MOCASSIM : A model for spectral solar irradiance

Cassandra Bolduc
Université de Montréal
cassandra@astro.umontreal.ca
Supervisors: Paul Charbonneau and Michel Bourqui

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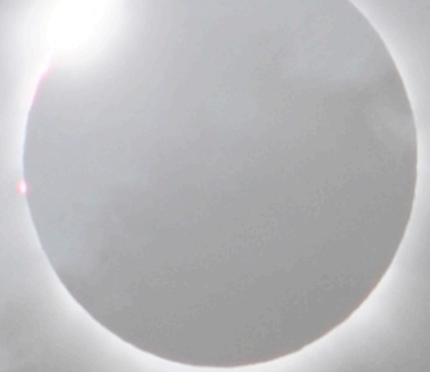

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Outline

- The model
  - Quiet Sun, spots and faculae contributions
  - Rotational modulation amplification and network contribution
- Spectral domain extension
- Temporal domain extension
- Results
  - Time series
  - Spectral reconstructions
    - ATLAS 1
    - Maunder minimum vs 2008 minimum
  - Stratospheric chemical species abundance variations
- Conclusions
- References

The Model

- Sunspots "injected" on a synthetic solar surface (observations of area and position compiled by D. Hathaway, from Greenwich and USAF records)

- Monte Carlo simulation of sunspots fragmentation and erosion + backside emergence on a one-day time cadence

  Fragments grouped in two categories :

  – Large-scale fragments : r>r* ("spots")

  – Small-scale fragments : r<r* ("faculae")

- Irradiance calculation :

  – Contribution from the quiet Sun, the spots and the faculae + stochastic network contribution and rotational modulation amplification.

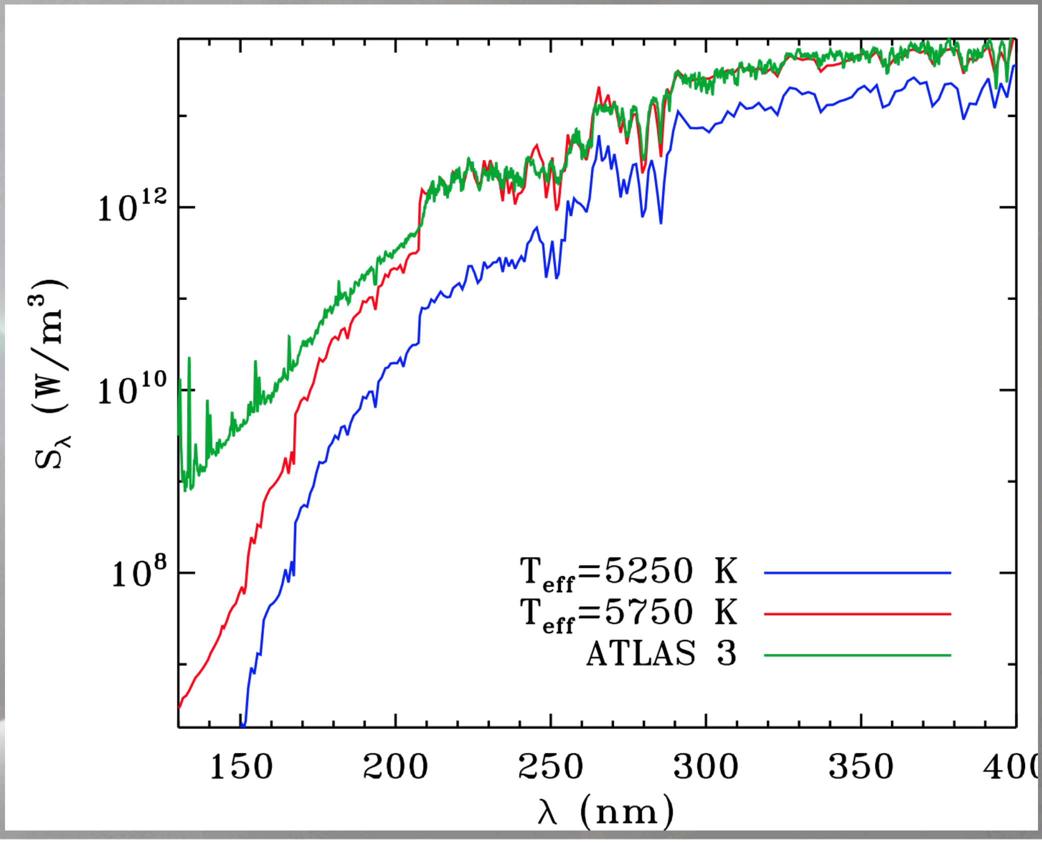
$$S_\lambda(t) = S_{\lambda,Q} + \sum_k \Delta S_{\lambda,S,k} + \sum_j \Delta S_{\lambda,F,j} + S_{\lambda,N}(t)$$

$$S_{\lambda,N}(t) = \alpha(1 - \beta A_{mag}(t)) \cdot (\pm 1)\left|S_\lambda(t) - \bar{S}_\lambda(t)\right| + \gamma|r_g|$$

Crouch et al., 2008, *Ap. J.*, 677, 723. Bolduc et al., 2012, *Sol. Phys.* 279:383.

The Model

- Quiet Sun contribution : interpolation on a synthetic, completely non-magnetic QS spectrum. (ex : Kurucz with Teff=5750K or observed ATLAS 3)
- Sunspots contribution : ratio of the monochromatic flux from a non-magnetic spectrum with Teff=5250K and the flux from a spectrum with Teff=5750K (the QS spectrum)



The Model

- Facular contribution : Black body inversion procedure

  (Solanki & Unruh (1998) A&A, 329:247)

  – Quiet Sun flux converted into temperature assuming a BB emissivity.

$$T = \frac{hc}{\lambda k}\left(\ln\left(\frac{2\pi hc^2}{\lambda^5 F_\lambda}+1\right)\right)^{-1} \quad \text{from} \quad F_\lambda = \frac{2\pi hc^2}{\lambda^5}\left(\exp\left(\frac{hc}{\lambda kT}\right)-1\right)^{-1}$$

  – Formation height from quiet Sun temperature profile

  (Fontenla *et al.* (2009) ApJ 707:482, model **B**)

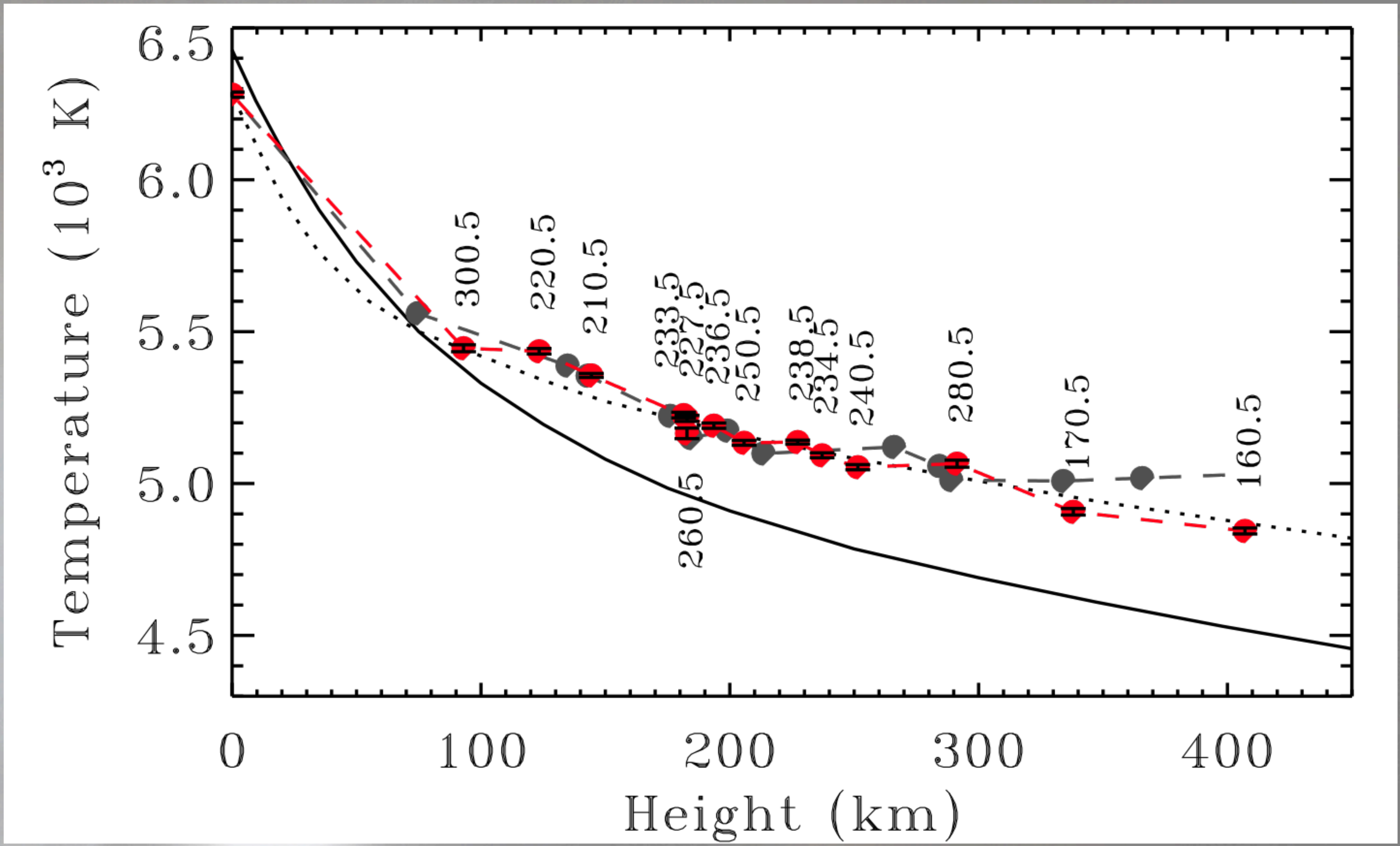
  – Assuming that the photons from the faculae are formed at the same height : emission temperature for the faculae from a temperature profile

  (Fontenla *et al.* (2009) ApJ 707:482, model **P**)

  – Conversion of this facular emission temperature into flux with the above formula

The Model

- Facular contribution : Black body inversion procedure



The Model

- Rotational modulation amplification and network contribution
  - Corrections necessary because our model lacks chromospheric plages

$$S_{\lambda,N}(t) = \alpha(1-\beta A_{mag}(t)) \cdot (\pm 1)\left|S_\lambda(t) - \bar{S}_\lambda(t)\right| + \gamma|r_g|$$

  - Rotational modulation :
    - By amplifying variations around the smoothed time series
    - Weighted by the surface coverage of the solar disk by small- and large-scale magnetic structures ($A_{mag}(t)$)
  - Network contribution :
    - Absolute value of a random number (mean=0, variance=1, generated daily), weighted with the factor γ

The Model

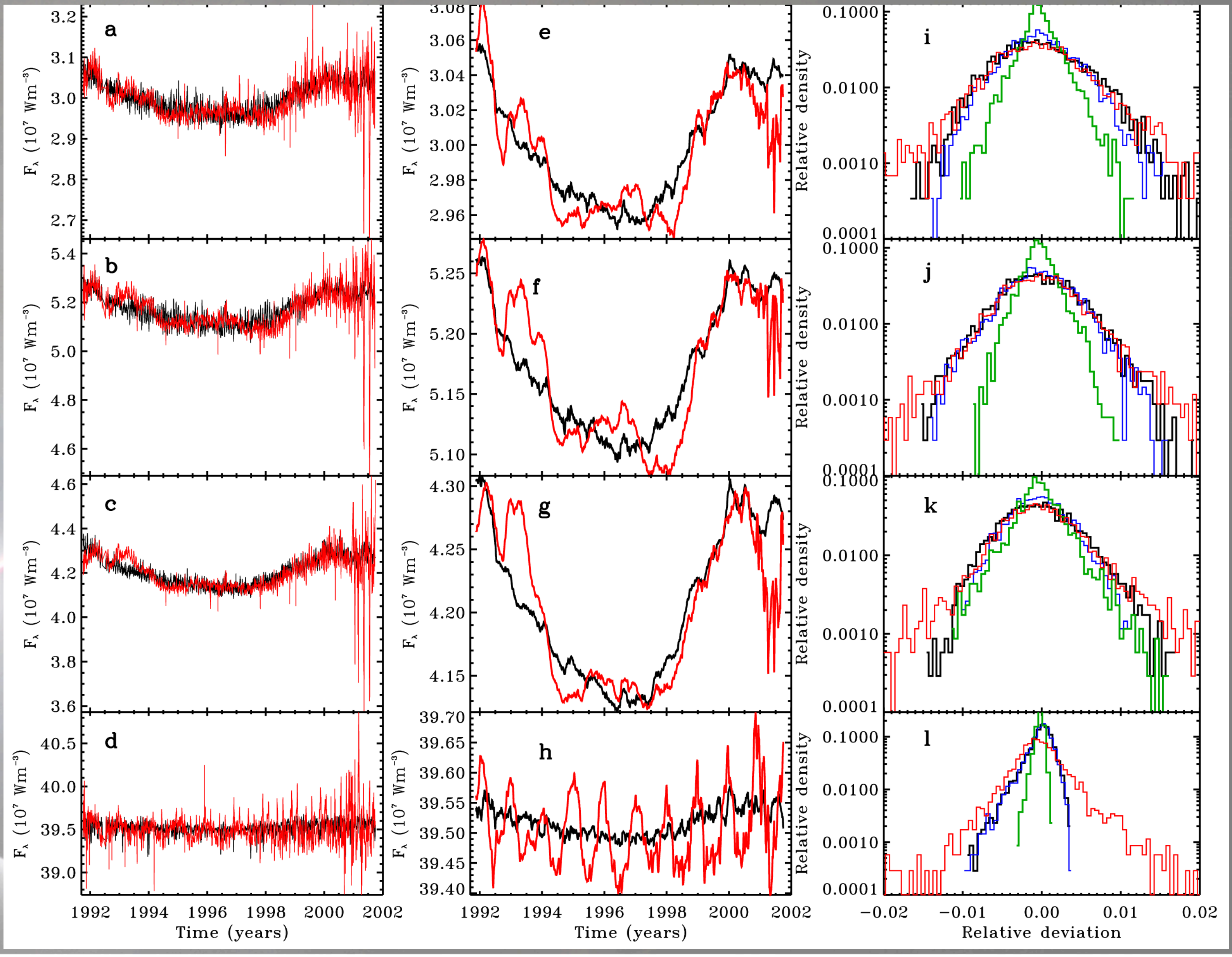
- First results (Bolduc et al. (2012) Sol. Phys. 279:383)

210 nm

220 nm

240 nm

300 nm



Spectral Domain extension

- Quiet Sun approximation with ATLAS 3 instead of Kurucz

  (Because of the discrepancy below ~200 nm)

- Optimization of a new facular temperature profile

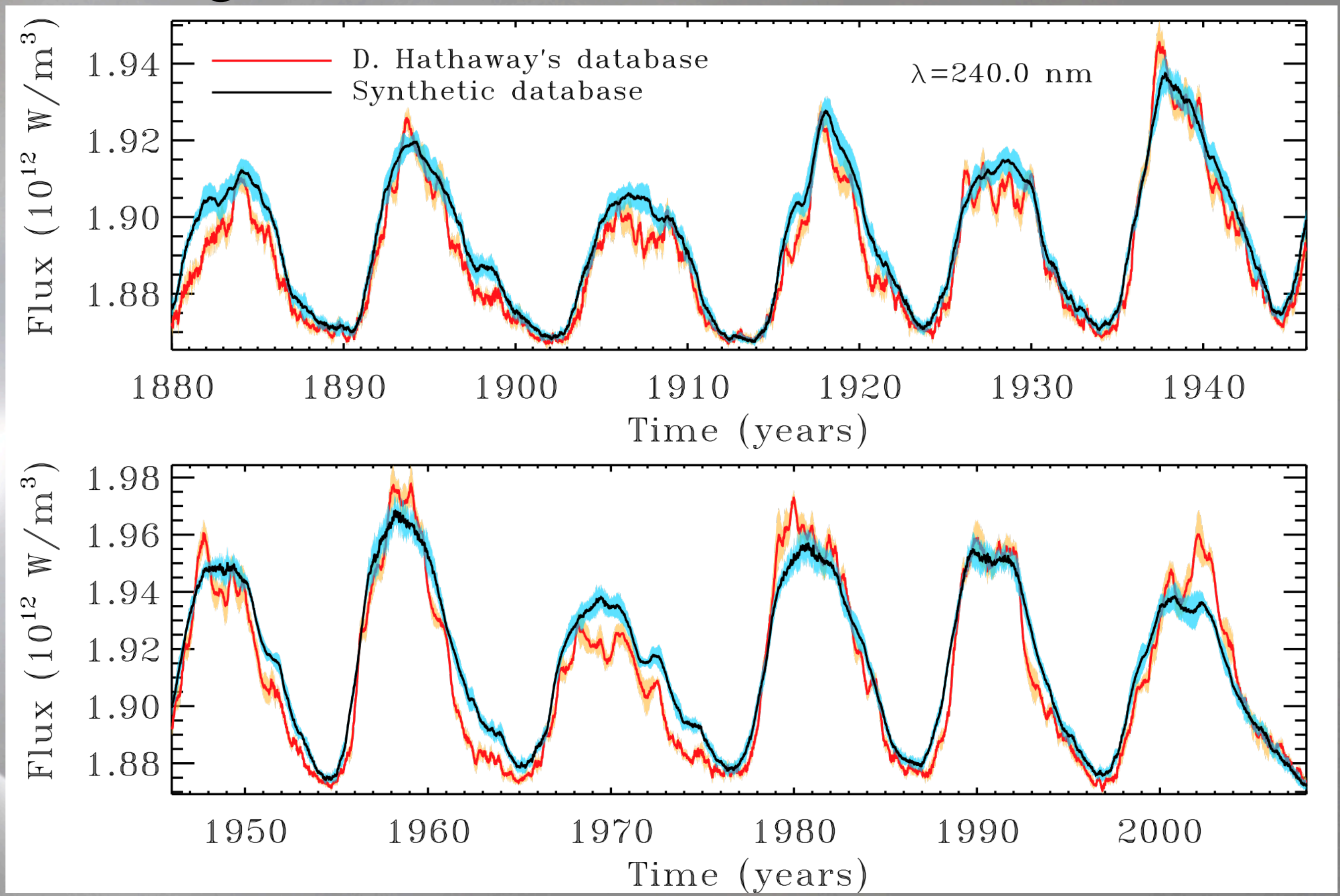
  (Because the monochromatic flux at every wavelenght is different -> different formation height -> inconsistent temperature)

- Optimization of the network contribution (weighting factor) in function of wavelength

Temporal Domain extension

- Simulation of SS distribution of area and position with the Wolf number as input, following statistical properties of emergences according to the cycle phase, amplitude, etc.

- Comparison of reconstructed SSI using Hathaway's database vs simulated emergences :



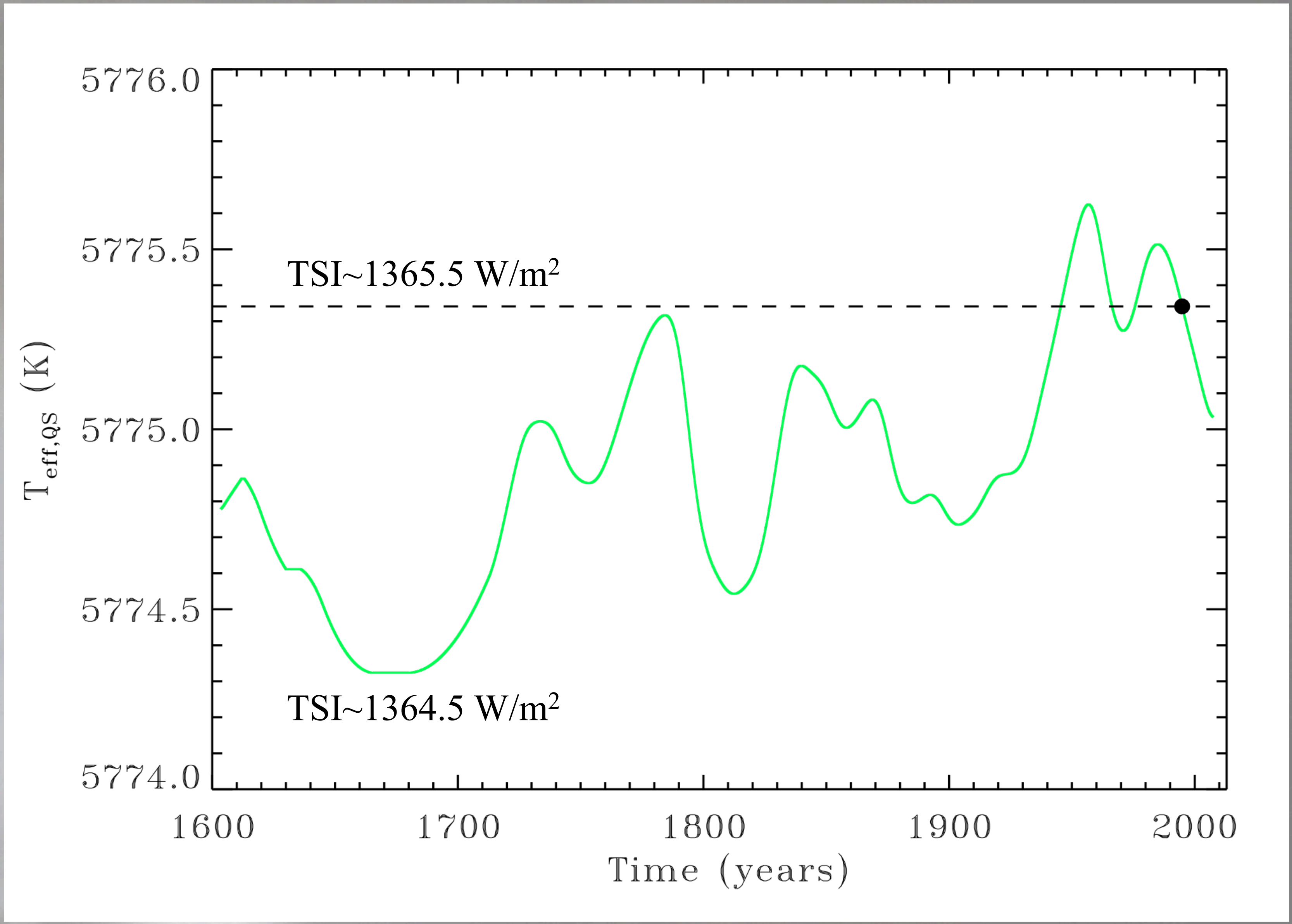
Temporal Domain extension

- Quiet Sun variation:
  - The radio flux at 10.7 cm is a good proxy for SSI (Dudok De Wit, private comm.)
  - We obtain the TSI with the slowly varying component of the F10.7 (Tapping et al. (2007), Sol. Phys., 246:309):

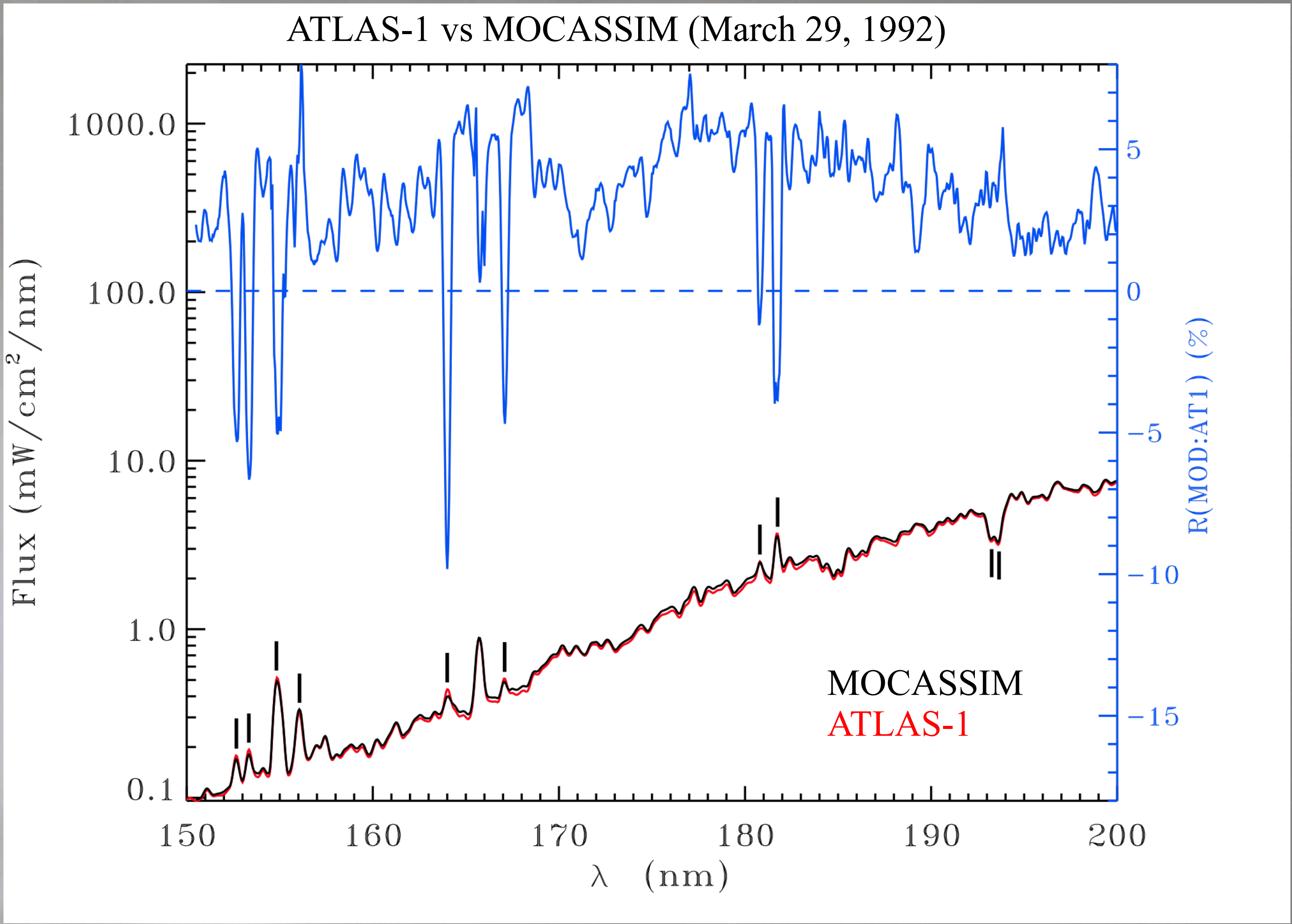
$$I_{\odot} = 0.017 S_{10.7} + 1364.5$$

  - We convert this irradiance into temperature assuming it is emitted by a black body;
  - We compare the temperature for each day with the temperature for 1994, November 11 (date of ATLAS 3 observation)
  - The difference is a «correction» on the quiet Sun emission temperature.

Temporal Domain extension

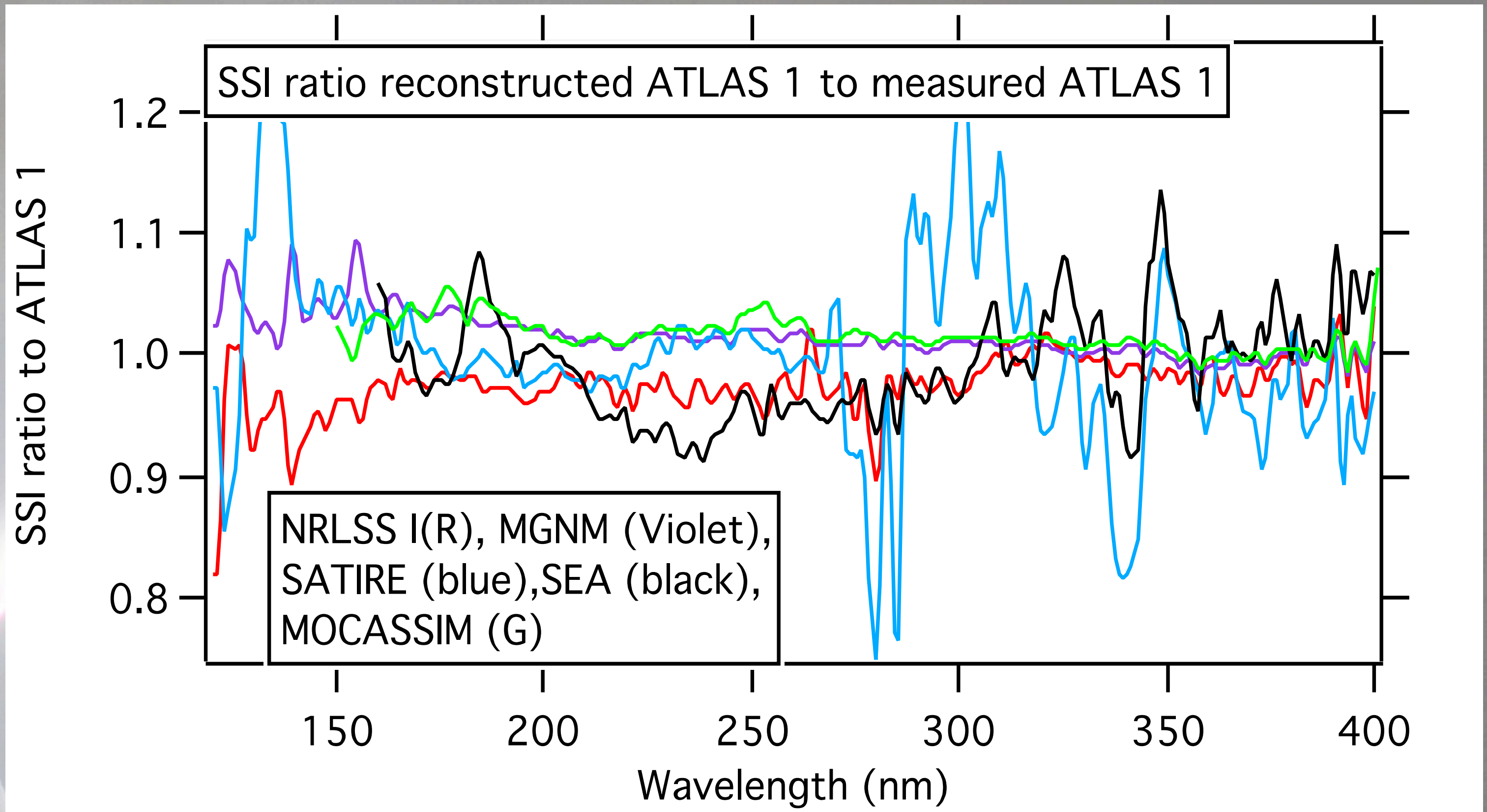


Results : spectral reconstruction

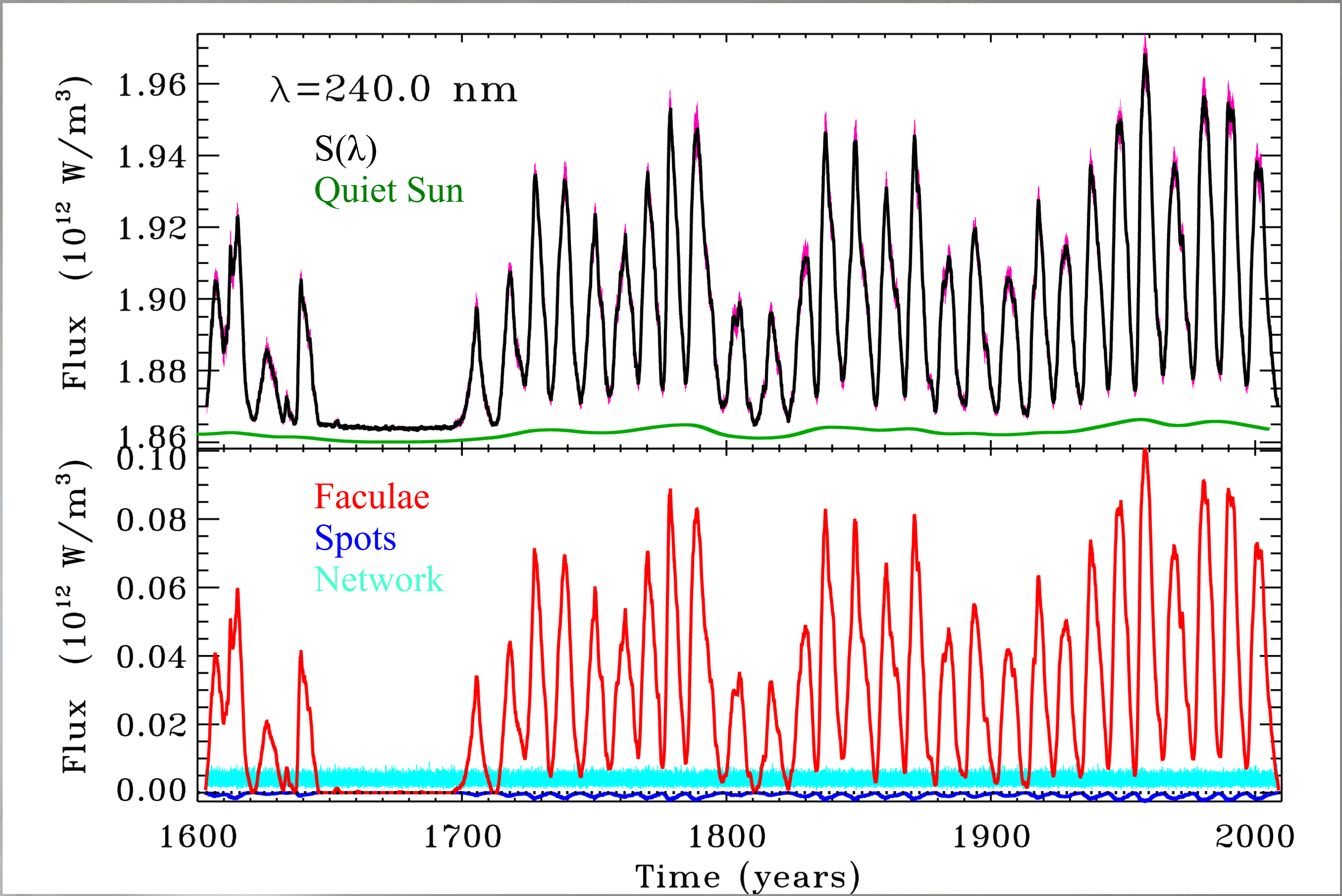


Results : spectral reconstruction

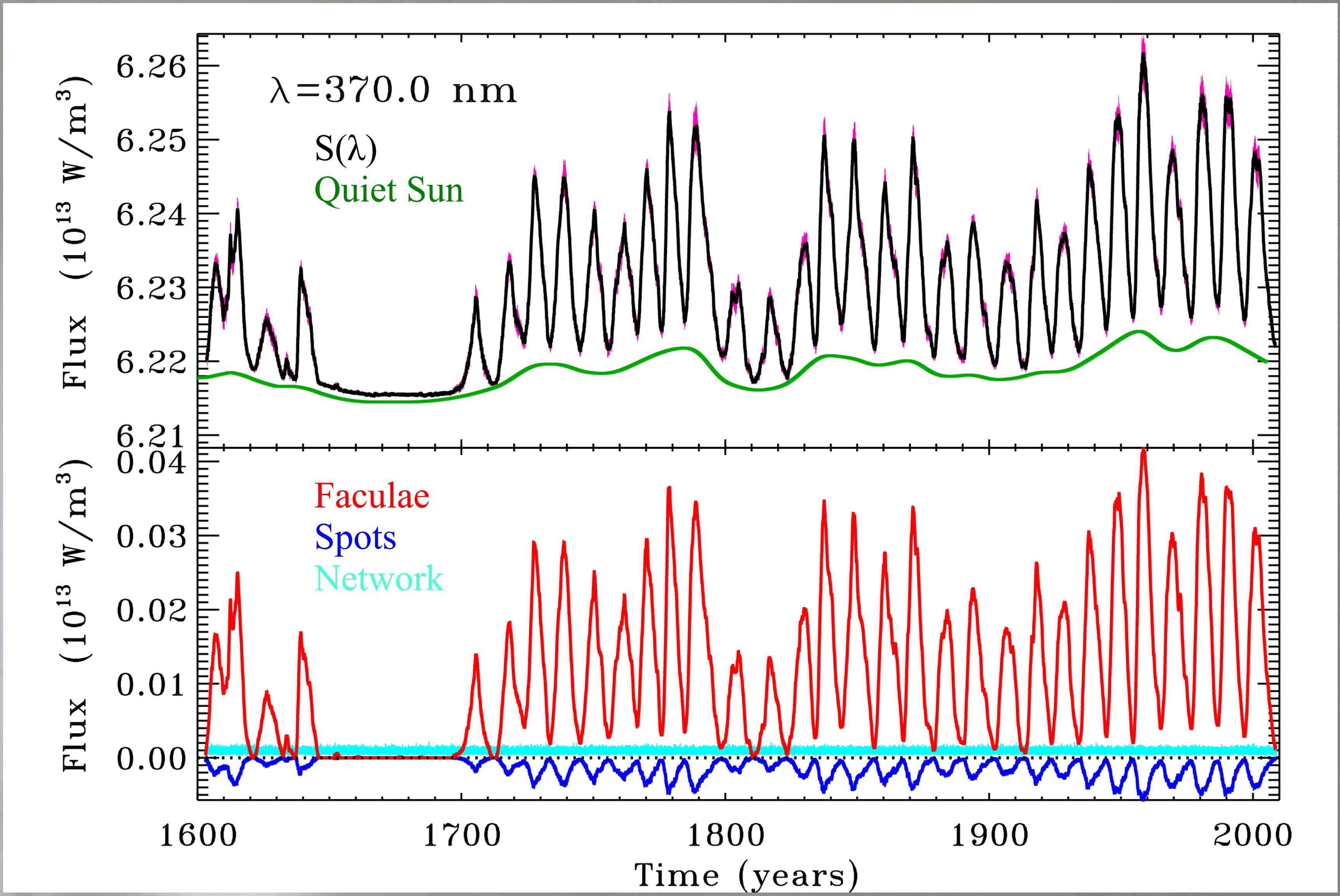
Comparison with other reconstructions (figure 4a of Thuillier et al. (2013) Submitted to Sol. Phys.)



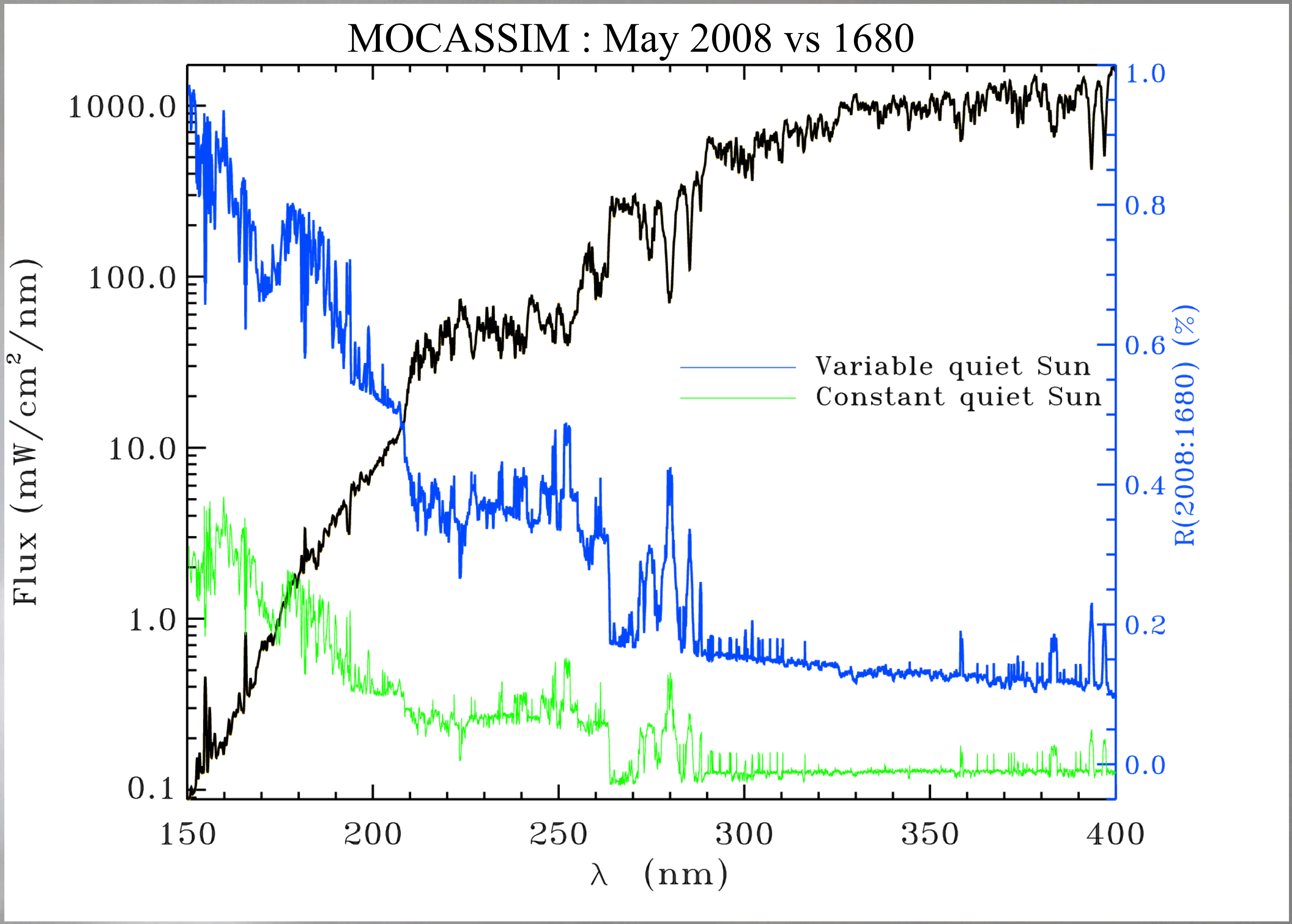
Results : time series (240 nm)

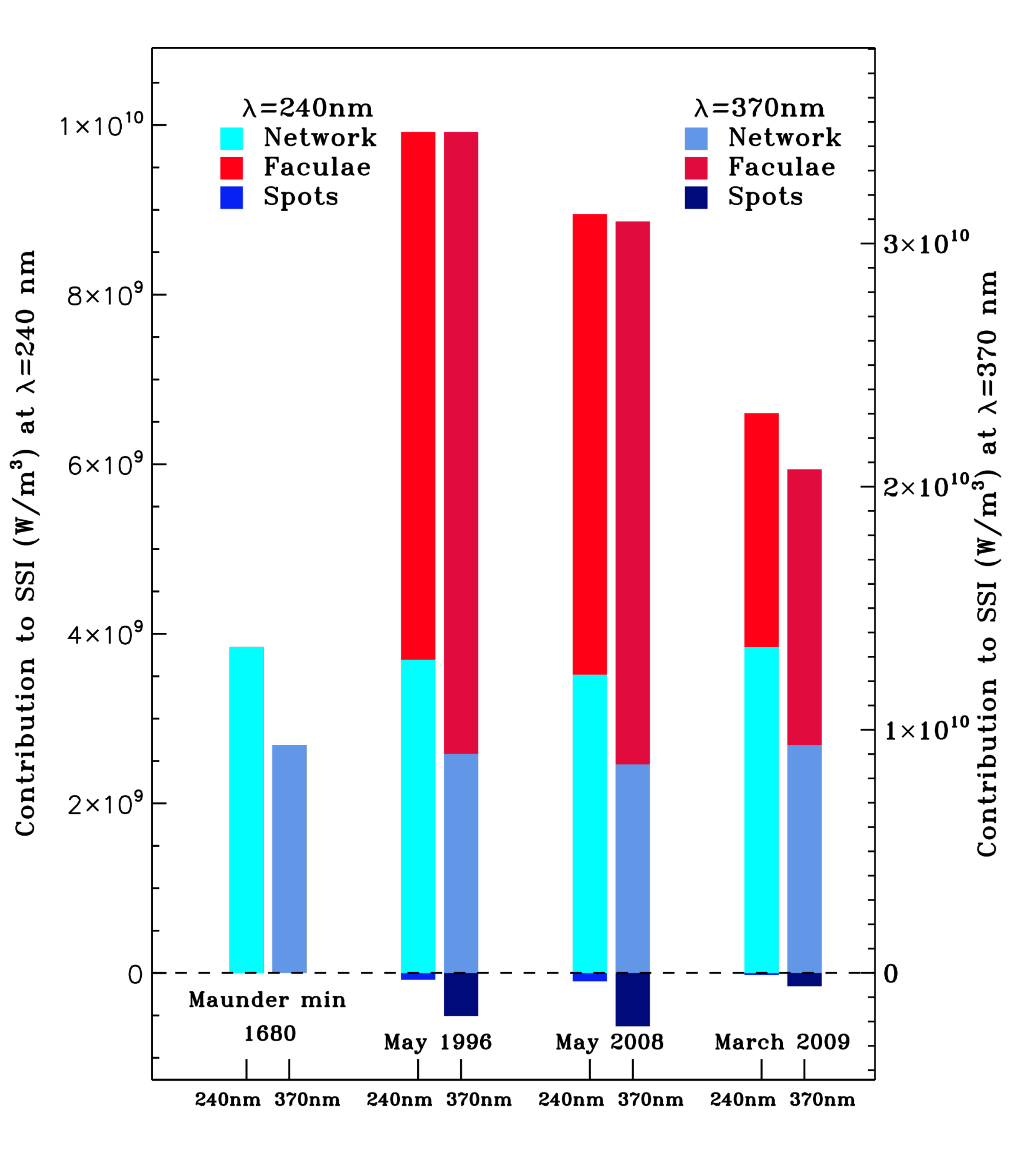


Results : time series (370 nm)



Results : spectral reconstruction




λ=240nm
Network
Faculae
Spots
λ=370nm
Network
Faculae
Spots
1×10¹⁰
8×10⁹
6×10⁹
4×10⁹
2×10⁹
0
3×10¹⁰
2×10¹⁰
1×10¹⁰
0
Contribution to SSI (W/m³) at λ=240 nm
Contribution to SSI (W/m³) at λ=370 nm
Maunder min
1680
May 1996
May 2008
March 2009
240nm 370nm
240nm 370nm
240nm 370nm
240nm 370nm

Stratospheric chemical species abundance variations

- Calculated with the photochemistry model presented in Muncaster et al. (2012) Atmos. Chem. Phys., 12:7707.
- No dynamics, no heating, equatorial conditions.
- Difference between solar max and solar min.
- Different solar spectra = different results!

Chapman cycle

$$O_2 + h\nu \rightarrow O + O$$

λ < 242 nm

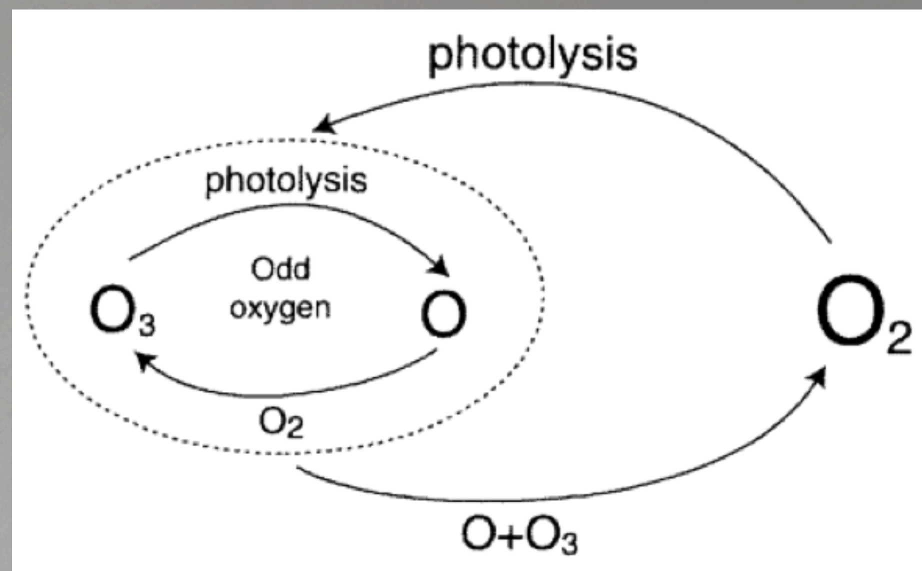
$$2 \times (O_2 + O \xrightarrow{M} O_3)$$

$$net: 3O_2 + h\nu \rightarrow 2O_3$$

$$O_3 + h\nu \rightarrow O_2 + O$$

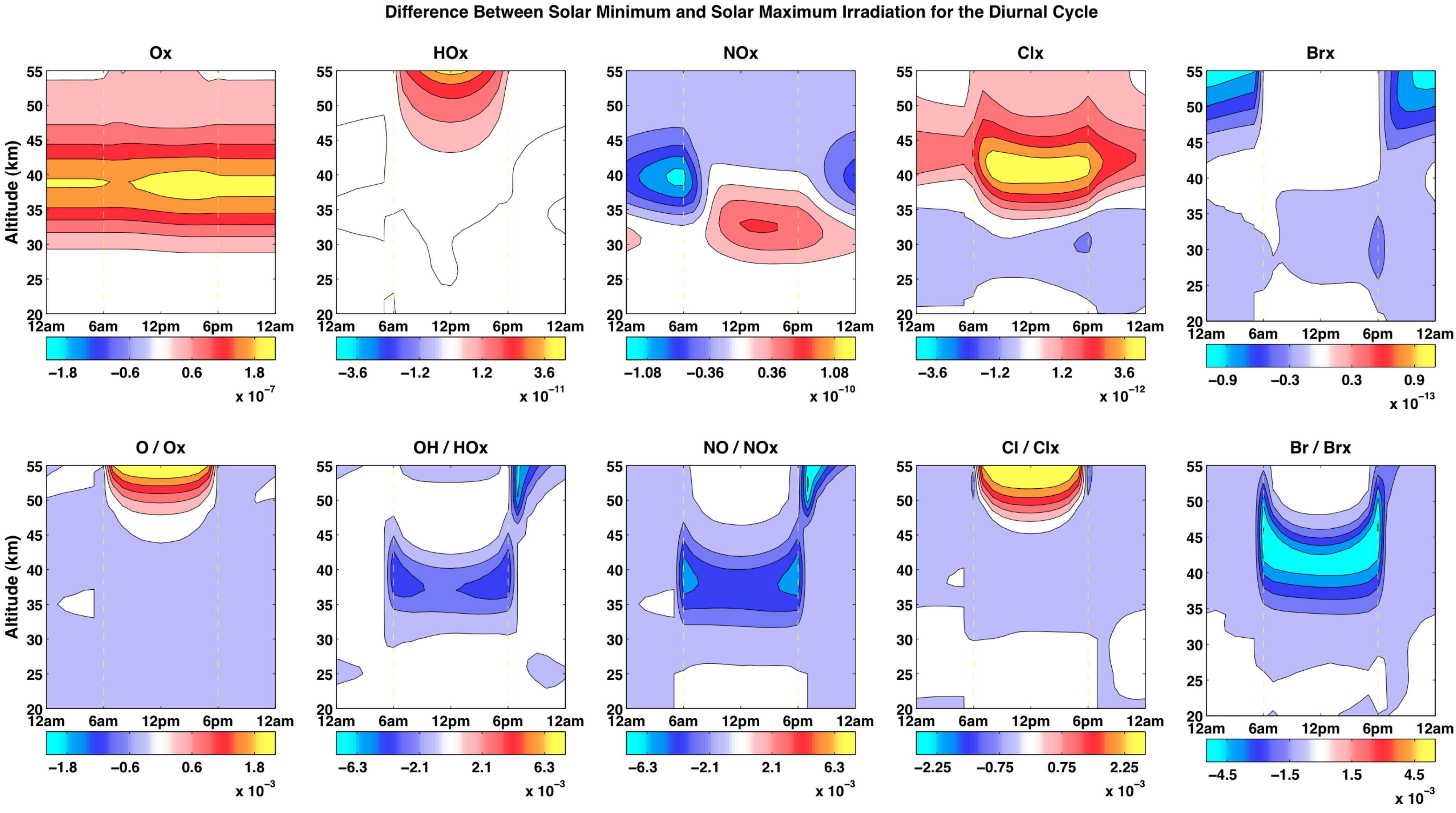
λ < 300 nm

$$O_3 + O \rightarrow O_2 + O_2$$



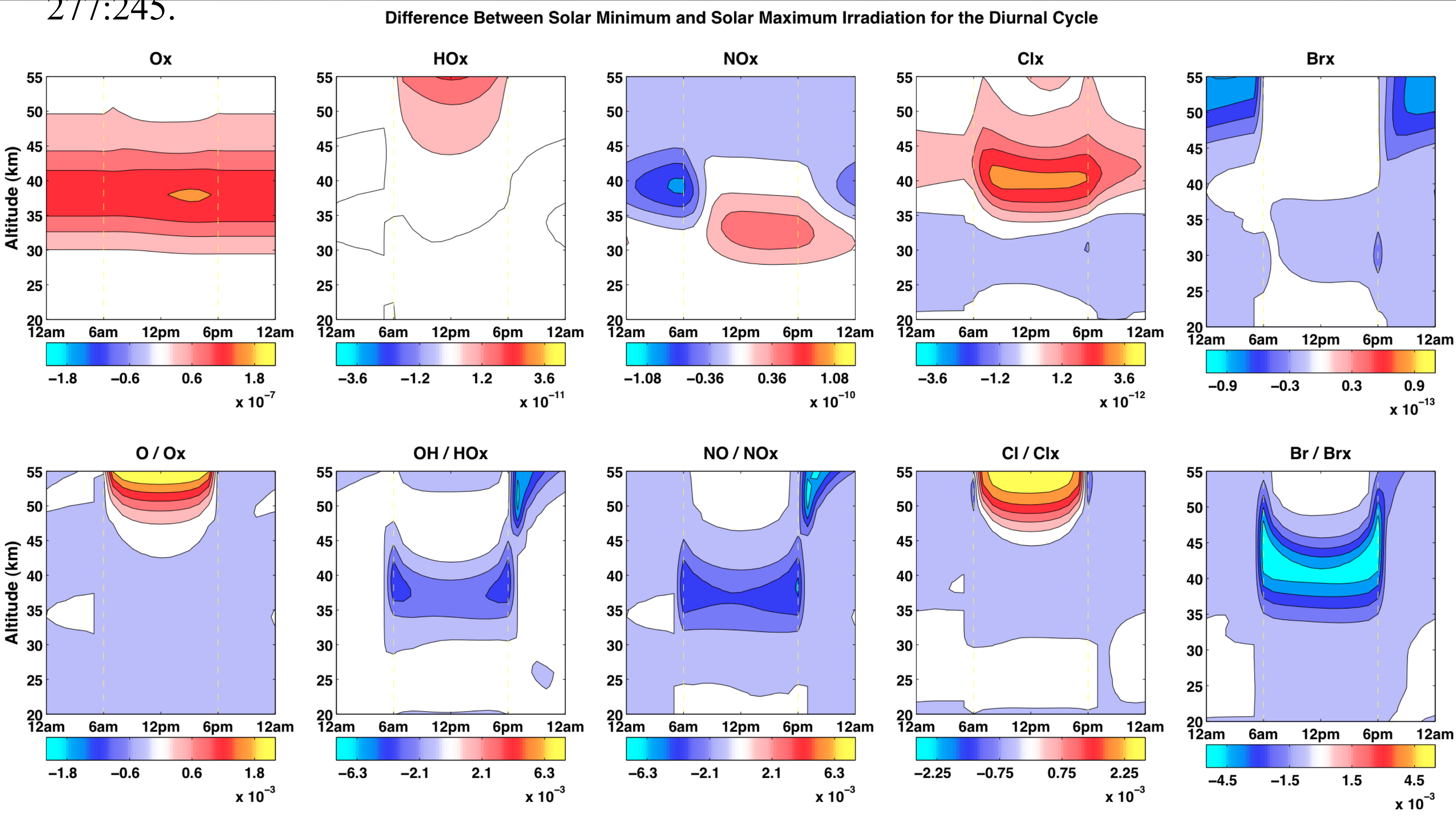
Stratospheric chemical species abundance variations

Using sept. 1986 (min) and nov. 1989 (max) spectra from Lean et al. (1997) JGR,102:29939.



Stratospheric chemical species abundance variations

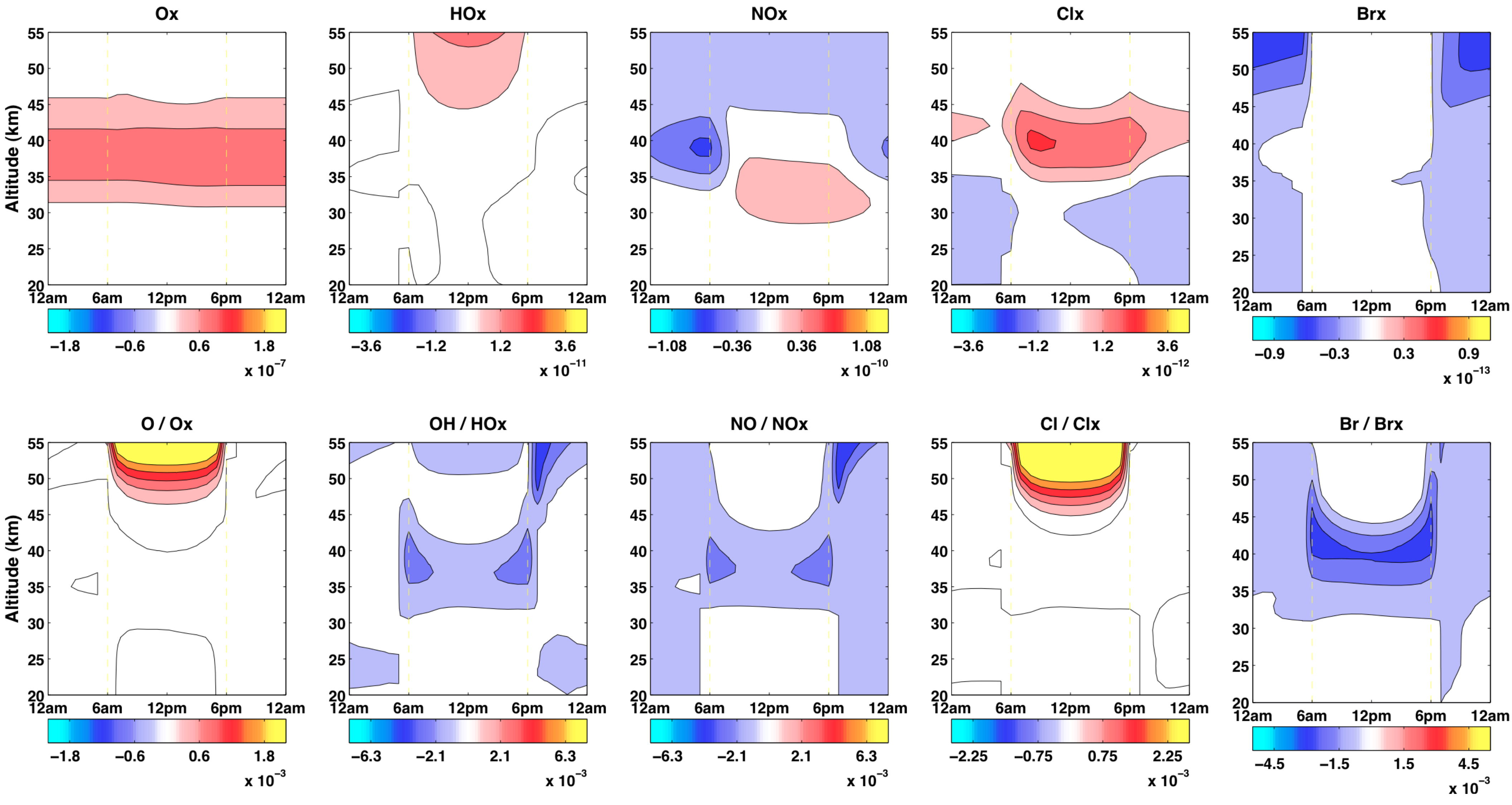
Using sept. 1986 (min) and nov. 1989 (max) spectra from Thuillier et al. (2012) Sol. Phys. 277:245.



Stratospheric chemical species abundance variations

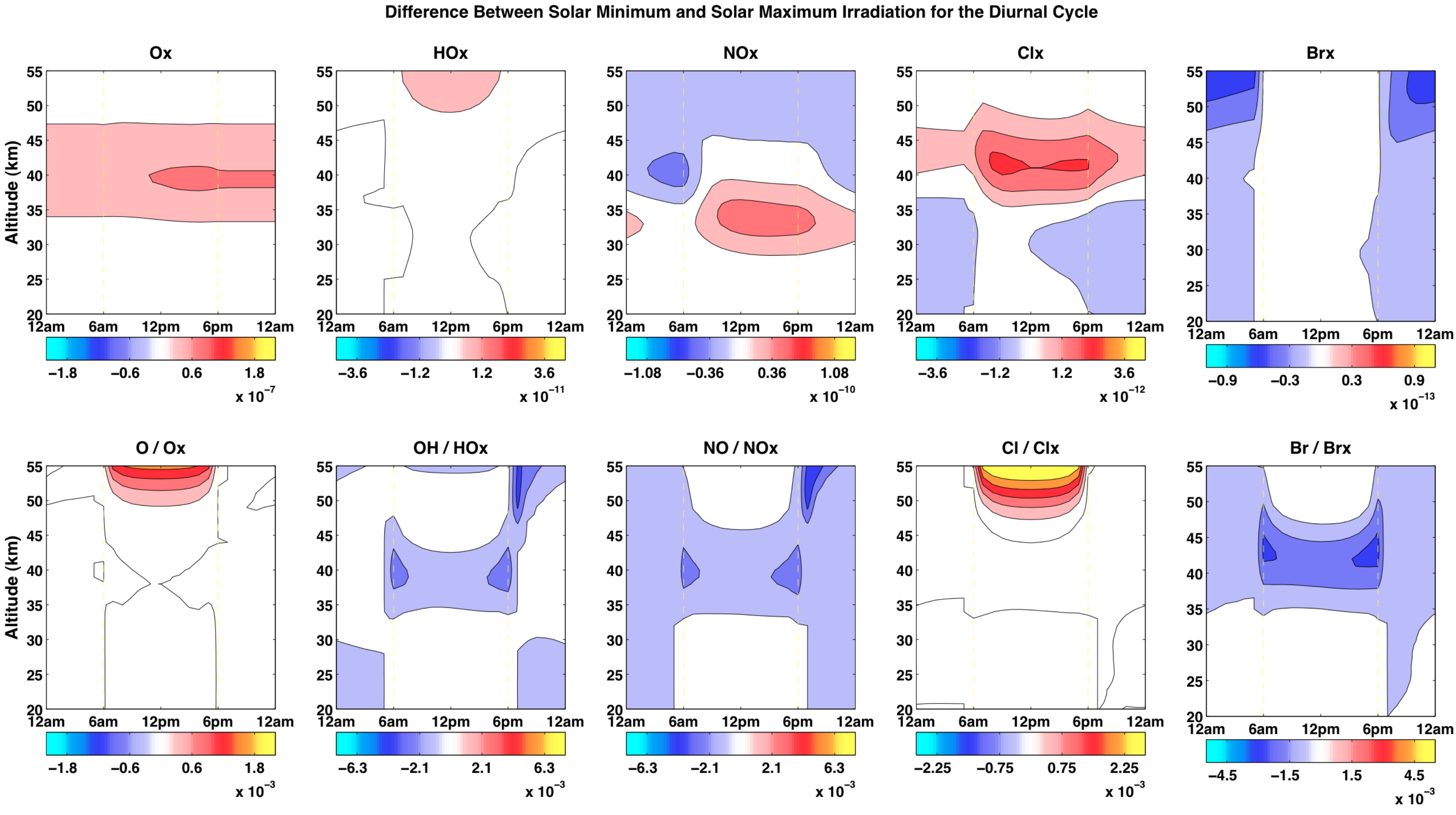
Using sept. 1986 (min) and nov. 1989 (max) spectra from MOCASSIM.

Difference Between Solar Minimum and Solar Maximum Irradiation for the Diurnal Cycle



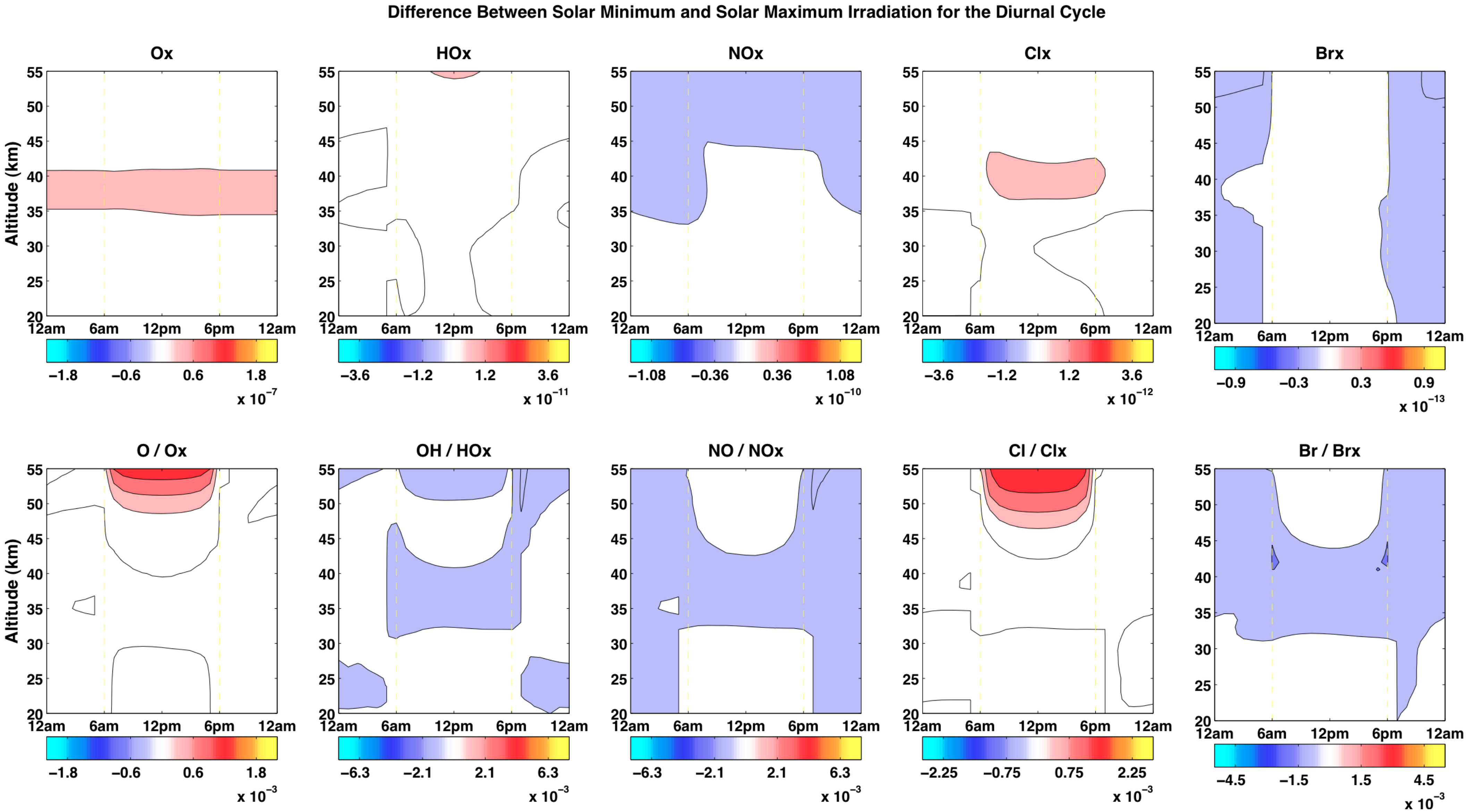
Stratospheric chemical species abundance variations

Using Nov 2007 (min) and Apr. 2004 (max) spectra from SORCE.



Stratospheric chemical species abundance variations

Using Nov 2007 (min) and Apr. 2004 (max) spectra from MOCASSIM.



Conclusions

- MOCASSIM 2.0 :
  - 4 components : quiet Sun, spots, faculae, network (+ rotational modulation amplification)
  - Spectral range : 150-400 nm
  - Temporal range : 1610-now
- Results :
  - Time series starting in 1610 showing the network importance during minima
  - Spectral reconstructions of ATLAS-1 spectrum (in agreement within 5%, except in emission lines) with an accuracy comparable to other reconstructions
  - Spectral reconstructions during important minima (Maunder, 2008)
    - According to our reconstructions, MM $\neq$ Cycle 23
  - Calculations of stratospheric chemical abundances variations over the cycle are strongly model-dependent!

References

Bolduc, Charbonneau, Barnabé and Bourqui. To be submitted to Sol. Phys. (June 2013)

Bolduc, Charbonneau, Dumoulin, Bourqui, Crouch. (2012) Sol. Phys., 279:383.

Thuillier, Melo, Lean, Krivova, **Bolduc**, Fomichev, Charbonneau, Shapiro, Schmutz, Bolsée. Submitted to Sol. Phys. (May 2013)

Muncaster et al. (2012) Atmos. Chem. Phys., 12:7707.

Crouch et al. (2008) ApJ., 677 :723.

Tapping et al. (2007), Sol. Phys., 246:309.

Solanki & Unruh (1998) A&A, 329:247.

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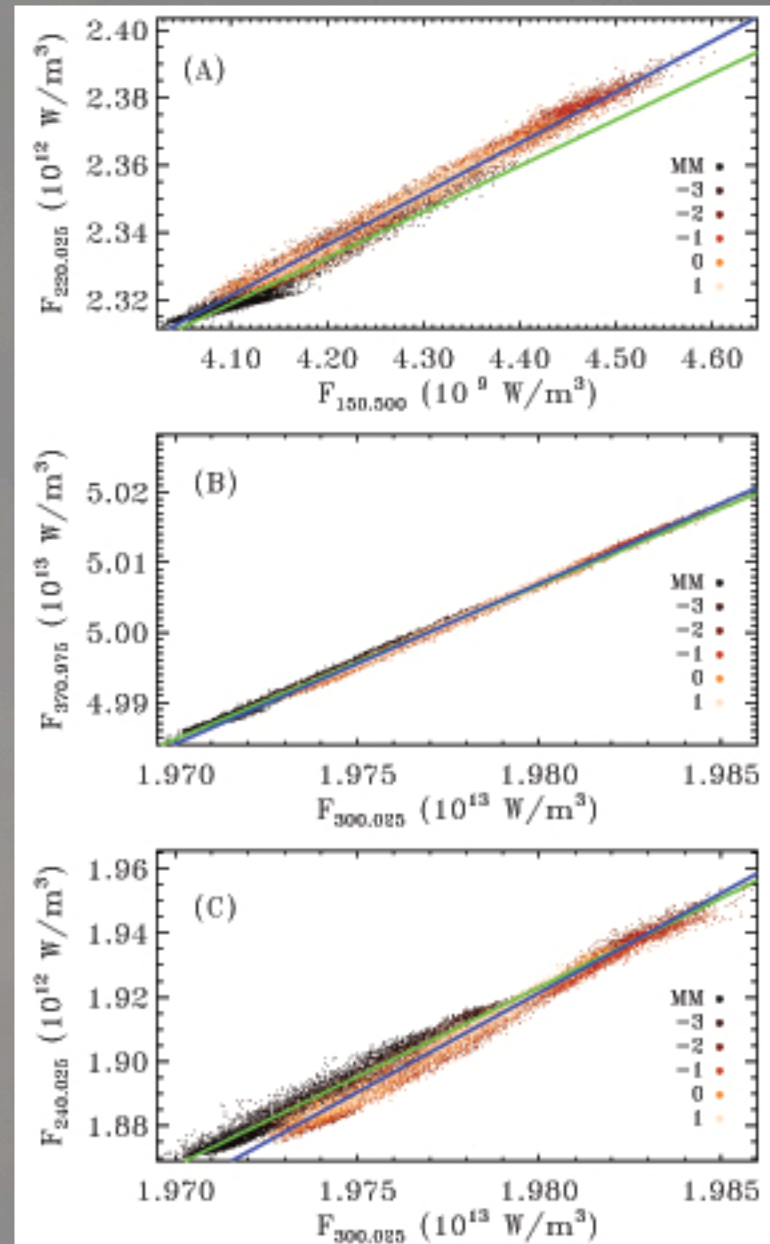
Bénédict Plante, Xavier Fabian, Vincent Dumoulin, Roxane Barnabé, Arnaud Carignan-Dugas.

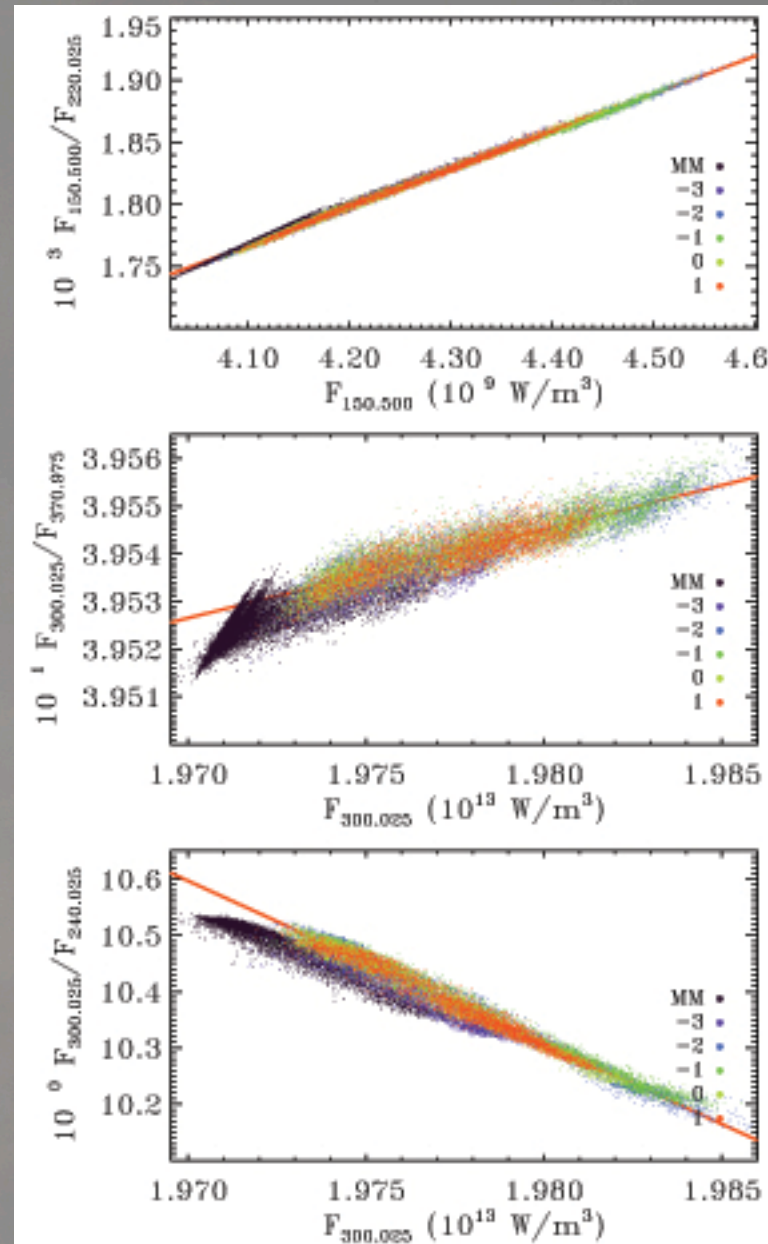
Correlations

- Plot the ratio of two monochromatic fluxes against one of them
  - one point per day,
  - different colors for Maunder minimum and following cycles



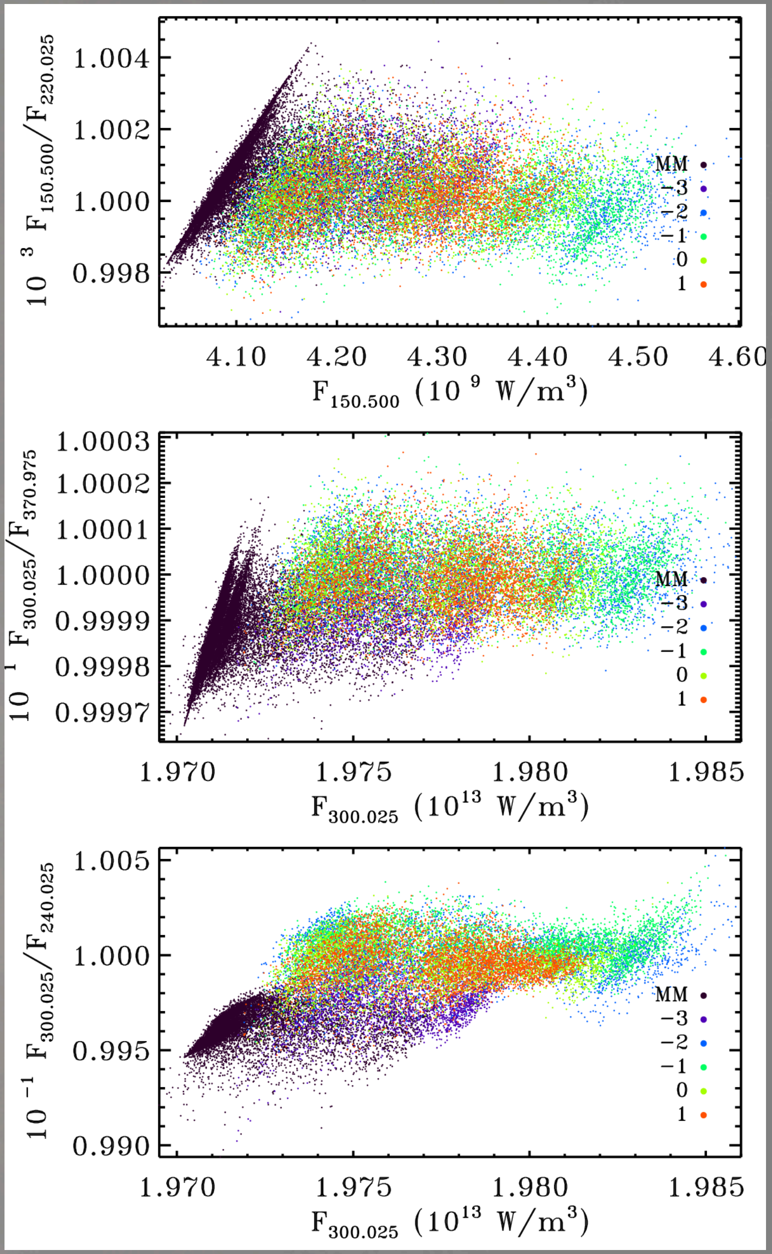
Correlations

- Plot the ratio of two monochromatic fluxes against one of them
  - one point per day,
  - different colors for Maunder minimum and following cycles
- Plot the flux ratio against one of them
- Linear fit on last cycle



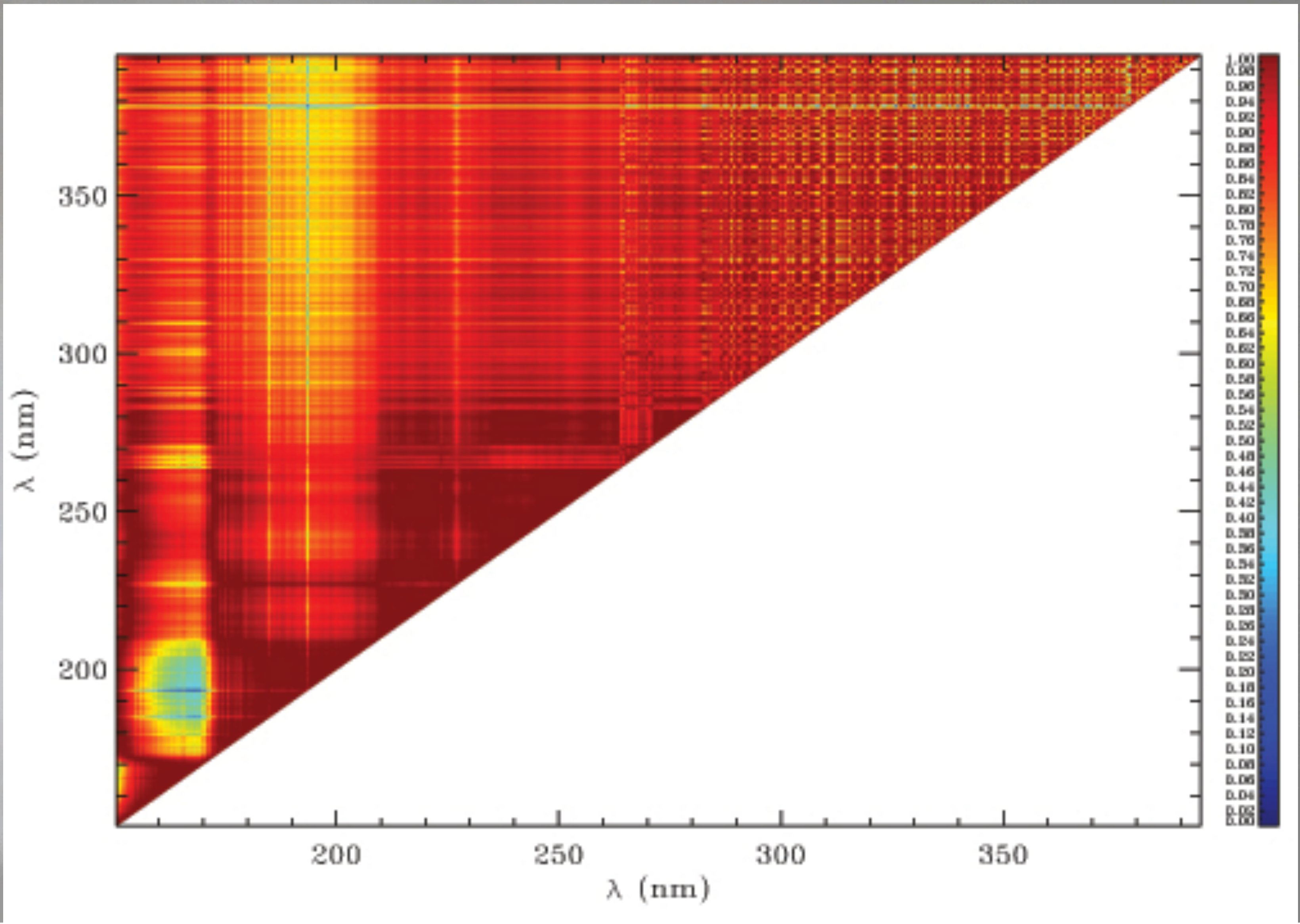
Correlations

- Plot the ratio of two monochromatic fluxes against one of them
  - one point per day,
  - different colors for Maunder minimum and following cycles
- Plot the flux ratio against one of them
- Linear fit on last cycle
- Divide the flux plotted on the y-axis by the linear fit to remove the trend and show the variations
- Conclusion : Maunder minimum and cycle -3 show a different behavior from the other cycles!



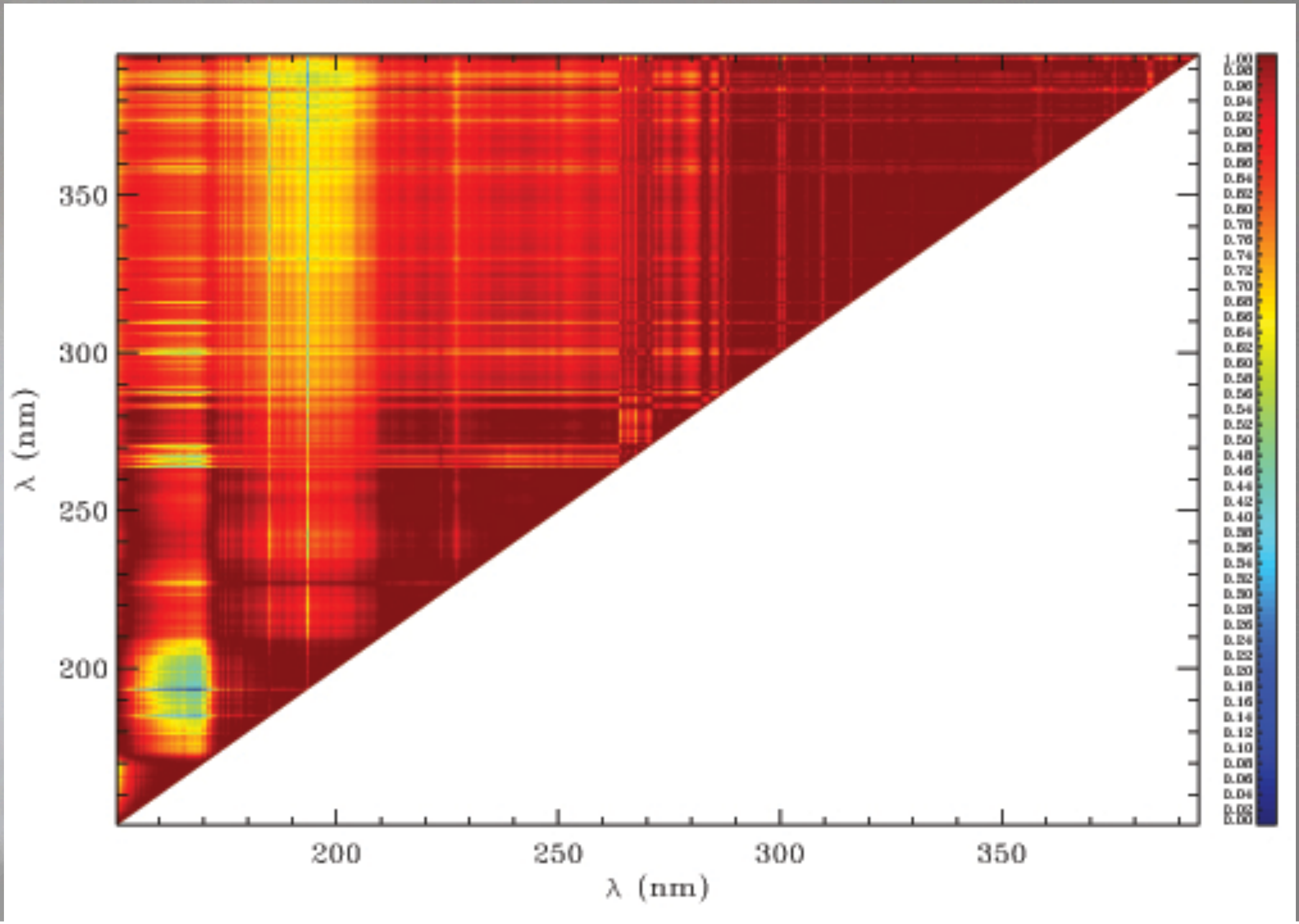
Correlations matrix

Maunder minimum (average between 1650-1715)

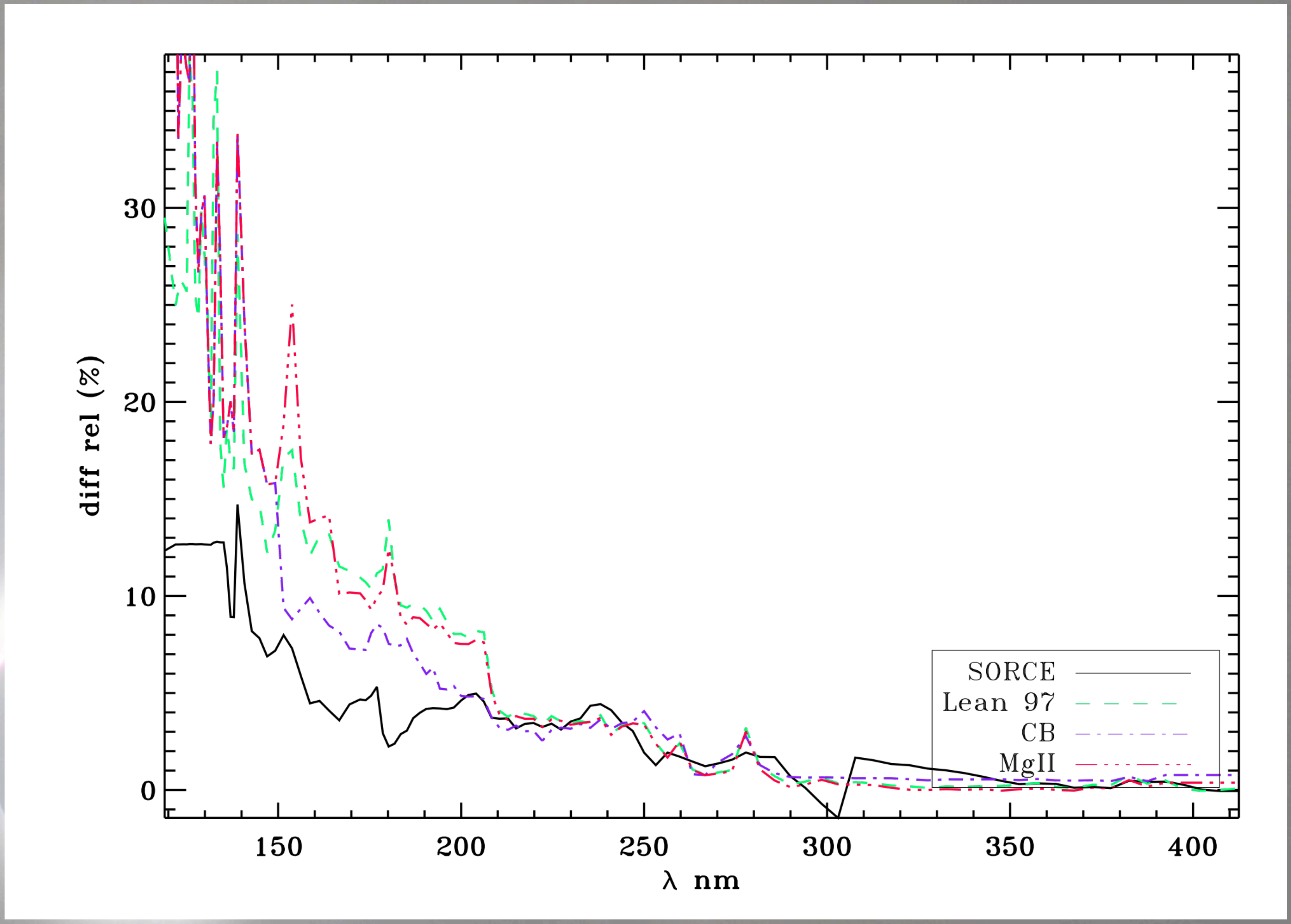


Correlations matrix

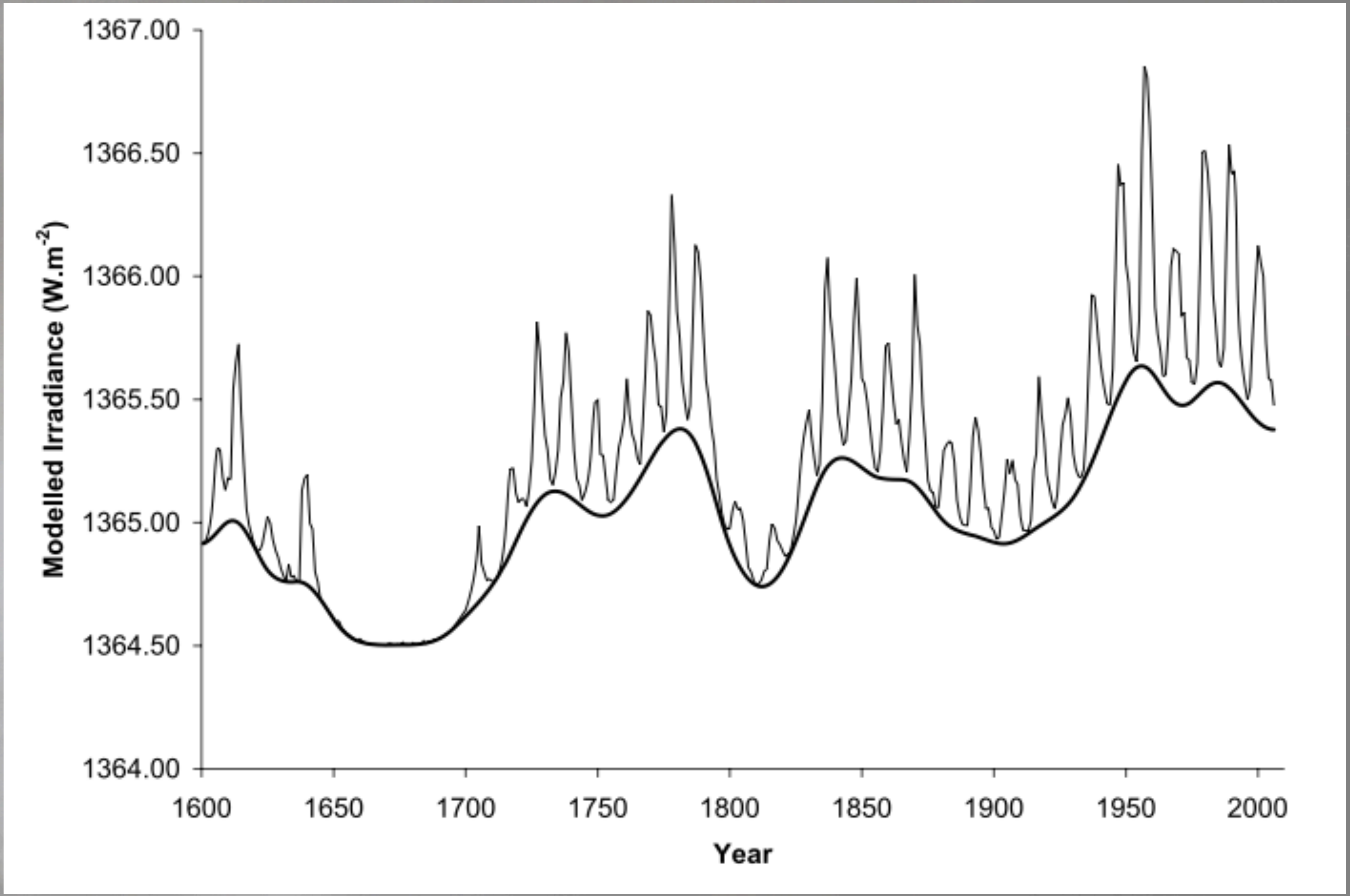
Cycle 20 (average on the whole cycle)

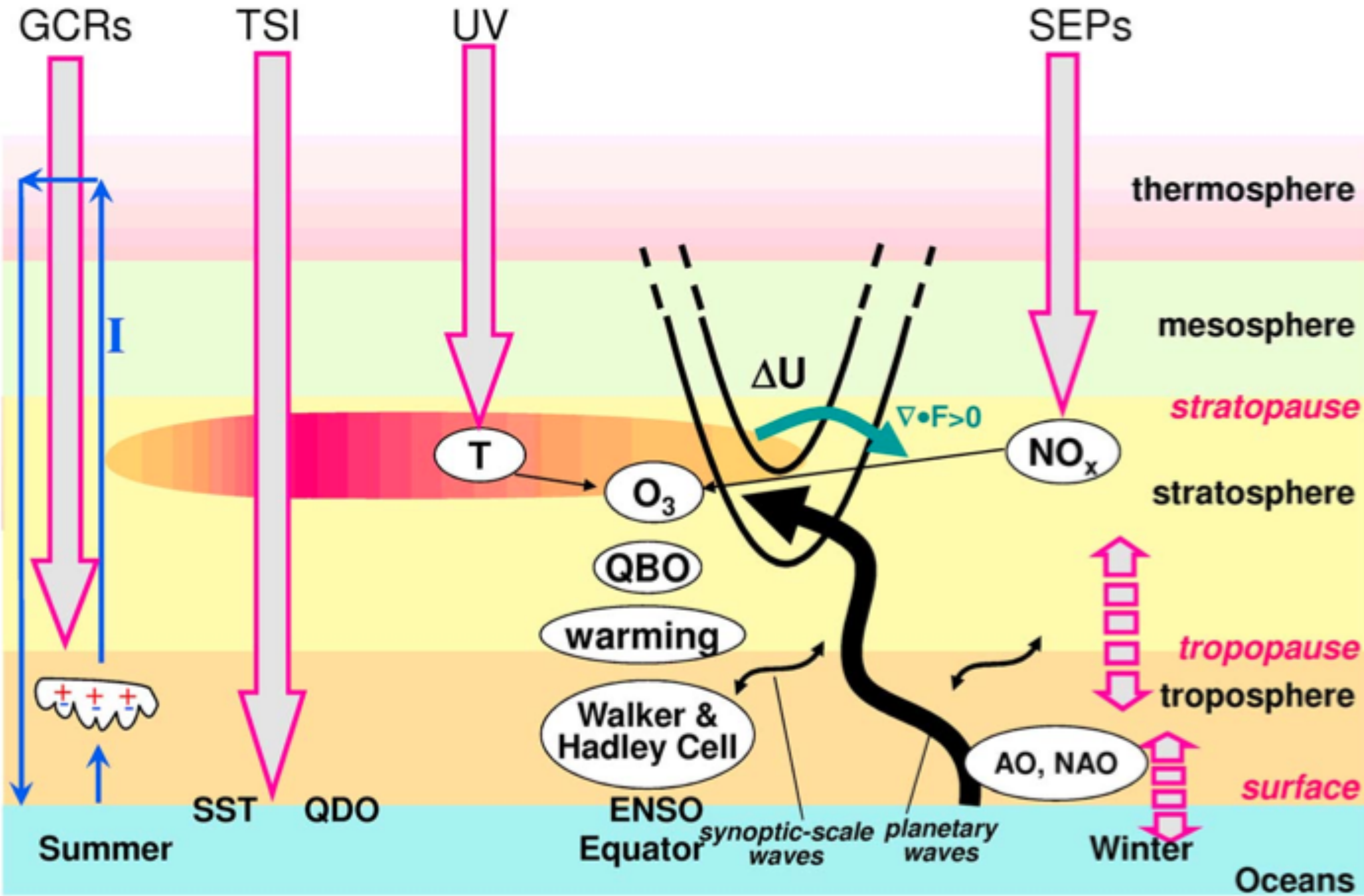


Variability for the reconstructions used for the photochemistry model



TSI reconstruction




GCRs
TSI
UV
SEPs
thermosphere
I
mesosphere
ΔU
stratopause
∇•F>0
T
NOx
O3
stratosphere
QBO
warming
tropopause
troposphere
Walker & Hadley Cell
AO, NAO
surface
SST
QDO
ENSO
Summer
Equator
synoptic-scale waves
planetary waves
Winter
Oceans