Coupled climate system modelling

Steven J. Phipps
ARC Centre of Excellence for Climate System Science
Climate Change Research Centre
University of New South Wales

ARC CoECSS Winter School
17–21 June 2013

Concepts and motivation

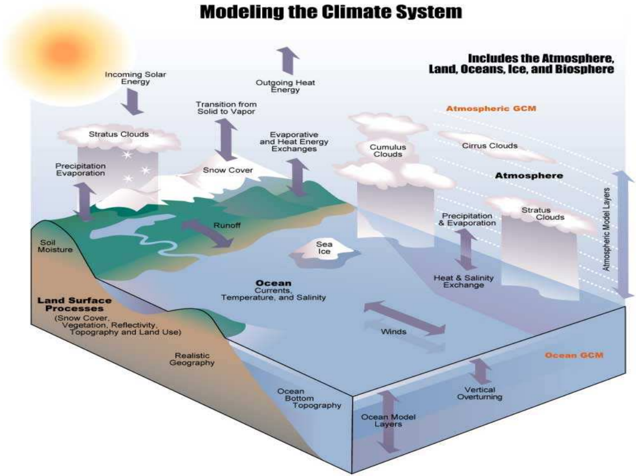
(What and why?)

Definition

A *coupled climate system model* is one that:

- describes multiple components of the climate system
- describes the interactions between them

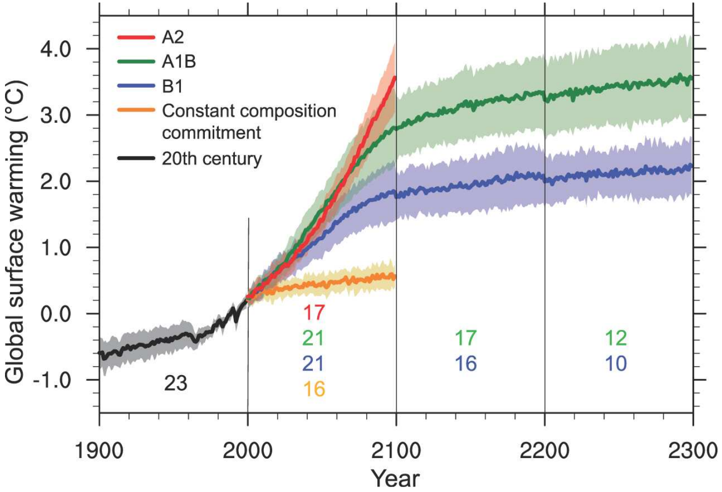
The Earth is a coupled system



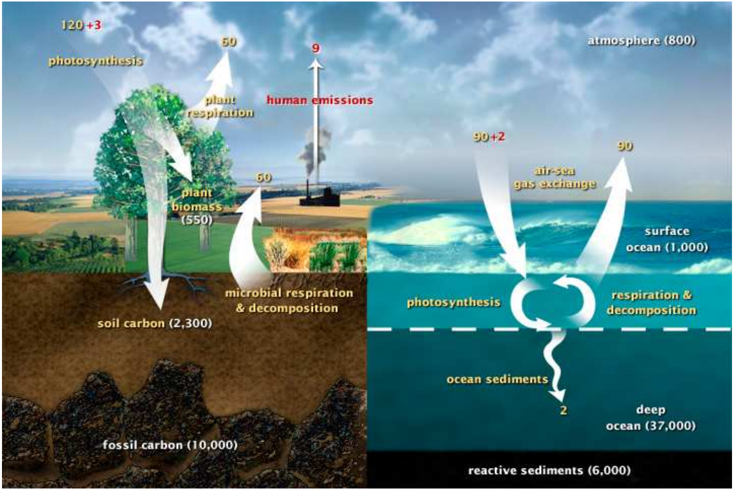
Why do we need coupled climate system models?

- We want to predict possible future climate states – for reasons of forecasting, adaption or mitigation.
- We want to understand past climatic changes.
- We want to detect and attribute human influences.
- We want to explore properties of the climate system.
- We want to answer *questions* – ranging from *scientific* questions to *policy* questions.
- There is only one Earth, and we can't (or at least shouldn't!) perform experiments on that.
- The Earth is too large and complex to be simulated in a laboratory, so numerical models are the only way of accomplishing this.
- Most of the things we care about are coupled phenomena.

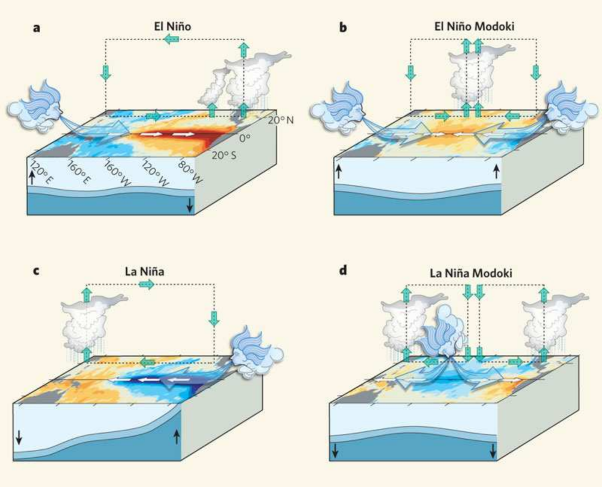
Example: future climate projections



Example: global carbon cycle

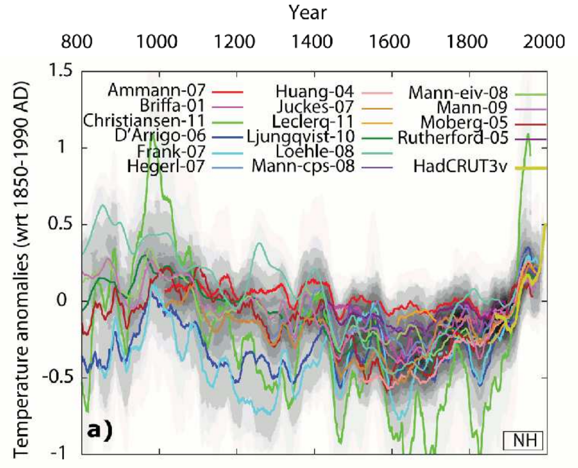


Example: El Niño–Southern Oscillation



Ashok and Yamagata (2009)

Example: past climatic changes



Fernández-Donado et al. (2013)

Building a coupled climate system model

(How?)

Different types of models

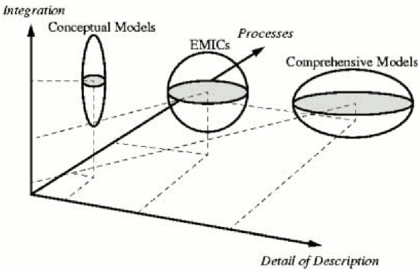


Fig. 1. Pictorial definition of EMICs. Adapted from Claussen (2000)

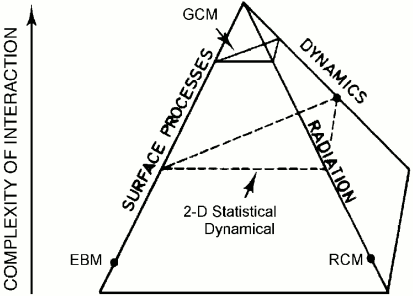


Fig. 2. The climate modeling pyramid. Adapted from Henderson-Sellers and McGuffie (1987)

Claussen et al. (2002)

Designing your coupled climate system model

- A model is a *tool* – the type that you use depends upon the question that you want to answer.
- Which components of the climate system do you need to model?
- Which processes do you need to model?
- Which quantities do you need to model?
- Do you need a regional or a global model?
- How much spatial resolution do you need?
- How long do you need to run the model for?
- These questions are inter-related – for example, it isn't feasible to run a high-resolution global model for 10,000 years!
- *No* model is a perfect representation of the real world.

Building your coupled climate system model

- Traditional approach:
  - Develop a computer program from scratch.
- Modern approach:
  - Take existing components and combine them.
- Test and debug.
- Determine the optimal parameter settings ("tuning").
- Evaluate, evaluate, evaluate...
- This is a very specialised and time-consuming process.
- A typical state-of-the-art coupled climate system model:
  - represents *hundreds* of person-years of work.
  - is an extremely large and complex piece of software.

Case study: ACCESS

- Australian Community Climate and Earth System Simulator
- Atmosphere: Unified Model (UK)
- Ocean: MOM4 (USA)
- Sea ice: CICE (USA)
- Land surface: CABLE (Australia)
- Coupler: OASIS (France)
- Around one million lines of source code
- Can simulate around 2-3 years per day
- Generates up to 50 GB of data for each year

Case study: ACCESS

CAWCR > Research > Earth System Modelling > Our Teams and People

CAWCR

- About Us
- Research
  - Atmosphere and Land Observation and Assessment
  - Climate Variability and Change
  - Earth System Modelling
    - Aims
    - Research Areas
    - **Our Teams and People**
    - Projects
  - Ocean Observation, Assessment and Prediction
  - Weather and Environmental Prediction
- News and Events
- Publications
- Staff
- Contacts
- Positions vacant
- Links
- Login for VPN users

Google Search

only search CAWCR

Earth System Modelling (ESM): Teams and People

Research Program Leader : **Kamal Puri**

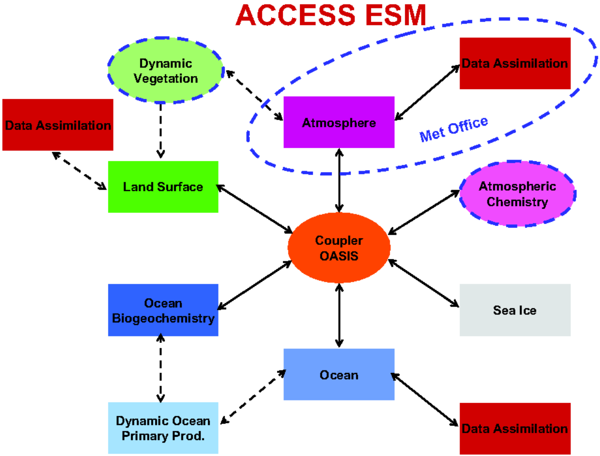
Deputy Research Program Leader : **Tony Hirst**

Personal Assistant : **Julie Siedses**

Atmospheric Modelling	**Data Assimilation**	**Ocean & Coupled Modelling**	**Land Surface & Carbon Cycle Modelling**
Team Leader : **Gary Dietachmayer (B)**	Team Leader : **Peter Steinle (B)**	Team Leader : **Tony Hirst (C, Asp)**	Team Leader : **Ying-Ping Wang (C, Asp)**
Greg Roff **(B)**	Brett Harris **(B)**	Dave Bi **(C, Asp)**	Eva Kowalczyk **(C, Asp)**
Michael Naughton **(B)**	Imtiaz Dharssi **(B)**	Harun Rashid **(B)**	Lauren Stevens **(C, Asp)**
Zhian Sun **(B)**	Chris Tingwell **(B)**	Simon Marsland **(C, Asp)**	Rachel Law **(C, Asp)**
Hongyan Zhu **(B)**	Xudong Sun **(B)**	Siobhan O'Farrell **(C, Asp)**	Richard Matear **(Hbt)**
Vaughan Barras **(B)**	Tomasz Glowacki **(B)**	Arnold Sullivan **(C, Asp)**	Matt Chamberlain **(Hbt)**
Holly Sims **(B)**	Xingbao Wang **(B)**	Petteri Uotila **(C, Asp)**	.....
David Smith **(B)**	Susan Rennie **(B)**	Hailin Yan **(C, Asp)**	Slobodanka Stojkovic **(S, C)**
Charmaine Franklin **(C, Asp)**	Justin Peter **(B)**		
Xingyou Huang **(B)**	Sergei Soldatenko **(B)**		
.....	Vinod Kumar **(B)**		
San Luo **(V, B)**			

Model Evaluation	**Model Systems**	**Chemistry & Aerosols**	**Complex Systems Science**
Team Leader : **Lawrie Rikus (B)**	Team Leader : **Martin Dix (C, Asp)**	Team Leader : **Peter Hurley (C, Asp)**	Team Leader : **John Finnigan (C, BM)**
B Hu **(B)**	Tan Le **(B)**	Julie Noonan **(C, Asp)**	David Miron **(C, Armidale)**
Ian Watterson **(C, Asp)**	Yi Xiao **(B)**	Holger Wolff **(C, Asp)**	David Newth **(C, BM)**
Tracey Elliot **(C, Asp)**	Ilia Bermous **(B)**	A Luhar **(C, Asp)**	Ian Harman **(C, BM)**
	Robin Bowen **(B)**		Don Gunasekera **(C, BM)**
	Asri Sulaiman **(B)**		Nicky Grigg **(C, BM)**
	Zhihong Li **(B)**		Danielle Stevens **(C, BM)**
	Bernard Pak **(C, Asp)**		
	Jhan Srbinovsky **(C, Asp)**		
	Mark Collier **(C, Asp)**		
	Say Teong Ng **(C, Asp)**		
	Wenming Lu **(B)**		
	Dobrohotoff Peter **(C)**		
	Ian Campbell **(C)**		
	Peter Uhe **(C, Asp)**		

Case study: ACCESS

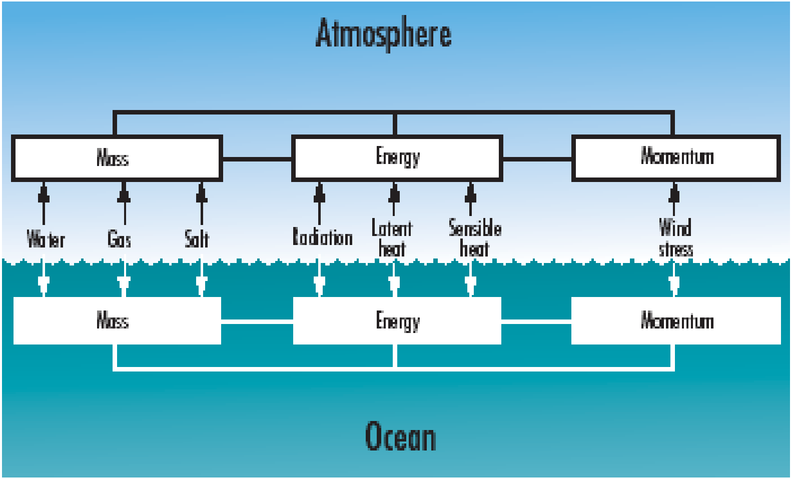


Coupled climate system modelling: Lego for adults?

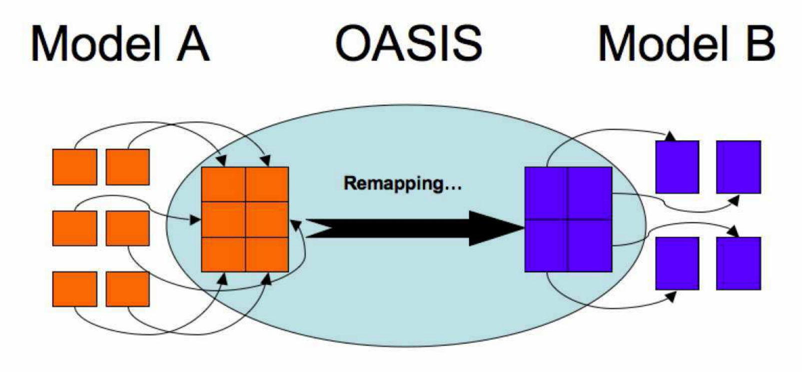
Challenges and solutions

- Coupling:
  - Interfaces may need to be developed for each component
    - ⇒ Modify each component as necessary
  - Components can use different spatial grids
    - ⇒ Use regridding – but make sure that physical quantities are conserved
  - Components can use different timesteps
    - ⇒ Use averaging or interpolation in time
- Errors in the climatology:
  - No model is perfect, so all models will exhibit errors
    - ⇒ Tuning can improve the agreement with observations
- Drift:
  - Feedback loops can cause systematic errors to grow over time, causing the model to drift away from its initial state
    - ⇒ This is a tricky one to fix, but tuning can help

Atmosphere–ocean coupling

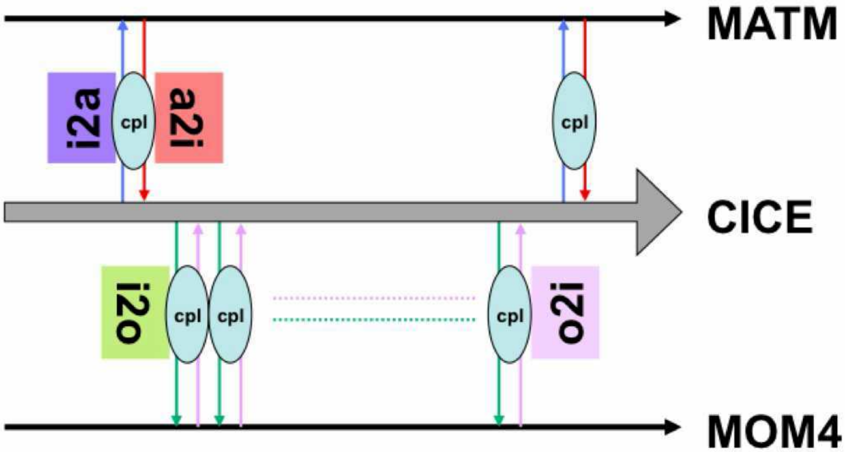


Coupling: spatial regridding within ACCESS



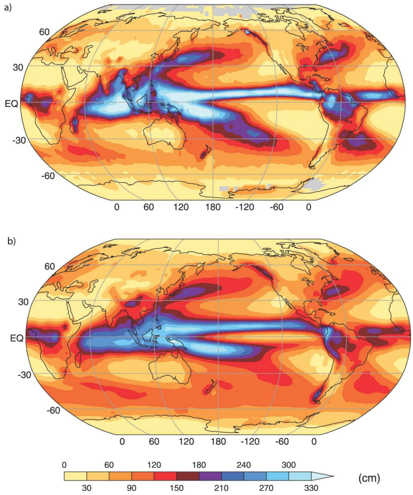
Bi and Marsland (2010)

Coupling: time management within ACCESS



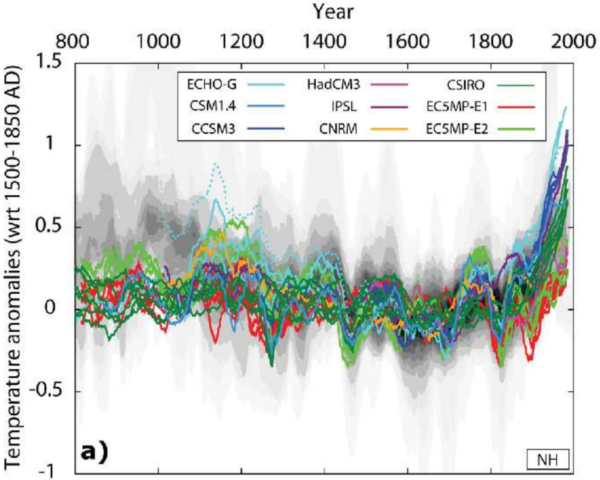
Bi and Marsland (2010)

Evaluation: present-day precipitation



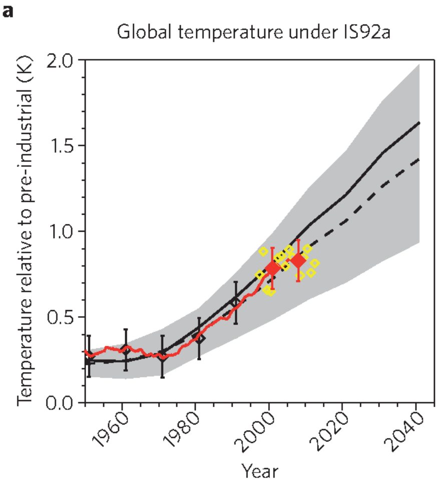
- The figures on the right show annual rainfall
- Which is observed and which is modelled?

Evaluation: past climatic changes



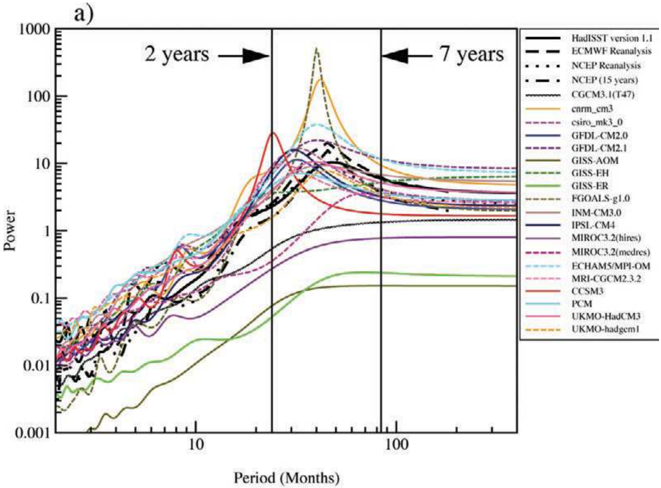
Fernández-Donado et al. (2013)

Evaluation: future climate?



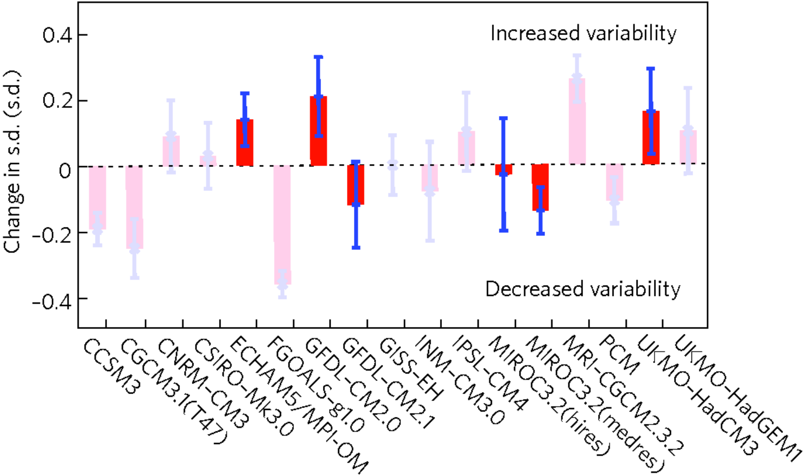
Allen et al. (2013)

Evaluation: El Niño–Southern Oscillation



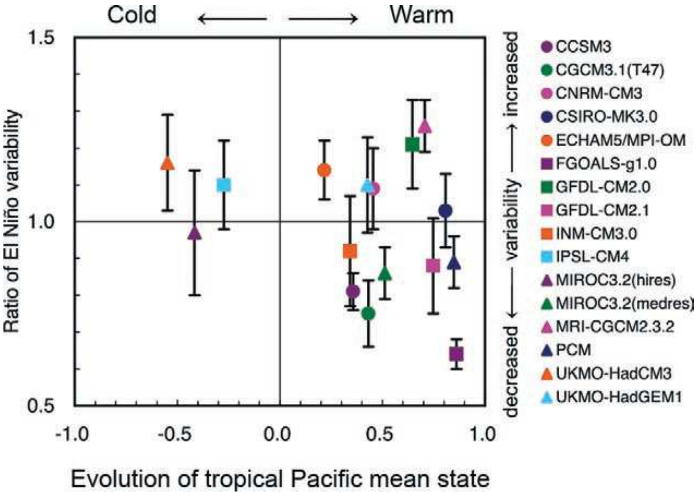
Guilyardi et al. (2009)

Model intercomparison: El Niño–Southern Oscillation

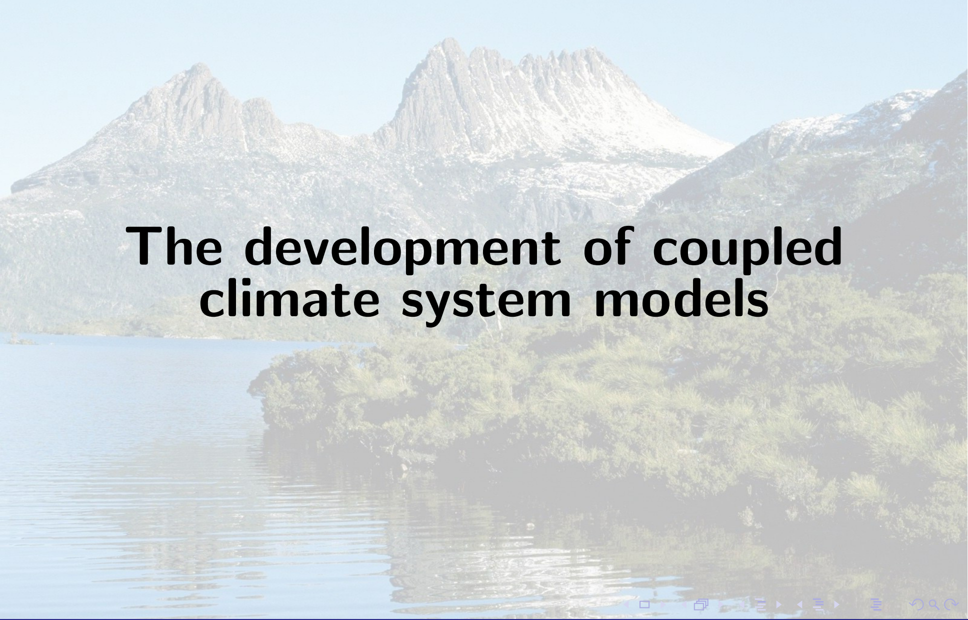


Collins et al. (2010)

Model intercomparison: El Niño–Southern Oscillation

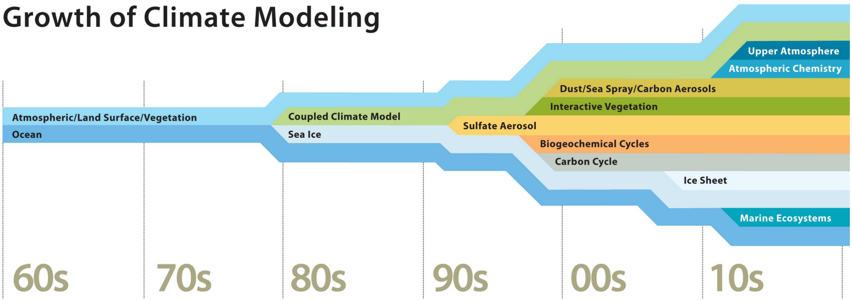


Guilyardi et al. (2009)



The development of coupled climate system models

The development of coupled climate system models



The first coupled atmosphere–ocean GCM

786 JOURNAL OF THE ATMOSPHERIC SCIENCES VOLUME 26

Climate Calculations with a Combined Ocean-Atmosphere Model

SYUKURO MANABE AND KIRK BRYAN

Geophysical Fluid Dynamics Laboratory, ESSA, Princeton University, Princeton, N. J.

13 March 1969 and 6 May 1969

Empirical evidence indicates that the poleward heat transport by ocean currents is of the same order of magnitude as the poleward transport of energy in the atmosphere (Sverdrup, 1957). A significant contribution to the heat exchange across latitude circles is also associated with polar pack ice. Thus, any serious attempt to calculate climate must take into account the entire fluid envelope of the earth, consisting of the atmosphere and the hydrosphere. Although the cryosphere, consisting of ice packs over the oceans and continental ice, is not a fluid in the usual sense, it must be included in a general climatic model because of its large reflectivity to the solar insolation and its ability to store and transport heat.

taken into consideration. Velocity, temperature, water vapor and surface pressure are calculated at each of the grid points which are spaced approximately 500 km apart. Calculations are carried out at 9 levels which are chosen so that they resolve the structure of the lower stratosphere and the Eckman boundary layer. The radiation model is essentially that described by Manabe and Strickler (1964). For the sake of simplicity, the seasonal and diurnal variation of solar insolation are not taken into consideration; instead, annual mean insolation is assumed for this study. The depletion of solar radiation and the transfer of terestial radiation is computed taking into consideration cloud and gaseous absorbers such as water vapor, carbon dioxide and

The first coupled atmosphere–ocean GCM

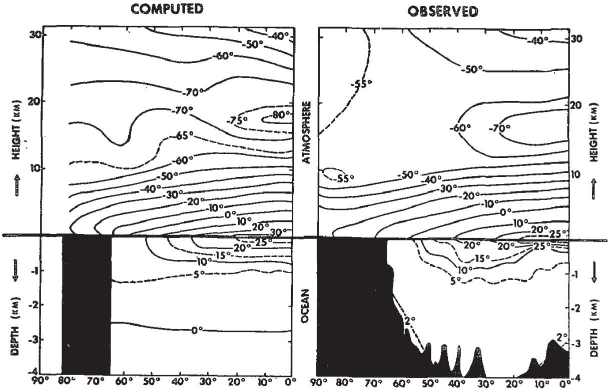


FIG. 2. Zonal mean temperature of the joint ocean-atmosphere system, left-hand side. This distribution, which is the average of two hemispheres, represents the time mean over two-sevenths of the period of the final stage of the time integration. The right-hand side shows the observed distribution in the Northern Hemisphere. The atmospheric part represents the zonally averaged, annual mean temperature. The oceanic part is based on a cross section for the western North Atlantic from Sverdrup *et al.* (1942).

Manabe and Bryan (1969)

High-performance computing, 1969-style

High-performance computing, 1969-style

Later coupled atmosphere–ocean modelling

AUGUST 1991 MANABE ET AL. 785

Transient Responses of a Coupled Ocean–Atmosphere Model to Gradual Changes of Atmospheric CO_2. Part I: Annual Mean Response

S. MANABE, R. J. STOUFFER, M. J. SPELMAN AND K. BRYAN

Geophysical Fluid Dynamics Laboratory/NOAA, Princeton University, Princeton, New Jersey

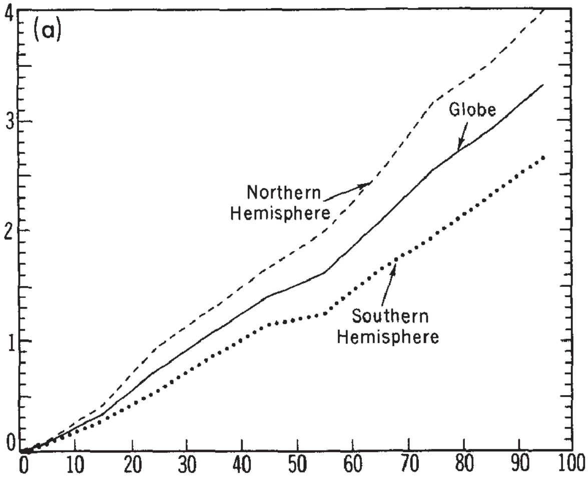
(Manuscript received 2 November 1990, in final form 4 March 1991)

ABSTRACT

This study investigates the response of a climate model to a gradual increase or decrease of atmospheric carbon dioxide. The model is a general circulation model of the coupled atmosphere–ocean–land surface system with global geography and seasonal variation of insolation. To offset the bias of the coupled model toward settling into an unrealistic state, the fluxes of heat and water at the ocean–atmosphere interface are adjusted by amounts that vary with season and geography but do not change from one year to the next. Starting from a quasi-equilibrium climate, three numerical time integrations of the coupled model are performed with gradually increasing, constant, and gradually decreasing concentration of atmospheric carbon dioxide.

It is noted that the simulated response of sea surface temperature is very slow over the northern North Atlantic and the Circumpolar Ocean of the Southern Hemisphere where vertical mixing of water penetrates very deeply. However, in most of the Northern Hemisphere and low latitudes of the Southern Hemisphere, the distribution of the change in surface air temperature of the model at the time of doubling (or halving) of atmospheric carbon dioxide resembles the equilibrium response of an atmospheric–mixed layer ocean model to CO_2 doubling (or halving). For example, the rise of annual mean surface air temperature in response to the gradual increase of atmospheric carbon dioxide increases with latitudes in the Northern Hemisphere and is larger over continents than oceans.

Later coupled atmosphere–ocean modelling



Manabe et al. (1991)

Later coupled atmosphere–ocean modelling

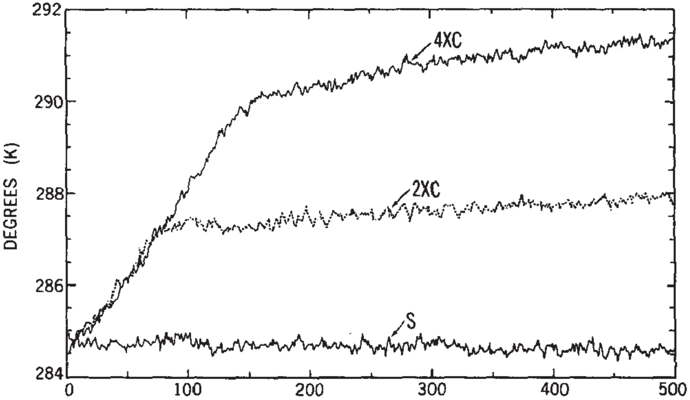


FIG. 2. Temporal variation of the global mean surface air temperature from the 4XC, 2XC, and S integrations. Units are in kelvin.

Manabe and Stouffer (1994)

Later coupled atmosphere–ocean modelling

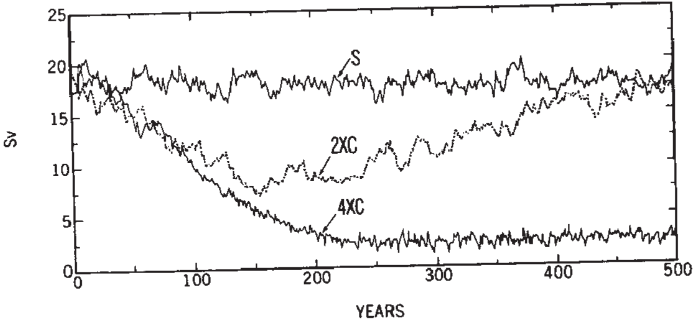
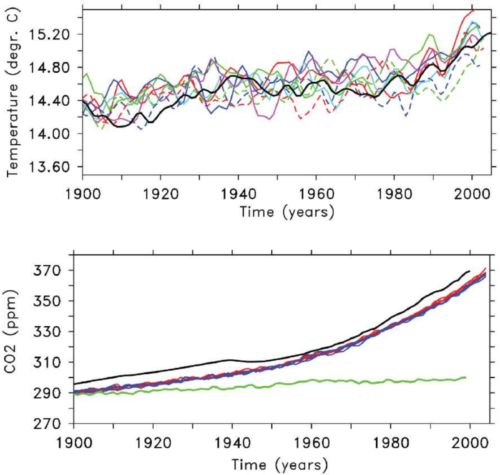


FIG. 4. Temporal variation of the intensity of the thermohaline circulation in the North Atlantic Ocean from the 4XC, 2XC, and S integrations. Here the intensity is defined as the maximum value of the streamfunction representing the meridional circulation in the North Atlantic Ocean (e.g., Fig. 5a). Units are in Sverdrups.

Manabe and Stouffer (1994)

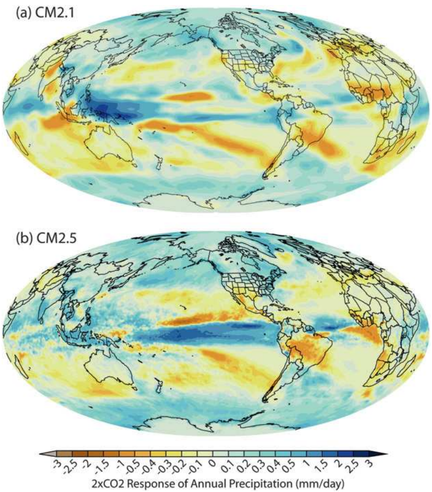
Rapid climate change?

Today: interactive carbon cycle



Jungclaus et al. (2010)

Today: increasing spatial resolution

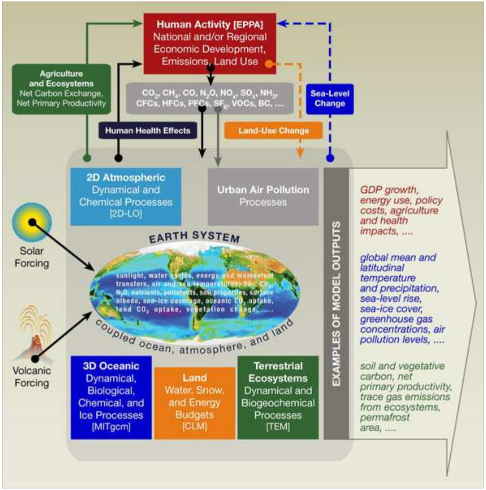


Delworth et al. (2012)

Future opportunities

Next steps: us

Coupling humans to the earth system



Dynamics of the coupled human–climate system

Clim Dyn
DOI 10.1007/s00382-013-1822-9

Dynamics of the coupled human–climate system resulting from closed-loop control of solar geoengineering

Douglas G. MacMartin · Ben Kravitz · David W. Keith · Andrew Jarvis

Received: 27 February 2013 / Accepted: 28 May 2013

Abstract If solar radiation management (SRM) were ever implemented, feedback of the observed climate state might be used to adjust the radiative forcing of SRM in order to compensate for uncertainty in either the forcing or the climate response. Feedback might also compensate for unexpected changes in the system, e.g. a nonlinear change in climate sensitivity. However, in addition to the intended response to greenhouse-gas induced changes, the use of feedback would also result in a geoengineering response to natural climate variability. We use a box-diffusion dynamic model of the climate system to understand how changing the properties of the feedback control affect the emergent dynamics of this coupled human–climate system, and evaluate these predictions using the HadCM3L general circulation model. In particular, some amplification of natural variability is unavoidable; any time delay (e.g., to average out natural variability, or due to decision-making) exacerbates this amplification, with oscillatory behavior possible if there is a desire for rapid correction (high feedback gain). This is a challenge for policy as a delayed response is needed for decision making. Conversely, the need for feedback to compensate for uncertainty, combined with a desire to avoid excessive amplification of natural variability, results in a limit on how rapidly SRM could respond to changes in the observed state of the climate system.

Keywords Geoengineering · Solar radiation management · Dynamics · Feedback · Control

1 Introduction

Solar radiation management (SRM) has been suggested as a possible tool to offset some or all of the radiative forcing due to anthropogenic greenhouse gases (GHG) and thus

Conclusions

Conclusions

- Coupled climate system models are able to reproduce the key features of the global climate.
- They are therefore incredibly powerful tools for exploring the past, present and future of the climate system.
- There is great potential to develop coupled climate system models even further, particularly by incorporating descriptions of additional components of the human–climate system.
- Remember what a great privilege is to be a climate system modeller.
- Think carefully when designing, building and using climate system models; no model is perfect.

With great power, comes great responsibility

References

- Allen, M. R., J. F. B. Mitchell and P. A. Stott (2013), Test of a decadal climate forecast, *Nature Geoscience*, 6, 243–244, doi:10.1038/ngeo1788.
- Ashok, K. and T. Yamagata (2009), Climate change: The El Niño with a difference, *Nature*, 461, 481–484, doi:10.1038/461481a.
- Bi, D., and S. Marsland (2010), Australian Climate Ocean Model (AusCOM) Users Guide, CAWCR Technical Report Number 027, ISBN 978-1-921605-92-5, `www.cawcr.gov.au/publications/technicalreports/CTR_027.pdf`.
- Claussen, M., L. A. Mysak, A. J. Weaver, M. Crucifix, T. Fichefet, M.-F. Loutre, S. L. Weber, J. Alcamo, V. A. Alexeev, A. Berger, R. Calov, A. Ganopoloski, H. Goosse, G. Lohmann, F. Lunkeit, I. I. Mokhov, V. Petoukhov, P. Stone and Z. Wang (2002), Earth system models of intermediate complexity: closing the gap in the spectrum of climate system models, *Climate Dynamics*, 18, 579–586.
- Collins, M., S.-I. An, W. Cai, A. Ganachaud, E. Guilyardi, F.-F. Jin, M. Jochum, M. Lengaigne, S. Power, A. Timmermann, G. Vecchi and A. Wittenberg (2010), The impact of global warming on the tropical Pacific Ocean and El Niño, *Nature Geoscience*, 3, 391–397, doi:10.1038/ngeo868.
- Delworth, T. L., A. Rosati, W. Anderson, A. J. Adcroft, V. Balaji, R. Benson, K. Dixon, S. M. Griffies and H.-C. Lee (2012), Simulated Climate and Climate Change in the GFDL CM2.5 High-Resolution Coupled Climate Model, *Journal of Climate*, 25, 2755–2781, doi:10.1175/JCLI-D-11-00316.1.
- Fernández-Donado, L., J. F. González-Rouco, C. C. Raible, C. M. Ammann, D. Barriopedro, E. García-Bustamante, J. H. Jungclaus, S. J. Lorenz, J. Luterbacher, S. J. Phipps, J. Servonnat, D. Swingedouw, S. F. B. Tett, S. Wagner, P. Yiou and E. Zorita (2013), Large-scale temperature response to external forcing in simulations and reconstructions of the last millennium, *Climate of the Past*, 9, 393-421, doi:10.5194/cp-9-393-2013.
- Guilyardi, E., A. Wittenberg, A. Fedorov, M. Collins, C. Wang, A. Capotondi, G. J. van Oldenborgh and T. Stockdale (2009), Understanding El Niño in ocean–atmosphere general circulation models: Progress and challenges, Bulletin of the American Meteorological Society, 90, 325–340, doi:10.1175/2008BAMS2387.1.

References

- Jungclaus, J. H., S. J. Lorenz, C. Timmreck, C. H. Reick, V. Brovkin, K. Six, J. Segschneider, M. A. Giorgetta, T. J. Crowley, J. Pongratz, N. A. Krivova, L. E. Vieira, S. K. Solanki, D. Klocke, M. Botzet, M. Esch, V. Gayler, H. Haak, T. J. Raddatz, E. Roeckner, R. Schnur, H. Widmann, M. Claussen, B. Stevens, and J. Marotzke (2010), Climate and carbon-cycle variability over the last millennium, *Climate of the Past*, 6, 723–737, doi:10.5194/cp-6-723-2010.
- MacMartin, D. G., B. Kravitz, D. W. Keith and A. Jarvis (2013), Dynamics of the coupled human–climate system resulting from closed-loop control of solar geoengineering, doi:10.1007/s00382-013-1822-9, in press.
- Manabe, S., and K. Bryan (1969), Climate Calculations with a Combined Ocean-Atmosphere Model, *Journal of the Atmospheric Sciences*, 26, 786–789.
- Manabe, S., R. J. Stouffer, M. J. Spelman and K. Bryan (1991), Transient Responses of a Coupled Ocean-Atmosphere Model to Gradual Changes of Atmospheric CO_2. Part I: Annual Mean Response, *Journal of Climate*, 4, 785–818.
- Manabe, S., and R. J. Stouffer (1994), Multiple-Century Response of a Coupled Ocean-Atmosphere Model to an Increase of Atmospheric Carbon Dioxide, *Journal of Climate*, 7, 5–23.
- Trenberth, K. E. (ed.) (1992), Climate system modeling, Cambridge University press, ISBN 0-521-43231-6.