Palaeo-Atmospheric Composition

Prof Alan M. Haywood

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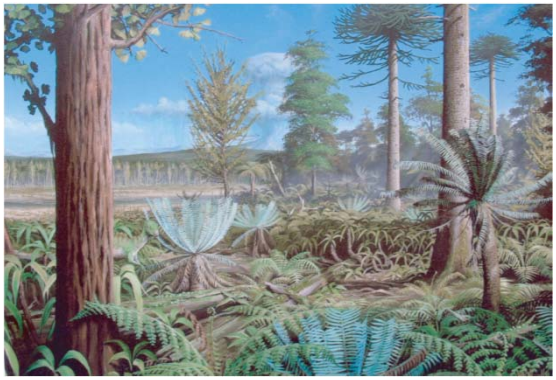

http://pubs.usgs.gov/of/2007/1047/kp/kp03/of2007-1047kp03.pdf

2

Learning Outcomes

- To gain an overview of atmospheric composition and climate during the Cenozoic Era.
- To understand the broad link between atmospheric composition (CO_2), ice sheets and climate.
- To appreciate climate and environmental change during the past with an analogous CO2 level.

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Why palaeoclimate?

• Uncertainties highlighted in climate prediction involve aspects of the climate that have changed in the past (e.g. ENSO, sea level).

• Palaeoclimatology can assess whether these changes are consistent with current theories of the climate system and if not, why not.

• Palaeoclimate provides a unique test-bed for models that project large changes in the future to be evaluated using true out-of-sample tests of comparable magnitude.

Brown University Library

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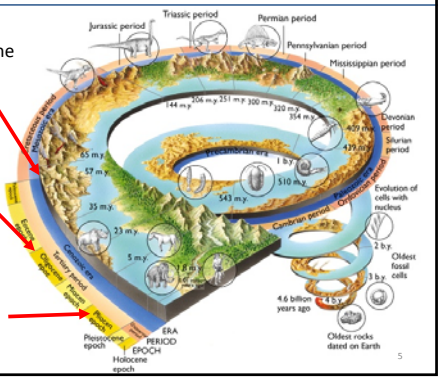
Earth History

Extinction of the dinosaurs

Onset of the Antarctic Ice Sheet

Warm Period analogous to Future?



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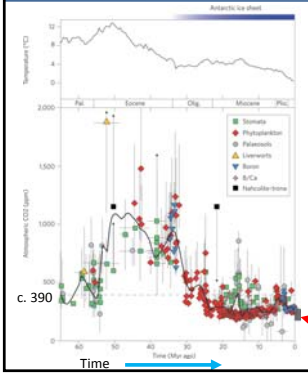
Cenozoic Climate



c. 390

- Deep sea temperatures track estimates of atmospheric CO_2
- Carbon Dioxide (CO_2) was higher during the 'Greenhouse' periods of the past
- Reduced over time due to silicate weathering
- CO_2 is the most frequently estimated atmospheric gas from proxy records

Vertical grey bar indicated glacial-interglacial CO_2 ranges from ice cores

(Beerling and Royer, 2011)

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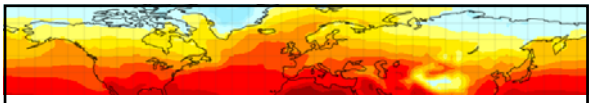

How can we measure palaeo-atmospheric composition?

Example of CO_2

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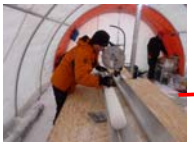
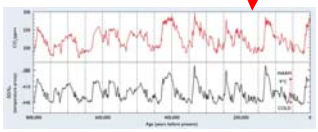
Measuring Palaeo CO_2





- Ice core drilling – high resolution records of CO_2 and also Methane (CH_4)
- Clearly defined glacial-interglacial cycles of the Pleistocene
- Oldest record based on age of oldest ice <1 million years

Ice core data from EPICA Dome C (Antarctica) ice core: deuterium (dD) is a proxy for local temperature; CO_2 measured from the ice core air *(Jouzel et al., 2007; Lüthi et al., 2008)*

Proxies for CO_2

Number of novel techniques for estimating CO_2 levels during Earth History (based on Boron, Leaf Stomata, Phytoplankton, Palaeosols)

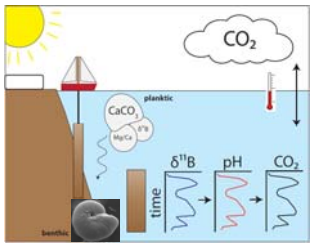


Image: James Rae

Boron has two stable isotopes ^{11}B and ^{10}B (isotopic composition expressed as $\delta^{11}B$ relative to a standard)

Formation of boron in seawater is pH-dependent

CO_2 of ocean can then be calculated from pH

(Rae et al., 2014)

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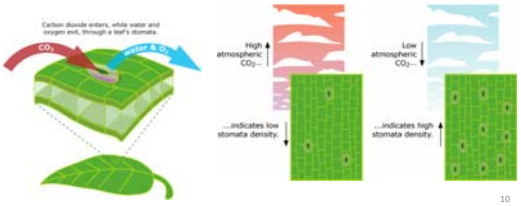
Proxies for CO_2 – Stomatal Density

- Stomata are specialized epidermal cells on the leaves of plants
- They allow CO_2 to enter the leaf from the air. In doing so water diffuses out of the leaf (evapotranspiration)
- Balance must be struck between CO_2 gain and H_2O loss
- High CO_2 concentrations in air cause plant to produce fewer stomata to conserve water (and vice versa) – this provides a basis for a CO_2 proxy based on leaf stomatal density



Images: University of California Museum of Paleontology's Understanding Evolution (http://evolution.berkeley.edu)

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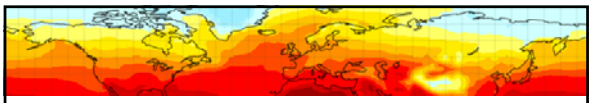

Understanding the links between climate and CO_2 (and Ice!)

1. Eocene-Oligocene Transition (Glaciation of Antarctica)
2. Late Pliocene Warm Period (Analogue for Future?)

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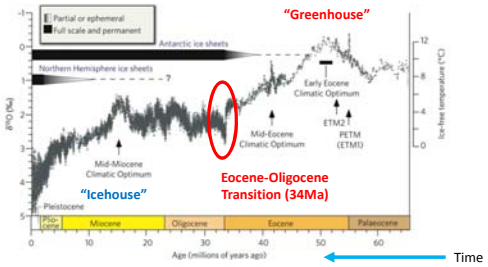
Eocene-Oligocene Transition



Benthic oxygen isotopes are combined measure of bottom water temperatures and global ice volume

(Zachos et al., 2008) 13

Eocene-Oligocene Climate

What caused the glaciation of Antarctica at the Eocene-Oligocene boundary?

Two main hypotheses: **(1) Thermal isolation of Antarctica due to Southern Gateway opening,** (2) Declining levels of atmospheric CO_2

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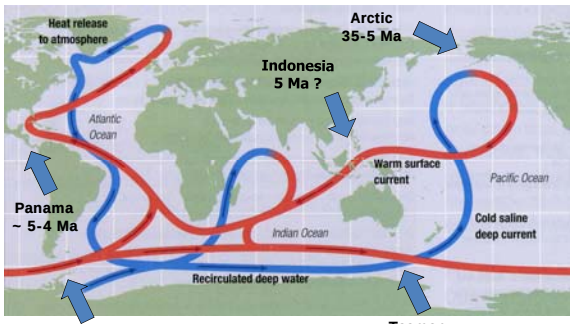
Cenozoic Gateways



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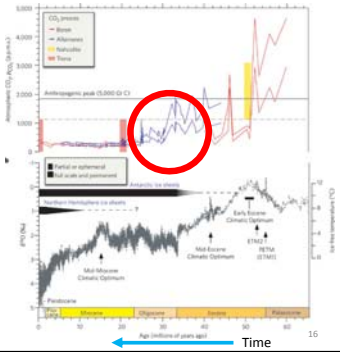
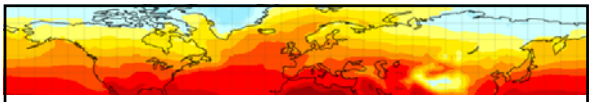
What caused the ice sheet growth?

What caused the glaciation of Antarctica at the Eocene-Oligocene boundary?

Two main hypotheses: (1) Thermal isolation of Antarctica due to Southern Gateway opening, **(2) Declining levels of atmospheric CO_2**



(Zachos et al., 2008) 16



Testing the Hypotheses

Climate and Ice Sheet Modelling Study
(DeConto and Pollard, 2003)

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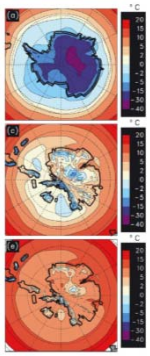
Modelling Antarctic glaciation

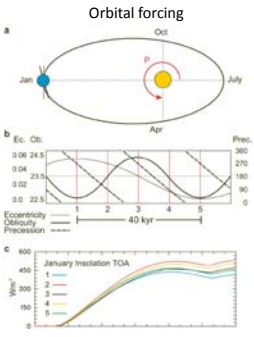


Climate model forcings

Present Day – Modern ANT

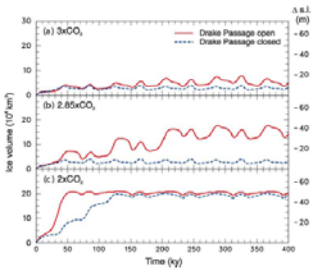
~34 Ma with No ANT (280 ppmv CO_2 = 1 x PAL CO_2)

~34 Ma with No ANT (3 x PAL CO_2)



(DeConto and Pollard, 2003) 18

Thresholds for Antarctic Glaciation



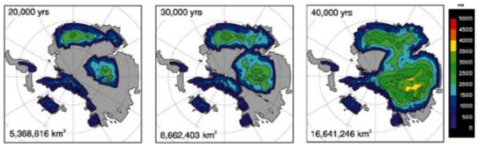
Simulations show that the threshold for height-mass balance feedbacks to trigger large ice sheet growth in a model lies between 2 x and 3 x pre-industrial levels of atmospheric CO_2 (PAL= 280 ppmv)

Robustness of this result tested compared to the other potential forcing (opening of the Drake Passage)

Overall the parameterised opening of the Drake passage has little effect on the ice sheet size at 2 x or 3 x PAL CO_2

(DeConto and Pollard, 2003)

Video?!

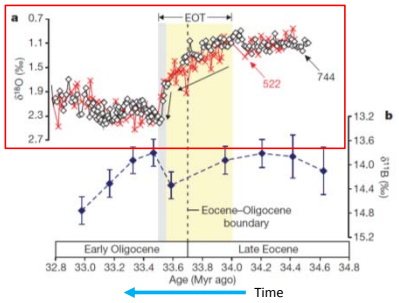


(DeConto and Pollard, 2003)

CO_2 Decline over E-OT

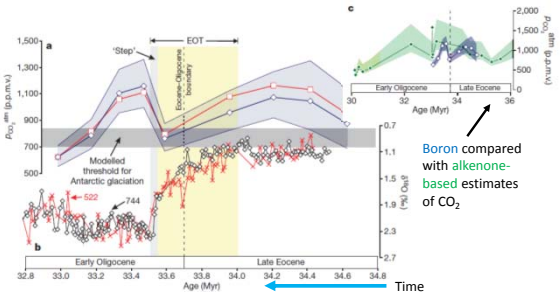
Sediment core from Tanzania – used boron isotope analysis of carbonate shells of upper-ocean planktonic foraminifera to establish palaeo-surface ocean pH and infer dissolved CO_2 concentration.

Oxygen isotopes from Tanzanian core display a positive shift suggesting a drop in temperature and increase in ice volume over the E-O transition



(Pearson et al, 2009)

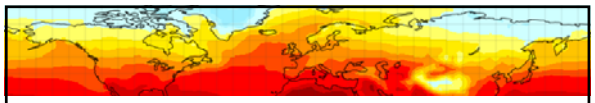
CO_2 Decline over E-OT



- Reconstructed CO_2 compared with the deep-sea benthic oxygen isotope record
- Data suggest reduction in CO_2 occurred before the main phase of ice growth – values consistent with modelled threshold

Summary

- Data shows that there was a significant CO_2 decline at the Eocene-Oligocene Transition (~34 million years ago)
- Temperature data from around the globe also shows a coeval cooling
- Modelling studies and data point towards a significant increase in the volume of ice on Antarctica over the Eocene-Oligocene Transition, driven by decreasing CO_2 levels
- Large oceanographic changes such as the opening of the Drake passage are not as important for ice sheet initiation as declining CO_2.



Analogues for the Future?

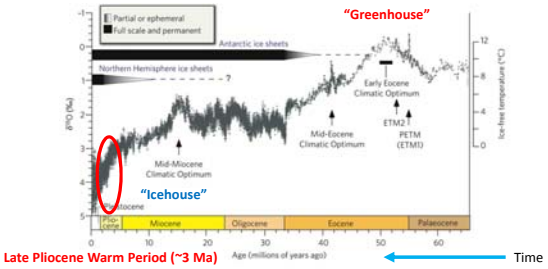
Late Pliocene Warm Period

"**The mid-Pliocene is the most recent time in Earth's history** when mean global temperatures were substantially **warmer for a sustained period**, providing an **accessible example** of a world that is similar in many respects to what models estimate could be the **Earth of the late 21st Century**"

IPCC AR4

Jansen et al (2007)

Late Pliocene

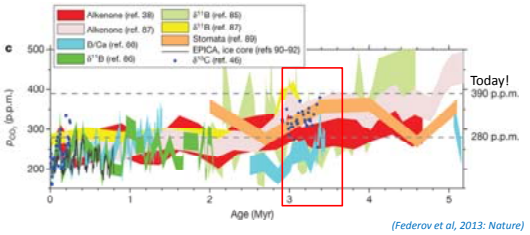


Late Pliocene Warm Period (~3 Ma) ← Time

Benthic oxygen isotopes are combined measure of bottom water temperatures and global ice volume

(Zachos et al., 2008) 25

CO_2 during the Pliocene



(Federov et al, 2013: Nature)

- Proxy CO_2 records from marine geochemical studies and ice-core inclusions
- Late Pliocene showed CO_2 levels of up to 400 ppmv

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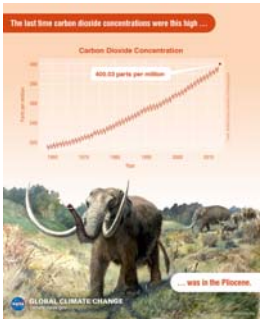
CO_2 during the Pliocene Warm Period



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Evidence of bi-pedalism in the Pliocene

Well known fossil "Lucy" discovered in Hadar, Ethopia in 1974
Australopithecus afarensis – Hominid lineage

© 2010 Photo S. Entressangle

Lucy skeleton reconstruction, Cleveland Natural History Museum

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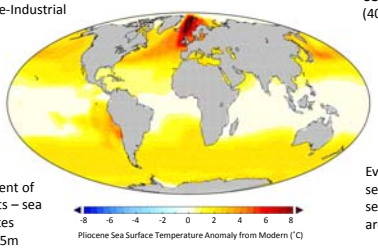
Characteristics of the Late Pliocene

Global mean temperatures 2-3 °C higher than pre-Industrial

CO_2 increase (400 *ppmv*)



Reduced extent of the ice sheets – sea level estimates suggesting 25m higher than today

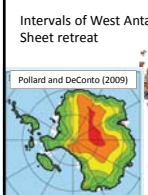
Evidence for seasonally sea ice free areas

Reduced equator to pole surface temperature gradient

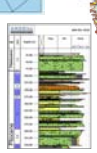
PRISM

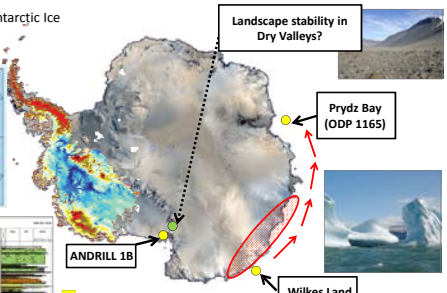
Antarctica during the Late Pliocene

Intervals of West Antarctic Ice Sheet retreat



Modelled WAIS collapse





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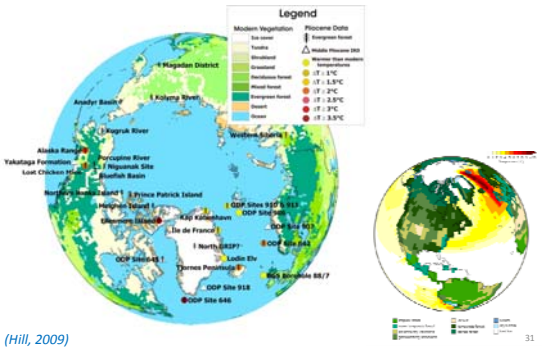
Greenland during the Late Pliocene



(Hill, 2009)

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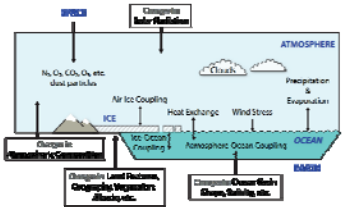
Palaeoclimate modelling at Leeds

Lead a project (PlioMIP) which compares climate model predictions of the Pliocene warm period

How well do models that are used for future projections simulate a warm climate of the past?



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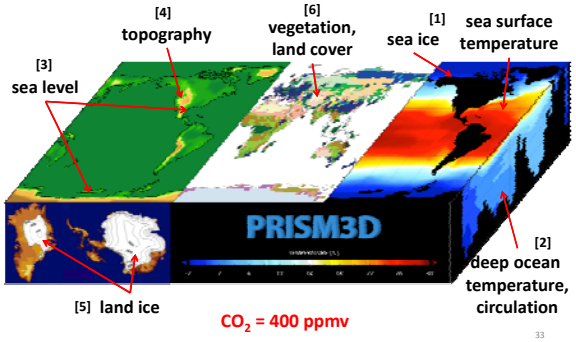
Pliocene Boundary Conditions



CO_2 = 400 ppmv

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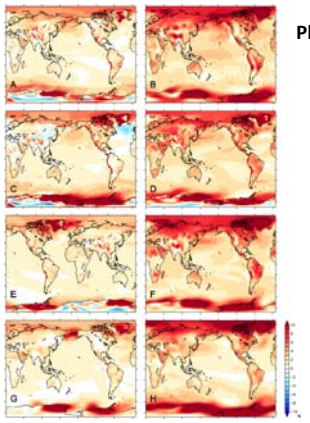
Pliocene Climate Simulations



Mean annual surface air temperature difference from pre-industrial for 8 atmosphere-ocean climate models

Large differences in the degree of polar amplification and the broad response over the ice sheet regions.

(Haywood et al., 2013 – Climate of the Past)

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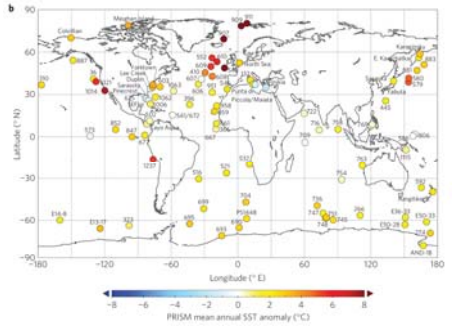
Data to test climate models



(Dowsett et al, 2013)

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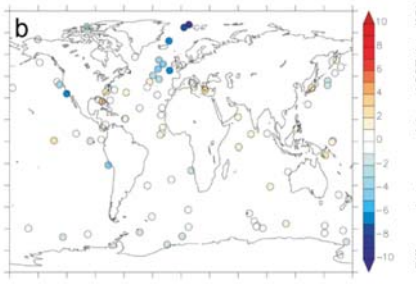
Data-Model Comparison

Point-based Mean Annual SST comparison



Red = model too warm

White = data and model agrees

Blue = model too cold

(Haywood et al., 2013 – Climate of the Past)

Summary

- Broad areas where models predict changes in temperature correctly for the Pliocene
- Regions such as the North Atlantic where models are too cold in comparison to the proxy-based estimates of sea surface temperature
- We need to understand why the models and the data disagree! Are the models wrong? Is the data uncertain?
- Interesting Blog (http://blogs.plos.org/models/)
- All models are wrong – some are useful!

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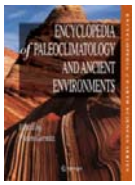
Further Reading



IPCC AR5 – information from Paleoclimate Archives
https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter05_FINAL.pdf

Royal Society special issue: 'The Pliocene. A vision of Earth in the late twenty-first century?' compiled by Alan M. Haywood, Harry J. Dowsett and Paul J. Valdes

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