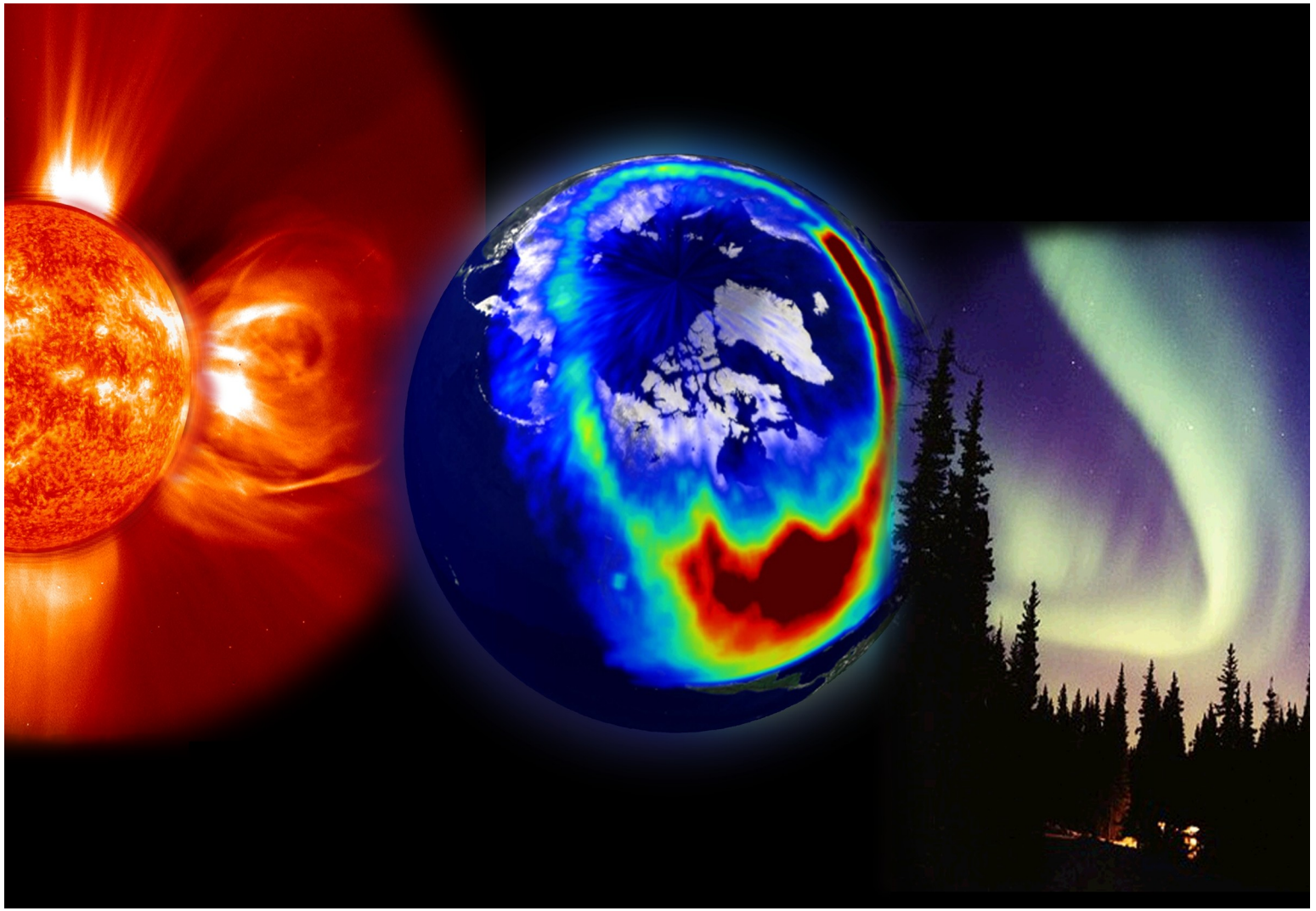
Chapter 11
Geomagnetic space weather

Previously



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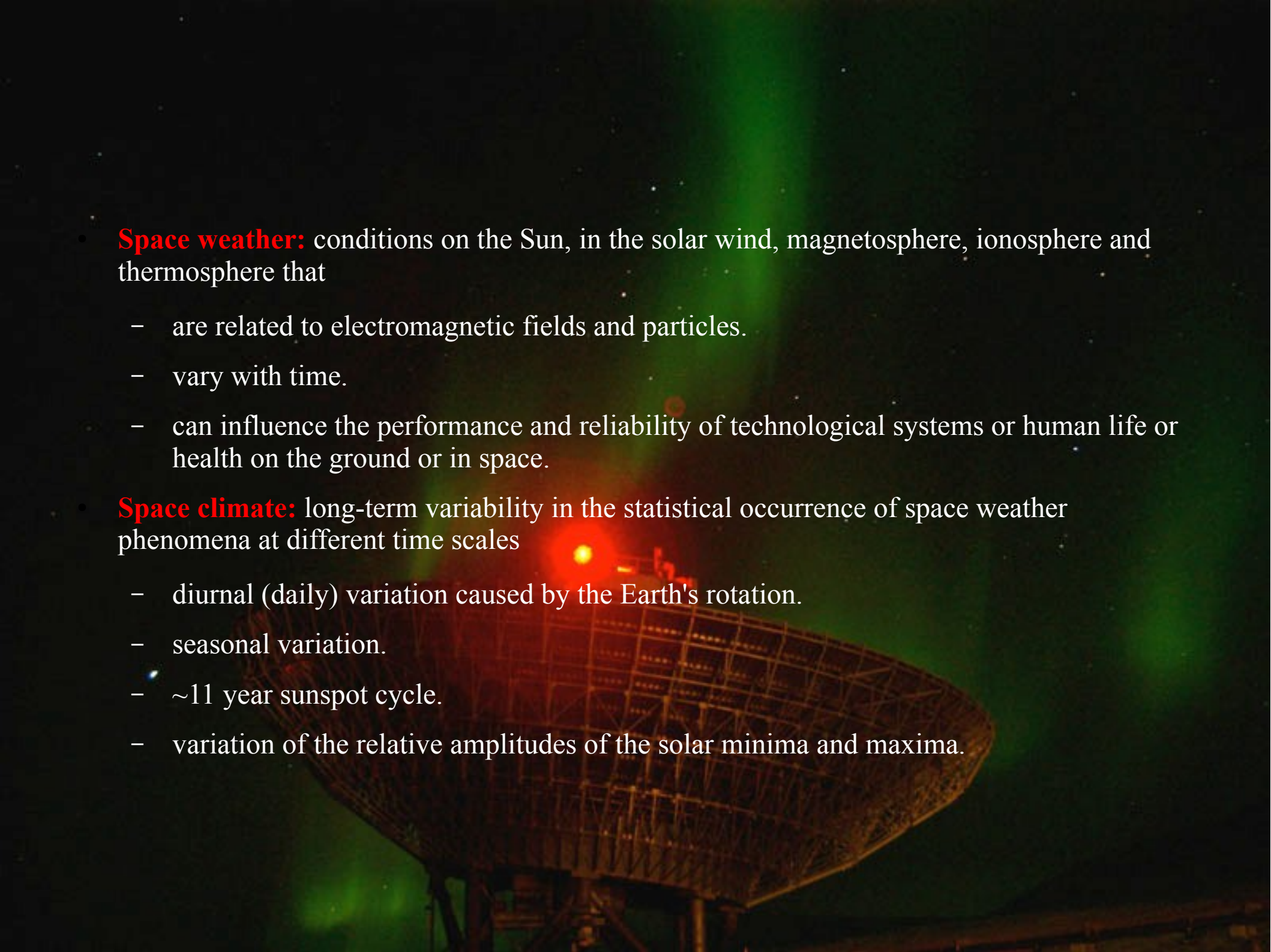
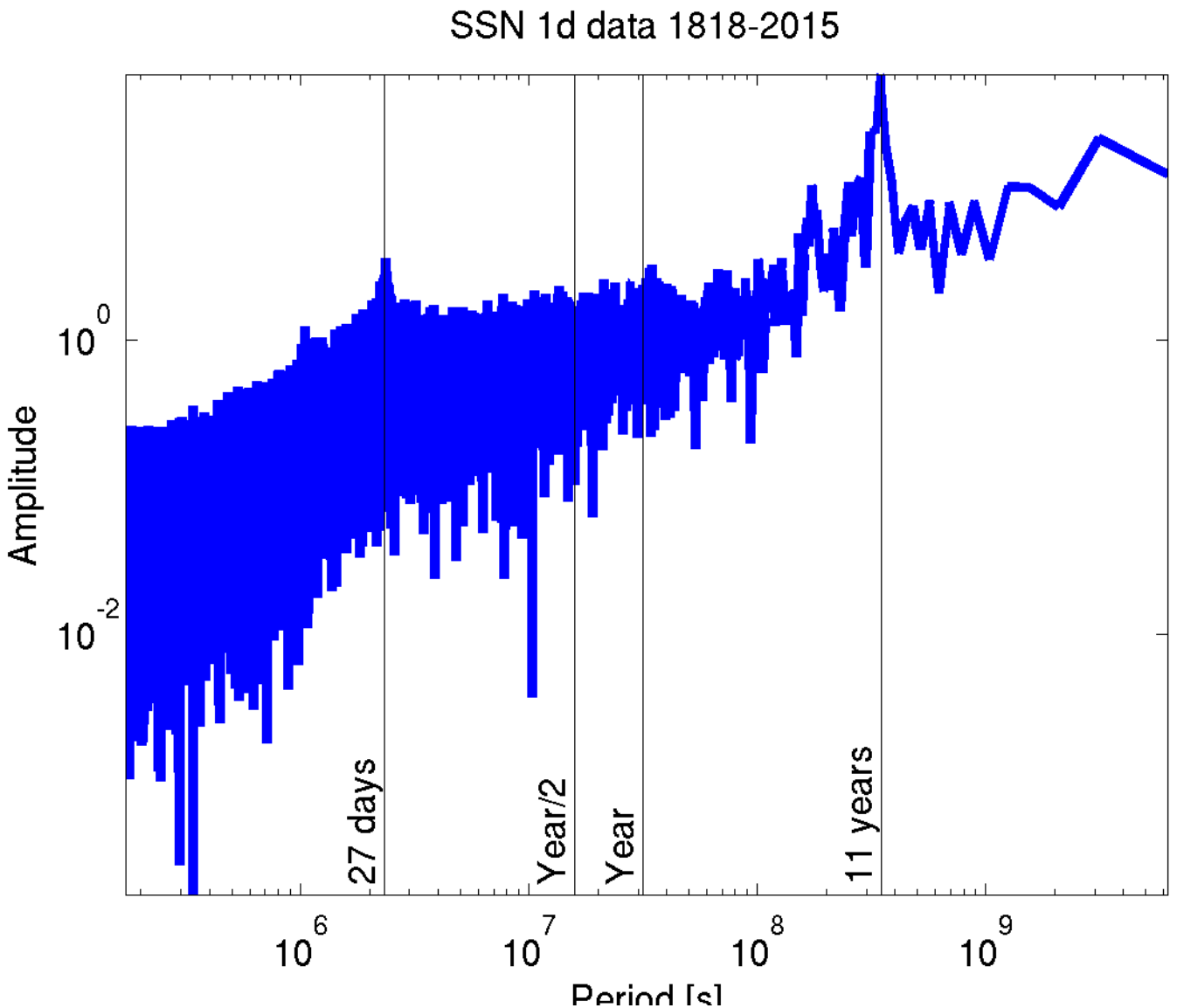
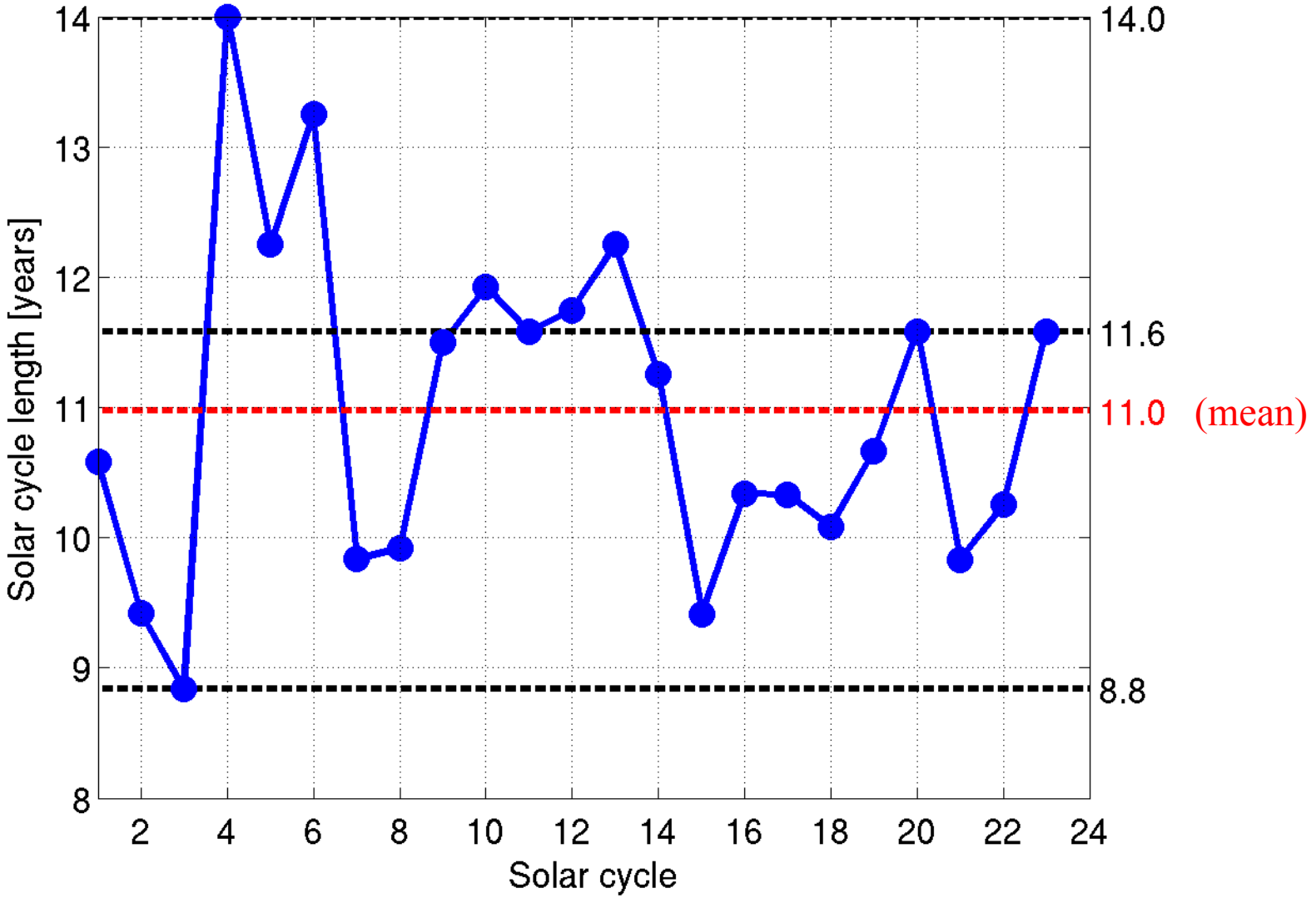
  - External magnetic field at high latitudes
  - External magnetic field at low latitudes
- Solar storms
- Real-time geomagnetic activity



- **Space weather:** conditions on the Sun, in the solar wind, magnetosphere, ionosphere and thermosphere that
  - are related to electromagnetic fields and particles.
  - vary with time.
  - can influence the performance and reliability of technological systems or human life or health on the ground or in space.
- **Space climate:** long-term variability in the statistical occurrence of space weather phenomena at different time scales
  - diurnal (daily) variation caused by the Earth's rotation.
  - seasonal variation.
  - ~11 year sunspot cycle.
  - variation of the relative amplitudes of the solar minima and maxima.

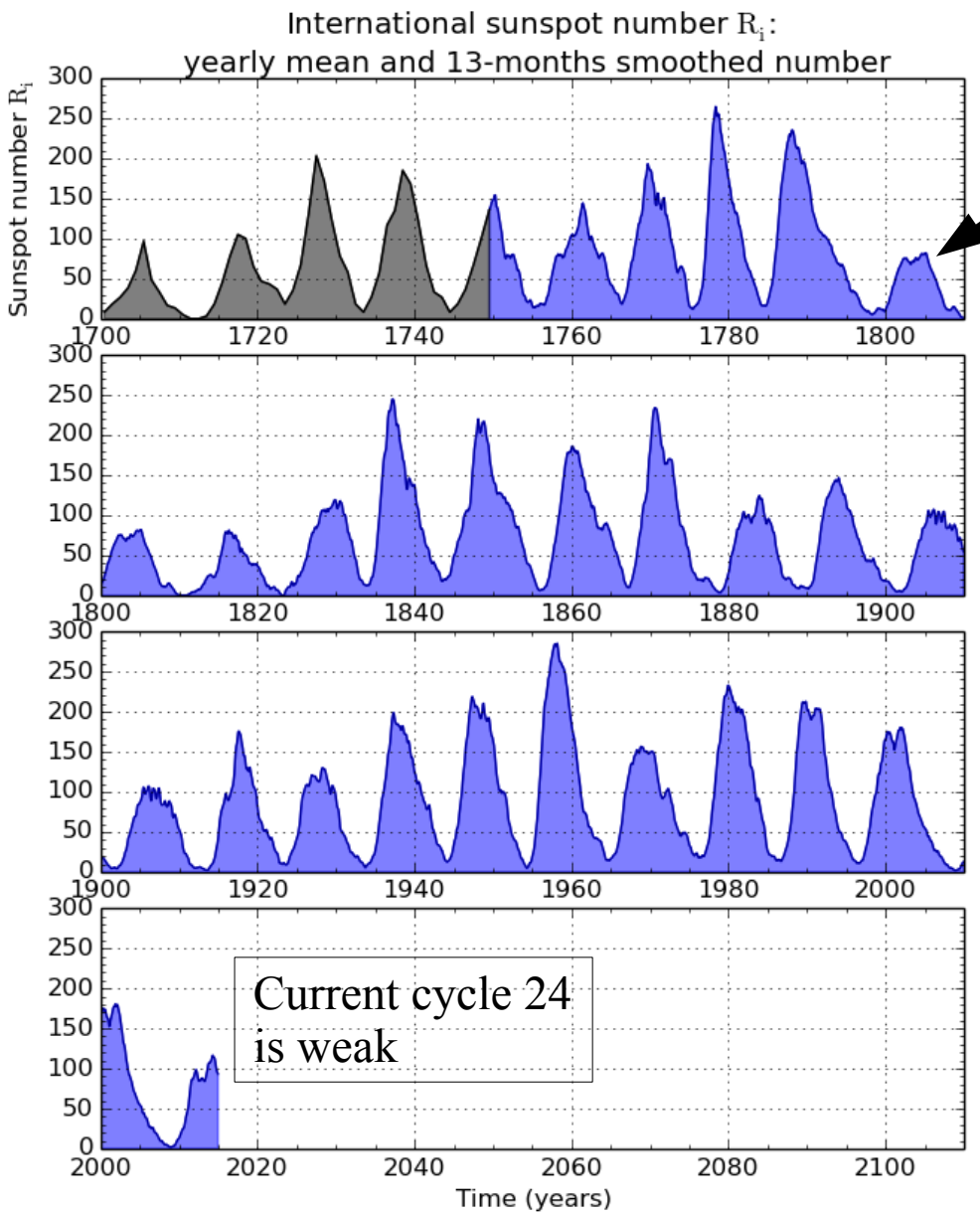
Solar activity


SSN 1d data 1818-2015
Amplitude
10^0
10^-2
27 days
Year/2
Year
11 years
10^6
10^7
10^8
10^9
Period [s]



(Note: depending of which source for the sunspot number is used, the exact values vary somewhat)

Long-term variation of sunspot numbers

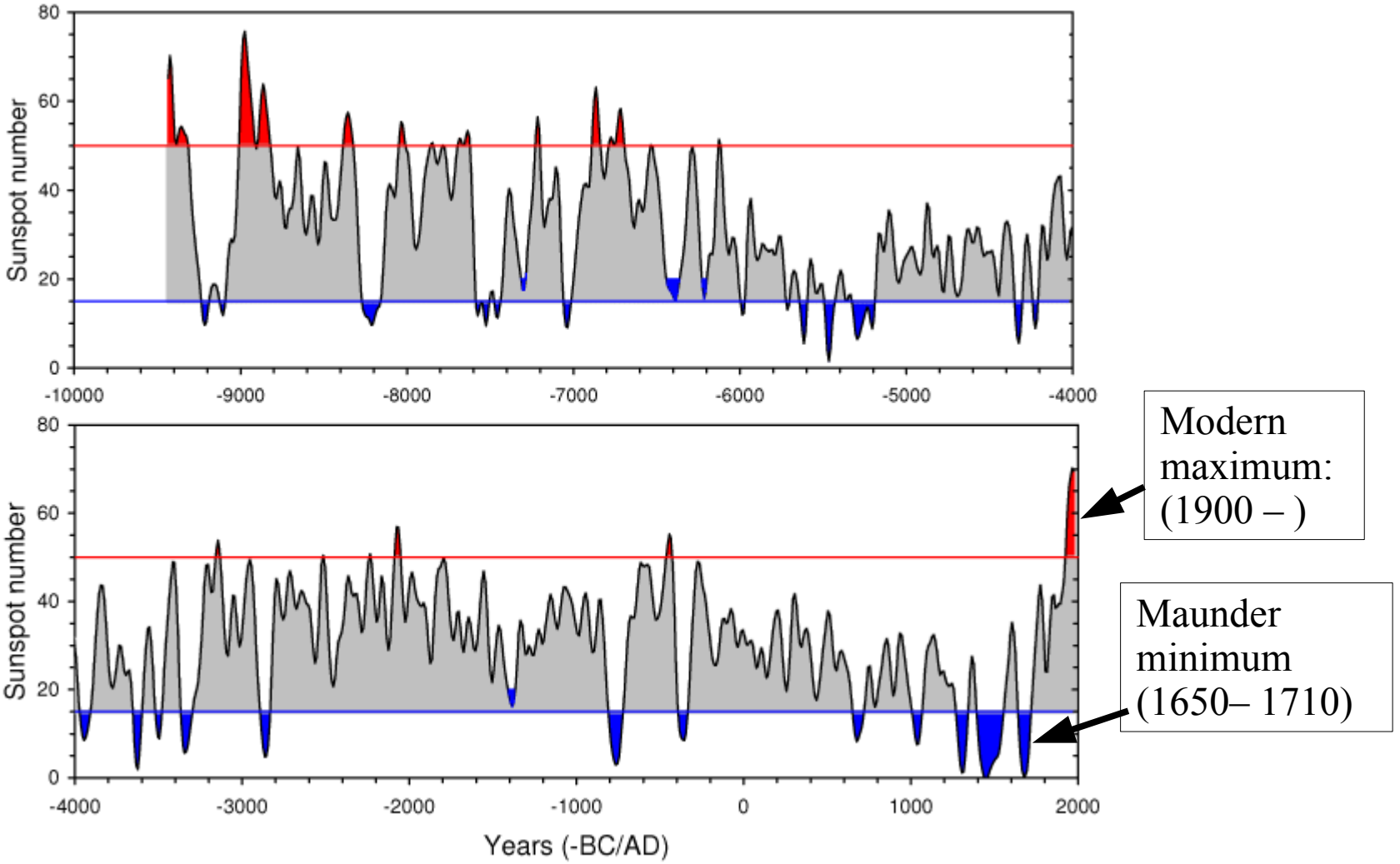


Dalton minimum (1790–1820)

Modern maximum: (1900 –)

Current cycle 24 is weak

Longer-term variation of sunspot numbers

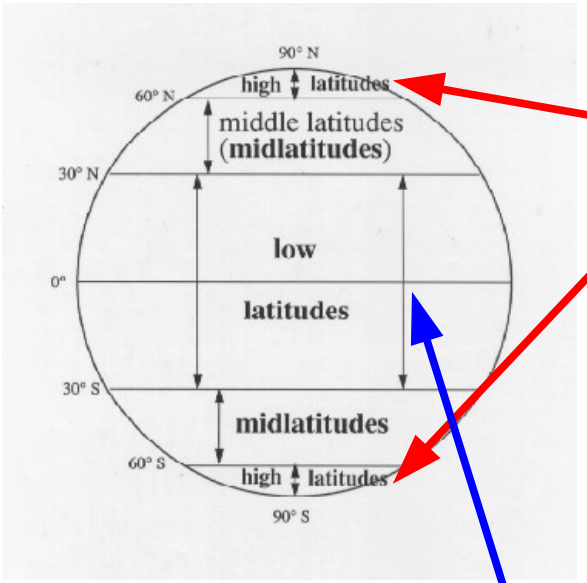


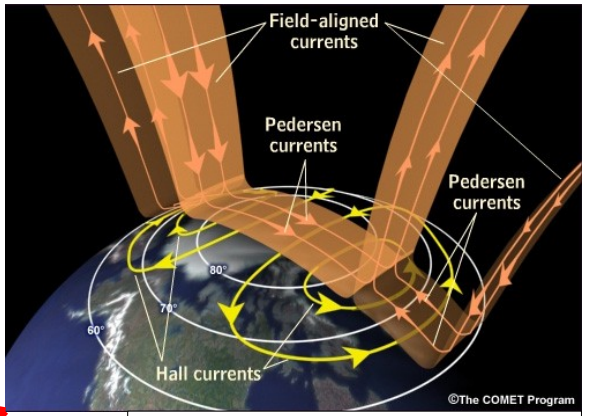
Sunspot activity throughout the Holocene, reconstructed from 14C by Usoskin et al. (2007) using geomagnetic data by Yang et al. (2000). Blue and red areas denote grand minima and maxima, respectively. From: Usoskin (2008).

Geomagnetic activity

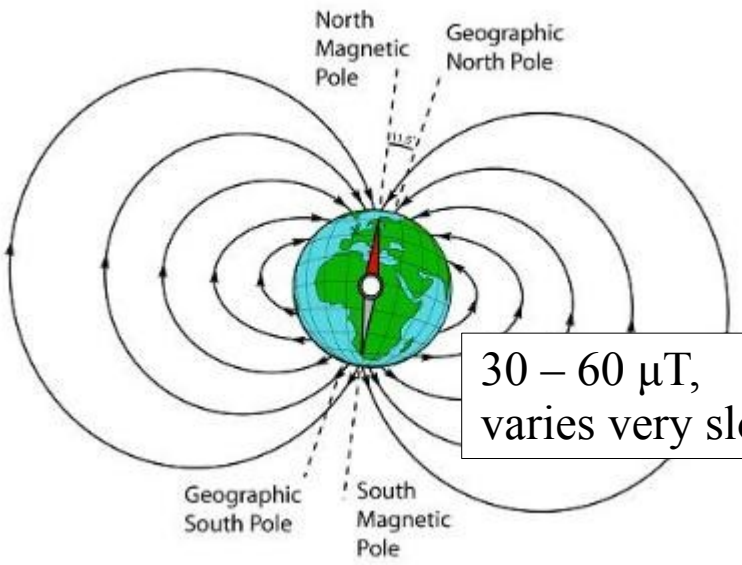
External magnetic field on the ground

- The magnetic field measured on the ground is a superposition of fields from several sources:
  - the Earth's internal field
  - magnetospheric currents
  - ionospheric currents.

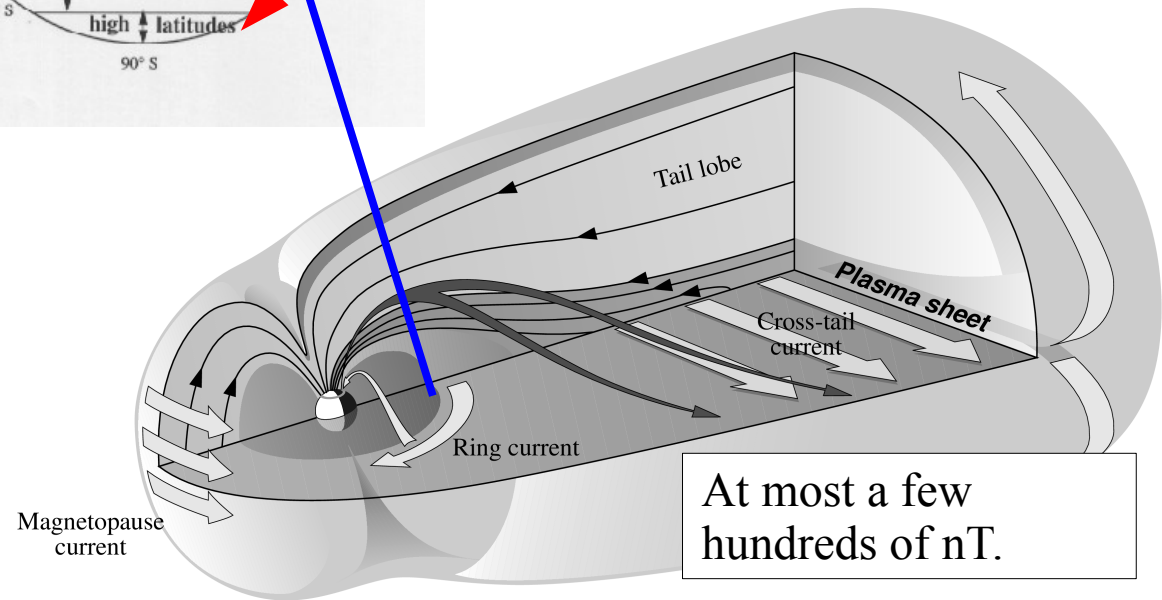




At most a few thousands of nT.



30 – 60 μT,
varies very slowly.

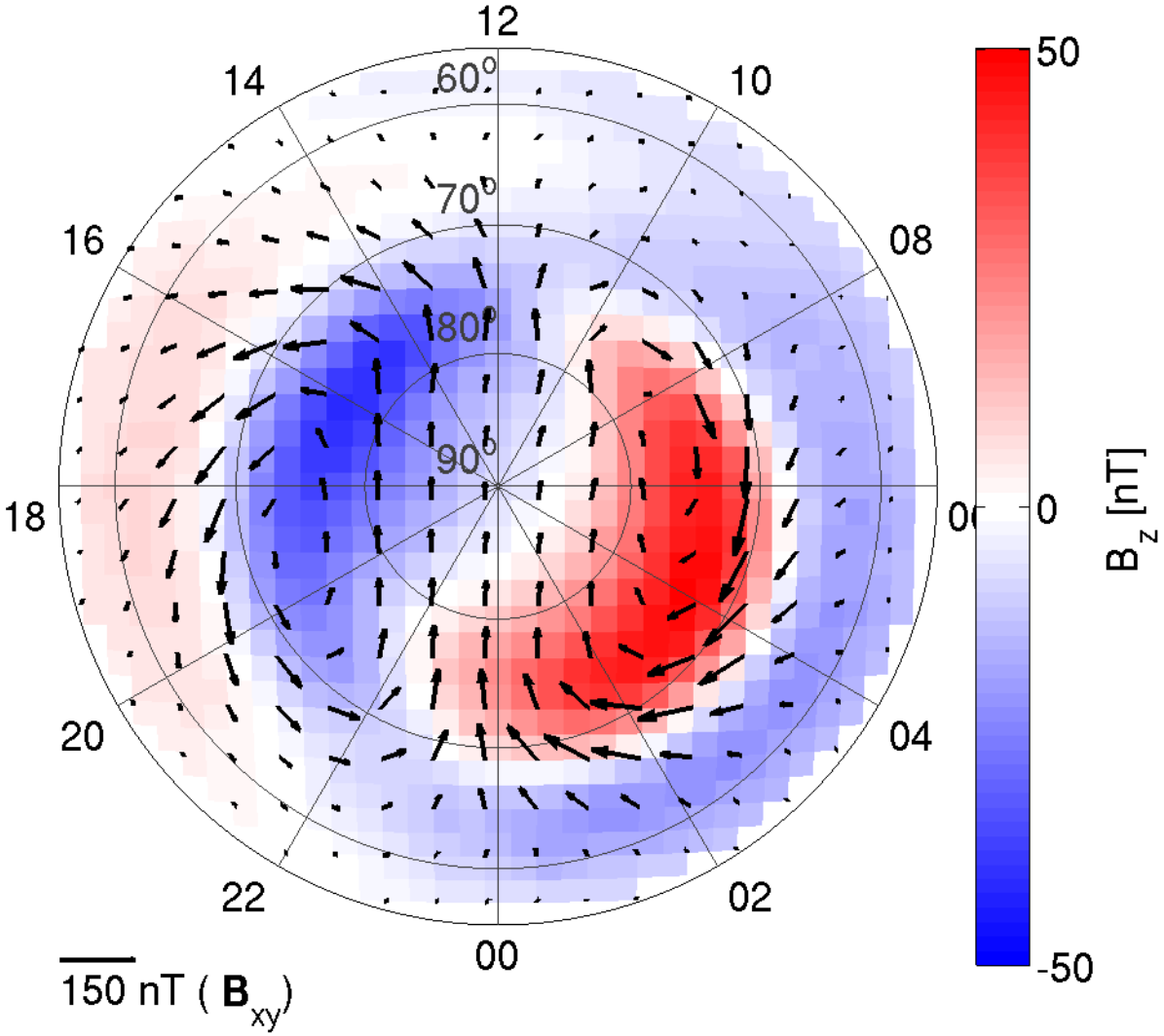


At most a few hundreds of nT.

Geomagnetic indices

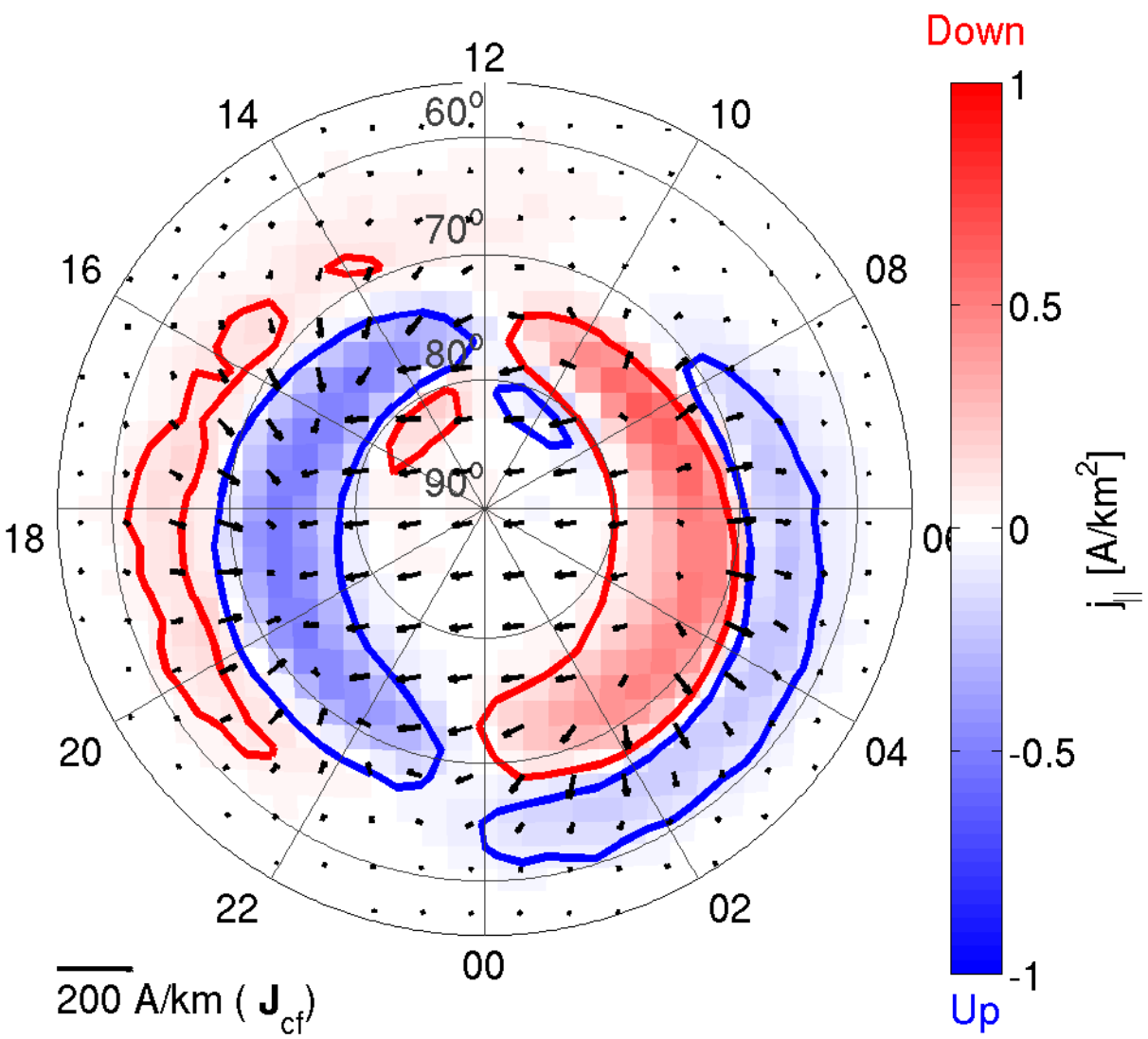
- The strength of geomagnetic disturbances is often described using various indices.
- Indices are numbers that characterize the level of magnetic disturbances during a certain time interval (i.e., 1 hour, 1 day, 1 month, etc.)
- Indices are derived from the continuous measurements of geomagnetic observatories (e.g., NUR).
- A global index (e.g., Kp, Dst, AE) is derived from a set of stations with geographically as extensive a coverage as possible, and describes the level of geomagnetic disturbances globally.

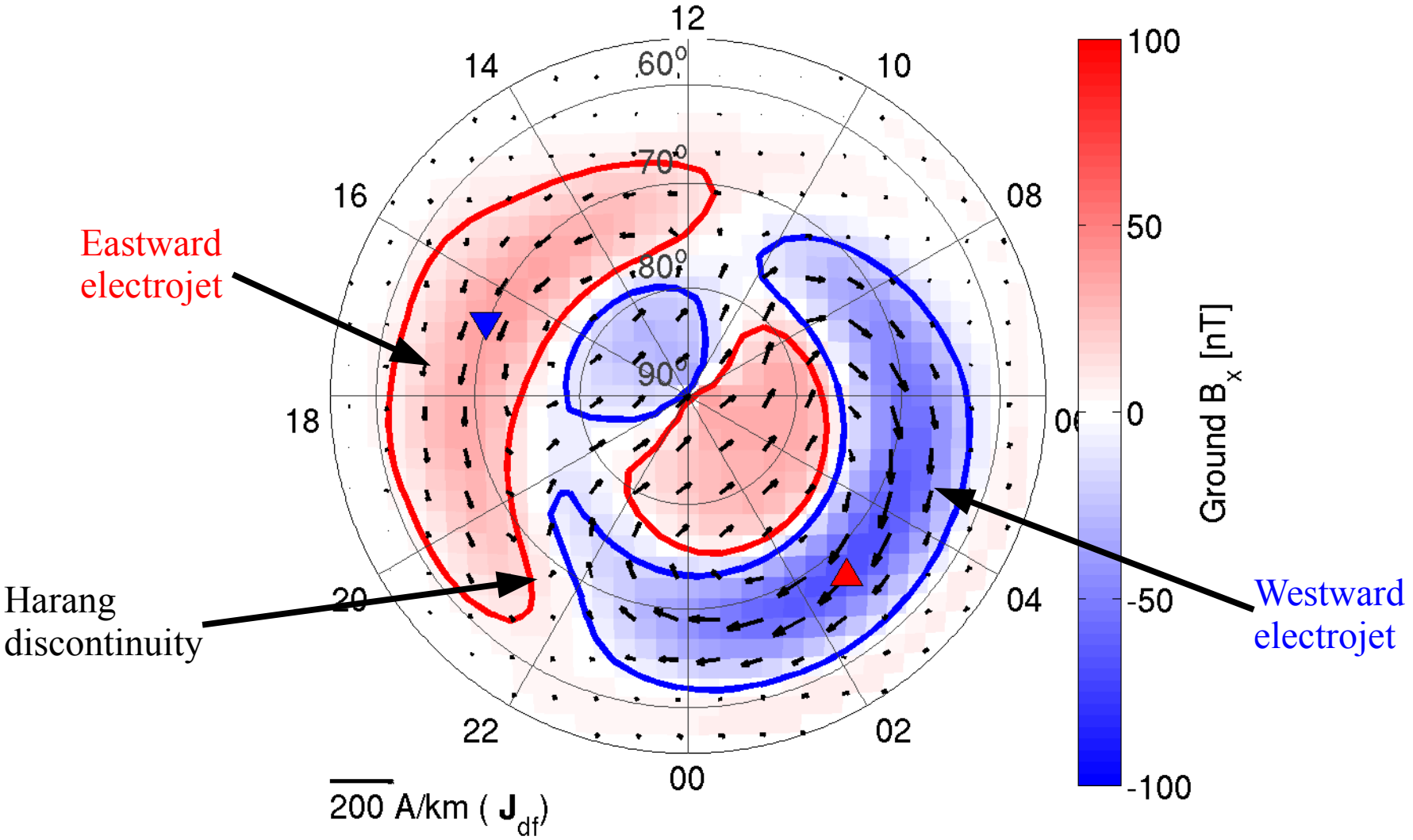
External magnetic field at high latitudes



Average disturbance magnetic field at ~350 km altitude obtained by subtracting the internal field according to the POMME geomagnetic field model from the magnetic field measured by the CHAMP satellite.

Arrows: Average curl-free component of the ionospheric current density ($\boldsymbol{J}_{cf}$) at 100 km altitude as a function geomagnetic latitude and magnetic local time. Color: Field-aligned current density at 100 km altitude.





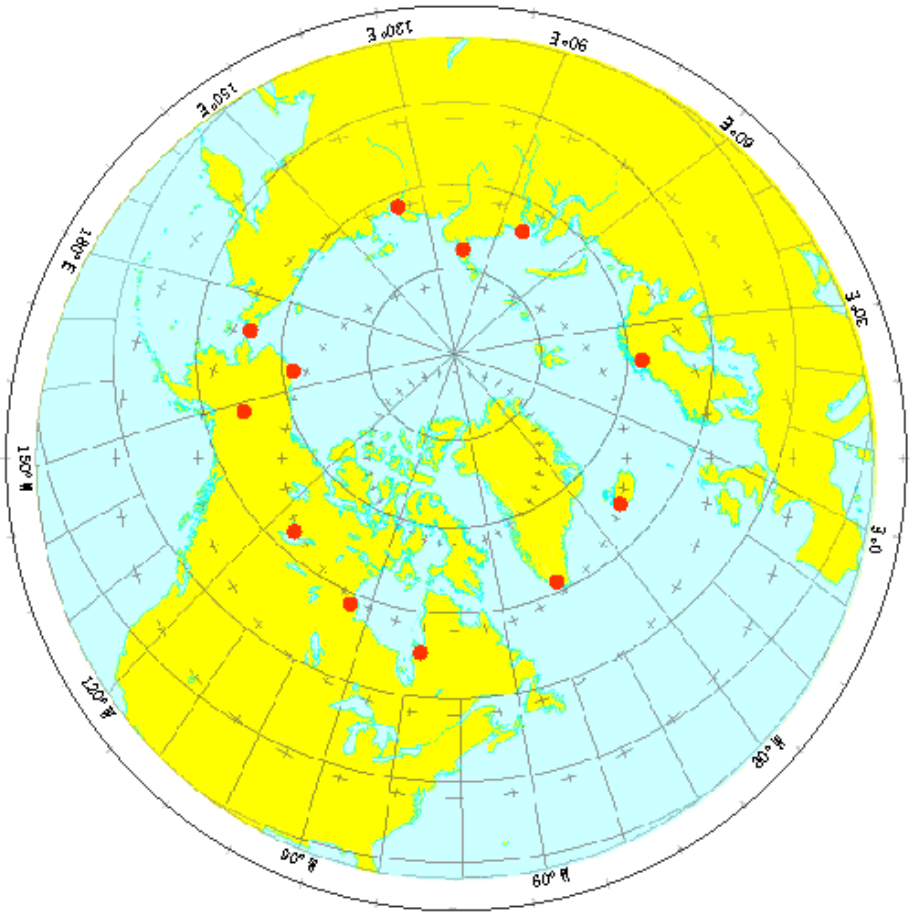
Arrows: Average divergence-free component of the ionospheric current density ($\boldsymbol{J}_{df}$) at 100 km altitude as a function geomagnetic latitude and magnetic local time. Because this component produces the same disturbance magnetic field on the ground as the full current system that also includes the curl-free component ($\boldsymbol{J}_{cf}$) and field-aligned currents, it is sometimes called equivalent current density ($\boldsymbol{J}_{eq}$).

Color: North-south component (B_x) of the disturbance magnetic field on the ground produced by $\boldsymbol{J}_{df}$.

Blue triangle: B_x maximum of 37 nT. Red triangle: B_x minimum of -67 nT.

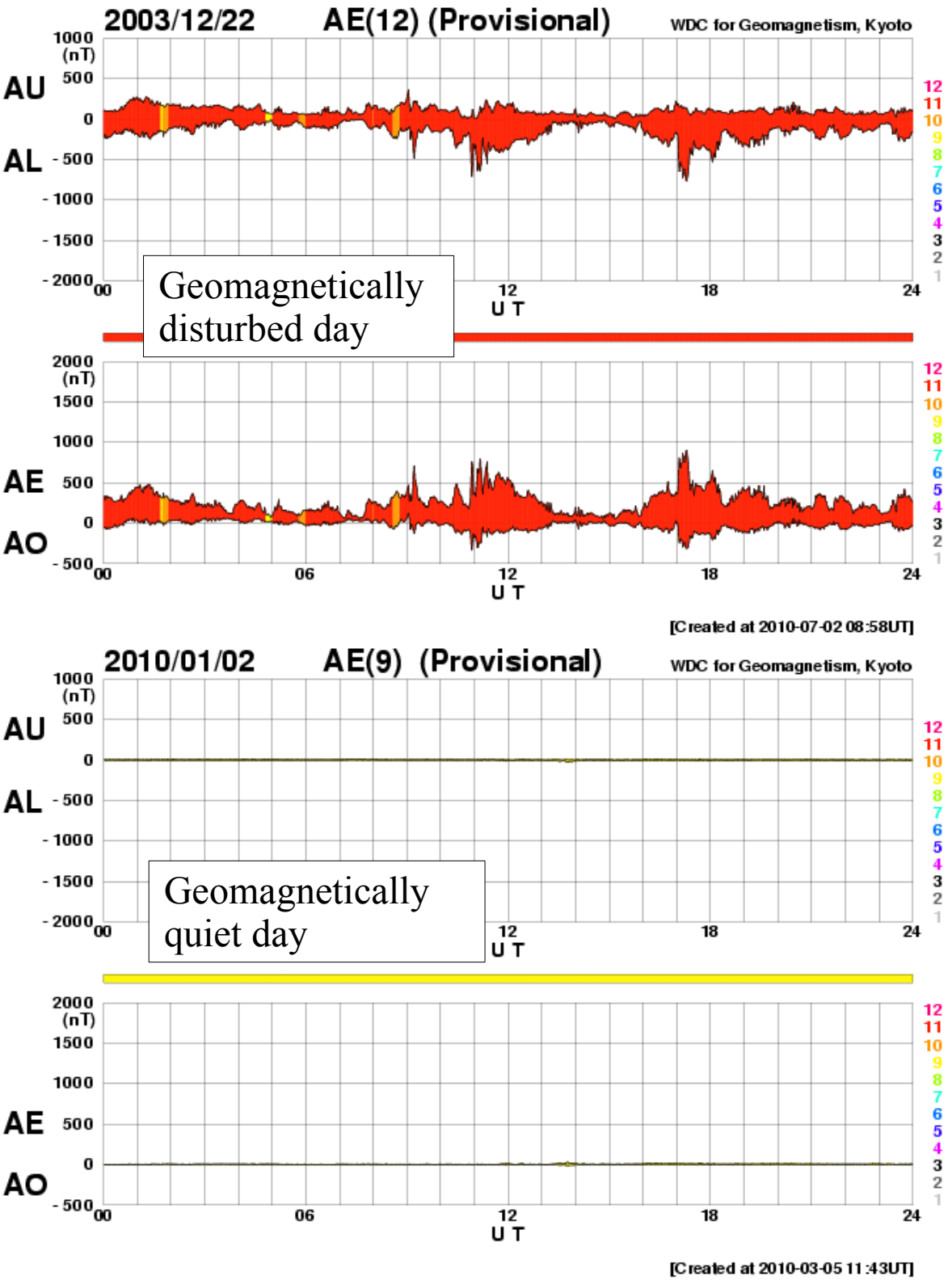
Magnetic activity indices: AE

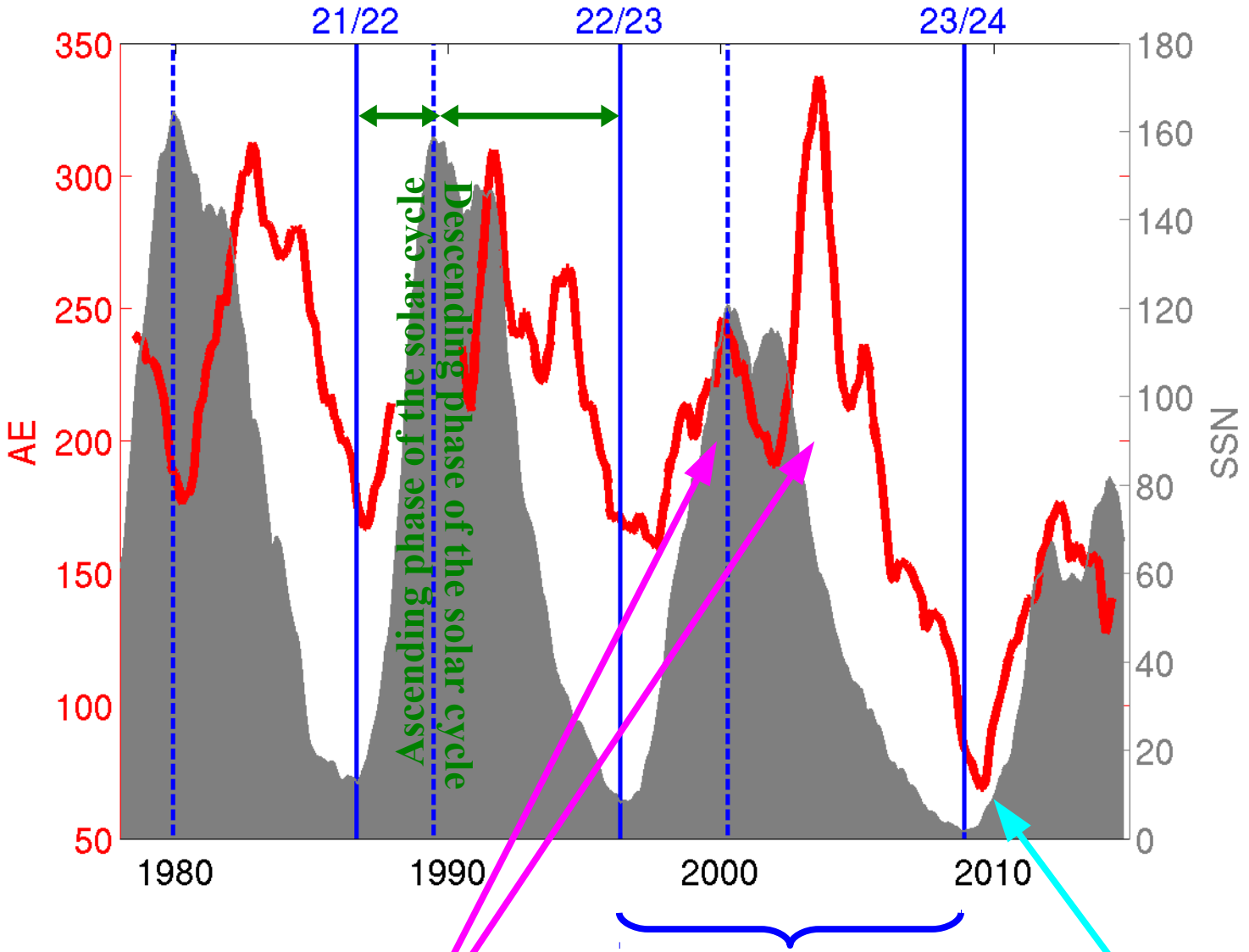
- The 1-min AL (AU) index is defined as the minimum (maximum) of the north-south component of the disturbance magnetic field on the ground (B_x) measured by 10 to 13 standard magnetic observatories located between about 60° and 70° geomagnetic latitude [Davis and Sugiura, 1966].
  - When a station is located under the westward electrojet, $B_x < 0$
  - When a station is under the eastward electrojet, $B_x > 0$
- The Auroral Electrojet index AE = AU – AL.
- AU and AL give some measure of the individual strengths of eastward and westward electrojets, while AE provides a measure of the overall horizontal current strength.



- After the Earth's internal field has been subtracted, the remaining part is mainly due to auroral ionospheric currents.
- As a baseline, measurement during a nearby quiet (no significant disturbances) day from the same station is typically used.
- Disturbances, i.e., excursions in the AL or AE index from a nominal daily baseline, are mainly caused by substorms and typically last from tens of minutes to some hours.

Real-time and archived AE indices:
http://wdc.kugi.kyoto-u.ac.jp/

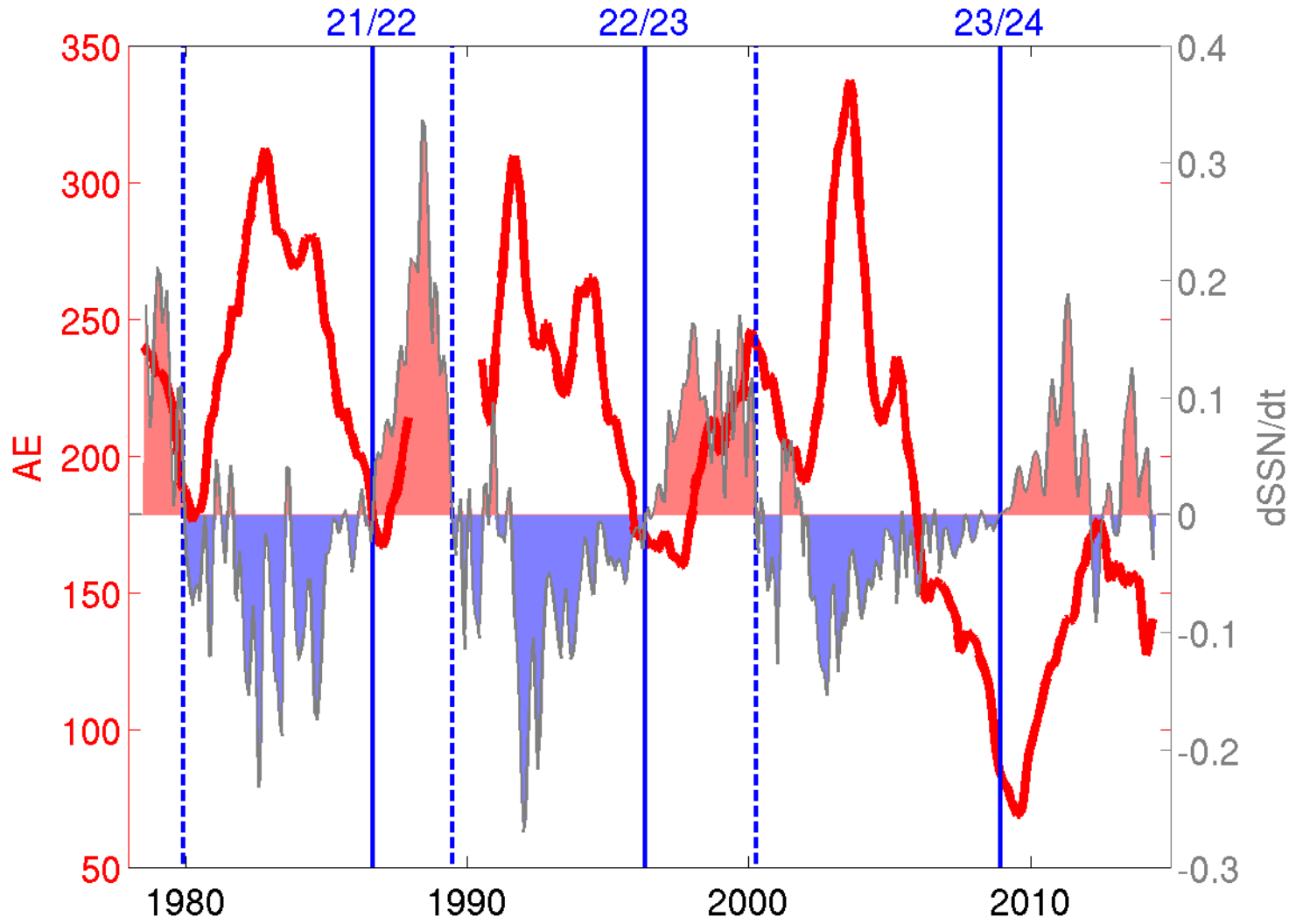


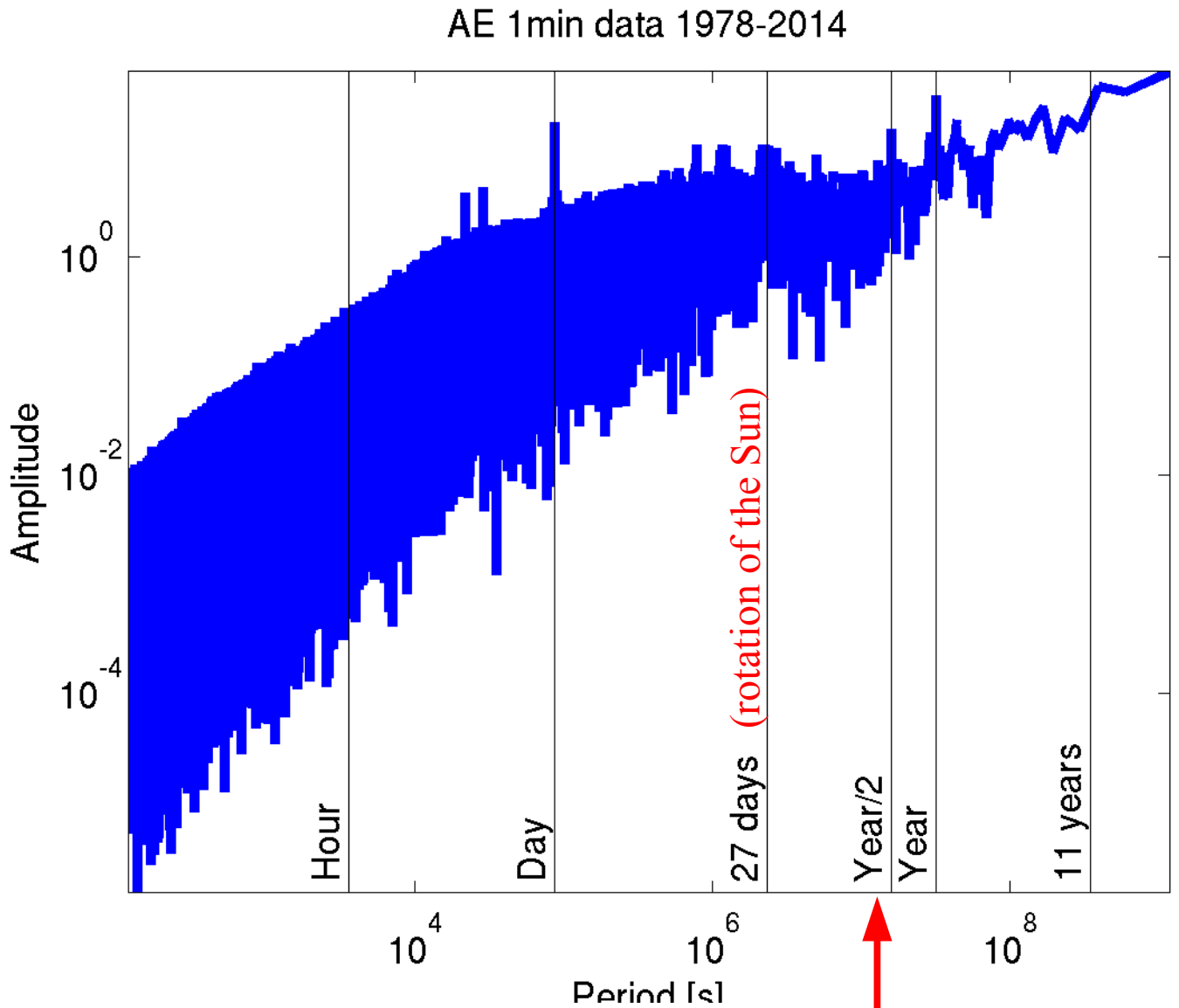


Two or more geomagnetic activity peaks often occur during a solar cycle. One peak before or around solar maximum (dashed vertical line) and one at the beginning of the declining phase are typical.

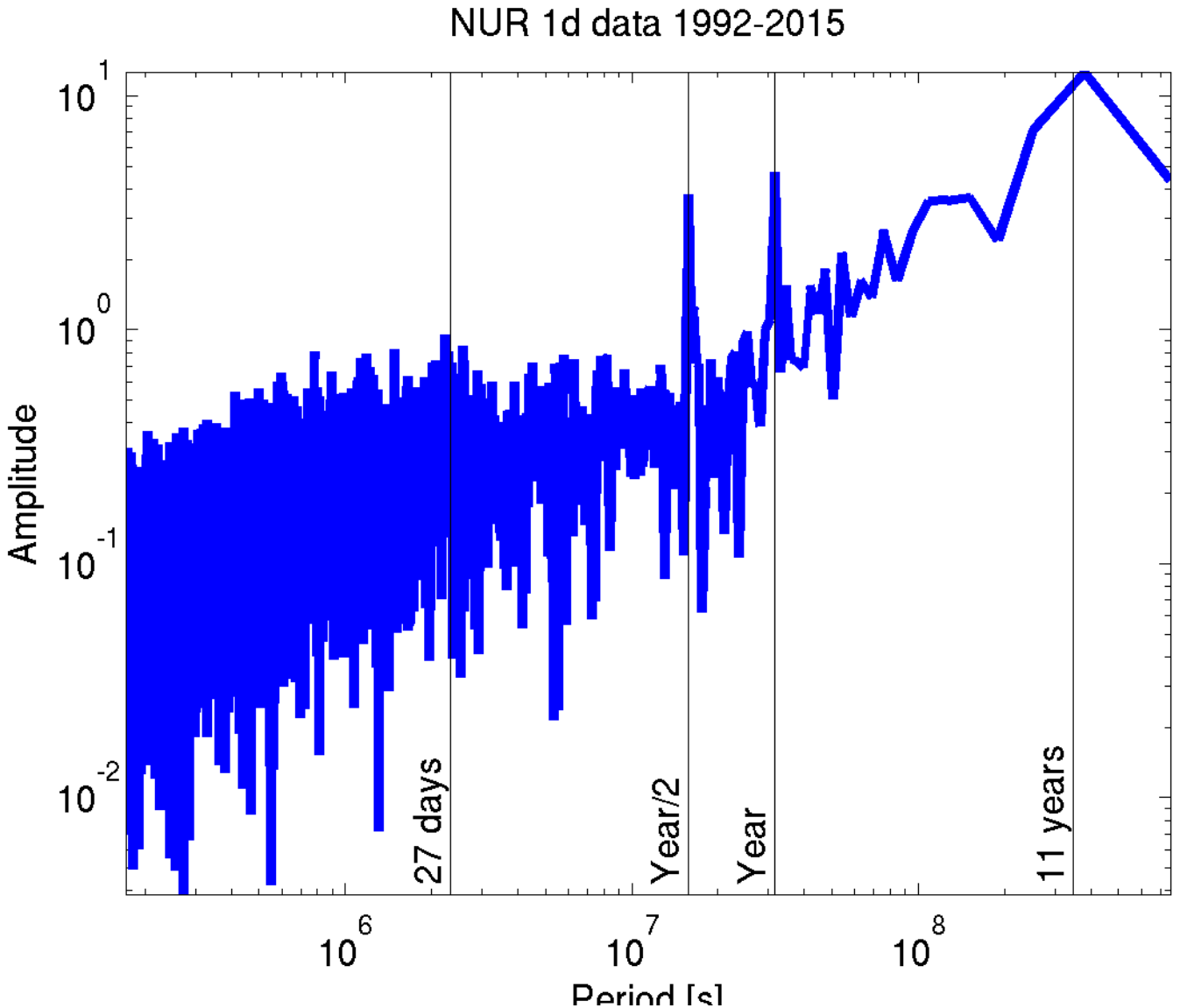
Sunspot or solar cycle

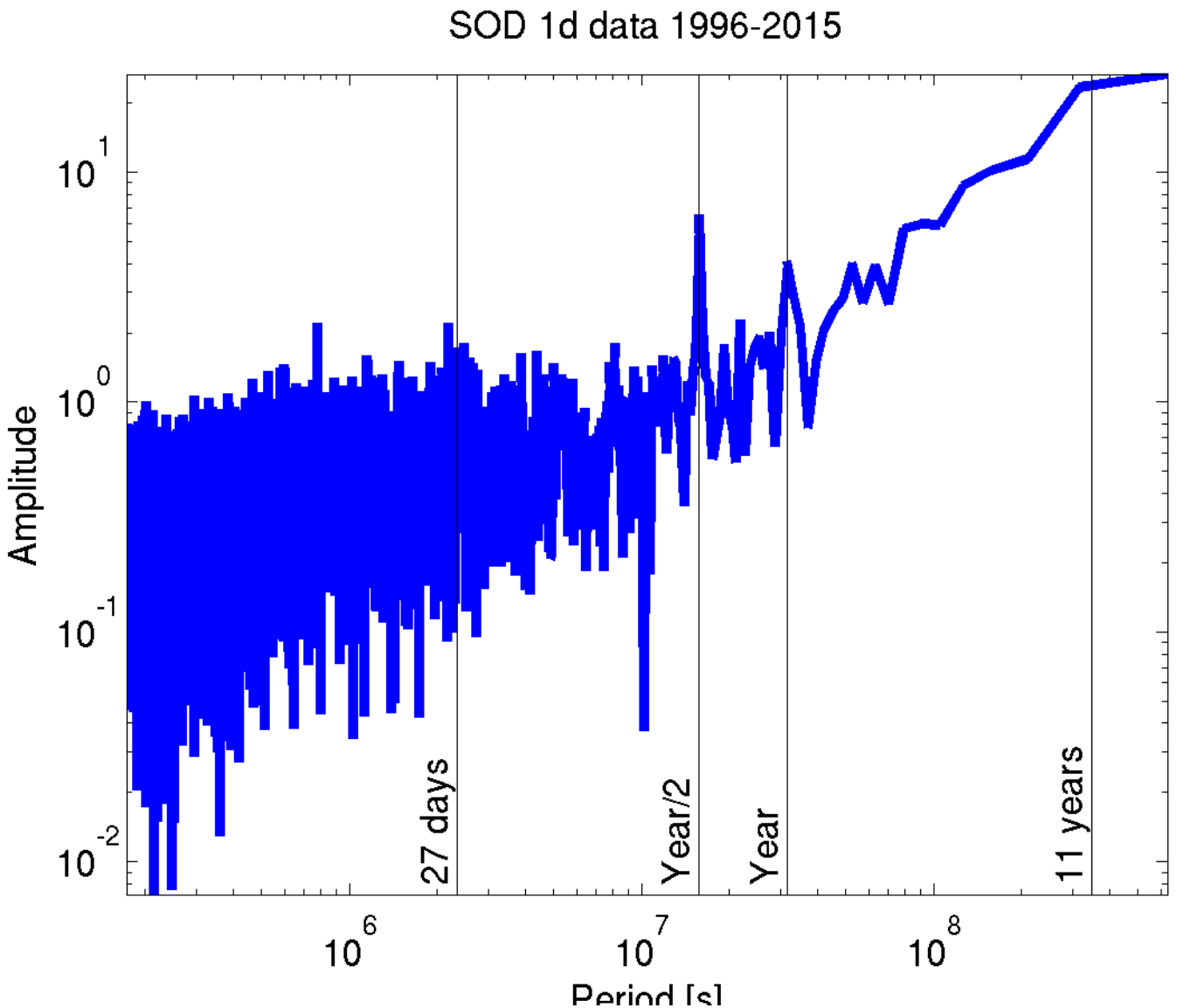
Geomagnetic activity minimum often occurs after sunspot minimum (solid vertical line).

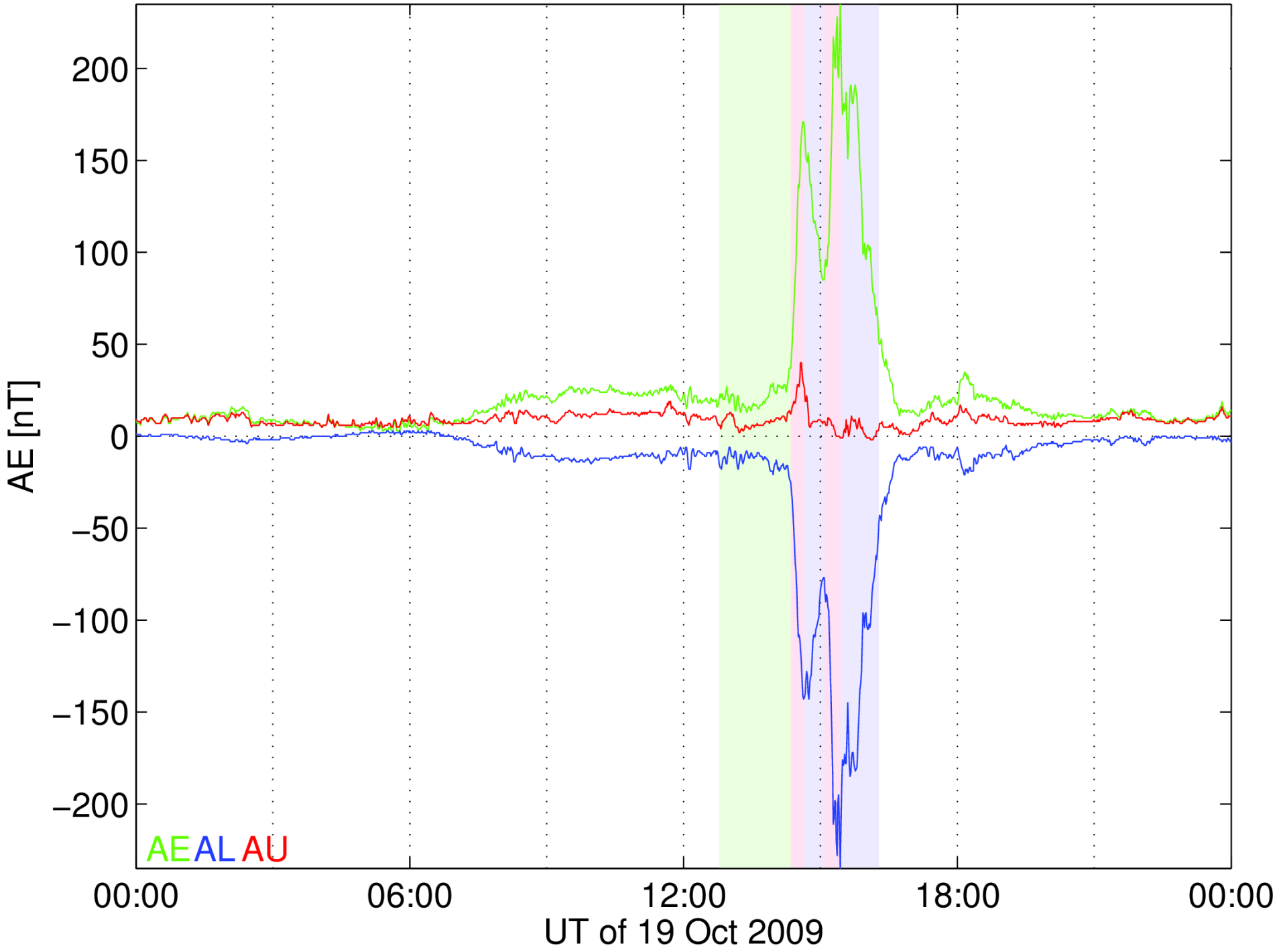

21/22
22/23
23/24
AE
dSSN/dt
350
300
250
200
150
100
50
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
1980
1990
2000
2010



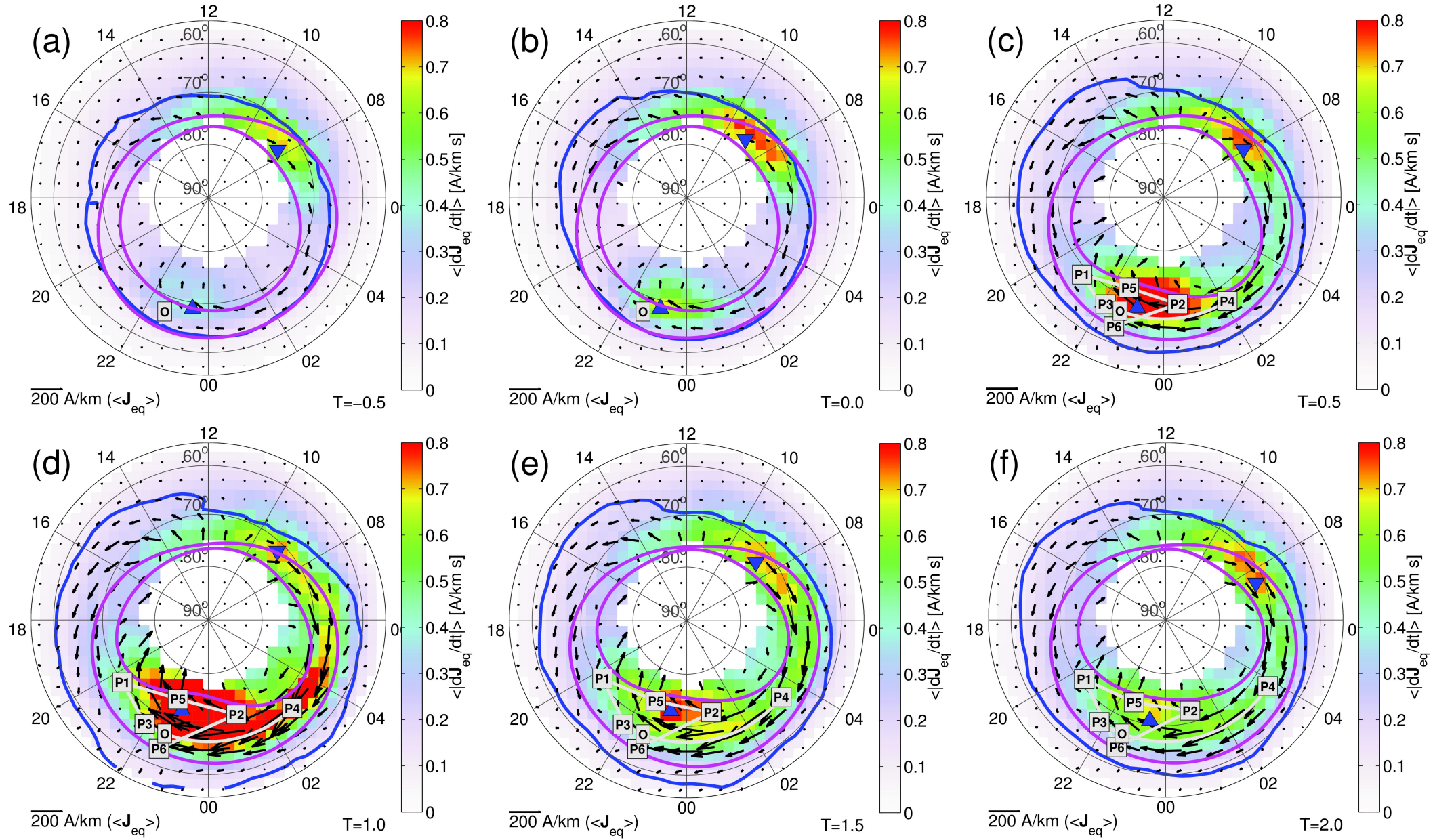
Statistical maxima of geomagnetic activity in spring and fall, minima in winter and summer (Russell and McPherron, 1973).


NUR 1d data 1992-2015
Amplitude
10^1
10^0
10^-1
10^-2
27 days
Year/2
Year
11 years
10^6
10^7
10^8
Period [s]

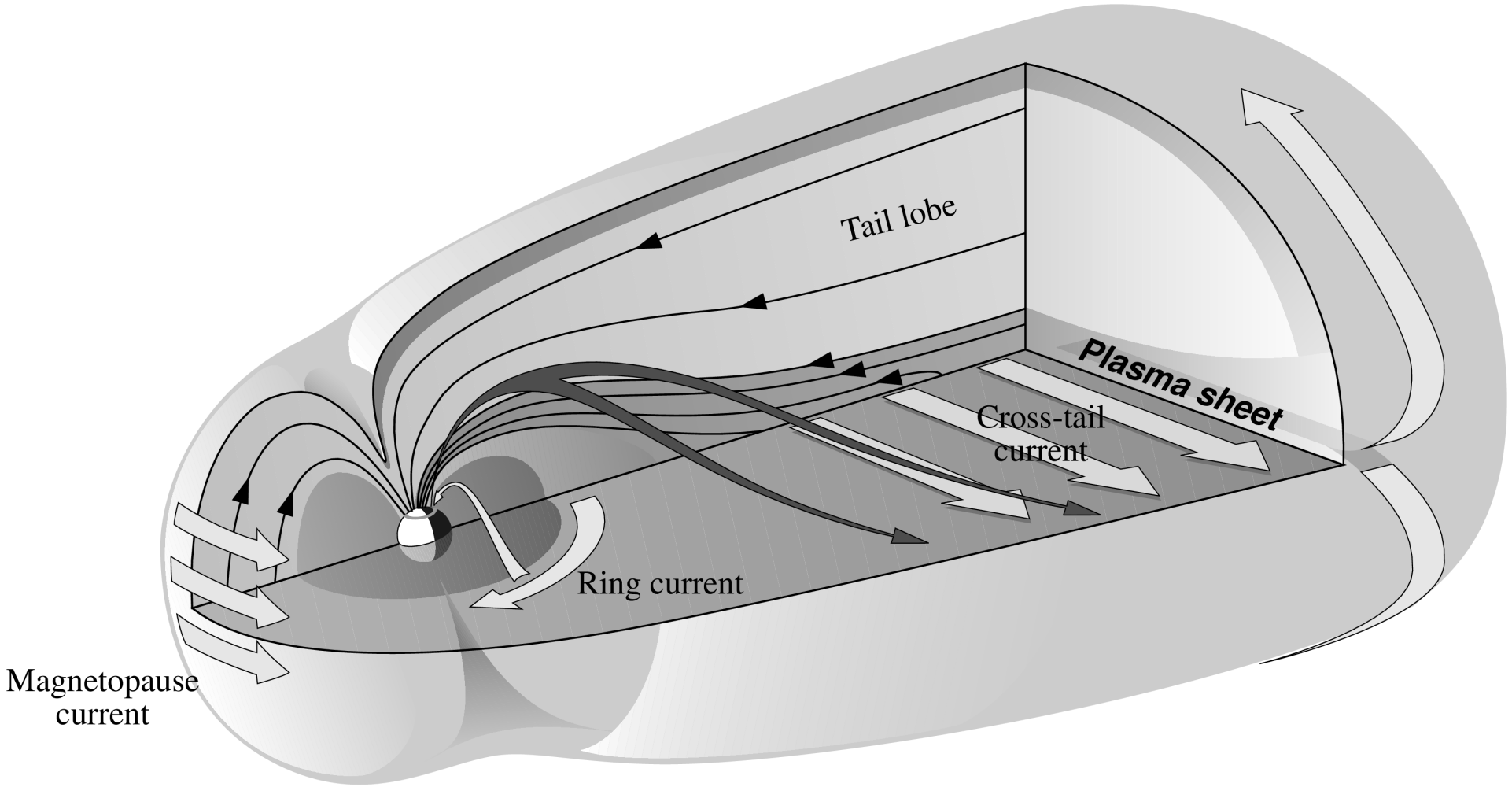

SOD 1d data 1996-2015
Amplitude
10^1
10^0
10^-1
10^-2
10^6
10^7
10^8
Period [s]
27 days
Year/2
Year
11 years


AE [nT]
200
150
100
50
0
−50
−100
−150
−200
AE AL AU
00:00
06:00
12:00
18:00
00:00
UT of 19 Oct 2009

Average substorm development of auroras and ionospheric equivalent currents



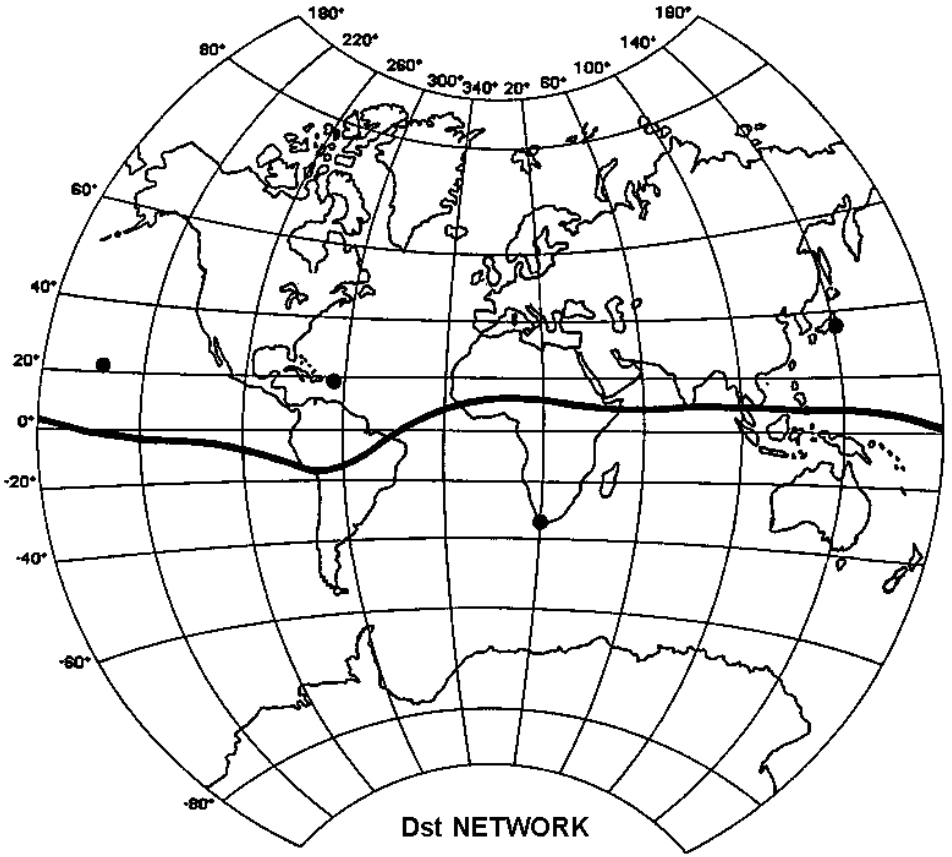
External magnetic field at low latitudes



The ring current is formed of trapped, westward drifting ions and eastward drifting electrons.

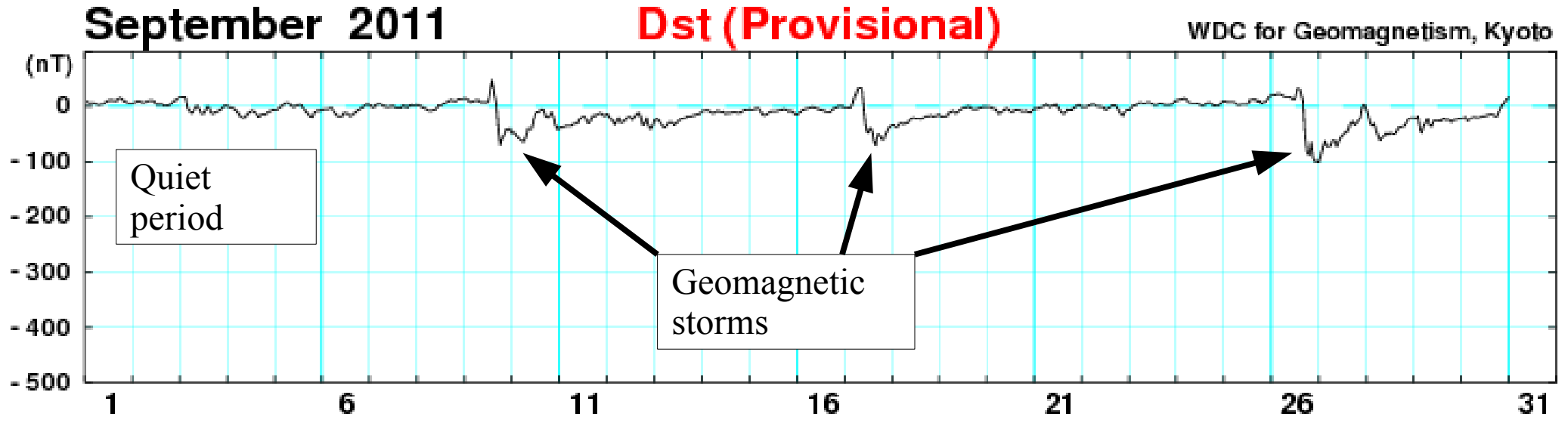
Magnetic activity indices: Dst

- The hourly Dst index (Sugiura, 1964) is obtained from magnetometer stations near the equator but not so close that the E-region equatorial electrojet dominates the magnetic perturbations seen on the ground.
- At such latitudes the B_x component of the magnetic perturbation is dominated by the intensity of the magnetospheric ring current.
- The Dst index is a direct measure of the hourly average of this perturbation.



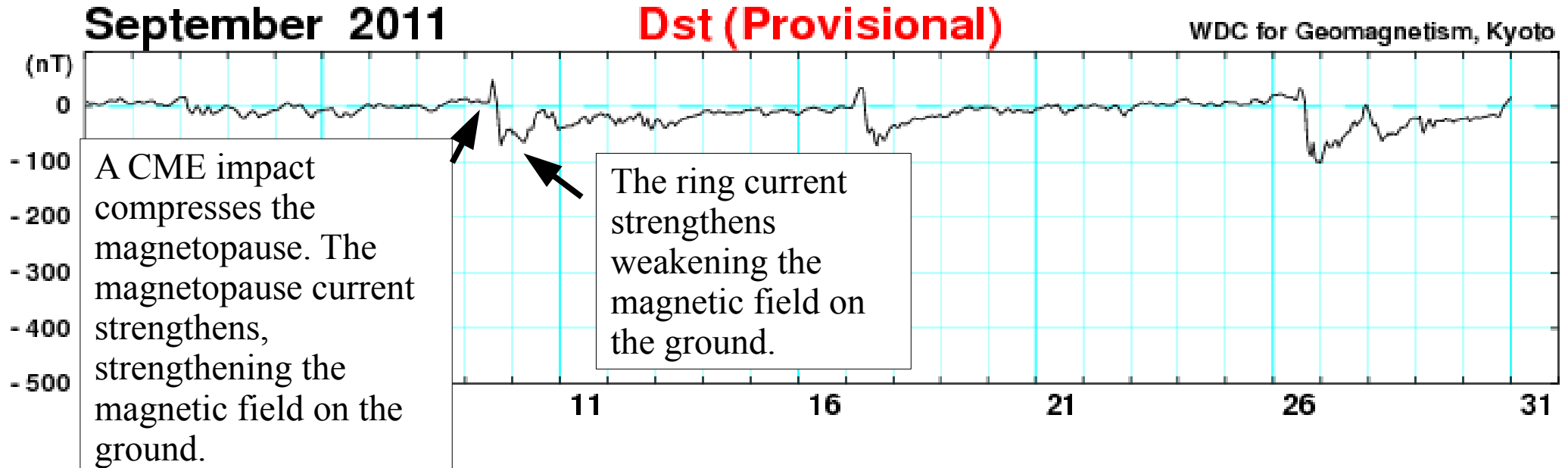
- After the Earth's main field has been subtracted, the remaining part is mainly due to magnetospheric current systems.
- Disturbances are mainly caused by geomagnetic storms and typically last for some days.

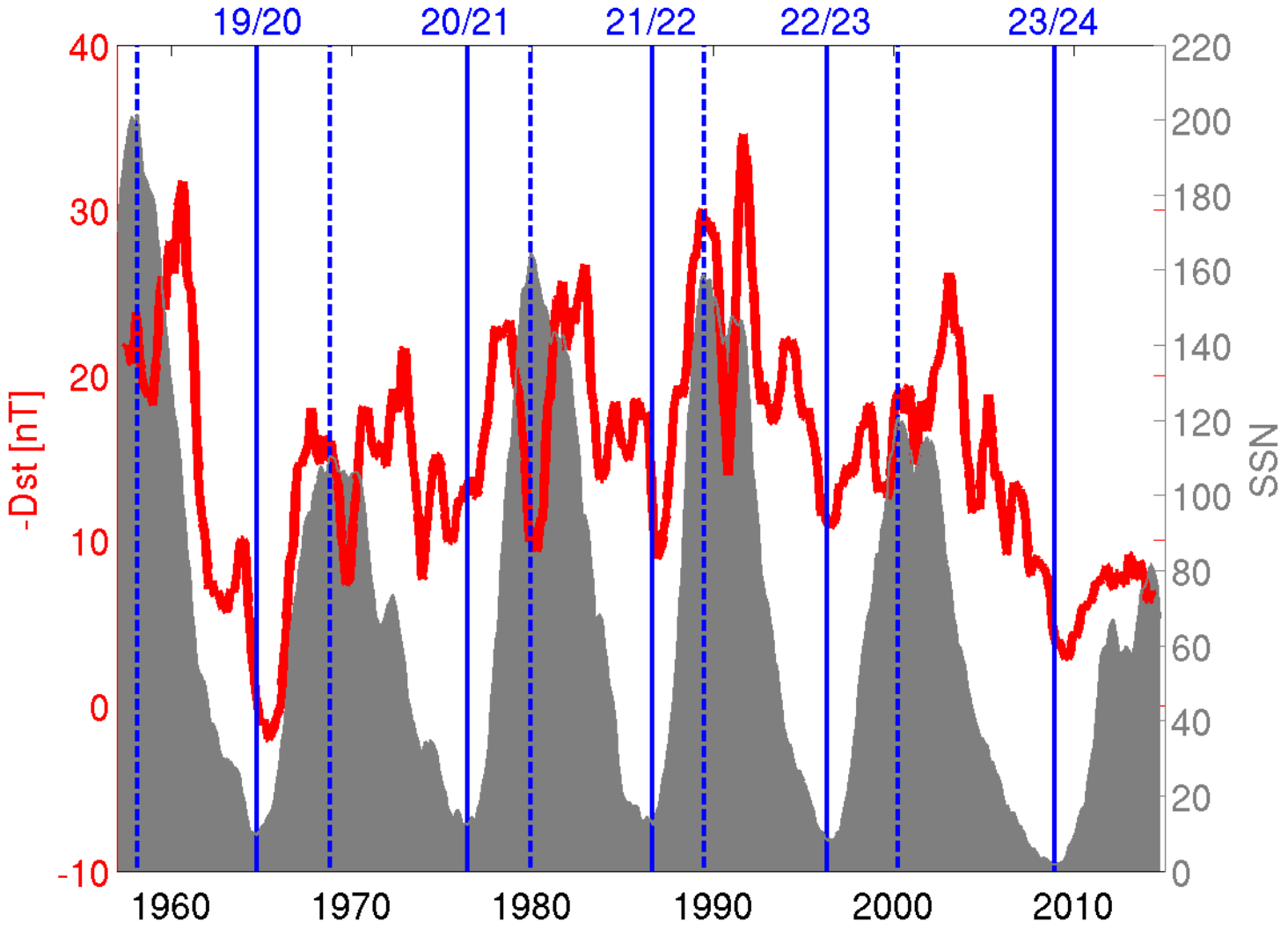
Real-time and archived Dst index:
http://wdc.kugi.kyoto-u.ac.jp/



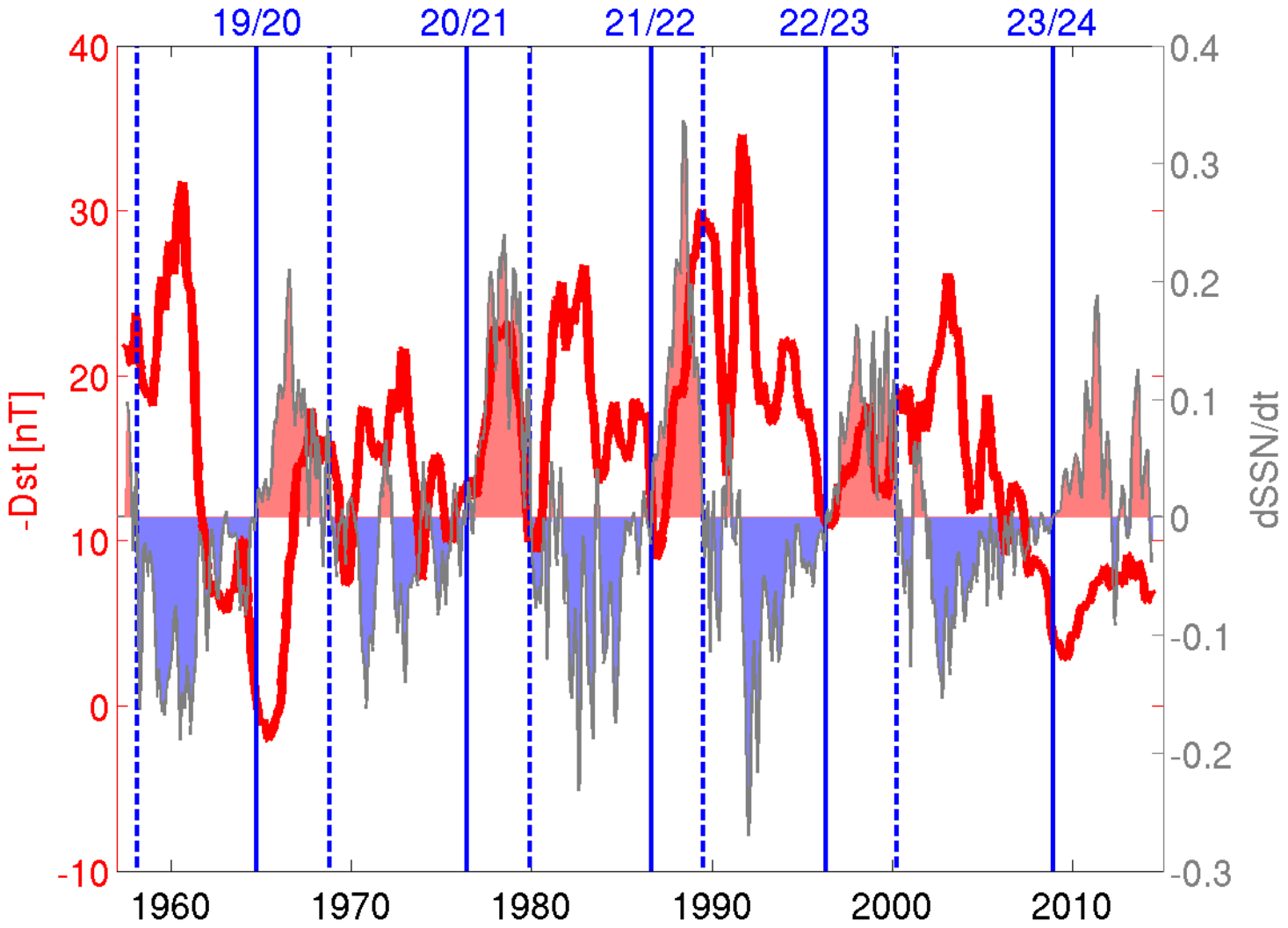
Geomagnetic storm

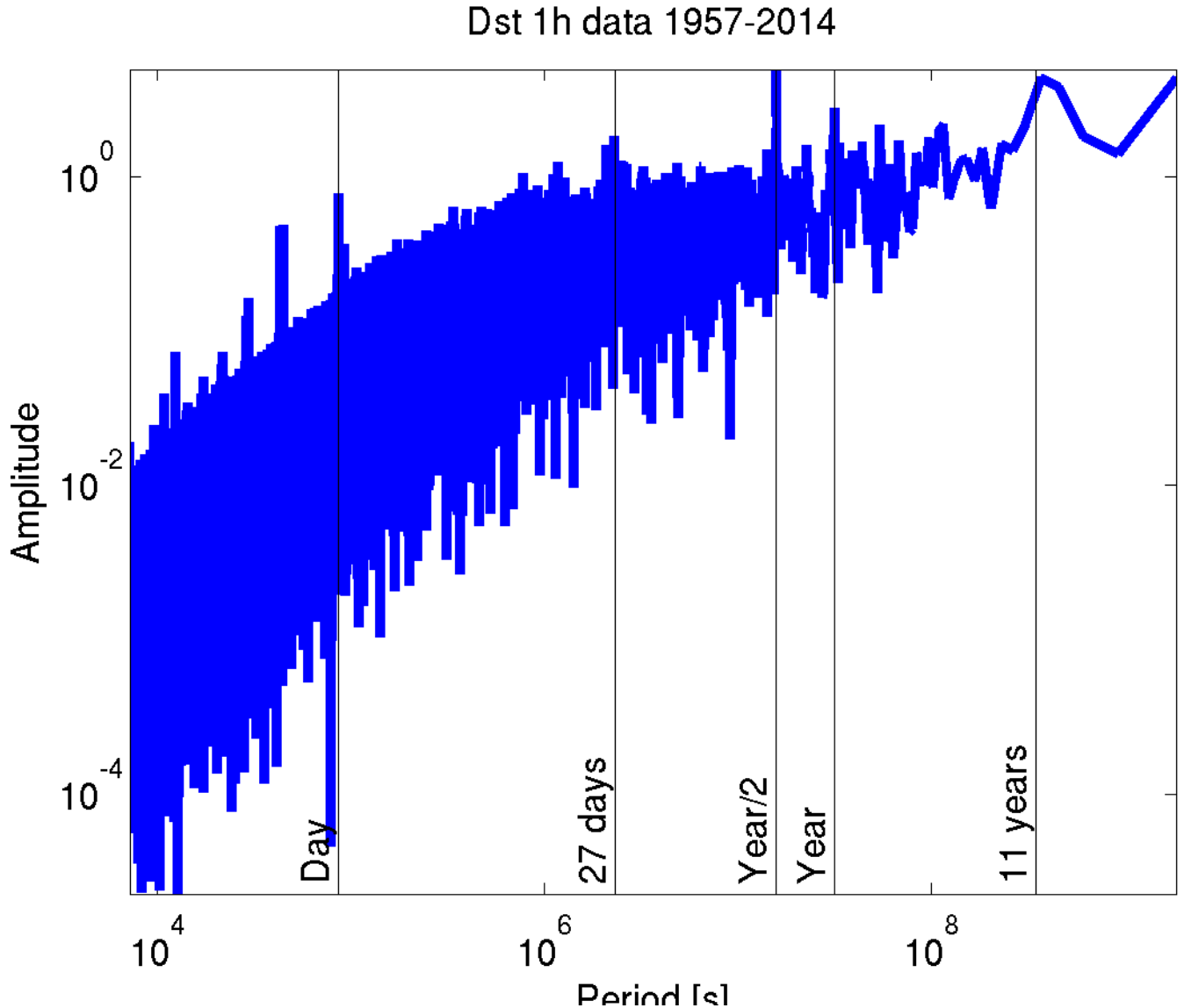
- At low latitudes, a geomagnetic storm can be detected as a weakening of the geomagnetic field.
- At high latitudes, the conditions are disturbed.
- Typically driven by a CME (strongest storms) or a solar wind high-speed stream.





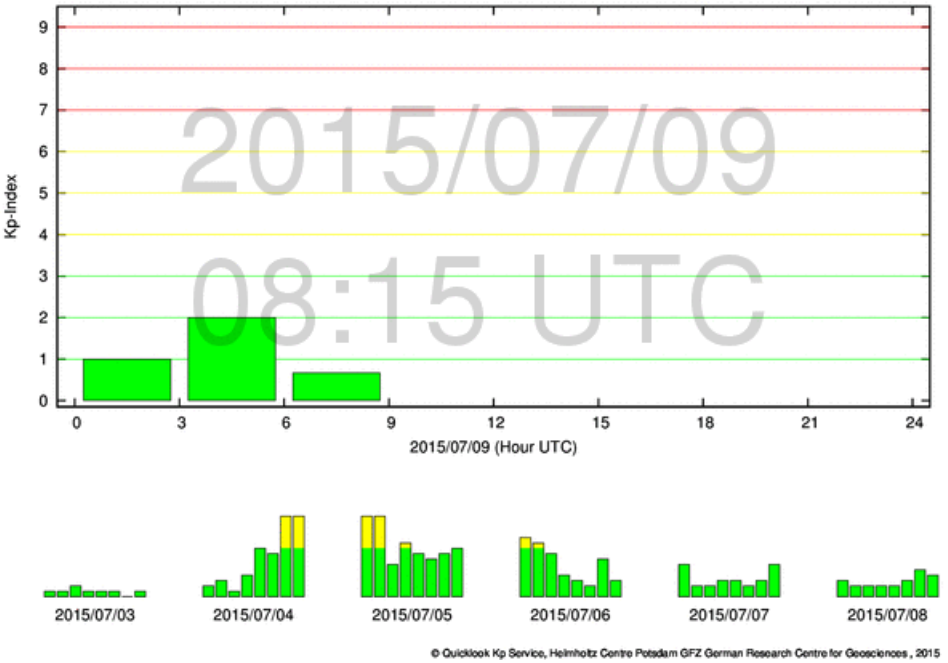
Geomagnetic activity tends to have two peaks during one solar cycle: a smaller peak before or around the sunspot maximum and a larger peak after the sunspot maximum. Nonetheless, geomagnetic storms can occur at any time, also during the solar minimum.


19/20
20/21
21/22
22/23
23/24
40
30
20
10
0
-10
-Dst [nT]
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
dSSN/dt
1960
1970
1980
1990
2000
2010

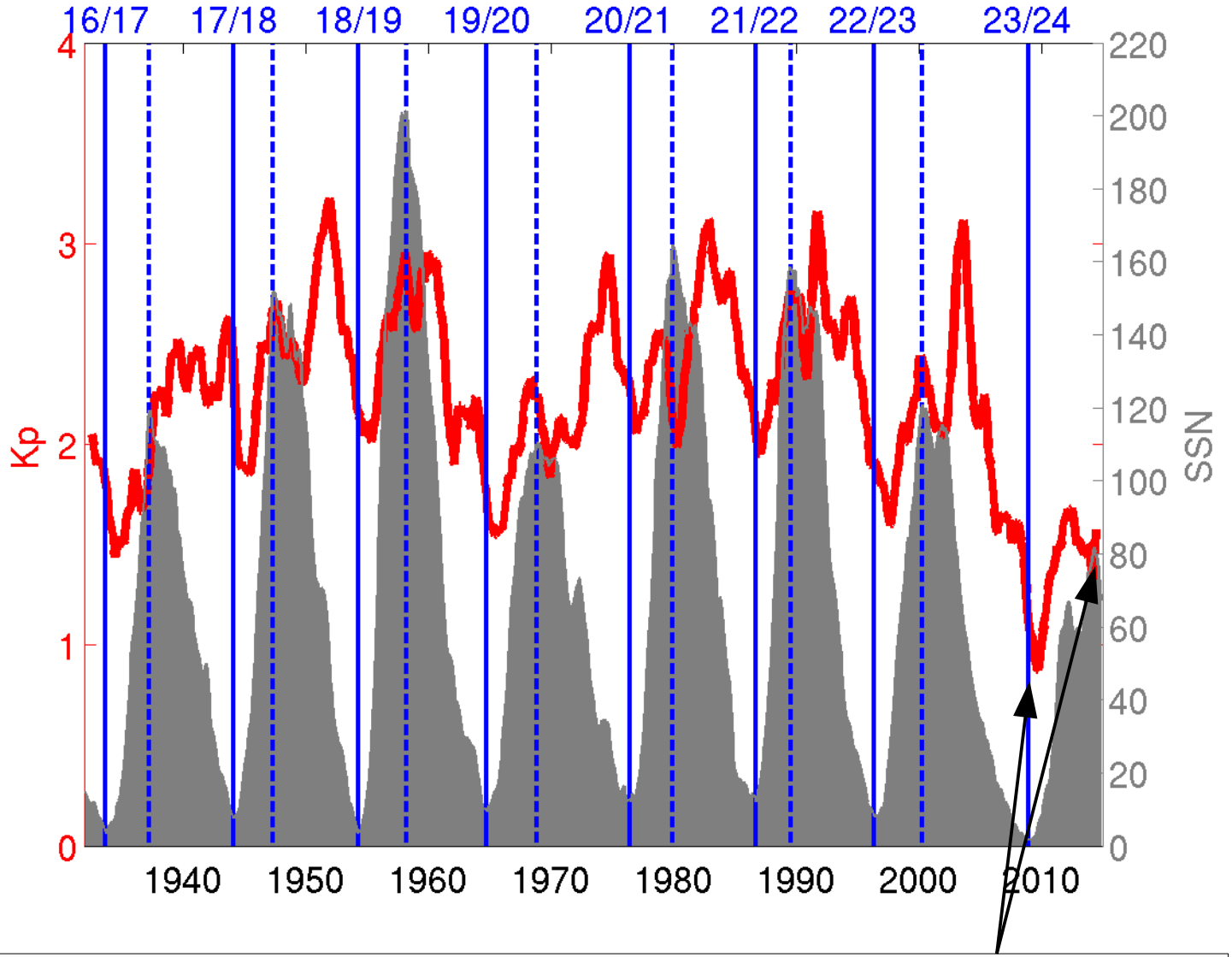

Dst 1h data 1957-2014
Amplitude
10^0
10^-2
10^-4
Day
27 days
Year/2
Year
11 years
10^4
10^6
10^8
Period [s]

Magnetic activity indices: Kp

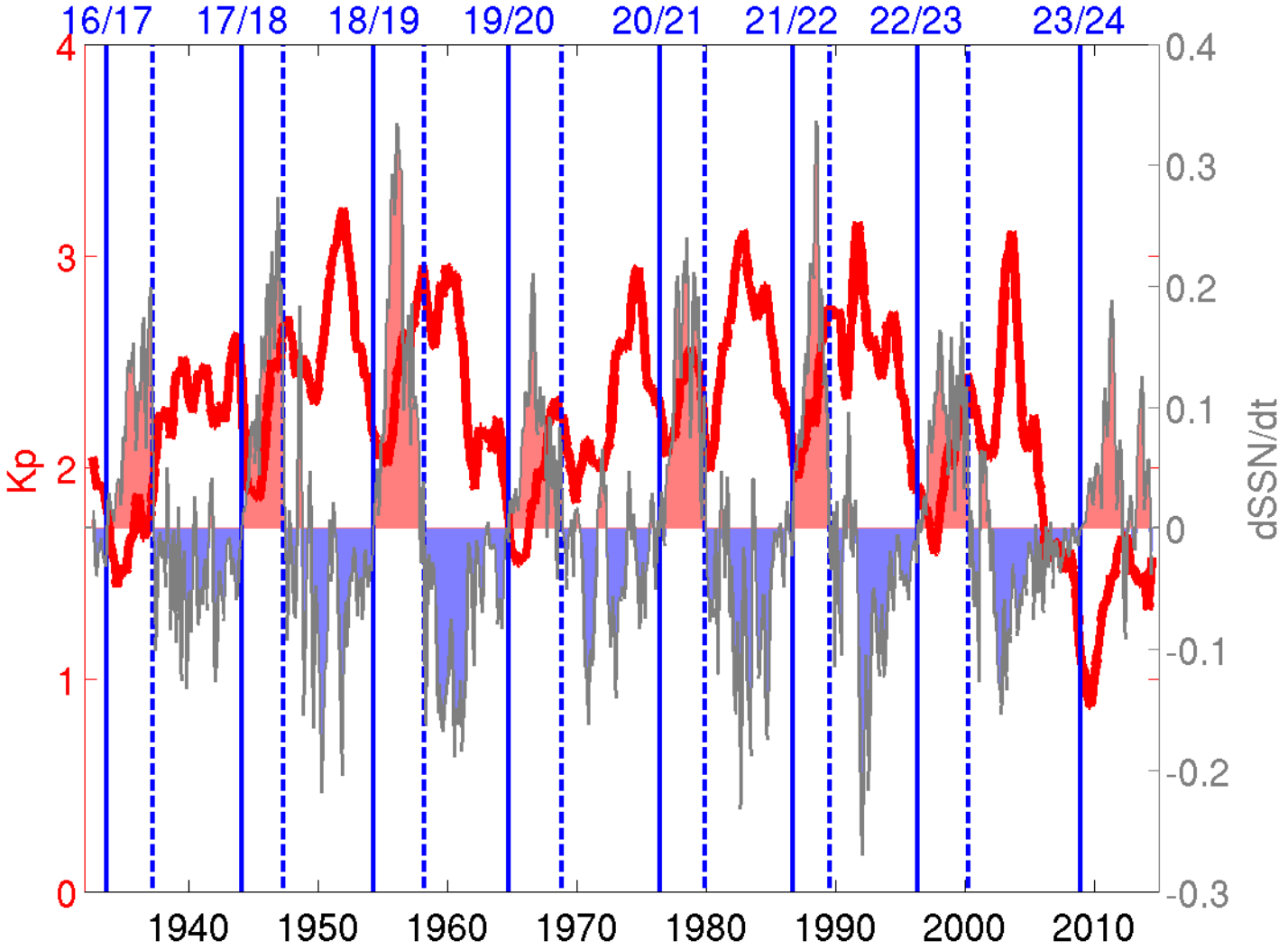
- The Kp index (Bartels et al., 1939) is obtained from a number of magnetometer stations at mid-latitudes.
- When the stations are not greatly influenced by the auroral electrojet currents, conditions are termed magnetically quiet.
- If the auroral zone expands equatorward, these stations can record the effects of the auroral electrojet current system and of the magnetospheric ring current and field-aligned currents. This occurs during magnetically disturbed periods.
- The mid-latitude stations are rarely directly under an intense horizontal current system and thus magnetic perturbations can be dominant in either the B_x or B_y component.
- The Kp index utilizes both these perturbations by taking the logarithm of the largest excursion in B_x or B_y over a 3-h period and placing it on a scale from 0 to 9.

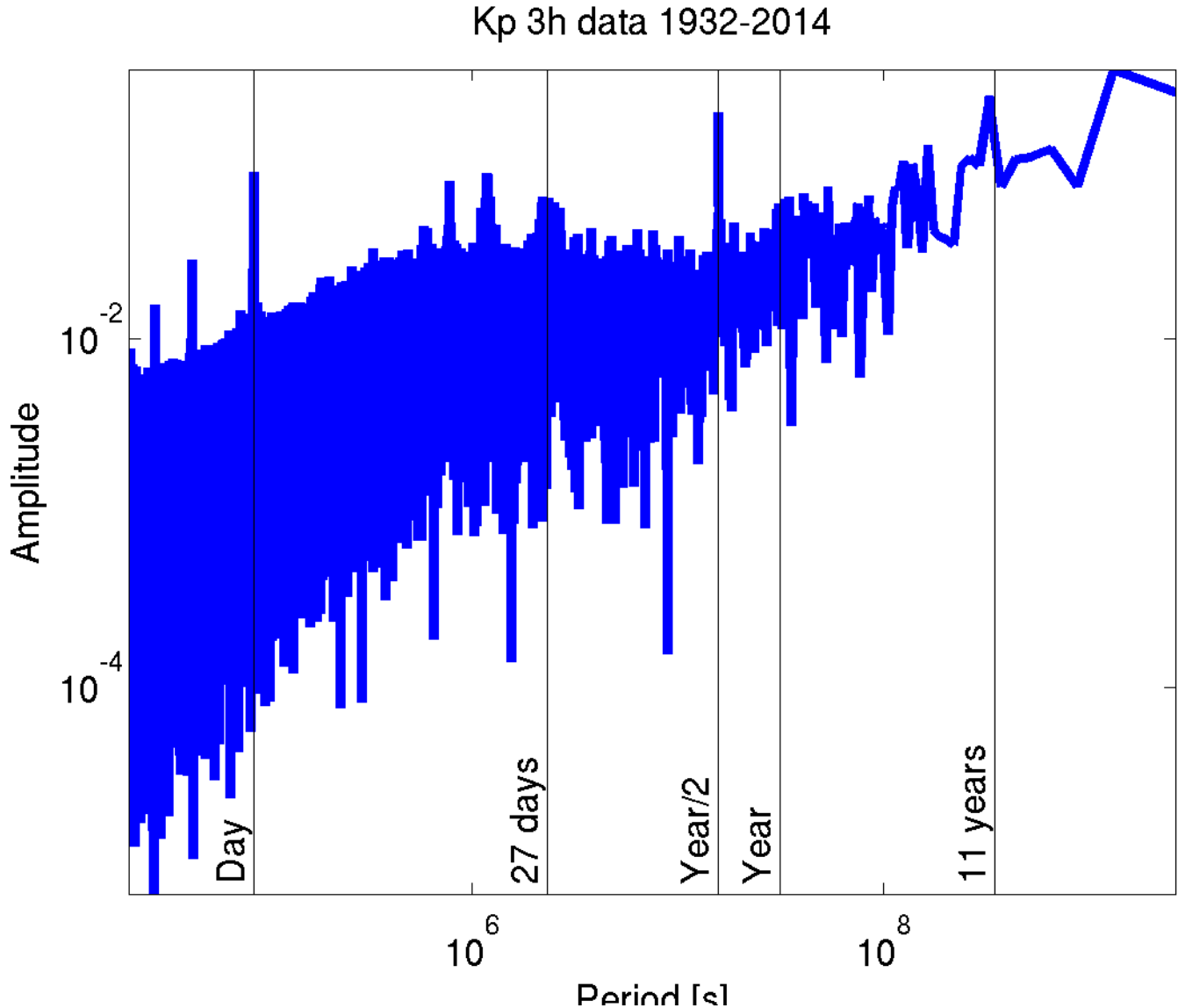


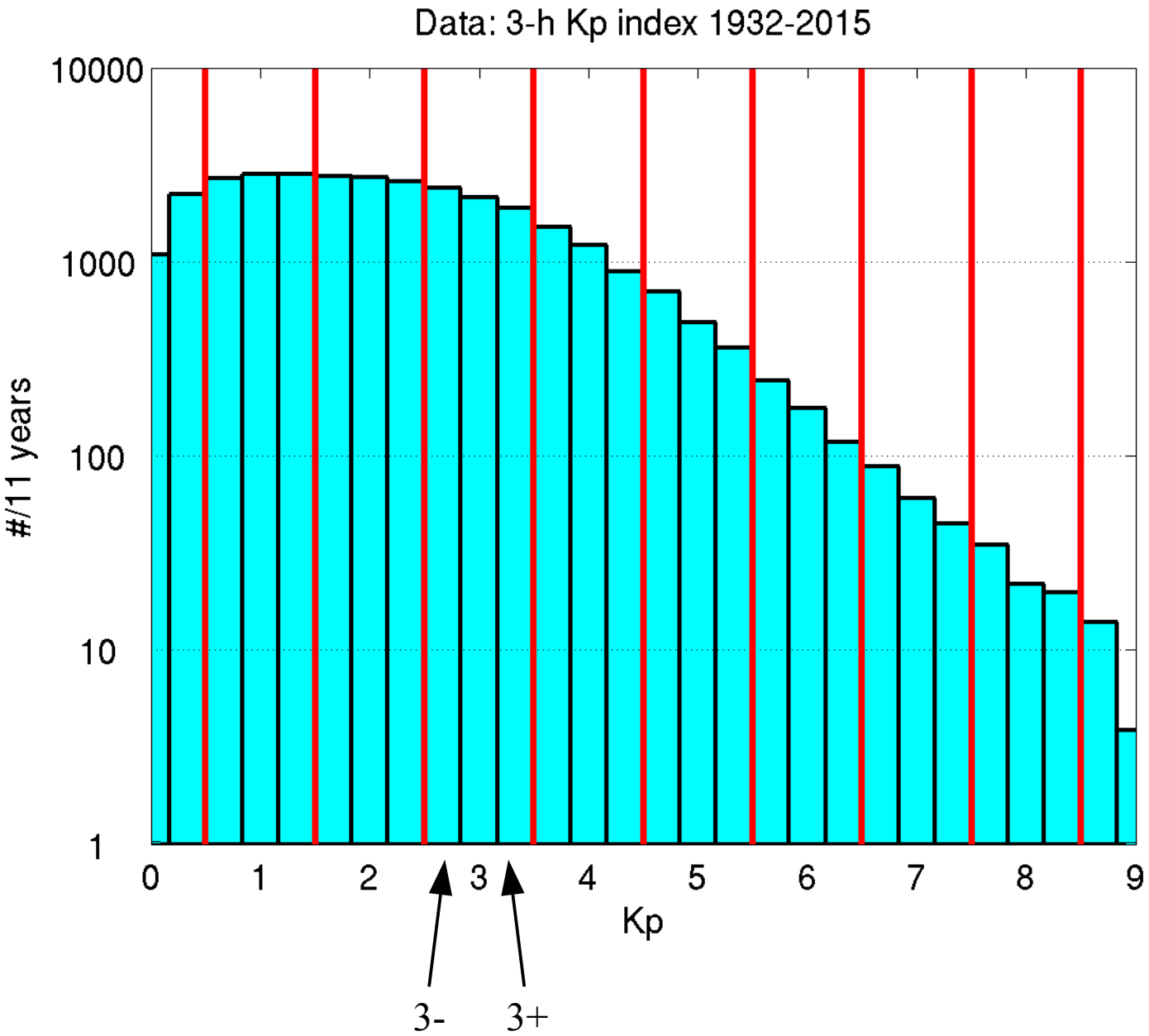
Real-time Kp index:
http://www.gfz-potsdam.de



The amplitude of the sunspot maximum can be predicted from the level of geomagnetic activity during the previous minimum.


16/17
17/18
18/19
19/20
20/21
21/22
22/23
23/24
Kp
dSSN/dt
0
1
2
3
4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
1940
1950
1960
1970
1980
1990
2000
2010

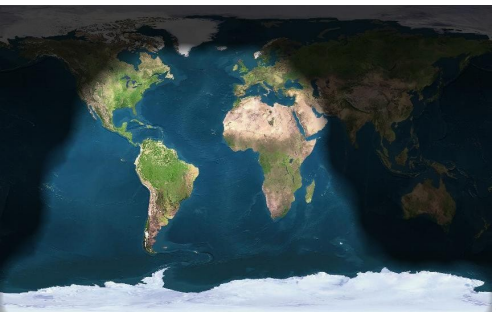

Kp 3h data 1932-2014
Amplitude
10^-2
10^-4
Day
27 days
Year/2
Year
11 years
10^6
10^8
Period [s]

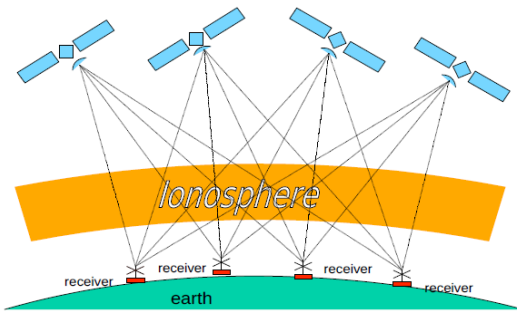

Data: 3-h Kp index 1932-2015
10000
1000
100
10
1
#/11 years
0
1
2
3
4
5
6
7
8
9
Kp
3-
3+

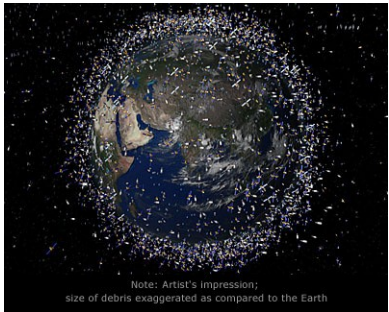
Solar storms

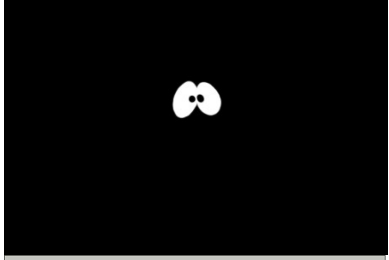
Phases of a solar storm

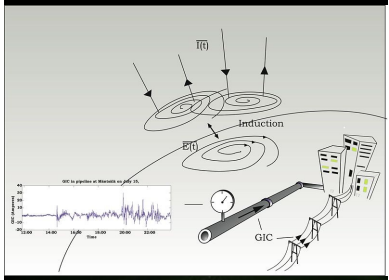
- A storm begins with a developing sunspot group (active region).
- The active region produces one or more flares that can be detected at the Earth 8 min later at radio, visible, and X-ray wavelengths → radio blackouts.
- High-energy (relativistic) particles can be detected a few minutes later both at satellites and on the ground. The particles continue to arrive for hours or even days, if there are new eruptions → solar radiation storm.
- A CME reaches the Earth in about 15-72 hours → geomagnetic storm.





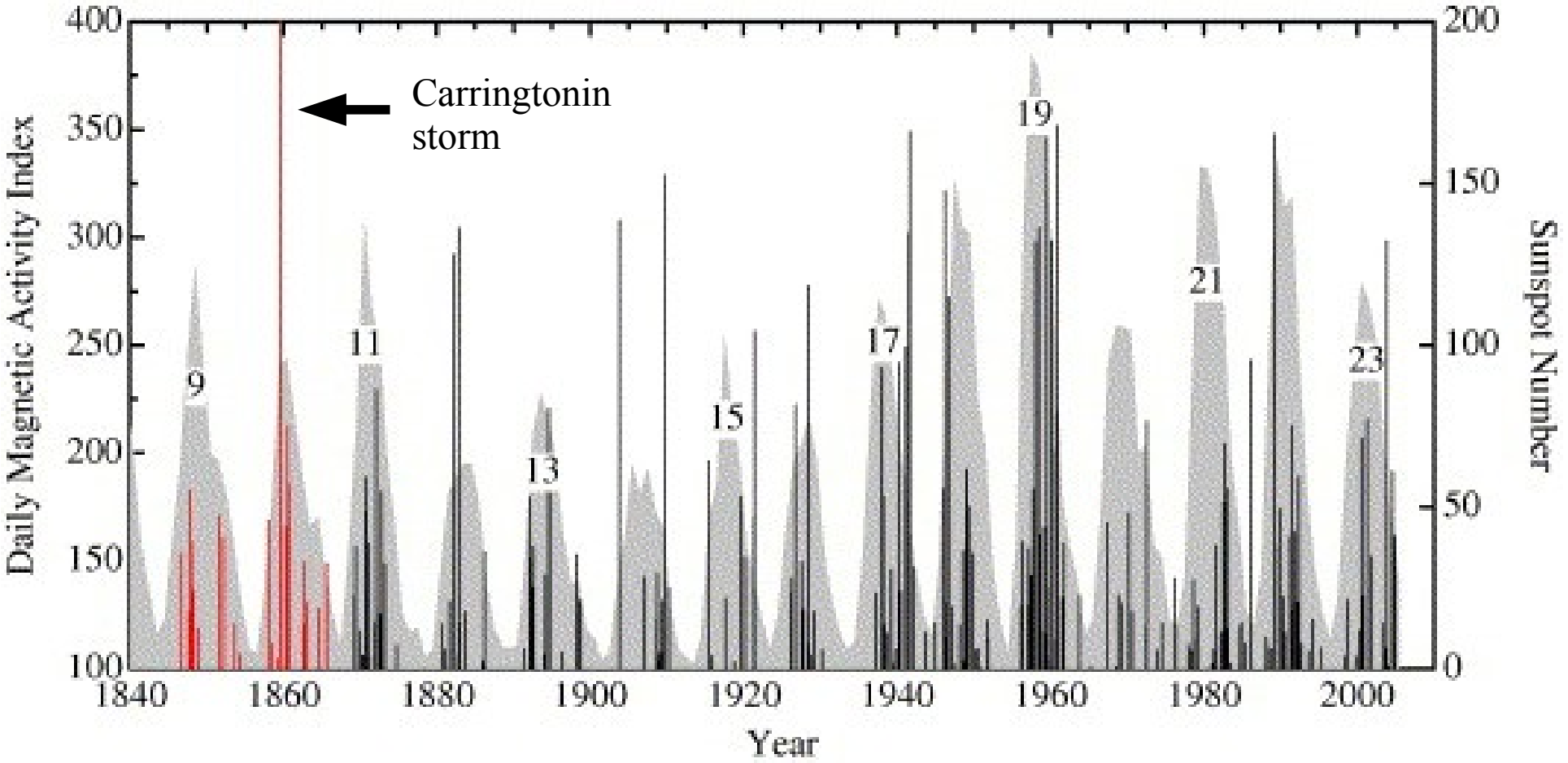






Examples of strong solar storms

- 2-3 Sep 1859 (Carrington storm)
  - The strongest recorded geomagnetic storm caused by an exceptionally fast CME.
  - Auroras were seen over the Caribbean.
  - Telegraph operators got shocked and there were fires. Some systems continued to send and receive messages despite having been disconnected from their power supply.
- 13 Mar 1989
  - Quebec, Canada: 6 million people hours without electricity.
  - New Jersey, USA: a high-voltage transformer was destroyed (figure).
- 19 Oct – 7 Nov 2003 (Halloween storms)
  - Malmö, Sweden: 50 000 people without electricity for an hour.



Geomagnetically stormiest days (aa>100)

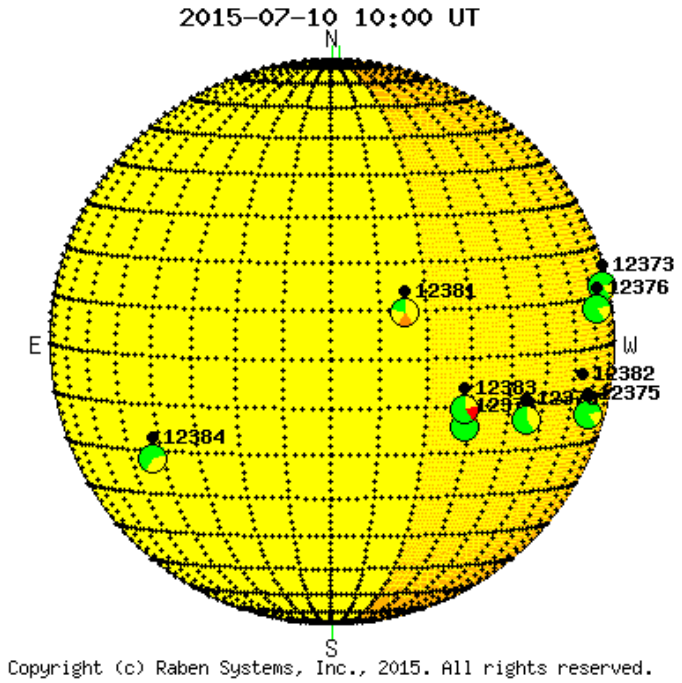
The global aa index (values 0...400) is derived from the measurements of two geomagnetic observatories, one in England and one in Australia. It is the longest continuous record of geomagnetic disturbances.

- The number of storms occurring during a solar cycle appears to be proportional to the maximum sunspot number.
  - The highest number of storms during cycle 19 (the highest detected sunspot number).
- Exceptionally strong storms can still occur even if the maximum sunspot number is small.
  - E.g., the 1903 and 1909 storms during cycle 14 (the smallest maximum sunspot number of the 20th century).
- Cycle 10, during which the Carrington storm occurred, was not exceptional in terms of geomagnetic activity or maximum sunspot number.
- Carrington-class storms are estimated to occur once in 100 years.
- The Sun probably produces several Carrington-class CMEs in 100 years, but most of them either do not hit Earth or their magnetic field points northward.

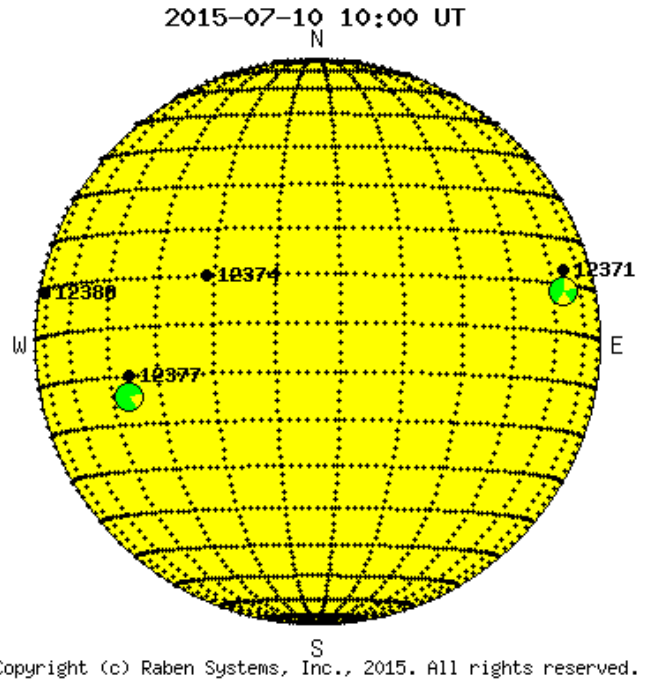
Real-time geomagnetic activity (examples)

Solar map of active regions

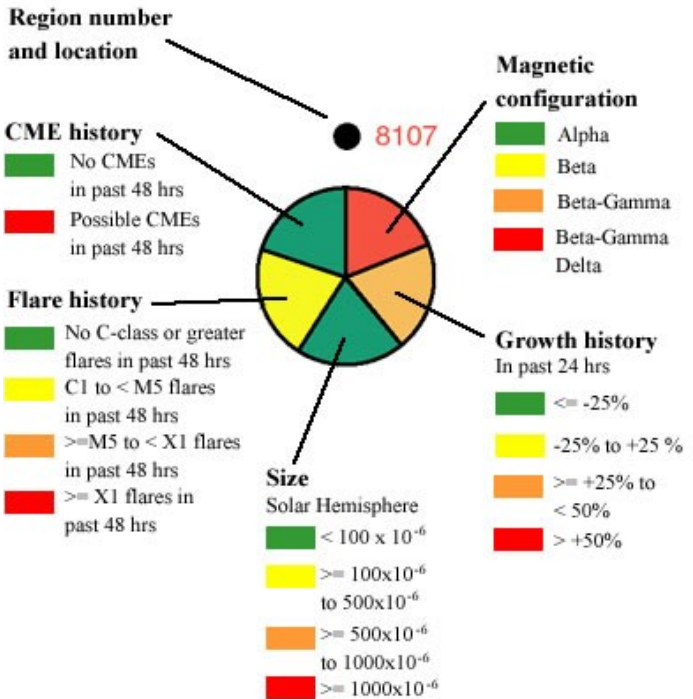
Earth Side View



Far Side View

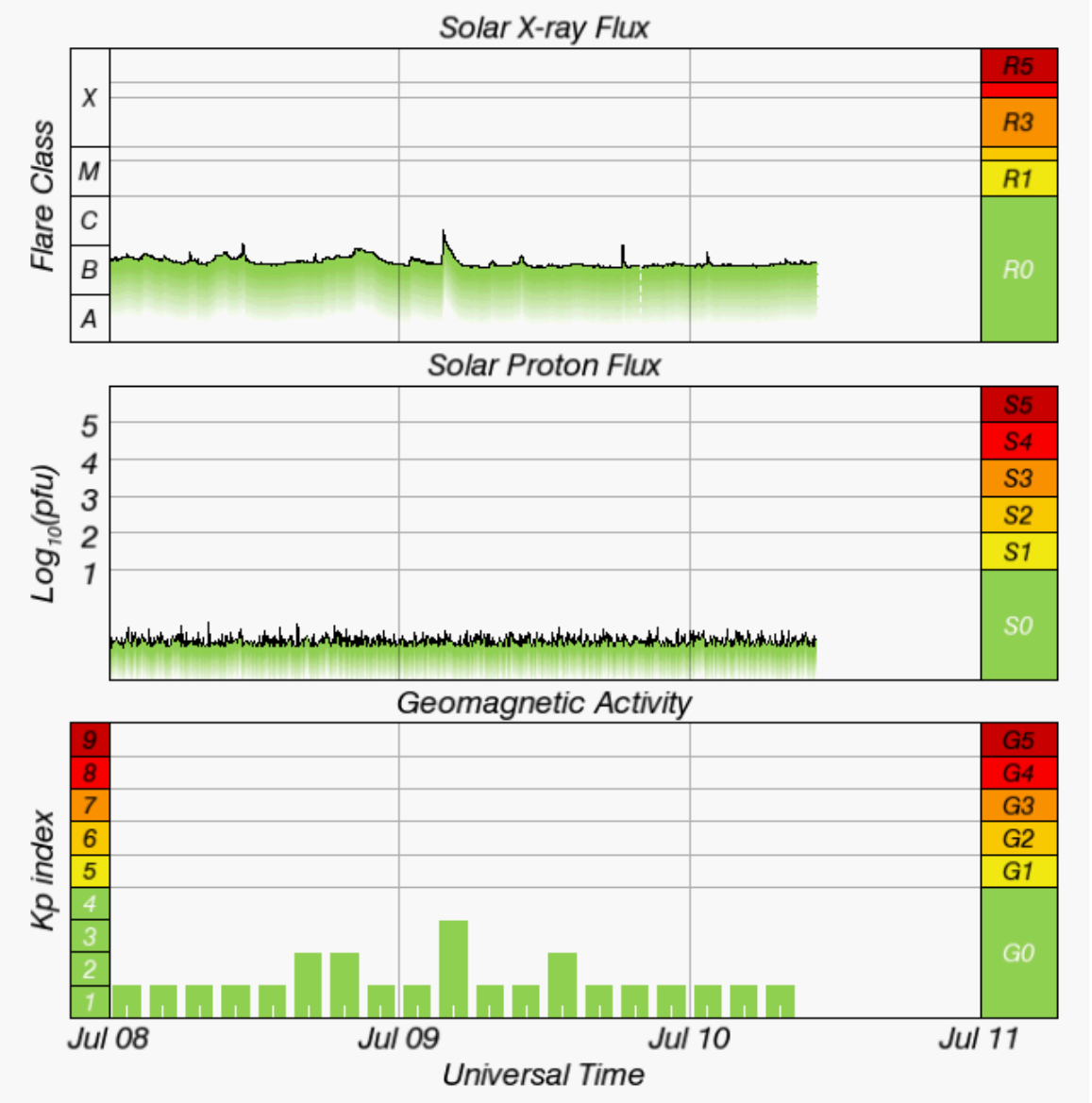


Any active regions that could produce CMEs that might arrive at the Earth within the next few days?



https://www.raben.com/maps/

Space weather summary

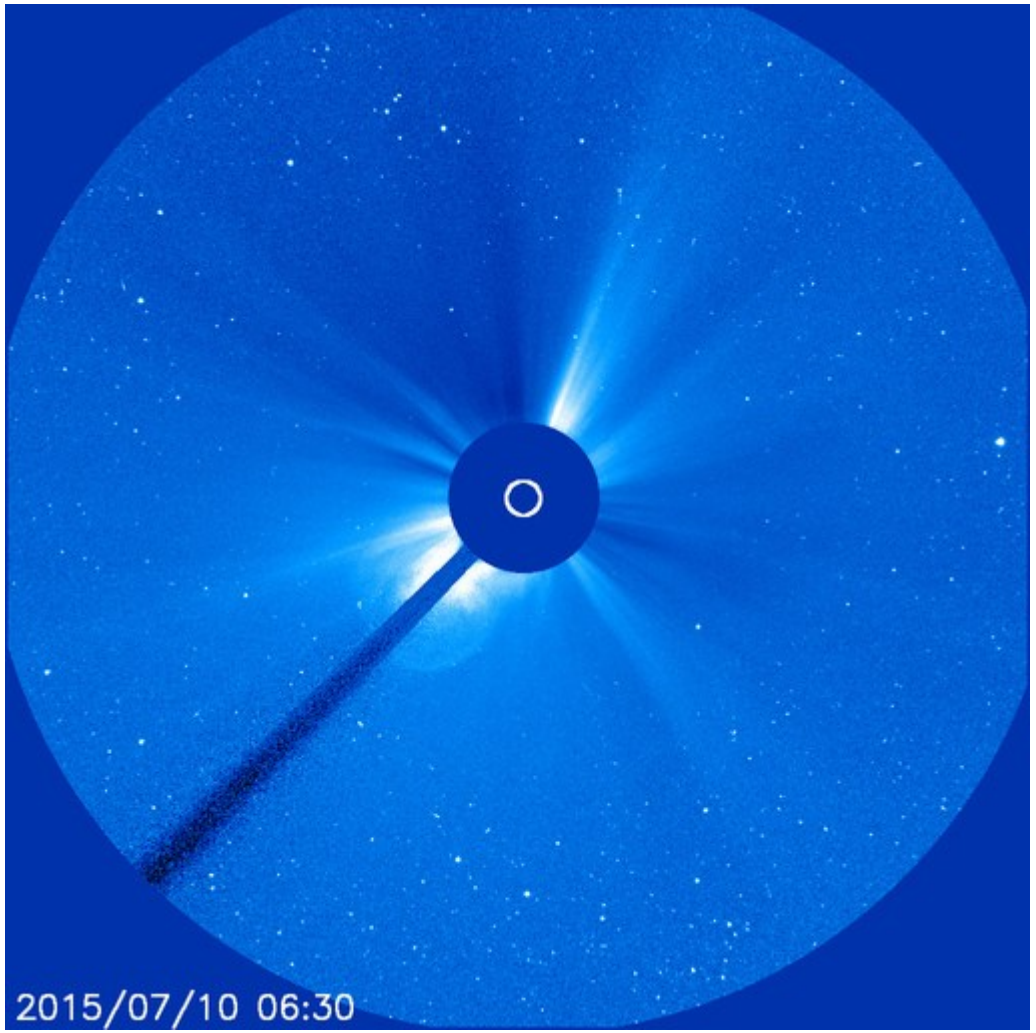


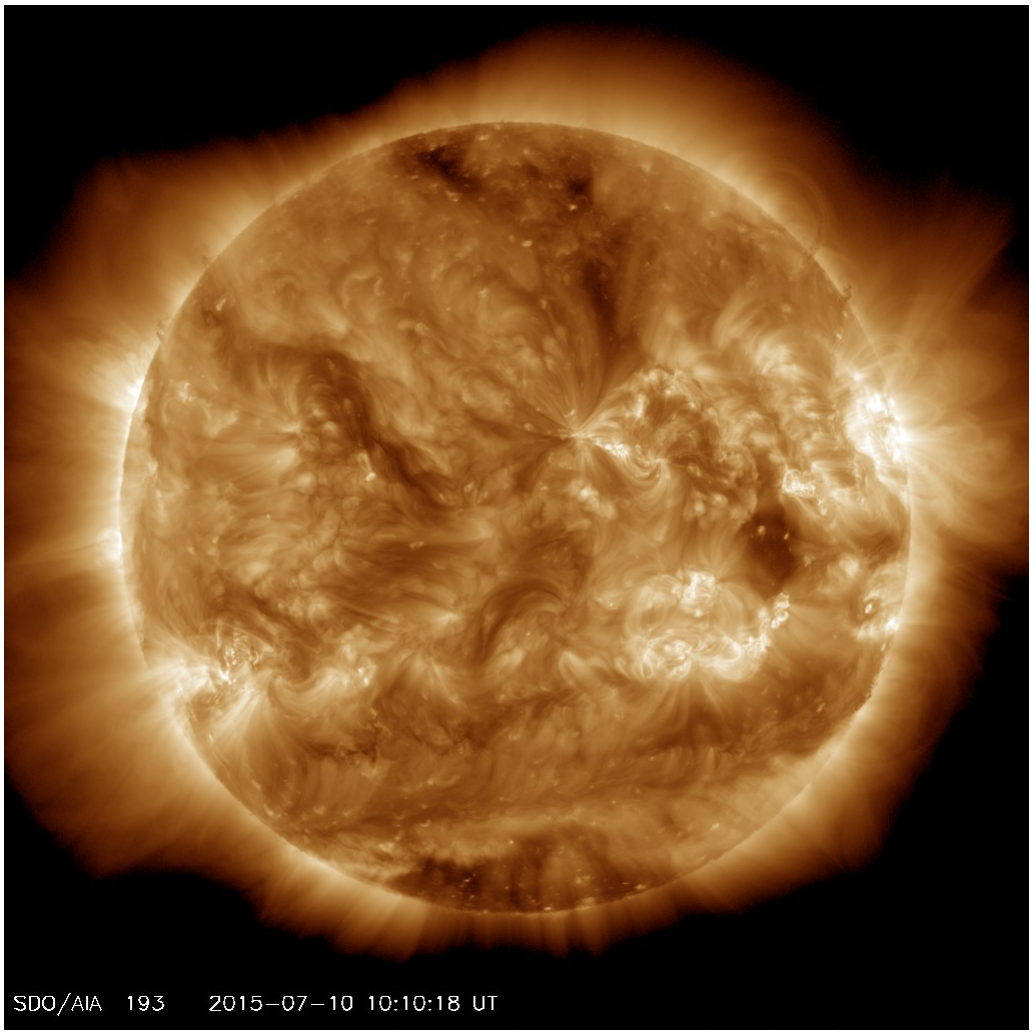
Any flares observed?

Any geomagnetic storms going on?

http://www.swpc.noaa.gov/communities/space-weather-enthusiasts

Solar corona



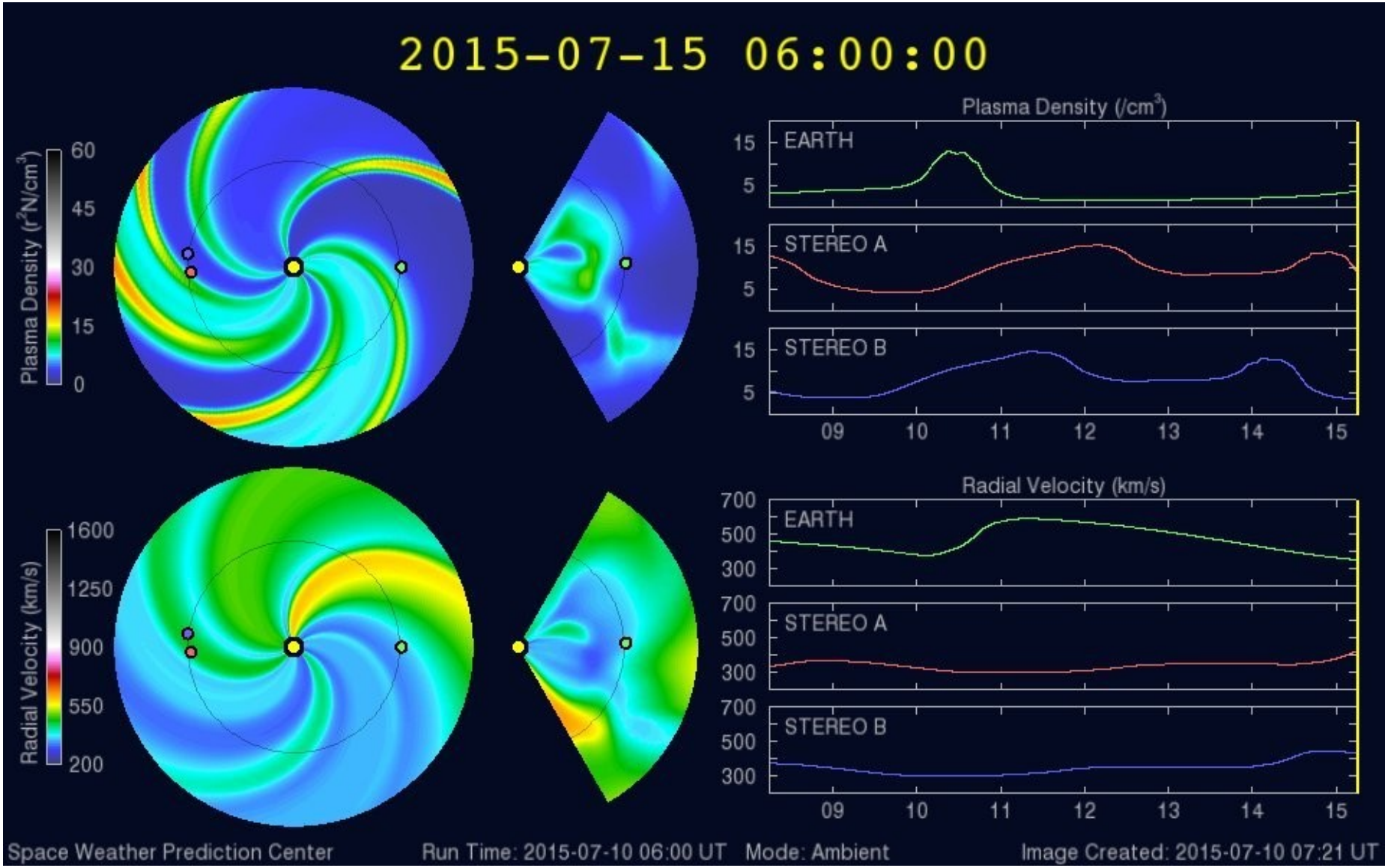


Any CMEs heading toward the Earth?

Any coronal holes from which high-speed solar wind could head toward the Earth?

http://www.swpc.noaa.gov/communities/space-weather-enthusiasts
http://sdo.gsfc.nasa.gov/data/

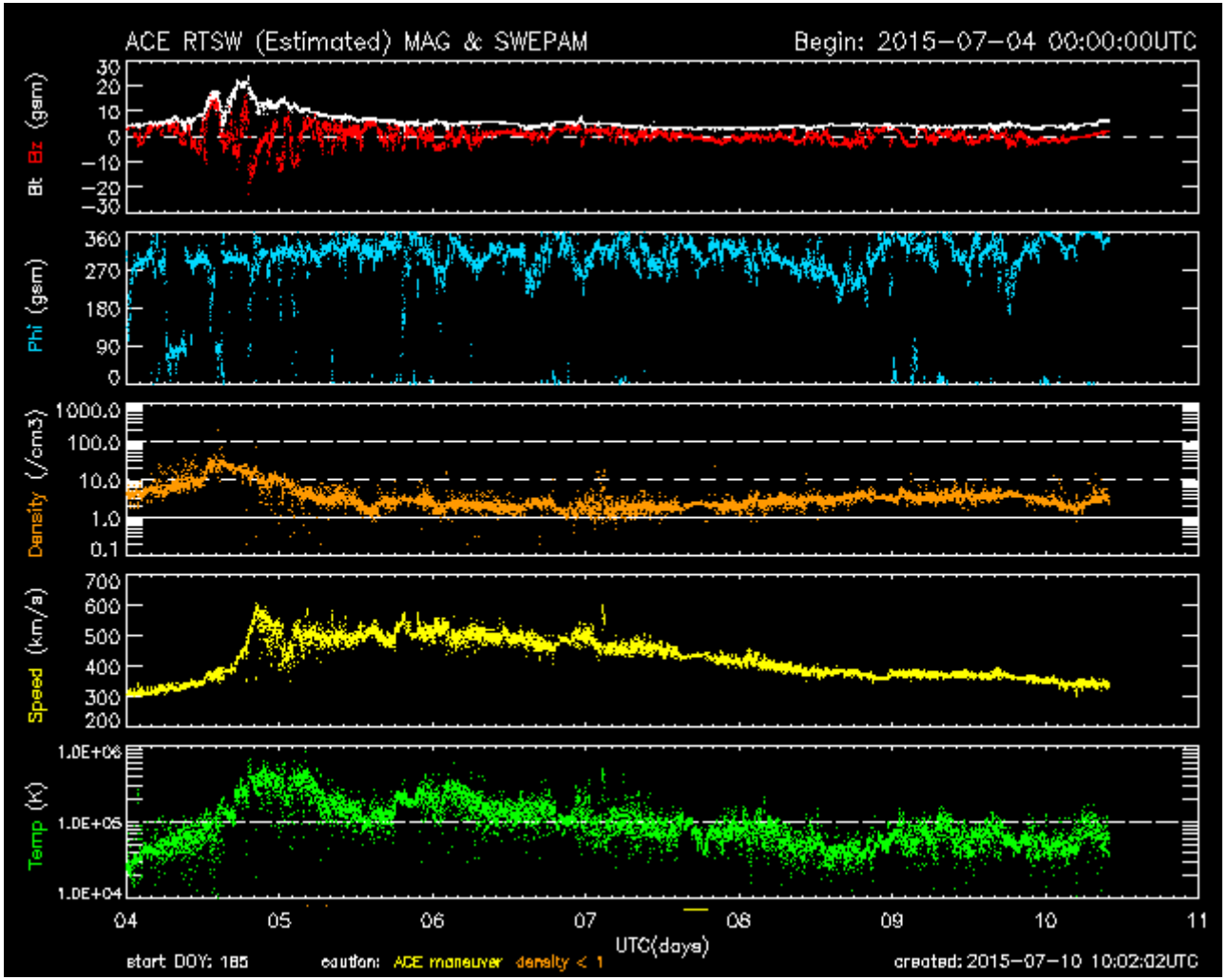
Solar wind prediction



Any high-speed solar wind streams predicted to arrive at the Earth?

http://www.swpc.noaa.gov/communities/space-weather-enthusiasts

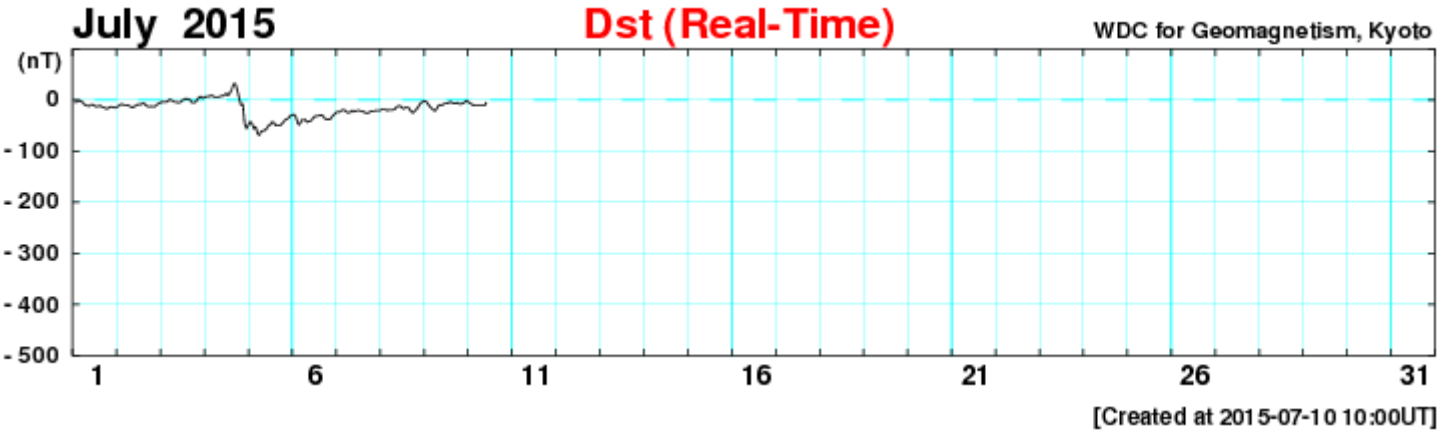
Solar wind measurement



Any CMEs or high-speed solar wind observed to approach the Earth within the next hour?

http://www.swpc.noaa.gov/products/ace-real-time-solar-wind

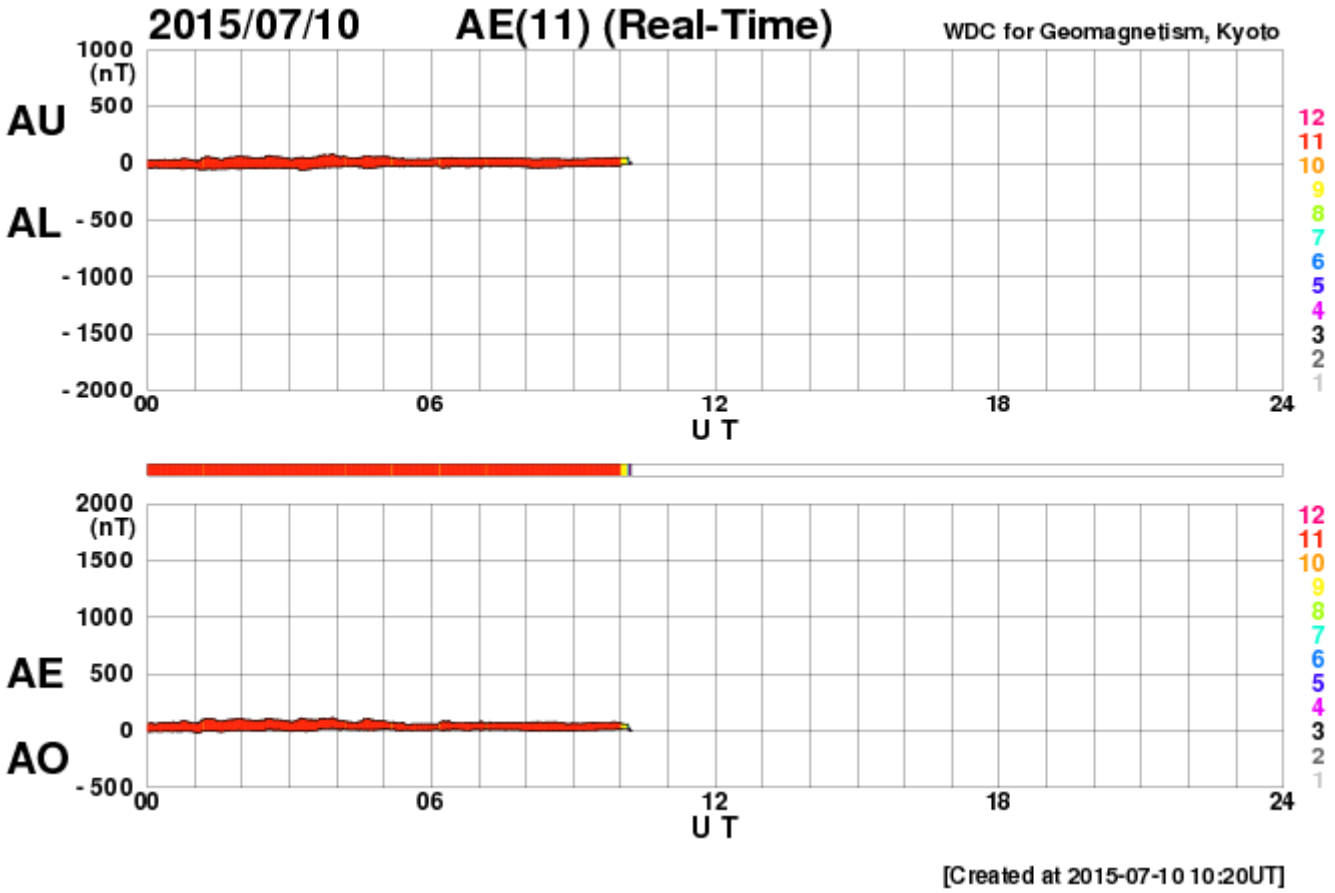
Dst index



Any geomagnetic storms going on?

http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/presentmonth/index.html

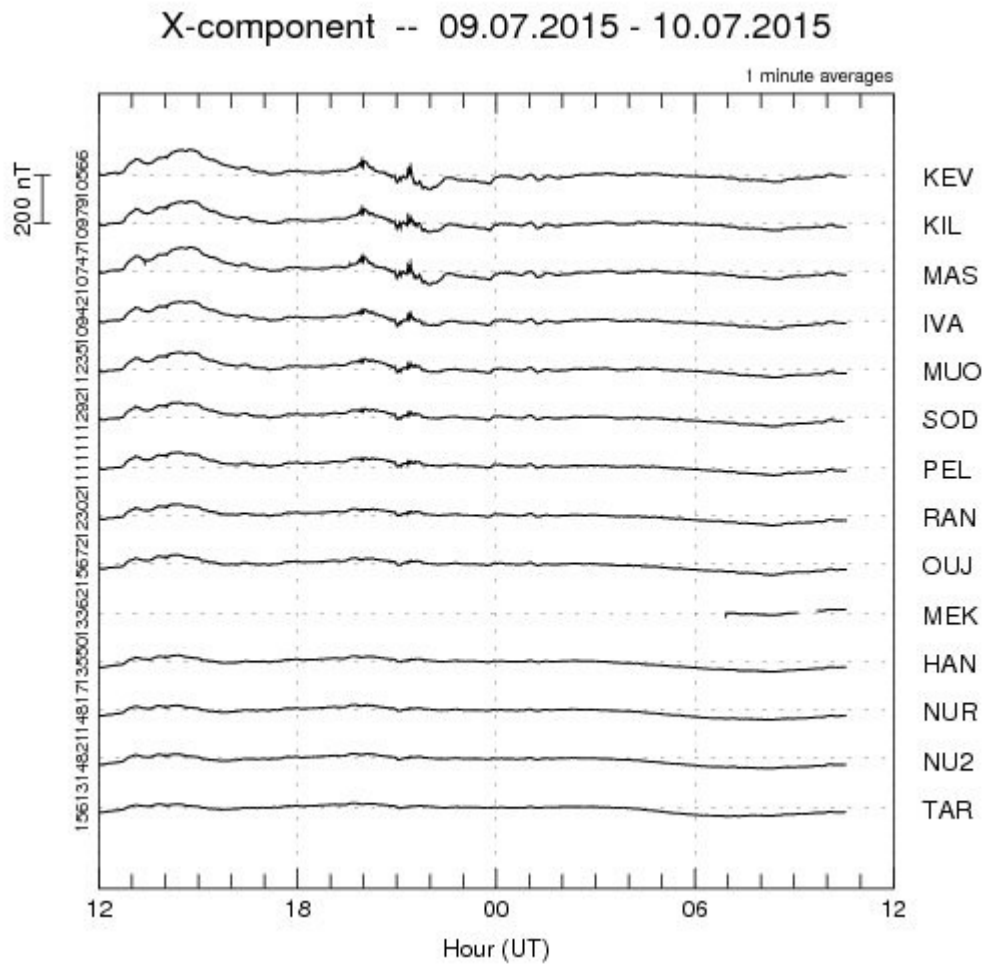
AE indices



Any substorms going on?

http://wdc.kugi.kyoto-u.ac.jp/ae_realtime/presentmonth/index.html

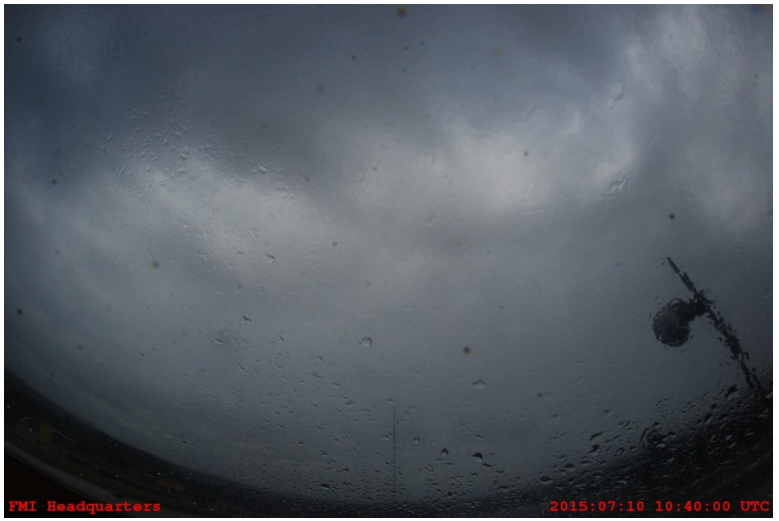
Local geomagnetic condition in Finland

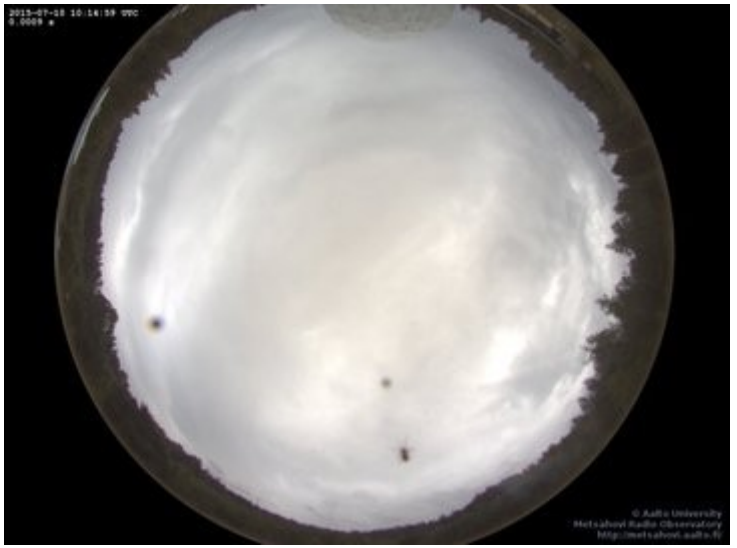


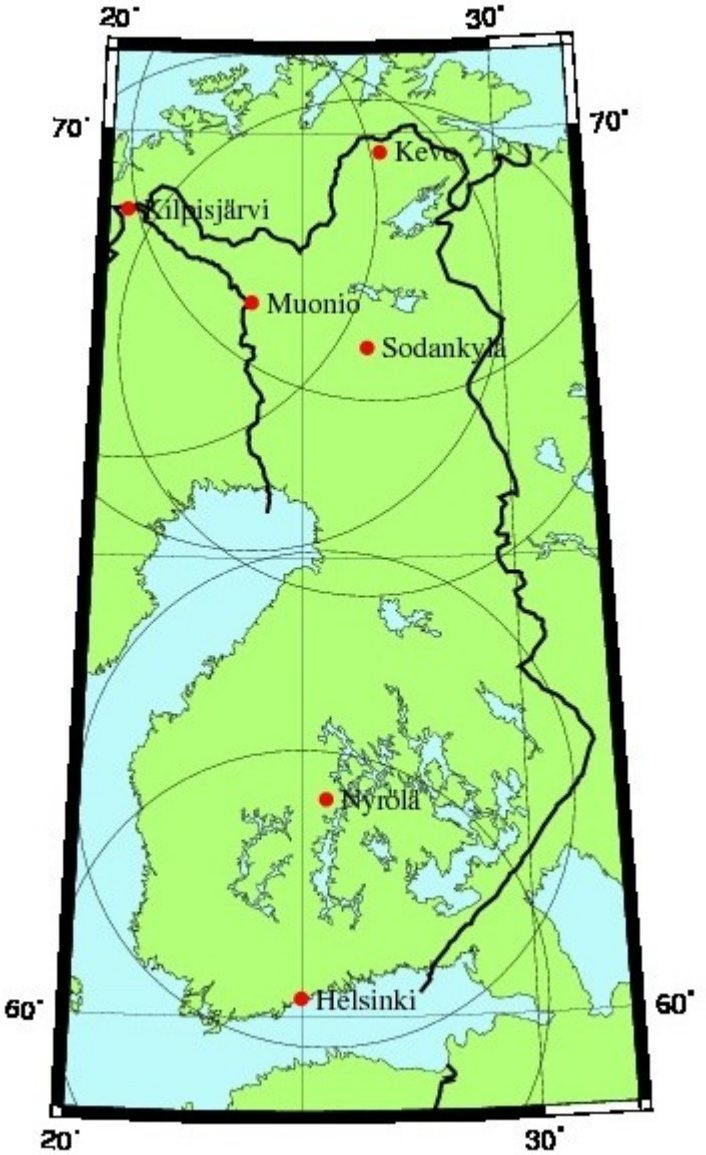
Any geomagnetic disturbances going on? Any possibility to see auroras?

http://www.space.fmi.fi/image/beta/?page=real_time

Monitoring of auroras in Finland



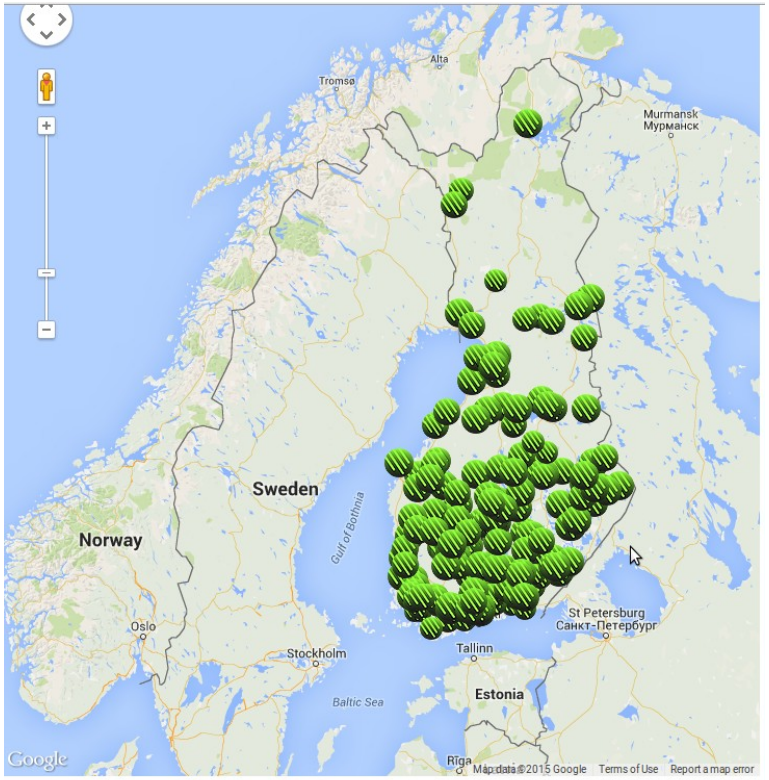


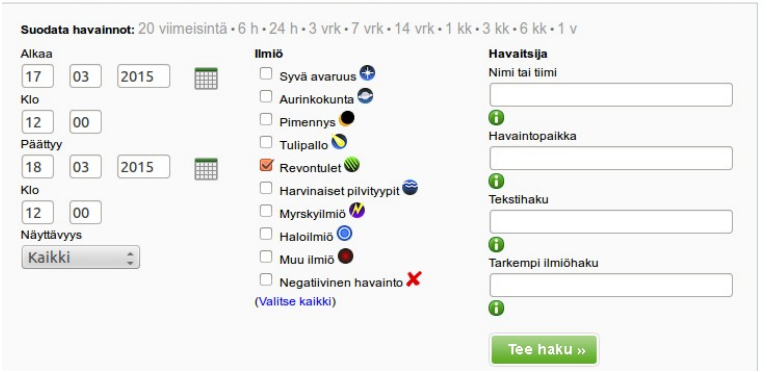


Should I go outside now to look at auroras?

http://aurora.fmi.fi/public_service/

Enthusiast auroral observations

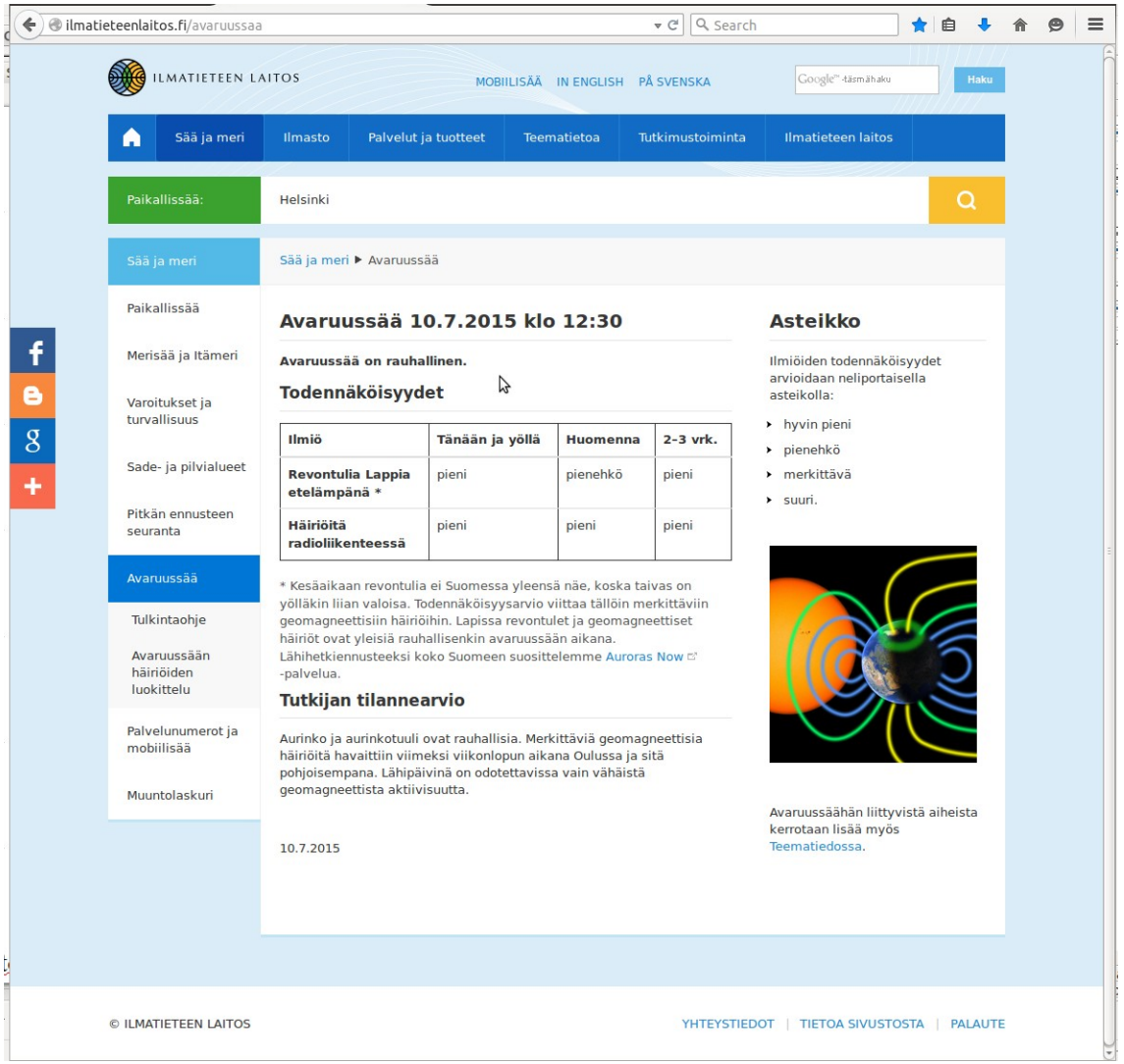




Did anyone see auroras in Helsinki last night?

http://www.taivaanvahti.fi/

Space weather report for Finland (in Finnish)



http://ilmatieteenlaitos.fi/avaruussaa