QUEST and Modelling of the Earth System

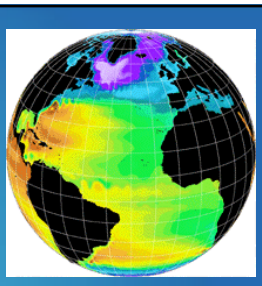
John Shepherd

School of Ocean & Earth Science
Southampton Oceanography Centre
University of Southampton
&
Tyndall Centre for Climate Change Research

Why is modelling a crucial component of QUEST ?

- **Because QUEST is about *Quantifying* the Earth *System***
  - on ***all*** time-scales (diurnal to geological)
- From hand-waving to quantitative ***explanation*** and ***interpretation*** (of observations)...
  - ideally using inverse modelling and data assimilation
- ...and (eventually) leading to ***prediction***
- Modelling provides an ***interpretative framework*** for observations
- and a guide to what ***needs*** to be known

What is the Earth System ?



The Earth System comprises

- *the solid Earth and the land surface*
- *the hydrosphere (oceans, rivers & lakes)*
- *the atmosphere*
- *the cryosphere (sea-ice, glaciers and the ice caps)*
- *the biosphere – both terrestrial and marine.*

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What is Earth System Science?

The components of the Earth system

- *interact over an enormous range of scales in space and time*
- *exhibit a range of fascinating phenomena, including*
  - *–the formation and movement of continents*
  - *–the opening and closing of ocean basins*
  - *–the formation and erosion of mountain ranges*
  - *–the waxing and waning of massive ice-sheets*
  - *–the inception and evolution of life*
  - *–climate change on all time scales*

Earth System Science and Modelling seeks to understand and model this system and these processes as a whole.

It is interdisciplinary science - "par excellence"

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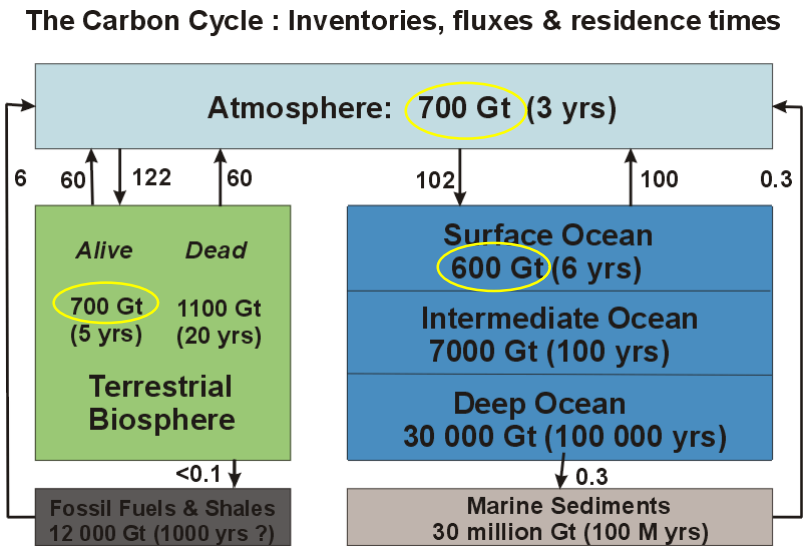
Key Issues

- ♦ Climate Change : the next millennium (?)
  - oceanic response (THC), exhaustion of fossil fuels
- ♦ Natural variability
  - palaeoclimate studies provide the context
- ♦ The Hydrological cycle: regime shifts ?
- ♦ The Carbon cycle
  - and so also nitrate, phosphate, oxygen, alkalinity**...**
- ♦ Carbon Management
  - especially sequestration of CO_2 (?)
  - Integrated Assessments (technology & socio-economics)
- ♦ Other Ecosystem level impacts
  - especially acidification & calcification problems ?

The Carbon Cycle



CO_2 & Climate : the last 300 Myr (after Retallack, Nature, 2001)

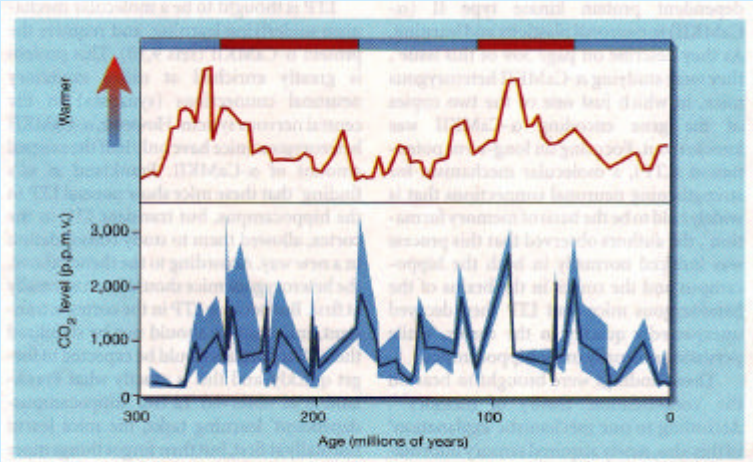
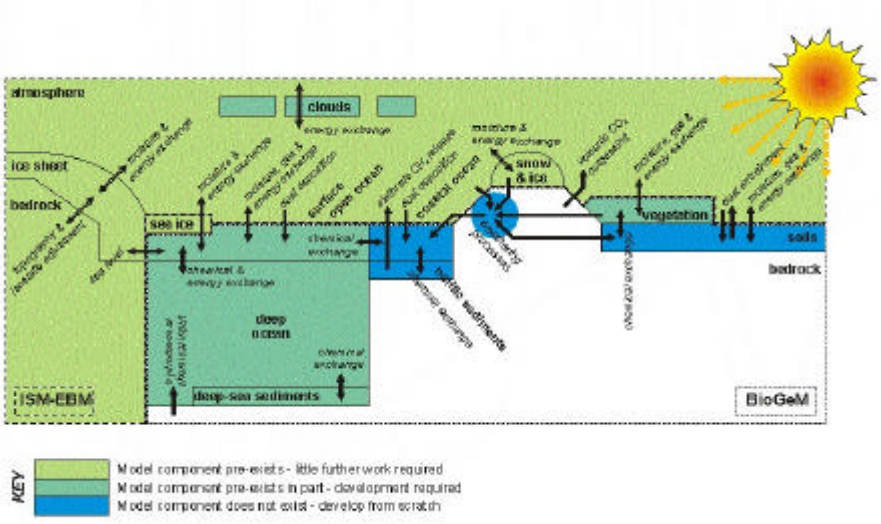


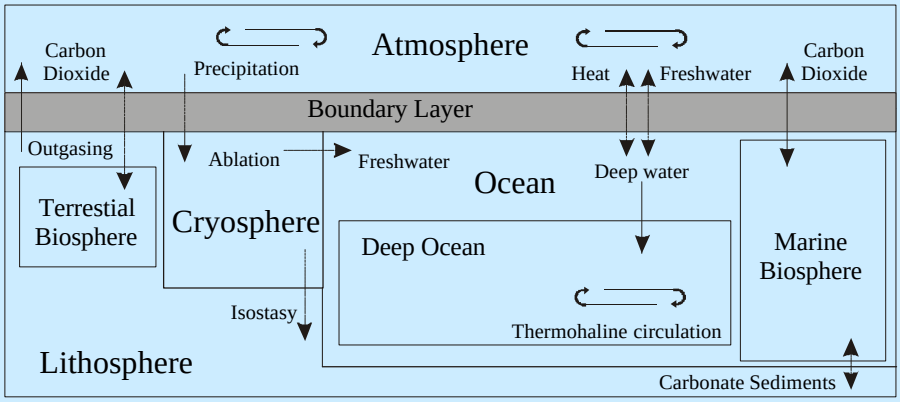
Figure 2 **Levels of CO_2 in the atmosphere (bottom) and temperature trends over the past 300 million years. The CO_2 curve is the mean, with the 'envelope' showing the standard deviation, and is based on Retallack's stomatal-index analysis[1] of *Ginkgo* leaves and the fossil leaves of closely related plants;**

The Earth System (according to GENIE)



Slide courtesy of
A. Ridgwell (Genie)

Schematic of the Earth System



Slide courtesy of P.Valdes (Genie)

Essential Earth System Processes

(on land and sea, and in the air)

- Plate tectonics & volcanic activity
- Weathering, erosion, sedimentation
- Biological production, biogeochemistry and the ***carbon cycle***
- Radiation (absorption, reflection, emission...)
- Convection (mantle, atmosphere and ocean)
- Oceanic transport (heat, salt, water, nutrients...)
- Atmospheric transport (heat, water, CO_2, etc)
- Hydrology (evaporation, precipitation, run-off...)
- Ice: accumulation, ablation, transport
- Soils & Sediments (formation & erosion)

Earth System Models

Processes & Timescales

Time-scale (years)	Planetary	Continents	Land	Sea	Atmosphere	Ice	Biosphere
Billions	Solar evolution	Formation & Accretion	Erosion & deposition	Formation & Evolution	Formation & Oxygenation	Snowball Glaciations ??	Origin of Life, "Mostly bacteria"
~1e8		Continental Drift	Colonisation by plants	Basin formation		Mostly warm & ice-free	Plants & animals
~1e7		Volcanic episodes	Mountain building	Sediment accumulation		Episodic Glaciations	Mass extinctions
Millions		Crustal weathering		Chemistry (calcium)		Polar ice-caps	Species extinctions
~1e5	Insolation (Eccentricity)			Sea-level changes		Glacial cycles	
~1e4	(Obliquity & precession)			Chemistry (phosphate)		Last glacial to Holocene	
Thousands	Solar Variations ?			Thermo-haline circulation	Millennial (DO) Oscillations		Eco-system evolution
~100	ditto				Abrupt Climate Changes		
~10	ditto			O-A Coupled Modes?	Decadal Modes?		
~1						Sea-ice variability	

Structure & Resolution versus Timescales

- Dimensionality & structure
  - from 0D (EBM's and box models) to 3D (GCM's)
  - Order of importance ≈ vertical, latitude, longitude...
  - N.B. Land/Sea/Ice distributions at sub-grid scales ?
- Resolution : how much is enough?
  - High/Fine : <1° lat/long, with >15 levels (atmosphere & ocean)
  - Moderate : 1° to 5°, with 5 to 10 levels
  - Low/Coarse : > 5°, with <5 levels
- Time-scales of major variations and **events of interest** determine the **integration times** needed
  - decadal, millennial, glacial and beyond (to >100 Myr)
- Time-scales of major variations of **forcing**...
  - diurnal, seasonal, annual, decadal, millennial, orbital...
- ...and the **rates of processes**, the spatial resolution & the methods used determine the max. permissible **time-step**

ESM's and "Complexity"

- **High spatial resolution** (especially of fluids...)
  - => **many variables** (of approx the same sort)
  - => short time-steps, and **high computational cost**
- **Many (diverse) processes**
  - **Hydrology** (evaporation, precipitation, run-off...)
  - **Sea-ice** (accumulation, melting, advection, fractures...)
  - **Ice-sheets** (accumulation, ablation, flow, deformation...)
  - **Carbon-cycle** (land, sea, plants, bacteria, animals (???)
    - production, respiration, nutrients, re-mineralisation, sediments
  - => **many (**diverse**) parameters**
- In future, we need **both** of these
  - => potentially **much higher computational cost**
  - a role for **Intermediate Complexity Models** (EMICS)
- Simpler models facilitate ***scientific understanding***

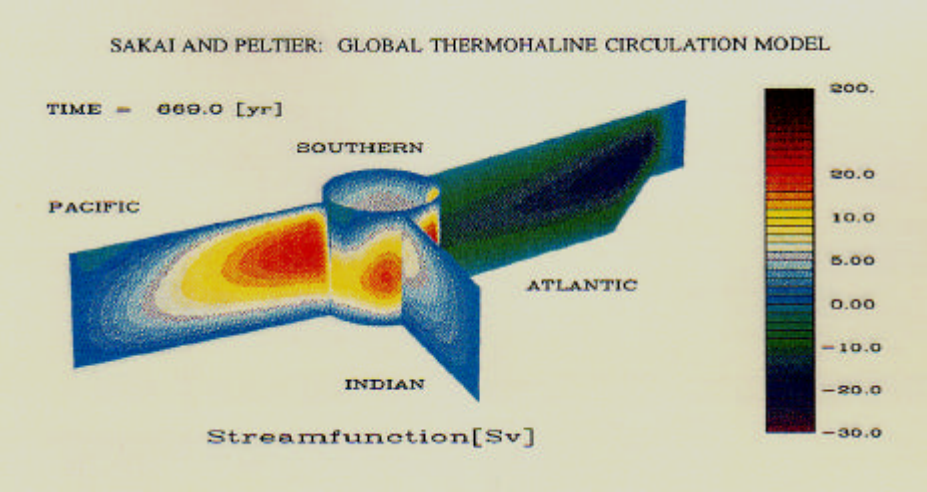
Existing EMICS

Information from M. Claussen (PIK) et al

Model	Institute	Dimension		Total "Cells"		M/C	CPU
		Ocean	Atmos	Ocean	Atmos	type	(hours
							per kyr)
Bern 2.5D	**Univ. of Bern**	**2.5**	**1**	504	17	WS	0.05
CLIMBER-2	**PIK**	**2.5**	**2.5**	4320	252	WS	2
ECBilt-2	**KNMI**	**3**	**2.5**	38912	6144	SG(2)	336
CLIO-E-V	**Louvain**	**3**	**2.5**	144000	6144	WS	300
RAS	**IAP Moscow**	**2.5**	**3**	7200	19200	WS	125
MPM	**McGill Univ**	**2.5**	**1.5**	648	216	WS	8
IGSM	**MIT**	**3**	**2**	60750	216	WS	200
MoBidiC	**Louvain**	**2.5**	**1.5**	1620	72	WS	3
PUMA-LSG	**MPI Hamburg**	**3**	**3**	28512	10240	Cray	24
ESCM	**U. Victoria (BC)**	**3**	**2**	190000	~10000	SP2	240
HADCM3	**Hadley Centre**	**3**	**3**	262656	87552	Cray	10000
FORTE	**SOC/Reading**	**3**	**3**	60750	45056	WS/PC	~1000
C-GOLDSTEIN	**SOC/Univ.Bern**	**3**	**2**	10368	1296	W/S	~ 1
"Target"	**GENIE (UK)**	**3**	**3**	11664	6480	WS	1

2.5D Ocean models

(Stocker, Wright & Mysak 1992)



CLIMBER-2

Petoukhov et al, Climate Dynamics (2000)

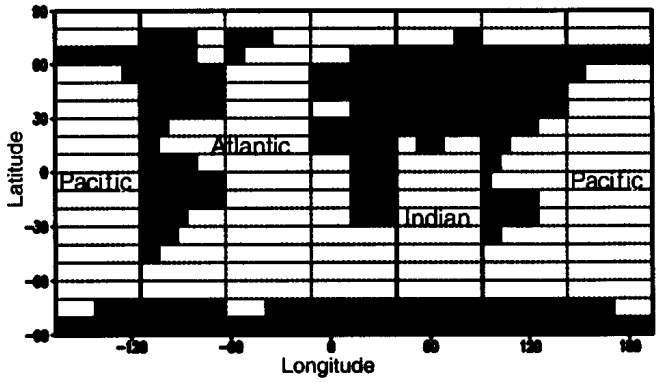
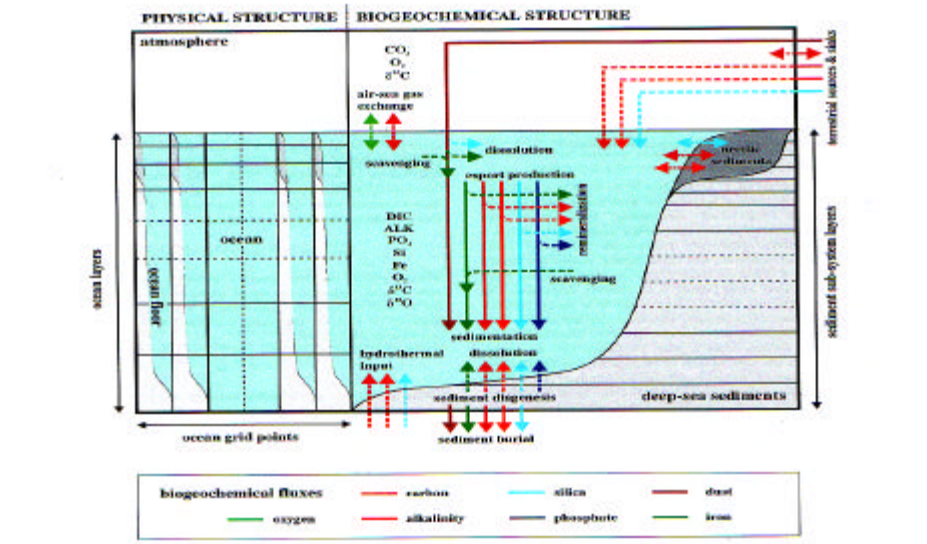


Fig. 1 Representation of the Earth's geography in the model. *Dashed lines* show atmospheric grid, *solid lines* separate ocean basins

Marine Biogeochemical Processes
(A. Ridgwell, 2001)



Variability & Predictability

- The Earth's Climate System apparently exhibits **Multiple quasi-stable states**
  - presumably due to positive feedbacks
- and **Quasi-periodic behaviour**
  - damped natural modes, paced by external forcing ?
- On all time scales (?) from **seasons to aeons**
- We need efficient ESM's
  - to **explore parameter-space**
  - to run decent-sized **ensembles,** to establish variability, and the extent of predictability
  - for proper **interpretation of palaeo-climate proxies**
- We need a diverse **spectrum of efficient models**, also to allow for **inter-comparison & replication**

Where next ? We need to...

- **run ensembles** and/or **explore parameter space**
  - hundreds to thousands of runs (also for **Integrated Assessments**)
- and/or **extend integration times** (to > 30 kyr)
  - for (e.g.) glacial cycles & nutrient residence times
- requires **moderate resolution** models and **faster schemes**
- go to **3D**, and **"populate the spectrum"** of models
  - in both ***structure*** and in ***resolution***
  - ***"horses for courses"***
  - inter-compare (up/down the spectrum)
- promote **scalability** and **modularity**
- develop new & better **parameterisations**...
- **Play !! (**to truly understand model behaviour)
  - and to allow for accidental discoveries ...
  - ...but this probably requires over-night runs (at most)

Populating the model spectrum
"horses for courses"

(where length of "course" ≈ simulated integration time)
=> ***processes which need to be represented***

- **> 10 Myr**: tectonics, subduction, vulcanism, ocean basin formation & destruction, carbonate rock formation & recycling
  - ***1D and box models***
- **30 kyr to 10 Myr**: silicate rock weathering, ocean calcium and carbonate balance, biological production, sedimentation
  - ***1D/2D models, to very coarse ICM's***
- **300 yr to 30 kyr:** ocean circulation, nutrient biogeochemistry & recycling, biological production
  - ***2.5D/3D models, moderate ICM's, to low-res GCM's***
- **up to 300 years:** well-resolved ocean & atmosphere circulations, land surface hydrology, terrestrial biosphere, etc
  - ***3D models, high-res ICM's to maximum-resolution GCM's***

Populating the model spectrum

Complexity ≈ detail × processes

resolution (space & time) *versus* maximum **integration time**

		Physical and Bio-geo-				Ocean/Atmos Dimensionality				
	Maximum	-chemical Processes								
Approx	Integration					0D	1D/1.5D	2D/2.5D	3D	
Cells	Time (yrs)	P	C	B	G					Examples
3	> 30M		*****	*	**	box				many
30	10M		*****	**	****	box	LCM			Pandora
300	3M	*	*****	***	***	box	LCM	L-ICM		Bern
1k	1M	**	****	****	**		L-ICM	L-ICM		Louvain
3k	100k	**	****	****	**			M-ICM	M-ICM	PIK(Climber)
10k	30k	***	***	****	*				M-ICM	C-Goldstein
30k	10k	***	***	****	*				H-ICM	GENIE
100k	3k	***	**	**					VH-ICM	FORTE
300k	1k	***	**	**					L-GCM	HADCM3
3M	300	****	*	*					M-GCM	
30M	30	*****							H-GCM	OCCAM
300M	10	*****							VH-GCM	

Towards multi-millennial 3D Earth System models on your desktop

- use **moderate** resolution
  - a few degrees lat/long
  - a few thousand cells (in 3D)
  - in both ocean & atmosphere
- and **clever parameterisations**
  - of turbulent transports (isopycnal mixing, etc)
  - of sub grid-scale frequency distributions
- more **efficient** ways to deal with the fluid systems
  - non eddy-resolving oceans and atmospheres ?
  - overcoming the CFL (etc) stability limitations

Parameterisation

- is a high order intellectual activity
  (J. McWilliams)
  - ***not a dirty word !***
- requires "asymptotic feasibilty" (credibility)
- should preferably be based on "sound science"
- we could & should
  - "cascade" parameterisations up/down the spectrum
  - use sub-grid scale statistical representations more extensively (c.f. hydrology)
    - i.e. work with p.d.f.'s (percentile values) within cells ?
    - for hydrology, topography, clouds, ice, vegetation, etc...

Efficient 3D IC climate models

- E.g. LSG/PUMA (MPI Hamburg) :
  - partly implicit scheme
  - neglects acceleration terms
- **Forte** (MOMA + Reading IGCM)
- Frictional (planetary) geostrophic (FG) models
  - solve equations for slow dynamics only
    - neglect acceleration & inertia, include (Rayleigh) friction
  - use the "thermocline equations" in realistic geometry
  - e.g. Winton & Sarachik (JPO, 1993)
  - & Edwards & Shepherd (Climate Dynamics, 2002)
    - the "Lego-box" model (minimal 3D geometry)
    - 1 million years overnight (18 x 18, low resolution)
- **C-Goldstein** (R. Marsh): FG Ocean + EMBM

“Lego-box” model layout
(Edwards & Shepherd, 2002)

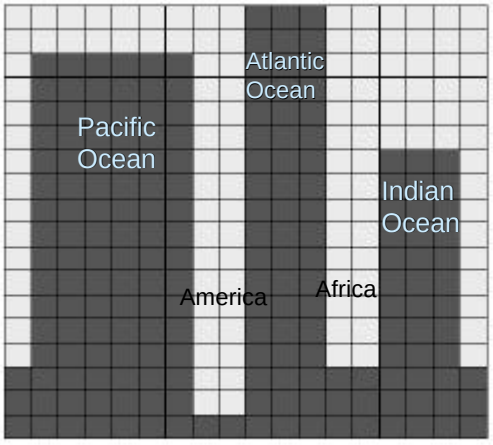
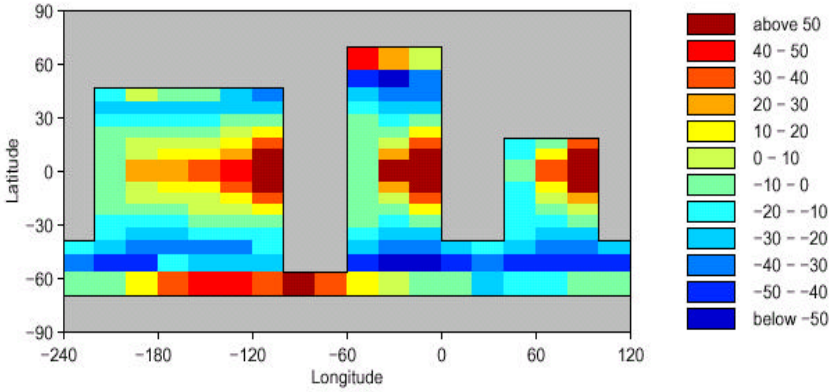


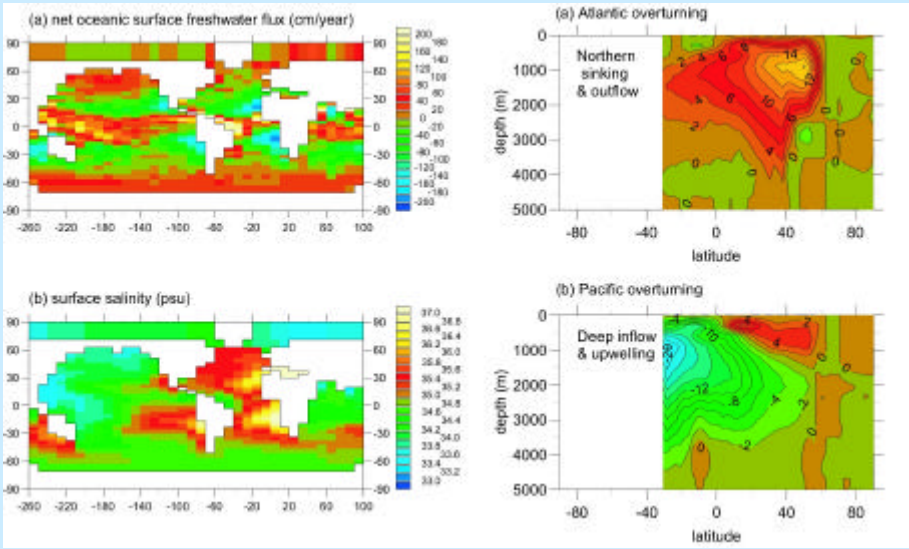
Figure 1: Diagram of the model domain, ocean cells are shaded dark grey. See text for explanation.

BioGEM : ocean-atmosphere pCO_2 difference (highlighting areas of in- and out-gassing). 1000 year run, PO_4-restoring (to zero)



(slide : A. Ridgwell)

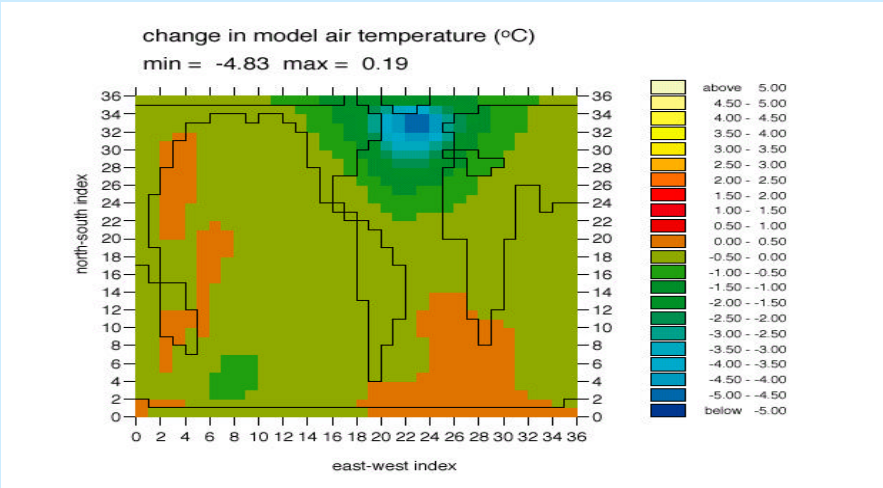
C-Goldstein



Slide : R. Marsh

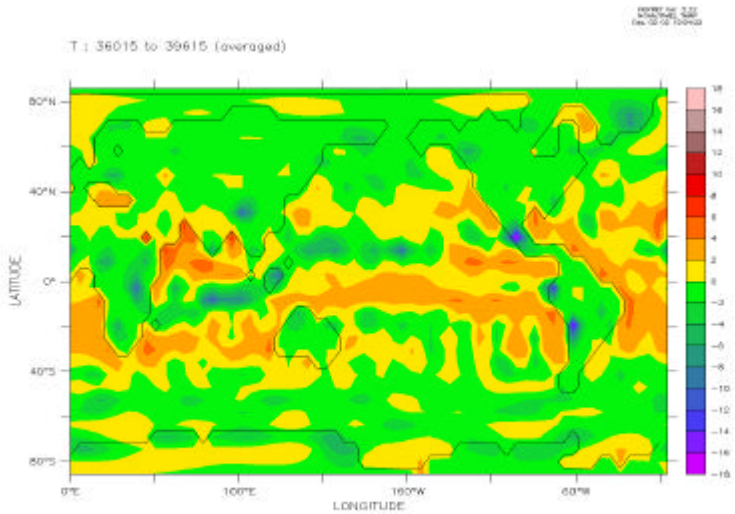
C-Goldstein: Sensitivity of the thermohaline circulation and climate to enhanced freshwater forcing

Change of surface air temperature after 25 years of a 1 Sv meltwater pulse, located in the Atlantic zone at 50-70°N.



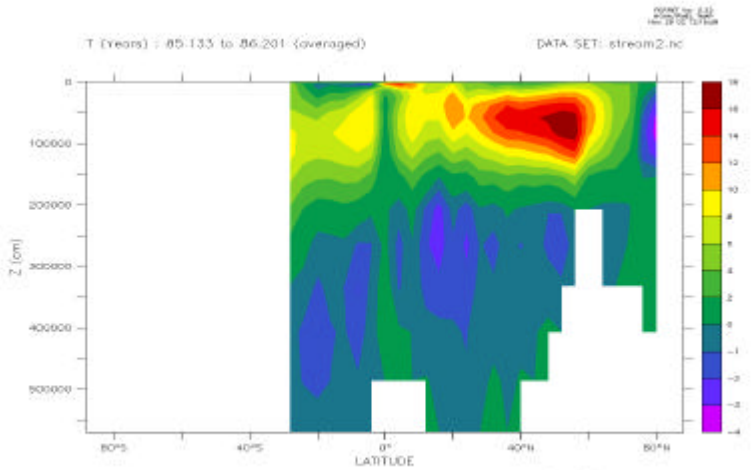
Slide : R. Marsh

FORTE: Coupled low-res OAGCM
Evaporation-Precipitation (slide courtesy of R. Smith)



E−P (mm/day)

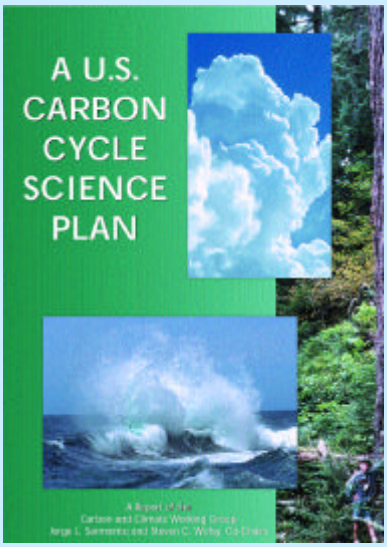
FORTE: Coupled low-res OAGCM
Atlantic meridional overturning (slide courtesy of R. Smith)



Atlantic Overturning Strm Fn (Sv)

Relevant activities elsewhere

- US Carbon Cycle Programme:
  - see http://www.carboncyclescience.gov/
- IGBP programmes, especially GAIM
- EU programmes, especially PRISM
- e-science (GENIE)
- Tyndall Centre (et al.)
  - Integrated Assessments



Conclusions

- **Earth System Models of Intermediate Complexity**
  - are necessary, desirable, and very useful tools
    - complementary to, and not "second best" to GCM's
  - are the **only** option (for the next decade or so)...
  - for **testing** our (seriously incomplete) understanding of **natural variations of climate**
  - because these occur **mainly** on palaeo (multi-millennial and longer) time-scales
  - EMIC's are still at an early stage of development, and are certainly **capable of major improvement**
  - We need more efficient representations of **fluid processes**, and more effective **parameterisations**
- Eventually, we need to use ***data assimilation***, and ***inverse modelling methods***, on palaeo-datasets...

Modelling & Philosophy

- **"Science may be described as the art of oversimplification: the art of discerning what we may with advantage omit."**
  - Karl Popper, “The Open Universe”, Hutchinson, London (1982)