Long-term solar activity: Knowns and unknowns

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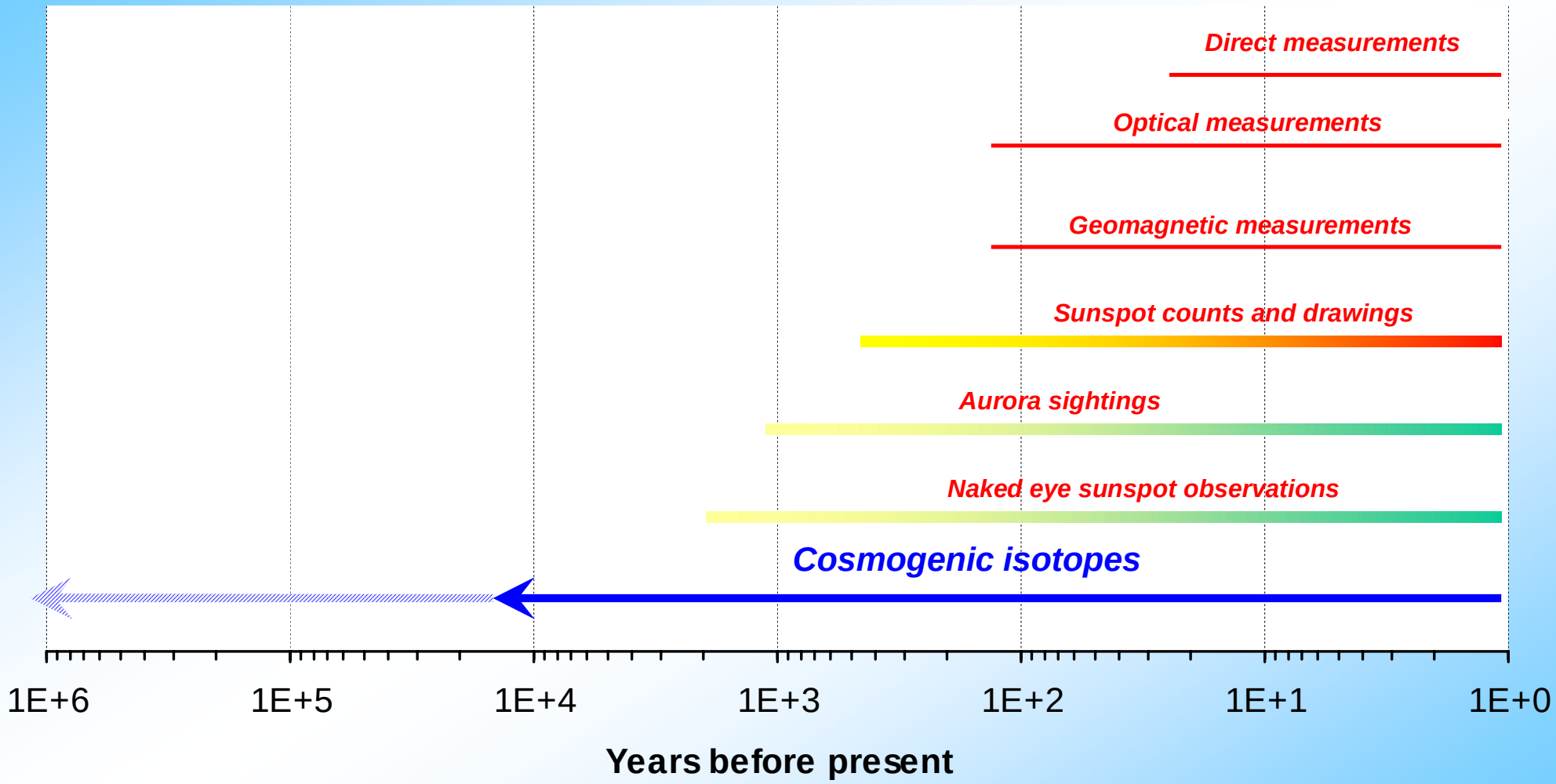
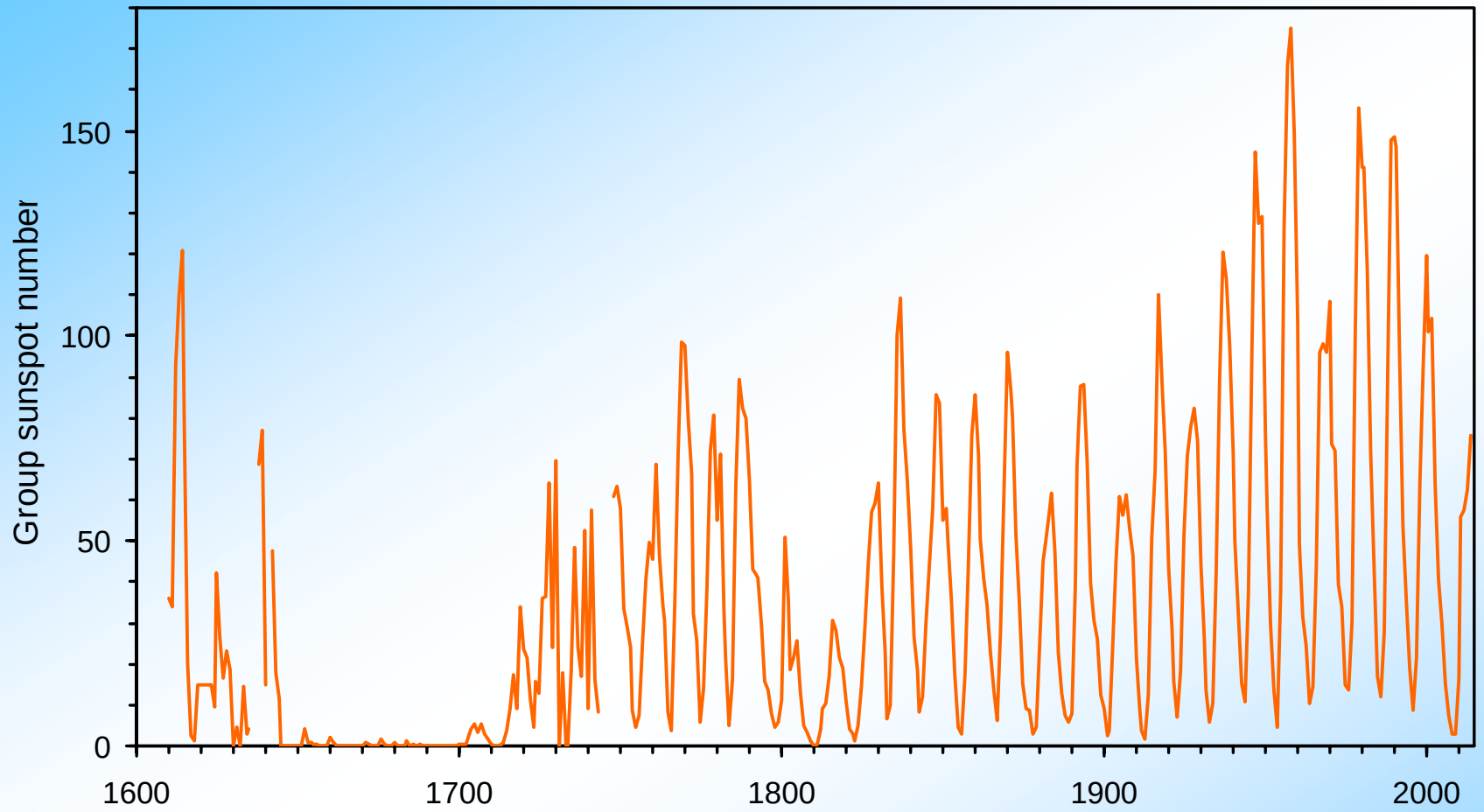
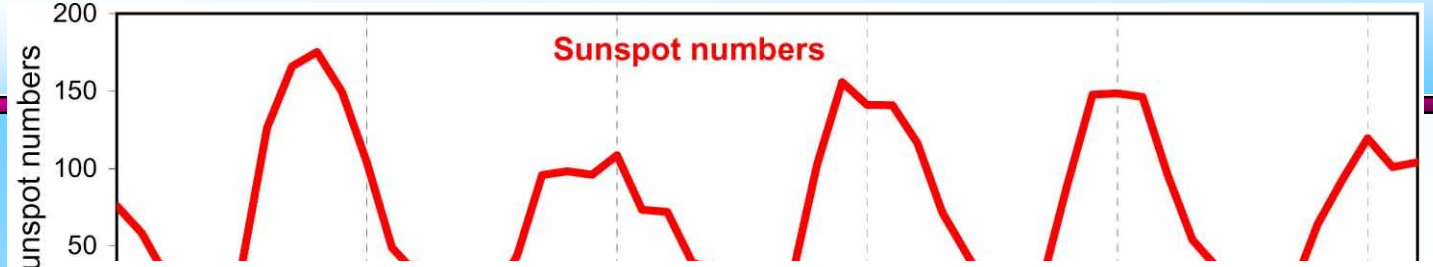
History

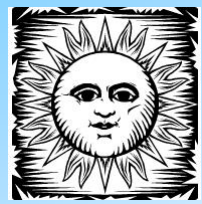

Direct measurements
Optical measurements
Geomagnetic measurements
Sunspot counts and drawings
Aurora sightings
Naked eye sunspot observations
Cosmogenic isotopes
1E+6
1E+5
1E+4
1E+3
1E+2
1E+1
1E+0
Years before present

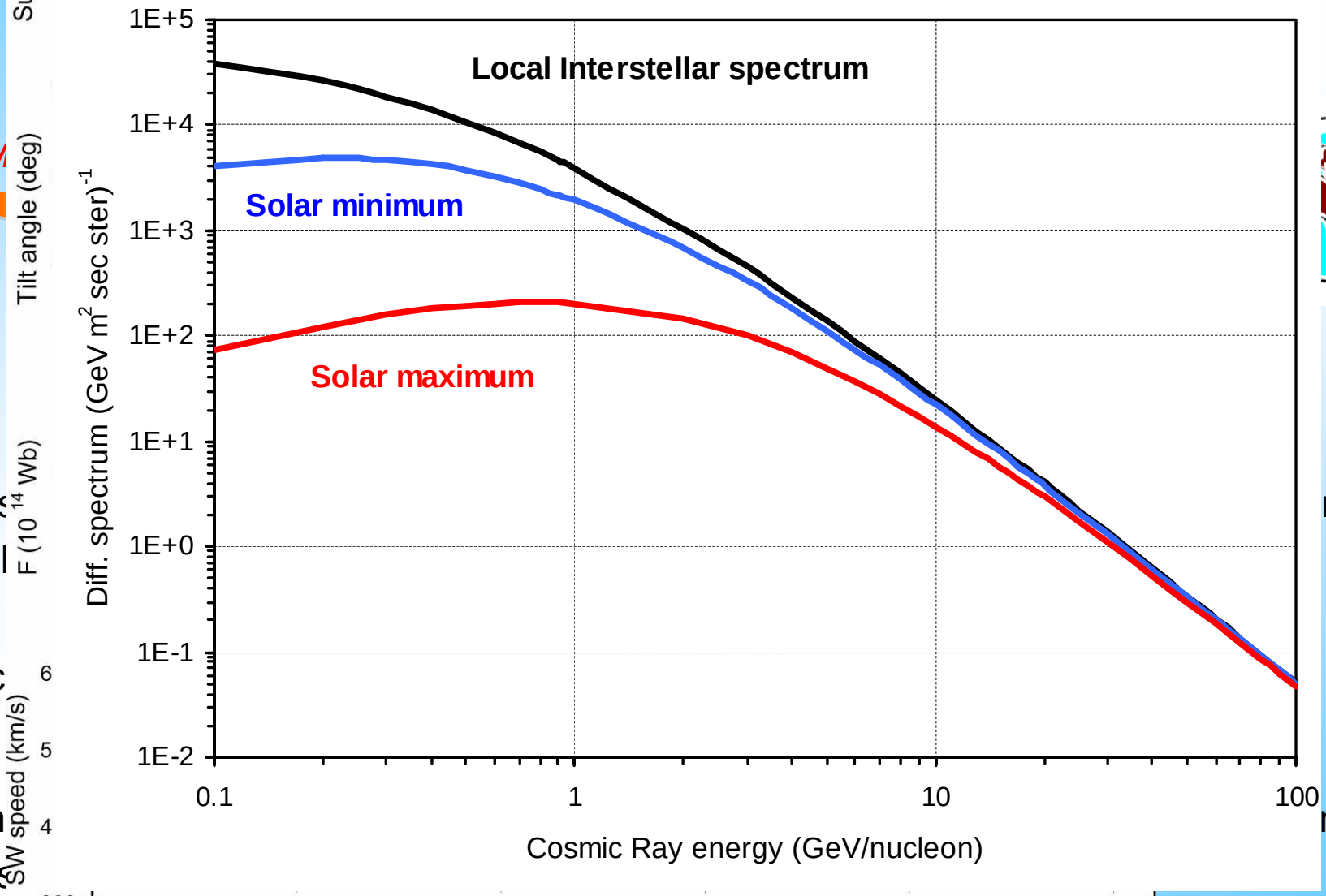
Solar activity changes



- 11-year solar cycle (Christian Horrebow – 1770s; Schwabe – 1843)
- Variable amplitude/envelope (Gleissberg – 1944);
- Maunder minimum (Hivelius; Eddy –1976);
- The contemporary level was high but is lower right now;







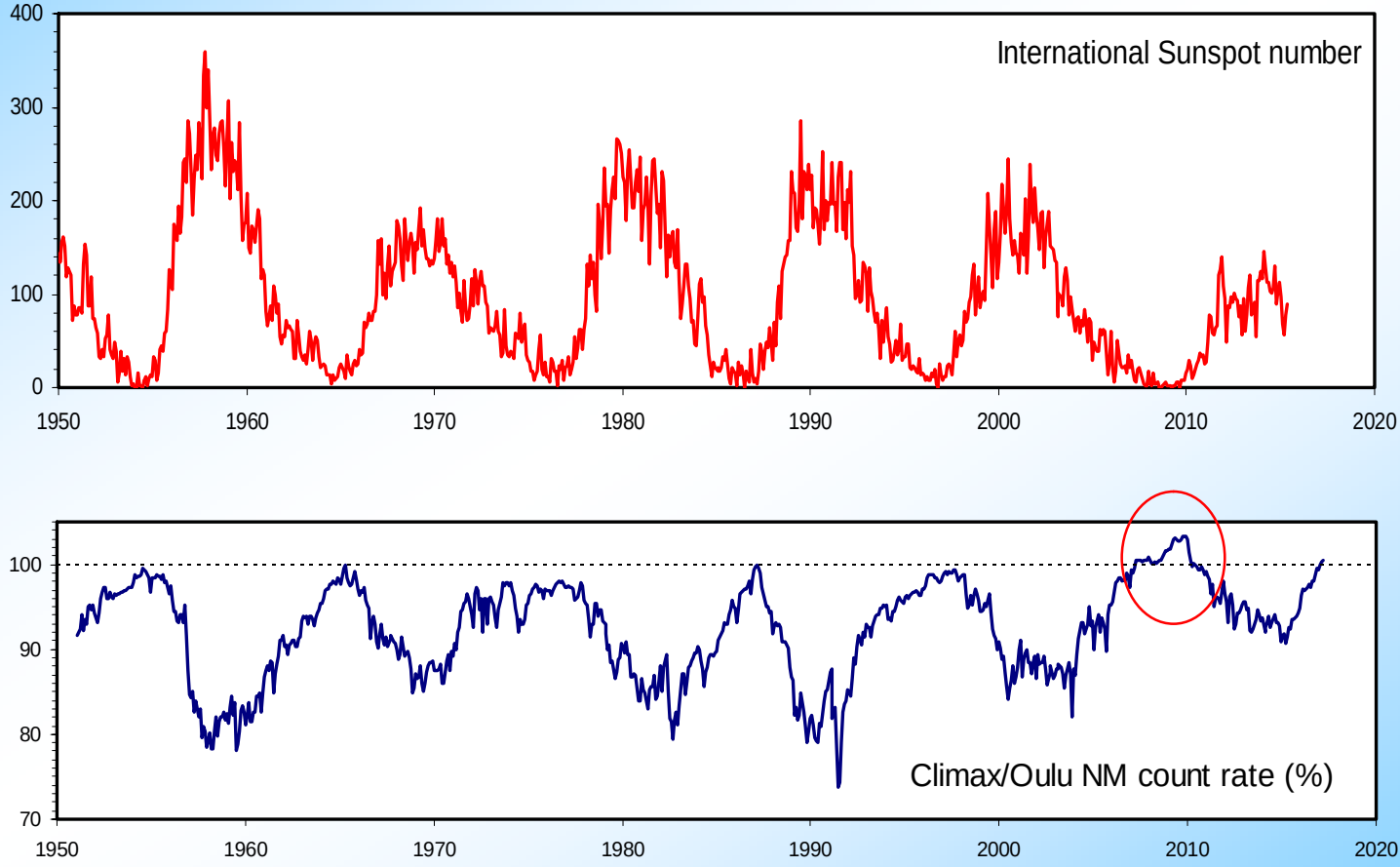
• Variable s netic field, interpl

• Galactic c

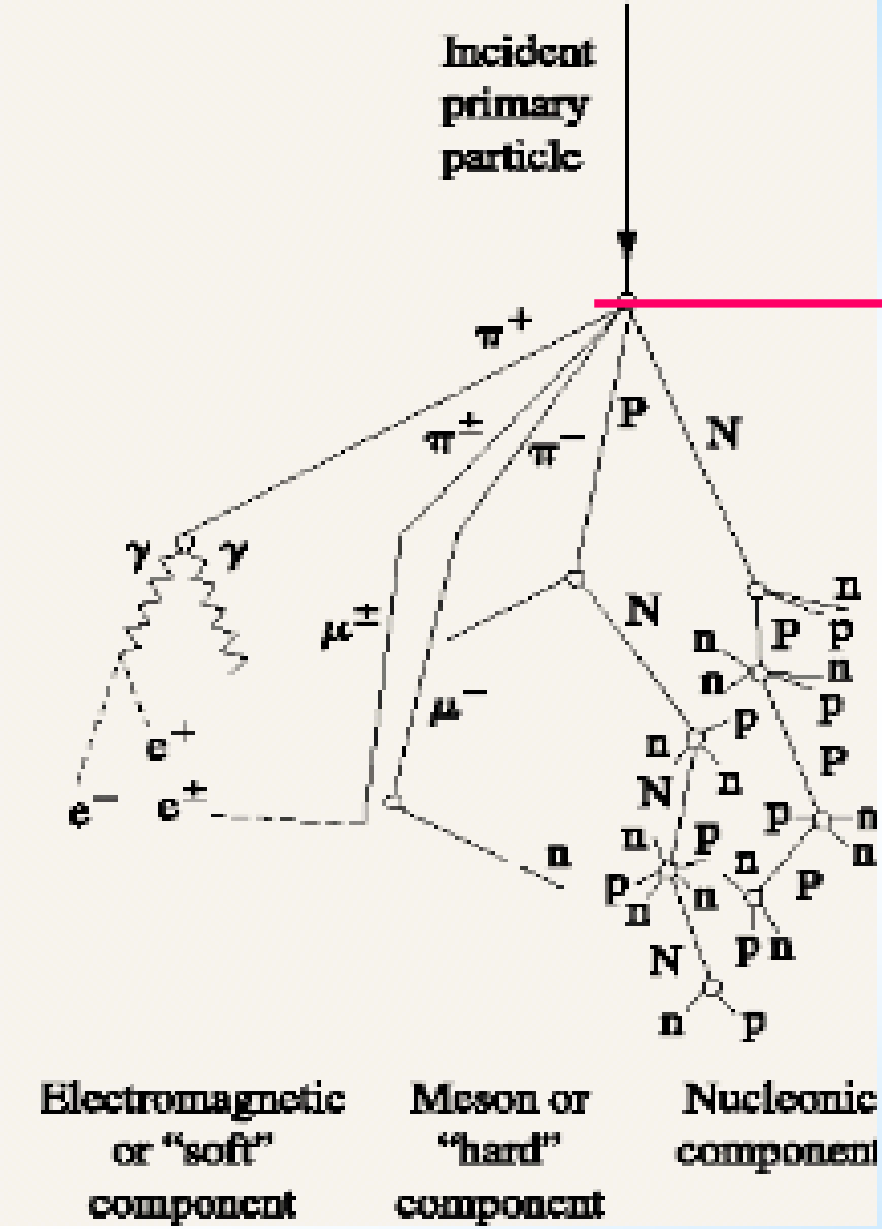
• Geomagn ming cosmic rays

solar cycle variations

- 11-year cycle due to solar activity
- Weak 22-year cycle due to charge-dependent drift effects
- short-term fluctuations.
- Centennial variability?



Cosmogenic isotope production



Atmospheric cascade

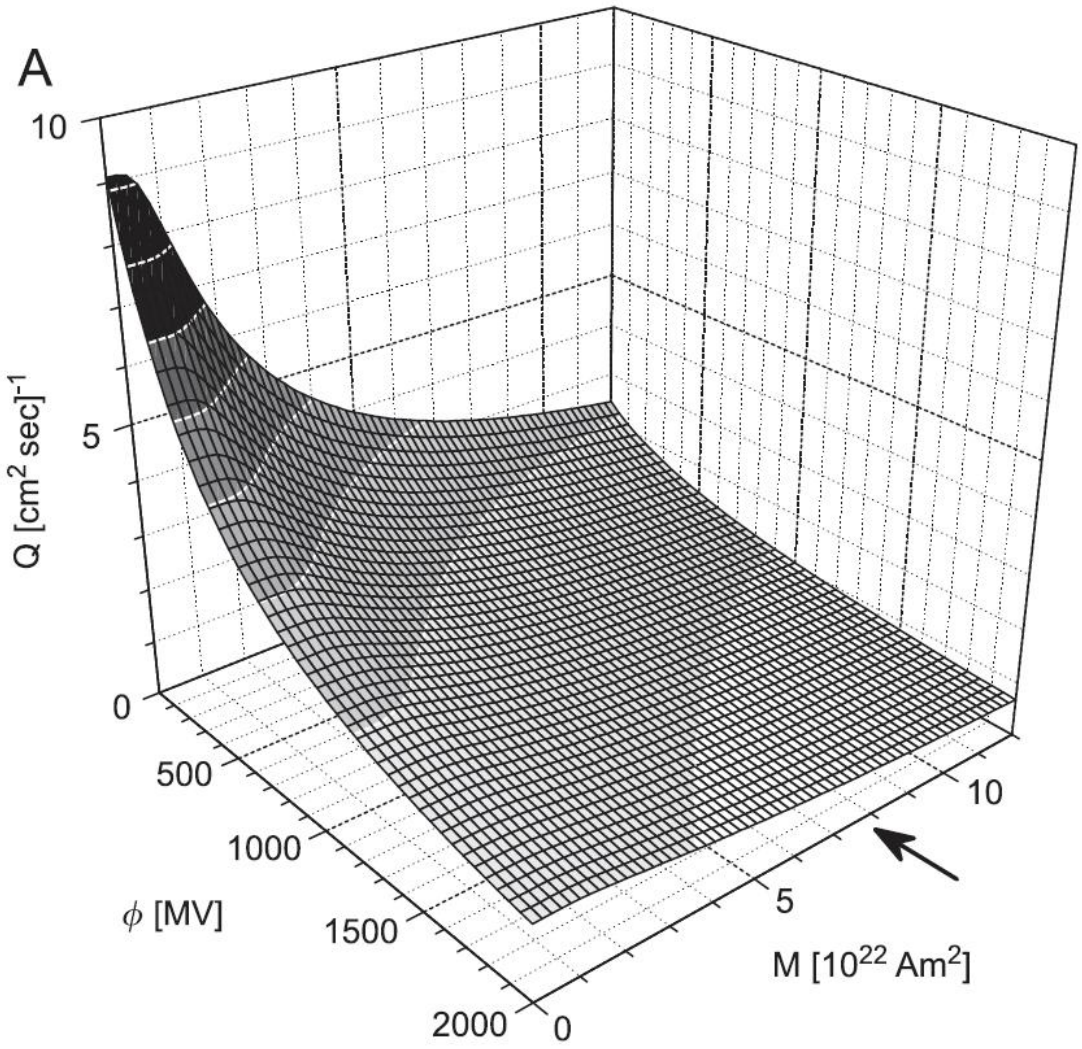
In the atmospheric cascade, nuclear reactions may take place, most important being:

Spallation reactions on *O, N, Ar* → ^{7}Be, ^{10}Be, ^{22}Na, ^{36}Cl, *etc.*

Neutron capture: $^{14}N+n \rightarrow {}^{14}C+p$

Storage in natural independetly dated archives: ice-cores, tree trunks, sediments, corals

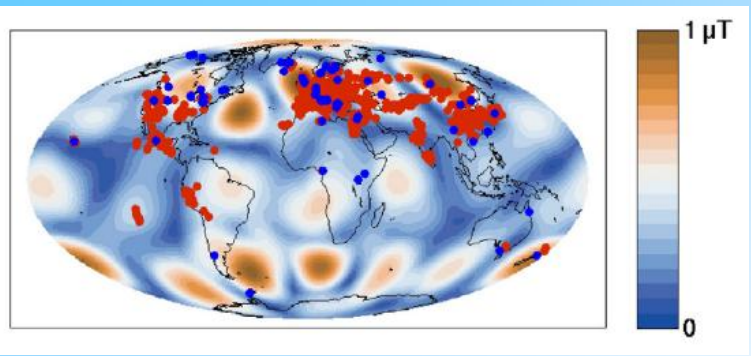
Production model

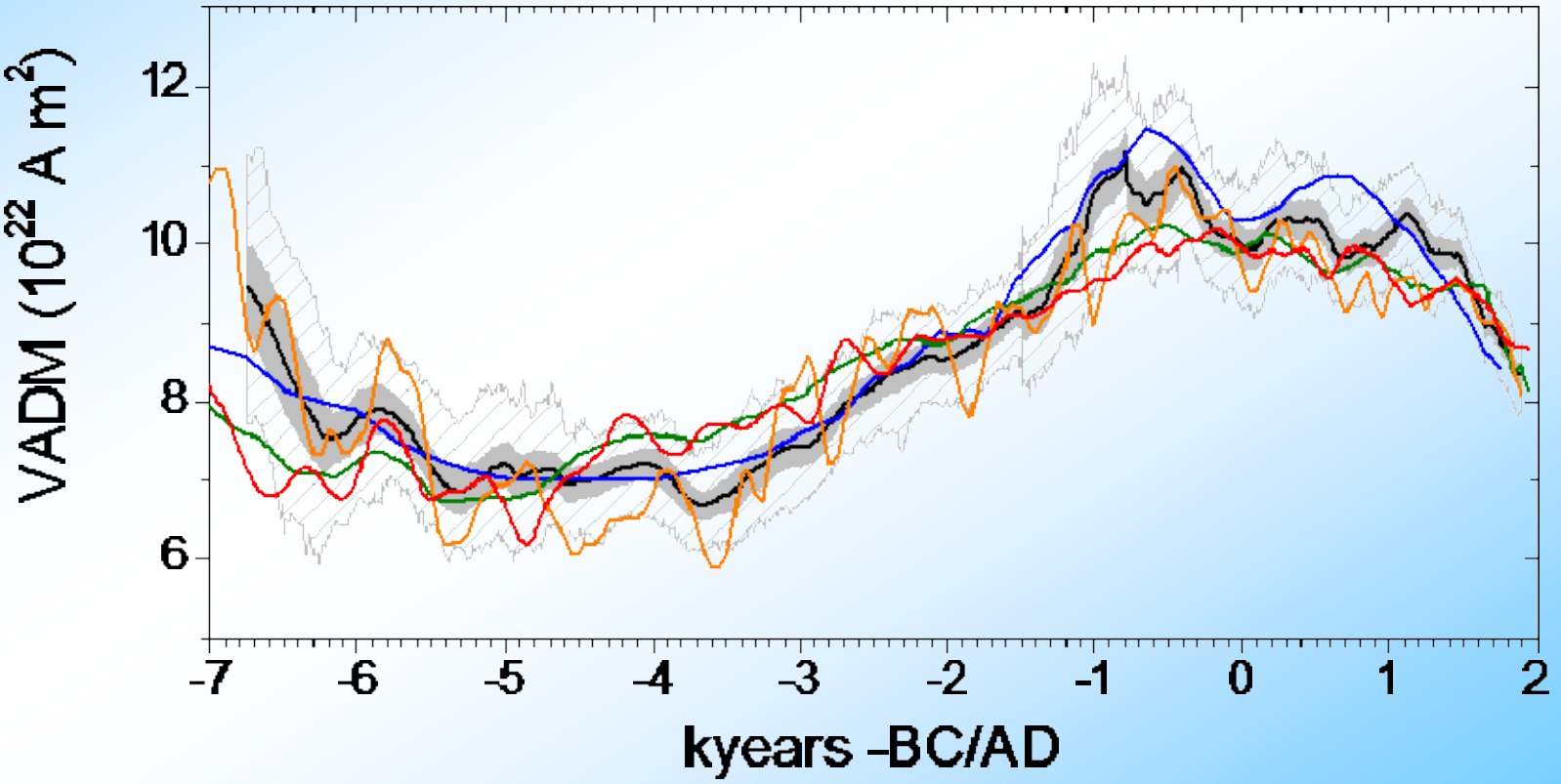


Kovaltsov, Mishev & Usoskin (EPSL, 2012)

- Full range of GCR energy (0.01-1000 GeV)
- Heavier species included explicitly

Paleomagnetic models





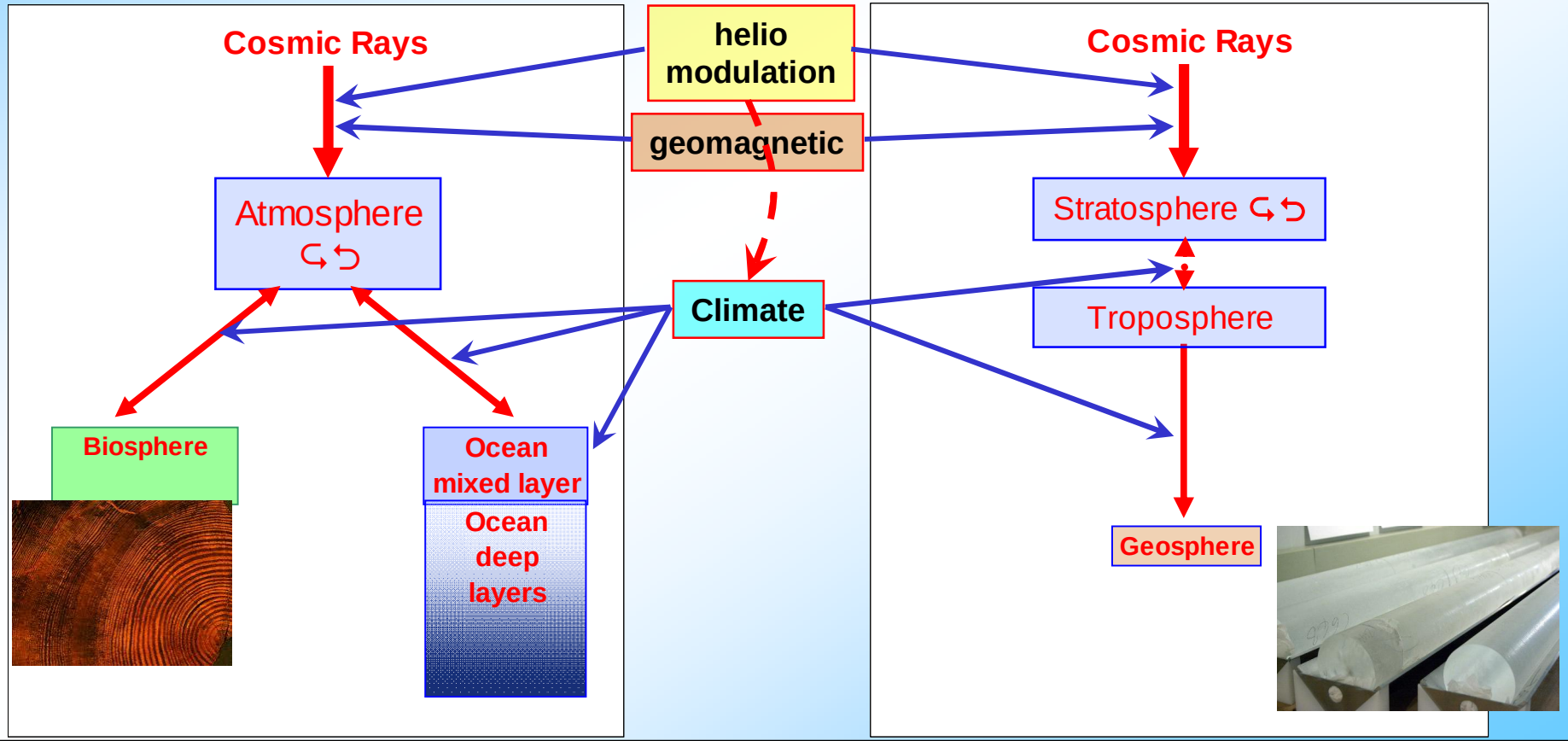
cosmogenic ^{14}C and ^{10}Be

$n + N \rightarrow {}^{14}C$
$CO_2 \rightarrow$ carbon cycle $\rightarrow$ tree rings

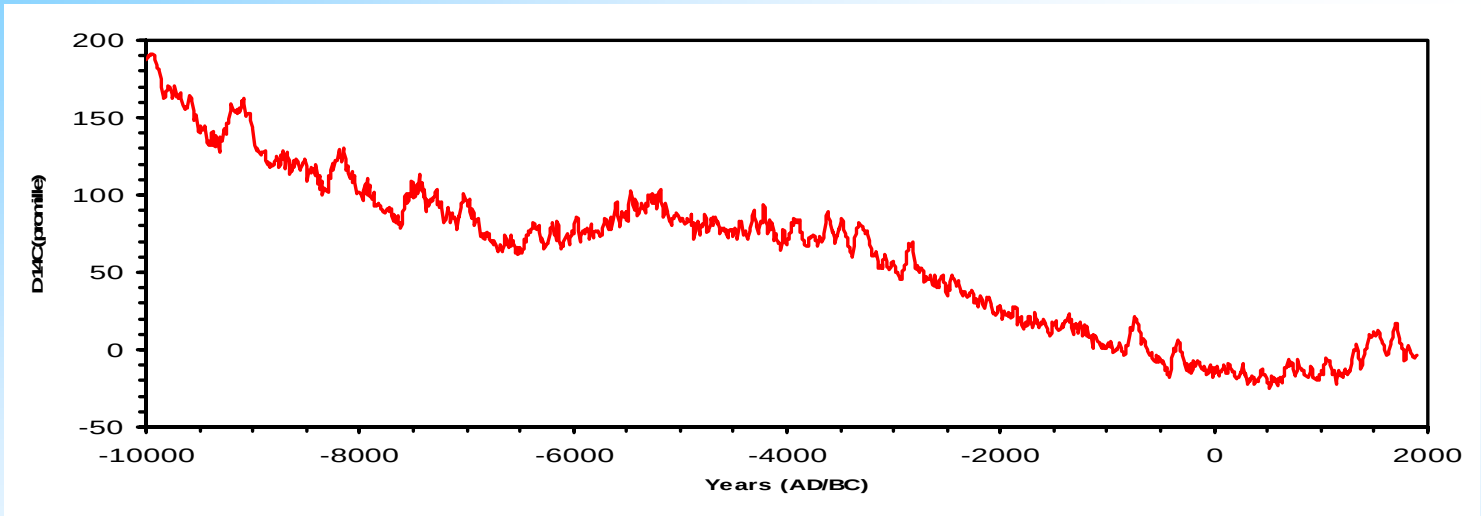
- Effective CR energy is ~ 3 GeV/nucleon;
- mean altitude: upper tropo, low stratosphere;
- measurements: normalized $^{14}C/^{12}C$ ratio

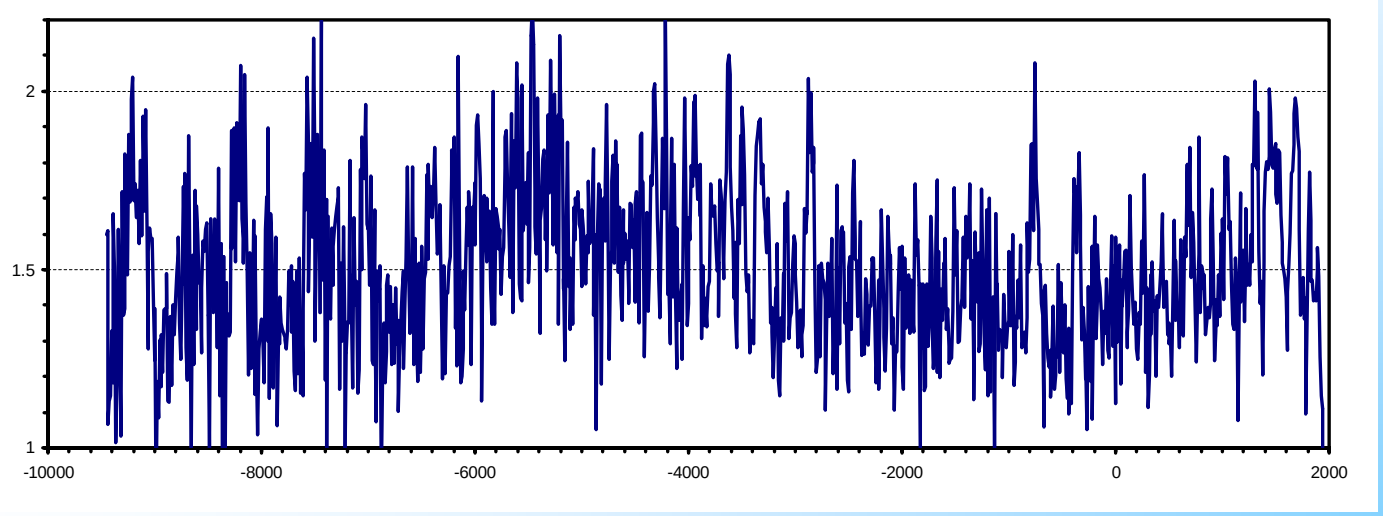
$CR + N,O \rightarrow {}^{10}Be$
aerosols $\rightarrow$ fall out

- Effective CR energy is 1–2 GeV/nucleon;
- mean altitude: upper tropo, lower stratosphere;
- measurements: abundance

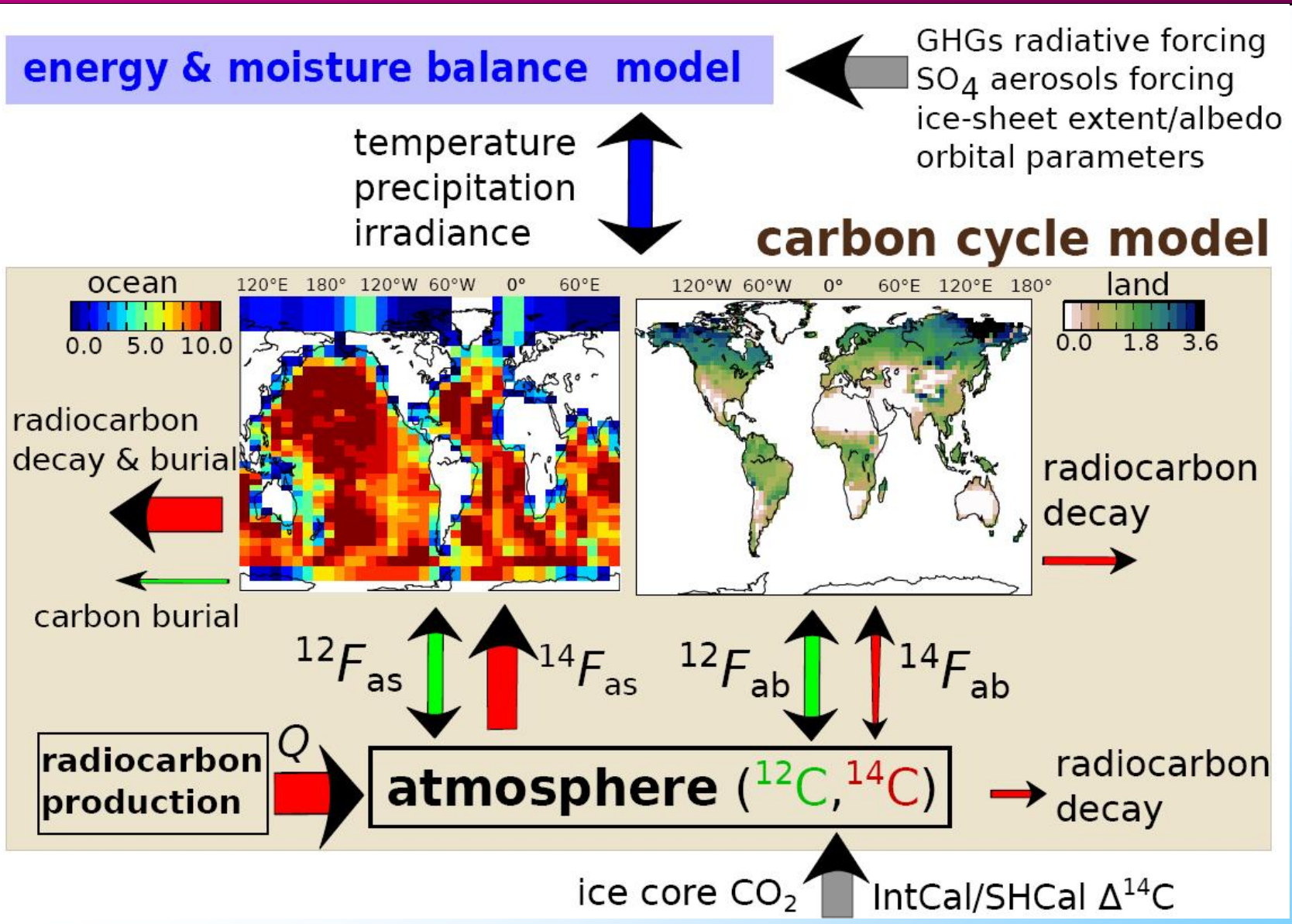


Radiocarbon data



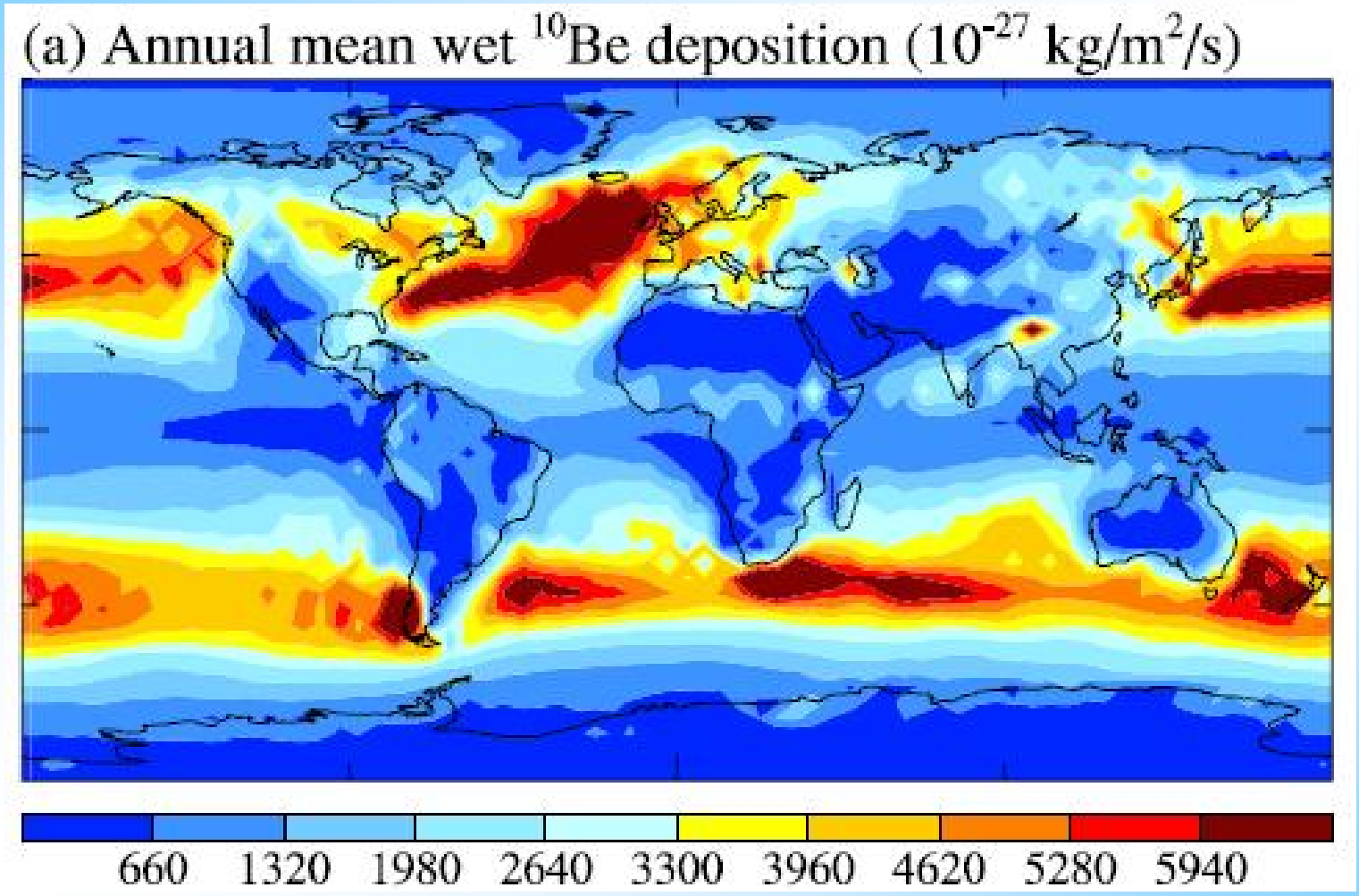


Bern3D-LPX model



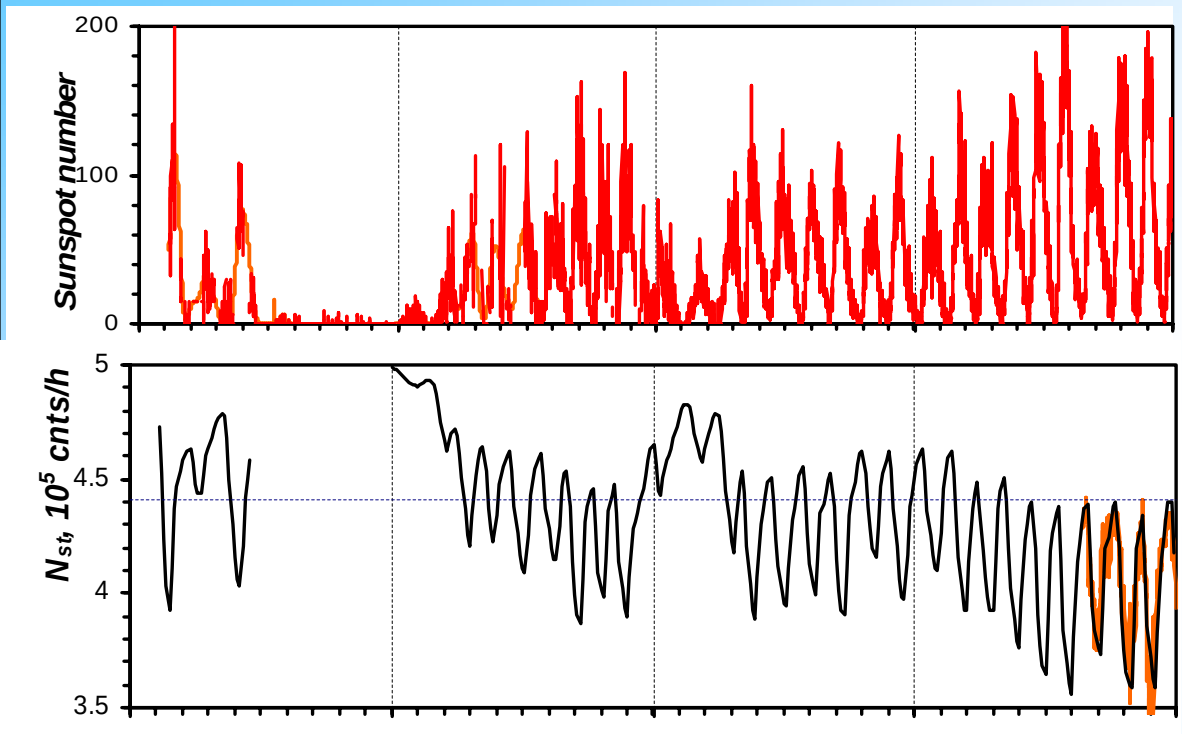
Roth & Joos (CP, 2013)

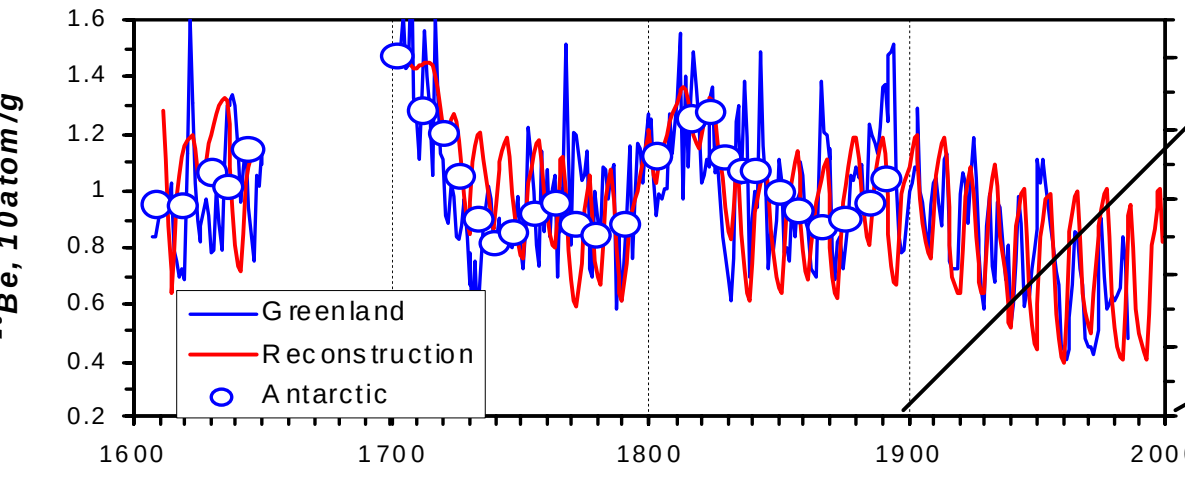
Atmospheric transport of ^{10}Be

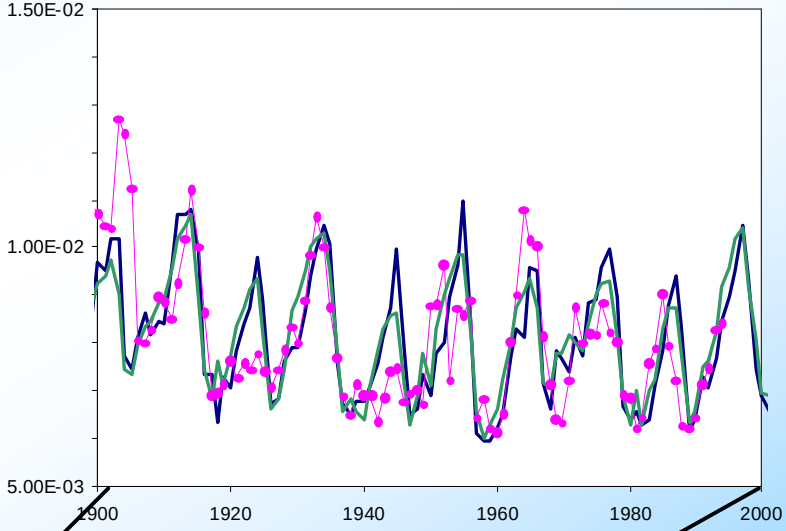


Annual Mean Wet ^{10}Be Precipitation- Field et al (JGR, 2006)

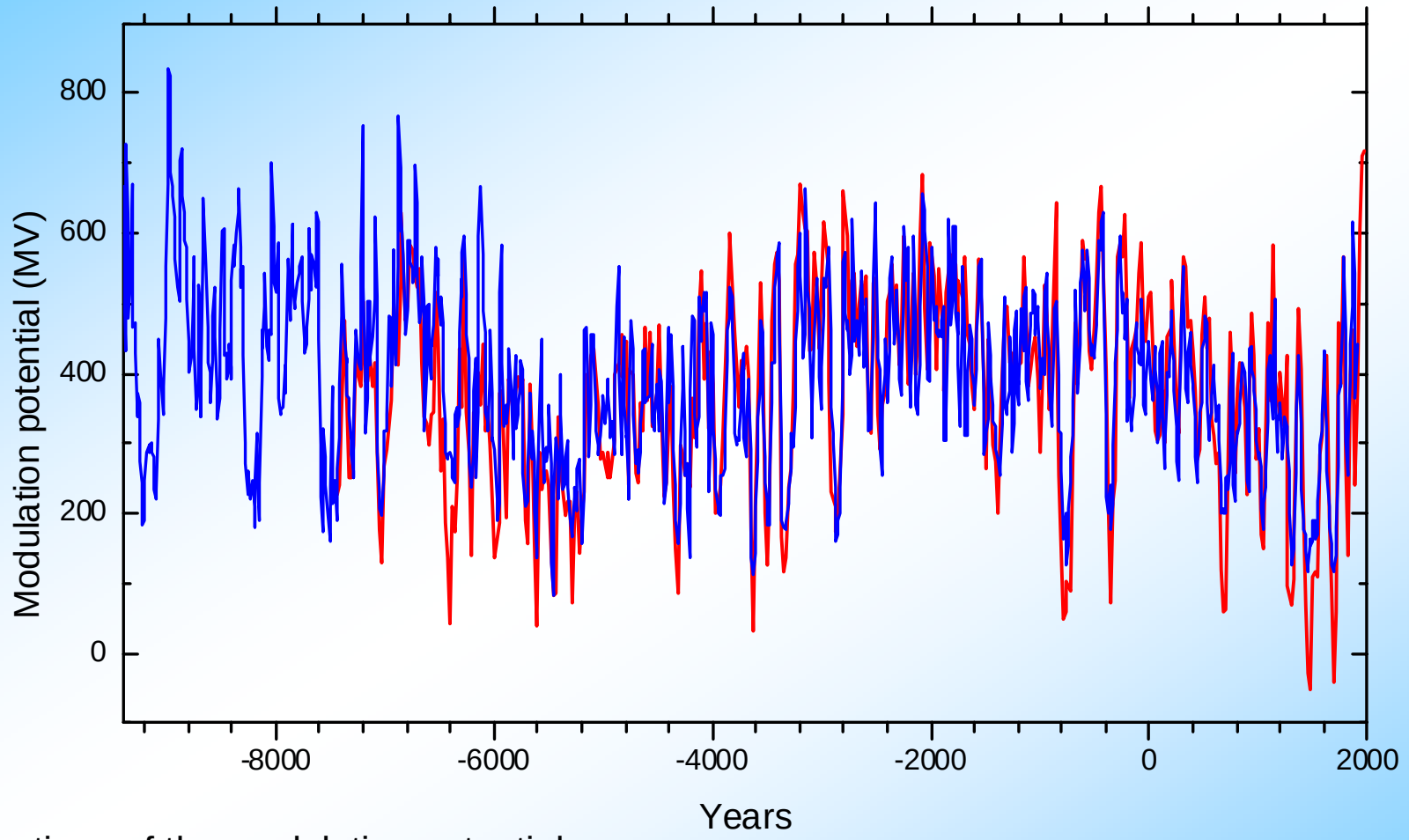
Quality of the model





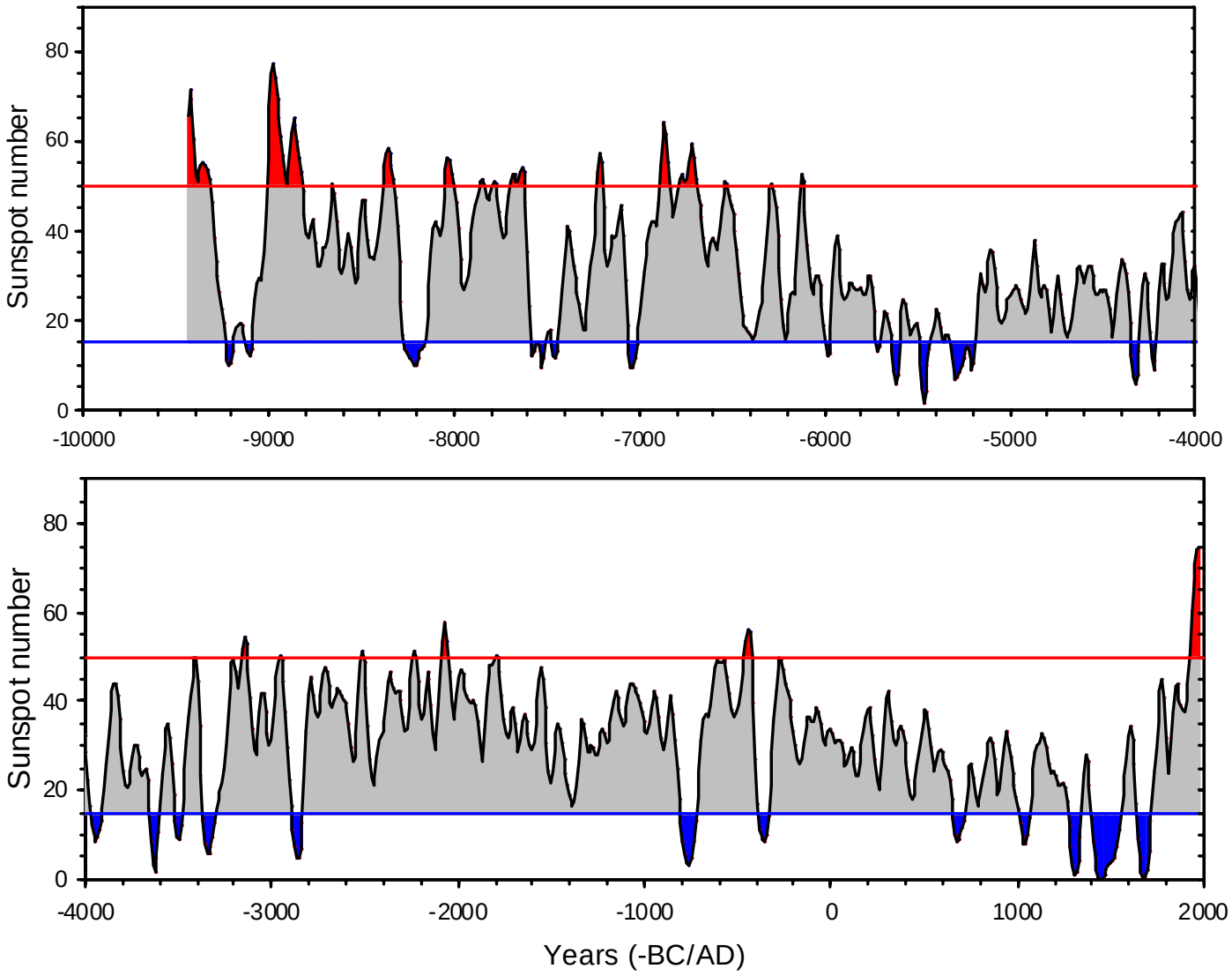


Long-term reconstructions



Reconstructions of the modulation potential φ:
^{14}C-based reconstruction (Solanki et al., Nature, 2004; Usoskin et al., A&A, 2007);
Composite ^{10}Be (Steinhilber et al., PNAS, 2012)

Sunspot activity during the Holocene



27 Grand minima
19 Grand maxima
can be identified:

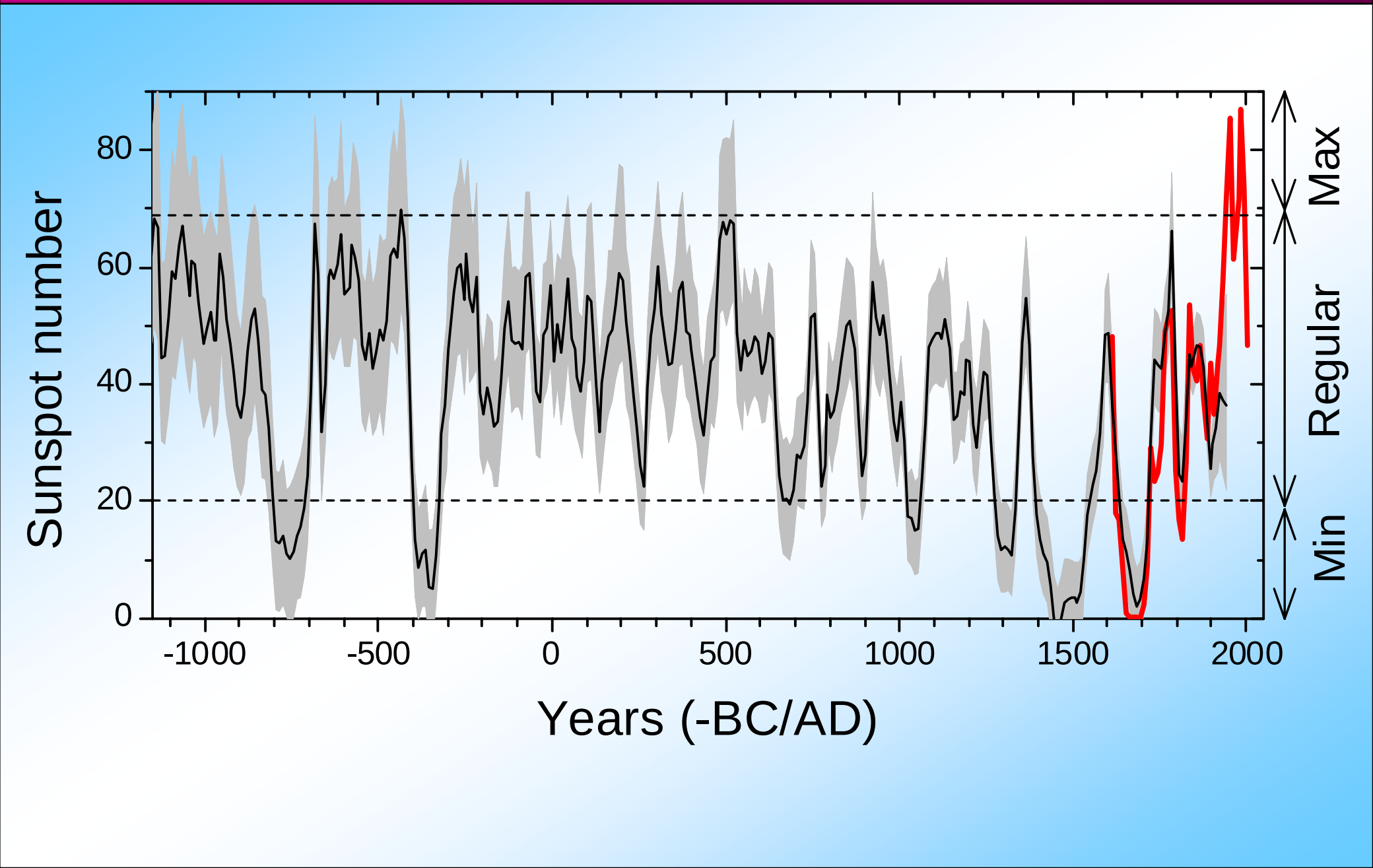
Minima (1880 yr – 17%)
Maxima (1030 yr – 9%)

No clear periodicity, but :

- clustering of Grand minima with 2000-2400 yr;
- ~200-yr periodicity inside the clusters;
- no apparent periodicity for Grand maxima;

Solanki, S.K., I.G. Usoskin, B. Kromer, M. Schuessler, J. Beer, *Nature*, 2004;
Usoskin, Solanki & Kovaltsov, A&A, 2007

SN reconstruction since 1000 BC



Observational facts

- Solar activity depicts a great deal of variability, from Grand minima to Grand maxima;
- Recent solar activity (1940-2008) was an Grand maximum, but now we are facing regular or weak activity;
- The Sun spends ~3/4 of the time at moderate activity, 1/6 in a Grand minimum and 1/10 in a Grand maximum state. The recent solar activity was a Grand maximum.
- Occurrence of Grand minima/maxima is not a result of long-term cyclic variations but is defined by stochastic / chaotic processes.

Summary: Knowns

- The main source of CR variability on time scales from days to millennia is the solar magnetic activity.
- CR variations, via cosmogenic isotopes, is the only source of information on the solar/heliospheric activity in the distant past.
- Solar activity varied essentially from the regular stable mode – from Grand minima to Grand maxima.
- The Grand maximum is over, the current ”weak” solar activity level is in fact ”normal” one.

Unknowns

- The very long-term (multi-millennial) trend in SA may be uncertain.
- The main uncertainty is the geomagnetic field in the past (before 3000 BC).
- Long-term climate variabilty (ocean circulation and large-scale atmospheric dynamic) may add uncertainties.
- Some Grand minima and Grand maxima can be less certain because of the noisy data, particularly 10Be.
- These uncertainties can be costrained by using multi-proxy records-

THANK YOU !