Intermediate Complexity Climate Models

Lecture 8

From 2D (meridional-vertical) models

to coarse resolution "GCMs"

EMICs : Earth (Climate) System Models (of intermediate complexity)

- ♦ What are they ?
- ♦ Where are we now ?
  - Examples
  - Overview
- ♦ Issues for debate...
  - Timescales, Structure & Purpose
  - Processes & Components
  - Dimensionality & Resolution
  - "Complexity"
- ♦ Where are we going ?

Model types

- ♦ Conceptual/illustrative
  - to build & test general understanding
    - e.g. simplified box models
- ♦ experimental
  - to test mechanisms, evaluate processes, etc
  - to model general (not specific) system behaviour
- ♦ explanatory
  - to explain past events
    - (fitted to some data, tested on the rest)
- ♦ simulation & prediction
  - as realistic as necessary/possible
  - for "operational" use
- ♦ **N.B. The model is a working hypothesis**

MIT Climate Modelling Initiative

Table 1. Heirarchy of Models

1D Radiative-Convective Equilibrium Model

1D Radiative Convective Equilibrium Model with interactive hydrological cycle

2D Coupled Atmosphere-Ocean Box Models (Hemispheric and inter-hemispheric

MIT 2D Land-Ocean Climate Model

Coupled 1D Atmosphere, 3D Ocean Model

Coupled 2D Atmosphere, 3D Ocean Model

3D Atmospheric Model with simplified physics/low resolution coupled to 3D Ocean Model

Proposed new State-of-the-Art 3D Coupled Atmosphere/ Ocean General Circulation Model

Examples of ESM's

(not all EMICS !)

- Hadley Centre (HADCM3)
  - moderate resolution, 3D at 3.75° (atm) by 1.25° (ocean)
- MPI Hamburg (ECHAM/LSG)
  - 3D at 5.6°/5.6°
- Potsdam (CLIMBER-2)
  - 2.5D at 10° (lat) by 52° (long)
- Genie
  - 3D at 5° (lat) by 10° (long)

CLIMBER-2

Ganopolski et al, Climate Dynamics (2000)

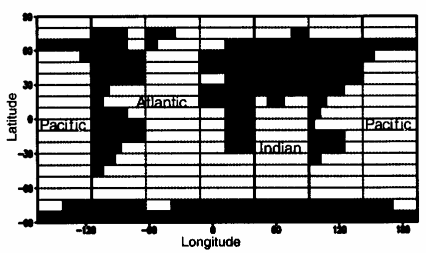


Fig. 1 Representation of the Earth's geography in the model. *Dashed lines* show atmospheric grid, *solid lines* separate ocean basins

“Lego-box” model layout
(Edwards & Shepherd 2001)

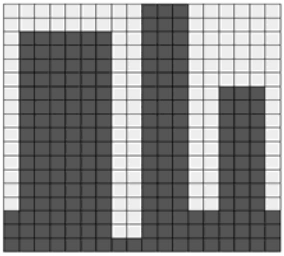
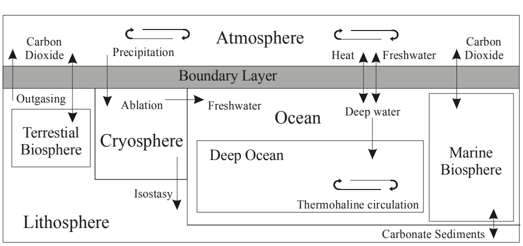


Figure 1: Diagram of the model domain, ocean cells are shaded dark grey. See text for explanation.

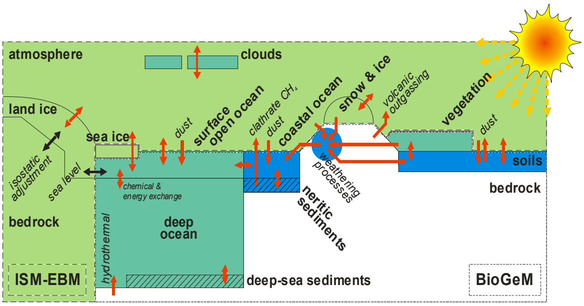
Reasons for wanting intermediate complexity (2D, 2.5D & 3D) models

- ♦ augment RCM’s to allow for spatial variation
  - include meridional transport of heat, water, etc ...
- ♦ augment EBM’s to treat radiation (etc) explicitly
  - include vertical transports of heat, water, etc...
- ♦ need to represent both **latitude** & **altitude**
  - transport both by MMC and turbulence (eddies)
    - (MMC = mean meridional circulation)
- ♦ also : heat & water transport by ocean
  - primarily due to **meridional** circulation
- ♦ Representation of continents & land surface…
  - The zonal dimension is also important !

What is an ESM ?



Developing fast and efficient climate models
The Earth (Climate) System
(according to Genie)



Slide by courtesy of A. Ridgwell (Genie)

Components of an ESM
(for the Climate System)

- Oceans
- Atmosphere
- Continents (configuration)
- Land and sea surfaces (albedo)
- Biosphere : marine and terrestrial vegetation
- Cryosphere : ice sheets and sea-ice

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	

Essential Processes

- Radiation (absorption, reflection, emission...)
- Convection (atmospheric and oceanic overturning)
- Oceanic transport (heat, salt, water, nutrients...)
- Atmospheric transport (heat, water, CO_2,)
- Hydrology (evaporation, precipitation, run-off...)
- Ice: accumulation, ablation, transport
  - (on both land & sea)
- Biological production, geochemistry, carbon cycle
  - (land & sea)
- Soils & Sediments
  - (land & sea)

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

Nature of intermediate complexity models

- are invariably (a) **Coarse** , & (b) **Statistical-Dynamical**
  - include explicit dynamics (buoyancy, friction, etc...) for the **mean flow only**
  - do not resolve eddies : treated statistically
  - but include fluxes due to **eddy correlations**
    - which need to be parameterised (turbulence closure)
- involve **parameterisation** of eddy fluxes
  - Usually use mixing length & flux-gradient methods
  - diffusivities (etc) $K = U^* L$, flux = $K \times$ gradient
  - U^* = characteristic **amplitude scale** for velocity fluctuations
  - L = characteristic **spatial scale** of velocity fluctuations (or of the spatial domain)

2 and 3D Atmospheric Models

- Involve meridional-vertical transports due to
  - **radiative forcing** (NB : surface albedo, clouds...)
  - **interaction with the land & ocean**
    - by radiation, heating and freshwater fluxes, & winds
  - **buoyancy forces** (moist convection)
  - **friction**
    - as Rayleigh drag or eddy viscosity (momentum transport)
  - **mixing** (lateral & vertical)
    - needs to be very carefully **parameterised**
  - **rotation** (which is very important)
- Examples of 2D models include...
  - Goddard Institute (GISS) (Hansen, Stone....)
  - Lawrence Livermore (MacCracken et al)

The Atmosphere : Winds

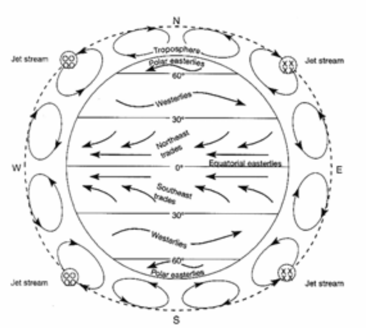


Figure 3.8 A view of the planet and atmosphere showing locations of major zonal wind directions and jet streams. The jet streams meander from mid to high latitudes in both hemispheres and flow predominately from west to east. The Earth revolves west to east, making one full anti-clockwise revolution about its N–S axis in 24 hours. (After Schneider and Londer, 1989.)

Mackenzie 1995

The Atmosphere : Winds

124 A CLIMATE MODELLING PRIMER

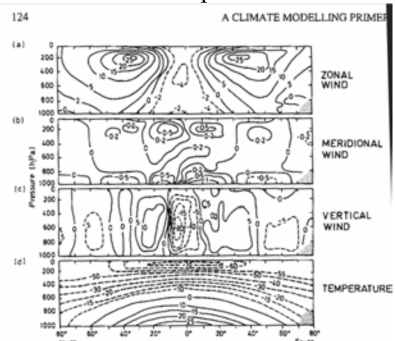


Figure 4.14 Observed zonal statistics for four atmospheric variables: (a) zonal wind ($m\ s^{-1}$); (b) meridional wind ($m\ s^{-1}$); (c) vertical wind ($\times 10^{-3}\ m\ s^{-1}$); (d) temperature (°C) (reproduced by permission of Academic Press from Oort and Peixóto, 1983)

Zonal Wind : the Jet Streams

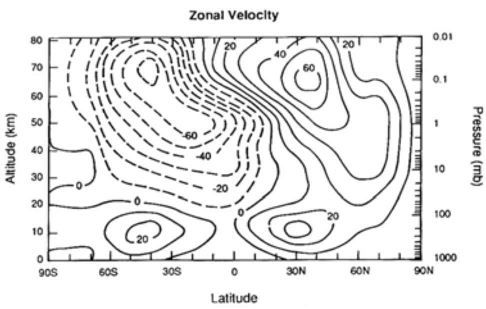


Fig. 3.4 Zonal-mean wind during January in m s^{-1}, as a function of latitude and altitude. After Fleming et al. (1988). Reprinted from Salby (1992) by permission of Academic Press.

Meridional temperature distribution

M. L. Salby: The atmosphere

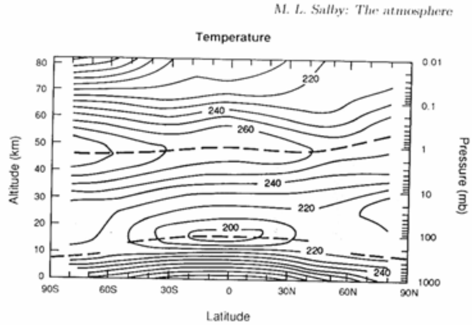


Fig. 3.3 Zonal-mean temperature during January, as a function of latitude and altitude. After Fleming et al. (1988). Reprinted from Salby (1992) by permission of Academic

Meridional water vapour distribution

M. L. Salby: The atmosphere

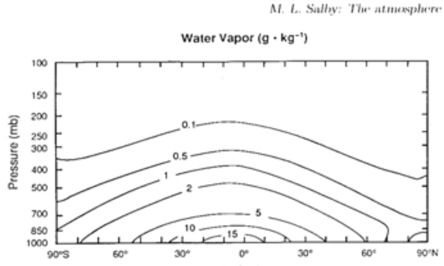


Fig. 3.5 Zonal-mean specific humidity (approximately equal to water vapor mixing ratio) for January, as a function of latitude and pressure. From European Centre for Medium Range Weather Forecasting (ECMWF) analyses: 1986–1989; courtesy K. Trenberth.

Evaporation & Precipitation

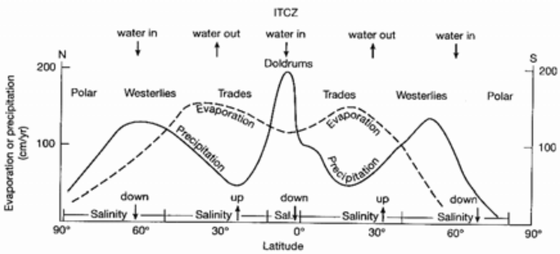
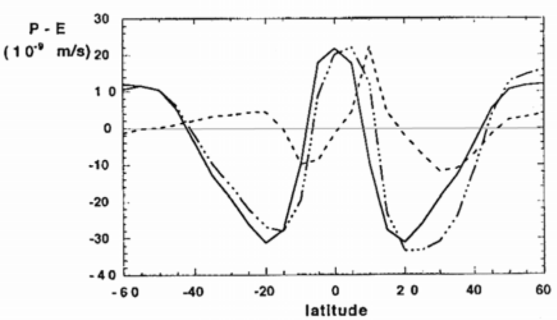


Figure 3.21 Latitudinal variation of global precipitation and evaporation and generalized relationship to zonal wind belts and the salinity of the ocean. (After Garrels, et al., 1975.)

Mackenzie 1995

Net Precipitation - Evaporation



Peixoto + Oort

Meridional processes in the Atmosphere

- Primary balance is between
  - **buoyancy forcing** (convection), and **friction**...
- Major features of the meridional circulation (existence and extent of Hadley & Ferrel cells) can be obtained from
  - transport of **zonal** (angular, total) **momentum**
    - by both the mean circulation, and by eddies
  - the **thermal wind** equation (buoyancy forcing)
- See review by MacCracken & Ghan (1988)
- Eddy transport of momentum is very important
  (especially in mid-latitudes : the storm tracks)

Eddies (and eddy correlations)

- are due to **Baroclinic Instability**
  - see Stone (1997) : [Venice lecture notes]
- lead to eddy viscosity, diffusivity (etc)
  - (Austausch coefficients)
- but cause transport of momentum **up** the gradient of **relative** angular momentum $\Rightarrow$ a problem !
  - "negative viscosity" (Starr, 1968)
- Can use parameterisations due to Green(1970) and Branscome (1980,1983)
  - see Stone & Yao, J Atmos Sci, 44, 3769- 3786, 1987
  - based on conservation of potential temperature and **potential vorticity**

Mixing Lengths & Eddy Diffusivities

parameterisation of Stone & Yao (1990)

$$\langle v'\theta' \rangle = 0.6 \frac{gd^2 N}{\theta f^2} \exp(-z/D) \left| \frac{d\theta}{dy} \right| \left(\frac{d\theta}{dy} \right)$$

where $d = H/(1+\gamma)$ and $\gamma = \beta H/\alpha f$

- Flux is proportional to $(\text{gradient})^n$
- Altitude-dependent
- Stability-dependent

Processes included in Statistical-Dynamical atmospheric models

- Heat fluxes
  - Sensible (dry) & Latent (moist)
- Moisture fluxes (moving freshwater)
  - Evaporation & Precipitation : E-P
- Momentum fluxes (zonal winds)
- Radiation
  - transmission, absorption, albedo, clouds (explicit)....
- Buoyancy & convection
  - leading to mean meridional circulation

What about Clouds ?

- ♦ At several (maybe all) levels
- ♦ Must allow for fractional cloud cover
  - to allow for zonal variations
  - and avoid "blinking" instabilities
- ♦ usually parameterised in terms of RH
  - as in many GCM's
  - incorporating type vs. altitude correlation
  - but one could model liquid water explicitly...

CLIMBER-2 : Atmosphere

Ganopolski et al, Climate Dynamics (2000)

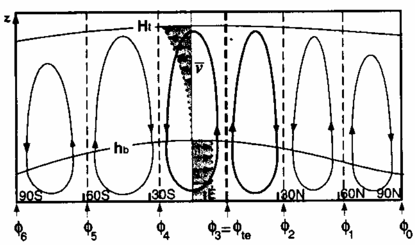
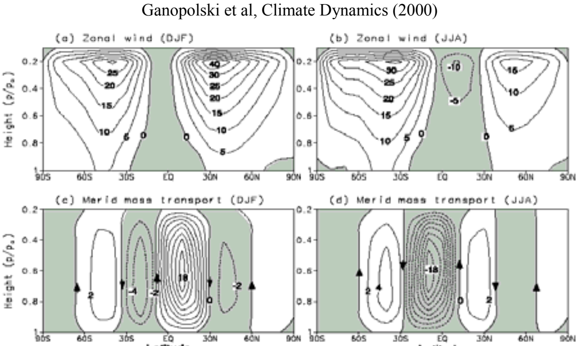


Fig. 3 Vertical structure of the zonally averaged atmospheric circulation in the model

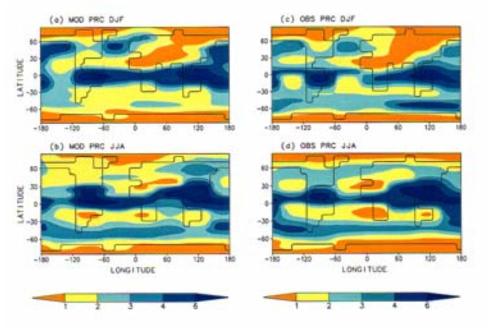
CLIMBER-2 : Atmospheric circulation (zonal wind and meridional overturning)

Ganopolski et al, Climate Dynamics (2000)



CLIMBER-2 : Precipitation

Ganopolski et al, Climate Dynamics (2000)



2 and 2.5D Ocean Models

Involve meridional & vertical transports due to

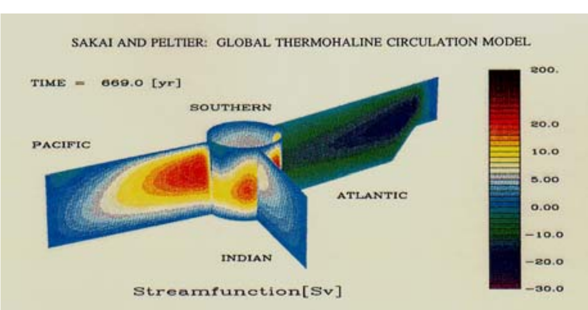
- **surface forcing** (interaction with the atmosphere)
  - by radiation, heating and freshwater fluxes (and winds ?)
- and thus **buoyancy forces**
- balancing **friction**
  - as Rayleigh drag or eddy viscosity
- **mixing** (lateral & diapycnal) : usually specified
- and effects of **rotation** (maybe, somehow)

♦ Examples include...

- Stocker & Wright
- Marotzke et al

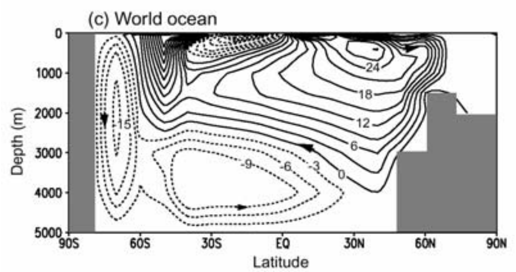
2.5D Ocean models

(Stocker, Wright & Mysak 1992)

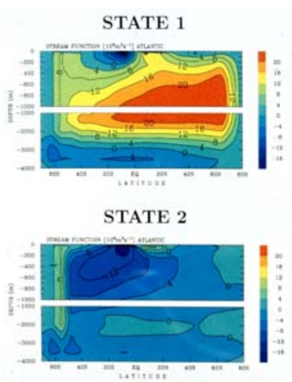


CLIMBER-2 : Global Meridional Overturning

Ganopolski et al, Climate Dynamics (2000)



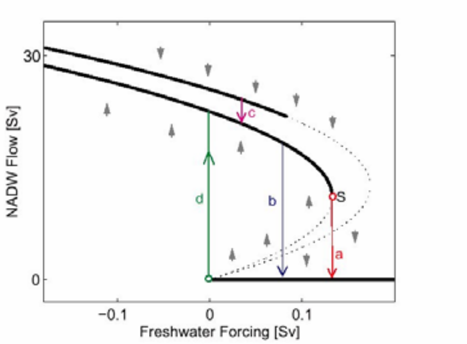
Suppression of Overturning (Stocker et al)



- How ??? Freshwater flooding (ice melt)
- Natural cycle : ~ bistable ? bipolar see-saw ?
- Forcing system with unknown dynamics
- Rapidity of transitions (<100 years): Not a distant problem

Multiple states of the Atlantic Thermohaline Circulation

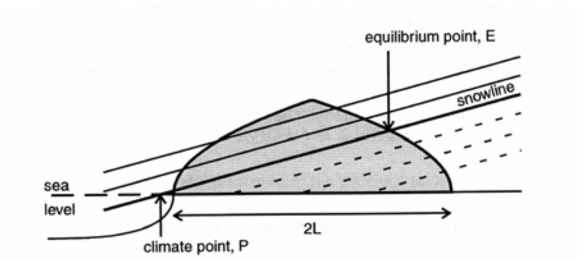
(S. Rahmstorf, Climatic Change, 2000)



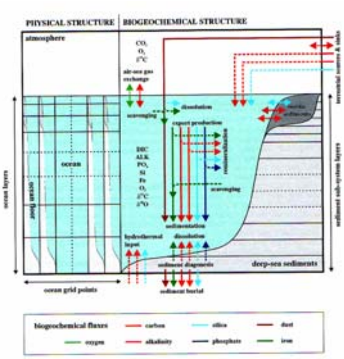
Land Surface Schemes

- Topography
  - elevation & slope
- Hydrology
  - soil moisture, runoff
  - drainage basins
- Vegetation
  - Carbon cycling
  - albedo...
- Ice sheets & glaciers

Simplified (2D) Ice-sheet models
(Van der Veen 1999)



Marine Biogeochemical Processes
(after A. Ridgwell, 2001)



Why build yet another model ?

- We need ***Fast & Efficient*** climate models
  - To do ***long runs*** (over many centuries, up to and ***beyond*** 2100)
    - N.B. : 5,000 year time horizon for exhaustion of fossil fuels and equilibration with marine sediments
  - To do ***many runs*** (to evaluate sensitivity & uncertainty requires thousands of simulations)
  - To serve as the climate module for an **Integrated Assessment** Model
    - (requires *both* of the above): many realisations
- Any climate model needs the ***Greenhouse Effect***
  - $\Delta CO_2 \Rightarrow \Delta T$: Climate Sensitivity
- To predict from emissions one needs a ***carbon cycle model*** (terrestrial and marine)
  - Emissions => ΔCO_2 : (c.f. 1/3 : 1/3 : 1/3)
- We need to allow for ***surprises…***
  - *E.g. thermohaline shut-down*

Efficient 3D ocean models

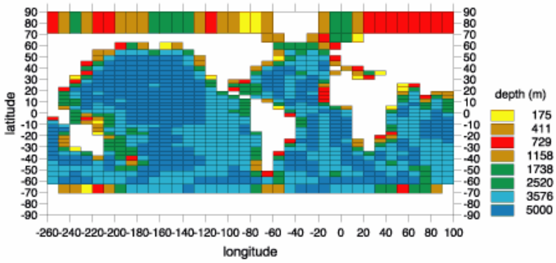
- MPI Hamburg (LSG)
  - partly implicit numerical scheme
  - neglects acceleration terms
- Frictional (planetary) geostrophic models
  - solve equations for slow dynamics only
    - neglect acceleration & inertia, include (Rayleigh) friction
  - the “thermocline equations” in realistic geometry
  - Winton & Sarachik (JPO, 1993)
  - Goldstein (Edwards et al, 1998)
  - Edwards & Shepherd (the “Lego-box” model)
    - Climate Dynamics, 2001
    - 1 million years overnight (18 x 18, low resolution)

C-GOLDSTEIN Version 1: Standard configuration

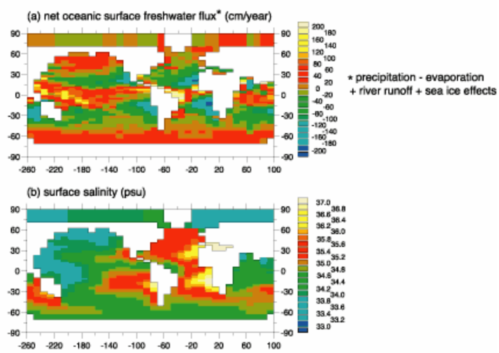
- realistic world geometry on a 36x36 horizontal grid
  - (~5^o latitude x 10^o longitude)
- basic 4-catchment runoff scheme
- smoothed ocean topography (8 ocean depth levels spanning 5000m)
- asynchronous coupled 2D EMBM atmosphere
  - one ocean time-step (of typically 3.5 days) every 5 atmospheric transport time-steps
- mixture of explicit (ocean, sea-ice) and implicit (atmosphere) timesteps
- Isopycnal oceanic mixing scheme
- 2000 years spinup in 1 to 2 hours on fast PC/workstation

A fast ocean-seaice-atmosphere model for Earth System Science, C-GOLDSTEIN* (Bob Marsh & Neil Edwards):

Ocean topography on model grid

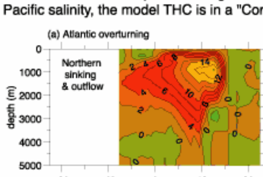


The strength and mode of the "thermohaline circulation" (THC) is sensitive to the global pattern of surface salinity, which is set up by the surface freshwater flux:

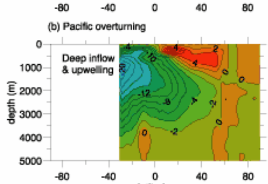


* precipitation - evaporation + river runoff + sea ice effects

Under the established pattern of high Atlantic salinity and low Pacific salinity, the model THC is in a "Conveyor Belt" mode:



combination of high Atlantic salinity + surface cooling leads to surface formation and sinking of NADW at ~60N



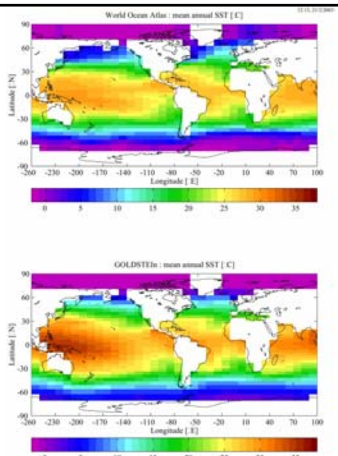
low Pacific salinity prohibits convection, hence no deep water formation in N.Pacific

Associated with the Conveyor Belt mode of the THC is strong northward heat transport in the Atlantic, leading to relatively mild climate in northwest Europe

BC-Goldstein

Sea surface Temperature

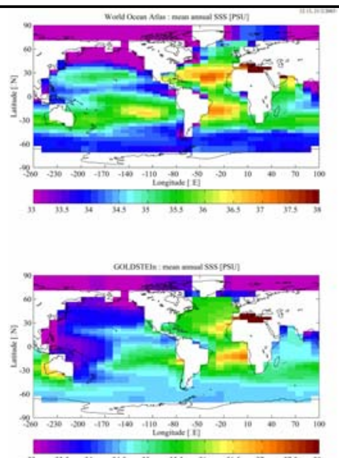
Comparison with observations



BC-Goldstein

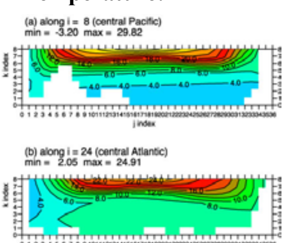
Sea surface Salinity

Comparison with observations



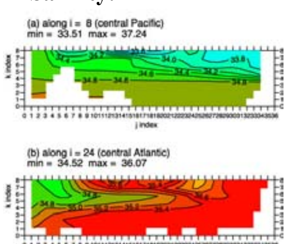
C-Goldstein: Water mass properties after 2000-year spinup

Temperature:



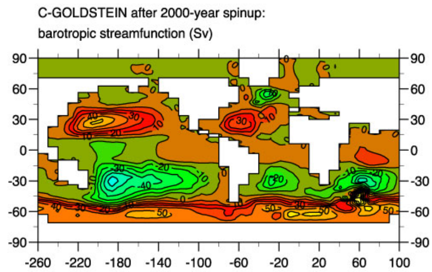
- strong & sharp thermocline
- deep Atlantic is too warm and too salty (deep sinking is located too far south)

Salinity:

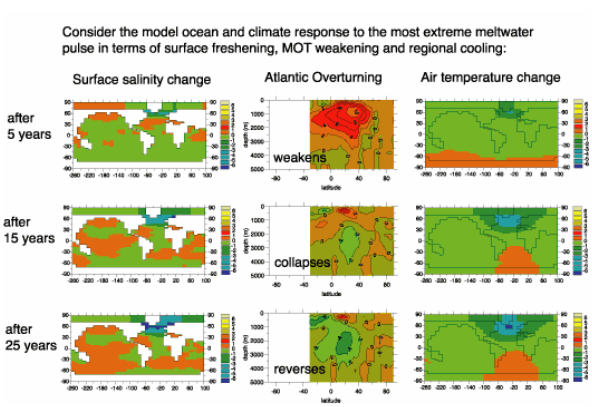


- Pacific is fresher than Atlantic
- salty "NADW" & fresh "AAIW" tongues extend south/north

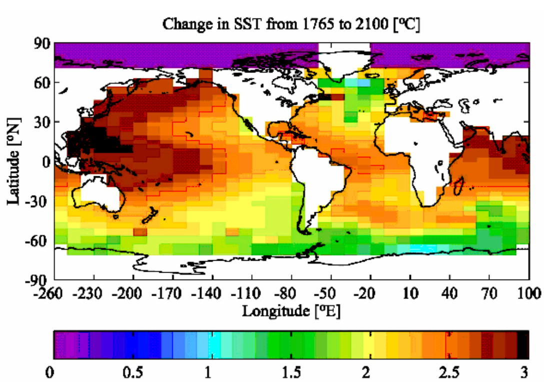
C-Goldstein : Wind-driven circulation:



- the above solution was obtained using ***enhanced wind stress***
- "standard" model (no enhanced wind stress) has a very weak wind-driven circulation due to the strong drag coefficient needed with real topography

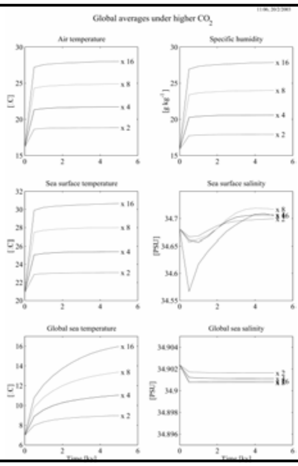


C-Goldstein : Global Warming Simulation (2 x CO_2)



C-Goldstein

5000 year Global Warming simulations for 2, 4, 8 and 16 times CO_2

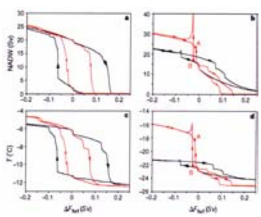


Multiple THC equilibria: Background

- Paleodata suggest at least three stable equilibria of the THC (and Atlantic climate) in the recent past: Holocene; Heinrich; Glacial
- Evidence that the THC "jumps" between such equilibria is found in "hysteresis loops" of THC strength vs. forcing - obtained in "slow" climate models by slowly varying an anomalous freshwater flux over selected regions of the North Atlantic

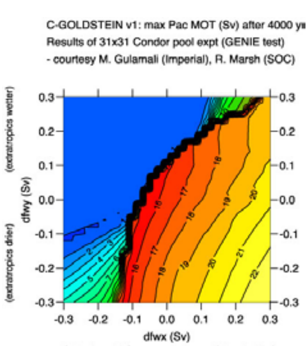
CLIMBER-2 hysteresis loops:

Under present climate | Under Glacial climate



black = anomalous flux applied 50-70°N
red = anomalous flux applied 20-50°N
(from Ganopolski & Rahmstorf 2001)

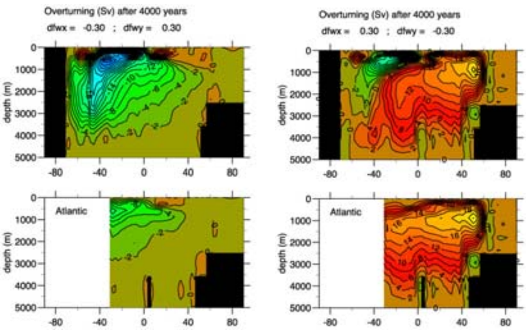
Using Condor pools to investigate equilibrium Atlantic overturning rate in dfwx-dfwy space



- 961 runs (3,844,000 model years!) took ~3 days, resolving at dfwx, dfwy intervals of just 0.02 Sv
- Two states of THC are apparent: ON (towards bottom right corner), OFF (towards top left corner)
- Present day overturning (at dfwx = 0, dfwy = 0) lies not far from the "cliff" between these states!

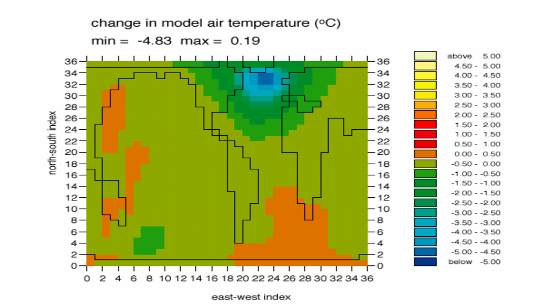
Meridional overturning circulation streamfunctions corresponding to two extremes of freshwater forcing

Weak FW forcing (S sinking) | **Strong FW forcing (N sinking)**

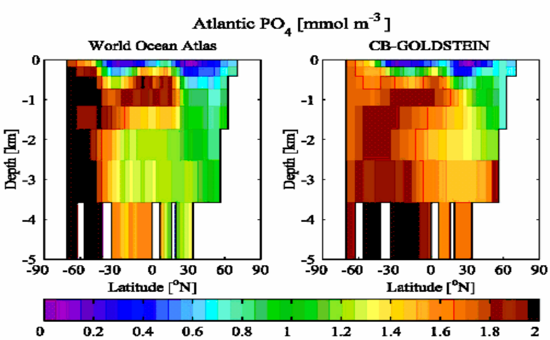


C-Goldstein: Sensitivity of the thermohaline circulation and climate to enhanced freshwater forcing

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



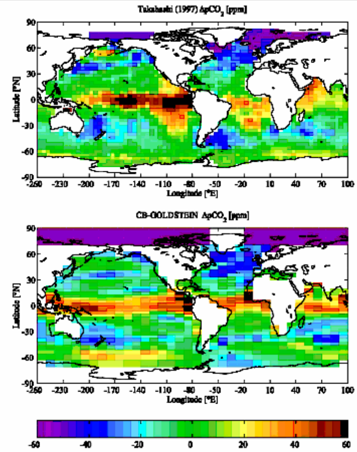
Biogeochemistry & Nutrients (PO_4) Comparison of model with observations



BC-Goldstein

Air-sea pCO2 differences modelled using phosphate depleting “biology”

Comparison with observations



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...

- **Play !!**
  - to allow for accidental discoveries
  - this requires over-night runs (at most)
- **run ensembles** and/or **explore parameter space**
  - this needs hundreds to thousands of runs
- **extend integration times** to >30 kyr
  - with moderate resolution models
- ∴ **develop faster schemes** (with longer time-steps)
- **“populate the spectrum”** of models
  - in both **structure** & in **resolution**
  - **inter-compare** (up/down the spectrum)
- promote **scalability** and **modularity**
- develop new & better **parameterisations...**

Parameterisation

- is a **high order intellectual activity**
- requires **"asymptotic credibility"**
- preferably based on **"sound science"**
- we could/should
  - **"cascade" parameterisations** up/down the spectrum
  - use **statistical representations** of sub-grid scale distributions
    - work with percentile values within cells
    - for hydrology, topography, clouds, ice, vegetation...

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)