

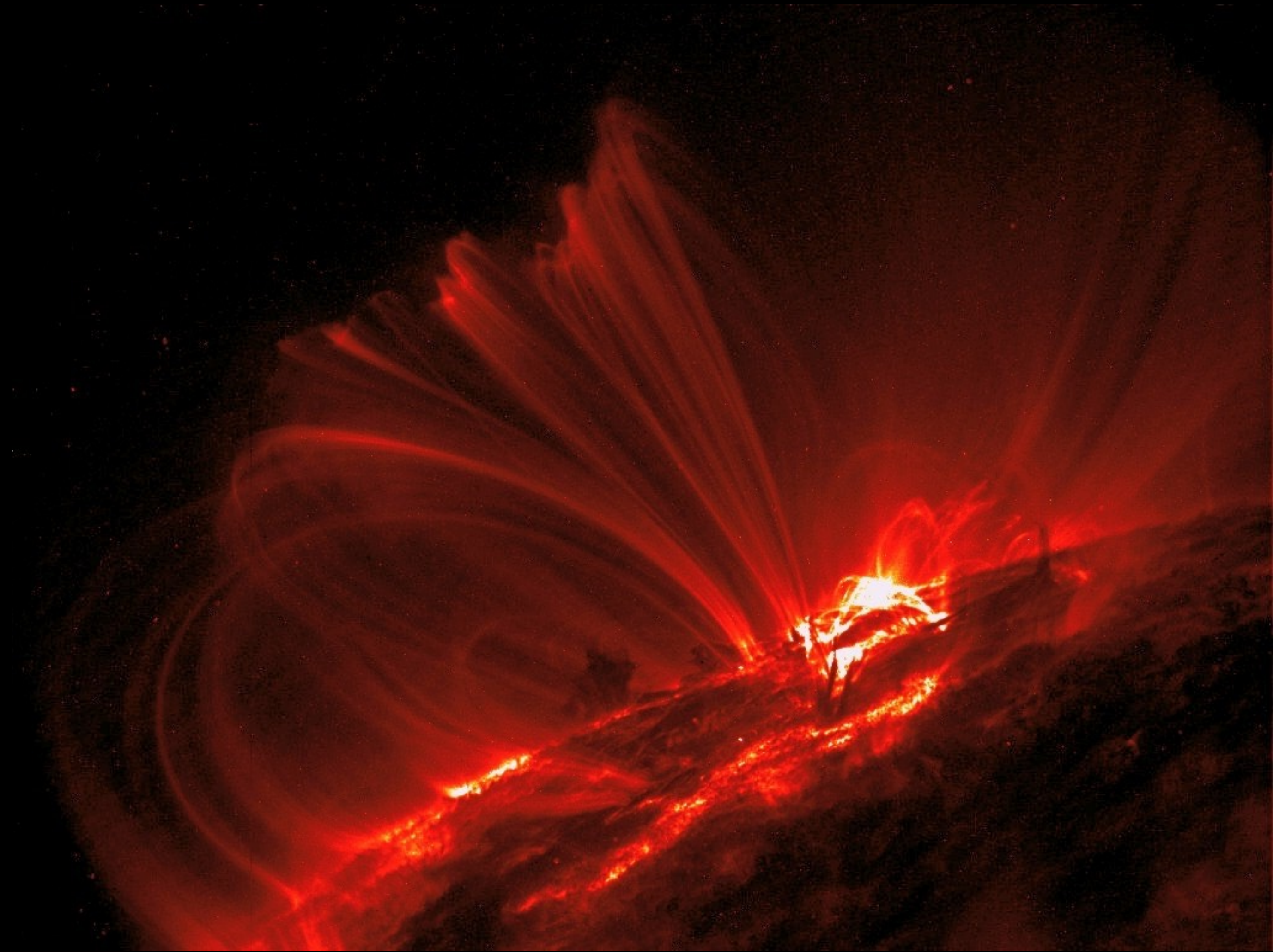
# Which solar inputs for the specification of the upper atmosphere ?

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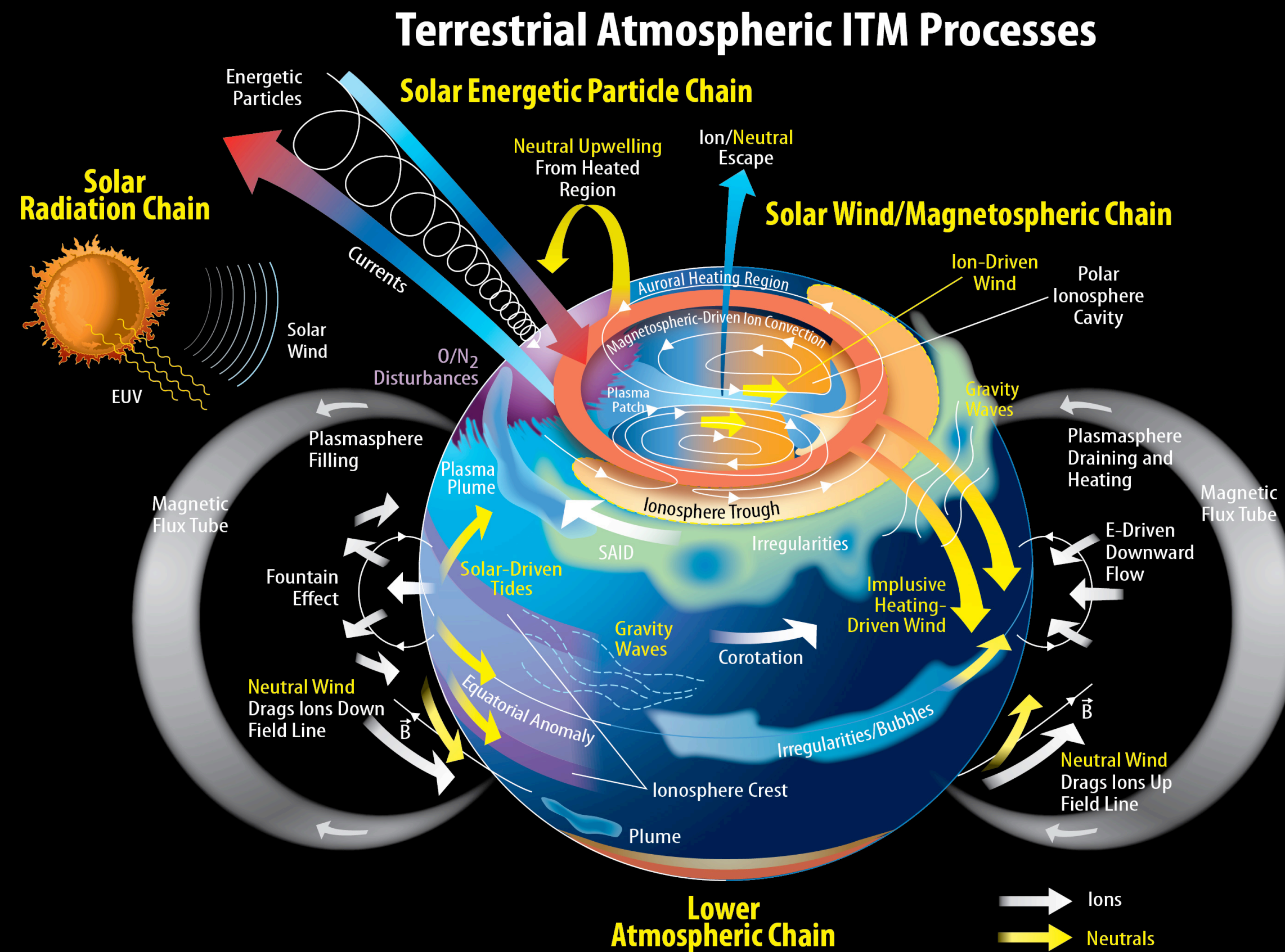


- Solar radiative forcing of the upper atmosphere
- Why use solar proxies
- Performance of solar proxies
- Forecasting solar proxies





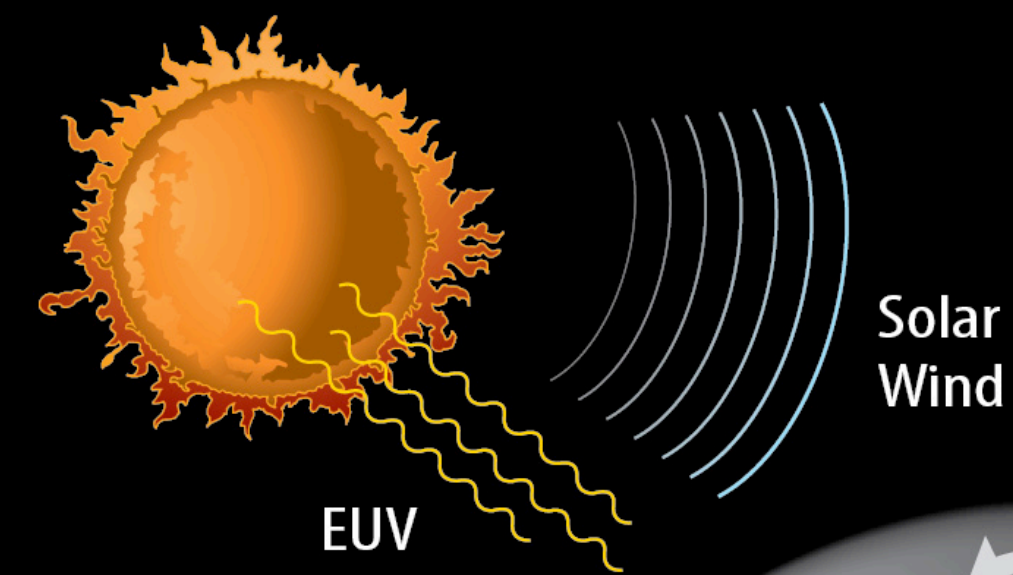
# The ionosphere-thermosphere system



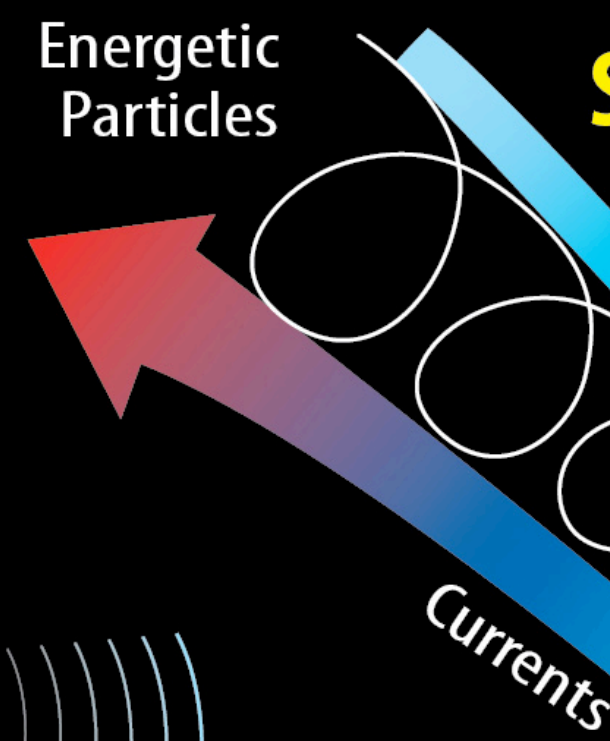
NASA/J. Grobowsky



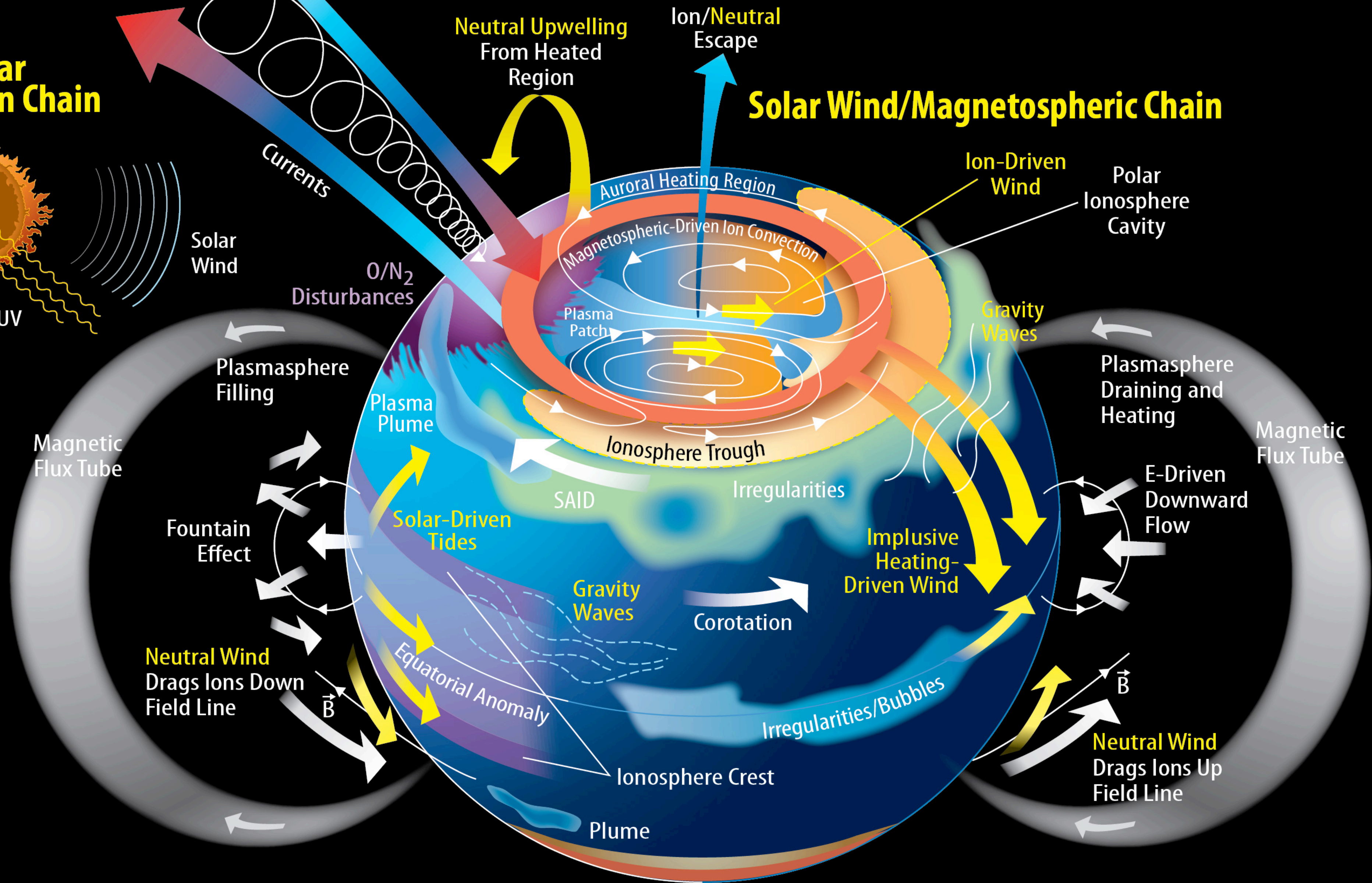
## Solar Radiation Chain



## Solar Energetic Particle Chain



## Solar Wind/Magnetospheric Chain



## Lower Atmospheric Chain





# Different types of forcings

- Solar radiative forcing in the EUV
  - daily-yearly variations, impulsive bursts during flares only
- Joule heating due to geomagnetic activity
  - highly variable in time

**external**



# Where the energy comes from

- Solar radiative forcing in the EUV
  - daily-yearly variations, impulsive bursts during flares only
- Joule heating due to geomagnetic activity
  - highly variable in time

**strong effect**

**external**

**strong but highly  
intermittent**

- Dynamical coupling with the mesosphere below
  - wave activity: energy and momentum exchange
- Infrared cooling by trace gases
  - continuous, caused by greenhouse gases (CO<sub>2</sub>, CH<sub>4</sub>, ...)

**weak and poorly  
known**

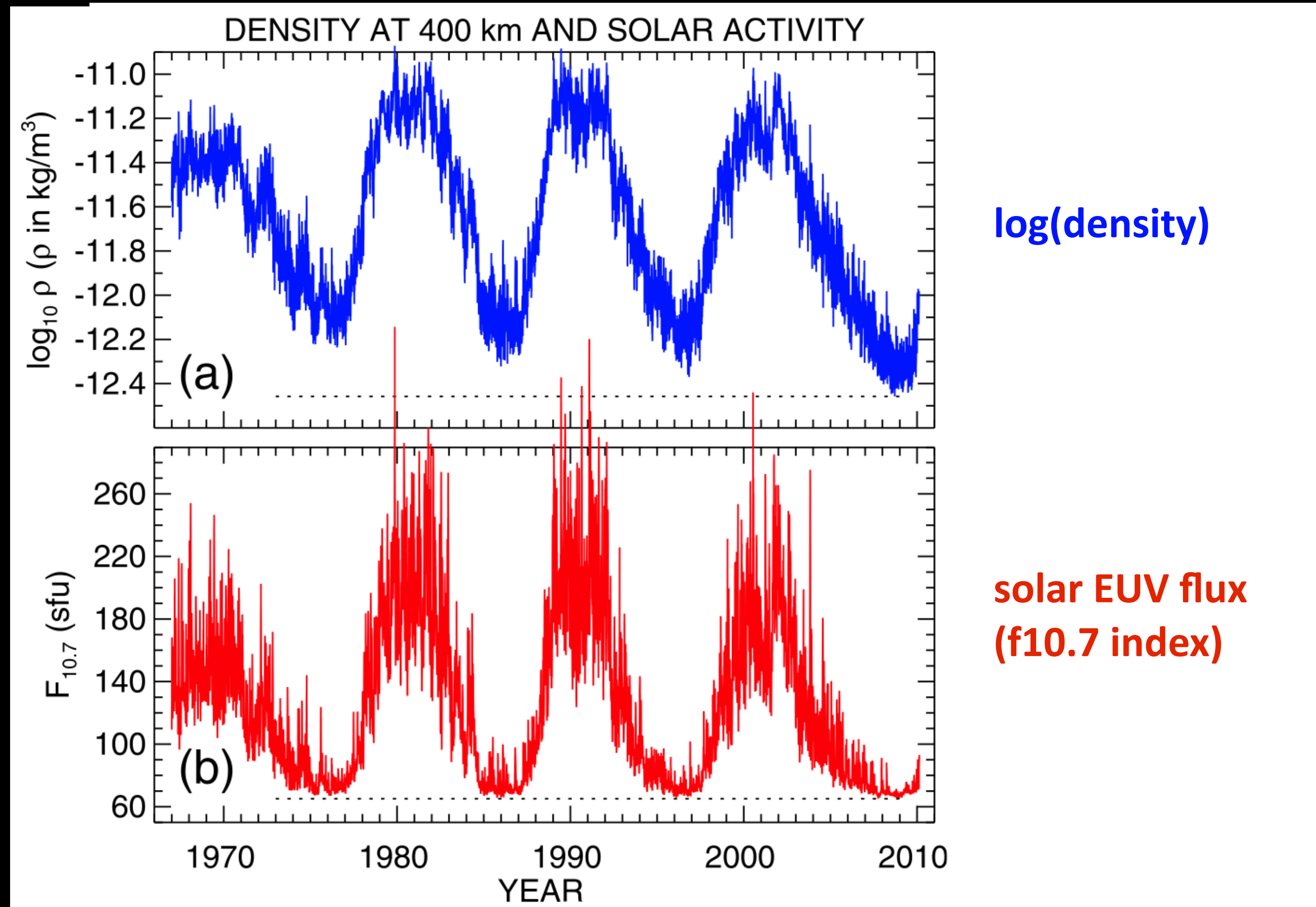
**internal**

**very weak but slow  
trend**



# What do we know ?

- Changes in the thermospheric density on time scales  $\gg 1$  day are primarily driven by solar EUV forcing

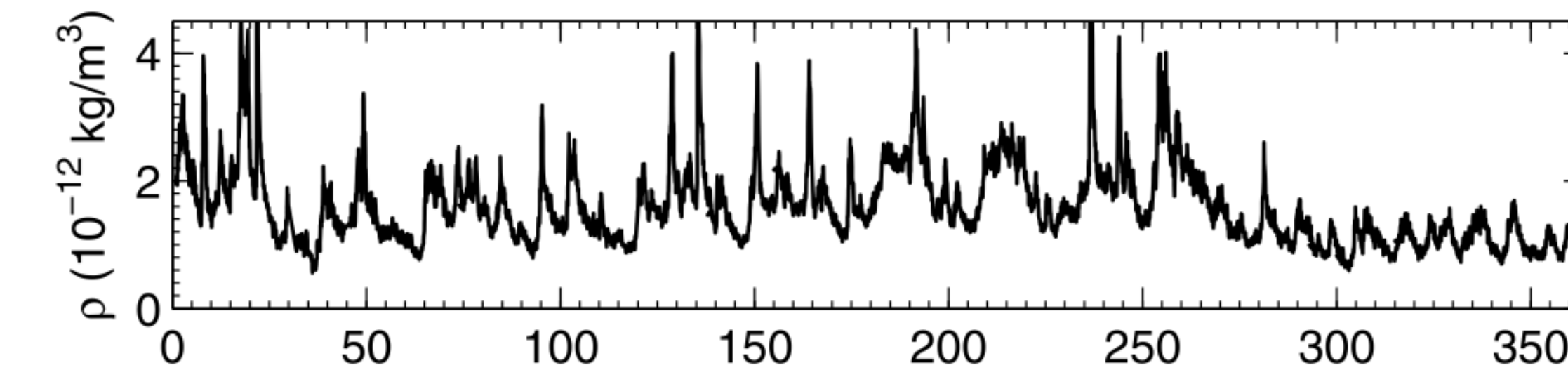


Emmert et al. GRL (2010)

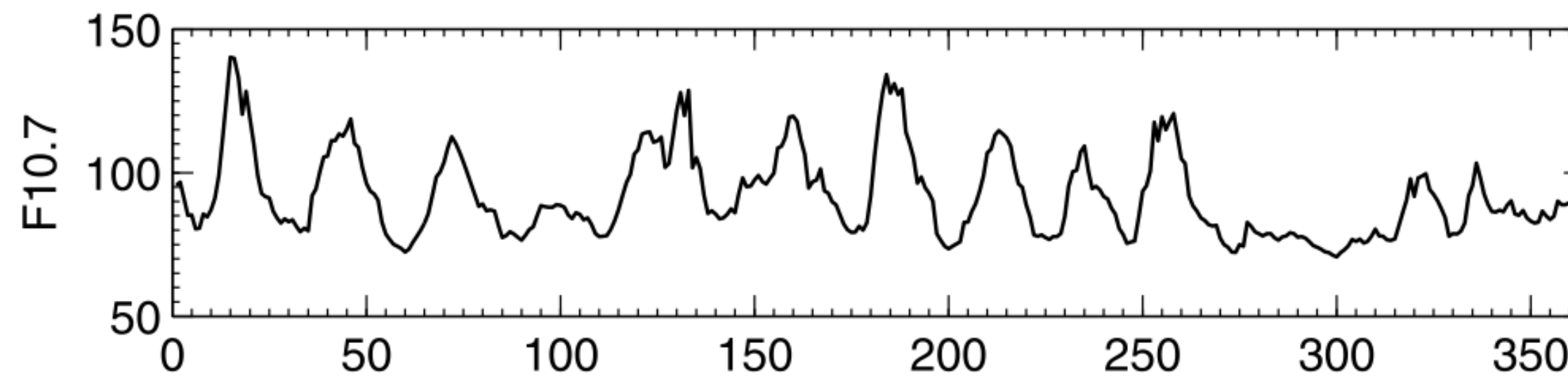


# What do we know ?

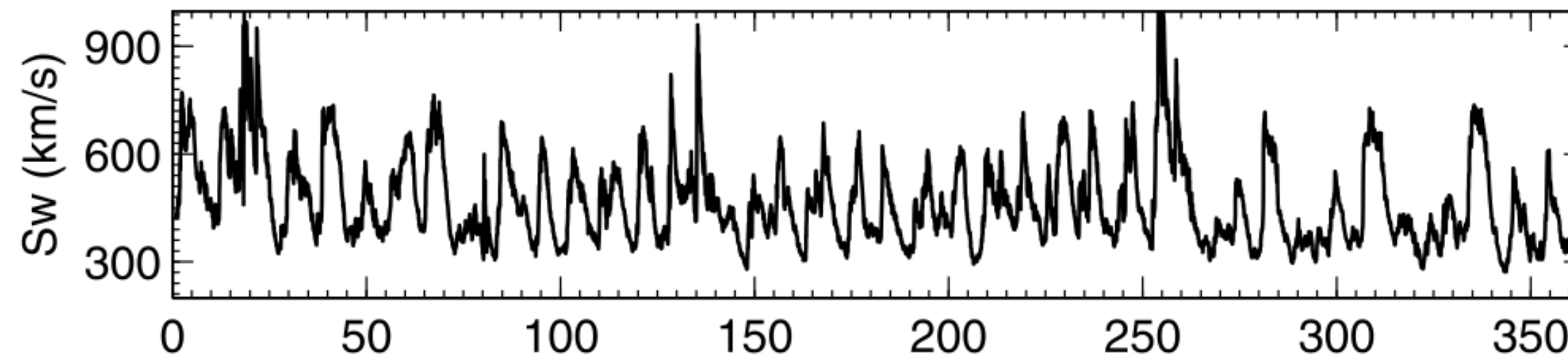
- Variability  $< 1$  day is driven by a mix of geomagnetic forcing and solar EUV variability



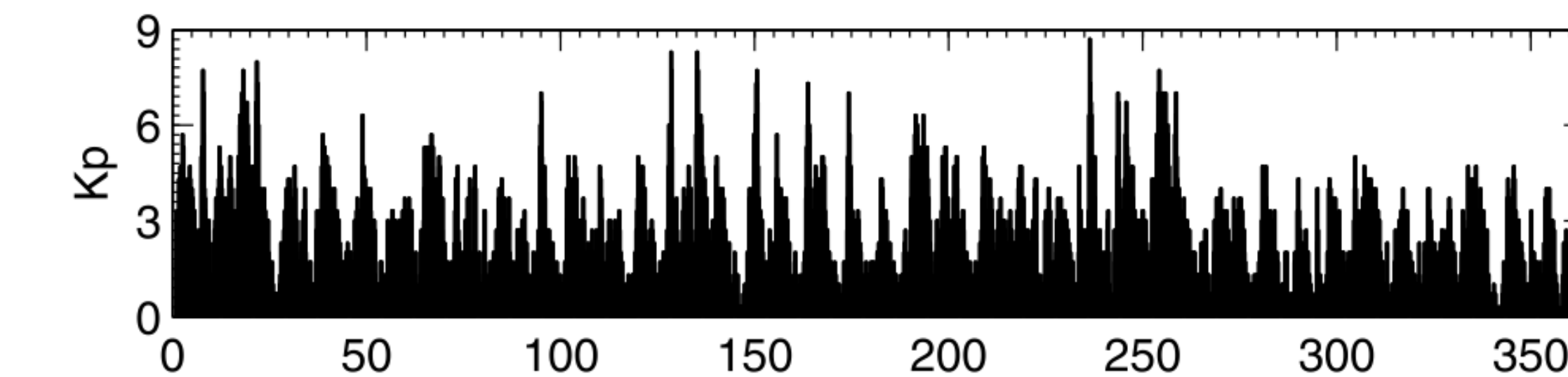
density



EUV flux



solar wind velocity



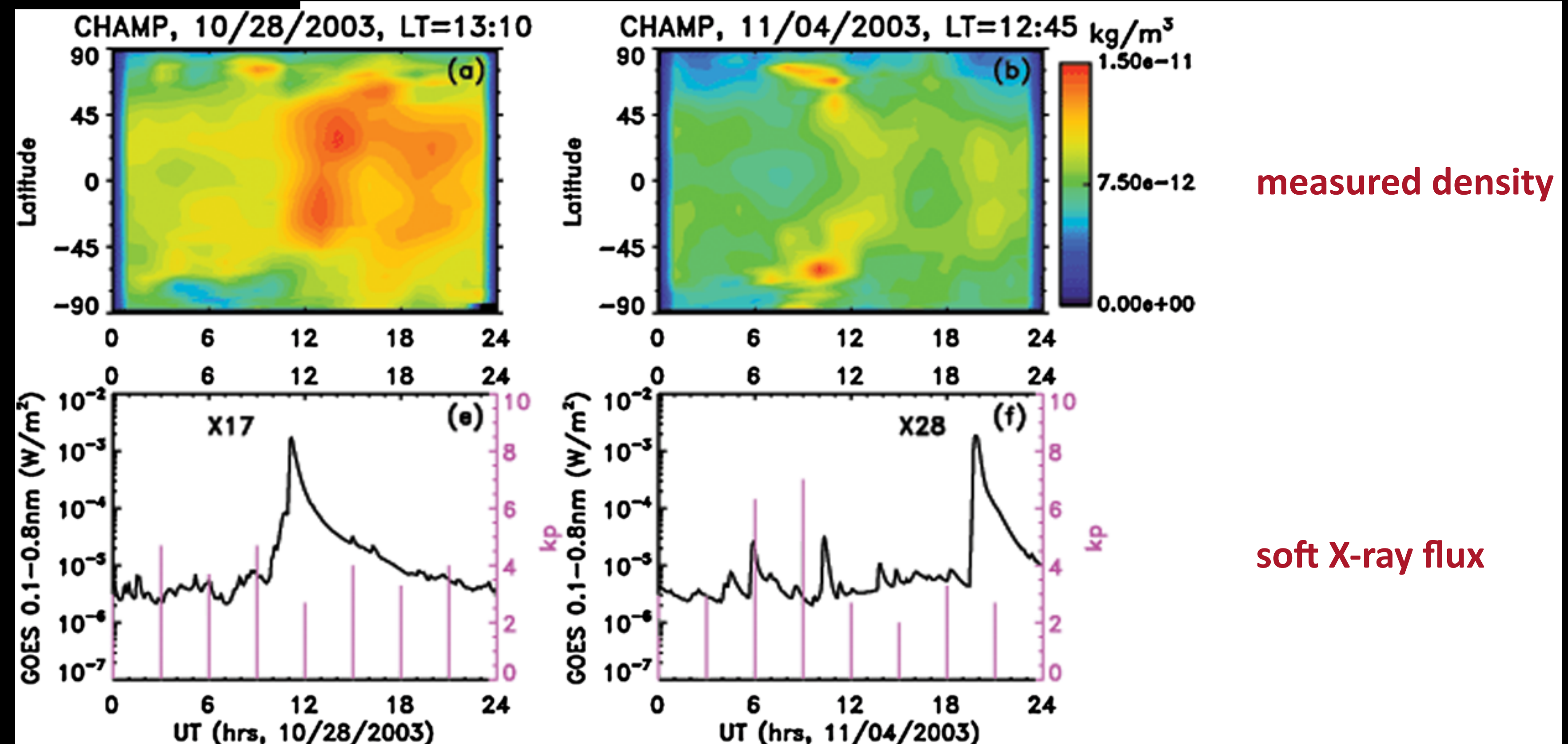
geomagnetic activity

Day of Year, 2005



# What do we know ?

- Impact on density of largest (X-class) flares is highly variable but globally weak



Sutton et al. GRL (2006)

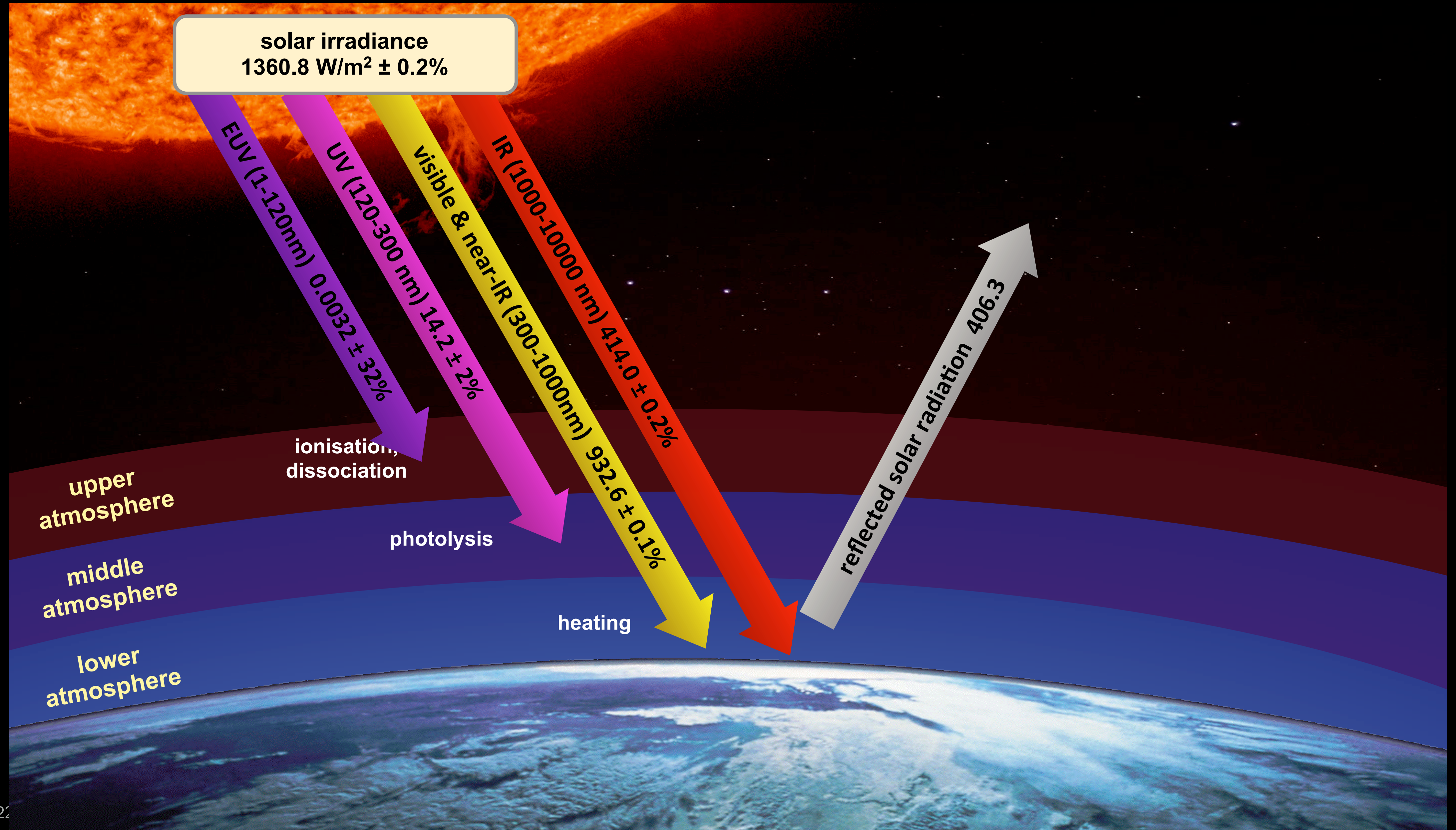


# Why solar proxies are needed





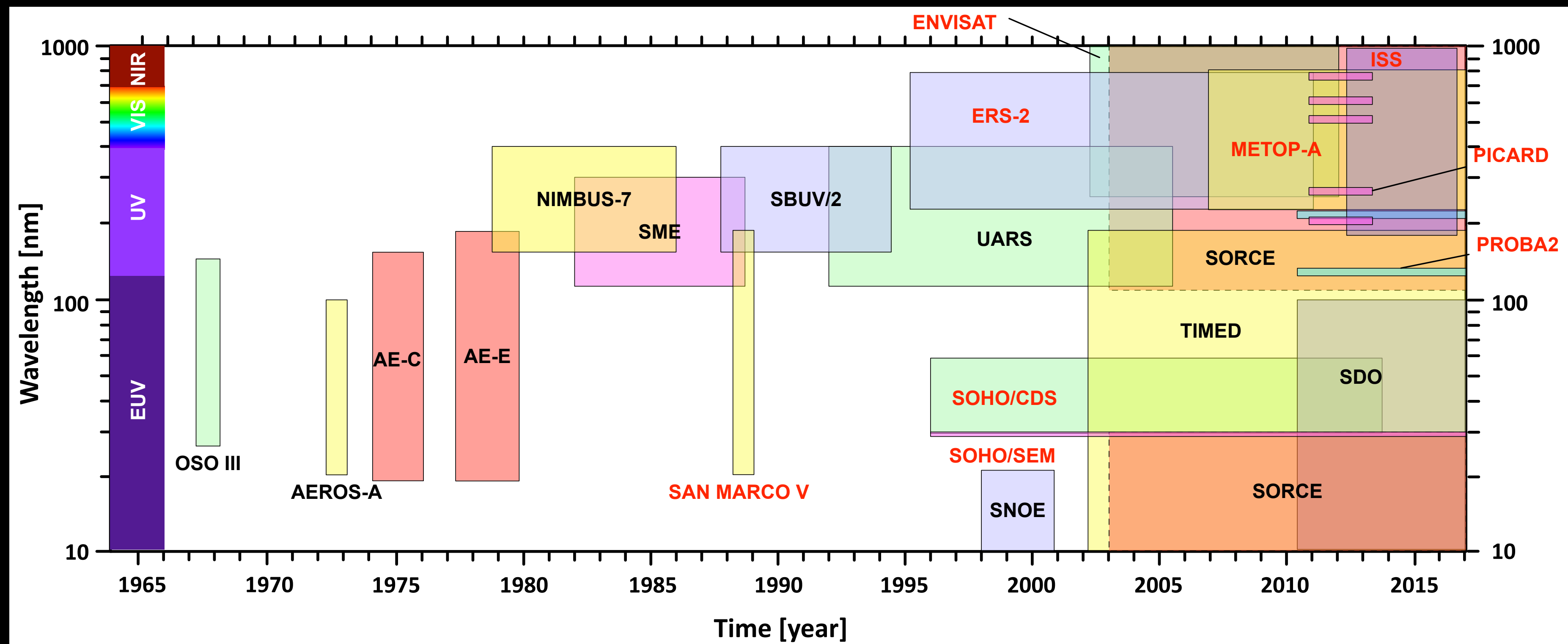
# Impact is highly wavelength-dependent





# EUV/UV observations are very challenging

- Instruments suffer from degradation and contamination (lifetime < 10yrs)
- Poor radiometric accuracy and stability
- Observations are highly fragmented



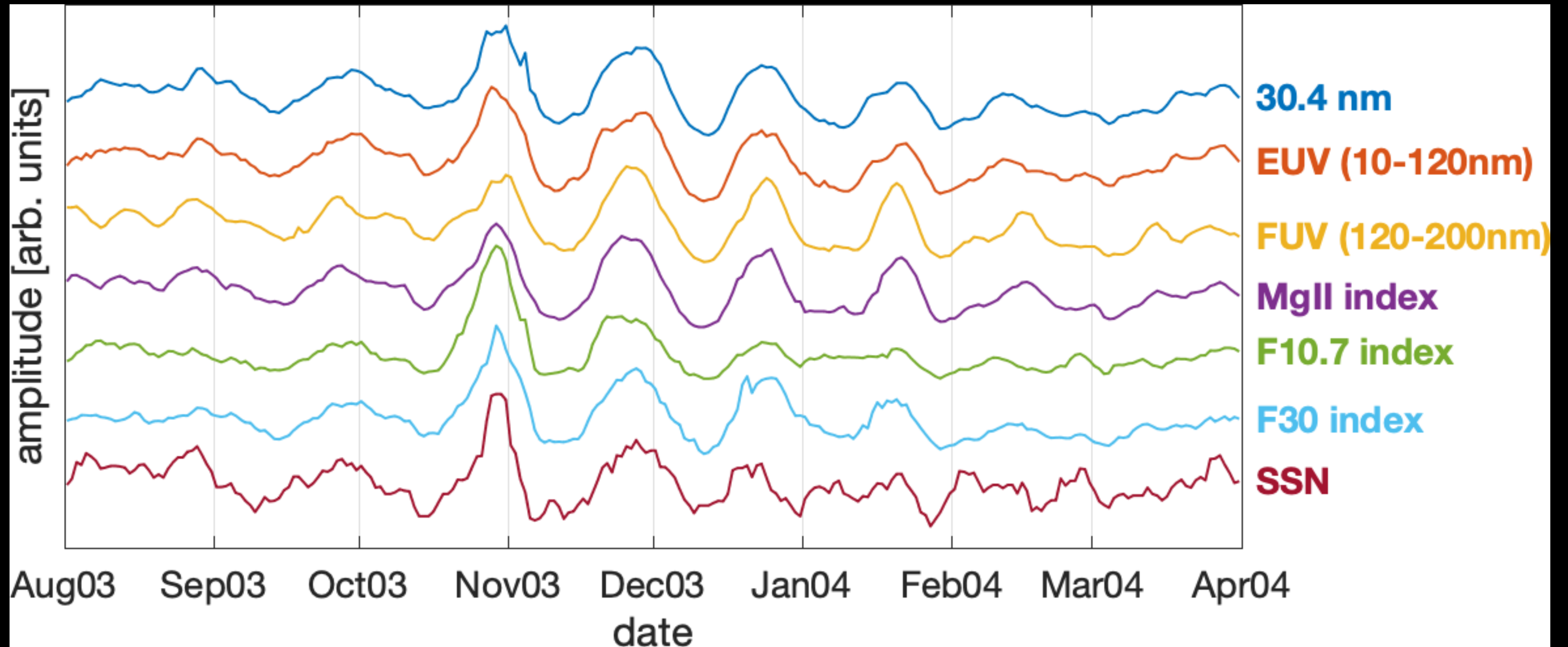


# Main solar proxies for the UV/EUV

Name	Definition	Origin	Coverage
Sunspot Number	number of spots / groups	Ground : counted by observers	daily since 1815
MgII index	core-to-wing ratio of Mg II line @ 280 nm	measured from space	daily since 1978
F10.7 index	radio emission @ 10.7 cm	Ground : Penticton observatory	daily since 1947
F30 index	radio emission @ 30 cm	Ground : Nobeyama observatory	daily since 1957



# Proxies and solar UV/EUV irradiance are highly correlated





**Which is the best proxy ?**



# Two different questions

**Question 1** : Which is the best proxy for reproducing a specific spectral band ?

**Question 2** : Which is the best proxy for describing the solar forcing of the thermospheric density ?



# Two different questions

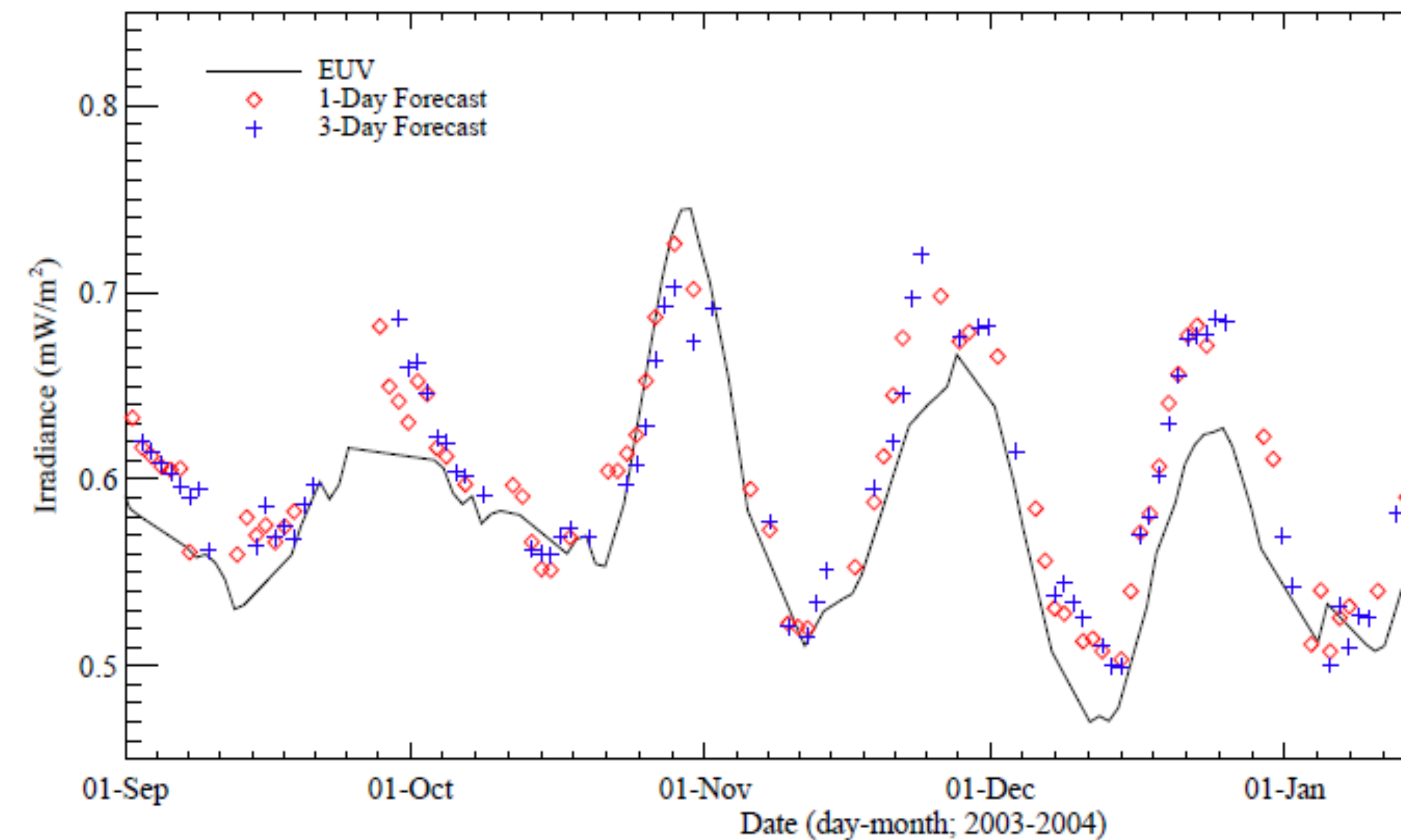
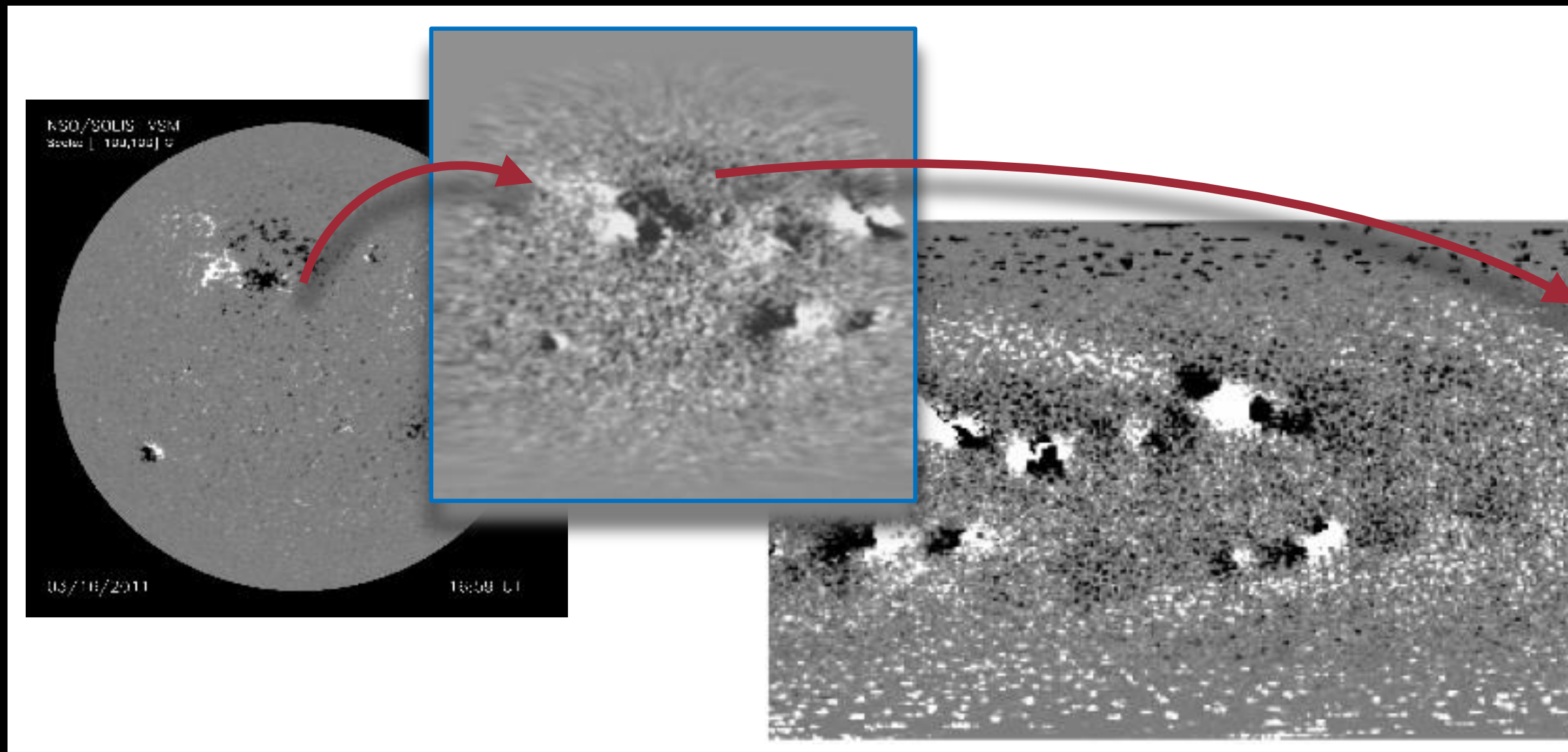
**Question 1** : Which is the best proxy for reproducing a specific spectral band ?

**Question 2** : Which is the best proxy for describing the solar forcing of the thermospheric density ?

**Question 3** : Can we reduce the solar radiative input to one single quantity ?

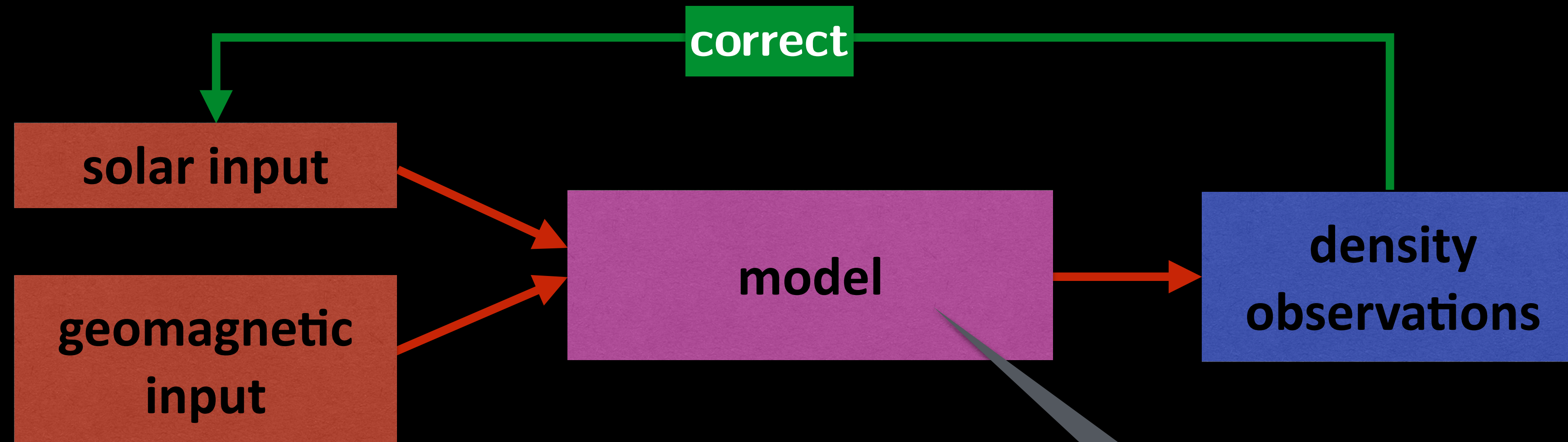
# Solution for question 1

- Use solar surface magnetism to nowcast/forecast the radiative output : ADAPT model [Henney et al. 2015, 2016]





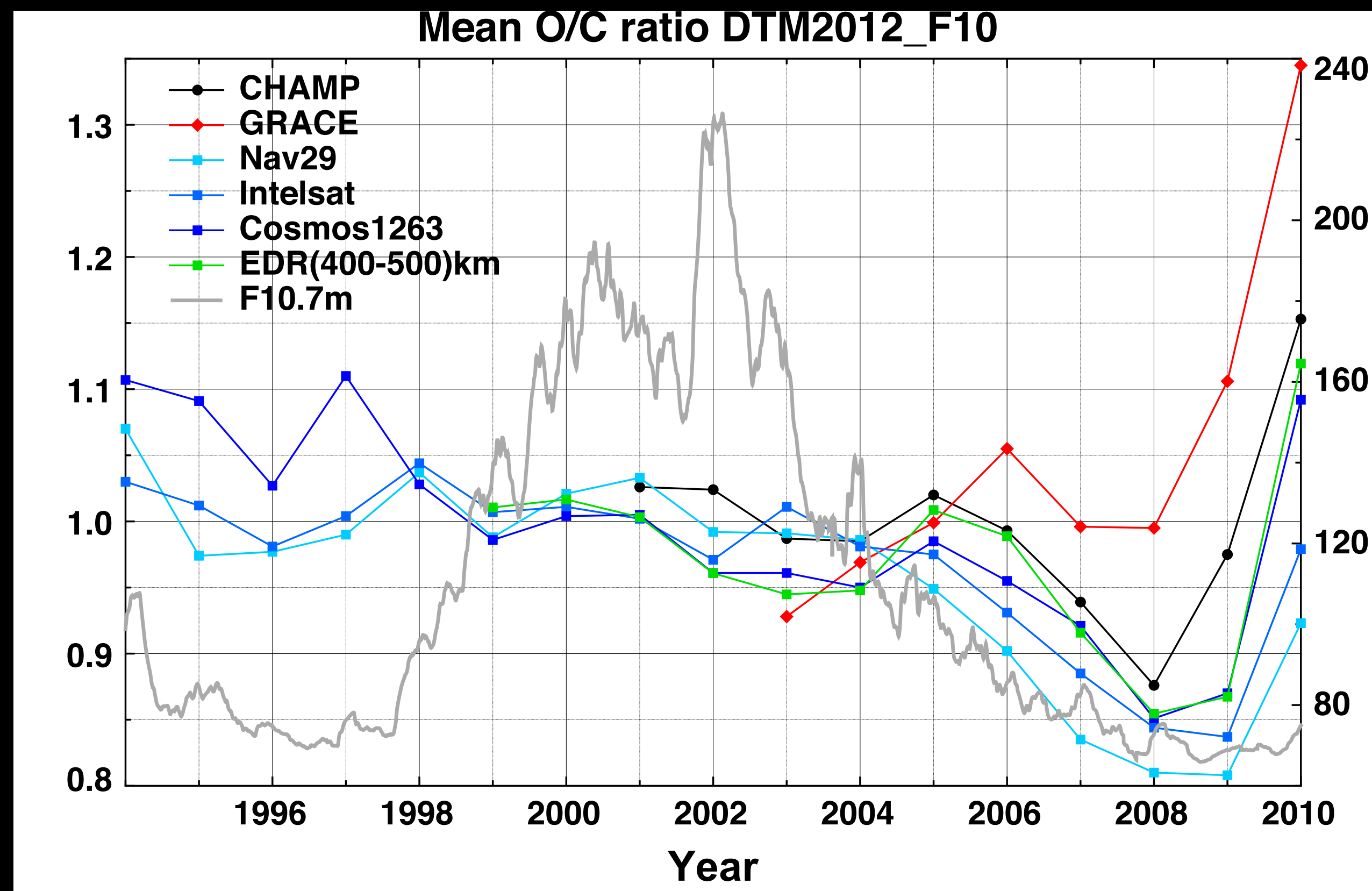
## Solution for question 2



empirical model (transfer function), or semi-empirical model (DTM, MSIS, ...)

# Testing proxies with the DTM2000 model

- Run the DTM2000 model with the 10.7 and the 30 cm flux
- Compare the ratios between observed and modelled density, using various observations



DdW & Bruinsma,  
2015, 2016



# Which is the best proxy for satellite drag modelling ?

Name	Performance
Sunspot Number	poor
MgII index	good
F10.7 index	good
F30 index	* best *
EUV flux @ 30.4 nm (SoHO SEM)	good



# Which is the best proxy for satellite drag modelling ?

Name	Performance	Stability	Outages	Latency	Long-term availability
Sunspot Number	poor	good	none	~ 1 day	no interruption
MgII index	good	average	a few	hours	probably no interruption
F10.7 index	good	good	none	hours	no interruption
F30 index	* best *	good	a few	hours	may end around 2024
EUV flux @ 30.4 nm (SoHO SEM)	good	average	a few	minutes	may end soon, replaced by GOES-R

← operational use →

# Forecasting solar proxies

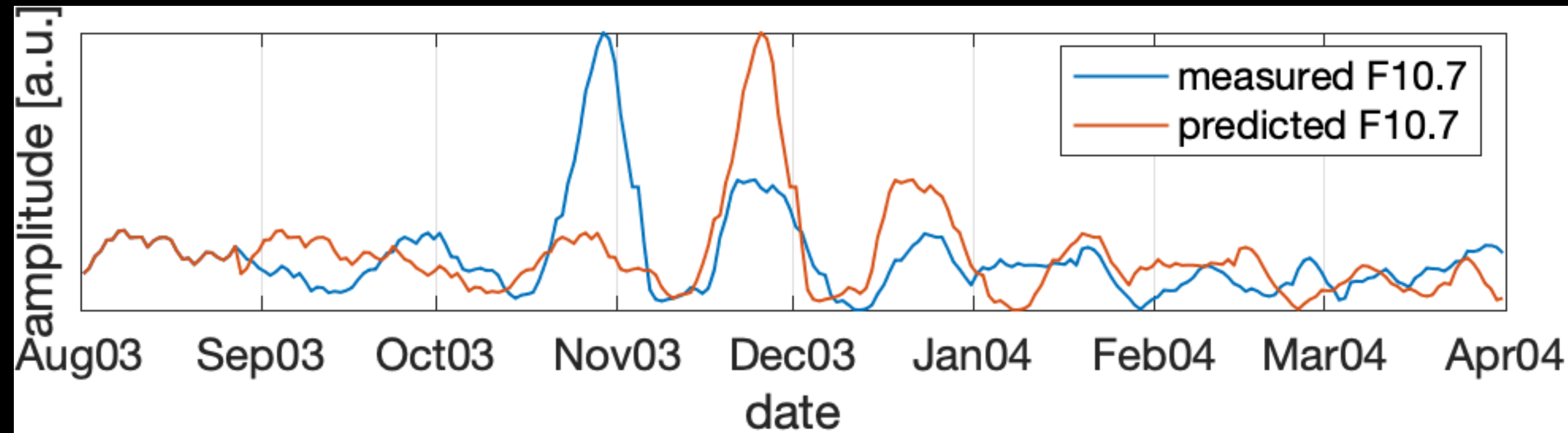




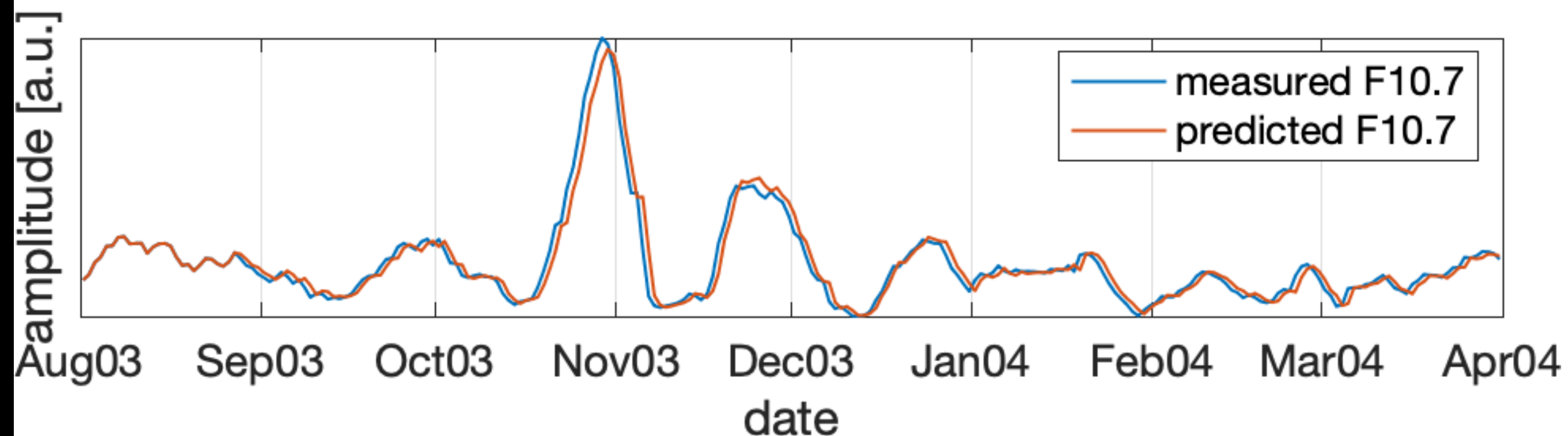
# What are we able to forecast ?

Time scale	Relevance for drag modelling	Ability to forecast
minutes (flares)	little	impossible (only probabilistic)
hours to weeks	important	average
months	less relevant	average
years	important for mission planning	average

# Example : forecasting the F10.7 index



$$y[k] = y[k - 27]$$



$$y[k] = \alpha y[k - 1] + \beta y[k - 27]$$



# Time scales of days to weeks : what improvements ?

- Empirical time series models (neural networks, etc.)
  - perform well except for a highly active Sun
  - no major improvements expected in performance
  - zoo of models, no benchmarking

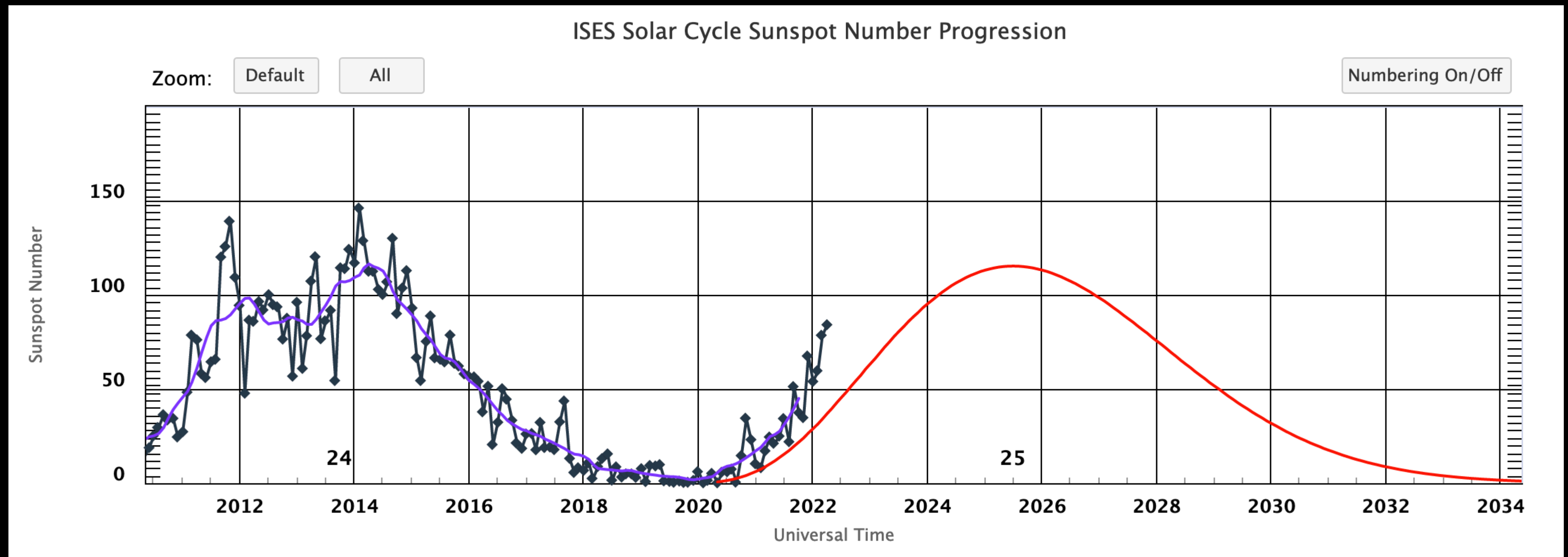
# Time scales of days to weeks : what improvements ?

- Empirical time series models (neural networks, etc.)
  - perform well except for a highly active Sun
  - no major improvements expected in performance
  - zoo of models, no benchmarking
  
- Semi-empirical models : use flux transport models to predict the surface magnetic field
  - are much better in capturing solar activity up to  $\sim 1$  month ahead
  - requires surface magnetic field observations + data assimilation + physical modelling
  - 1 operational model : ADAPT





# Long-term forecasts



<https://www.swpc.noaa.gov/products/solar-cycle-progression>

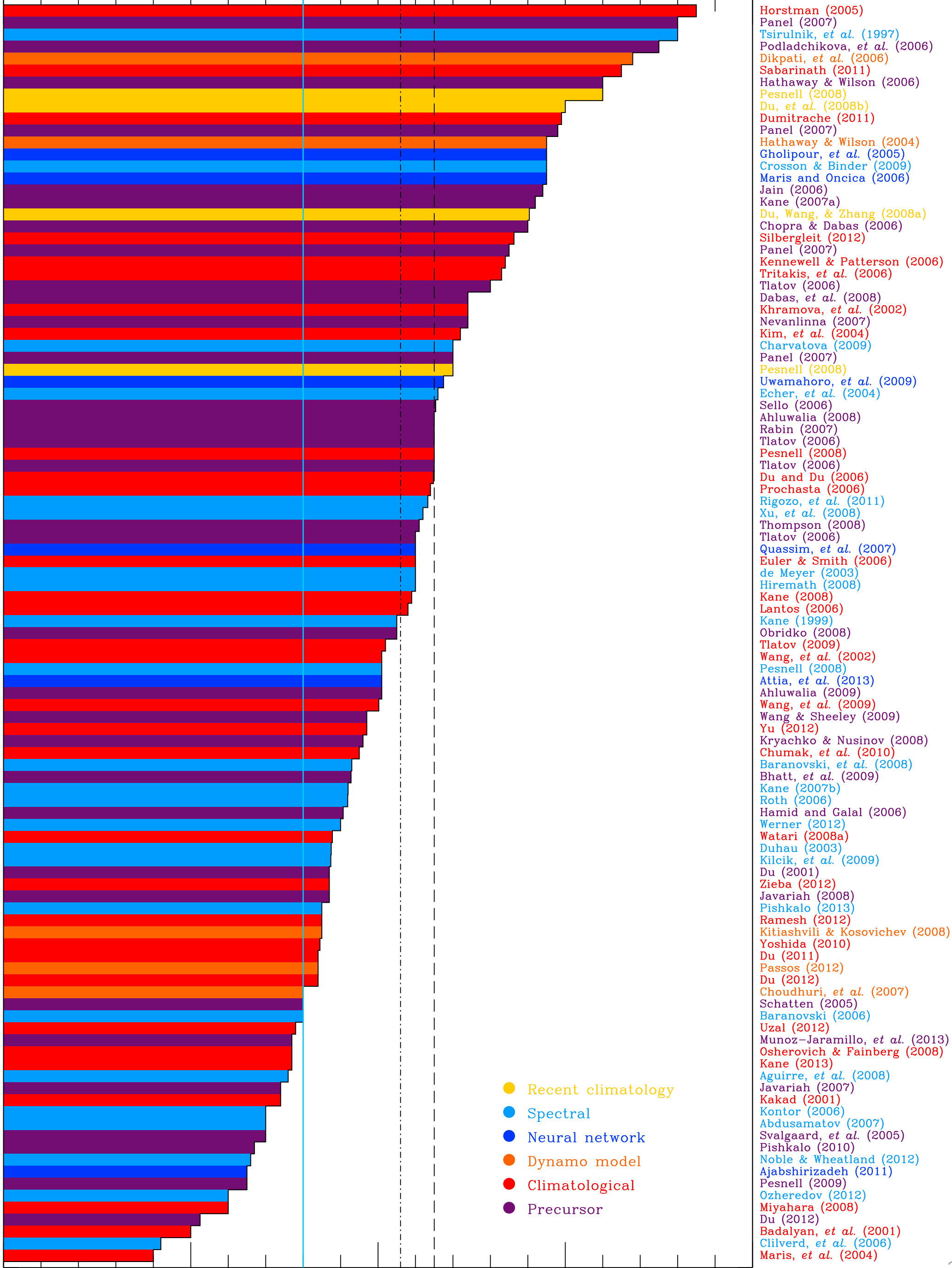
- Many different types of models have been tested : physical (dynamo) models, precursor models, empirical models, ...
- Considerable scatter in the predicted amplitude of the next solar maximum ( $> 30\%$ ) [Pesnell 2012, 2016]
- Prediction horizon = 1 cycle at best

but

- Dynamo models are improving



Predicting the amplitude of  
solar cycle 24 [Pesnell, 2018]



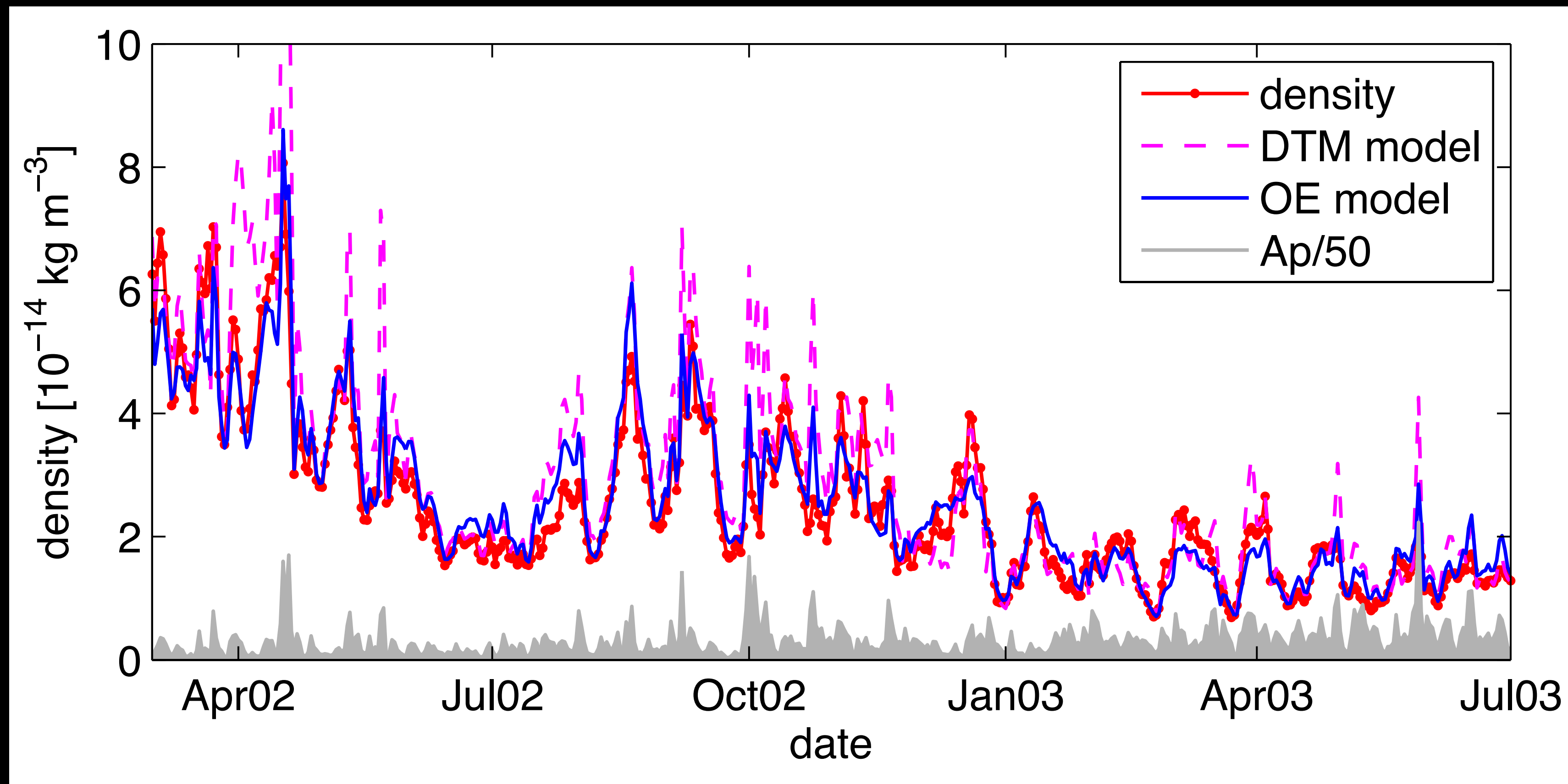
- Solar proxies still offer an excellent trade-off between performance and capacity for operational use
  
- The future
  - Continue the measurement of these solar proxies :
    - interruptions are a curse - redundancy is a blessing
  - Need a framework to compare/benchmark their performance
  - Prepare the transition from solar proxies to solar EUV observations
  - Physical models using solar magnetism (flux transport / dynamo) are the future
    - need operational measurement of solar magnetism





# Transfer function approach

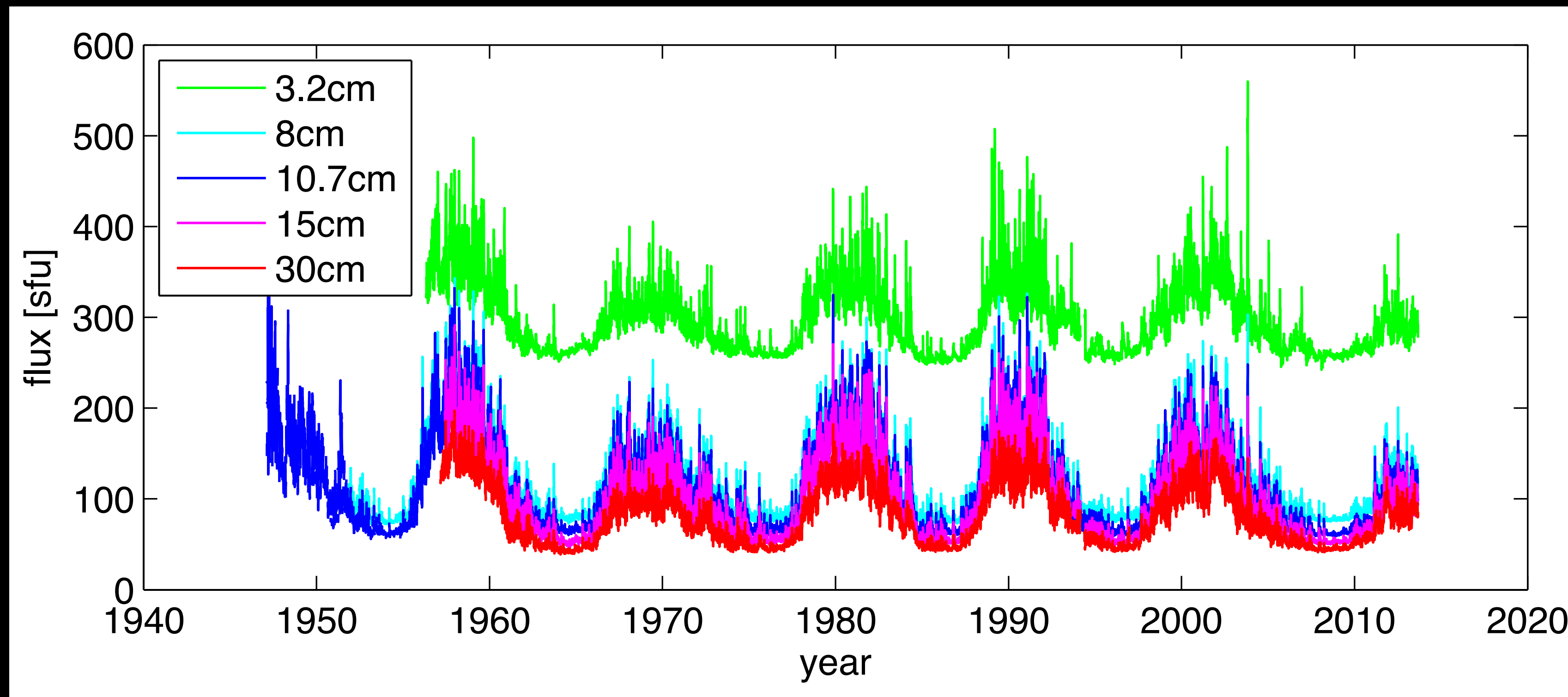
- Satisfactory model performance is obtained with parsimonious models (2-3 poles)



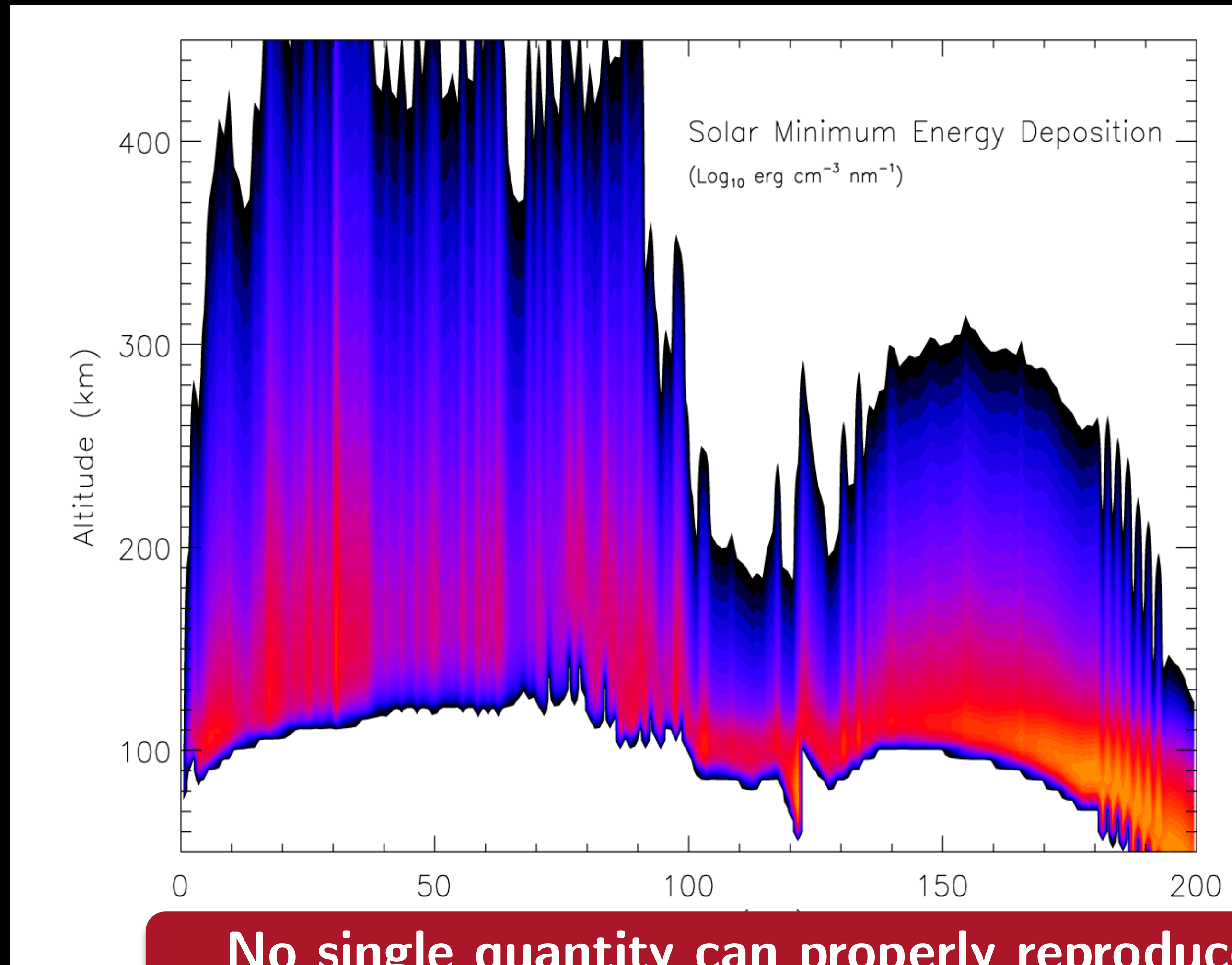


# And the winner is ...

■ > 60 years of daily observations of the solar radio flux are available



# Energy deposition is highly wavelength-dependent



No single quantity can properly reproduce the complex interplay with the atmosphere