Modelling Ancient Earth Climate: Methods & Models

Prof. Alan M. Haywood

Learning Outcomes

palaeo-*prefix* MAINLY UK SPECIALIZED (US USUALLY paleo-) /palaeo/
From Greek *palaios* 'ancient' older or ancient, especially relating to the geological past

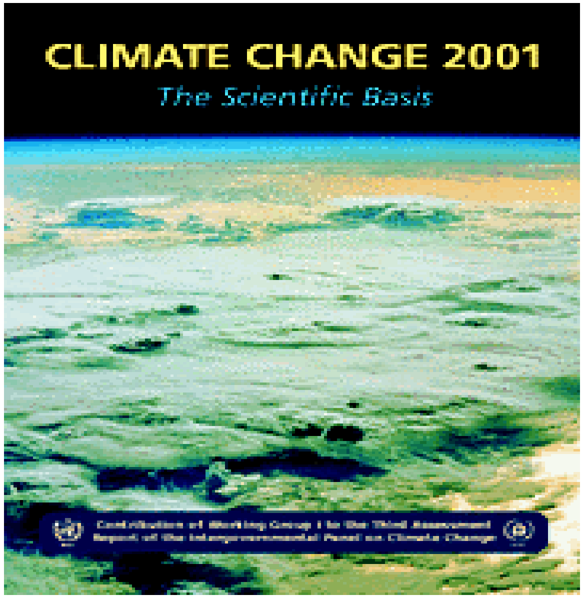
- To understand why it is important/interesting to study palaeoclimates.

- To learn about the development of Climate and Earth System Models.

- To appreciate how these models can be applied to understand the evolution of climate over geological time.

Why?

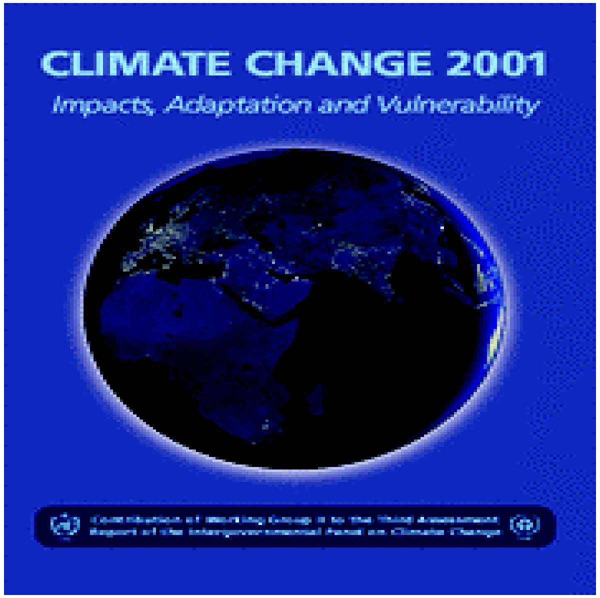
- **Understand the dynamics of warm climates**
- **Test Earth System Models**



CLIMATE CHANGE 2001

The Scientific Basis

Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change



CLIMATE CHANGE 2001

Impacts, Adaptation and Vulnerability

Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change

Primary Research Focus in Climate Change Science

- Simulation of the historical or near-historical record
- Analysis of the observed record of variability
- Projection for the next 100 years

Greatest Strengths

Spatial and temporal character of the Observations.

Measurement of physical quantities that define the state of the atmosphere and ocean.

Greatest Weaknesses

Sense of change.

Sense of the integration of the Earth System.

In contrast: A Research Focus in Earth History

Greatest Strengths

Spectacular sense of change (*Furry Alligator Syndrome*)

True integrated system response

Greatest Weaknesses

Proxies rather than state variables

Limited spatial and temporal resolution

"The greatest weaknesses in a research focus on the modern record are the greatest strengths of Earth System History"

We Should Worry

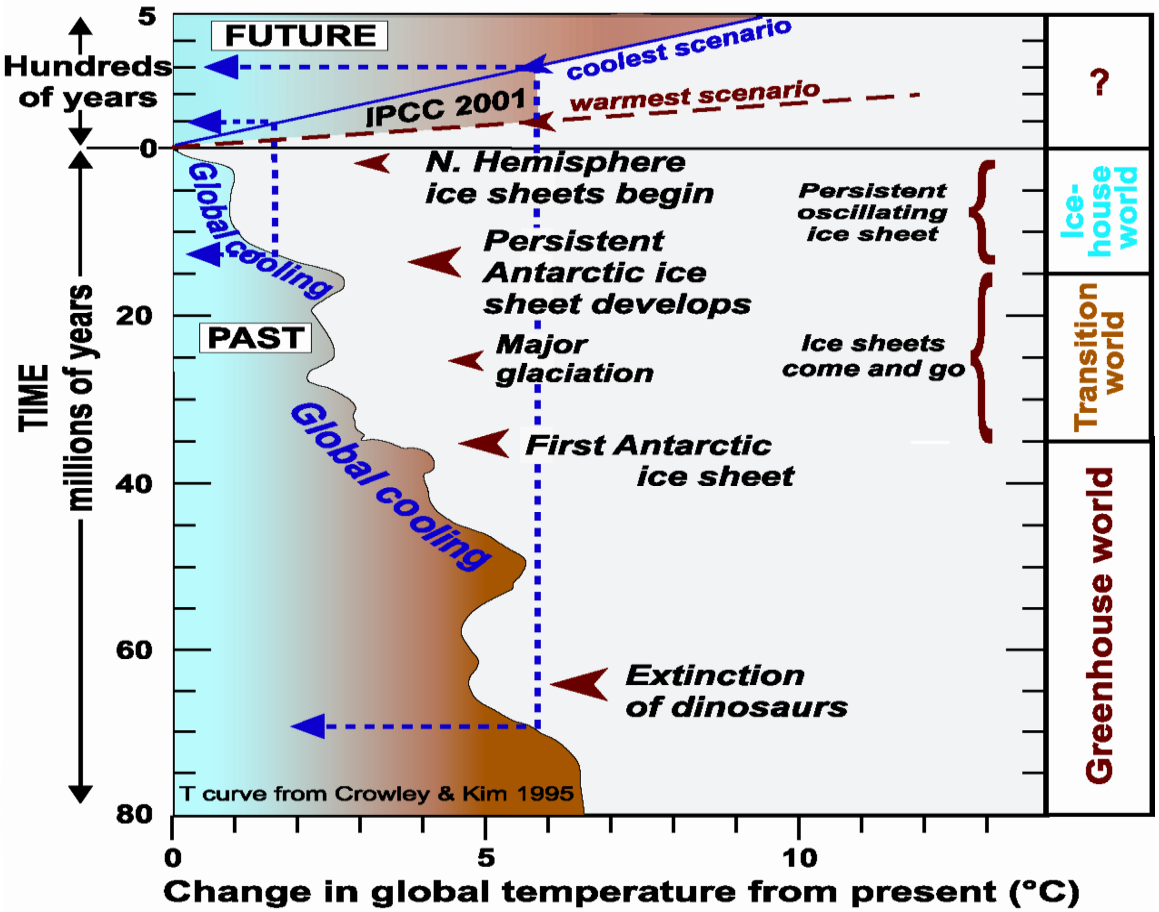
IPCC Climate Sensitivity: Roughly 1.5 to 4.5 C globally averaged surface temperature increase for a doubling of carbon dioxide.

Hundreds of GCM experiments have been completed for time periods throughout the Phanerozic using a wide variety of climate models.

Many experiments focused on either glacial climates or warm climates (the extremes).

"There are few legitimate example of a climate model simulation in which the past climate conditions were overestimated"

Climate History



T curve from Crowley & Kim 1995

1.1 Introduction: What exactly is a “model” ?

model n. [Fr. Modele, It. Modello, from L. modellus]

A miniature representation (small measure) of a thing, with the several parts in due proportion.

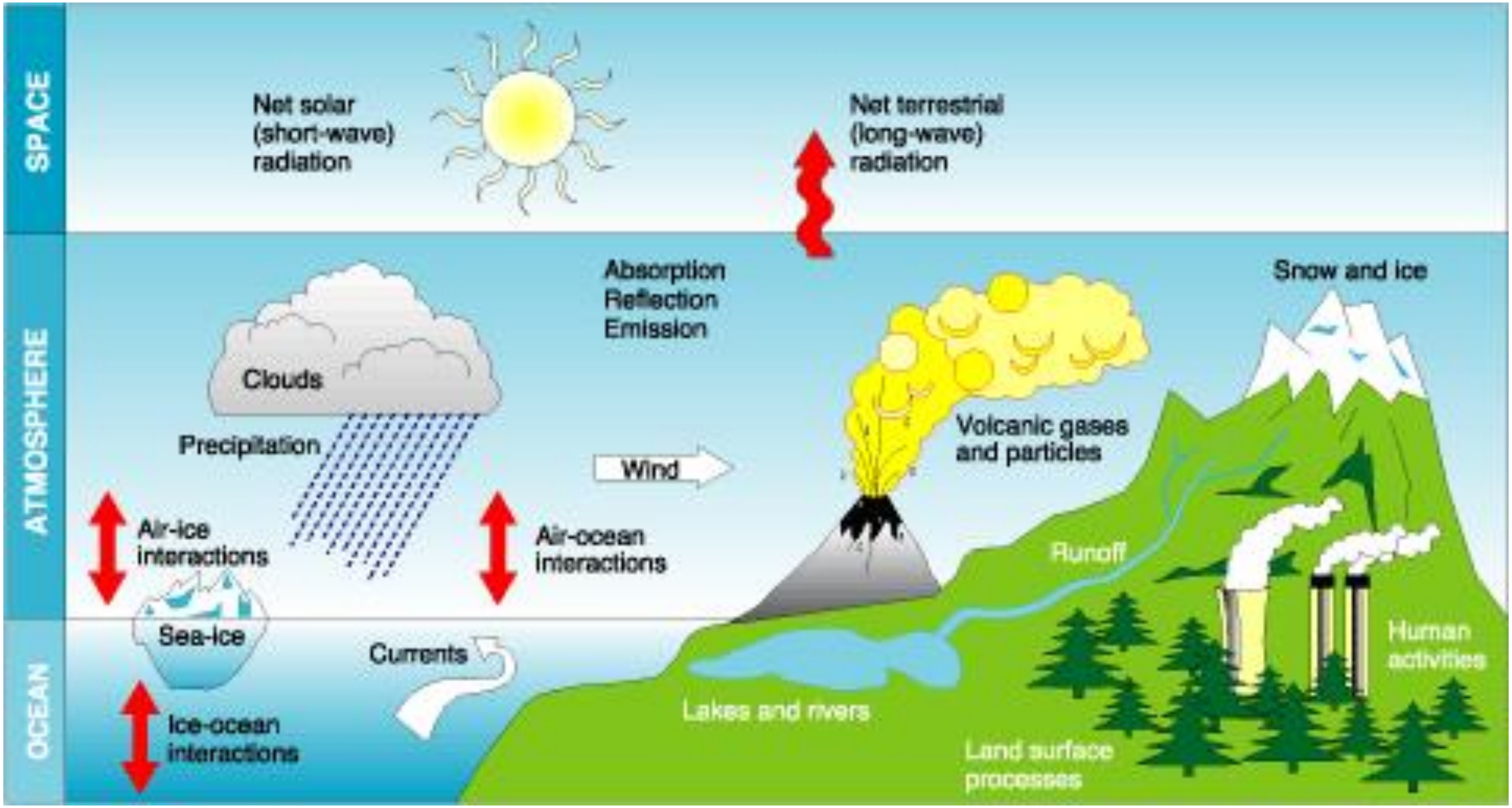
- A model is only a “representation” of reality (e.g. a street plan of reality)
- Good modellers know the strong AND weak points of their models
- “Modelling” (English) and “Modeling” (American)
- Some quotations:

“All models are wrong, but some are useful” – George Box

“The purpose of models is not to fit the data but to sharpen the questions” – Samuel Karlin

“A theory has only the alternative of being right or wrong. A model has a third possibility, it may be right, but irrelevant.” – Manfred Eigen

The Climate System

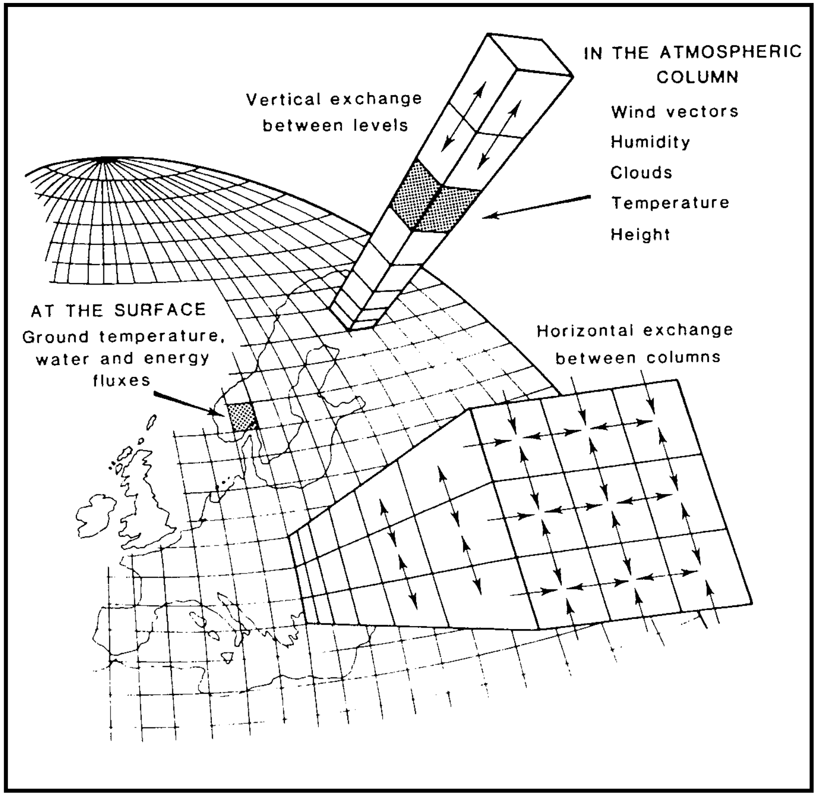


General Circulation Models

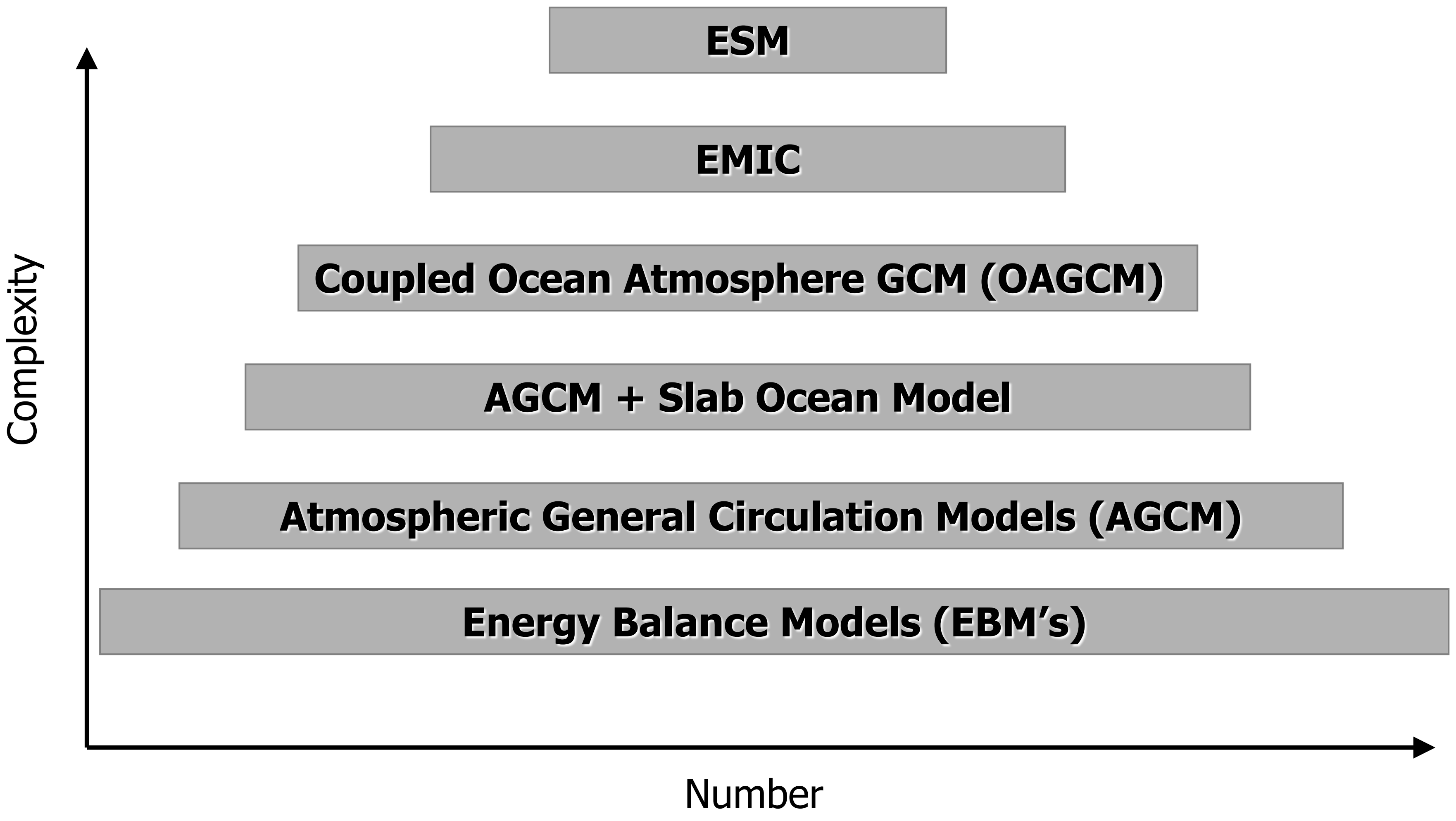
Model needs to simulate albedo, emissivity and general circulation.

Use “first principles”

- Newton's Laws of Motion
- 1st Law of Thermodynamics
- Conservation of Mass and Moisture
- Hydrostatic Balance
- Ideal Gas Law



Spectrum of Climate Models



ESM

EMIC

Coupled Ocean Atmosphere GCM (OAGCM)

AGCM + Slab Ocean Model

Atmospheric General Circulation Models (AGCM)

Energy Balance Models (EBM's)

Components of an Earth System Model

Aerosols:
Dust and Sulphates

Regional Model:
High Resolution

Cryosphere-Lithosphere Model

Atmospheric Chemistry

Atmospheric General Circulation Model

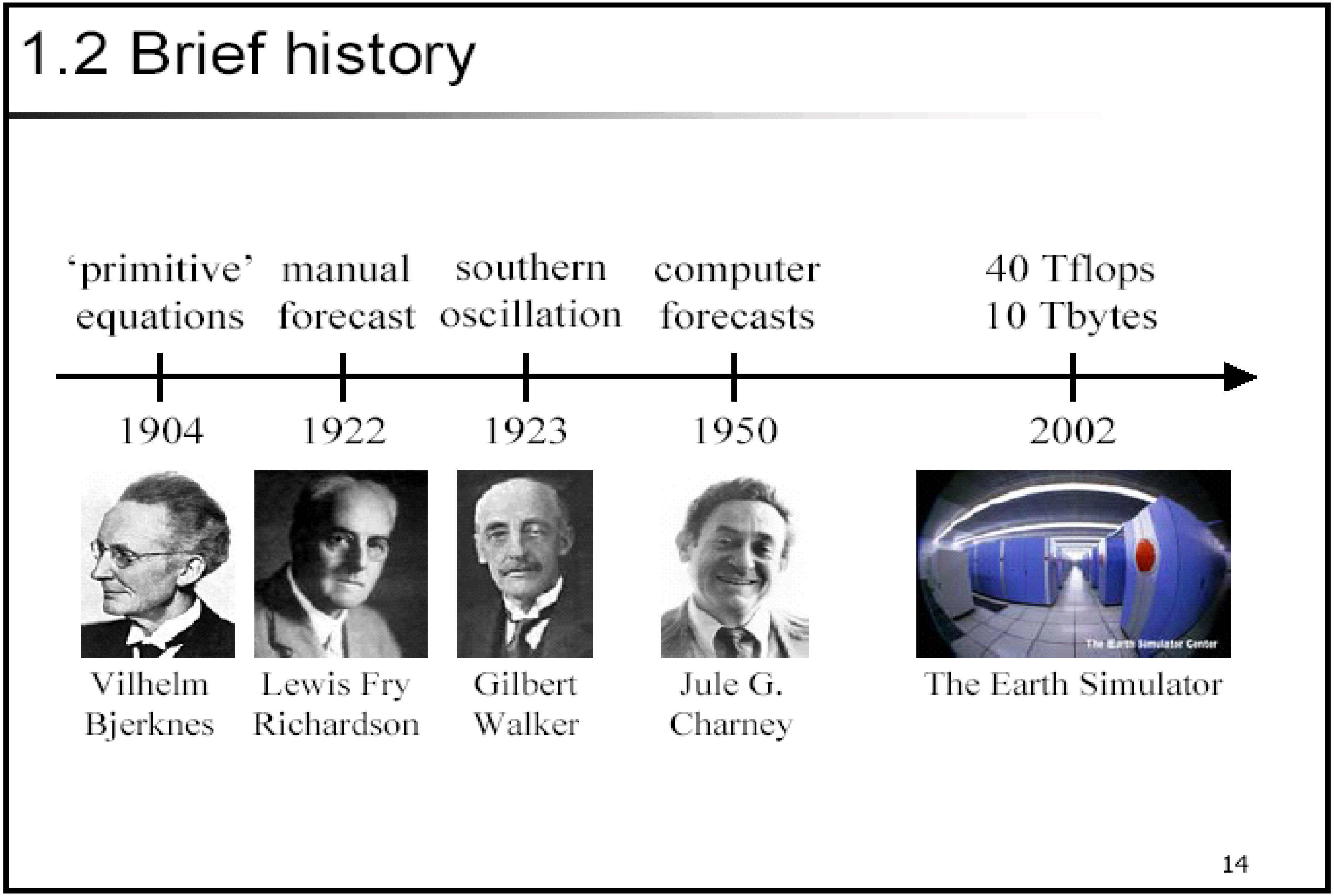
Land Surface Hydrology

Ocean Carbon Cycle

Ocean General Circulation Model

Terrestrial Carbon Cycle

Brief history of numerical modelling



1.2 Brief history

1904	1922	1923	1950	2002
‘primitive’ equations	manual forecast	southern oscillation	computer forecasts	40 Tflops 10 Tbytes
Vilhelm Bjerknes	Lewis Fry Richardson	Gilbert Walker	Jule G. Charney	The Earth Simulator

The Earth Simulator Center

Development of Met. Office Climate Models

Present	ATMOSPHERE	LAND	OCEAN	ICE	SULPHUR	CARBON	CHEMISTRY
1999	ATMOSPHERE	LAND	OCEAN	ICE	SULPHUR	CARBON	
1997	ATMOSPHERE	LAND	OCEAN	ICE	SULPHUR		
1992	ATMOSPHERE	LAND	OCEAN	ICE			
1990	ATMOSPHERE	LAND	OCEAN				
1985	ATMOSPHERE	LAND					
1960s	ATMOSPHERE						

Component models are constructed off-line and coupled in to the climate model when sufficiently developed

Physical basis of climate models

- The atmosphere is a fluid on a rotating planet:
  - Drag at the surface and within the atmosphere affects the momentum budget
  - Water vapour evaporates from the surface, condenses to form clouds and heats the atmosphere when it is lost through precipitation
  - Heating from solar radiation and cooling from thermal radiation

- Models therefore need to include equations for;
  - 3 components of wind (or vorticity & divergence), including Coriolis and drag
  - equation of state and conservation of water
  - thermodynamics, including heating by condensation and radiation

Physical basis of climate models

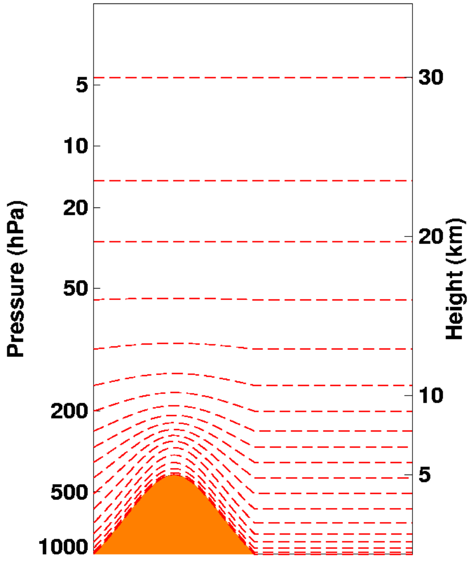
- The ocean is also a fluid, but incompressible. It is heated by solar radiation and cooled by evaporation and thermal emission from the surface. No internal heating, but salinity strongly affects the density and hence the circulation

- Additional models have been developed to include the land surface, cryosphere, atmospheric chemistry and aerosols, carbon cycle etc

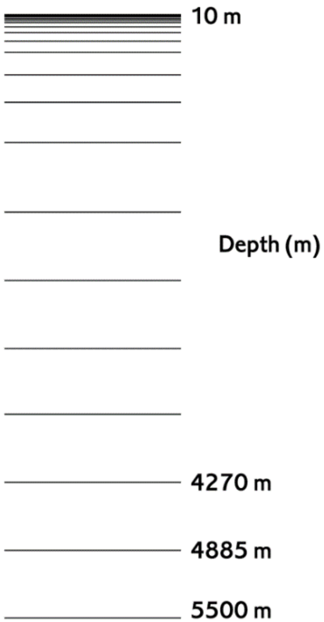
- **Processes that are sub-grid in scale are modelled by *parametrizations***

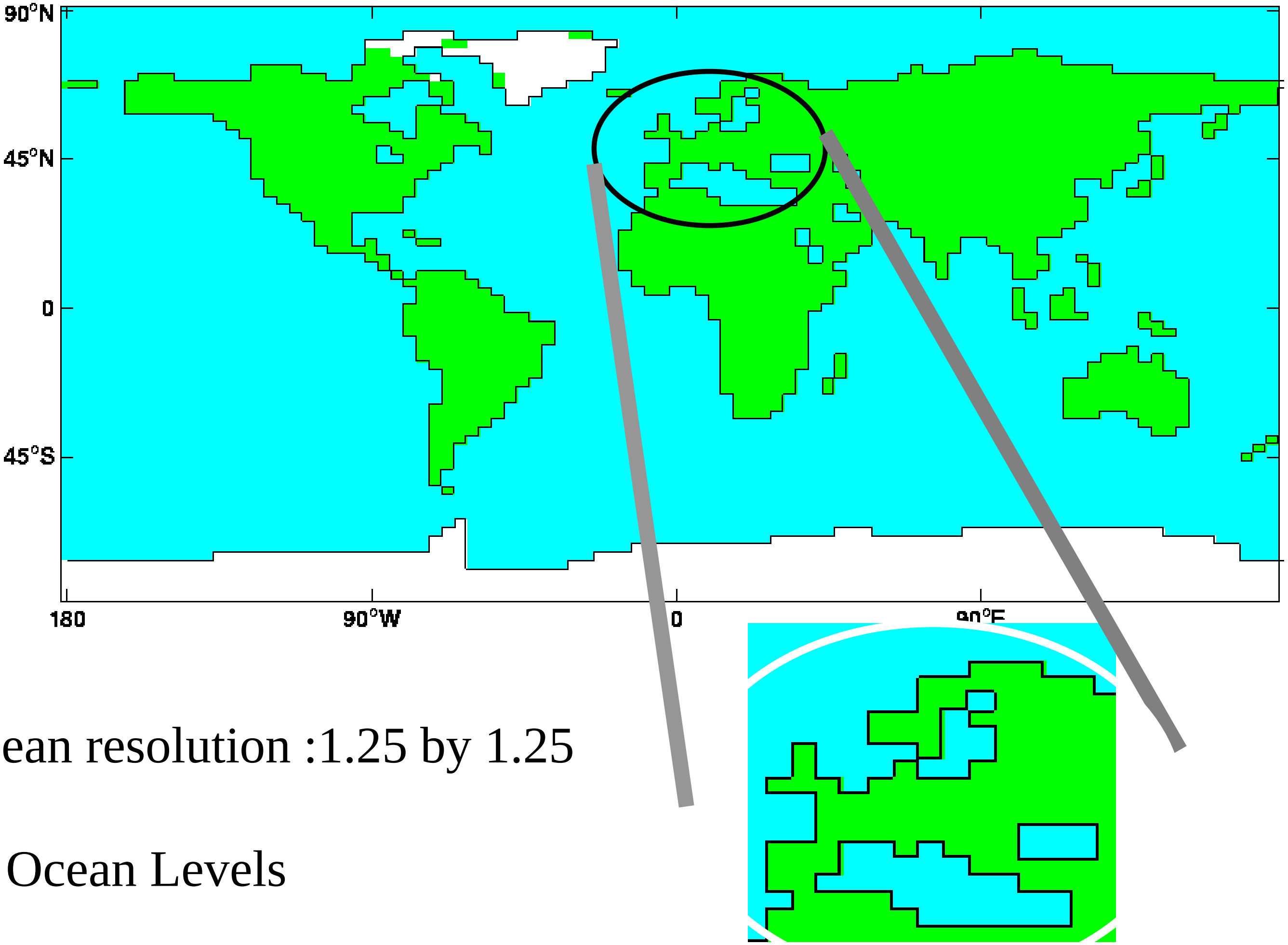
HadCM3 GCM

Atmospheric resolution: 3.75 by 2.5 degrees



19 Atmospheric Levels

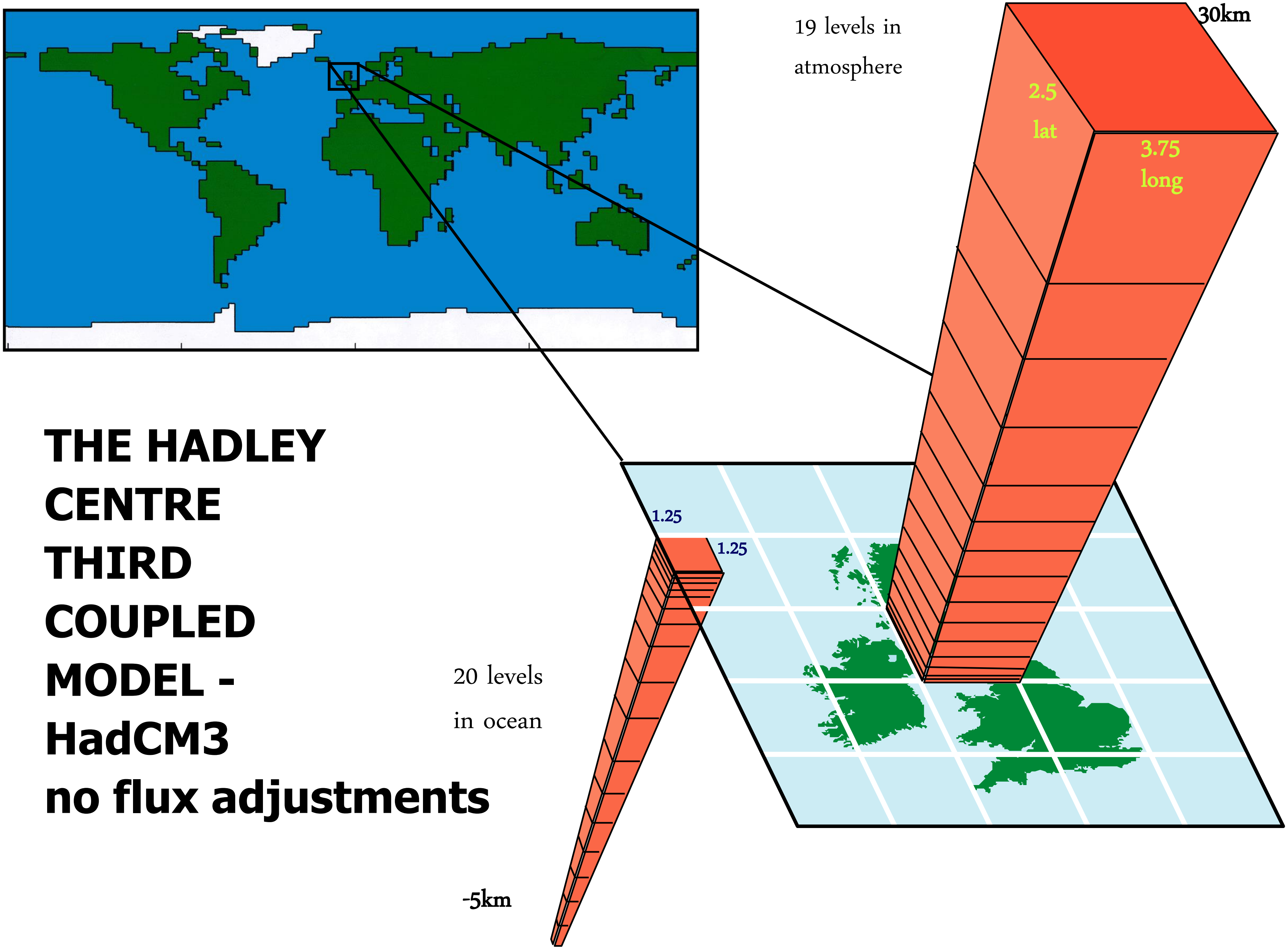




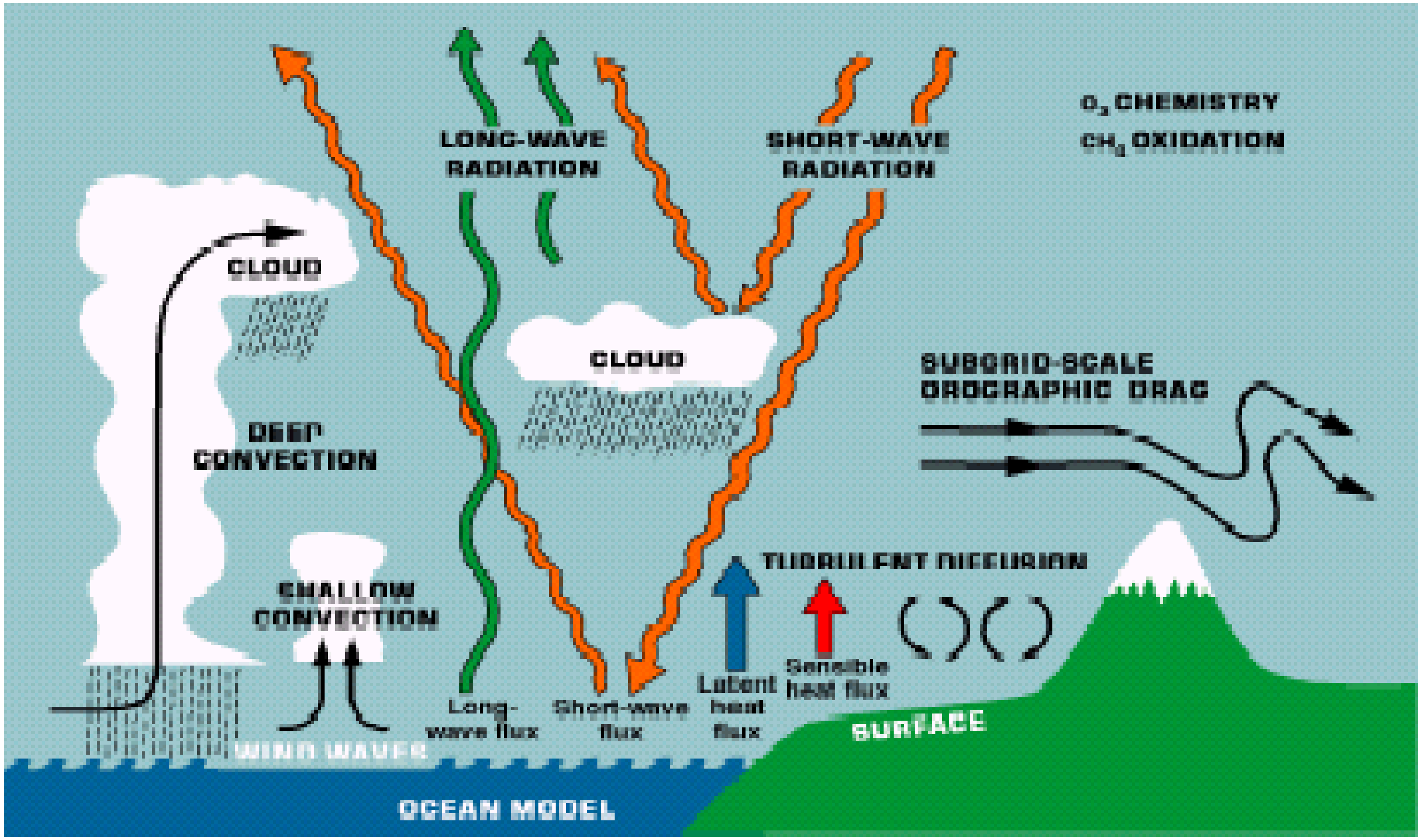
Ocean resolution :1.25 by 1.25

20 Ocean Levels

THE HADLEY CENTRE THIRD COUPLED MODEL - HadCM3 no flux adjustments



Parametrized processes in the ECMWF model

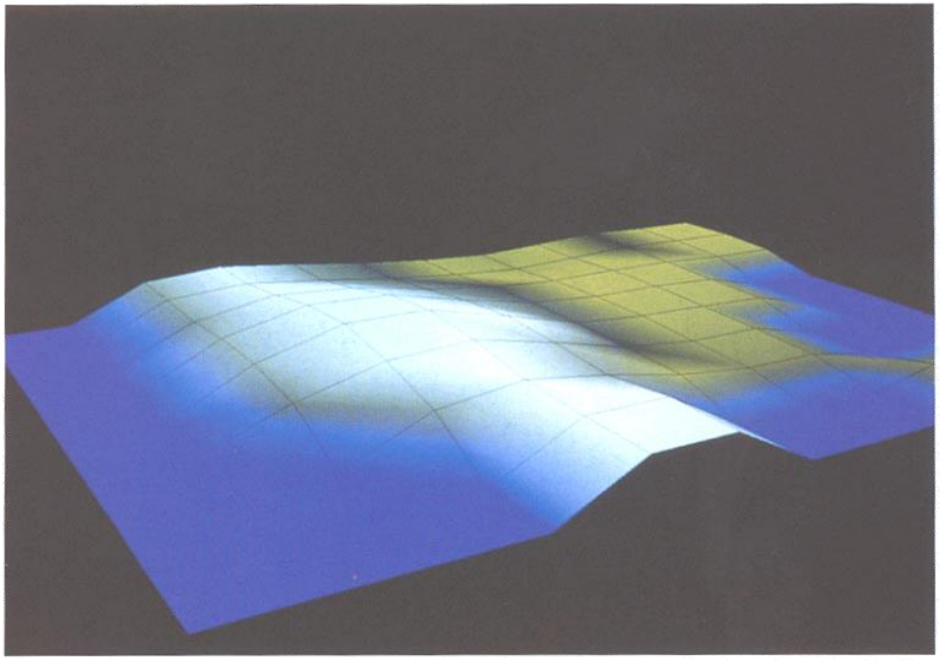


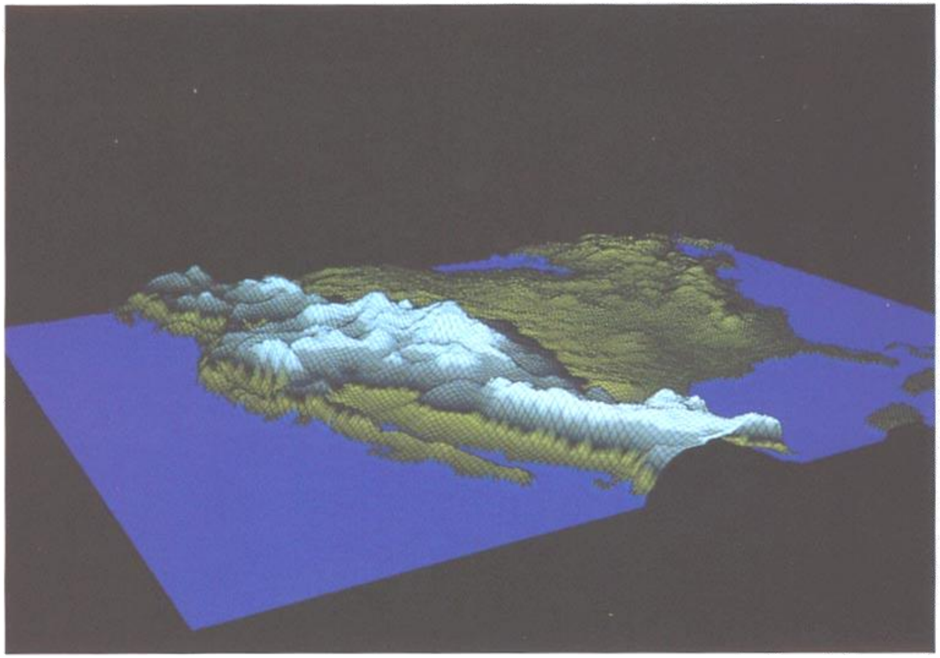
Representation of orography; the importance of resolution

The upper figure shows the surface orography over North America at a resolution of 480km, as in a low resolution climate model.

The lower figure shows the same field at a resolution of 60km, as in a weather forecasting model.

Remember that orographic processes are highly non-linear.



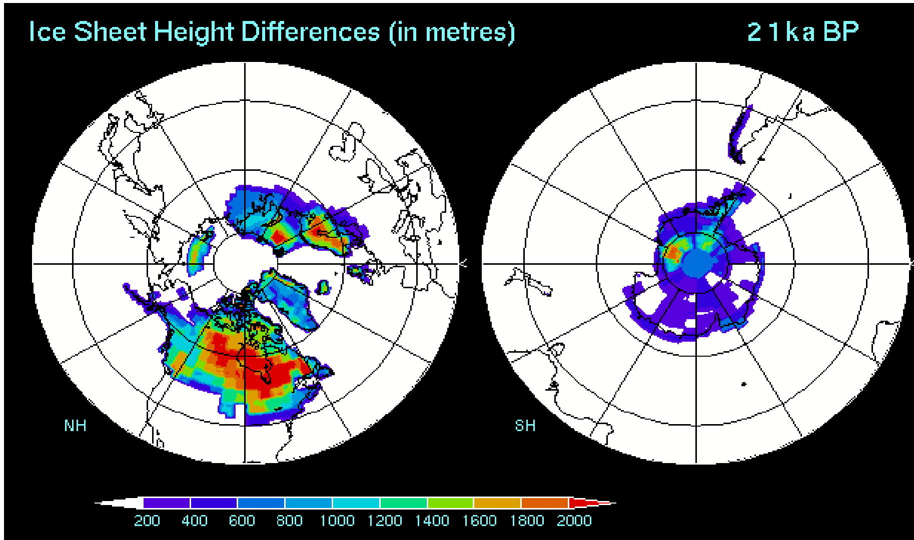


So………

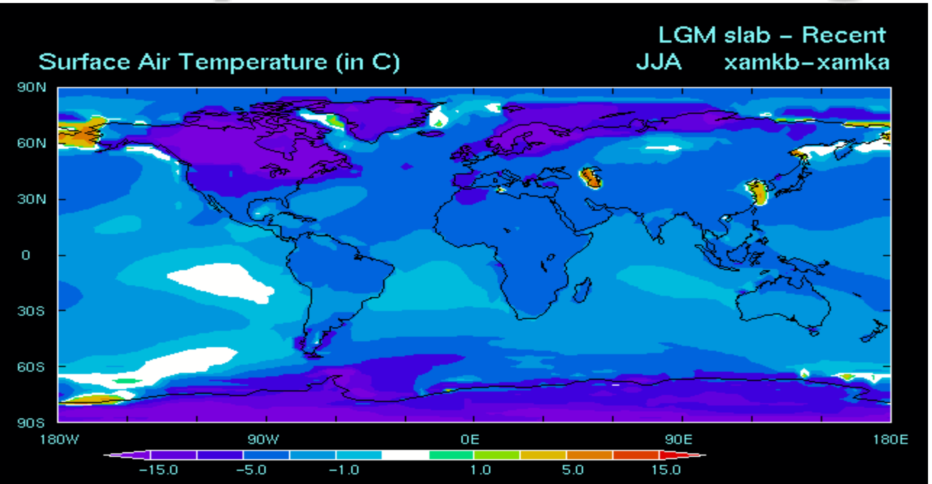
The horizontal and vertical resolutions of climate models need to be high enough to avoid numerical errors and to resolve the basic dynamical and transport processes

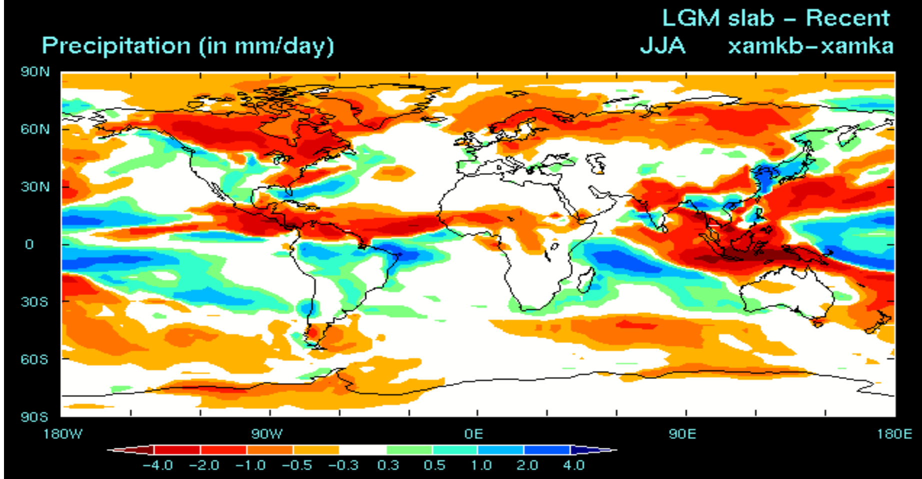
There is a trade-off between resolution and computing time, but model resolutions are increasing continually, as more computer power becomes available

Ice Sheet Elevation

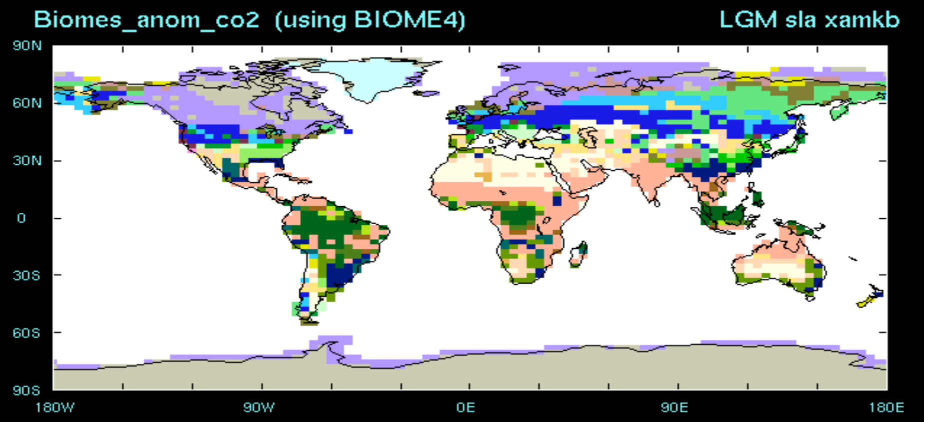


Temperature Change





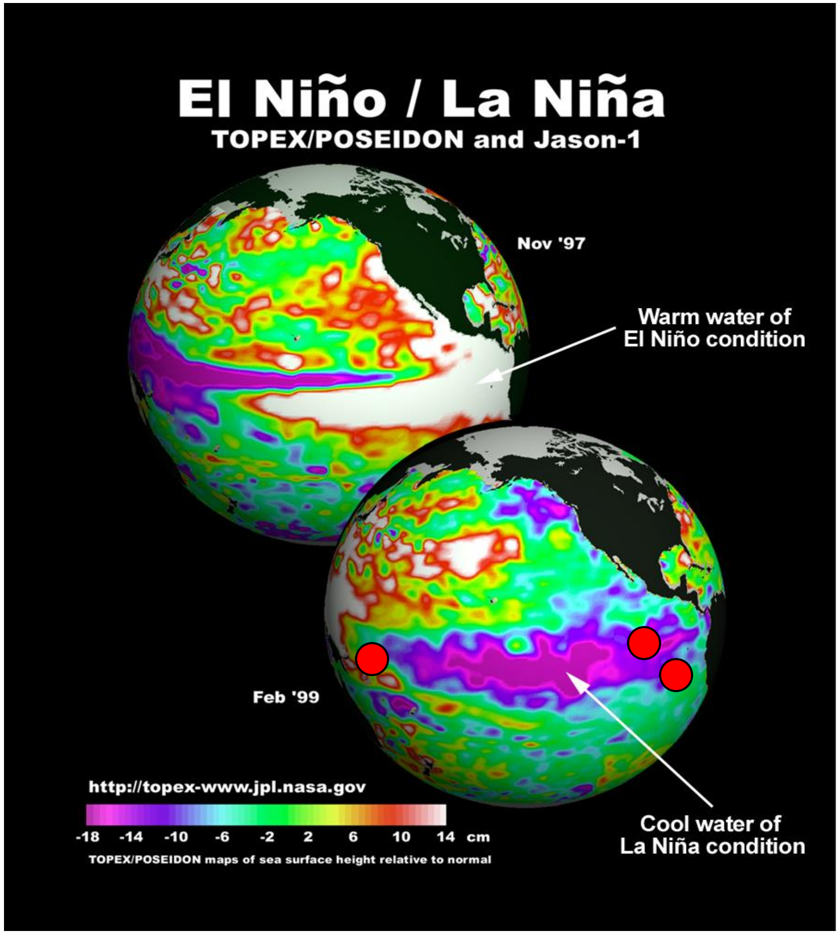
Precipitation



Biomes

Case Studies

1. Palaeo ENSO (El Niño Southern Oscillation)



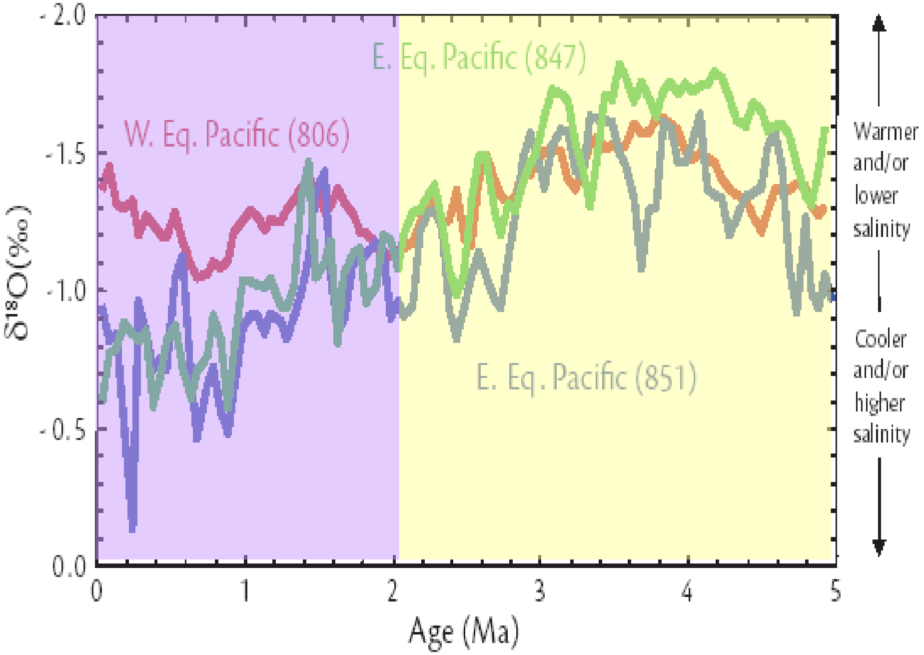
- Coupled ocean-atmosphere phenomena

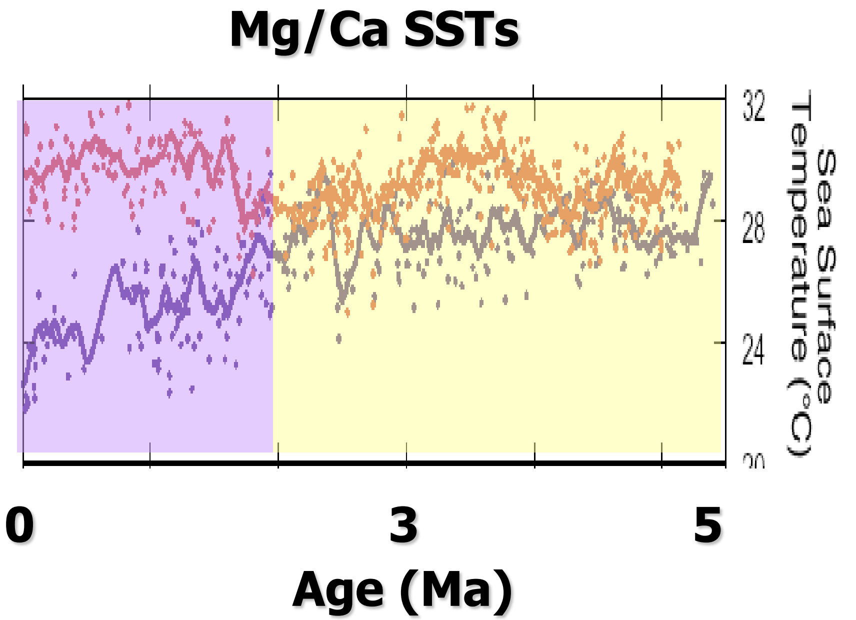
- Involves large scale fluctuations in a number of oceanic/atmospheric variables (e.g. sea surface temps. & sea level pressure)

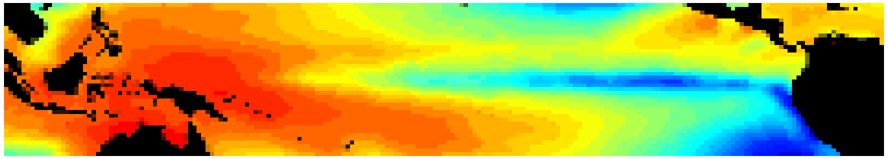
- El Niño & La Niña opposite extremes of ENSO

The Pliocene: a Permanent El Niño-like state?

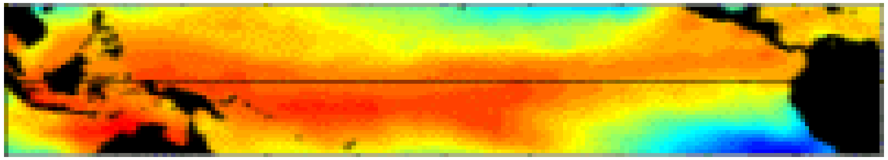
(Wara et al., 2005; Philander & Federov, 2003)




Mg/Ca SSTs

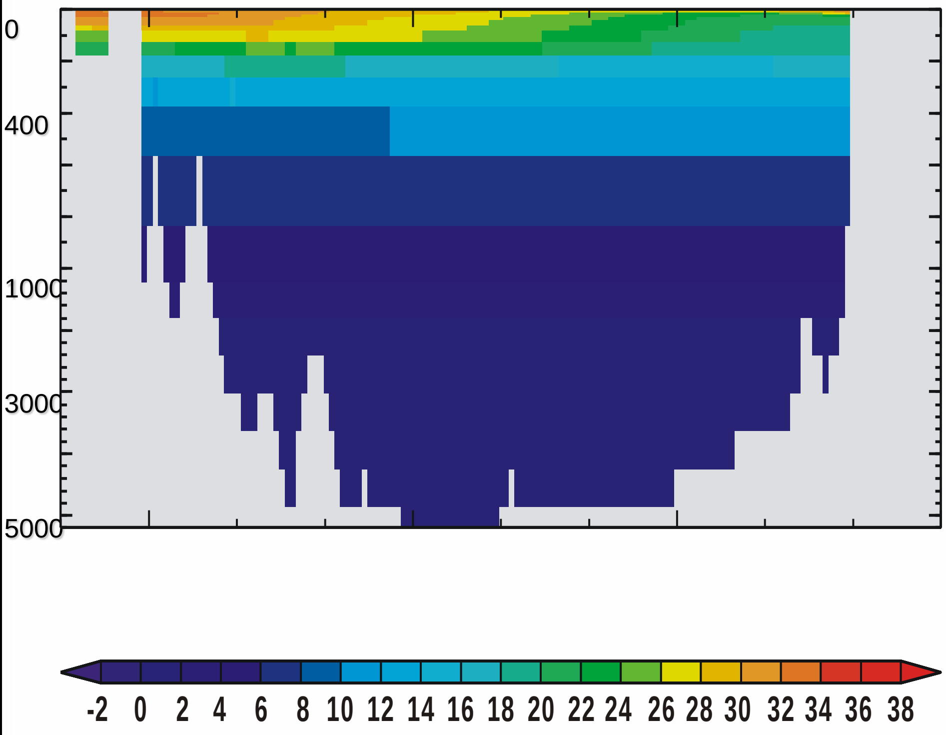


Strong Gradient

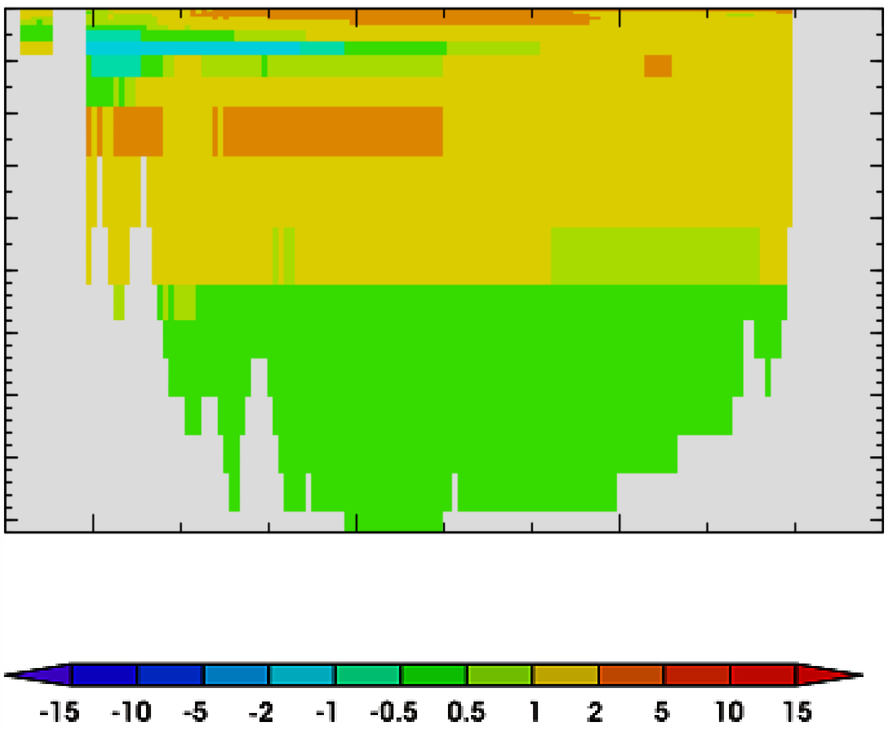


No Gradient

Can a model reproduce this change?

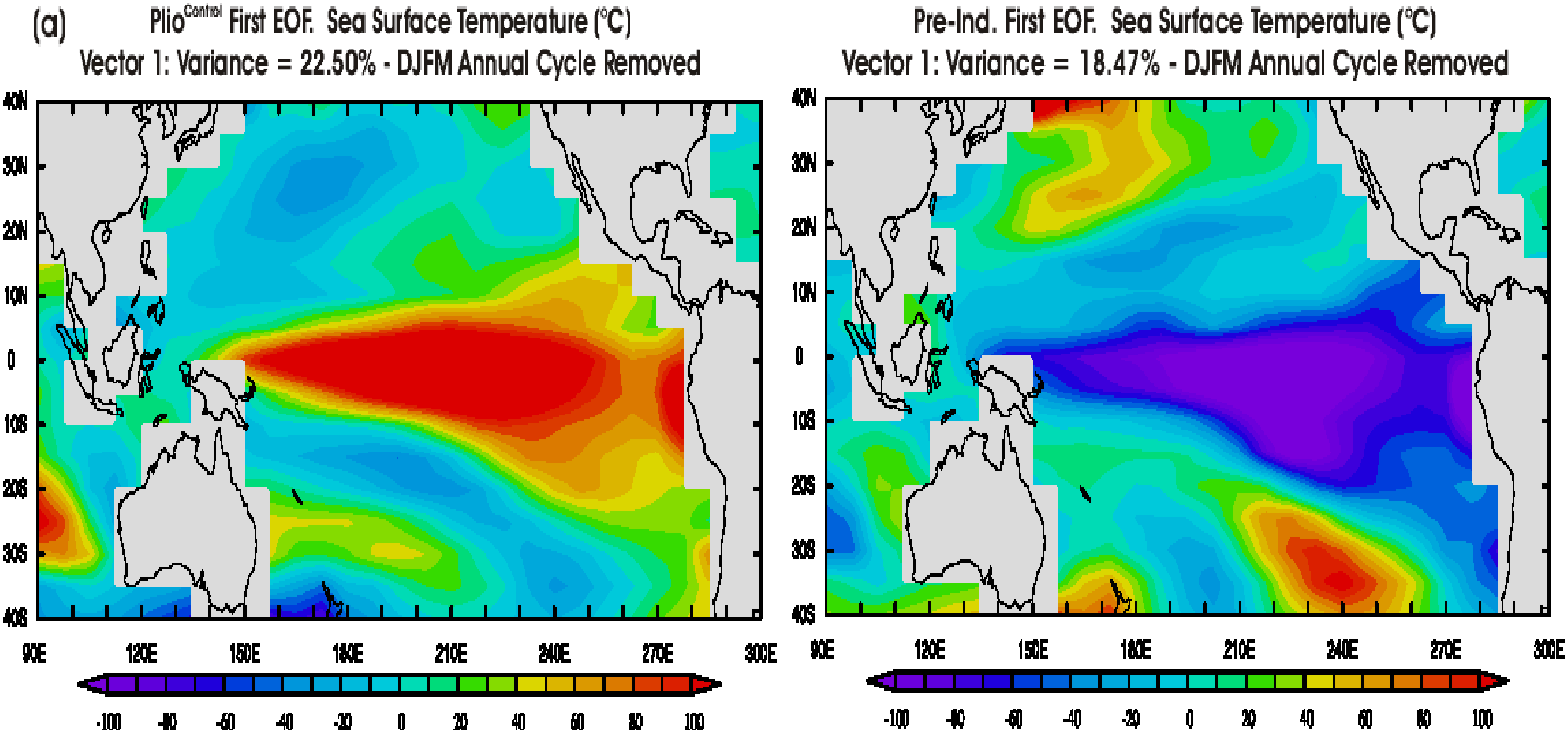


Plio$^{\text{Control}}$ ocean temperatures (°C) across the Pacific at 0°N



Difference between Pliocene$^{\text{Control}}$ and Pre-Ind (°C)

ENSO rather than permanent El-Niño!

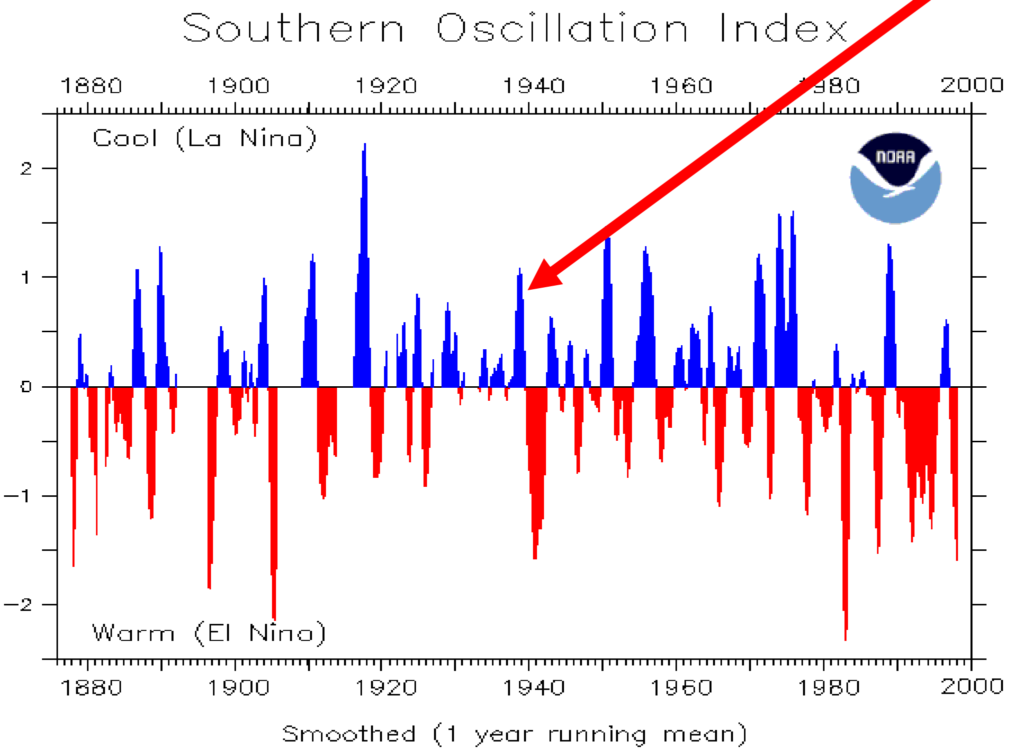


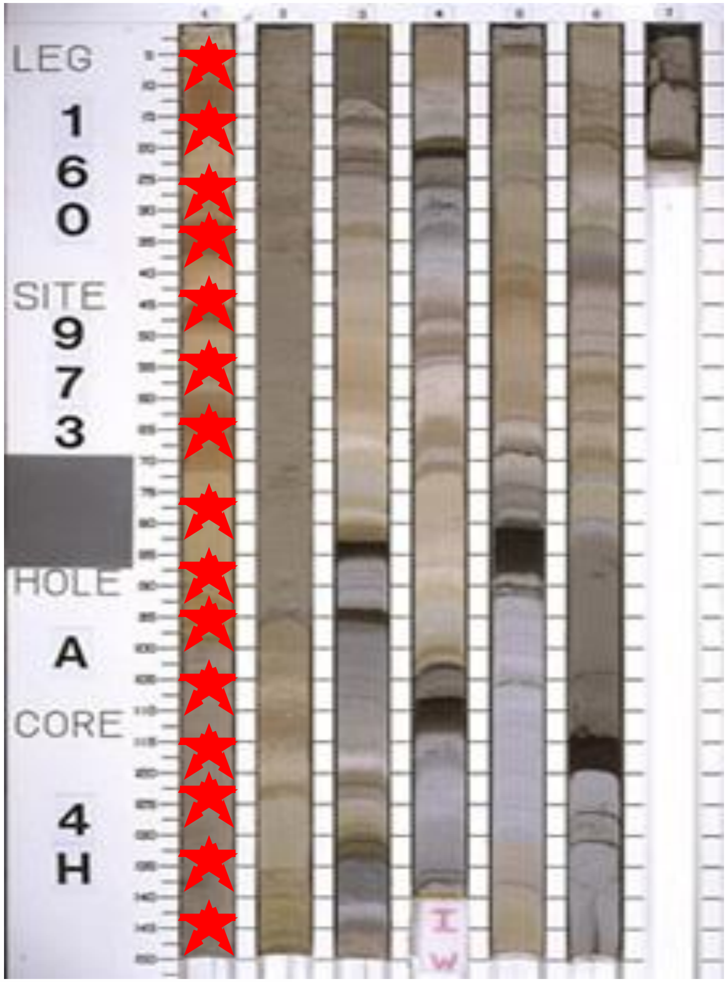
(a) $\text{Plio}^{\text{Control}}$ First EOF. Sea Surface Temperature (°C)
Vector 1: Variance = 22.50% - DJFM Annual Cycle Removed

Pre-Ind. First EOF. Sea Surface Temperature (°C)
Vector 1: Variance = 18.47% - DJFM Annual Cycle Removed

Haywood et al. (in-press). Paleoceanography

“In search of palaeo-ENSO: significance of changes in the mean state”

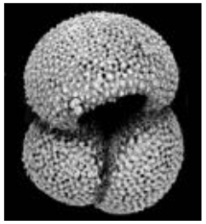




1 sample per 10,000 years

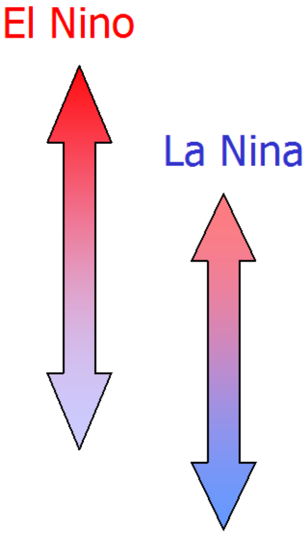
ENSO - Interannual variability

Single specimen analyses however, may provide insight to the range of seasonal extremes within time slices, similar to modern studies in the Gulf of California.



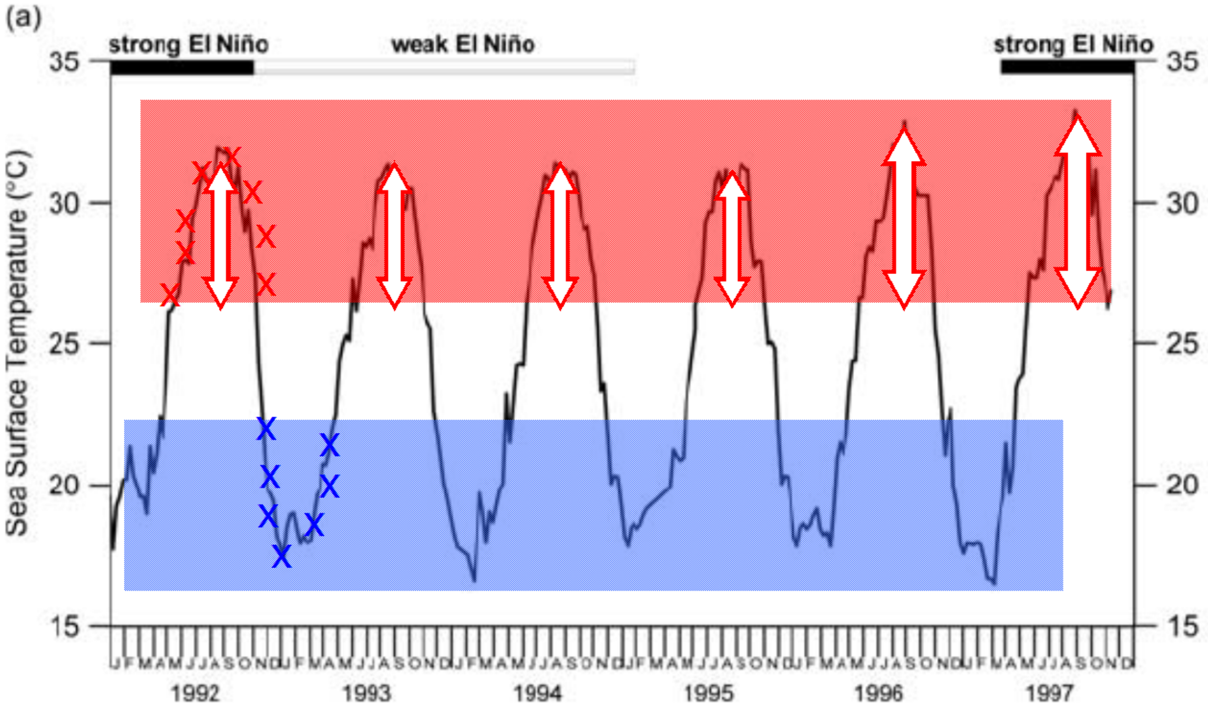
G. ruber

summer



El Nino

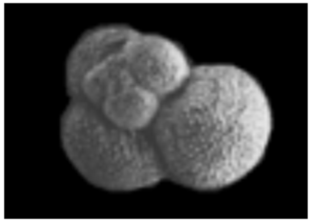
La Nina



McConnell & Thunell, 2005

G. bulloides

Upwelling



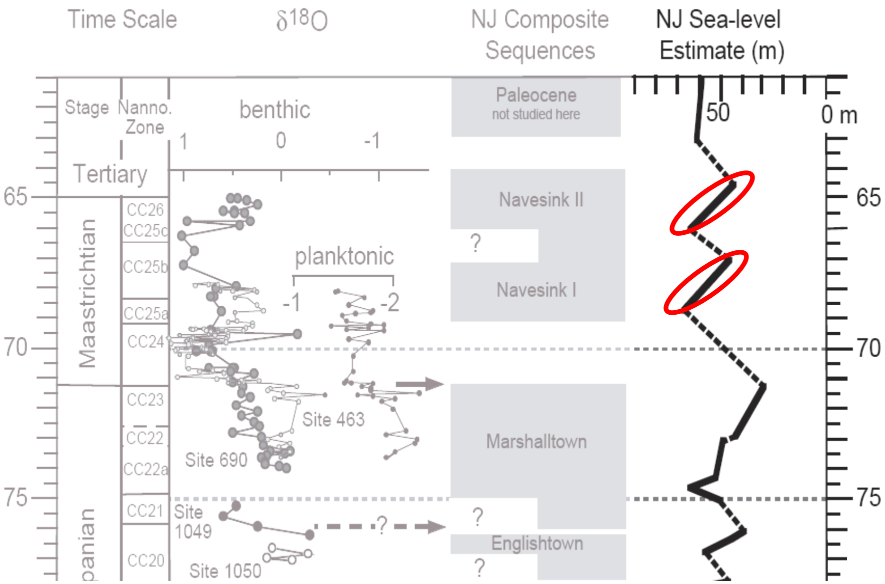
Case Studies

2. Cretaceous Climates & Ice-Sheets

Palaeobotanical Evidence

Cretaceous forest 120 million years ago on the Antarctic Peninsula. reconstruction based on PhD of Jodie Howe, University of Leeds/BAS, painted by Robert Nichols.

Evidence for large, rapid sea-level changes *(Miller et al., 2005)*

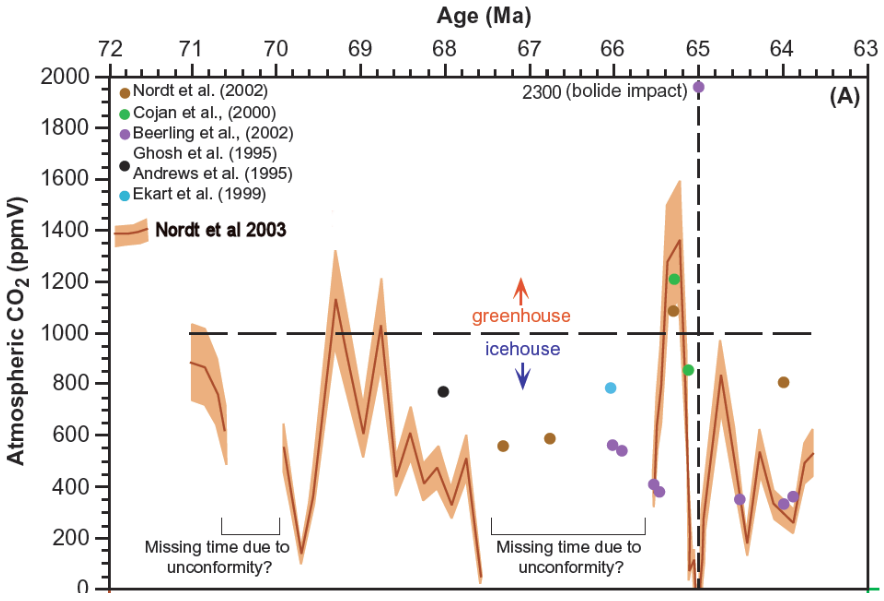


- Evidence for eustatic nature
- Pace and magnitude suggest glacial origin.
- Suggest moderate-sized ice sheets (5 - 10 × 10^6 km^3).
- Paced by Milankovitch forcing.

CO_2 levels through the Maastrichtian

- 2 *greenhouse* episodes 1000-1400 ppm
- But suggestions of CO_2 low-points at ~70 and 66 Ma.

(*Nordt et al., 2003; Beerling et al., 2002*).

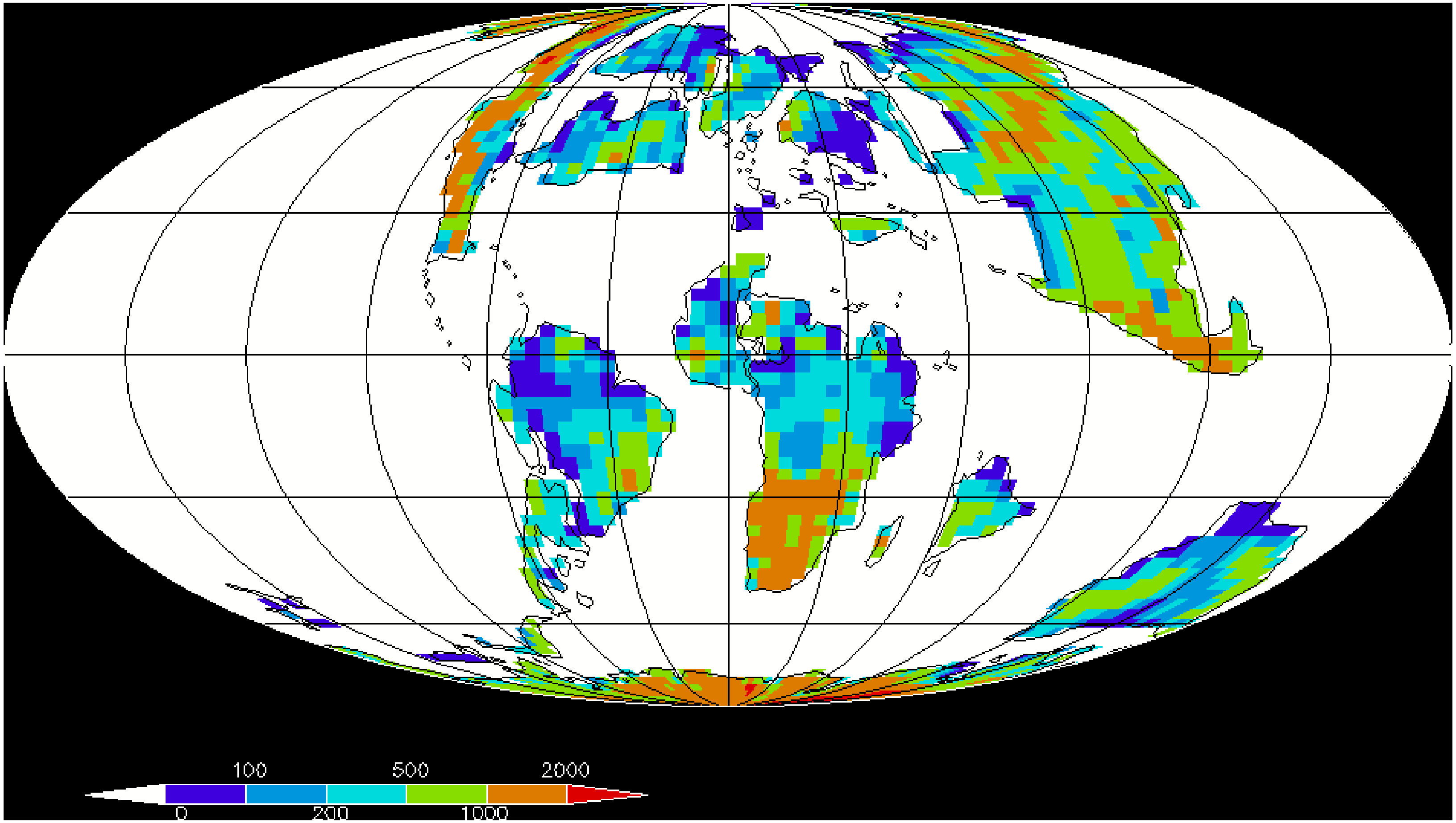


How to create a Maastrictian model

Change solar output	~0.6% less than present
CO_2 (and other gases)	4 x pre-industrial (but could be 2x to 8x.
Volcanic activity	Assume same as today.
Change in orbit	Same as present, but perform sensitivity simulations
Palaeogeography	Including sea-level/ orography/ bathymetry/land ice

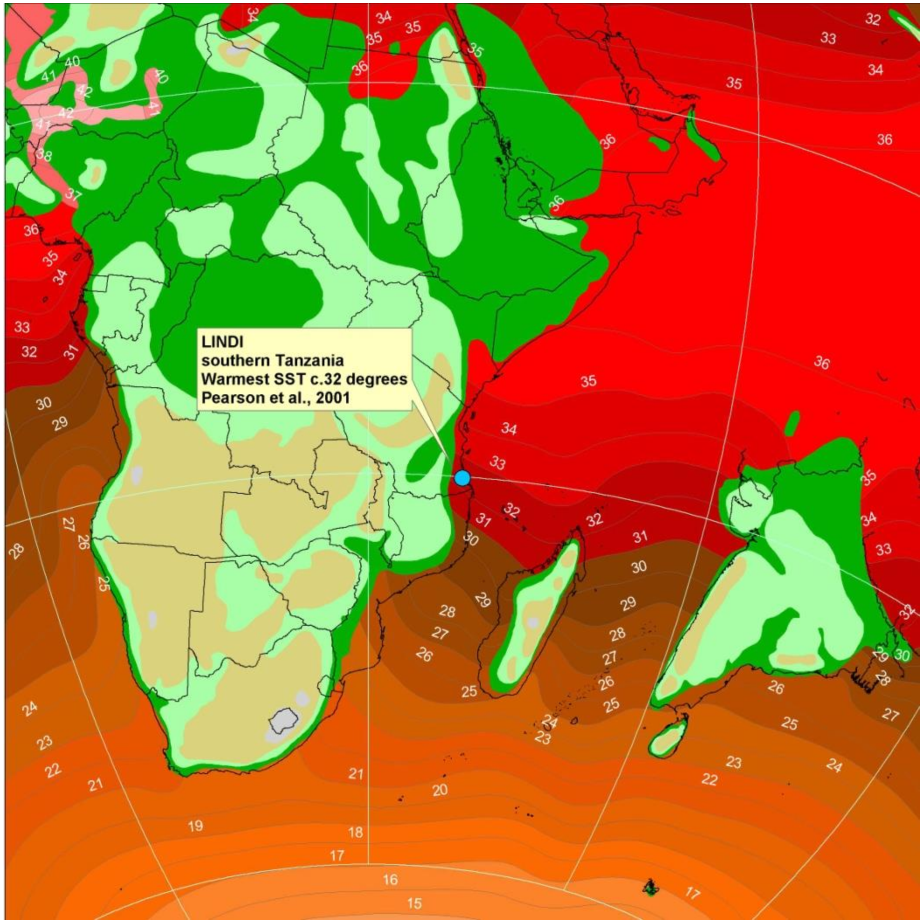
Previous modelling also required prescription of vegetation, and sea surface temperatures (or ocean heat transport) but this is no longer needed.

Maastrictian Orography



At climate model resolution. Original palaeogeographies from Paul Markwick

Coupled Ocean-Atmosphere Simulation: Comparison to Oxygen Isotopes



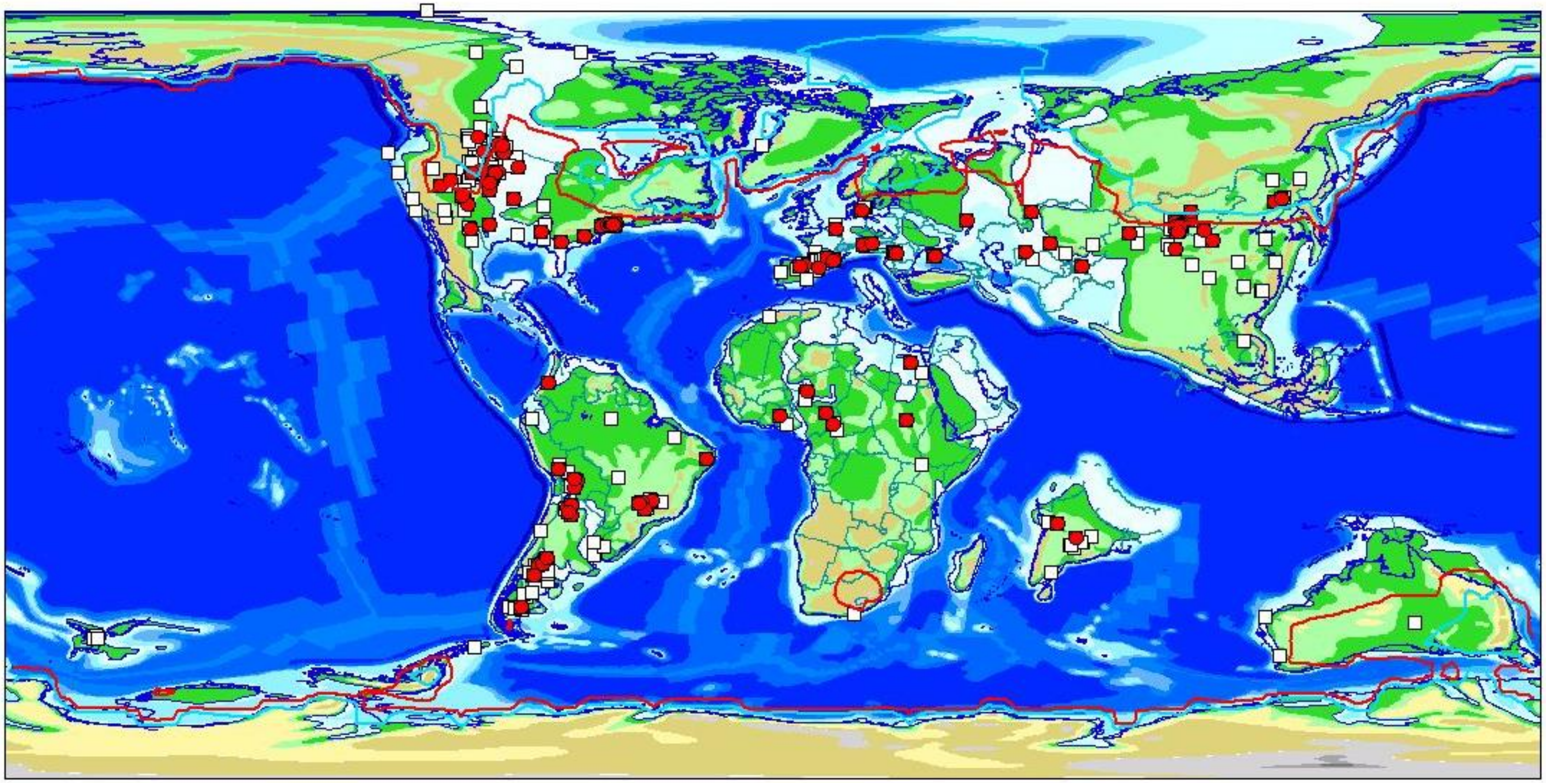
LINDI
southern Tanzania
Warmest SST c.32 degrees
Pearson et al., 2001

Model predicted temperatures approx. 10C at 1000m, 8C at 2000m, and 7C at 3000m

c.f. temperatures from 14C to 7C from D’Hondt & Arthur (2002)

Paul Pearson's Maastrictian data

Coupled Ocean-Atmosphere Simulation: Comparison to Vertebrate Data



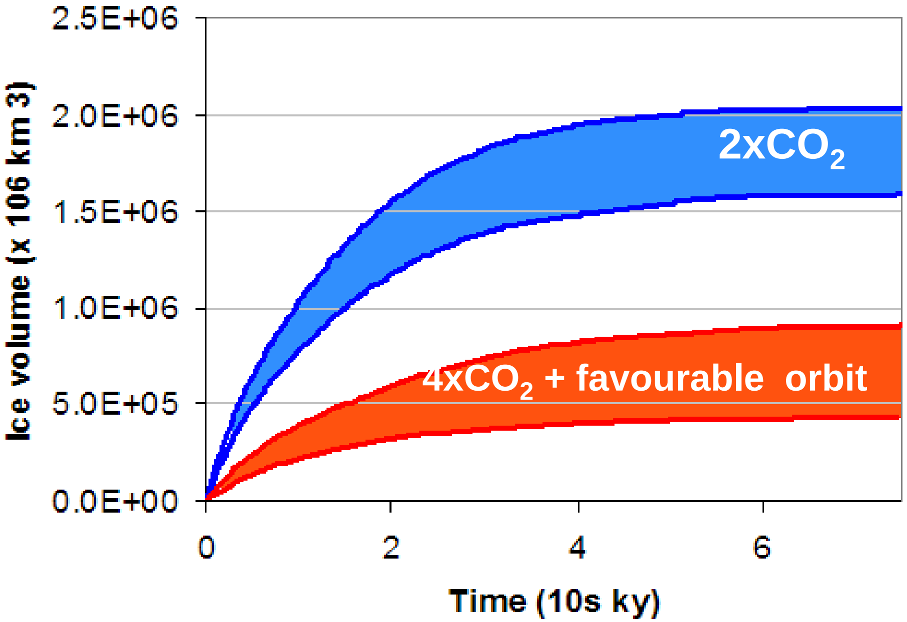
Red squares= all crocs, Orange= Dinosaurs, White = Other Vertebrates

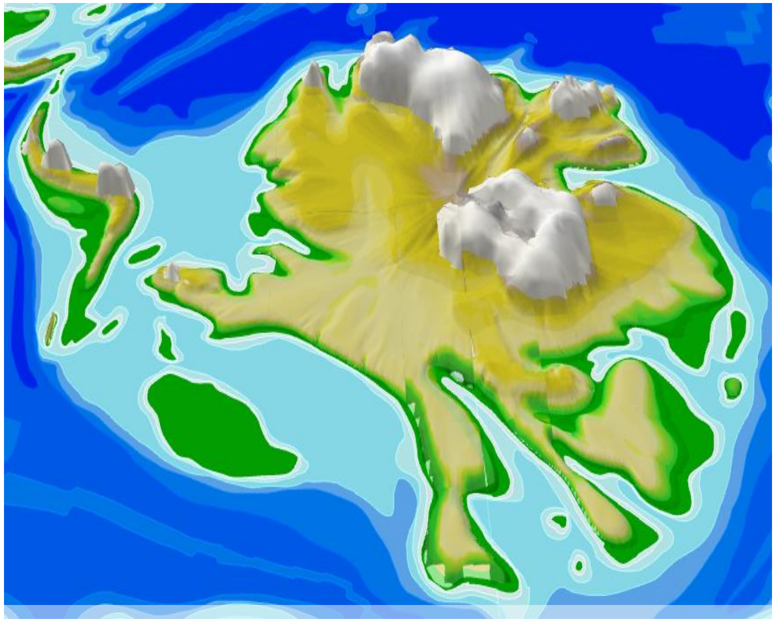
Model predicted cold month mean shown by 5C contour (red) and 0C (blue)

Paul Markwick's database

Ice Sheets in a Greenhouse World

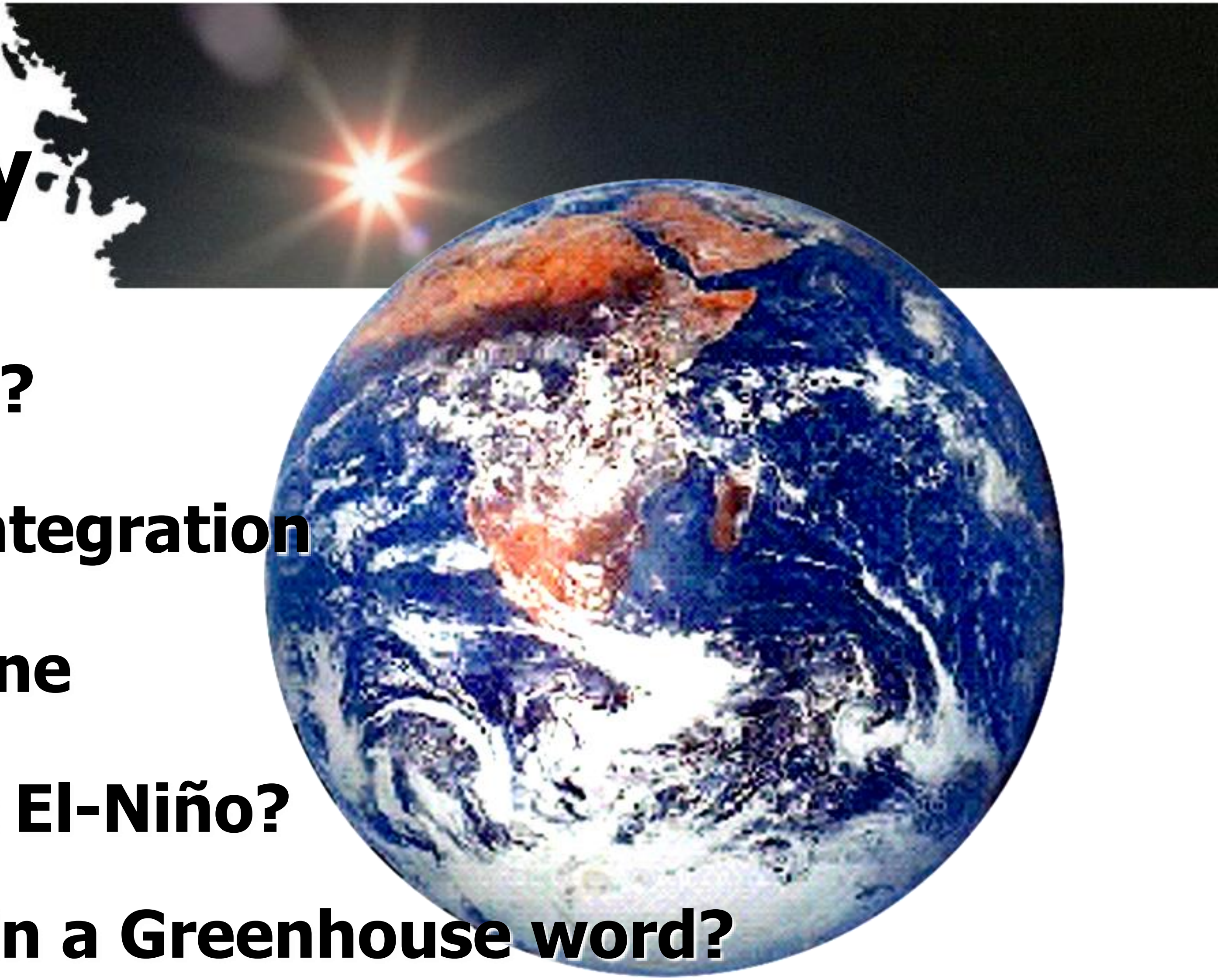
- Suite of HadCM3 derived palaeoclimates
  - 2, 4, and 6 x CO_2
  - Further runs being carried out including 1 x CO_2
- Comparison against climate proxy database
- Climate then used to drive a BAS ice-sheet model.





$2xCO_2$ - ~ 2 x 10^6 km^3 ice

Summary



- **Why Model?**
- **Need for Integration**
- **How its Done**
- **Permanent El-Niño?**
- **Glaciation in a Greenhouse word?**

NO PROBLEM