MAST602

Lecture 3

Oceanic balance of heat, salt, & water

Seasonal heat storage
Heat advection
Salt & water balance
Sea ice
Global heat balance
Interannual climate variability: El Niño & La Niña

MAST 602

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Steady state

Ref.: Knauss, Chapter.3

Where does the heat go in the ocean?

= Globally, it's almost trivial:
conservation for steady state is
heat in = heat out
or,

$$\int_{\text{globe}} \text{heat in} = \int_{\text{globe}} \text{heat out}$$

We can write the same thing for salt and water:

$$\int_{\text{globe}} \text{salt in} = \int_{\text{globe}} \text{salt out}$$

$$\int_{\text{globe}} \text{water in} = \int_{\text{globe}} \text{water out}$$

If these relations don't hold,
there will be long-term change.

i.e., change =
what goes in - what goes out.

Let's return to heat.
We had, averaged globally,

$$Q_s = Q_b + Q_e + Q_h$$

This only holds for all
the ocean's surface, s,
and over at least a year, t :

$$\int_t \int_s (Q_s - Q_b - Q_e - Q_h)\, ds\, dt = 0$$

But, locally, we know that heat is

- transported, by ocean currents
- gained in low latitudes
- lost in high latitudes
- stored in the surface layer in summer
- released to the atmosphere in winter

Thus, for local or short-term processes,
we need additional terms
in the heat equation:

$$Q_s = Q_b + Q_e + Q_h + Q_T + Q_v$$

Q_T = heat warming the ocean (storage)
Q_v = heat transported away (advection).

Seasonal heat storage, Q_T

The upper meter of the ocean
absorbs > 50% of incoming energy.
Less than 1% reaches 100m,
even in clear water.
As a result of energy absorption,
the surface layer undergoes
a temperature cycle.

The heat available is

$$\int_0^t Q_T \, dt = \int_0^t (Q_s - Q_b - Q_e - Q_h - Q_v) \, dt$$

Thus, over a layer *z* and a time *t*:

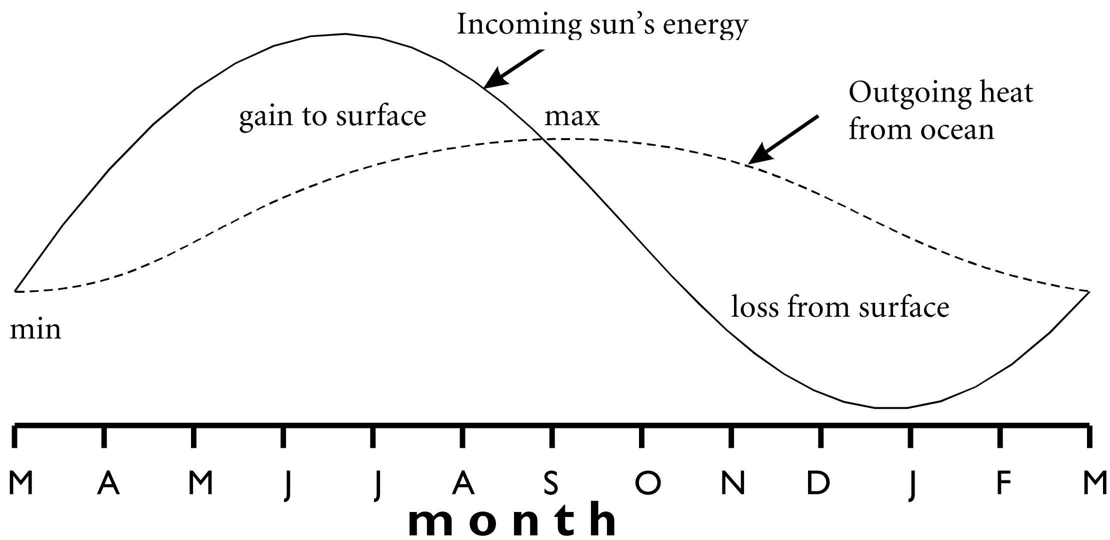
$$\int_0^t Q_T \, dt = \int_0^z c_p \, \rho \, \Delta T \, dz$$

c_p is the specific heat of seawater
ρ is the density of the water in the layer
ΔT is the temperature change in the layer

Alas, the ocean is too complex
to determine ΔT.
We must resort to observation,
or simple models.

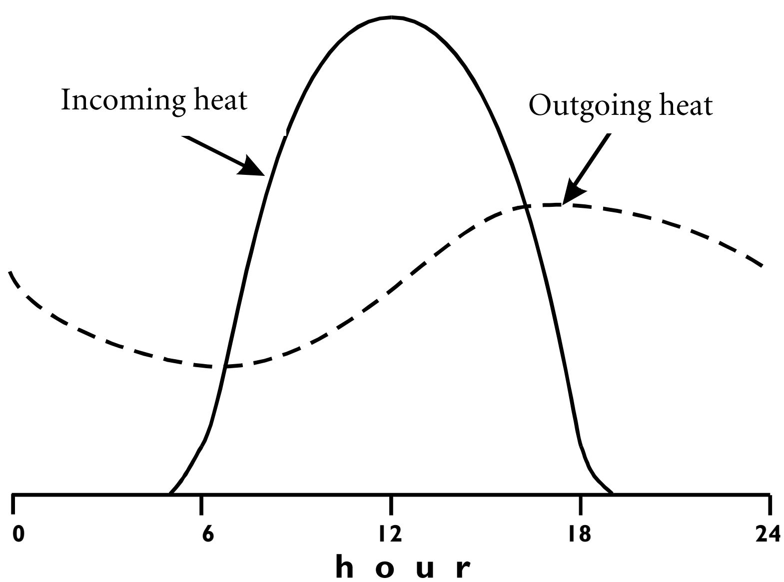
Annual & daily cycles

Fig 3- 1 The annual N. Hemisphere cycle of ocean surface heating



Why is there so much time lag between the maximum of incoming energy and the maximum of stored heat in the surface?

Fig 3- 2 The daily cycle of ocean surface heating



Note the similarities (and differences) between the daily and annual curves.

Incoming heat is absorbed over a few meters.

There's a net loss of heat to the atmosphere
in the upper millimeter of the ocean

Observations show how this works.

Fig 3- 3 Seasonal temperature cycle in the upper ocean **KNAUSS, Fig. 3.8**

Why does the vertical gradient of temperature
become so intense in late summer?
Why so weak (or nonexistent) in late winter?

The *seasonal thermocline*:

- develops during the summer
- mixes down due to wind
- the stronger the thermocline, the more stability
- as summer progresses, becomes shallower and stronger
- weakens in fall, as the daily loss exceeds the heat gain
- is driven deeper in fall, as it becomes less stable and as winds increase

General seasonal thermocline properties:

Summer	*Winter*
shallow	deep
strong	weak

The seasonal thermocline disappears in late
winter (February) and the cycle restarts.

How deep can the *surface mixed layer* get?
usually, ~ 100m;
sometimes as deep as 200m.

A *diurnal thermocline*

- develops during the day
- can mix down a few meters
- can mix and cool during the night
- often persists for many days
- may have a depth ~10 m $\Rightarrow$ 20 m

Fig 3- 4 Growth and decay of the diurnal thermocline **Knauss, Fig. 3.10**

Do you see any similarities with the annual
thermocline?

The surface cools by radiation
from a thin skin at the surface

This surface cooling sets up
a gradient of heat from below
to the surface

The cooler, denser surface water
easily mixes downward

Advection of heat, Q_V

Ref. Knauss, Chapter 4

Recall that there is a net energy input
equatorward of ~40°
and a net loss poleward of ~40°.

If there is no long-term temperature change,
there must be a transport of heat
from the tropics poleward:

$$\int_0^t Q_v \, dt = \int_0^t (Q_s - Q_b - Q_e - Q_h) \, dt$$

We can disregard the term Q_T because

$$\int_0^t Q_T \;\; dt \cong 0$$

over a time long with respect to
the annual cycle

We can see estimates of Q_v
determined by Budyko:

Fig 3- 5 Heat flux from the ocean surface to underlying water (Budyko 1974), Fig. 35

What do the large negative values signify?
Why are there no intense positive values?

Later North Atlantic work by Bunker
is more precise:

Fig 3- 6 Annual average net surface heat flux into the ocean (Gill 1982), Fig. 2.7

What do the large negative values off
Delaware signify? What processes
account for them?

The heat flux from the surface to the
underlying ocean is equivalent to
the flux in and out of the region, Q_v

What does the flux, Q_v correspond to?
= ocean currents, e.g., the Gulf Stream.

There is, in general a poleward flux of
heat at the surface in all the ocean basins.

Fig 3- 7 Northward transport of energy (Gill 1982), Fig. 1.8

Why is the oceanic northward transport of
energy a maximum at about 30°N?

Salt and water balance

Water and salt are conservative

Water

Evaporation of 1.26 m yr^{-1}
$\Rightarrow$ 450 × 10^{12} m^3 yr^{-1}
or 0.03% of the ocean.

This evaporation is replaced
by rainfall (90%)
and river runoff (10%).

Evaporation at the surface increases salinity.

97% of Earth's water is in the ocean
2% is ice: polar ice caps, icebergs, glaciers
(3/4 of fresh water is in the form of ice)
Only 0.02% is in lakes and rivers

[note error on p 64 of Knauss: volume of fresh water is 360,200,000 km^3]

Salt

Evaporation at the sea surface
leaves salt behind, increasing salinity

Rain dilutes seawater, decreasing salinity
Rivers dilute seawater near their mouths

Rivers bring in ~ 3×10^{12} kg
of dissolved solids per year
~10^{-7} of total salt in the ocean.

(It would take about 500 years
to detect the change in salinity.)

Sea Ice

Ice covers ~6 ⇒ 8% of the ocean

Ice-covered regions have high albedo
and ice is a barrier to the penetration
of solar radiation; which is absorbed
in the upper few millimeters of ice

Since ice is always colder than the water
below, heat conduction is always
from water to ice.

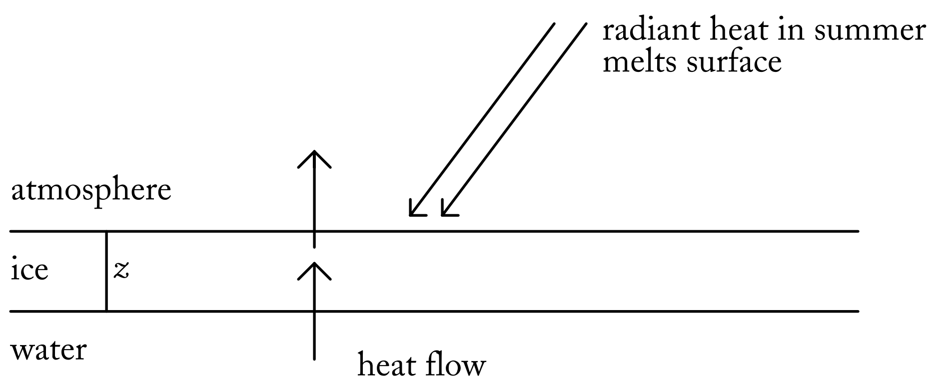


Fig 3- 8 Schematic of heat flow through ice

Why is the heat flow shown as being upward? Can heat penetrate at all into the ocean below the ice?

Ice thickens in winter,
thins in summer:

$$\frac{\partial z}{\partial t} = \frac{Q_h}{C_f\ \rho}$$

where
z is the ice thickness
Q_h is the sensible heat loss
C_f is the latent heat of freezing
0.335 x 10^{-6} J kg^{-1} @ 0°C
ρ is the density of ice
~917 kg m^{-3}

and

$$Q_h = k_i \frac{\Delta T}{z}$$

where
k_i is the thermal conductivity
~ 5.5 × 10^{-3} cal deg^{-1} cm^{-1}s^{-1}

so that

$$\frac{dz}{dt} = \frac{k_i}{\rho c_f} \frac{\Delta T}{z}$$

Assume the temperature at the
lower boundary of the ice is 0°C.

We can integrate…

$$z \approx \left[\frac{2k_i}{\rho c_f} \int_{t_1}^{0} \Delta T\, dt \right]^{\frac{1}{2}}$$

we can put

$$\chi = \int_{t_1}^{0} \Delta T\, dt = \text{"cold degree days"}$$

so that $z = 0.036\ \chi^{1/2}$ m

[Observations show that this formula
tends to over-estimate ice thickness.]

Halocline

In ice-covered regions, a
halocline occurs near the surface,
analogous to the thermocline.

Fresh water, recall, has its maximum
density above the freezing point,
but seawater above $S = 24.7$ increases
in density with decreasing temperature

Why isn't all the water (down to the
bottom) in such regions cooled
down to the freezing point?

= Because a layer of less saline (lighter)
water (the *halocline*) sits above
denser, more saline water
in ice-covered regions.

This layer freezes without becoming
denser than the water below.

A typical halocline depth is 50 – 200 m

Sea-ice formation freezes the fresh water,
leaving behind pockets of brine

Salt-enriched water can sink and mix
with water below the halocline

Global heat balance

On average, there's an energy balance
over the globe.

Fig 3- 9 Global average components of Earth's energy balance (Trenberth 1992), Fig 1.2

Fig. 4.1 in KNAUSS is similar, but does not
show the two-way back radiation
between Earth and atmosphere.
There is also a figure on page 17 of the
Units & Values paper handed out at the
beginning of the semester showing the
values in W m^{-2}

> *The values are approximate, global, long-term averages. There is considerable climate variability. The differences in the values between the figures reproduced here and those in* KNAUSS *probably reflect uncertainty in estimating the global averages.*

From this figure, we note that:

- 45 % of solar energy is absorbed by Earth's surface
- Albedo of Earth is 30% (5% + 25%) [as seen from space]
- Albedo of Earth's surface is 10 %
- The atmosphere is heated by the earth, not the sun
  25 % is absorbed directly from the sun
  129 % (100% + 5% + 24%) is taken up from the earth
- At Earth's surface back radiation exceeds incoming radiation
  104 % vs. 45 %
- Earth's surface receives more heat from the atmosphere than from the sun
  88 % vs. 45 %
- Evaporation is the largest term in the ocean-atmosphere heat transfer

These results are based on global averages; there can be enormous regional variability

They also assume a long-term stability and there can be variability in time.

Climate variability has been a subject of intense recent study i.e., El Niño & La Niña

Year-to-year variations (interannual climate variability)

El Niño/Southern Oscillation (ENSO)
is the prime example of
interannual climate variability

ENSO is an ocean-atmosphere phenomenon

- involving heat storage in the upper ocean
- anomalous warming in the eastern tropical Pacific
- atmospheric (climate) impacts on a global scale
- economic impacts on a global scale

Strictly speaking, the term *El Niño* (EN) refers
to an oceanographic phenomenon
which oscillates with an opposite swing
known as *La Niña*.

The linked atmospheric counterpart
of El Niño (EN)is the *Southern Oscillation* (SO)

The name *El Niño* is frequently used
for *ENSO*, particularly in the press.

Fig 3- 10 Correlations with Darwin atmospheric pressure (Philander 1990), Fig. 1.1

The patterns of correlation have global scale.
What do large areas with positive and
negative correlation likely represent?

ENSO is a large-scale mass oscillation
centered over the Pacific

It can be detected by looking at
sea-level pressure (slp) differences
across the Pacific

Such as Tahiti slp - Darwin slp.

This quantity is referred to as the
SOI = Southern Oscillation Index
(the value is negative during El Niño,
positive during La Niña.)

Fig 3- 11 Sea-level pressure at Tahiti and Darwin (Philander 1990), Fig. 1.2

Note how this fits in with the see-saw pattern of the previous figure. When pressure is high at Darwin, it can be low at Tahiti.

Walker Cells are intense regions of tropical convection and rainfall (one is generally found over Indonesia)

They are generally associated with low sea-level pressure and a corresponding surface inflow

Walker cells general displace eastward during an ENSO event

The "opposite" of an El Niño event when the Walker cell is at its most westward position, is sometimes called *La Niña*, an *anti-ENSO*, *El Viejo* or a *cold event*. El Niño may be referred to as a *warm event*.
Why all the names?

SO and EN were independently discovered (by meteorologists and oceanographers)

The two were discovered to be linked by Jakob Bjerknes.

What is the nature of the linkage between the Southern Oscillation and El Niño?

- ENSO is basically an equatorial process
- Eastward displacement of the Walker cell changes the trade winds [the trades normally blow to the West in equatorial regions]
- The eastward inflow on the west side of the Walker cell results in weaker trade winds over the W Pacific
- In turn, sea level, normally maintained by the trades, drops in the W

- The slump in sea level in the W Pacific propagates to the E Pacific as a Kelvin wave
- Arriving in the E Pacific, the Kelvin wave water produces a deepened thermocline
- The deeper thermocline produces warming of surface water in the E tropical Pacific
- The warmer surface water is known as *El Niño*

Fig 3- 12 Response of thermal structure to changing winds (Peixoto and Oort 1992), Fig. 16.7

As the trade winds weaken, warm water sloshes eastward as an equatorial Kelvin wave [more on Kelvin waves in a few weeks].

The associated change in sea level across the Pacific produces warming off Ecuador, Peru

However, upwelling continues off South America,
Even during a warm event, the area is normally cool.

Fig 3- 13 Sketch of upwelling processes during El Niño

Even during an El Niño event, upwelling continues, but the upwelled water is less cool.

Upwelling brings up less cold water during El Niño when the thermocline is deeper

There is a regular annual cycle of surface temperature in the eastern tropical Pacific:

Fig 3- 14 SST along the equator, 1957-1976 (Philander 1990), Fig. 1.12

The normal annual cycle, is the old-fashioned "El Niño". Some years the surface warming is stronger, the new-fashioned El Niño.

The thermocline off the coast of Peru deepens during an El Niño event:

Deepening of the thermocline propagates across the Pacific

It can be seen off Peru

Fig 3- 15 Time-longitude diagram: wind speed and sea level (Enfield 1989), Fig. 4

A particularly strong El Niño occurred in 1982-83. Note the eastward movement of the winds, associated with the Walker cell.

What's the typical ENSO cycle?
- how long does it last?
- what are the climatic elements?

= Let's look at some observations

There is considerable variability among ENSO events

However, certain elements are common to all ENSO cycles

The pattern of winds over the Pacific is linked to the Walker cell and its associated precipitation

Fig 3- 16 Schematic of air-sea interactions (Philander 1990), Fig. 1.21

Cool cloud tops, sensed by satellite, indicate regions of precipitation.

Walker Cells migrate eastward, with warm surface waters and wind anomalies

Fig 3- 17 Time/Longitude section of outgoing longwave radiation (Philander 1990), Fig. 1.14

> The 1982-82 El Niño shows clearly. Other events with a much shorter time scale (a month or two?) can also be seen propagating eastward.

ENSO impacts

The great interest in El Niño is stimulated by economic impacts

For example, drought in India, linked to failure of the monsoon linked to El Niño

Fig 3- 18 ENSO-related global precipitation anomalies (Peixoto and Oort 1992), Fig 16.10

> ENSO seems to have a global reach. However, the press likes to exaggerate, to make the story better. All climate anomalies are not provoked by ENSO.

Fig 3- 19 Precipitation indices (Philander 1990), Fig. 1.16

> The Indian bars show why Sir Gilbert Walker started on his quest to understand the Southern Oscillation

The fisheries off South America are often cited as a prime example of the economic effects of enso.

Fig 3- 20 Anchoveta landings off Peru, SST and soy price (Enfield 1992), Fig 5.1

> Be wary of this diagram, which has been frequently used. The collapse of the anchoveta fishery may be due as much or more to overfishing as to the effects of natural phenomena.

ENSO prediction

- The evolution of an ENSO event within the cycle can be predicted with some confidence
- When the next ENSO will occur still can't be predicted well
- Nor can how long an ENSO event will last

Other climate variability

North Atlantic Oscillation (NAO)

www-pcmdi.llnl.gov/cmip/CMIP_Subprojects/Stephenson/proposal.html

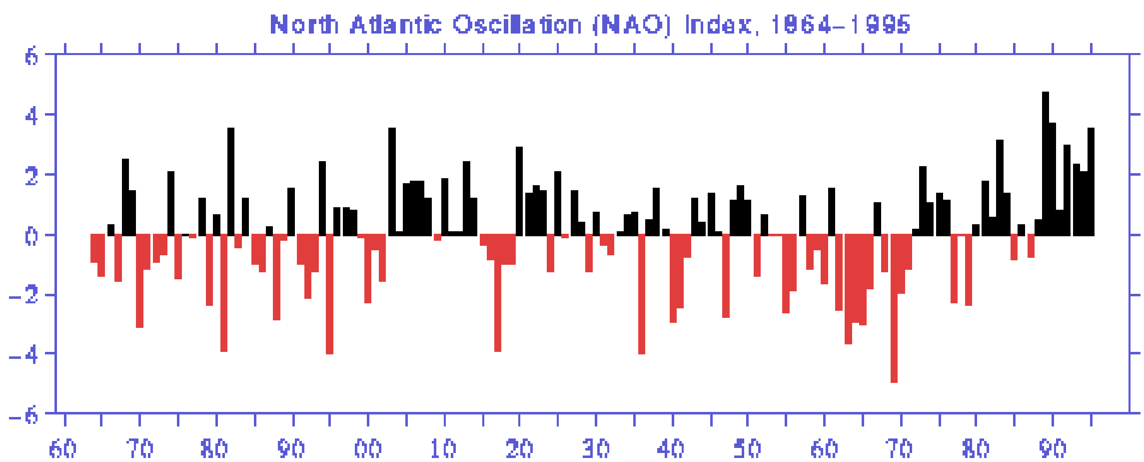


Fig 3- 21 Winter values of the NAO Index

[Based on the pressure difference across middle latitudes of the North Atlantic sector (mb). Winters (December-March) are positioned by the year of the January.]

For positive index, westerly flow across the North Atlantic & western Europe is enhanced

During the winter half-year, strengthened westerly winds bring warmer, maritime air over northwest Europe causing a rise in temperature.

For low index, the opposite occurs: temperatures fall over northwest Europe and rise over northwest Atlantic.

The NAO exerts a strong influence on year-to-year climate variability, with evidence of longer-term trends

Recently, the NAO has been suggested
to be the Atlantic-sector manifestation
of a global phenomenon,
the Arctic Oscillation(AO)

Pacific Decadal Oscillation (PDO)

tao.atmos.washington.edu/pdo/

The PDO is a long-lived El Niño-like
pattern of Pacific climate variability

The two climate oscillations have similar
spatial climate fingerprints, but have
very different behavior in time

Two main characteristics distinguish PDO from ENSO:

- PDO "events" persist for 20-to-30 years
- the climatic fingerprints of the PDO are
most visible in the North Pacific/North American sector,
while secondary signatures exist in the
tropics—the opposite is true for ENSO

"Cool" PDO regimes prevailed from 1890-1924
and again from 1947-1976

"Warm" PDO regimes dominated from 1925-1946
and from 1977 through the mid-1990's

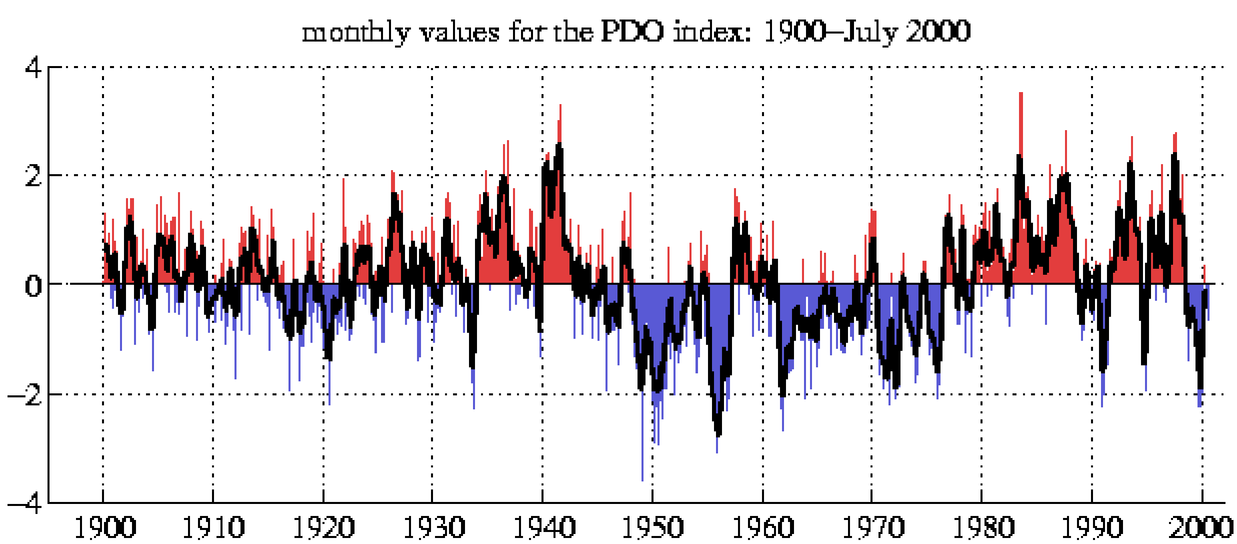


Fig 3- 22 Monthly values for the PDO index: 1900-July 2000

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