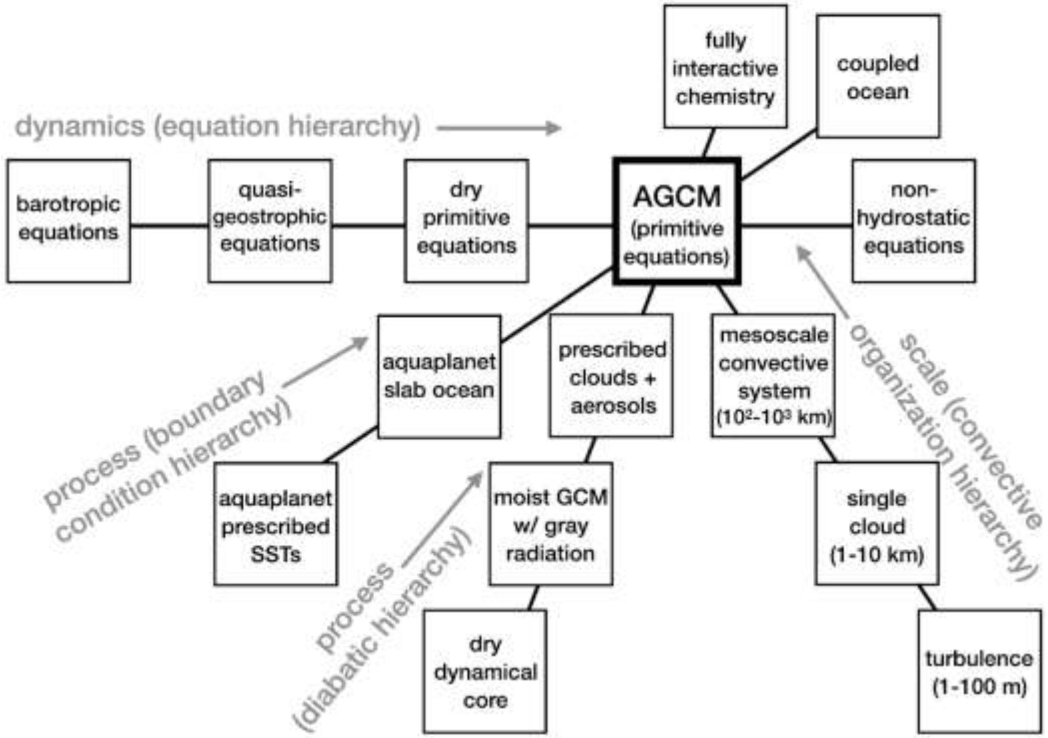


Figure 6. The connection between simple models of the atmosphere and the comprehensive models used for weather and climate prediction. This figure complements Figure2, illustrating the connections to atmospheric General Circulation Models (AGCMs) afforded by model hierarchies. Each arm illustrates a different hierarchy: a dynamical hierarchy in terms of the equations, process hierarchies in terms of the boundary conditions (the representation of the ocean) and treatment of diabatic processes, and a hierarchy of scale, focused on convective organization across very different domain sizes and resolutions.

Solar Influence on Climate

1. Improved quantitative description of all solar forcing component (radiation and particles)
2. Better understanding of the atmospheric / climate response to individual solar forcing components
3. Better understanding of involved coupling mechanisms
4. Assessment of solar forcing responses in climate models

Modelled Solar Influence (Atmospheric Research Model)

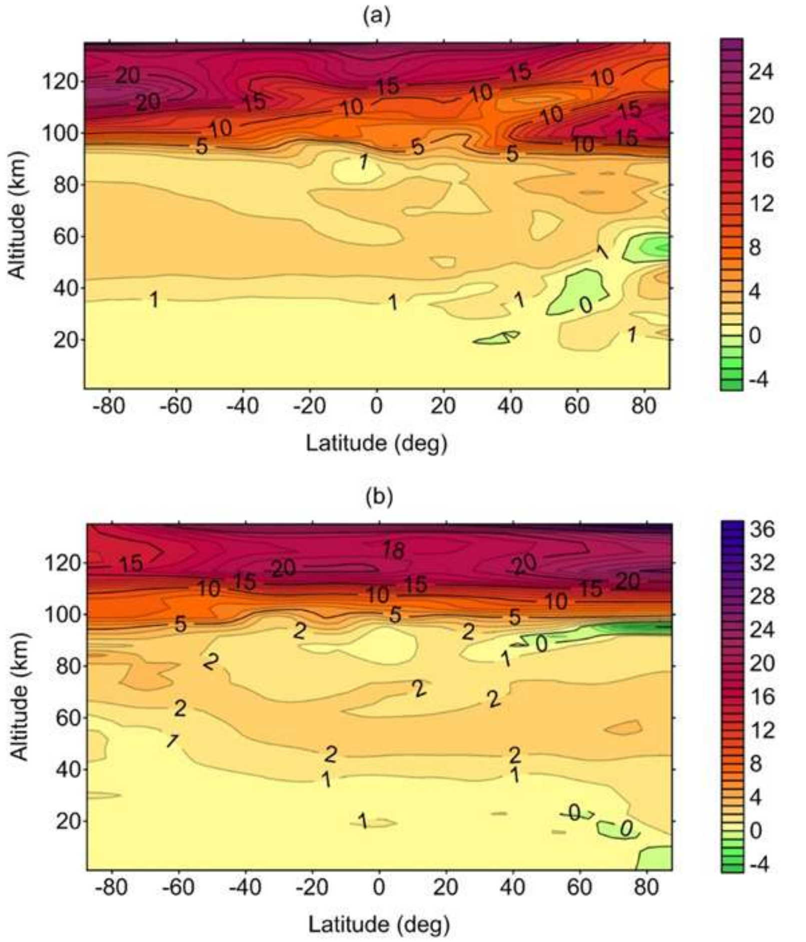


Figure 6. Changes in temperature caused by solar cycle in January (a) and July (b) (simulations with ARM).

Krivolutsky et al., 2016

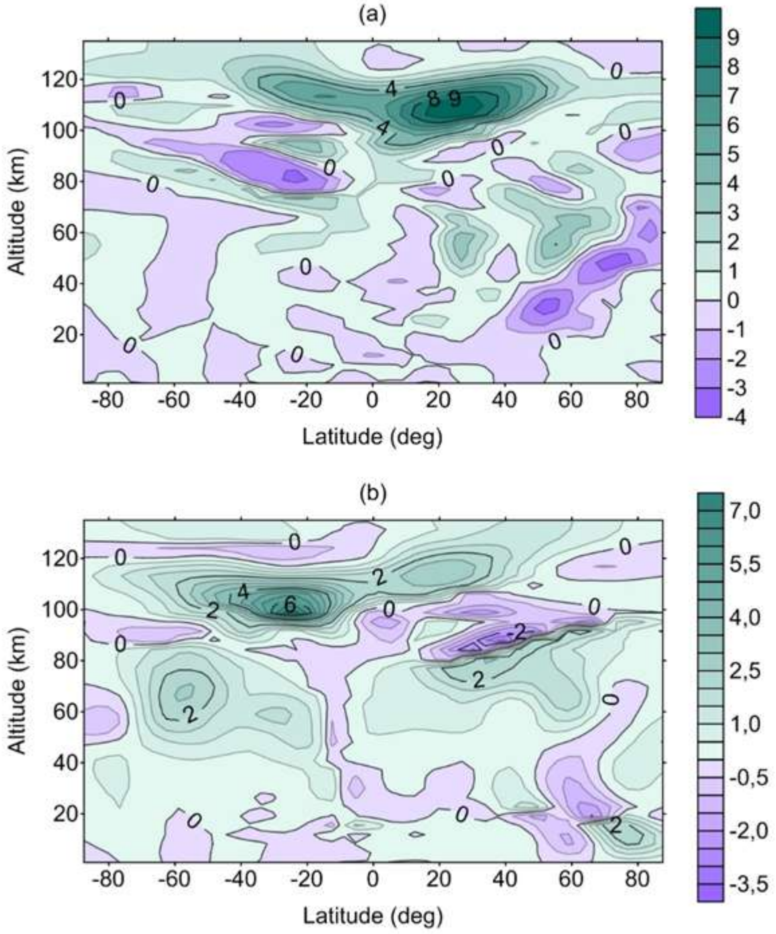
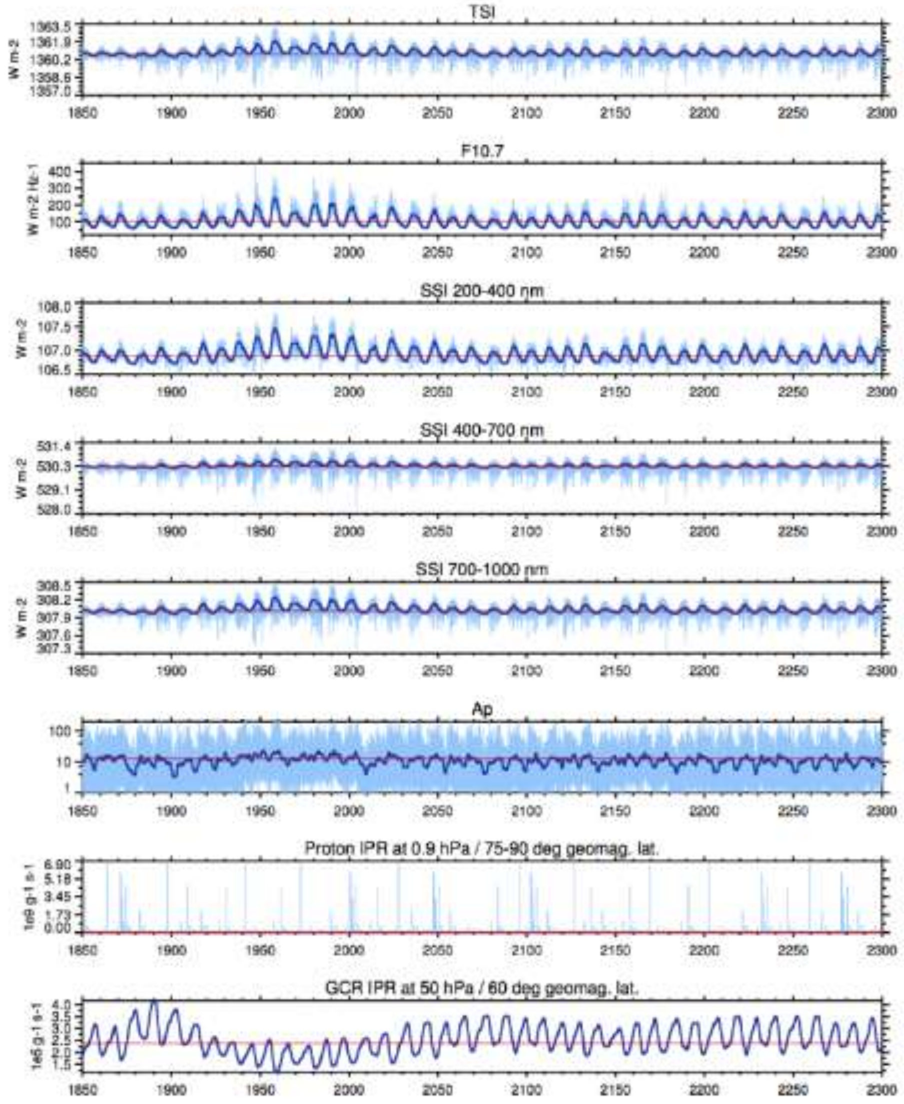


Figure 10. Changes in zonal wind speed (m/s) caused by solar cycle in January (a) and July (b) (simulations with ARM).

Solar forcing dataset for Coupled Model Intercomparison Project Phase 6 (CMIP6) of the World Climate Research Program (WCRP)

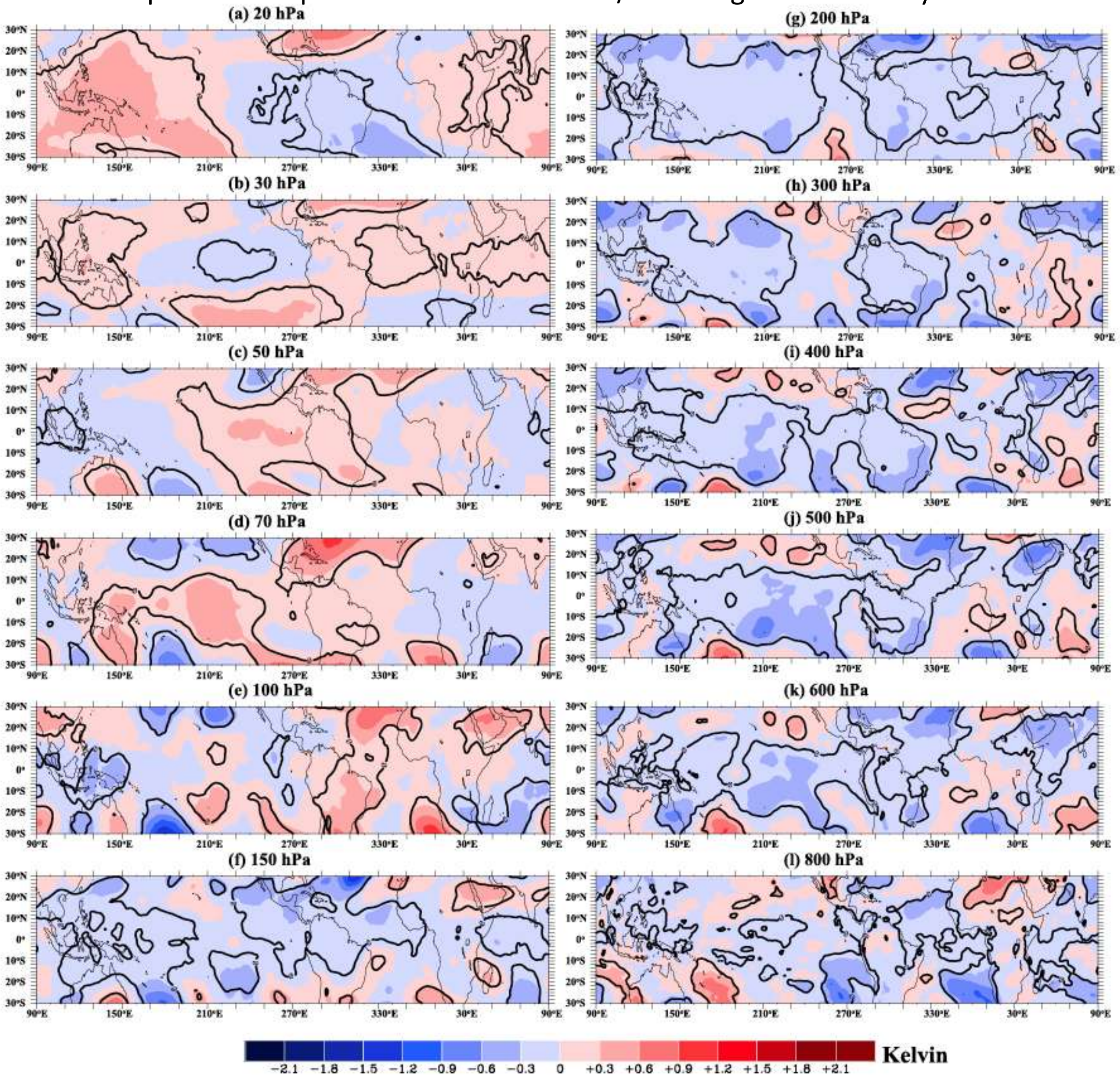


- For the first time particle forcing (solar protons, auroral and radiation belt electrons, GCR) included.
- Historical dataset (1850-present) based on TSI/SSI reconstructions (NLRSSI2+SATIRE-T/S) + reconstructions of geomagnetic indices (Ap/Kp)and solar modulation potential ϕ.
- Future scenario (present – 2300) based on weighted ensemble average of several statistical prediction methods for ϕ, resulting in a Gleissberg-type solar activity minimum around 2050.

Matthes et al., GMD, 2017

Tropical tropospheric temperature response to intra-seasonal UV variations (solar rotation)

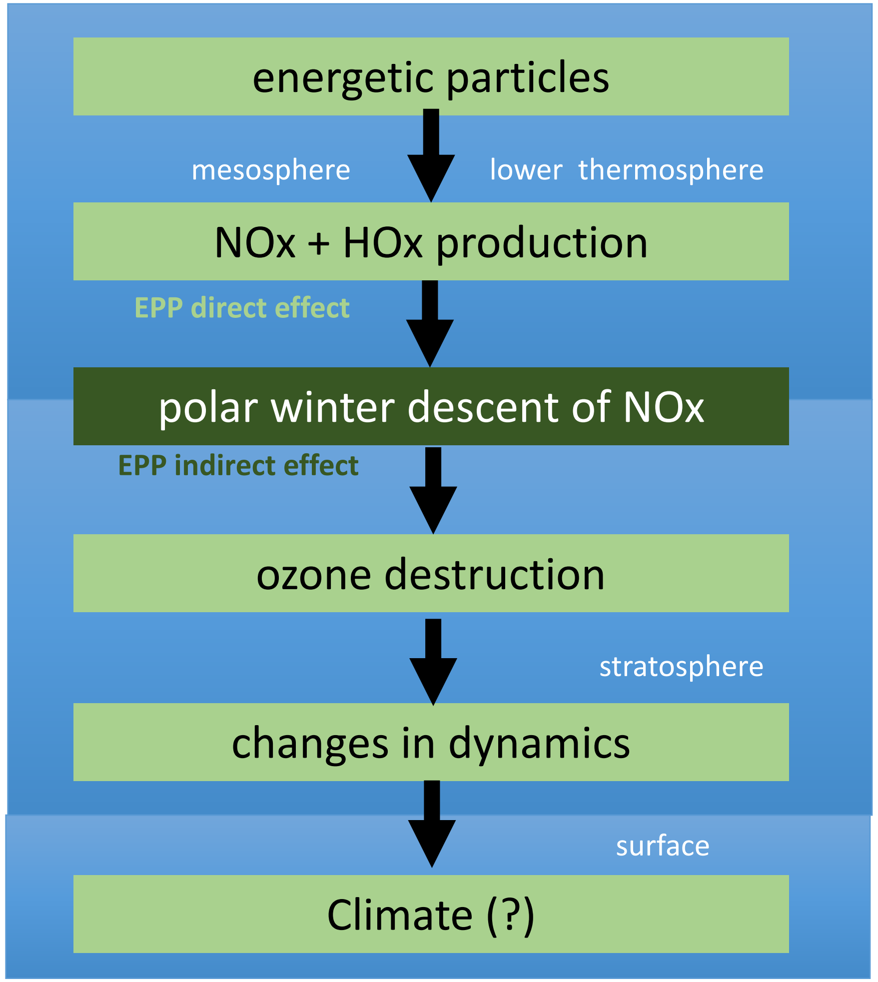
Temperature response to F205 of 0.6 mW/m2 at lag time of +8 days

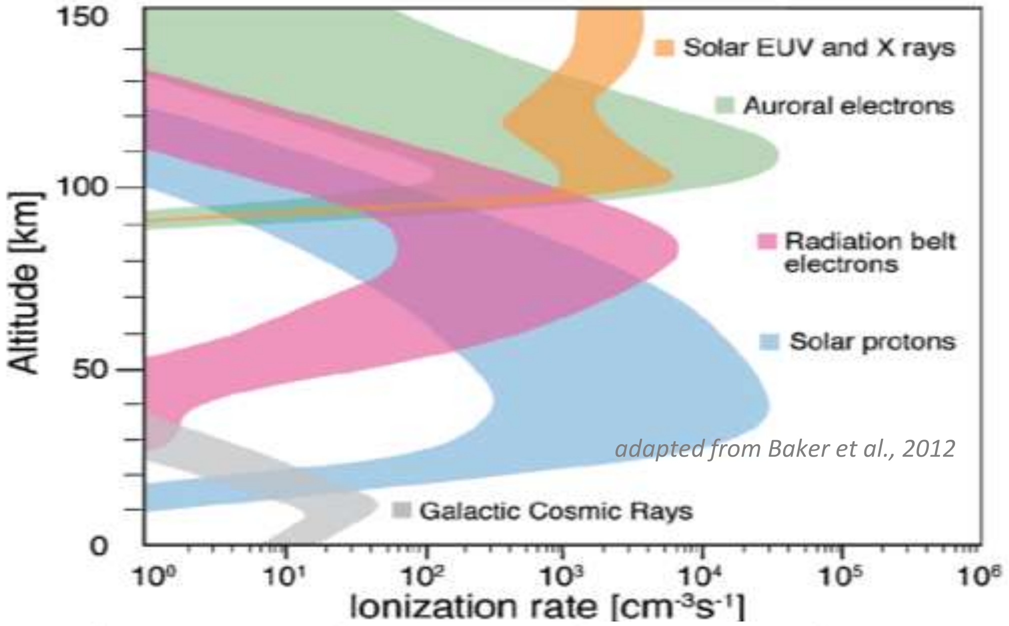


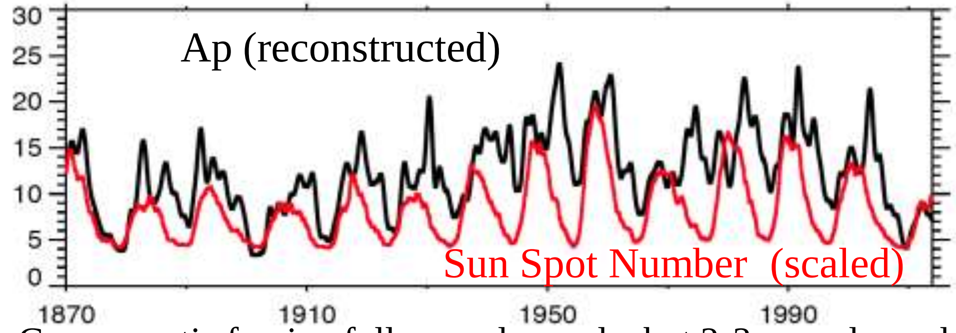
- T response lagged by 6-10 days.
- Warming in the lower stratosphere (slowing of Brewer Dobson Circulation).
- Cooling in the troposphere.
- mid-tropospheric response most pronounced in tropical Pacific.

Hood et al., GRL, 2016

Energetic Particle Precipitation: a solar coupling pathway



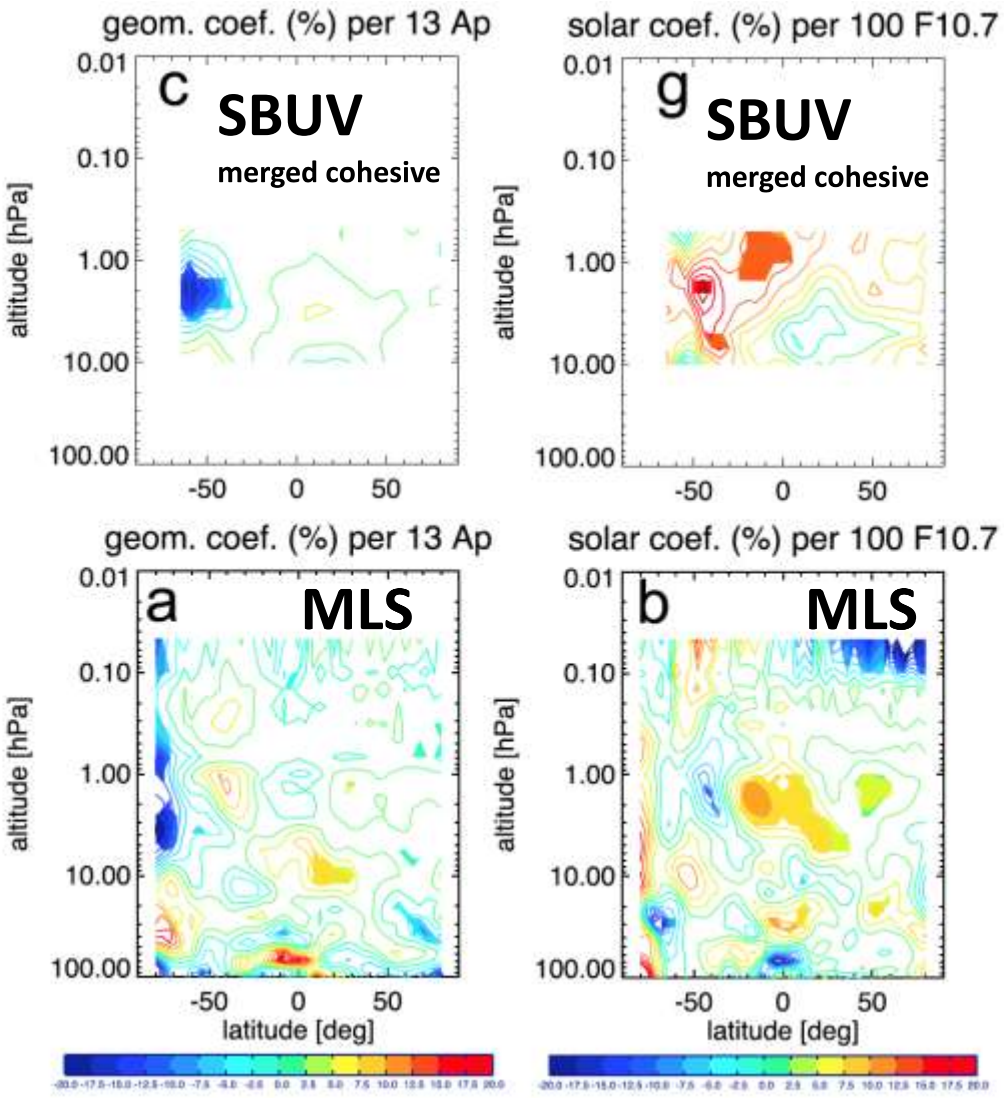




Geomagnetic forcing follows solar cycle, but 2-3 years lagged

Particle versus UV O3 responses in the polar winter SH from observational datasets

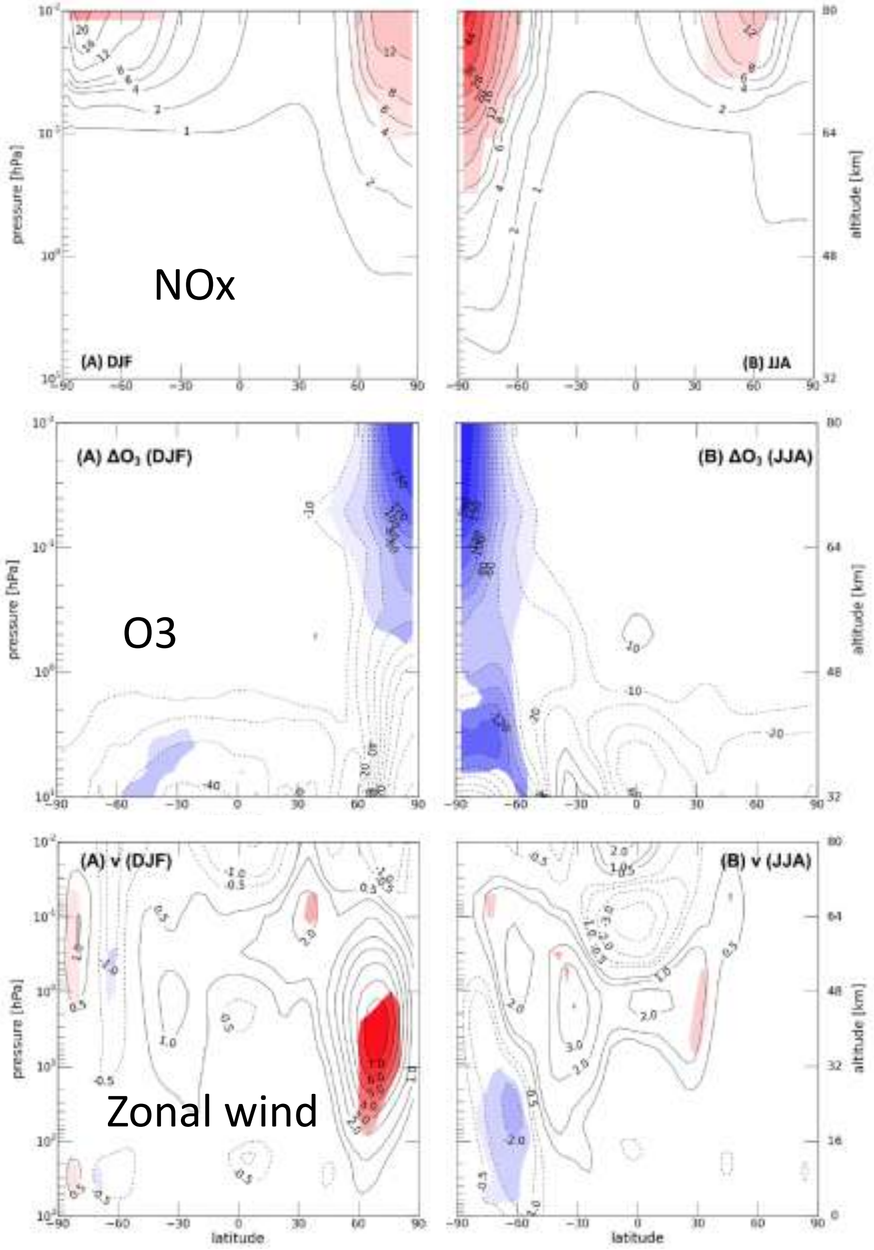
Regression to August composites of SBUV (1979-2014) and MLS (2005-2014):



- Stratospheric O3 responses to solar variations commonly estimated with MLR using F10.7 (or similar) as predictor.
- Inclusion of Ap in MLR: large particle-induced response in the polar mid-stratosphere

Damiani et al., GRL, 2016

Atmospheric impact of the EPP direct effect: mid-energy electron precipitation

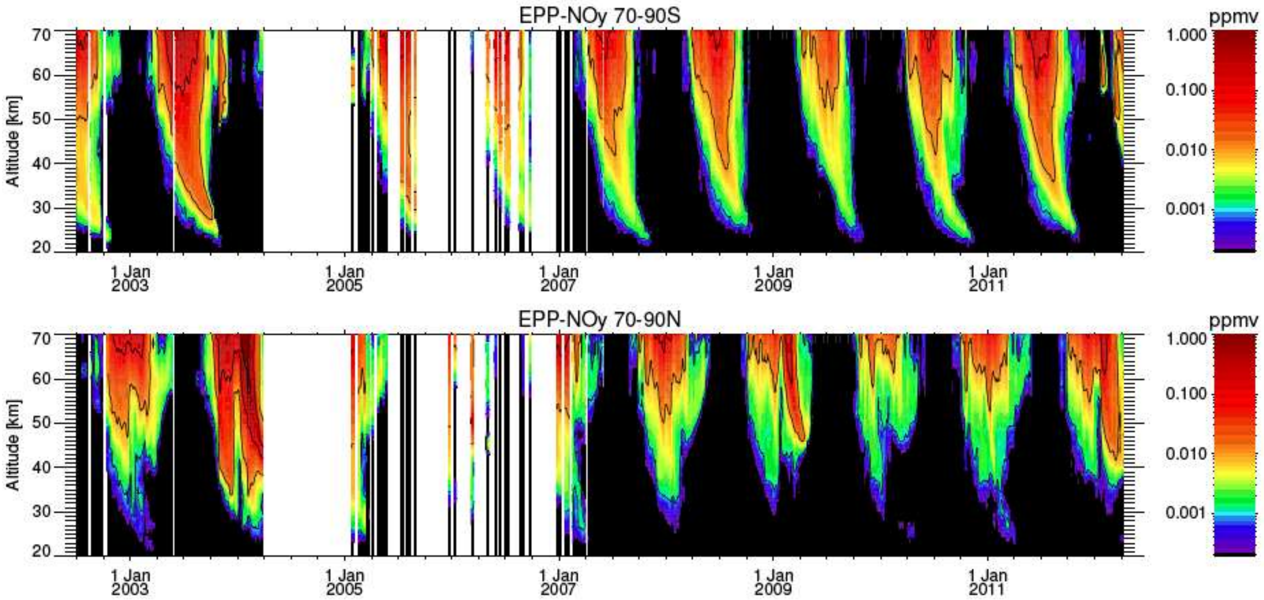


Inclusion of mid-energy electron precipitation (AIMOS-1.6) in AOCCM SOCOL3-MPIOM:

- Significantly enhanced mesospheric NOx (in better agreement with obs)
- Significant O3 response in the Upper Stratosphere Mesosphere.
- Significant zonal wind response in the upper strat. (and propagation to surface)

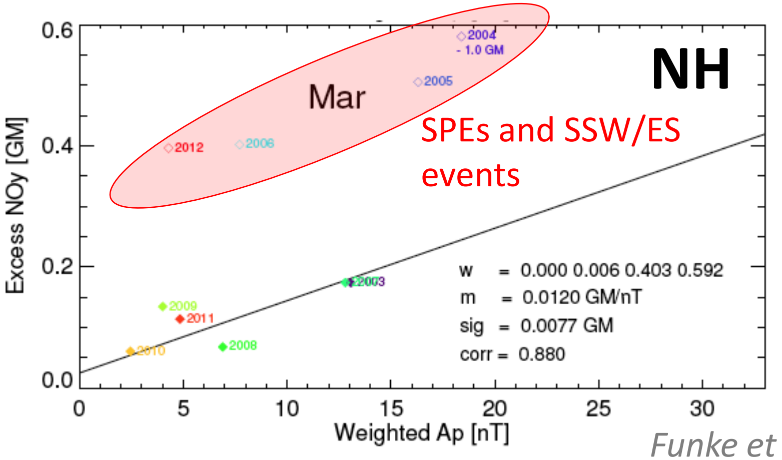
Arsenovic et al., JASTP, 2016

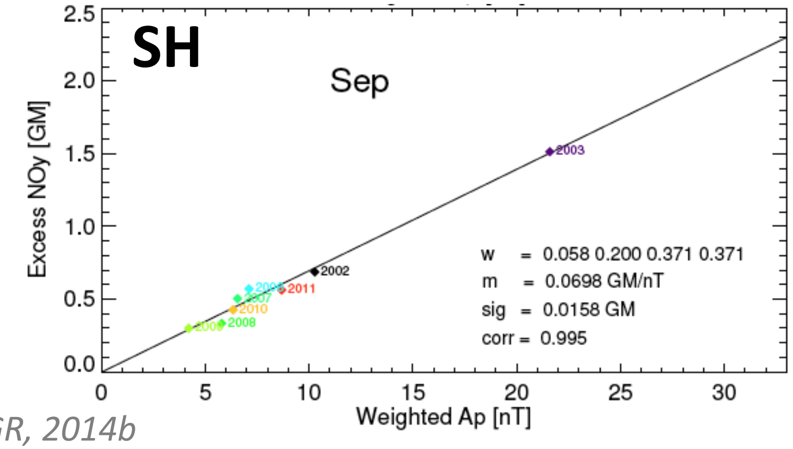
MIPAS NOy: a measure of the EPP indirect effect



- NOy enhancements in every winter due to EPP down to 25 km.
- Highly correlated with geomagnetic Ap index in the SH (when considering transport lags)
- Dynamical variability (SSW/ES) events leads to amplified responses!

Funke et al., JGR, 2014a





Funke et al., JGR, 2014b

Time evolution of NO volume mixing ratio (VMR; ppb)

8 different altitude regions (daily mean, altitude mean ±1 km.

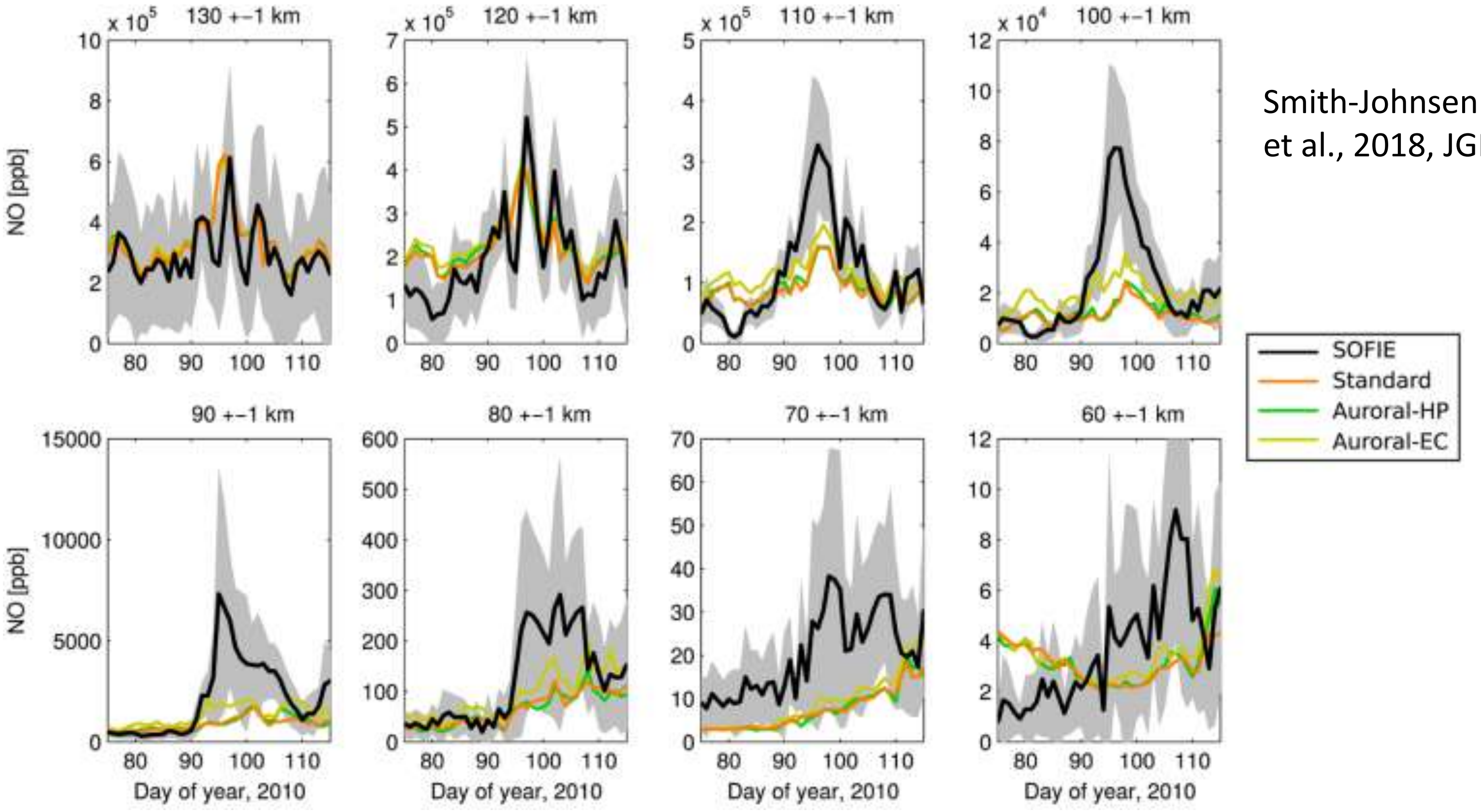
Zonal mean of latitude band where Aeronomy of Ice in the Mesosphere-SOFIE is measuring).

The black line represents SOFIE observations of NO VMR, where the observational spread is shown as the gray shaded region.

The orange line represents the NO VMR from the Standard Whole Atmosphere Community Climate Model run,

The green line represents auroral-hemispheric power run,

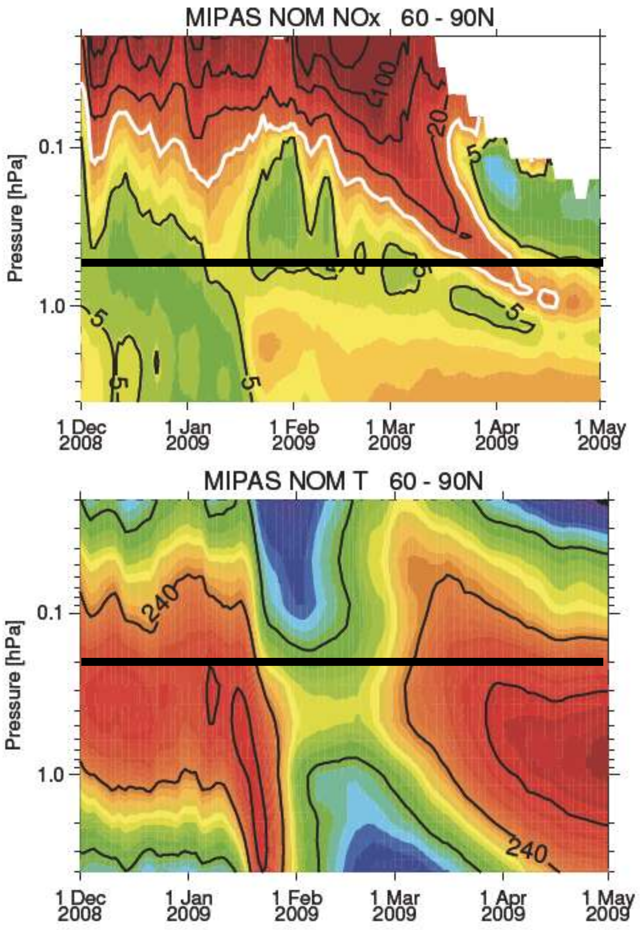
The yellow line from the auroral-EC run.

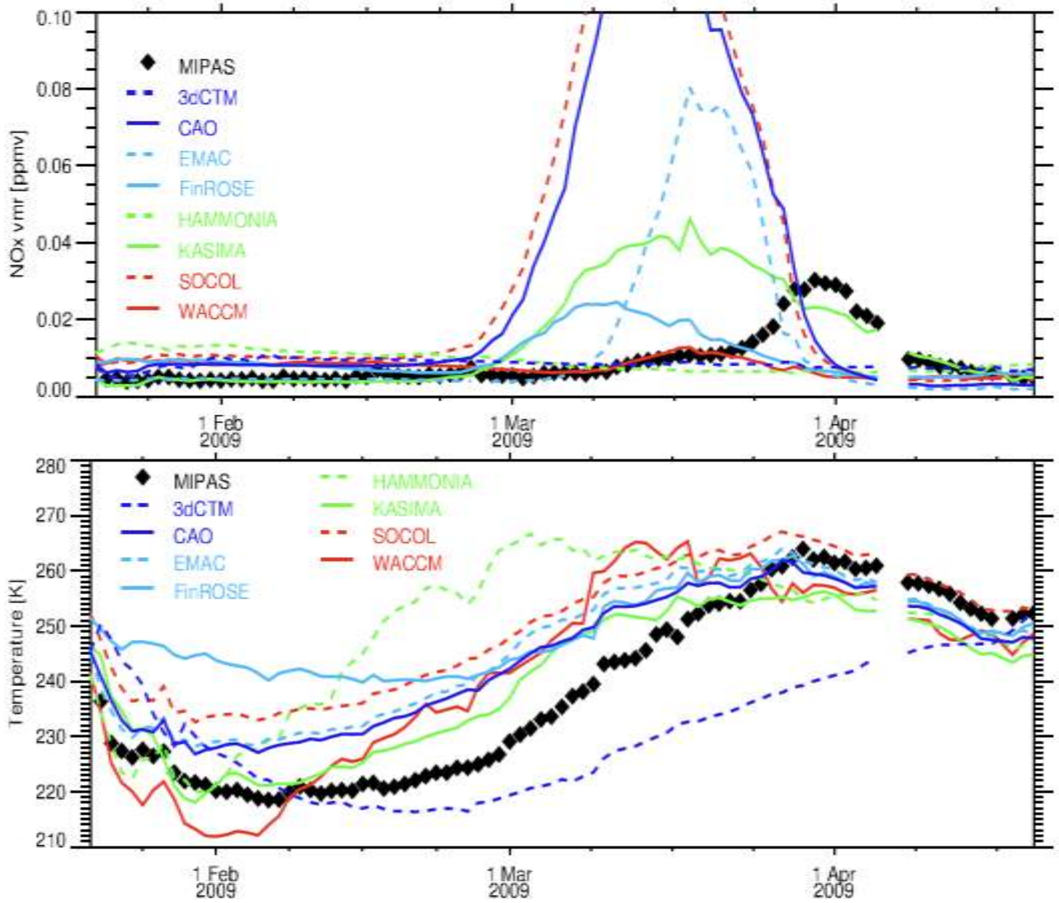


Smith-Johnsen et al., 2018, JGR

The two CMEs arrive at days of year (DOY) 95 and 101. EC = characteristic energy; SOFIE = Solar Occultation For Ice Experiment; HP = hemispheric power.

Model representation of the EPP indirect effect during dynamically perturbed NH winters

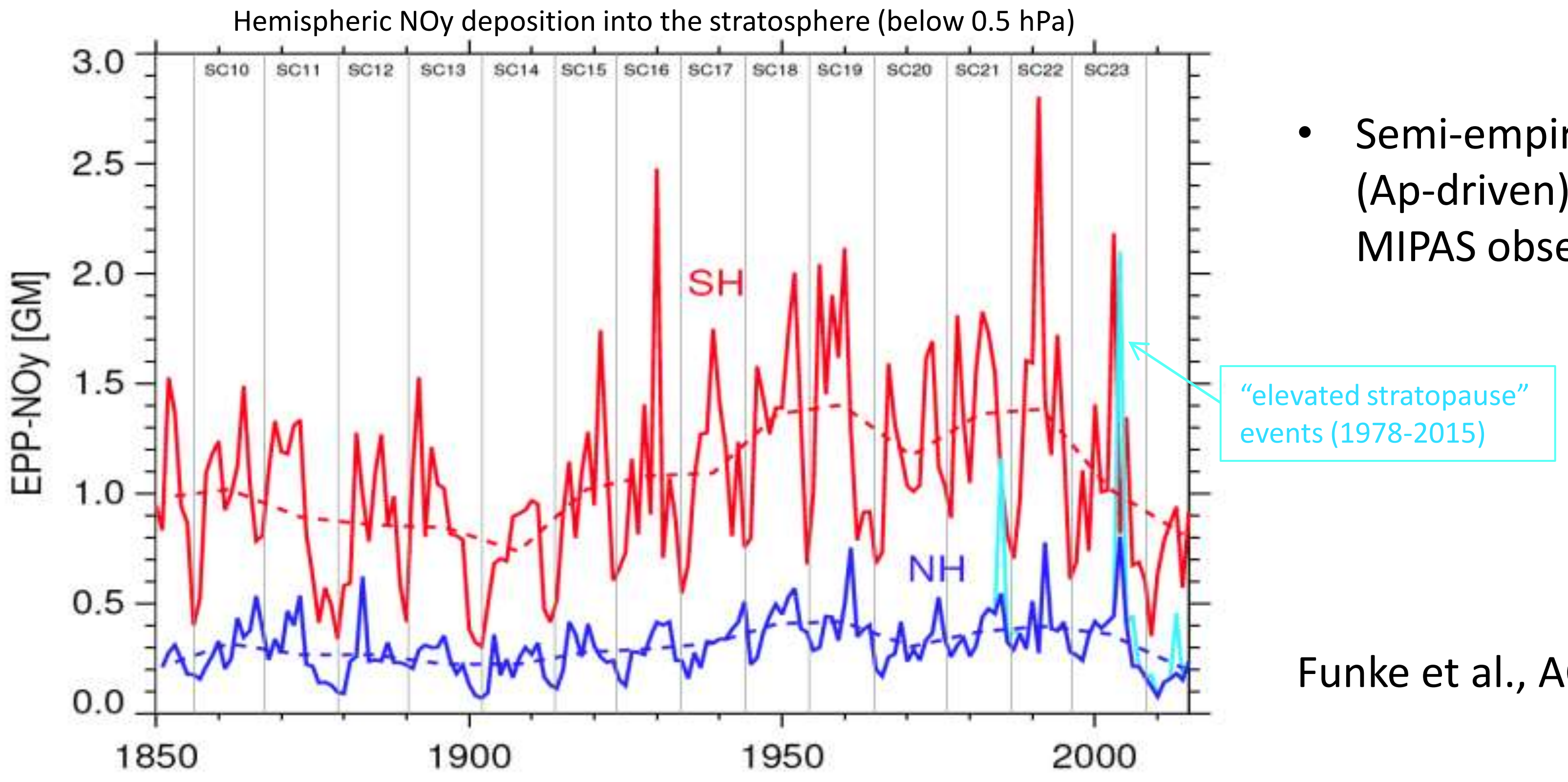




Funke et al., ACP, 2017

Large model biases in amplitude and timing of descending EPP-NOx during elevated stratopause events

Reconstruction of EPP indirect effect (polar winter NOy deposition into the stratosphere (1850-present)



- Semi-empirical model (Ap-driven) based on MIPAS observations

Funke et al., ACP, 2016

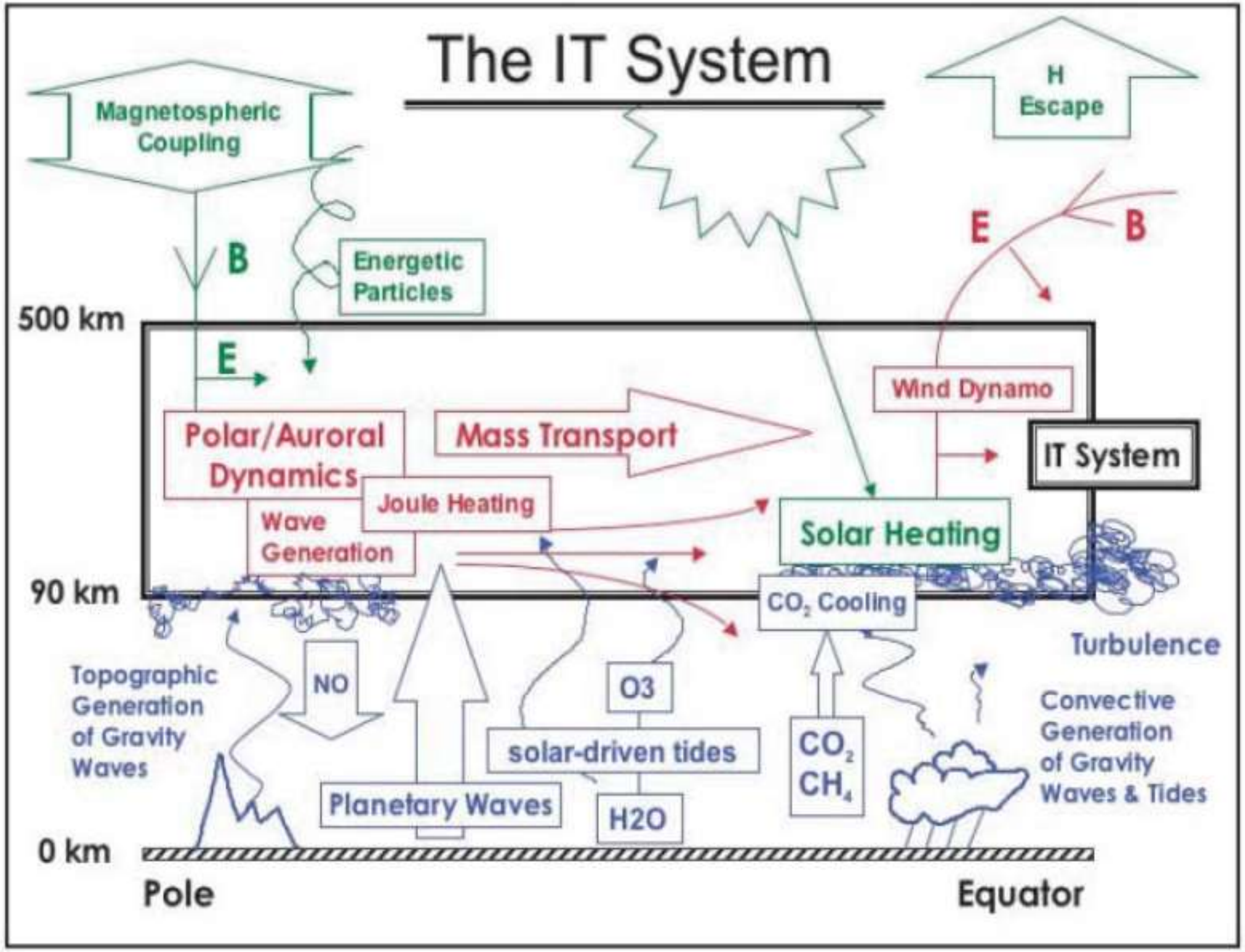
- SC23 is among the three cycles with highest EPP-IE during the last 130 years.
- lowest EPP-IE in the minimum of SC23 since SC13 (~1900).
- longterm decrease of EPP-IE since "Grand Maximum" (~0.6 GM, equiv. to 0.5% of N_2O oxidation) might counteract increase due to growing N_2O emissions.

Coupling by Dynamics

1. What are the influences of lower atmospheric waves on the state and evolution of the thermosphere/ionosphere?

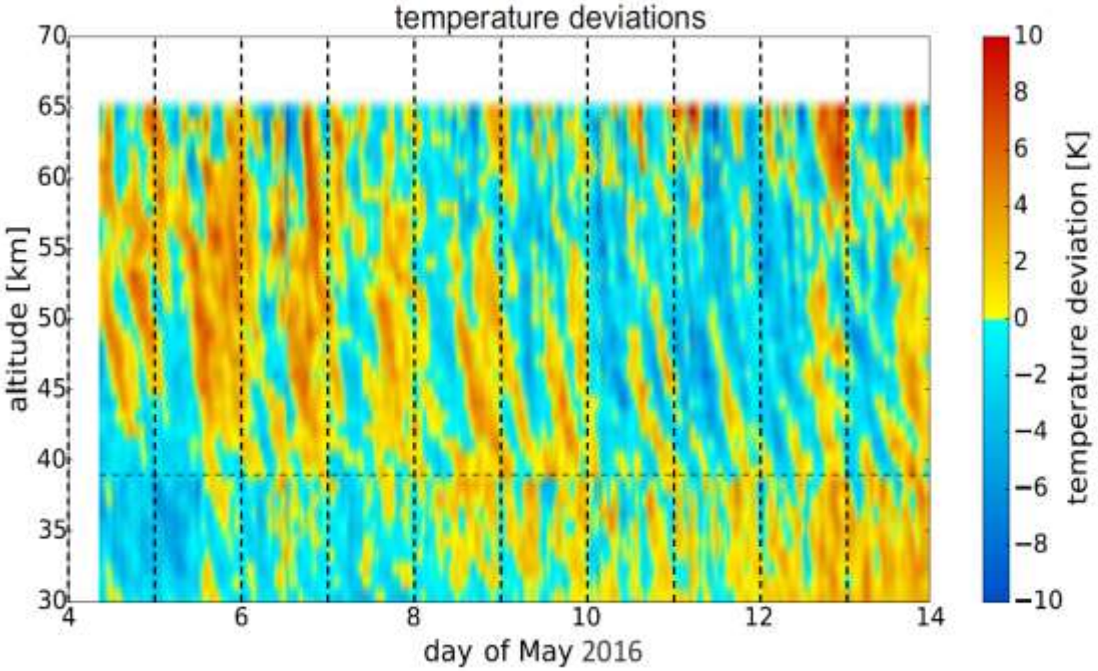
2. How does atmospheric dynamics constrain electro-dynamics in the ionosphere?

3. How can we characterize the significance of small scale structures for the large-scale features in the upper atmosphere?

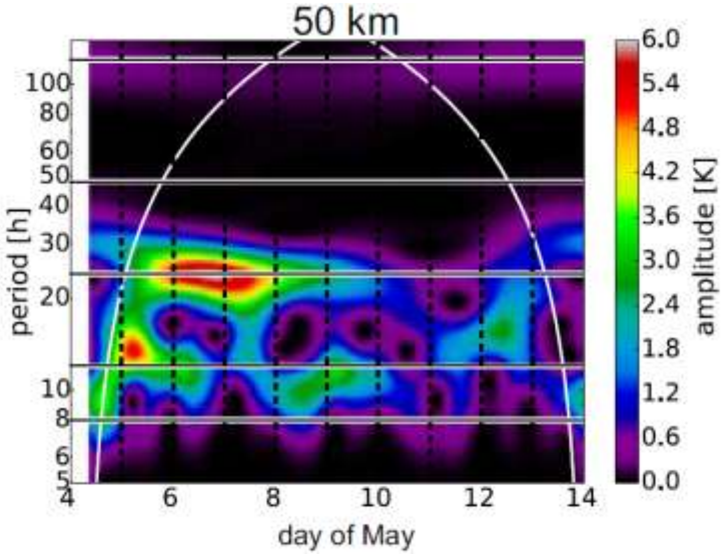


Schematic of the processes relevant to the Ionosphere-Thermosphere system showing the upward and downward coupling processes which influence this region of the atmosphere (after Forbes, JMSJ, 2007).

tidal amplitudes vary within few days



IAP lidar
Kühlungsborn, 54°N
Germany



K. Baumgarten et al., ACP, 2018

the longest continuous lidar temperature series in the MA ever: 10 days !

Thermospheric Variability – Upward Coupling

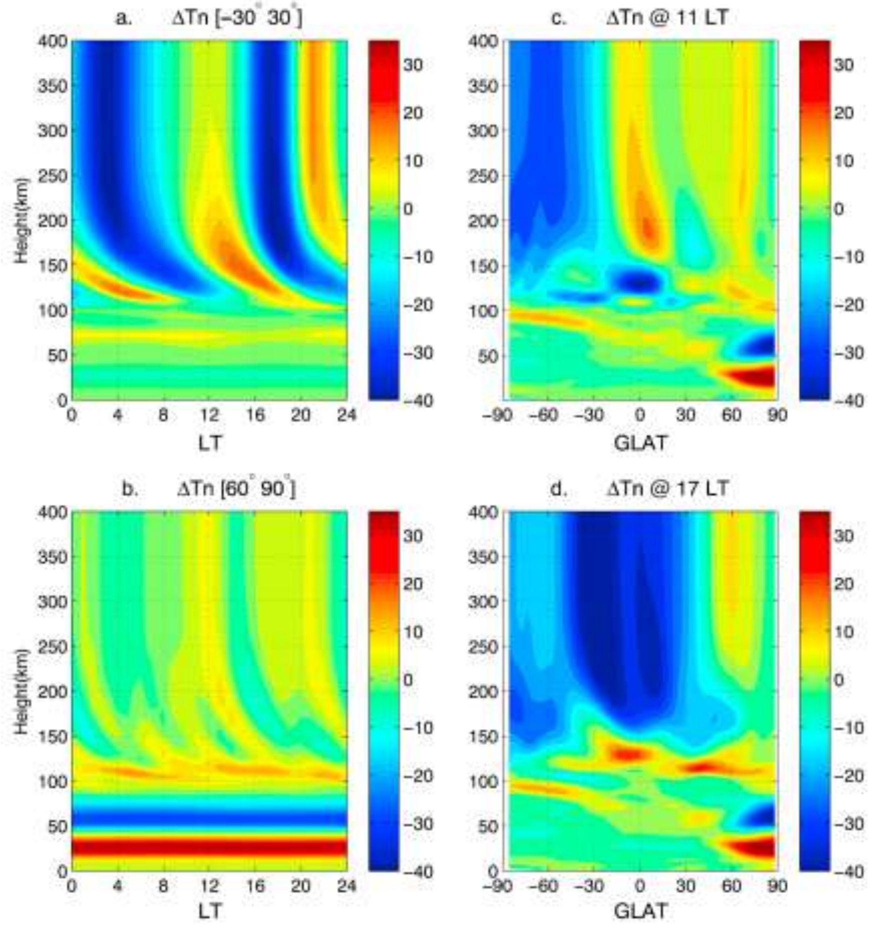


Figure 3. Temperature perturbations (ΔTn (K)) averaged during day of year 25–30. (a and b) Height versus LT distribution in tropical (30°S–30°N) and northern polar regions (60°N–90°N). (c and d) Height versus geographic latitude distribution at 11 and 17 LT. In the tropics, ΔTn exhibits strong LT dependence above 100 km, with downward phase propagation between 100 and 200 km [from *Liu et al.*, 2013].

Liu et al., Space Weather, 2017

Table 1. Non–Storm Time Density Variability at 400 km[a]

	Magnitude (%)	LT (hour)	Season	Latitude (deg)
Cusp	30–40	10–14	all	[±70 ±80]
Alfvén wave	±(20–40)	all	all	all
Helium	30–70	?	local winter	midlatitude
EMA	1–6	10–20	all	[−40 40]
EPB	−(1–4)	18–03	?	[−20 20]
MDM	20–30	23–01	local summer	[−10 10]
SSW	±(5–30)	0–24	Dec to Feb	all
Wave 3/wave 4	±(2–5)	0–24	all	[−40 40]
Terminator	±(2–6)	18–06	all	[−60 60]
GW	±(1–7)	?	?	all
ENSO[b]	±(1–3)	?	Oct to Feb	[−40 40]
CO_2[b]	−(2–7)/decade	?	?	?

[a]MDM: midnight density maximum; EMA: equatorial mass density anomaly; EPB: equatorial plasma bubble; SSW: stratosphere sudden warming; ENSO: El Niño Southern Oscillation; GW: gravity waves.

[b]These magnitudes are given as global mean. The question marks indicate areas that need to be clarified.

Atmospheric Waves (Thermosphere, Ionosphere

H.L. Liu, Space Weather, 2017

Table 1. A Brief Summary of the Major Atmospheric Waves of Interest to the Thermosphere and Ionosphere

	Primary Restoring Force	Wave Sources	Temporal/Spatial Scales	Propagation
Solar thermal tides	Buoyancy	Solar radiative heating, latent heat	Harmonics of a solar day/planetary	Migrating: westward following the Sun Nonmigrating: not following the Sun
Lunar tides	Buoyancy	Lunar gravitational force	Harmonics of a lunar day/planetary	Following the Moon
Rossby waves, mixed Rossby-gravity waves	Coriolis force/buoyancy	Tropospheric processes: topography, land-ocean contrast, diabatic heating	Days to quasi-stationary/planetary	Westward relative to background wind
Equatorial waves: Kelvin waves, equatorial Rossby waves, equatorial mixed Rossby-gravity waves, equatorial inertio-gravity waves	Buoyancy/Coriolis force	Tropical tropospheric processes: deep convection	Days/planetary	Equatorially trapped Kelvin waves: eastward Equatorial Rossby mixed Rossby-gravity waves: westward Equatorial inertio-gravity waves: eastward and westward
Gravity waves	Buoyancy	Deep convection, orography, frontal system, adjustment of jet, body forcing from wave breaking	Longer than buoyancy period and less than inertial period/km to thousands of kilometers	Horizontal and vertical
Acoustic waves	Air pressure	Deep convection, orography	Shorter than buoyancy period/km to hundreds of kilometers	Horizontal and vertical

Spatial Correlation of Specific waves

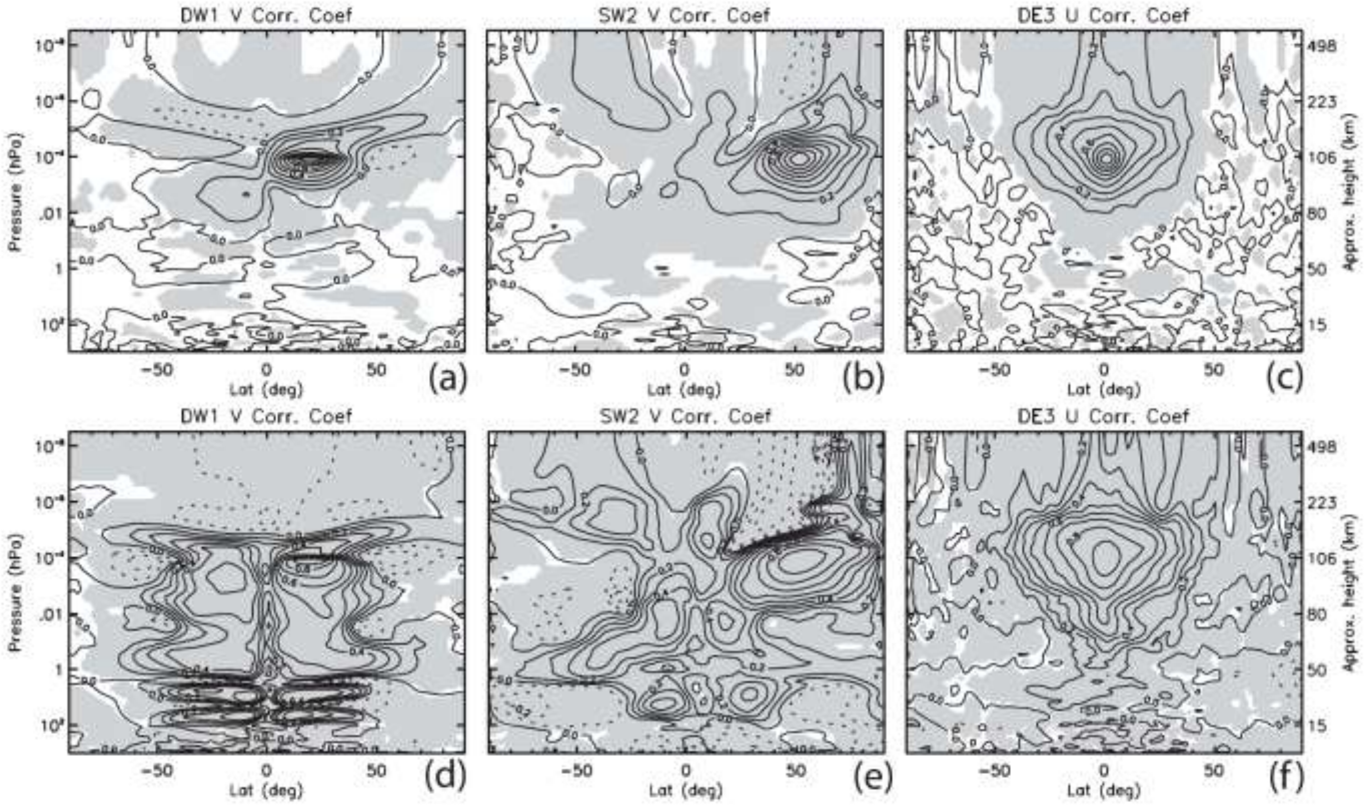
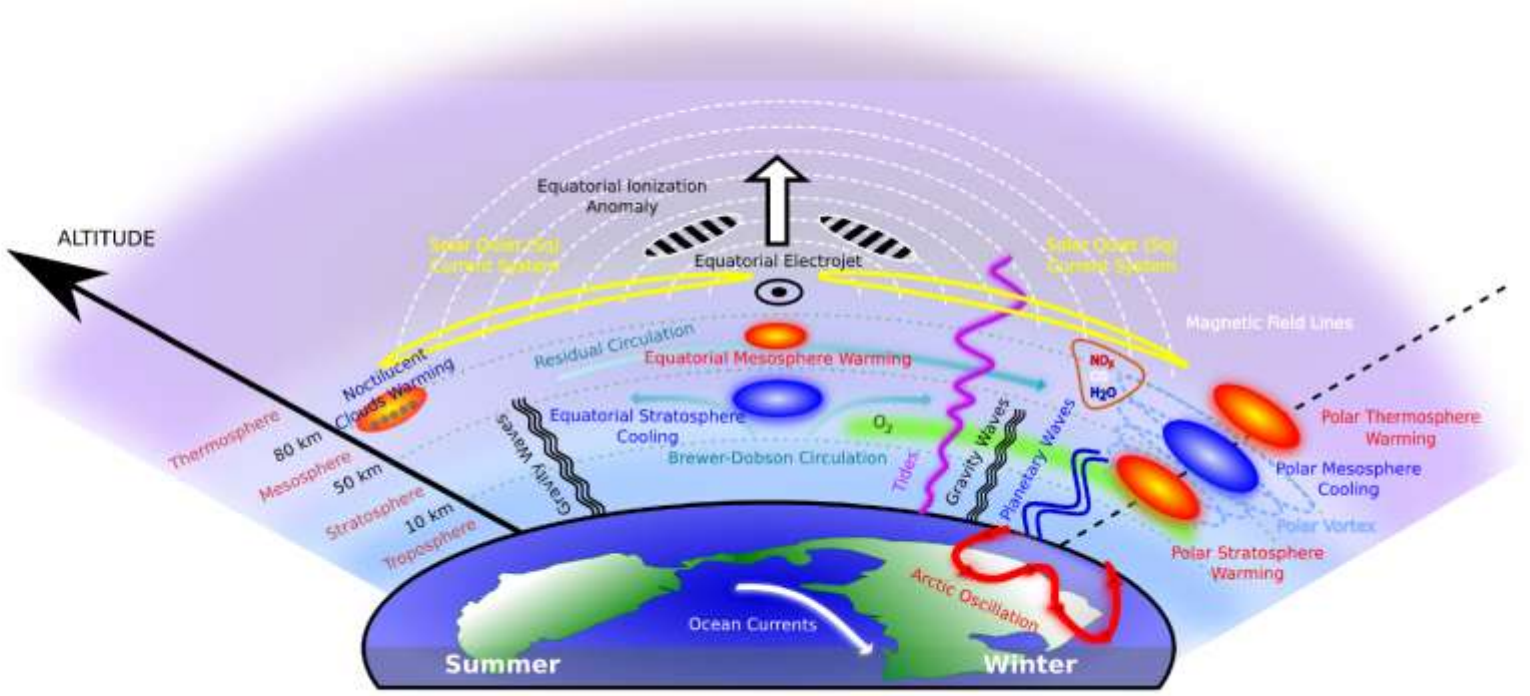


Figure 2. Spatial correlation coefficients of tidal amplitudes with (top row) short-term and (bottom row) long-term variability. (a and d) Migrating diurnal tide (DW1), (b and e) migrating semidiurnal tide (SW2), and (c and f) nonmigrating diurnal tide (DE3). The reference points are at the latitudes where the respective tidal amplitudes maximize in the MLT region. Statistically significant correlation is highlighted with gray shade. Contour intervals: 0.1.

H.L. Liu, Space Weather, 2017

Sudden Stratospheric Warming Influences

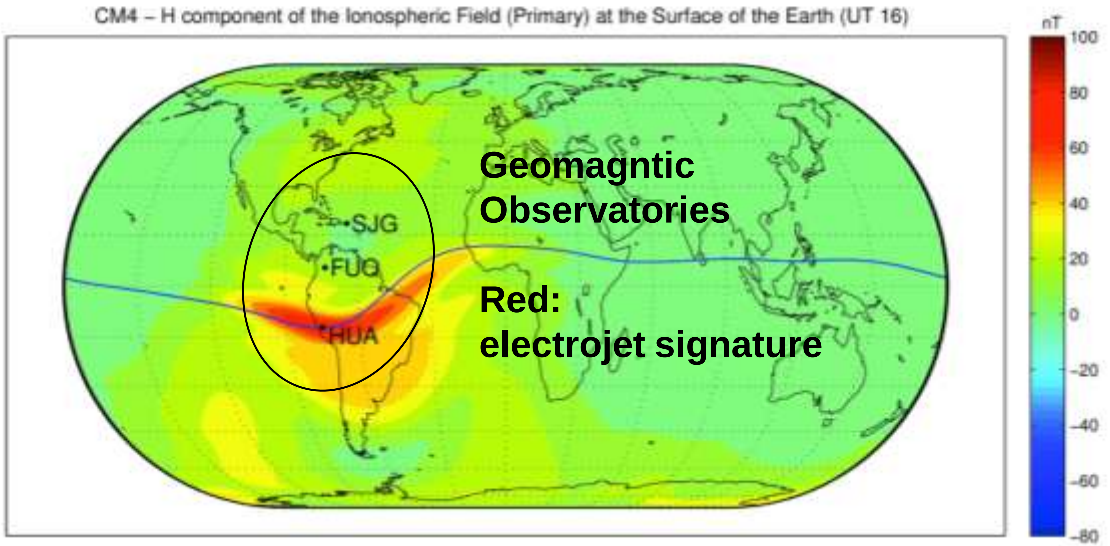


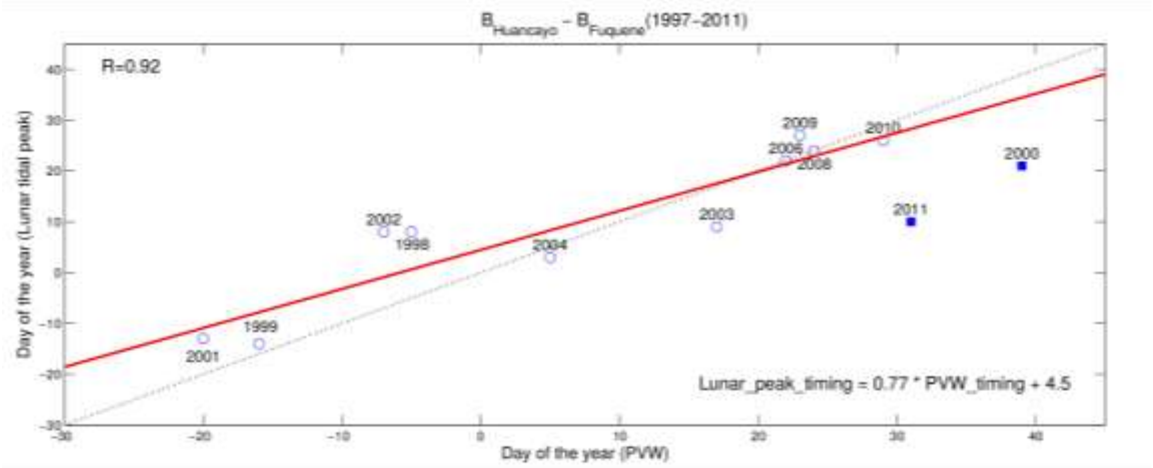
IMPACTS OF SUDDEN STRATOSPHERIC WARMINGS

Figure 1. Schematic diagram of the coupling processes and atmospheric variability that occurs during sudden stratospheric warming events.

Pedatella et al., EOS, 2018

Relation between stratospheric warming events and enhanced lunar tides in the equatorial electrojet (EEJ)





Siddiqui, Stolle, Lühr, Matzka, 2015, JGR

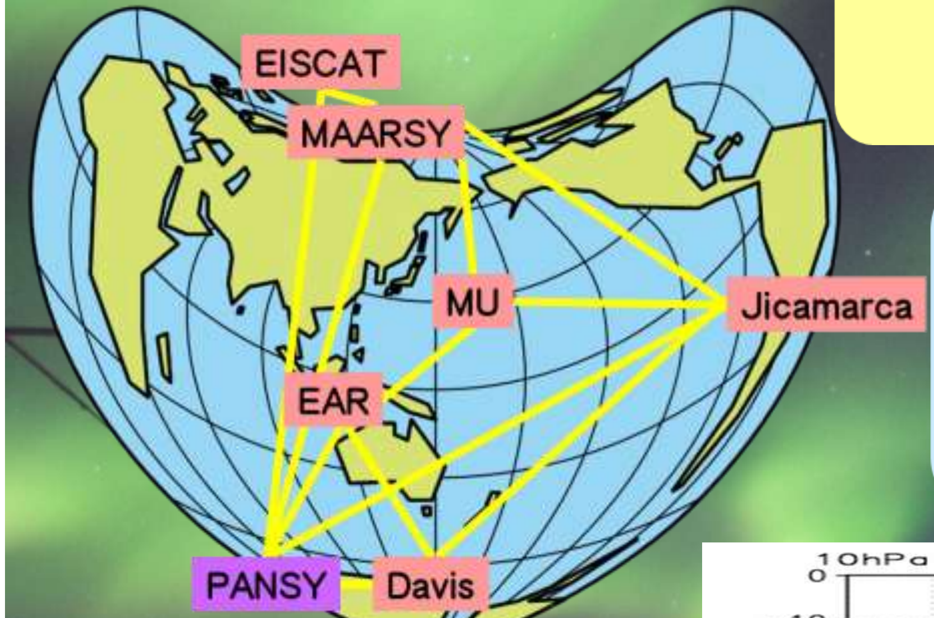
- 13 years of magnetic observations compared to MERRA-analyses
- **Timing** of lunar tide peaks in EEJ correlate to **92%** with timing of stratospheric polar vortex weakening (PVW)
- **Amplitude** of lunar tide peaks in EEJ correlate to **75%** with amplitude of stratospheric polar vortex weakening events (not shown here)
- Analysis confirms **close interaction** between middle and upper atmosphere

SCOSTEP/VarSITI/ROSMIC

Interhemispheric Coupling Study by Observations and Modelling (ICSOM)

PI: K. Sato

ICSOM MST radar network



Two minor SSWs were successfully captured

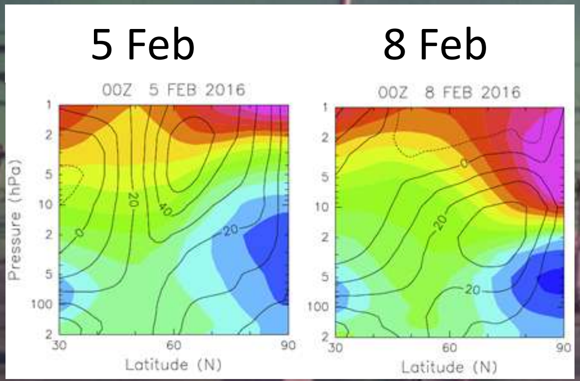
ICSOM campaign : 22 Jan-5 Feb 2016

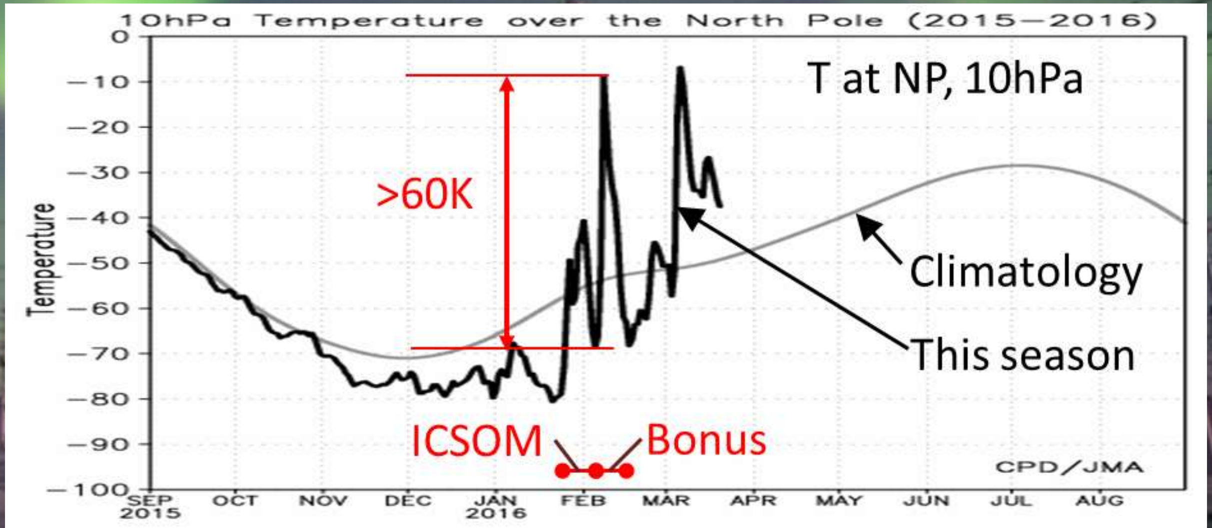
Bonus campaign :6-16 Feb 2016

MF radars
Meteor radars
Lidars
Imagers
High-resolution
Satellite obs.

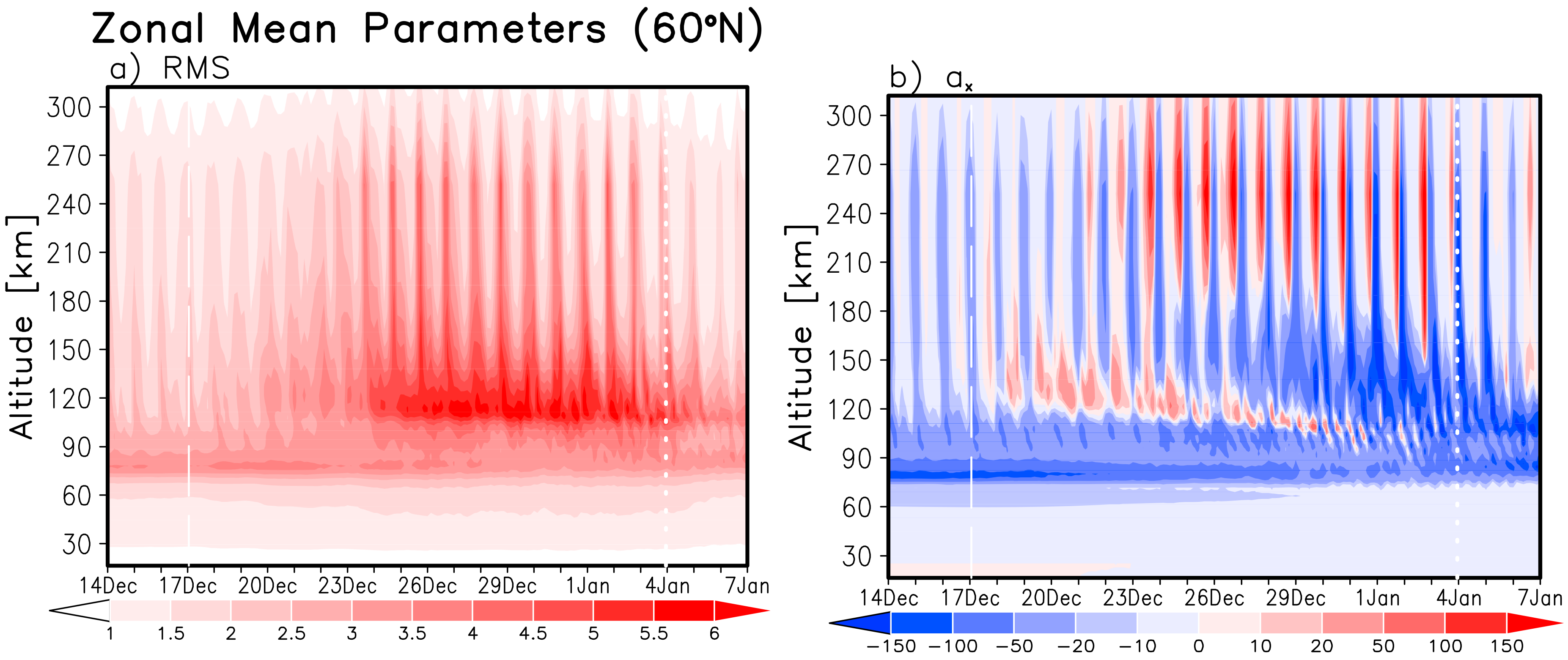
Real atmosphere simulations by GCMs (JAGUAR, NICAM)

More than 30 participants in eight countries





Gravity waves during SSWs

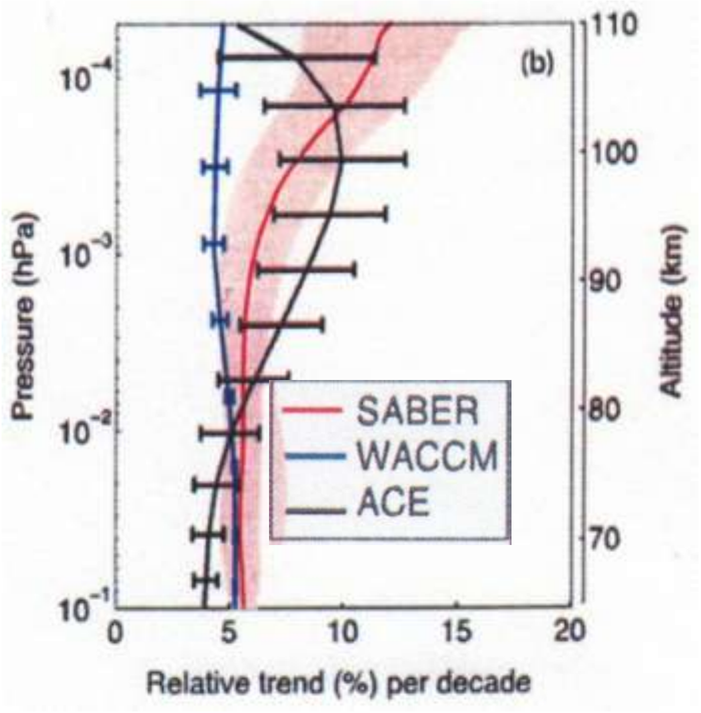


- Gravity wave penetration into the thermosphere during an SSW simulated by CMAT2-GCM coupled with the extended gravity wave parameterization of Yiğit et al., [2008]. Yiğit and Medvedev [2012, Figure 2, GRL]

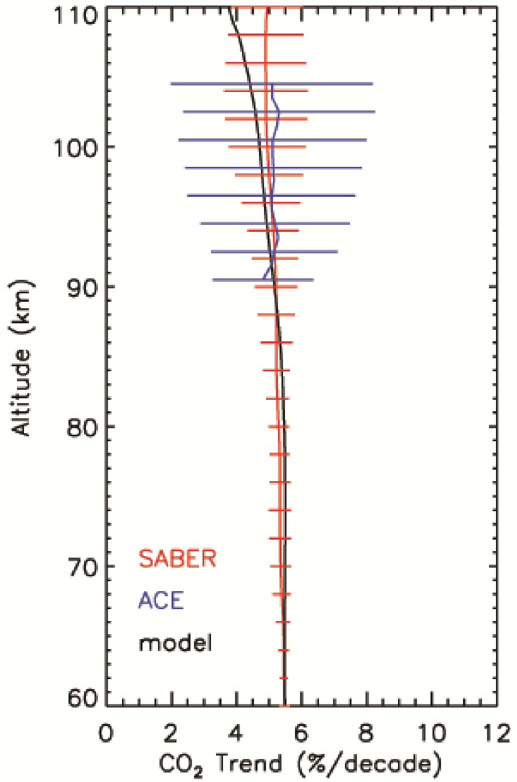
Trends in the MLT

Which parameters in the MLT show long term variations and why?

CO_2 volume mixing ratio (VMR) in the mesosphere and lower thermosphere



Original CO_2 retrievals summarized by Yue et al. (2015) – observed values in the MLT region are significantly larger than model values.

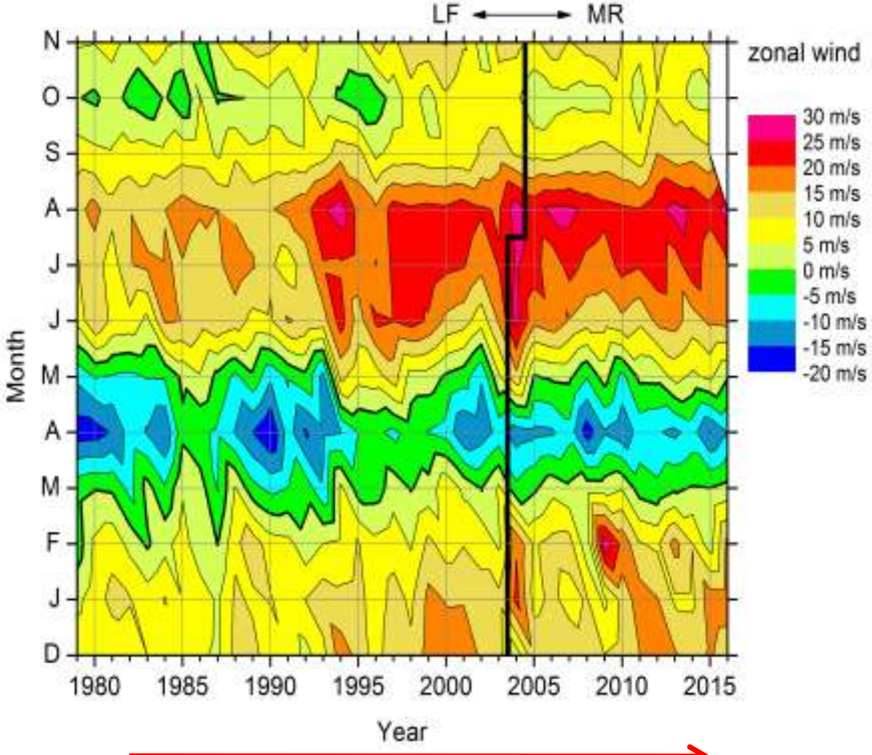


Qian et al. (2017) corrected issues with methodologies used to derive CO_2 trends – observed values now agree with model values.

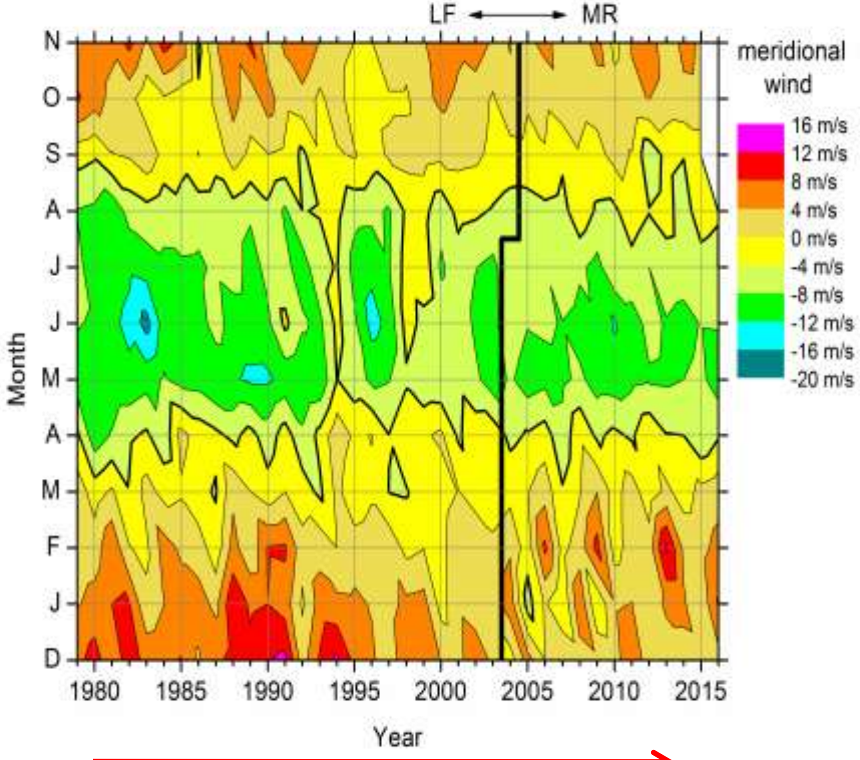
Combined LF and Meteor Radar time series at Collm

1979-2016 - attributed to ~90 km

Zonal wind



Meridional



increase towards more westerly winds

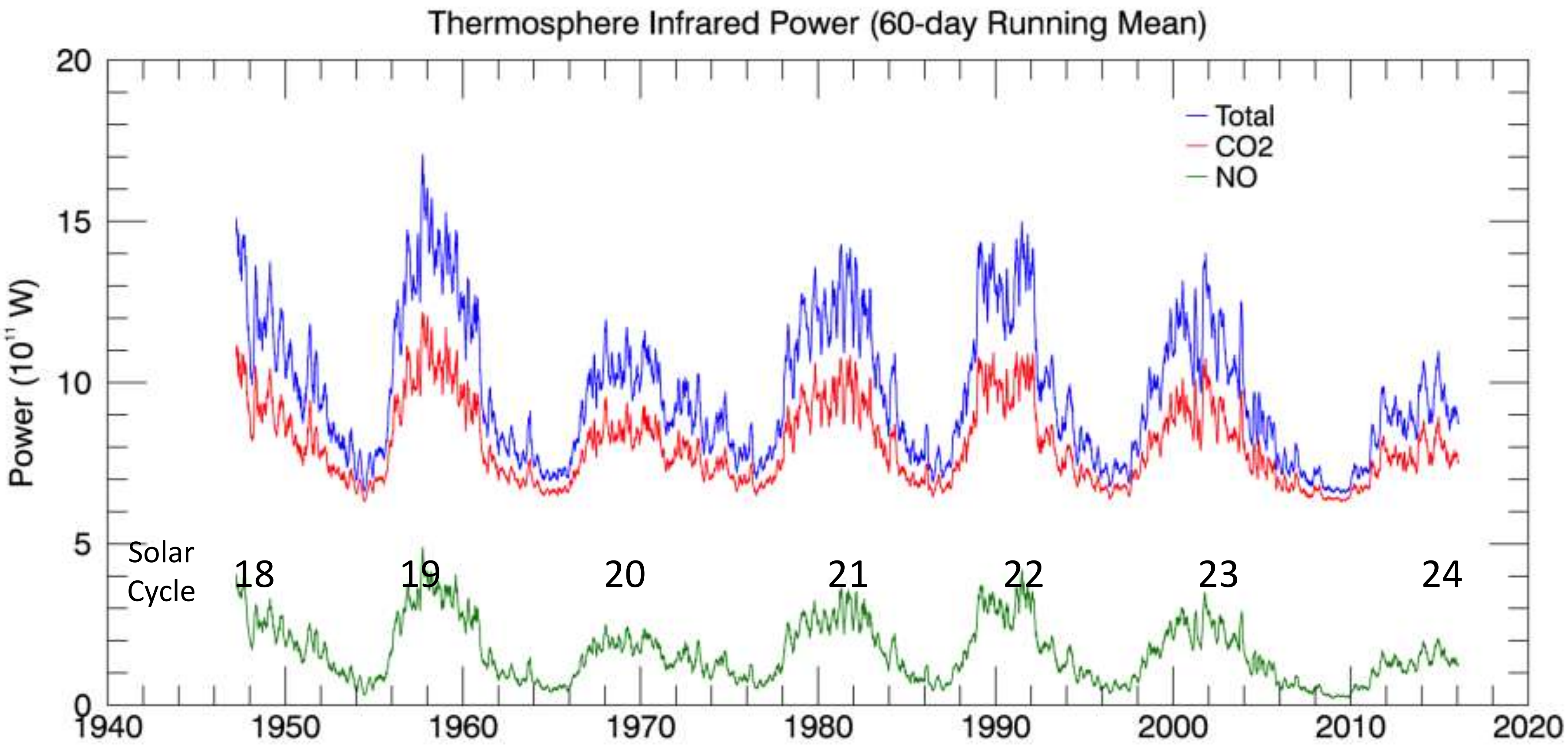
decrease of the magnitude

overall tendency of decreasing trends with time

Jacobi

Saskatoon summer (not winter) opposite – increasing meridional wind

Reconstruction of Thermosphere Infrared Power



Reconstructed cooling time series back to 1947 using extant F10.7, Ap, Dst

CO_2 is the dominant cooler– depends less on solar activity

Solar cycle is stronger in NO than CO_2 IR cooling.

Integrated IR power over solar cycle is rather stable

M. Mlynczak

Is solar correction for trend studies stable? No.

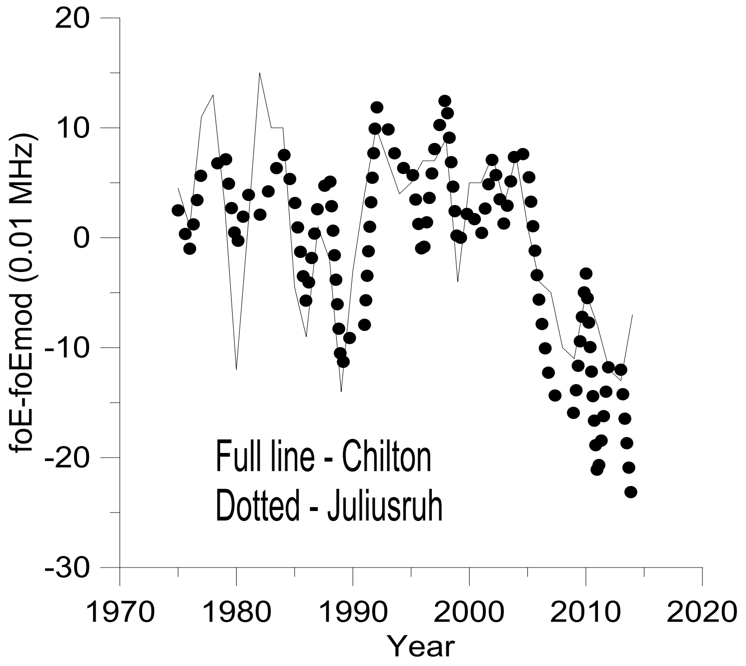
	F10.7	Fα
1975-2014	0.88/0.91	0.89/0.92
1975-1990	0.96/0.91	0.93/0.92
1990-2005	0.94/0.98	0.93/0.95
2006-2014	0.79/0.96	0.86/0.96

foE = A + B * solar

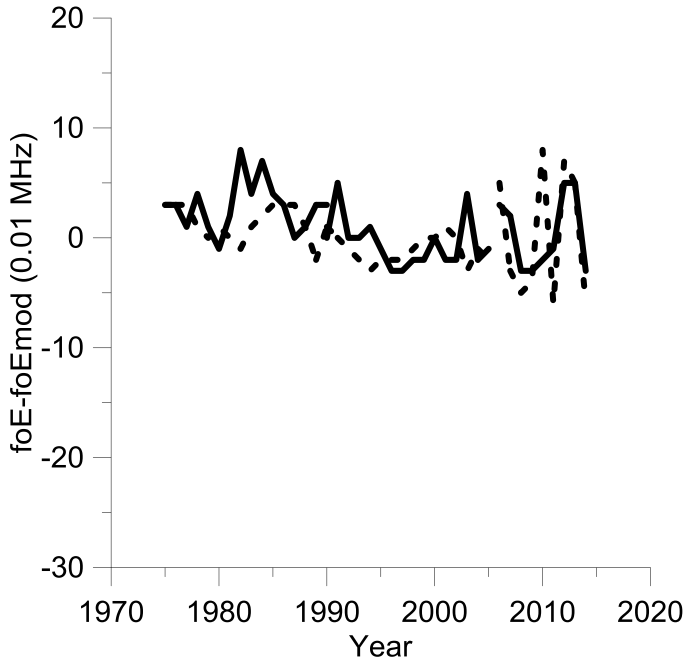
Percentage of total variance of **foE** explained by eq. foE = A + B*solar for **Juliusruh/Chilton**, yearly values, and solar proxies F10.7 and Fα.
Clearly better for three separate corrections.

Laštovička et al. (2016)

One solar correction



Three solar corrections



Dependence of foE on solar activity was apparently weakening.

Future investigations of trends in MLT

Filling in gaps in scenario of trends in the upper atmosphere and removal/explanation of controversies.

Main areas:

1. Investigations of trends in atmospheric wave activity – key problem of trends in MLT region.

2. Further development and improvement of complex models.

3. Monitoring and investigations of changes of secondary (= non-CO2) trend drivers and their impacts on trends.

4. Further investigations of stability of solar activity correction, important particularly for ionized component trends.

Trends and Solar Influence in the Thermosphere

What are the trends in the ionosphere/thermosphere?

Are there implications for technical systems such as satellites?

Upper atmospheric dynamics: Solar flux vs. waves from below

Continuous daytime OI 630.0nm emission behavior (in year 2001; <SSN> = 110) showed the daily variability in emissions to be dependent on solar activity *[Pallamraju et al., 2010, JGR]*

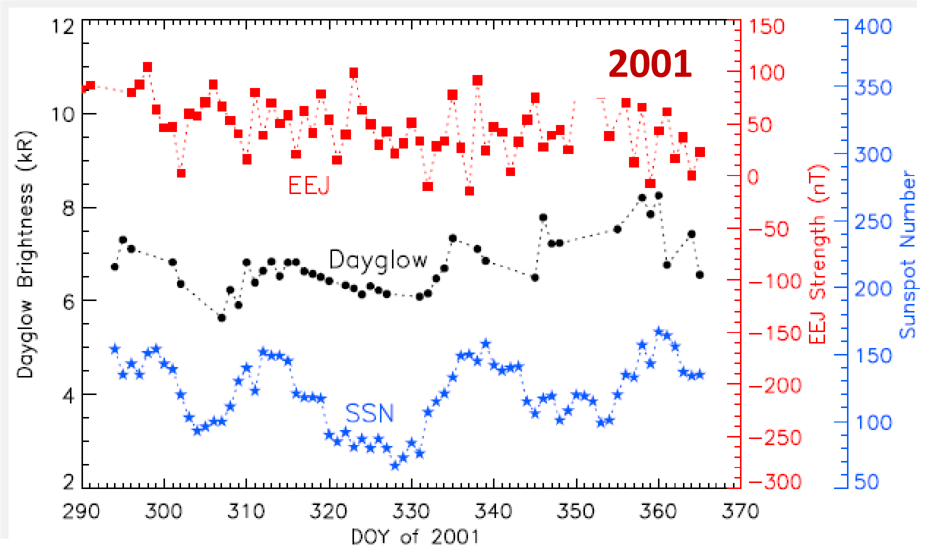
In year 2011 (when <SSN> = 35), the influence of lower atmospheric phenomena in the upper atmospheric dynamics were greater

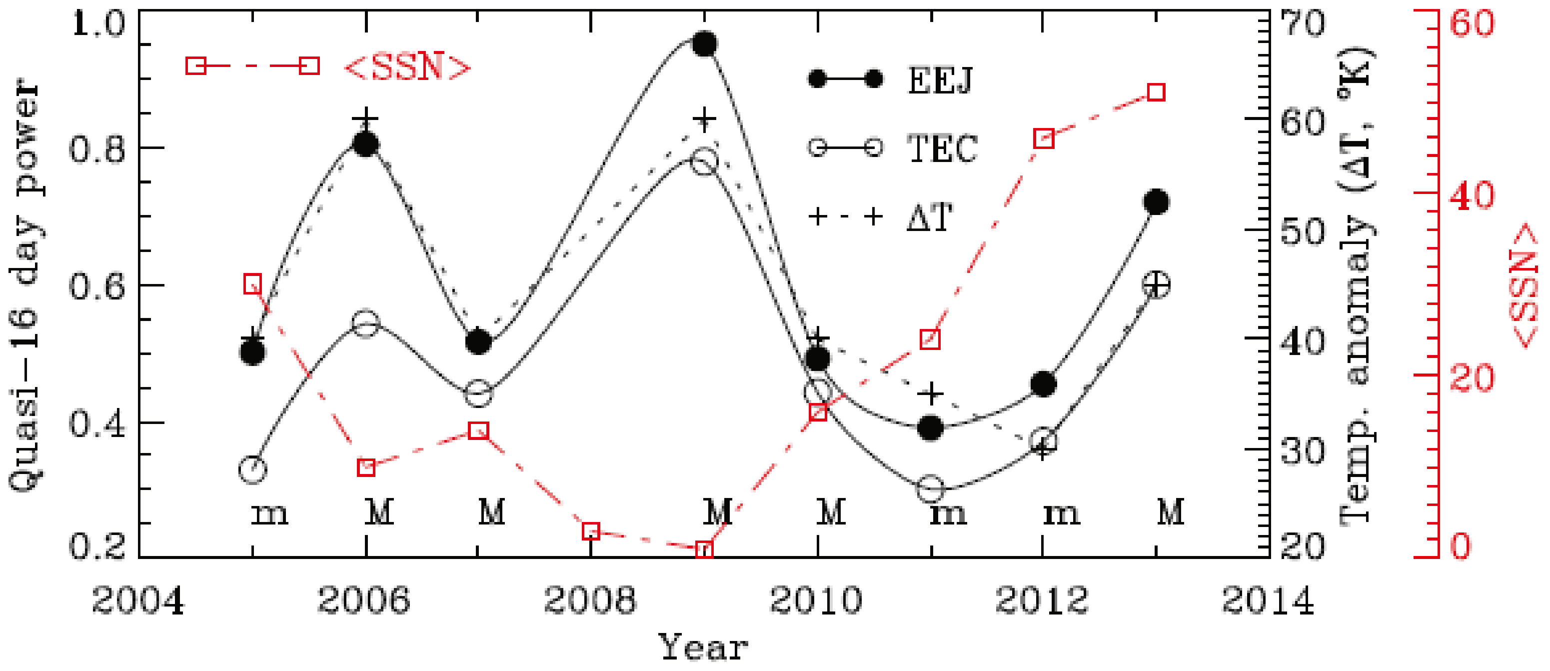
In year 2012 (when <SSN> = 52), the influence of both lower atmospheric phenomena and solar flux were seen in the upper atmospheric dynamics. *[Laskar, Pallamraju, et al., 2014, JGR]*

Thus, the solar influence on the UA dynamics can be summarized as:

Forcing from below when SSN < 35
Mixed effects, when 35<SSN<110
Forcing from above when SSN>100

[Laskar, Pallamraju, et al., 2014; JGR]





Some years phenomena called "SSW" Stratospheric Sudden Warming occur !! (Major and minor SSW indicated by 'M' and 'm')

Excellent similarity in seen between EEJ, TEC, and Delta_T indicates a clear planetary scale influence on the upper atmospheric parameters !!

Further, the SSW events provide additional energy for lower atmospheric waves to propagate to upper atmosphere even during high solar activity !!

Laskar, Pallamraju, Veenadhari 2014 (EPS)

Recent Progress on the Whole Atmosphere Community Climate Model - eXtended (WACCM-X)

- Ion and electron energetics implemented:
  — Now calculating T_i and T_e in WACCM-X.
- Equatorial electrodynamo installed:
  — Mostly parallel, ESMF interpolation from geographic to geomagnetic coords.
- Ionospheric dynamics implemented:
  — Vertical diffusion and horizontal transport of O^+ in the upper ionosphere.
- Variable mean molecular mass and heat capacity (C_p) included in dynamical core
- Capability for using Assimilative Mapping of Ionospheric Electrodynamics (AMIE)

- WACCM-X v. 2.0 released as a component of CESM 2, June 2018
  (but still based on CAM 4 physics)

H.-L. Liu et al. (2018), J. Adv. Mod. Earth Sys., doi:10.1002/2017MS001232

WACCM-X Global Change Simulation Methodology

Solar minimum conditions:

$F_{10.7}$ = 70, K_p = 0.3

Solar maximum conditions:

$F_{10.7}$ = 200, K_p = 3.0

- Four sets of five-year runs to simulate change in a 29-year interval:
  two with CO_2, CH_4, and CFCs from 1972–1976
  two with CO_2, CH_4, and CFCs from 2001–2005
  secular change of geomagnetic field is included

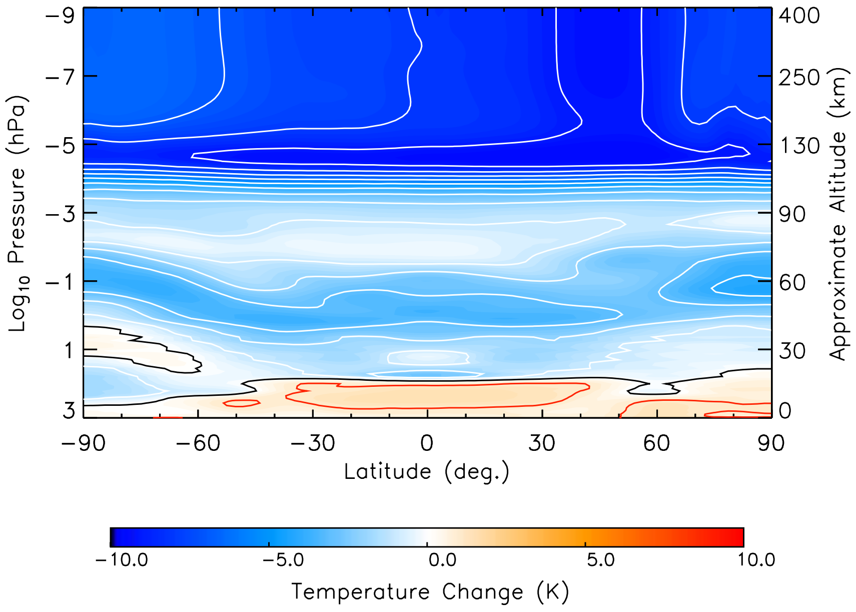
Solomon et al., 2019

- Full WACCM-X free-running climate simulations
  but using specified SSTs — no interactive ocean or sea ice, etc.
  2° resolution using FV dycore

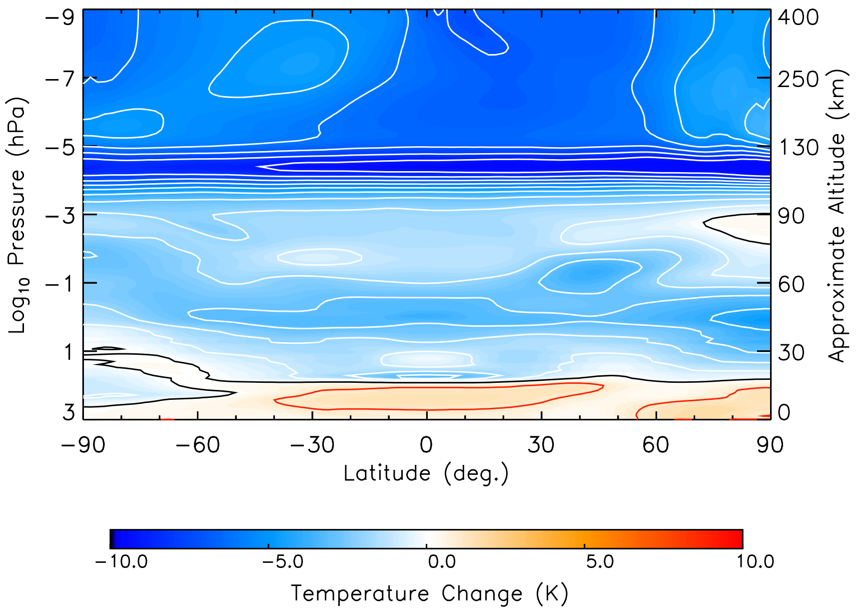
- Decadal change rates estimated by scaling from 29-year interval to 10 years

Temperature Variations – Height and Latitude Structure

Zonal Mean Temperature Change, 1974 to 2003
Solar Minimum, 5-Year Annual Averages

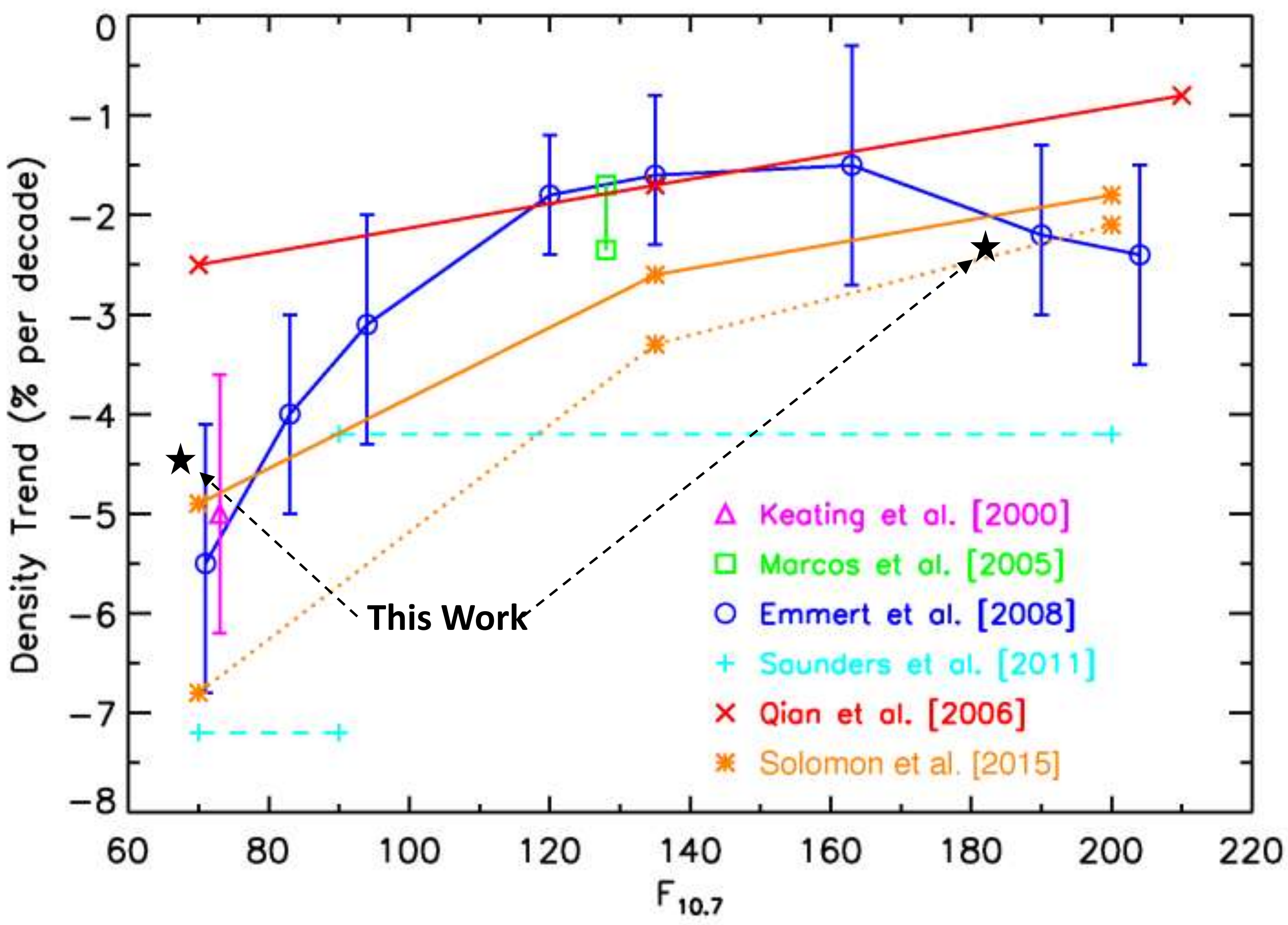


Zonal Mean Temperature Change, 1974 to 2003
Solar Maximum, 5-Year Annual Averages



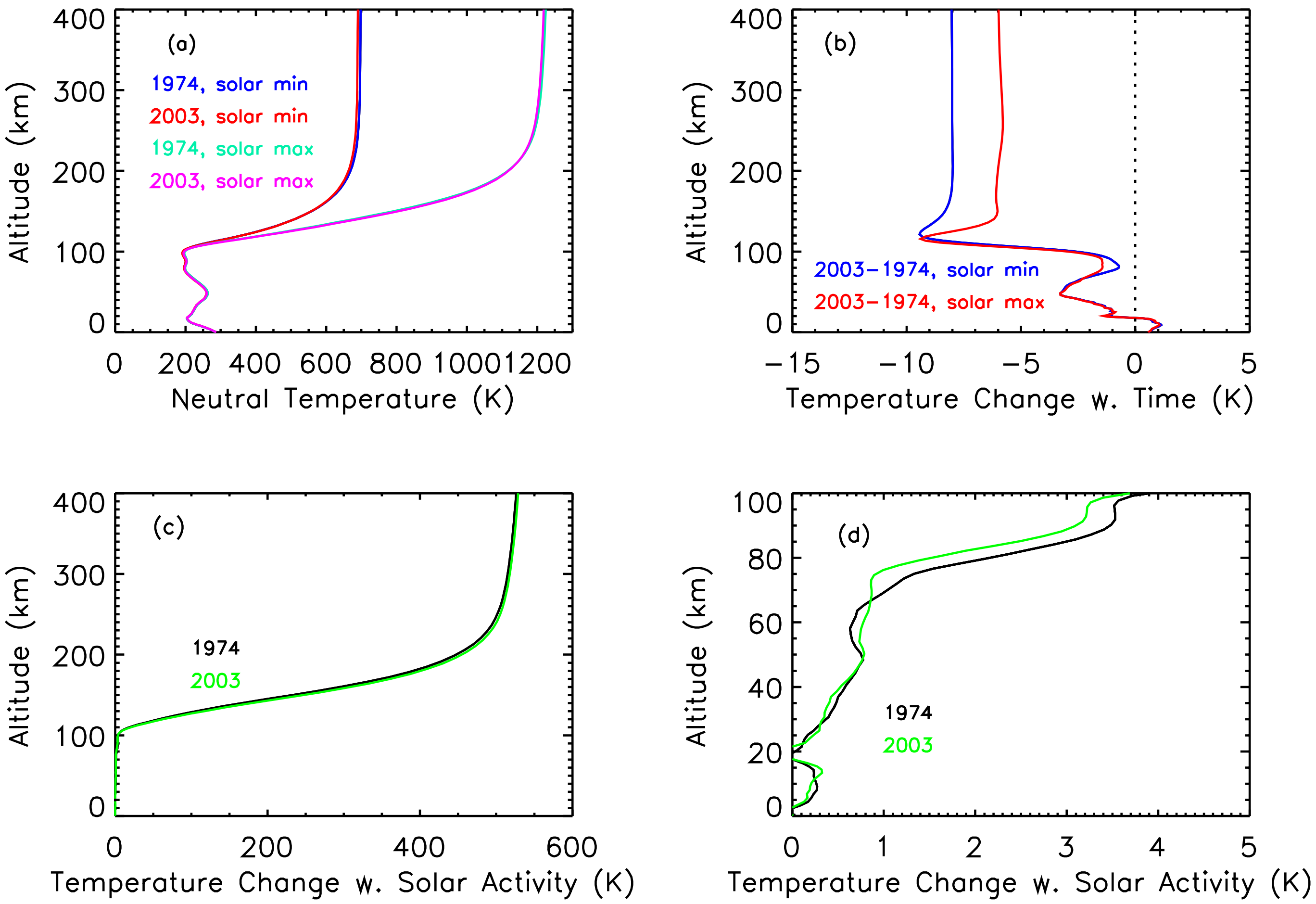
Solomon et al., 2019

Comparison of Density Trends at 400 km



Solomon et al., 2019

Mean Temperature Changes (1974 – 2003)



"Warm Down, Cool Up"

Summary

- A significant effort is still required to fully understand the Sun-Earth system.
- Inroads have been made during VarSITI in identifying downward coupling processes through which solar influences manifest themselves and upward processes modify the manner in which the solar energy is “absorbed”.
- Understanding trends remains a challenging subject, both because of the considerable variability in the atmosphere/ionosphere and because the response appears to be height and latitude dependent.
- An understanding of the processes underlying the trends remains incomplete although progress is being made

Many thanks for your attention
and
Thanks to the members of the ROSMIC team and associated scientific community for their passion and creativity in addressing these scientific issues