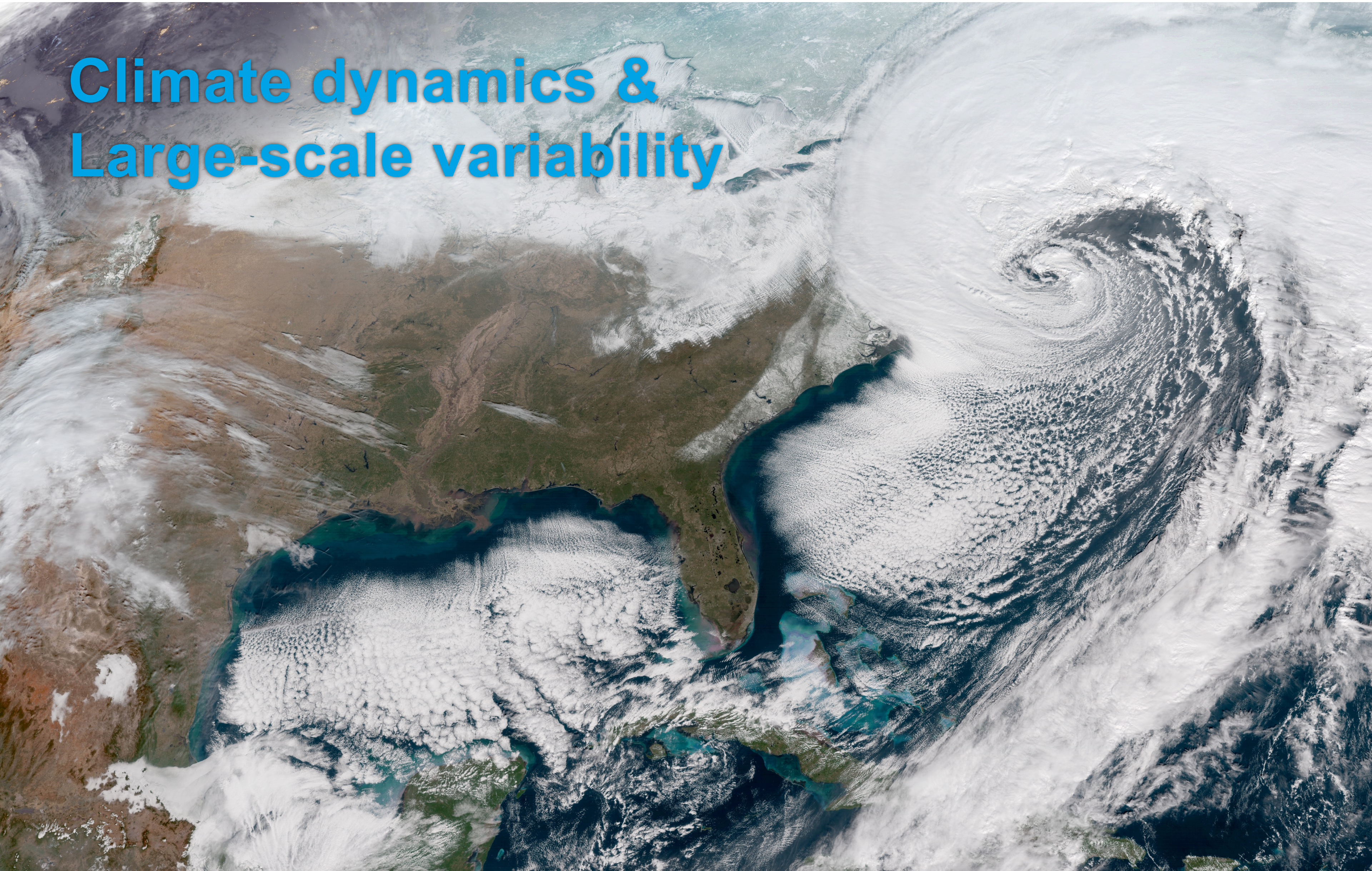
Lecture 8

ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR-
UND MEERESFORSCHUNG

Climate dynamics & Large-scale variability



Todays content

1. Applied dynamics in the context of meteorology
    1. Radiative budget
    2. Geostrophy
    3. Vorticity
2. Large-scale climate variability (internal vs. external variability)
    1. External variability (external forcing)
        1. Sun
        2. Volcanoes
        3. GHG
    2. Internal variability (variability modes)
        1. AMO
        2. NAO
        3. ENSO
3. If time: Climate detective game

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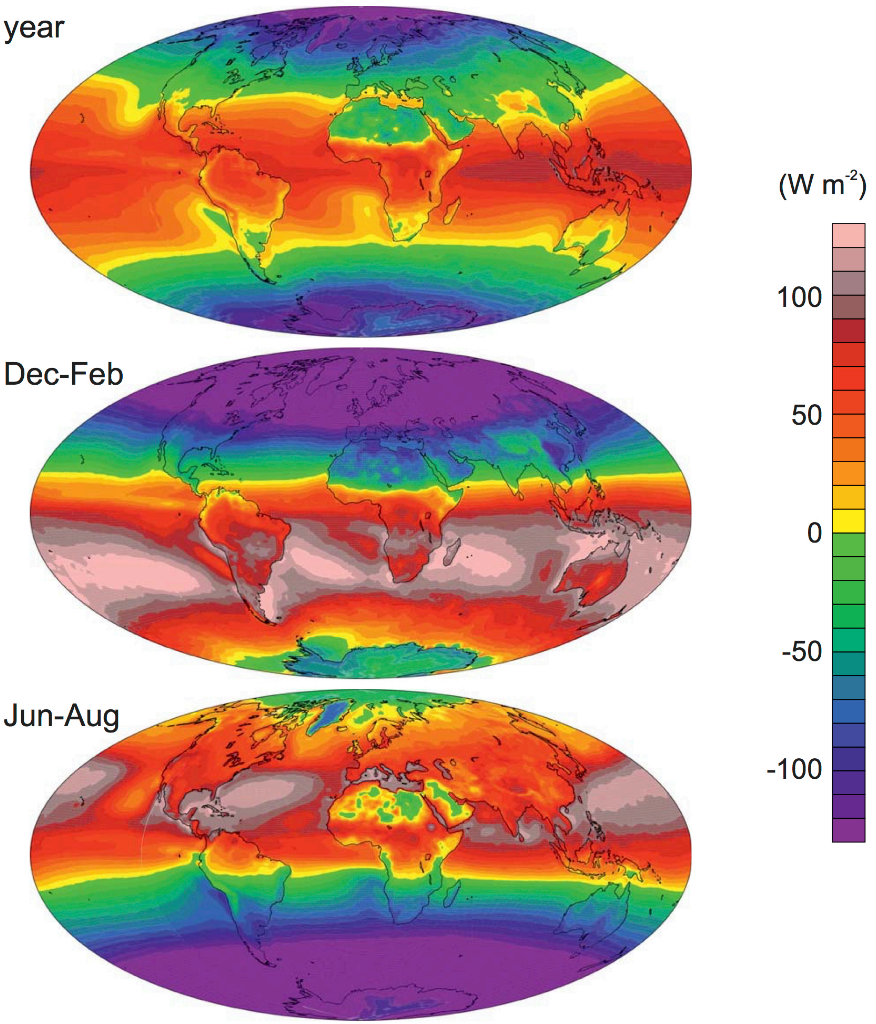
Energy budget

Top of atmosphere

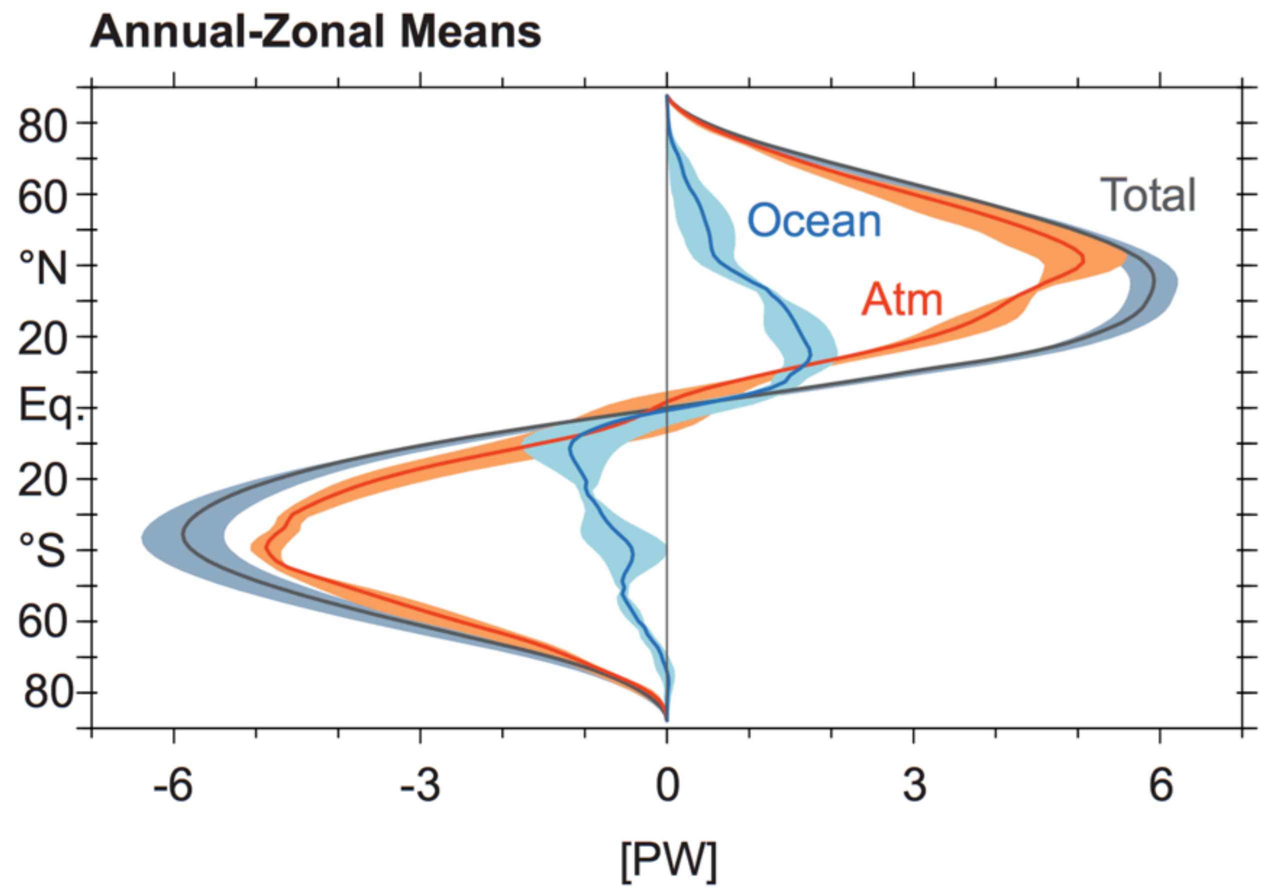
Net radiation



Source: NASA & CERES

Energy budget

Heat transport from the tropics to the poles



Source: Fasullo & Trenberth 2008

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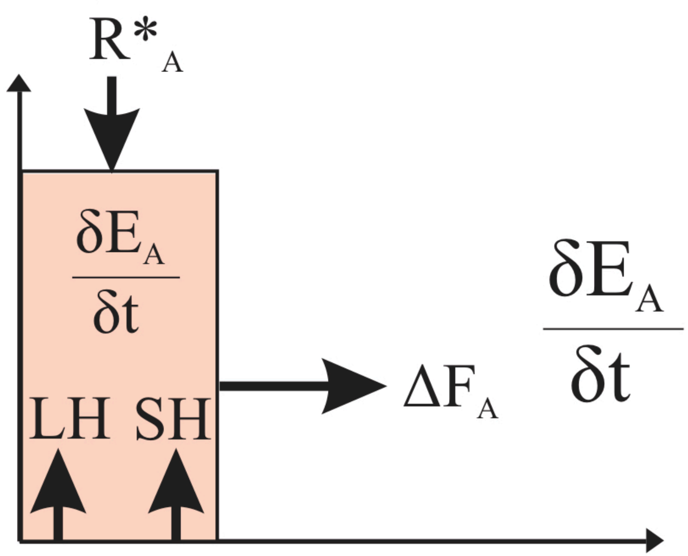
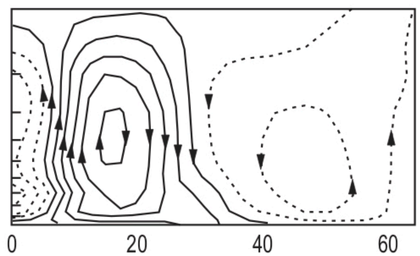
Energy budget

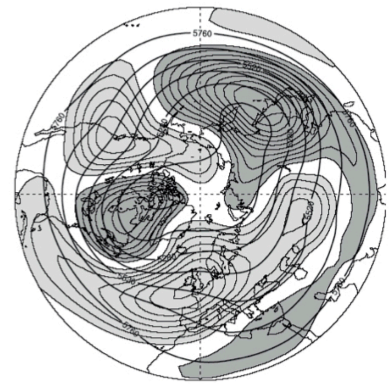


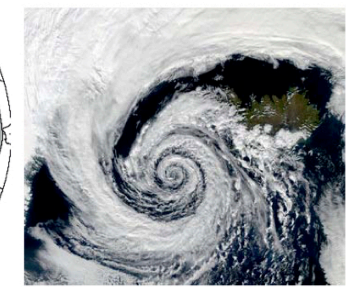
Atmospheric energy transport

$$\frac{\delta E_A}{\delta t} = R_A + LH + SH - \Delta F_A$$

Flux decomposition







In this case
heat transport

F_A →

$$[\overline{vT}] = [\overline{v}][\overline{T}] + [\overline{v}^{*}\overline{T}^{*}] + [\overline{v'T'}]$$

meridional heat flux | mean meridional circulation | stationary waves | transient eddies

Transient: Deviation from the time mean

$$x' = x - \overline{x}$$

Eddy: Deviation from the zonal mean

$$\overline{x}^{*} = \overline{x} - [\overline{x}]$$

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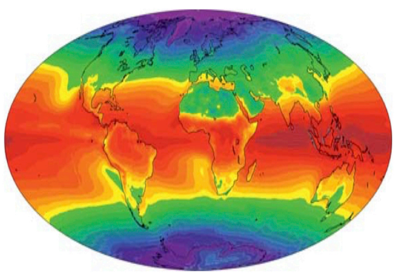
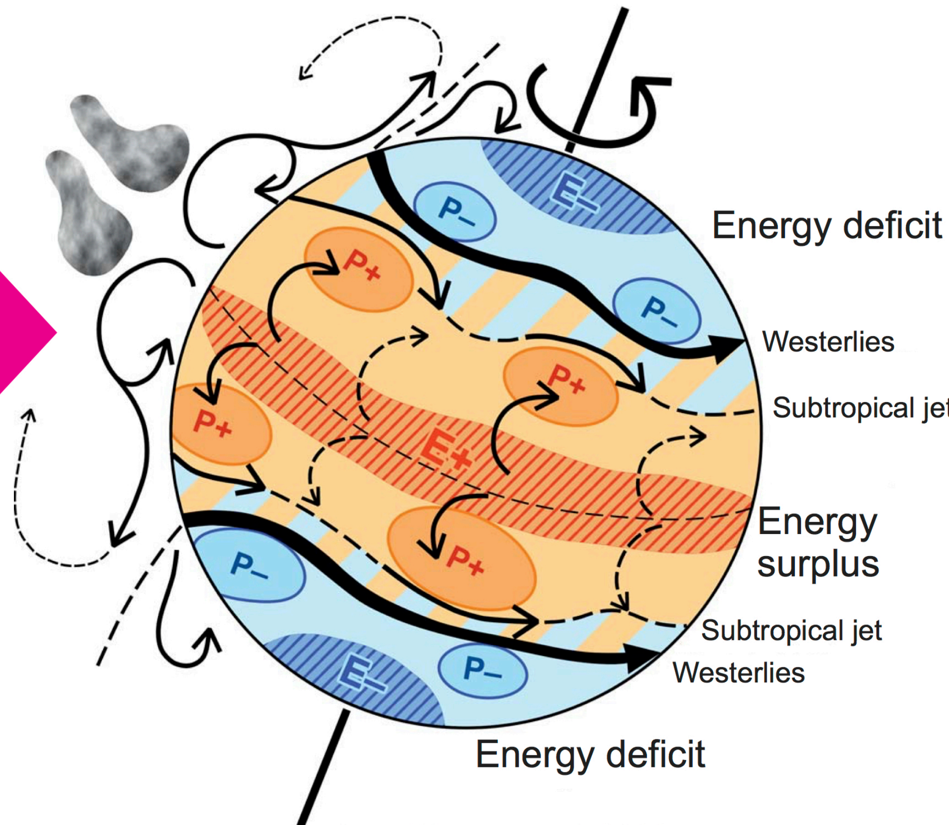
Fuel for dynamics

net radiation





from Wanner et al. 2000

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Dynamics: Geostrophy

- Horizontal temperature and density gradients lead to pressure gradients, which will lead to air movement
- Air motions are constraint by
  - Density stratification
  - Earth rotation
- To describe the atmospheric dynamics, we treat air as a fluid
  → Fluid dynamics

Dynamics: Geostrophy

Equation of motion with rotation
Considering all forces:

Pressure Gradient Force — Coriolis Force — Friction — Gravity

$$\frac{d\vec{v}}{dt} = \vec{F}_p + \vec{F}_c + \vec{F}_R + \vec{F}_G$$

$$\frac{d\vec{v}}{dt} = -\frac{1}{\rho}\vec{\nabla}p - 2\vec{\Omega} \times \vec{v} - a\vec{v} + \vec{g}$$

Will later appear as f

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Dynamics: Geostrophy

There is this whole set of equations used to describe atmospheric dynamics called the **Primitive equations**

$$\frac{d\vec{v}}{dt} = -\frac{1}{\rho}\vec{\nabla}p - 2\vec{\Omega} \times \vec{v} - a\vec{v} + \vec{g}$$

Equation of motion

$$p = \rho R T$$

Gas law

$$\frac{dT}{dt} = \frac{1}{c_p \rho}\frac{dp}{dt} + \frac{\dot{Q}}{c_p}$$

1st law of thermodynamics

$$\frac{d\rho}{dt} + \rho\vec{\nabla} \cdot \vec{v} = 0$$

Continuity equation

Dynamics: Geostrophy

Coming back to the
Equation of motion with rotation

x,y,z components:

Neglect friction in free atmosphere

Horizontal part

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv + f^* w = -\frac{1}{\rho}\frac{\partial p}{\partial x}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu = -\frac{1}{\rho}\frac{\partial p}{\partial y}$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} - f^* u = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g$$

Vertical part

Dynamics: Geostrophy

In horizontal form:

Neglect friction in free atmosphere

Total derivative for u

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - fv = -\frac{1}{\rho}\frac{\partial p}{\partial x}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + fu = -\frac{1}{\rho}\frac{\partial p}{\partial y}$$

$$= -\frac{1}{\rho}\frac{\partial p}{\partial z} - g$$

This is the hydrostatic equilibrium

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Geostrophic wind

$$v_g = \frac{1}{f\rho}\frac{\partial p}{\partial x}$$

$$u_g = -\frac{1}{f\rho}\frac{\partial p}{\partial y}$$

Neglect friction in free atmosphere

Things to note:

- Geostrophic wind is parallel to isobars
- The denser the isobars the higher the wind speed
- Geostrophic wind can not change pressure imbalance
- For this we need eddies and friction

Geostrophic wind

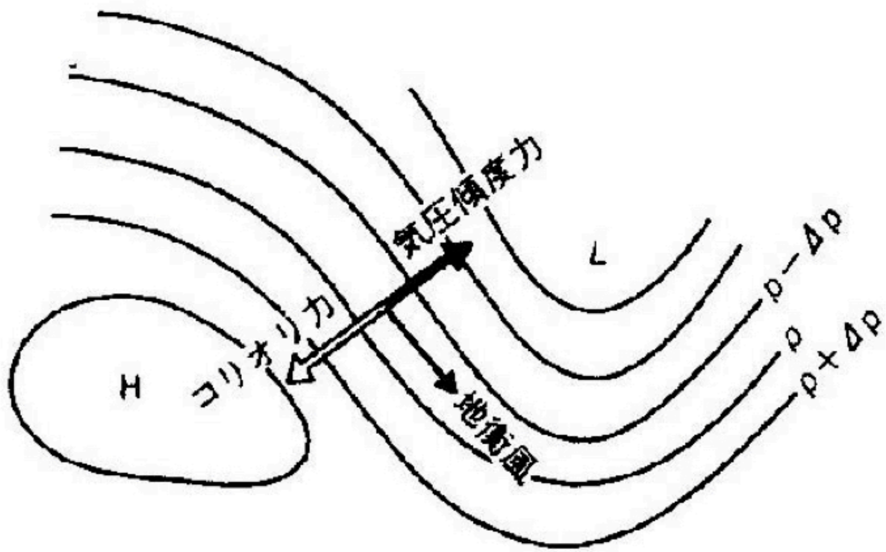
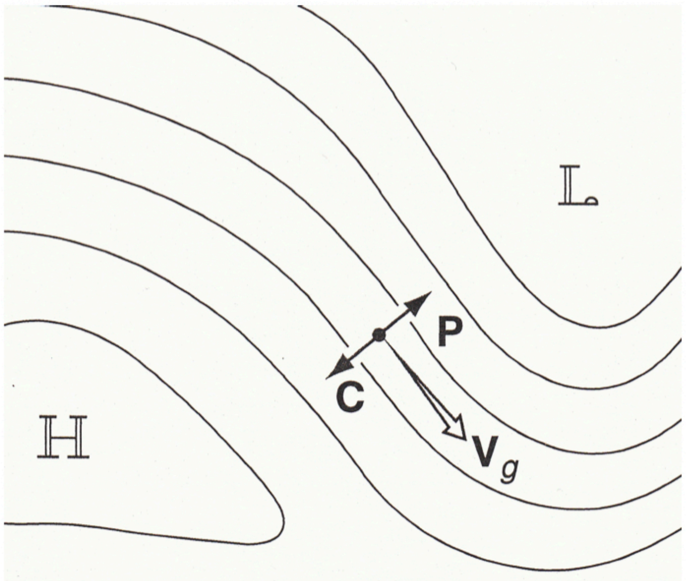


図8　地衡風ならびに地衡風と水平気圧傾度力とコリオリの力の関係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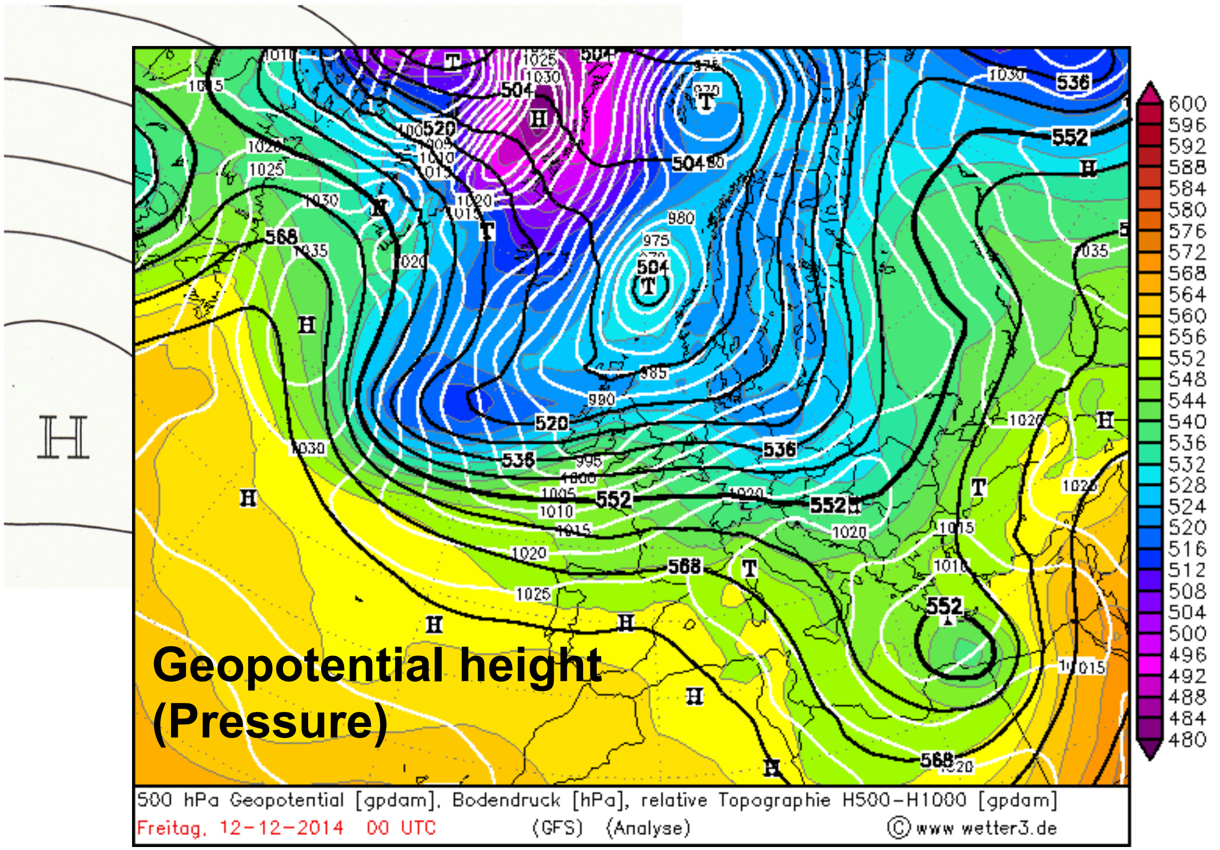
H
Vg


Geopotential height
(Pressure)
500 hPa Geopotential [gpdam], Bodendruck [hPa], relative Topographie H500-H1000 [gpdam]
Freitag, 12-12-2014 00 UTC
(GFS) (Analyse)
© www.wetter3.de
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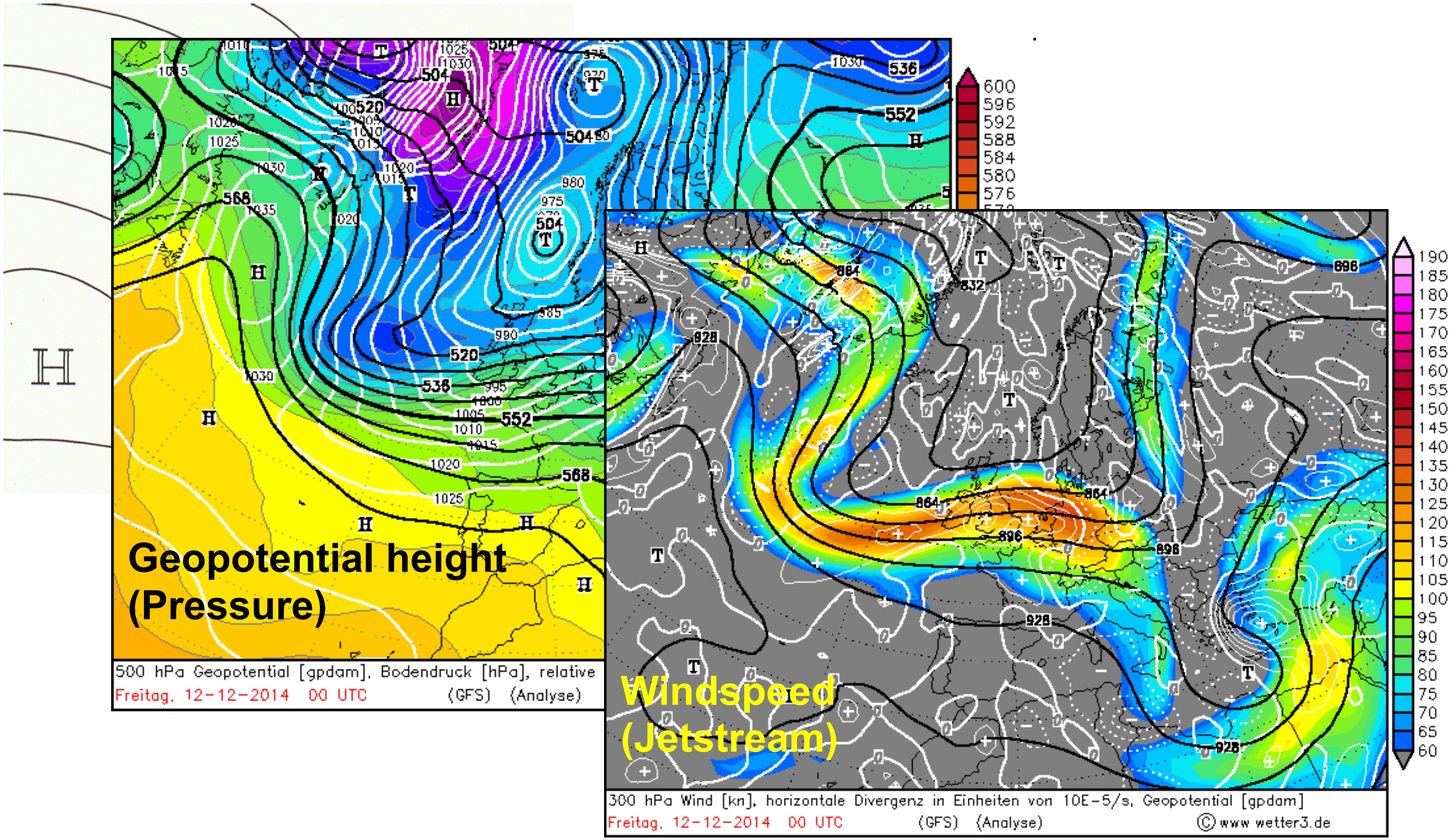
Geopotential height
(Pressure)
500 hPa Geopotential [gpdam], Bodendruck [hPa], relative
Freitag, 12-12-2014 00 UTC (GFS) (Analyse)
Windspeed
(Jetstream)
300 hPa Wind [kn], horizontale Divergenz in Einheiten von 10E-5/s, Geopotential [gpdam]
Freitag, 12-12-2014 00 UTC (GFS) (Analyse) © www.wetter3.de

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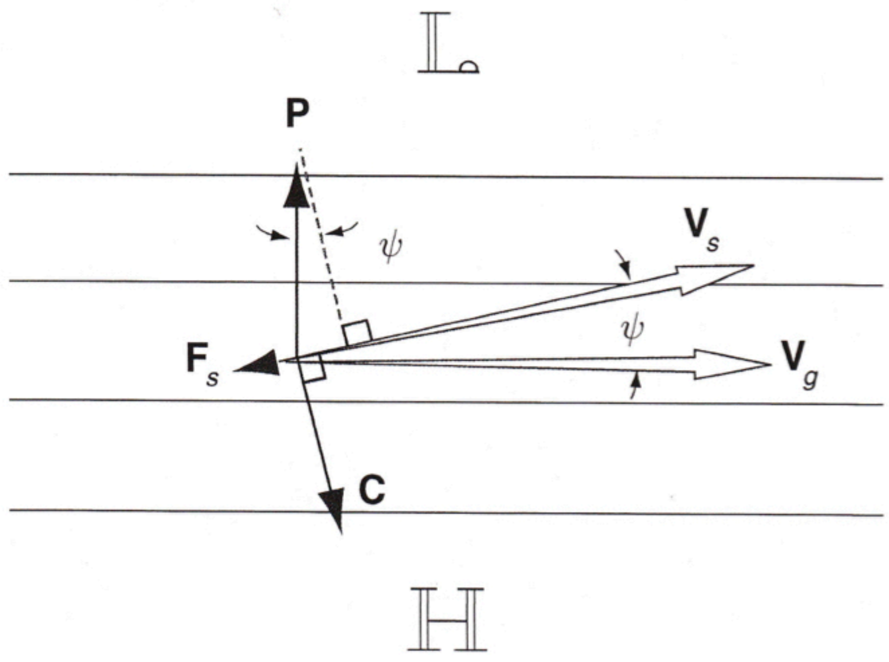
Subgeostrophic wind

Friction will turn the wind towards the low pressure side, changing V_g to V_s
V_s is also called sub- or ageostrophic wind



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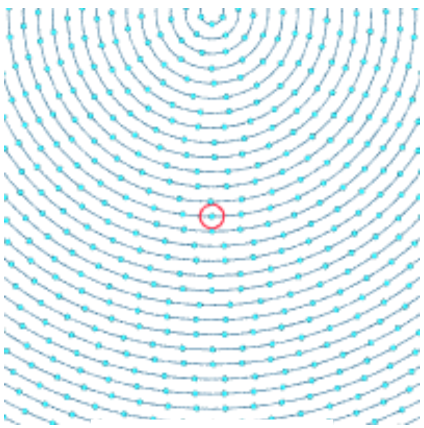
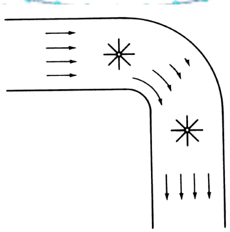
Vorticity

Vorticity is a microscopic measure of rotation in a fluid.

Vorticity is defined as the curl of the velocity, $\left(\nabla \times \vec{V}\right)$ or the vertical component of a rotation of the velocity

Curved flow vorticity





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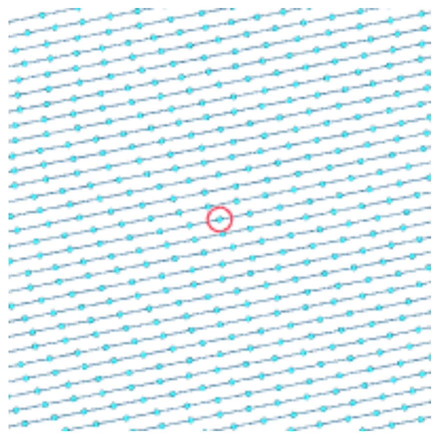
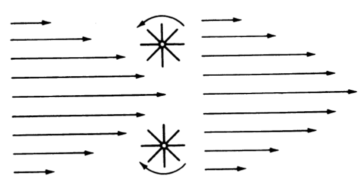
Shear vorticity





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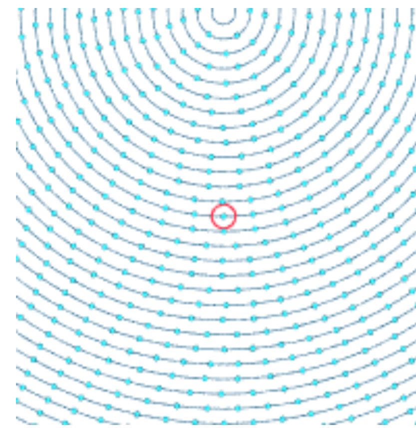

Vorticity

Vorticity is a microscopic measure of rotation in a fluid.

Vorticity is defined as the curl of the velocity, $\left(\nabla \times \vec{V}\right)$
or the vertical component of a rotation of the velocity

There are a bunch of (confusing) vorticity terms:

1. Planetary vorticity
2. Relative (local) vorticity
3. Absolute vorticity
4. Potential vorticity

Planetary Vorticity

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Vorticity is defined as the curl of the velocity, $\left(\nabla \times \vec{V}\right)$ or the vertical component of a rotation of the velocity

There are a bunch of (confusing) vorticity terms:

1. **Planetary vorticity**
   Planetary vorticity is basically the coriolis force f. Everything on earth (water, atmosphere, your breakfast orange juice) rotates with earth.
   Latitudinal gradient: Biggest at the poles
   BUT: Objects do not have to be in motion to have vorticity

Relative Vorticity

Vorticity is a microscopic measure of rotation in a fluid.

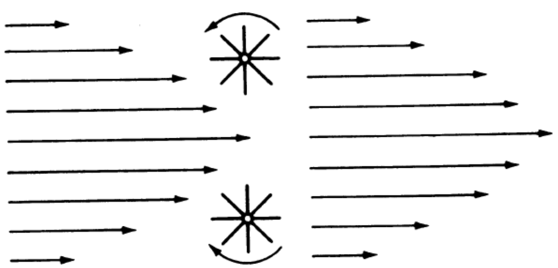
Vorticity is defined as the curl of the velocity, or the vertical component of a rotation of the velocity $\left(\nabla \times \vec{V}\right)$

There are a bunch of (confusing) vorticity terms:

1. Planetary vorticity
2. **Relative (local) vorticity**

$$\zeta = \vec{\nabla}_z \times \vec{v} = \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y} = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

Cyclonic: positive relative vorticity



Anticyclonic: negative relative vorticity

Absolute Vorticity

Vorticity is a microscopic measure of rotation in a fluid.

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There are a bunch of (confusing) vorticity terms:

1. Planetary vorticity
2. Relative (local) vorticity
3. **Absolute vorticity**

   Is the sum of planetary and relative vorticity

$$\eta = \zeta + f$$

Vorticity

Vorticity is a microscopic measure of rotation in a fluid.

Vorticity is defined as the curl of the velocity, $\left(\nabla \times \vec{V}\right)$ or the vertical component of a rotation of the velocity

There are a bunch of (confusing) vorticity terms:

1. Planetary vorticity
2. Relative (local) vorticity
3. **Absolute vorticity**

   Absolute vorticity is CONSERVED in adiabatic, frictionless, non-divergent flow (i.e., columns of air cannot stretch or contract vertically)

   - Usually applied to barotropic atmosphere
   - $\eta = \zeta + f$ is constant

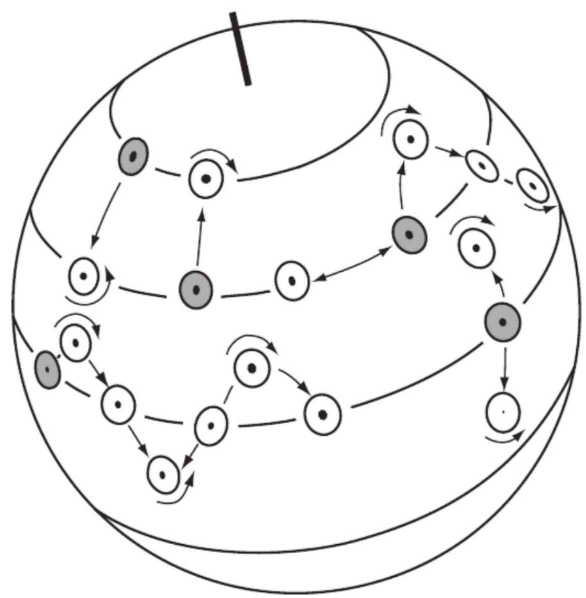
Absolute Vorticity

- Changes in latitude require a corresponding change in ζ.

- As a column of water/air moves equatorward, f decreases, and ζ must increase .

- If this seems somewhat mysterious, von Arx (1962) suggests we consider a barrel of water at rest at the north pole. If the barrel is moved southward, the water in it retains the rotation it had at the pole, and it will appear to rotate counterclockwise at the new latitude where f is smaller.

- In the NH, earth vorticity (+) is usually always larger than relative vorticity in magnitude → Absolute vorticity is positive, but smaller for Clockwise flow (relative vorticity <0) than Counterclockwise flow (relative vorticity >0).



$$\eta = \zeta + f$$

Potential Vorticity

Vorticity is a microscopic measure of rotation in a fluid.

Vorticity is defined as the curl of the velocity, $\left(\nabla \times \vec{V}\right)$ or the vertical component of a rotation of the velocity

There are a bunch of (confusing) vorticity terms:

1. Planetary vorticity
2. Relative (local) vorticity
3. Absolute vorticity
4. **Potential vorticity**

$$\text{Potential vorticity} = \frac{\text{Absolute vorticity}}{\text{Vortex depth}} \qquad \frac{\zeta + f}{h}$$

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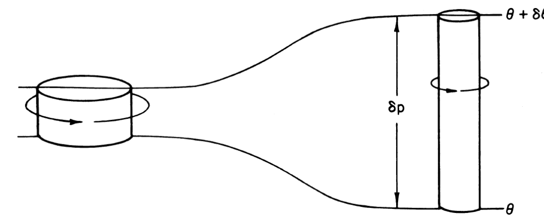
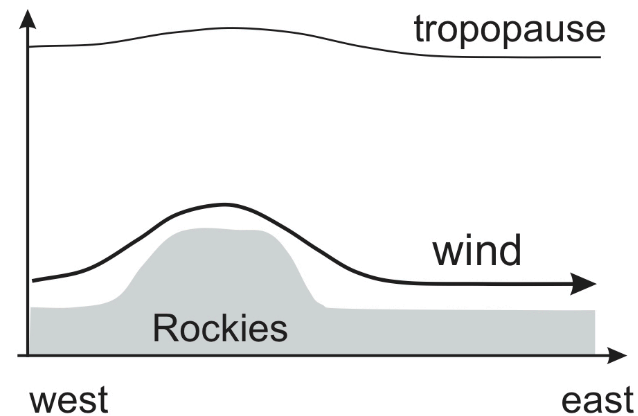
Potential Vorticity

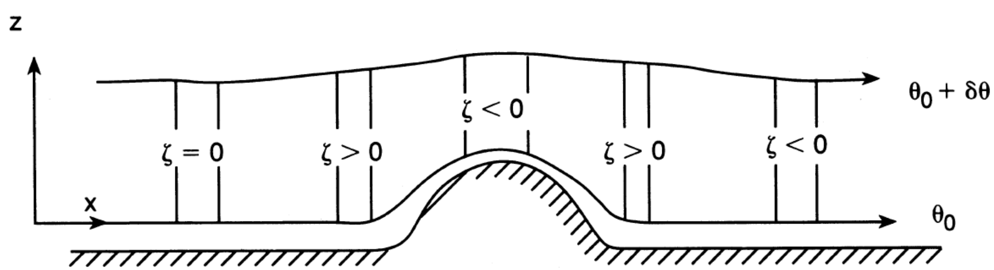
Under adiabatic conditions PV is conserved:

$$P \equiv (\zeta_\theta + f)\left(-g\frac{\partial\theta}{\partial p}\right) = Const$$

$$\frac{\zeta + f}{h} = \frac{\eta}{h} = Const$$







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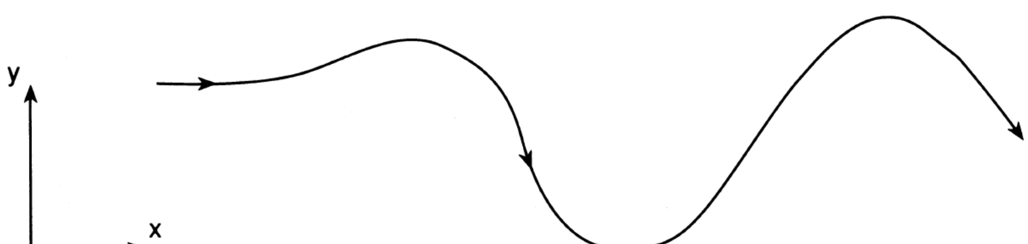
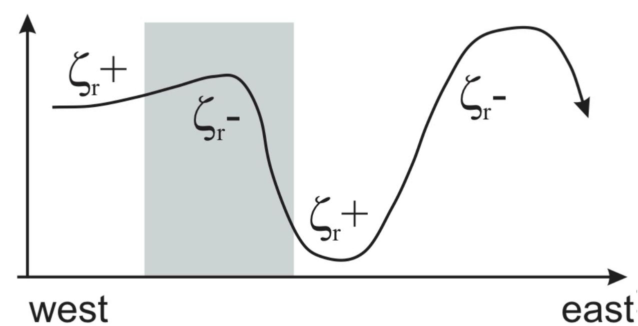
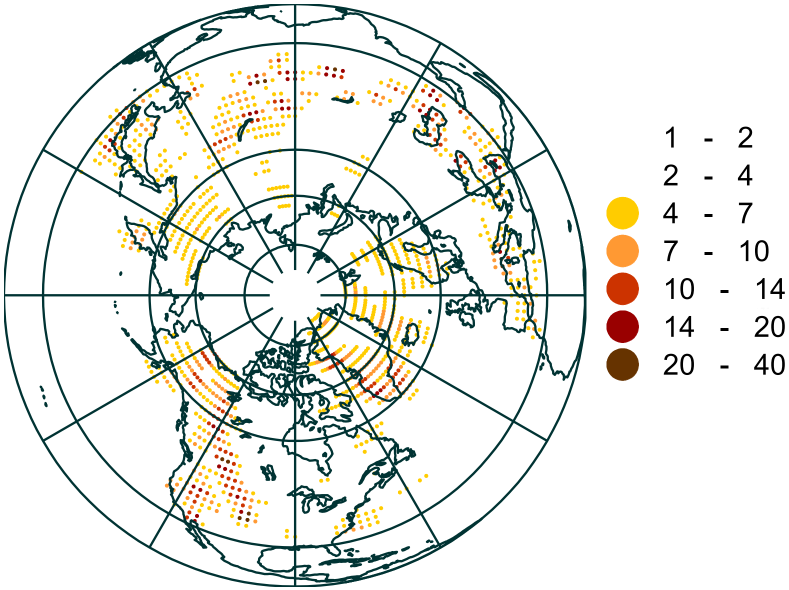




Potential Vorticity



Generation of cyclones
NCEP CFSR

Source: Olga Zolina, personal communication

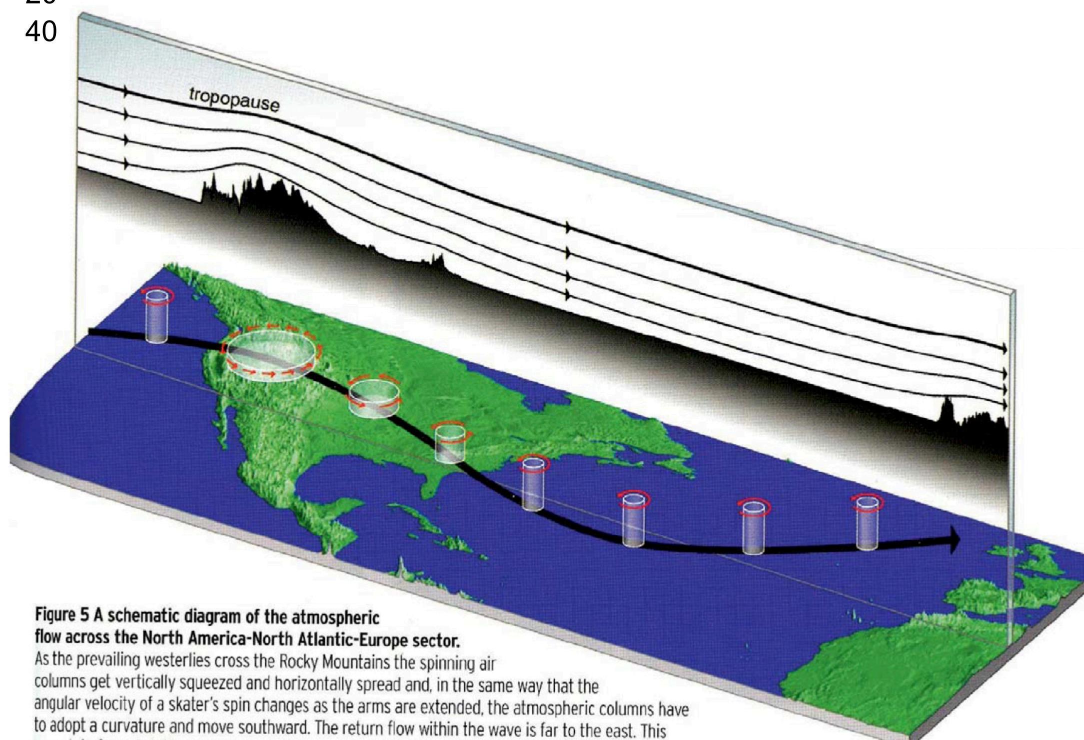
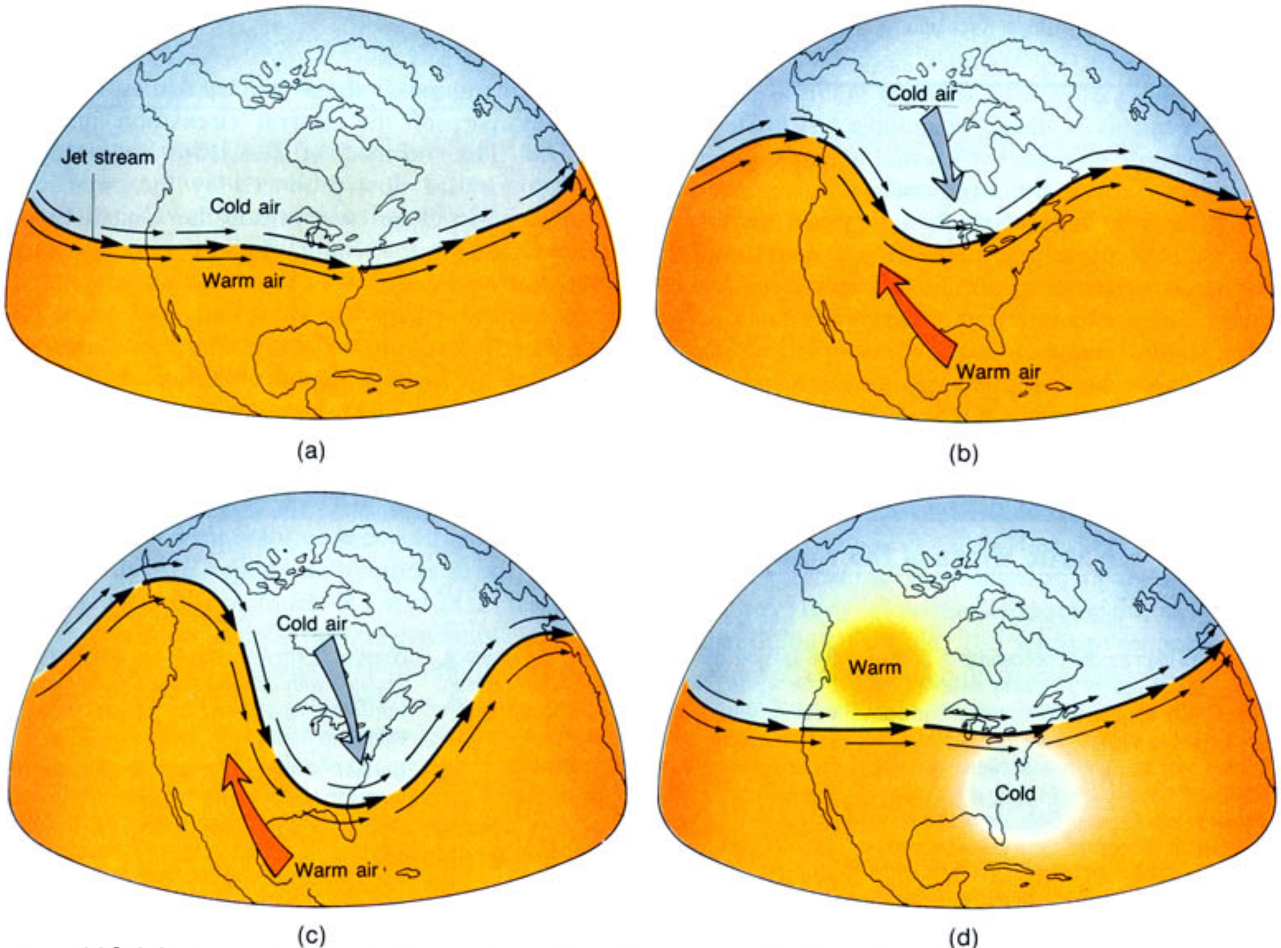


Figure 5 A schematic diagram of the atmospheric flow across the North America-North Atlantic-Europe sector.
As the prevailing westerlies cross the Rocky Mountains the spinning air columns get vertically squeezed and horizontally spread and, in the same way that the angular velocity of a skater's spin changes as the arms are extended, the atmospheric columns have to adopt a curvature and move southward. The return flow within the wave is far to the east. This mountain-forced stationary wave has an enormous scale, bringing cold air south into central and eastern North America and warm air north into the eastern Atlantic and western Europe. It explains about half of the difference in winter temperatures across the Atlantic Ocean

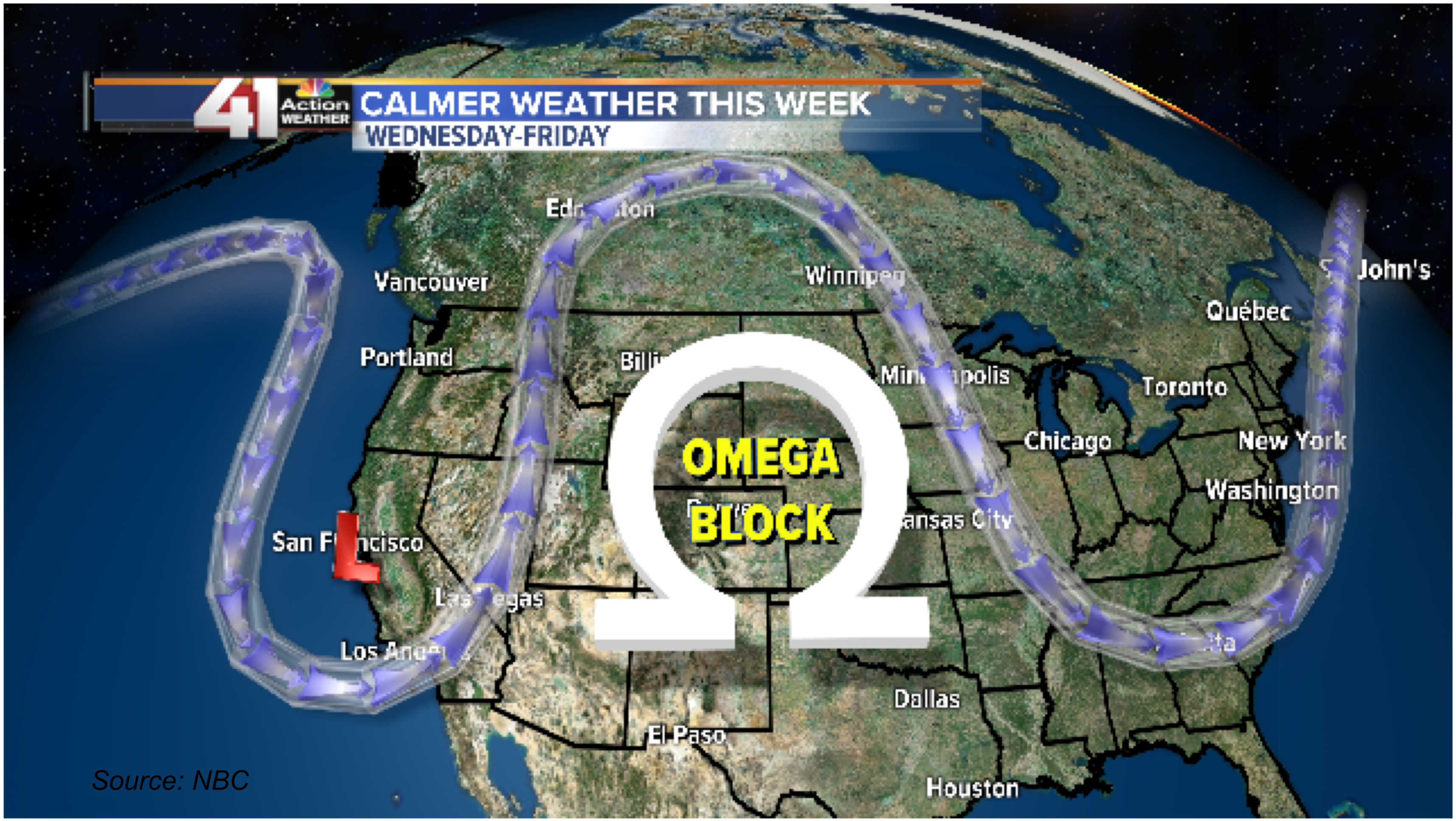
Source: Richard Seager, The American Scientist

Energy transport



Source: NOAA

Blocked waves



Source: NBC

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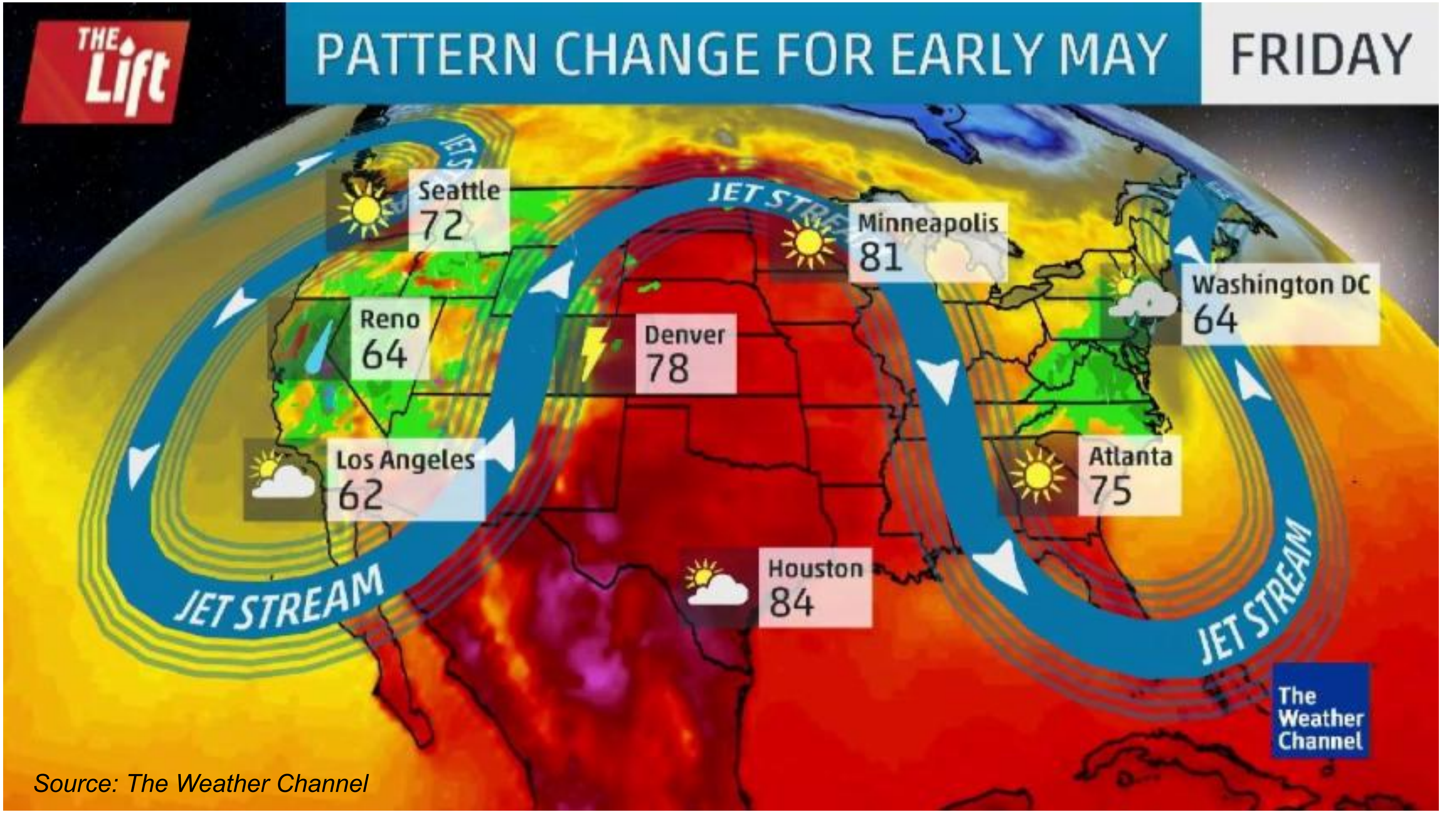
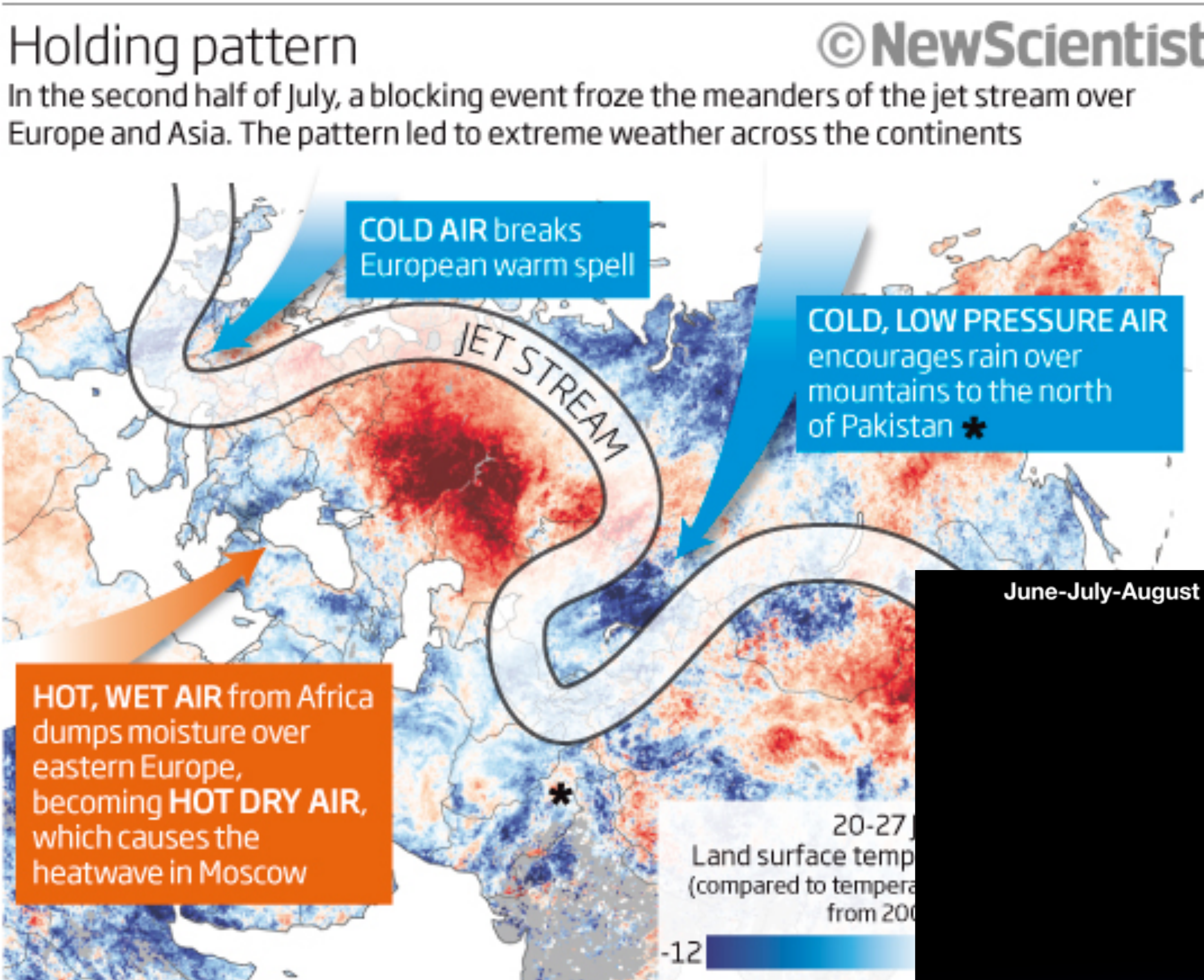
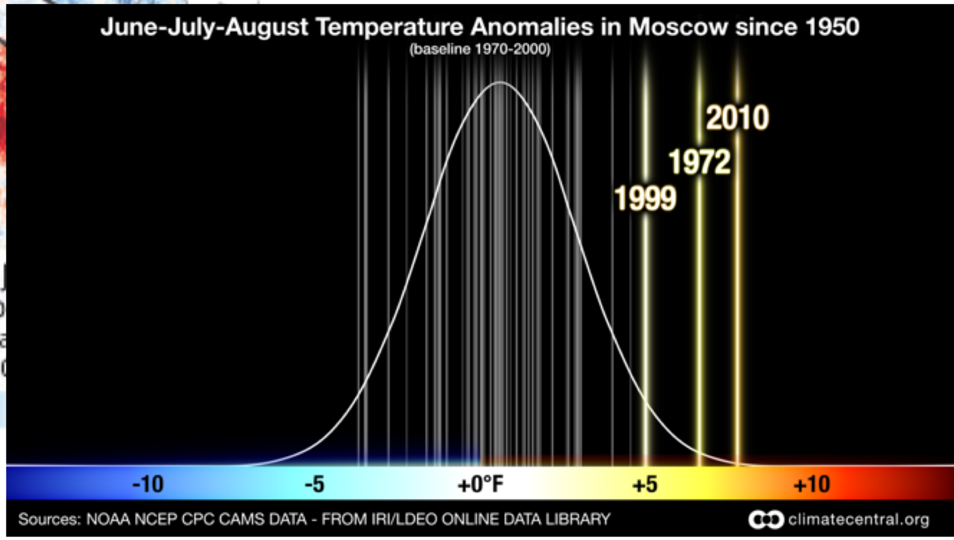
Blocked waves



Source: *The Weather Channel*

Blocked waves





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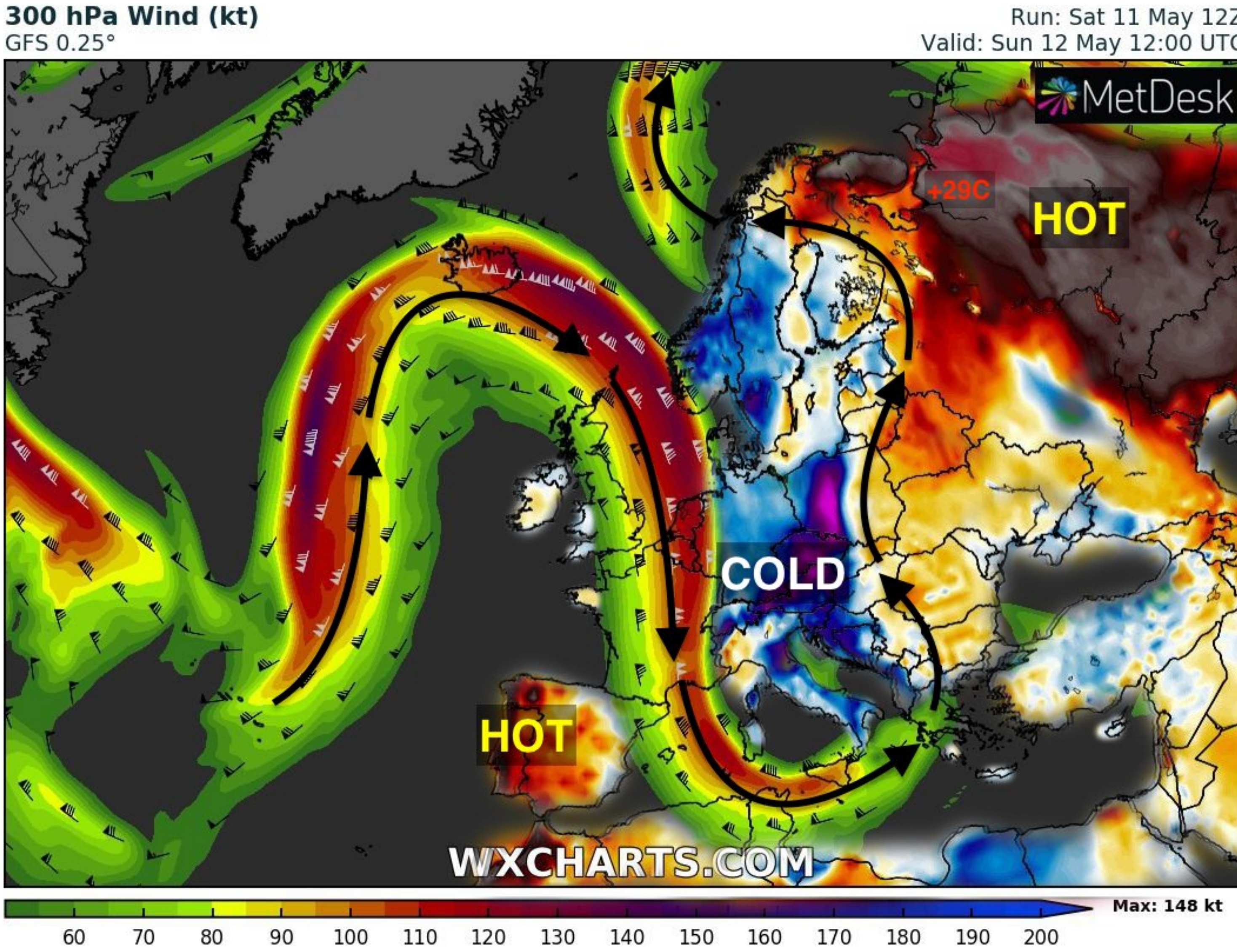
Blocked waves



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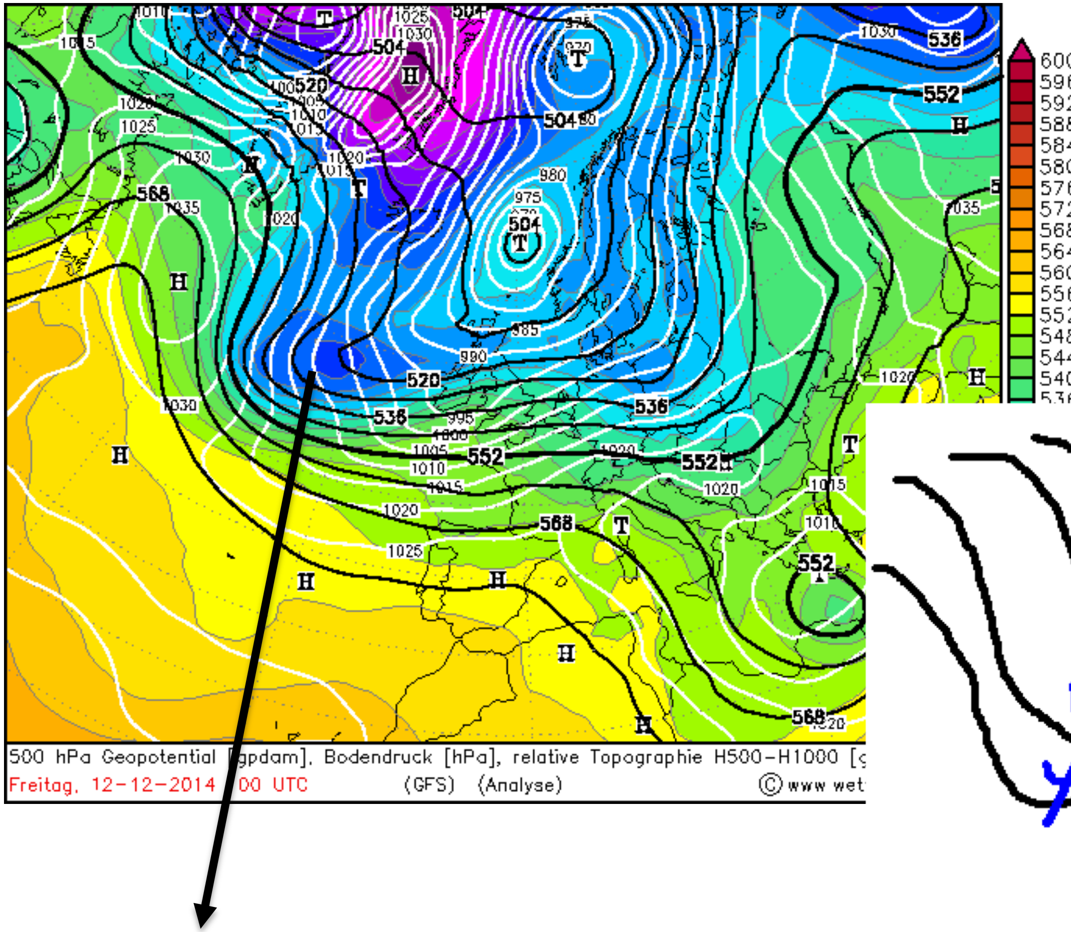
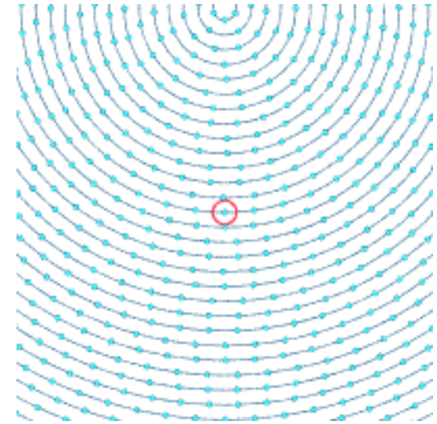
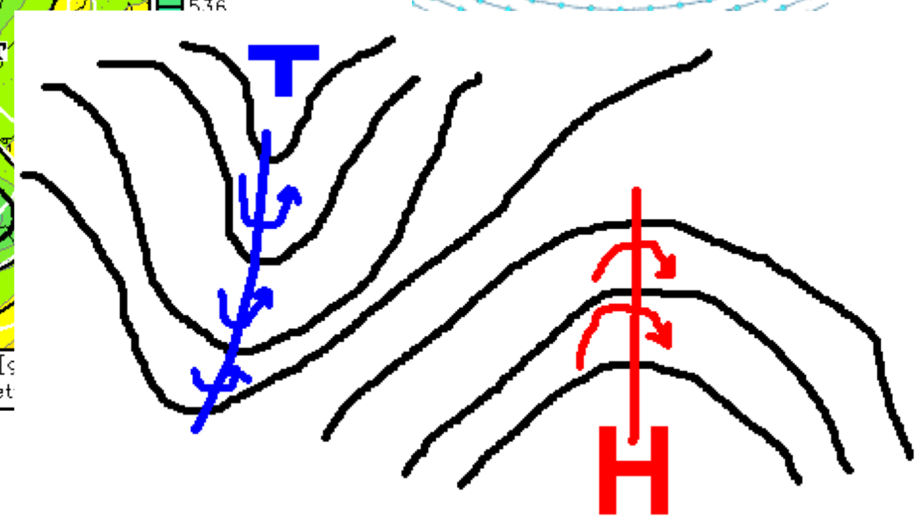
Vorticity in Weather







Vorticity maximum

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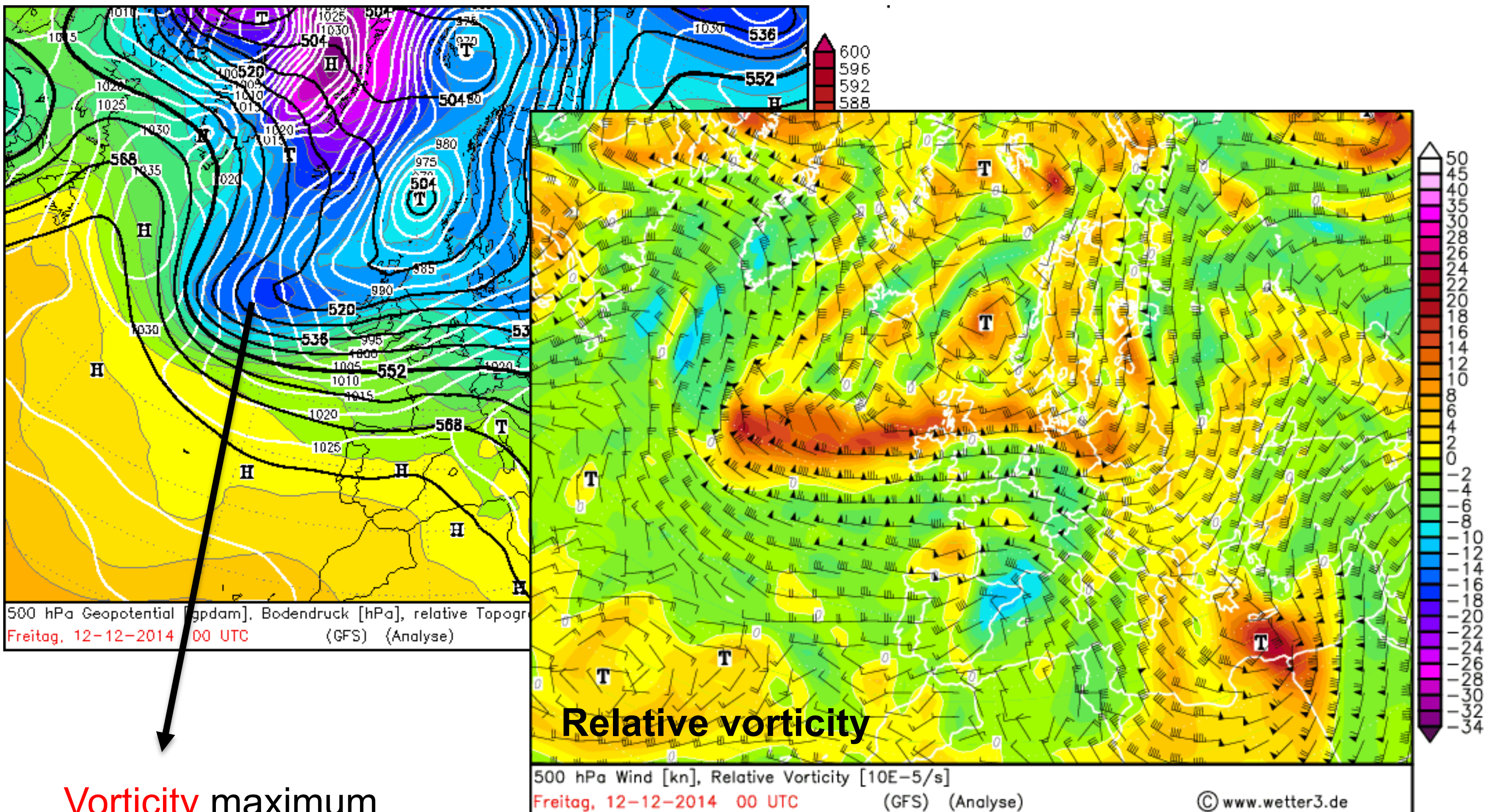
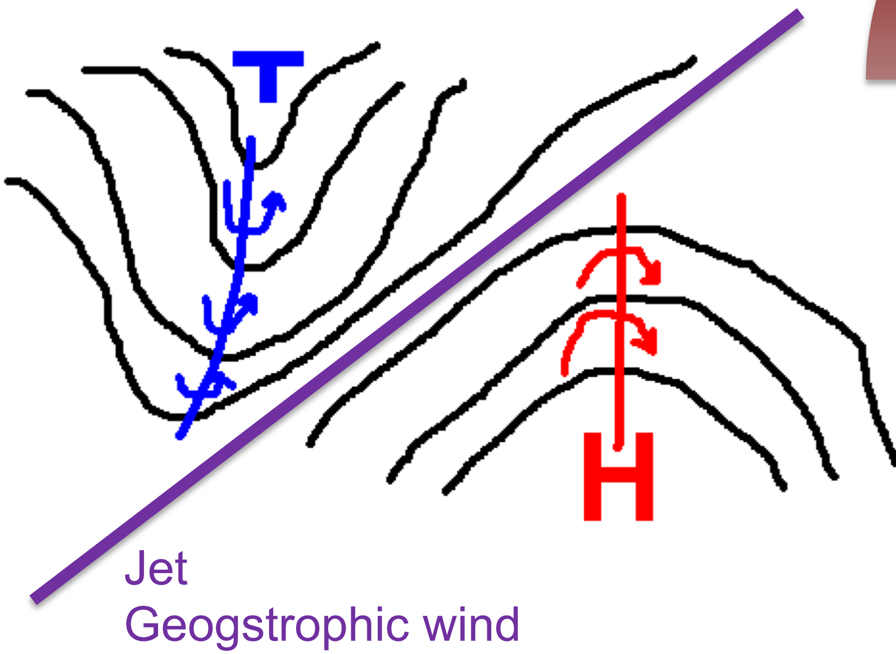
Vorticity in Weather

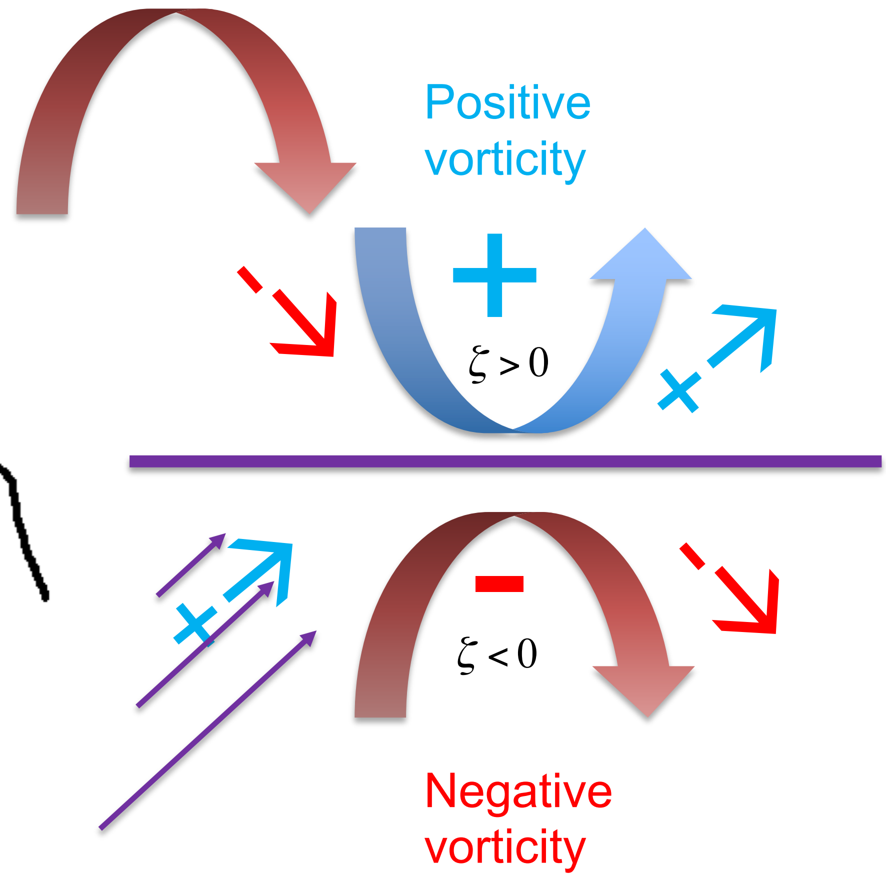


Vorticity maximum

Cyclogenesis

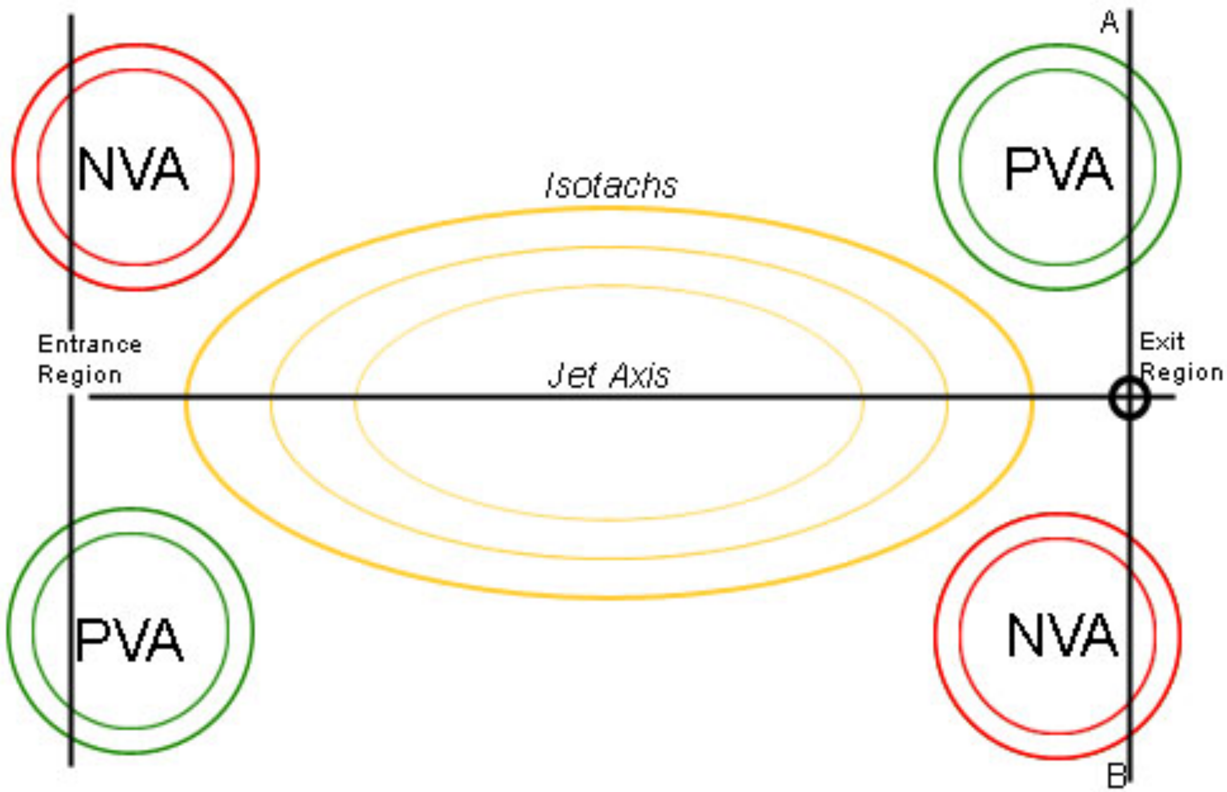
- Upper atmosphere





Cyclogenesis

- Upper atmosphere

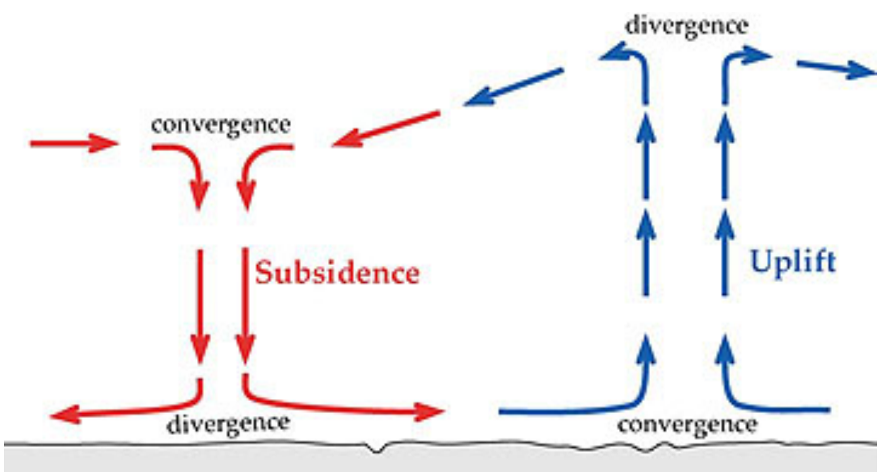


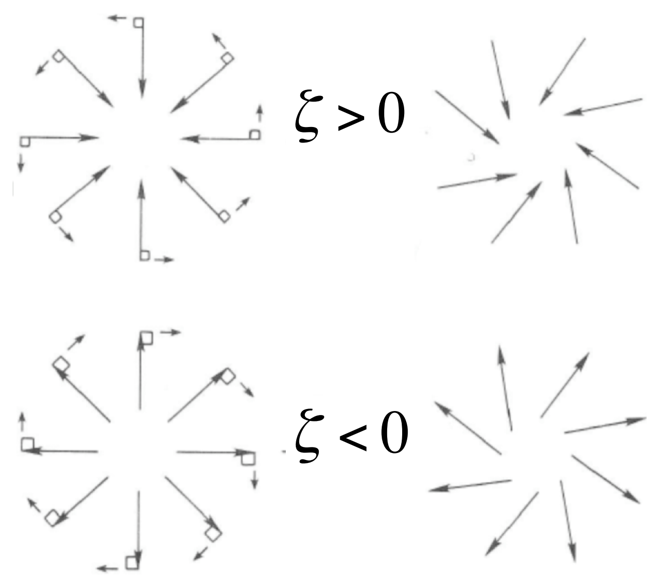
PVA= Positive vorticity advection → low pressure cell can form → bad weather
NVA= Negative vorticity advection → high pressure cell can form → fair weather

Cyclogenesis

- Convergence of air aloft creates low level divergence (due to mass continuity)=> Downward vertical motion => The column of air in between is squashed and widened and must now spin at a slower rate (due to conservation of angular momentum) => vorticity decreases.

- Divergence of air aloft creates low level convergence => Upward vertical motion => The column of air in between is stretched and made thinner and will now spin faster => vorticity increases.

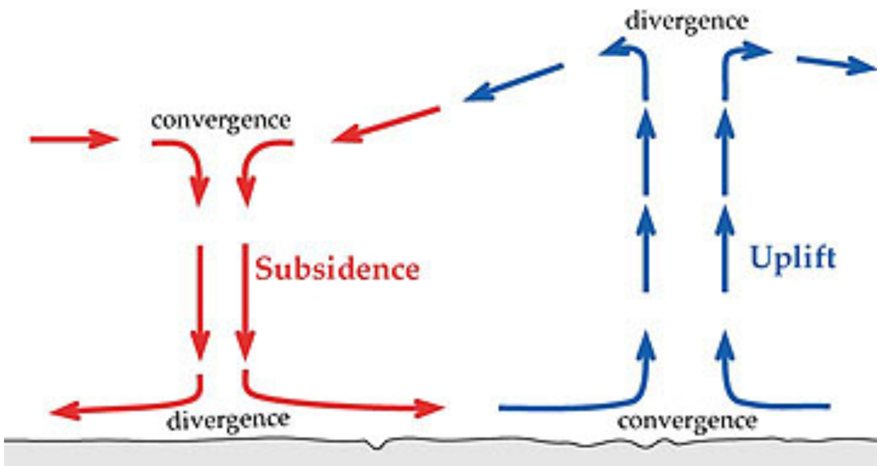


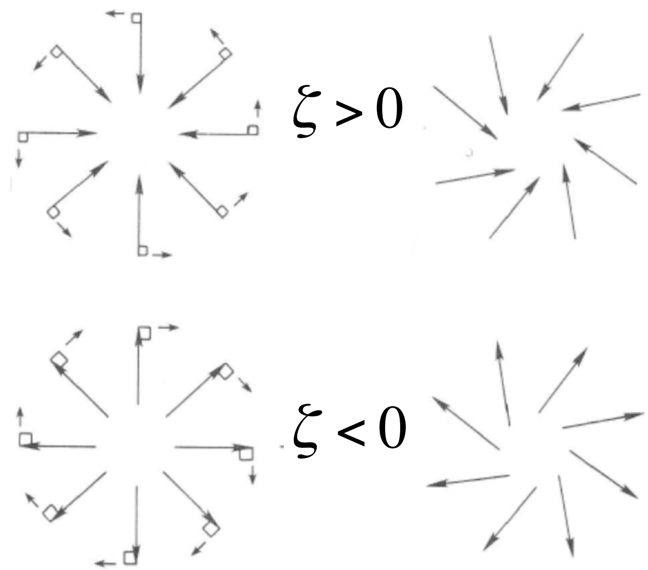


Cyclogenesis

- PVA → Cyclonic flow → Convergence surface *(tube is stretched)*

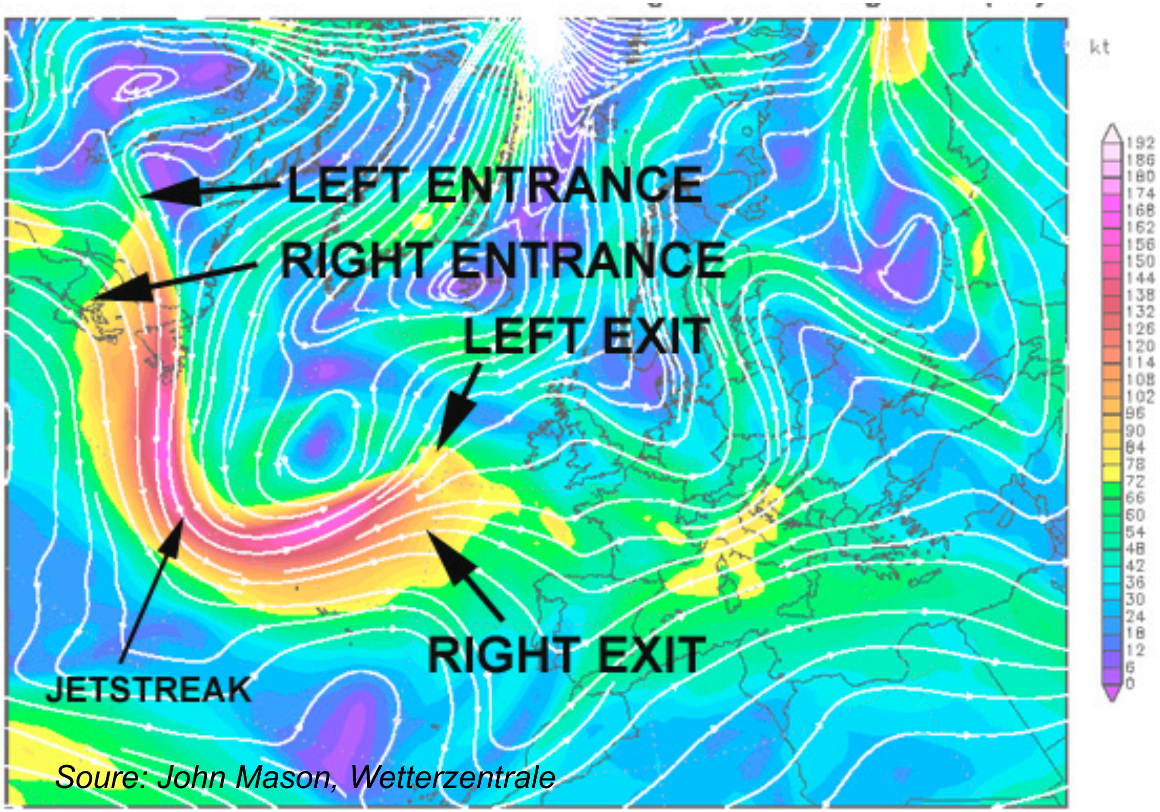
- Upper Atmosphere:
  - Divergence → Anti cyclonic flow
- Lower atmosphere
  - Air is sucked in → Convergence → low is filled up slowly thanks to friction force → Air rises and condensation occurs → energy release and snow/rain





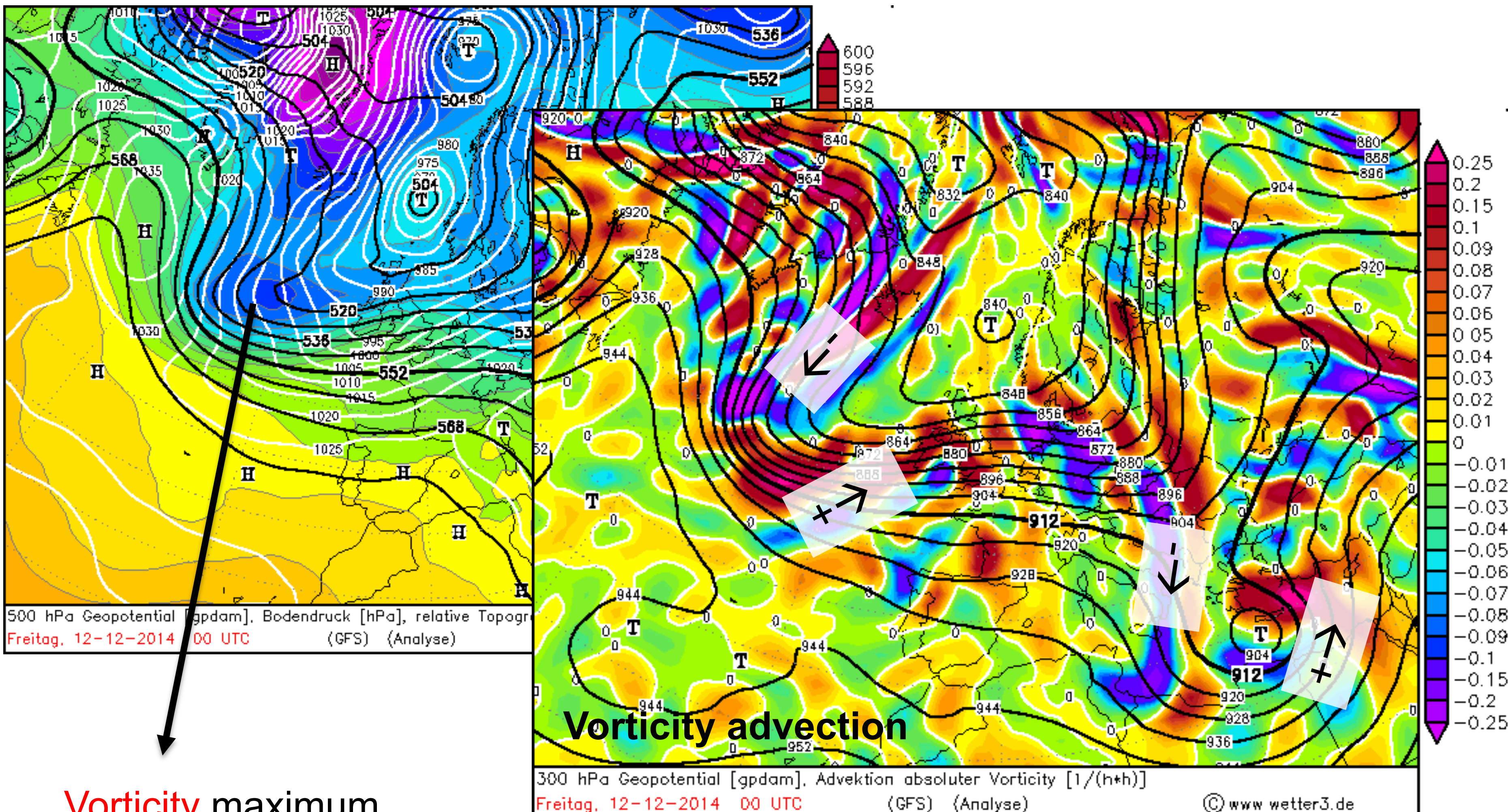
Cyclogenesis

- Upper atmosphere



PVA= Positive vorticity advection → low pressure cell can form → bad weather
NVA= Negative vorticity advection → high pressure cell can form → fair weather

Vorticity in Weather



Vorticity maximum

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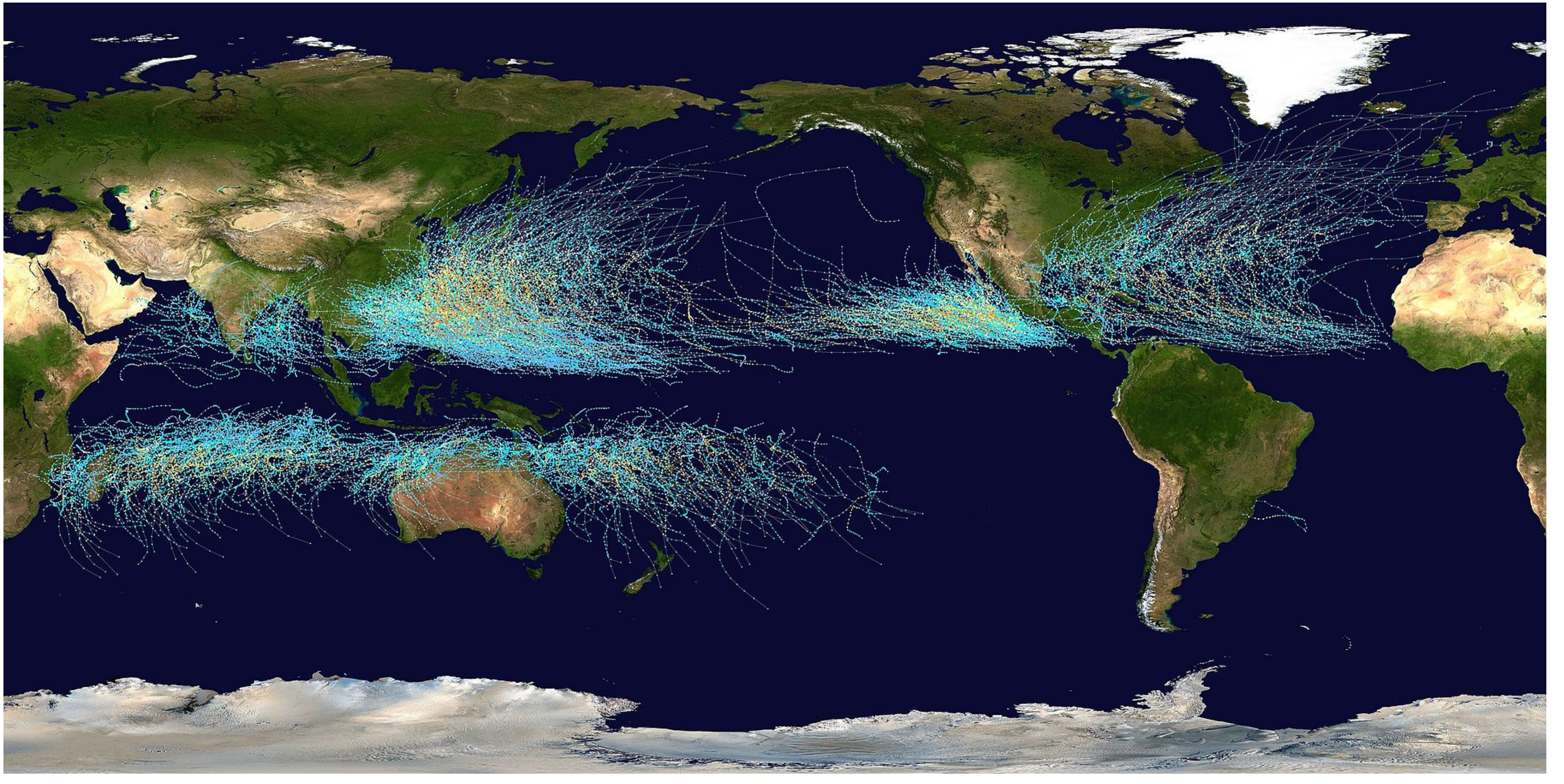
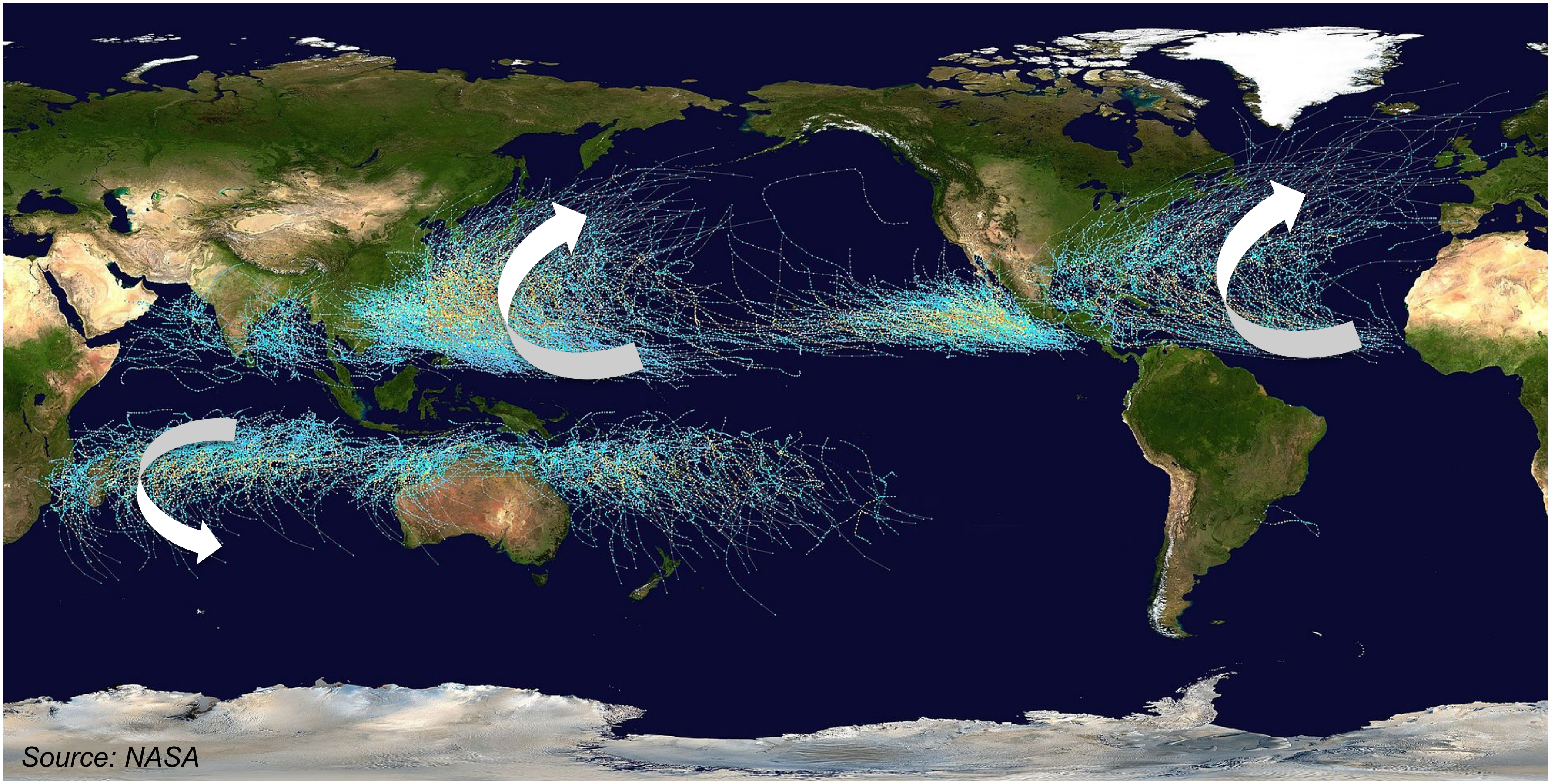
Hurricane climatology



Why this distribution?

Hurricane climatology



Warm water, no wind shear, coriolis force, initial low pressure….
But why do they turn??

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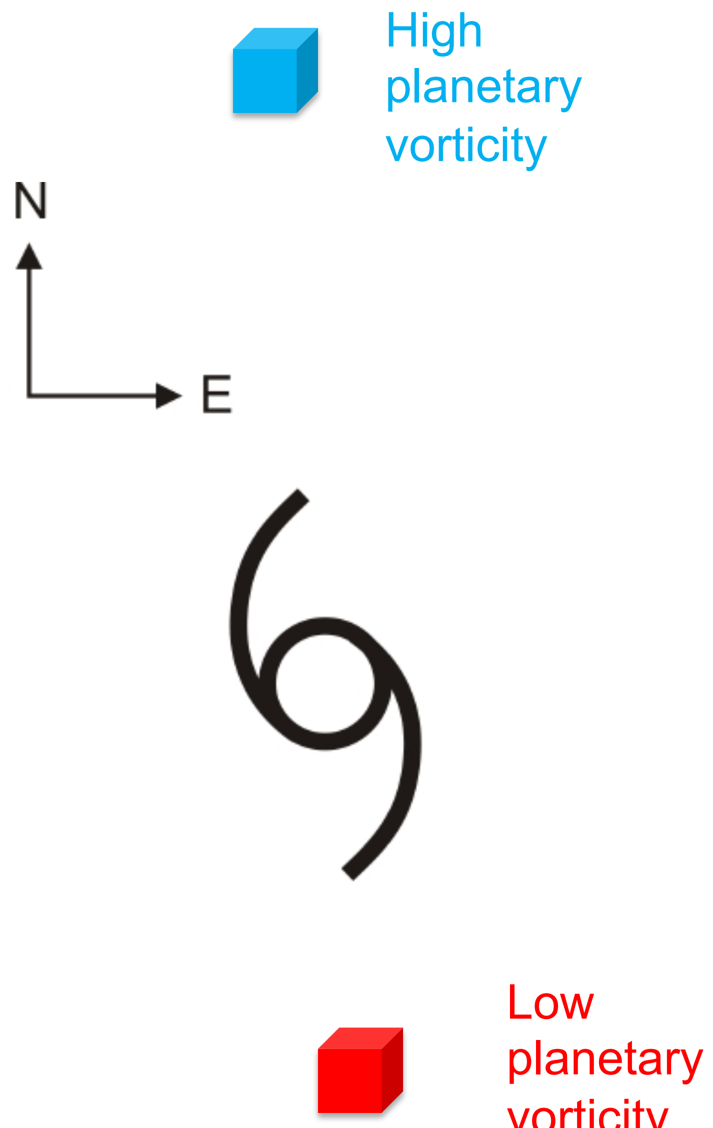
Beta drift



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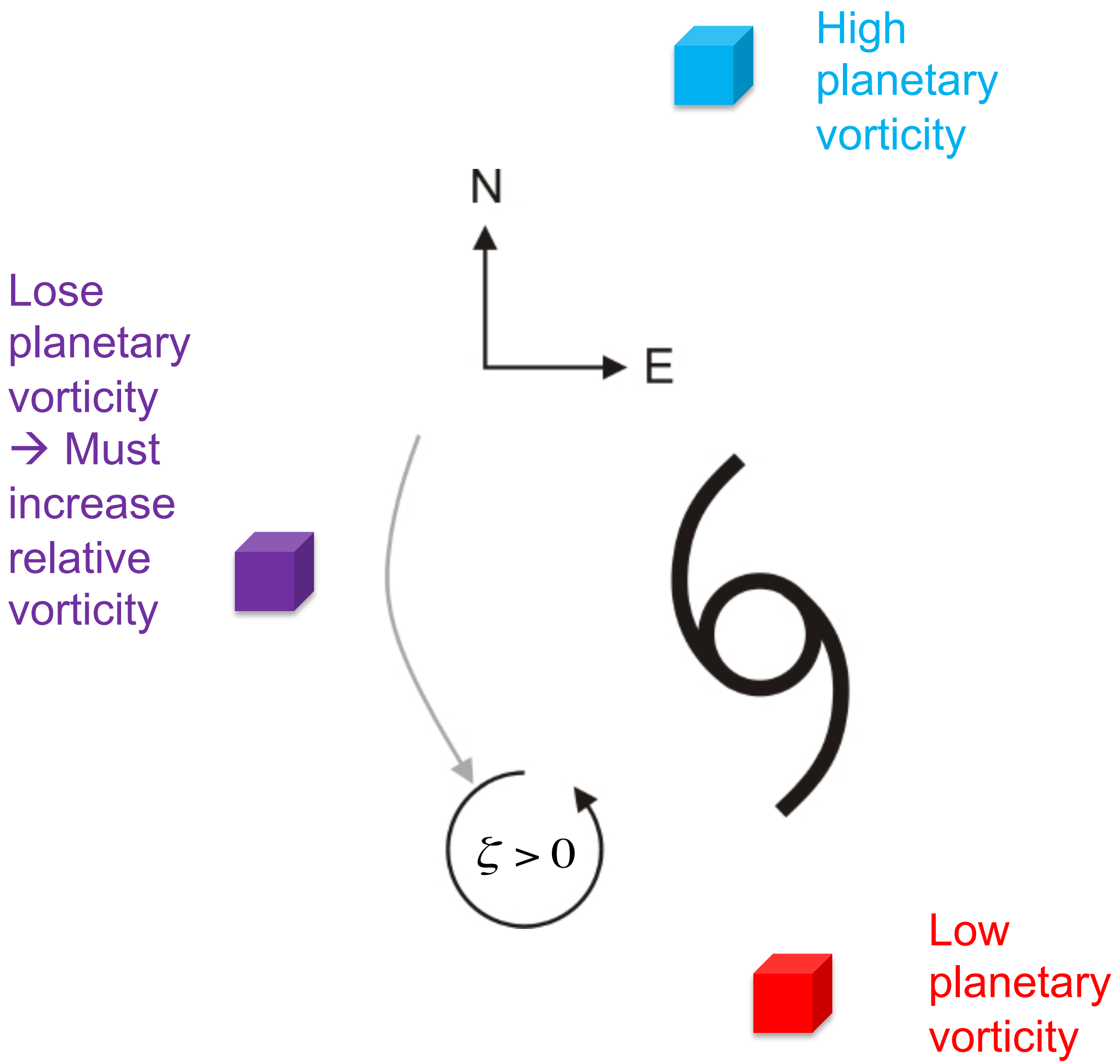
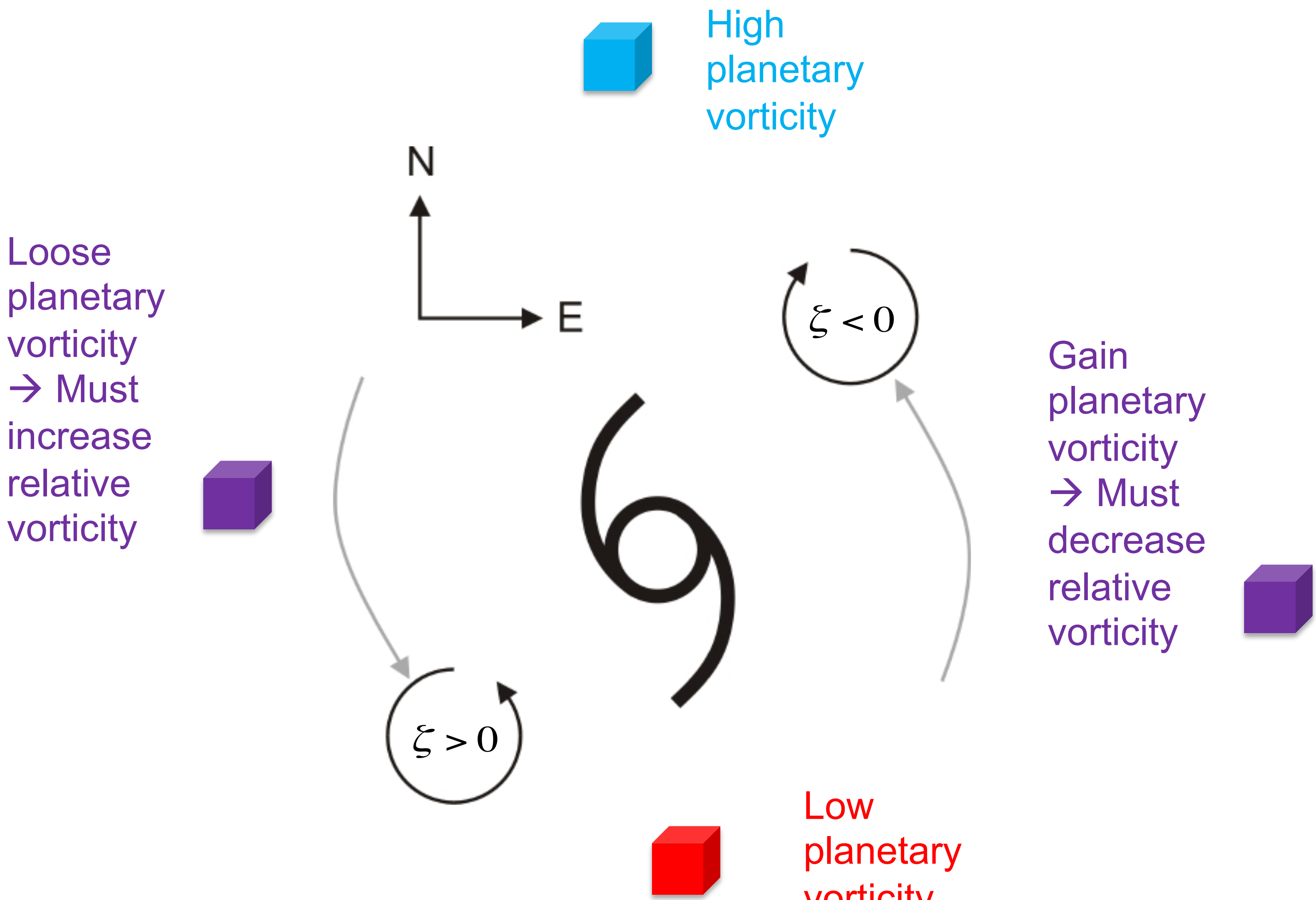
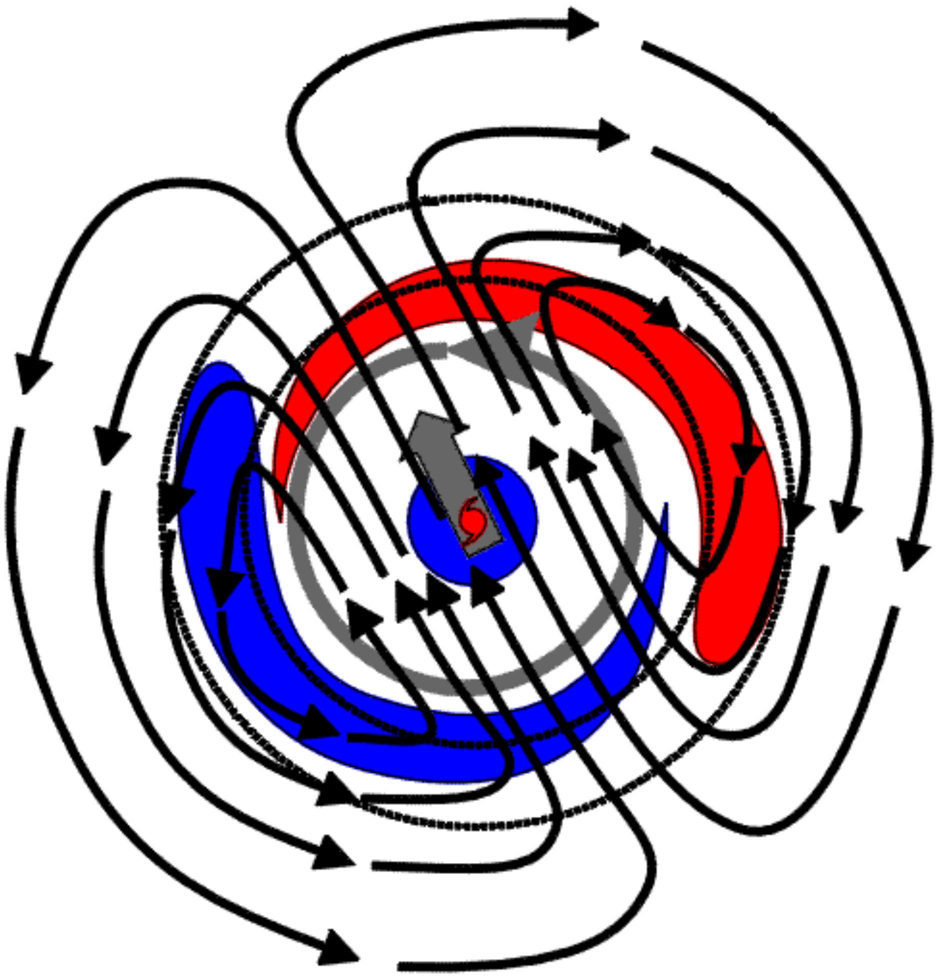
Beta drift


High planetary vorticity
N
E
Lose planetary vorticity → Must increase relative vorticity
$\zeta > 0$
Low planetary vorticity

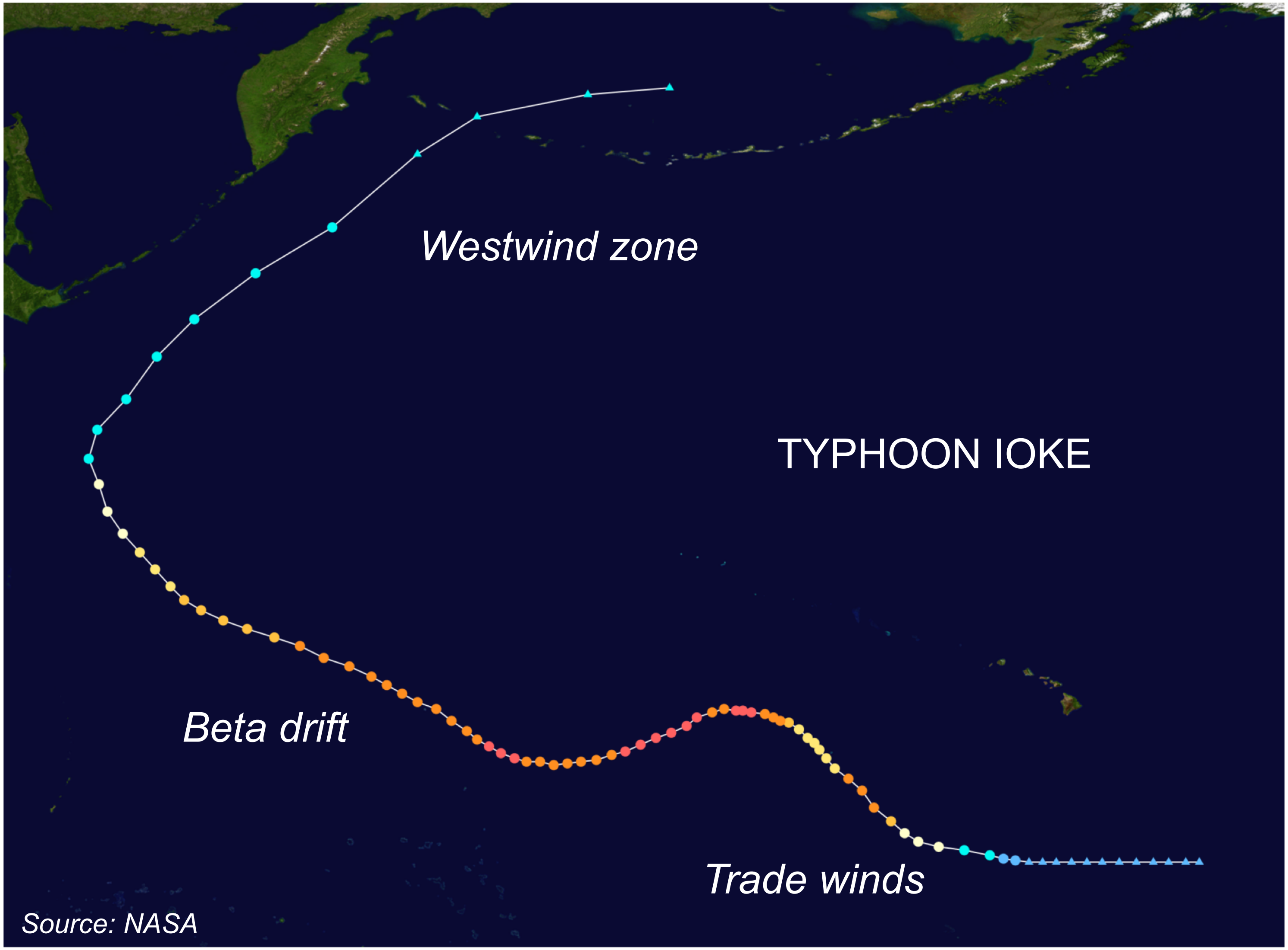
Beta drift


High planetary vorticity
N
E
Loose planetary vorticity → Must increase relative vorticity
$\zeta < 0$
Gain planetary vorticity → Must decrease relative vorticity
$\zeta > 0$
Low planetary vorticity

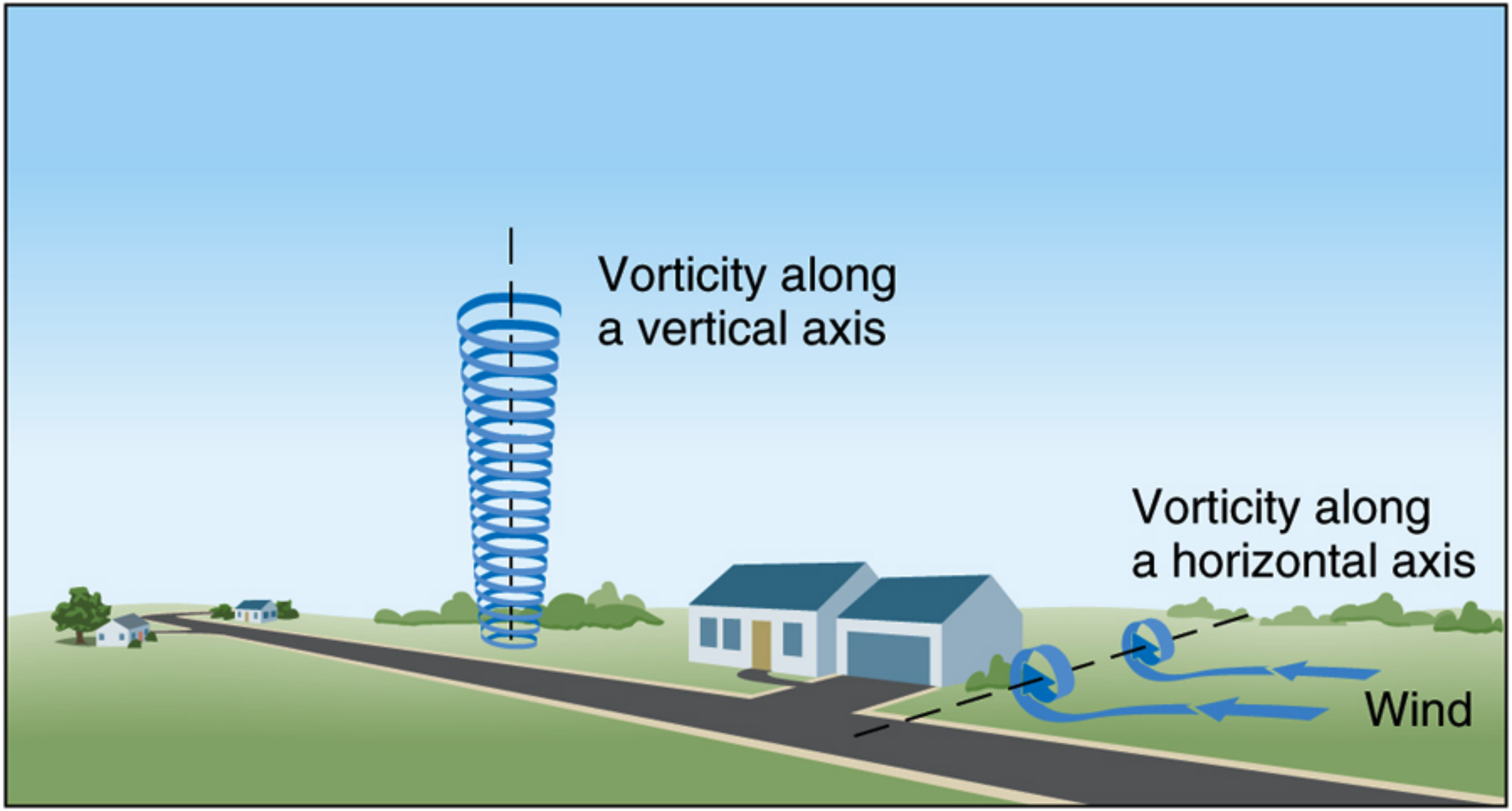
Beta drift



Beta drift


Westwind zone
TYPHOON IOKE
Beta drift
Trade winds
Source: NASA

Vertical vorticity



Both are important for tornado formation!!

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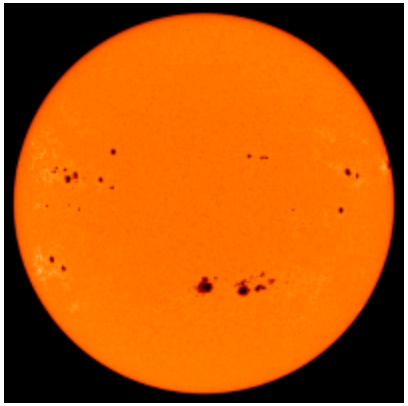
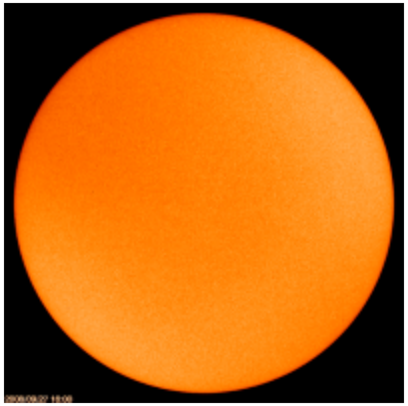
The Sun

- The activity of the sun is dependent on the turbulence of hot gases and changes in the magnetic field.
- Solar activity is tracked by the number of sunspots, which appear in cycles
- The most well known cycle has a period of 11 years
- The radiated energy of sun varies by approximately 0.1%.





Source: NASA

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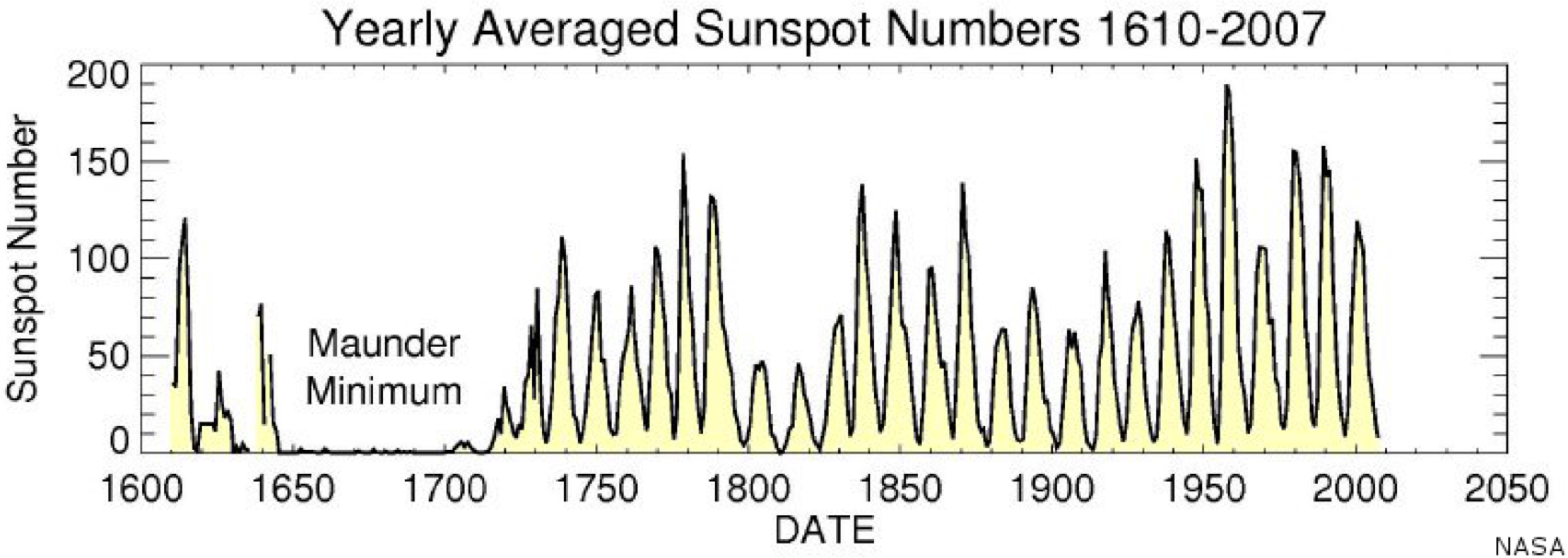
The Sun



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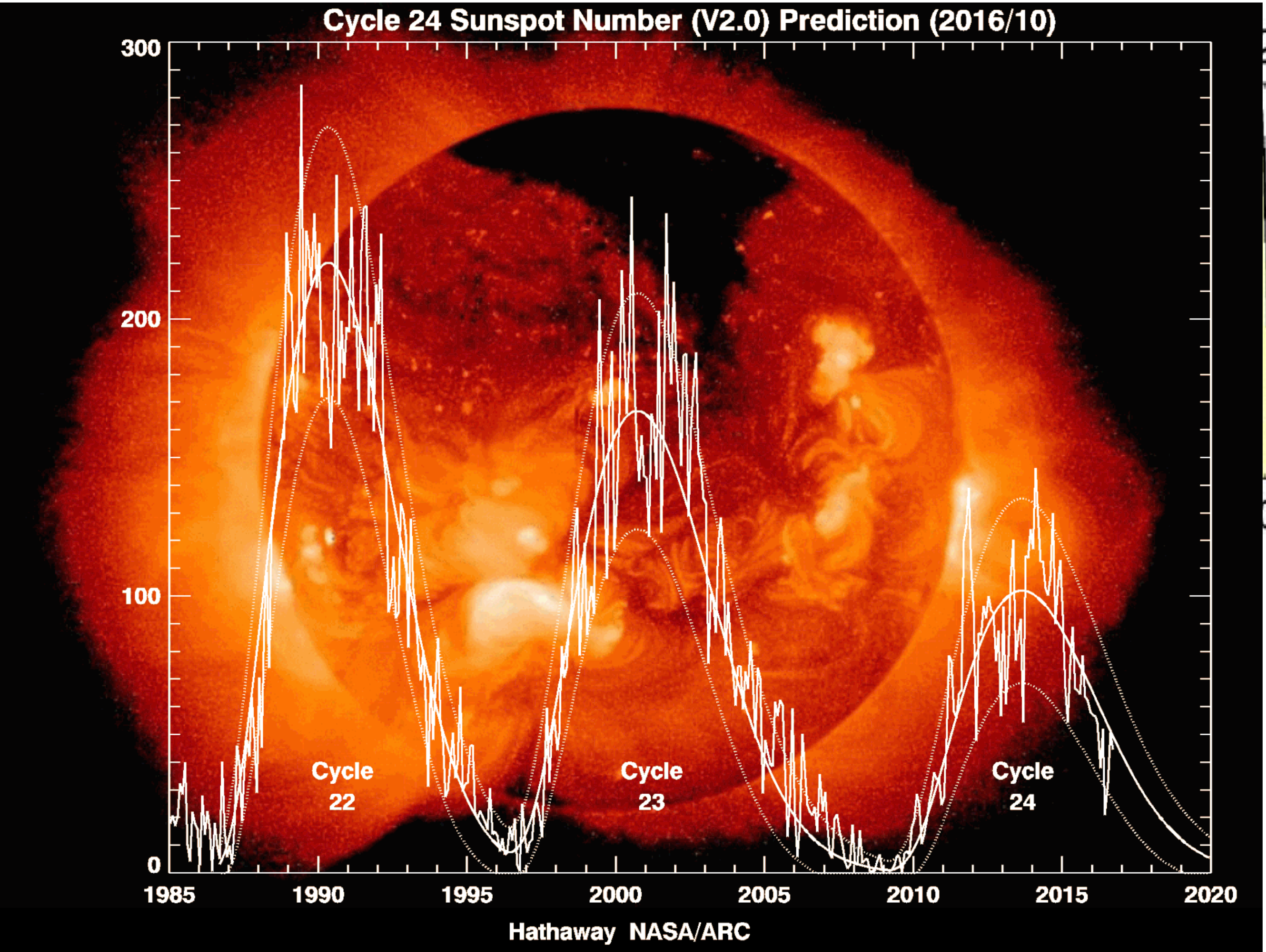
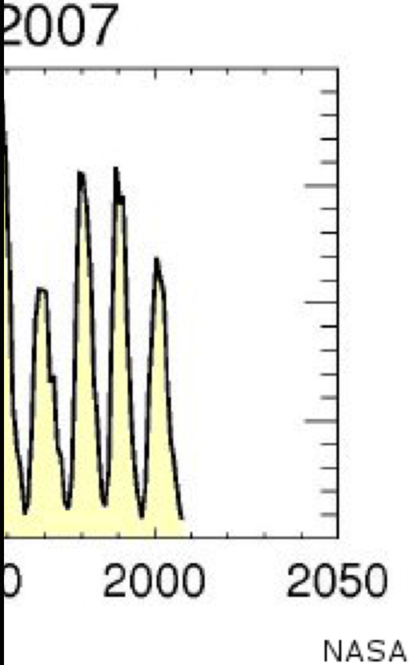
The Sun



Cycle 24 Sunspot Number (V2.0) Prediction (2016/10)
300
200
100
0
1985
1990
1995
2000
2005
2010
2015
2020
Cycle 22
Cycle 23
Cycle 24
Hathaway NASA/ARC



2007
2000
2050
NASA

The Sun

- Not discussing orbital cycles (will follow later)
- These orbital cycles last many thousands of years, and therefore hardly have an influence on climate change within a relatively short period of time ranging from years to centuries
- The solar influence on weather is strongly debated in the literature. Even with good statistics (100s of years), weather patterns change only slightly with solar irridiance changes. Cosmic rays, energetic particles and UV radiation are among candidates that could influence weather.
- There are reconstructions of solar variability based on isotopic analysis (Be^{10} on rock surfaces)

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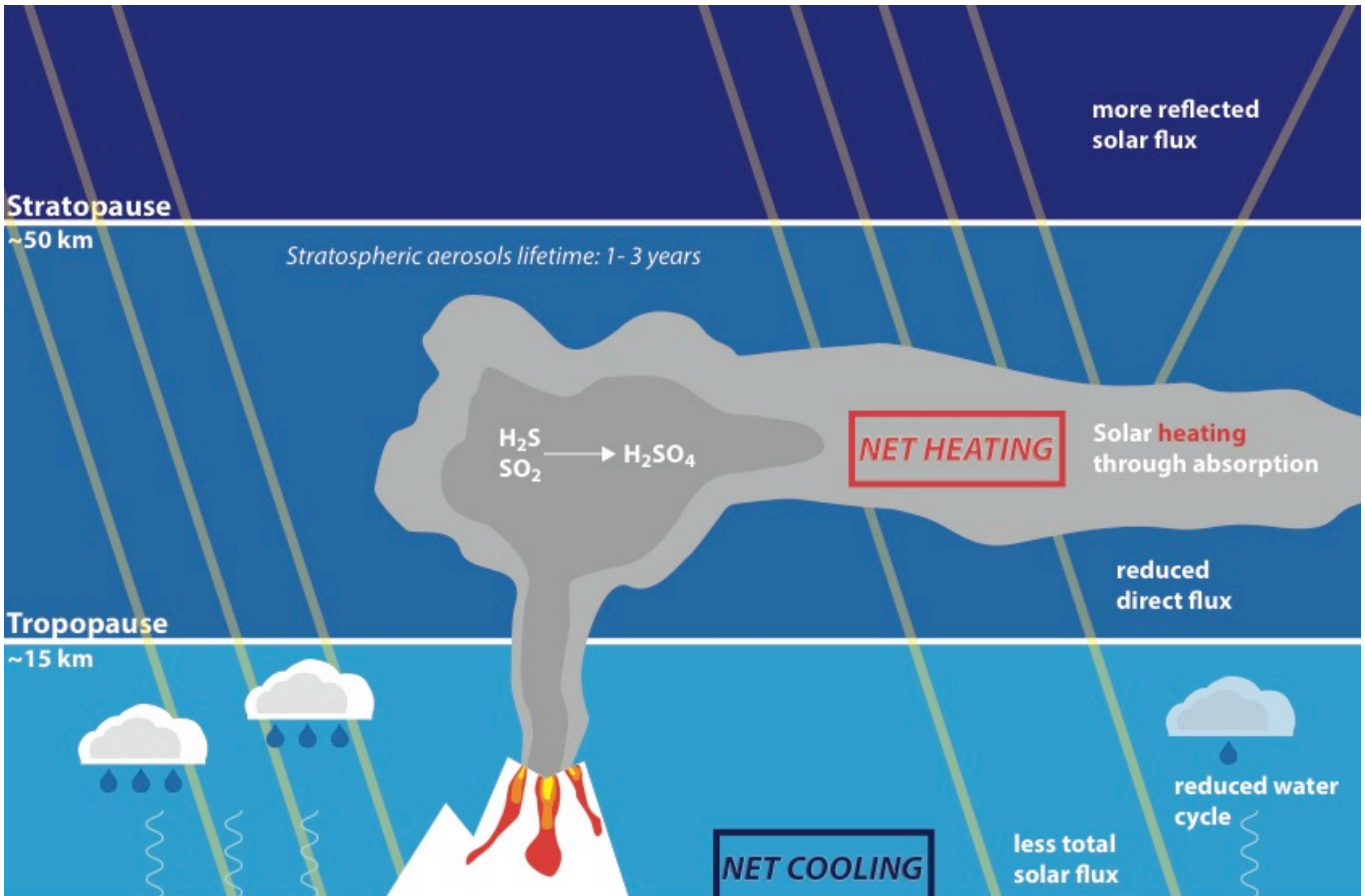
Volcanoes

- Strong explosive volcanic eruptions can lead to a multi-year long cooling of the Earth´s surface (and a reduced water cycle strength)
- Sulfurous gases have the biggest influence on the climate during a volcanic eruption. Sulfate aerosols are created from the gas by a photochemical reaction. These aerosols reflect a portion of sunlight back into space and thus cause a cooling of the Earth surface
- Location and time of year are deciding factors for the effects of a volcanic eruption on the climate.
- The greatest coolings are observed after volcanic eruptions located close to the equator. Due to the stratospheric wind conditions here, the aerosols are most able to spread out extensively in the atmosphere.

Volcanoes



Modified from Robock 2000

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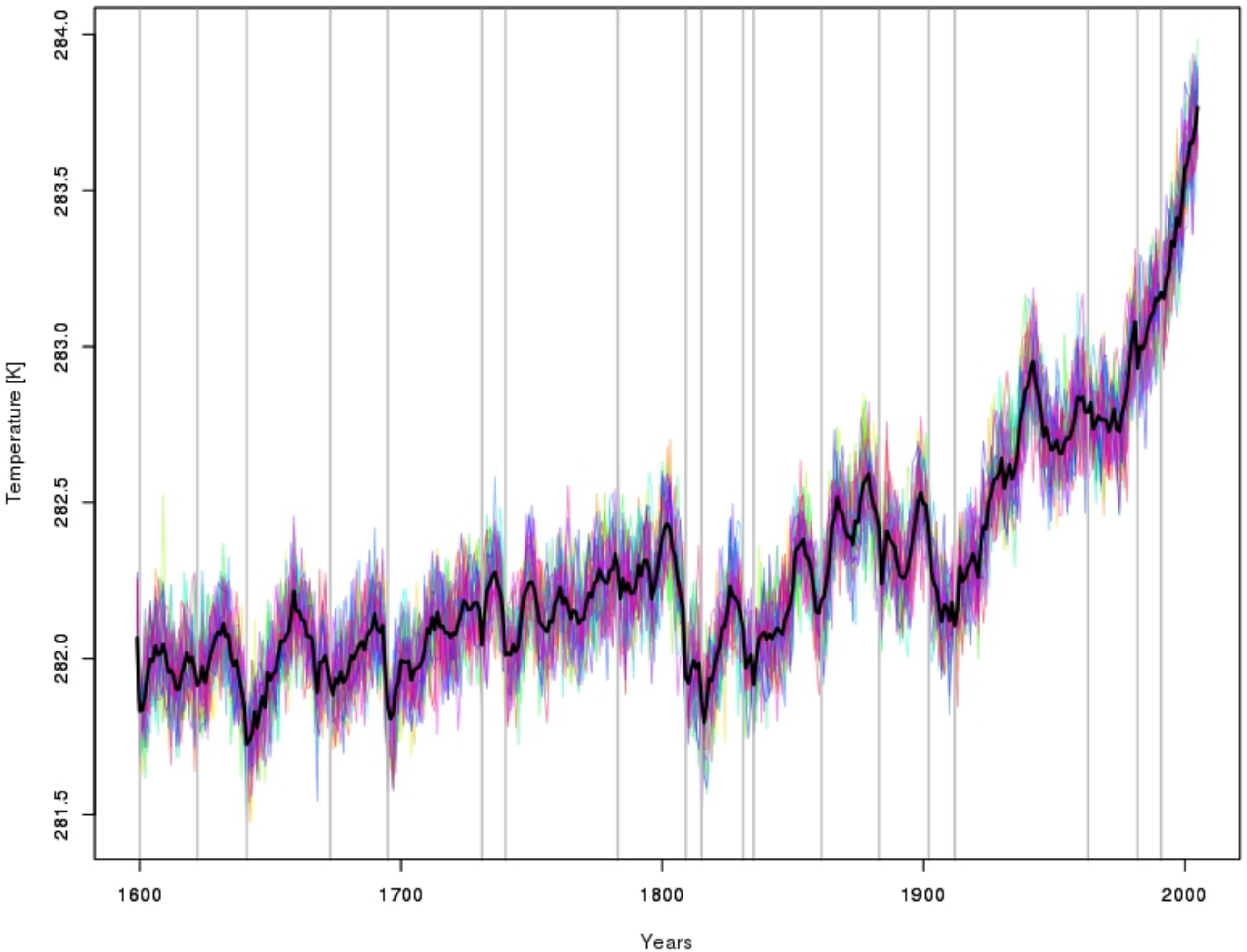
Volcanoes

Global land surface temperature timeseries from a model



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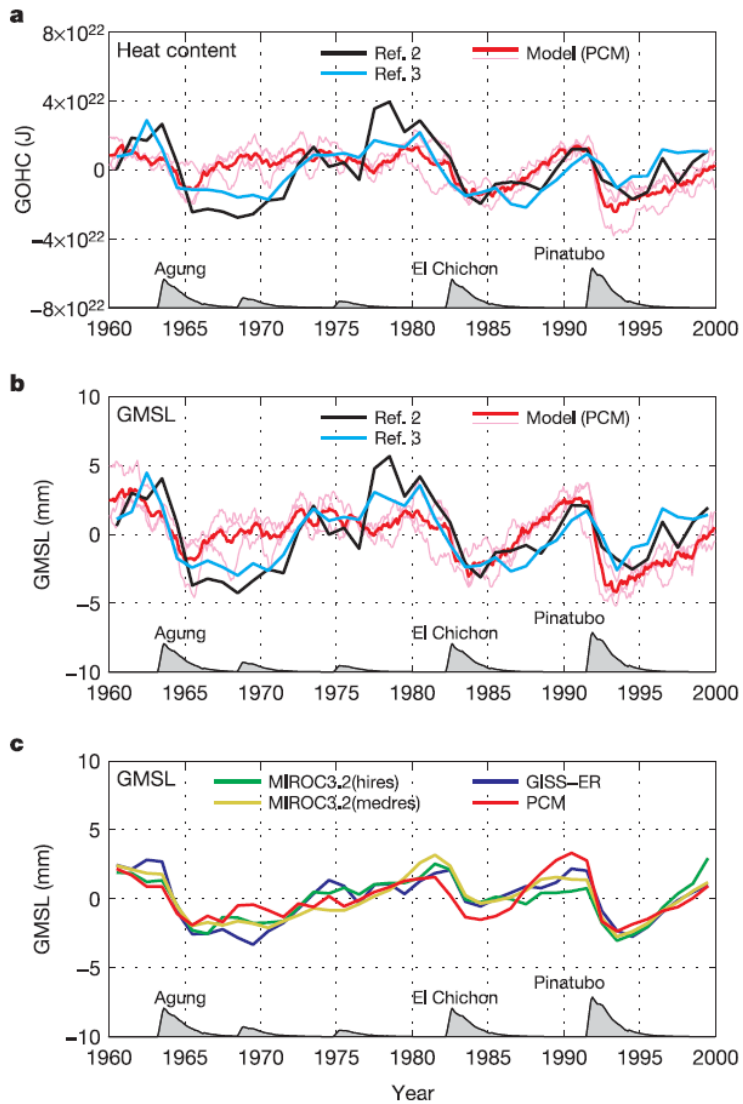
Volcanoes

Global ocean heat content in models

Global mean sea level in models

Global mean sea level in data



Church et al. 2005

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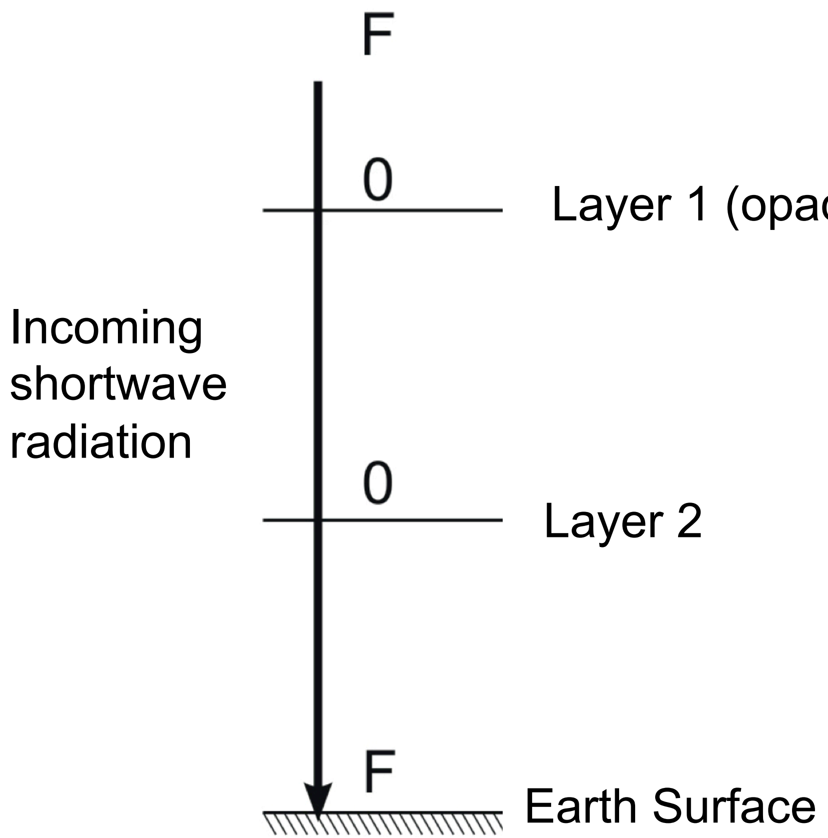
Greenhouse gases

- Without naturally occurring greenhouse gases, the Earth would be almost inhabitable with an average temperature of only -18°C. Thanks to greenhouse gases, the global average temperature is around 15°C
- The most important greenhouse gases are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3).
- Greenhouse gases in the atmosphere allow passage of incoming shortwave radiation from the sun, while blocking the escape of some outgoing longwave radiation from the Earth. As a consequence, the atmosphere is warmed.

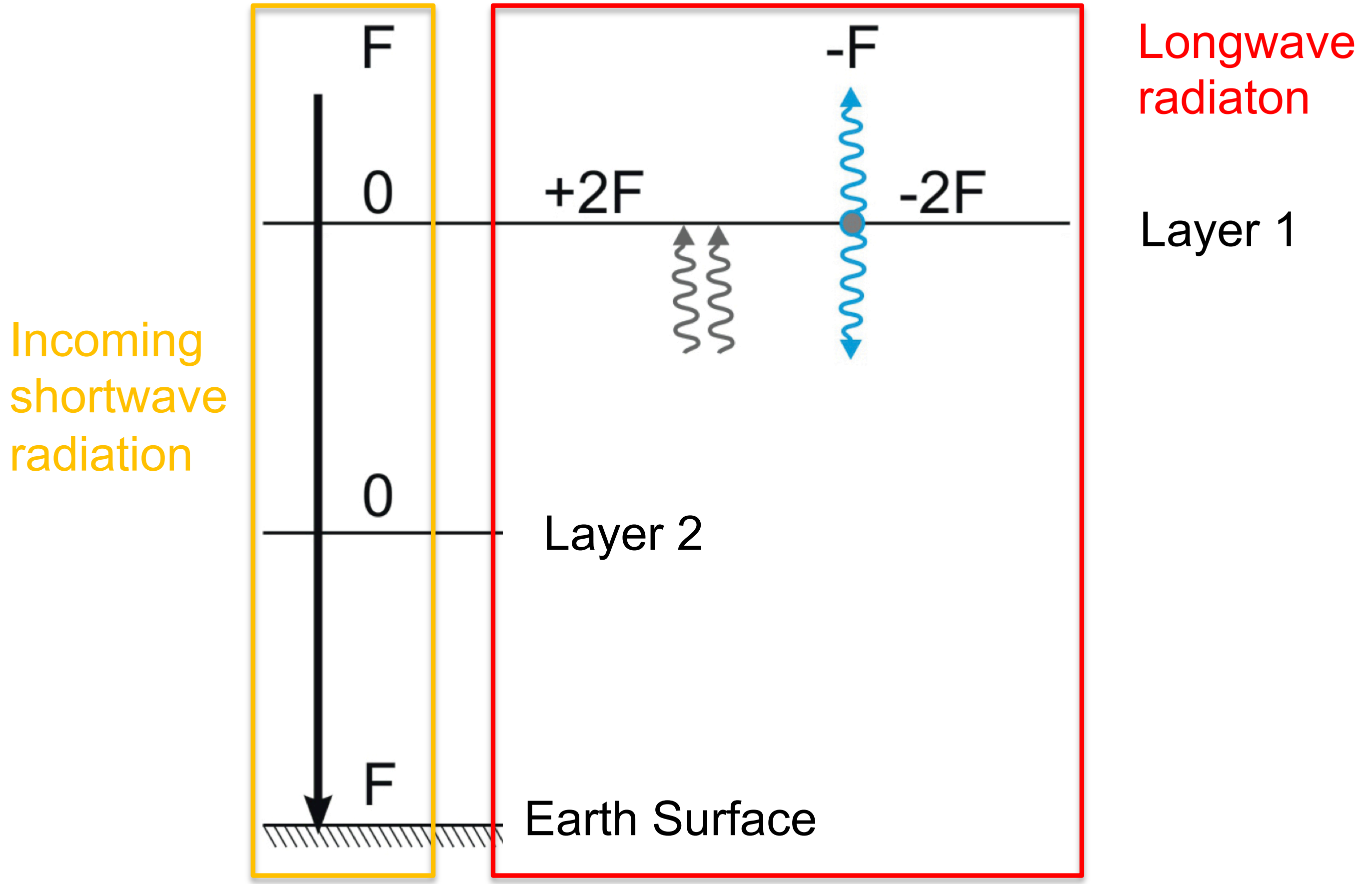
Greenhouse gases

- From radiation physics we know: Outgoing radiation must balance incoming radiation



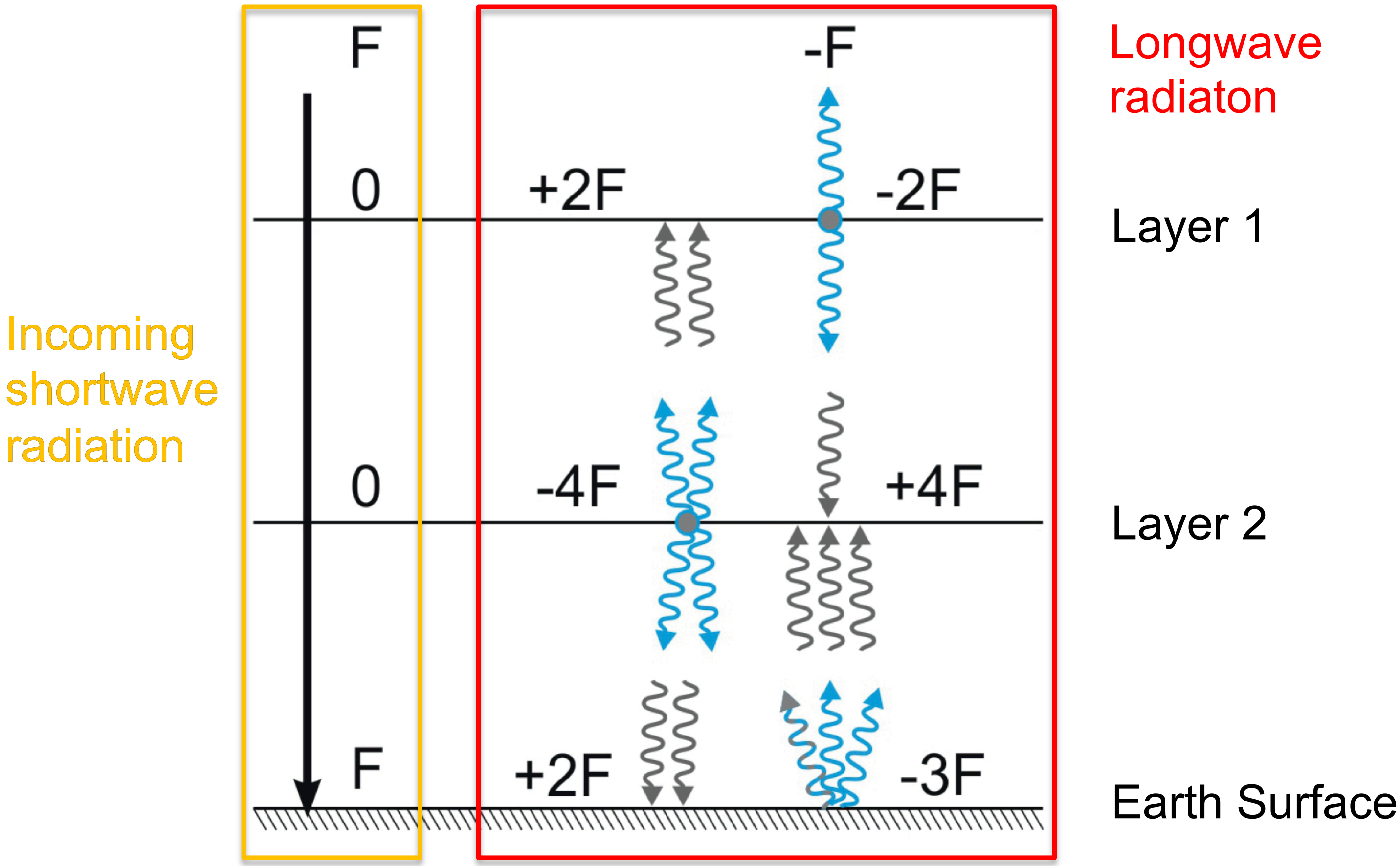
Greenhouse gases

- From radiation physics we know: Outgoing radiation must balance incoming radiation
- The GHG molecule radiates energy in all directions equally



Greenhouse gases

- From radiation physics we know: Outgoing radiation must balance incoming radiation
- The GHG molecule radiates energy in all directions equally

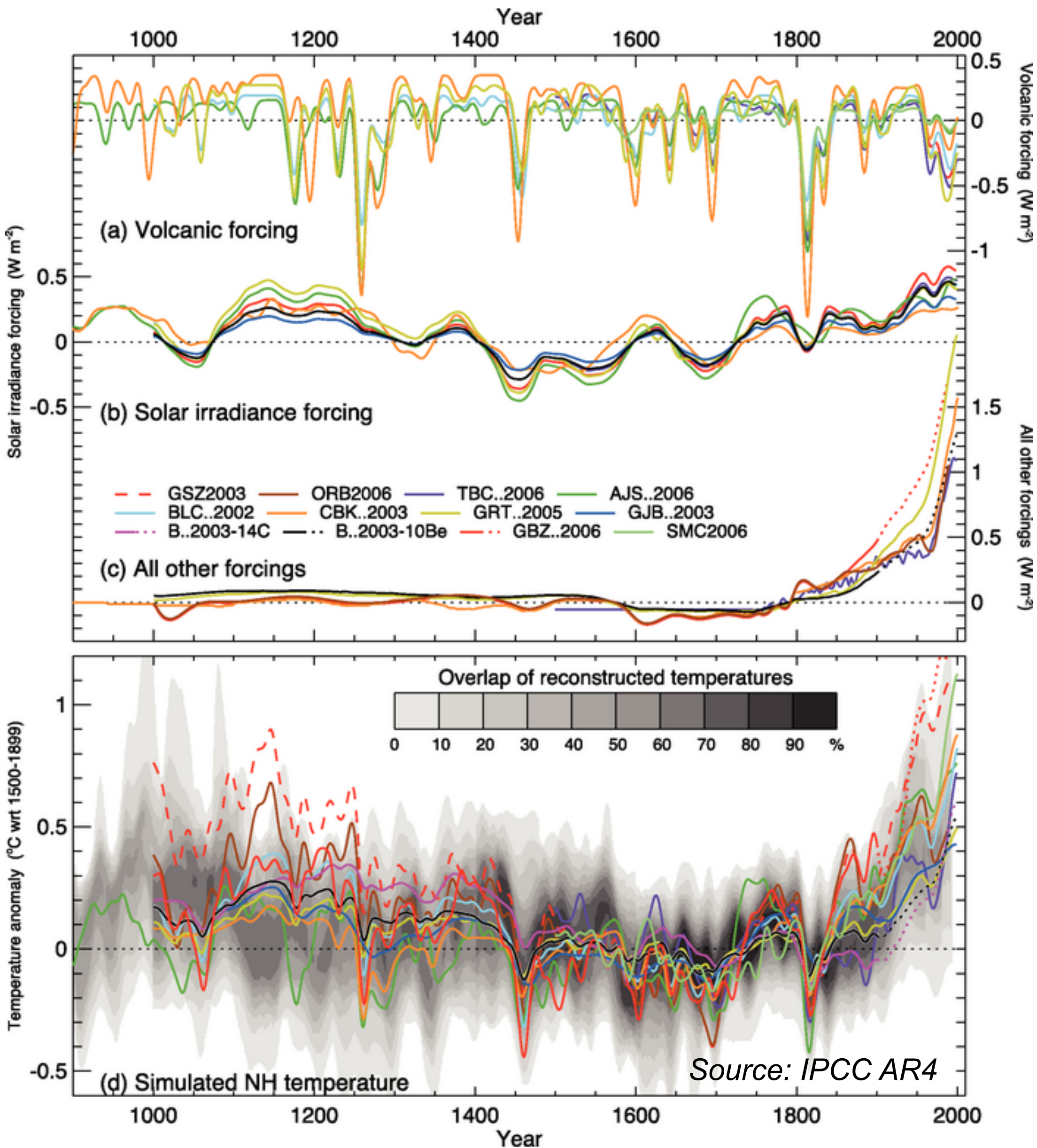


Source: Brönnimann 2015

Greenhouse gases

- Particularly strong temperature increases are observed around the North Pole. An important factor here is the ice albedo feedback: snow and ice have a high albedo (reflect sunlight).
- The Northern Hemisphere warms much stronger due to the higher amount of contintental land masses, which warm up faster than the ocean.
- CO_2 in particular is well mixed in the troposphere, so that Arctic and Antarctic ice cores are very good proxies for a global CO_2 reconstruction.

Greenhouse gases



GHG leads temperature right now.

On paleoclimatic scales, temperature lead GHG

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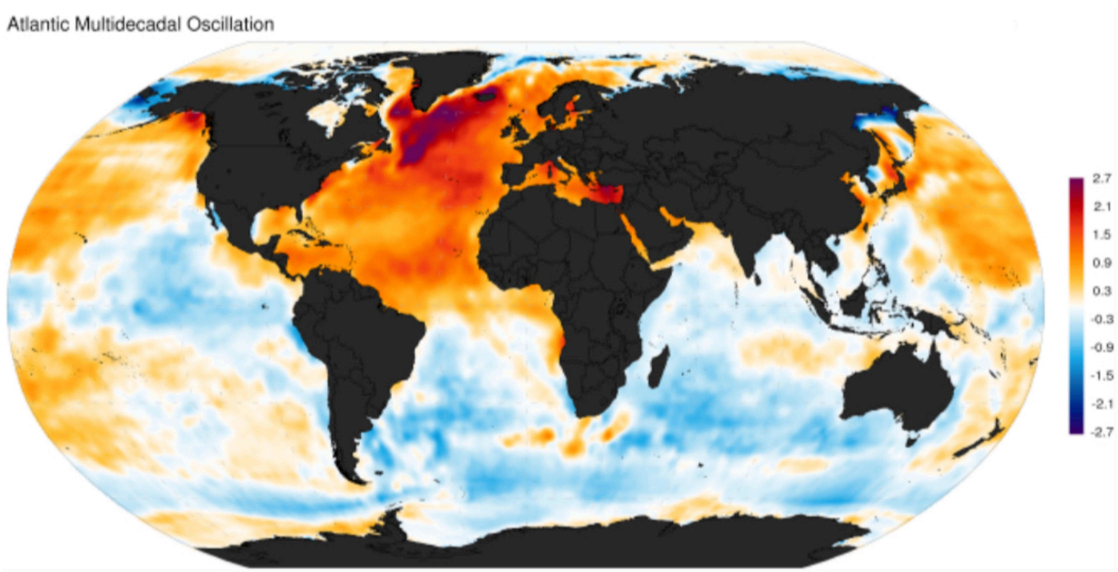
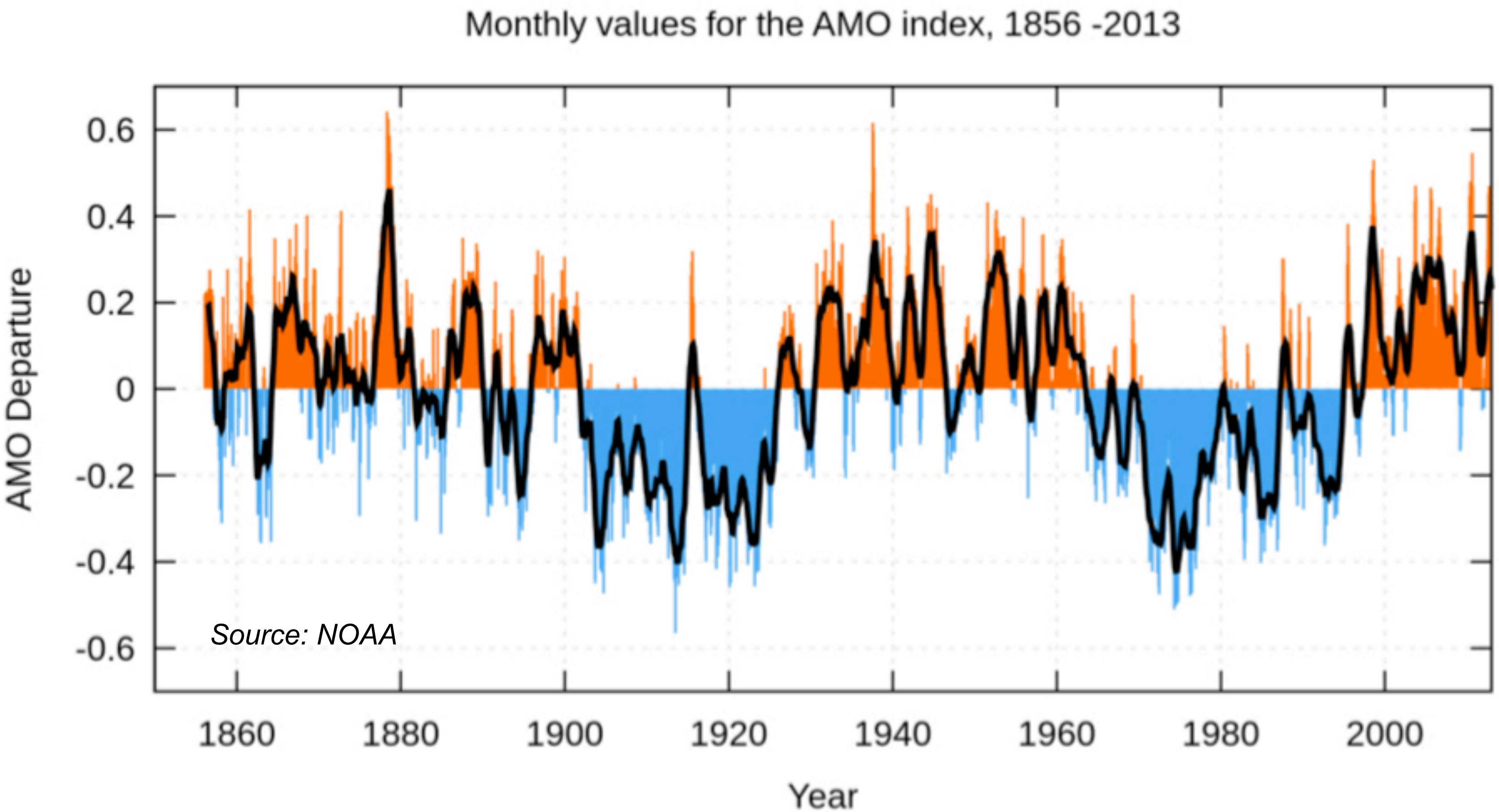
AMO

- The Atlantic multidecadal oscillation (AMO) is a mode of natural variability occurring in the North Atlantic Ocean and which has its principle expression in the sea surface temperature (SST) field.
- The AMO assumedly runs through an 70-year cycle, and its current warm phase (after peaks in 1880 and 1950) is projected to peak in 2020.



AMO

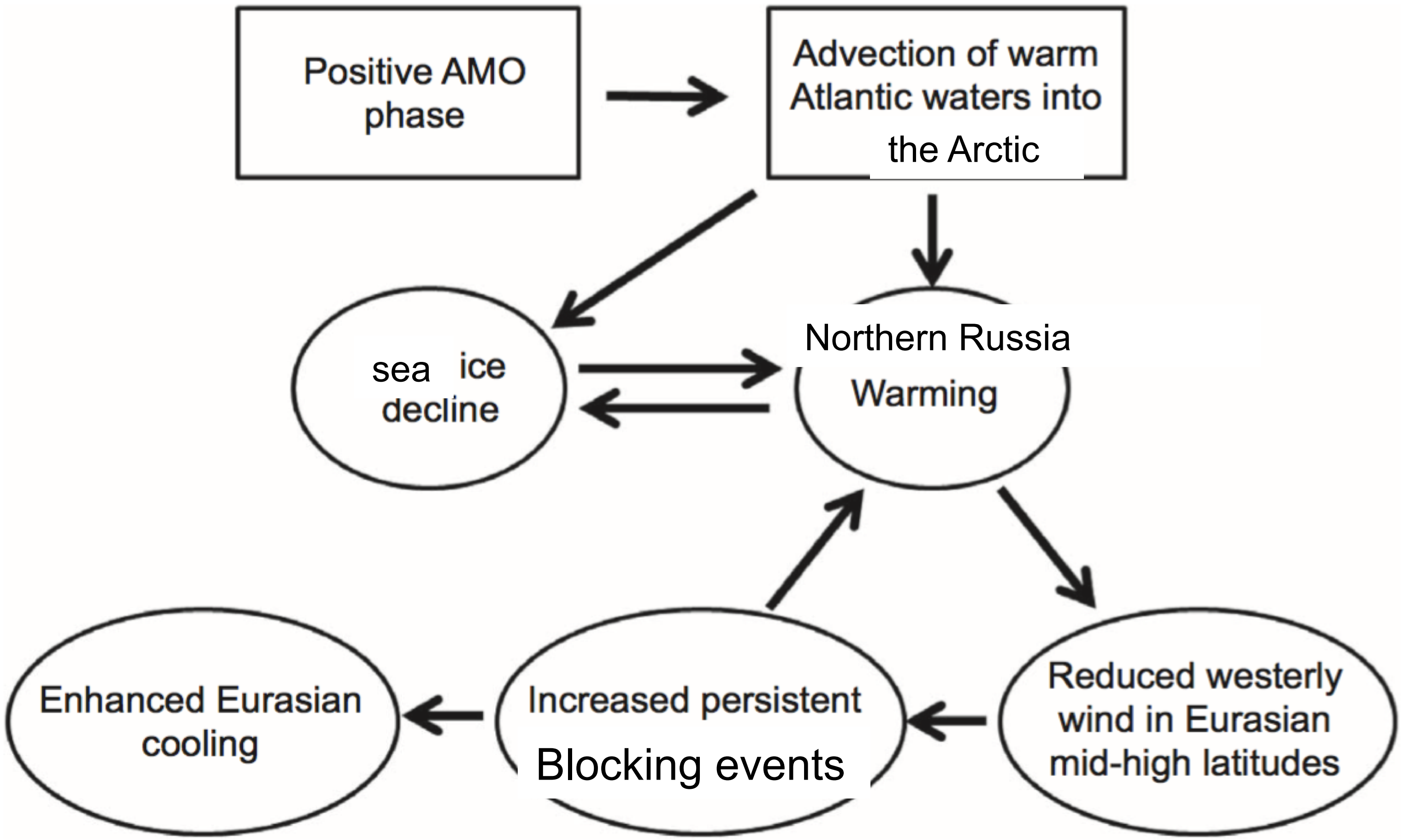


Monthly values for the AMO index, 1856 -2013
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
AMO Departure
1860
1880
1900
1920
1940
1960
1980
2000
Year
Source: NOAA

AMO

- The AMO index is correlated to air temperatures and rainfall over much of the Northern Hemisphere. Moreover, the AMO seems to be connected to cyclone activity and blocking frequency for the Euro-Atlantic domain.
- Recent research suggests that the AMO is related to the past occurrence of major droughts in the Midwest and the Southwest. When the AMO is in its warm phase, these droughts tend to be more frequent or prolonged

AMO and sea ice



Source: Luo et al. 2018

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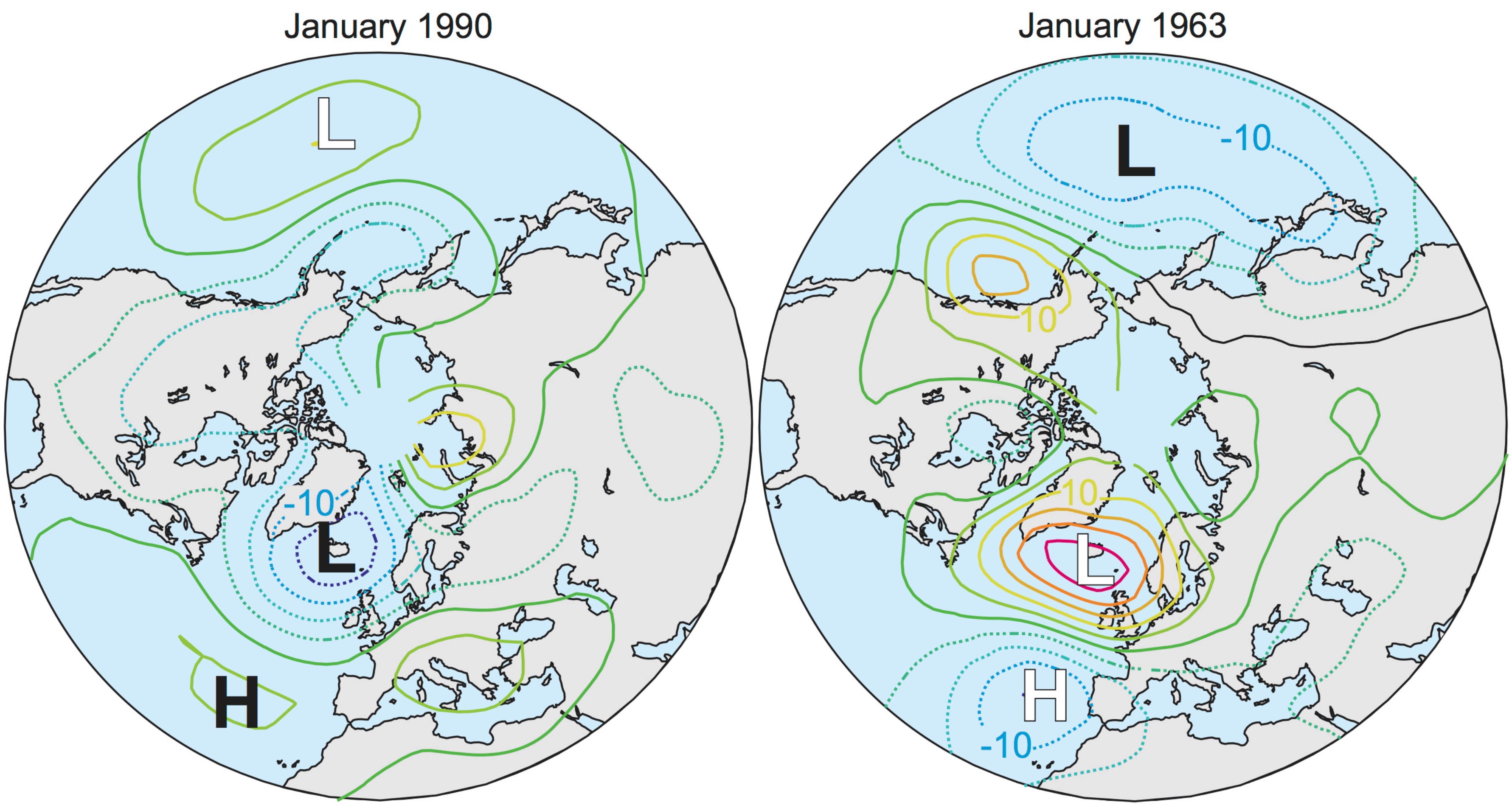
NAO

> Danish Egede Saabye wrote down 1745:
> *‚In Greenland, all winters are severe, yet they are not alike. The Danes have noticed that when the winter in Denmark was severe, as we perceive it, the winter in Greenland in its manner was mild, and conversely.‘*

NAO

- The calculation of the NAO index is based on atmospheric pressure measurements in the area around the Icelandic low and the Azores high. The measurements generally come from Iceland and Portugal (mainland or Azores).
- If the index is positive, the Iceland low and Azores high are well developed. A negative index indicates weaker pressure systems.
- The NAO is especially relevant for the climate during the northern hemisphere wintertime. A positive NAO leads to mild, moist and stormy weather conditions over the greater part of Europe. During a negative NAO, cold air masses often arrive from the northeast.
- The North Atlantic Oscillation is closely related to the Arctic oscillation (AO) or Northern Annular Mode (NAM), but should not be confused with the Atlantic Multidecadal Oscillation (AMO).

NAO



Source: Brönnimann 2015

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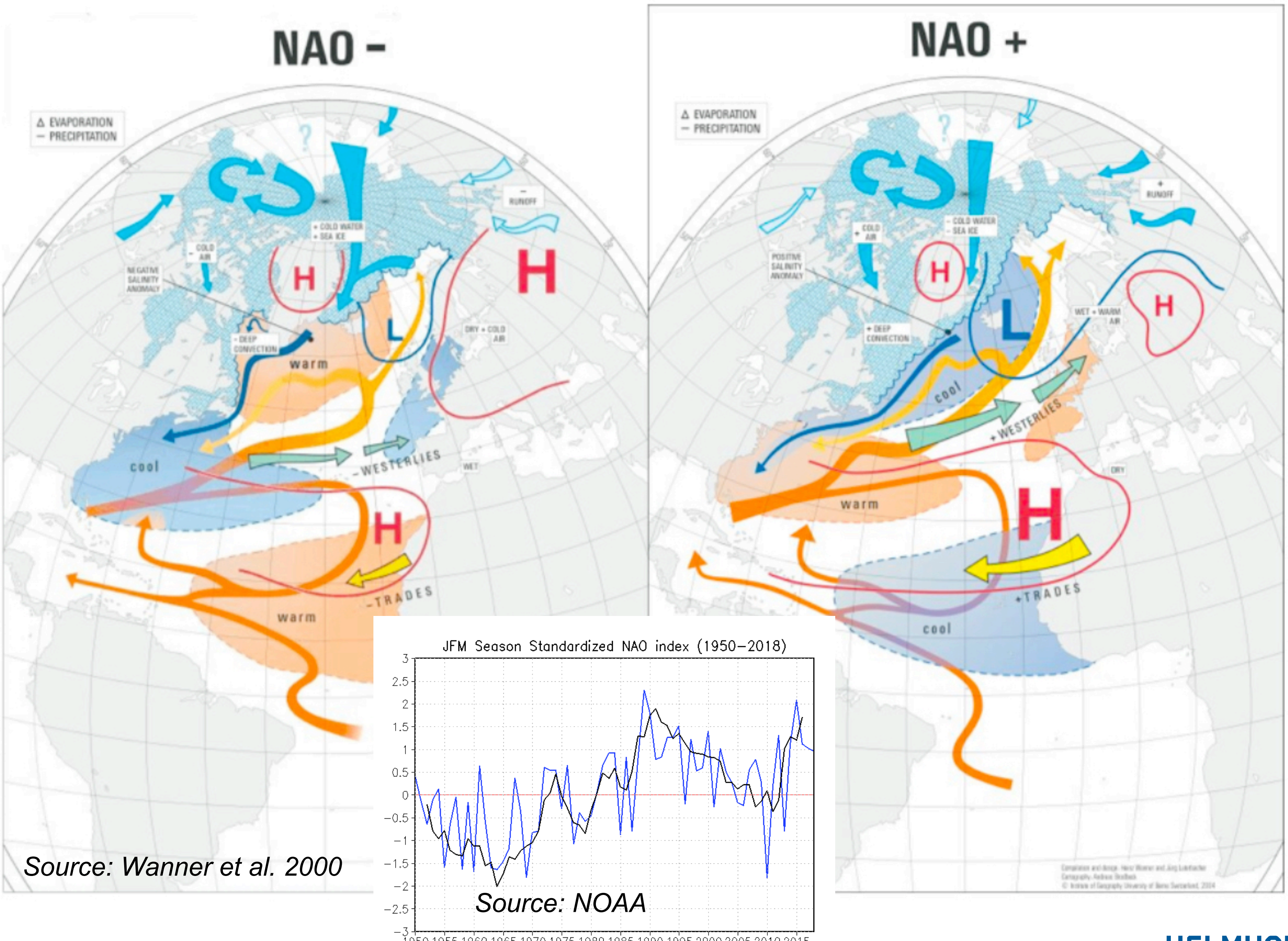
NAO



Source: Wanner et al. 2000

Source: NOAA

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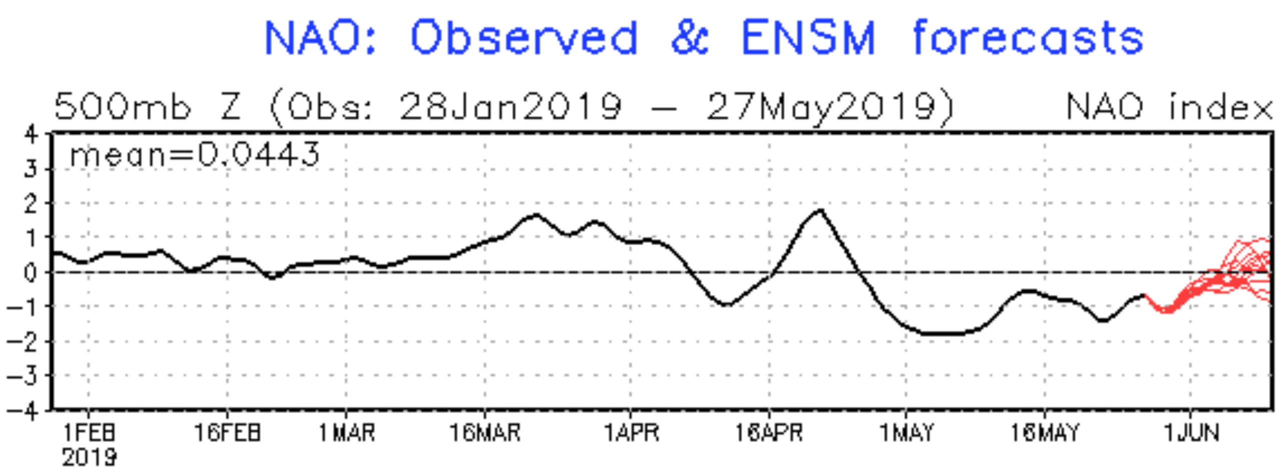
NAO

- NAO mode can be influenced by:
  - Volcanoes
  - Sea ice
  - Sea surface temperatures
  - Snow?
  - GHG?
  - Sun?
- Forecasting the NAO mode is of high societal relevance



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ENSO

"In the year 1891, Senor Dr. Luis Carranza, President of the Lima Geographical Society, contributed a small article to the Bulletin of that Society, calling attention to the fact that a counter-current flowing from north to south had been observed between the ports of Paita and Pacasmayo. The Paita sailors [...] name this counter-current the current of "El Nino", because it has been observed to appear immediately after Christmas"

1895, address to the Sixth International Geographical Congress by Senor Federico Alfonso Pezet, Lima Geographical Society

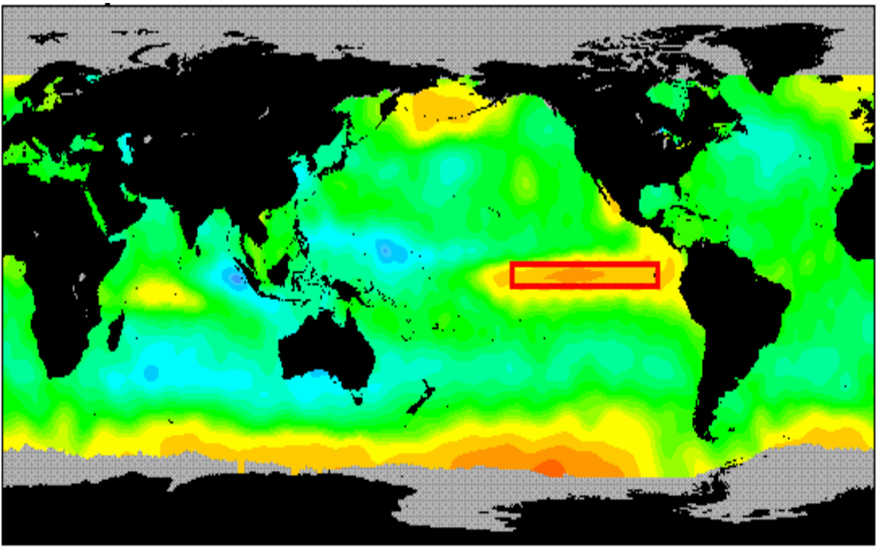
In that year (1891) [...]

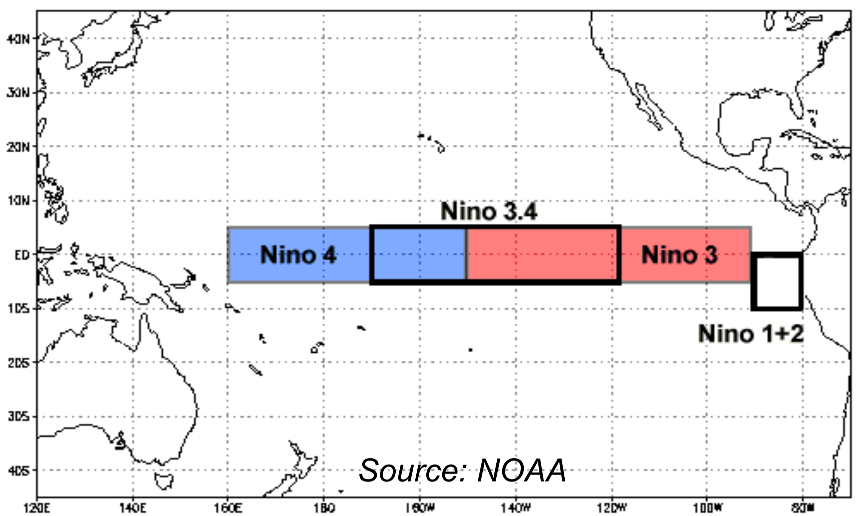
- the desert became a garden
- the soil is soaked by heavy downpour
- cotton can be grown in places where in other years vegetation seems impossible
- birds and marine life disappear temporarily

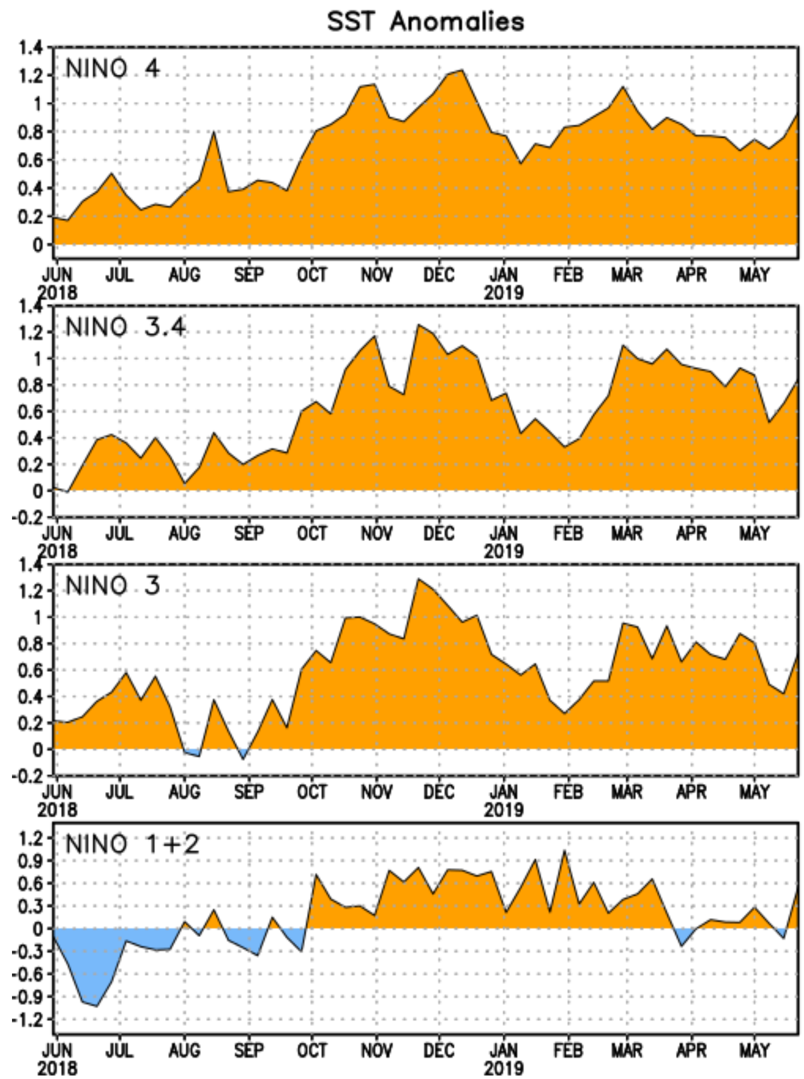
ENSO

- El Nino Southern Oscillation (ENSO), refers to the effects of a band of sea surface temperatures which are anomalously warm or cold for long periods of time that develops off the western coast of South America
- "Southern Oscillation" refers to variations in the temperature of the surface of the tropical eastern Pacific Ocean, with warming known as El Nino and cooling known as La Nina
- El Nino accompanies high air surface pressure in the western Pacific, while the cold phase, La Nina, accompanies low air surface pressure in the western Pacific. The two phases relate to the Walker circulation, discovered by Gilbert Walker during the early twentieth century.

ENSO

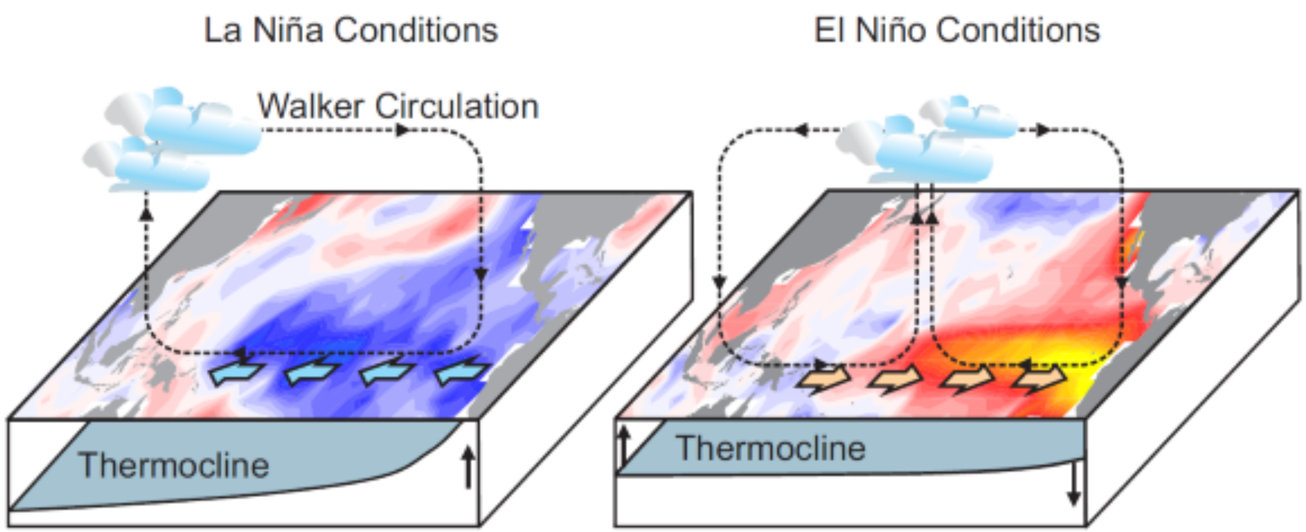



Nino 3.4
Nino 4
Nino 3
Nino 1+2
Source: NOAA


SST Anomalies
NINO 4
NINO 3.4
NINO 3
NINO 1+2
JUN 2018
JUL
AUG
SEP
OCT
NOV
DEC
JAN 2019
FEB
MAR
APR
MAY

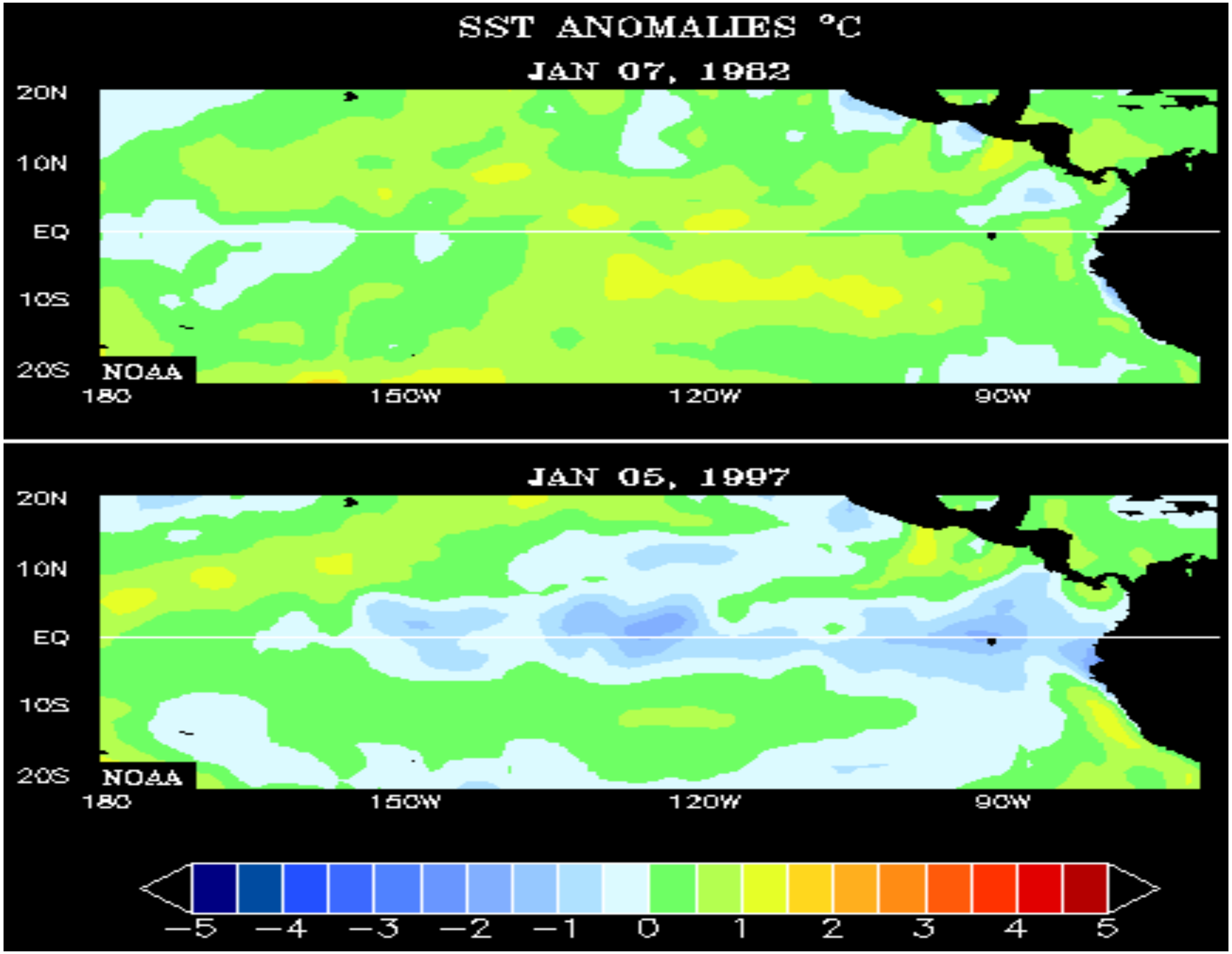
ENSO

- Walker circulation: Consists of upwelling in the region of deep convection over the warm waters of the western tropical Pacific, eastward flow along the equator in the upper troposphere, downwelling over the cool waters of the eastern tropical Pacific, and return flow as trade winds. This circulation cell is called the "Pacific Walker cell"



Source: Brönnimann 2015

ENSO



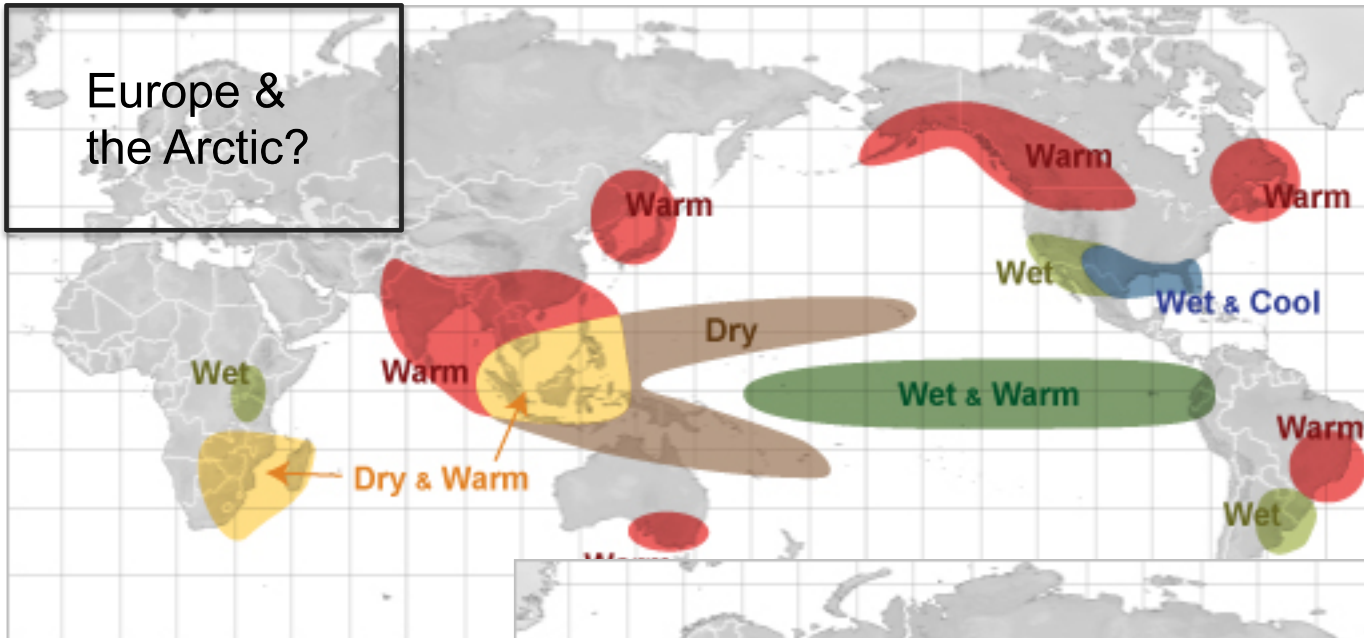
Source: NASA

ENSO

- ENSO can thus be seen as the result of coupling a positive (stabilizing) feedback with an oscillatory oceanic mode. Since ENSO also affects the local Hadley cells, it affects not only the tropics but also the extratropics.
- Mechanisms that cause the oscillation remain under study (includes Kelvin Waves). The extremes of this climate pattern’s oscillations cause extreme weather (such as floods and droughts) in many regions of the world.
- ENSO is considered the most important variability mode. The effects of La Niña and El Niño modes are global, and their effects vary from boreal winter (December-February) to boreal summer (June-August).

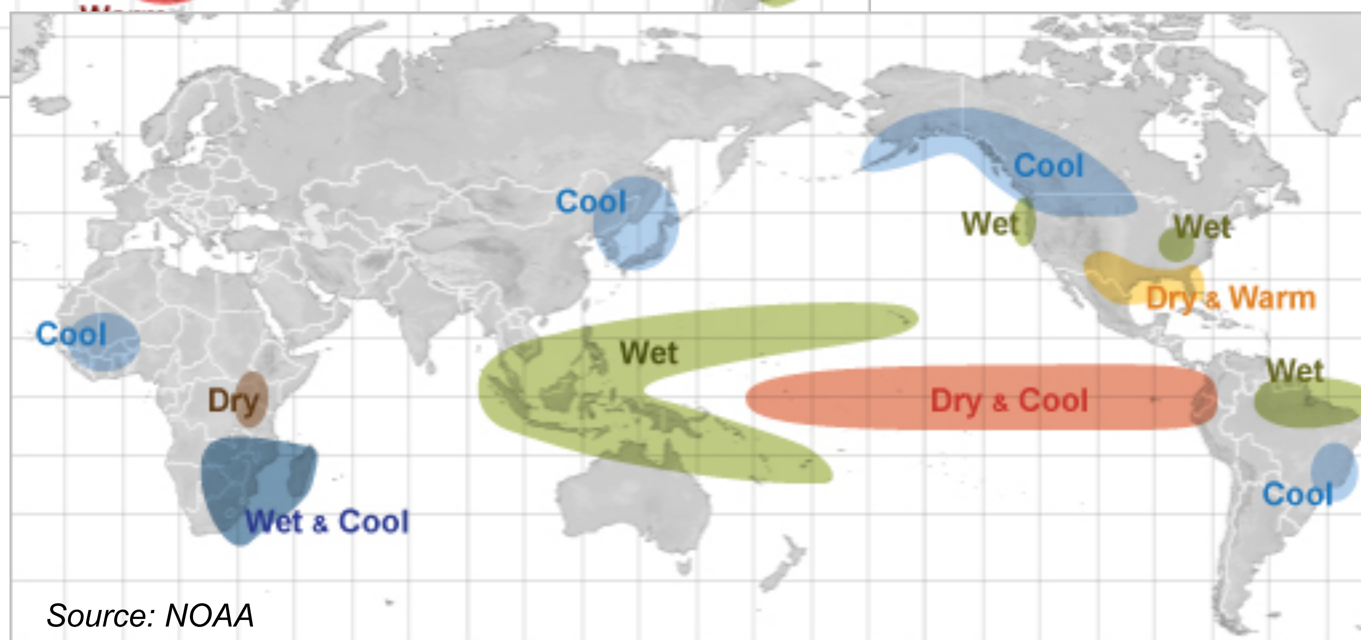
ENSO

Europe & the Arctic?



← El Nino in winter

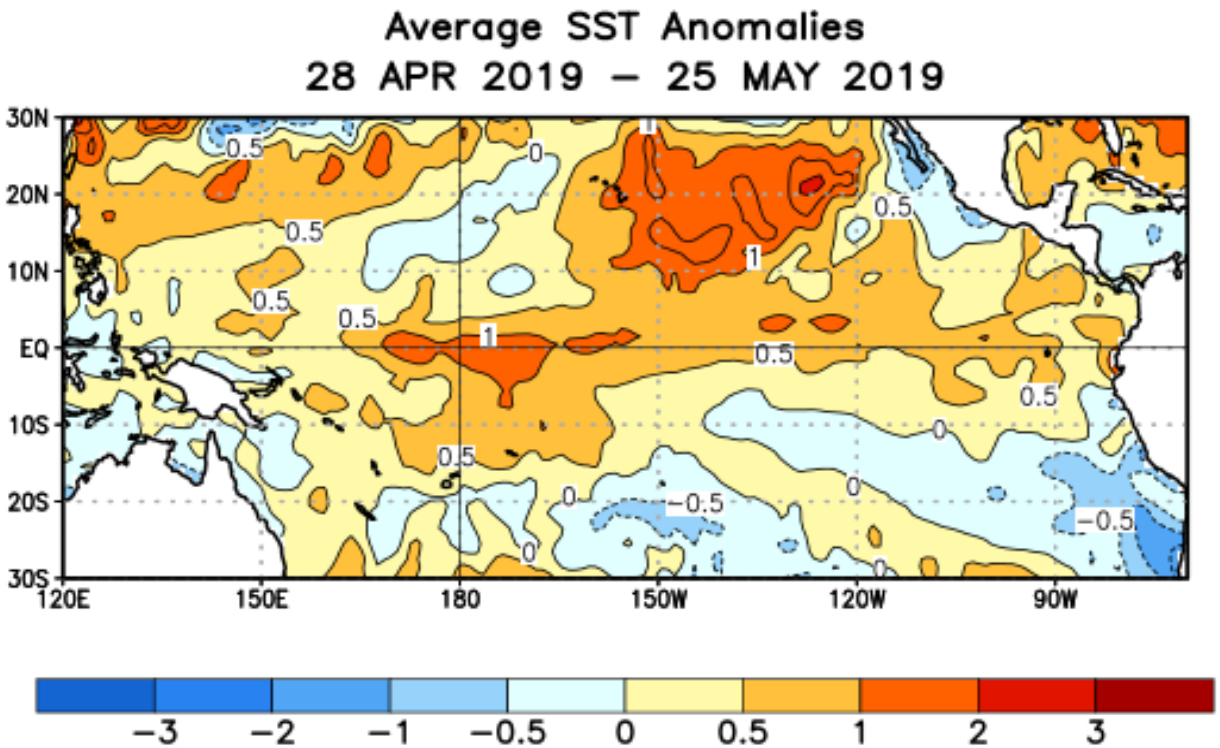
La Nina in winter →



Source: NOAA

ENSO now

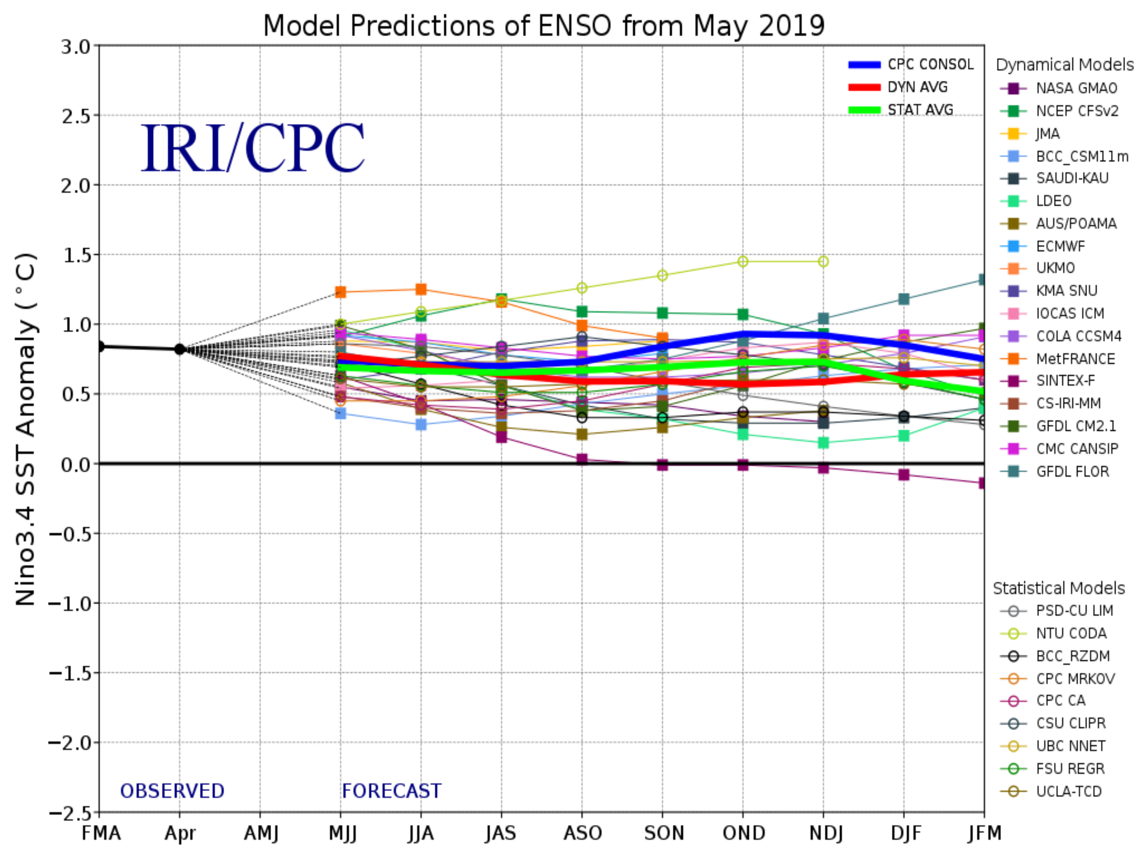
During the last four weeks, equatorial SSTs were above average across most of the Pacific Ocean, with the largest departures near the Date Line. SSTs were near-to-below average around Indonesia.



Source: NOAA

ENSO now

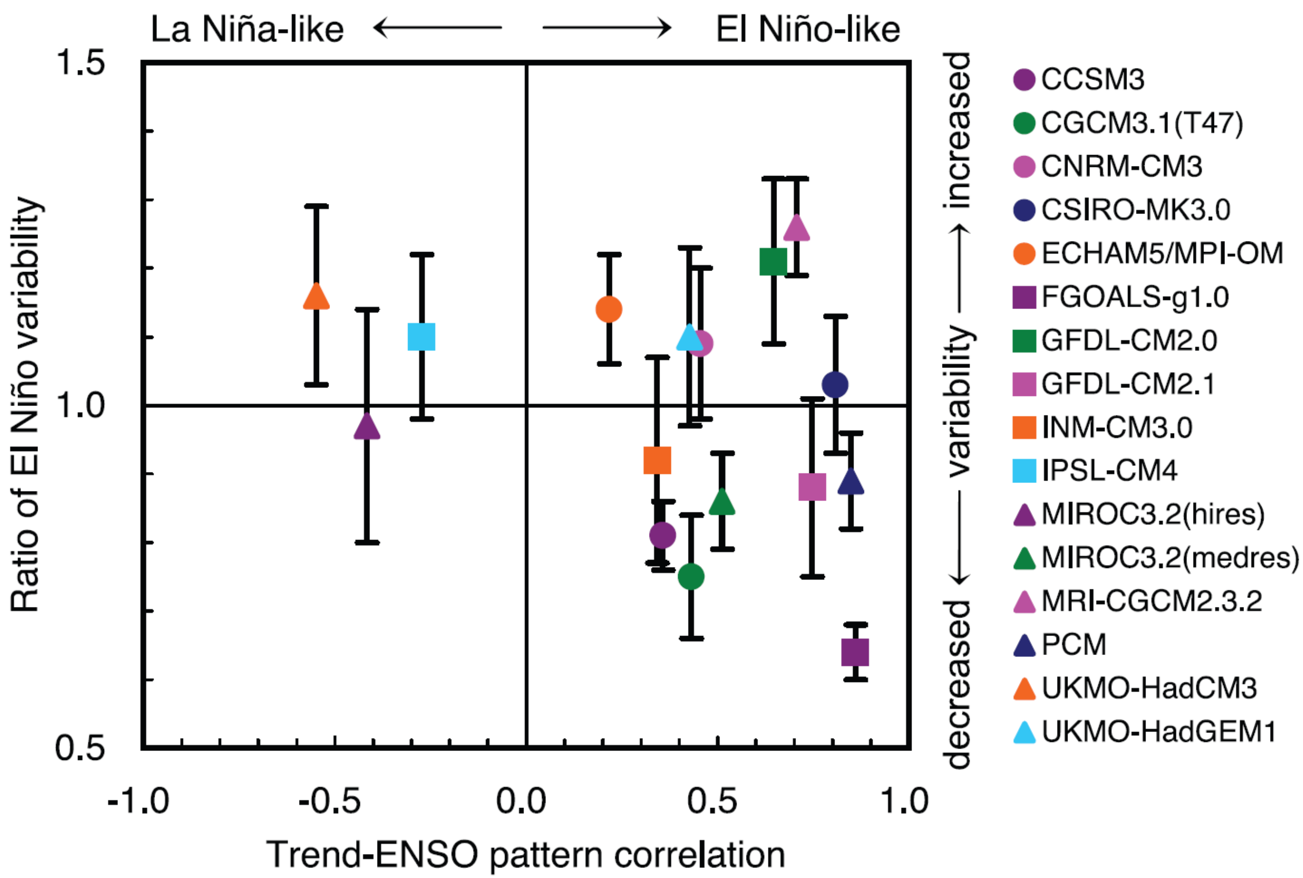
The majority of models predict a weak El Niño to continue into the Northern Hemisphere winter 2019-20.



Source: NOAA

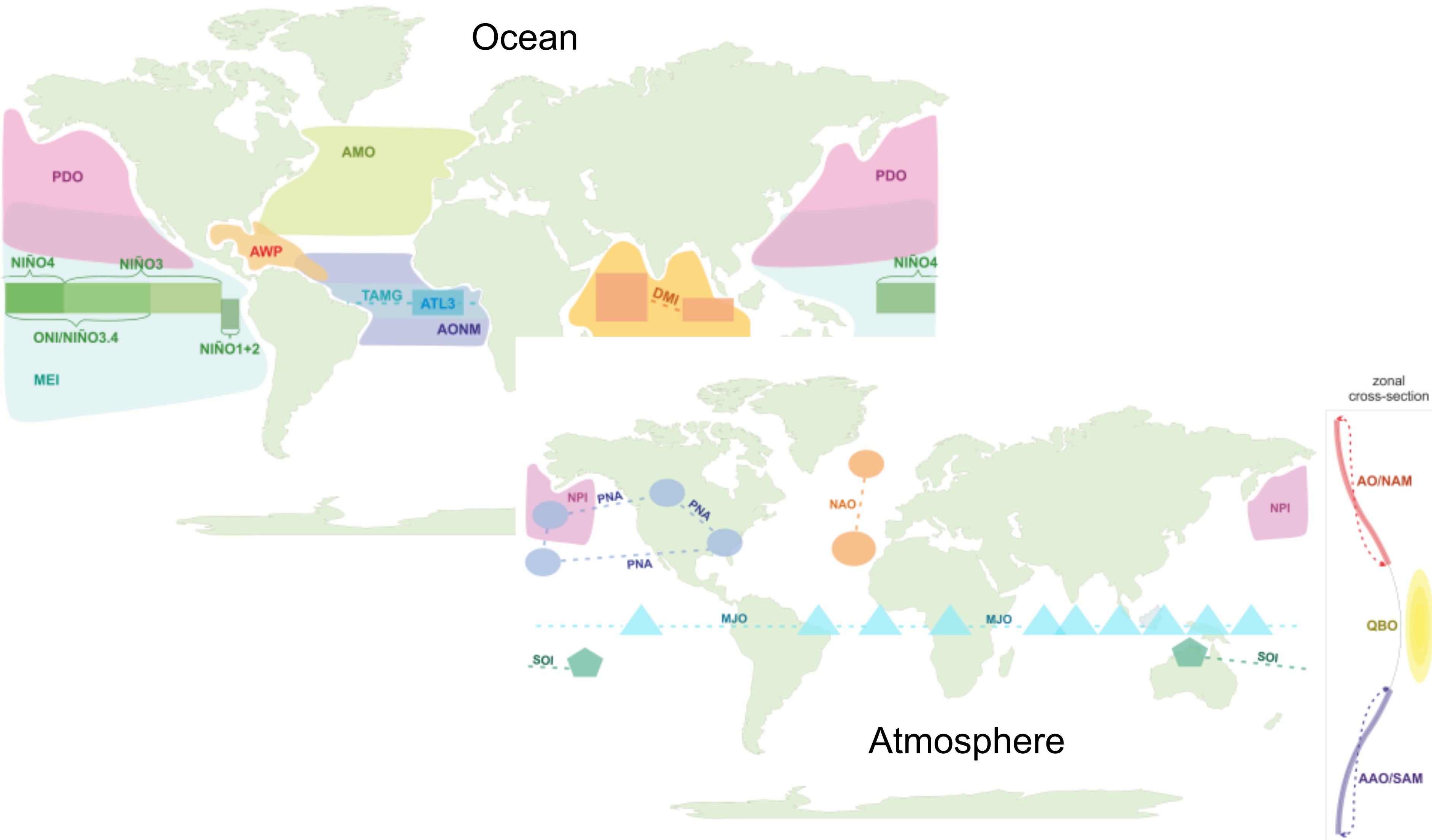
ENSO now

Will ENSO frequency change with AGW?



Source: IPCC AR4

More modes



Source: Alena Giesche, Climandes, University of Bern

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