Dynamics II: Statistical data analysis identifying mechanisms of climate change

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14.6.2021

University of Bremen
& Alfred Wegener Institute

Dynamics of the Ocean System

Momentum equation

$$\overbrace{\rho\left(\underbrace{\frac{\partial \mathbf{v}}{\partial t}}_{\substack{\text{Unsteady}\\\text{acceleration}}} + \underbrace{\mathbf{v}\cdot\nabla\mathbf{v}}_{\substack{\text{Advective}\\\text{acceleration}}}\right)}^{\text{Inertia (per volume)}} = \overbrace{\underbrace{-\nabla p}_{\substack{\text{Pressure}\\\text{gradient}}} + \underbrace{\mu\nabla^2\mathbf{v}}_{\text{Viscosity}}}^{\text{Divergence of stress}} + \underbrace{\mathbf{f}}_{\substack{\text{Other}\\\text{body}\\\text{forces}}} .$$

$$\left(\underbrace{\frac{\partial \mathbf{v}}{\partial t}}_{10^{-4}} + \underbrace{\mathbf{v}\cdot\nabla\mathbf{v}}_{10^{-4}}\right) = \underbrace{-\frac{1}{\rho}\nabla p}_{10^{-3}} + \underbrace{\nu\nabla^2\mathbf{v}}_{10^{-12}} + \underbrace{2\boldsymbol{\Omega}\times\mathbf{v}}_{10^{-3}} .$$

Geostrophic balance: Pressure gradient Coriolis force

Ocean: Depth integrated flow

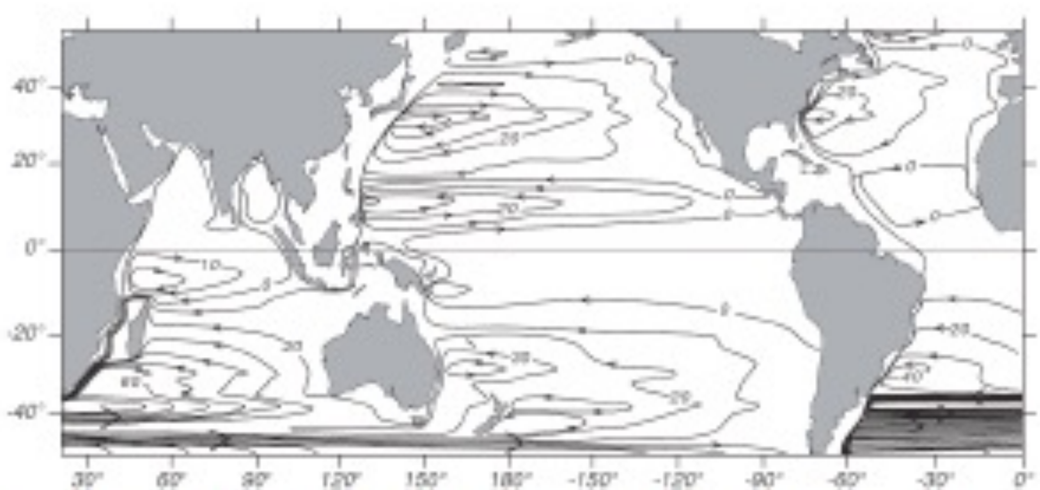
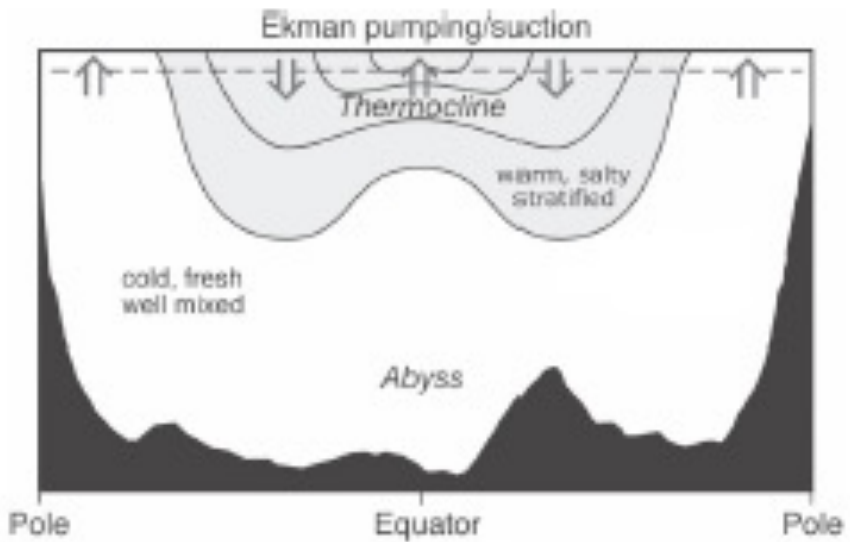


Figure 2.8: Depth-integrated Sverdrup transport applied globally using the wind stress from Hellerman and Rosenstein (1983). Contour interval is 10 Sverdrups. After Tomczak and Godfrey (1994: 46).

Deep water

Vertical structure of the ocean



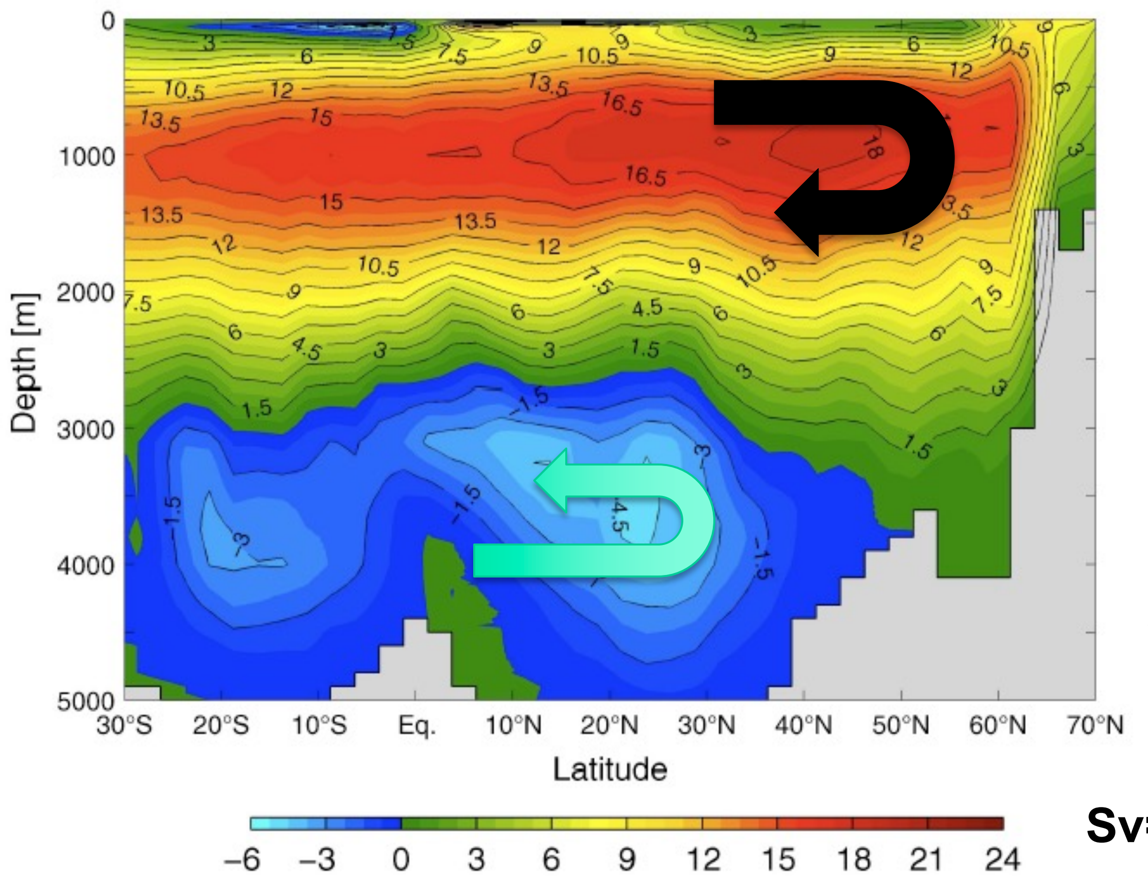
Warm, salty, stratified

Cold, fresh, well mixed

Meridional overturning circulation

Looking to the west

Atlantic Ocean deep sea circulation



NADW: 18 Sv

AABW: 4 Sv

Sv=10^6 m^3/s

Symmetric solution

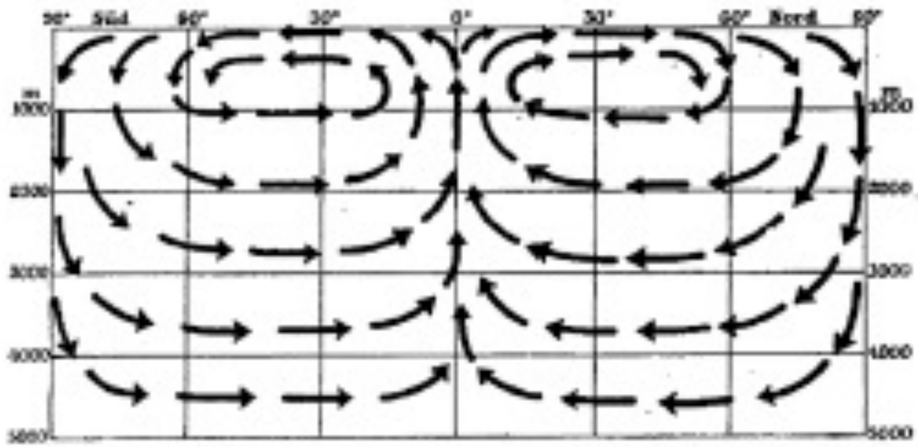


Figure 2.15: Atlantic circulation model according to (von Lenz, 1847a, b), figure after (Merz and Wüst, 1922)

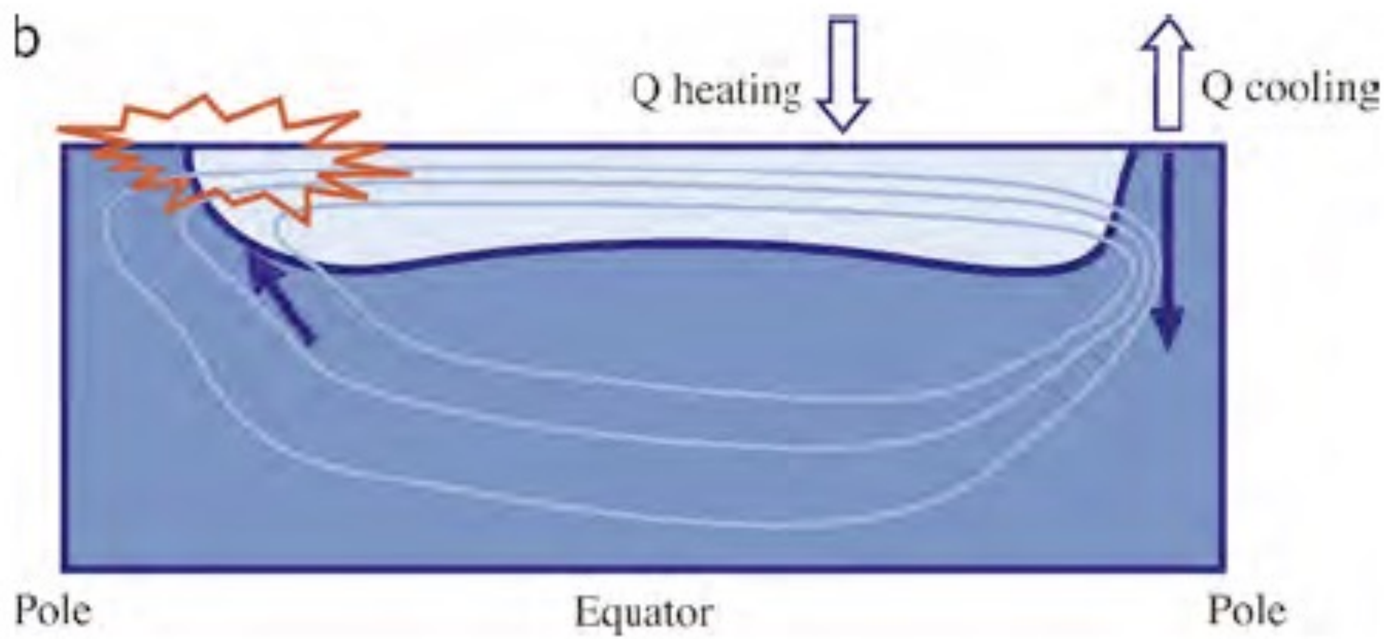
Von Lenz, 1847

-> water planet

Mixing

- without mixing heavy water with lighter water in rising areas or in the surface layers of MOC, the circulation system cannot be closed.
- Since mixing consumes turbulent mechanical energy generated by wind in the surface layer and/or by tides and breaking of internal waves in the interior, the overturning can only work on the basis of mechanical driving.

MOC and mixing



the upwelling can be wind-induced (Ekman pumping), isopycnals must outcrop at the surface as in the Southern Ocean.

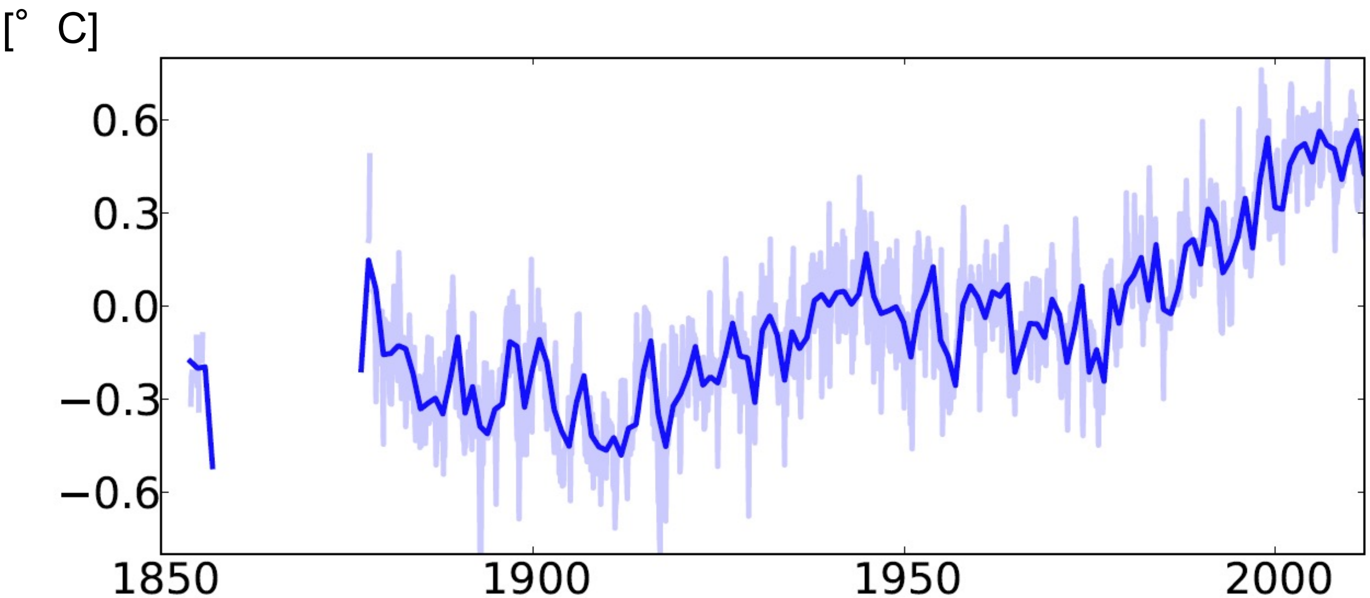
Dynamics II:
Statistical data analysis identifying mechanisms of climate change

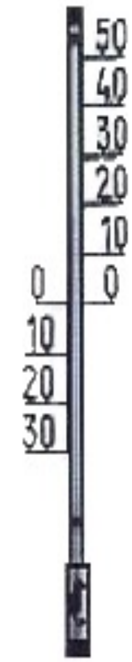
Lecture and Practicals

Climate Trends at different Timescales

Temperature of the last **150 years** (instrumental data)

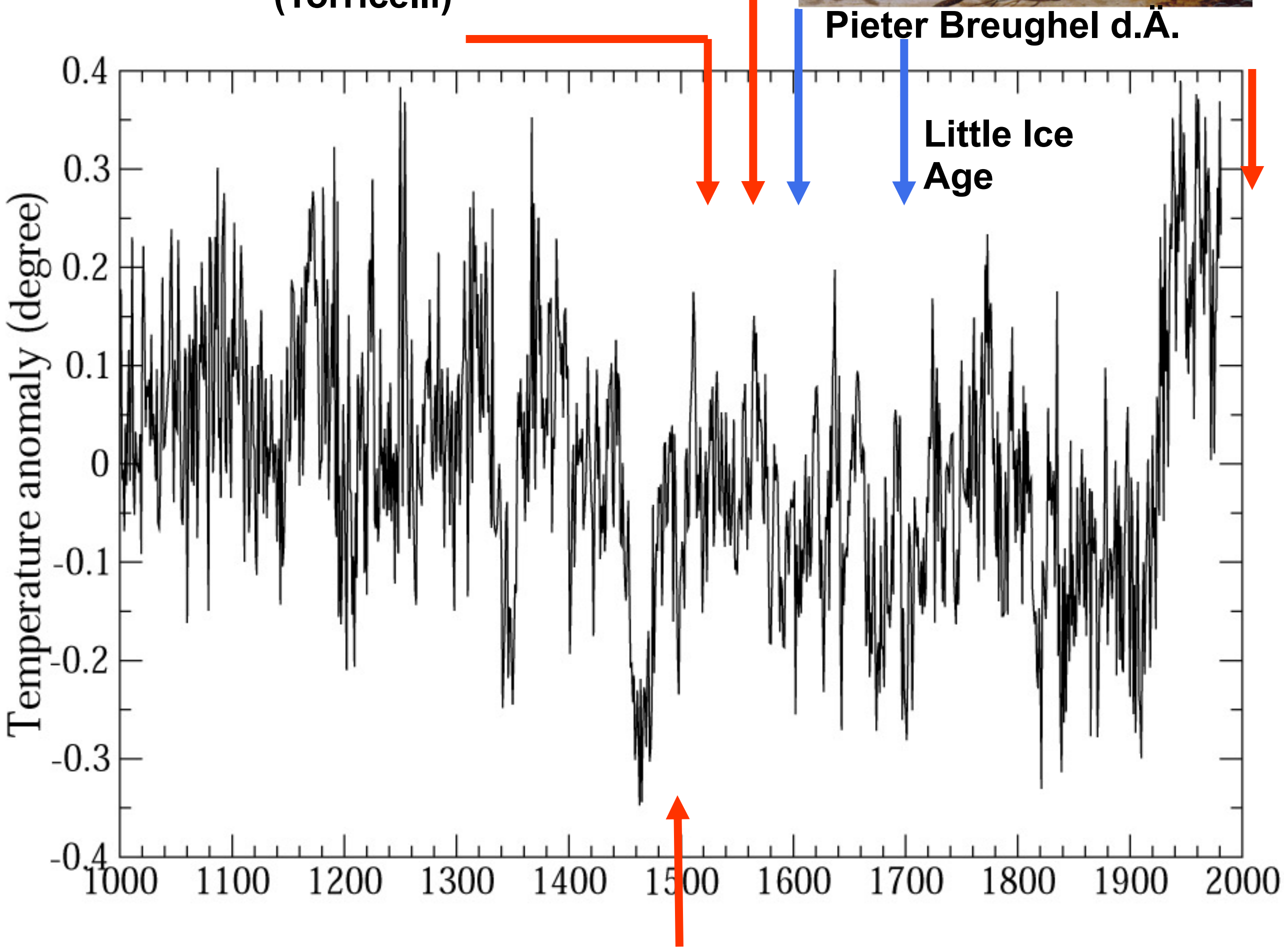
Northern Hemisphere Temp. anomaly
HadCRU

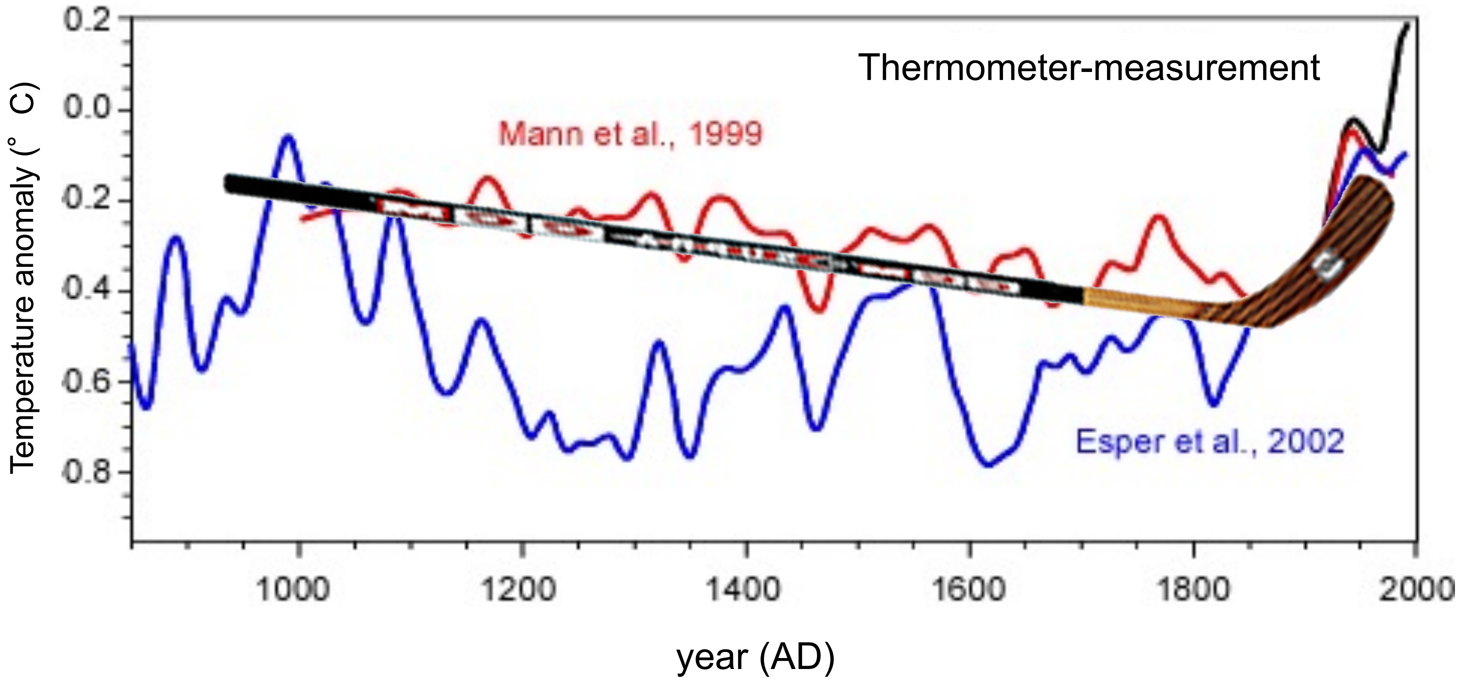




History

last **1000 Years**

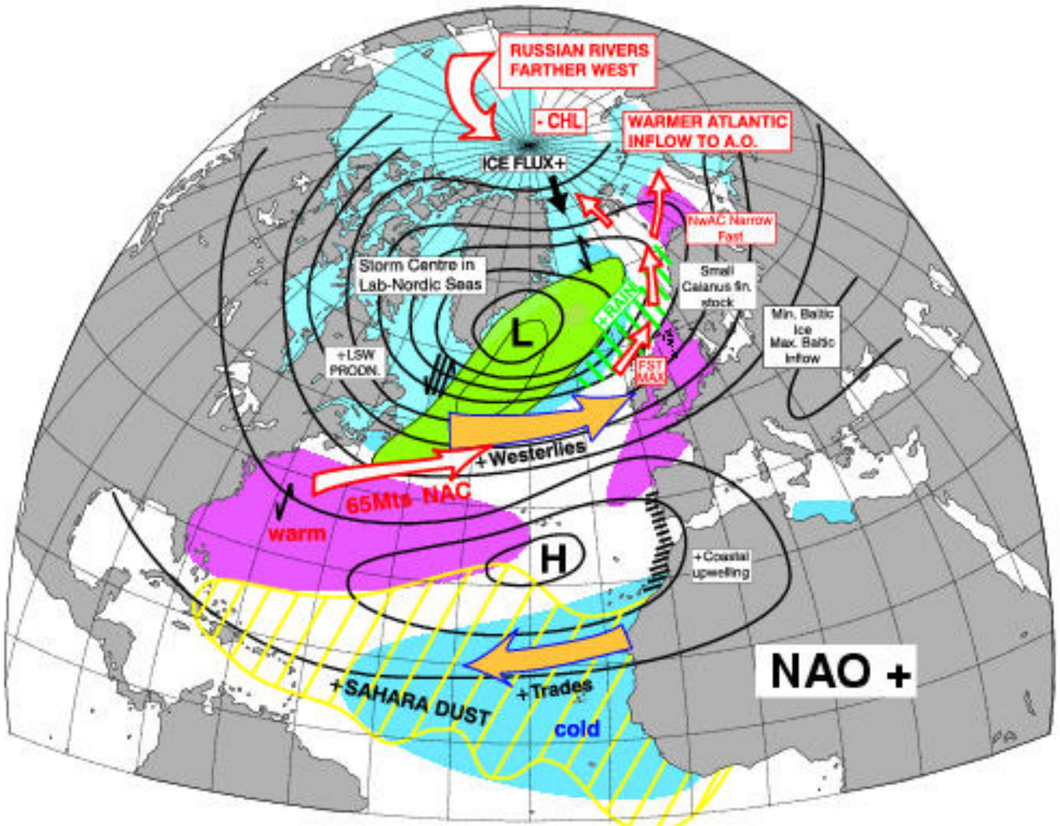




Further back in time? -> Climate System II

Analysis of spatio-temporal pattern

The Phases of the North Atlantic Oscillation



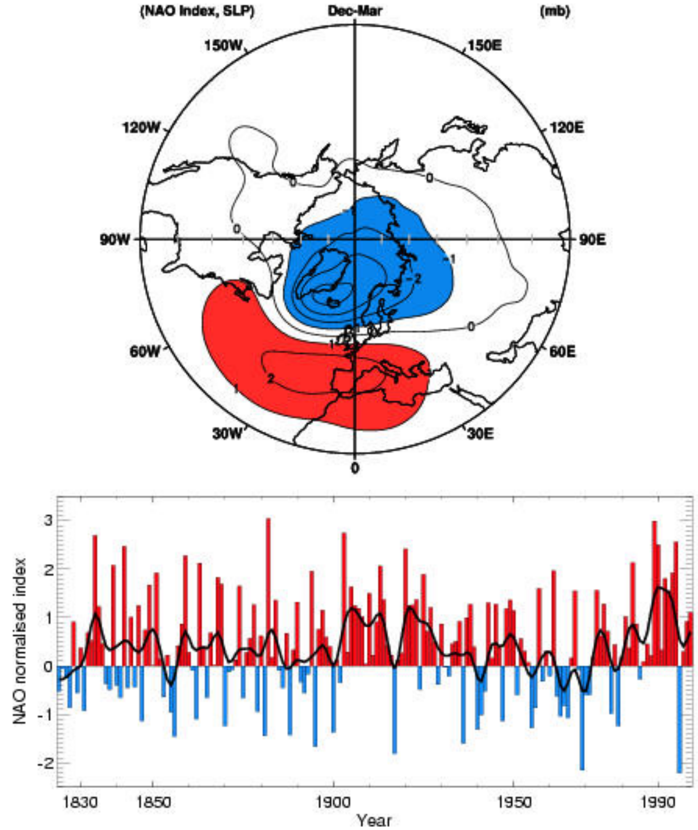
During the high phase of the NAO westerlies in the North Atlantic are enhanced, resulting in mild and wet winter conditions over Northern Europe. (Courtesy of CEFAS, UK)

AV/D1/99-1

Analysis of spatio-temporal pattern

- NAO, ENSO
- Definitions

The North Atlantic Oscillation



Upper panel: Observed Dec-March change in SLP associated with a 1 standard deviation change in the NAO index (after Hurrell, 1995, Science, 269, 676-679).

Lower Panel: Winter (December to March) index or the NAO based on the difference of normalized pressure between Lisbon, Portugal and Stykkisholmur, Iceland from 1864 to 1995. The SLP anomalies at each station were normalized by division of each seasonal pressure by the long-term mean (1864-1995) standard deviation. The heavy solid line represents the meridional pressure gradient smoothed with a low pass filter with seven weights (1,3,5,6,5,3, and 1) to remove fluctuations with periods less than 4 years (after Hurrell, 1995, Science, 269, 676-679, this version: courtesy of T. Osborn, CRU, UEA.

LB/D1/99-1

The North Atlantic oscillation (NAO)

is a climatic phenomenon in the North Atlantic Ocean of fluctuations in the difference of sea-level pressure between the Icelandic Low and the Azores High.

It controls the strength and direction of westerly winds across the North Atlantic

The NAO was discovered in the 1920s by Sir Gilbert Walker. The NAO is one of the most important drivers of climate fluctuations in the North Atlantic and surrounding continents.

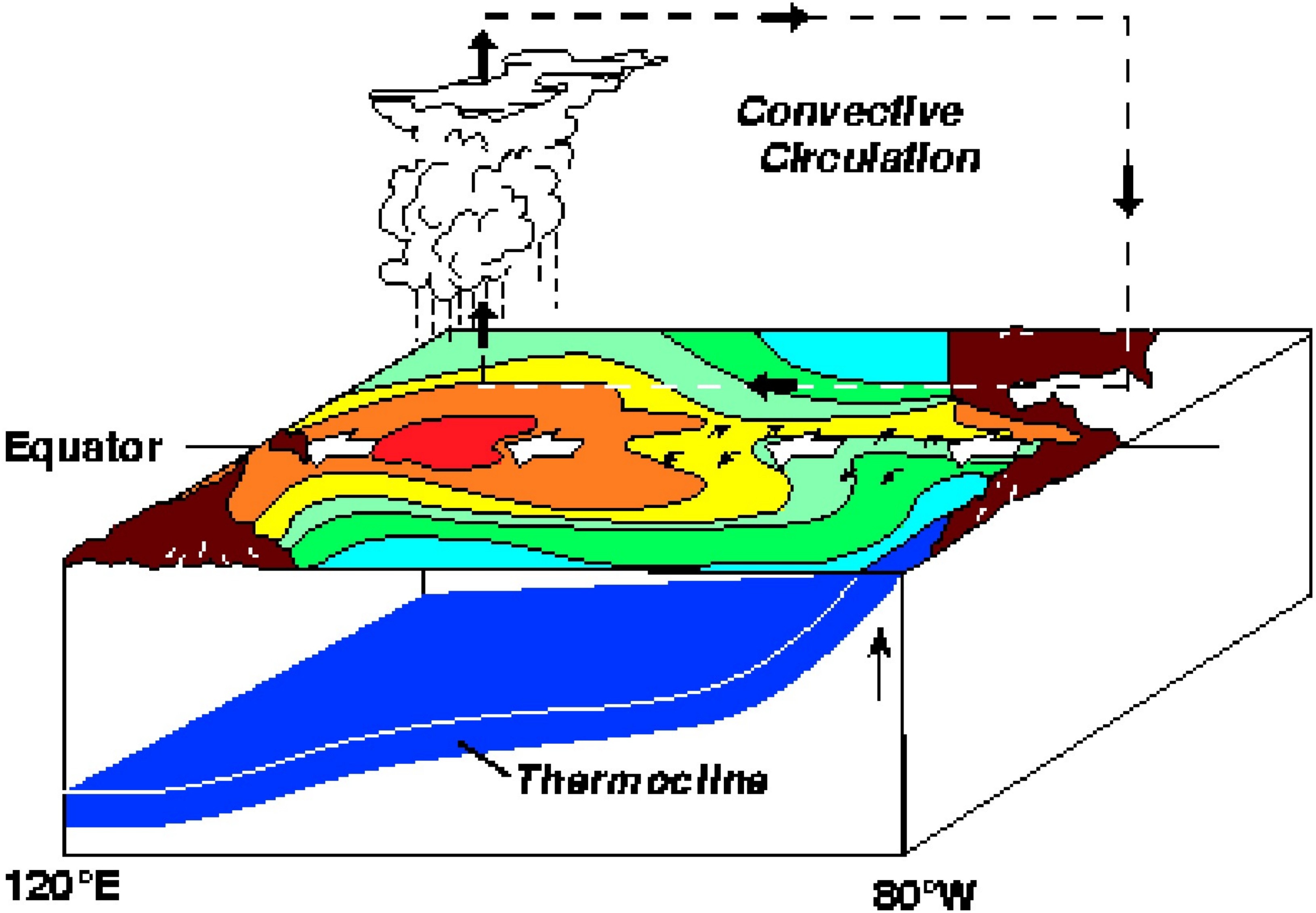
El Niño-Southern Oscillation (ENSO)

El Niño and **La Niña** are important temperature fluctuations in surface waters of the tropical Eastern Pacific Ocean.

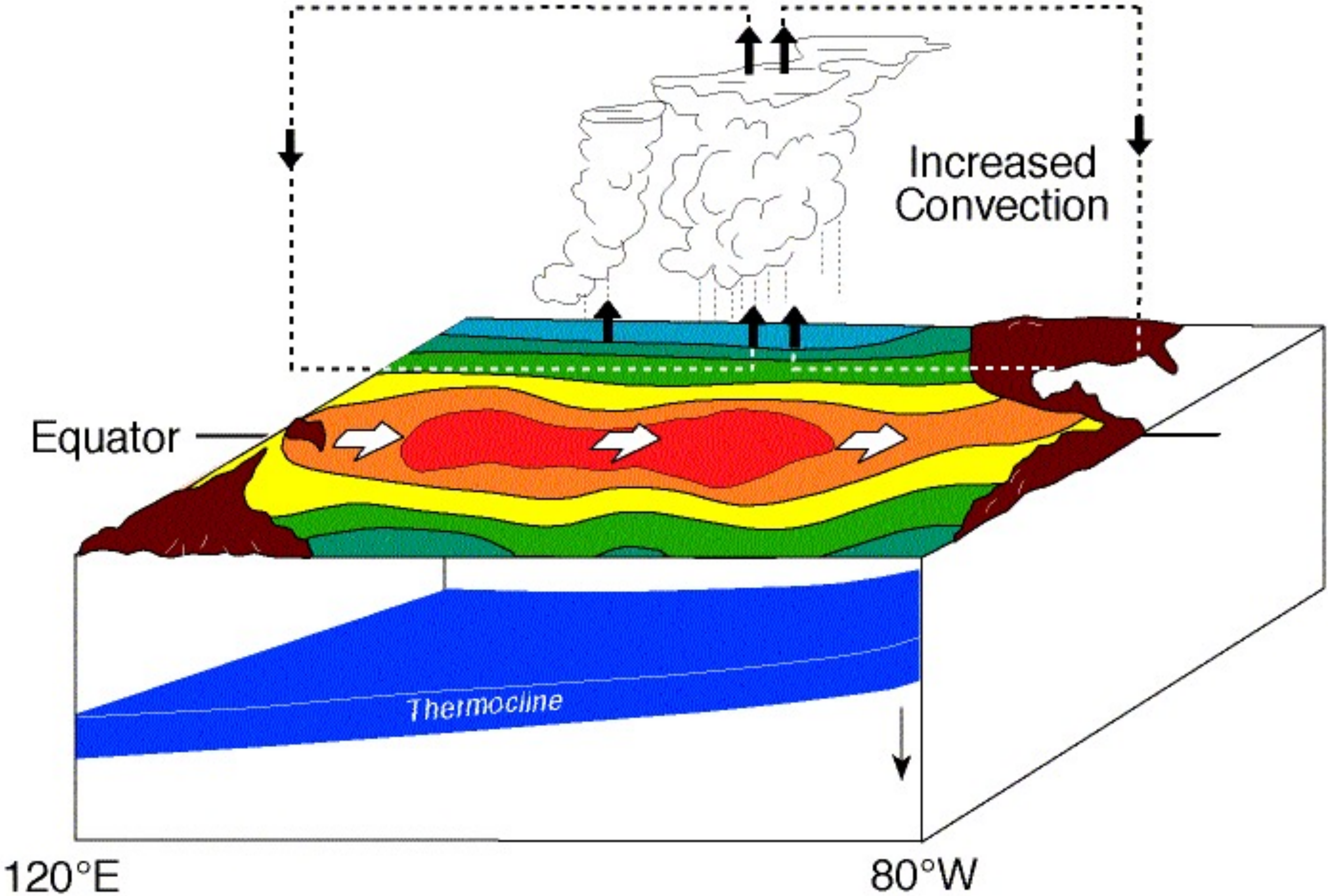
The name El Niño, from the Spanish for "the child", refers to the Christ child, because the phenomenon is usually noticed around Christmas time in the Pacific Ocean off the west coast of South America. La Niña means "the little girl".

These effects were first described in 1923 by Sir Gilbert Walker Walker circulation, an important aspect of the Pacific ENSO phenomenon. The atmospheric signature, the **Southern Oscillation** (**SO**) reflects the monthly or seasonal fluctuations in the air pressure difference between Tahiti and Darwin.

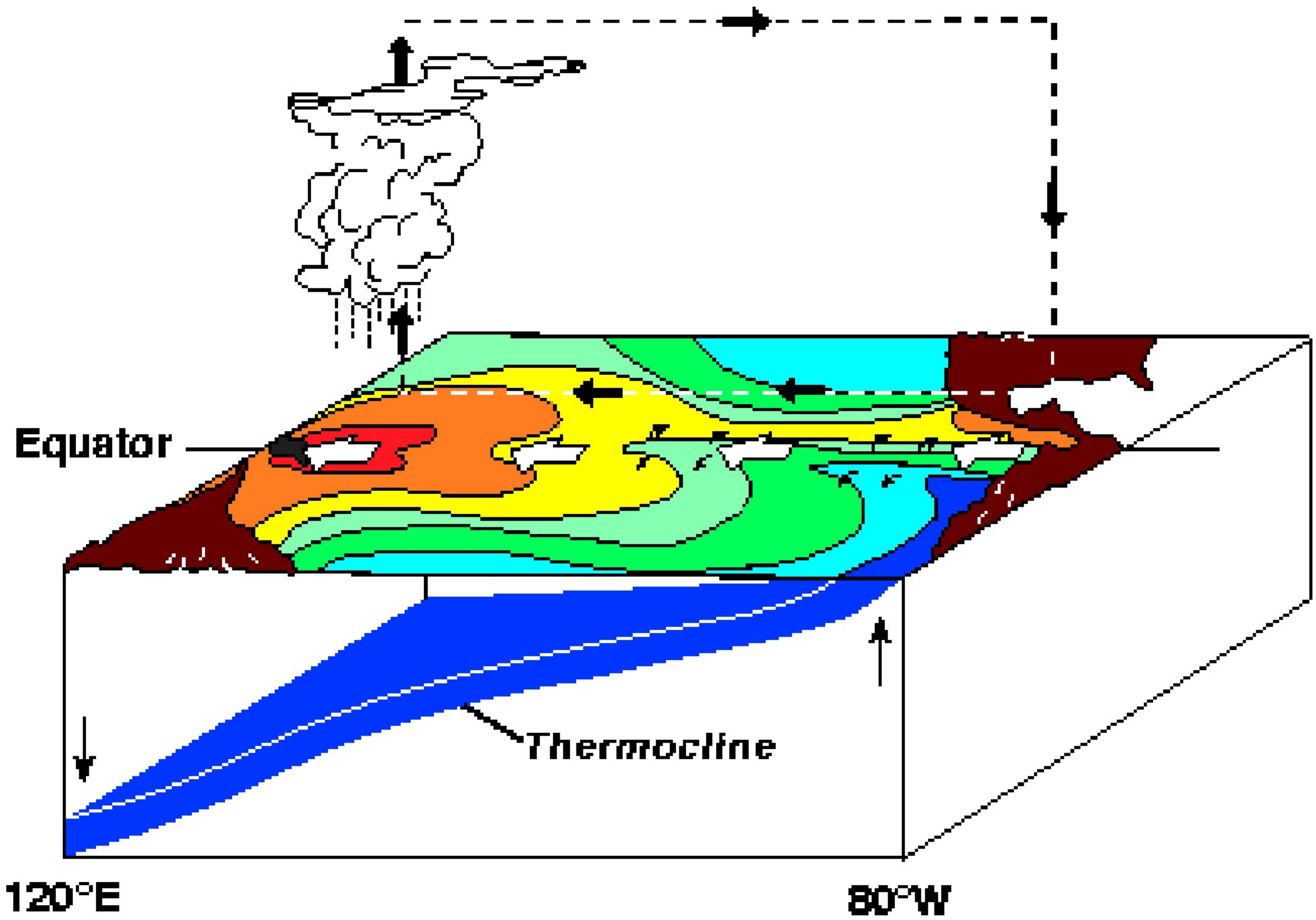
Normal Conditions



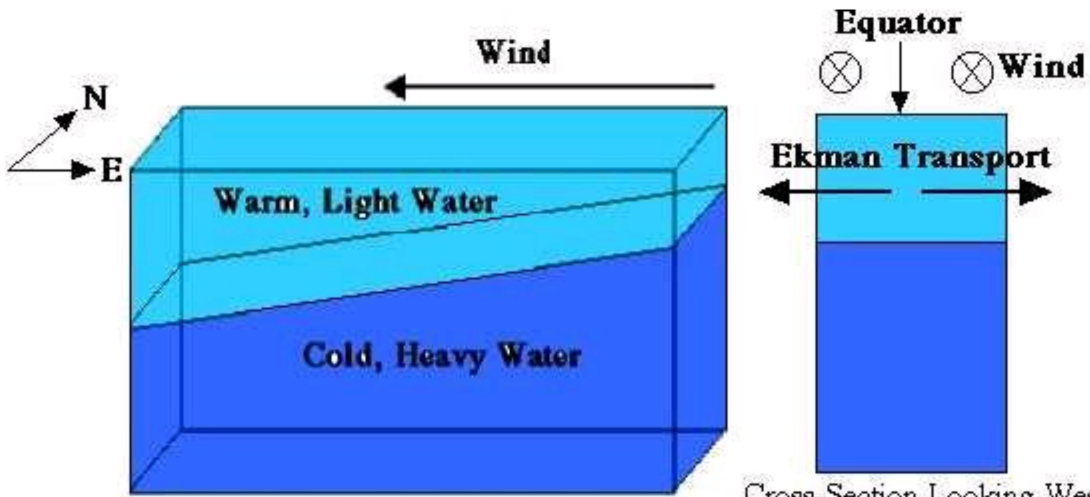
El Niño Conditions



La Niña Conditions



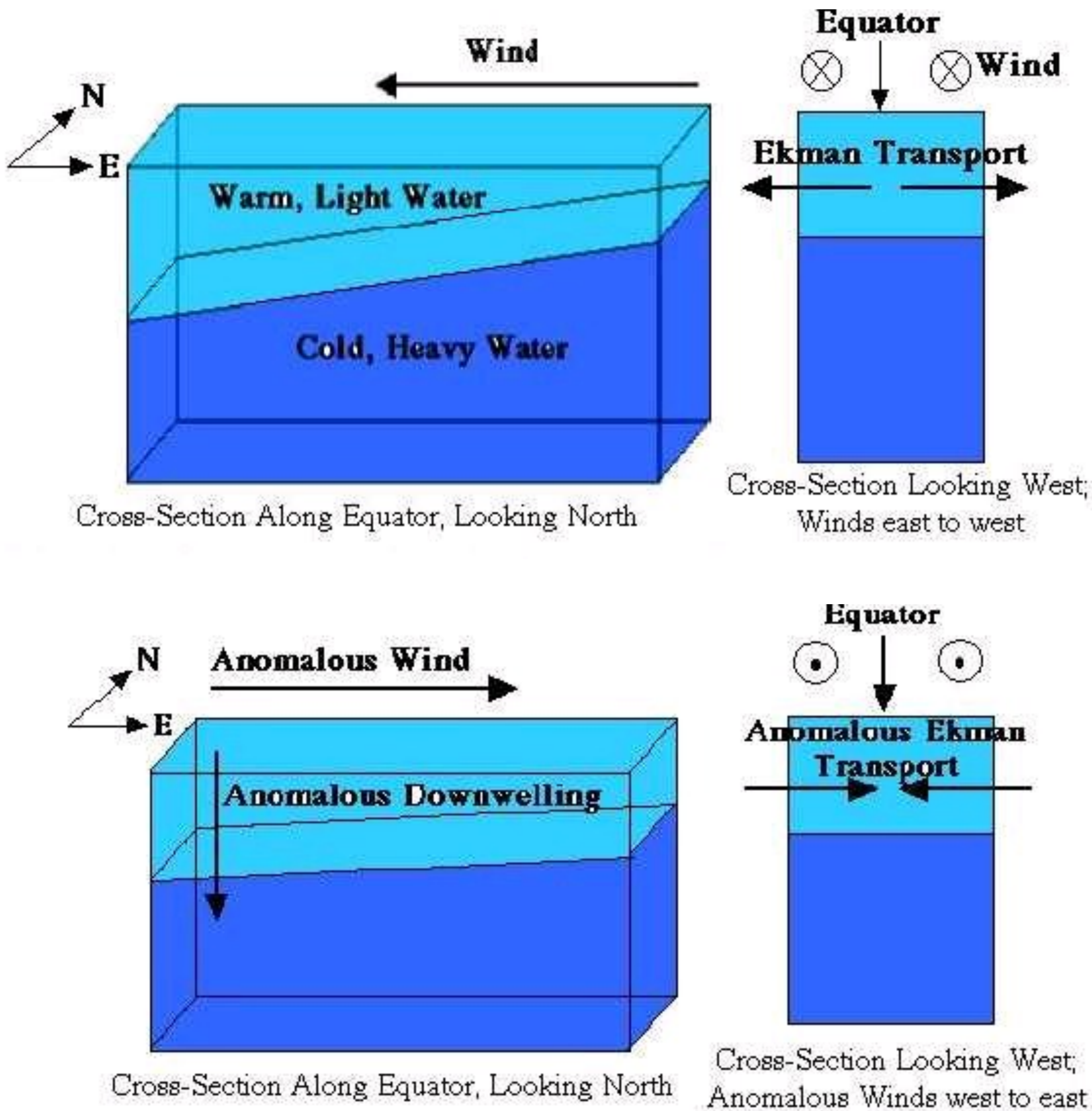
Change in the Ekman transport

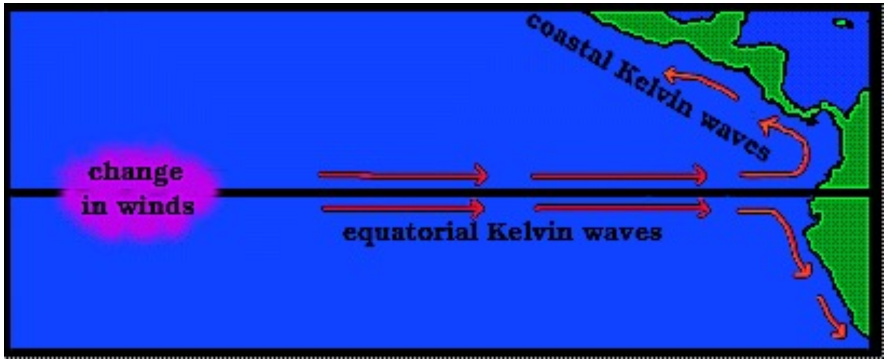


Cross-Section Along Equator, Looking North

Cross-Section Looking West;
Winds east to west

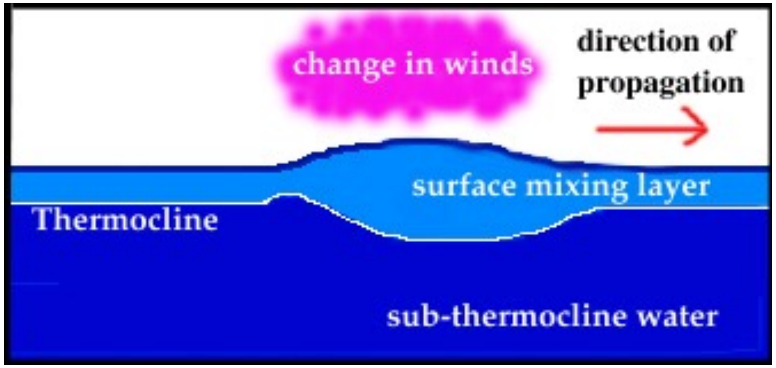
Change in the Ekman transport





There are two types of Kelvin waves, coastal and equatorial, and they are both gravity driven and non-dispersive. They are often excited by an an abrupt change in the overlying wind field, such as the shift in the trade winds at the start of El Niño.

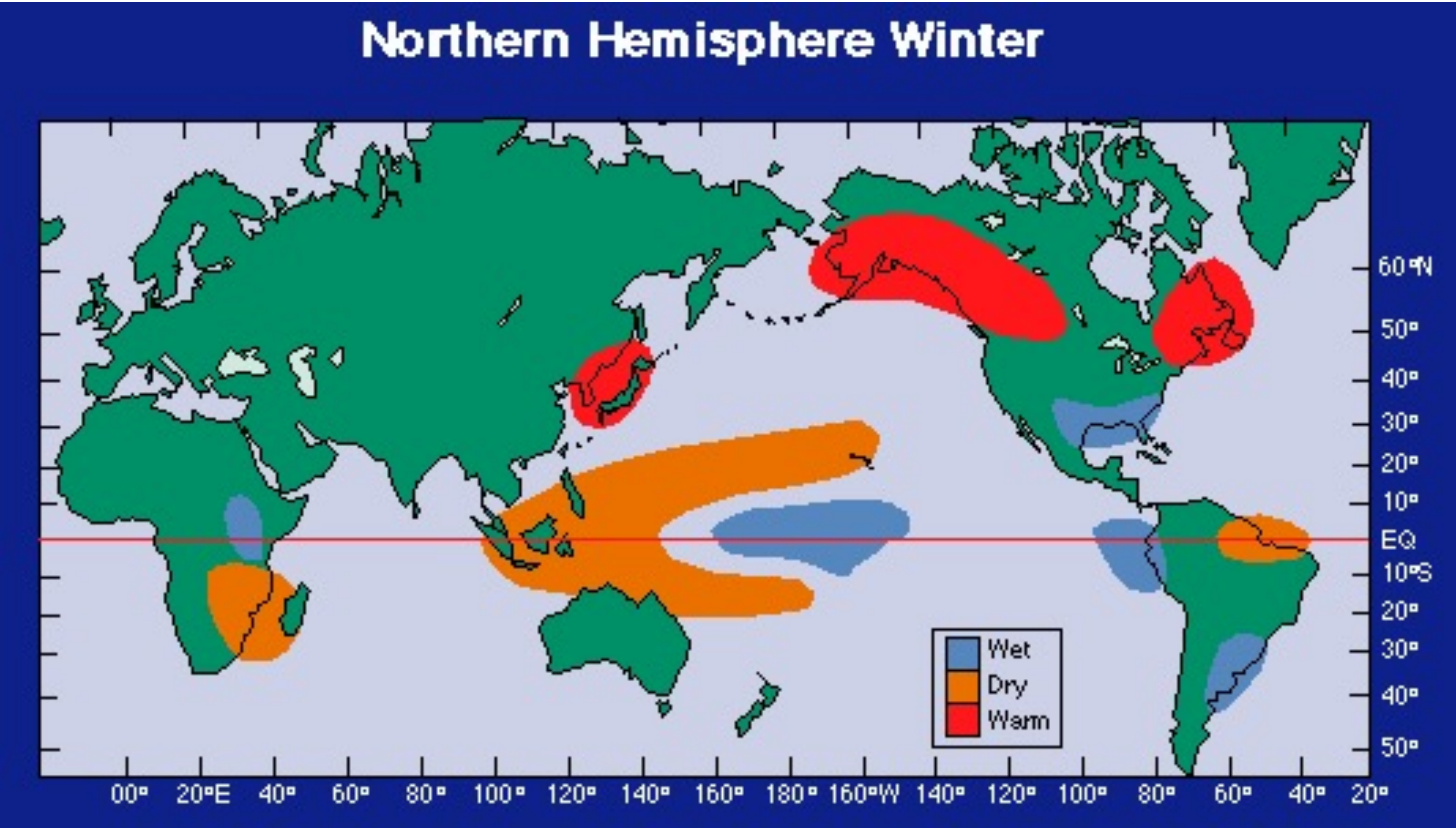
$$c = (gH)^{1/2},$$



The surface waves are very fast moving, typically with speeds of ~2.8 m/s, or about 250 kilometers in a day. A Kelvin wave would take about

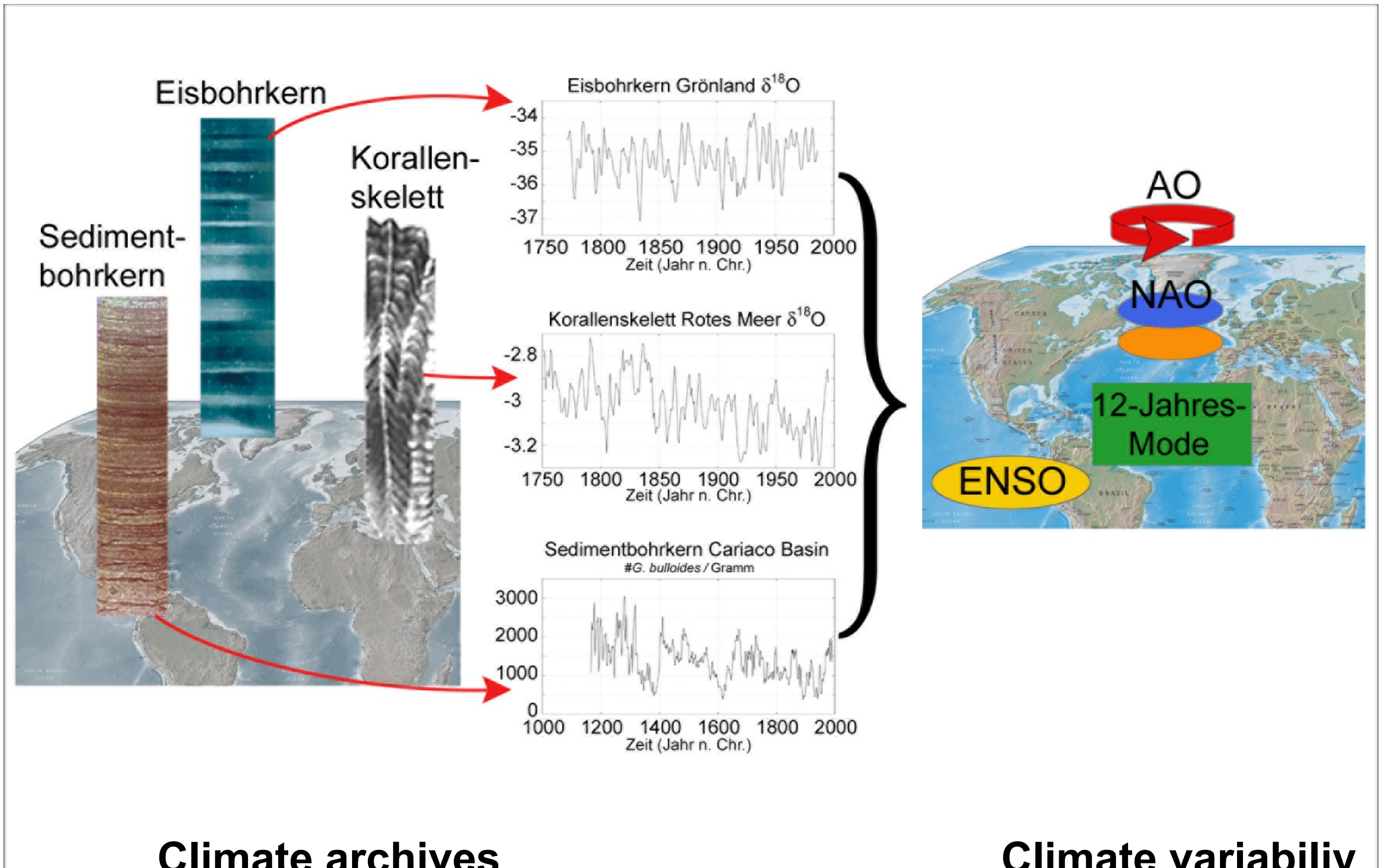
2 months to cross the Pacific from New Guinea to Peru.

ENSO teleconnections



Upscaling

Interpretation of Climate Data



Correlation (cross, auto)

$$\rho_{xy} = \frac{\gamma(\Delta)}{\text{normalized}}$$

measures the tendency of x (t) and y (t) to covary

The correlation coefficient indicates **the strength and direction of a linear relationship** between two random variables.

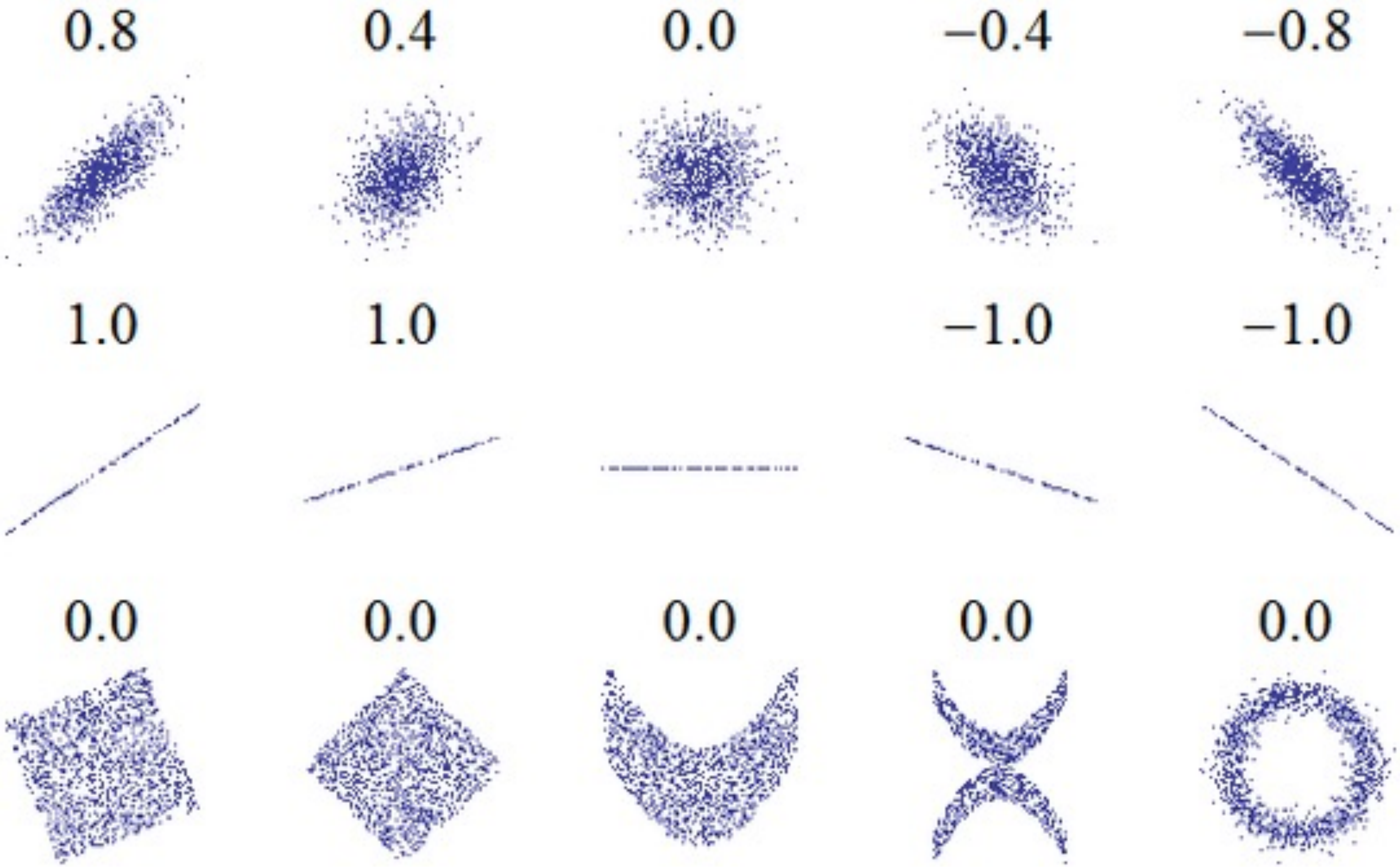
Correlation refers to the departure of two variables from independence, although correlation does not imply causation.

Pearson product-moment correlation coefficient: dividing the covariance of the two variables by the product of their standard deviations.

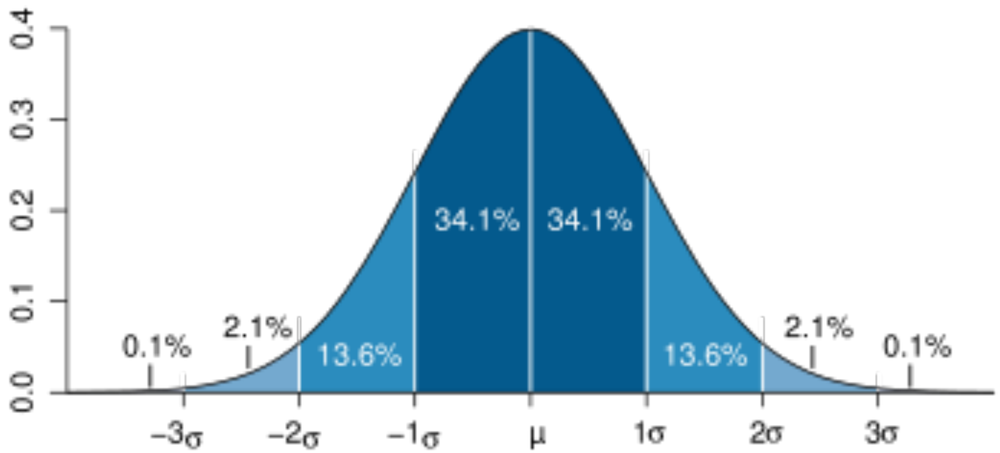
$$\rho_{X,Y} = \frac{\mathrm{cov}(X,Y)}{\sigma_X \sigma_Y} = \frac{E((X-\mu_X)(Y-\mu_Y))}{\sigma_X \sigma_Y},$$

BSP<-c(1,2,3,5,8)
Mean(BSP)=3.8
Var(BSP)=7.7

correlation



Rules for normally distributed data



Dark blue is less than one standard deviation from the mean. For the normal distribution, this accounts for 68.27 % of the set; while two standard deviations from the mean (medium and dark blue) account for 95.45 %; and three standard deviations (light, medium, and dark blue) account for 99.73 %.

Geometric Interpretation

The correlation coefficient can also be viewed as the cosine of the angle between the two vectors of samples drawn from the two random variables.

Example: five countries gross national products of 1, 2, 3, 5, and 8 billion $. same five countries have 11%, 12%, 13%, 15%, and 18% poverty.

Then let **x** and **y** be ordered 5-element vectors containing the above data:

x = (1, 2, 3, 5, 8) and **y** = (0.11, 0.12, 0.13, 0.15, 0.18).

```
BSP<-c(1,2,3,5,8)
poverty<-c(0.11,0.12,0.13,0.15,0.18)
cor(BSP,poverty)
```

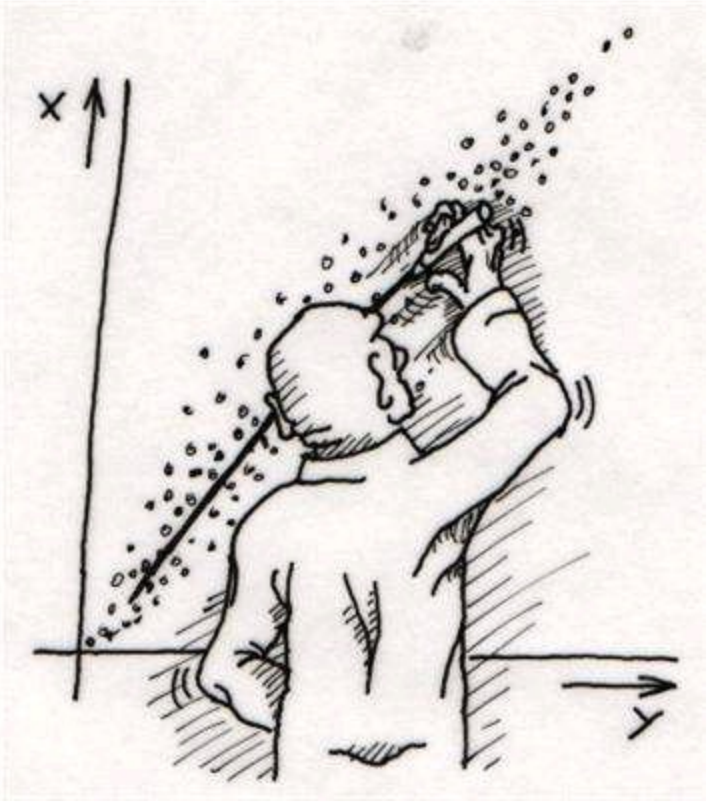
Note that the data were chosen to be perfectly correlated: $y = 0.10 + 0.01\,x$. The Pearson correlation coefficient must therefore be exactly one. Centering the data (shifting **x** by E(**x**) = 3.8 and **y** by E(**y**) = 0.138) yields **x** = (-2.8, -1.8, -0.8, 1.2, 4.2) and **y** = (-0.028, -0.018, -0.008, 0.012, 0.042), from which

$$\cos\theta = \frac{\mathbf{x}\cdot\mathbf{y}}{\|\mathbf{x}\|\,\|\mathbf{y}\|} = \frac{0.308}{\sqrt{30.8}\sqrt{0.00308}} = 1,$$

Spatial pattern

- Regression
- Correlation
- Composite maps

Regression



Regression

Linear function $f(x) = a\,x + b$

Task: find $f(x)$ given data points $g(x_i)$

Such that $(\,f(x_i)-g(x_i)\,)^2$ is minimal

Linear regression

models the relationship between a dependent variable *Y*, independent variables X_p, and a random term *ε*. The model can be written as

$$y_i = \beta_0 + \beta_1 x_{i1} + \cdots + \beta_p x_{ip} + \varepsilon_i = \mathbf{x}_i^\mathsf{T}\boldsymbol\beta + \varepsilon_i, \qquad i = 1, \ldots, n,$$

where $^\mathsf{T}$ denotes the transpose, so that $\mathbf{x}_i^\mathsf{T}\boldsymbol\beta$ is the inner product between vectors $\mathbf{x}_i$ and $\boldsymbol\beta$.

Often these *n* equations are stacked together and written in matrix notation as

$$\mathbf{y} = X\boldsymbol\beta + \boldsymbol\varepsilon,$$

where β_0 is the intercept ("constant" term), the β_i are the respective parameters of independent variables, and *p* is the number of parameters to be estimated in the linear regression.

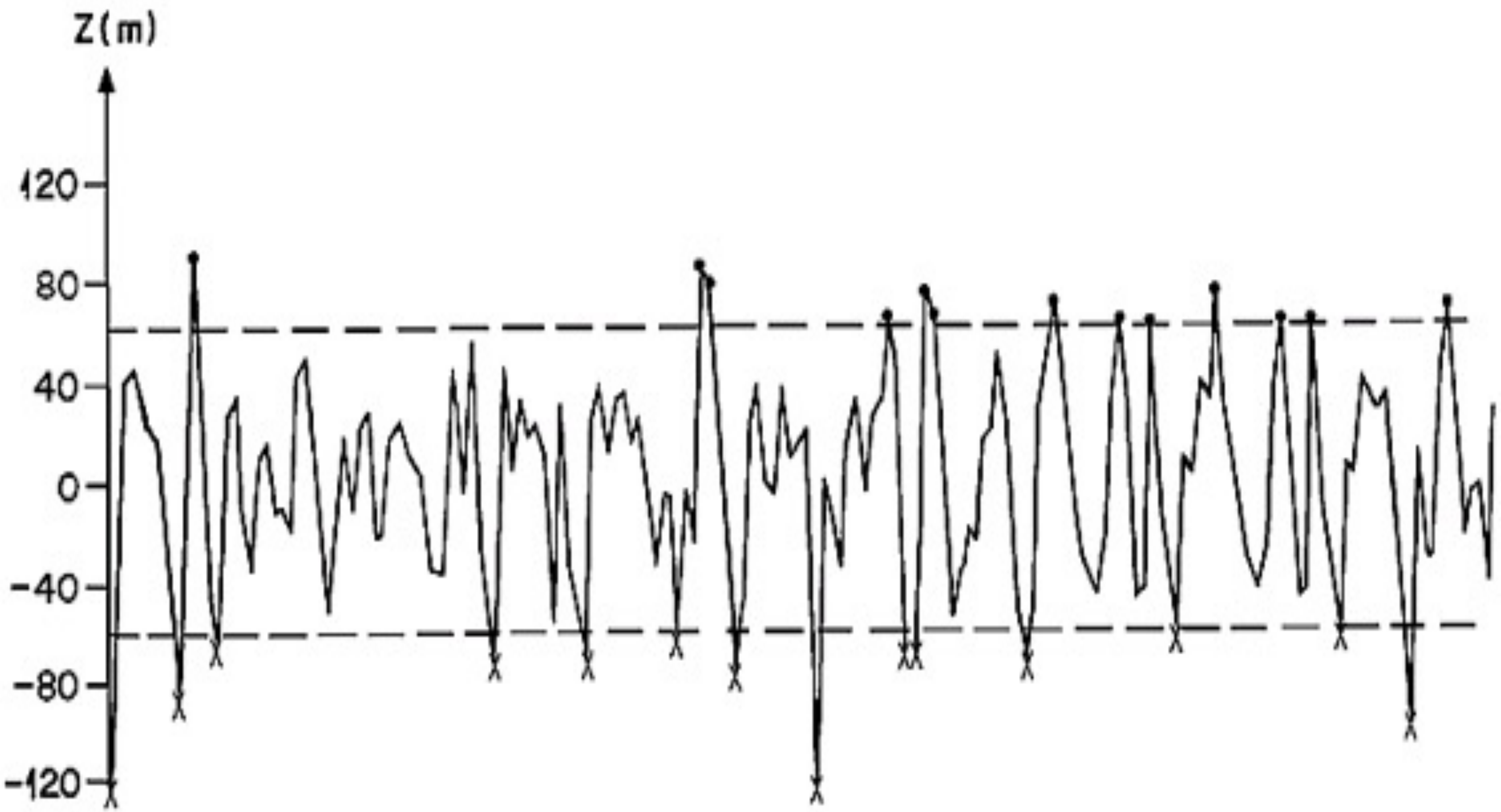
Least-squares analysis

was developed by Carl Friedrich Gauss in the 1820s. This method uses the following assumptions:

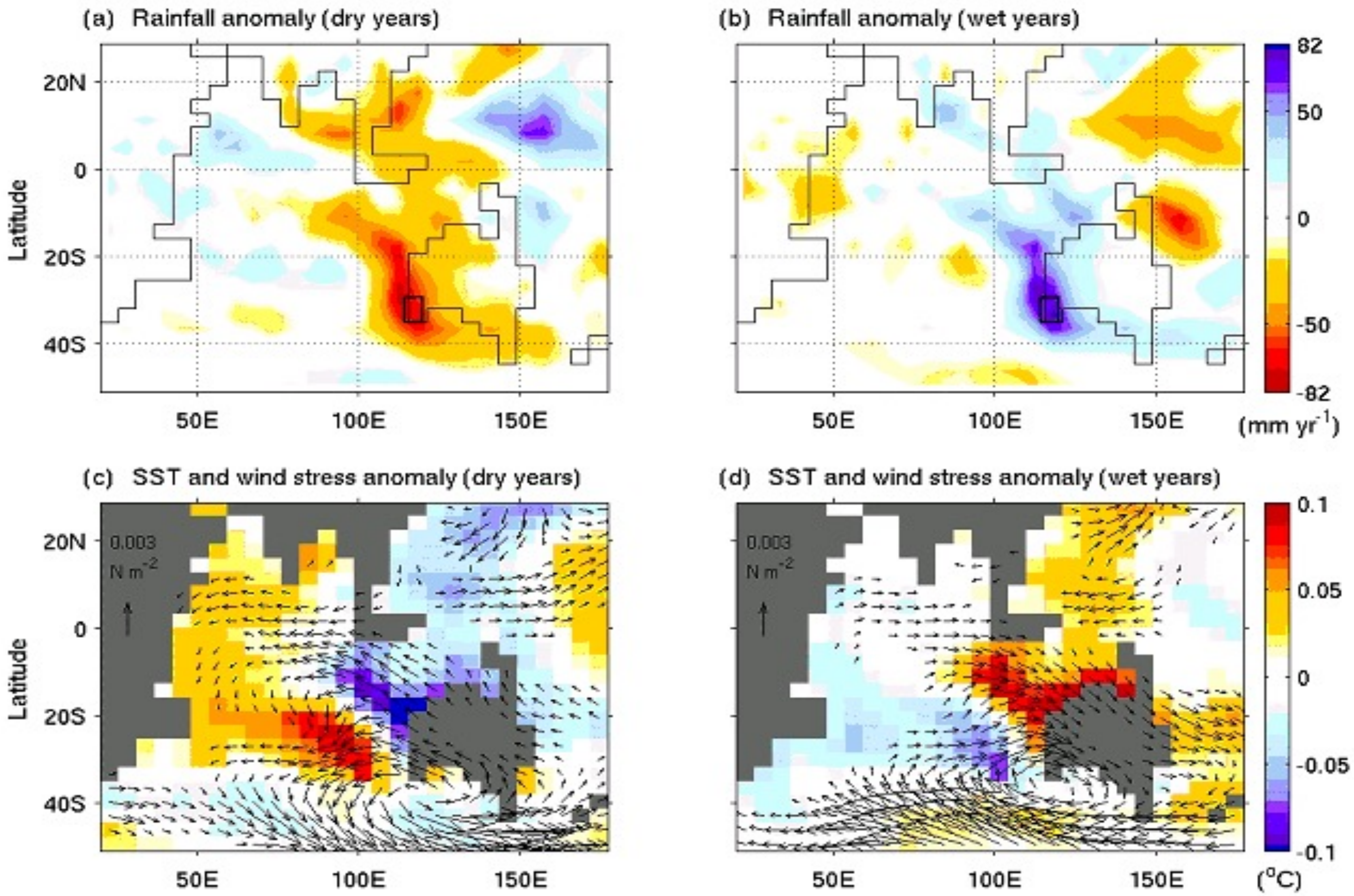
- The random errors ε_i have expected value 0
- The random errors ε_i are uncorrelated
- The random errors ε_i all have the same variance.

Composite Maps

dt.: Kartenzusammenstellung



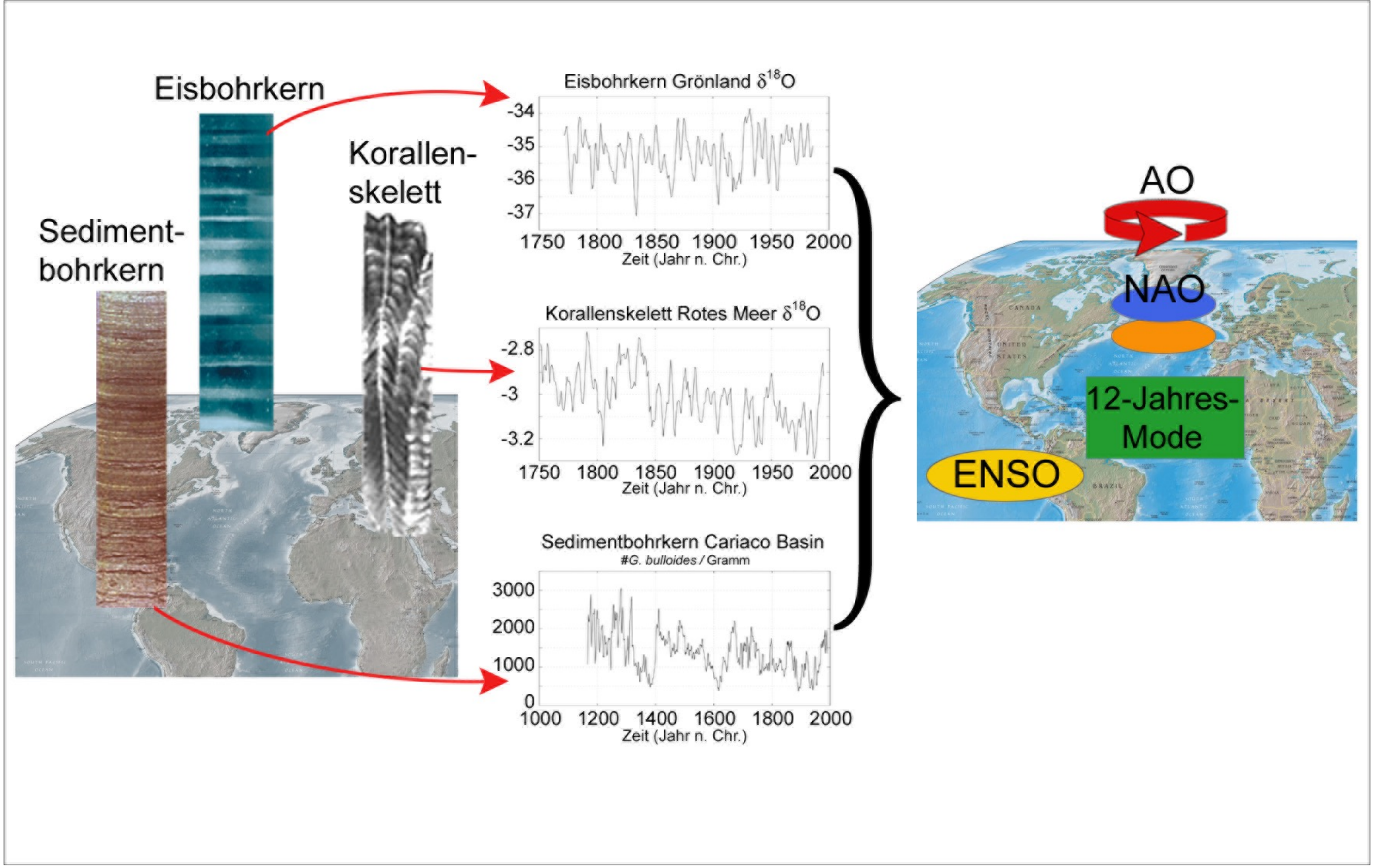
Example



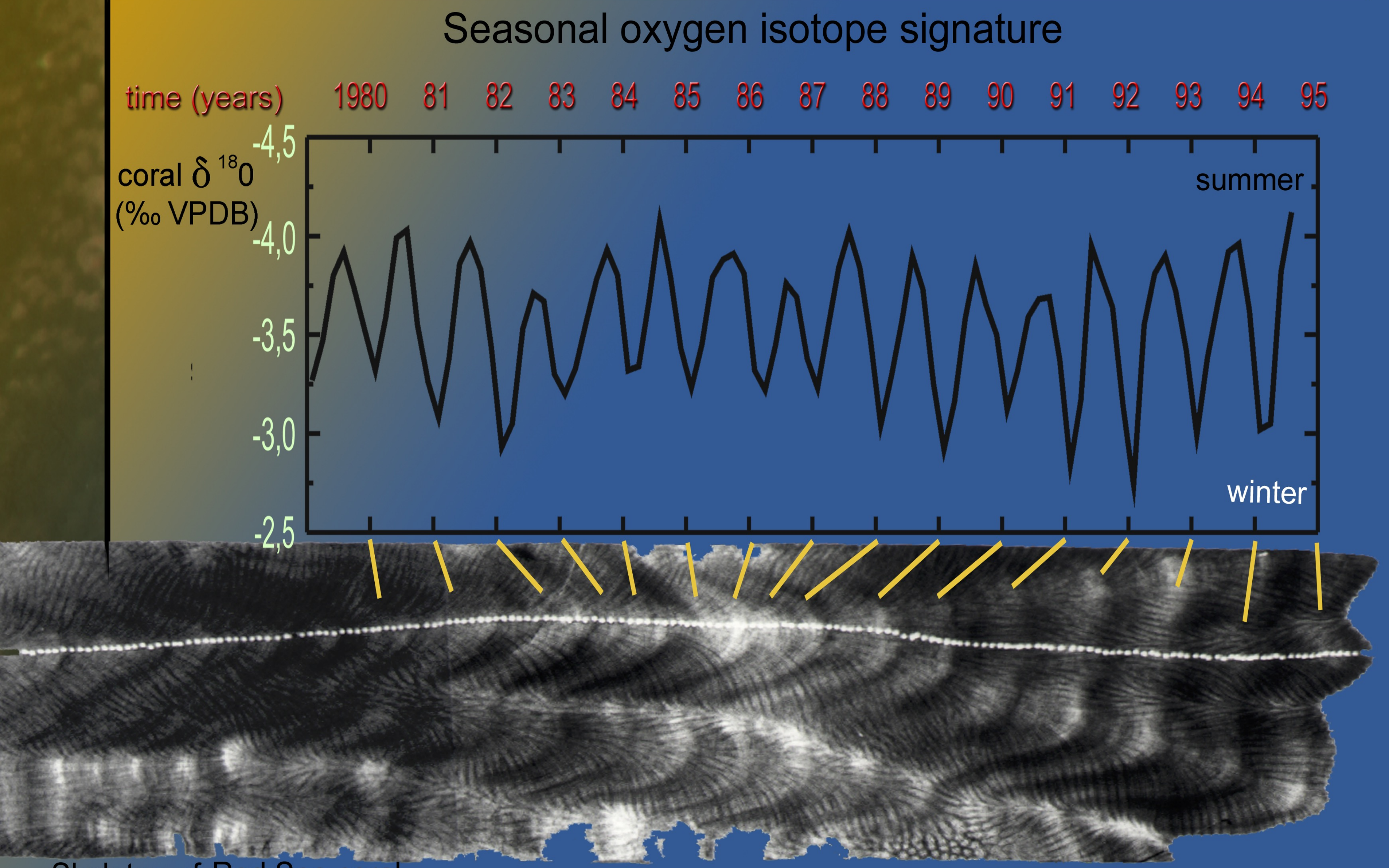
(a) Rainfall anomaly (dry years)
(b) Rainfall anomaly (wet years)
(c) SST and wind stress anomaly (dry years)
(d) SST and wind stress anomaly (wet years)
Latitude
20N
0
20S
40S
50E
100E
150E
82
50
0
-50
-82
(mm yr^{-1})
0.003
N m^{-2}
0.1
0.05
0
-0.05
-0.1
(^{o}C)

Upscaling

Interpretation of Proxy Data



ARCTIC OSCILLATION SIGNATURE IN A RED SEA CORAL



Skeleton of Red Sea coral

Felis et al. Paleoceanography 2000

Statistic

Covariance (cross, auto)

$$\gamma(\Delta) = E\Big((x(t) - \bar{x})\,(y(t+\Delta) - \bar{y}) \Big)$$

e.g. coral e.g. meteorol. data

Correlation (cross, auto)

$$\rho_{xy} = \frac{\gamma(\Delta)}{\text{normalized}}$$

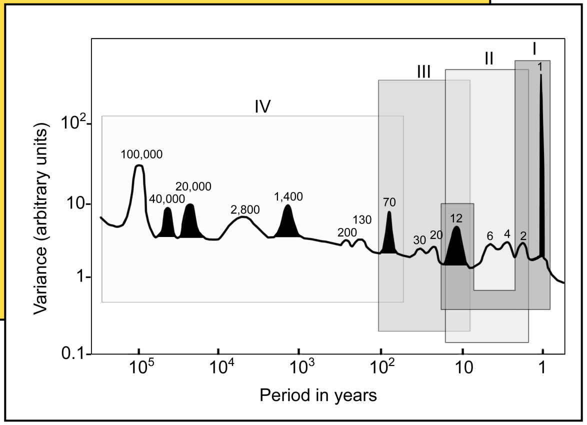
measures the tendency of x (t) and y (t) to covary

Spectrum (cross, auto)

(spectral density)

$$\Gamma(\omega) = \sum_{\Delta=-\infty}^{\infty} \gamma(\Delta)\, e^{-2\pi i \Delta}$$

measures variance



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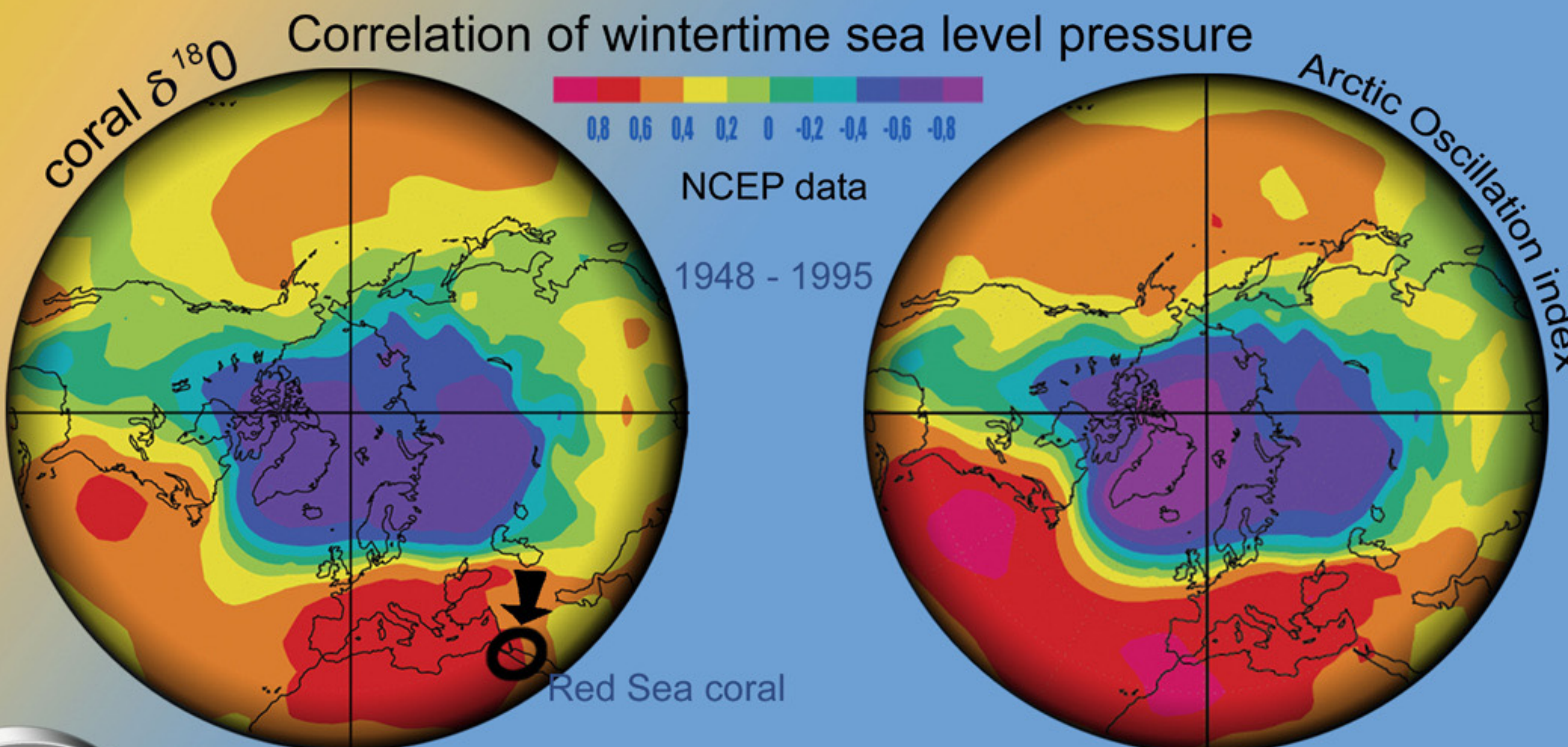
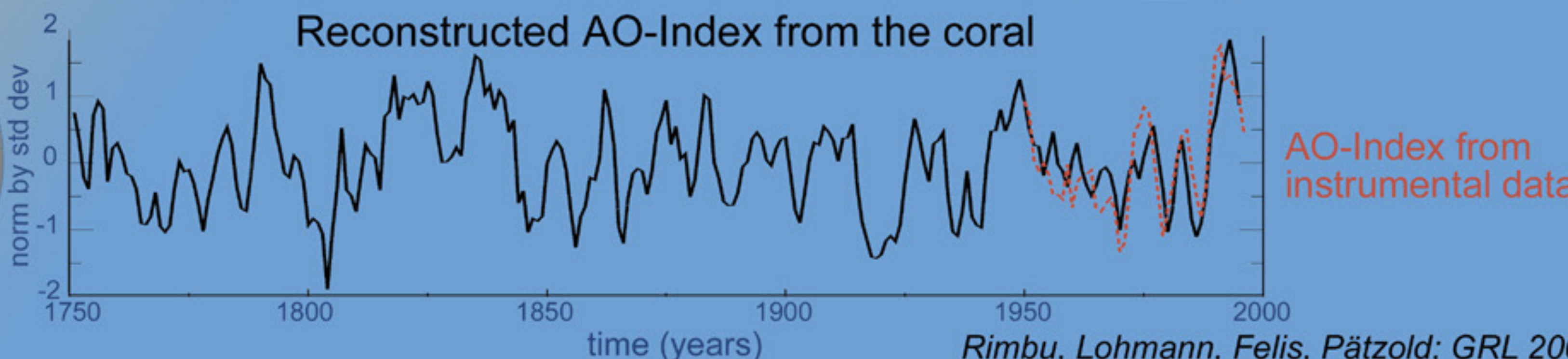
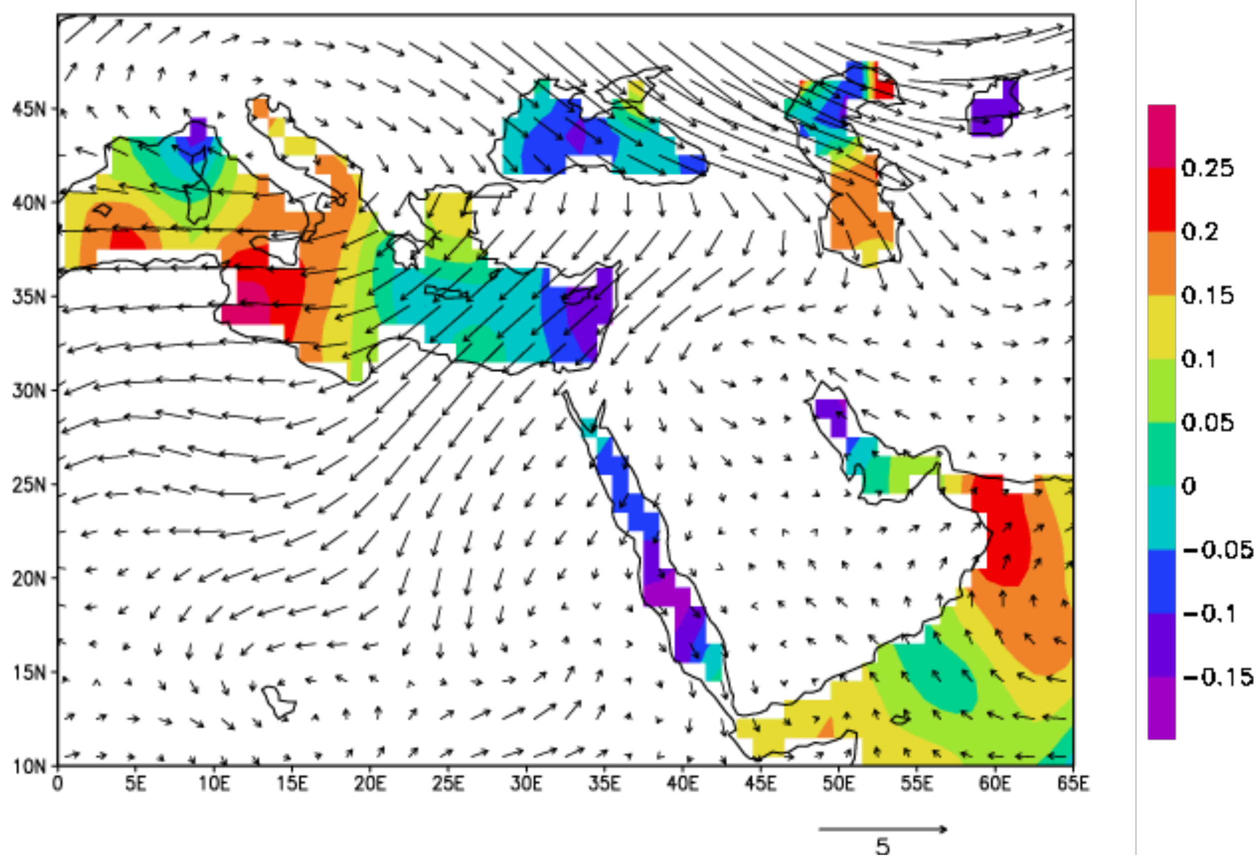




Rimbu, Lohmann, Felis, Pätzold; GRL 2001

ARCTIC OSCILLATION SIGNATURE IN A RED SEA CORAL



Composite Map of SST [° C] and 925 hPa wind [m/s] for 1948 -1995, January - February

mechanistic understanding

Software

In R, cor.test(X,Y) calculates Pearson's correlation coefficient.

- rho = corrcoef(X) returns a matrix rho of correlation coefficients calculated from an input matrix X whose rows are observations and whose columns are variables.

Example

```
#Correlation and significance

a<-1:1000
noise<-rnorm(1000)*500
b<-a + noise

plot(a,b)
cor(a,b)   #correlate a,b
cor.test(a,b)  #correlation + significance test
```

Statistical significance

A result is called **significant** if it is unlikely to have occurred by chance.

"A statistically significant difference" simply means there is statistical evidence that there is a difference

it does not mean the difference is necessarily large

T-test

A test of the null hypothesis that the means of two normally distributed populations are equal. Given two data sets, each characterized by its mean, standard deviation and number of data points, we can use a *t*-test to determine whether the means are distinct, provided that the underlying distributions can be assumed to be normal.

If the *t* value is above the threshold chosen for statistical significance (usually the 0.05 level), then the null hypothesis that the two groups do not differ is rejected in favor of an alternative hypothesis, which typically states that the groups do differ.

R-example

```
> mean(a)
[1] 500.5
> mean(b)
[1] 492.4706
```

$$t = \frac{\overline{X}_1 - \overline{X}_2}{s_{\overline{X}_1 - \overline{X}_2}} \text{ where } s_{\overline{X}_1 - \overline{X}_2} = \sqrt{\frac{s_1^2 + s_2^2}{n}}$$

t = 19.0316

df = 998, p-value < 2.2e-16

T-test

Significance is usually represented by the Greek symbol, α (alpha). Popular levels of significance are 5%, 1% and 0.1%. If a **test of significance** gives a p-value lower than the α-level, the null hypothesis is rejected.

If the *t* value is above the threshold chosen for statistical significance (usually the 0.05 level), then the null hypothesis that the two groups do not differ is rejected in favor of an alternative hypothesis, which typically states that the groups do differ.

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t = 19.0316

df = 998, p-value < 2.2e-16

http://climexp.knmi.nl

Monthly climate indices

Correlation!

Calculate different regions on the world
(e.g. Bremen)

Dynamics 2, 14.06.2021

Lecturer: Prof. Dr. G. Lohmann
Exercise 8, Summer Semester 2021

Due date: 21.06.2021
Tutors: Justus Contzen, Lars Ackermann

Motivation: We analyse climate data and explore teleconnections using http://climexp.knmi.nl

1) **Monthly climate indices (4 points)**
a) Select one pre-defined index (NAO or ENSO). Plot the index for each month.
b) Correlation with temperature, precipiation, SLP
c) Explain the teleconnections for different seasons with your knowledge in Dynamics (e.g. geostrophy)

2) Home town climate (4 points)
a) Calculate the climate (temperature or precipiation) in different regions on the world (select your home town, or Bremen has 53° N, 8.8° E)
b) Correlation with large-scale temperature and SLP for different seasons
c) Explain the teleconnections for different seasons. Any relation to modes of climate variability ? (e.g. ENSO, PDO, NAO, Monsoon)

3) Composite Map (2 points)
a) Calculate the composite map of 1b) instead of correlation, any difference?
b) Calculate the composite map of 2b) instead of correlation, any difference?

Select a monthly time series

Climate indices

Select a time series by clicking on the name		
ENSO	Relative NINO12, NINO3, NINO3.4, NINO4 (1880-now, ERSST v5, relative to 20S-20N, i.e., without global warming trend)	i
	NINO12, NINO3, NINO3.4, NINO4 (1880-now, ERSST v5)	i
	NINO12, NINO3, NINO3.4, NINO4 (1870-now, HadISST1)	i
	SOI (1866-now, Jones)	i
	SOI (1882-now, NCEP)	i
	Precipitation Niño indices: GPCC, CRU TS land , CMORPH satellite	i
	1979-now: MEI v2, 1950-2018: MEI (NOAA/ESRL/PSD)	i
	Niño cold tongue, warm pool reconstructions (1617-2008, CSIRO)	i
	Warm Water Volume (5°S-5°N, 120°E-80°W, 1980-now, PMEL/TAO)	i
	WWV (5°S-5°N, 120°E-80°W, 1960-sep2020, POAMA/PEODAS)	i
	temperature averaged to 300m (130°E-80°W, 1979-now, GODAS)	i
NAO	NAO Gibraltar-Stykkisholmur (1821-now, Jones)	i

Select a time series

- Daily station data
- Daily climate indices
- Monthly station data
- Monthly climate indices
- Annual climate indices
- View, upload your time series

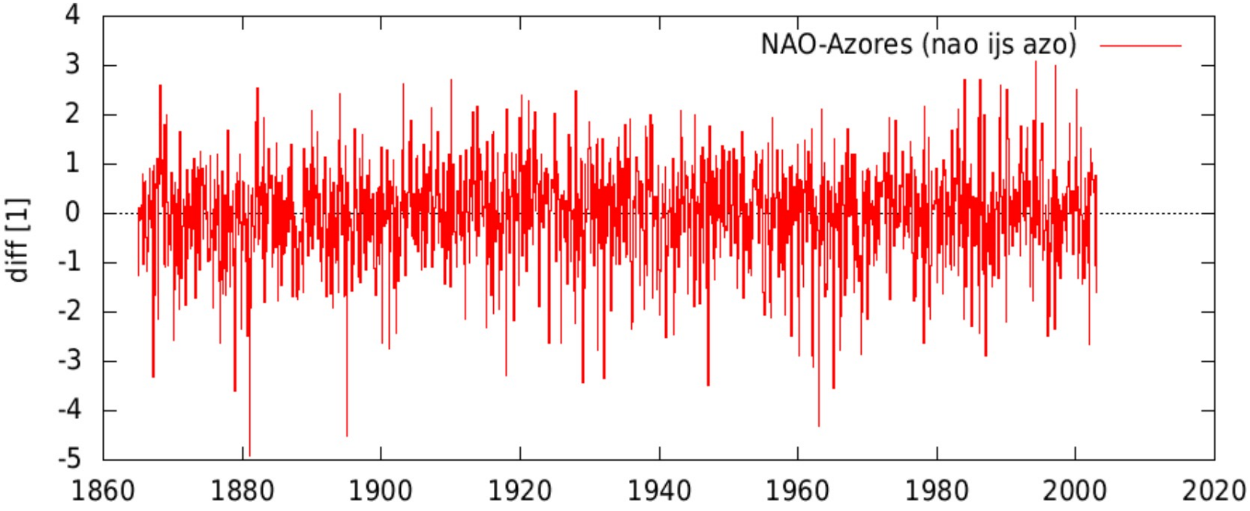
Select a field

- Daily fields
- Monthly observations
- Monthly reanalysis fields
- Monthly and seasonal historical reconstructions
- Monthly seasonal hindcasts
- Monthly CMIP3+ scenario runs
- Monthly CMIP5 scenario runs
- Annual CMIP5 extremes
- Monthly CMIP6 scenario runs
- Monthly CORDEX scenario runs

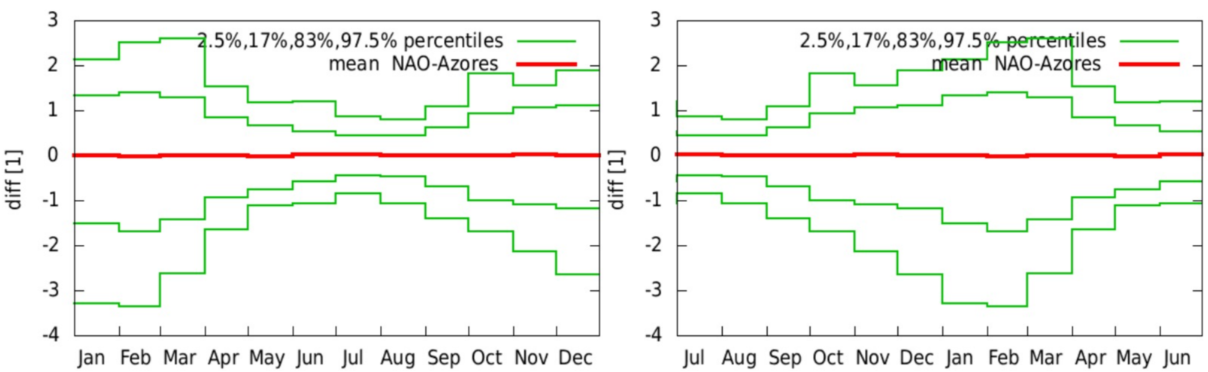
Time series

monthly NAO-Azores

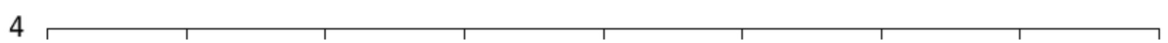
Difference between nao azo new.dat and nao ice new.dat, Timeseries are normalized per year, Timeseries are normalized per year, diff [1] normalised difference of and , (eps, pdf, metadata, raw data, netcdf)



Annual cycles, computed with all data available (Jan-Dec: eps, pdf, raw data,. Jul-Jun: eps, pdf, raw data).



Anomalies with respect to the above annual cycle (eps, pdf, raw data, netcdf, analyse this time series)



Plot options

Variable: correlation / covariance / significance
regression (error) / reverse / relative regression
composite (error)
extreme dependence measures χ, χbar, threshold 90 %

Demand at least [ ] % valid points

Map type: North polar stereographic projection

Region: 20 °N to 90 °N, [ ] °E to [ ] °E in a lat-lon plot

Contours: [ ] to [ ] mask out : p> 10 % logarithmic scale

Colours: blue-grey-red

Shading: shading and contours / shading / contours / grid boxes

Plot options: no color bar, no title on plot, no grid, no political boundaries
label distance [ ] × [ ] ° or no labels

Output to: browser / Google Earth (kml) / GIS (geotiff)

Units: convert to standard units / use original units

Options

Starting month: all of timeseries

Season: averaging over 1 month(s) of the timeseries same month(s) of the field.

Anomalies: subtract seasonal cycle

Lag: 0 months
(lag positive: NAO-Azores lagging field)

Years: [ ] – [ ]

Only for: [ ] < field selected above < [ ]
[ ] < NAO-Azores < [ ]

Apply: logarithm, sqrt to NAO-Azores

Output: rank correlation

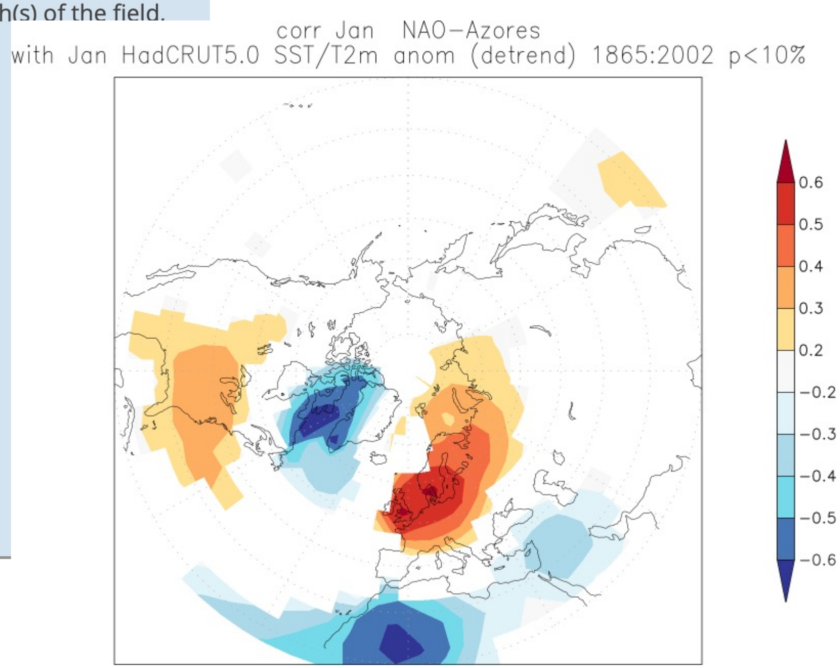
Detrend: detrend everything

Filters: take year-on-year differences
subtract mean of [ ] previous years

Running correlation: show/hide running correlation options

Fit: straight line, parabola,

Correlate



Select a monthly field

.... and select a position

Observations

Select a field by following its link (old list)

Temperature	1850-2018 anomalies: HadCRUT5 median, 1850-now HadCRUT4 median	i
	1880-now anomalies: GISS 250km, 1200km	i
	1880-now anomalies: NOAA v5	i
	1850-now anomalies: HadCRUT4 ,HadCRUT4/HadSST4 filled-in by Cowtan and Way	i
	1900-2018 anomalies: CMST	i
Land	1850-now anomalies: CRUTEM4, CRUTEM5	i
	1880-now anomalies: GISS 250km, 1200km	i
	1880-now anomalies: NCDC v3.2.1	i
	1948-now: CPC GHCN/CAMS t2m analysis (land) 0.5°, 1.0°, 2.5°	i
	1901-2019: CRU TS 4.04 (land) 0.5°, 1.0°, 2.5°, #/value, 4.03 0.5°, 1.0°, 2.5°, #/value	i
	1750-now: Berkeley 1°	i
	1900-2018 5° homogenised anomalies: CL-SAT 1.3	i
	0.25° 1950-now: E-OBS v23.1e Tg (Europe)	i
	1895-now: PRISM 4km, PRISM 0.25°, (Contiguous US only)	i

Select a time series

- Daily station data
- Daily climate indices
- Monthly station data
- Monthly climate indices
- Annual climate indices
- View, upload your time series

Select a field

- Daily fields
- Monthly observations
- Monthly reanalysis fields
- Monthly and seasonal historical reconstructions
- Monthly seasonal hindcasts
- Monthly CMIP3+ scenario runs
- Monthly CMIP5 scenario runs
- Annual CMIP5 extremes
- Monthly CMIP6 scenario runs
- Monthly CORDEX scenario runs
- Attribution runs
- View, upload your field