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Modeling of the spectral solar irradiance and energetic particle effects on the atmospheric chemistry and climate.

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with contribution from FUPSOL (J. Anet, F. Arfeuille, J. Beer, S. Brönnimann, Y. Brugnara, S. Muthers, T. Peter, C. Raible, A. I. Shapiro, A. V. Shapiro, W. Schmutz, F. Steinhilber) and COST (T. Egorova) teams

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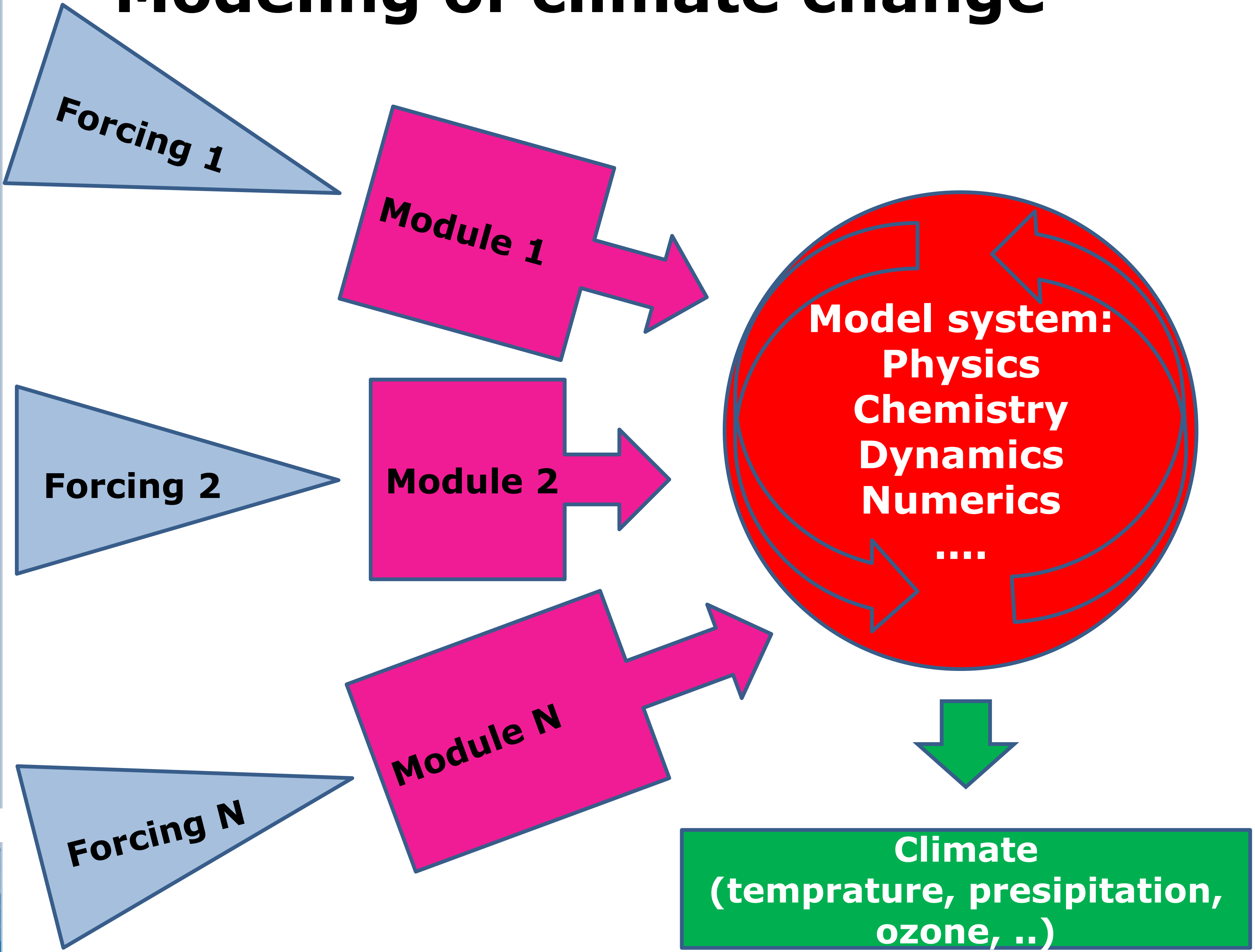
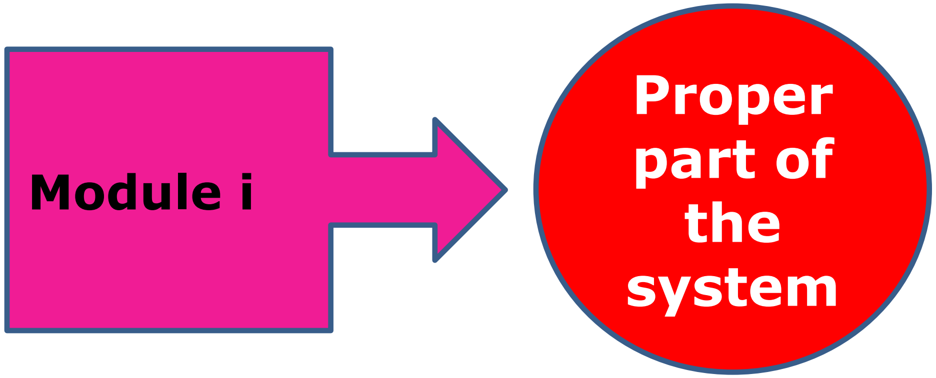
Modeling of climate change

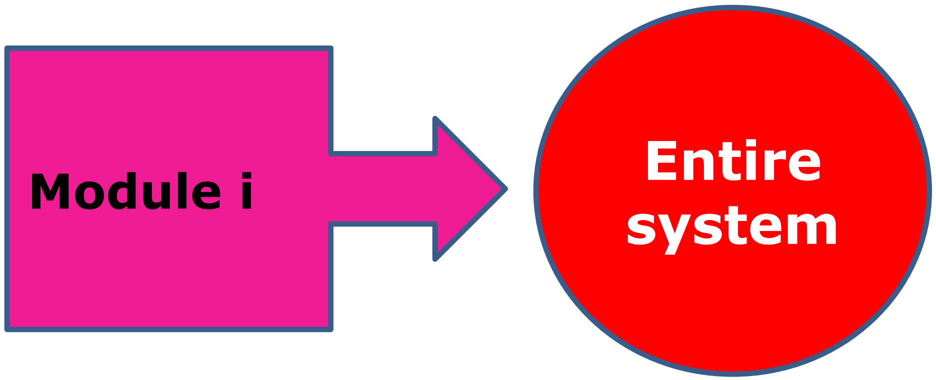


Direct response



Shorter time scales
Lower noise
Useful for model validation

Indirect response

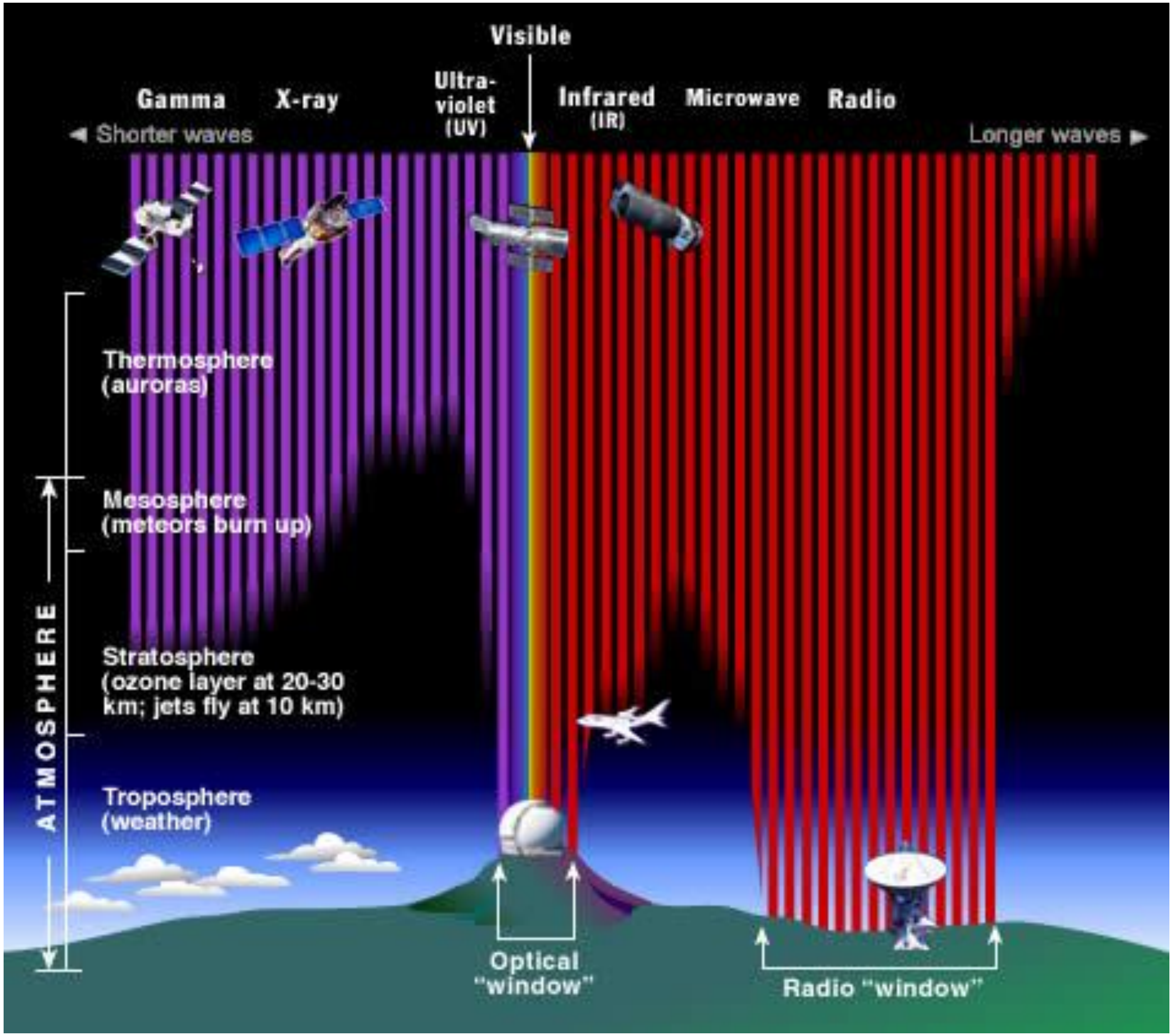


Longer time scales
Higher noise
Difficult to analyze
Important for the outcome

Drivers related to the Sun

- Solar irradiance in UV, visible and near infrared
- Magnetospheric/auroral electrons
- Radiation belt electrons
- Solar protons (SPE)
- Galactic cosmic rays

Penetration depth



From http://www.windows2universe.org

Solar irradiance in UV (>300 nm), visible and near infrared

Linked to:

- Radiation code
- Energy balance at the surface

Direct effects :

- Absorption/reflection in the troposphere and by the land/ocean/clouds
- Absorption by water vapor, ozone and some other GHG

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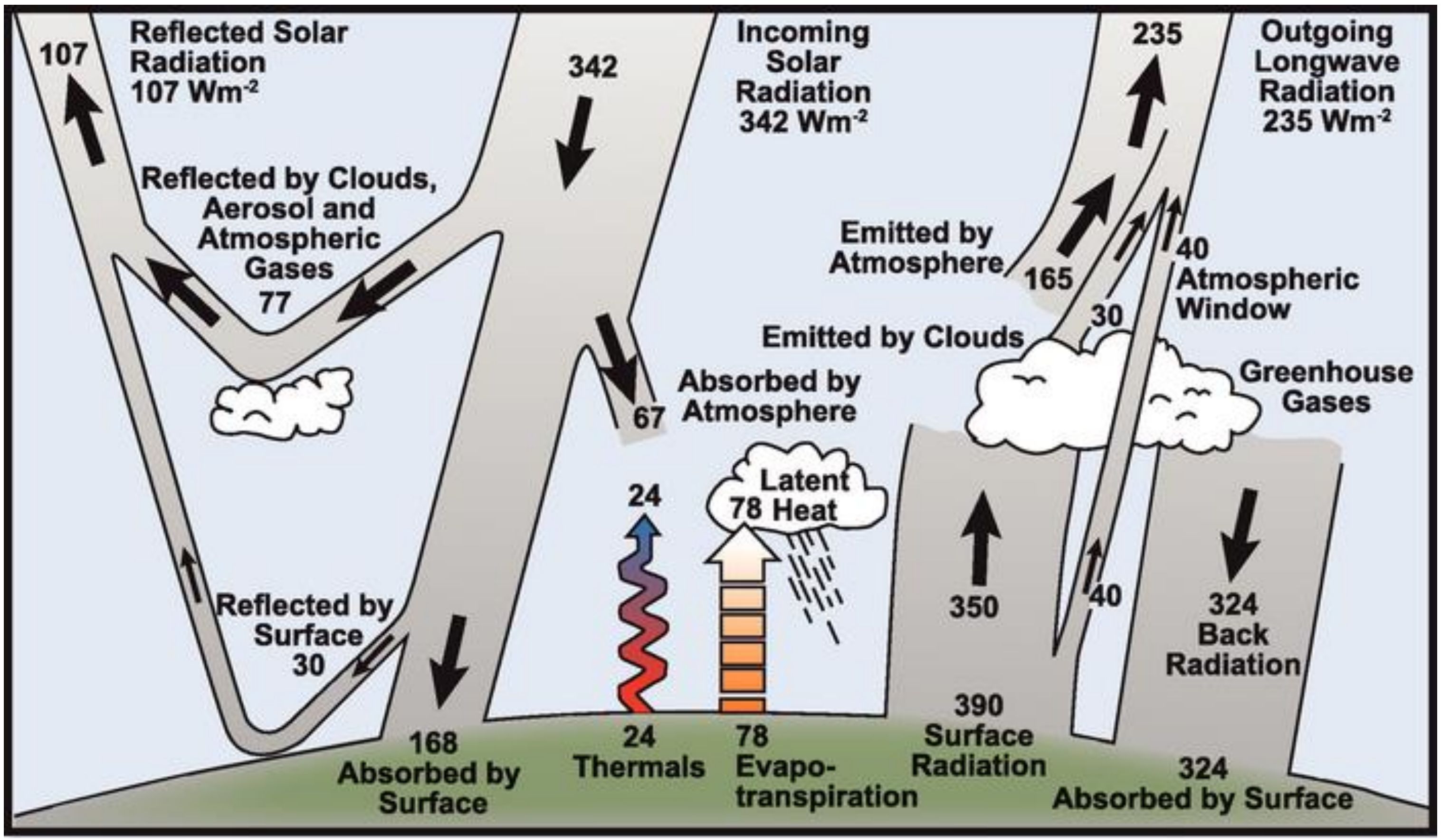
Earth's annual and global mean energy balance.



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Solar UV irradiance

Linked to:

- **Radiation code**
- **Chemical code**

Direct effects:

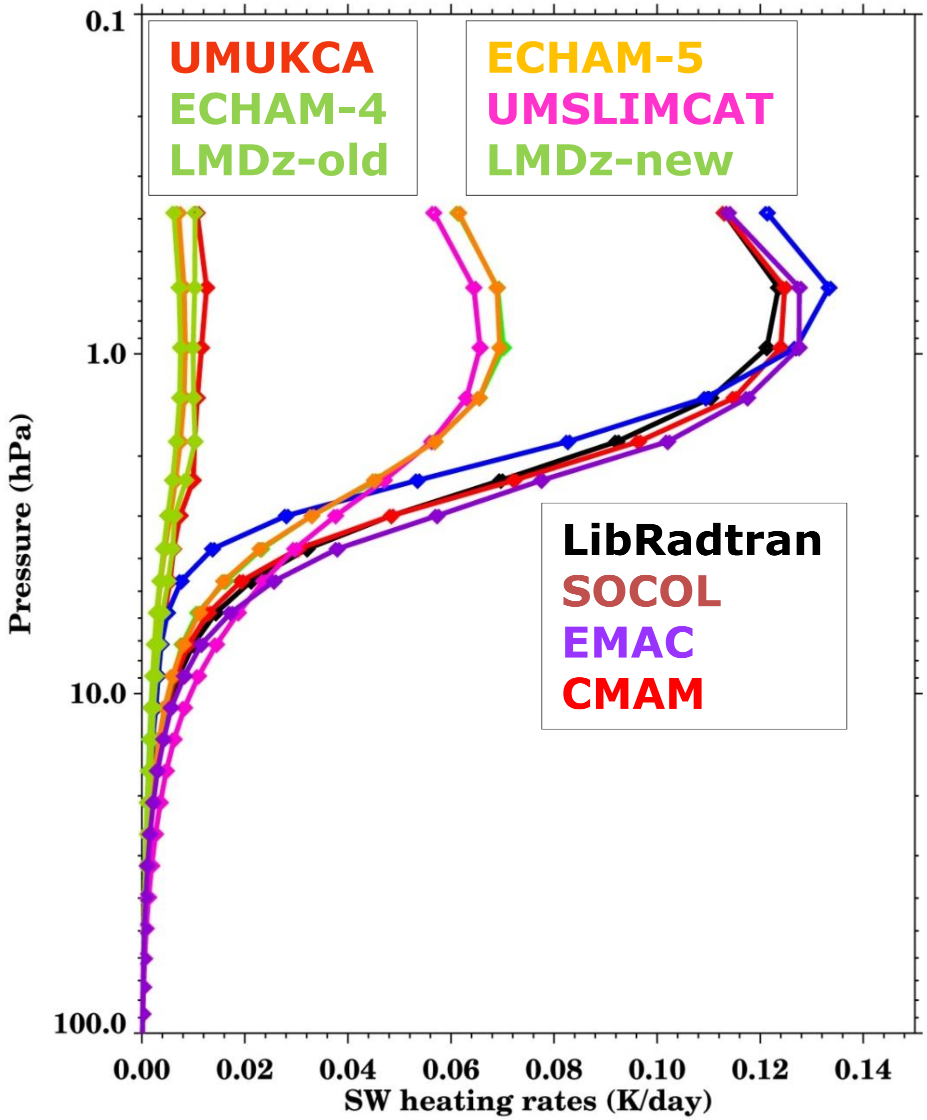
- **Heating of the atmosphere by ozone and oxygen absorption**
- **Ozone production**

(O_2+hv=>O+O; O_2+O+M=>O_3)

- **Activation of radicals:**
  O_3+hv=>O(^{1}D)+O_2 followed by
  SG + O(^{1}D) => RO

SG - source gas; RO - radicals

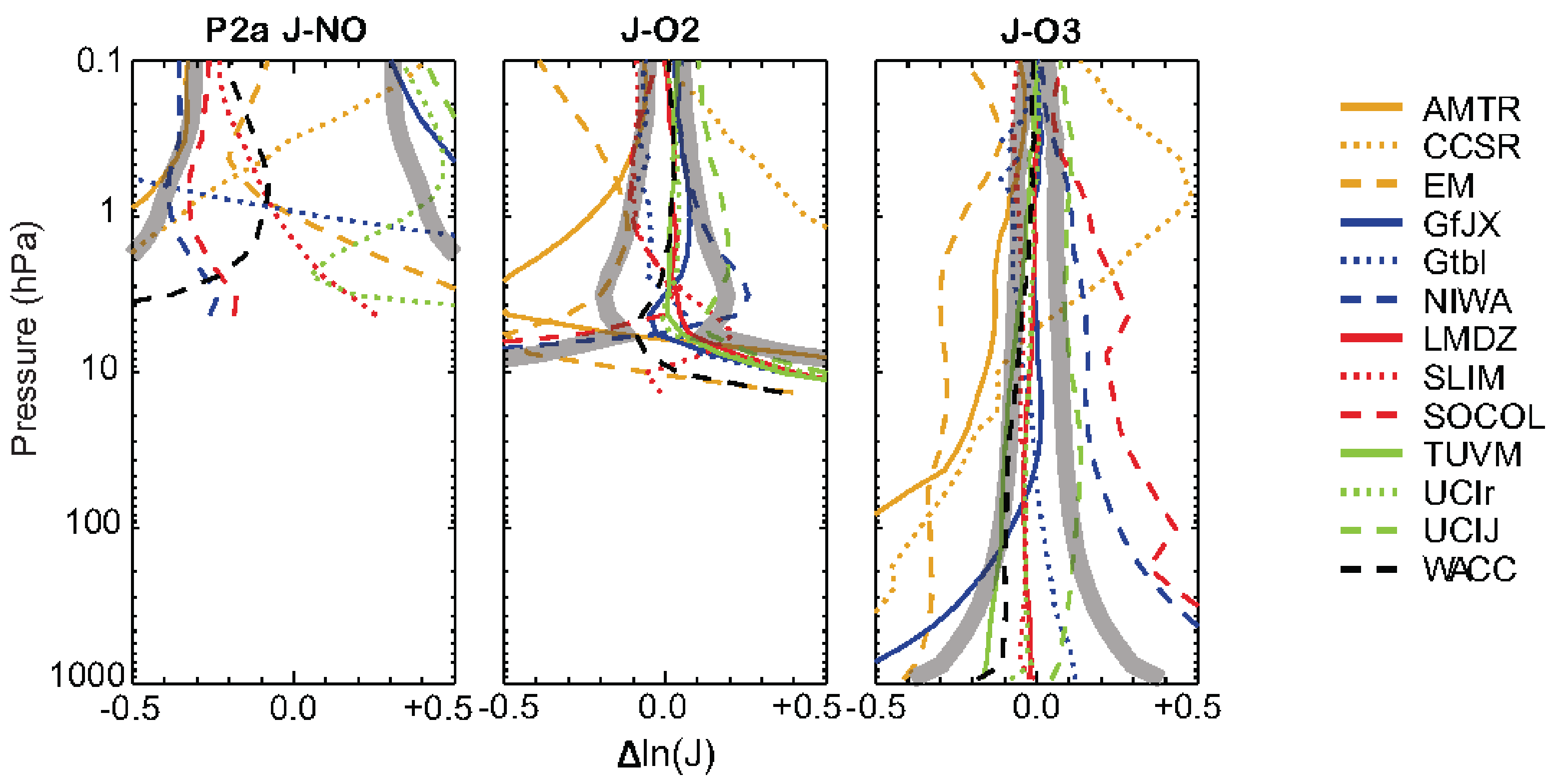
Performance of the radiation codes



CCMVal-2 data,
All models

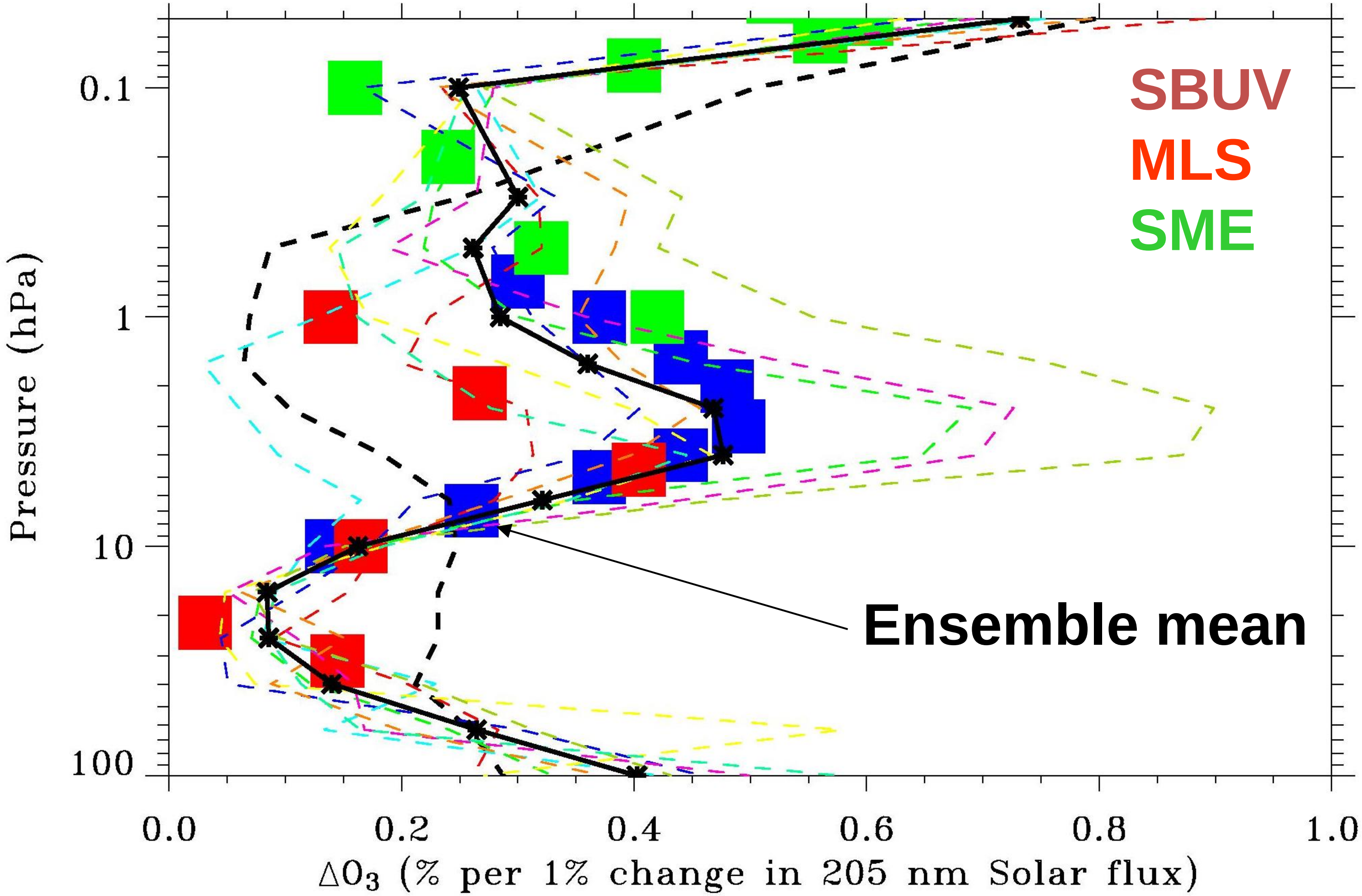
Near-global mean, short-wave heating rate differences between minimum and maximum of the 11-year solar cycle in January (K/day), from Forster et al. (2011)

Comparison of the photolysis rates



SPARC CCMVal report, chapter 6, Photocomp

Ozone response to SUV 27-day variability



Rozanov et al., 2006; similar results in Gruzdev et al., 2006

Precipitating energetic particles

Linked to:

➢ **Chemical code**

Direct effects :

➢ **Production of NO_x and HO_x followed by ozone destruction in the stratosphere**

NOx production by energetic particles

Ionization by auroral electrons leads to the enhancement of N or NO, e.g.,

$N_2 + e^* \Rightarrow N^+ + N(^4S) + 2e^-$

$N_2 + e^* \Rightarrow N(^2D) + N(^4S) + e^-$

$N_2 + e^* \Rightarrow N_2^+ + 2e^-$

$N_2^+ + O \Rightarrow NO^+ + N(^4S)$

$N_2 + N^+ \Rightarrow N_2^+ + N(^4S)$

$N_2^+ + e^- \Rightarrow N(^2D) + N(^4S)$

$N(^2D) + O_2 \Rightarrow NO + O$

But

$NO + h\nu \Rightarrow N(^4S) + O$

$N(^4S) + NO \Rightarrow N_2 + O$

From Rozanov et al., 2012

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HOx production by Auroral electrons

Ionization by auroral electrons leads to the enhancement of HOx, e.g.,

$$O_2^+ + O_2 \rightarrow O_4^+ \quad (R-13(a))$$

$$O_4^+ + H_2O \rightarrow O_2^+(H_2O) + O_2 \quad (R-13(b))$$

Larger cluster ions can then be formed by reaction pathways like:

$$O_2^+(H_2O) + H_2O \rightarrow H_3O^+(OH) + O_2 \quad (R-14(a))$$

$$O_2^+(H_2O) + H_2O \rightarrow H^+(H_2O) + OH + O_2 \quad (R-14(b))$$

Those can then be followed by the formation of larger protonised water cluster ions, like

$$H_3O^+(OH) + H_2O \rightarrow H^+(H_2O)_2 + OH \quad (R-15(a))$$

$$H^+(H_2O)_n + H_2O \rightarrow H^+(H_2O)_{n+1} \quad (R-15(b))$$

During all these reaction chains, recombination reactions with electrons can take place:

$$H_3O^+(OH) + e^- \rightarrow H_2O + H + OH \quad (R-16(a))$$

$$H^+(H_2O)_n + e^- \rightarrow H + nH_2O \quad (R-16(b))$$

From Sinnhuber et al., 2012

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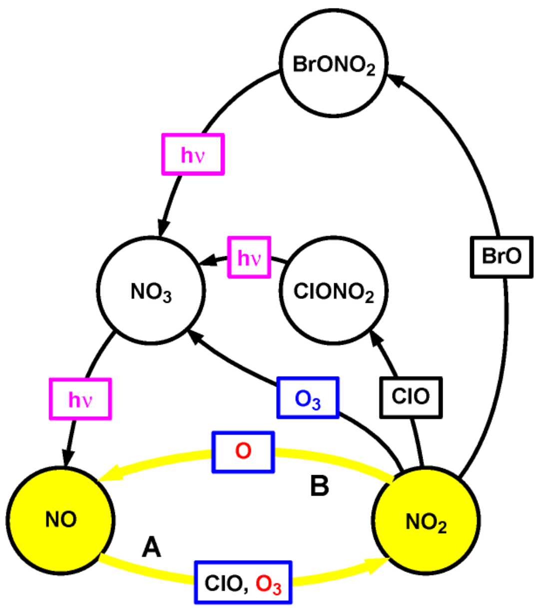
Ozone depletion by NOx and HOx

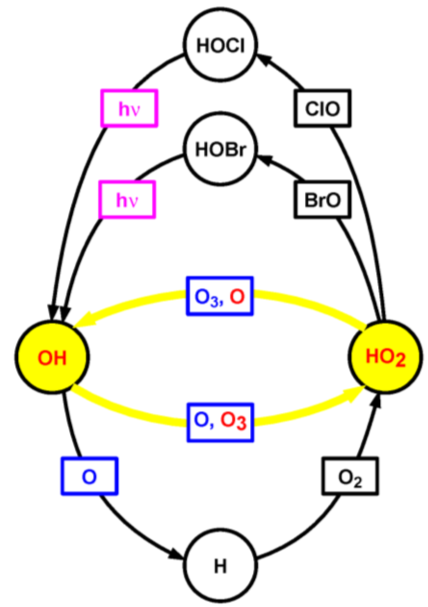
Nitrogen:

$NO + O_3 \rightarrow NO_2 + O_2$
$NO_2 + O \rightarrow NO + O_2$
========================
$O_3 + O \rightarrow 2O_2$

Hydrogen:

$OH + O_3 \rightarrow HO_2 + O_2$
$HO_2 + O \rightarrow OH + O_2$
========================
$O_3 + O \rightarrow 2O_2$

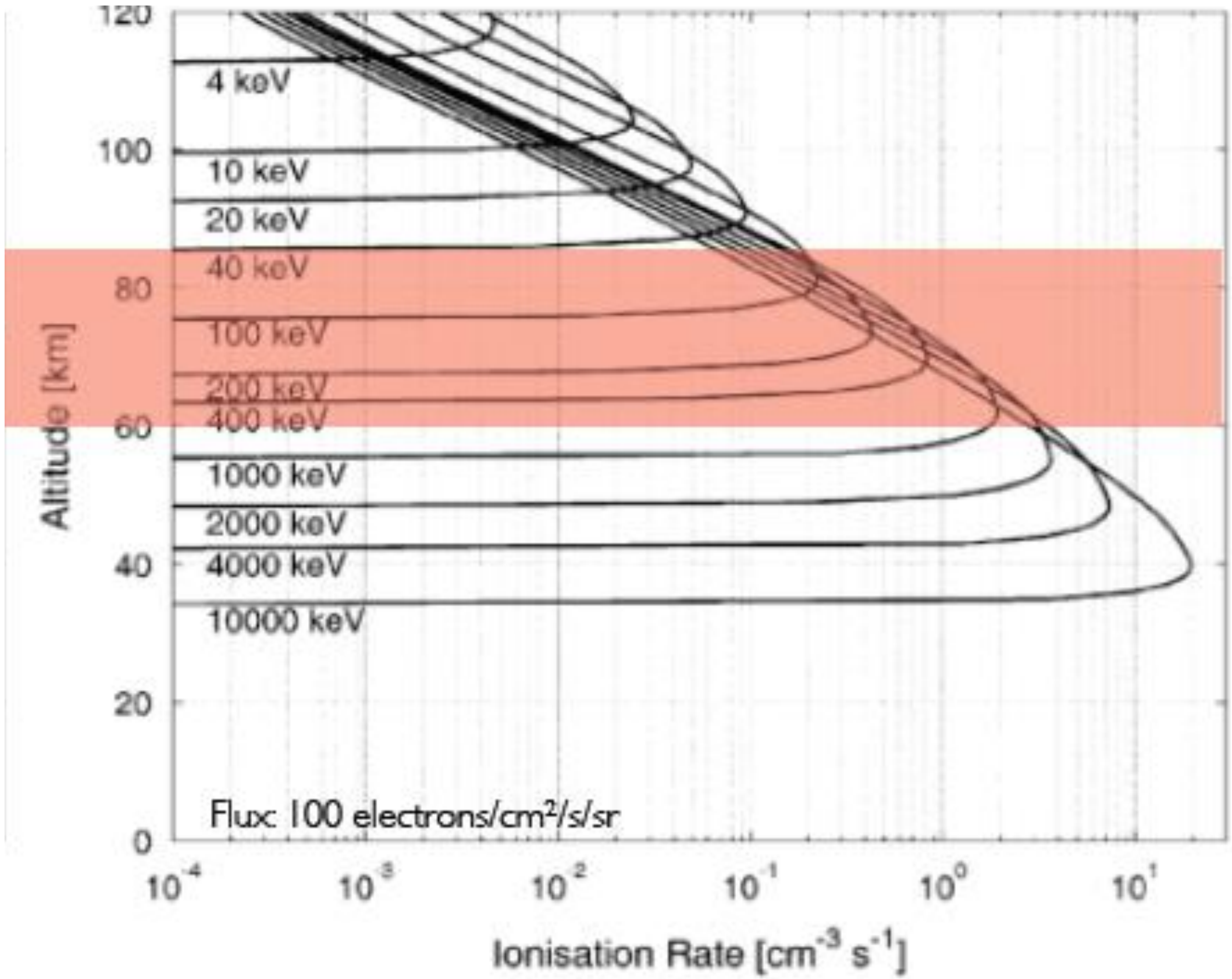




From D. Lary

Response to magnetospheric electrons

Ionization by electrons

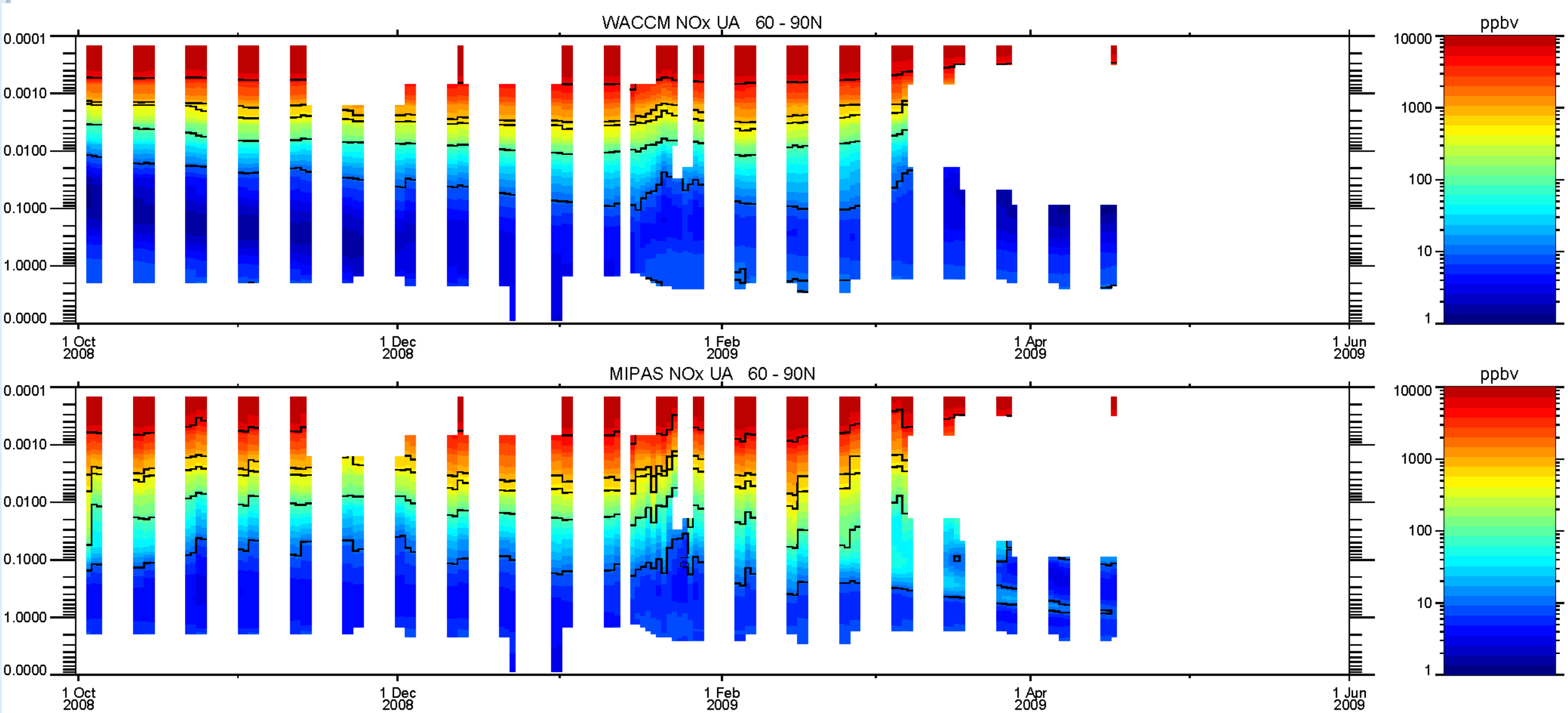


Turunen et al., 2009

Treatment of the auroral electrons (WACCM)

- Model top at 130 km
- Simplified ion chemsitry, major ions (N_2^+, N^+, O_2^+ and O^+) => works only above 90 km
- Ionization rates are based on hemispheric power/ Kp index
- Ionization by electrons (>40 KeV) is absent

MIPAS-WACCM, winter 2008-2009



Treatment of the auroral electrons (EMAC, SOCOL)

- Model top at 80 km
- NOx influx to the model domain is parameterized using Ap index
- Advective and diffusive transport
- Ionization by electrons (>30 kEV) is absent

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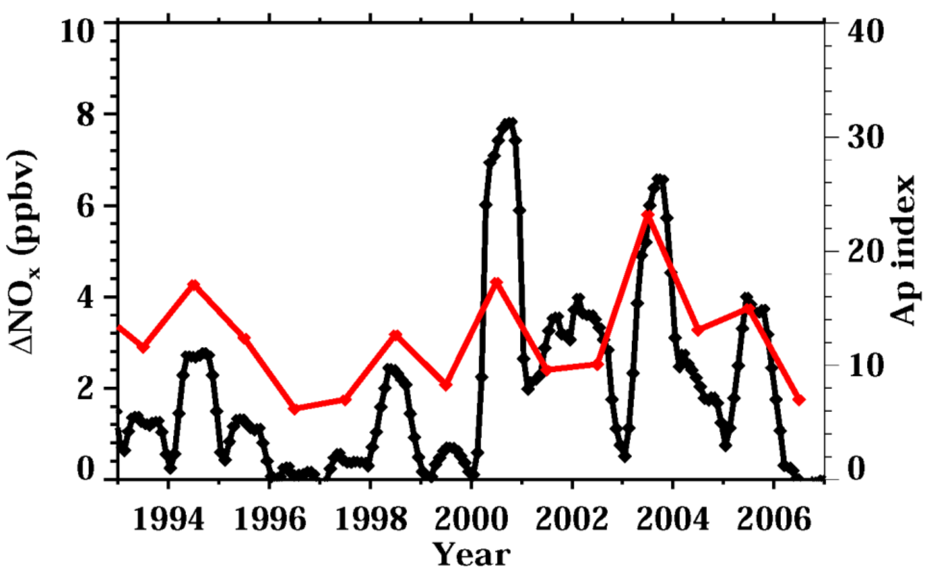
Treatment of the auroral electrons (EMAC, SOCOL)

following time dependency was chosen:

$$F = A_p^{2.5} \cdot c \cdot 2.20 \times 10^5 \mathrm{cm}^{-2}\mathrm{s}^{-1} \cdot \max\left(0.1, \cos(\pi / 182.625 \cdot (d - 172.625))\right), \quad (4)$$

where d is day of year. This sinusoidal variation centered around solstice represents the minimum requirement of a seasonal variation with maximum in winter. The 10% flux

Baumgartner et al, 2009



Rozanov et al., 2012

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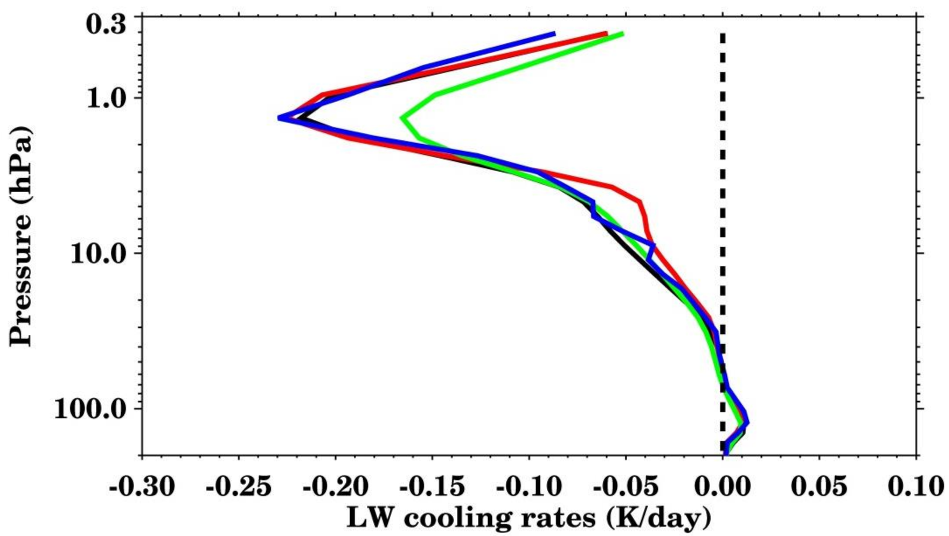
Effects of the auroral electrons

Rozanov et al., 2012



January
Polar
AER LBL code

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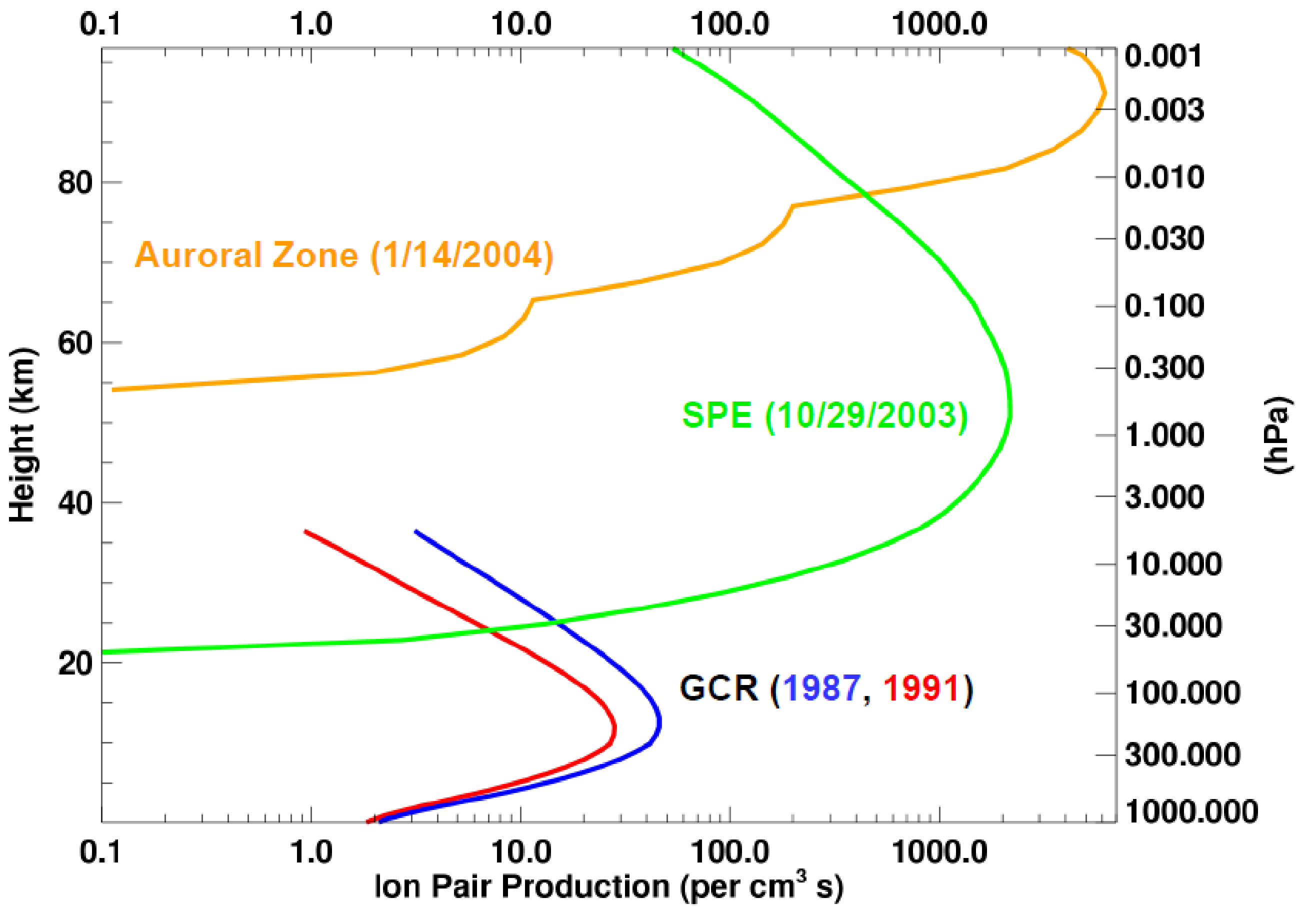
Treatment of the magnetospheric (30-300 KeV) electrons in CMAM

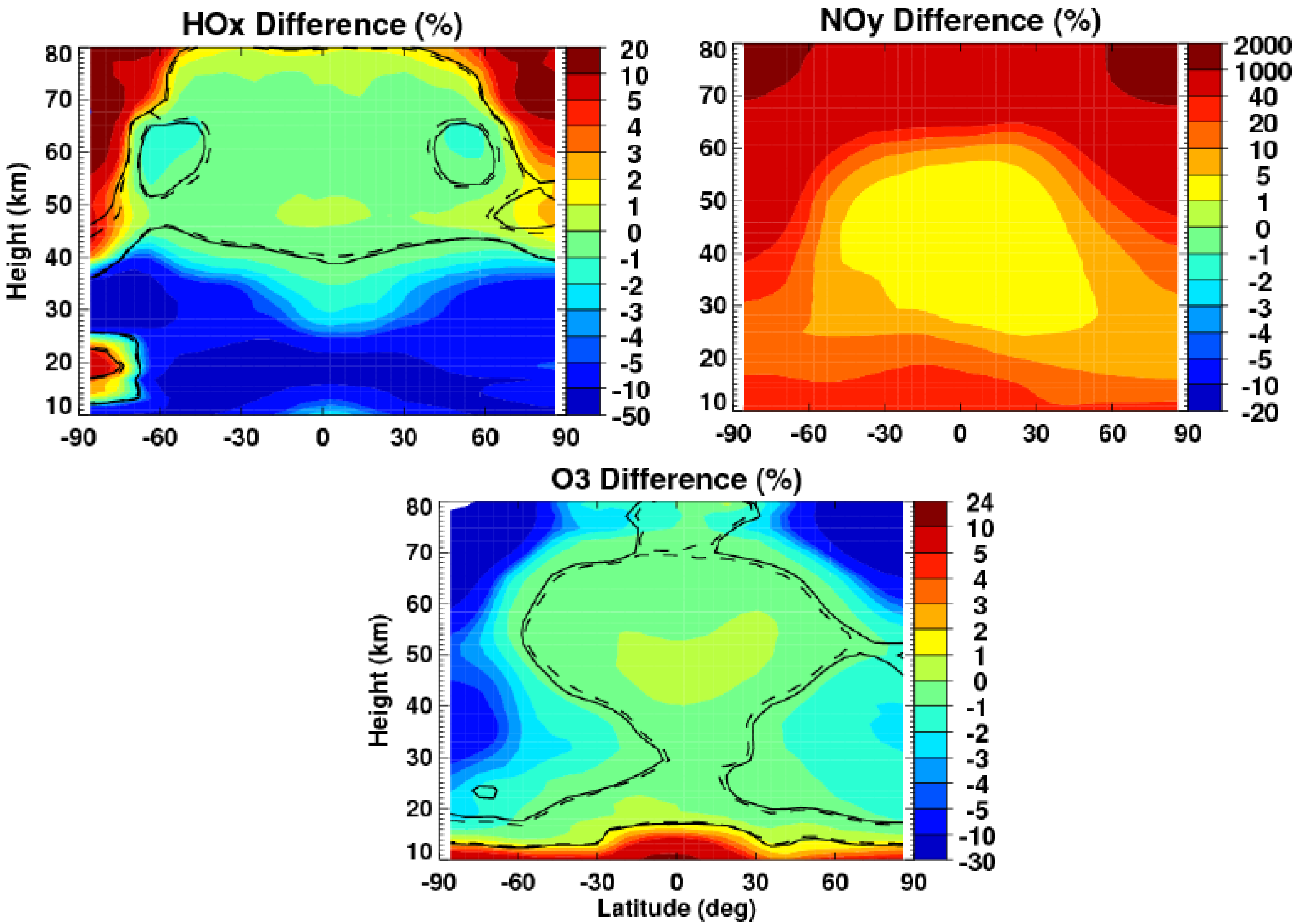
- Model top at 90 km
- Parameterized source of NO_x and HO_x. Production of 0.7 $N(^2D)$ and 0.55 $N(^4S)$ per ion pair
- Ionization rates from electrons (>30 kEV) are based on satellite data and energy deposition code,
- No thermospheric NO_x

Treatment of the magnetospheric electrons (CMAM)



Semeniuk et al., 2011

Effects of the magnetospheric electrons



Semeniuk, 2011

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Response to solar proton events

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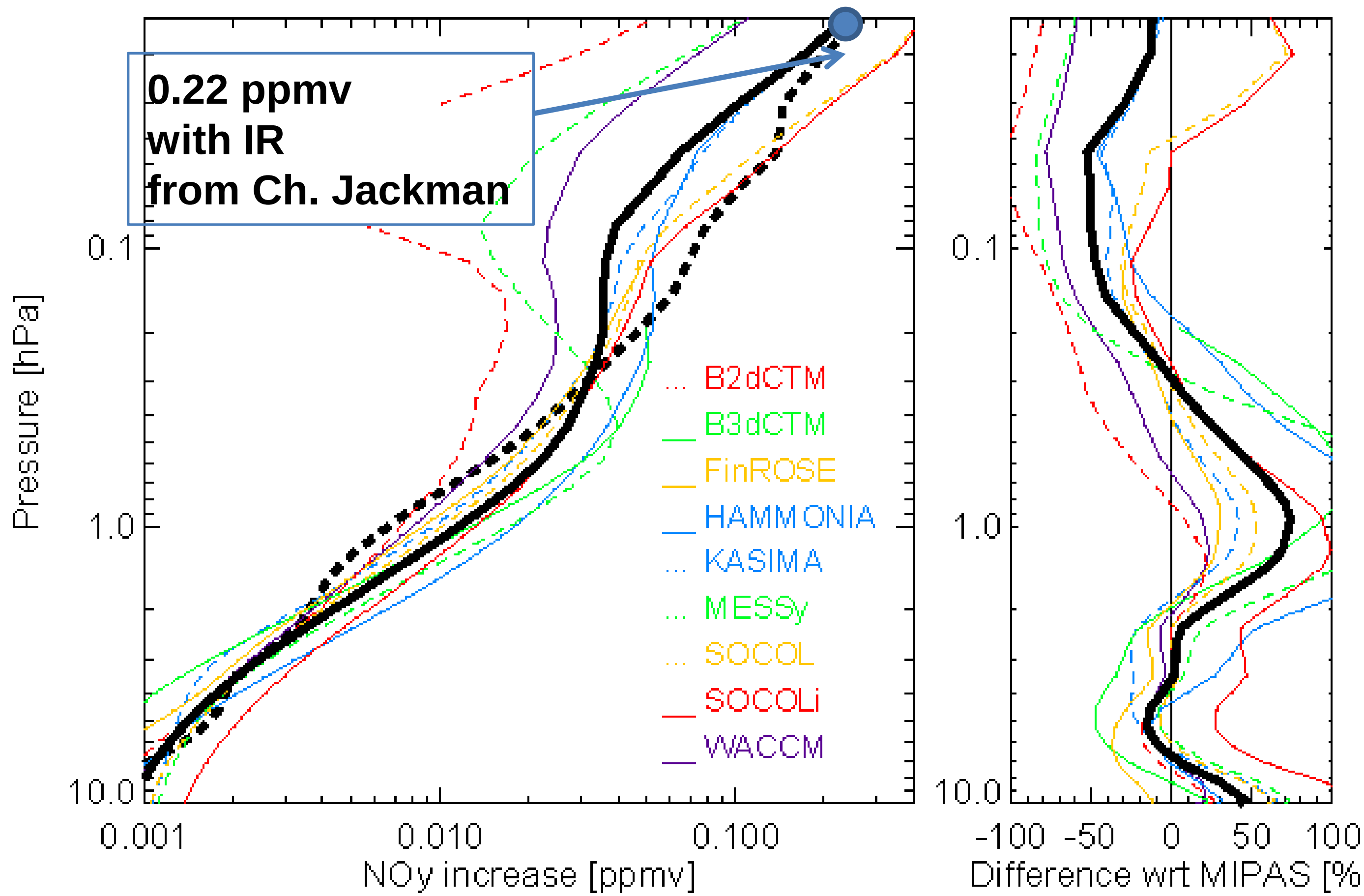
NO_y changes due to Haloween storm SPE

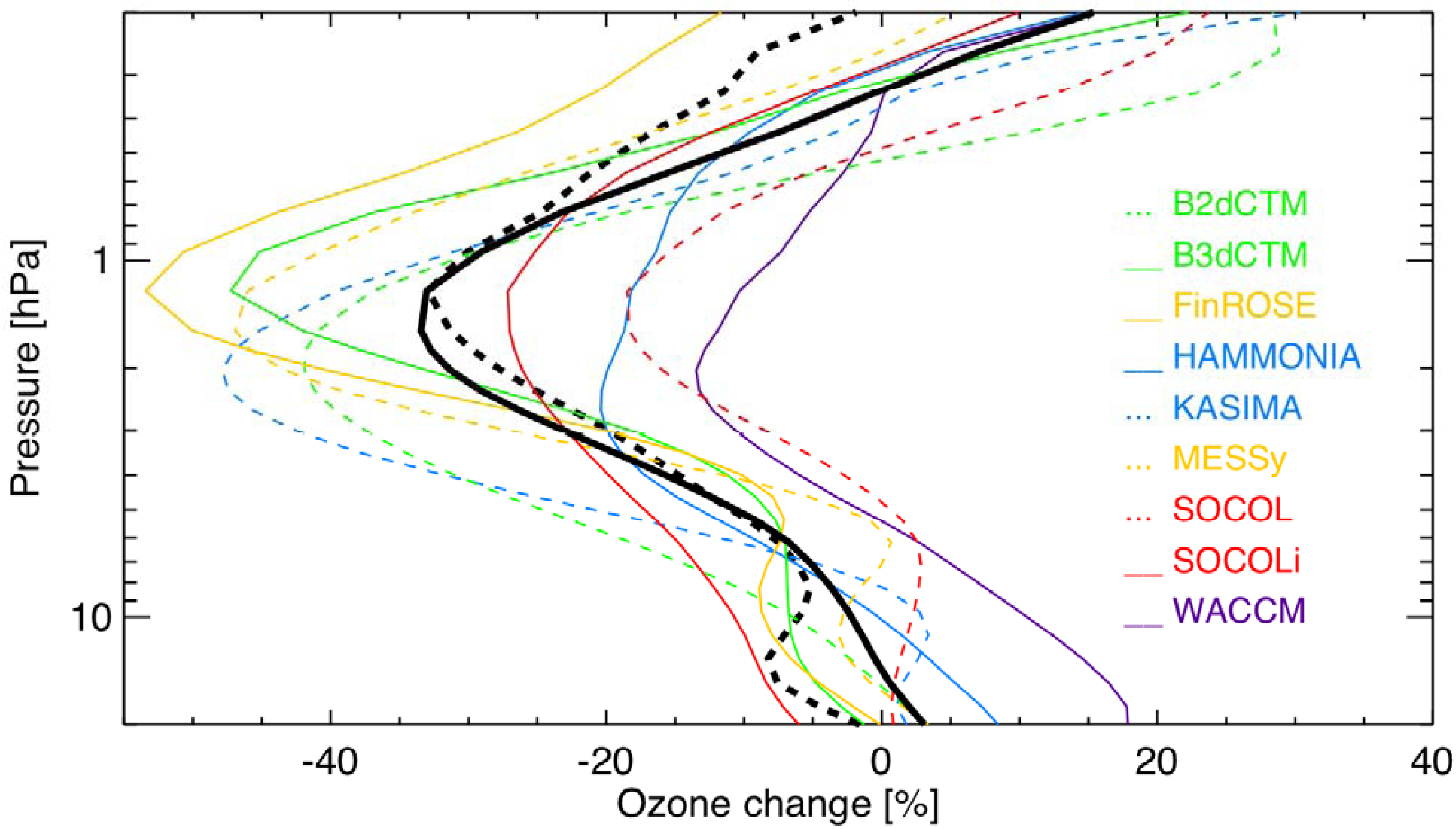
(70º-90ºN mean, 16-26.11 mean relative to 26.10)



Funke et al.,2011

Ozone changes due to Haloween storm SPE

(70º-90ºN mean, 16-26.11 mean relative to 26.10)



Funke et al.,2011

Response to GCR

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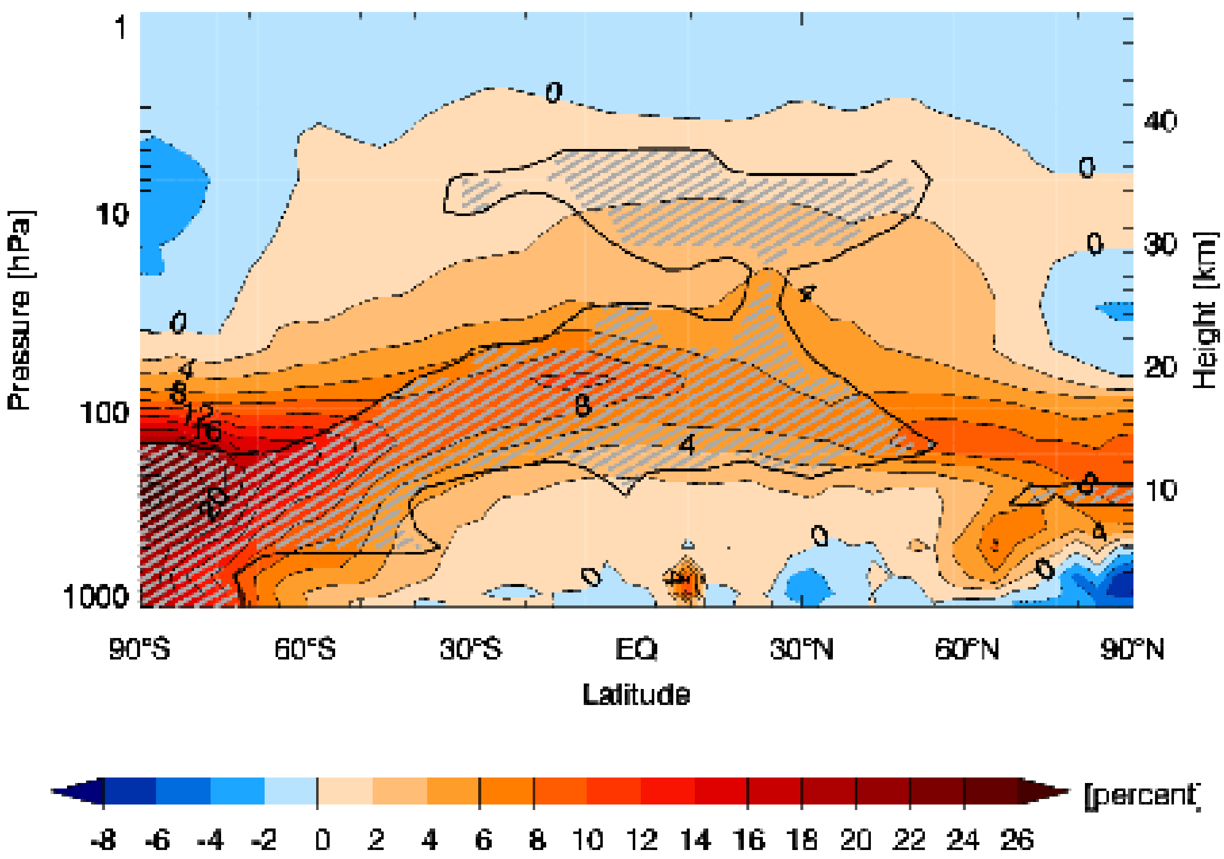
Effects of GCR on NOy



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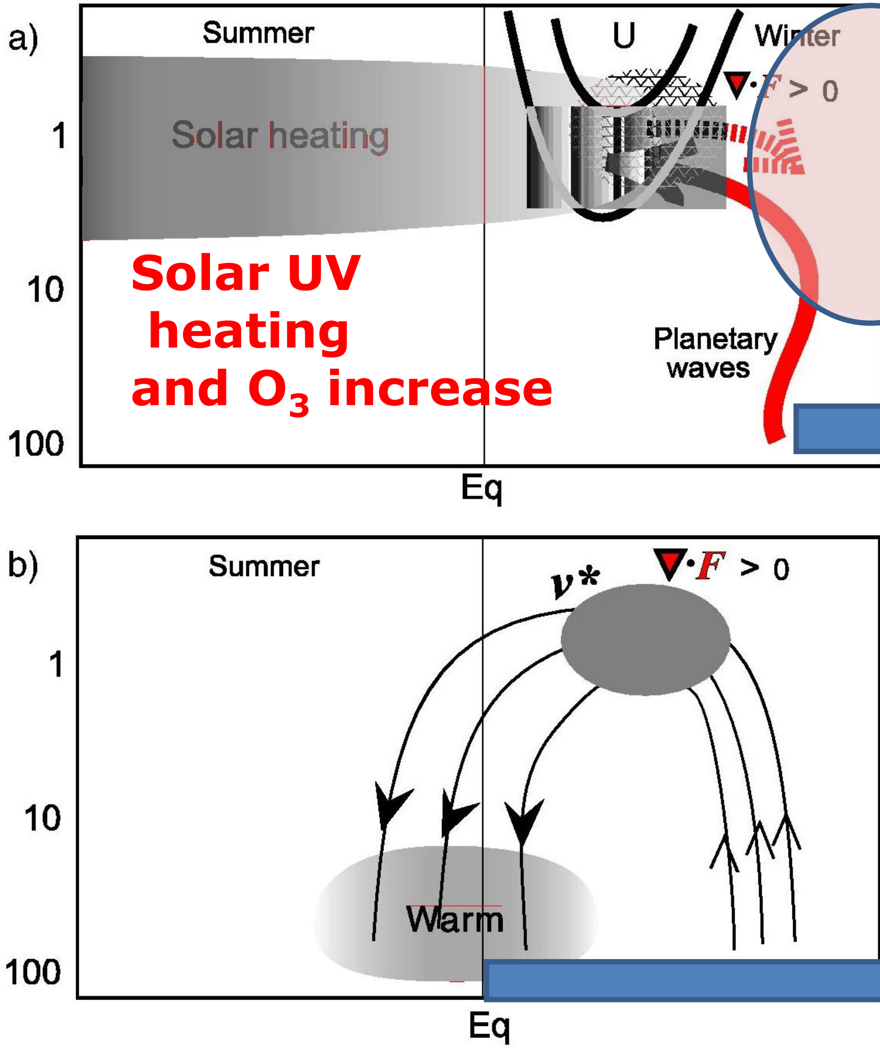
Indirect effects

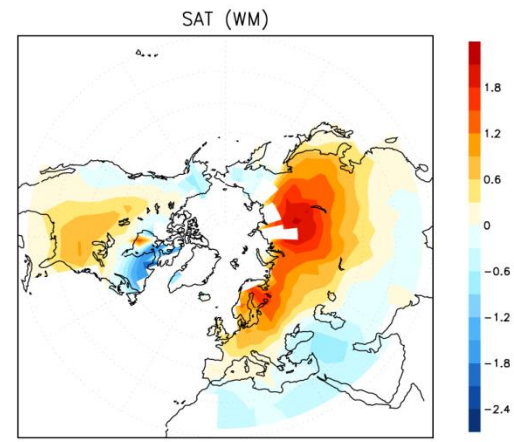
- **Downward propagation of the EPP NO_x**
- **Tropospheric climate response to the stratospheric perturbations**

Downward propagating response or ‘top-down’ route



Kodera and Kuroda, (2002)

EPP cooling and O_3 decrease

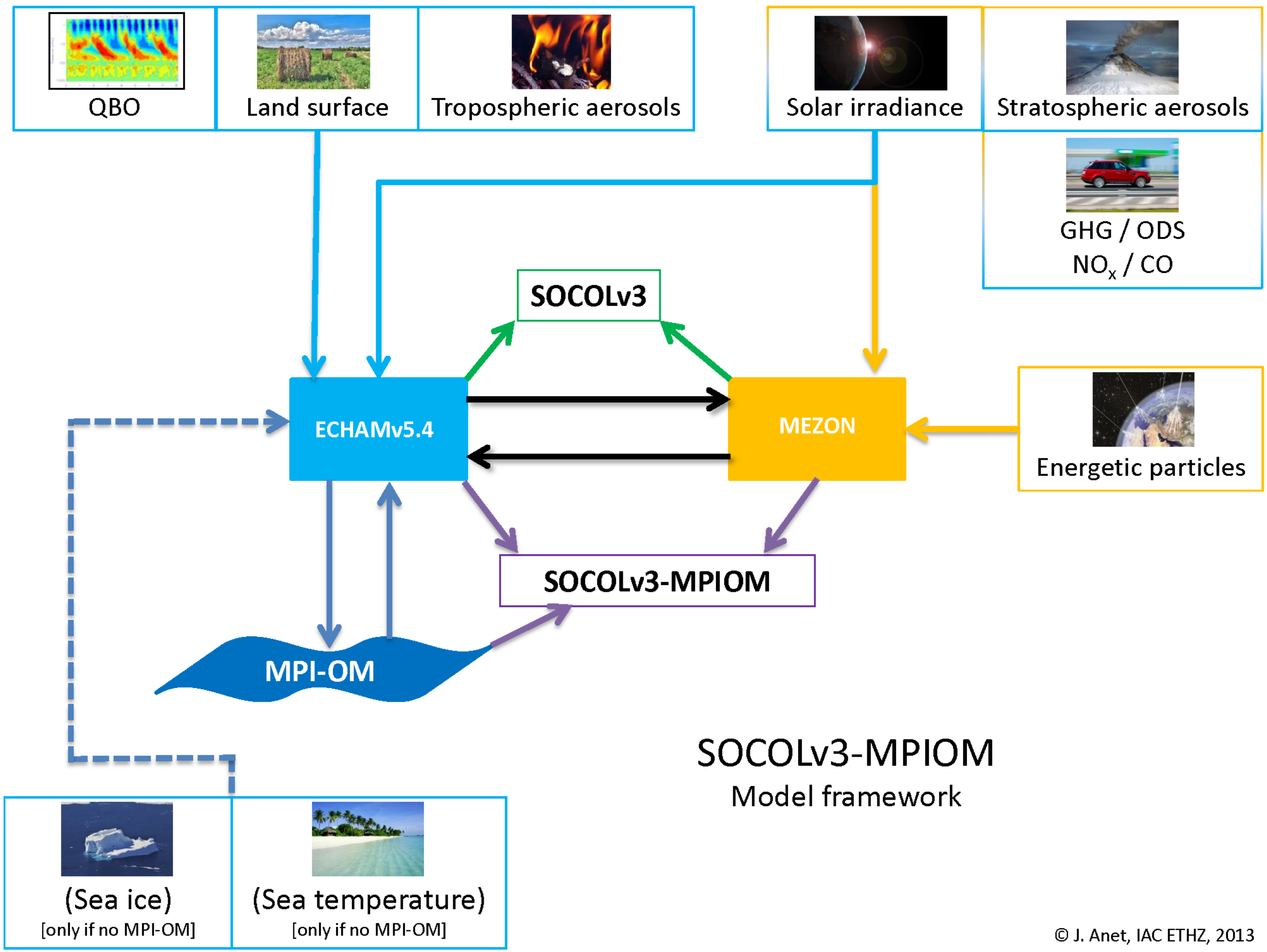


Thomson & Wallace (1998)

Hadley sell shift and ... (J.Haigh)

Future

AO CCM SOCOL/MPI-OM



SOCOLv3-MPIOM
Model framework

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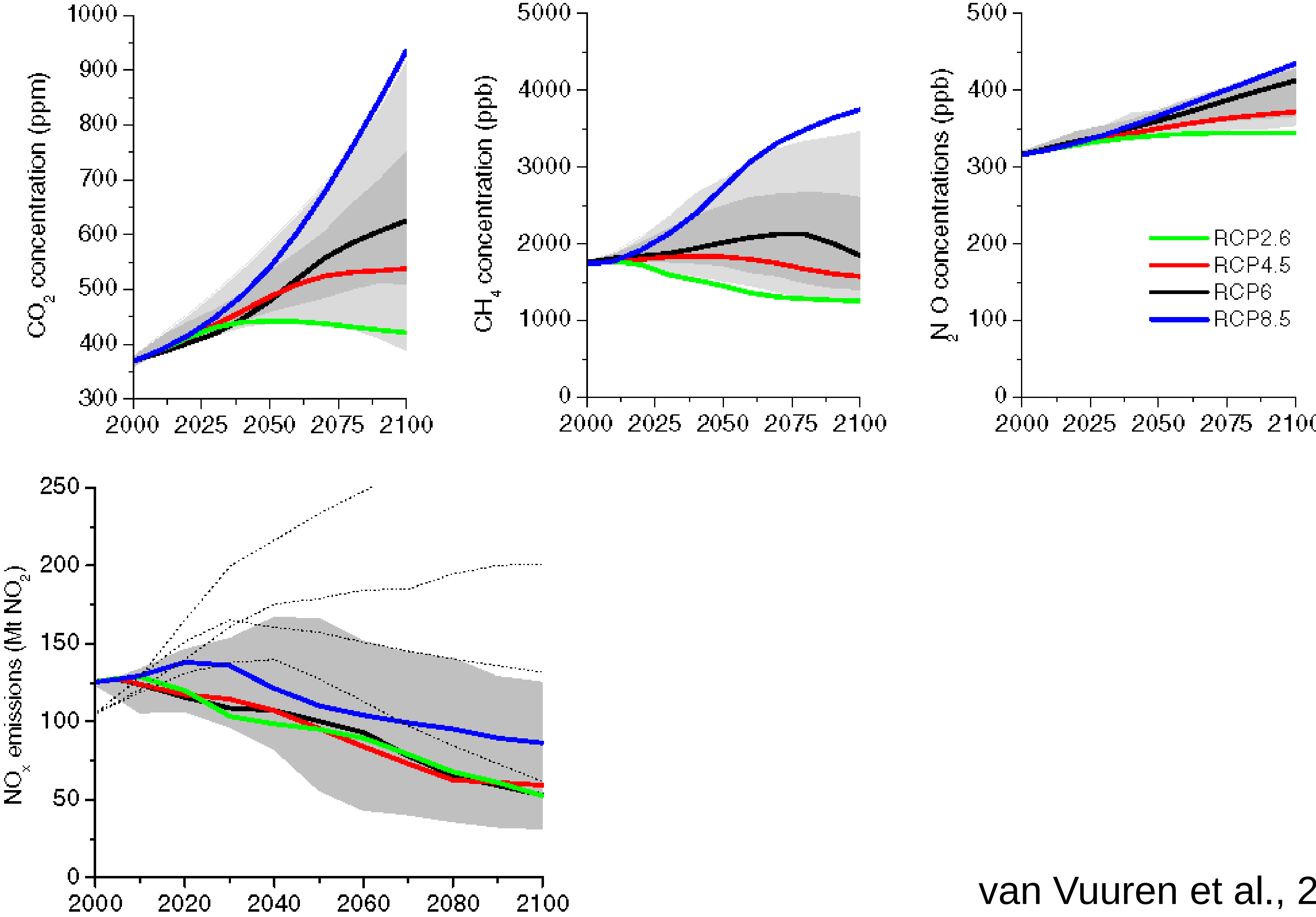
Applied evolution GHG mixing ratio and NO_x emission.



van Vuuren et al., 2011

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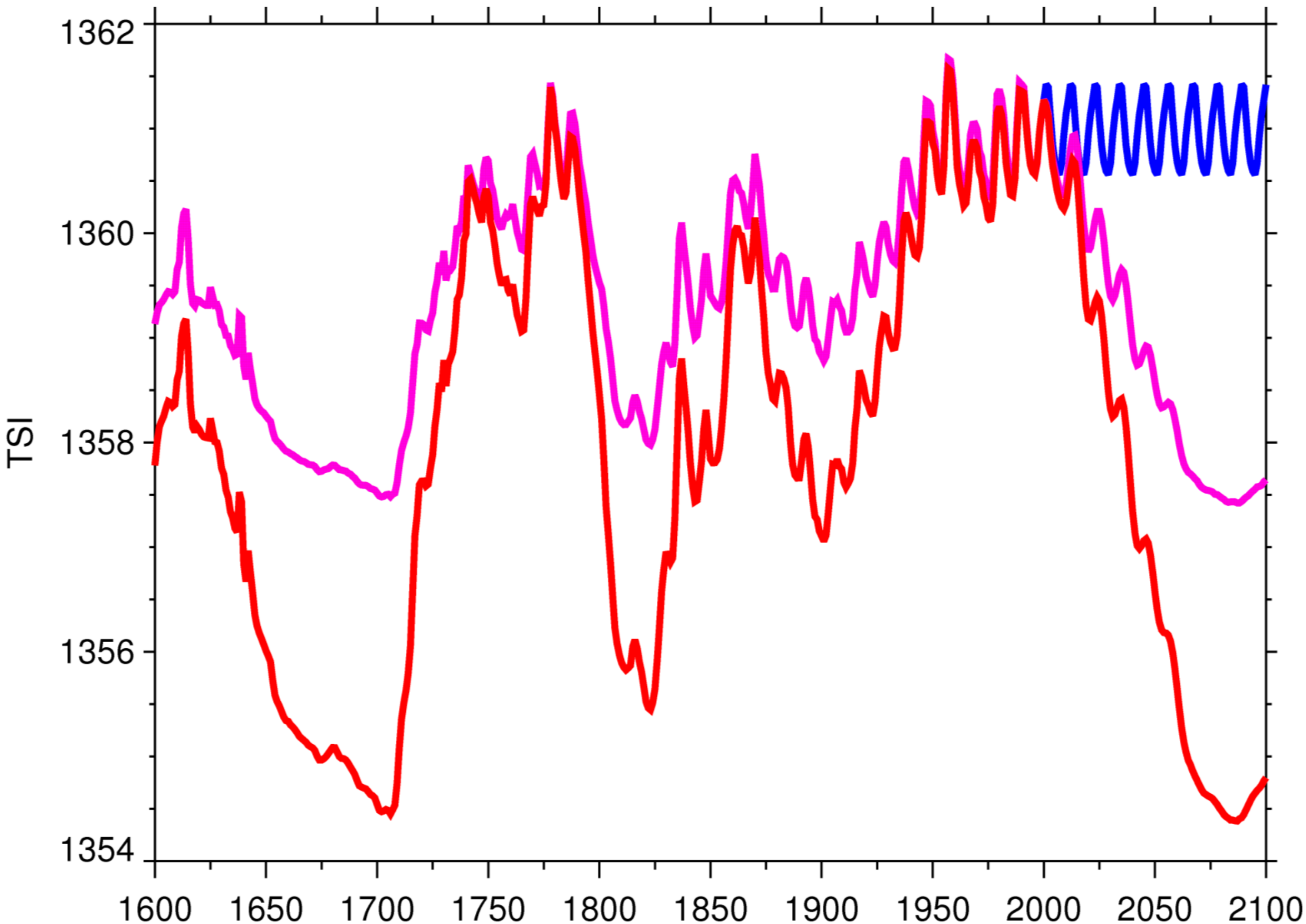
Applied evolution of TSI



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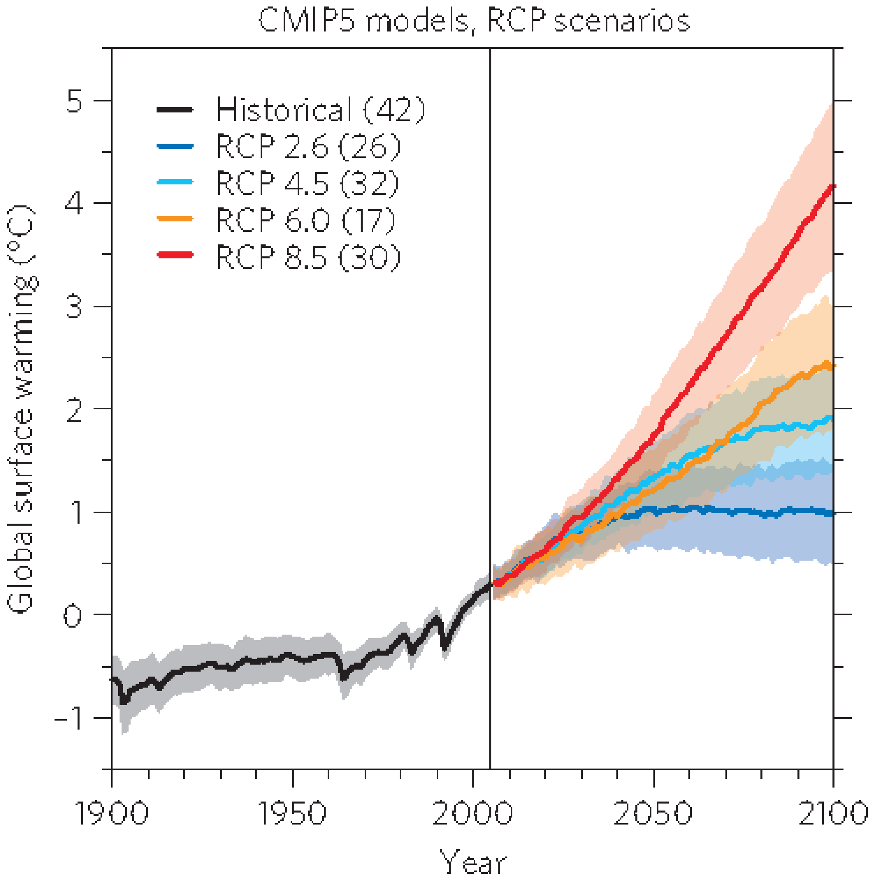
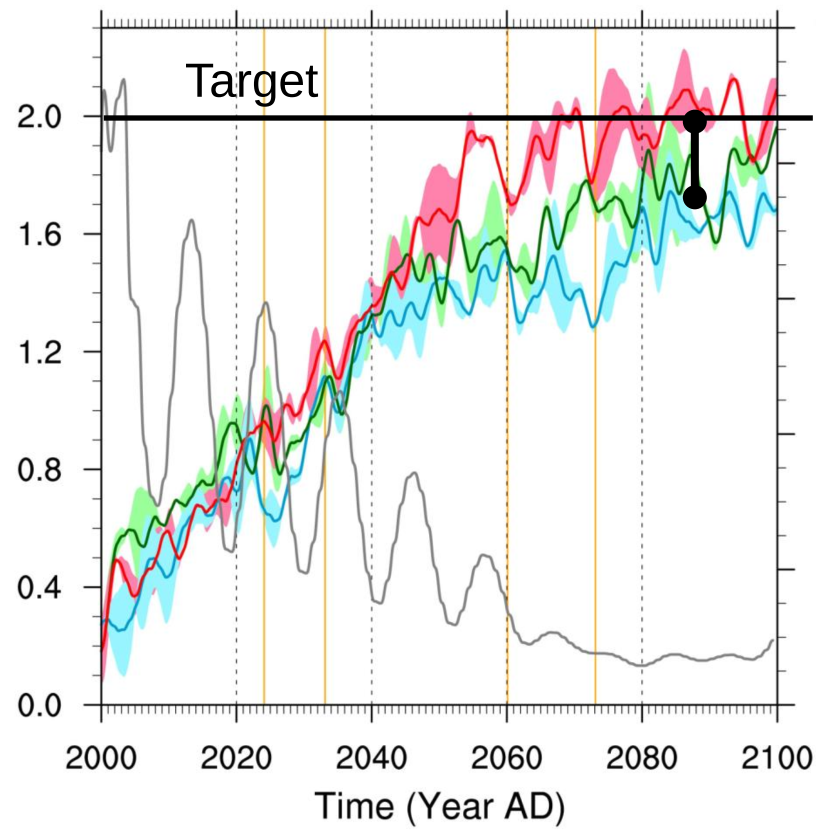
Surface air temperature evolution in CMIP-5 models

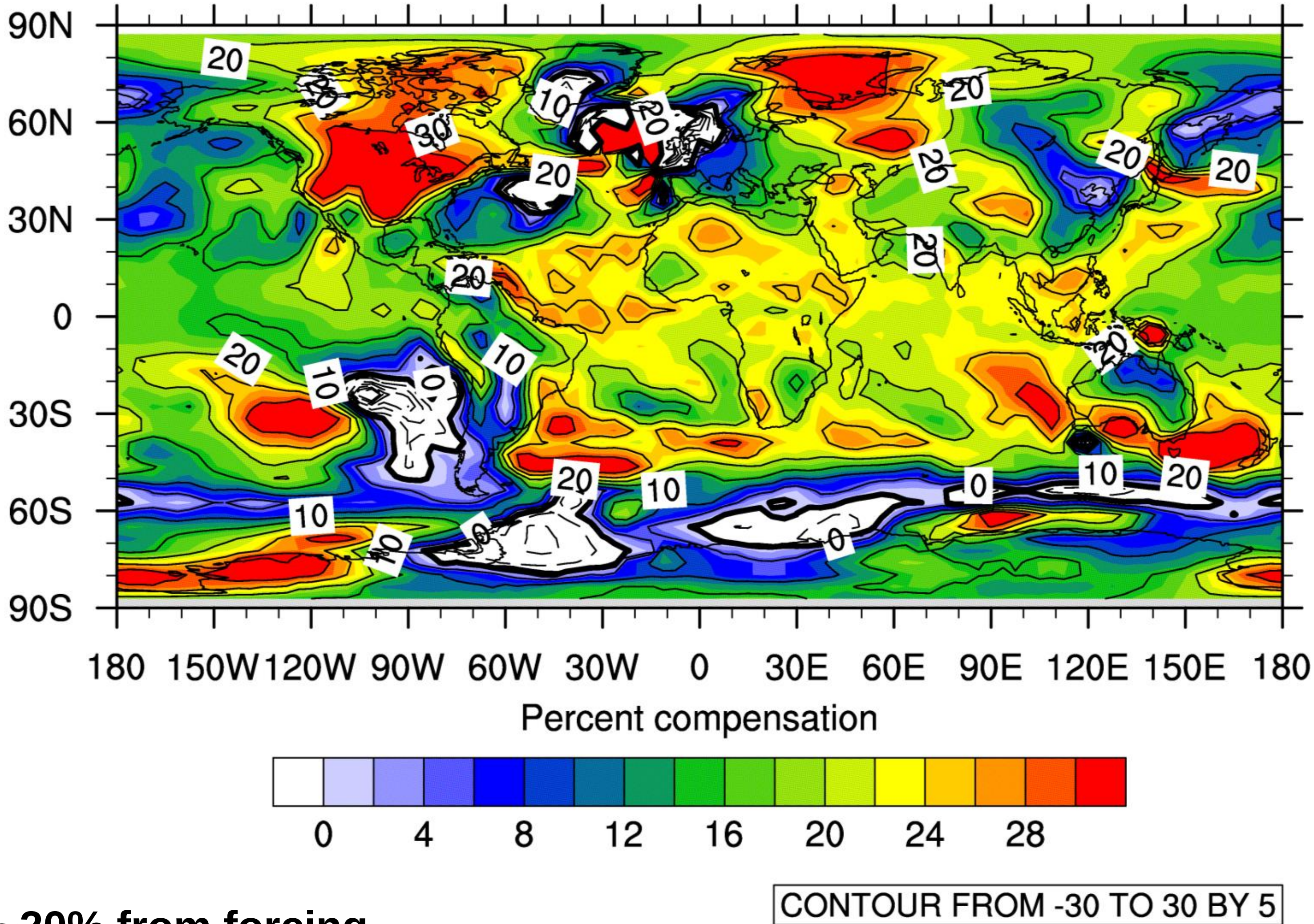


From Knutti and Sedlácek, 2013



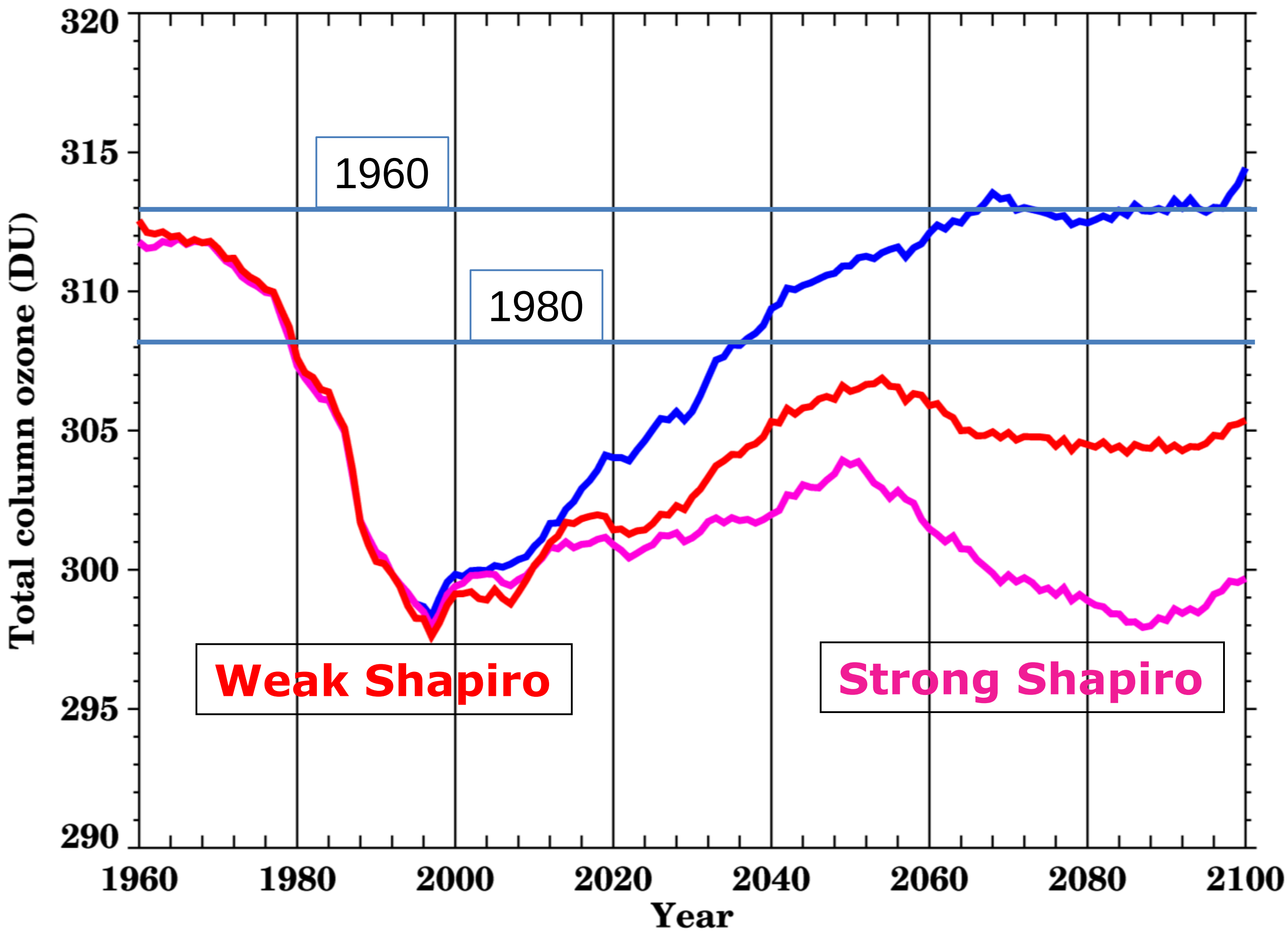
~20% or ~0.3 K from rad. Forcing 4.5 W/m² vs. 0.9 W/m²

Annual mean greenhouse warming compensation (%) due to solar activity decline



~20% from forcing

Solar influence on the global mean ozone layer recovery



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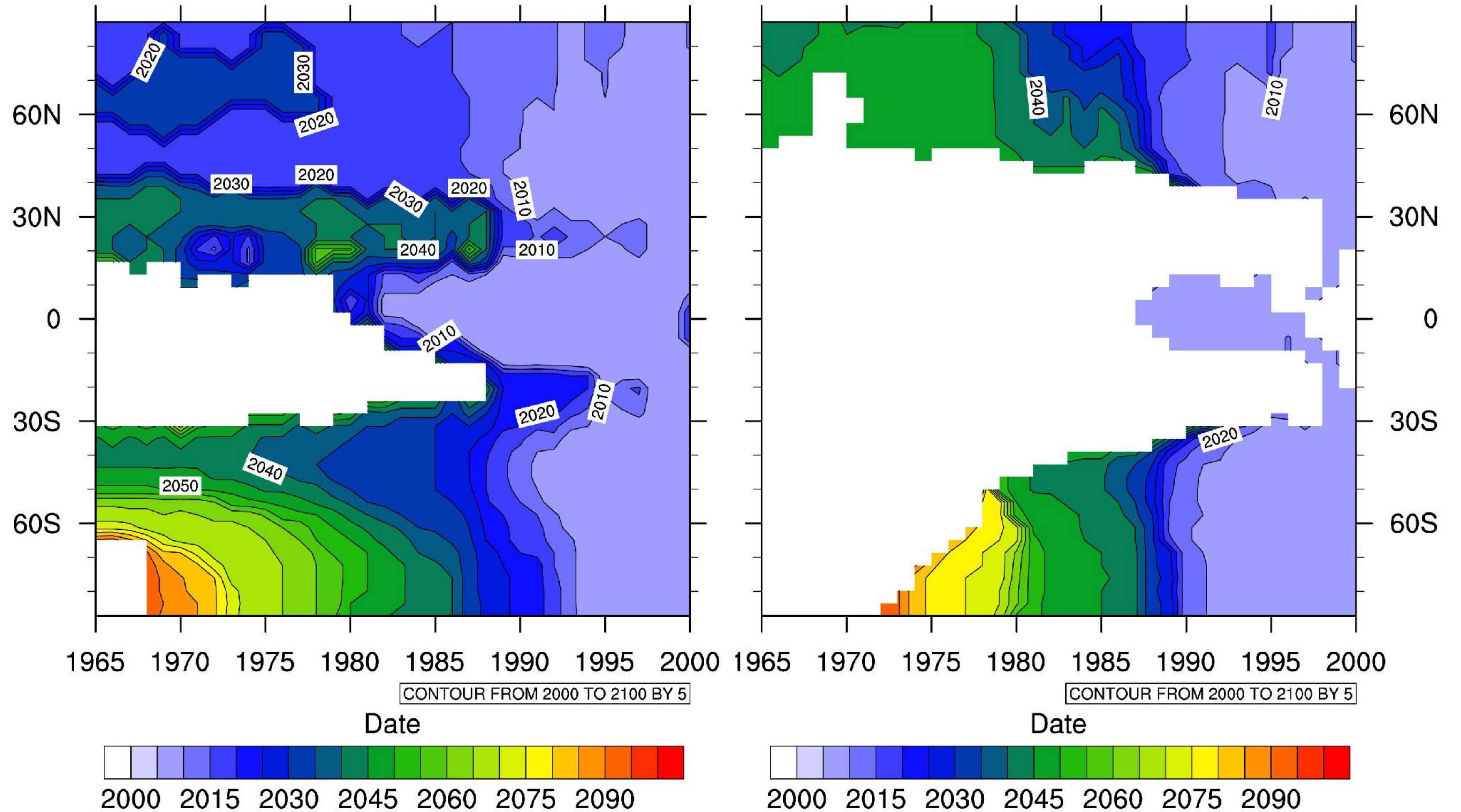
Solar influence on the ozone layer recovery



Anet et al., 2013

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Conclusions

- Considered solar related drivers operate in several climate models. There is a room for improvements (electrons, photolysis);

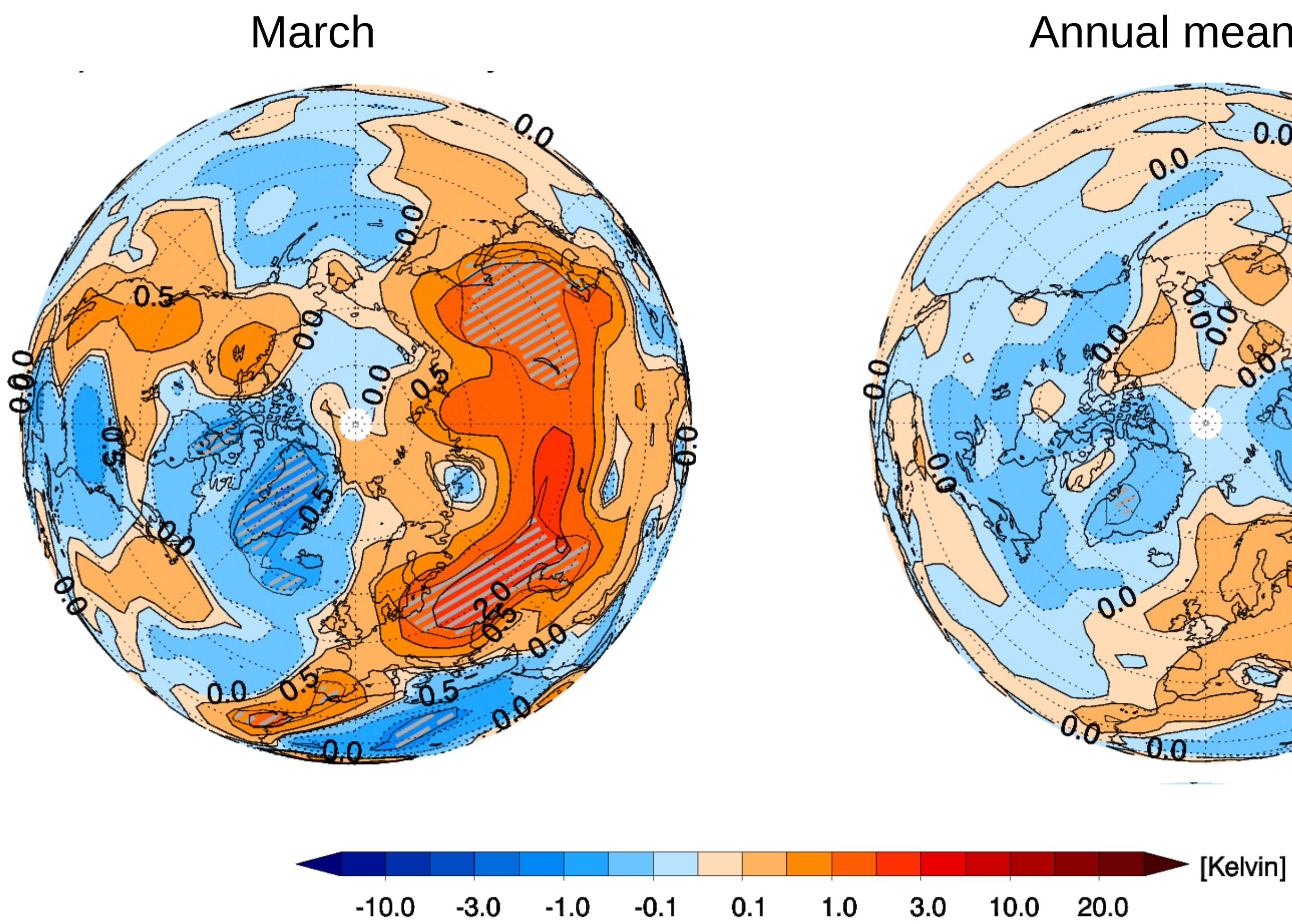
- More attention should be paid to the forcing by high energy electrons, which is not properly represented at the moment;

- The mechanism behind downward propagation of the stratospheric perturbation is currently the most important problem;

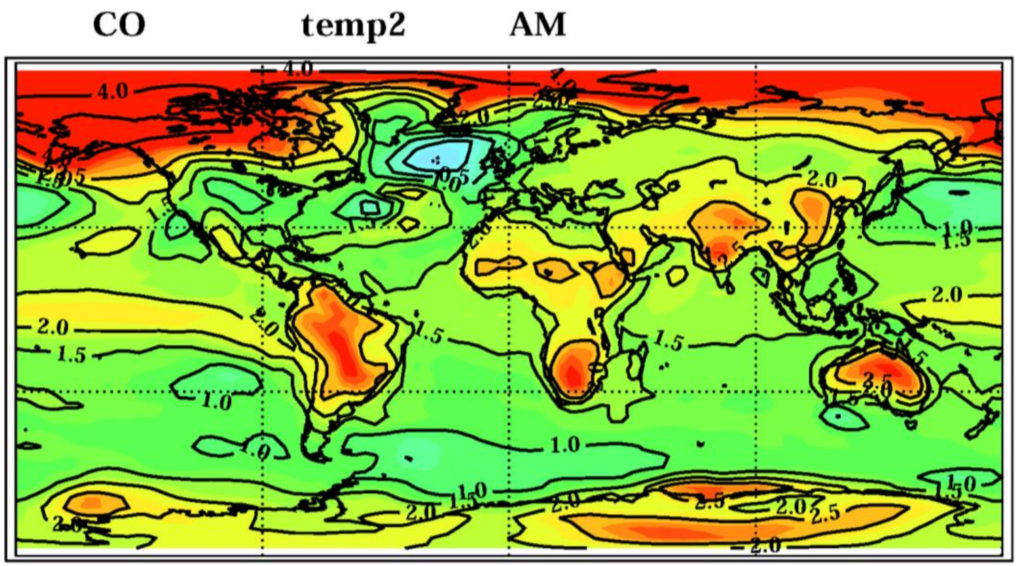
- Possible decline of the solar activity in the future can partially compensate greenhouse warming and postpone ozone layer recovery. In our model the main role is played by weaker solar irradiance.

End

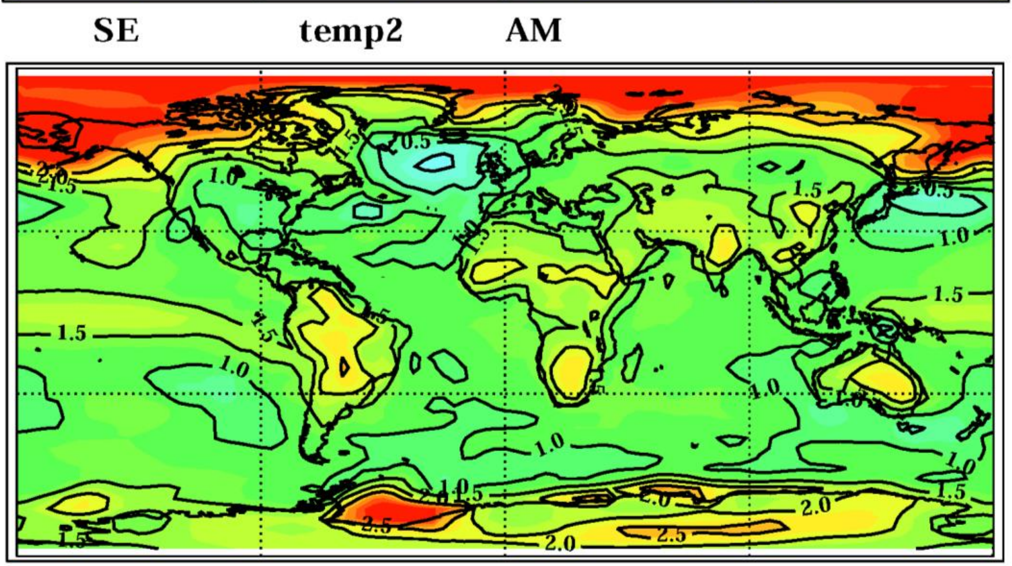
GCR effect on SAT (K)



Surface air temperature changes (K) future (2100) – past (2000)

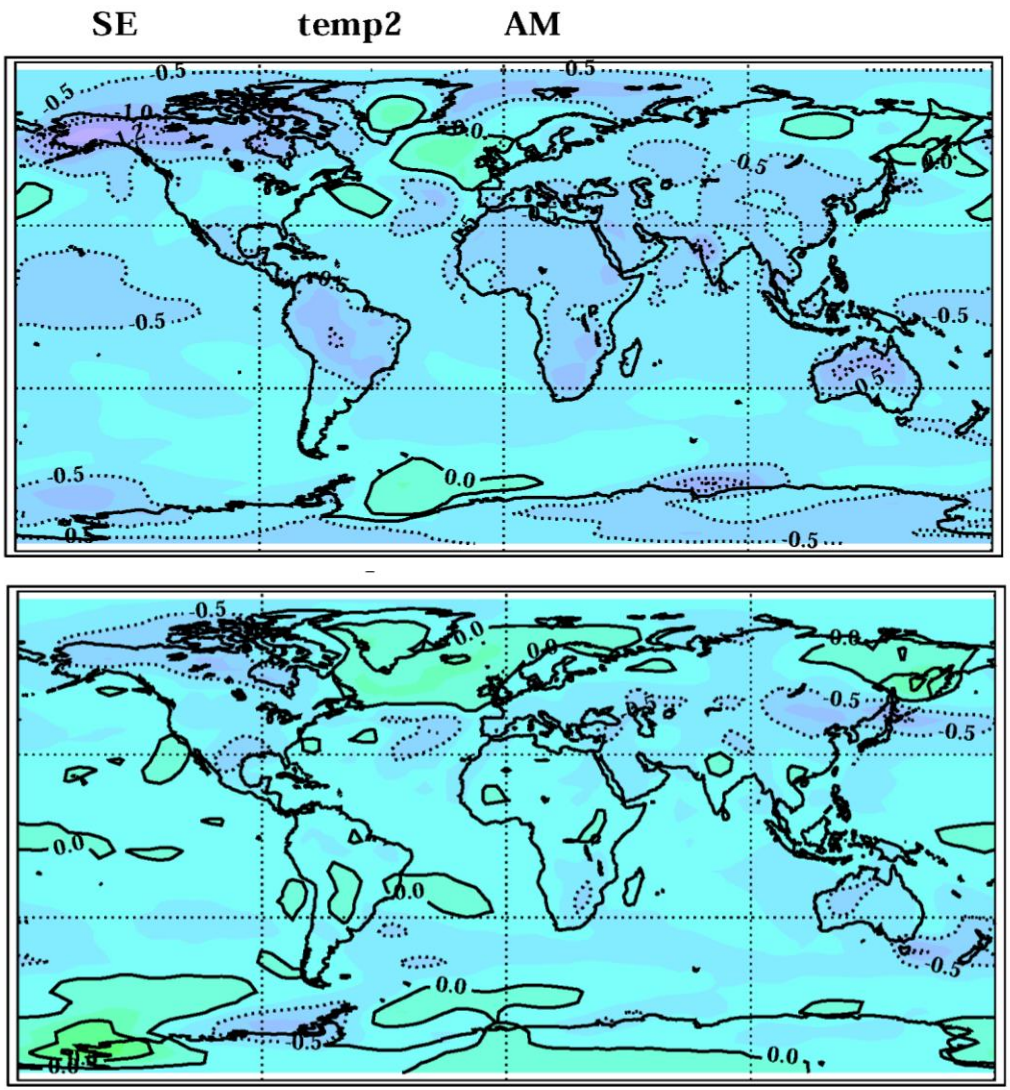


Constant solar forcing



Strong solar forcing

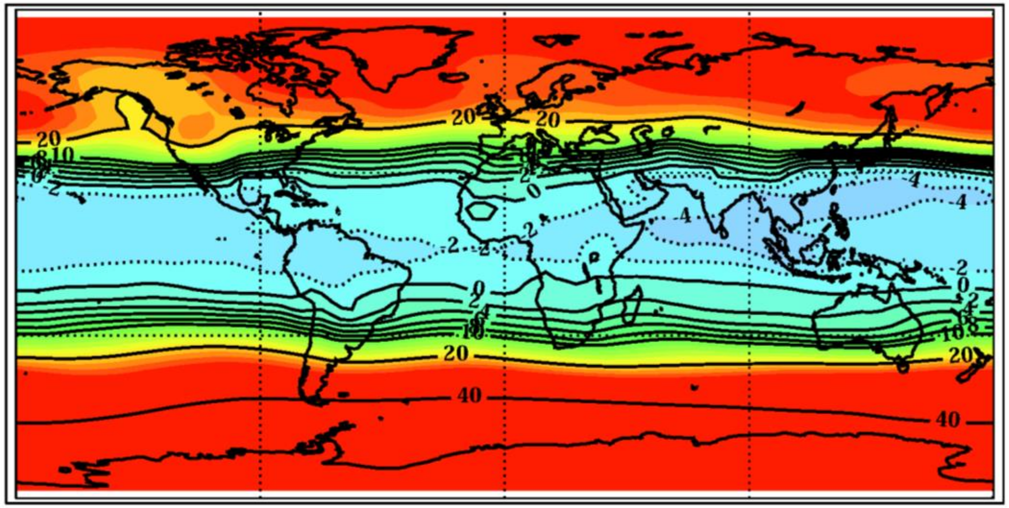
Solar contribution to the surface air temperature changes



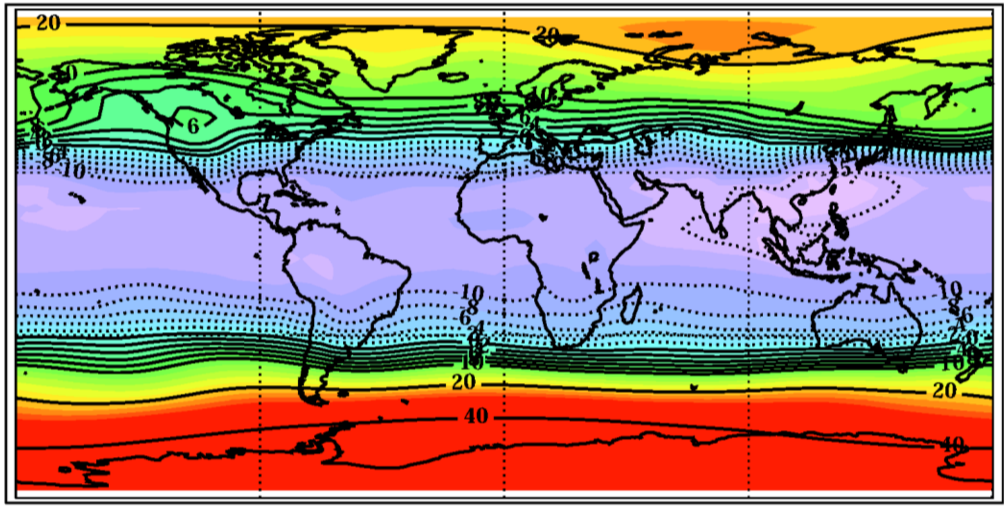
Strong

Weak

Total column ozone changes (DU) future – past



Constant solar forcing



Strong solar forcing