Climate Dynamics (7)
Palaeoclimatology & Ice Ages

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Biogeochemistry & Climate
Useful References

- Books (used as source of many illustrations)
  - Kump, Kasting & Crane (1999) "The Earth System"
  - Skinner & Porter (1995) "The Blue Planet : An Introduction to Earth System Science"
  - Crowley & North (1991) "Palaeoclimatology"
  - Broecker (1974) "Chemical Oceanography"
  - Butcher, Charlson, Orians & Wolfe (eds) (1992) "Global Biogeochemical Cycles"
  - Imbrie & Imbrie (1979) "Ice Ages : Solving the Mystery"
- Proto-book (source of much inspiration)
  - Broecker (1995) "The Glacial World According to Wally"

History

- Observations in the Alps & Scotland
  - Agassiz, Buckland, Lyell et al...
  - Gunz, Mindel, Riss & Wurm...
- The astronomical theory
  - Adhemar, Croll, Milankovitch (1910-1940)
  - ... and also Wegener!
- Low-latitude (equatorial?) glaciation

Major Ice Ages
(NB: Northern Hemisphere bias ...)

♦ Huronian	2700 to 2300 Myr BP (??)
♦ Late Precambrian	900 to 600 Myr BP (?)
♦ Ordovician-Silurian	ca 450 Myr BP
♦ Permo-Carboniferous	300 to 270 Myr BP
♦ Pliocene/Pleistocene	last 10 Myr (approx)

Past Climate : the Evidence

- Rocks : Classical Geology (to ~4 Gyr BP)
  - Nature & type (sedimentary, composition, etc)
  - Contents (fossils, plant & animal distributions)
  - Morphology (landforms, moraines, scratching & polishing...)
- Deep Sea Sediments (to ~100 Myr BP)
  - especially foraminifera
- Ice cores (to ~400 kyr BP (Antarctic))
  - composition of ice, gas bubbles, dust, etc
- Lake Sediments & Palaeosols (episodic & patchy)
- Tree rings (last few kyr only)

Oxygen Isotopes as proxies for climate

- $\delta^{18}O = 1000\times \{[^{18}O]/[^{16}O]/[^{18}O]/[^{16}O]_{ref}-1\}$
  - isotopes are fractionated by **evaporation (**light isotope evaporates preferentially leaving ^{18}O behind)
  - meteoric waters (source of all fresh water including ice) are depleted in ^{18}O, and so is precipitation...
    - effect is progressive and dependent on latitude and temperature
  - deep ocean $\delta^{18}O$ (benthic forams) indicates **ice volume**
    - and thus indirectly is a proxy for global temperature
  - surface ocean $\delta^{18}O$ (planktonic forams) indicates salinity and surface temperature
    - but the **transfer function** is complicated (& not unique)
- $\delta^{18}O$ can be measured in ice, trapped air, calcite, etc...

Other stable isotope ratios used as climate proxies

- Deuterium (heavy isotope of hydrogen) : δD : fractionated by evaporation & precipitation
  - indicator of evap/precip & temperature (of rainfall)
- Carbon : $\delta^{13}C$: fractionated during photosynthesis
  - indicator of biological production
- Nitrogen : $\delta^{15}N$: fractionated by nitrogen fixation & denitrification
  - indicator of new biological production
- also phosphorous, silicon, boron...
- Need to know processes & transfer functions....

Possible Long-term Causes of Episodes of Glaciation ...

- Solar radiation variations (including but not limited to orbital effects)
- Continental configurations & plate tectonics
  - land/sea albedo, ice accumulation, ocean circulation
- Carbon Dioxide variations and GH effects
  - Volcanic activity *versus* biogeochemistry
- Ice sheet growth & instability
- Oceanic & Atmospheric Circulations (modes & rates)
- NB: Amplification by positive feedbacks
  - ice-albedo feedback
  - water-vapour greenhouse effect

Linear & Non-linear System Dynamics

- Positive feedbacks
  - multiple alternative states (separated by **repellors**)
  - hysteresis & rapid transitions (switching)
- Negative feedbacks
  - if instantaneous : stabilisation, stable states (**attractors**)
  - if delayed : resonance (amplification) & possibly oscillations (at characteristic frequencies)
- Oscillations : if **total** loop gain > +1
- Reservoir effects : finite response times
  - (N.B. relation to residence times)
- Relaxation oscillations : due to positive feedbacks
  - rapid switching between alternative **transient** states
  - reservoir effects lead to typical saw-tooth character

Ice-Age Characteristics

- Presence/Absence (as function of geological time)
- Low latitude extent? (land & sea ice edges)
- Polar ice accumulation : in either or both Northern and Southern hemispheres?
- Variability : may be considerable
  - stability & periodicity may also vary
- Sea-level changes ? (due to land-based ice only)
- Inceptions & Terminations (are usually/invariably fast ???)
- Ice sheets destroy evidence of their predecessors...
- ... So detailed analysis is possible for recent glaciations only

Pliocene-Pleistocene glaciations

- Antarctic glaciers etc since ~25 Myr BP
  - due to separation from Australia and S. America??
- N. Hemisphere ice-sheets since ~ 5 Myr BP only
  - due to closure of Panama ???
- Notably & strongly periodic
  - mainly at period of 40 kyr (obliquity) up to 800 kyr BP
  - mainly at period of 100 kyr (eccentricity) since then...
  - ... Milankovitch, but why this resonance (???)
- Terminations occur very fast
  - main temperature changes in a few decades
- Inceptions are apparently not so fast

Primary mechanisms for recent glacial/interglacial oscillations

- The existence & persistence of the **extreme states** is relatively easy to understand...
- The triggers for, and mechanisms of, the rapid **transitions** are much more difficult to explain...
- There is still no generally accepted mechanism...
- Candidates include :-
  - Ice sheet dynamics & instability (with isostatic effects) {Peltier, Denton et al}
  - Solar (orbital) forcing and CO_2 interactions {Berger}
  - Salinity/Ice/Sea-level relaxation oscillations {Shaffer}
- NB : All modified and/or amplified by variations of oceanic & atmospheric circulations, ice-albedo feedback and the water-vapour greenhouse effect, etc (*ad libitum*)

Problems

- G/IG change of global mean temperature is ~ 5 C
- Orbital insolation changes are too small
  - less than a few W/m^2 on average...
  - seasonal maxima/minima are bigger : enough ??
- Climate sensitivity to CO_2 is too small
  - ~ 2 C per doubling/halving
  - are the changes cause or effect ?
  - and what are they caused by, anyway ?
- Ice albedo effects are only effective at high latitudes (and already included in sensitivities)
- What is the sequence of events & feedbacks?
- Especially, what triggers inceptions/terminations ?

Possible Sequence of Events : Inception

- Reduced Summer Insolation
- Snow/Ice Accumulation (with albedo F/B)
- Cooler & Drier
- Reduced hydrological cycle & precipitation (?)
- Inc'd Pole-Equ ΔT... Ice-cap Growth
- Inc'd Wind & Storms Reduced Sea-level
- Inc'd Dust & Fe Supply Inc'd Phosphate
- Increased Biological Production (and cooler)
- Reduced atmospheric CO2
- Cooling....

Possible Sequence of Events : Termination

- Increased Summer/Winter insolation (?)
- Snow/ice melting (with albedo F/B)
- Reduced Pole-Equ ΔT... Ice-cap retreat
- Reduced Wind & Storms Increased Sea-level
- Increased hydrological cycle (?)
- Increased (or relocated ?) precipitation : Wetter
- Reduced Dust (and Biological Production)
- Reduced Atmospheric Albedo & Increased CO_2
- Warming...

Other factors to be included...

- Hydrological cycle & global freshwater fluxes
  - Evaporation and precipitation (alteration and/or relocation of maxima)
  - Atmospheric circulation changes ?
  - Lapse rates, water vapour feedback (?)
- Ocean thermohaline circulation
  - Alternative Modes ?
  - Bipolar warming/cooling ?
  - Asymmetry between hemispheres ?
- Other effects of sea-level ? Salinity ?
- Calcite formation/dissolution : effects on CO_2
- Ice-sheet dynamics ...

Abrupt Climate Change (decadal to millennial time-scales)

- Millennial scale oscillations
  - including Mediaeval Warm Period & the Little Ice Age
  - these may involve sea-ice variations (Bond et al 1999)
- Events such Younger Dryas (at ~ 11.5 kyr BP)
  - sudden sharp cooling : lasted ~ 1kyr in total
  - interrupted the last termination (Bolling-Allerod warming at ~ 14 kyr BP)
- Also the 8.3 kyr BP cold event
- Transitions occur in decades ...
- Events may last up to ~ 1 millennium

Ice Ages : Conclusions

- Causes and mechanisms are still very uncertain
- Recent ice ages have been strongly periodic
  - almost certainly “paced” by orbital insolation changes
- Possibly involve CO_2 changes (biologically driven?)
- ... and re-organisations of the hydrological cycle ?
- Interactions of the ice/ocean/atmosphere system may still be found to be sufficient ...
- Biogeochemistry may only matter for times > 1 Myr
- The role of the oceans remains **very** uncertain
- Warm periods (e.g. Cretaceous) are equally well worth study!