It is a good morning exercise for a research scientist to discard a pet hypothesis every day before breakfast. It keeps him young.

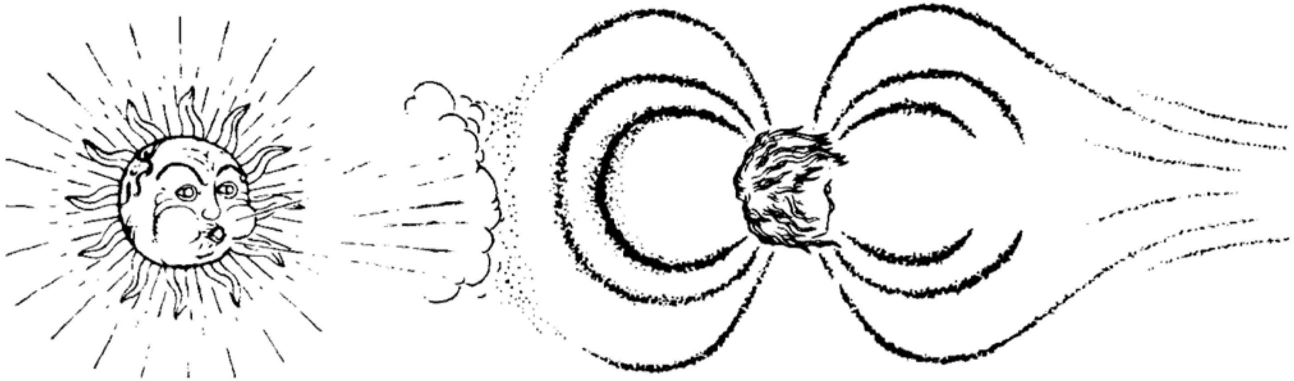
K. Lorenz, *The So-called Evil*

Solar terrestrial relations

- Overview:
  - Solar activity, climate and culture,
  - Electromagnetic radiation and climate,
  - Energetic particles and ozone,
  - Protective shield magnetosphere,
  - Blocking patterns.

- Classical aspects: geomagnetic disturbances, aurora (Chap. 8)

- Pre-requisites:
  - Solar output and variation with the solar cycle.



Continuous Emission:

Electromagnetic Radiation	→	Solar Constant	→	Climate, Structure of the Atmosphere
Solar Wind and Solar Magnetic Field	→	Structure of the Interplanetary Medium	→	Magnetosphere, Indirectly also Upper Atmosphere

Solar-Cycle-Dependent Emission:

Electromagnetic Radiation	→		→	Upper Atmosphere
Coronal Mass Ejections	→	Magnetic Clouds and Interplanetary Shocks	→	Geomagnetic Activity, Upper Polar Atmosphere
Energetic Particles	→		→	Upper Polar Atmosphere

Climate and history

(12) Sumerian **Maximum** 2700 BC, first advanced civilization

(11) Pyramid **Maximum** 2300-2050 BC

(10) Stonehenge **Maximum** 1850-1750 BC

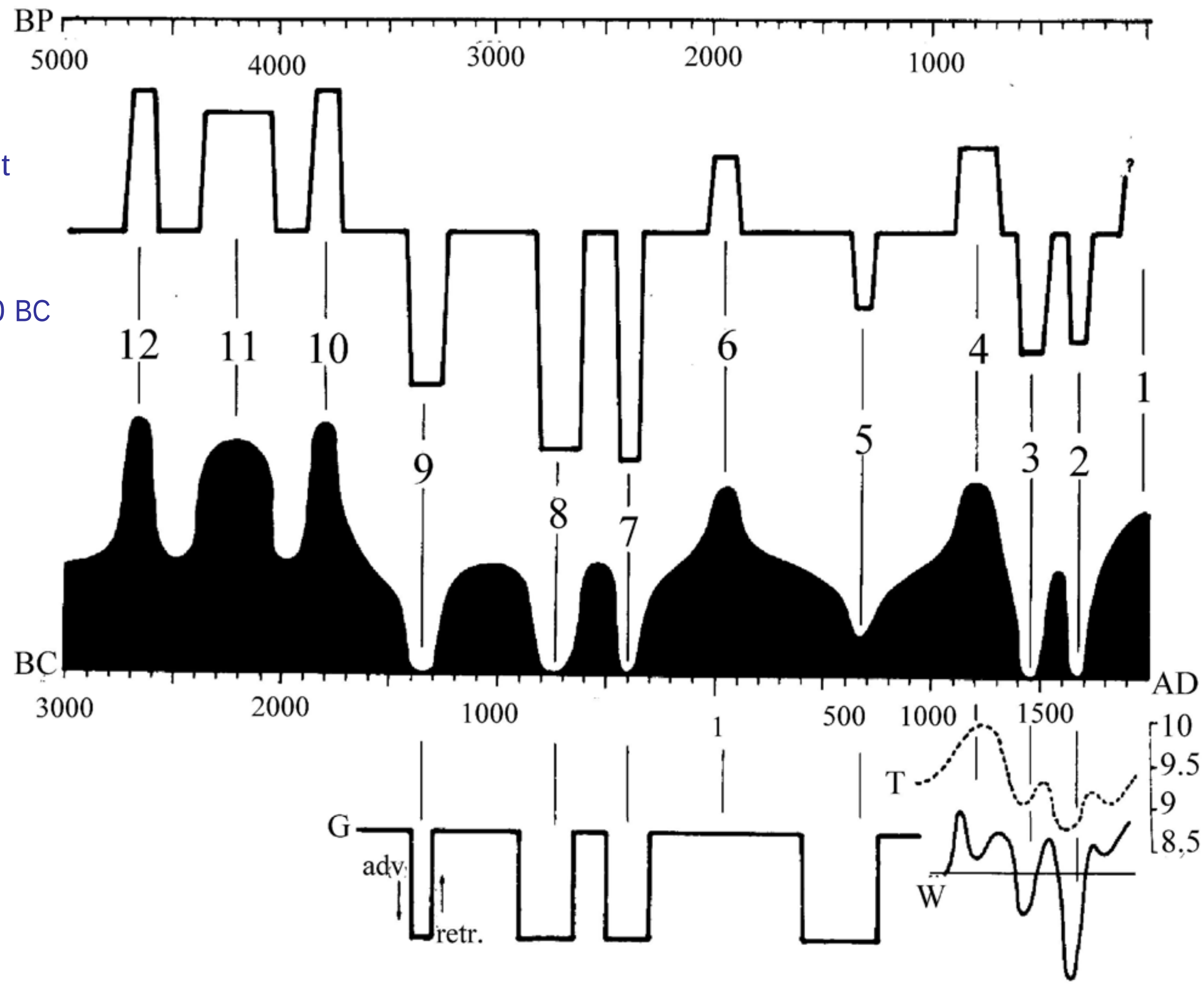
(6) Roman **Maximum**

(5) Medieval **Pessimum**, migrations

(4) Medieval **Optimum**, Vikings in Greenland,

(3) Maunder **Minimum**, Little Ice Age

(2) Spörer **Minimum**, Little Ice Age



Eddy, 1976, in Physics of solar planetary environments, American Geophys. Union

Parameter climate system

Climate is what you expect, weather is what you get. (Pollack, 2003)

- Input:
  - Incident electromagnetic radiation (solar constant),
  - Solar wind,
  - Energetic particles.

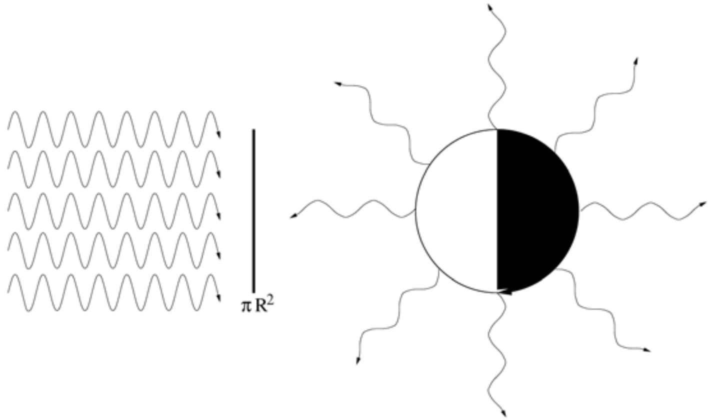
- Output:
  - Outgoing long-wave radiation,
  - Hydrogen escaping from the exosphere (geocorona).

- Balance modified by:
  - Albedo,
  - Natural and anthropogenic greenhouse effect, trace gases,
  - Circulation.

Effective temperature of Earth

- Simplest approach: ingoing radiation equals outgoing, no atmosphere:

$$T_{\mathrm{eff}} = \sqrt[4]{\frac{(1-A)\,S_{\odot}}{\sigma}} \approx 253\ K$$



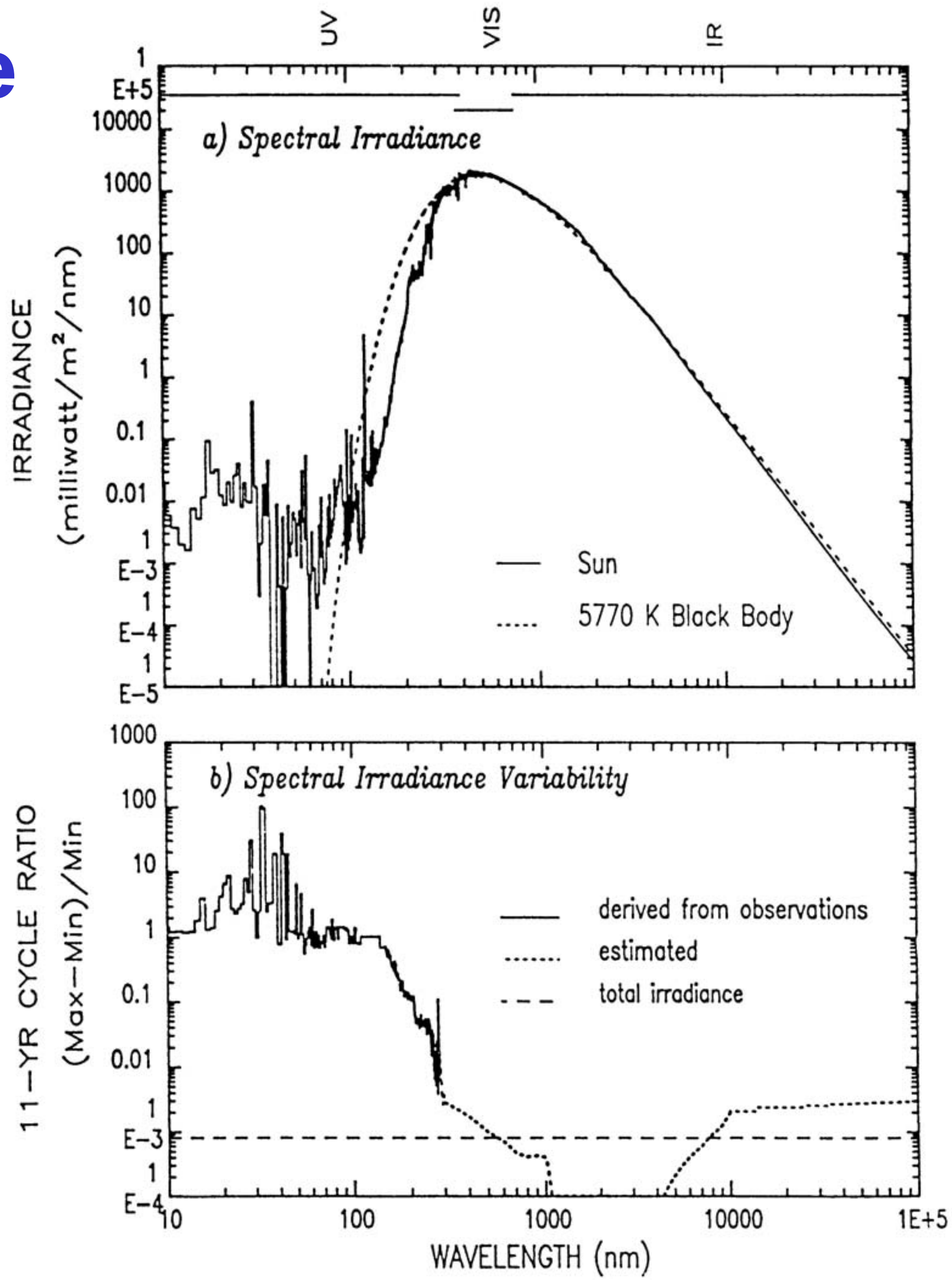
- Variation of the solar constant:

$$\frac{\delta T_{\mathrm{eff}}}{T_{\mathrm{eff}}} = \frac{1}{4}\frac{\delta S_{\odot}}{S_{\odot}}$$

- Observation: variation of solar constant during the solar cycle about 0.08%, corresponds change in temperature by 0.07 K.

Variation of the solar constant

- Spectral variation much more pronounced (up to factor of 10).
- Hard electromagnetic radiation is absorbed in the thermosphere, thus no obvious influence on climate.
- Variation in UV radiation relevant for ozone chemistry about 15%; more ozone expected during solar maximum than during minimum.



Lean, 1992, Rev. Geophys. 29, 505

Energetic particles in the atmosphere

- Primary consequence: ionization of the atmosphere in height ranges otherwise not ionized (10 to 80 km),
- Secondary consequences: chemical reaction, in particular generation of chemically reactive NOx and HOx and destruction of ozone.
- Continuous source with low intensity: galactic cosmic rays (globally),
- Sporadic source with high intensity: solar energetic particles (only above the polar caps).

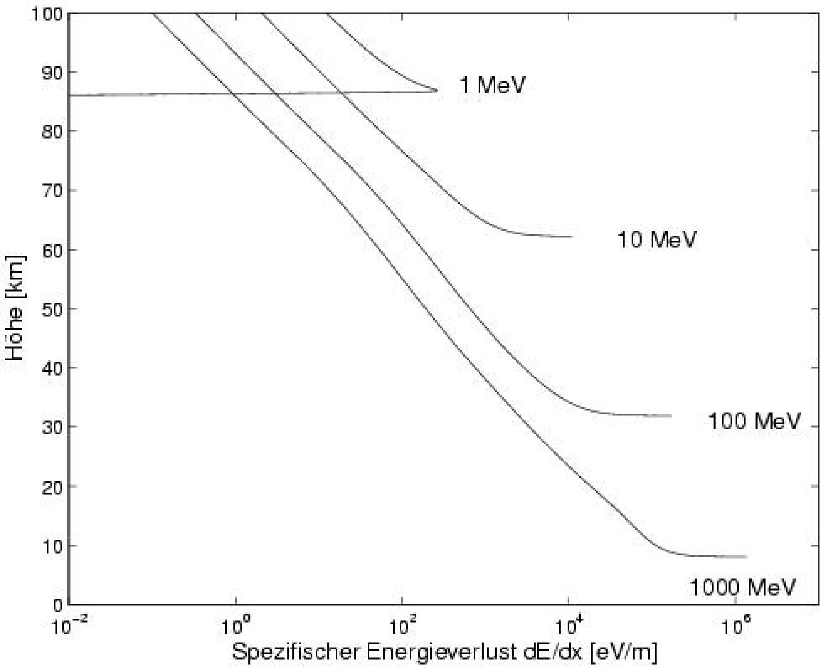
Bethe-Bloch

- Interaction with the atmosphere described by Bethe-Bloch:

$$\frac{\mathrm{d}E}{\mathrm{d}x} = -\frac{e^4}{4\pi\varepsilon_o m_e}\frac{Z^2}{v^2} n_e \left[\ln\frac{2m_e v^2}{\langle E_B \rangle} - \ln(1-\beta^2) - \beta^2\right]$$

or simplified:

$$\frac{\mathrm{d}E}{\mathrm{d}x} \sim \frac{Z}{v^2}$$



Quack,2001

- Consequences:
  - Energy loss maximum for low particle speeds, that is close to the end of the particle track (Bragg peak).
  - Particles with high speeds produce only small ionization density.
  - Energy loss and thus ion pair production can be determined by numerical integration only.

Bethe-Bloch simplified

- Simplification to avoid numerical integration:
  - Ionization rated depends only on flux of incident particles and specific energy loss:

$$q_{\mathrm{e}}(z) = F_{\mathrm{e}} \frac{\mathrm{d}E}{\mathrm{d}x}$$

  - The latter can be approximated as $\frac{\mathrm{d}E_{\mathrm{o}}}{\mathrm{d}z} = \kappa_{\mathrm{e}}\, E_{\mathrm{ion}} \sigma_{\mathrm{n}} n$
  - Combined with the barometric height formula:

$$q_{\mathrm{e}}(z) = \kappa_{\mathrm{e}} F_{\mathrm{e}} E_{\mathrm{ion}} \sigma_{\mathrm{n}} n_{\mathrm{o}} \exp(-z/H)$$

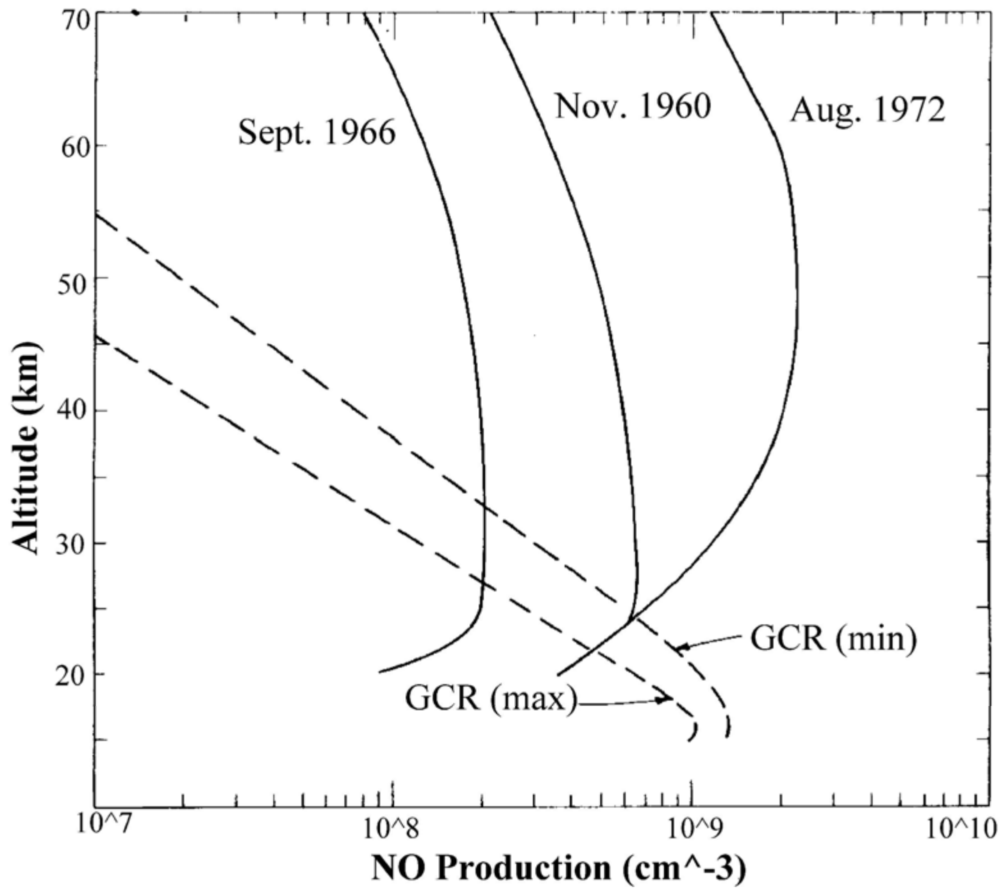
  - On the other hand, the total energy implies

$$E_{\mathrm{o}} = \int_0^E \mathrm{d}E = \int_{\infty}^{x_{\mathrm{s}}} \kappa_{\mathrm{e}} W_{\mathrm{ion}} \sigma_{\mathrm{n}} n_{\mathrm{o}} \exp(-x/H)$$

  - This gives a stopping height: $x_{\mathrm{s}} = H \ln\left(\kappa_{\mathrm{e}} \sigma_{\mathrm{n}} n_{\mathrm{o}} H \frac{E_{\mathrm{ion}}}{E_{\mathrm{o}}}\right)$

NOx-Production

- Conversion factors allow to determine production factors of NOx und HOx from ion pair production rates.
- One individual solar energetic particle event can produce more NOx than the galactic cosmic radiation during an entire solar cycle although the height distribution is different.



Reid, 1986, in Physics of the Sun III, Reidel

Destructive ozone chemistry

- Destruction due to singly ionized O2:

$$O_2^+ \cdot H_2O + H_2O \rightarrow H_3O^+ \cdot OH + O_2$$

- HOx than participates in one of the following reactions:

$$\begin{array}{lcl} H + O_3 & \rightarrow & OH + O_2 \\ OH + O & \rightarrow & H + O_2 \end{array}$$

$$\begin{array}{lcl} OH + O_3 & \rightarrow & HO_2 + O_2 \\ HO_2 + O_3 & \rightarrow & OH + 2\,O_2 \end{array}$$

$$\begin{array}{lcl} OH + O_3 & \rightarrow & HO_2 + O_2 \\ HO_2 + O_3 & \rightarrow & OH + 2\,O_2 \end{array}$$

- Net effect upper chain:

$$O + O_3 \rightarrow 2\,O_2 .$$

- Net effect lower chain:

$$O_3 + O_3 \rightarrow 3\,O_2$$

- Destruction due to singly ionized N2:
  - dissociative recombination gives two neutral N atoms.
  - These react with molecular oxygen to NOx

$$N + O_2 \rightarrow NO + O$$

- NOx contributes to ozone destruction
  - direct reaction with NO

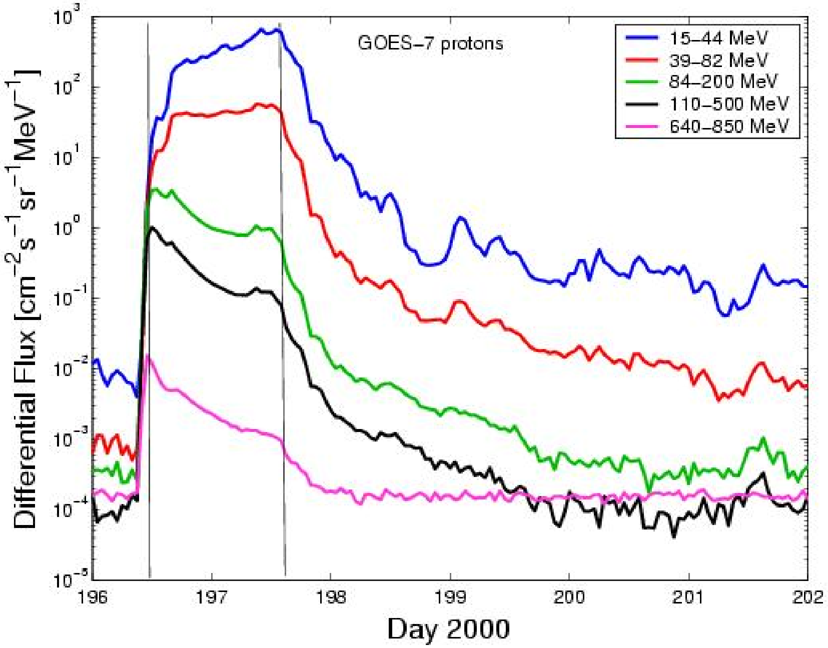
$$NO + O_3 \rightarrow NO_2 + O_2$$

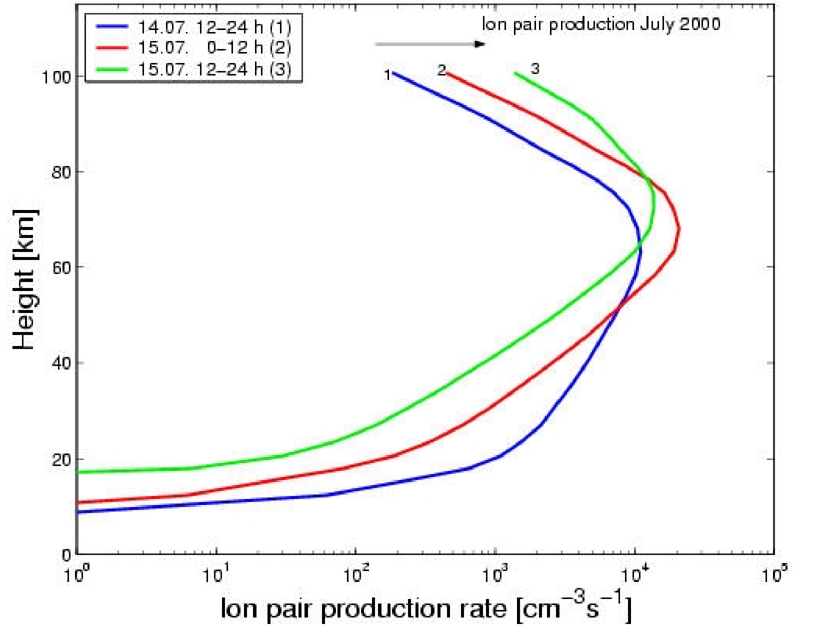
  - Capture of an oxygen atom (middle step of ozone formation)

$$NO_2 + O \rightarrow NO + O_2$$

Bastille Day Event

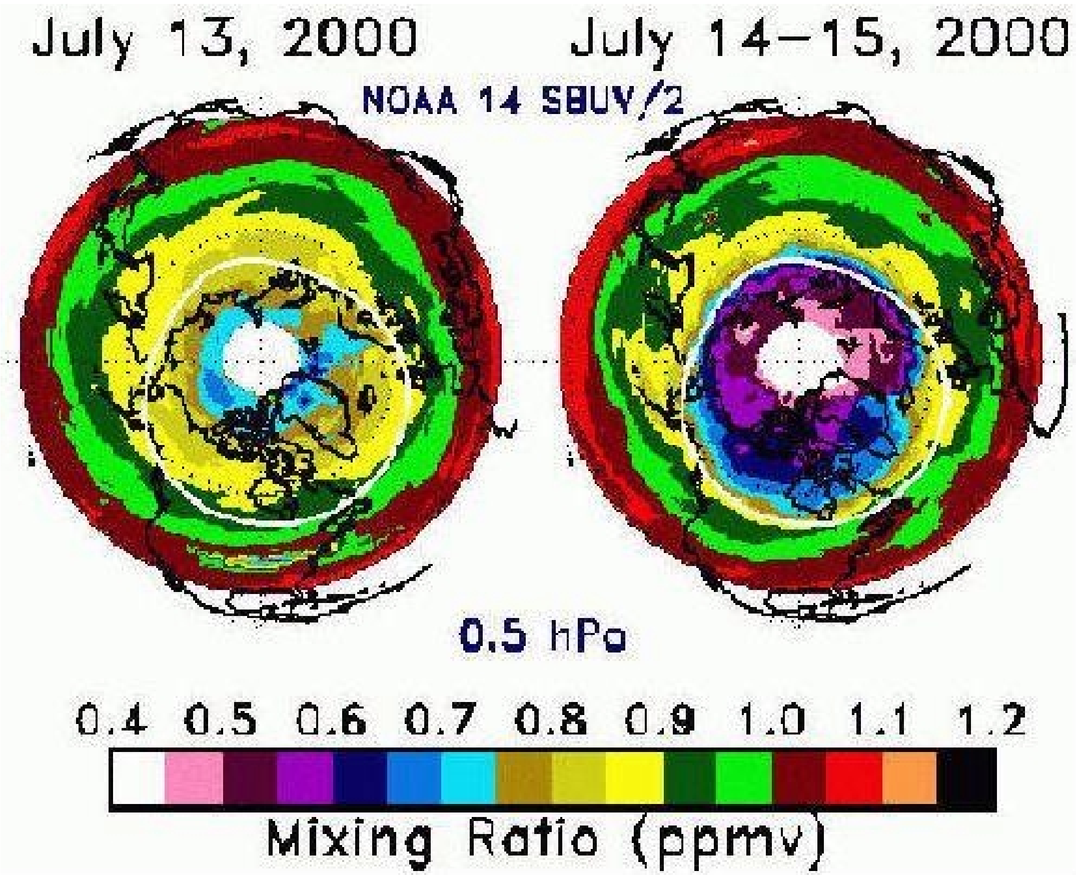
- Ionization down to 10 km.
- Early in the event ionization at lower altitudes.
- In the time course of the event ionization shifts to higher altitudes because the spectrum softens.
- Ion pair production rates up to about 1E4/cm³s





Quack,2001

Bastille-Day Ozone



Jackman et al., 2001, Geophys. Res. Lett. 28, 2883

- Ozone reduction above 50 km by 40% for 2 days.
- Ozone depletion:
  - Decreases with decreasing height,
  - Lasts longer at lower altitudes.
- During the last solar maximum total of three events with comparable effects, October 2003 and January 2005 even larger because longer lasting.

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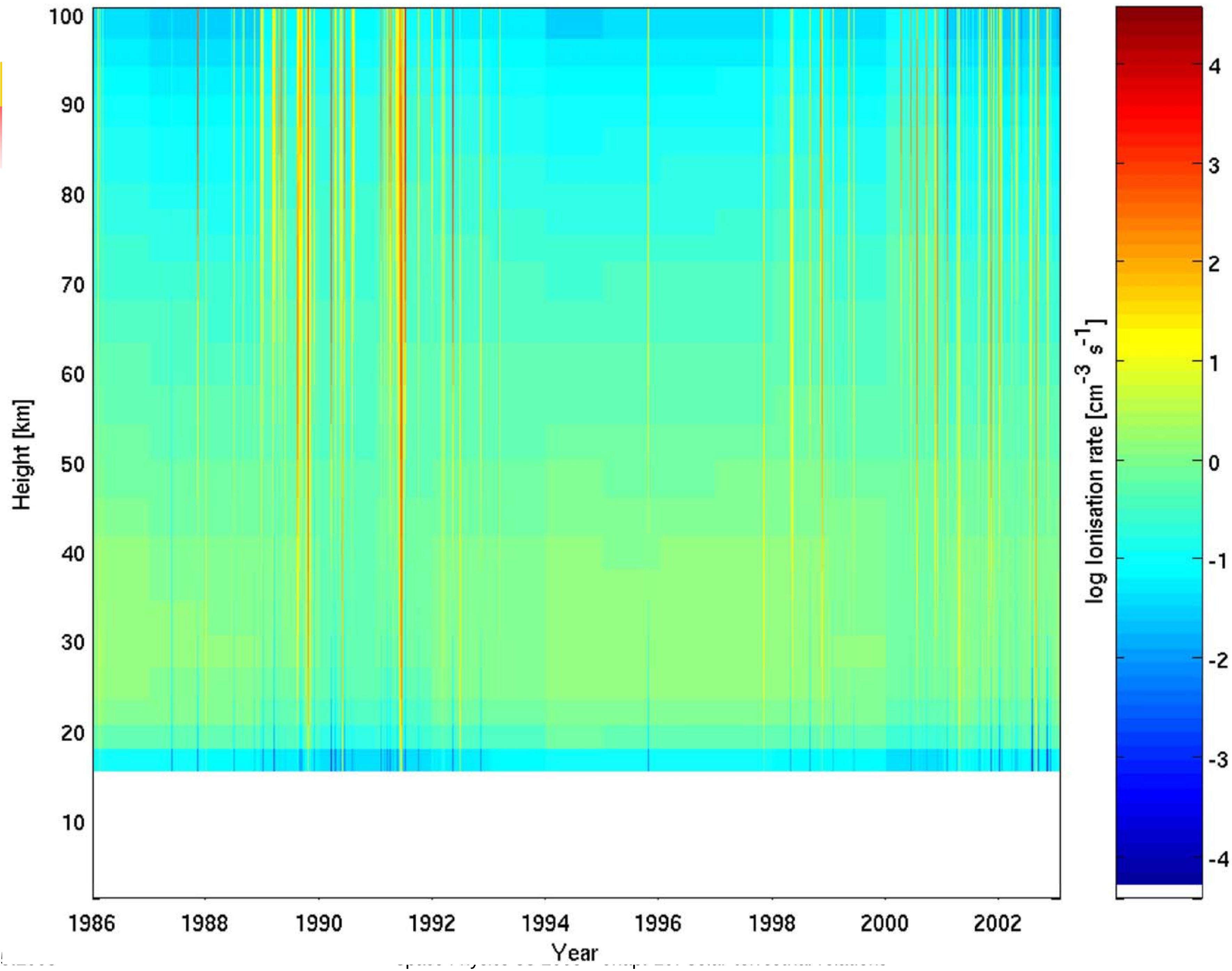
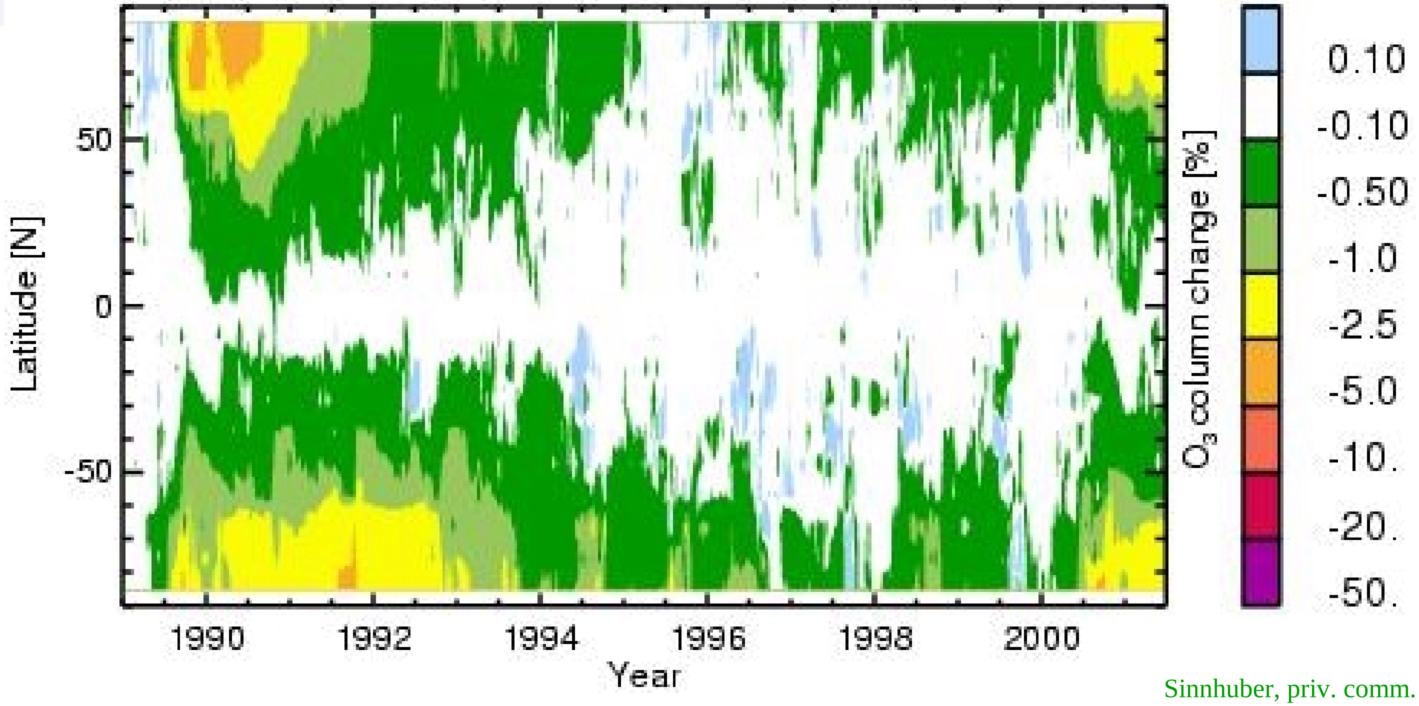

100
90
80
70
60
50
40
30
20
10
Height [km]
1986
1988
1990
1992
1994
1996
1998
2000
2002
Year
4
3
2
1
0
-1
-2
-3
-4
log Ionisation rate [cm^{-3} s^{-1}]

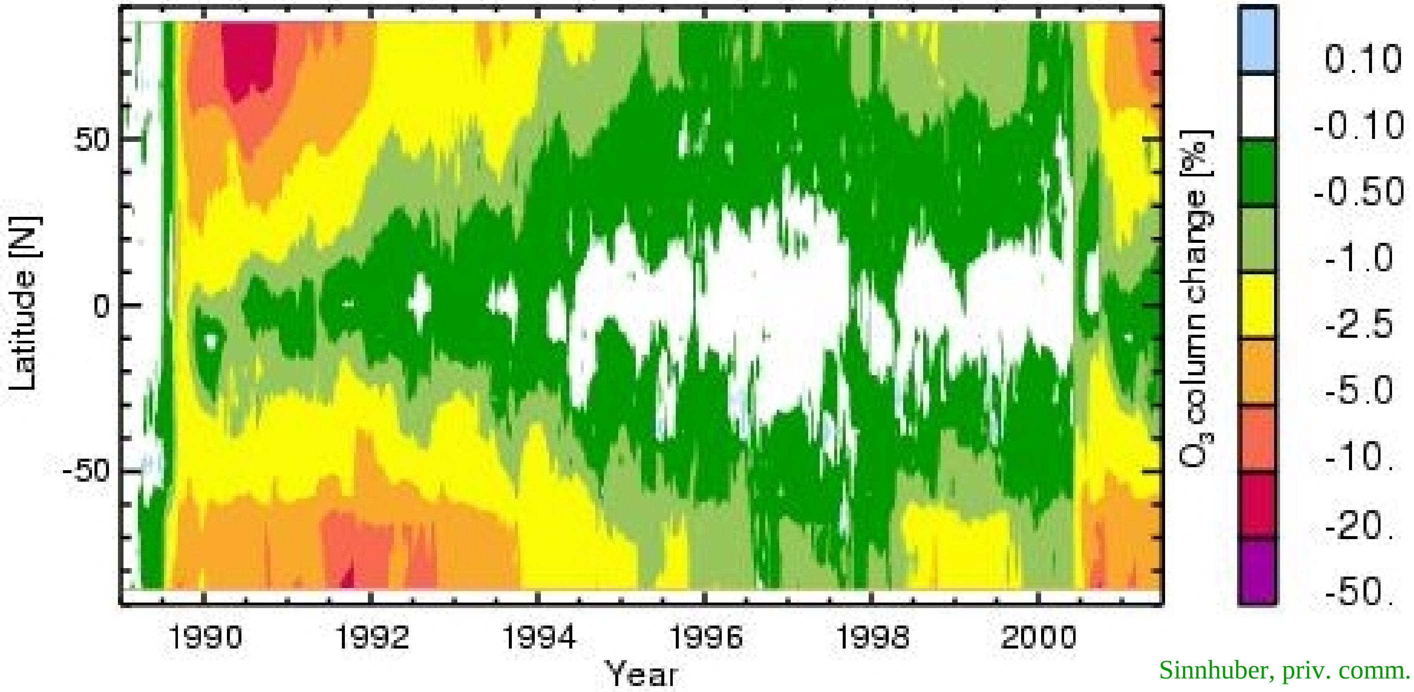
Ozone during the solar cycle



Sinnhuber, priv. comm.

- Ozone depletion more pronounced during solar maximum than minimum,
- Ozone depletion extends down to mid-latitudes (during solar max even to low latitudes) although particles are incident only over the polar cap,
- Ozone depletion during maximum fits observations better than ozone increase expected for solar max on basis of hard electromagnetic radiation (combination of both effects required for a better understanding)

Vanishing magnetic field



Sinnhuber, priv. comm.

- Particles precipitate globally but strongest ozone depletion again at high latitudes (circulation, NOx destruction at low latitudes),
- Asymmetries between northern and southern hemisphere,
- Depletion in polar ozone large enough to influence circulation.

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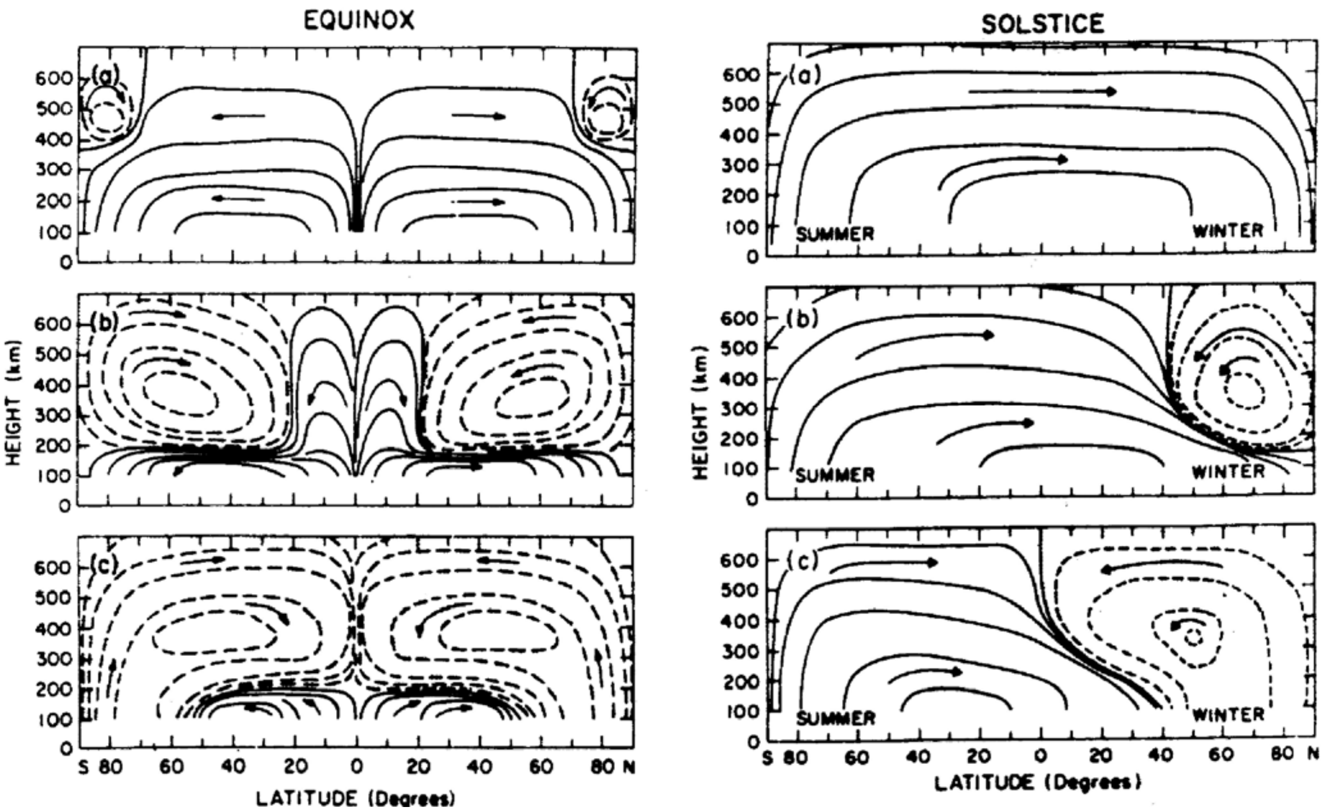
Thermospheric circulation

Very quiet sun

Average activity

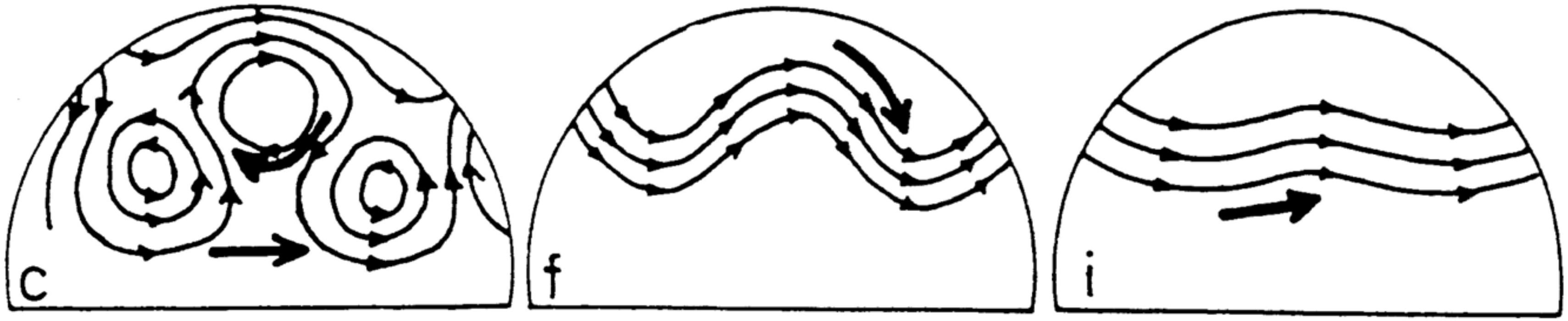
Very active sun



Roble, 1977, The upper atmosphere and magnetosphere, Nat. Acad. Sciences

- Particle induced circulation cell in high latitudes during solar max,
- One global cell from winter to summer hemisphere,
- Two cells equator-pole during equinoxes.

Tropospheric circulation

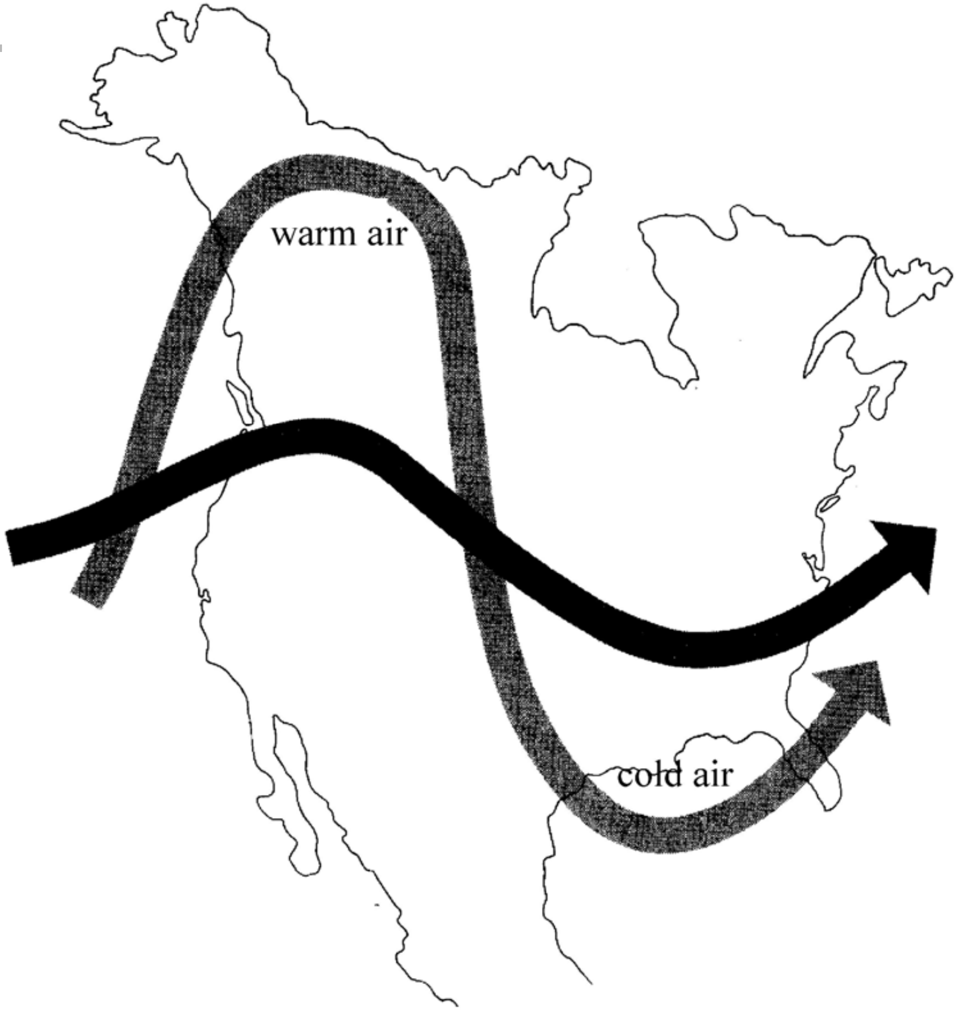


Bucha, 1980, Ann. Geophys. 6, (5)513

- Low geomagnetic activity (solar minimum): jet stream meanders strongly, blocking pattern, many vortices (low and high pressure regions) develop,
- Average geomagnetic activity (solar minimum with many strong CIRs or average solar activity): meandering jet stream without vortices,
- High geomagnetic activity (solar maximum): jet stream almost aligned with a parallel.

Blocking patterns

- Jet stream aligned with a parallel allows for westward propagation of pressure systems.
- Meandering jet stream causes superposed meridional motion of pressure systems: warm air masses are transported polwards while cold ones move to lower latitudes (blocking pattern).



Roberts and Lansford, 1979, The climate mandate, Freeman