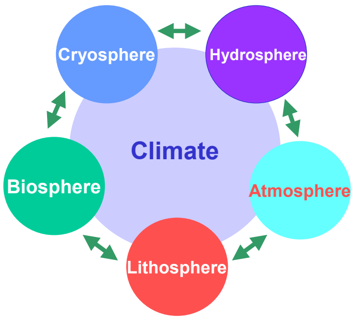
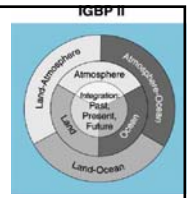
EOSC 112

Feedbacks and connections





IGBP: **International Geosphere-Biosphere Programme**

'to understand how processes such as enzyme discrimination contribute to the global atmosphere, we need to include the concept of scaling and new research tools in biology training programmes' ***Dan Yakir, 2002.***

Reductionism – dissection of complex ecosystems into elementary parts, while global-change science seeks to integrate components of Earth systems into regional and global patterns

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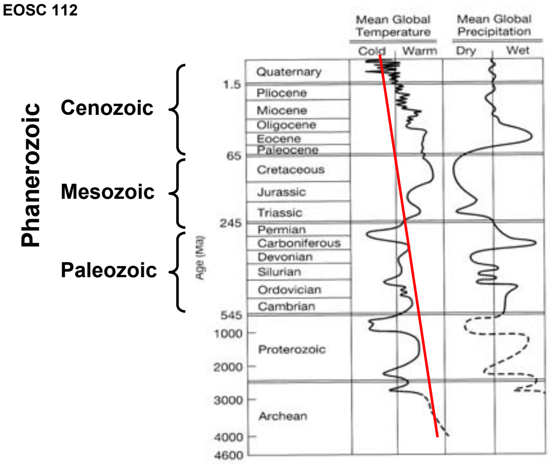

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Gaia hypothesis: (book "Gaia" by J.E. Lovelock) idea that living organisms manipulate their environment so it best suits their needs. The planet Earth is similar to an organism, cycles that occur on it are similar to physiologic systems, carefully controlled by the regulatory properties of the organism.

The Gaia hypothesis has spurred great controversy in the fields of geology, environmental science and biogeochemistry. Whether or not this theory correct, it is forced scientist to think about the Earth as a complex and interactive system. Feedbacks in the biochemical cycles is a vital part of the continued success of life on Earth.

Without volcanoes, plate tectonics and the light of the Sun geochemical cycles could not be sustained and life on the planet could not be possible

EOSC 112

Ways to reconstruct past climate

	Information	**Resolution**	**Time range**
• Dendrochronology	T, rainfall	annual	500-700 y ago (11000 – present)
• Palynology	T, moisture	~ 50 y	Several mil y back
• Geomorphology	Extent of gla-ciers/ice sheets, sea level	varies	2.9 billion y to the Little Ice Age of the 19th century
• Ice cores	Ice volume, CO_2 conc, dust, T, …	decadal	~450000 y back
• Corals	SST, S, river discharge, sea level	Months, (weeks!)	typically 400 y back (fossil 130000 y ago)
• Marine sediments	T, S, CO_2, ice volume	1000 to 100 y	~180 mil y back
• Pores in leaves	T, CO_2, rainfall	1000 to 100 y	~300 mil y back
• SIR of bones	Vegetation	100 y to decades	~1000 y back

EOSC 112

Oxygen stable isotopes: best proxies

^{18}O – 0.2% of total oxygen atoms

^{16}O – 99.8% of total oxygen atoms

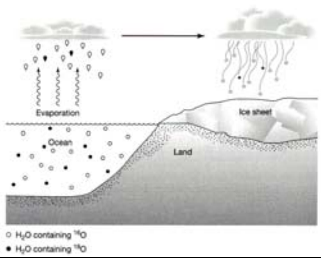
$r = {}^{18}O/{}^{16}O$

$$\delta^{18}O = \left(\frac{r_{sample} - r_{standard}}{r_{standard}}\right) \text{ X } 1000$$

Fractionation affected by:

- temperature – the colder the water, the greater the tendency for min to incorporate ^{18}O → larger r in $CaCO_3$;
- evaporation rates – ^{16}O molecules evaporate faster, leaving water enriched in ^{18}O. After forming ice cups, ice tend to be enriched in ^{16}O, while oceans are enriched in ^{18}O.

{$\delta^{18}O$ of foraminiferan $CaCO_3$ reflect seawater $\delta^{18}O$ → foraminiferan sediments may provide record of ice volume on continents}



EOSC 112

Paleoclimate: time scales

Objectives

- what is causing the Earth system to oscillate?
- what are the causes of glaciation?
- which components of the Earth system amplify climate responses?

Evidence of past glaciations

- parallel groves scoured in large rocks (glacial striations)
- moraines left behind by retreating glacier (tillites)
- dropstones occurring in finely laminated marine sediments

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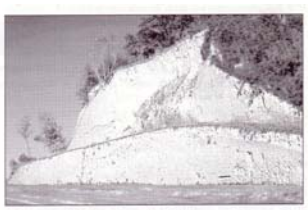
Moraines left behind by retreating glacier

Glacier striations



Dropstones

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On land: glacial advance wipes out evidence of previous ice age

Oceans: accumulated sediments retain a record of climate change

Sediment record is chemical and is contained in the isotopic composition of the skeletons of marine organisms

Oxygen stable isotopes are used as a proxy to reconstruct past climate

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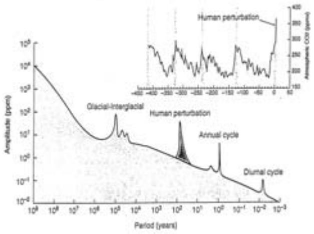
Temporal scales

Geological time scales



Political time scales
- 5 sec – engineer to decide on new development
- 2 y. – engineer to decide to initiate environmental assessment
- 3 y. – ecologist's pragmatic pre-development study proposal
- 3 m. – actual pre-development environmental assessment
- 20 y. – useful life-span of developm ≈ ecologist to be satisfied with len of pre-development data set
- 10000 y. – adverse ecological effect of development
- 5 y. – Politician's time horizon

Biological time scales
- min-hours - community metabolism
- hours-days - algal generation time
- years - macroinvertebrate life cycle
- 10-1000 y - rate of gene replacement

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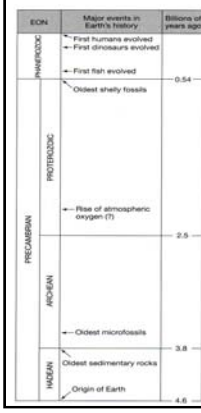
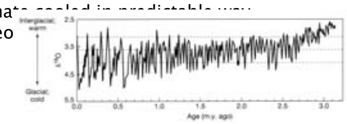
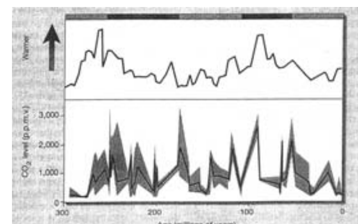
Paleoclimate: time scales

Geologic time scale



Warmer planet, high CO_2 concentration
Sun brightened → CO_2 conc. dropped → Earth's
clima
paleo





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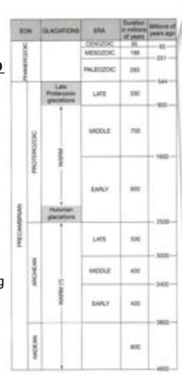
Geologic time scales

Five main periods of glaciatio

- Huronian: 2.2-2.4 b.y. ago
- Late Proterozoic: 0.6-0.8 b.y. ago "Snowball Earth" model
- Late Ordovician: 440 m.y. ago
- Permo-Carboniferous: 280 m.y. ag
- Pleistocene: 1.8 m.y. ago



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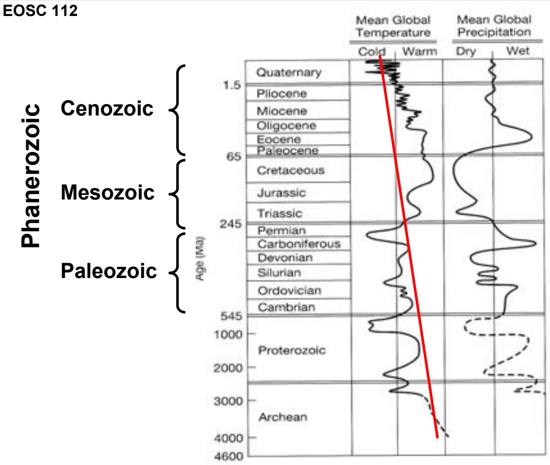

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Causes of long-term Climate Change

- **Changes in continental positions**: large continents near poles; unexplained presence of glaciers at low latitudes during Late Proterozoic Era and absence glaciers at high latitudes during the Mesozoic Era

- **Variations in atmospheric CO_2**: could be affected by plate tectonics, volcanism, precipitation patterns and the biota

- **Biological influences**: photosynthesis vs decay

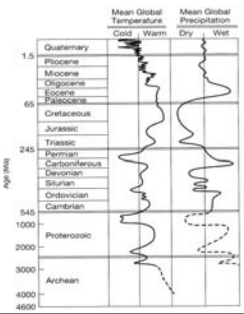
$$CO_2 + H_2O \underset{\text{respiration \& decay}}{\overset{\text{photosynthesis}}{\rightleftarrows}} CH_2O + O_2$$

Correlation between CO_2 drawdown and coal deposits formation during the Carboniferous Period, 286 to 360 m.y. ago

EOSC 112

Climates of the past 300 million years

Warm Mesozoic and Cenozoic Eras
- alligators in Siberia, dinosaurs in Alaska → temperatures 20 to 60ºC warmer at the poles
- deep ocean temperatures were as high as 15ºC



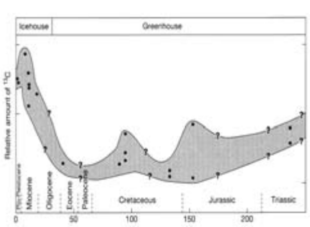
High CO_2 levels are responsible

[sea floor fast spreading rates → faster subduction of carbonate sediments → increased of CO_2 production from carbonate metamorphism. Also, more CO_2 released by outgassing at mid-ocean ridges. Finally, absence of polar ice → higher sea level → less land area on which to weather silicate rocks.

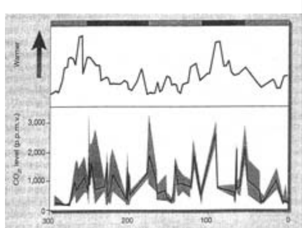
EOSC 112

Evidence of high Mesozoic CO_2 levels

- **Carbon isotopic evidence**
  $^{13}C/^{12}C$
  [when CO_2 is plentiful, organic matter is depleted in ^{13}C, while if CO_2 is scarce relative isotopic abundances do not change dramatically]



- **Evidence from fossil plants**
  [variability in the leaf pore density]



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Climates of the past 300 million years

- High CO_2 concentrations
- Ice albedo feedback (no ice cups → decrease in the albedo → polar regions warm significantly
- Reversed thermohaline circulation of the oceans (warm, but slightly saline, deep water formed at low latitudes welled up near the poles and warmed the climate through evaporation (?)
- Tropical Hadley circulation extended further poleward (?)

About 80 m.y. ago (Cenozoic Era) Earth's climate began to cool
[decrease in mid-ocean ridge spreading ??]

This accelerated *ca* 30 m.y. ago
[theory: collision of India and Asia created a gigantic chain of mountains
and huge area of uplifted terrain, which provided fresh, readily erodable
surfaces for silicate weathering. The uplift created a seasonal rainfall.
Both above factors may have accelerated silicate weathering rates →

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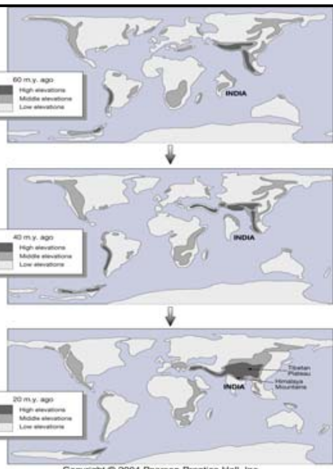
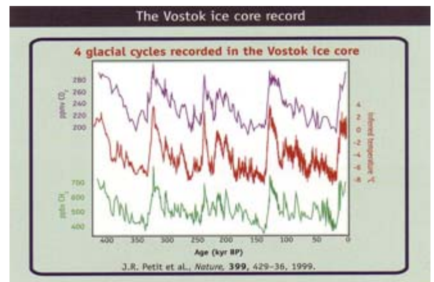


EOSC 112

Pleistocene Glaciations

Presently, Earth is in a glacial interval. Convincing evidence is now available on regular cycles (glacial and interglacial intervals of growth and decay polar ice sheets (Pleistocene Epoch). We are now in the warmer interval known as Holocene Epoch.

Evidence for self-regulating system



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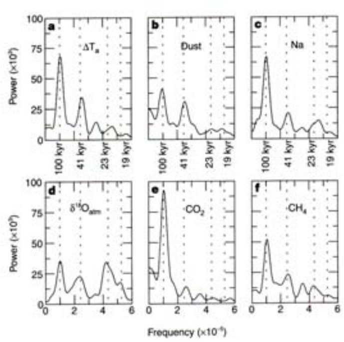
Pleistocene Glaciations

Spectral properties of the Vostok time series revealed several periodicities across many parameters

The main maxima and minima of T and atmospheric gases follow a regular pattern through time, each cycle spanning approximately 100,000 years



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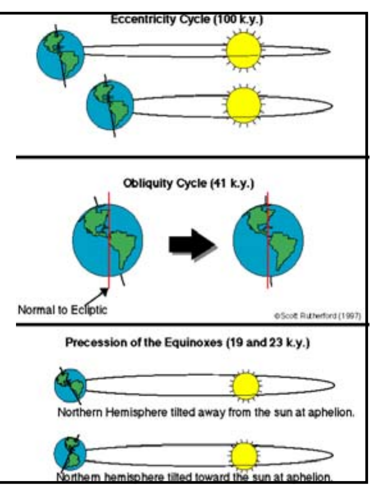
Milankovitch Cycles

Milutin Milankovich: Serbian mathe-matician provided quantitative basis for long suspected hypothesis that Pleistocene glacial-interglacial cycles are caused by variations in Earth's orbit around the Sun.

Essentricity – degree to which the orbit of a planet is elliptical. Varies between 0 and 0.06 (0.017).

Obliquity – planet's spin axis is tilted 22-24.5 degrees from the perpendicular to the plane of its orbit (creates contrast between seasons).

Precession – time during which spin axis wobbles around one complete circle (25,700 years). Two major periods: 19,000 and 23,000 years. Promotes seasonal contrast between hemispheres.



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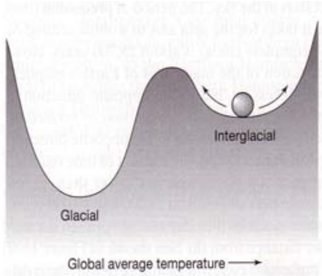
Pleistocene Glaciations

The optimal conditions for glaciation

low obliquity and high eccentricity, which, with a precession angle that places the Northern Hemisphere summers at aphelion, minimazes the amount of summertime insolation at high northern latitudes

What initiates ice age? Degree of snow melting in summer and NOT amount of snow in winter. Lower than normal sunlight in summer would preserve high albedo. Over years, compressed snow → ice → "ice age" begins

The combination of various orbital forcing results in oscillation of Earth's climate between two stable states



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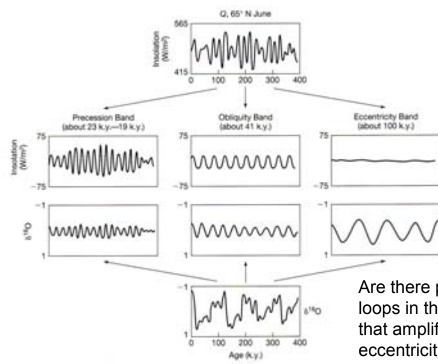
Pleistocene Glaciations

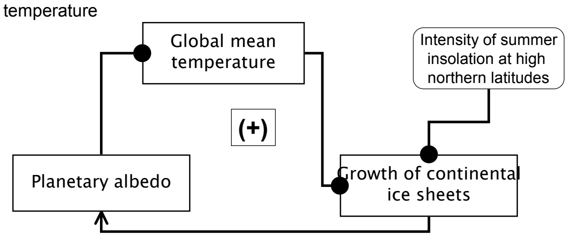


Are there positive feedback loops in the climate system that amplify the weak eccentricity forcing into the major climatic response to orbital fluctuations?

EOSC 112

Glacial Climate Feedbacks

Ice-Albedo Feedbacks: small change in the intensity of summer insolation may potentially trigger large changes in ice-sheet coverage and global temperature



Coupling with the Northern Hemisphere ice sheet dynamics as well as with CO_2 levels and amount of cloud condensation nuclei in the atmosphere

EOSC 112

Glacial Climate Feedbacks

Feedbacks affecting CO_2 concentrations

Portioning between atmospheric and oceanic carbon pools: <u>limestone weathering and deposition need not be balanced</u>

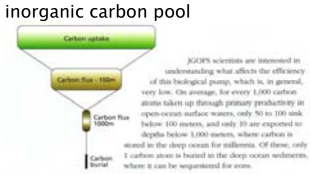
Surface water CO_2 exchange is ~ 90 gigatons (Gt)

Solubility pump: depends on the thermohaline circulation and on latitudinal and seasonal changes in ocean ventilation

{CO_2 is more soluble in cold, saline waters → sequestration of atmospheric CO_2 in the ocean interior is therefore controlled by the formation of cold, dense water masses at

Biological pump: 25% fixed carbon sinks into the ocean interior, ~ 11-16 Gt per year, lowering *ca* 150-200 ppmv from atmosphere

<u>Carbonate pump</u>: $CaCO_3$ in sinking shells lowers surface inorganic carbon pool



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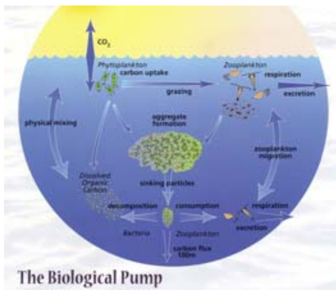
Glacial Climate Feedbacks

Biological pump:
280 ppm – intermediate
165 ppm – 100% efficient, 100% utilization of ocean nutrients
720 ppm – biological pump ceases
360 ppm – presently
Thus, low CO_2 concentrations of glacial intervals might be the result of a more efficient biological pump



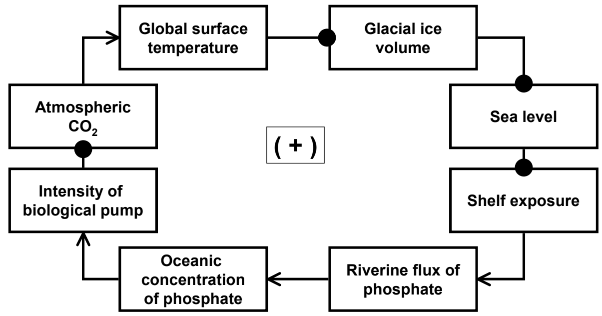
Efficiency may be increased:
- enhancing utilization of excess nutrients in the upper ocean;
- addition of nutrients limiting primary production;
- changing elemental ratios of the organic matter in the ocean;
- increasing the organic carbon/calcite ratio in the sinking flux.

EOSC 112

Glacial Climate Feedbacks

Why might the glacial ocean support greater biological productivity?

Shelf nutrient hypothesis: nutrient supply is a balance between supply by rivers and removal by sedimentation. For some nutrients bacterial processes might be also important (atmospheric nitrogen → nutrient nitrate)



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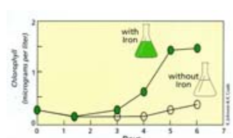
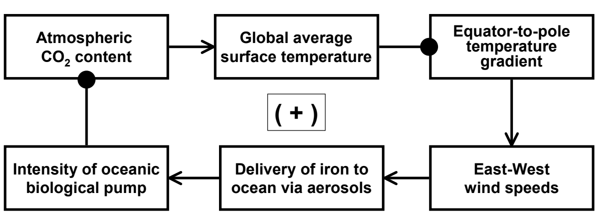
Glacial Climate Feedbacks

Iron fertilization hypothesis:
record of windblown dust in ice cores supports this hypothesis





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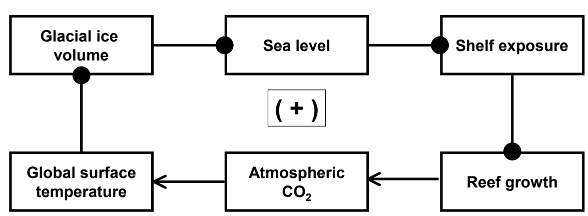
Glacial Climate Feedbacks

Coral reef hypothesis:

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O$$

Growth of coral reefs adds temporarily CO_2 to the atmosphere (excess of CO_2 becomes eventually converted to bicarbonate as a result of mineral weathering and re-deposited as $CaCO_3$). Reef can grow quickly with rising sea level but dissolution of reef is much slower (agrees with Vostok ice data



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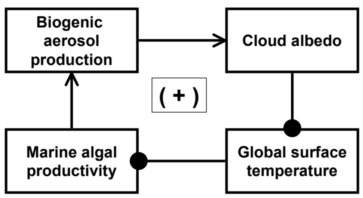
Glacial Climate Feedbacks

Cloud-albedo feedbacks

Formation of cloud condensation nuclei is stimulated by methane sulfonic acid (MSA) and sulfur dioxide (SD)

Marine algae → dimethyl sulfide (DMS, by-product of osmoregulation) → chemical transformation into MSA or/and SD → aerosols → condensation of water vapor → formation of clouds



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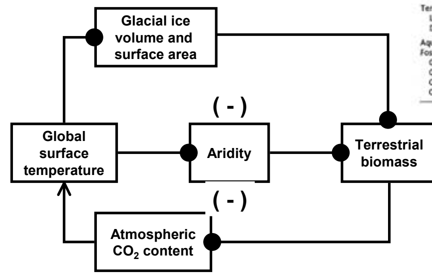
Glacial Climate Feedbacks

Changes in terrestrial biomass

Table 1. Carbon pools in the major reservoirs on Earth.

Pools	Quantity (Gt)
Atmosphere	720
Oceans	38,400
Total inorganic	37,400
Surface layer	670
Deep layer	36,730
Total organic	1,000
Lithosphere	
Sedimentary carbonates	>60,000,000
Kerogens	15,000,000
Terrestrial biosphere (total)	2,000
Living biomass	600–1,000
Dead biomass	1,200
Aquatic biosphere	1–2
Fossil fuels	4,130
Coal	3,510
Oil	230
Gas	140
Other (peat)	250



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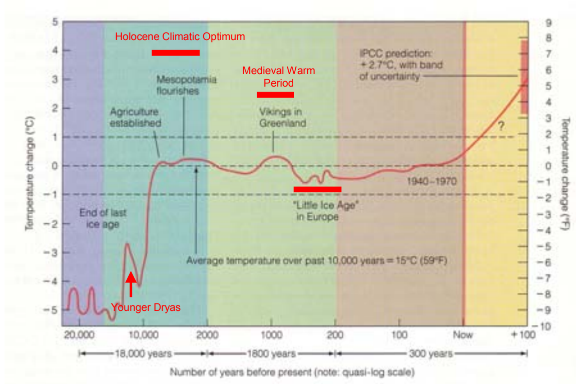
Climate variability during last 20,000 years



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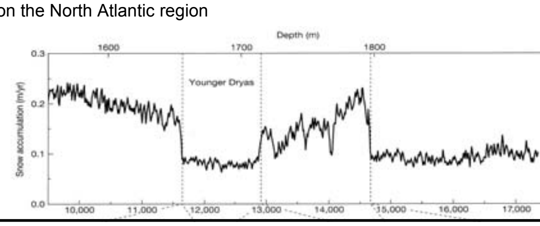
Short-term climate variability

Holocene: Earth started warming up 15 kyr BP after last ice age
- not with the same magnitude in all locations;
- small changes in mean global T°C resulted relatively large changes in physical environment (Viking colony in Greenland for 400 years)

Younger Dryas – Dryas flower (flourish in cold climate) became widespread
Abrupt cooling around 11.5 kyr (Younger Dryas event)
Although visible in other locations, Younger Dryas was primarily centered on the North Atlantic region



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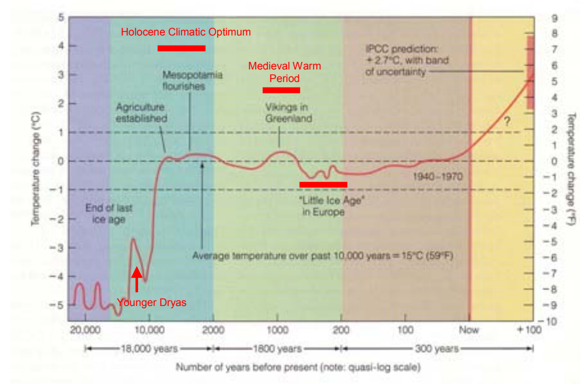
Causes of Younger Dryas event

- North Atlantic deep-water formation
  - redirection of cold fresh water runoff
  - ice coverage increase in the North Atlantic
  - cut off the formation of the North Atlantic deep water
- On-off switch in the North Atlantic
  - build up of Northern Hemisphere glaciers has intensified
  - lead to increased winds
  - more dust blown to the ocean
  - fertilization and CO_2 draw-down

EOSC 112

Climate variability during last 20,000 years



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Short-term climate variability

Holocene Climatic Optimum: warm conditions for several thousand years in the mid Holocene (5-6 kyr ago). Slightly warmer than present conditions.

Medieval Warm Period: temperatures fell after Holocene Climate Optimum, reaching minimum at ~ 3 kyr ago, but rose to a new maximum during ~ 1100-1300 A.D.

Little Ice Age: rapid cooling in late 1500s till mid 19th century. Lowering tree lines, increased erosion and flooding, sea-ice expansion, freezing of canals and rivers, readvancement of glaciers… Holland's canals and rivers froze in winter up to 3 months.

Glaciers in Swiss Alps reached several villages. The Little Ice Age had a strong regional focus, centered primarily on western Europe and the North Atlantic.

EOSC 112

Short-term climate variability

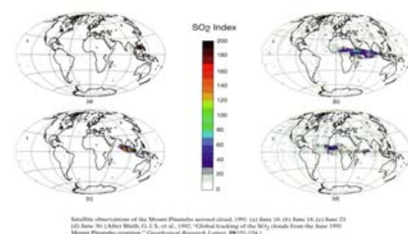
Causes of Holocene climate changes orbital changes and greenhouse variations cannot explain short time scale variability.

Anthropogenic activity

Volcanic eruptions

Volcanic aerosol forcing: aerosol blocks solar radiation → cooling lasting only few years

Volcanic ash forcing: ash injected into atmosphere would increase global albedo and reduce the solar input.



Effects are short living. Acidic ice in ice core data points well on volcanic eruptions. Greenland ice cores show: 1100-1250 A.D. low volcanic activity; 1250-1500 and 1550-1700 A.D. high volcanic activity. Consistent with temperature record.

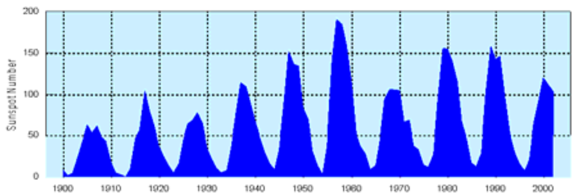
EOSC 112

Short-term climate variability

Causes of Holocene climate changes

Changes in thermohaline circulation: if surface waters in high latitudes of North Atlantic gets fresher, deep waters may not form.
If warm water transport from Gulf Stream stops, Western Europe cools by several degrees.

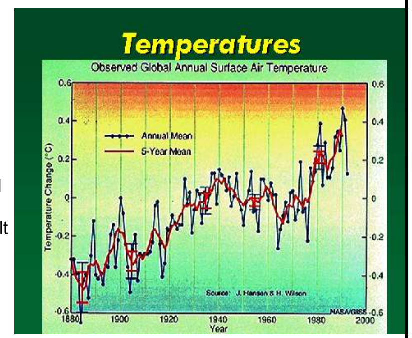
Solar variability: Sun output not as constant in the short-term as one would assume from the long period of Earth's history.



EOSC 112

Present–Day climate variability

- Trend in temperature is consistent with the CO_2 induced global warming
- Closely linked to the sunspot cycle
- 1940-1970 cooling could be due to increases in sulfate aerosols as a result of the burning of coal.
- Visible year-to-year variability in the record. Oceans "memory" of change.



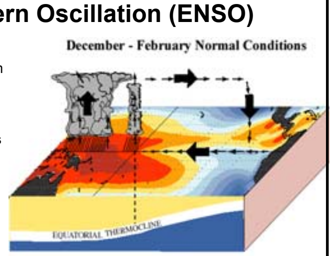
EOSC 112

El Nino – Southern Oscillation (ENSO)

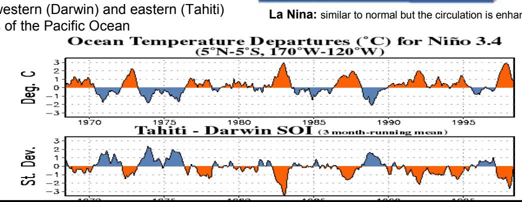
El Nino: (Spanish for 'the boy Christ-child') referred to the appearance of unusually warm water in the tropical Pacific, which is closely linked to major changes in the atmosphere through the phenomenon known as the **Southern Oscillation** (SO): which reflects differences in the sea-level pressures in the west and east

ENSO

Southern Oscillation Index (SOI): measure of the pressure difference between the western (Darwin) and eastern (Tahiti) parts of the Pacific Ocean



La Nina: similar to normal but the circulation is enhanced



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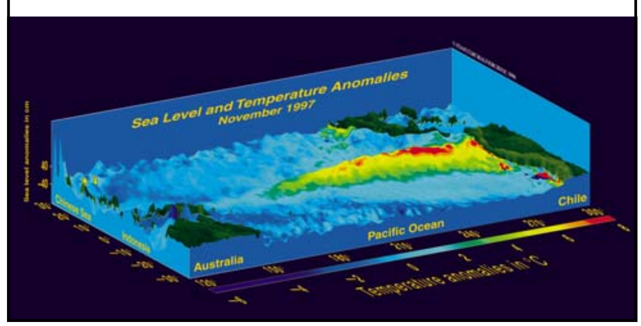
El Nino – Southern Oscillation (ENSO)

Kelvin wave: takes ~ 60 days to travel back across the Pacific



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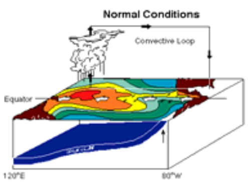
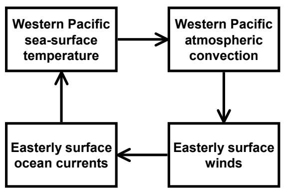
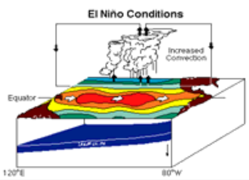
El Nino – Southern Oscillation (ENSO)







Paleorecords confirm that ENSO has been going on for millennia. It has, however, intensified in recent decades and started occurring more often

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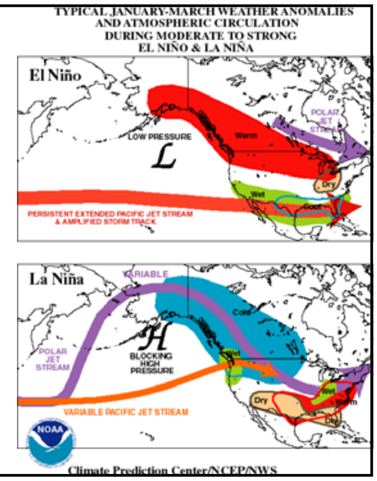
ENSO effects in the Northern Hemisphere



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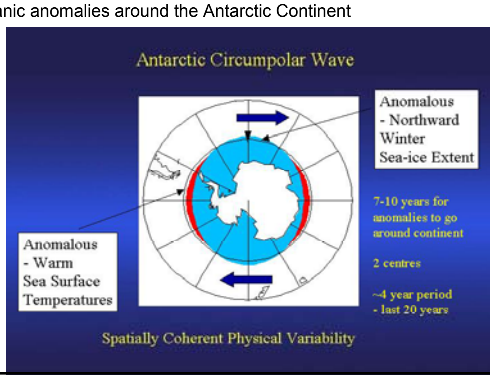
El Nino – Southern Oscillation (ENSO)

ENSO events are not confined to the tropics

Antarctic Circumpolar Wave (ACW): propagation of atmospheric and oceanic anomalies around the Antarctic Continent



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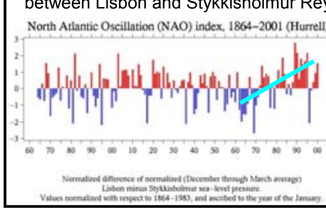
North Atlantic Oscillation (NAO)

NAO dictates climate variability from the eastern seaboard of the USA to Siberia and from Arctic to the subtropical Atlantic

NAO refers to a north-south oscillation in atmospheric mass with centers of action near Iceland and over the subtropical Atlantic from the Azores across to the Liberian Peninsula. It is strongest during December through March

NAO index is calculated as the difference of normalized sea level pressure between Lisbon and Stykkisholmur Reykjavik



- little periodicity indicating that much of the atmospheric circulation variability (NAO) arises from processes internal to the atmosphere
- periods of extended anomalous NAO's; unprecedented upward trend during past 30 years

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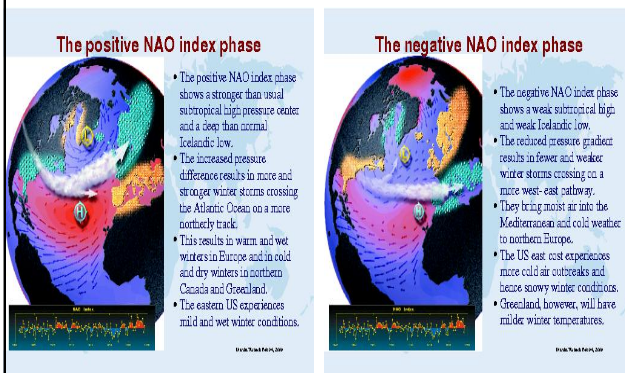

from www.ldeo.columbia.edu/~visbeck/nao/presentation/html

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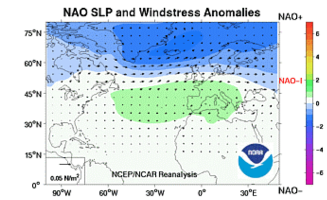

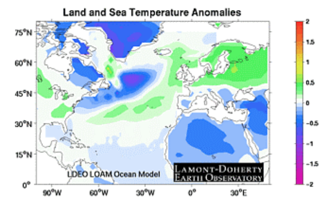

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North Atlantic Oscillation (NAO)

Impacts of NAO

• exerts a dominant influence on winter-time temperatures across much of the northern hemisphere, explaining about one-third of the inter-annual surface temperature variance
• affects precipitation pattern
• changes intensity and number of storms, their paths and their associated weather
• initiates the SST and salinity anomalies
• changes variability in the sea ice extent between the Labrador and Greenland seas
• determines large-scale distribution patterns of fish and shellfish

Variability of the atmosphere, surface, stratospheric or **anthropogenic** may influence the NAO's phase and amplitude

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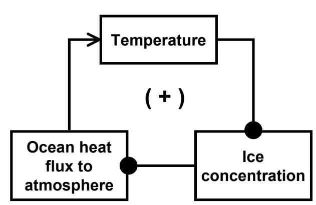
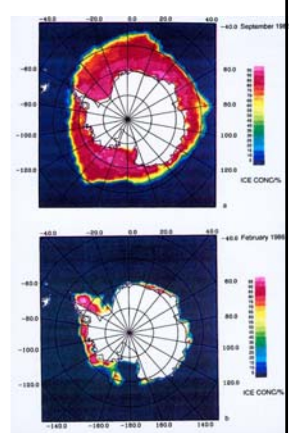
Sea Ice and Climate

Northern Hemisphere: min 8.5 x 10^6 km^2; max 15 x 10^6 km^2

Southern Ocean: min 4 x 10^6 km^2; max 20 x 10^6 km^2

Ocean heat-flux feedback





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Summary

- ➢ Earth's climate changes over all time scales from decades and centuries to millions of years. Since the last glaciation maximum, Earth has undergone several changes in climate global in extent
- ➢ Earth experienced sudden and very rapid climate reversals (switching in thermohaline circulation?)
- ➢ Two major warm periods occurred during the Holocene (orbital forcing?)
- ➢ Little Ice Age (volcanic eruptions, sunspot cycle)
- ➢ Century-long time scale variability (ENSO, NAO, ice-ocean heat flux feedback)

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"Anthropocene" Era

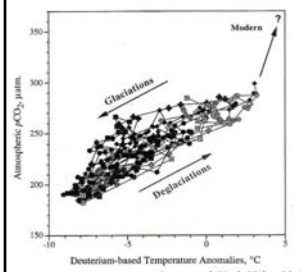

Table 2. Examples of human intervention in the global biogeochemical cycles of carbon, nitrogen, phosphorus, sulfur, water, and sediments. Data are for the mid-1900s.

Element	Flux	Magnitude of flux (millions of metric tons per year)		% change due to human activities
		Natural	Anthropogenic	
C	Terrestrial respiration and decay CO_2	61,000		
	Fossil fuel and land use CO_2		8,000	+13
N	Natural biological fixation	130		
	Fixation owing to rice cultivation, combustion of fossil fuels, and production of fertilizer		140	+108
P	Chemical weathering	3		
	Mining		12	+400
S	Natural emissions to atmosphere at Earth's surface	80		
	Fossil fuel and biomass burning emissions		90	+113
O and H (as H_2O)	Precipitation over land	111×10^{12}		
	Global water usage		18×10^{12}	+16
Sediments	Long-term preindustrial river suspended load	1×10^{10}		
	Modern river suspended load		2×10^{10}	+200

Global warming and Ozone Depletion