The general circulation in the atmosphere and oscillations in the climate system

Semjon Schimanke

Summer school, Askö, 2016

Semjon Schimanke

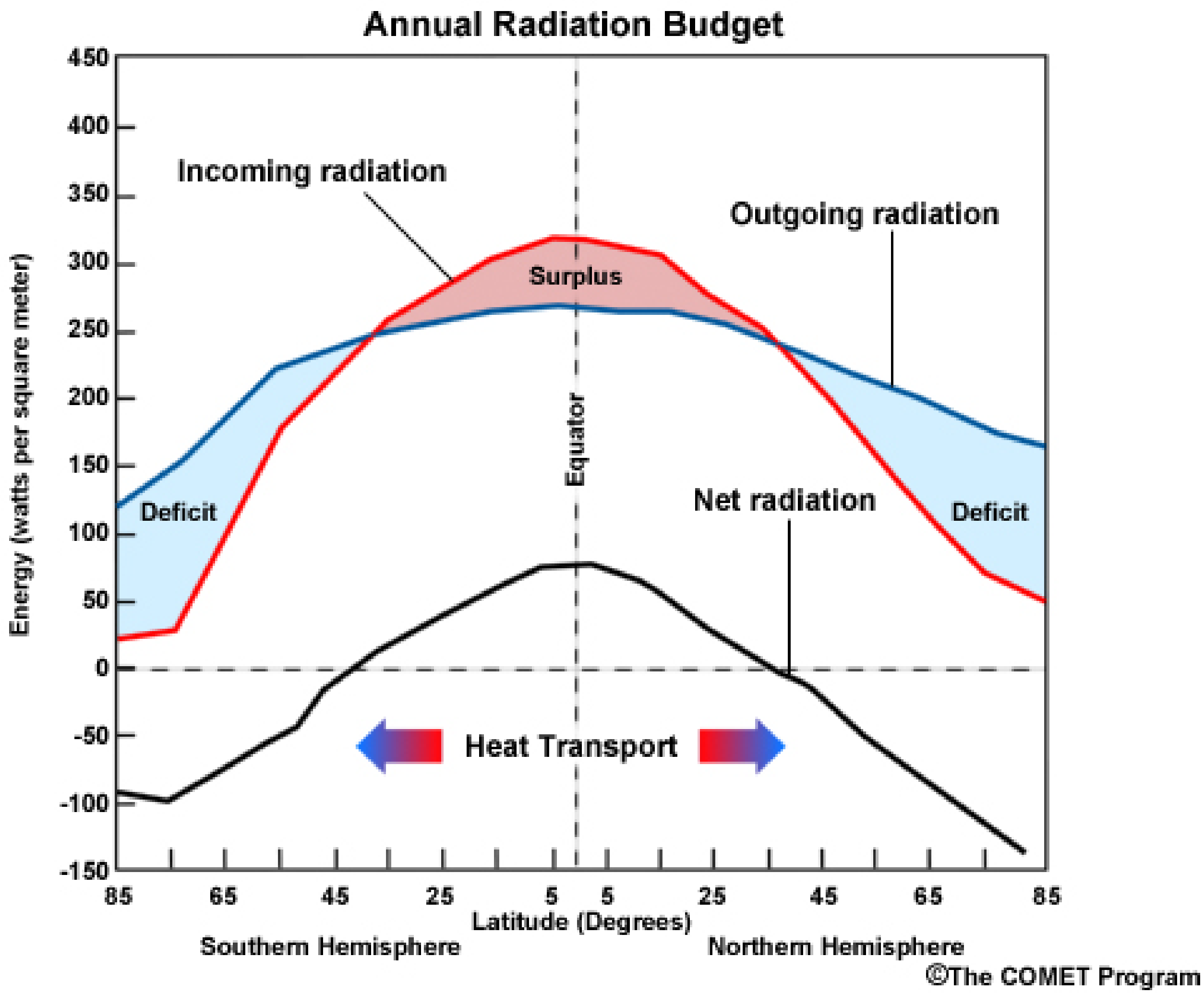
- study of meteorology at the Freie Universität of Berlin, 2001-2006
- doctoral thesis: “Sudden stratospheric warmings: Long-term variability and future trends”, 2011, FU-Berlin
- 2011-present, SMHI, research leader within the group of oceanographic research, topic: regional climate modelling for the Baltic Sea, the North Sea and the Arctic

Overview

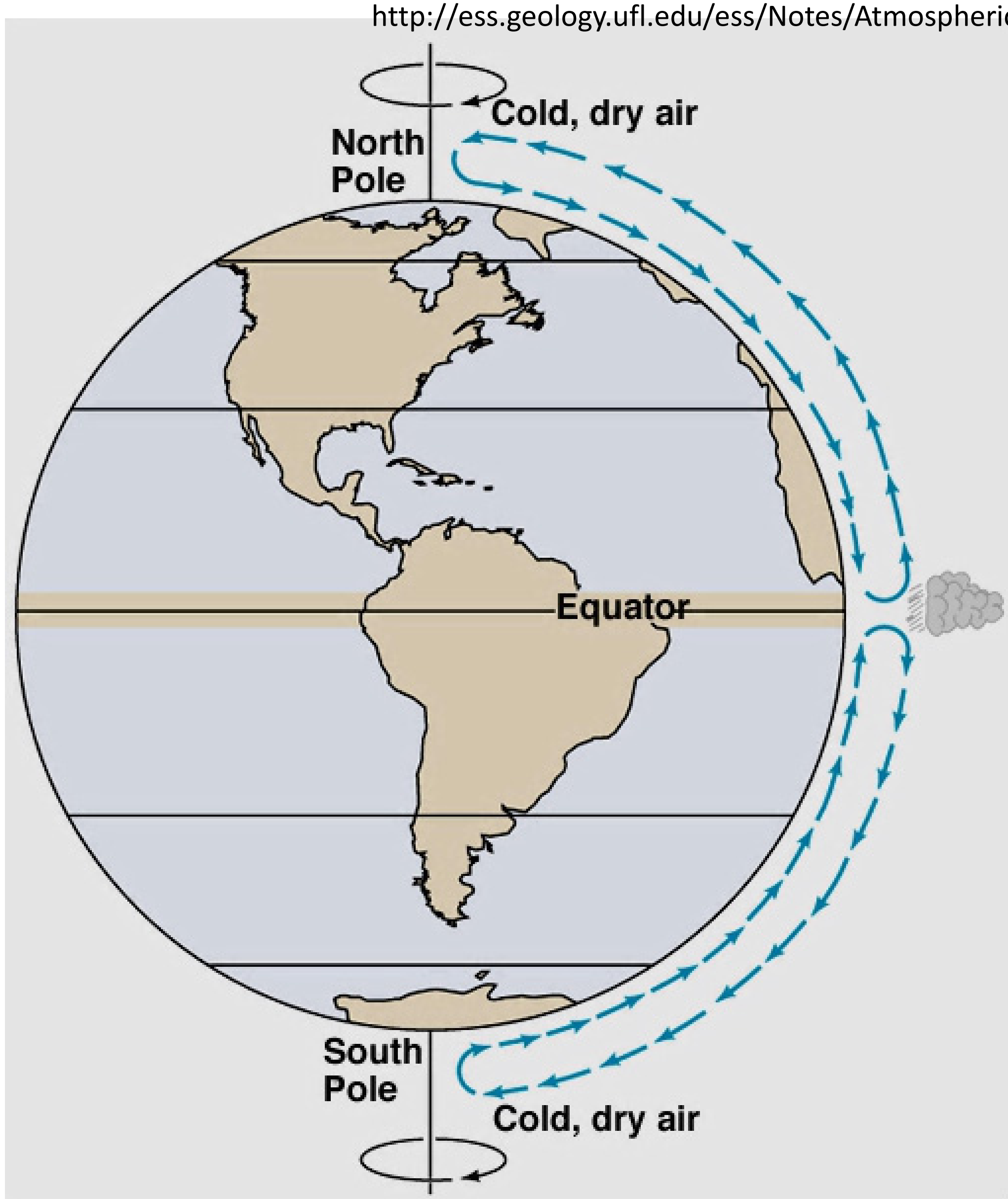
- the general circulation in the troposphere
- climate of the stratosphere
- large scale circulation patterns, e.g. NAO
- periodic oscillations in the climate system, e.g. ENSO, QBO

The general circulation in the troposphere

Energy balance of the earth

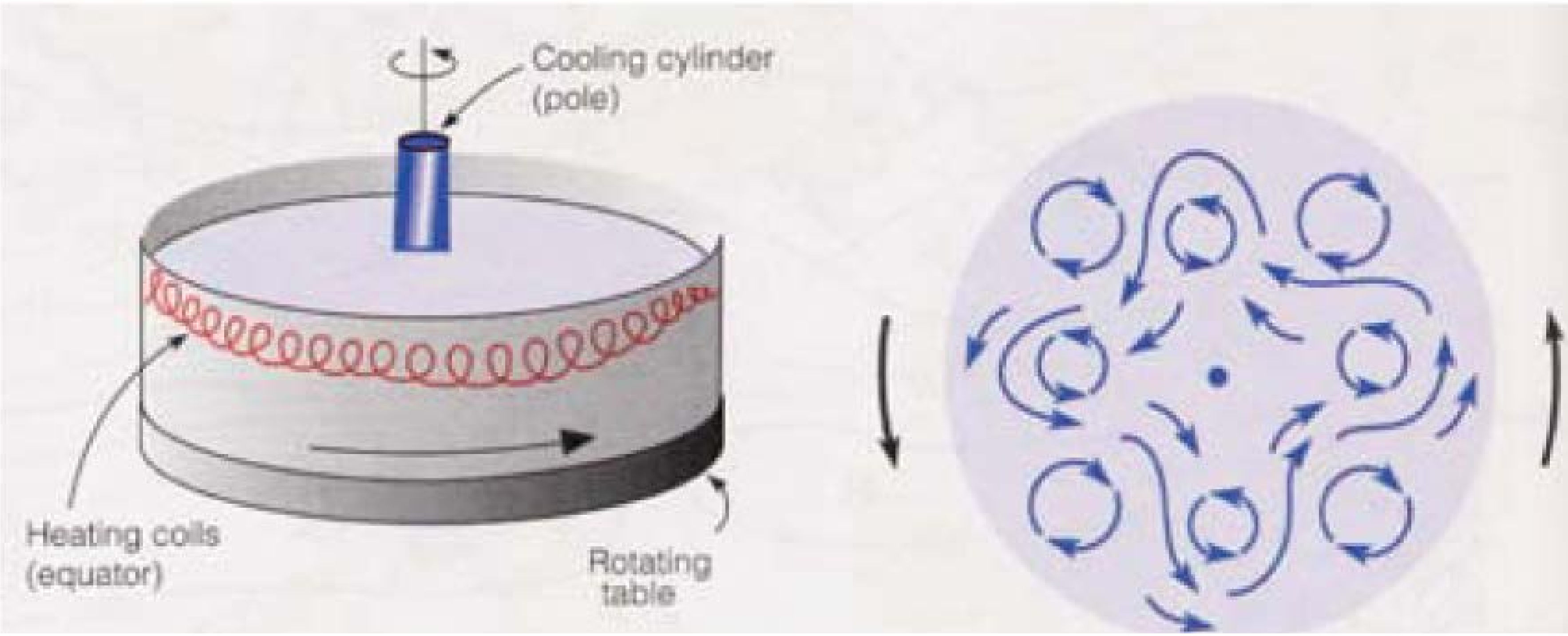


http://ess.geology.ufl.edu/ess/Notes/AtmosphericCirculation/atmosphere.html



Circulation without rotation of the earth

Laboratory experiments



Dishpan experiment (schematic)

Dishpan experiments

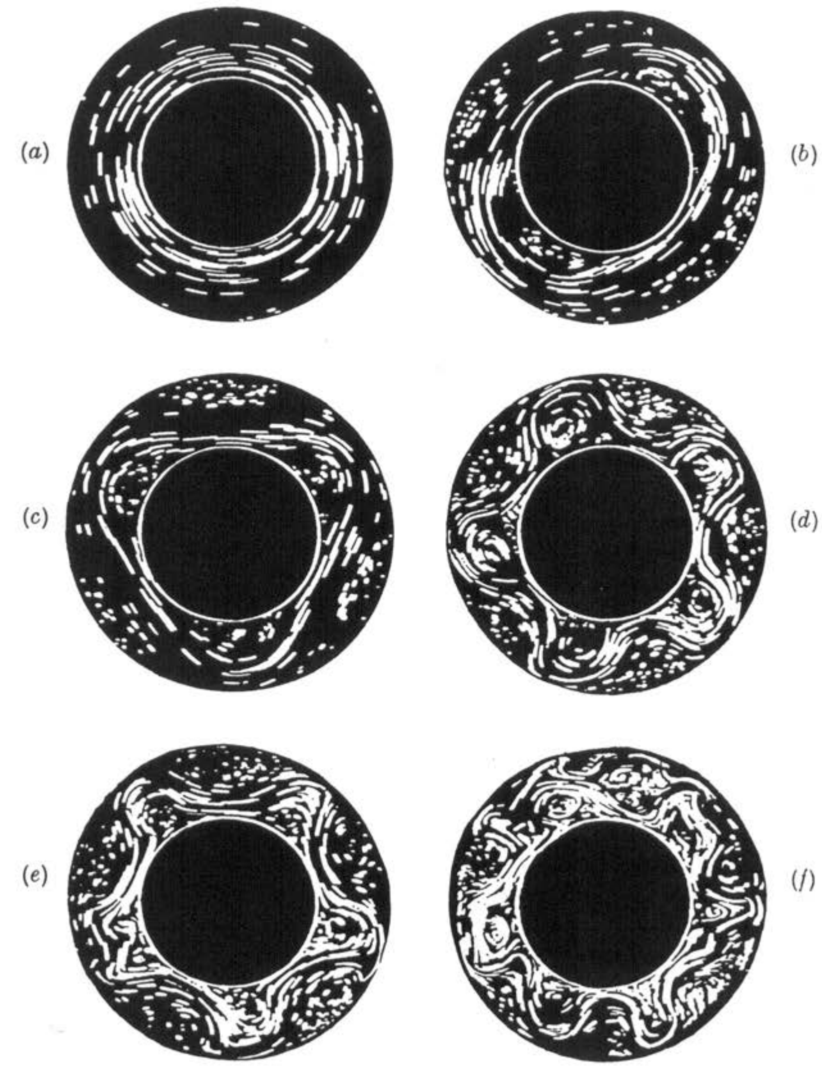
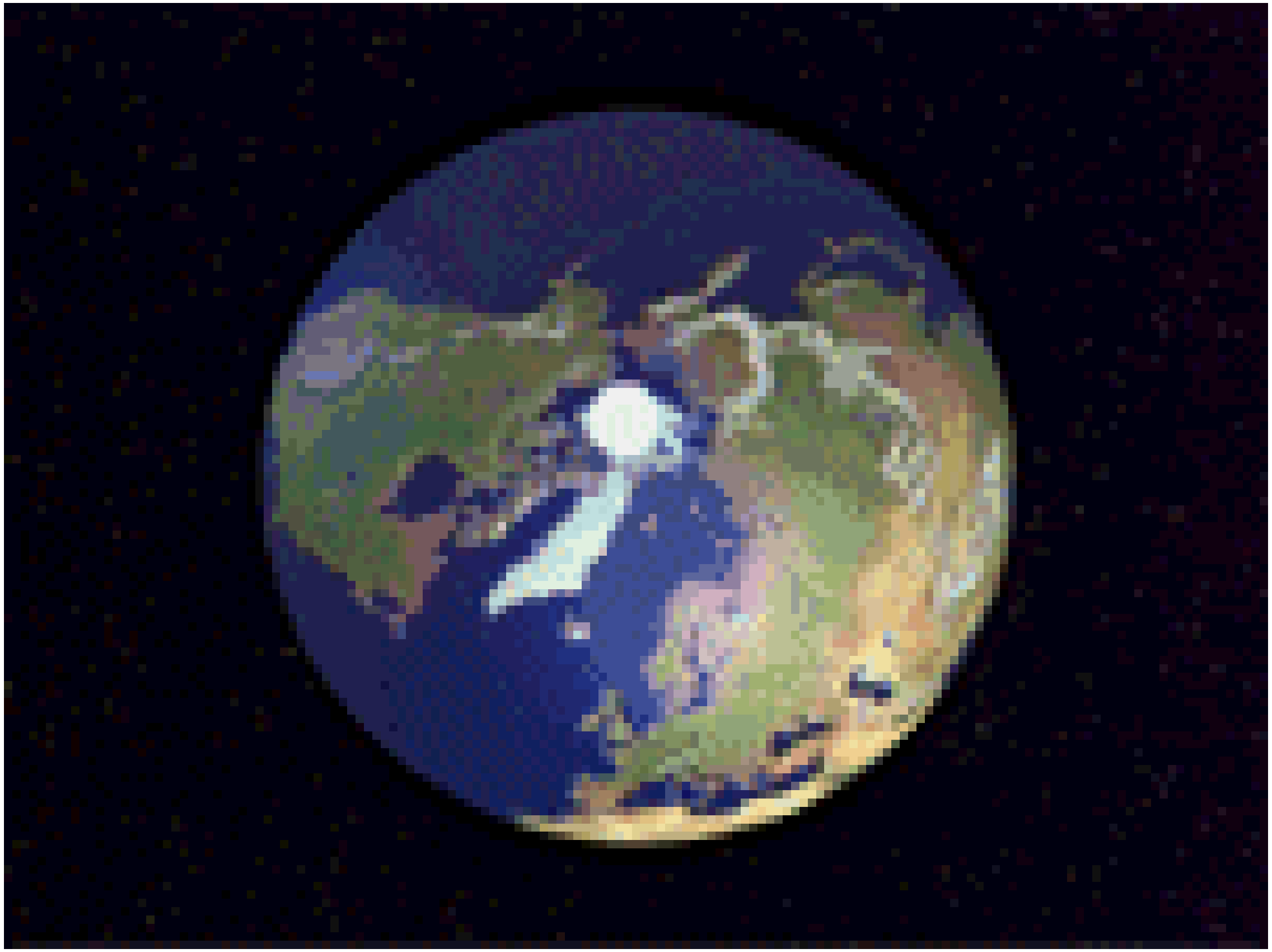


Bild VI.1.11 Experiment mit einem rotierenden Tank (Einzelheiten s. Text). Die Bildfolge demonstriert die Abhängigkeit des Strömungs-Typs von der Winkelgeschwindigkeit. Diese beträgt (Angaben in rad s^{-1}) 0,41 in Teilbild (a), 1,07 (b), 1,21 (c), 3,2 (d), 3,9 (e) und 6,4 (f). Aus Hide and Mason, 1975.

Coriolis force

When a particle on the rotating earth moves from one point to another, it is deflected. The force that causes this is called the Coriolis force (after Gaspard-Gustave de Coriolis, 1835). In the northern hemisphere it directs a moving particle to the right, in the southern hemisphere to the left.

The Coriolis force



Coriolis force

- The vector formula of the Coriolis force:

  $\mathbf{F}_c = -2m\,\boldsymbol{\Omega} \times \mathbf{v}$

  m = mass of the particle

  $\boldsymbol{\Omega}$ = angular velocity (with the direction along the earth axis and the magnitude equal to the rotation rate ω)

  v = velocity and direction of the particle

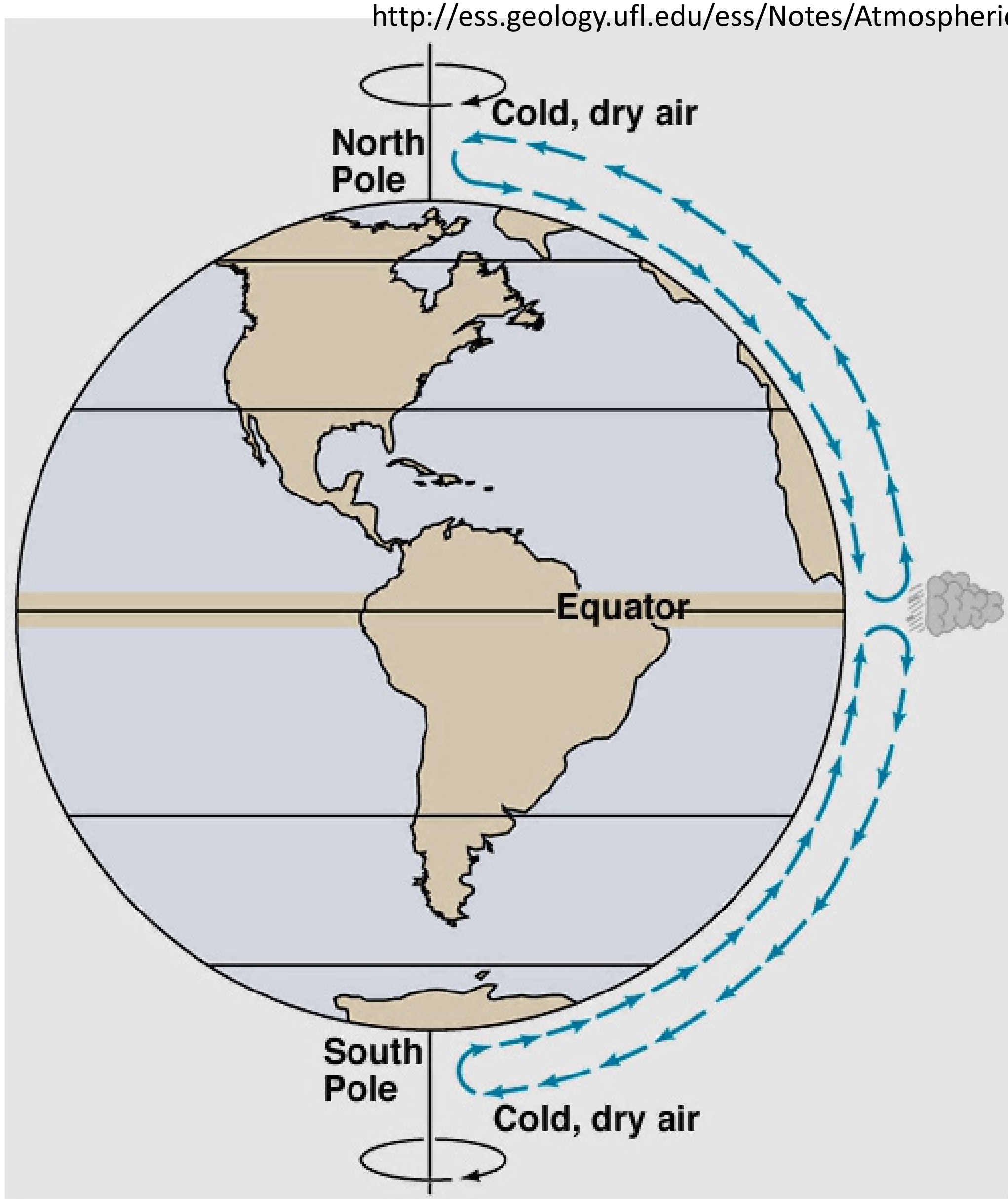
- quite common is also the use of the Coriolis parameter *f*:

  $f = -2\,\Omega \sin\phi$

  ϕ = geographical latitude

The Coriolis force acts on all movements, which are not parallel to the earth axis. (if $v \parallel \Omega \Rightarrow v \times \Omega = 0$).

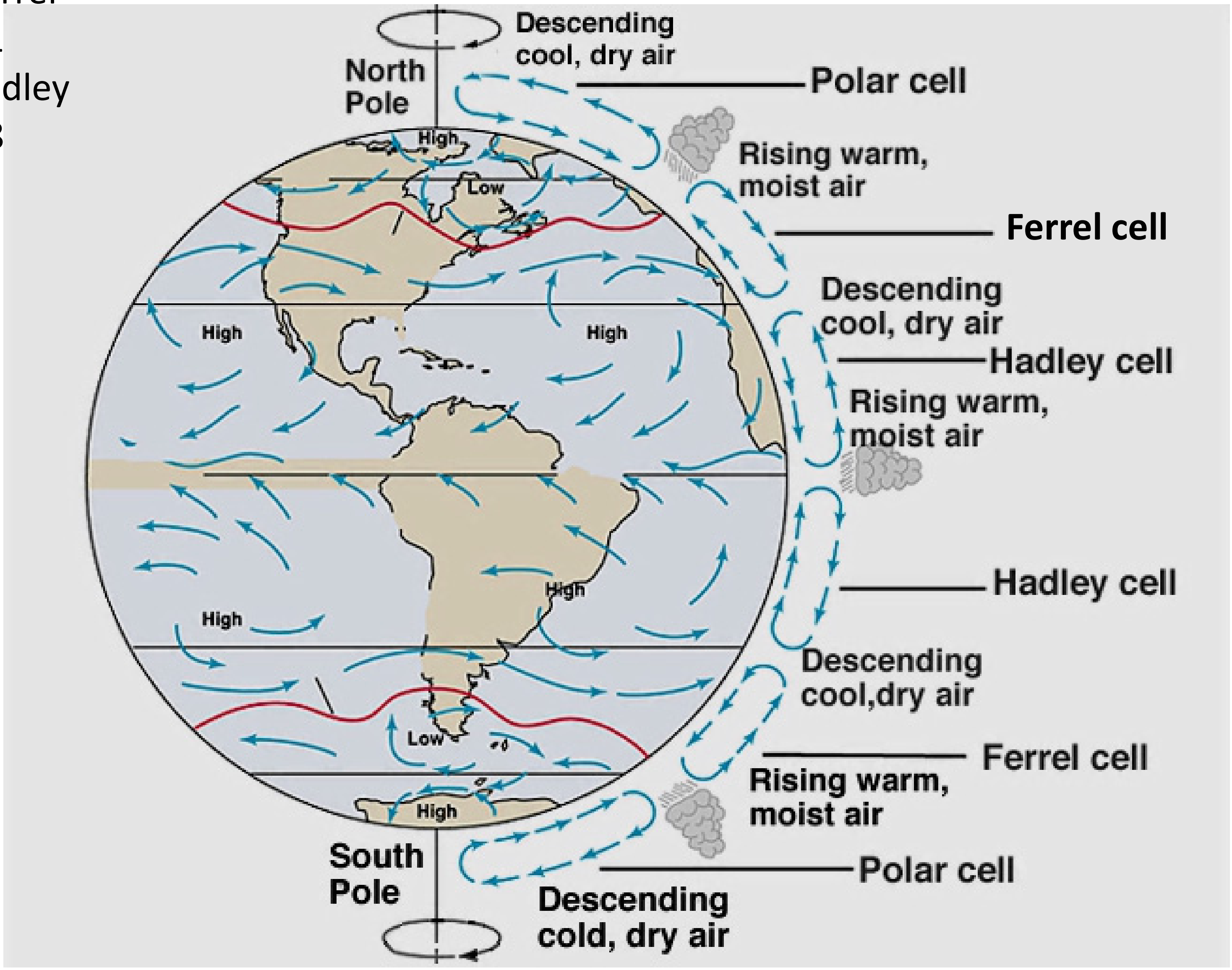
http://ess.geology.ufl.edu/ess/Notes/AtmosphericCirculation/atmosphere.html



Circulation without rotation of the earth

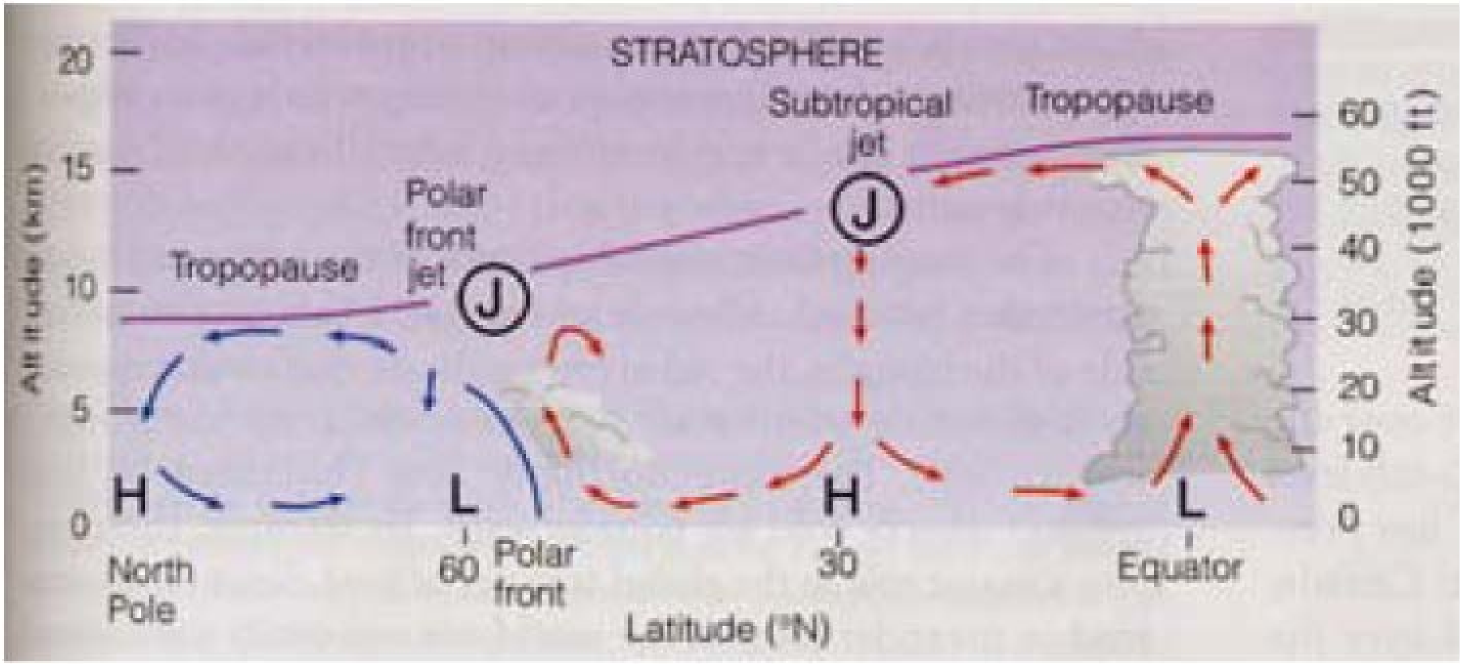
http://ess.geology.ufl.edu/ess/Notes/AtmosphericCirculation/atmosphere.html

William Ferrel
1817-1891
George Hadley
1685-1768



3-dimensional circulation on earth

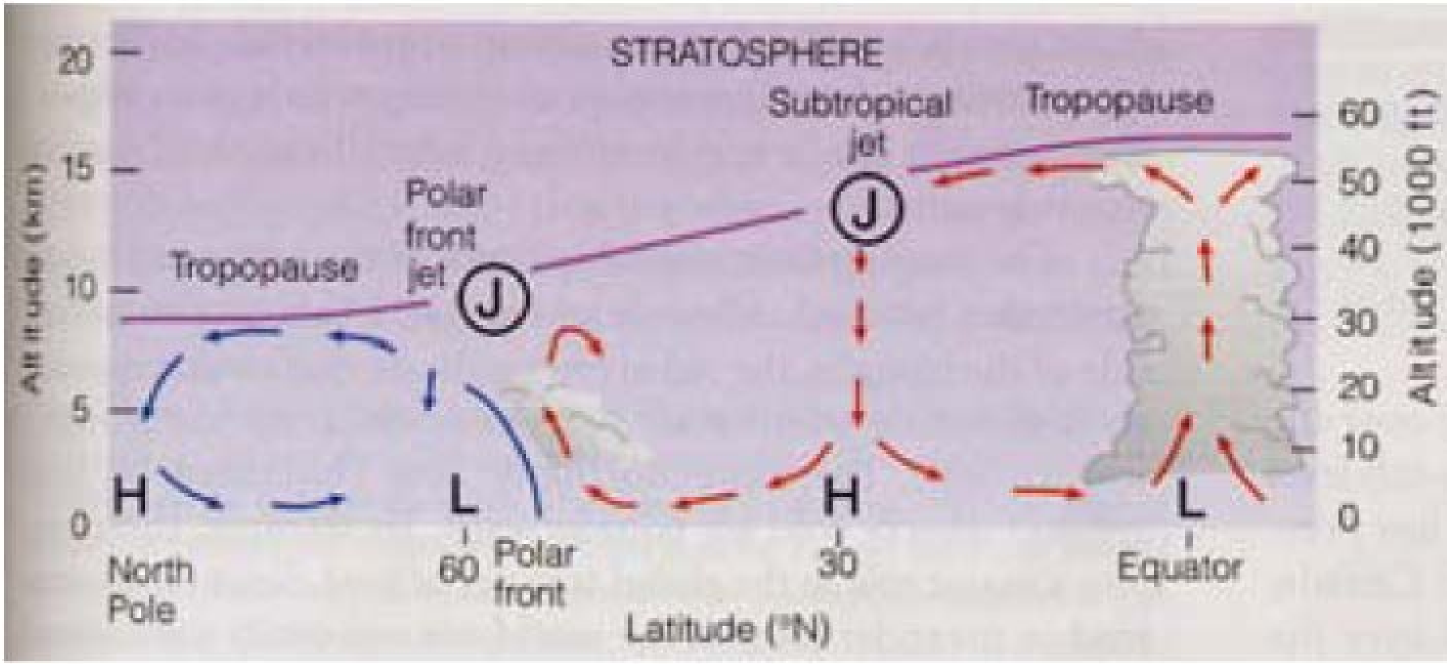
Meridional cross section



Hadley cell

- strong heating at the equator rises warm and moist air
- low pressure is prevailing at the surface of the equator while relative high pressure is present at higher levels
- sinking air in the subtropics cause generally high pressure at the surface and low pressure at higher latitudes
- balancing winds between high and low pressure close the Hadley circulation

Meridional cross section



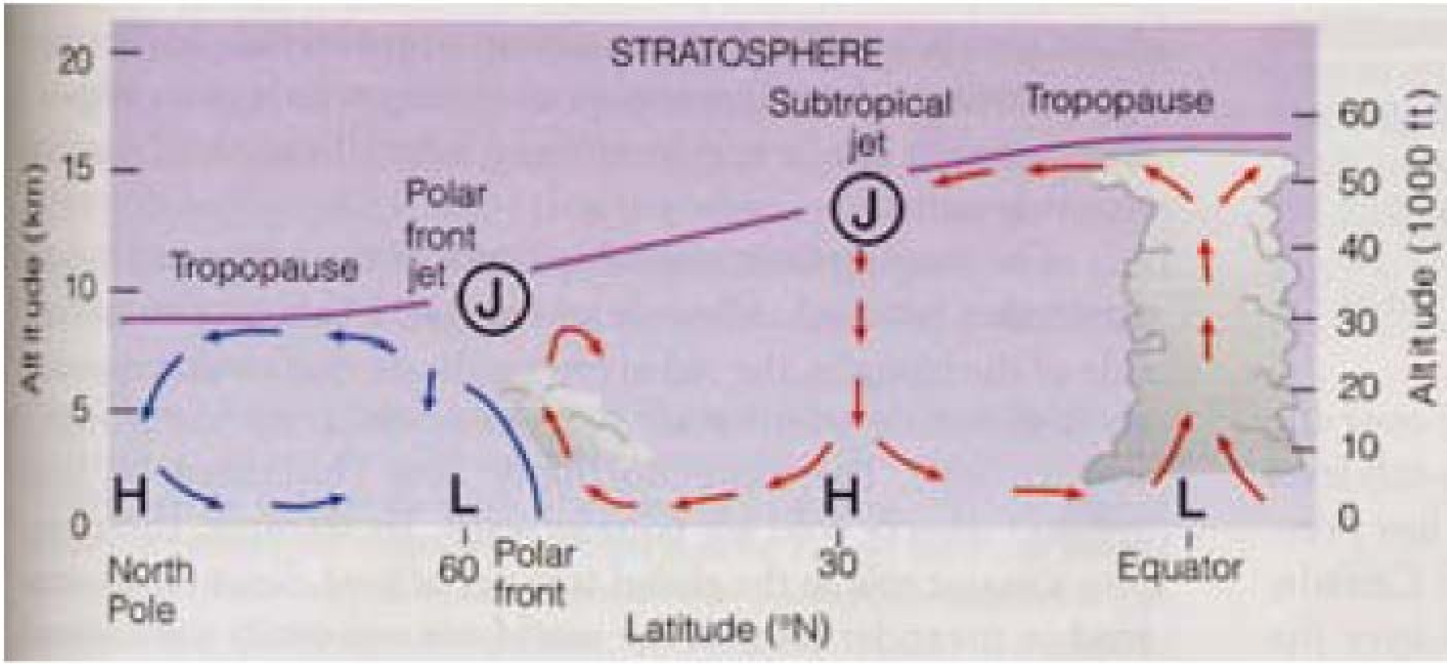
Polar cell

- driven by cooling (densening), air descends at the pole and creates cold and dry high pressure
- relative warm and moist air rises at 60°
- likewise the Hadley circulation, the polar cell is a thermally direct circulation

Ferrel cell

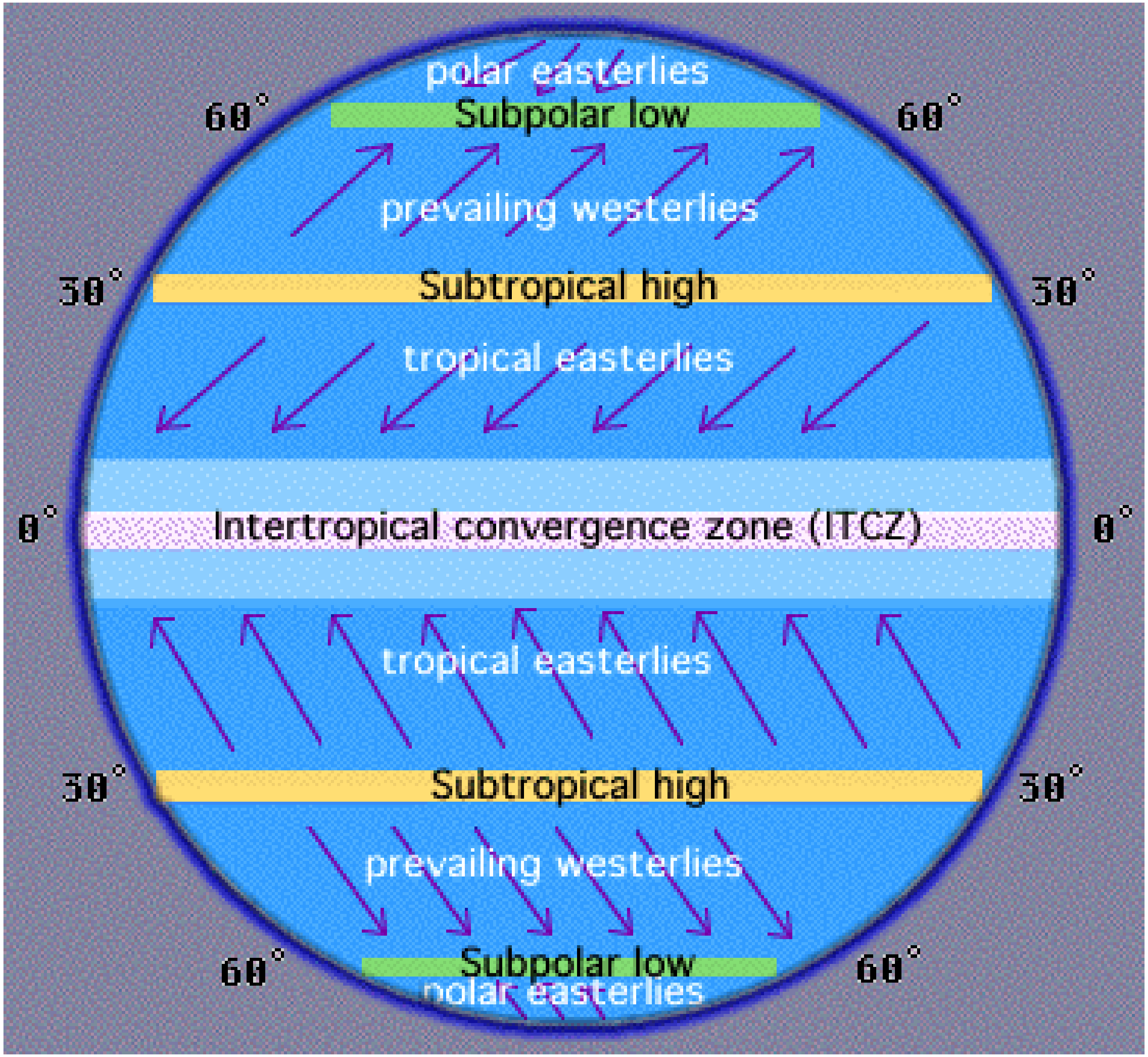
- the Ferrel cell is a secondary circulation feature
- its existence depends upon the Hadley and polar cell

Meridional cross section

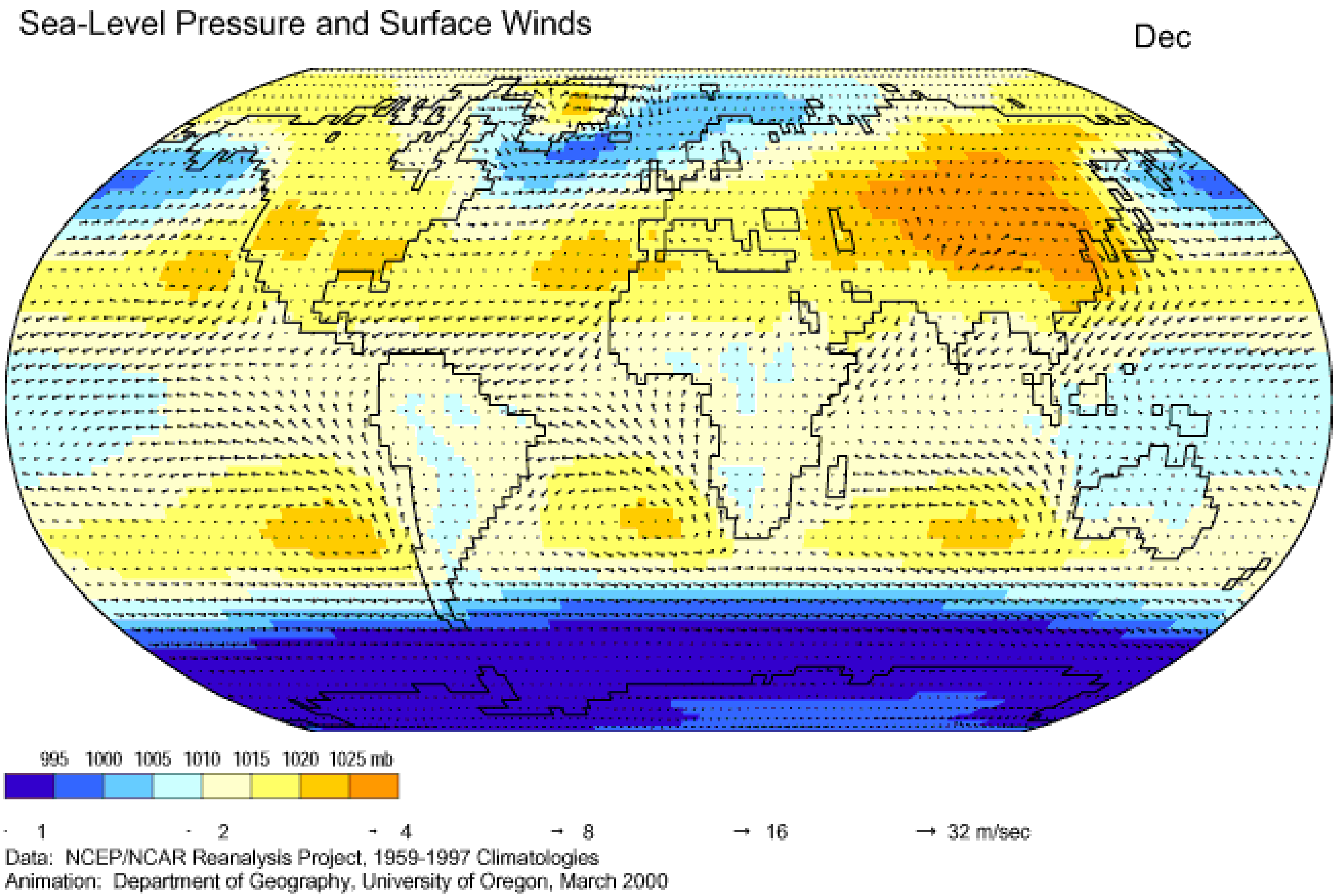


Jet streams

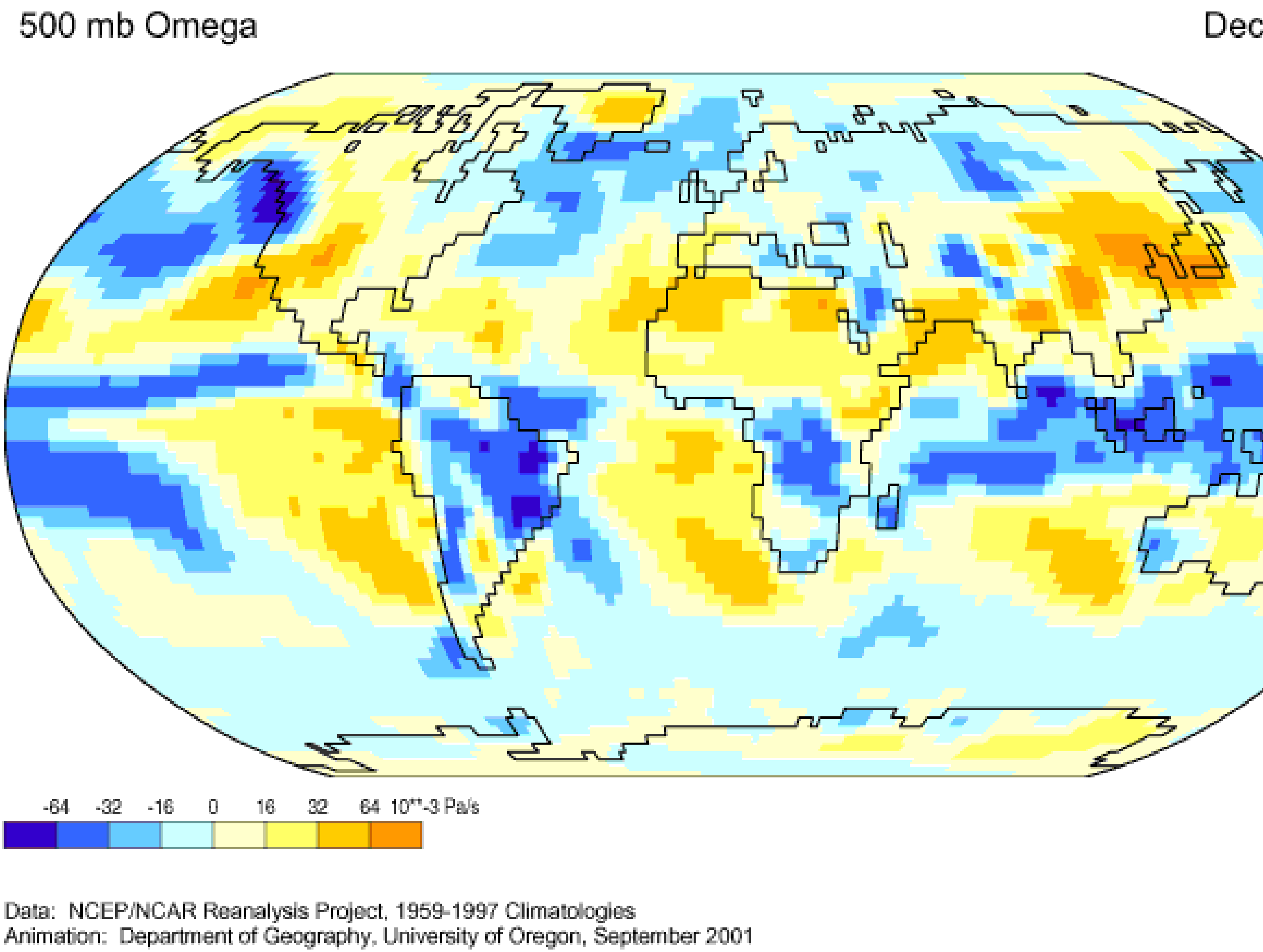
- jet streams form near the boundary of the cells. They are directed towards the east, which is a consequence of the Coriolis force and conservation of momentum



Schematic circulation close to the surface



http://geography.uoregon.edu/envchange/clim_animations/



Horizontal distribution of vertical air movement

http://geography.uoregon.edu/envchange/clim_animations/index.html

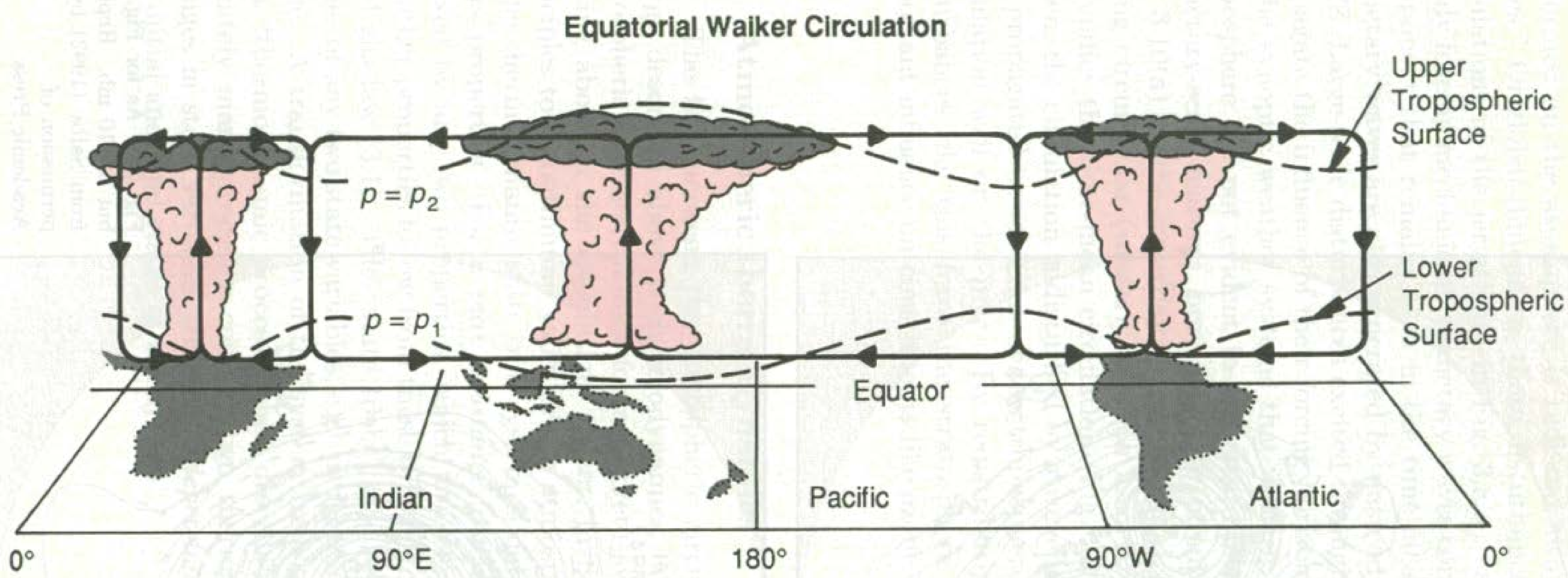
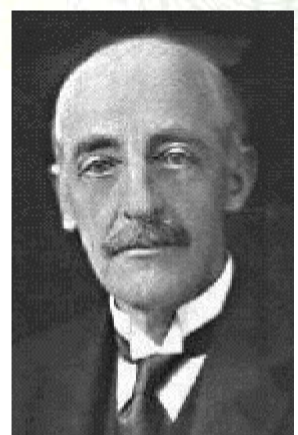
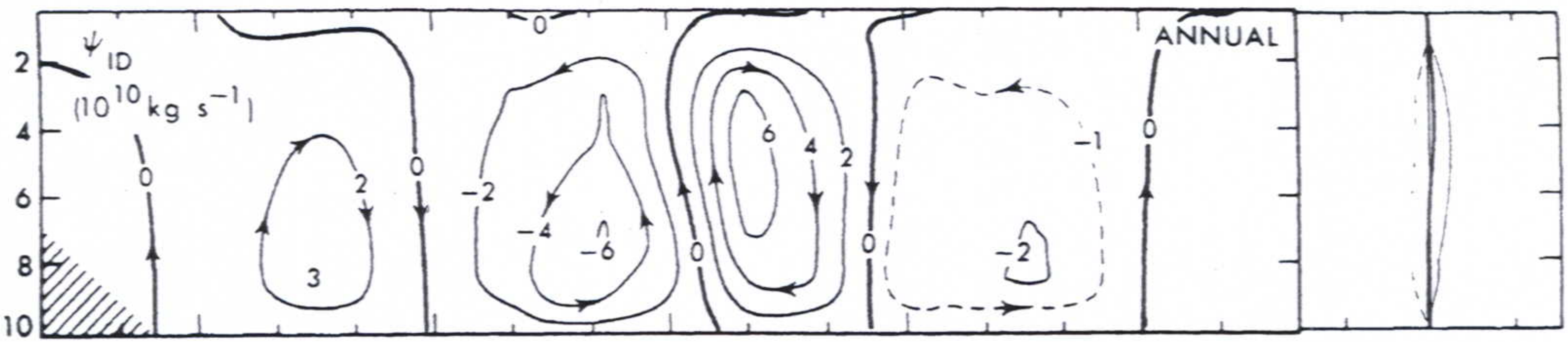


Fig. 3.9 Pacific Walker circulation, as function of longitude and altitude over the equator. Adapted from Webster (1983). Reprinted from Salby (1992) by permission of Academic Press.

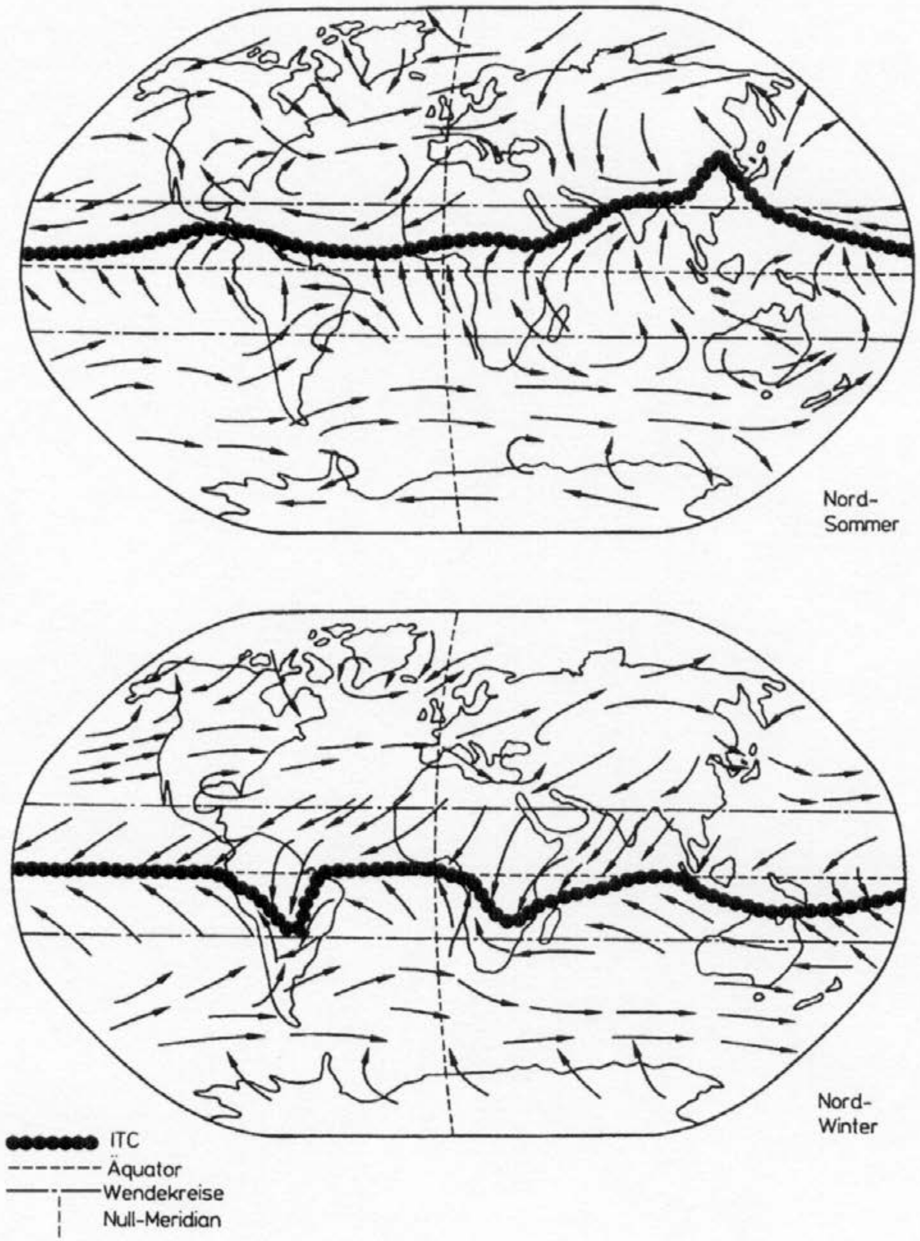


Sir Gilbert Walker 1868-1958

Meridional circulation as mass stream function



Annual

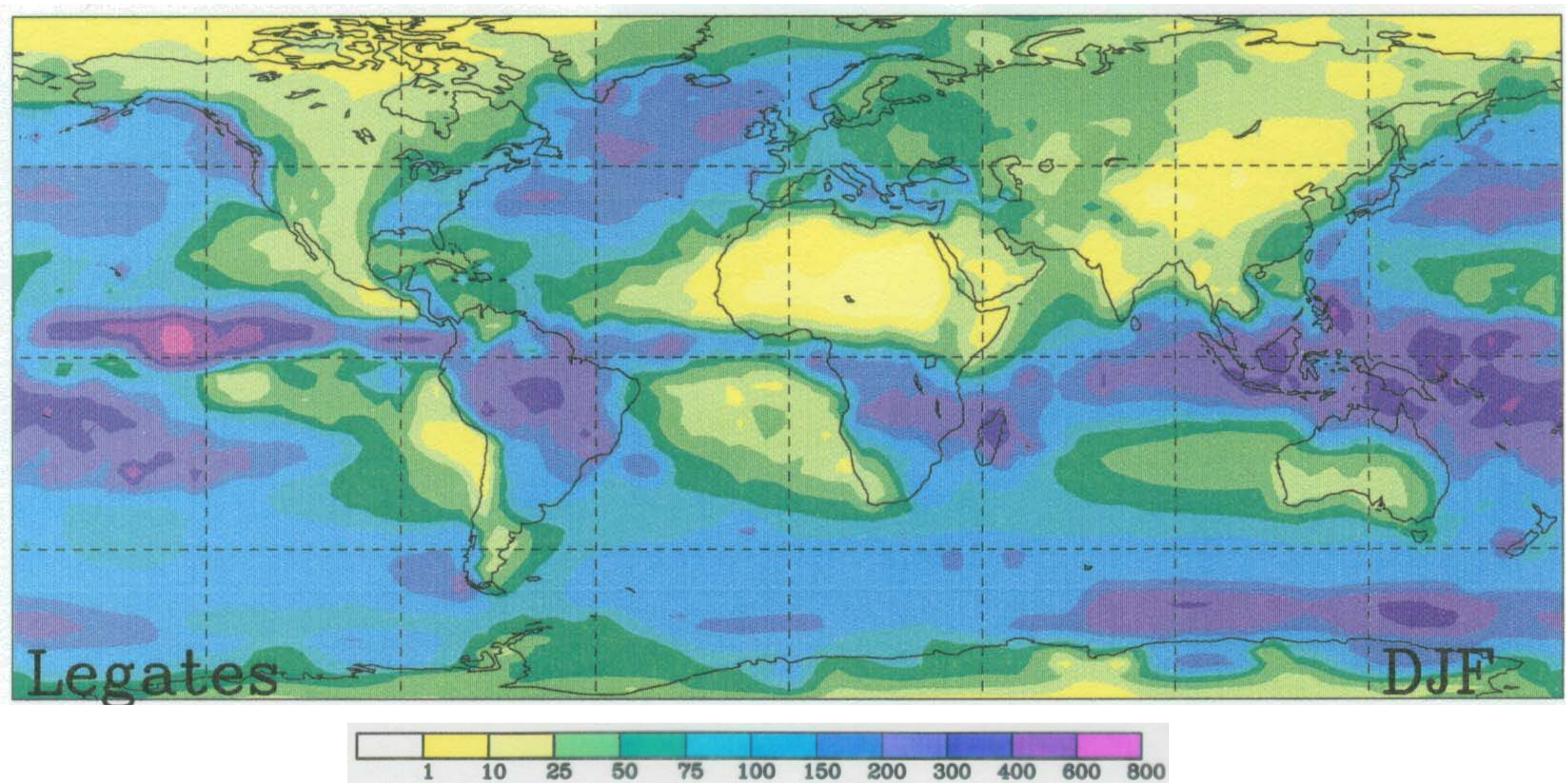


Northern summer

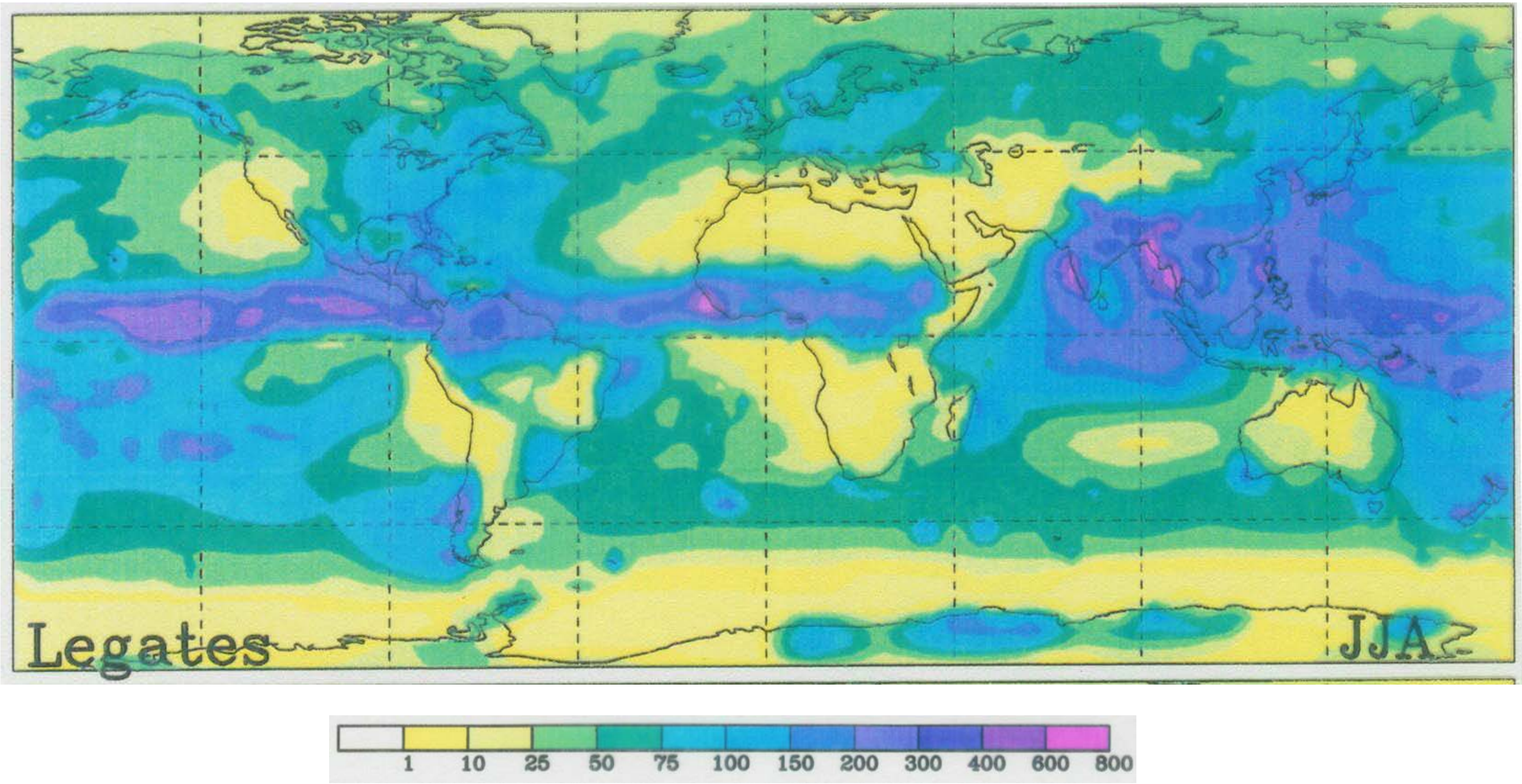
Northern winter

The Position of the ITCZ in different seasons

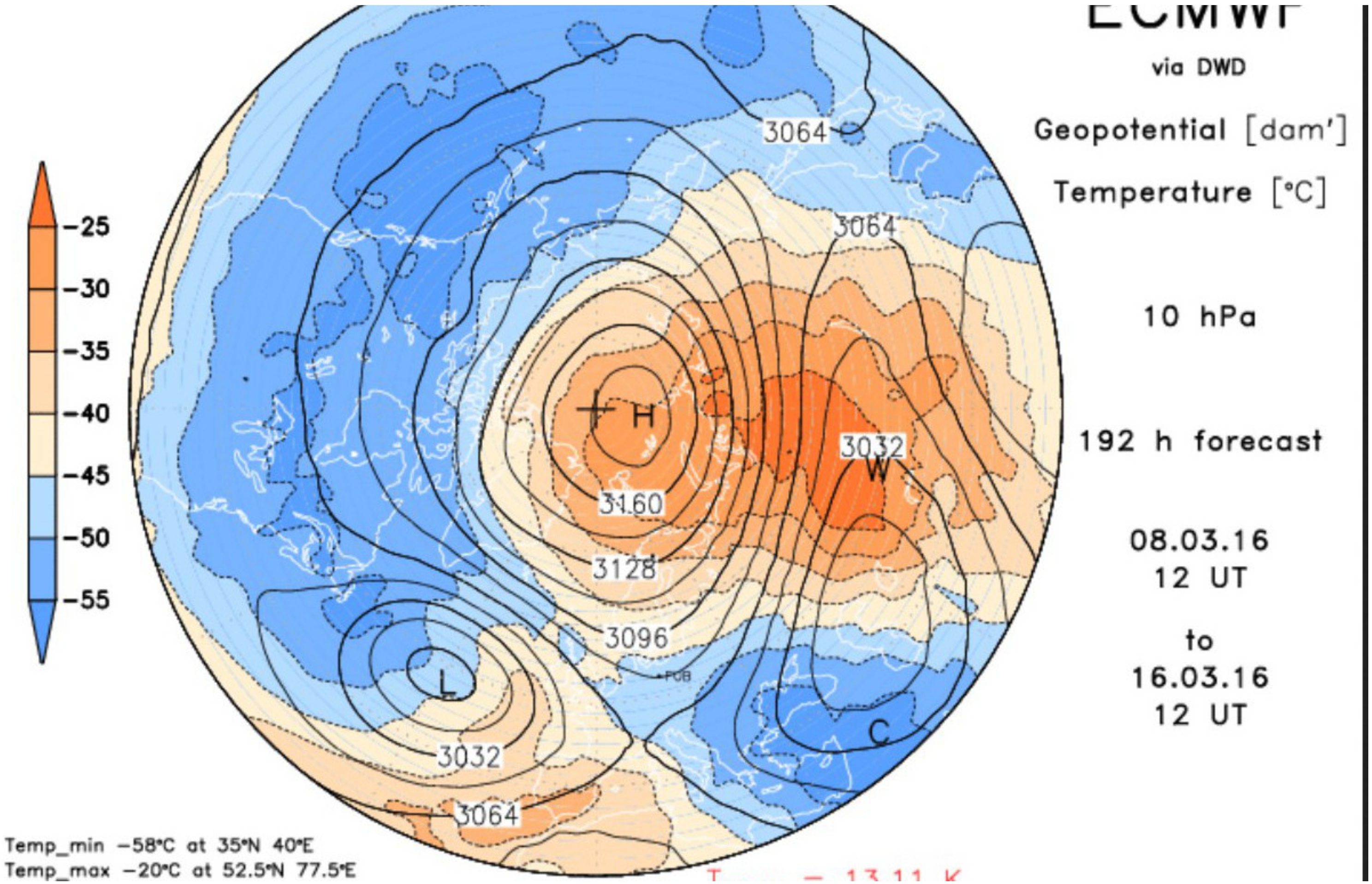
Mean precipitation during winter – DJF [mm/month]



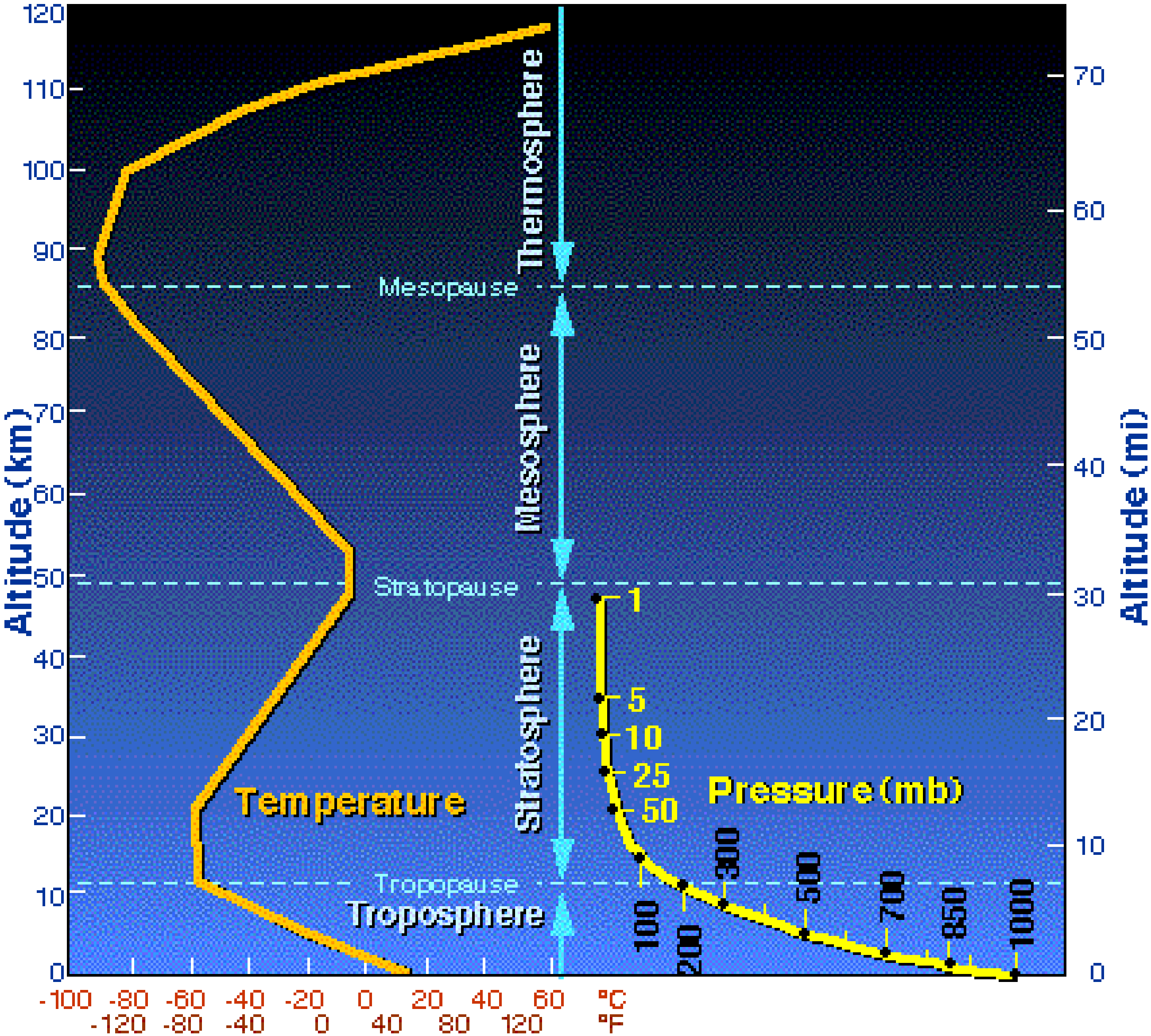
Mean precipitation during summer – JJA [mm/month]



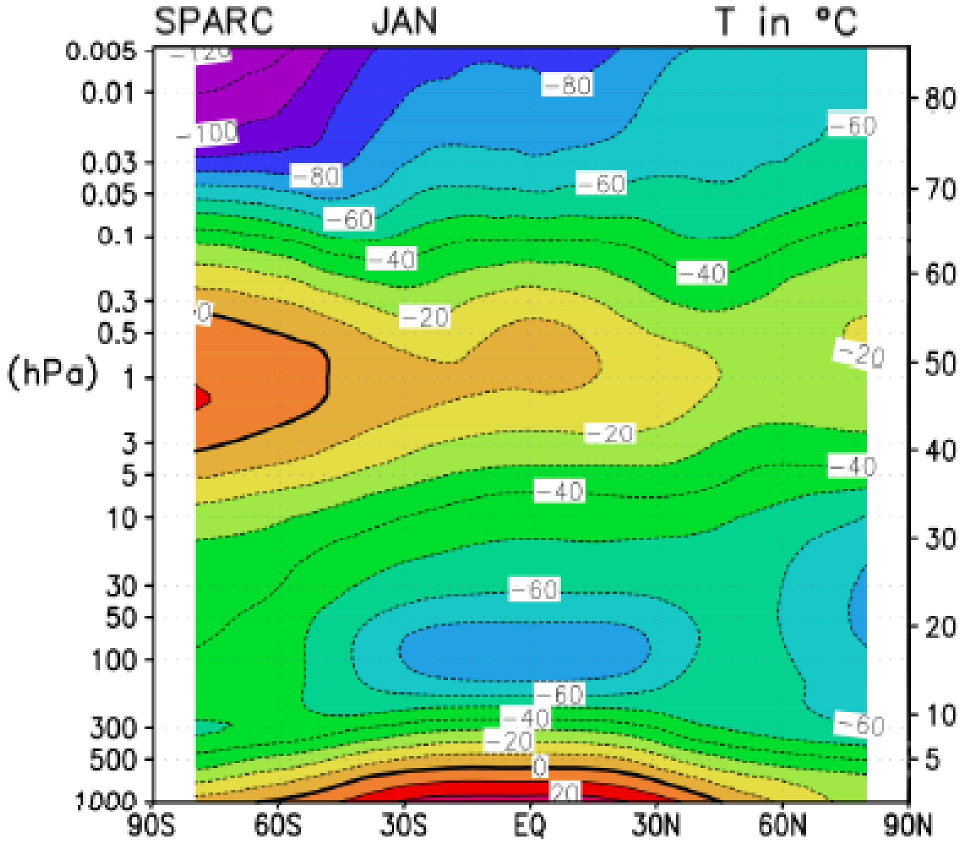
Climate of the stratosphere



Average atmospheric temperature and pressure in the atmosphere



Zonal mean temperature in January

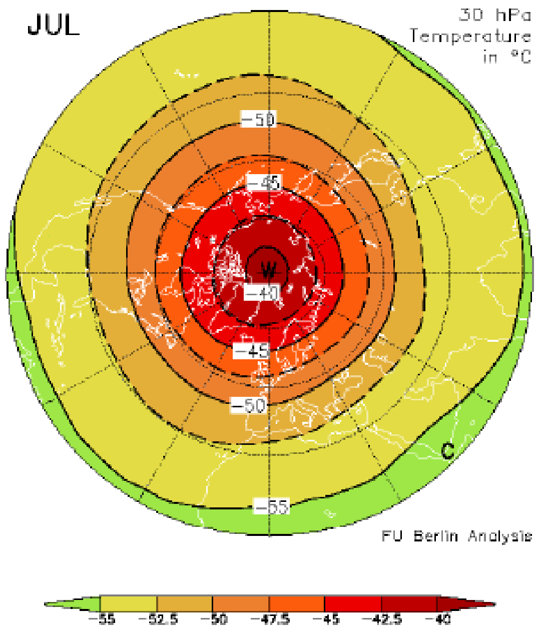


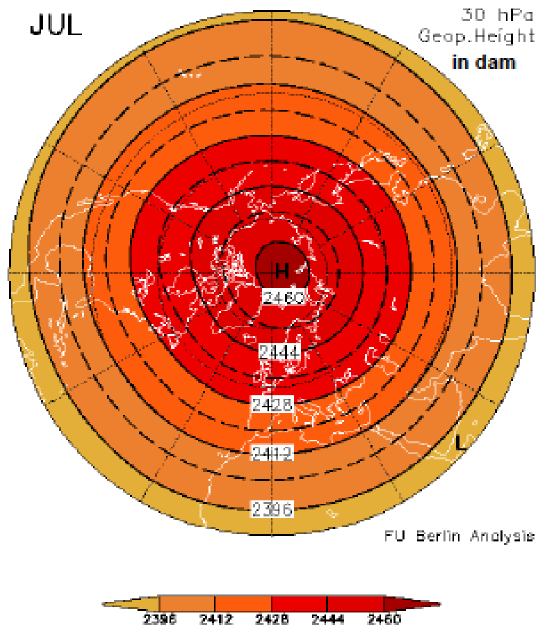
- cold tropical tropopause
- cold polar stratosphere during winter
- warm polar stratopause during summer
- cold mesopause during summer

http://www.sparc-climate.org/

Temperature and geopotential height at 30 hPa (24 km)

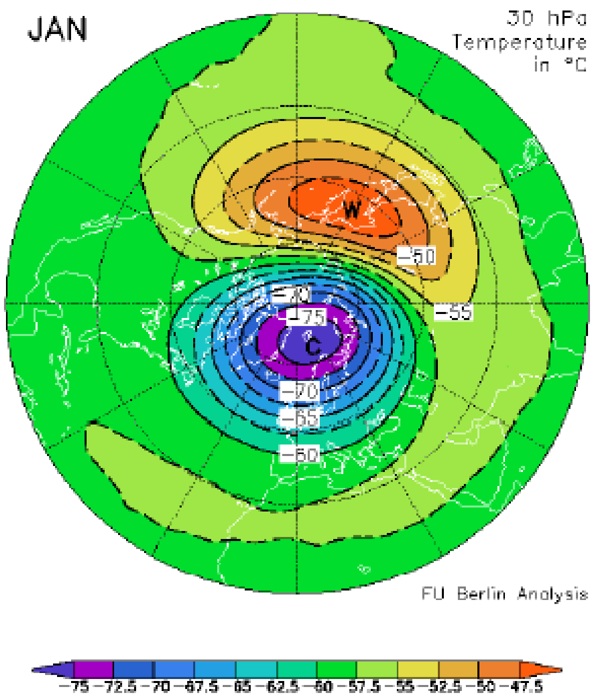
Summer average, northern hemisphere

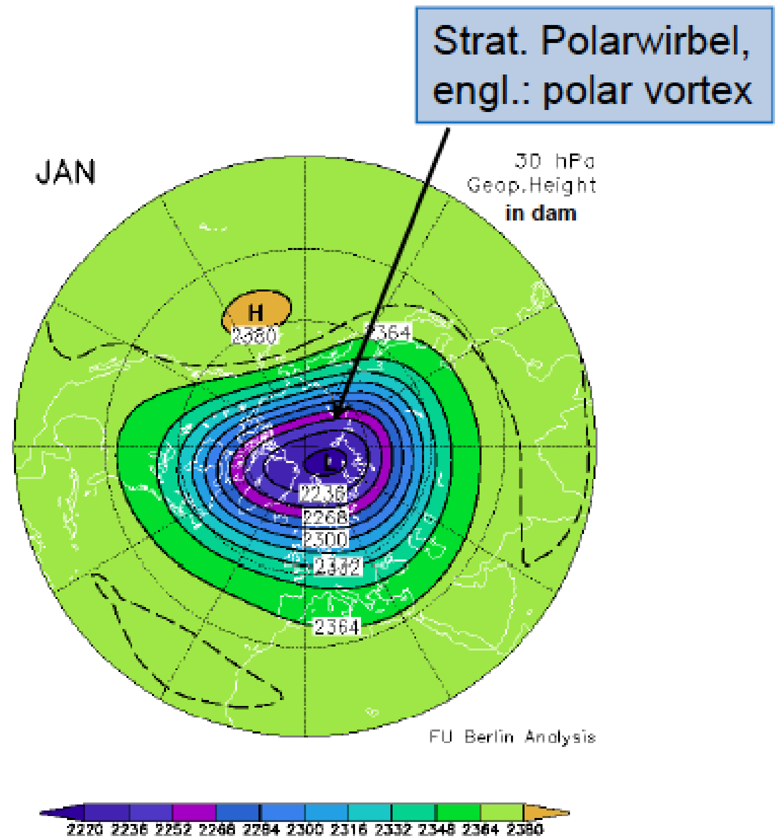




Temperature and geopotential height at 30 hPa (24 km)

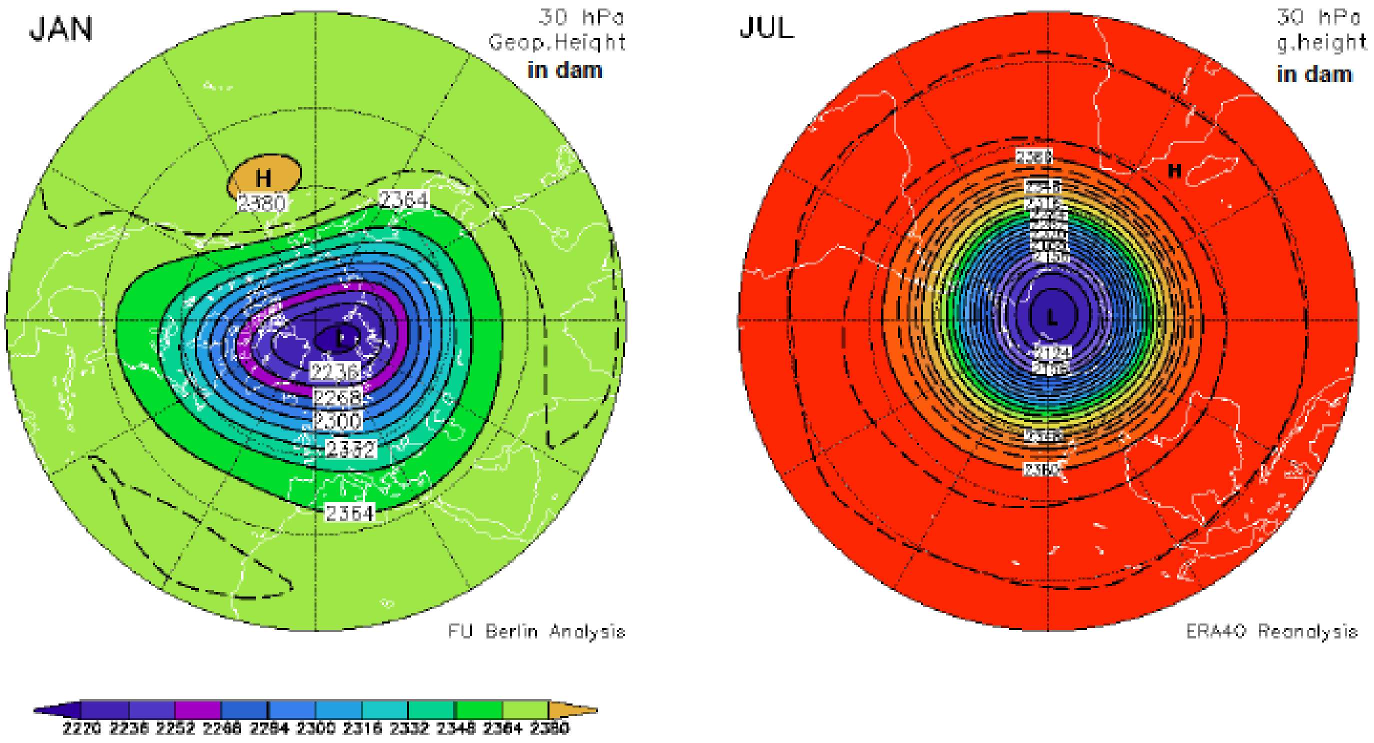
Winter average, northern hemisphere

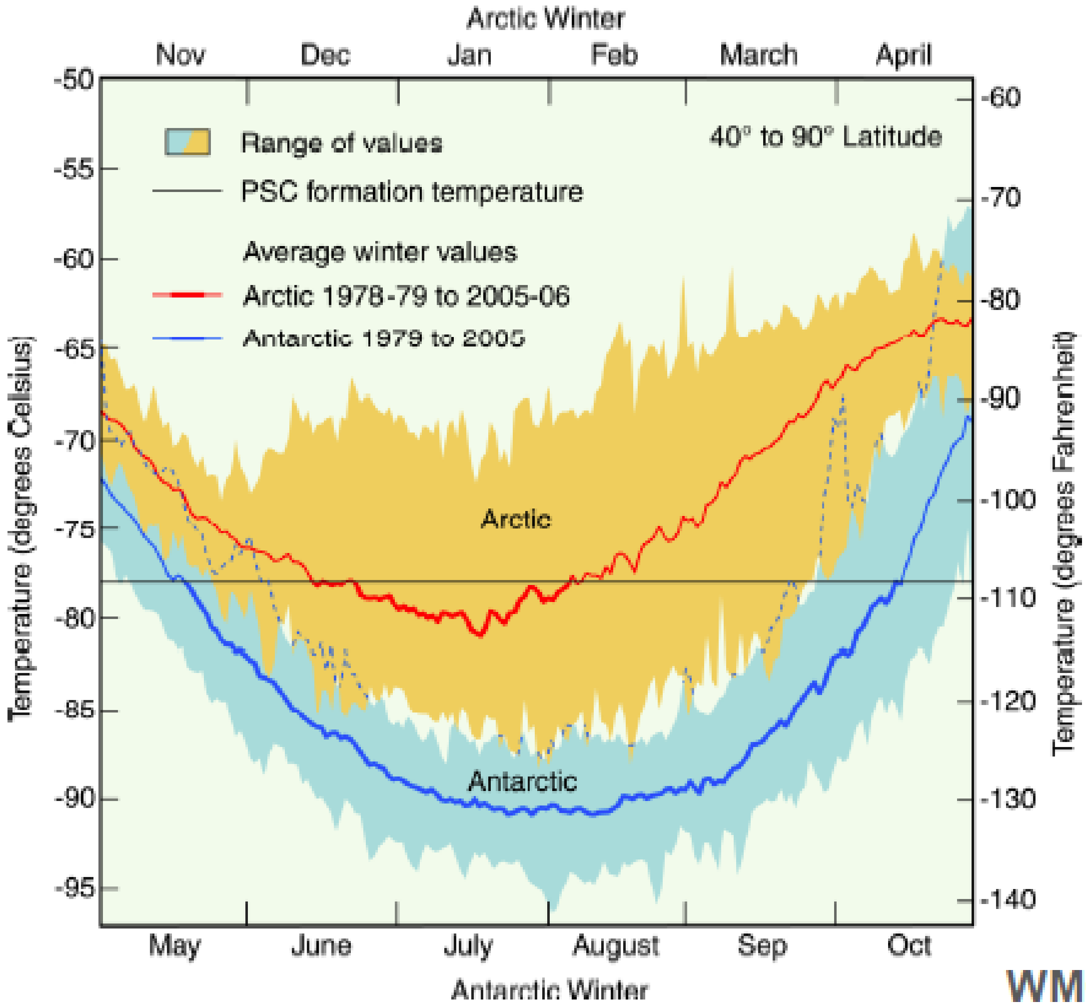




Geopotential height at 30 hPa (24 km)

northern winter ←→ southern winter

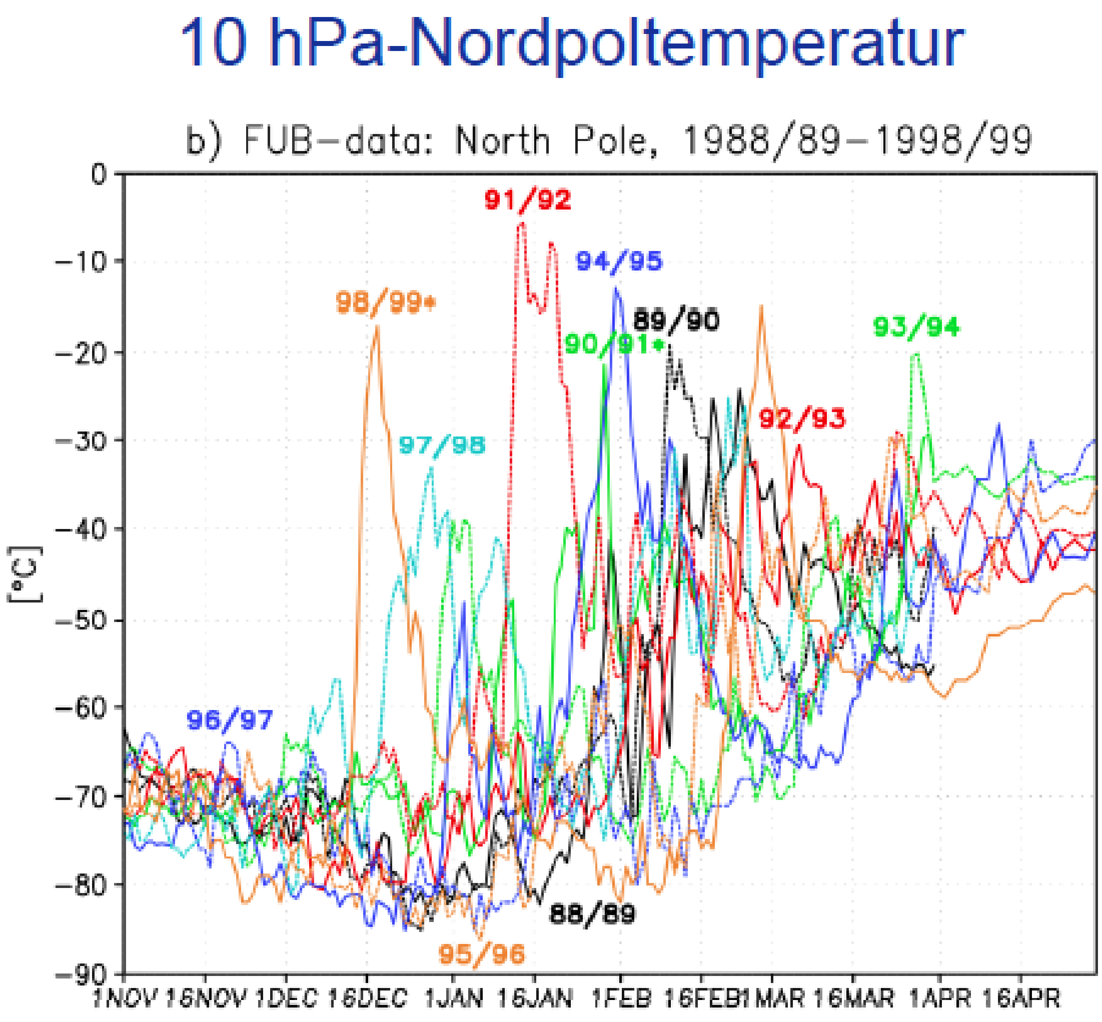




WMO (2007)

The Antarctic stratosphere is colder during winter than the Arctic stratosphere!

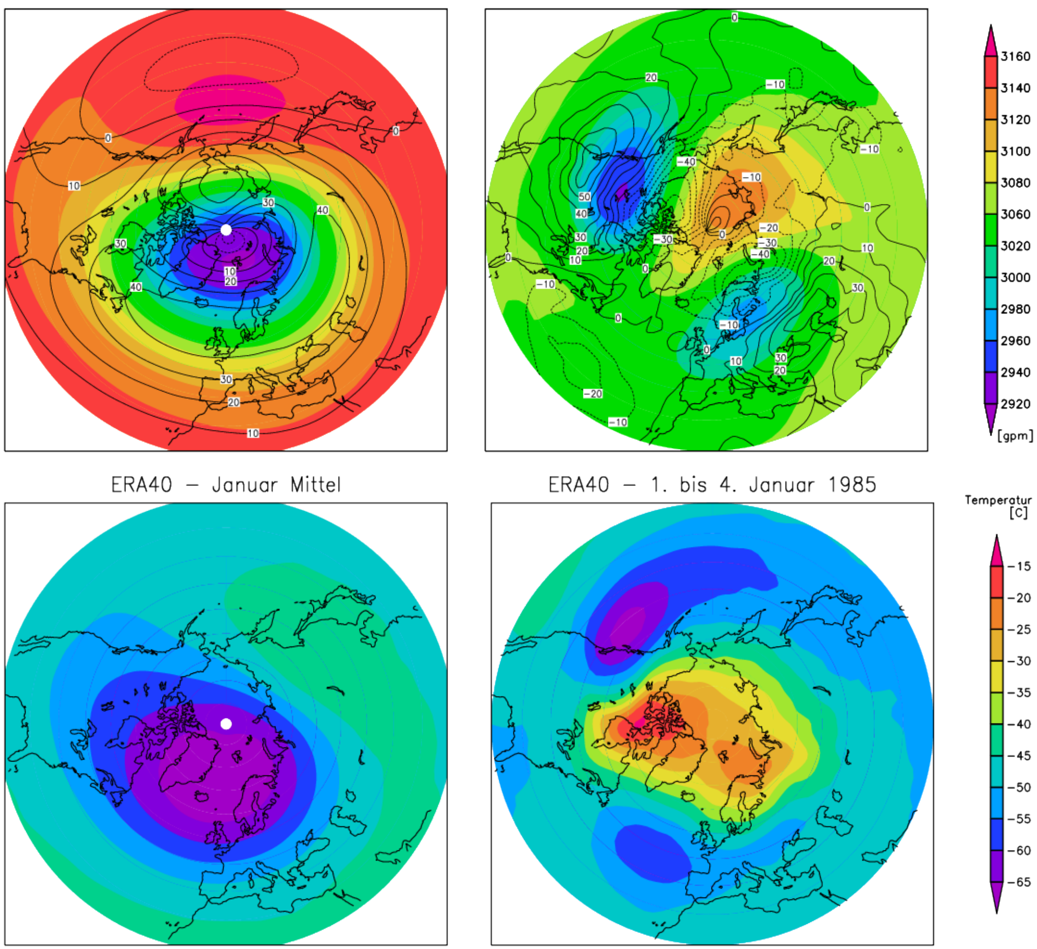
North pole temperature evolution in certain years



January average and the state at the beginning of 1985

ERA40 in 10hPa

January climatology　　　1.-4. Januar 1985

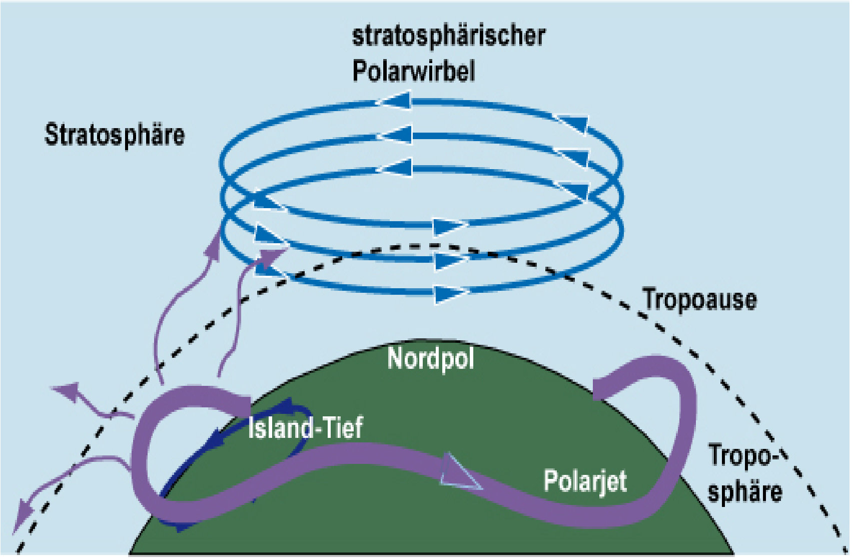


- Reversal of climatological state during SSWs:
– high geopotential over the pole
– polar region is warmer by more than 50K

- definition of SSWs by:
- easterly winds around at 60°N and 10hPa
- reversal of temp. gradient

- polar split,
but pure displacements of the polar vortex are also possible

Development of SSWs

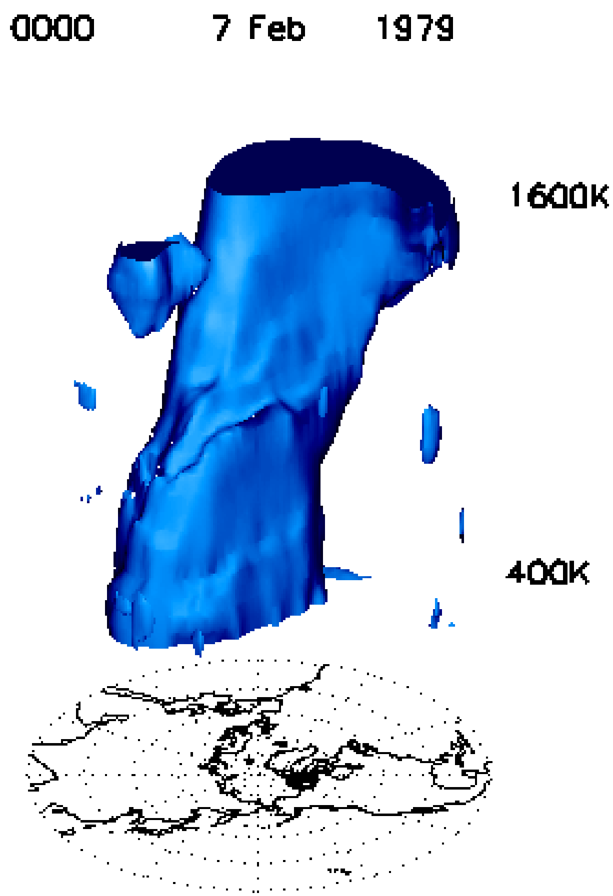


Hamburger Bildungsserver (based on Ambaum und Hoskins (2002))

- long tropospheric waves penetrate into the stratosphere
- by wave breaking, a meridional transport of heat induces a secondary circulation
- due to the deflection by the Coriolis force the zonal mean flow is reduced

- tropospheric blockings can increase the wave flux from the troposphere into the stratosphere and herewith weaken the polar vortex

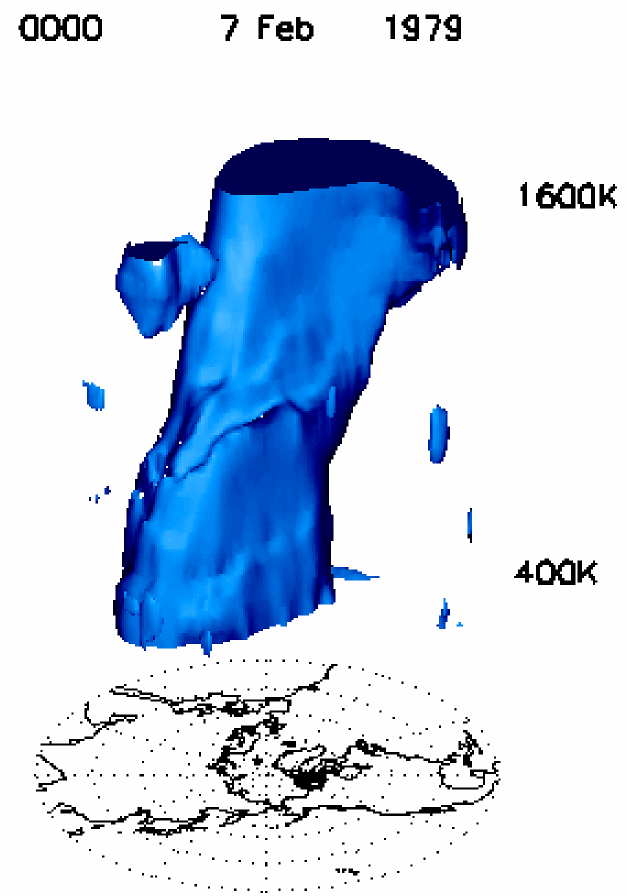
The split of the polar vortex in Feb/Mar 1979



ERA40-data
Matthewman et. al (2009 und pers. Kommunikation)

- PV-isosurface, representing the edge of the polar vortex and the area with highest wind speeds
- the polar vortex is an area with increased PV
- the polar vortex extends over the entire stratosphere into the mesosphere, shown 14-44km

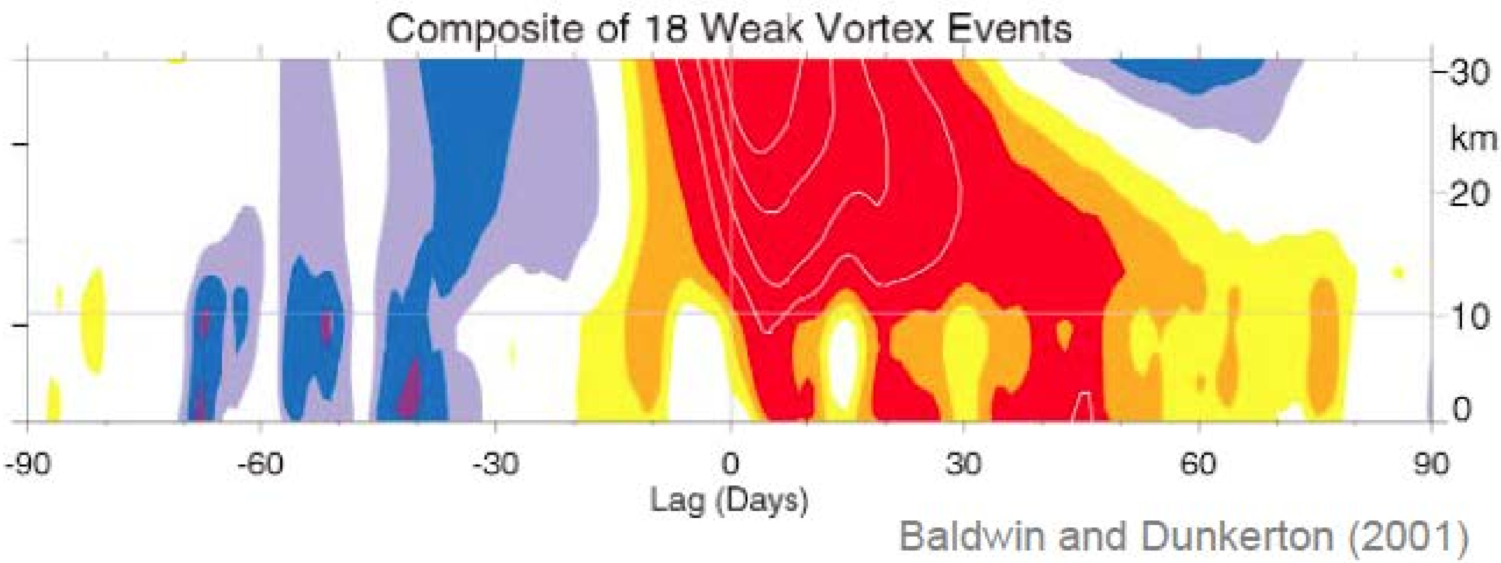
The split of the polar vortex in Feb/Mar 1979



- starting as a stable vortex, then it starts to stretch
- SSW (Split) on 21th of February
- the split happens almost simultaneously throughout the vertical extension

ERA40-data
Matthewman et. al (2009 und pers. Kommunikation)

Stratosphere-troposphere coupling



Changes in the strength of the polar vortex
can reach the earth surface.

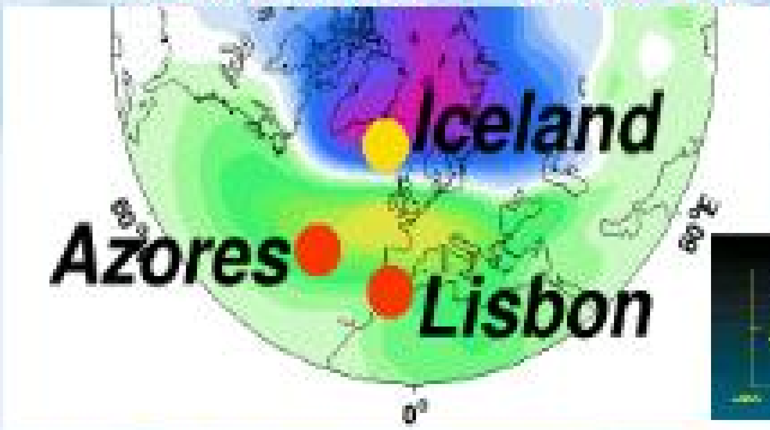
Potential of improved weather forecasts
by using stratospheric information.

- the general circulation in the troposphere
- climate of the stratosphere
- large scale circulation patterns, e.g. NAO
- periodic oscillations in the climate system, e.g. ENSO, QBO

NAO

North Atlantic Oscillation

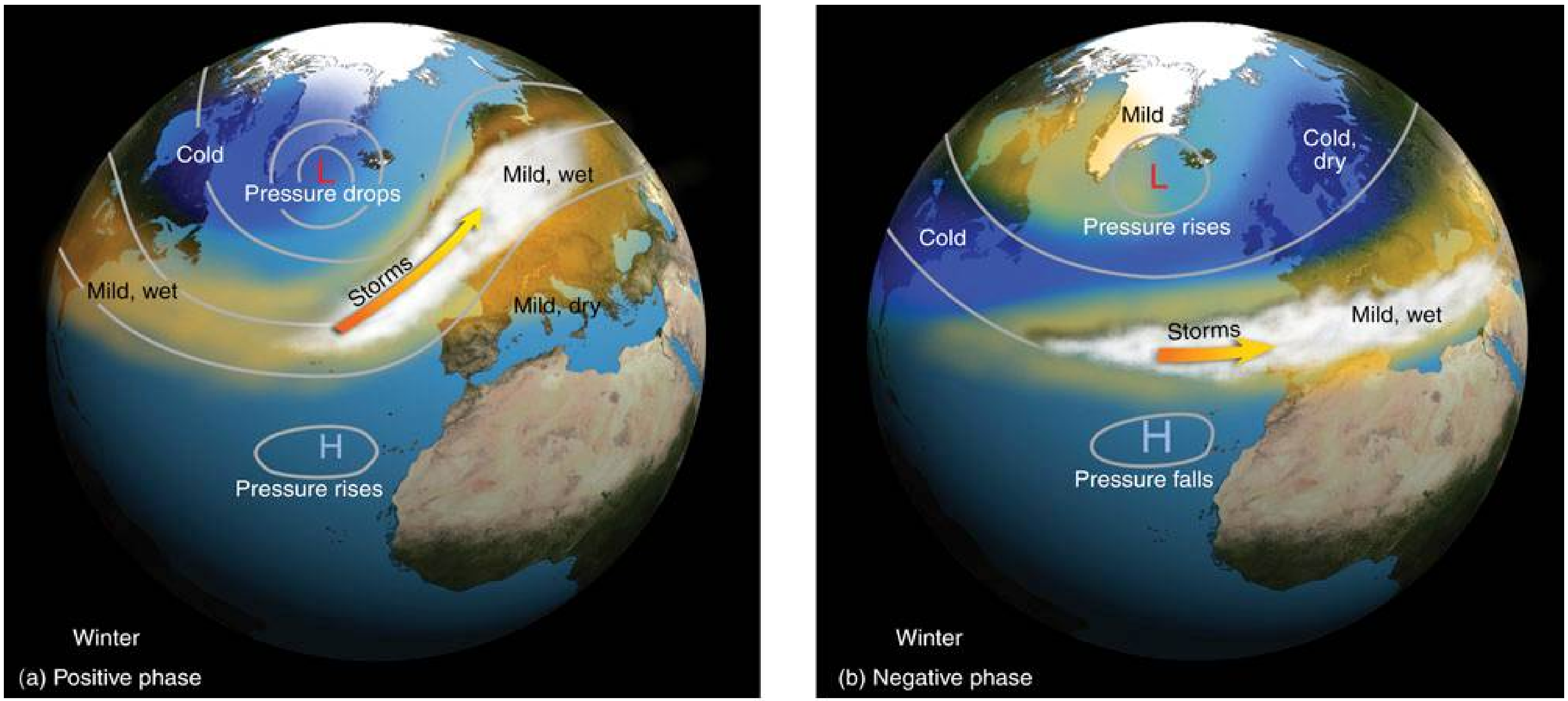
The North Atlantic Oscillation Index



- An Index can be constructed that represents the phase of the NAO. Most commonly the NAO index is based on the surface pressure (SLP) difference between the Subtropical (Azores) high and the Subpolar (Island) low.
- Very often the pressure readings from two stations one on Iceland and the other either the Azores, Lisbon or Gibraltar are used to construct the NAO index. The twice daily reading are averaged from November through March and the difference in then the winter NAO index.

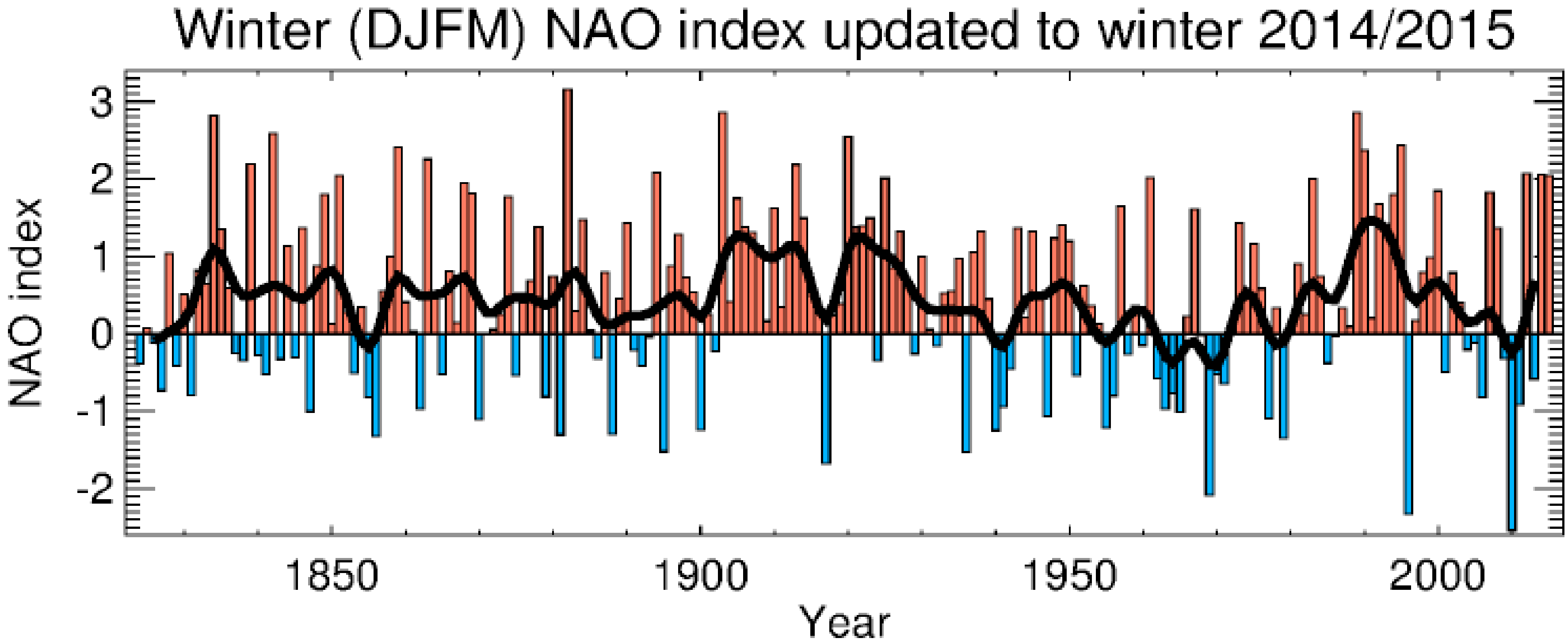
Martin Visbeck Feb04, 2000

http://www.ldeo.columbia.edu/~visbeck/nao/presentation/html/NAO.htm



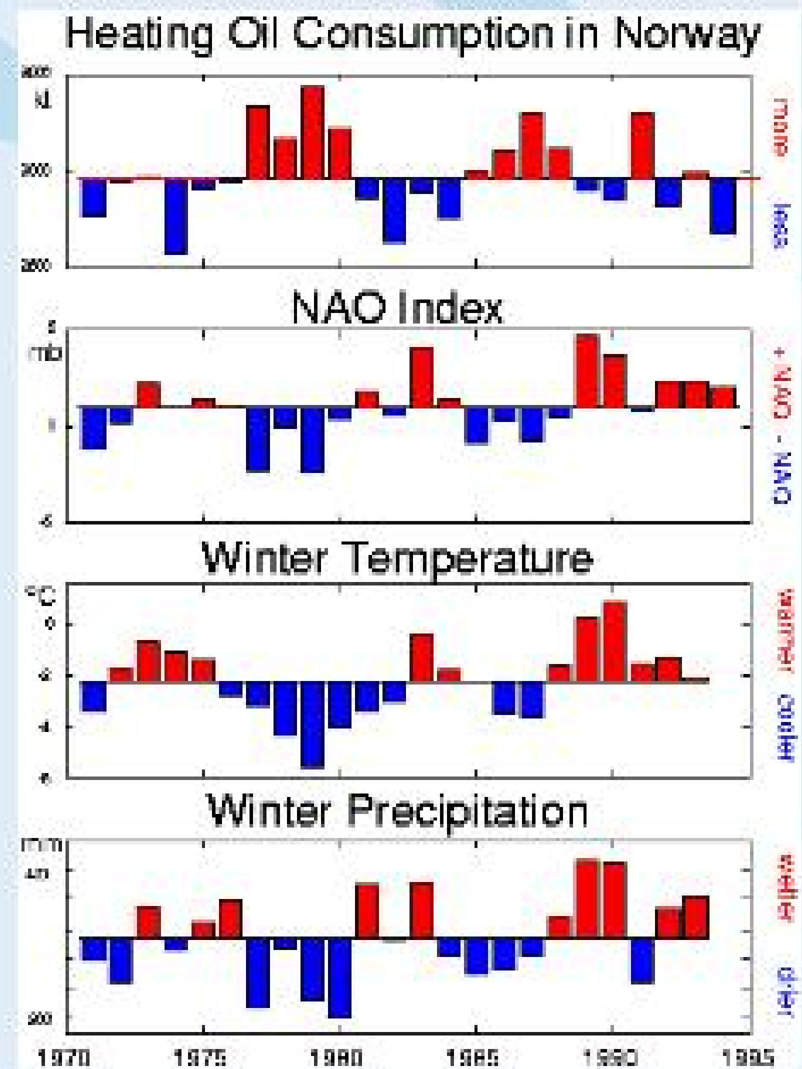
- NAO positive: - mild and wet in northern/central Europe
  - dry in the Mediterranean area
- NAO negative: - cold and dry in northern/central Europe
  - wet in the Mediterranean area

http://apollo.lsc.vsc.edu/classes/met130/notes/chapter10/nao.html



https://crudata.uea.ac.uk/~timo/datapages/naoi.htm

NAO and Energy in Norway

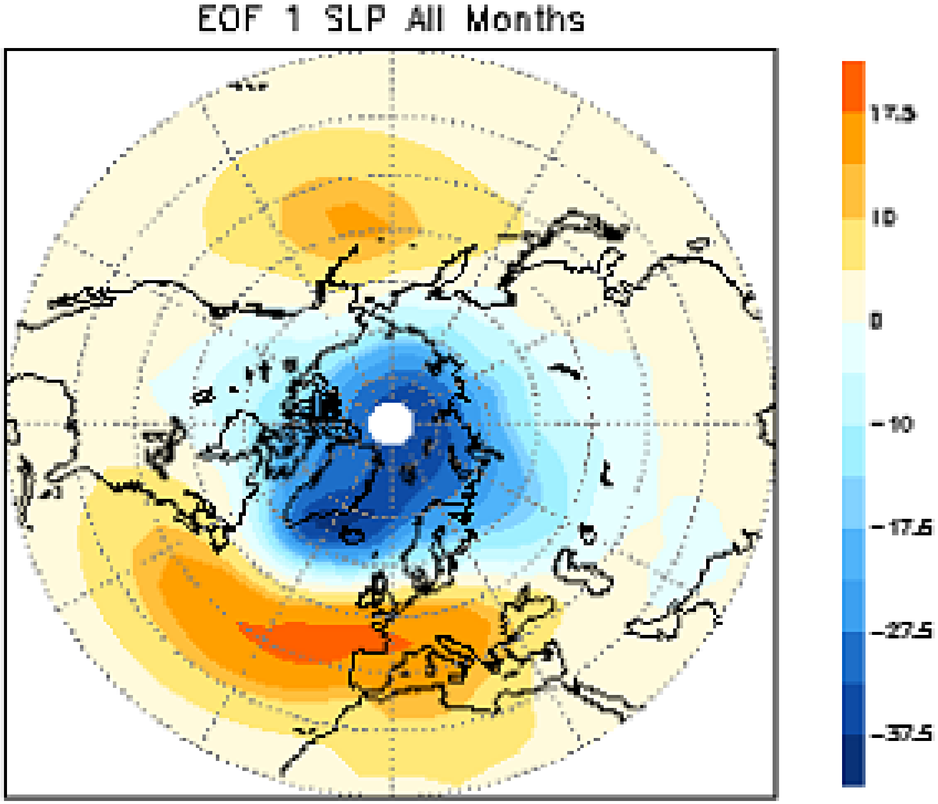


- Norway experience cold winters during a negative NAO phase.
- Heating Oil consumption in Norway varies by 30% in good (anti) correlation with the NAO.
- Correlation with precipitation results in variability in hydropower generation.

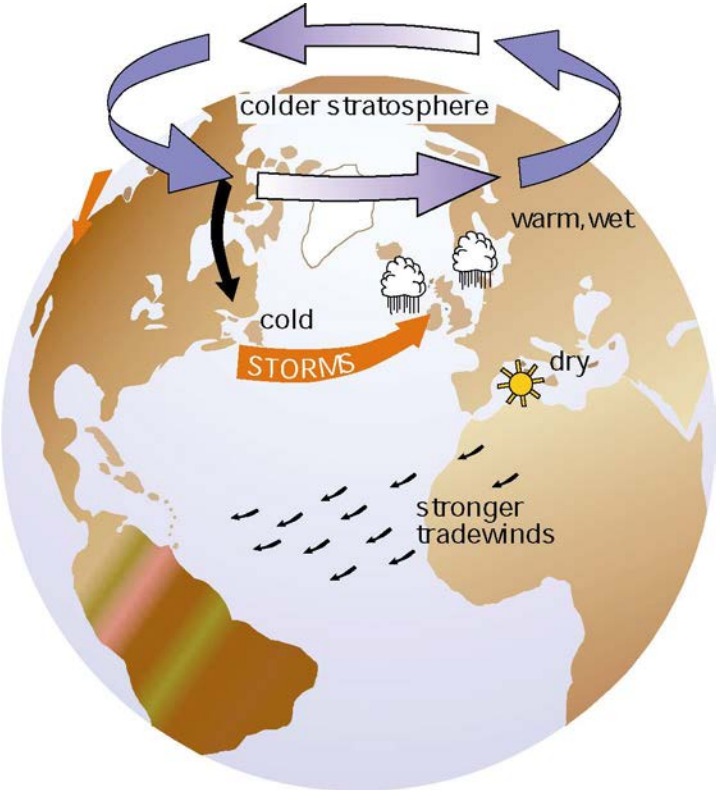
Martin Visbeck Feb 04, 2000

http://www.ldeo.columbia.edu/~visbeck/nao/presentation/html/NAO.htm

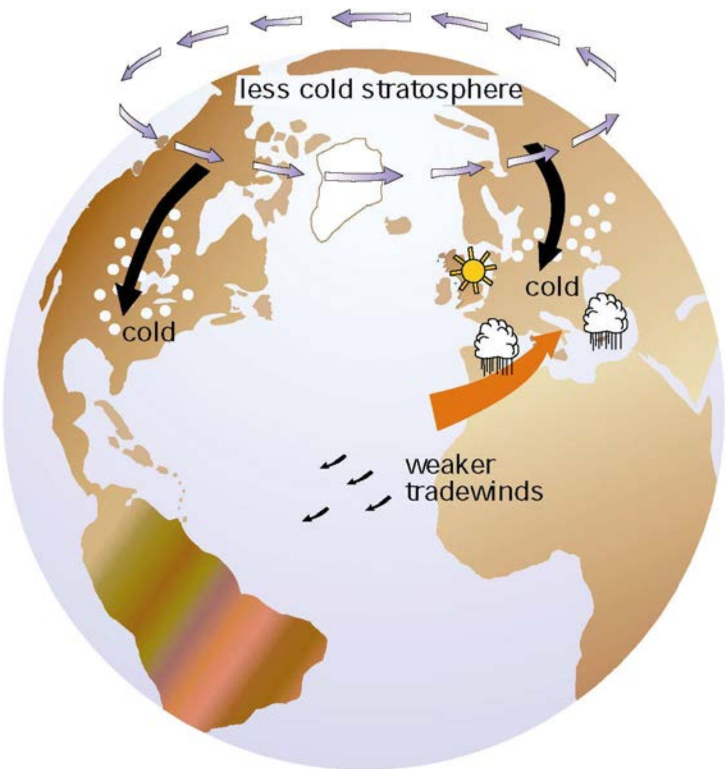
Arctic oscillation (AO)



http://www.atmos.colostate.edu/ao/Figures/index.html



Positive phase of the AO

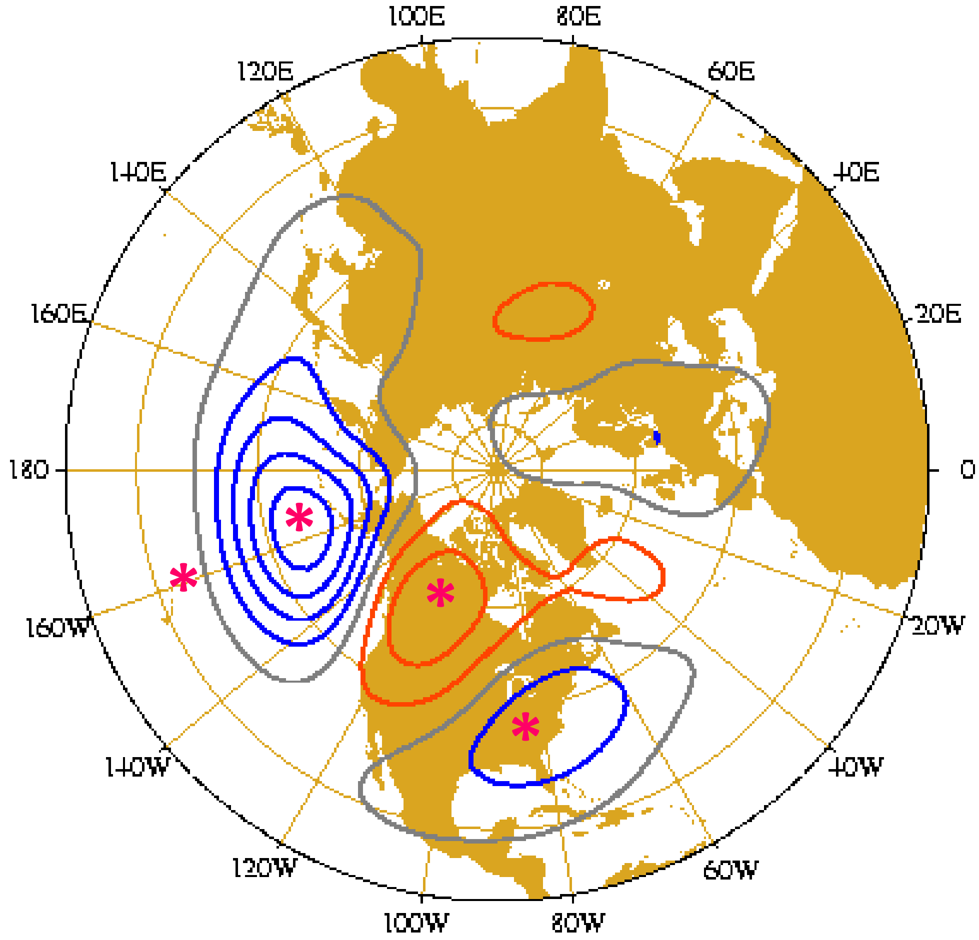


Negative phase of the AO

PNA

Pacific North American oscillation

http://tao.atmos.washington.edu/data_sets/pna/



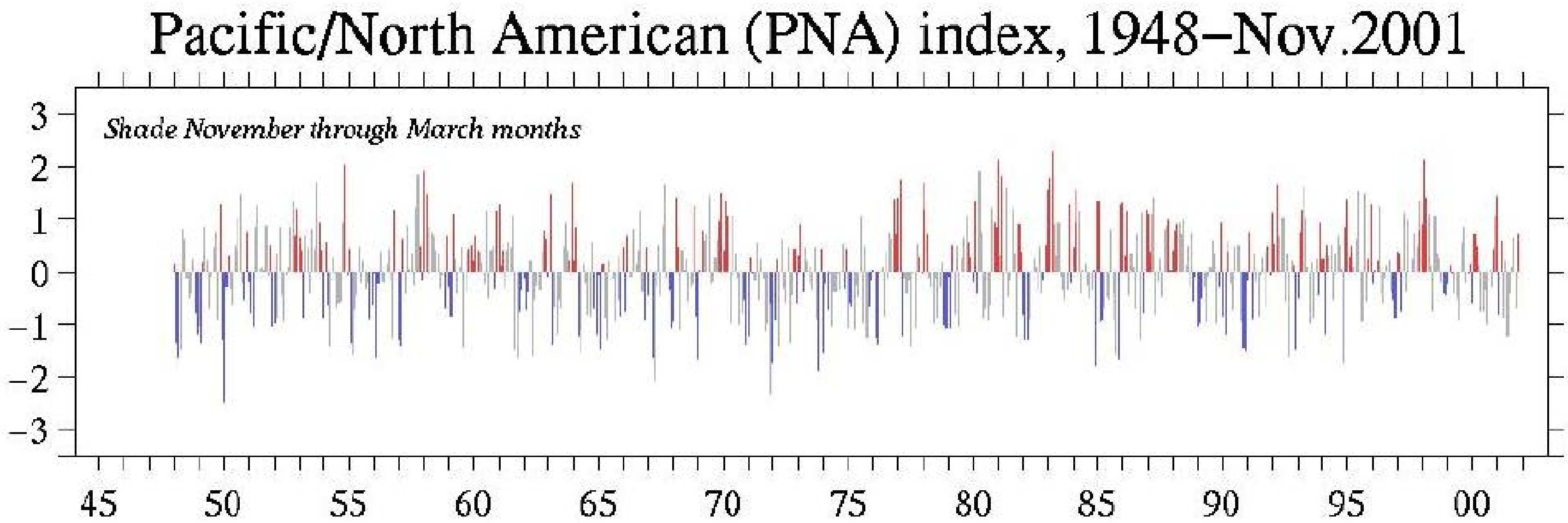
PNA index derived from the formula in Wallace and Gutzler (1981):

PNA = 0.25 * [Z(20N,160W) - Z(45N,165W) + Z(55N,115W) - Z(30N,85W)]

Z are standardized 500 hPa geopotential height values.

PNA pattern in December, January, February 1948-2004, presented as correlation map

http://tao.atmos.washington.edu/data_sets/pna/



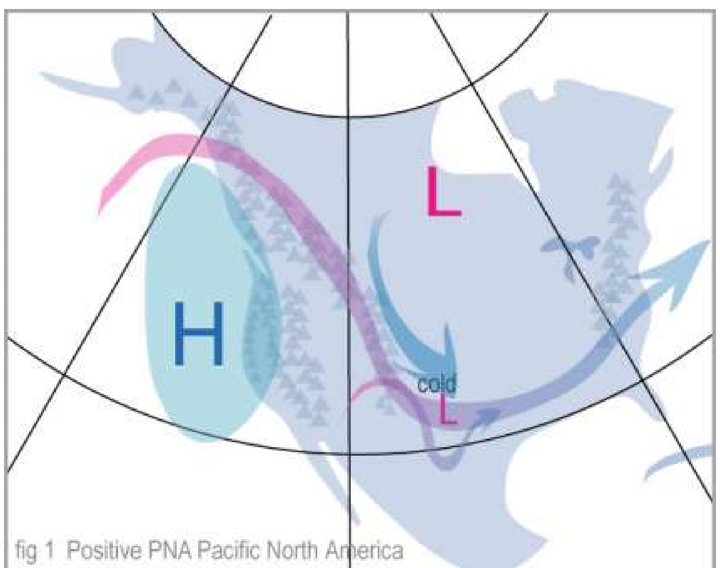


fig 1 Positive PNA Pacific North America

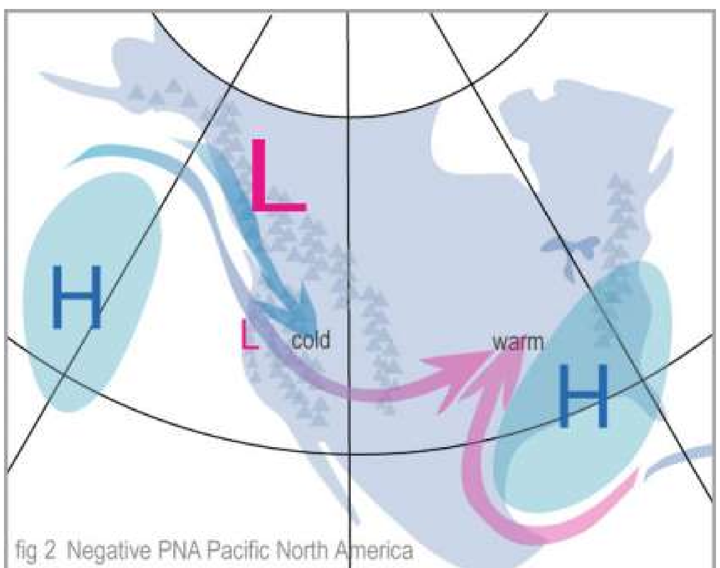


fig 2 Negative PNA Pacific North America

Images from www.docweather.com

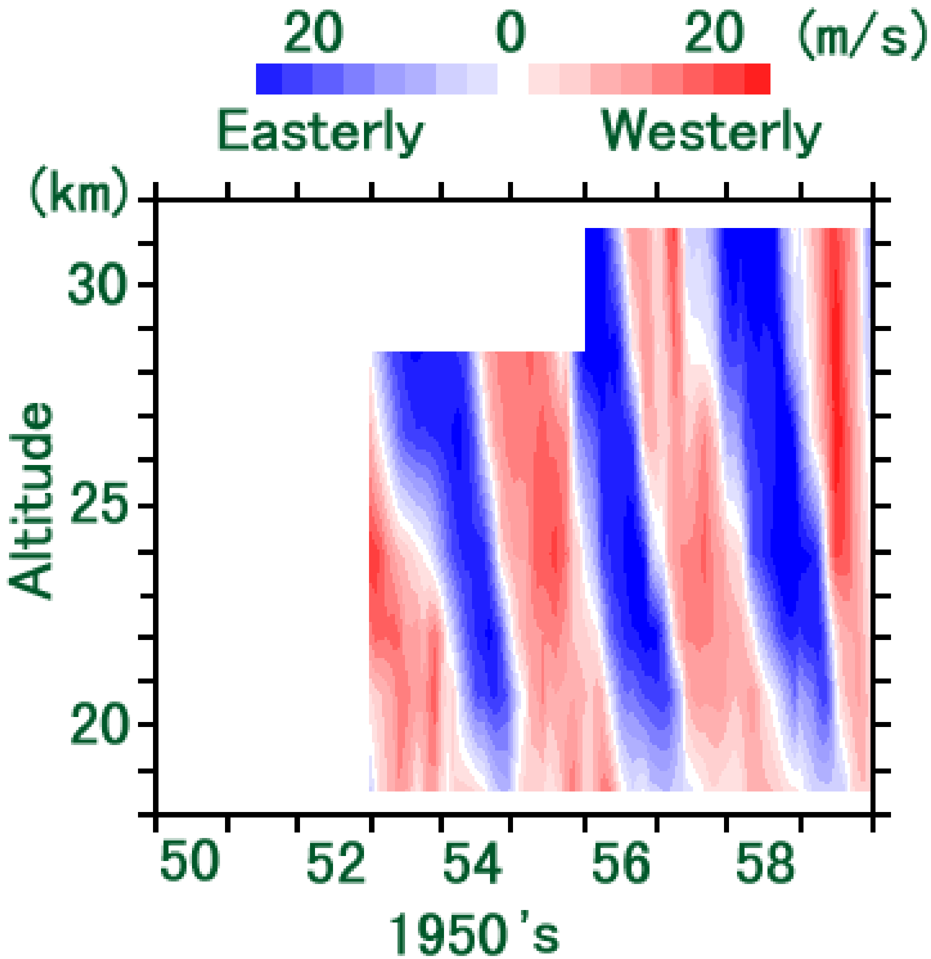
- the general circulation in the troposphere
- climate of the stratosphere
- large scale circulation patterns, e.g. NAO
- periodic oscillations in the climate system, e.g. ENSO, QBO

Oscillations

Quasi-bi-annual oscillation (QBO)

http://dennou-k.gaia.h.kyoto-u.ac.jp/library/gfd_exp/exp_e/doc/bo/guide01.htm

Krakatoa 1883

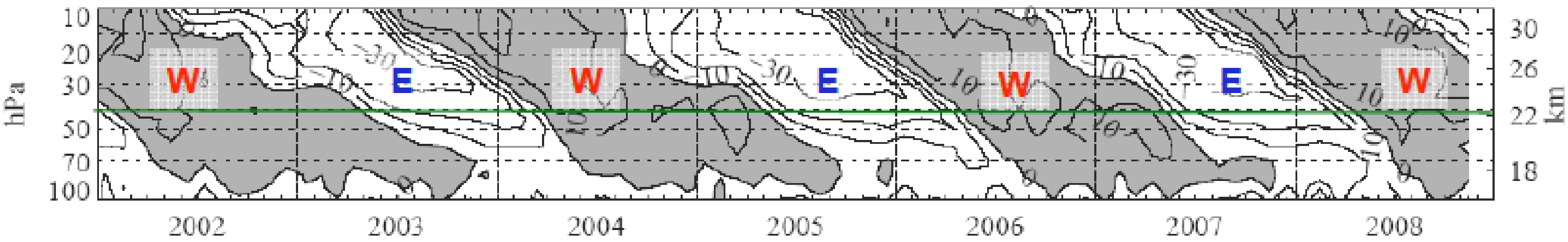


The contradicting results of these two observations remained a mystery for a half a century from then. In 1961, it was solved by Reed and independently by Veryard and Edbon. They discovered that the wind in the equatorial stratosphere was changing direction in **a 26-month cycle.**

The Krakatoa easterly and the Berson westerly were both correct. The oscillation of this wind, which has a cycle of a little more than two years, is called the **Quasi-Biannual Oscillation (QBO)**.

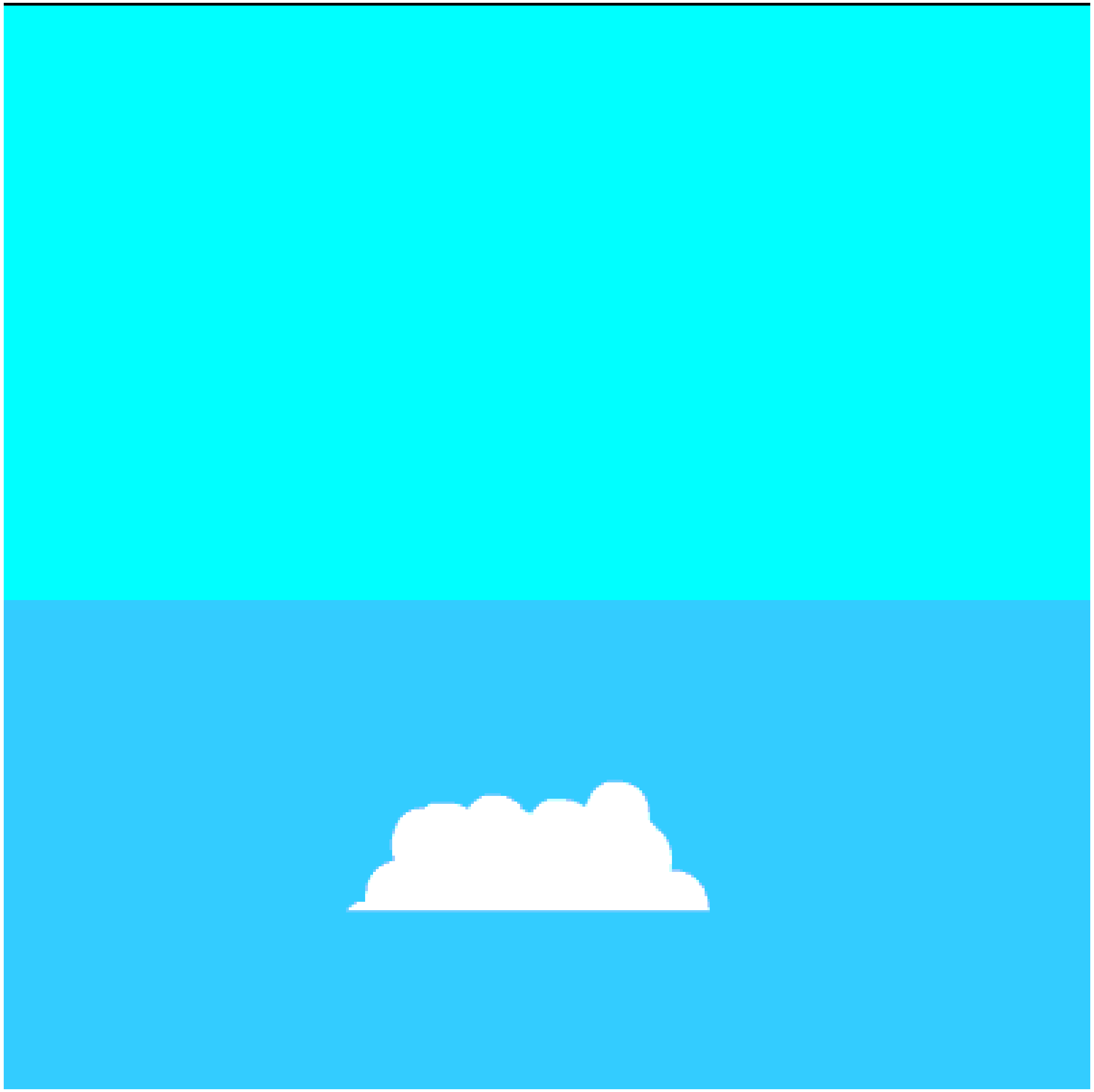
http://dennou-k.gaia.h.kyoto-u.ac.jp/library/gfd_exp/exp_e/doc/bo/guide01.htm

Characteristics of the QBO



- almost constant amplitude 40-10hPa
- easterly phase stronger than westerly
- downward movement of wind regimes (ca. 1km/month, 2.28cm/min)
- westerly phase (0.48mm/s) sinks faster than easterly (0.28mm/s)
- at 20hPa the easterly phase prevails ca. 4 months longer than the westerly phase

- variable period with 20-36 months
- a mean of 28 months
  Quasi-biennial oscillation => QBO
- it is not related to the annual solar cycle!
- The QBO-phase is defined at 40hPa



Mechanism

If there is a current present, the waves heading in the same direction as the current are selectively absorbed by the current. On the other hand, waves that head against the current penetrate it and are transmitted to a greater distance.

http://dennou-k.gaia.h.kyoto-u.ac.jp/library/gfd_exp/exp_e/doc/bo/guide01.htm

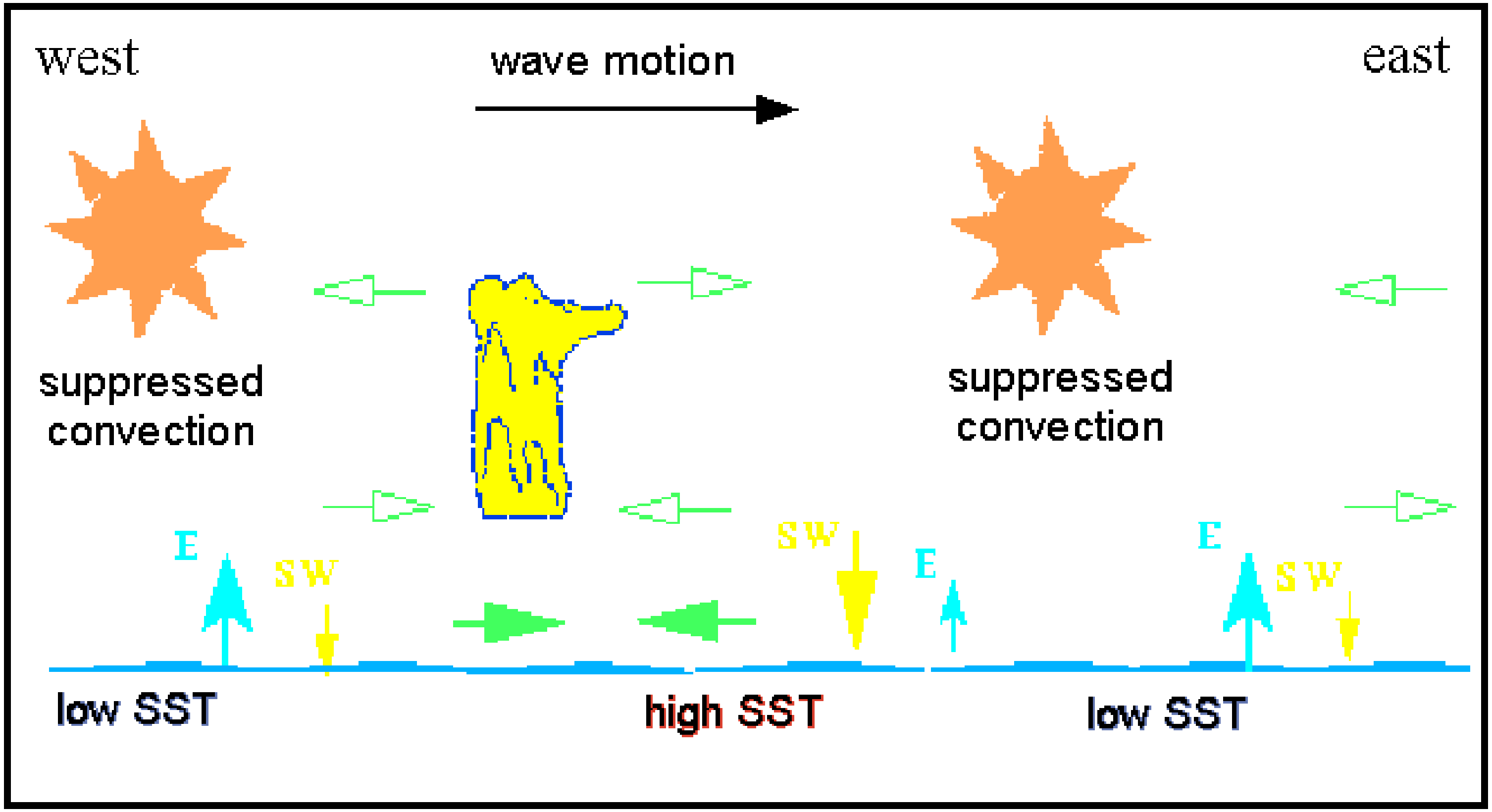
MJO

Madden-Julian-Oscillation

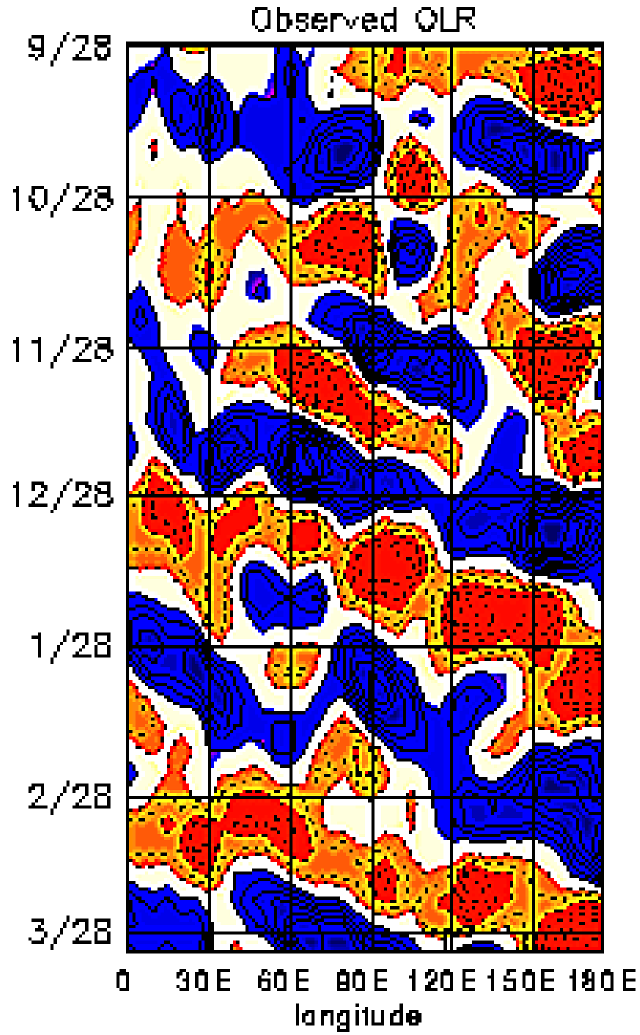
Madden-Julian-Oszillation

- fluctuations of wind, SST, cloud cover and precipitation in the tropics
- fluctuations travel eastward with a speed of 5m/s
- discovered 1971 by Madden and Julian
- 40-50 (30-60) days for an oscillation

http://www-das.uwyo.edu/~geerts/cwx/notes/chap12/mjo.html



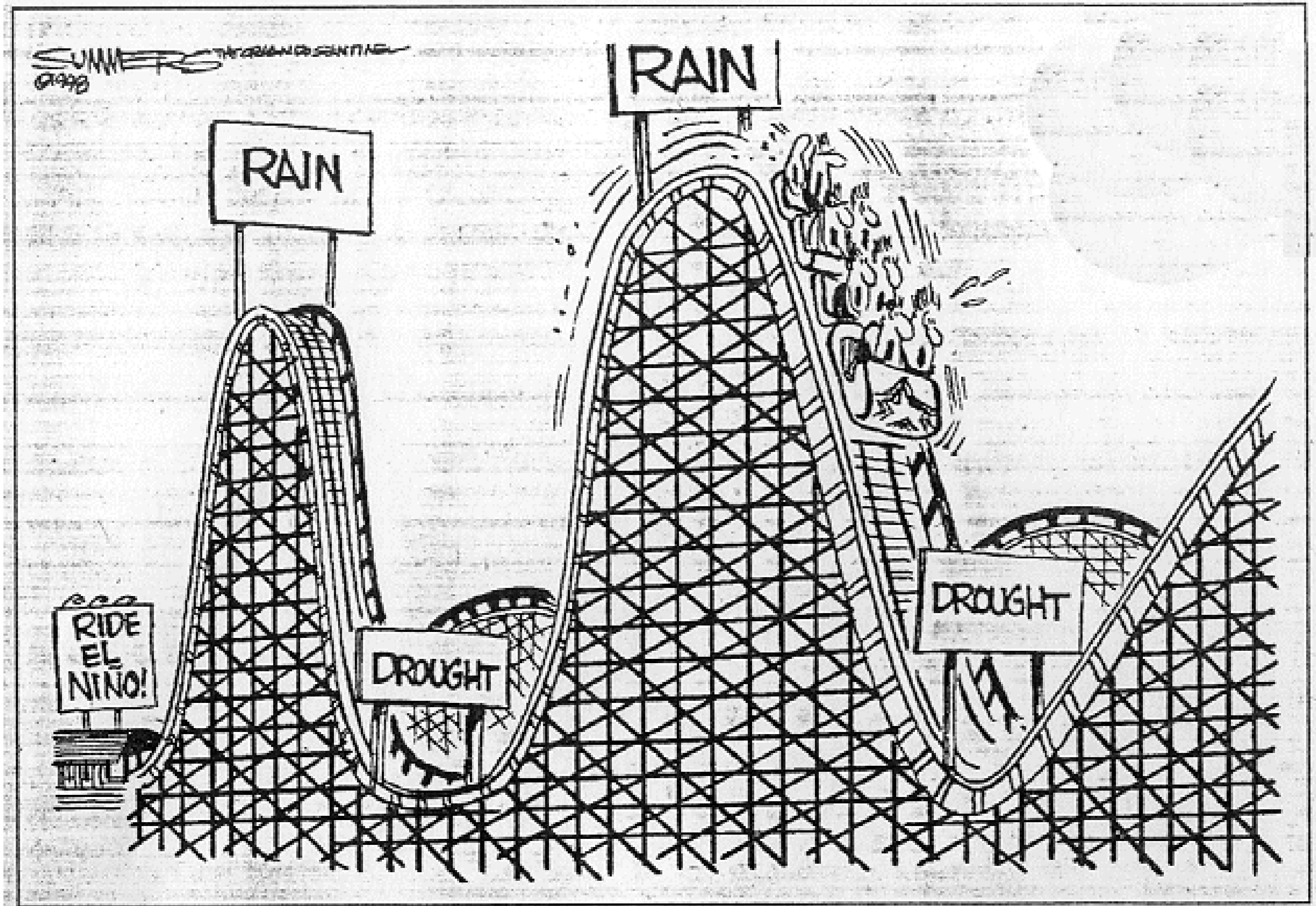
Schematic of the MJO. The cross section represents the equatorial belt around the globe, or just the eastern hemisphere. E stands for evaporation, SW for net shortwave radiation absorbed by the ocean. The converging bold green arrows indicate the location of strongest moisture convergence. The hollow green arrows show the anomalous circulation associated with the MJO. The areas of enhanced convection are indicated by the yellow schematic thunderstorm. (adapted from Elleman 1997) http://www-das.uwyo.edu/~geerts/cwx/notes/chap12/mjo.htm



Departures from normal outgoing longwave radiation around the globe between 5° S and 5° N during 6 months (10/'91 through 3/'92). The contour interval is 5 Wm^{-2}. Areas in blue have a negative anomaly exceeding 5 Wm^{-2}, and areas in red have positive anomalies over 5 Wm^{-2}.

ENSO

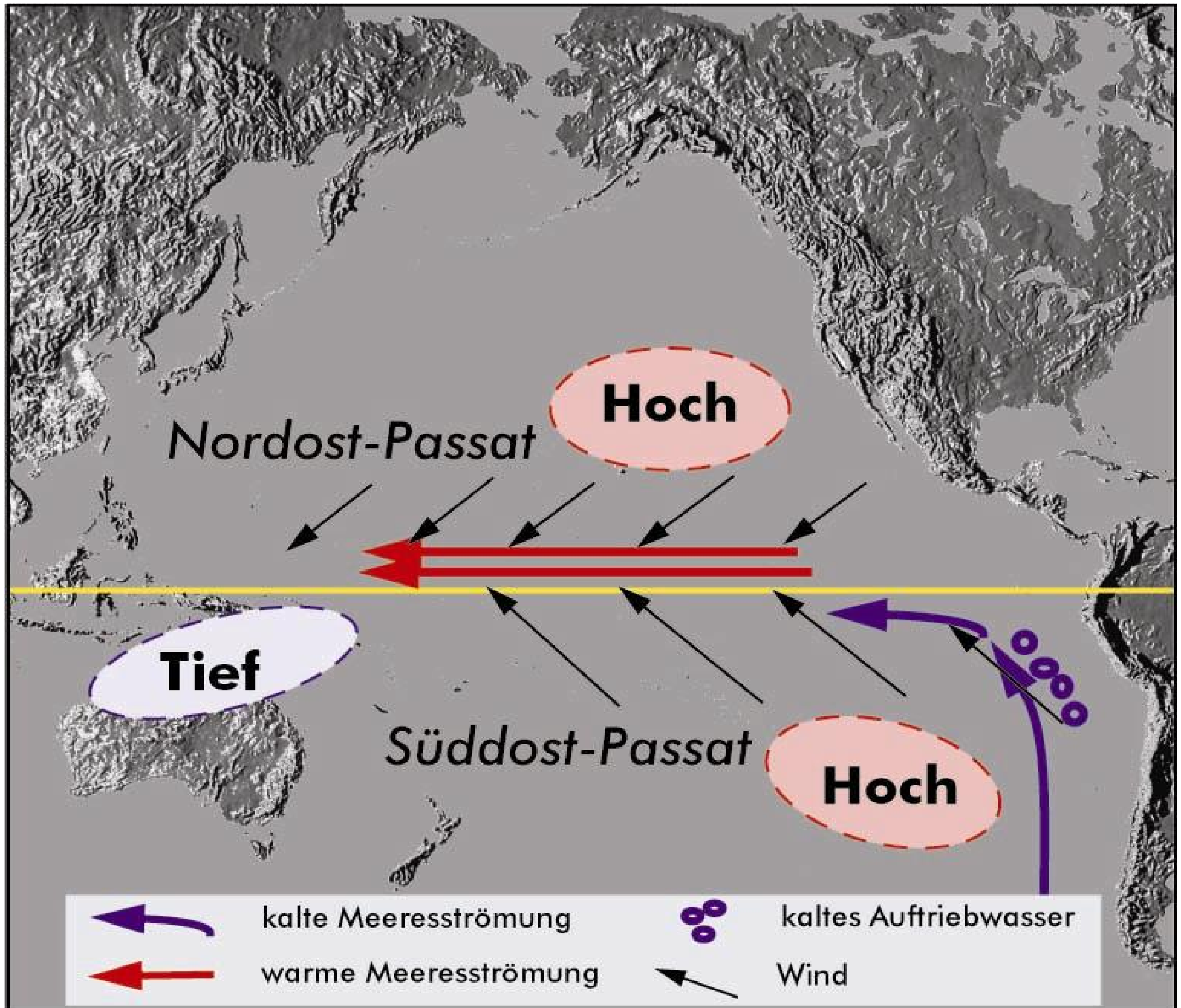
El – Nino Southern Oscillation



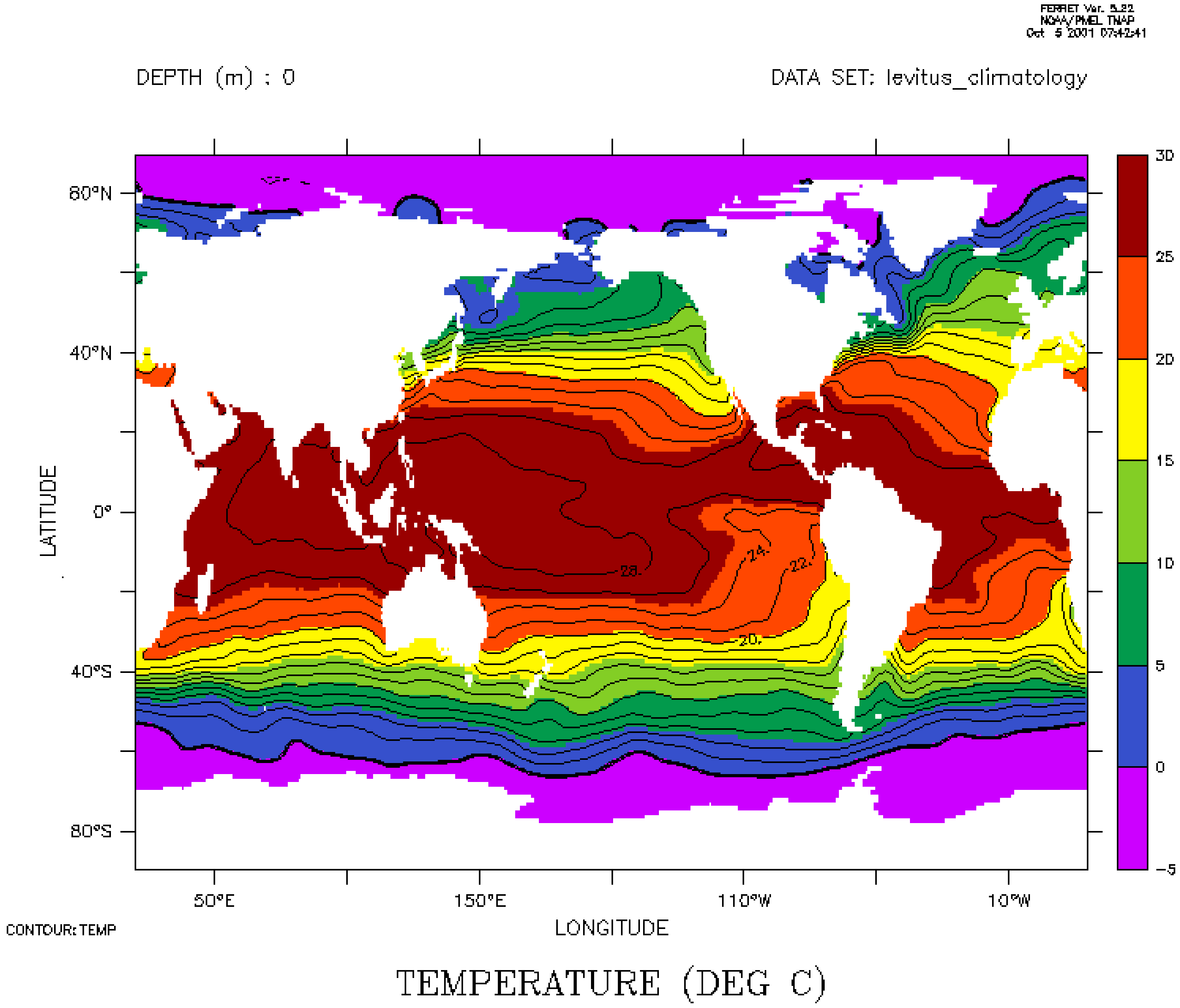
By Dana Summers, The Orlando (Fla.) Sentinel, Tribune Media Services

www.coaps.fsu.edu/lib/climatoons

Climatological conditions in the tropical Pacific

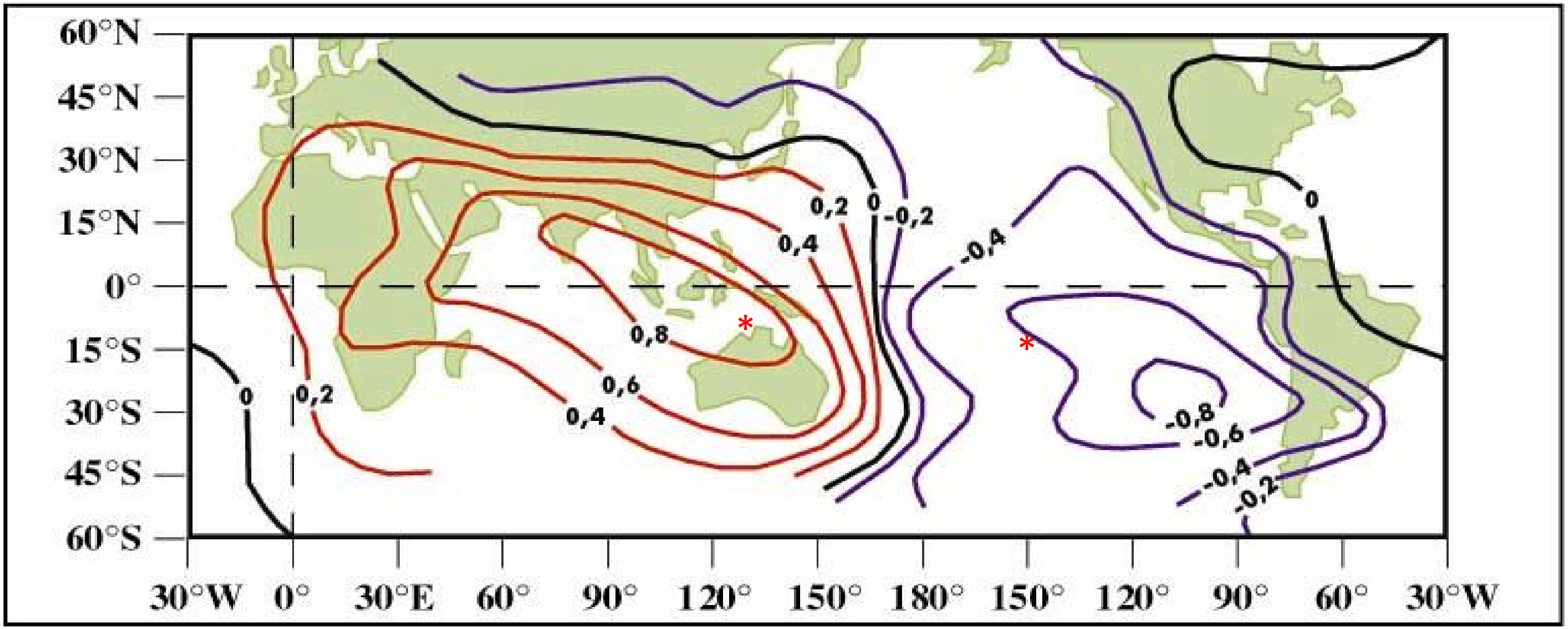


Cubasch and Kasang (2000)



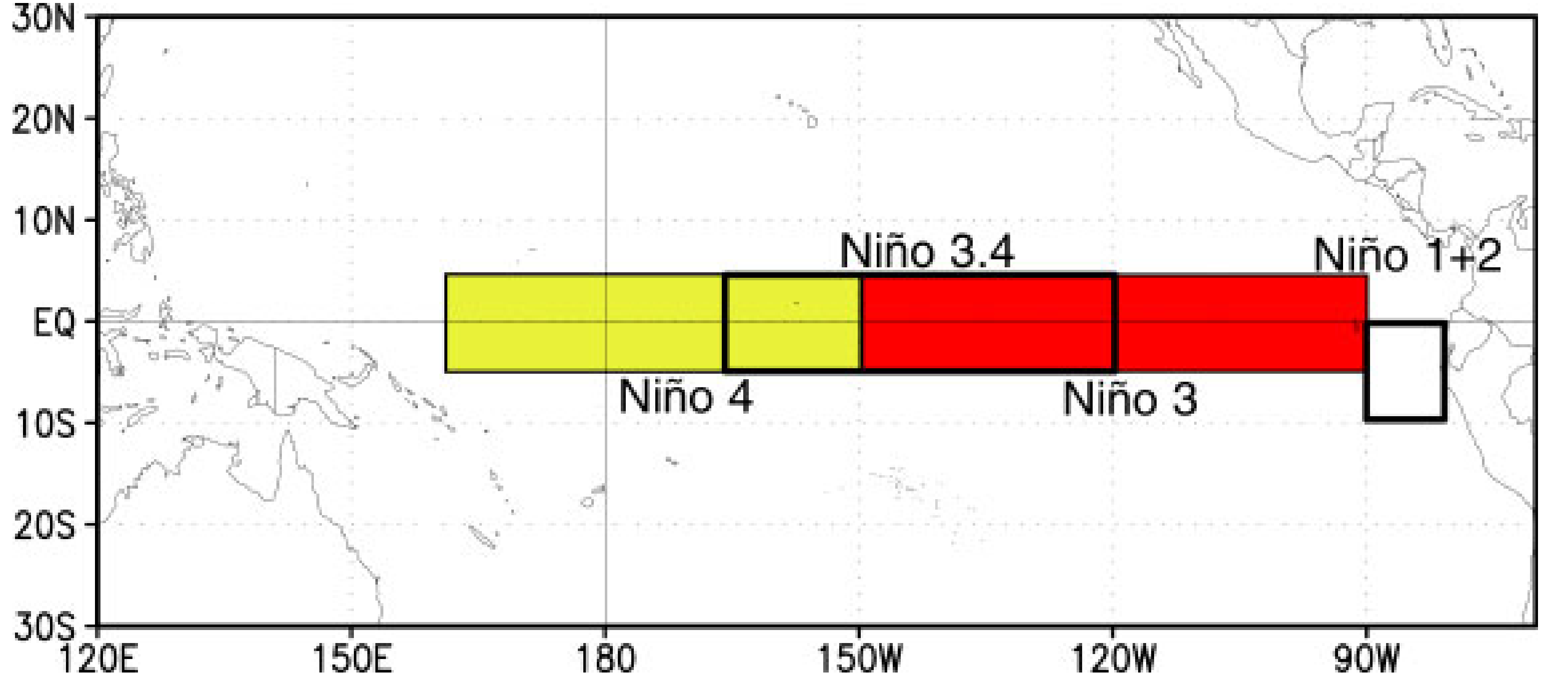
Annual mean SST

The Southern oscillation



The Southern Oscillation Index (SOI) is based on the observed sea level pressure difference between Tahiti and Darwin.

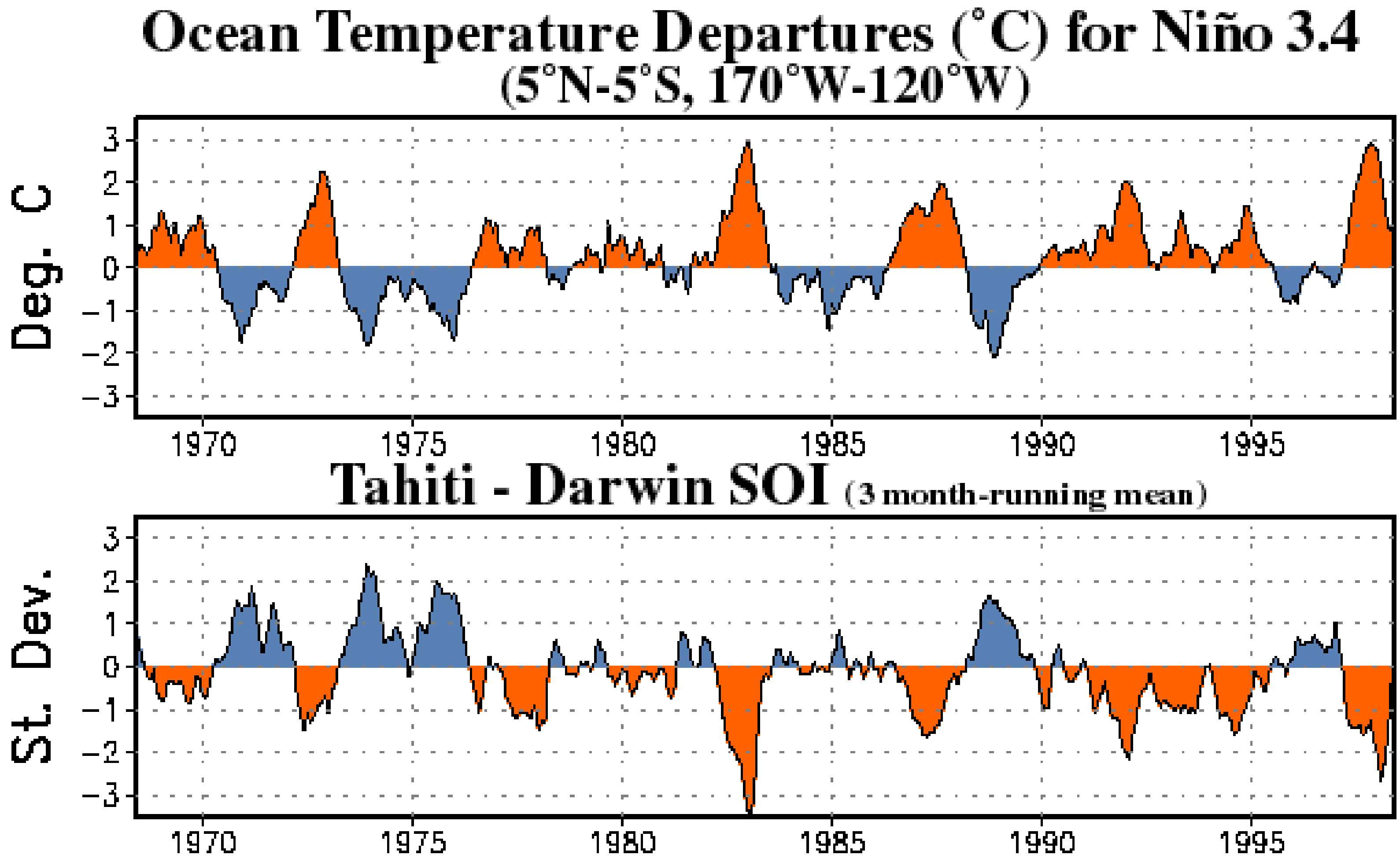
Cubasch und Kasang



Definition of Nino regions

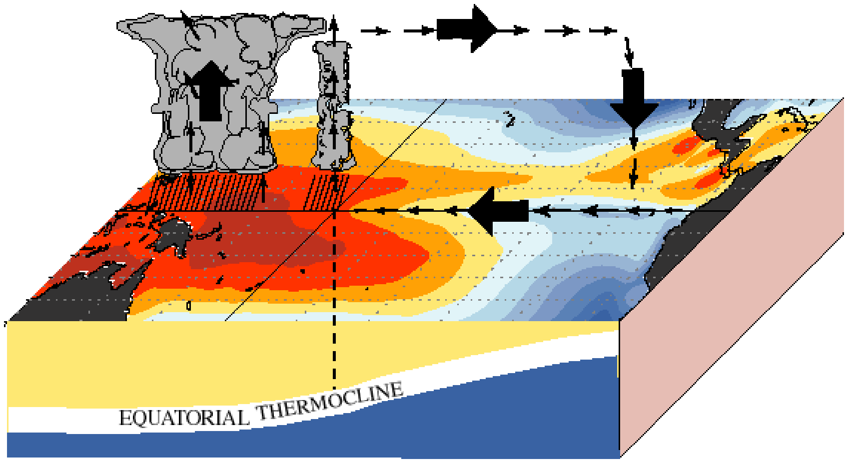
http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensocycle/meanrain.html

http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensocycle/meanrain.htm

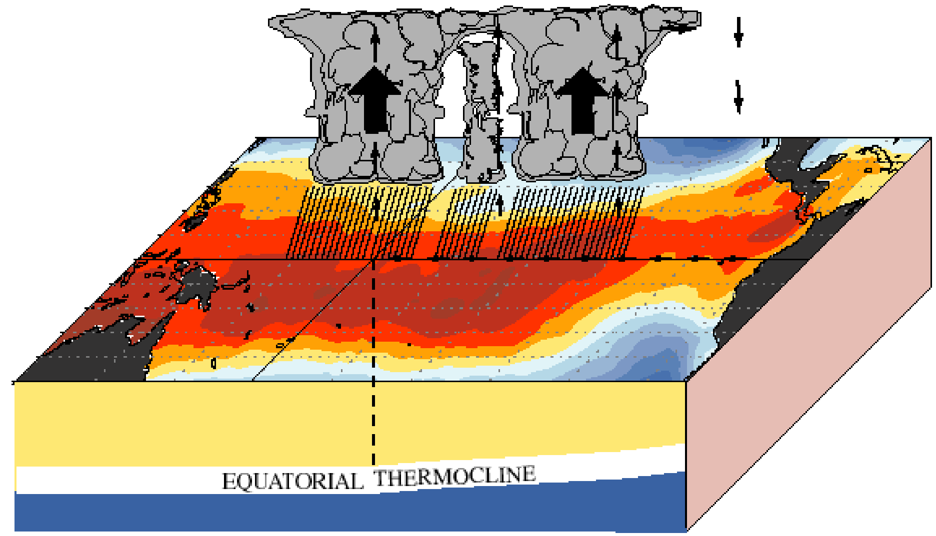


The temperature anomaly of the Nino 3.4 region and the Southern Oscillation Index

December - February Normal Conditions

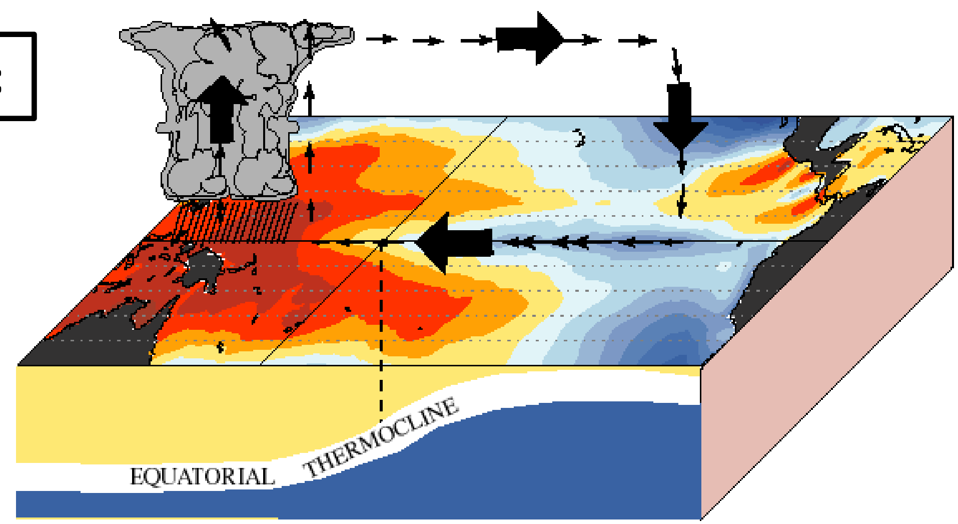


December - February El Niño Conditions

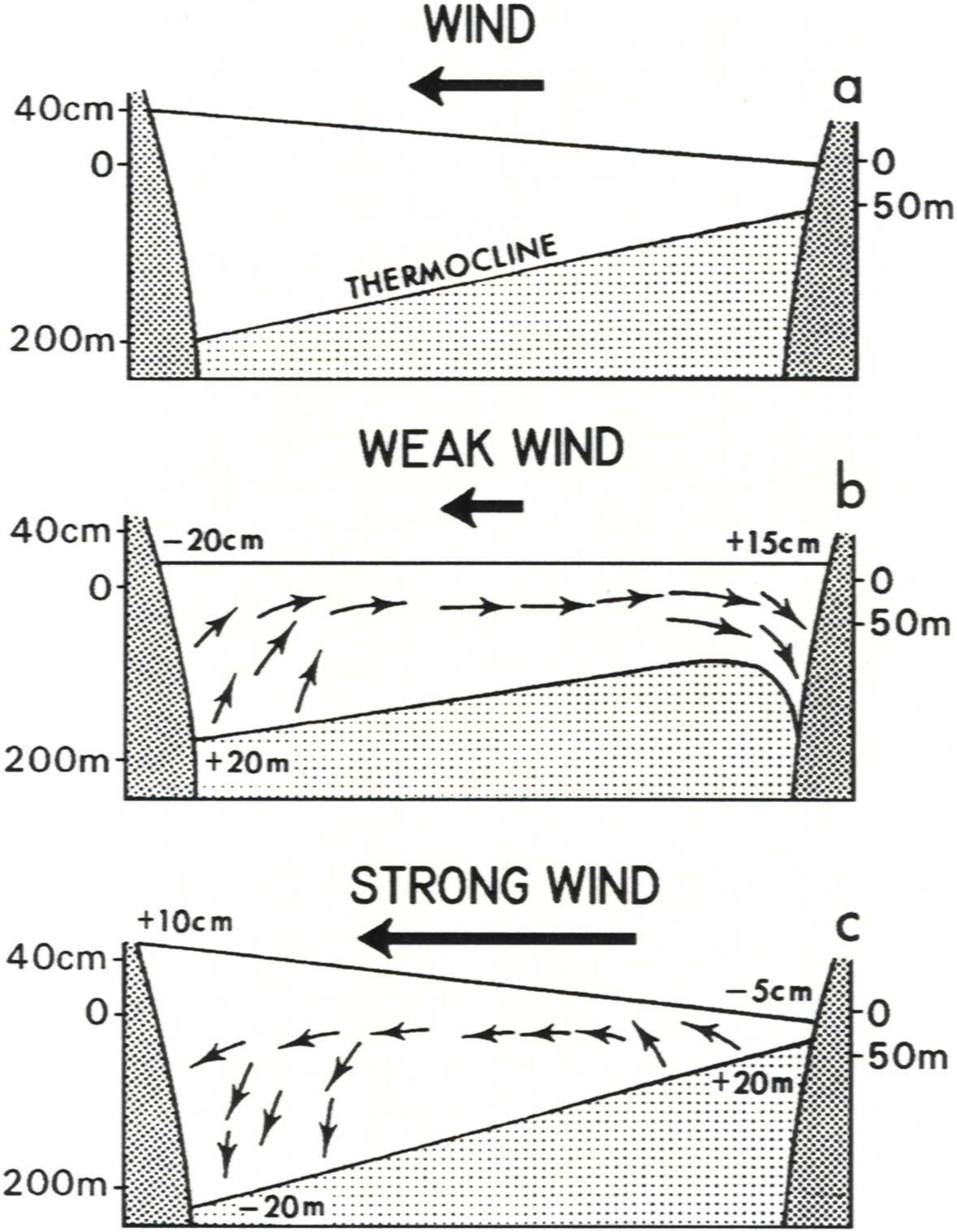


Different states in the tropical Pacific

December - February La Niña Conditions



http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensocycle/meanrain.htm

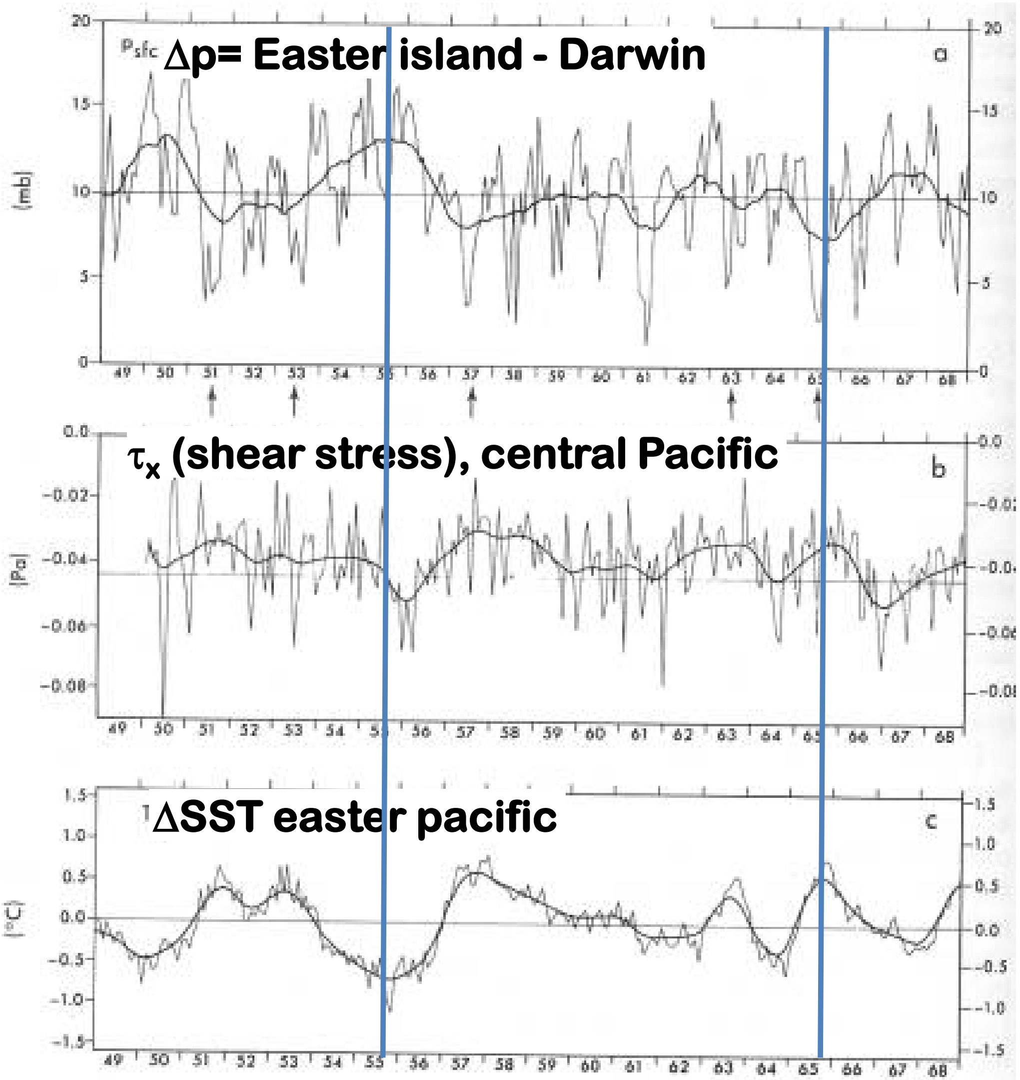


normal

El Nino

La Nina

Evolution of an ENSO event



Correlation analysis

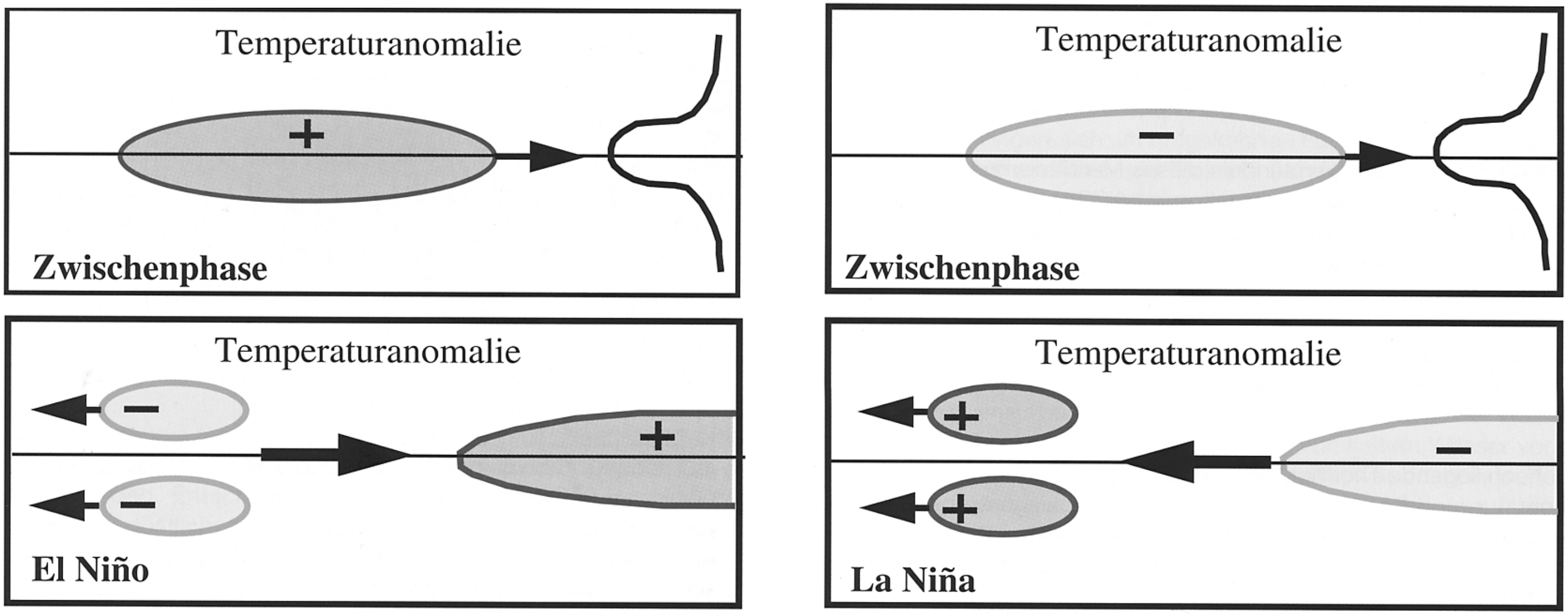
Searching for the max. correlation including possible time lags

$r_{max}(\Delta p, \tau_x) = -0.65$ with $\Delta t = 2$ mon

$r_{max}(\Delta p, \Delta SST) = -0.83$ with $\Delta t = 4.5$ mon

Changes in the pressure gradient establish first a change in wind patterns and then these change the SST.

ENSO mechanism

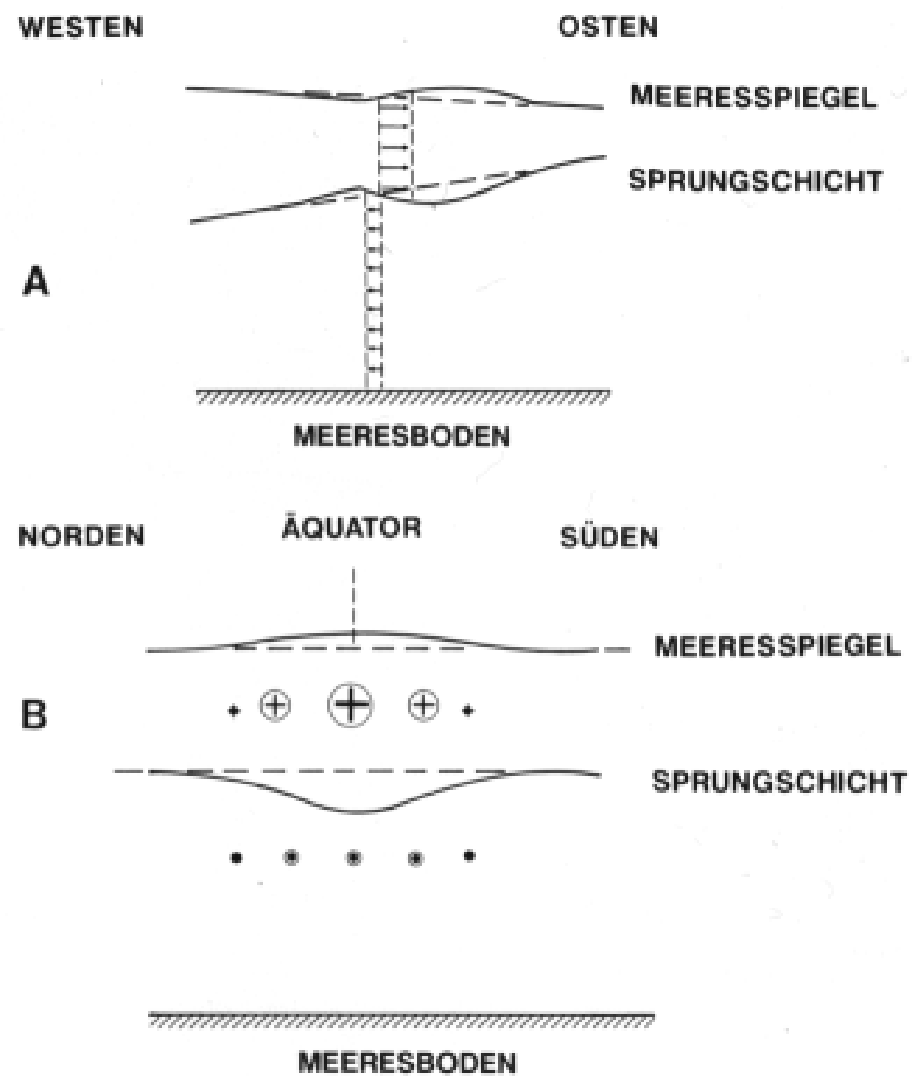


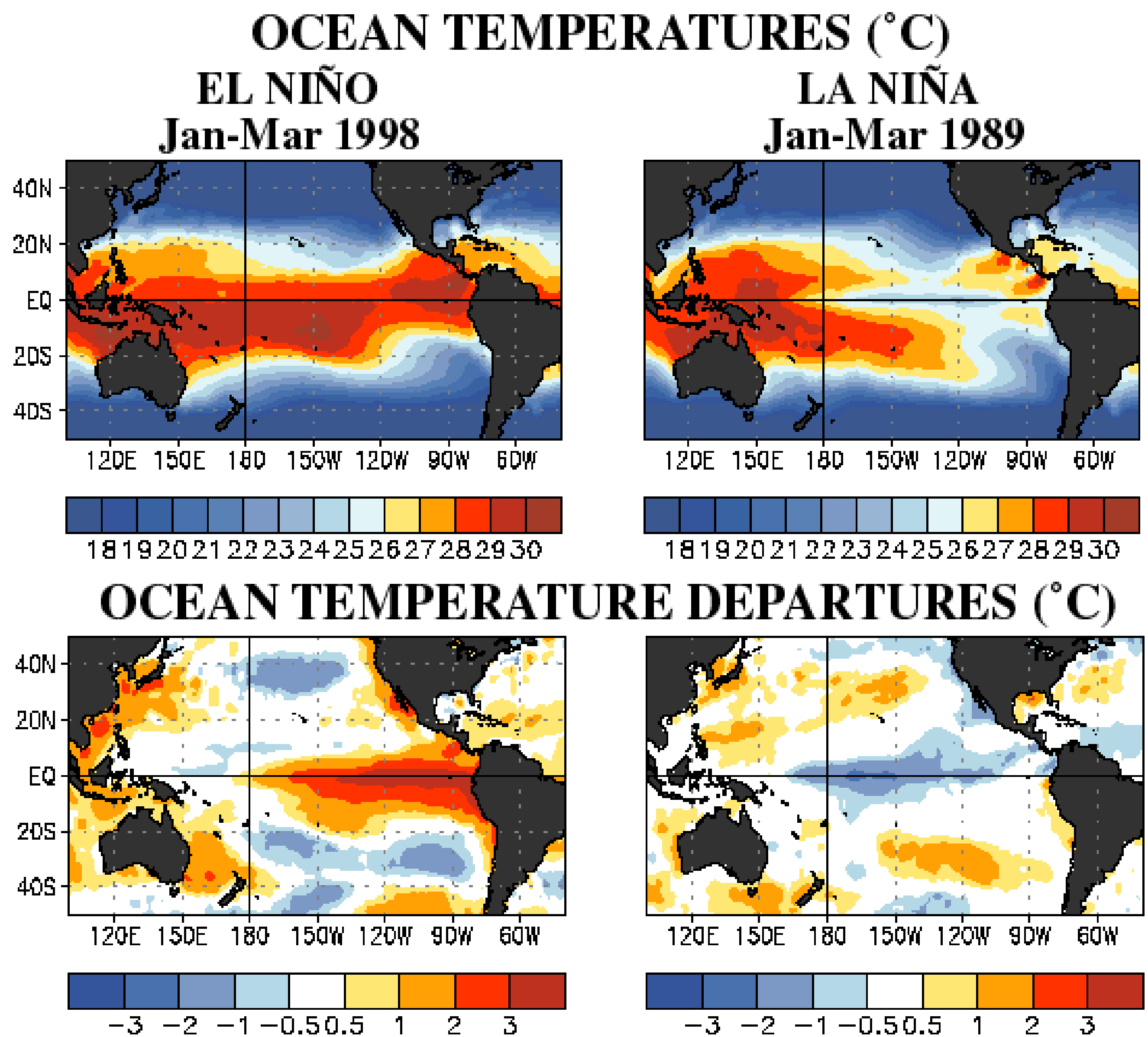
Interaction of eastward travelling Klevin-waves and westward traveling Rossby-waves in the ocean

ENSO mechanism

An equatorial Kelvin-wave is a linear wave with reduced or enhanced temperatures.

- Kelvin-waves tavel eastward along the equator with a speed of ca. 2,5 m/s (ca. 200 km/day)
- Pacific in 2-3 months
- equator works as waveguide
- the coast redirects the wave to the north and south (coastal Kelvin wave)
  → this triggers a Rossby wave that will travel westward

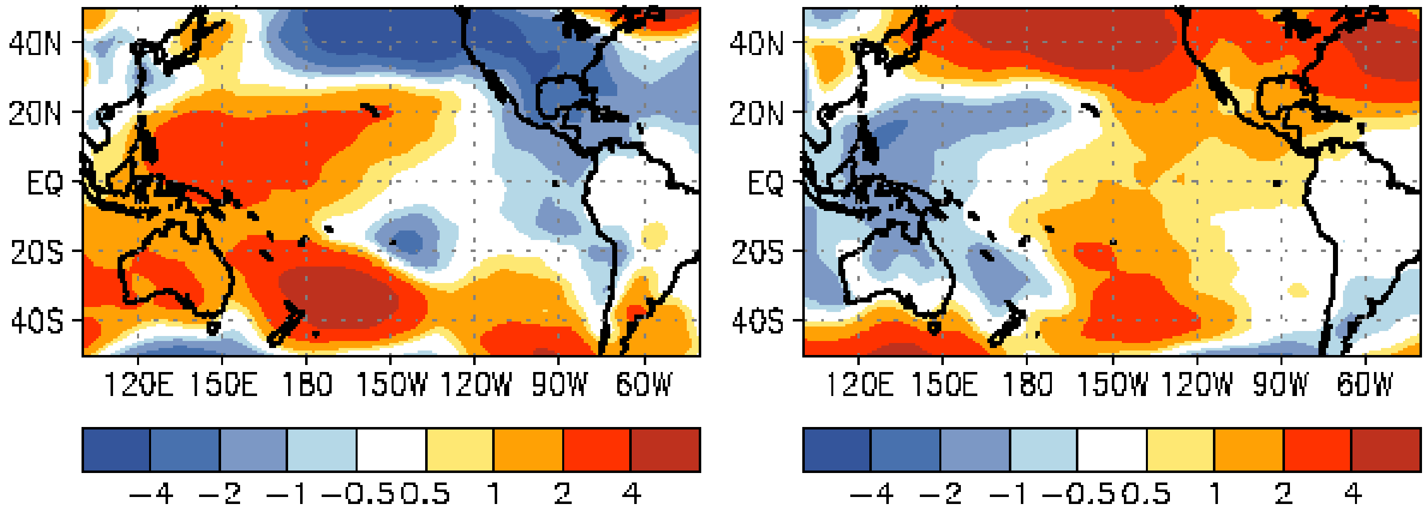




http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensocycle/meanrain.html

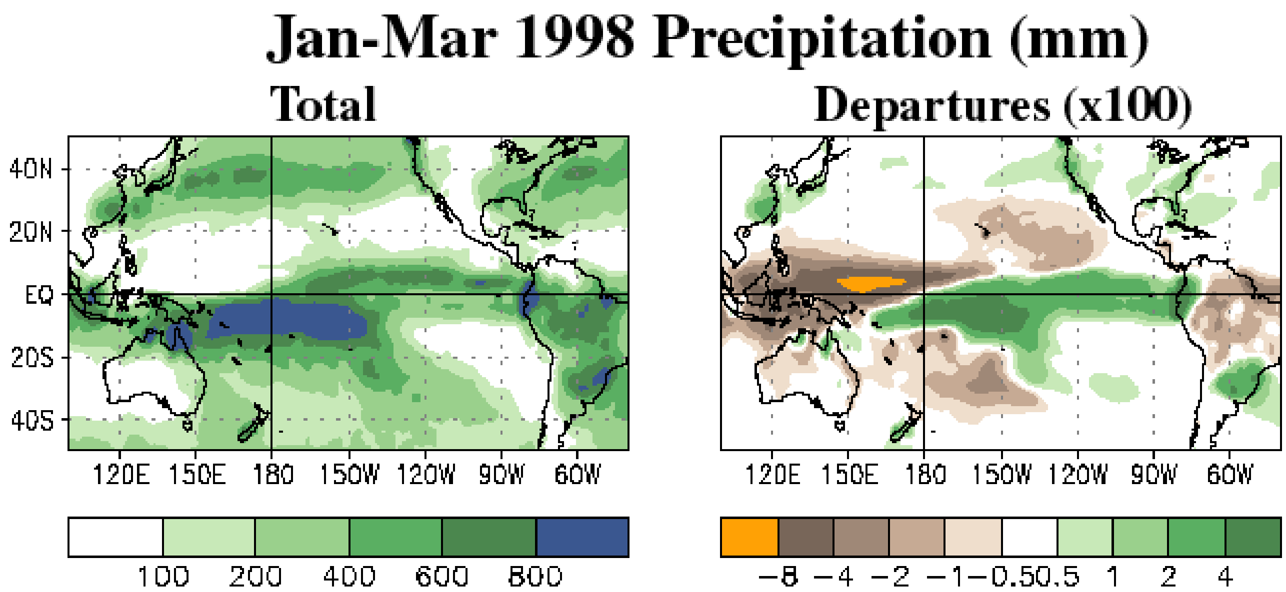
PRESSURE DEPARTURES (mb)

EL NIÑO — Jan-Mar 1998 | LA NIÑA — Jan-Mar 1989

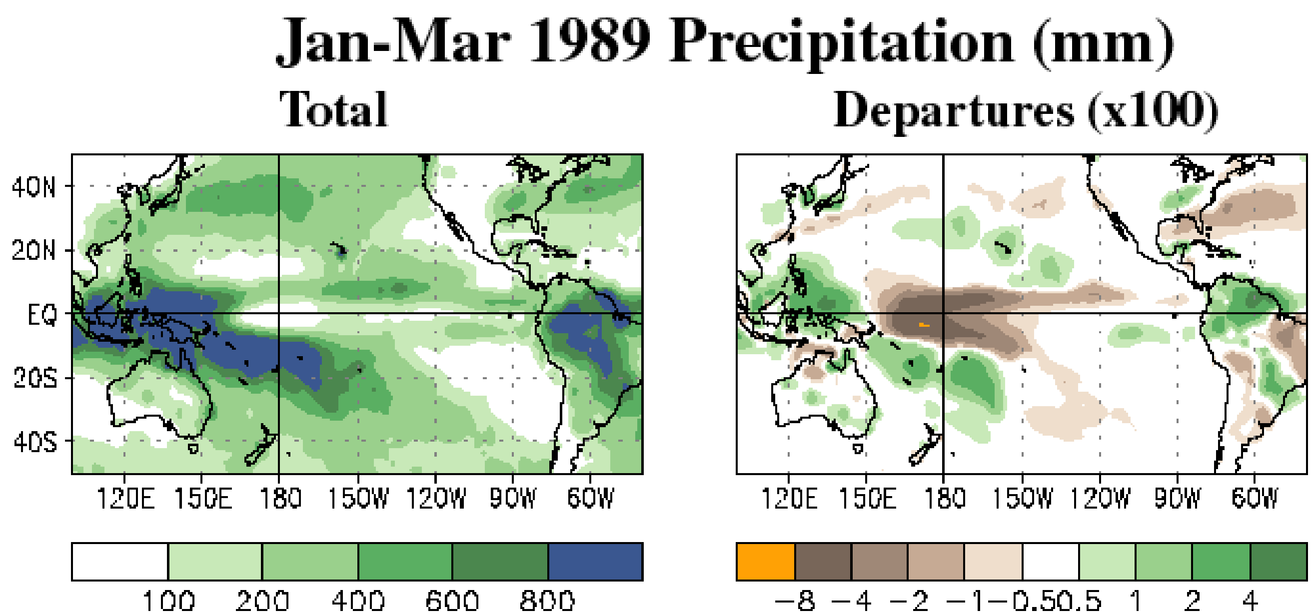


http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensocycle/meanrain.html

El Nino

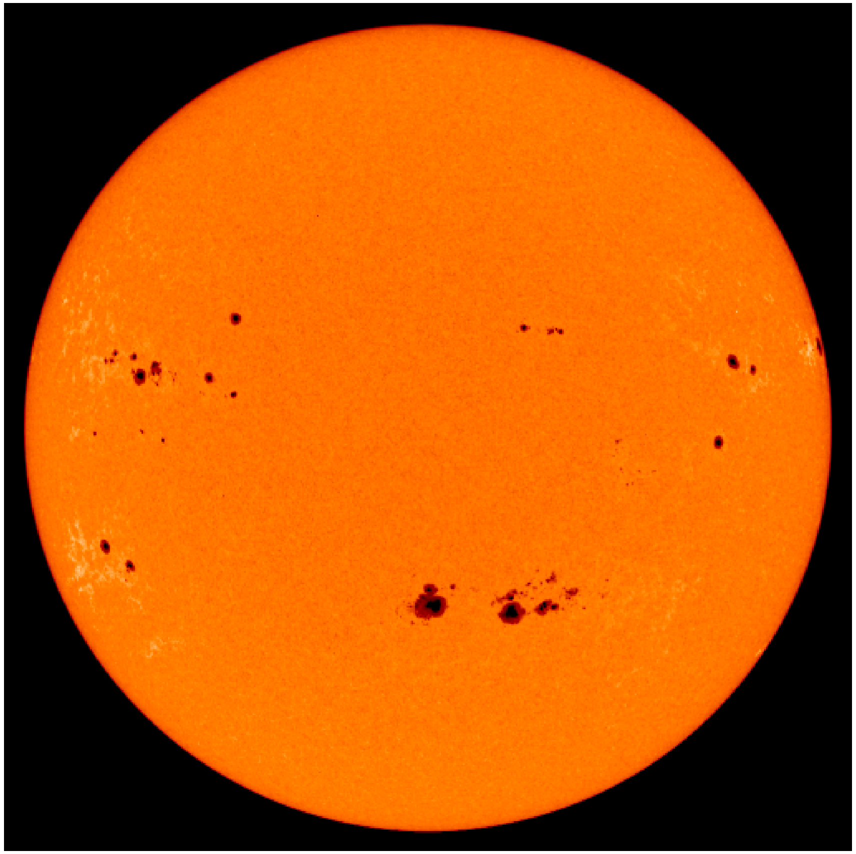


La Nina

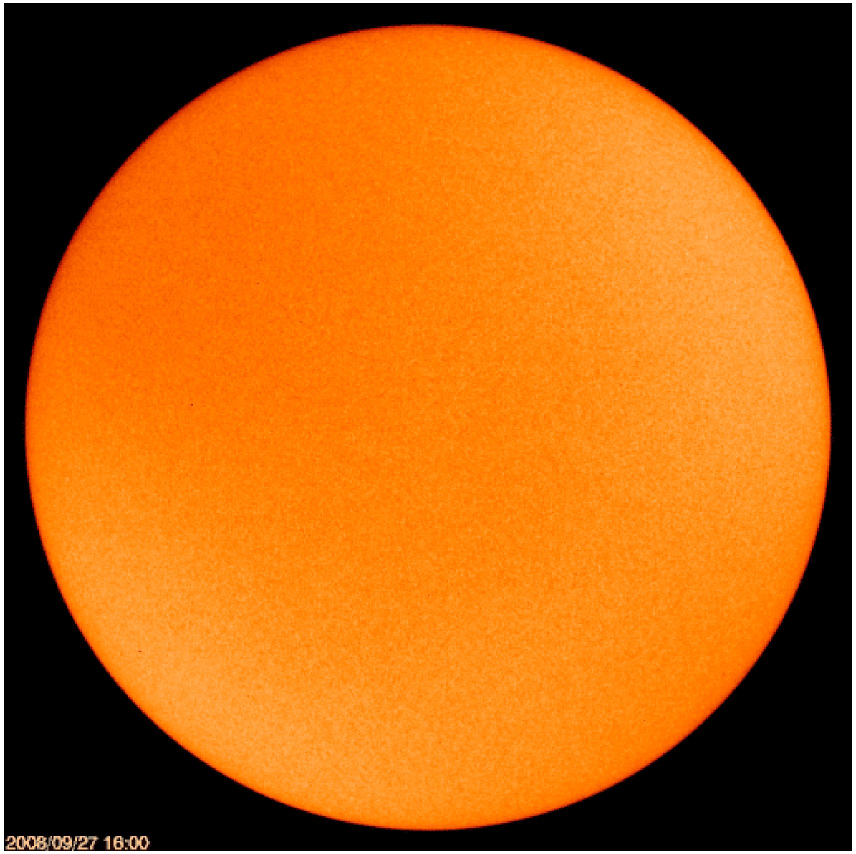


http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensocycle/meanrain.html

The 11-year solar cycle

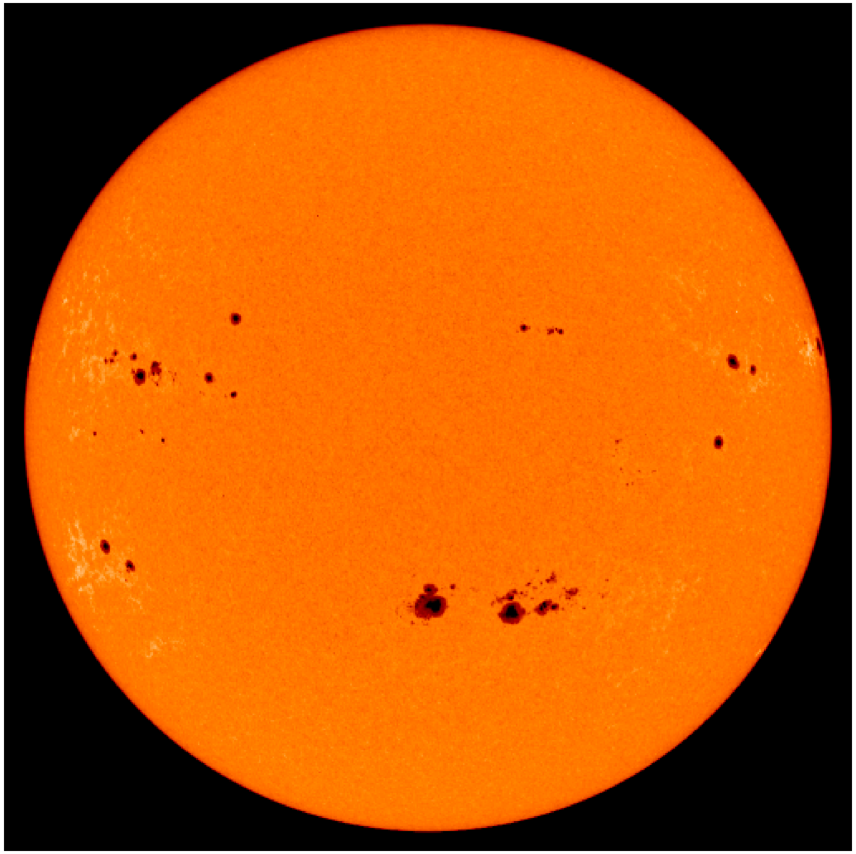


Solar max in 2001



Solar min in 2008

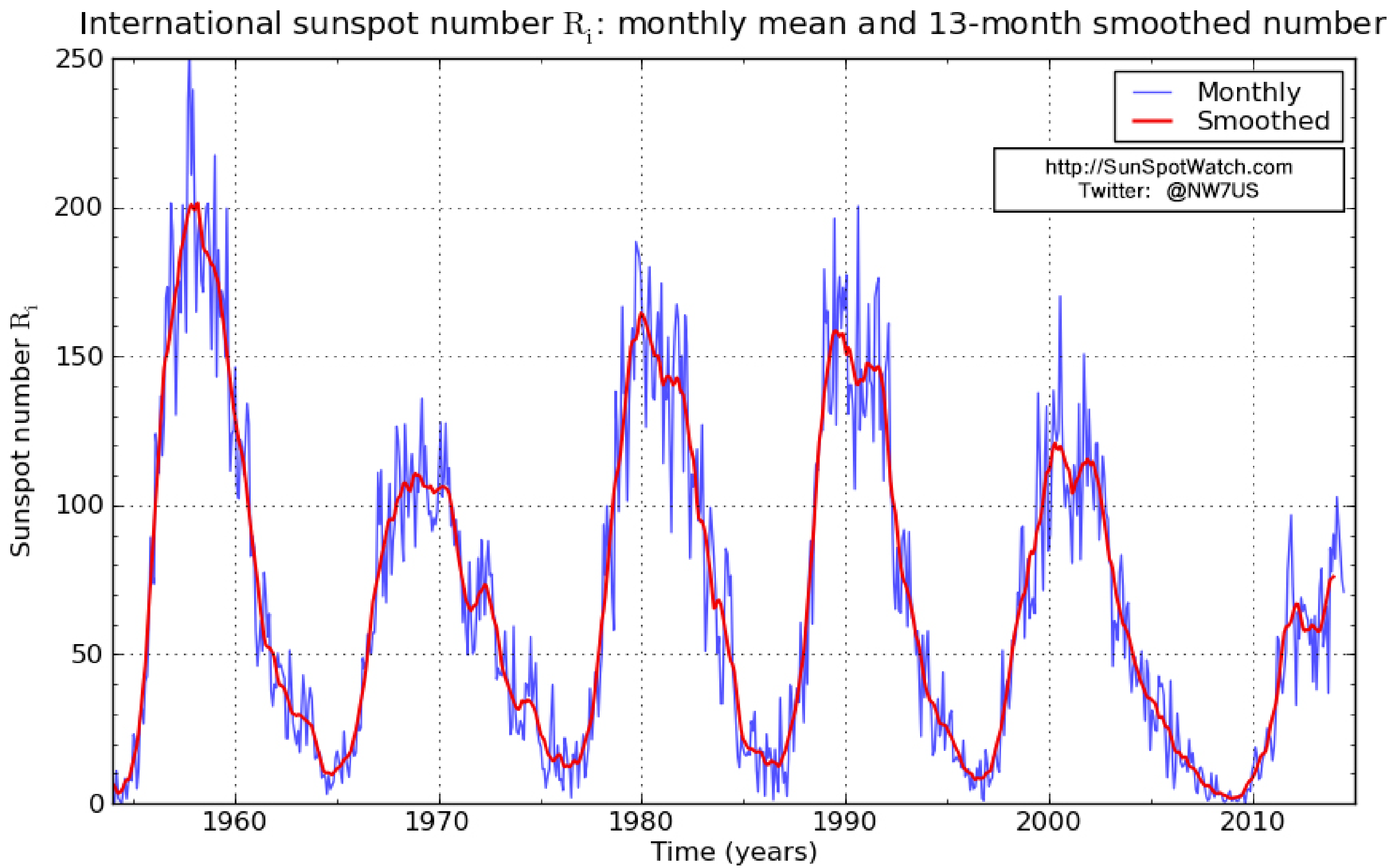
Sunspots



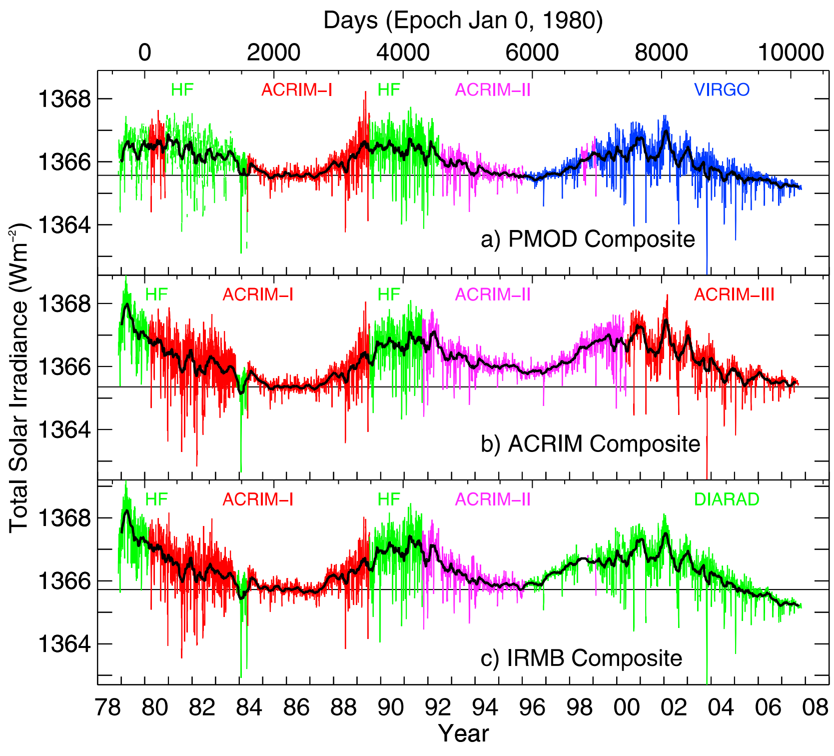
Solar max in 2001

Sunspots…

- are triggered by the suns magnetic field
- have a temperature of 4200K-5700K compared to 6050K of the quiet photosphere
- are compensated by much more numerous brighter regions having a temperature of 6200K


International sunspot number R_i: monthly mean and 13-month smoothed number
Sunspot number R_i
Time (years)
Monthly
Smoothed
http://SunSpotWatch.com
Twitter: @NW7US
0
50
100
150
200
250
1960
1970
1980
1990
2000
2010

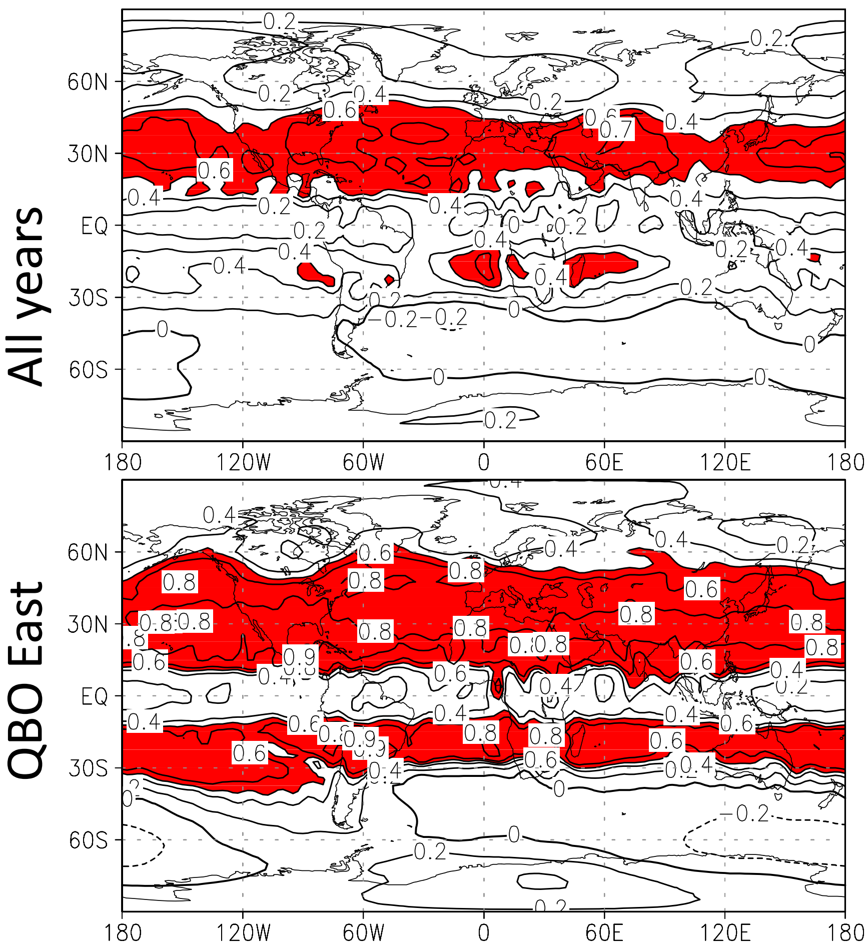
Total solar irradiance (TSI)



Gray et al. 2009

- the solar sunspot cycle has an average period of 11 years
- peak-to-peak amplitude of ~1W/m^2 (0.07% of TSI)
- up to 4% in the region 240– 320 nm where absorption by stratospheric ozone is prevalent

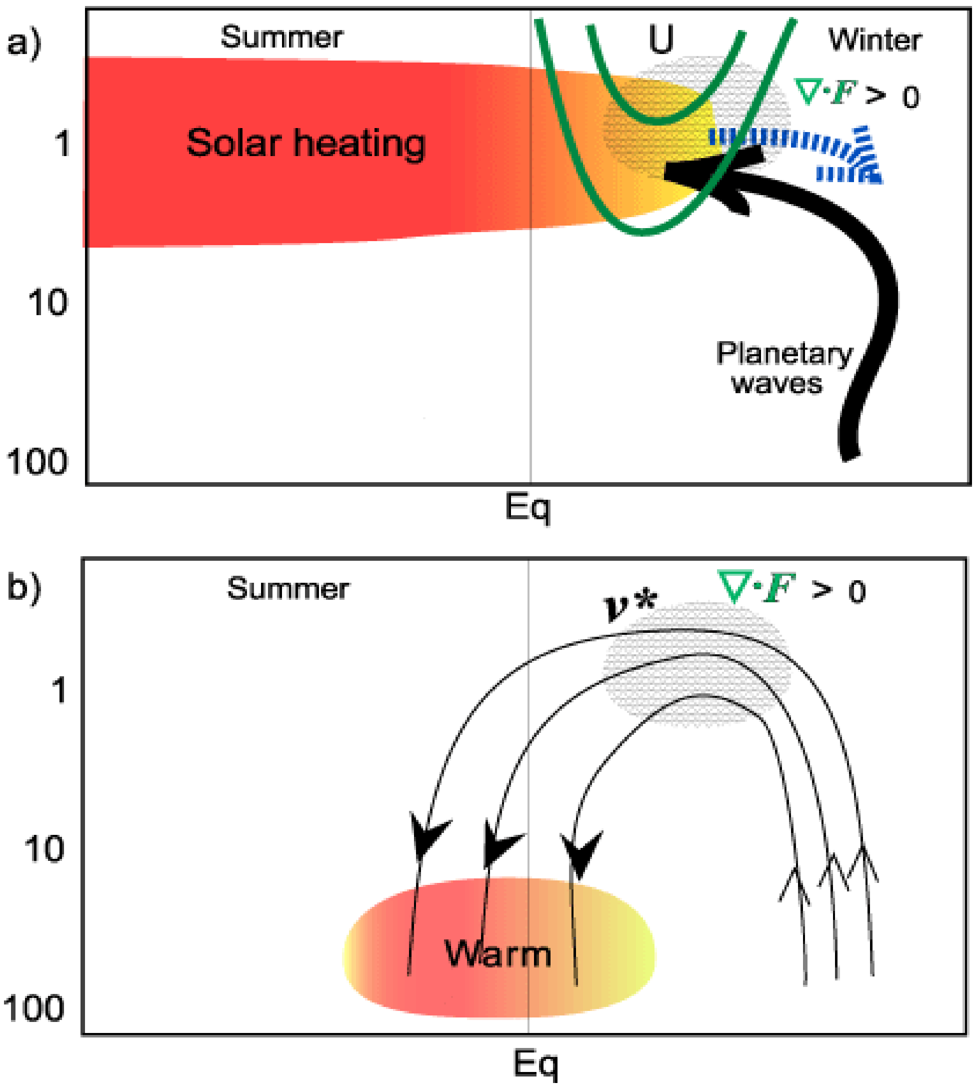
30hPa-temperatures



Labitzke 2003

- correlations between the 10.7cm solar flux and detrended 30hPa temperatures in July (red: correlation > 0.5)
- highest correlation is 0.71 and 0.92, respectively

Solar effect in the stratosphere
(top-down mechanism)

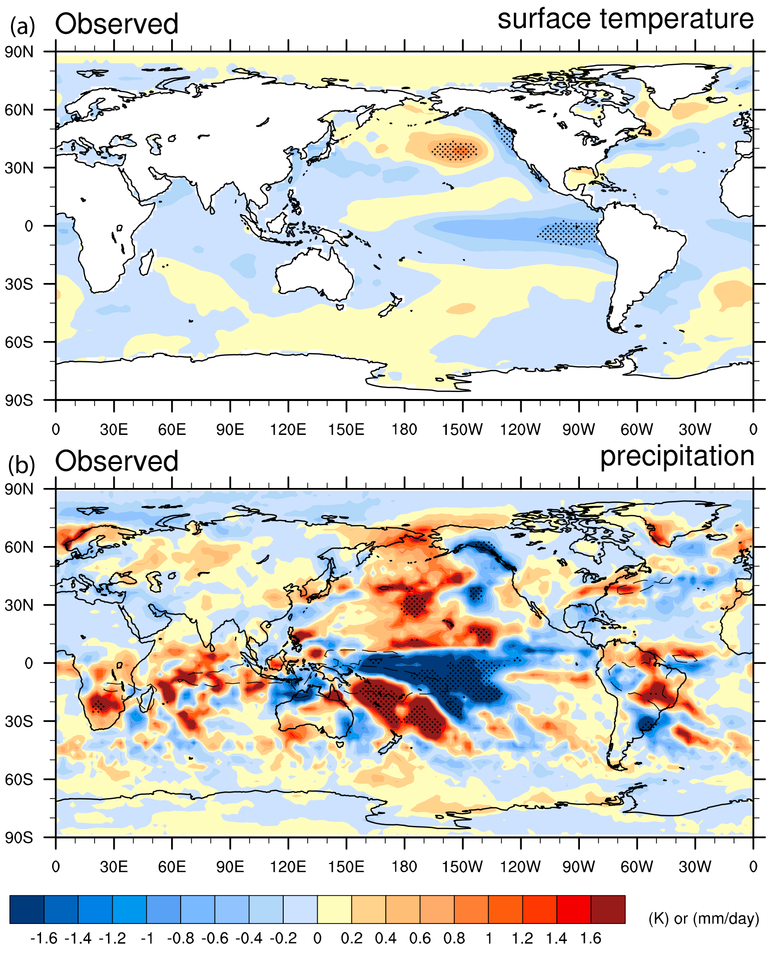


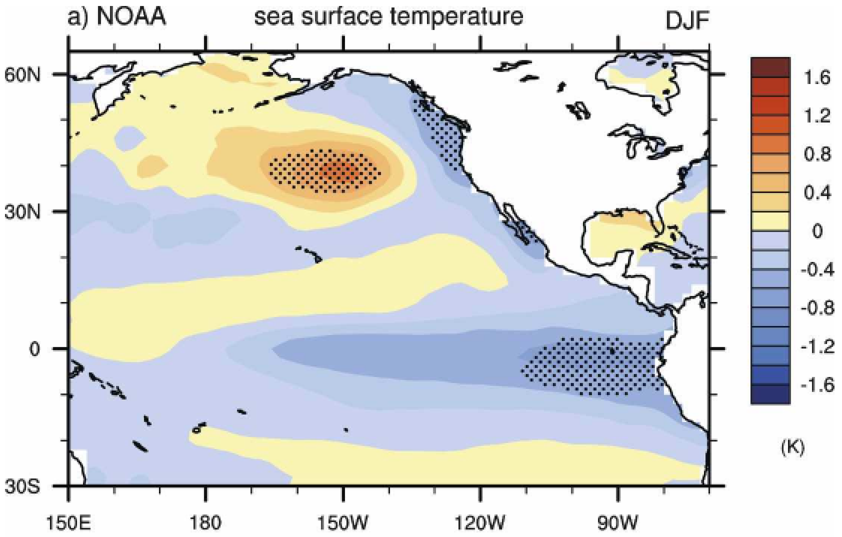
Kodera and Kuroda (2002)

Mainly during early winter (radiative controlled state)

- solar heating modifies meridional temperature gradients in the upper stratosphere/ lower mesosphere
- reinforcement of zonal winds deflects planetary waves, which induces positive divergence of Eliassen-Palm-flux
- this results in a weakening of the Brewer-Dobson-circulation aligned with positive temperature anomalies in the lower tropical stratosphere

Surface response





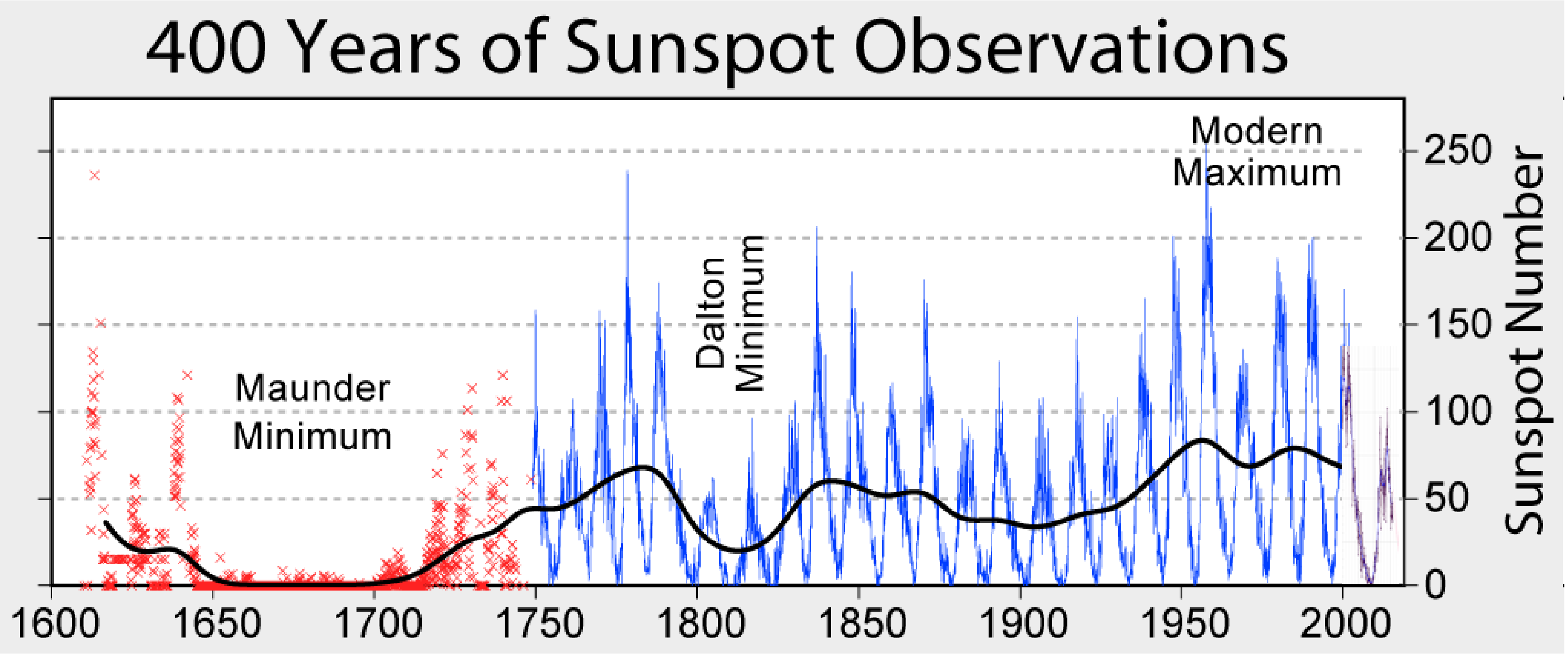
- DJF, 11 peak years relative to all other years
- La Niña like situation

Meehl et al. (2009), J. Clim.

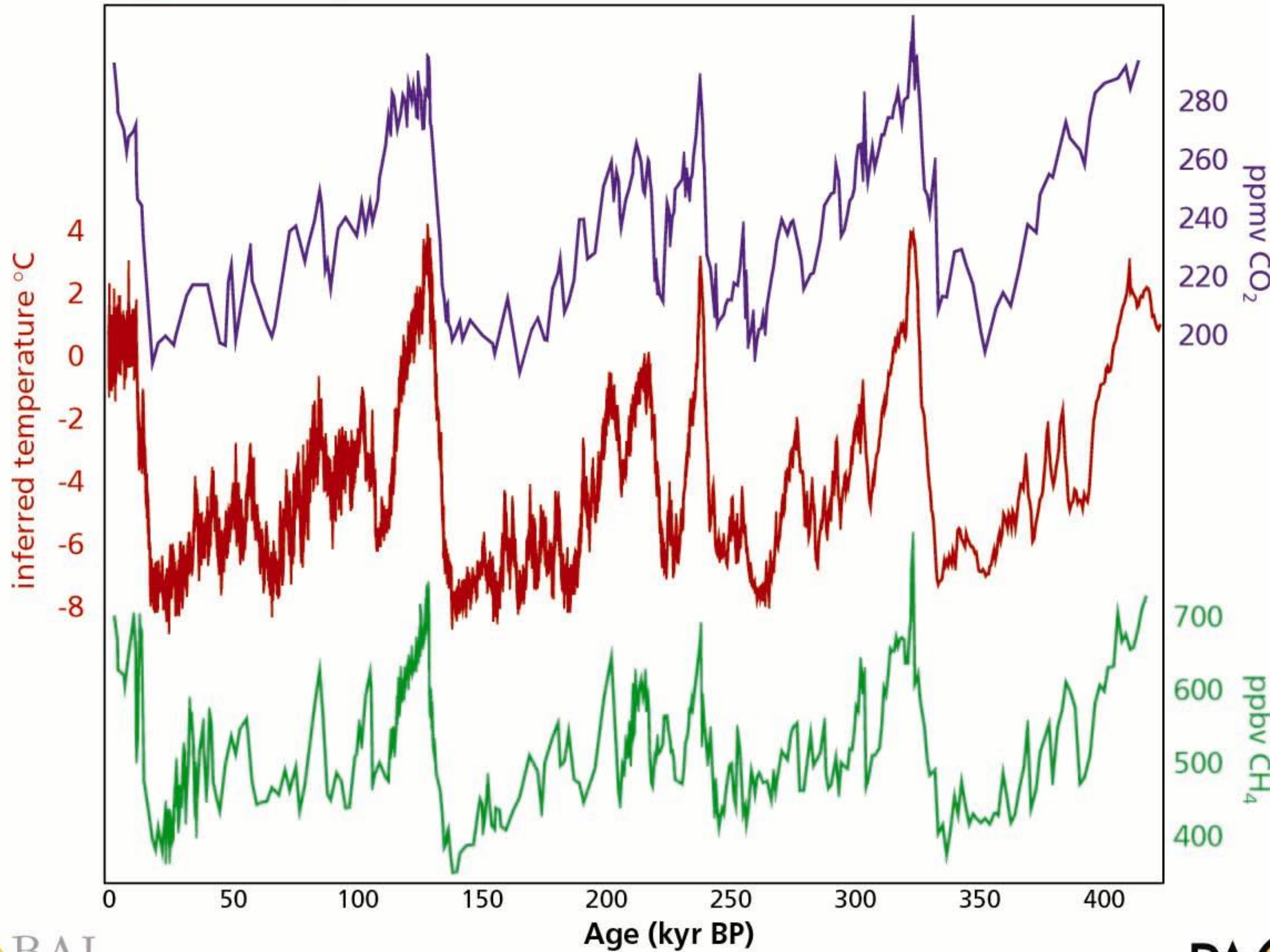
The bottom-up mechanism

(following Meehl et al. 2008)

Sunspots since 1600



4 glacial cycles recorded in the Vostok ice core



GLOBAL IGBP CHANGE

J.R. Petit et al., *Nature,* **399**, 429–36, 1999.

PAGES PAST GLOBAL CHANGES

6.1

Eccentricity

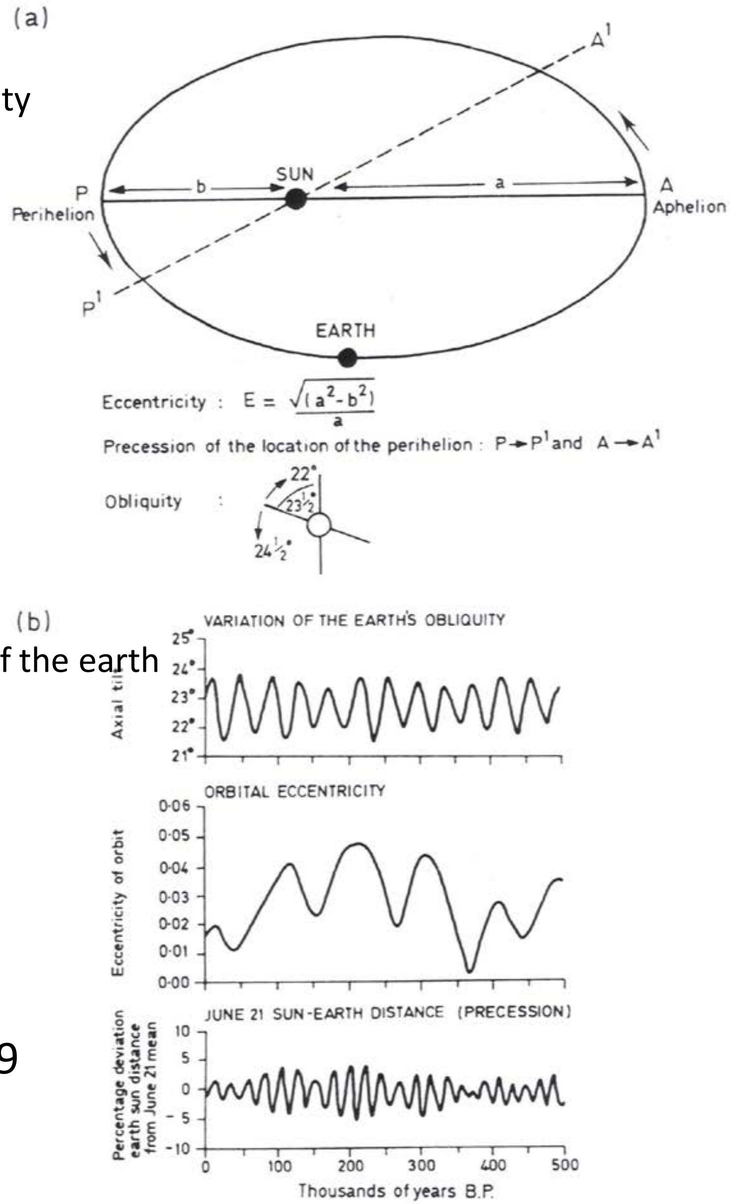


Figure 1.9 (a) Schematic diagram showing the variations in the three orbital components: obliquity (axial tilt), orbital eccentricity and precession of perihelion. (b) Variations in these three components, from 500 000 years ago to the present, as a function of time (reproduced by permission from Broecker and Van Donk (1970) *Rev. Geophys.*, **8**, 169–196. Copyright by the American Geophysical Union)

Tilt of the axis of the earth

~41 ky

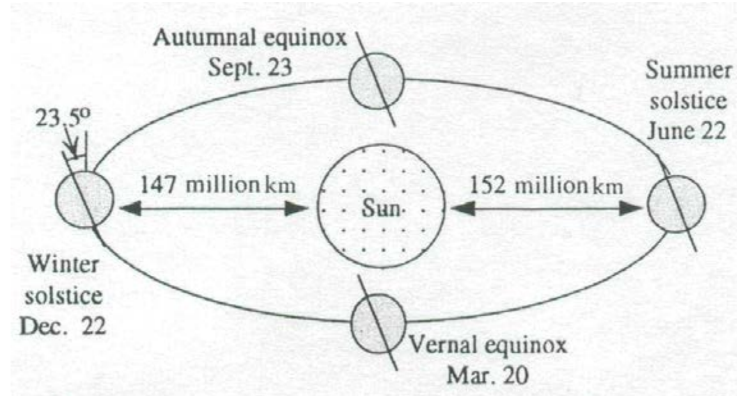
Eccentricity

~100 ky

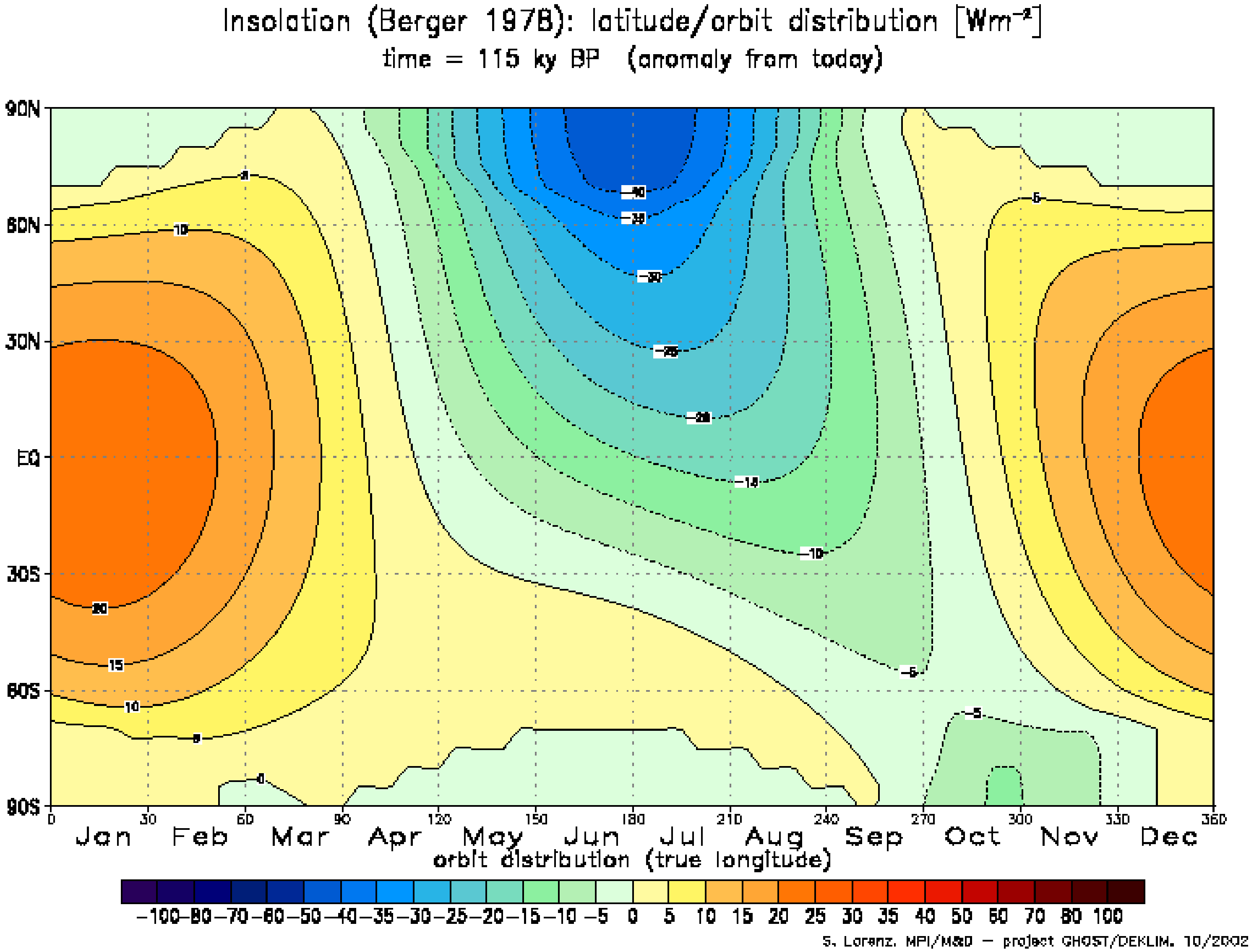
Precession

~ 23 und 19 ky

Precession



Changes of the insolation due to changes in orbital elements



Changes in insolation between 115 ky bp and today (last glacial inception)

That’s it!