Influence of the 11 years solar cycle on the chemistry of MLT-region

M. Grygalashvyly, G. R. Sonnemann, and U. Berger

Leibniz-Institute of Atmospheric Physics at the University Rostock in Kühlungsborn, Schloss-Str.6, D-18225 Ostseebad Kühlungsborn, Germany

LEIBNIZ-INSTITUT FÜR ATMOSPHÄREN PHYSIK IAP

Introduction

The 11 years solar cycle one of the most significant variations of solar radiation. The Lyman-alpha flux varies in frame of the 11 years cycle with factor ~1.5. It has the strongest impact on water vapor (~80 % of dissociation above 70 km). Besides water vapor Lyman-alpha radiation takes part in dissociation of molecular oxygen (~20 % at 70-90 km), carbon dioxide (~90 % in region 65-95 km) and methane. Thus, in upper mesospher - mesopause - lower thermosphere the direct photochemical effect is expected. By the influence on enumerated above chemicaly long-living species the 11 years solar cycle act on short-living chemically active constituents as atomic oxygen, ozone, hydroxyl, etc. As a result, it effects on the dynamics by the exothermic chemical heat and radiative cooling and heating processes. In addition to a solar cycle effect, the distributions of chemical constituents and dynamical parameters are under the influence of inter-annual and short-term variability as planetary waves, gravity waves, quasi-biennial oscillation (QBO), etc. With such superposition of effects it is not easy identify in the data of measurements and realistic modelling the solar signature and separete it from other sources of variability. In the presented research we make an attempt infer direct photochemical effect of the impact of the 11 years solar cycle on the chemistry of the mesosphere/lower thermosphere (MLT) based on the calculations with global 3D-model LIMA (Leibniz-Institute Middle Atmosphere) .

Description of LIMA

LIMA (Leibniz-Institute Middle Atmosphere):

- Global 3D-Model of the dynamics
- Height 0-150 km (118 vertical levels)
- Triangular grid (41804 horizontal grid points)
- Assimilation of ECMWF-Date (1961- 2010) u, v, T below 35 km (6 h,1°x1°)
- daily Lyman-alpha
- Spectral solar irradiance [Lean 1997] relative to Lyman-alpha variability
- Solar heating by EUV lyman alpha [Chabrillat and Kockarts, 1997].
- Infrared cooling: CO2 non-LTE collisional coefficient has been enhanced to same value as in the SABER temperature retrieval calculations.
- Infrared cooling: Mesospheric water vapor for rotational and 6.3 μm bands [Zhu, 1994].
- Small-scale temperature fluctuations associated with gravity waves cause additional radiative cooling in the mesopause region [Kutepov et al., 2007].
- Numerical method of time integration (Asselin time filter) after Williams [2009] allows computation of larger wave activity (50 % increase in eddies).

Description of CTM

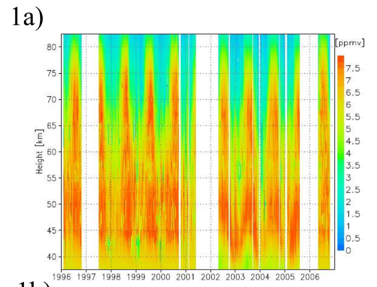
The dynamical fields calculated in LIMA are used in the chemistry transport model (CTM) consisting of a chemical, radiation and transport code.

CTM:

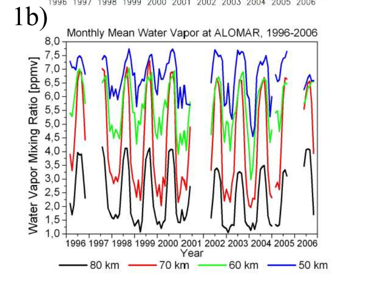
- vertical range 0-150 km
- horizontal resolution: 64 lon.g.p., 72 lat.g.p., 118 alt.g.p.
- prescribed vertical diffusion
- 22 chemical constituents: O, O(^{1}D), O_2, O_3, N, N_2, N_2O, NO, NO_2, NO_3, H, H_2, H_2O, OH, HO_2, H_2O_2, CO, CO_2, Cl, ClO, Br, BrO
- 58 chemical and 14 photodissociation reactions [Sander et al., 2006]
- On-line calcualtions for temperature-dependent reaction rates
- family concept for HX and NX
- 3D advecive transpor with Walcek-scheme characterised by low numerical diffusion [Walcek, 2000]
- Parameterization of Lyman-alpha impact on H_2O, O_2, CO_2 and CH_4 according with [Chabrillat and Kockarts, 1997]

Description of Numerical Experiment

1a)



1b)



Because of acting numerous variabilities with different time-scales it is hard to detach from measurements and modelling influence of 11 years solar cycle and proof it. Figures 1a and 1b [Hartogh et al., 2010] illustrate this fact on the example of water vapor measurements at ALOMAR (69° N).

To solve this problem we perform 2 numerical experiments.

1) with realistic variation of Lyman-alpha flux (Fig. 2) according with data of Laboratory for Atmospheric and Space Physics at the University of (ftp://laspftp.colorado.edu/pub/SEE-DATA/composite-lya) in both, dynamical and chemical parts

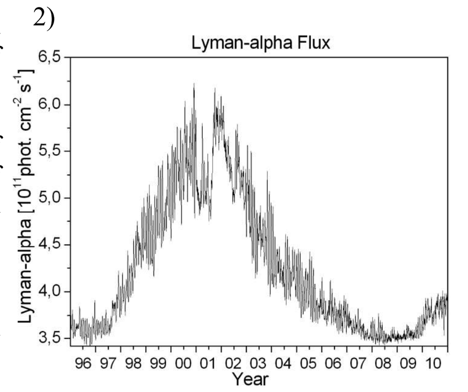
In this numerical experiment we calculate realistic distributions of minor chemical constituents X_{real}

2) with realistic variation of Lyman-alpha only in dynamical part of the model, when chemical part is assumed at solar minimum (Lyman-alpha flux 3.42d11 phot. $cm^{-2}s^{-1}$)

In this numerical experiment we calculate distributions of minor chemical constituents which are determined only by influence of dynamical variability X_{dyn}

The difference $X_{chem} = X_{real} - X_{dyn}$ allow exclude variation due to the dynamics and study the direct photochemical effect of 11 years solar cycle.

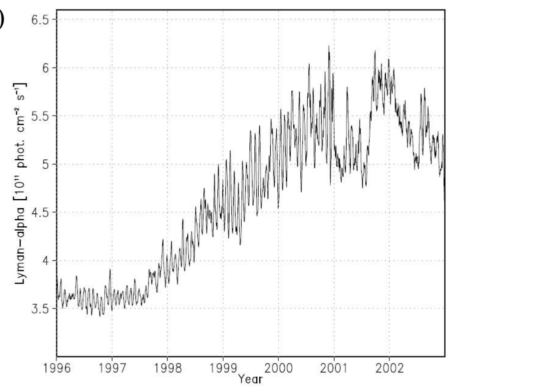
2)



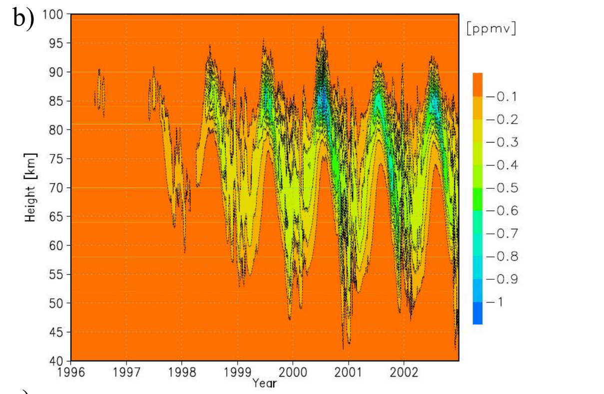
Inter-annual Variability

The figures show direct photochemical effect of 11 years solar variability at ascending phase of cycle (a) for water vapor (b), ozone (c), atomic oxygen (d) hydroxyl (e) and carbon dioxide (f) at 68.75° N.

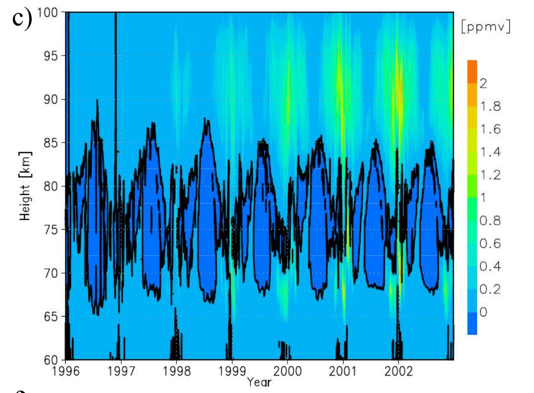
a)



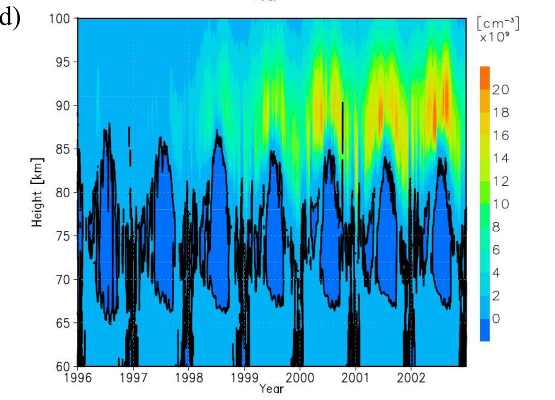
b)



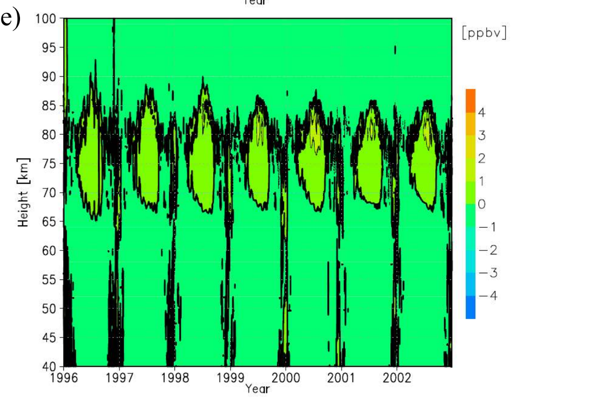
c)



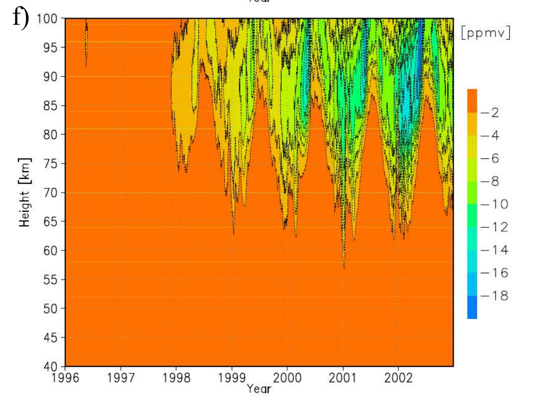
d)



e)



f)



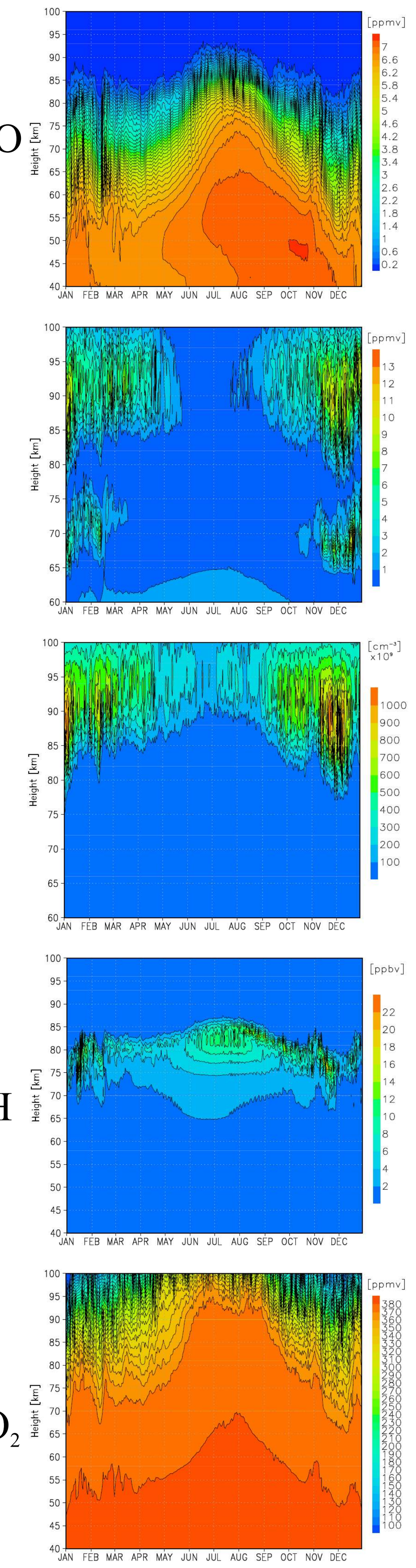
Impact on Annual Cycle

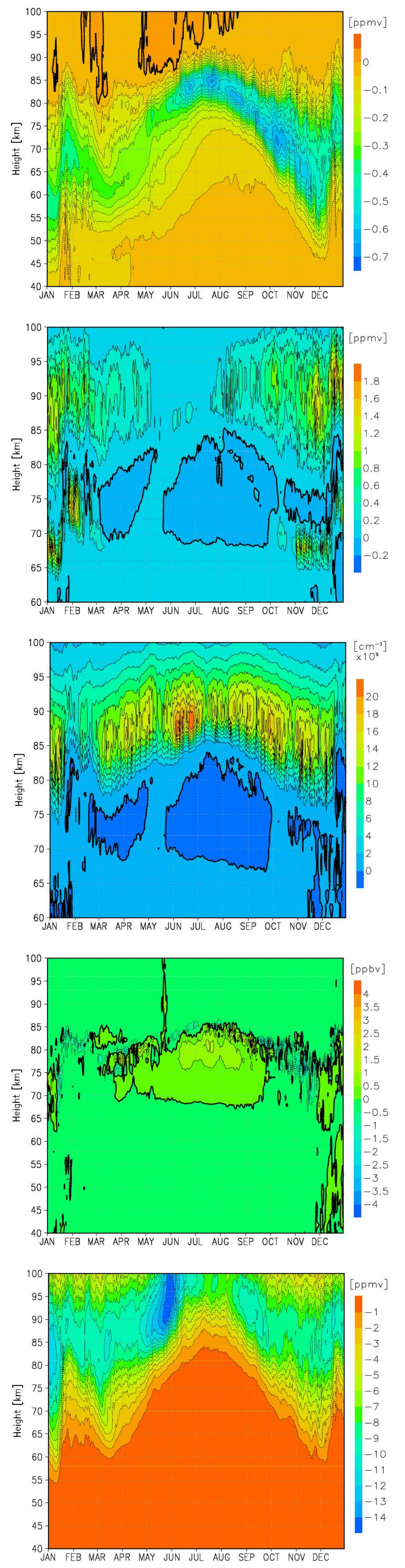
The figures in left column below show zonally averaged absolute values for minor chemical constituents calculated at realistic dynamics and realistic Lyman-alpha flux $\overline{X}_{real}$ at 68.75° N for the year of solar minimum (1996) . The figures in right column show the absolute deviation between the years of solar minimum (1996) and solar maximum (2001) of difference between realistic calculations and calculations with the same dynamics but constant Lyman-alpha flux (at min. condition 3.42d11 phot. $cm^{-2}s^{-1}$) - X_{dyn}. The deviation $(\overline{X}_{real}-\overline{X}_{dyn})_{2001}-(\overline{X}_{real}-\overline{X}_{dyn})_{1996}$ mirror the direct influence of Lyman-alpha 11 years cycle on photochemistry.

Absolute Values at 68.75° N for Year of Solar Minimum (1996) Zonally Averaged

Absolute Difference at 68.75° N Solar Max(2001) -Solar Min(1996) Zonally Averaged

H_2O, O_3, O, OH, CO_2





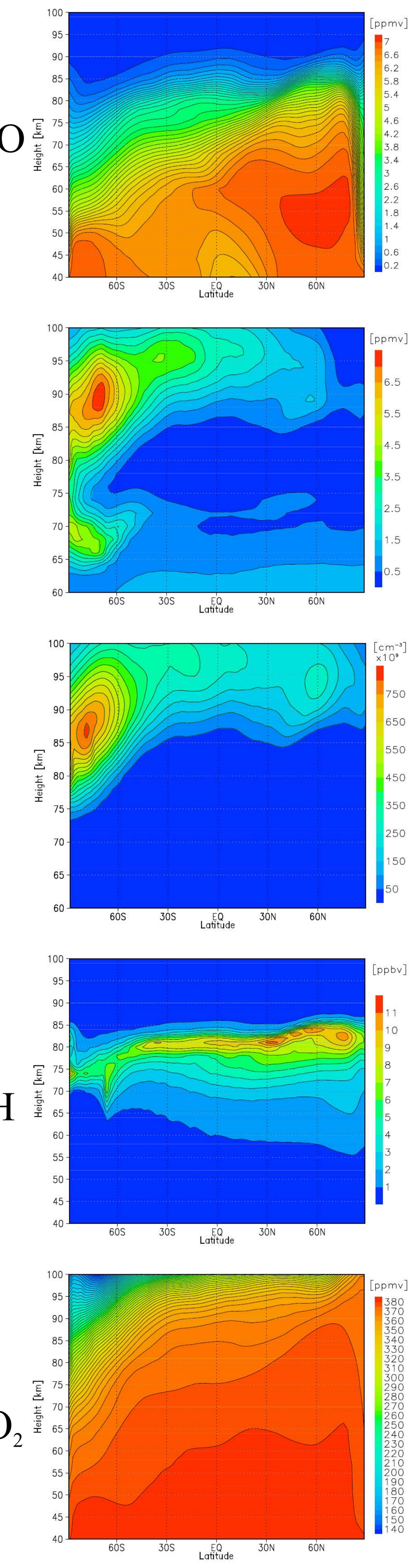
Seasonal Impact, Summer

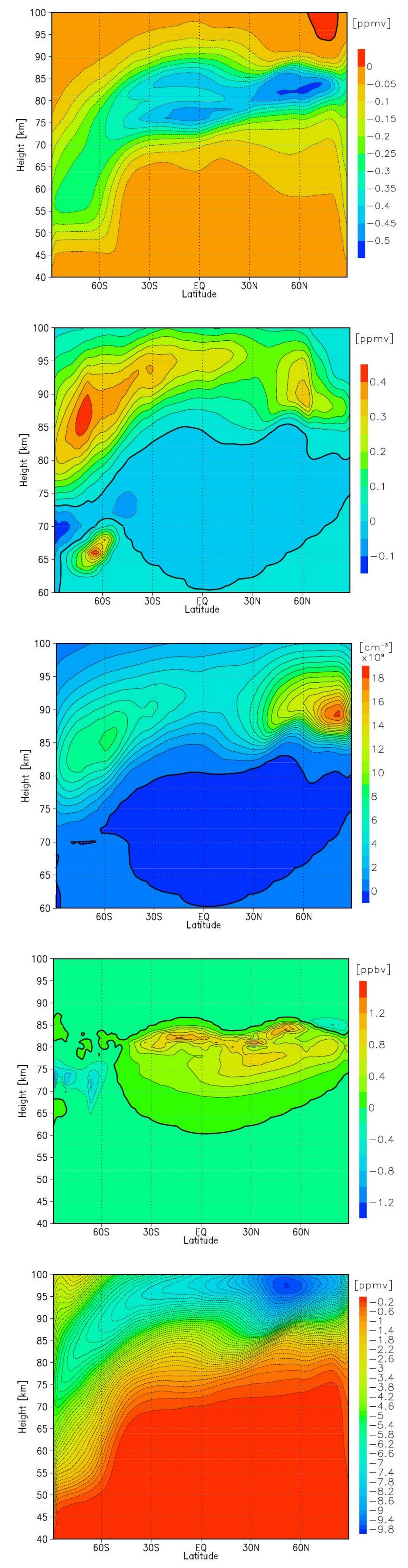
To avoid the small-scale variability we can analize seasonally averaged values. The figures in left column below show zonally and summer averaged absolute values for minor chemical constituents calculated at realistic dynamics and realistic Lyman-alpha flux $<X_{real}>$ for the year of solar minimum (1996) . The figures in right column show the absolute deviation between the years of solar minimum (1996) and solar maximum (2001) of difference between realistic calculations and calculations with the same dynamics but constant Lyman-alpha flux (at min. condition 3.42d11 phot. $cm^{-2}s^{-1}$) - X_{dyn}. The deviation $<X_{real}-X_{dyn}>_{2001}-<X_{real}-X_{dyn}>_{1996}$ reflect the direct influence of Lyman-alpha 11 year cycle on photochemistry for the north summer conditions.

Absolute Values for Year of Solar Minimum (1996) Averaged Zonally and Seasonally

Absolute Difference Solar Max(2001) -Solar Min(1996) Averaged Zonally and Seasonally

H_2O, O_3, O, OH, CO_2

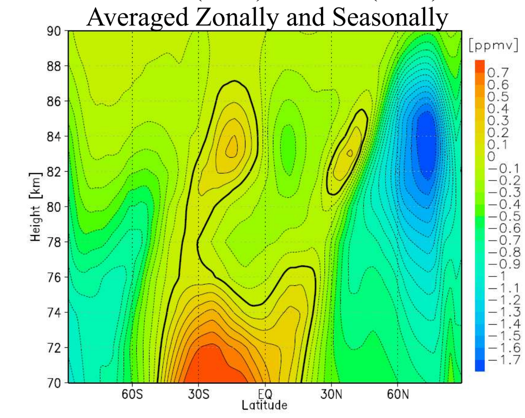




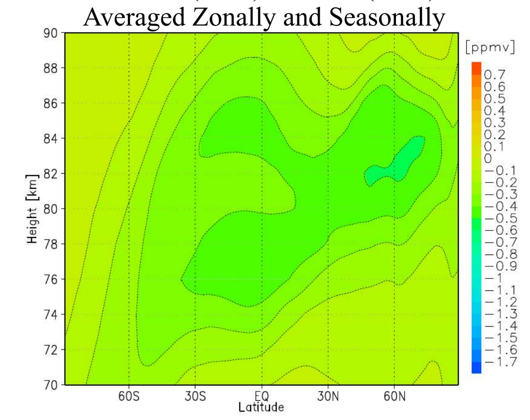
Relative Significance of the Direct Photochemical Effect

In order to infer where and how the direct photochemical effect of Lyman-alpha solar cycle is significant, we calculate the ratio of total changes for given chemical constituent to the changes determined by direct photochemical effect. The figures below illustrate such estimation on example of water vapor for the summer of solar minimum (1996) and solar maximum (2001). If the ratio lower than 2 and higher than -1 the direct photochemical effect of colar cycle exceed the variability due to the dynamics and we can consider it as significant. At zero line dynamical variability changes the direction of influence and in negative area it act oppsitely to the solar cycle effect. In positive area the dynamical variability surpass the direct photochemical effect. For example, at high summer latitudes the ratio equel ~3-4 that means the direct photochemical influence consists 25-30 % of total variability.

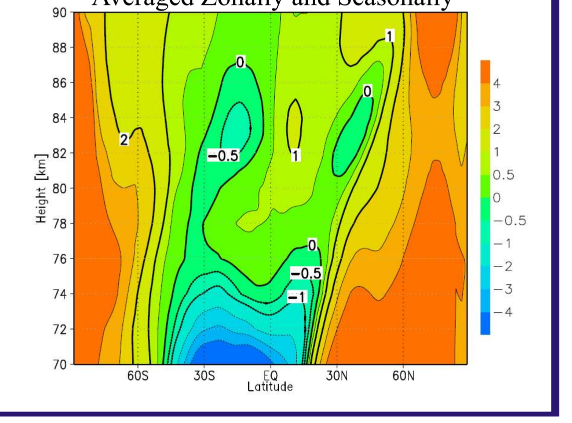
Total Changes of H_2O Sol. Max(2001)-Sol. Min(1996) Averaged Zonally and Seasonally



The Changes of H_2O due to Direct Photochemical Impact Sol. Max(2001)-Sol. Min(1996) Averaged Zonally and Seasonally



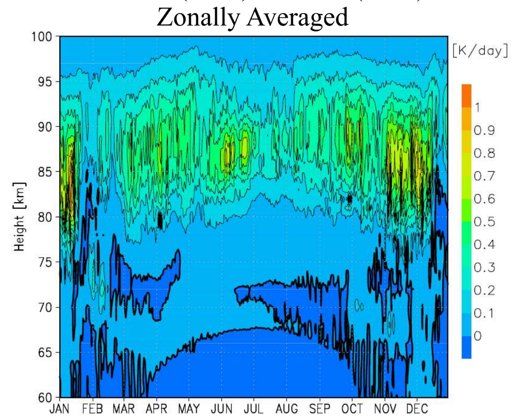
Ratio of the Total Changes of H_2O to the Changes Determined by Direct Photochemical Impact Sol. Max(2001)-Sol. Min(1996) Averaged Zonally and Seasonally



Influence on Thermal Regime

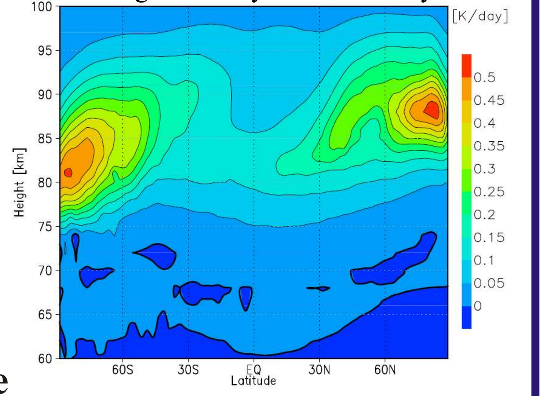
Exothermic Chemical Heat

The Changes of Exothermic Chemical Heat due to Impact of 11-years Cycle at 68.75° N Sol. Max(2001)-Sol. Min(1996) Zonally Averaged



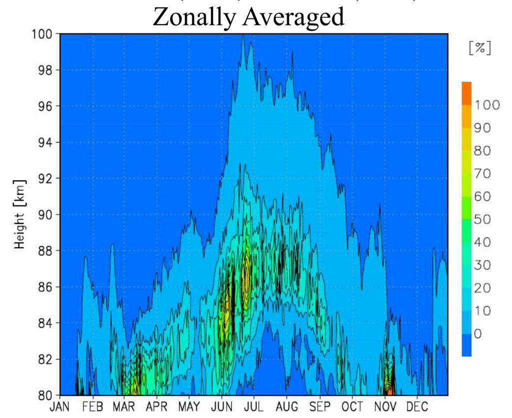
The growth of chemical heat at ~80-85 km in years of solar maximum mainly results from the increase of reaction yield of $O+O+M \rightarrow O_2+M$, which is determined by rise of atomic oxygen in this region. The change of the thermal regime by the exothermic chemical heat feeds back to the dynamical system, influences the chemical reaction rates, and may influence on GWs, as was described by Leovy [1966]

The Changes of Exothermic Chemical Heat due to Impact of 11-years Cycle Sol. Max(2001)-Sol. Min(1996) Averaged Zonally and Seasonally



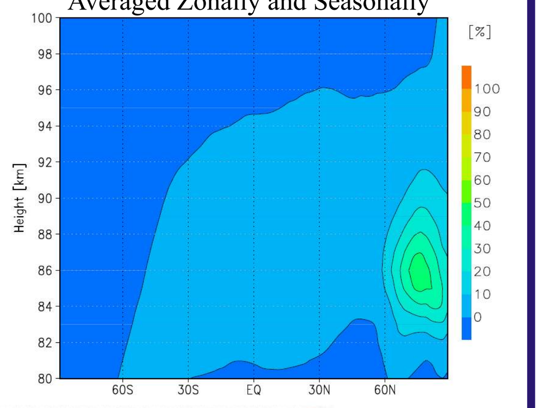
Microwave Cooling by Carbon Dioxide

Relative Deviation of Cooling Rate at 68.75° N Sol. Max(2001)-Sol. Min(1996) Zonally Averaged

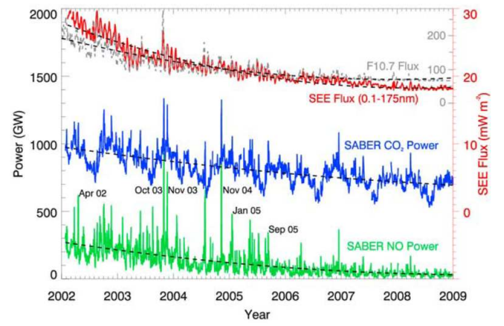


Carbon dioxide is the main radiative cooling agent in the middle atmosphere. The stronger dissociation of molecular oxygen in years of solar maximum generates more atomic oxygen. As a result, the anelastic collisions between atomic oxygen and carbon dioxide reduce non-LTE, and this becomes the dominant pathway for radiative cooling in this region. Assuming that the cooling rate (CR) due to infrared emission by carbon dioxide is proportional to the number density of carbon dioxide, [CO_2], and the number density of atomic oxygen, [O], we can estimate the relative deviation of the cooling rate at about 80-100 km

Relative Deviation of Cooling Rate Sol. Max(2001)-Sol. Min(1996) Averaged Zonally and Seasonally



From the SABER observation a large decrease in the radiative cooling by carbon dioxide was derived at the descending phase ofsolar cycle [Mlynczak et al., 2010; Lu et al., 2010]. The figure (right) shows time series of daily solar EUV flux from 0.1 to 175 nm as measured by the Thermosphere Ionosphere Mesosphere Energetics and Dynamics satellite Solar EUV Experiment (SEE) instrument (red), the F10.7 index (gray), and the daily global CO2 15 mm (blue) and NO 5.3 mm (green) radiative power integrated over the altitude range of 100–200 km. The dashed lines represent the least squares fit to the solar flux and cooling power.



Summary and Conclusions

- The solar Lyman-α radiation impacts the water vapor mixing ratio particularly in winter above 60 km, in summer above75 km.
- The difference of water vapor due to direct photochemical effect of 11 years solar cycle has maximum around mesopause with values ~0.5-1 [ppmv]
- The direct effect of 11 years solar cycle on water vapor in summer mesopause reach 25-30 % of total variation.
- Lyman-alpha variation with 11 years period strongly modulate chemistry of MLT.
- The impact is strong enough to produce 11 years cycle in NLC and PMSE occurrence rate.
- The Lyman-alpha variation with 11 years period modulate exothermic chemical heat and radiative cooling, thus influence on thermal regim of MLT.
- The change of the thermal regime by the exothermic chemical heat radiative cooling feeds back to the dynamical system.

References

- Berger, U., Modeling of the middle atmosphere dynamics with LIMA, J. Atmos. Sol. Terr. Phys., 70, 1170-1200, 2008.
- Hartogh, P., G. R. Sonnemann, M. Grygalashvyly, L. Song, U. Berger, and F.-J. Lübken, Water vapor measurements at ALOMAR over a solar cycle compared with model calculations by LIMA, J. Geophys. Res., 115, D00I17, doi:10.1029/2009JD012364, 2010.
- Mlynczak, M. G., et al., Observations of infrared radiative cooling in the thermosphere on daily to multi year timescales from the TIMED/SABER instrument, J. Geophys. Res., 115, A03309, doi:10.1029/2009JA014713, 2010
- Walcek, C. J., Minor flux adjustment near mixing ratio extremes for simplified yet highly accurate monotonic calculation of tracer advection, J. Geophys. Res., 105, 9335-9348, 2000.
- Lu, G., M. G. Mlynczak, L. A. Hunt, T. N. Woods, and R. G. Roble, On the relationship of Joule heating and nitric oxide radiative cooling in the thermosphere, J. Geophys. Res., 115, A05306, doi:10.1029/2009JA014662, 2010.