Ocean Circulation and Climate: Observing and Modelling the Global Ocean

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- Brief overview of the ocean circulation, range of scales, complexity
- Observing the global ocean
- Modelling the global ocean

Two problems:

- (i) Understanding the role of Southern Ocean eddies in glacial cycles
- (ii) Will the Gulf Stream shut down?

JAMES MARTIN 21ST CENTURY SCHOOL **VERSITY OF OXFORD**

Cartoons of the global ocean circulation:

Atlantic meridional overturning circulation (AMOC)

(figure: Holloway)

MICOM 1/12 0 numerical model

Plus a myriad of smaller-scale processes:

breaking internal waves:

convective plumes:

double diffusion:

(figure: Federov)

⁽figure: Timmermans)

The oceans are a **complex** system in the scientific sense (according to most definitions):

- interactions between many processes at many different scales
- emergent properties
- non-equilibrium
- self-organise into states that show quasi-stability
- feedback to external manipulation

... and also a complex system in the misused sense, i.e., *complicated!*

Obs Allectrically, treated oceans as steady **or allectrically** of the bistorically, treated oceans as steady

WOCE Hydrographic Programme One-Time Survey
(Penny Holliday, WOCE IPO)

Some key elements of the present-day global observing system:

Altimeter - sea surface elevation:

topex-www.jpl.nasa.gov

60N 40N **20N** $\mathbf 0$ **20S** 40S 60S **120E 160W** 40E **80E** 160E **120W 80W** 40W $\mathbf 0$ O -132 44 88 132 176 -176 88 44 ΜМ

ARGO profiling floats:

Jason-2 Sea Level Residuals JAN 30 2010

www.argo.ucsd.edu

Mooring time series:

+ always room for new ideas:

biology.st-andrews.ac.uk/seos/

+ process experiments to develop improved parameterisations of small-scale processes

the apparent gravity, including

In principle, we know the equations of motion for the ocean $\sum_{i=1}^{\infty}$ clude the Coriolis and Cen- (10.3) $\int_{\mathcal{A}}^{\rho} \alpha^{\rho} e^{i\omega} d\omega$ acceleration can be combined and appointent weather easy $\mu_{\rm HII}$ equation is the refore: i
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¦∩ Here a unit vertical vertical definition oplem en to to the subscription leggis aften ressurehevoly parent gravity, including **Modelling the global ocean**

> $g_a {\bf k} = \nu \nabla^2 {\bf u}.$ (10.3)

parallel to elocal needbration equa-
P^ahellohiininy equation: pdheressb $\mathbf s$ ereipt in g_a is often

 $= 0.$ (10.4)
∂apparent gravity, including

 $\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}.\nabla \mathbf{u} + 2\boldsymbol{\Omega} \times \mathbf{u} + \frac{1}{\rho}$ ρ $\nabla p + g_a \, \mathbf{k} = \nu \nabla^2 \mathbf{u}$ $\frac{H}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$ due to the apparent gravity. For convenience, the subscript in g^a is often $\beta = \beta(v, \omega, p)$ the centrifugal contribution $\partial \theta$ T and T and T additional equation must now be supplemented by additional equation \mathcal{A} $\frac{\partial f}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} + 2 \mathbf{v} \times \mathbf{u} + - \nabla p + g_a \mathbf{k} = \nu \nabla \mathbf{u}$ $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0.$ $=$ κ perature via the ideal gas equation: the ideal gas equation: $\frac{1}{2}$ $\frac{p}{\beta}$ ∇p $+ g_a \, \mathbf{k} = \nu \nabla^2 \mathbf{u}$ In the ocean we have $\rho = \rho(\theta, S, p).$ $\frac{1}{20}$. $\frac{1}{20}$ $\overline{\mathcal{L}}$ the atmosphere and ocean, the potential temperature is conserved by $\overline{\mathcal{L}}$ 1 of \int ∂t is the potential temperature is conserved by ∂t is conserved by ∂t is conserved by ∂t fluid parcels in the absence of heating and molecular conduction of heat. $T = T \sqrt{2 \pi r}$ $\frac{\partial \theta}{\partial t} + \mathbf{u}.\nabla \theta = \kappa \nabla^2 \theta + \mathcal{H}$ $\frac{\partial S}{\partial t}$ + **u**. $\nabla S = \kappa_S \nabla^2 S + (\mathcal{E} - \mathcal{P})$ fusivity of heat (very much analogous to the role of viscosity in the model of viscosity in the mo-The potential temperature equation can thus be written: $\nabla \mathbf{u} + 2\mathbf{\Omega} \times \mathbf{u} + \frac{1}{\rho} \nabla p + g_a \mathbf{k} = \nu \nabla^2 \mathbf{u}$ ∂t if $\mathbf{v} \cdot (\rho \mathbf{u}) = 0$ fusivity of $\rho = \rho(\theta \ S \ n)$ mentum equation.) Here \mathcal{H}^{max} is the the theory in the theory is the the theory in the theory is the the In the ocean, we need a similar equation for the saling ∂t

fluid parcels in the absence of heating and molecular conduction of heat.

where \sim is the diffusivity of salt and (E \sim P) represents changes to the diffusivity of \sim

fusivity of heat (very much analogous to the role of viscosity in the model of viscosity in the mo-

 $\frac{1}{2}$

 $\mathcal{O}(\mathcal{O}_\mathcal{A})$

 $S = \frac{1}{2}$

bined with the gravitational acceleration to give an apparent gravity (as

discussed in lecture 6.) The resulting momentum equation is the resulting momentum equation is the result of α

In the atmosphere and ocean, the potential temperature is conserved by $\mathcal{L}_\mathcal{D}$

fluid parcels in the absence of heating and molecular conduction of heat.

In the atmosphere the atmosphere the density is related to pressure and potential temperature and potential tem-

ρ = ρ(θ, S, p). (10.5b)

 Θ le potential temperature equation can thus be written: Θ In prime 4 the continuity equation: salinity due to evaporation, precipitation and sea-ice formation. \ldots however, these apply to each fluid parcel.

102 and anthur airman B m ented by additional equa- α 10²⁷ degrees of freedom θ assuming each θ θ . θ . θ . θ 6×10^{27} degrees of freedom assuming each 1mm³ of seawater evolves independently gives 6 x 10²⁷ degrees of freedom

ure dmpractical to solve for each fluid parcel, nor would we want to! + impractical to solve for each fluid parcel, nor would we want to!

 $|3$

le continuity equation:

 (10.4)

Instead, solve approximation to the equations of motion on a finite grid: \blacksquare

10 (climate) resolution

1/12 0 resolution

viscous less viscous

- many processes are sub-grid scale and need to be parameterised (i.e., separately modelled)

- smallest scales can affect the largest scales and vice-versa

Equivalent resolution for atmospheric weather systems as a 1 degree model for ocean eddies?

- isopycnal mixing, Gent a. McWilliams, partial steps ... \mathbb{R}^n ... \mathbb{R}^n ... \mathbb{R}^n ... \mathbb{R}^n ...

(after Killworth)

Part of the answer is increased resolution, e.g., HiGEM:

(www.higem.nerc.ac.uk)

but brute force is not sufficient ... (NB: Bob Bishop - 18 Mar)

$\boxed{\n *Sublam (i) Undavationalian the xolo of Coulombary Oaean addica in alaoial avala*\n$ **Problem (i) Understanding the role of Southern Ocean eddies in glacial cycles**

b. The global pycnocline and atmospheric CO2 (with David Munday, Lesley Allison, Helen Johnson)

Q: Why is glacial $CO₂$ much lower than interglacial $CO₂$?

c. *Processes controlling the global pycnocline depth*

Level of scientific understanding

Antarctic Circumpolar Current (ACC)

snapshot of sea surface height, DRAKKAR 1/4° resolution

Simple model:

2-d circulation model:

An **"eddy permitting box model"** - able to integrate to equilibrium $($ \sim 5000 years) with explicit eddies: surface salinity

50

40

36.5

Problem (ii) Is the Gulf Stream going to collapse?

Atlantic Meridional Overturning Circulation (AMOC) or thermohaline circulation:

Northward heat transport (PW) in each basin:

Surface temperature anomalies 20-30 years after the AMOC is removed in the HadCM3 coupled ocean-atmosphere model.

(Vellinga and Wood, 2001)

Abrupt change?

Can the AMOC possess more than one stable mode of operation under identical surface boundary conditions?

• box models (Stommel, 1961)

to not know, with confidence, whether the strength of the ic overturning circulation is also changing.

12-11 • however, **no** state of the art coupled ocean-atmosphere model has yet shown multiple equilbrium states

What is going to happen to the AMOC over the next century?

Summer in SpitsBritain

 \blacksquare ARLIER this year, the \Box Department of the Environment painted a picture of the effects of global warming on Britain, writes Tim Radford.

The experts spoke of a climate appropriate to the Loire Valley, starting in the south of England and gradually making its way north over the decades.

But from the start, climate scientists have had reservations. Britain's place in the sun depends entirely on an oceanic accident: the curl of the Gulf Stream transporting tropical heat from the Bermuda triangle to the Bristol Channel.

With global warming and the Gulf Stream, there would be a landscape of sunflower fields and vineyards.

With global warming but without the Gulf Stream, the picture would be very different.

Now the scientists of Columbia University have at least taken a guess. In a Spitsbergen summer, temperatures sometimes soar to 15C and ships have even been known to land visitors there.

In winter, temperatures fall to -13C or lower-occasionally a lot lower.

There would be consolations in a SpitsBritain: rainfall in the northern islands would be relatively light at an average of about an inch a month. Tiresome trees would not obscure the view; only little polar willows and stunted dwarf birch would grow amid the mosses and lichens.

Birdwatchers would see snow buntings, ptarmigan, sandpipers and eider ducks.

Instead of red deer and badgers, there would be musk-ox and polar bears. There would be no crops, but hardly any weeding either.

(from *The***Guardian**)

Gulf Stream safe if wind blows and Earth turns

Sir — Your News story "Gulf Stream probed for early warnings of system failure" (*Nature* **427,** 769; 2004) discusses what the climate in the south of England would be like "without the Gulf Stream". Sadly, this phrase has been seen far too often, usually in newspapers concerned with the unlikely possibility of a new ice age in Britain triggered by the loss of the Gulf Stream.

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European readers should be reassured that the Gulf Stream's existence is a consequence of the large-scale wind system over the North Atlantic Ocean, and of the nature of fluid motion on a rotating planet. The only way to produce an ocean circulation without a Gulf Stream is either to turn off the wind system, or to stop the Earth's rotation, or both.

Real questions exist about conceivable changes in the ocean circulation and its climate consequences. However, such discussions are not helped by hyperbole and alarmism. The occurrence of a climate state without the Gulf Stream any time soon — within tens of millions of years has a probability of little more than zero. **Carl Wunsch**

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discrete nature of the stars in the Milky

telescope, such as the perspective glasses (MIT) of the sixteenth-century \sim scientists Leonard and Thomas Digges. *George Eastman Visiting Professor, 2011-2012*

WHERE WILL YOU BE?

JOUR BARROW THE DAY AFTER TOMORROW

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FROM THE DIRECTOR OF INDEPENDENCE DAY

THOSE'S CASHET TO ALSO 2 25 TOPOS INTEGRATED ON GAS. MAKE DRIVE WAS ARRESTED TO THE UNIT OF THE WAY OF THURSDAY JUNE OF FAMILY AND NOT ASSESSED. WHEN THE JUNE BOOK IS TAKEN DOG ASSESSED AND STANDARD STORE CLIMPS THAN DOG BLANCARD TRUNKING

WWW.THEDAYAFTERTOMORROW.CO.UK IN CINEMAS WORLDWIDE MAY 28, 2004

IPCC model projections: IDCC model projections:

 $S_{\rm{N}}$ Stream and North Atlantic Current (Dai et al., 2005). This can be called α

Chapter 10 Global Climate Projections

 \sim Snow cover is projected to contract. With a representation increases in that \sim

for model details) from 1850 to 2007 to 2100 using 20th Century Climate in Coupled Models (1900 σ) simulations for 1850 to 1999 and the SRES A1B emissions scenario for 1999 σ

idealised increase in atmospheric CO2 by 1% yr–1 to various

 $\frac{1}{100}$ we are the MOC in future can we can consider the MOC in future can change can consider the $\frac{1}{100}$ of $\frac{1}{100}$ in $\frac{1}{100}$ in $\frac{1}{100}$ in $\frac{1}{100}$ in $\frac{1}{100}$ in $\frac{1}{100}$ in $\frac{1}{100}$ i surface temperature (SST) and saling in the sales of the region of the Gulf of $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ working the assessed with eartidance In the MOC cannot be assessed with connective. 2100. Some of the models continue the integration to year 2200 with the forcing held constant at the values of year 2100. Observationally based estimates of year 2100. Observationally based estimates of late-20th century b Based on current model simulations, it is *very likely* that the meridional overturning circulation (MOC) of the Atlantic Ocean will slow down during the 21st century. The multi model everges reduction by 2100 is the Atlantic Ocean will slow down during the 21st century. The multi-model average reduction by 2100 is 25% (range from zero to about 50%) for SRES emission scenario A1B. Temperatures in the Atlantic region are projected to increase despite such changes due to the much larger warming associated with projected increases of greenhouse gases. It is very unlikely that the MOC will undergo a large abrupt transition during the 21st century. Longer-term changes in the MOC cannot be assessed with confidence.

PROJECTIONS OF SURFACE TEMPERATURES

PROJECTED PATTERNS OF PRECIPITATION CHANGES

multi-model

 $A1B$

DJF multi-model

 $A1B$

*(IPCC, 2007)***JJA**

Observations?

There is evidence of a wide-spread freshening of the high-latitude North Atlantic over the past 40 years

(Dickson et al. 2002)

(although recent reversal)

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transport in the 2004 section are closed uncertainty are closed uncertainty are closed uncertainty. The 2004 s
The 2004 section are closed uncertainty are closed uncertainty and the 2004 section are closed uncertainty and Slowing of the Atlantic meridional overturning $aⁱ$ not define the increase southward southwa circulation at 25°N

tainty in deep transport of \mathcal{C} in deep transport of \mathcal{C} increased southward the increased southward thermo-

Harry L. Bryden¹, Hannah R. Longworth¹ & Stuart A. Cunningham¹

atmospheric carbon dioxide will result in a slowdown of the Atlantic

Values of meridional transport are given in Sverdrups. Positive transports are northward. per cent decrease in the southward transport of lower North values of inerigional transport are given in svergrups. pairs east of the western boundary region where current metern boundary region where current metern where current metern where α Sitive transports are northward.

> sition between the two reference levels is identified from the distribution of dissolved oxygen concentration that marks the eastern edge of the boundary region \mathcal{B} and \mathcal{B} and \mathcal{B} with \mathcal{B} with \mathcal{B} with \mathcal{B} with \mathcal{B} with \mathcal{B} concept behind the analysis is to estimate the annual average overturning, so the annual averaged wind-driven surface Ekman trans-

LETTERS

26.5N: AMOC component from E-W density gradient

internal transport fluctuations [200-4750m] rel. 4750 m

Sea change: why global warming could leave Britain feeling the cold

· No new ice age yet, but Gulf Stream is weakening Atlantic current came to halt for 10 days in 2004

James Randerson, science correspondent Friday October 27, 2006 **The Guardian**

Science, Nov 2006:

GLOBAL CLIMATE CHANGE

False Alarm: Atlantic Conveyor Belt Hasn't Slowed Down After All

before the cha would be notice above the noise.

The full rea tion of the Atlar capriciousness c with the first cor ous monitoring o ocean's north-s flows. In March 2 saarahars ol

Not interested only in abrupt change - potential predictability?

CLIVAR Exchanges

Atlantic sea surface temperature, GFDL climate model ensemble under IPCC A1B forcing:

(courtesy: Isaac Held)

$\frac{1}{2}$ **Atlantic Multidecadal Oscillation (AMO)**

mean of North Atlantic SSTs:

(Sutton and Hodson, 2005)

SST anomaly: (1930-1960) - (1960-1990) T_{max} can do minimate S trends on \mathbb{R} 45N 45S 90S 180 90W $\,$ $\,$ 90E -0.9 -0.6 -0.3 0.3 0.6 0.9 \circ

link to AMOC?

Cautionary note: most of the critical processes for the AMOC (convection, overflows, boundary waves, boundary currents, eddies, ...) are either sub-grid scale or poorly resolved by the current generation of ocean models

Concluding remarks

- Ocean circulation spans a bewildering array of spatial and temporal scales.
- The smallest scales can affect the largest scales and vice-versa.
- The ocean is grossly undersampled in both space and time, but the modern observing system gives global coverage for the first time (at least of the upper ocean).
- Making progress requires a careful combination of observations, simple models to test and develop physical understanding, and global numerical models.
- While dramatic scenarios such as "collapse of the Gulf Stream" make good headlines, we need to be careful not to over-dramatise: this can damage the field in the long term and trivialise important (if somewhat less dramatic) issues.