The Earth's Climate

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The planets Venus, Earth and Mars

Properties	**VENUS**	**EARTH**	**MARS**
Distance to sun	0.72 AU	1 AU	1.5 AU
Sol. constant	2614 W/m^2	1368 W/m^2	589 W/m^2
Albedo	0.76	0.30	0.30
Eq. temperature	**- 41 °C**	**-18 °C**	**-72 °C**
Sur.temperature	**+ 473 °C**	**+15 °C**	**- 63 °C**
Diurnal cycle	0 °C	20 °C	200 °C
Atmos. mass	90	1	0.006
O_2 in %	0	20.9	0
CO_2 in %	96.5	0.039	95.3

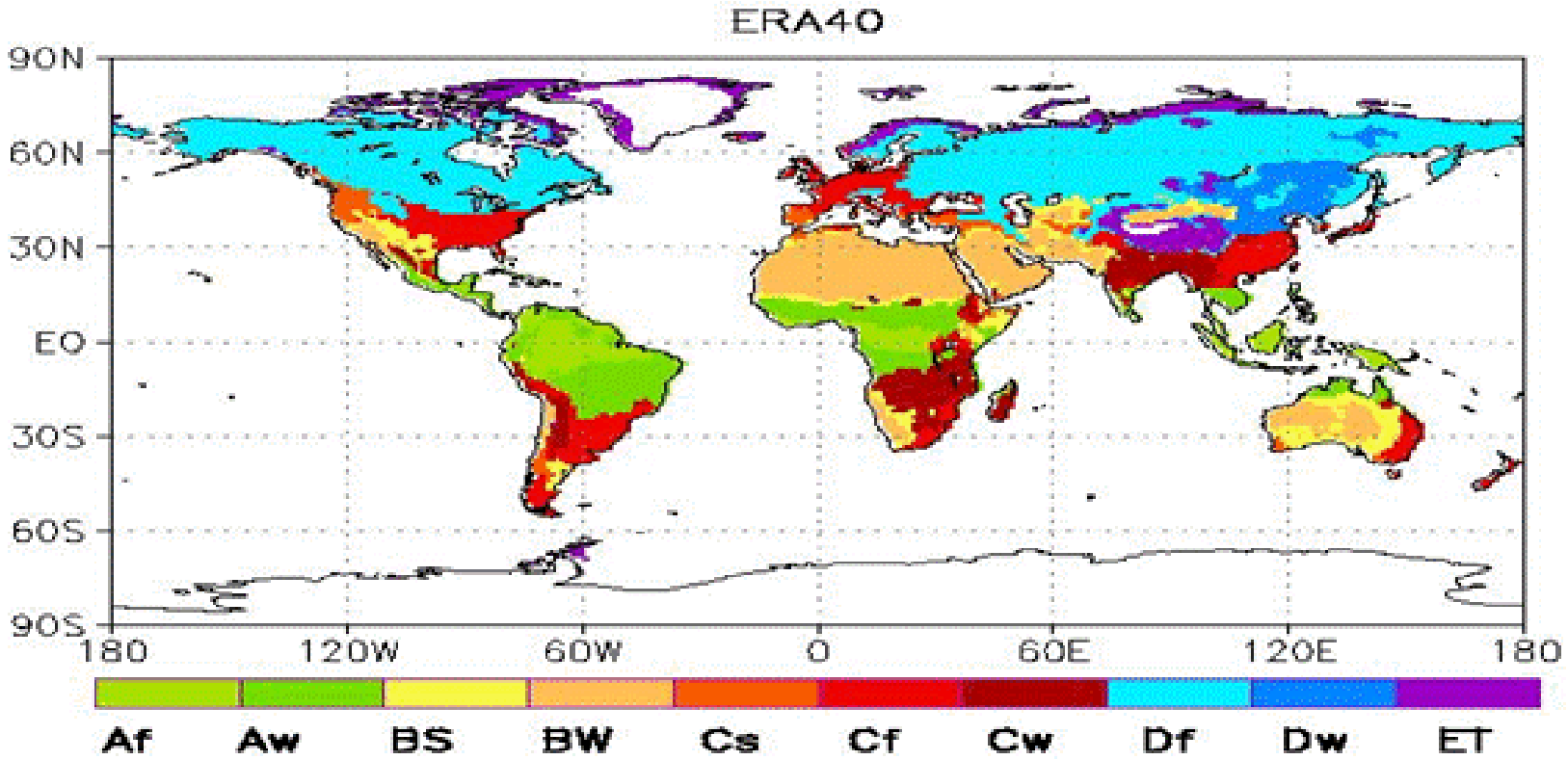
Our understanding of the Earth's climate in the period 1850-1950

- Simple dynamical concepts based on the conservation of angular momentum going back to Hadley, during the early 20th century extended to consider the role of transient eddies (Bjerknes, Jeffries etc.).
- A descriptive view on climate, Köppen with ideas going back to von Humboldt.
- **However, the physical and dynamical knowledge of climate was very limited.**

- The forcing was lacking in many key details: the value of the solar constant, the planetary albedo, atmospheric composition and concentration of absorbing gases.

- We also lacked global observation from the polar region from the free atmosphere and from the oceans.

- We lacked the methods to consider the climate as a physical system and the ability to address climate as a mathematical/computational problem.



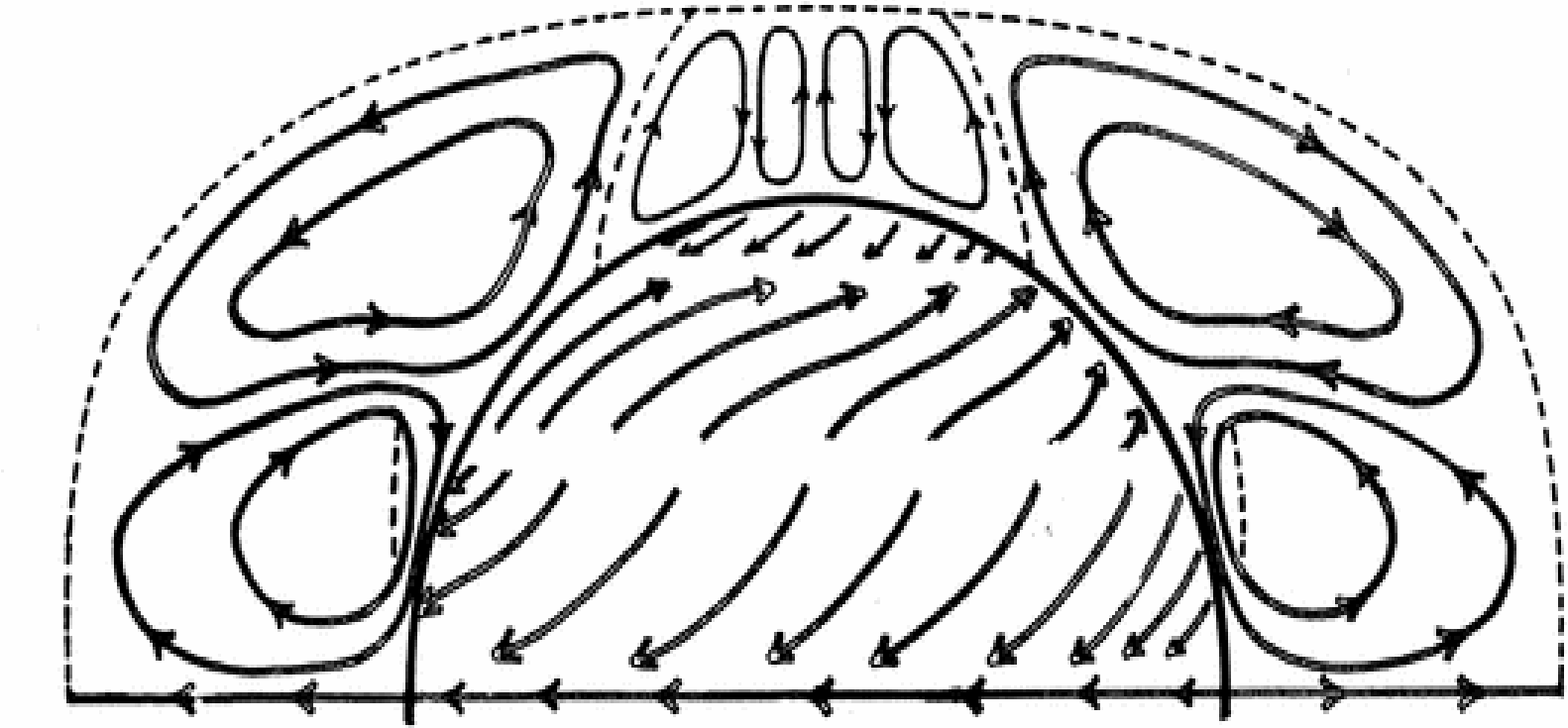
- **A : tropical vegetation climate**
- **BS : stepp**
- **BW : desert**
- **C : temperate climate**
- **D : boreal climate**
- **E : tundra**

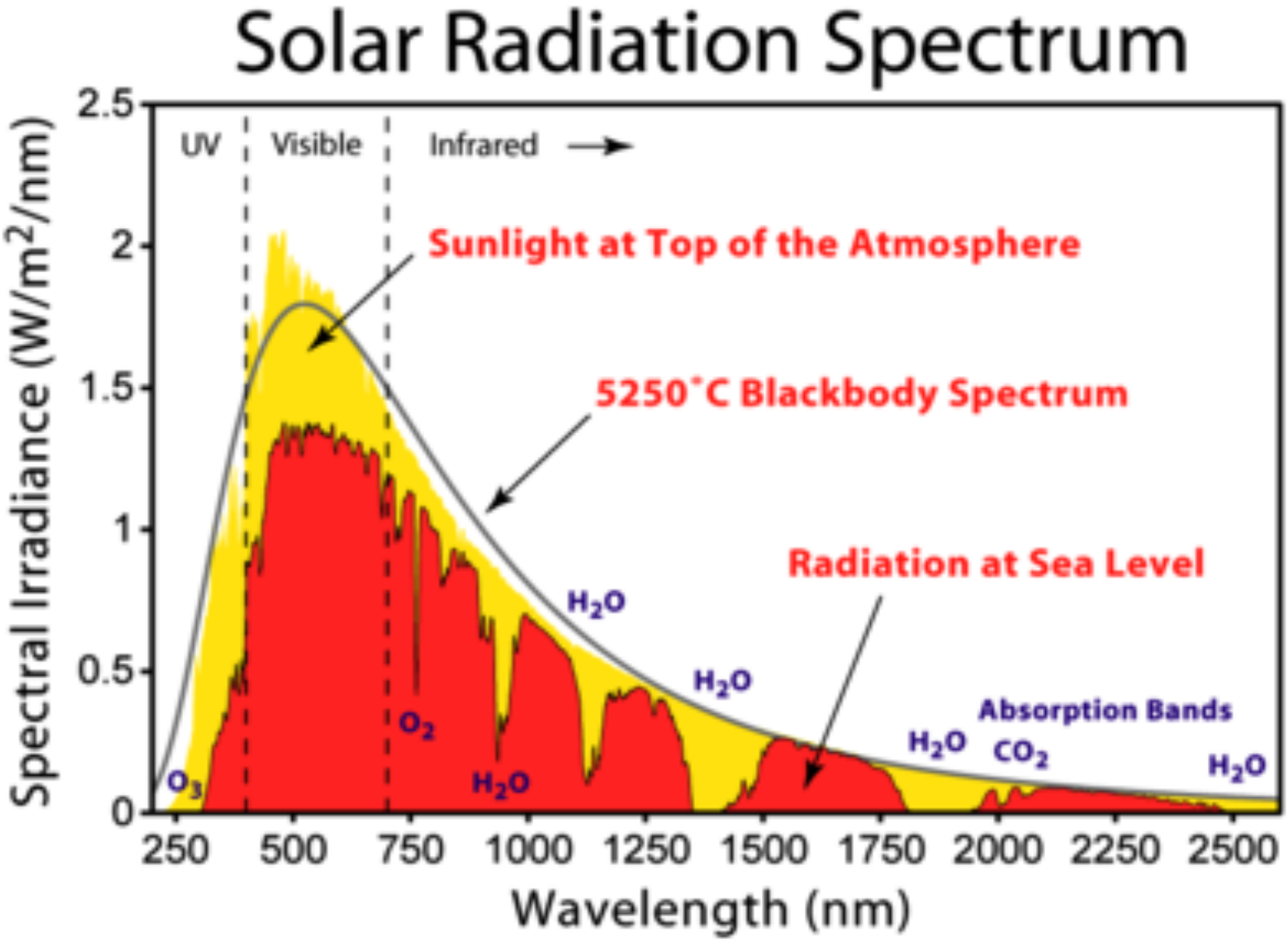
Köppen (1846-1940)

Climate classification system

- **Example for D: coldest month < -3°C, warmest month > +10°C**

General circulation after Bjerknes 1921




Solar Radiation Spectrum
Spectral Irradiance (W/m²/nm)
2.5
2
1.5
1
0.5
0
UV
Visible
Infrared
Sunlight at Top of the Atmosphere
5250˚C Blackbody Spectrum
Radiation at Sea Level
H2O
H2O
H2O
O2
O3
Absorption Bands
H2O
CO2
H2O
250
500
750
1000
1250
1500
1750
2000
2250
2500
Wavelength (nm)

The physics and dynamics of Climate

Essential contributions from space observation

- **The solar constant** (earlier units: Langley (ly): cal/cm^{2}min)
- Langley after corrections by Abbot: 1318-1548 Wm^{-2}
- Typical value ca 1950: 1327 Wm^{-2}
- (my textbook in meteorology, Haltiner and Martin) 1957: 1358 Wm^{-2}

  Now 1368 Wm^{-2}

- **The planetary albedo**
- Danjon(1936): 0.39, Aldrich(1952): 0.42, Fritz(1951): 0.35

  Now 0.30 (first done by V. Suomi)

Planetary emissivity estimated in 1950: **0.52**, now using space obs. : **0.61**

(An emissivity of 0.52 requires an increase in surface temp by +12°C)

- **The radiation balance (Earth's energy flows)**
- Trenberth et al (2009)
- Typical accuracies **1**-5+ Wm^{-2} in annual, global averages

Total solar Irradiation (1978-2005)
After C Frölich (2005) ISSI, Bern

10 C. FRÖHLICH

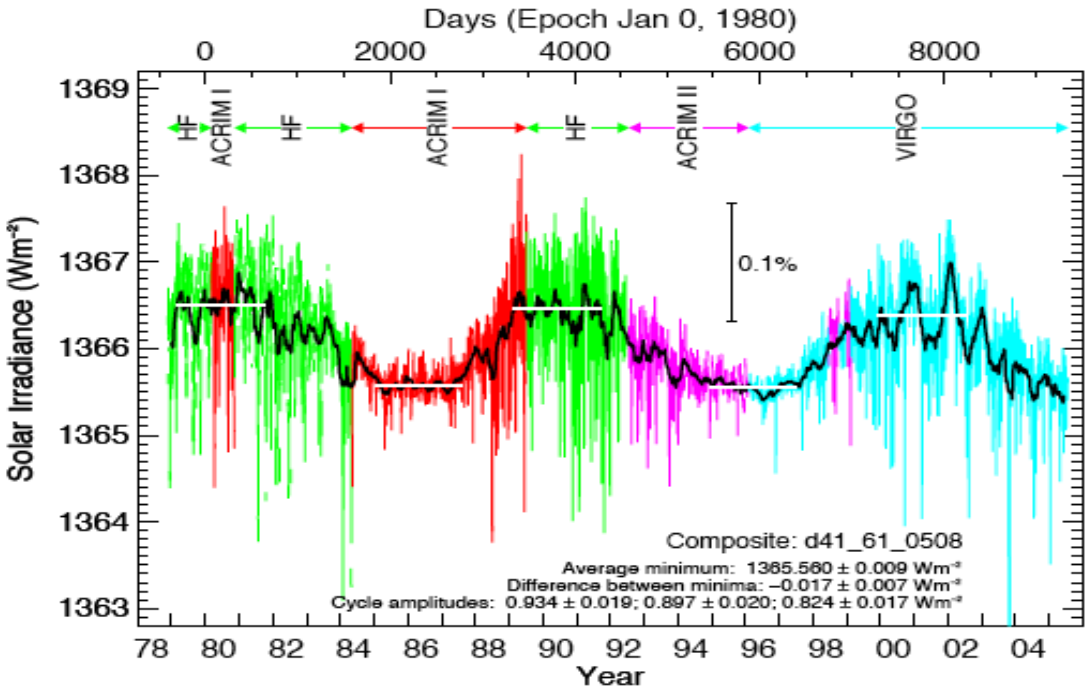
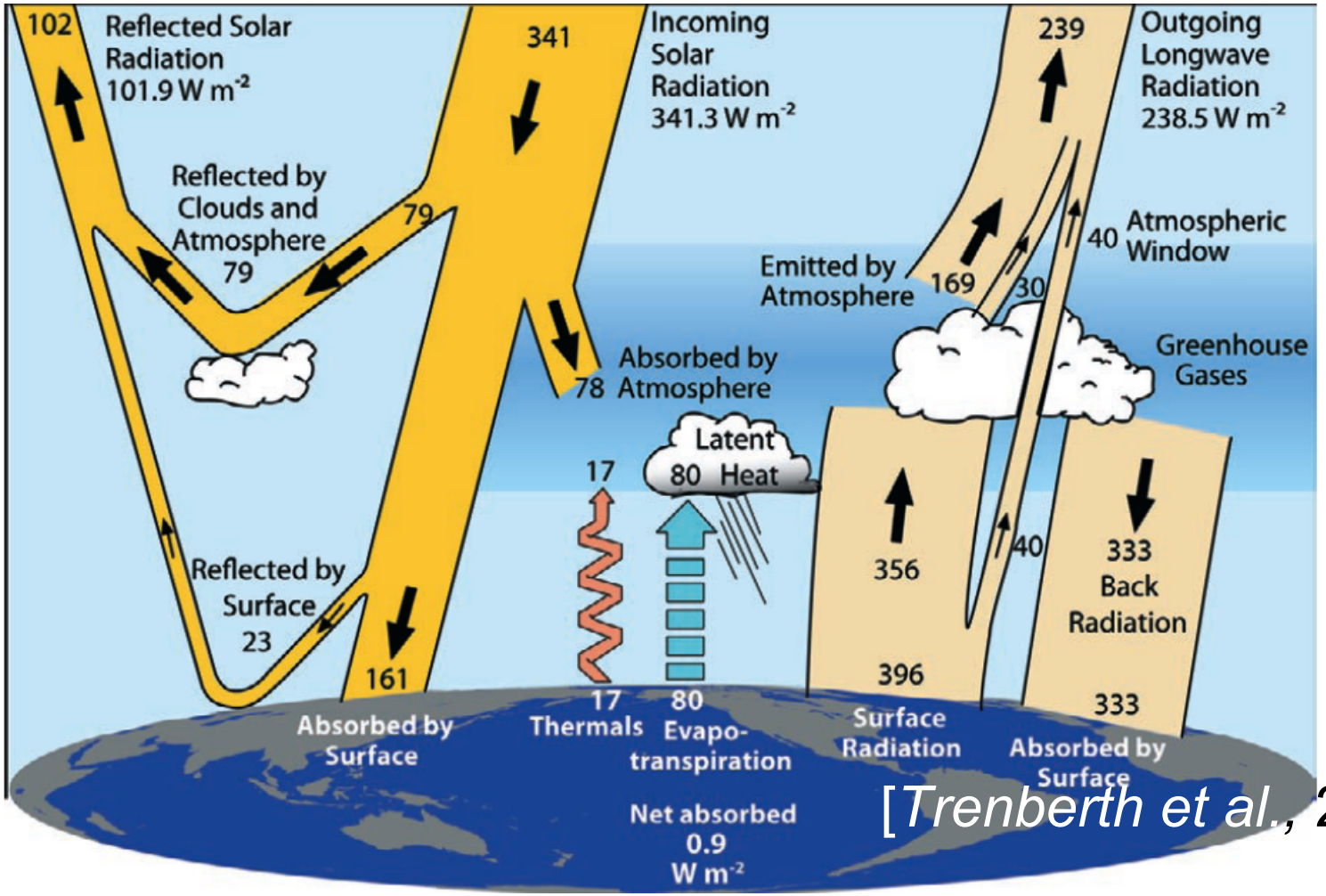


Figure 11. Shown is the final version of the PMOD composite. Compared to the earlier versions the maximum of cycle 21 is at about the level as before, but has less noise, especially in the early part. This may indicate that the early HF corrections have indeed been improved. Finally, the difference between the minima has also not changed.

The radiation budget of the Earth

$$E_{in} = E_{out} \Leftrightarrow \tfrac{1}{4} S_0 (1 - \alpha) = \varepsilon \sigma T_s^4$$

Annual averages of global energy flows W m^{-2}



[*Trenberth et al.*, 2009]

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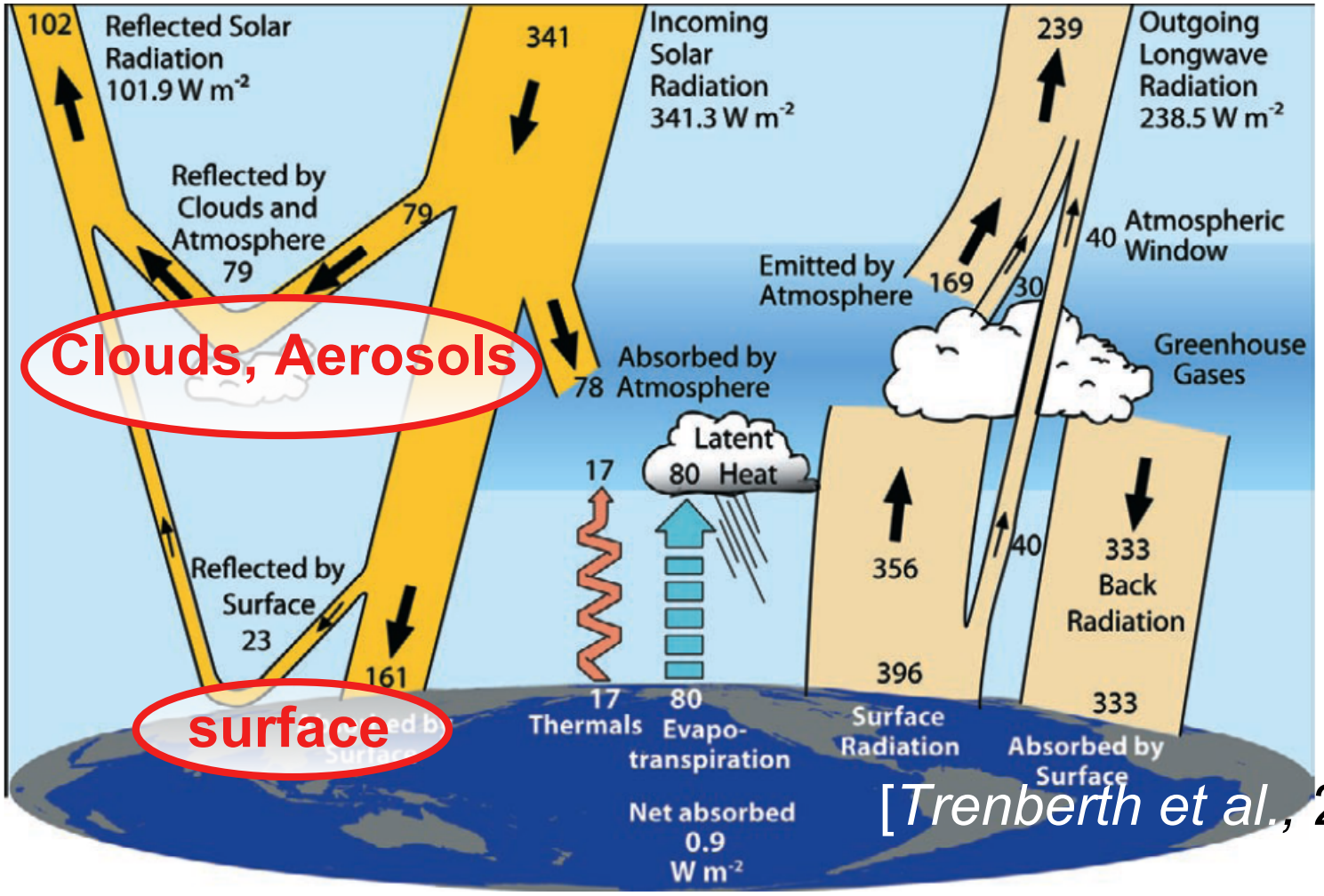
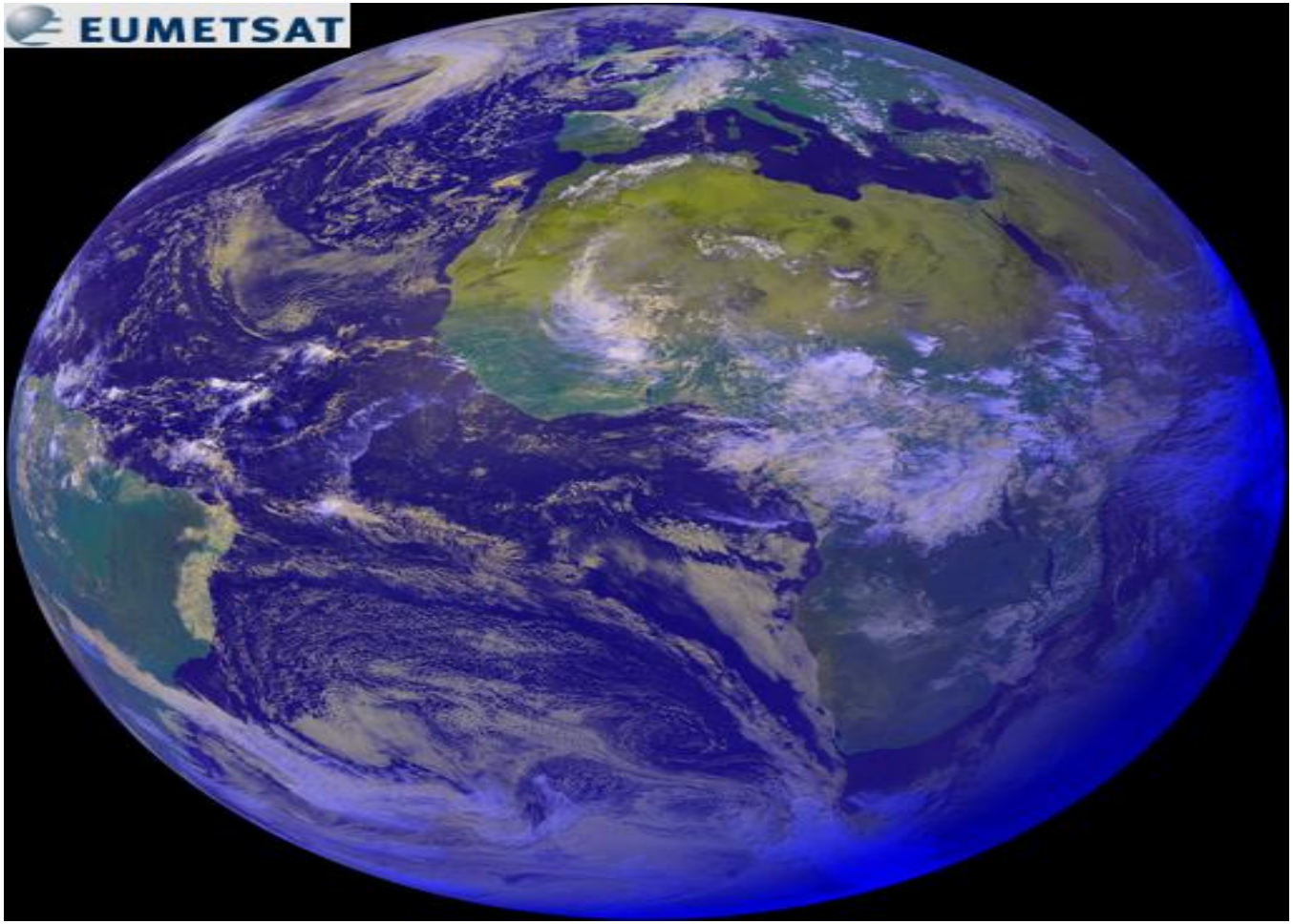


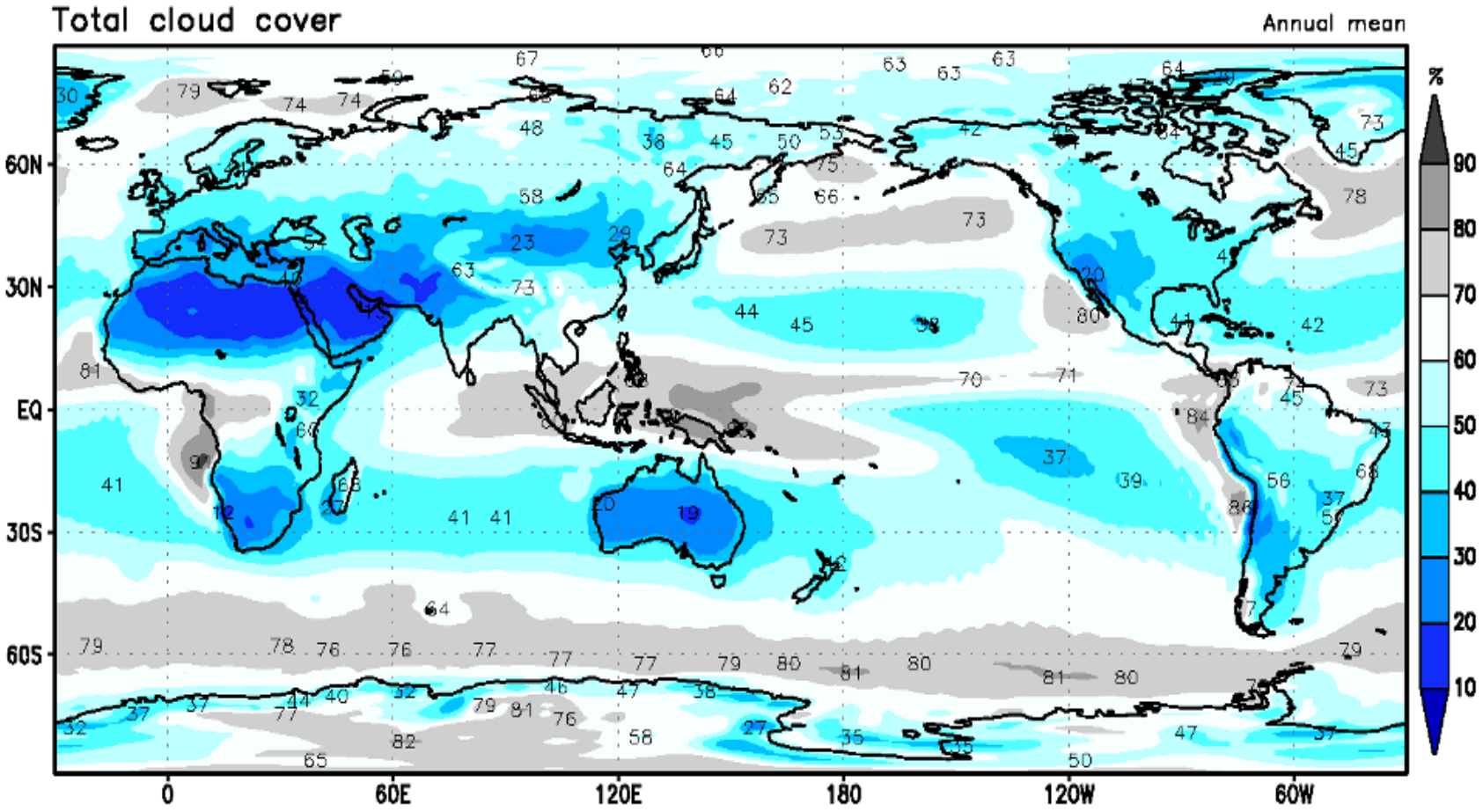
[*Trenberth et al.*, 2009]

Alpbach

EUMETSAT 22 July 2010 at 1600z
Global cloud cover



Total cloud cover, annual mean



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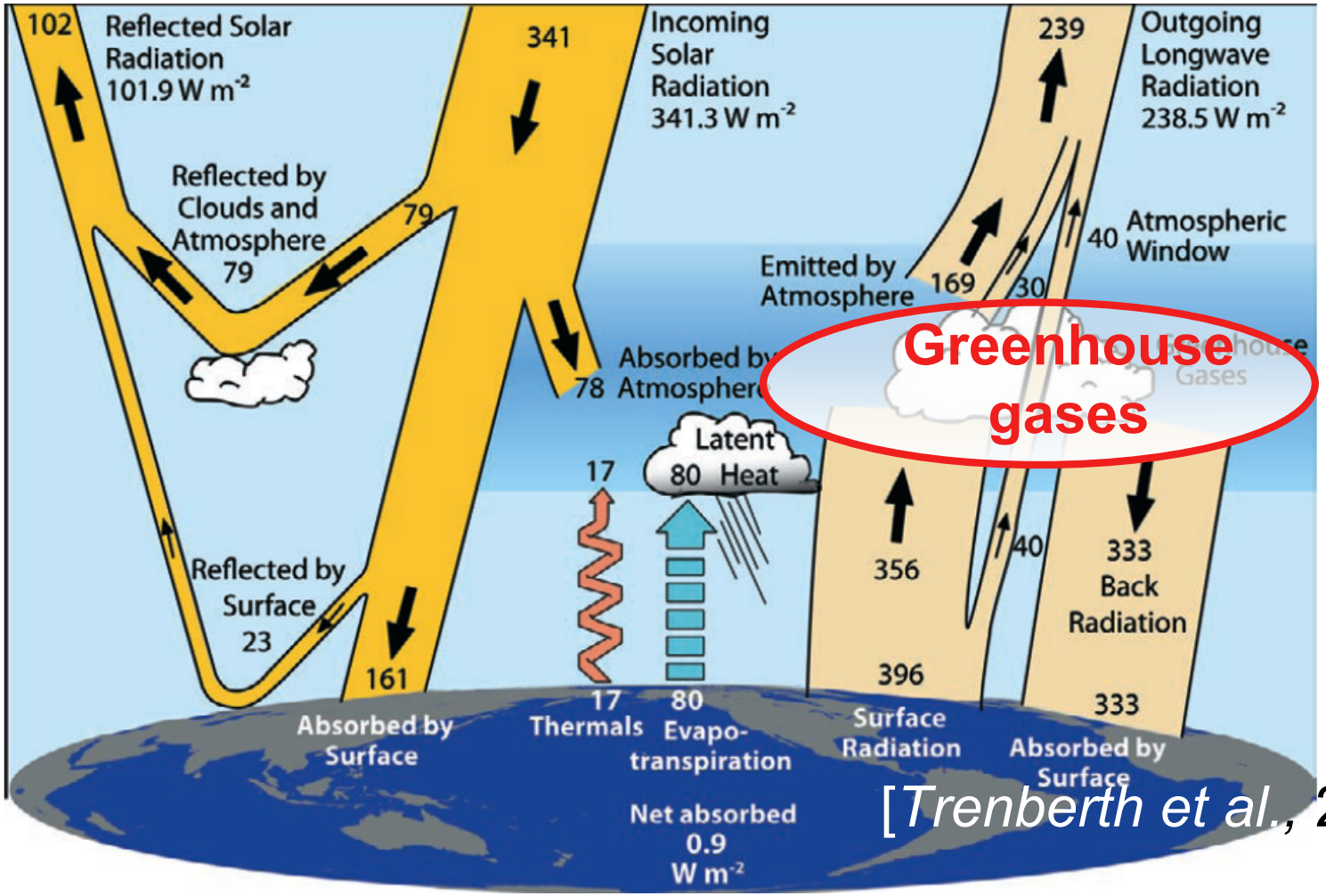
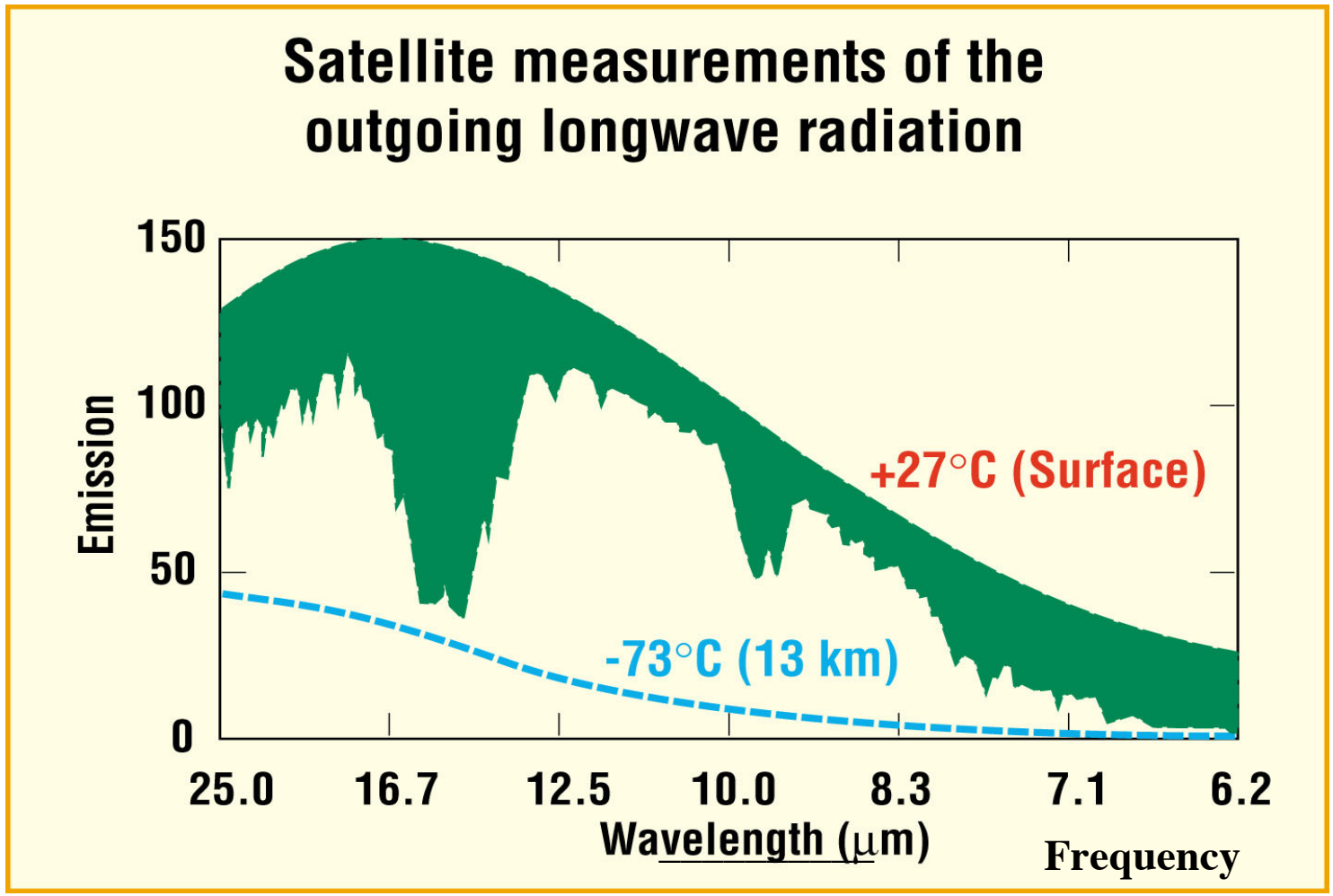


[*Trenberth et al.*, 2009]

Alpbach

During cloud free conditions over the central tropical Pacific.

- ***The greenhouse effect***



H_2O = 75%

CO_2, CH_4 etc = 25%

Some observations

- So far it is estimated (theoretical spectroscopy) that due to increased concentration of greenhouse gases the planetary emissivity has been reduced by **about 1%** since 1850 or from 0.615 to 0.608.

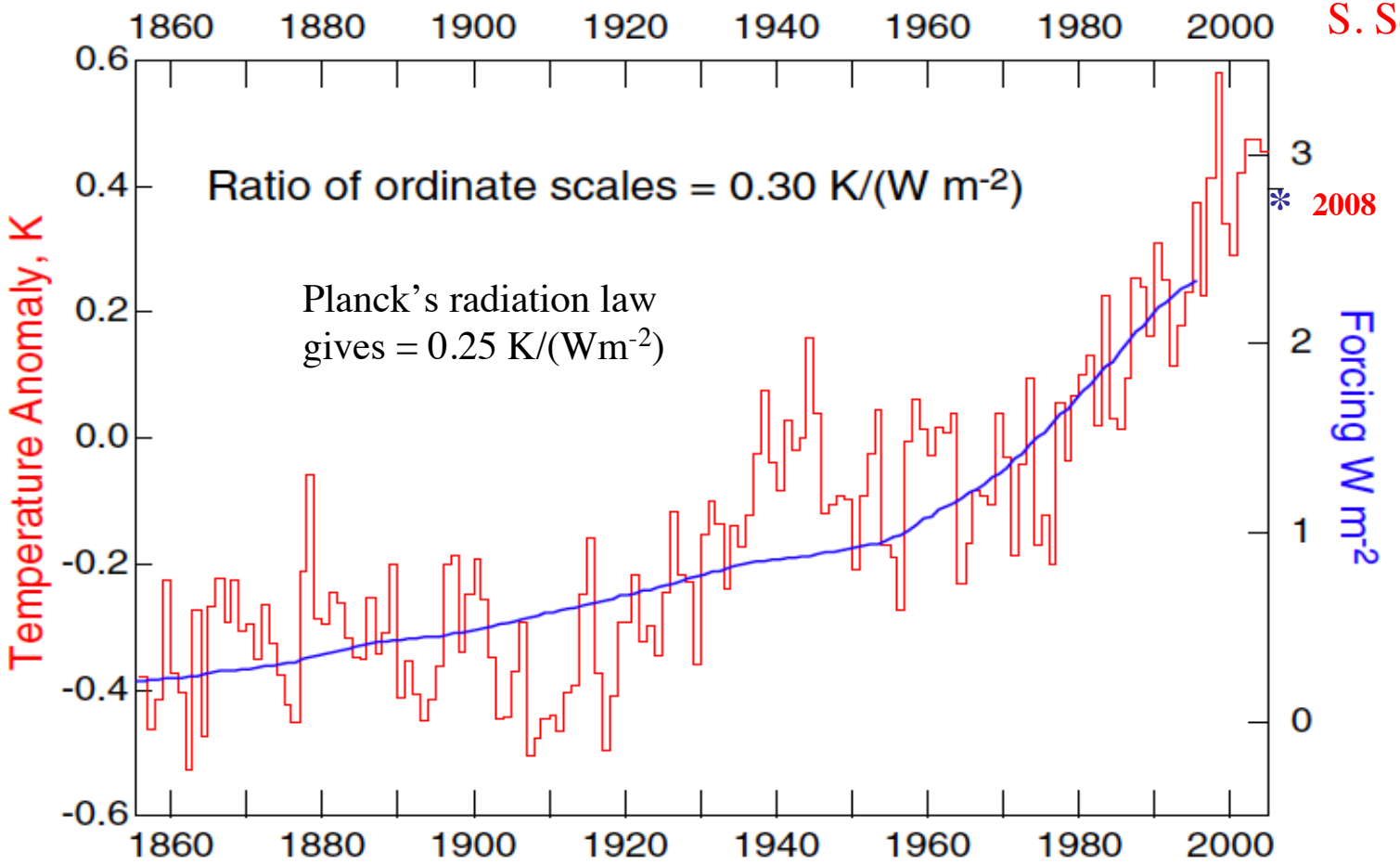
- Long term satellite records(J Harries et al) indicate a reduced outgoing terrestrial radiation.

- To obtain an equivalent surface warming the solar irradiation must increase by **13 W/m^2** or reducing the planetary albedo by **1%.**

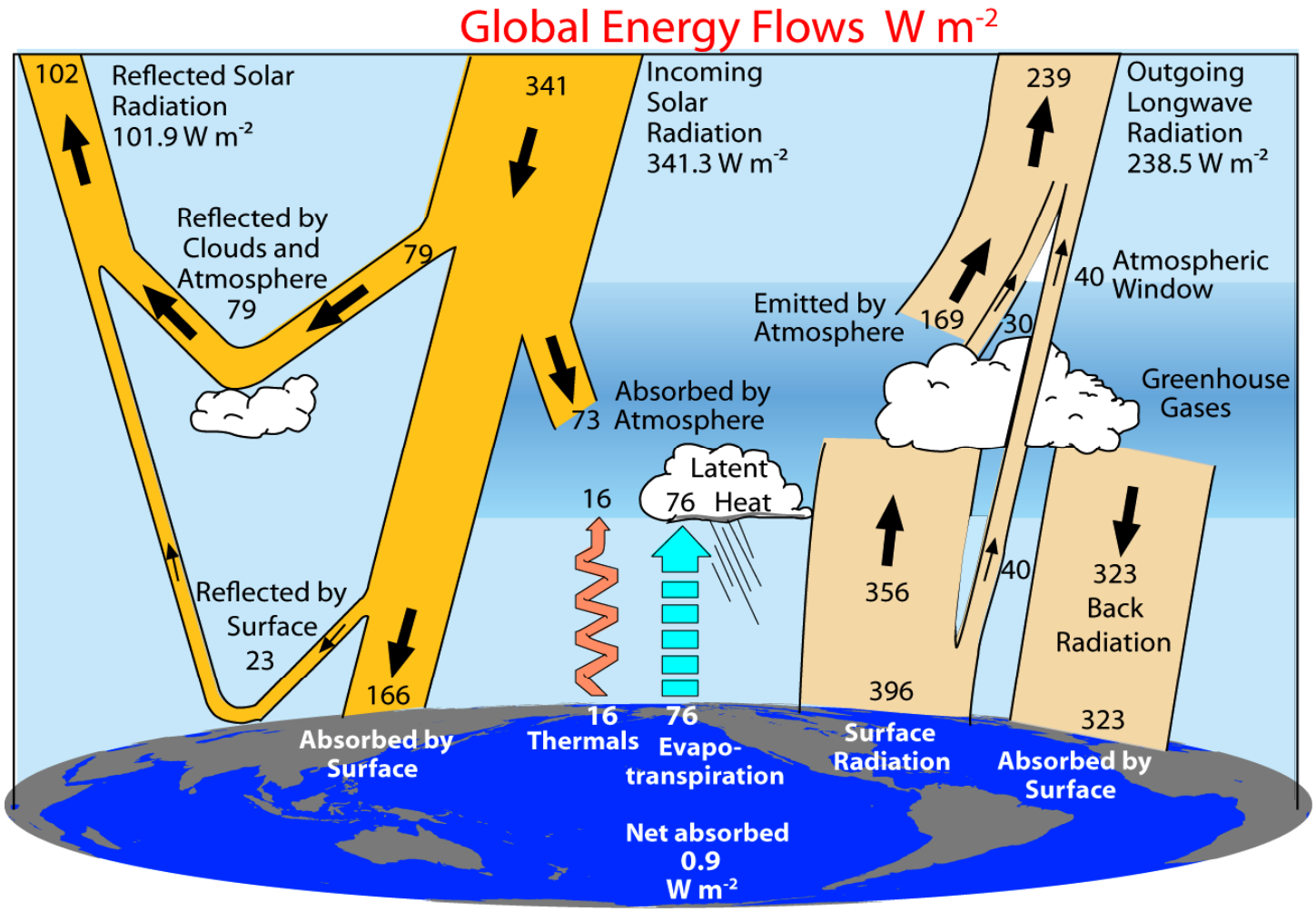
- Because of the ongoing increase in greenhouse gases and hence reduction in planetary emissivity, part of the heat accumulation has been stored into the deep oceans, some radiated back into space and a small part used to melt ice and to warm the atmosphere.
- Present net flux of heat into the oceans is estimated to 0.5-1 W/m^2

Global mean surface temperature and forcing by well mixed greenhouse gases, CO_2, CH_4, N_2O and CFC

S. Schwartz

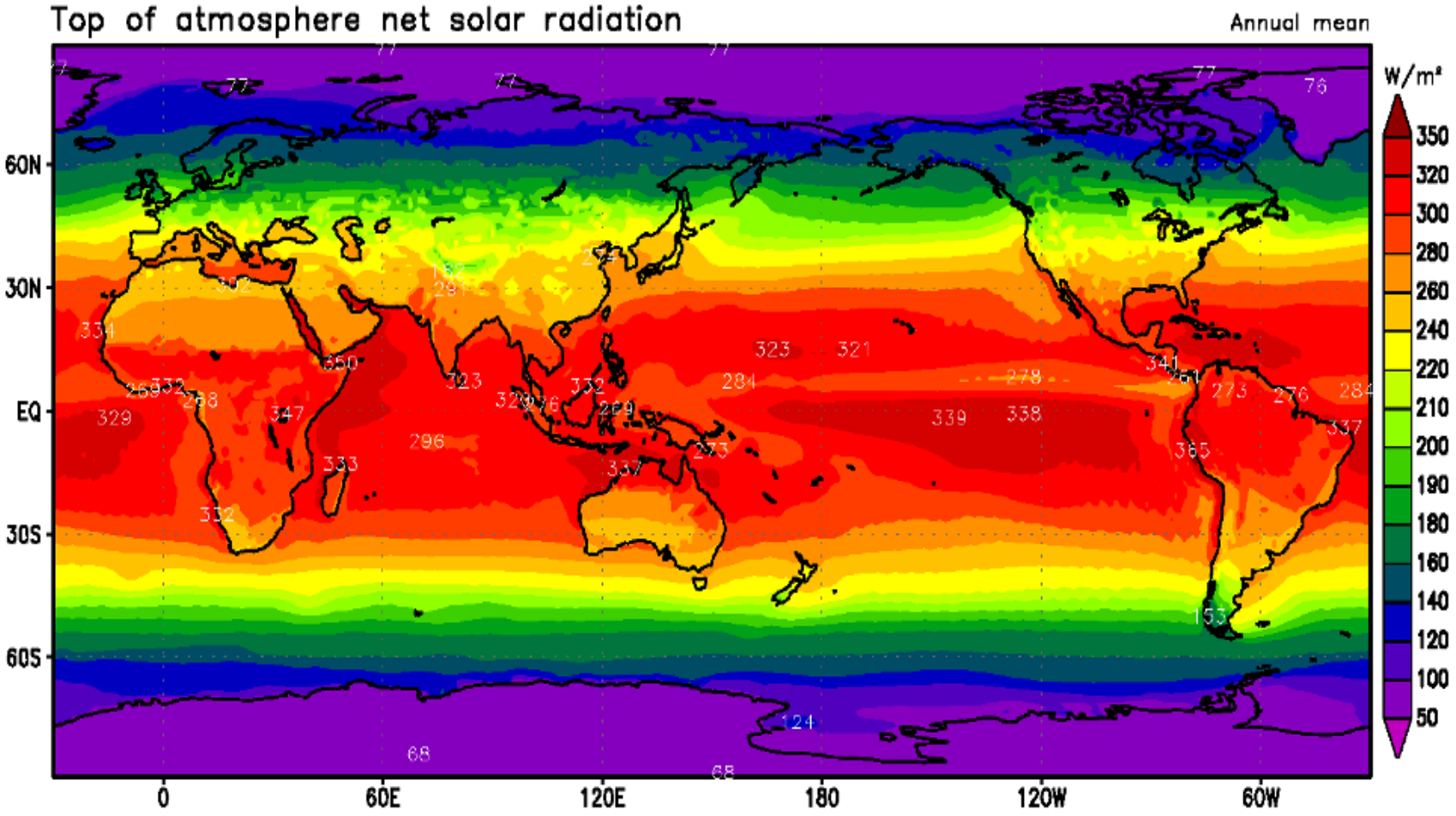


The global energy balance (Trenberth et al 2008)
Annual averages. (Accuracy 1-5 Wm^{-2})

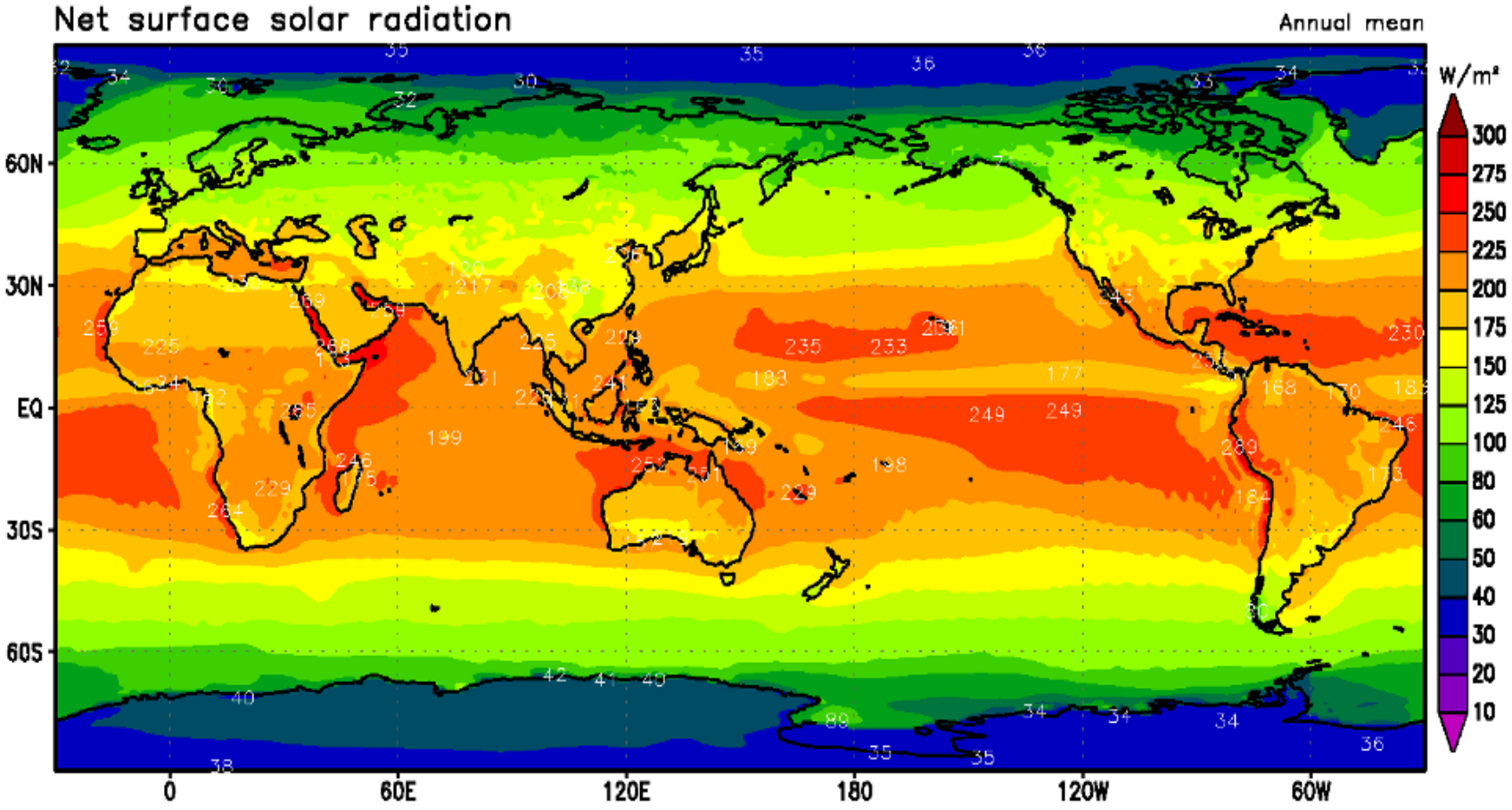


Net solar radiation, top of the atmosphere, unit W/m^2

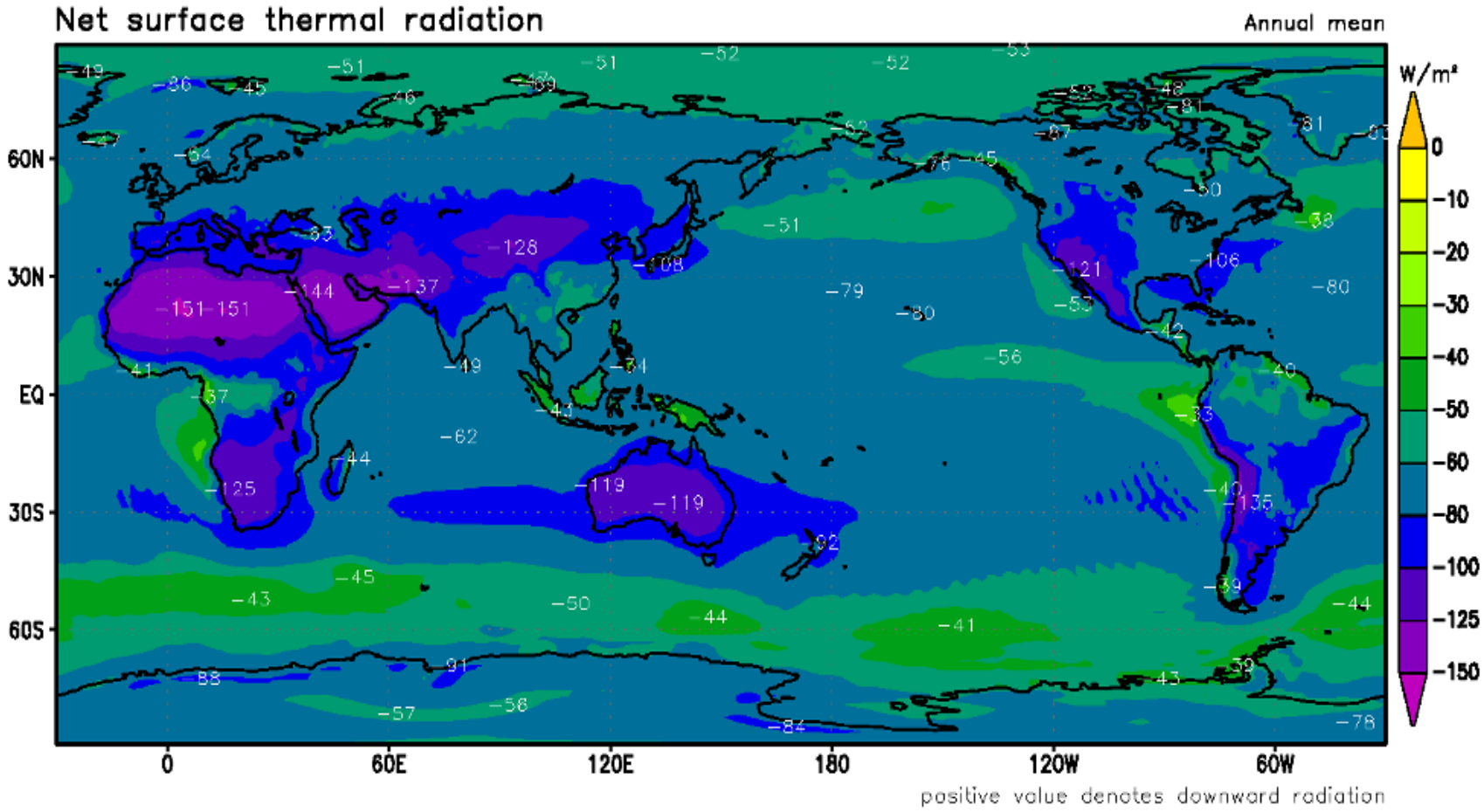
Global mean +239 W/m^2



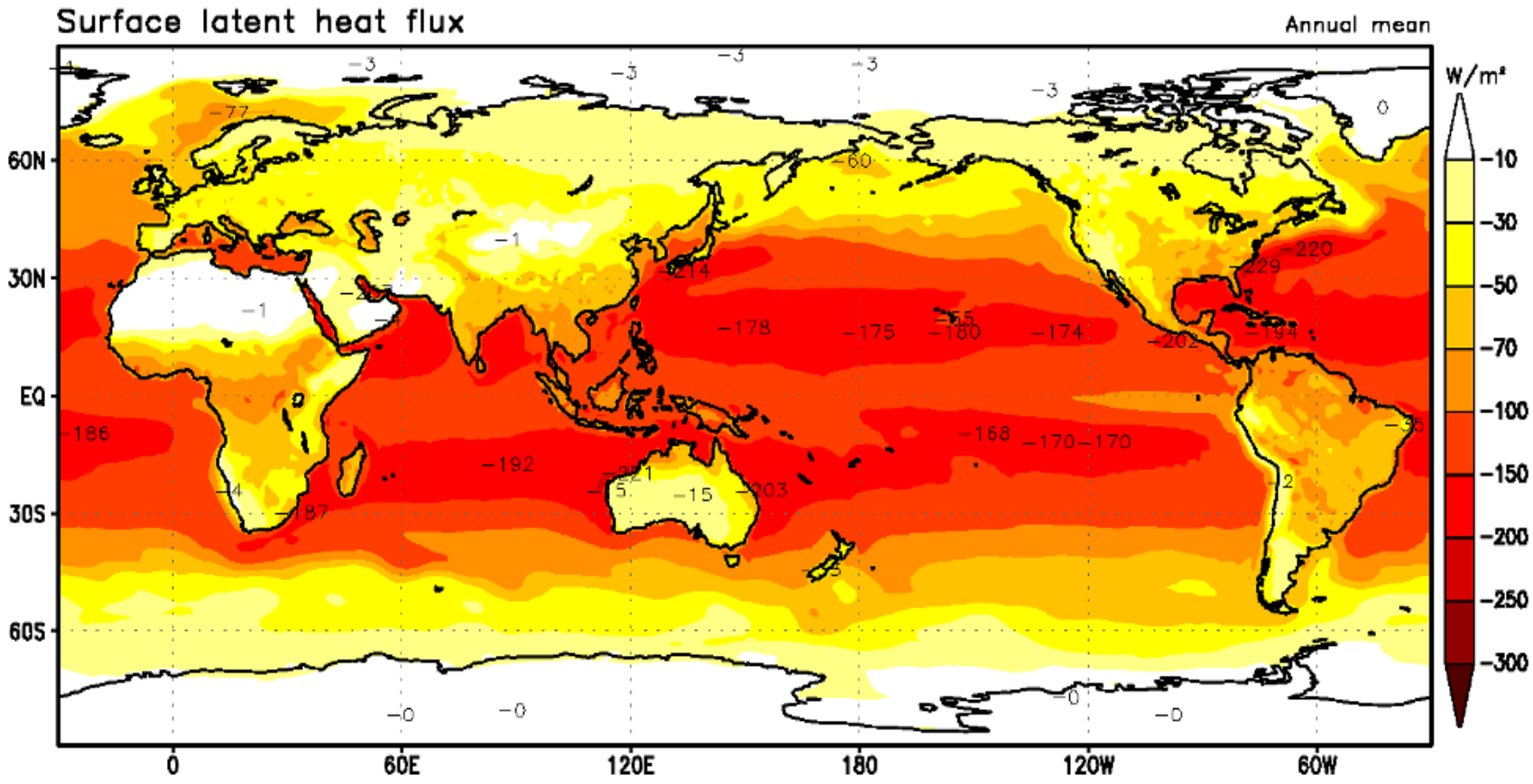
Net surface solar radiation
Annual mean (Watts/m2) +166



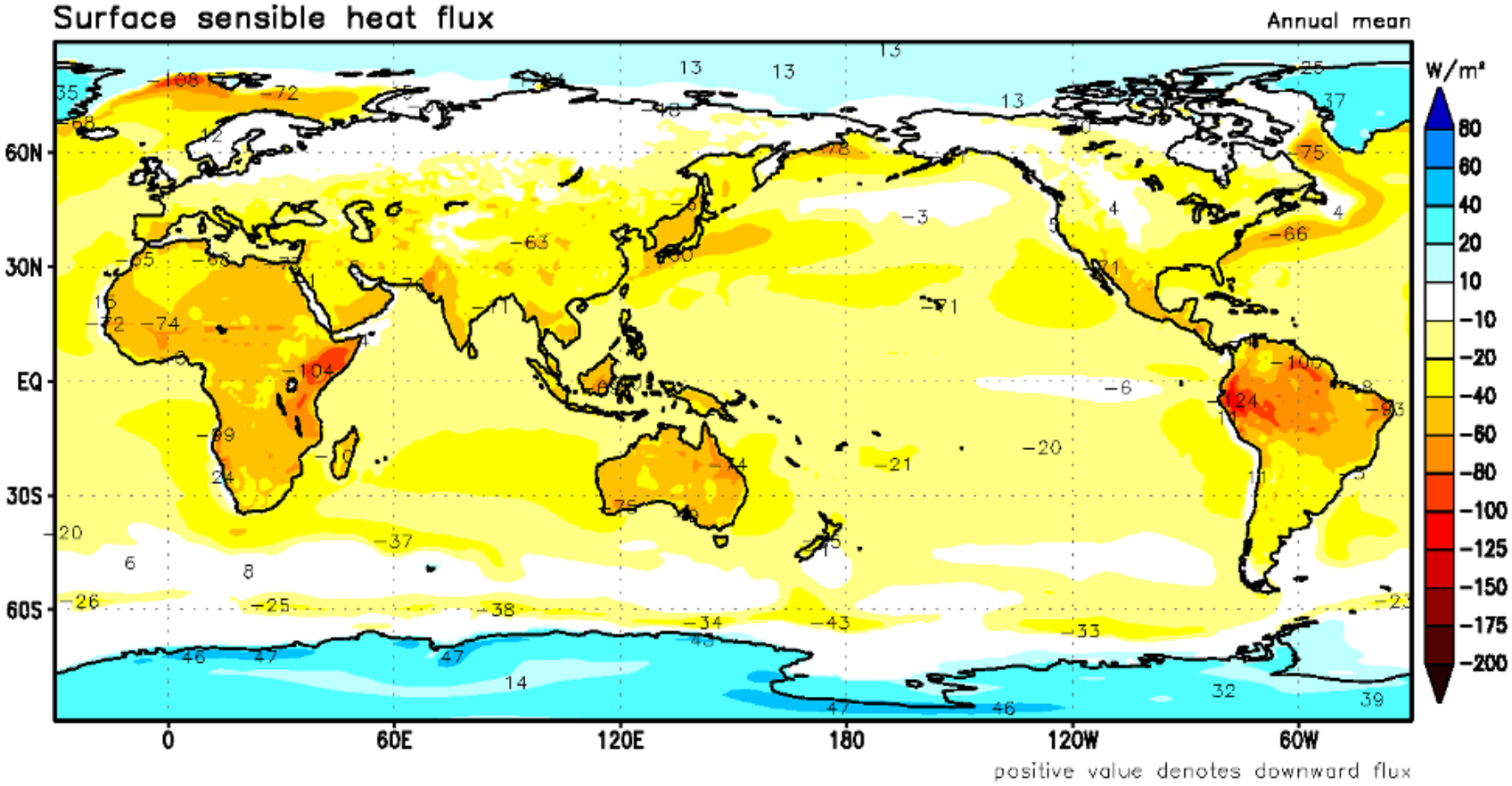
Net surface thermal radiation
Annual mean (W/m^2) -63



Surface latent heat flux
Annual mean (W/m^2) - 76



Surface sensible heat flux
Annual mean (W/m^2) -16



Net thermal radiation, top of the atmosphere, unit W/m^2

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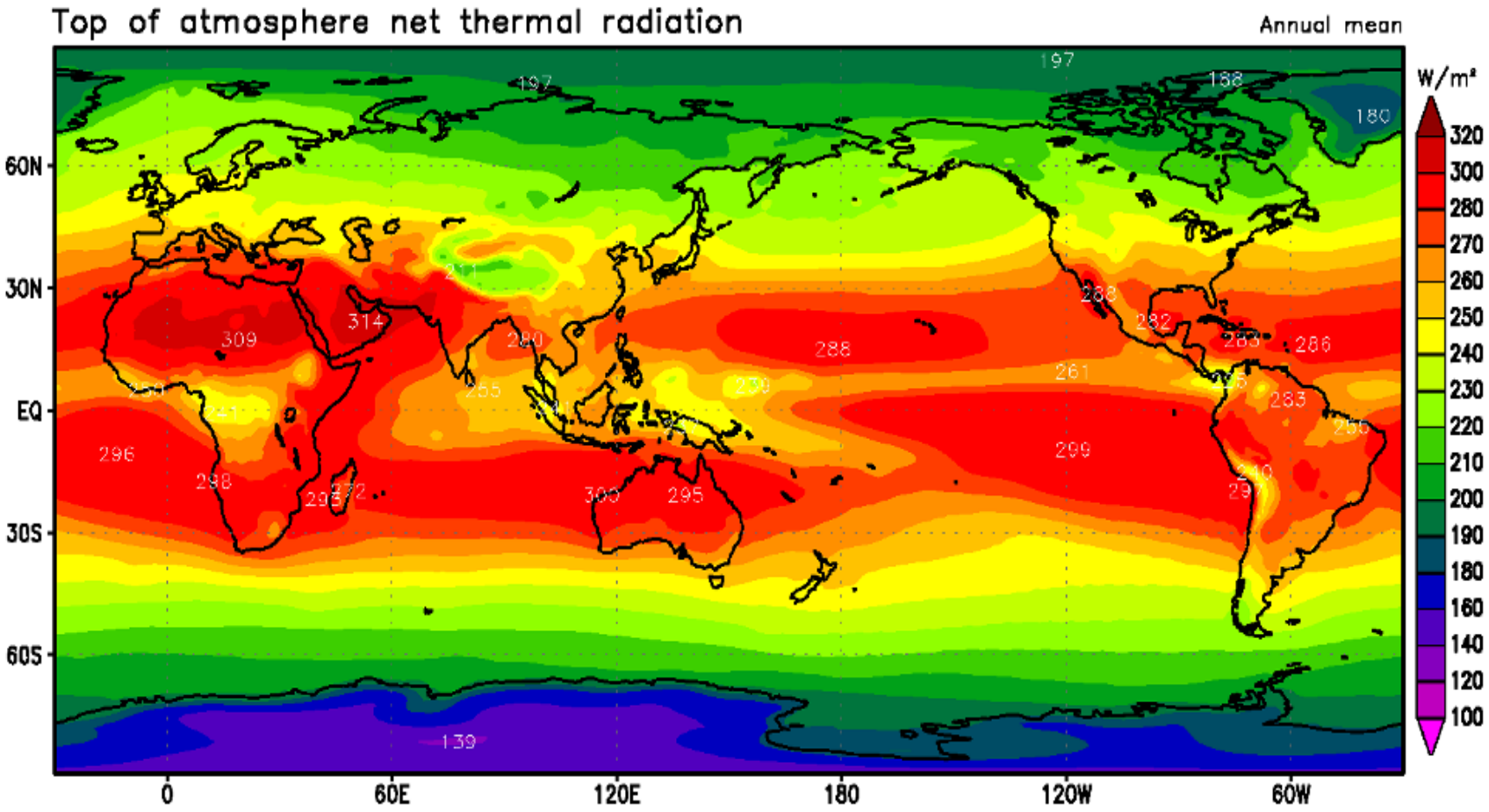
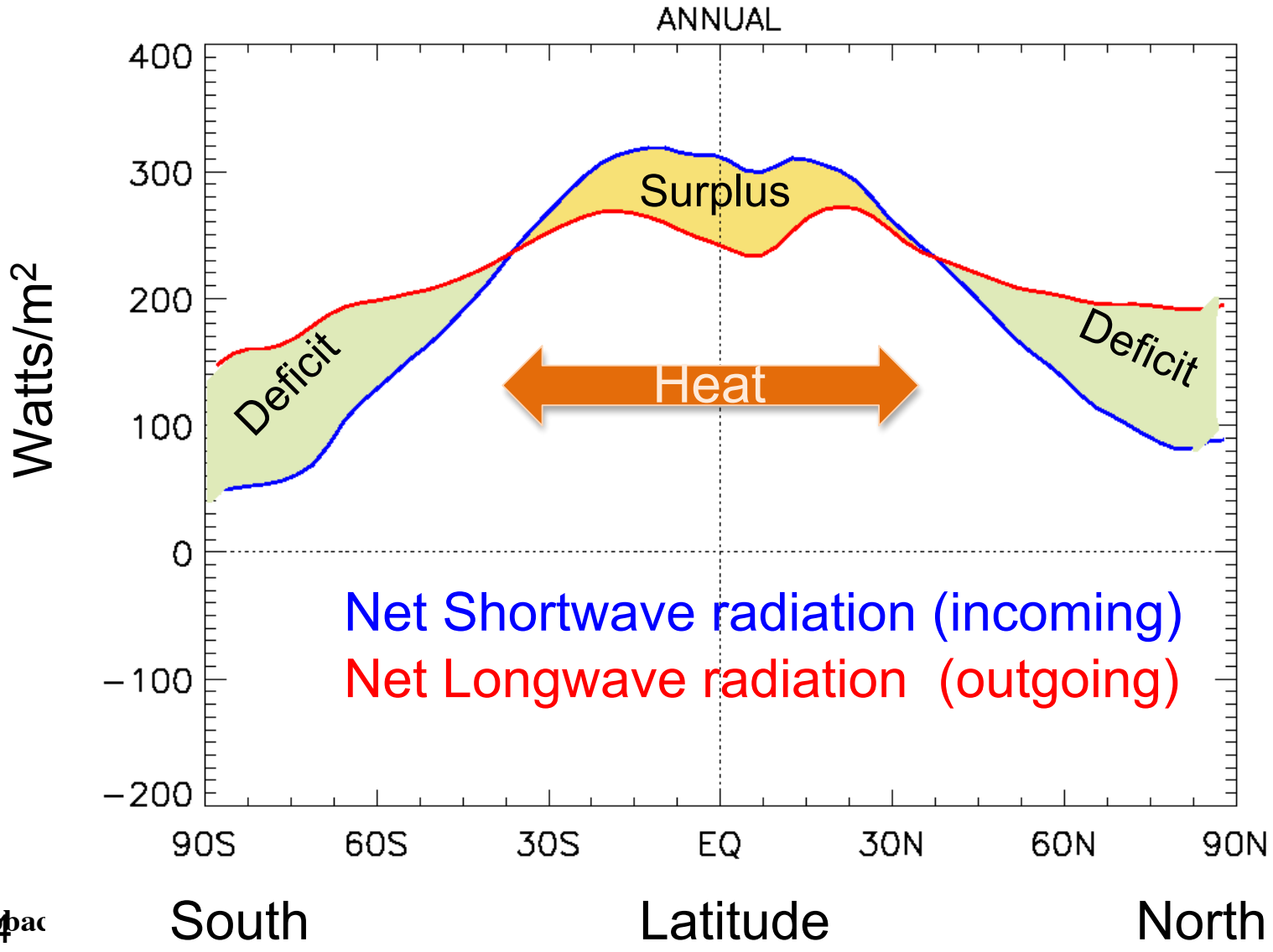


Latitudinal variation of net fluxes



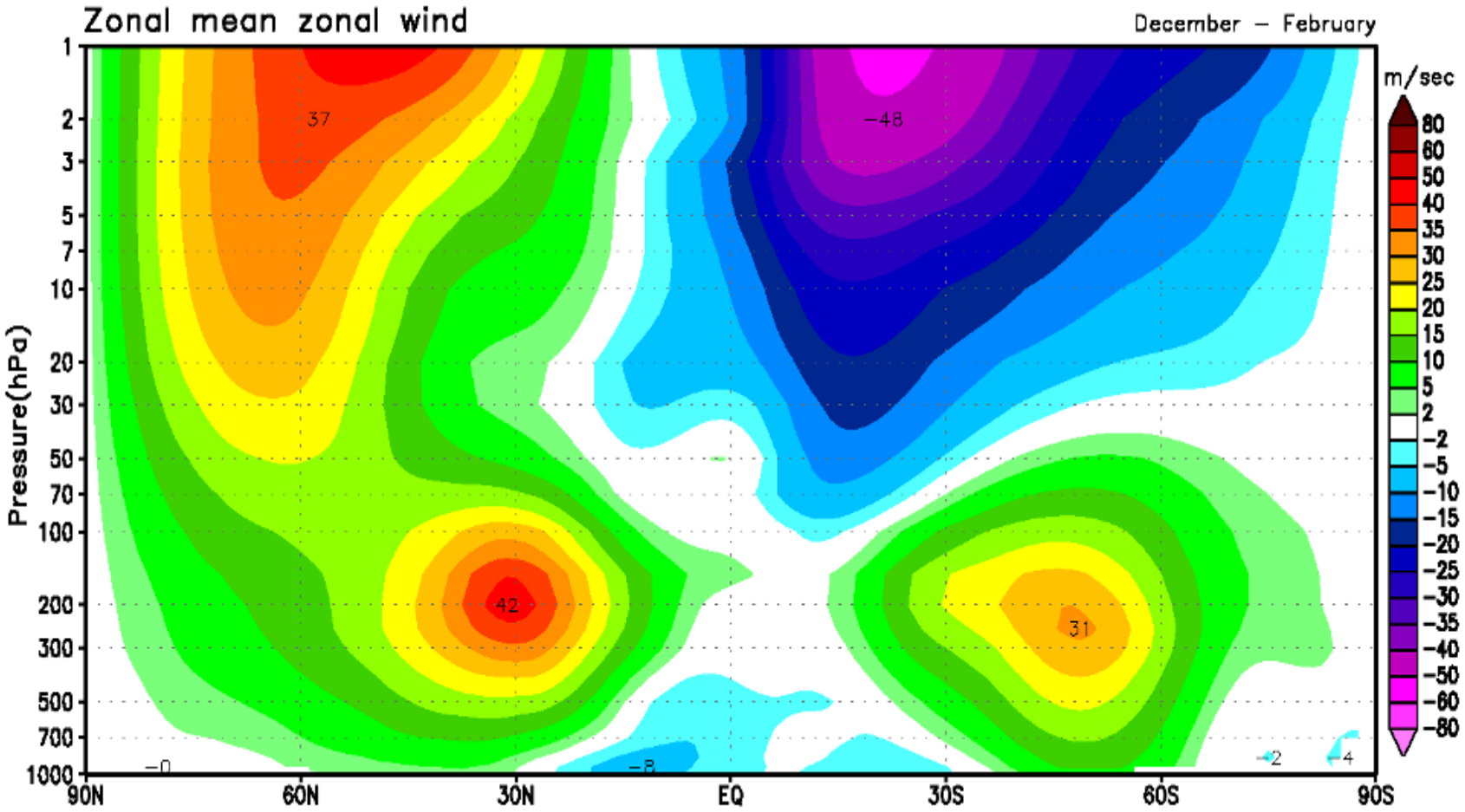
How does the climate system responds to radiative forcing?

- Anomalies in radiation give rise to atmospheric instabilities
- Vertical instabilities are corrected by convection, transporting heat vertically
- Horizontal instabilities generate baroclinic instabilities transporting heat and momentum horizontally
- There are considerable deviations from radiation balance, e.g Sahara, parts of the upper atmosphere

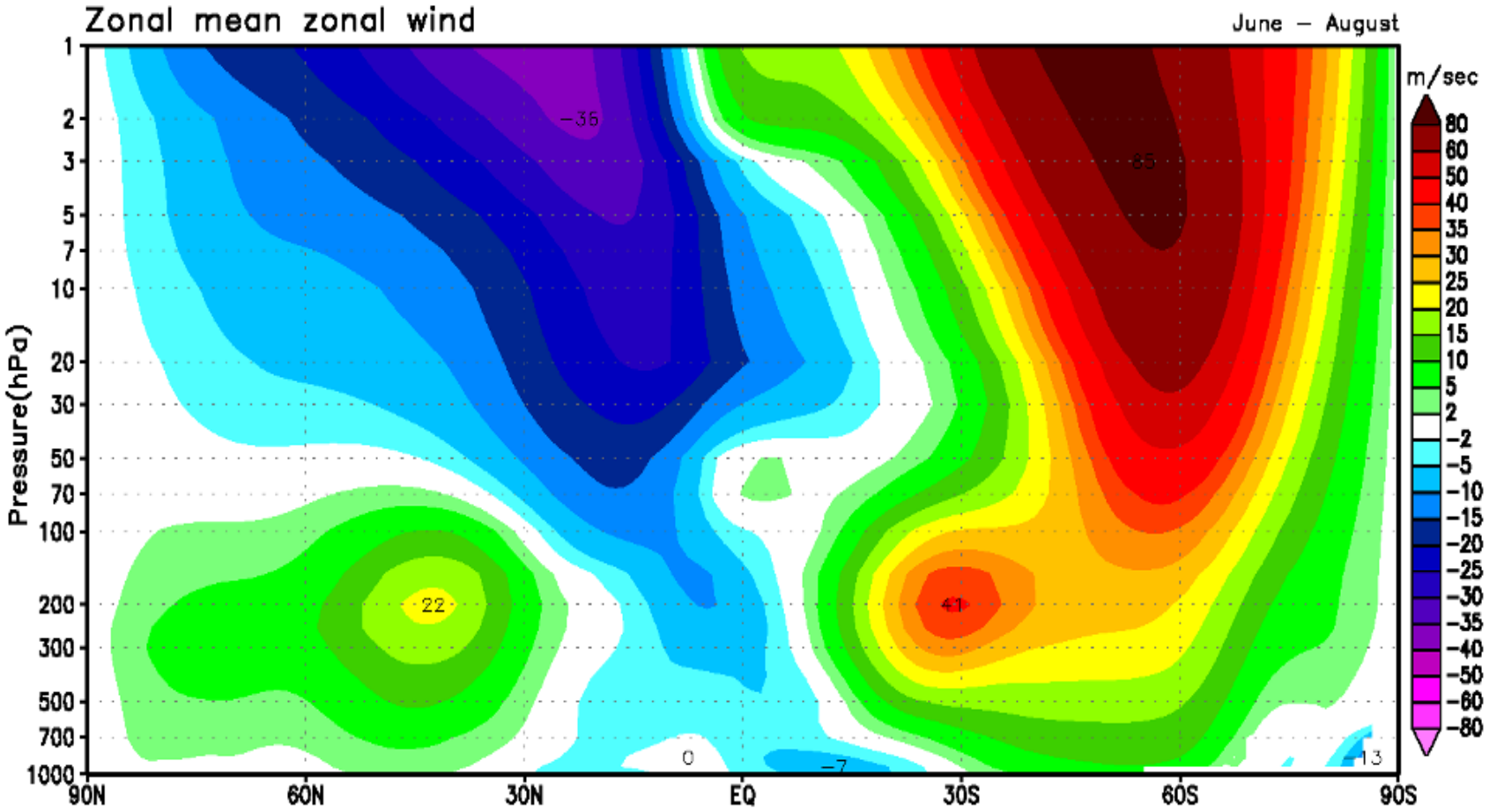
Vertical distribution of temperature and wind

- Transport of heat and momentum
- Heat must be transported from low to high latitudes
- Momentum must be preserved.
  (Persistent westerlies in some areas must be compensated by easterlies elsewhere)
- Momentum is exchanged between the solid Earth and the atmosphere (and oceans)
  This effects the rotation of the Earth and thus the length of the day.

Zonal wind in winter

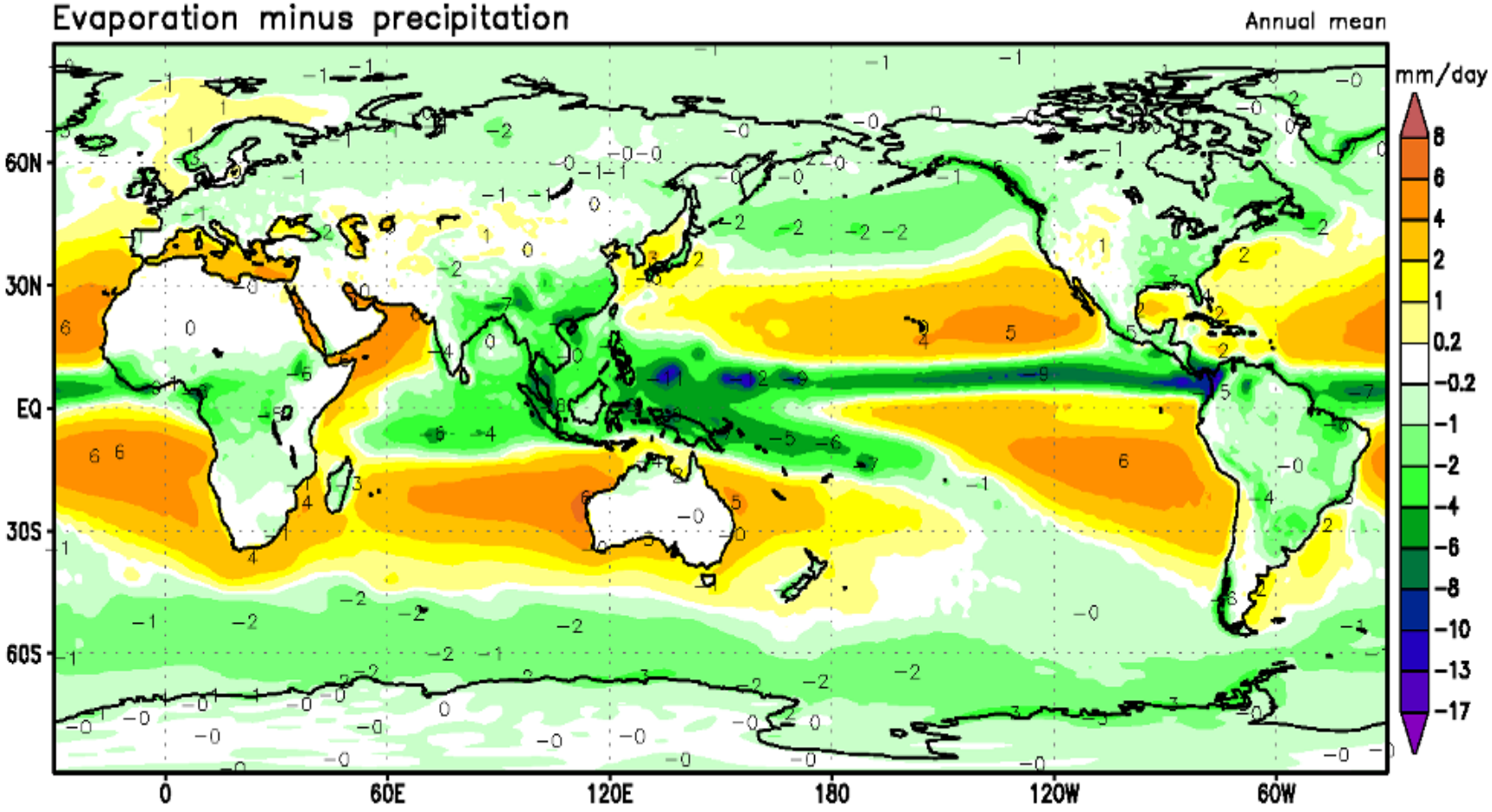


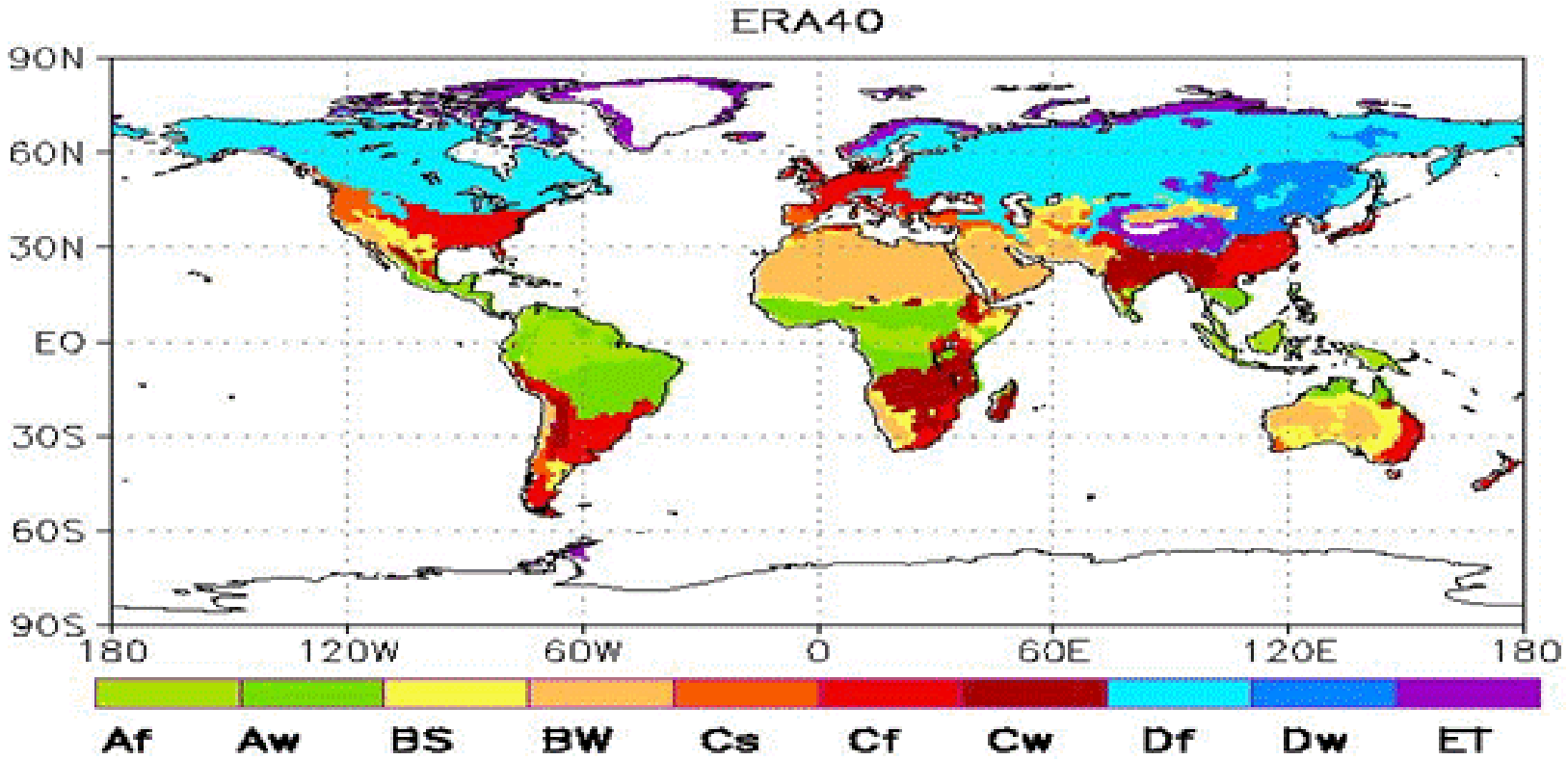
Zonal wind in summer



Transport of water vapour

Evaporation-Precipitation





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Köppen (1846-1940)

Climate classification system

- **Example for D: coldest month < -3°C, warmest month > +10°C**

Theories of the general circulation

Edward Lorenz

The Nature and Theory of the General Circulation of the Atmosphere

WMO, 1967

Available potential energy

- Kinetic energy in atmosphere is generated via temperature differences and transformed to kinetic energy mainly through the conversion of potential energy into kinetic energy in the extra-tropical cyclones. This was first realized by:
-
- Max Margules (1903): **Die verfügbare kinetische Energie**
- And later developed by
- Edward Lorenz (1955, Tellus): **Available potential energy**

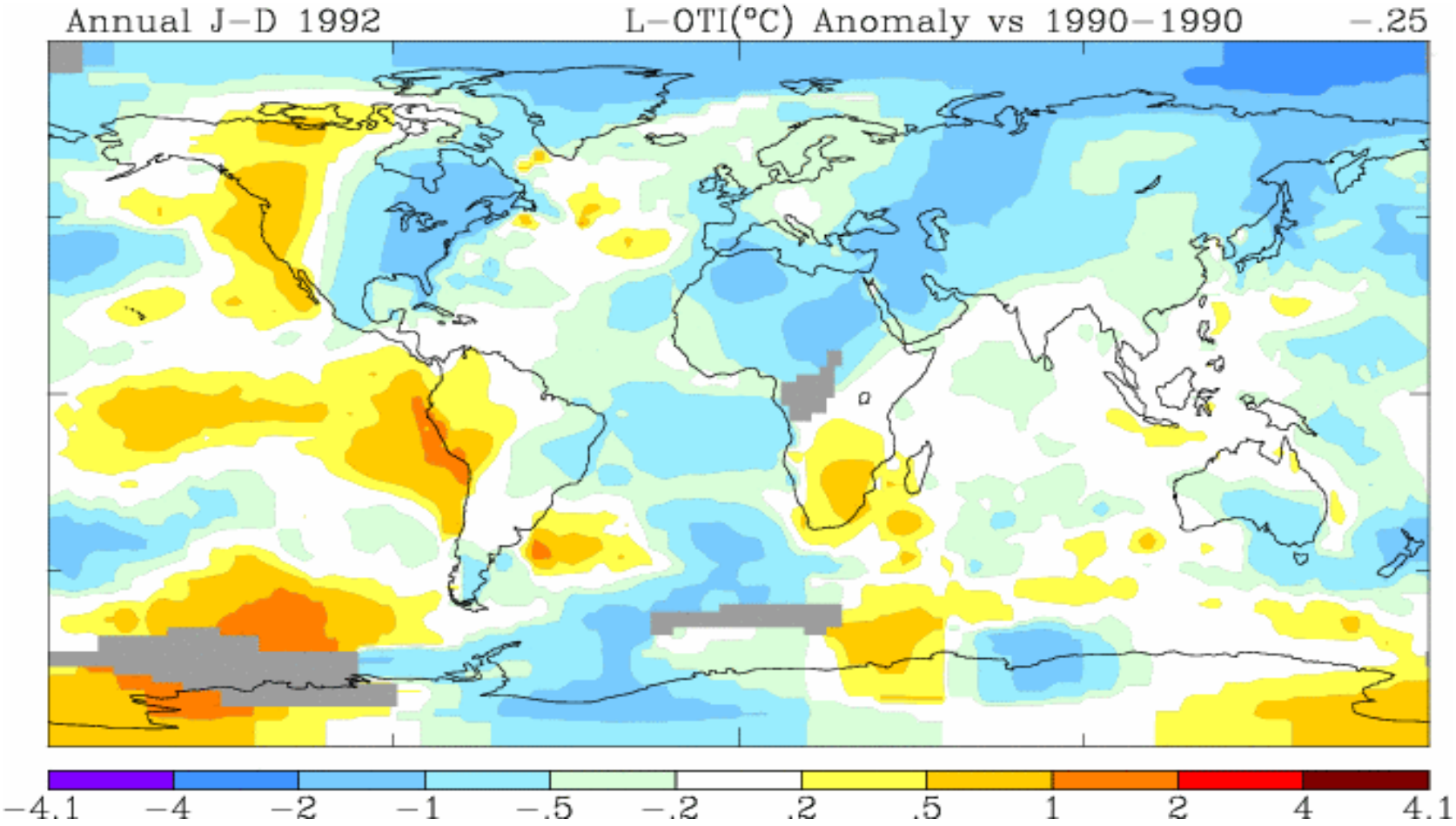
The amount of generated kinetic energy is ca 3 Wm^{-2}

This is only ca 1% of the incoming energy from the sun and this is why solar energy is ca 100 times larger than wind energy. The atmosphere is an engine with a poor efficiency.

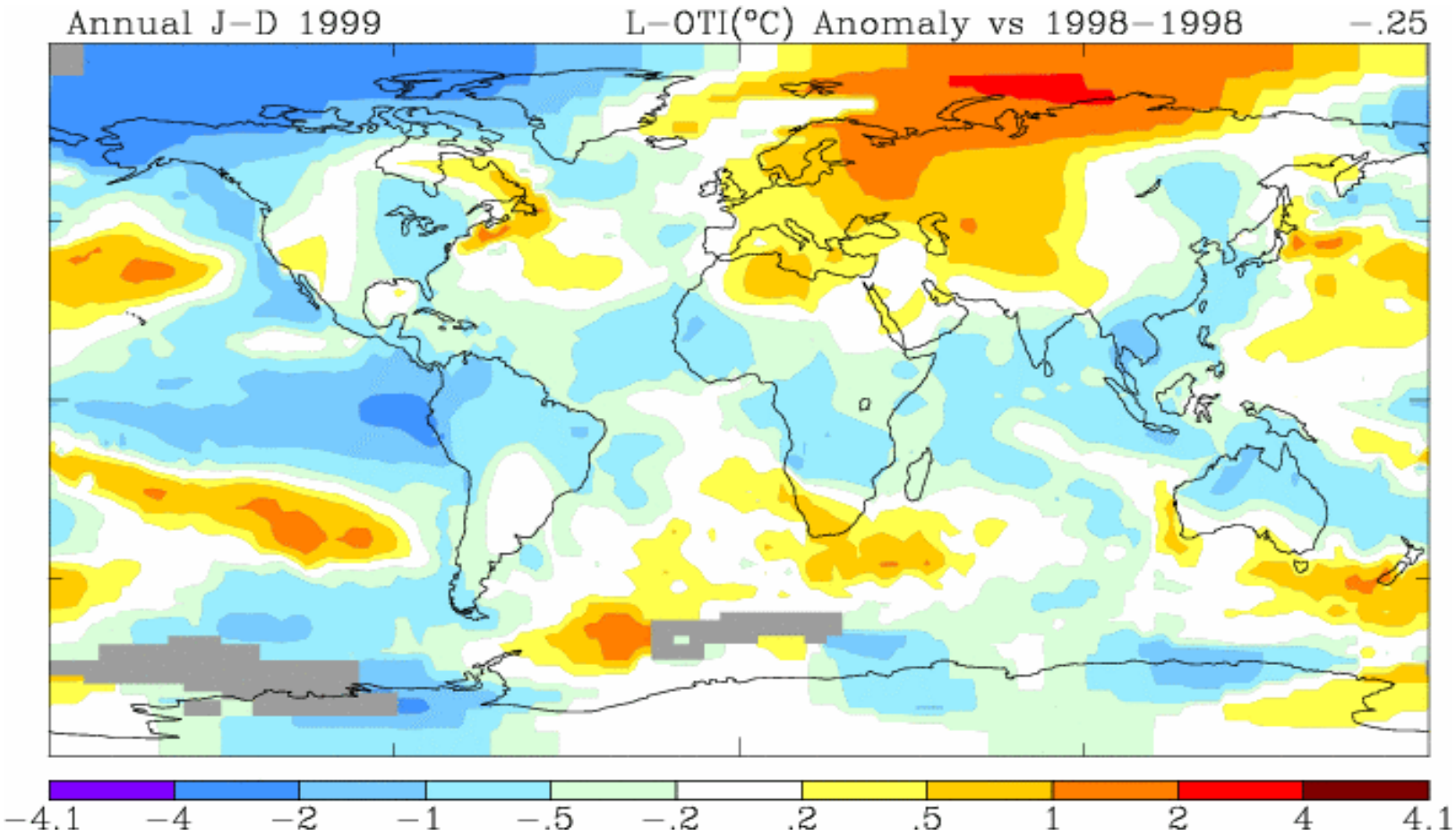
Climate variability

- How can we separate natural climate variations from climate variations that are due to external processes including changes in greenhouse gases and aerosols?

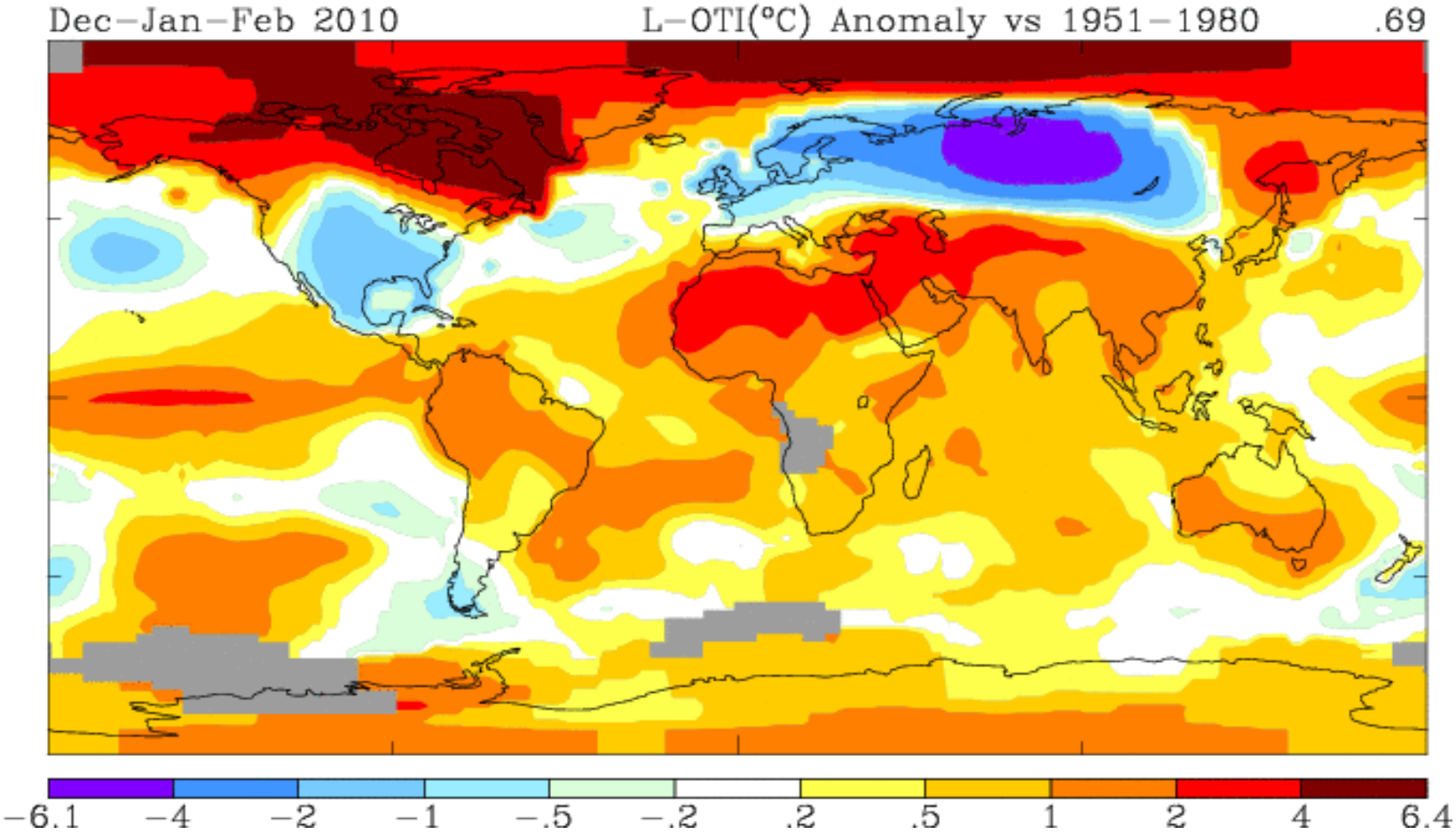
Surface cooling after the Pinatubo eruption June 1991



Global cooling after the 1998 El Nino



Global temperature anomaly for the winter 2009/2010



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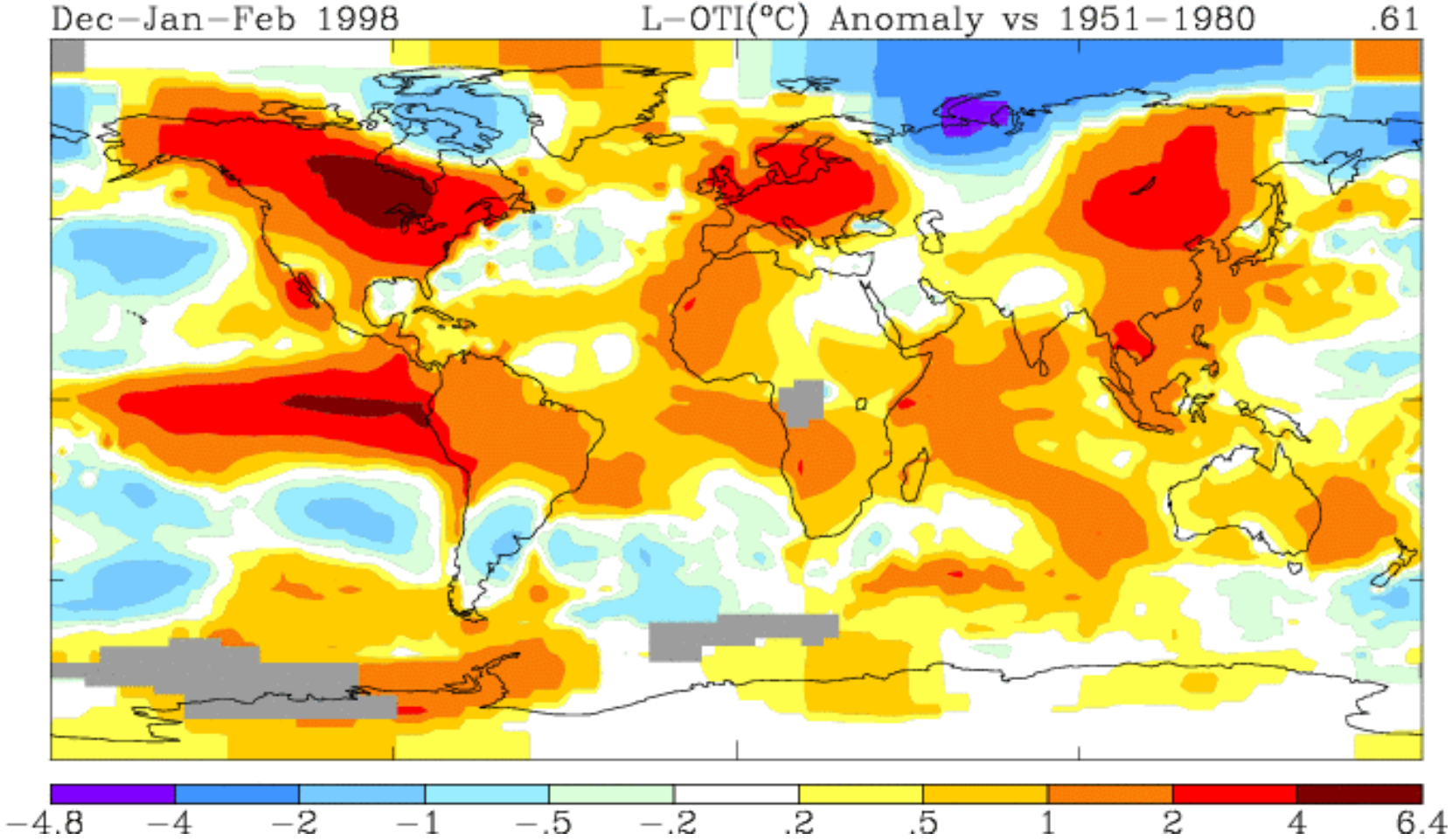


Climate predictability

- How predicable is climate and how do we separate weather predictability from climate predictability?

- E. Lorenz: **Predictability of the first kind**

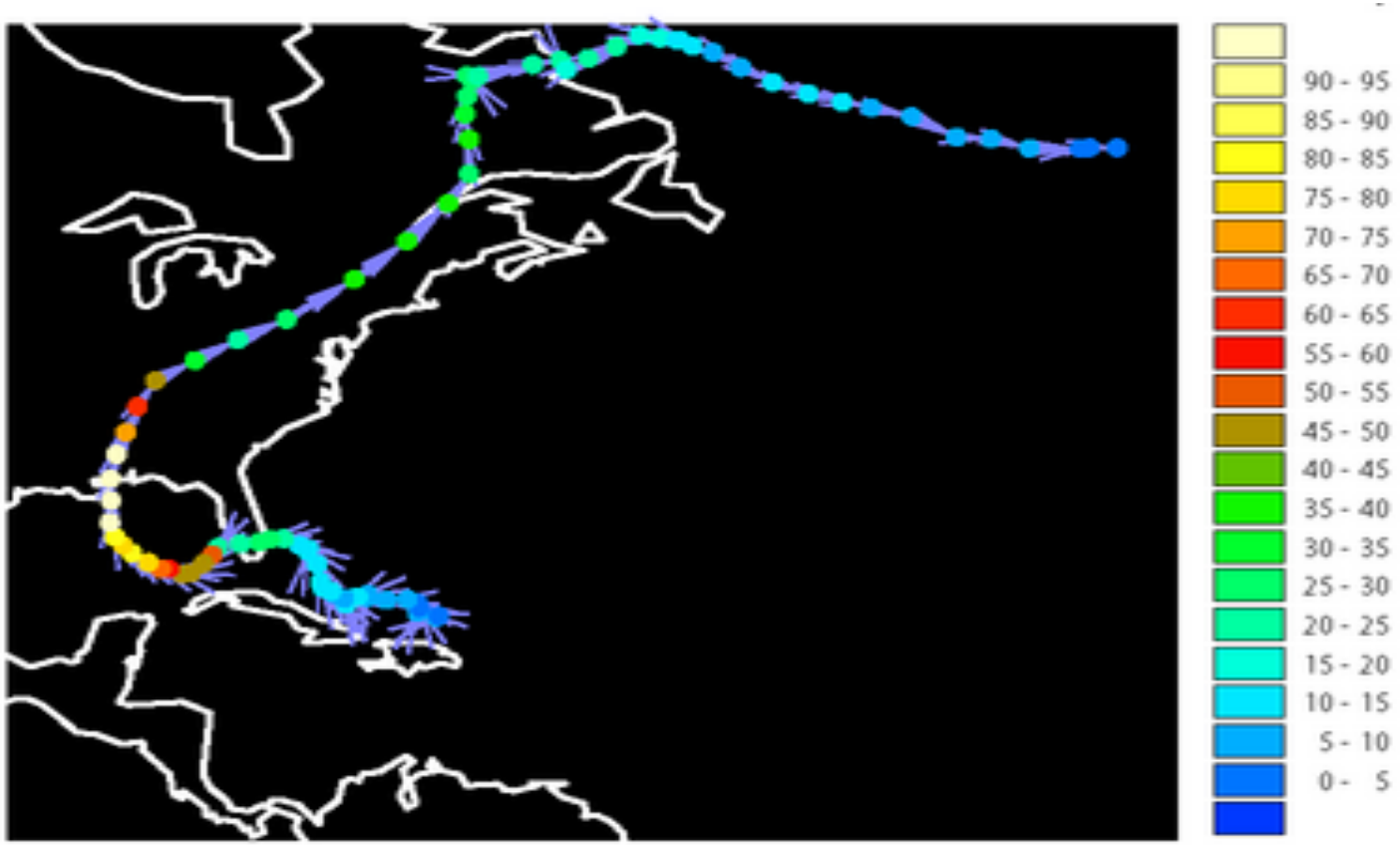
  Predicting when and where certain weather pattern will occur

- E. Lorenz: **Predictability of the second kind**

  Predicting persistent deviations from the climate that is changes of the present statistics of weather

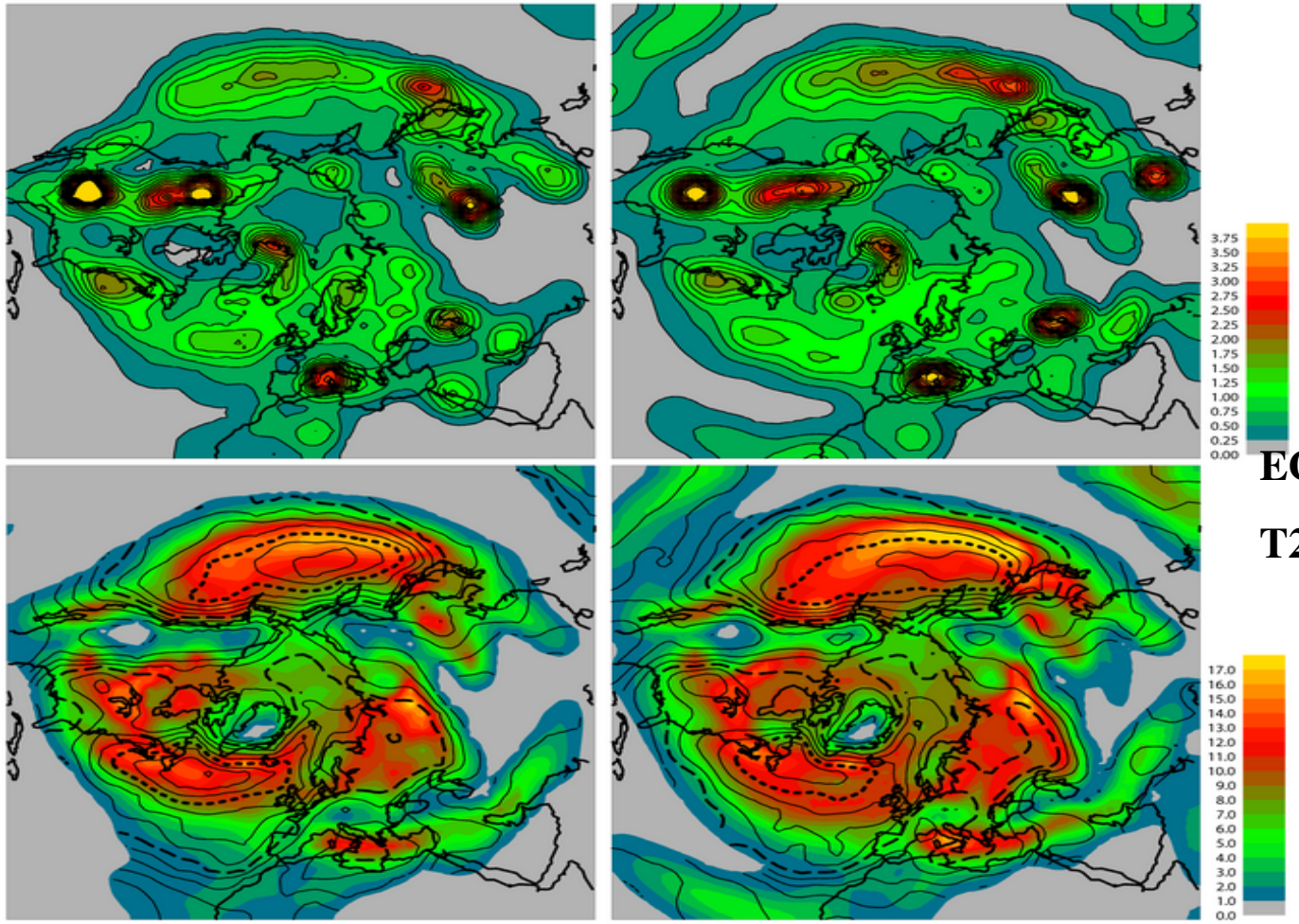
Hurricane Katrina August 2005

ECMWF operational analyses, 850 hPa vorticity

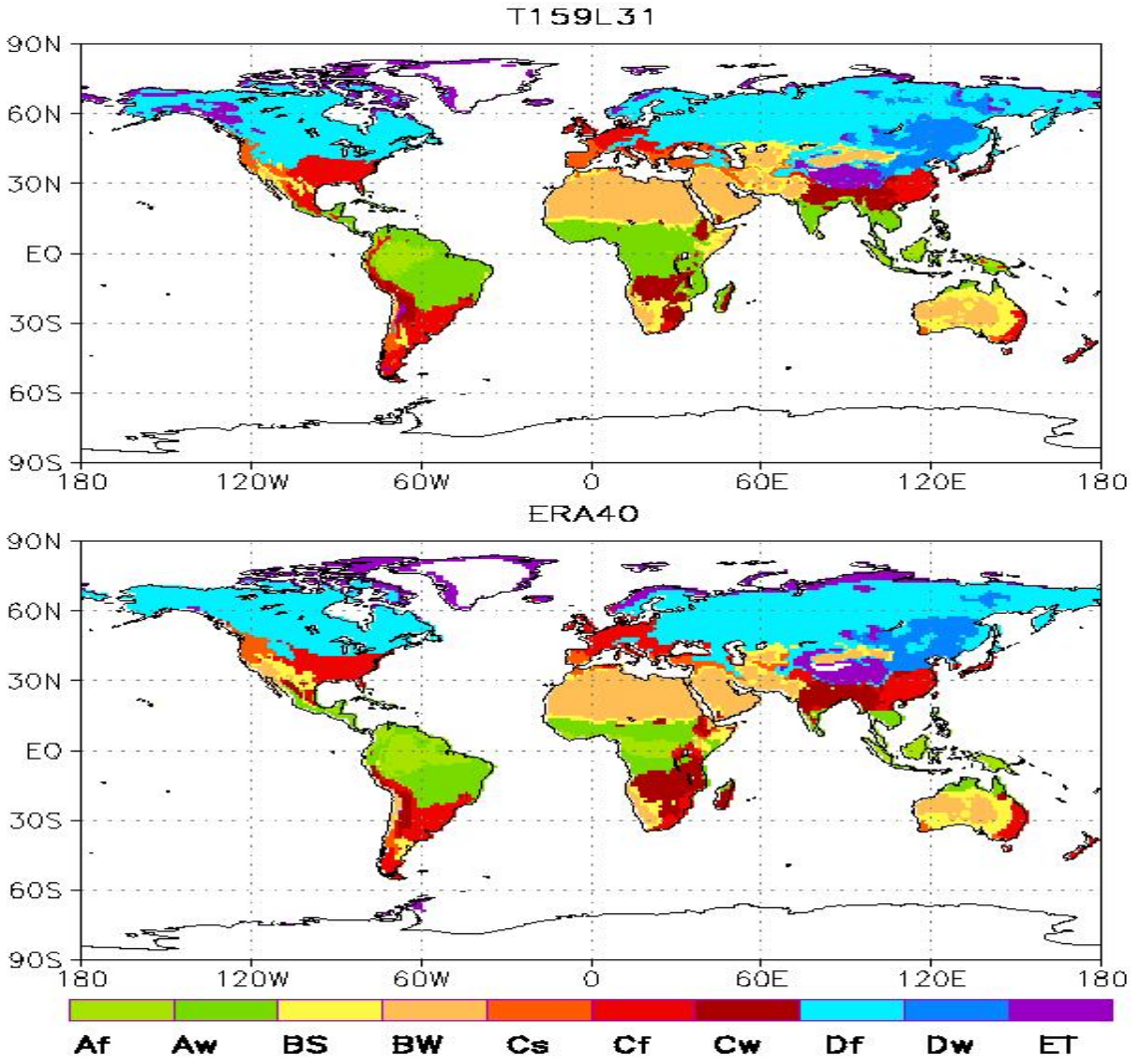


(c)

Storm track genesis (top) and storm track density (below) for DJF 1970-1999
left ERA40 analysis, right ECHAM5 (Clim.run, T213)



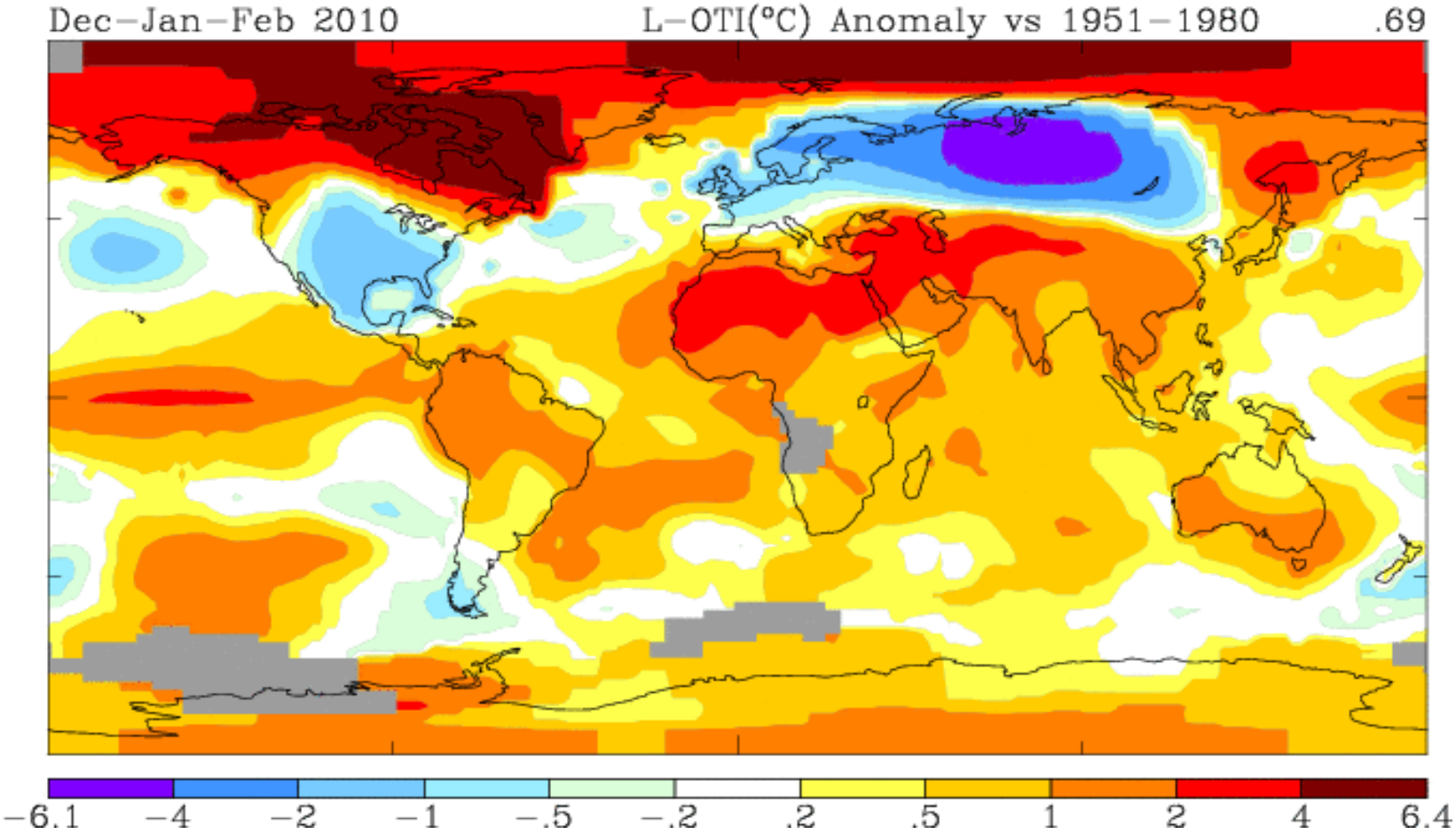
Köppen climate zones



Modeled climate

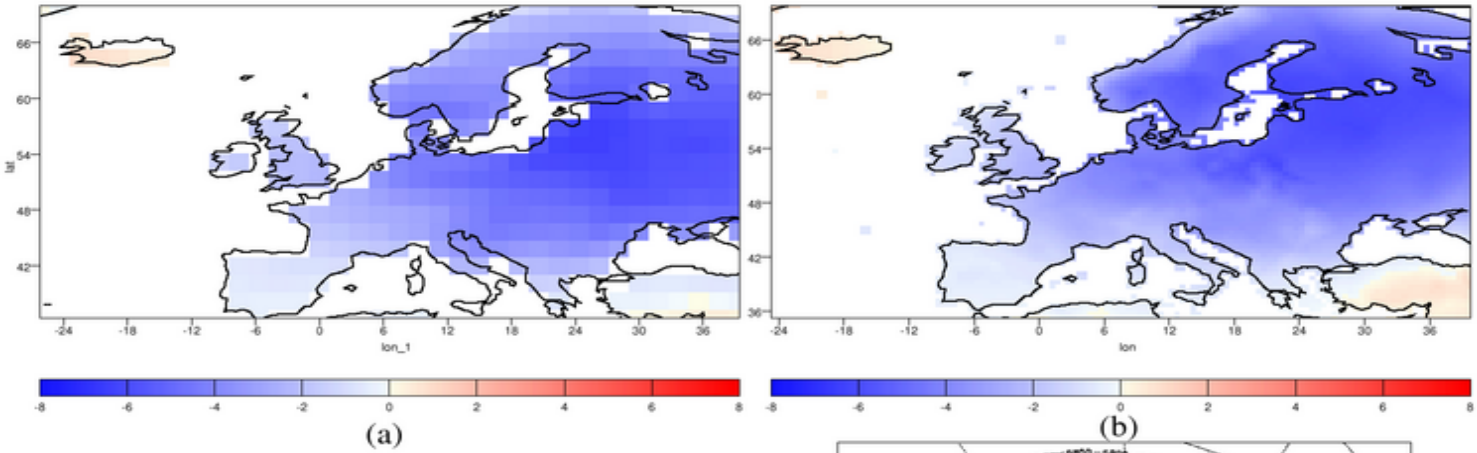
Observed climate.

Global temperature anomaly for the winter 2009/2010



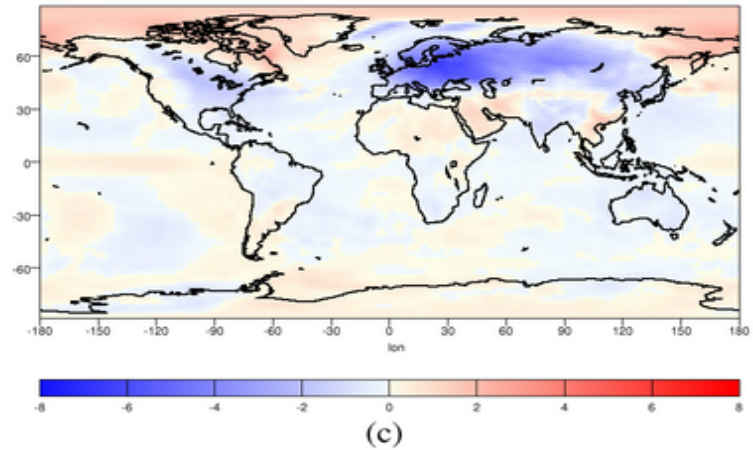
Ten coldest European winters
model and "observations" (Luterbacher, 2005)

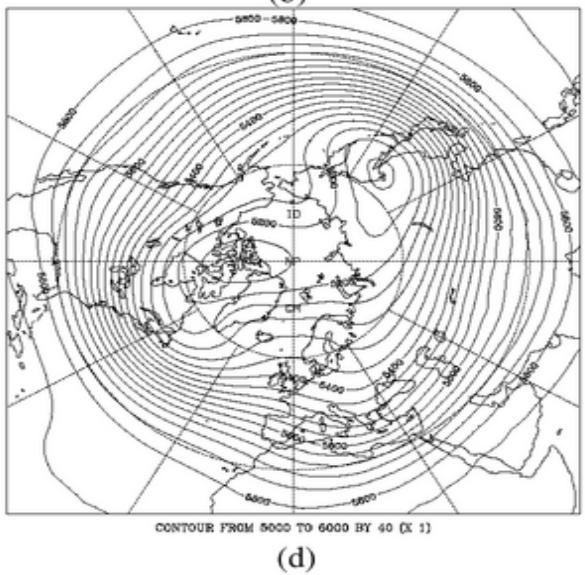
Model



Obs

Model global anomaly

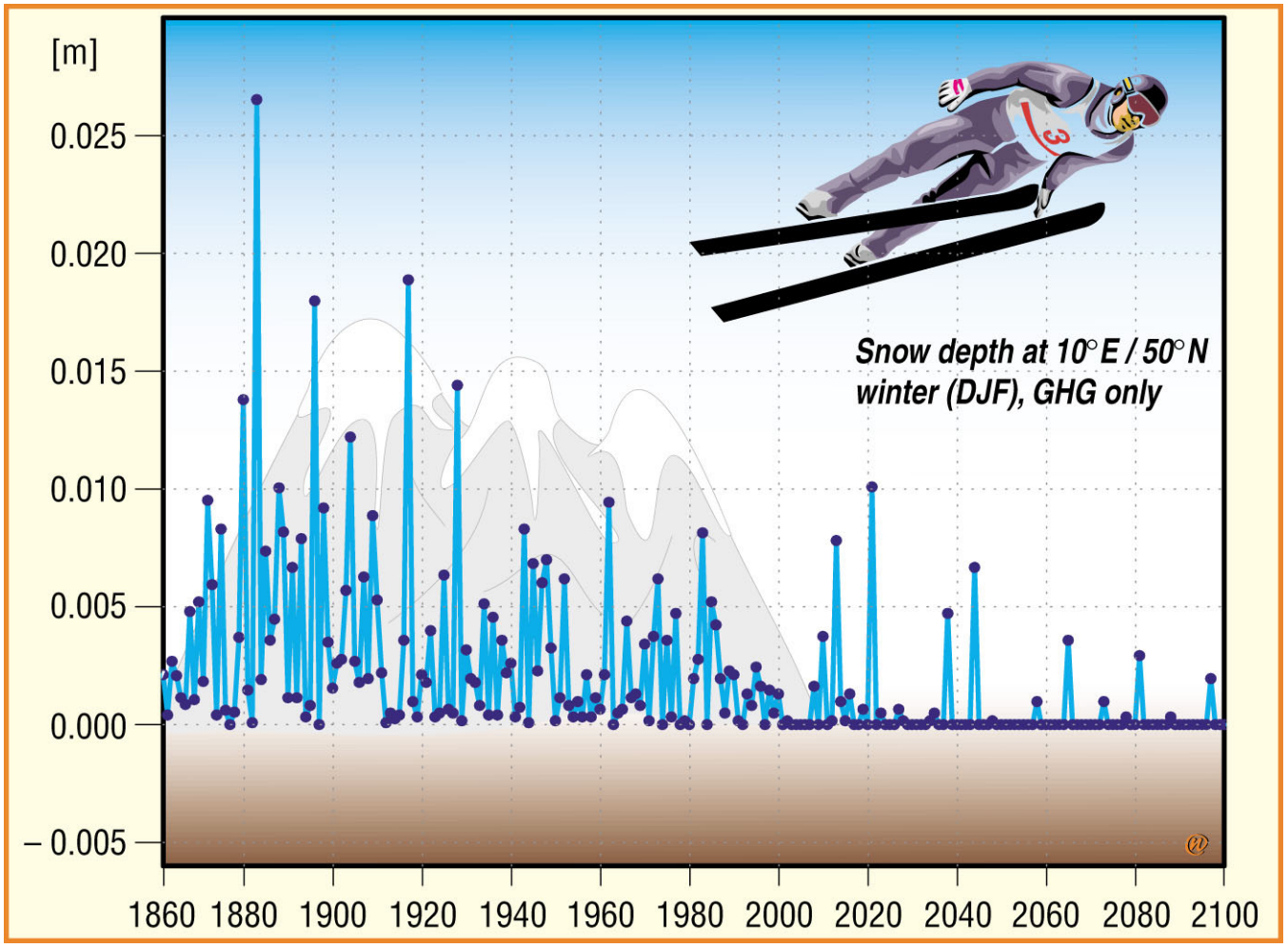




Model height 500 hPa

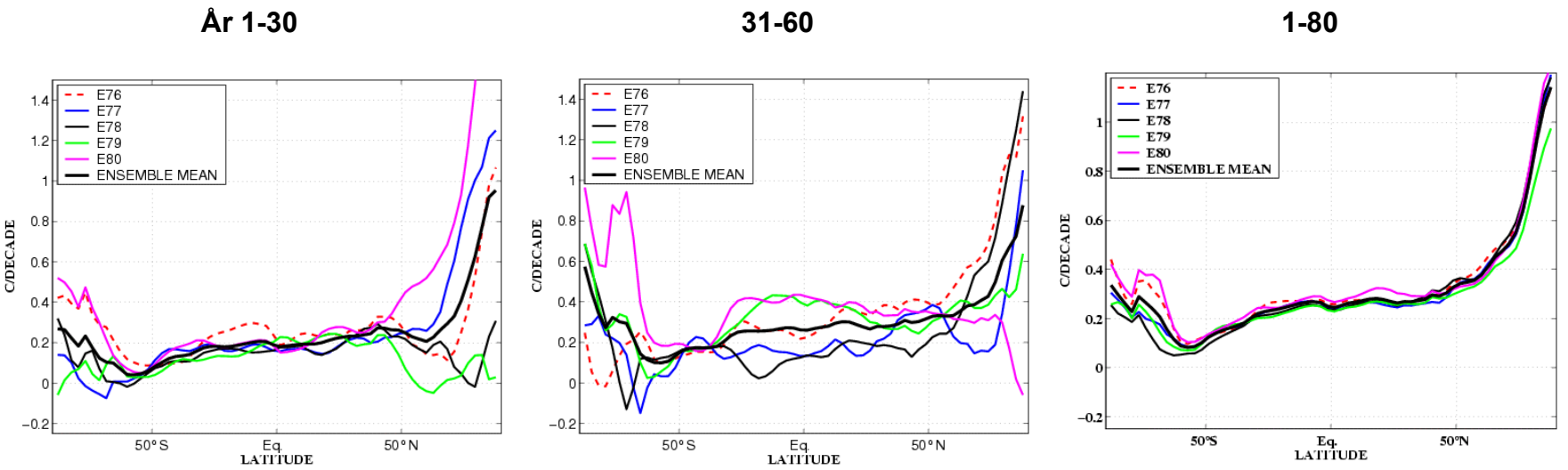
Example of climate variability in a model

- ***Predictability of snow in Germany***



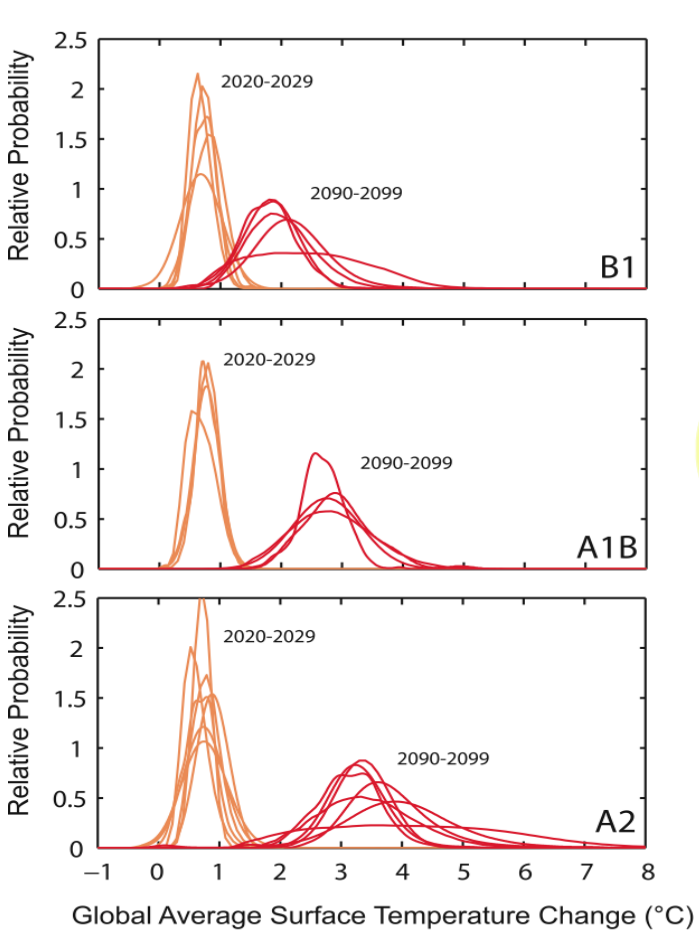
Zonal mean temperatur change
Bergen Climate model

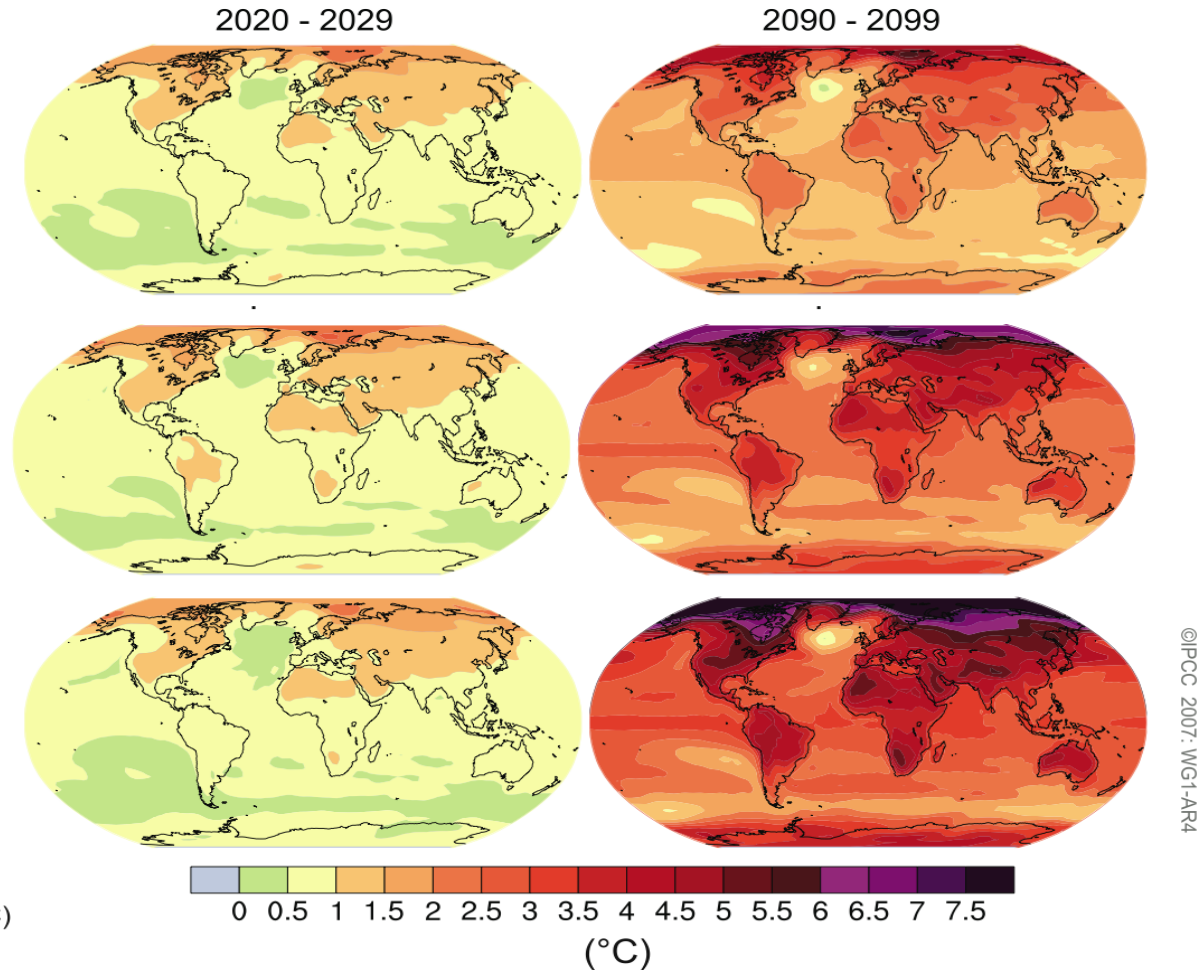
Trend (°C/10-år)



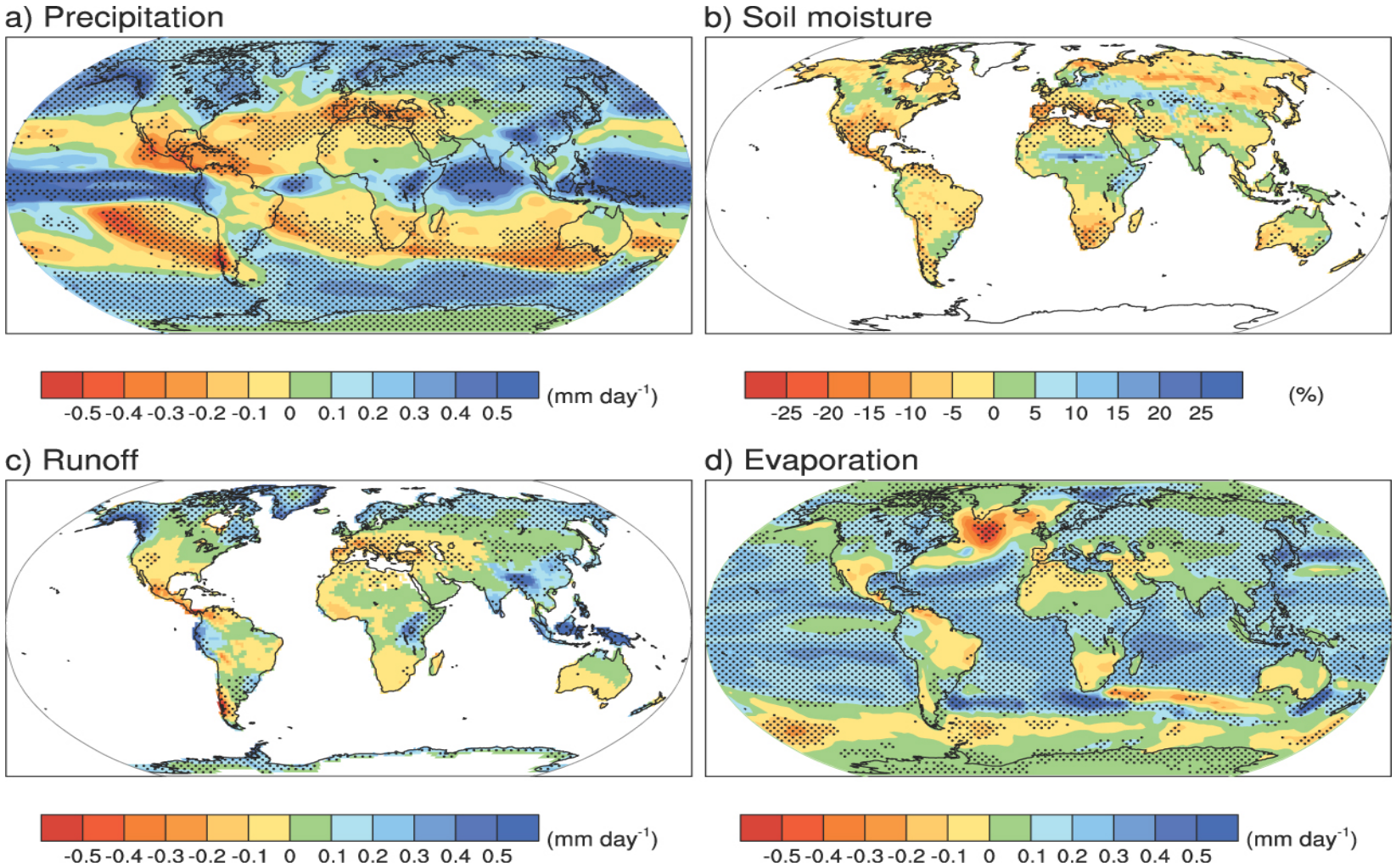
IPCC projections of the surface temperature changes for two decades of the 21st century

(compared to the end of the last century)

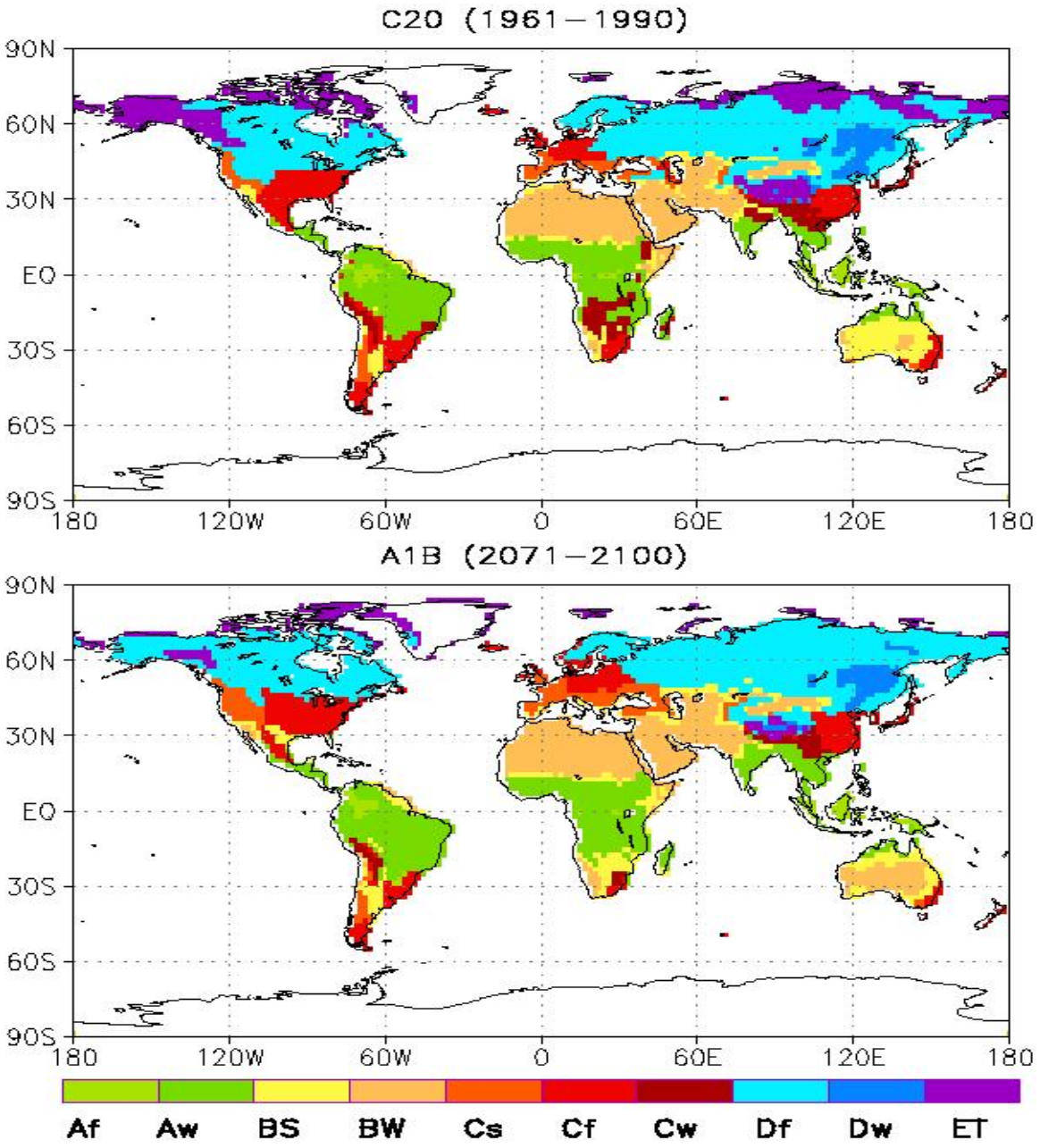




Changes in the hydrological cycle



Present climate



MPI Hamburg climate model

Future climate

Köppen climate zones

Is the climate of the Earth unique?

- Assume that we start from an Earth with an atmosphere and ocean at rest, with uniform temperature and without any form of vegetation.
- How will it respond to the present solar radiation?
- Will the climate obtain any form of steady state?
- Will it be different from the present climate?
- How long time will it take?

Is the climate of the Earth unique?

- We do not really know.

- However, if we start a model integration from present ocean temperatures than an atmospheric model with “interactive vegetation” does reproduce the present observed climate with very small deviations.

- If we start from an ocean at constant temperature the result is likely to strongly depend on the initial sea surface temperature. It may be unique but it will require very long integrations

Climate stability

- How stable is the present climate?
- How likely are irreversible changes of the climate?
- What are the theoretical ground for “tipping points”

Climate stability

- The global change in radiation between an ice-age and an inter-glacial is small but regional changes are substantial.
- Is is possible that the global climate can change into a different climate if exposed to greenhouse gases over a few centuries?
- If the land ices on Greenland or Antarctica melt below a certain limit will it at all recover?
- Could a super volcanic eruption or a nuclear war through the climate into an ice age?
- Will the Earth climate change into a Venus climate if green house gases increase beyond control?

Climate stability

Some tentative answers

- The global change in radiation between an ice-age and an inter-glacial is small but regional changes are substantial.

- Is is possible that the global climate can change into a different climate if exposed to high concentration of greenhouse gases over a few centuries? (Cannot be excluded)

- If the land ices on Greenland or Antarctica melt below a certain limit will it at all recover? (Probably not)

- Could a super volcanic eruption or a nuclear war through the climate into an ice age? (Not very likely)

- Will the Earth climate change into a Venus climate if greenhouse gases increase beyond control? (Highly unlikely)

END

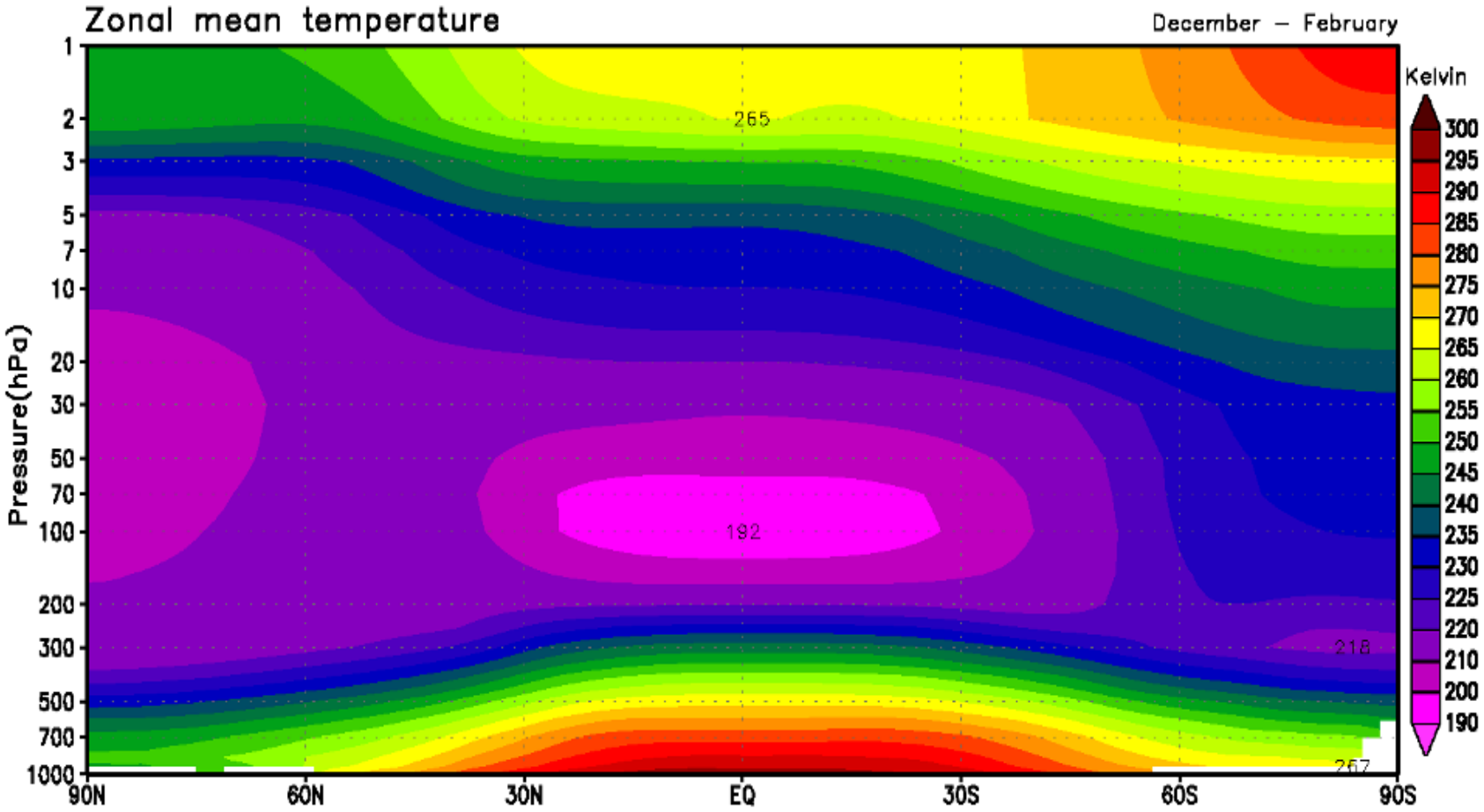
Determining the state of the climate

- Climate is nothing else that the integral of the weather and associated parameters over a suitable period of time.
- 30 years is often seen as a suitable time and has been used in traditional climatology for a long time. However, recent research suggest rather a longer period perhaps a century.
- While meteorological observations prior to WWII mainly consisted of surface observations the constitute today a magnitude of additional observations with global coverage and including the depth of the atmosphere from the surface to some 100 km above the ground.
- In order to bring this multitude of different observations together it is required to make use of data-assimilation of a kind presently used in weather prediction.
- So called re-analyses have been produced in recent years by different organizations including ECMWF, NOAA and JMA. Some of the results I will show are from these data sets.

The physics and dynamics of Climate

- What is climate?
- A well behaved chaotic system
- The predictability of climate

Zonal temperature in winter



Zonal temperature in summer