Introduction to climate modelling

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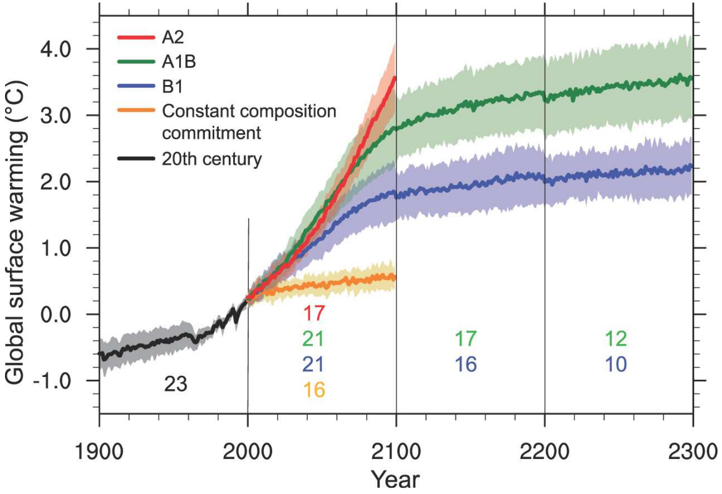
Why do we need climate models?

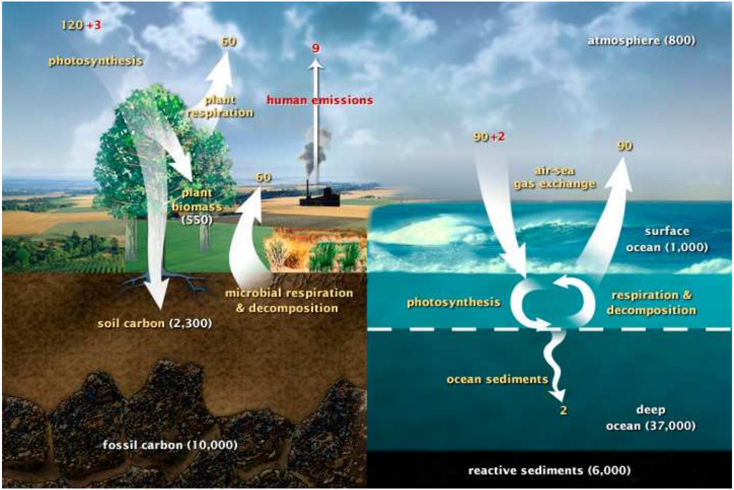
Why do we need climate models?

- 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.

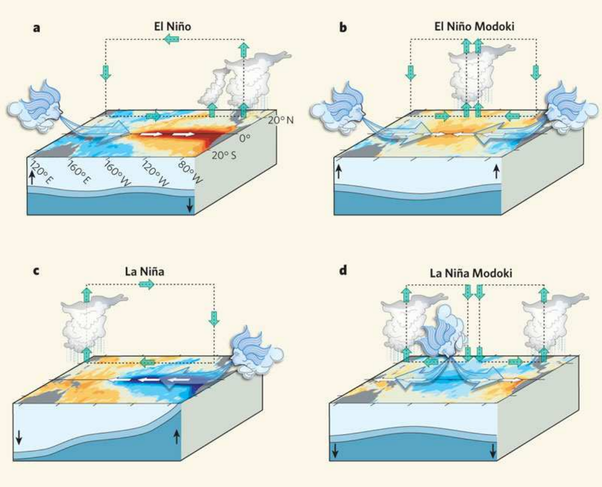
Example: future climate projections



Example: global carbon cycle

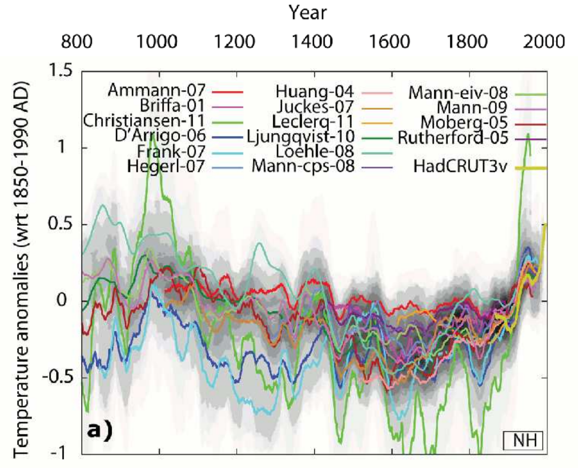


Example: El Niño–Southern Oscillation

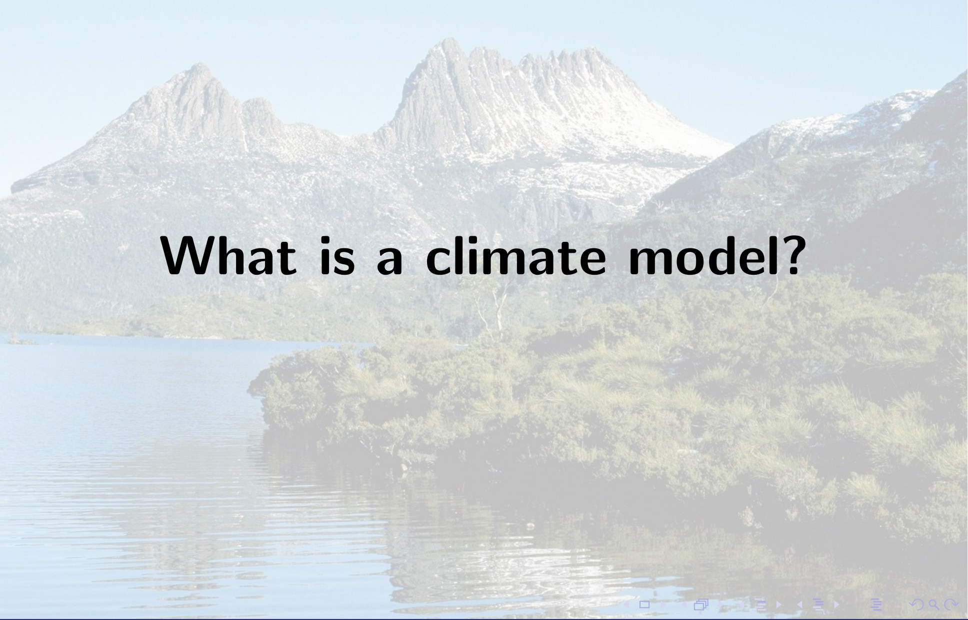


Ashok and Yamagata (2009)

Example: past climatic changes



Fernández-Donado et al. (2013)

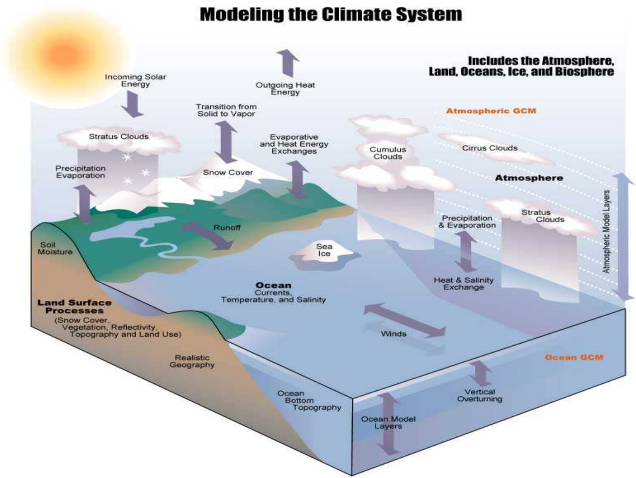


What is a climate model?

What is a climate model?

- A *virtual* Earth.
- A computer program (usually very long and complex).
- Solves the fundamental physical equations that describe the evolution of the climate system.
- Divides the Earth into discrete components.
- Different types of models: simple versus complex, low-resolution versus high-resolution, regional versus global.
- A model is a *tool* – the type that you use depends upon the question that you want to answer.
- *No* model is a perfect representation of the real world.

A virtual Earth



A computer program

```
c...  Calculate density
      p2 = p*p
      p3 = p*p2
      do i = 1, imt
        s15(i) = s(i)*sqrt(s(i))
        s2(i) = s(i)*s(i)
        t2(i) = t(i)*t(i)
        t3(i) = t(i)*t2(i)
        t4(i) = t(i)*t3(i)
        rho(i) = (a0 + a1*t(i) + a2*t2(i) + a3*t3(i) + a4*s(i) +
     &            a5*s(i)*t(i) + a6*s2(i) + a7*p + a8*p*t2(i) +
     &            a9*p*s(i) + a10*p2 + a11*p2*t2(i)) /
     &           (b0 + b1*t(i) + b2*t2(i) + b3*t3(i) + b4*t4(i) +
     &            b5*s(i) + b6*s(i)*t(i) + b7*s(i)*t3(i) + b8*s15(i) +
     &            b9*s15(i)*t2(i) + b10*p + b11*p2*t3(i) + b12*p3*t(i))
      end do
```

Solves fundamental physical equations

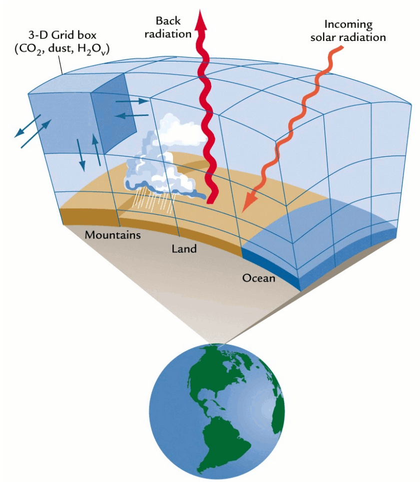
$$\rho(S,\theta,p) = \frac{P_1(S,\theta,p)}{P_2(S,\theta,p)} \tag{1}$$

where

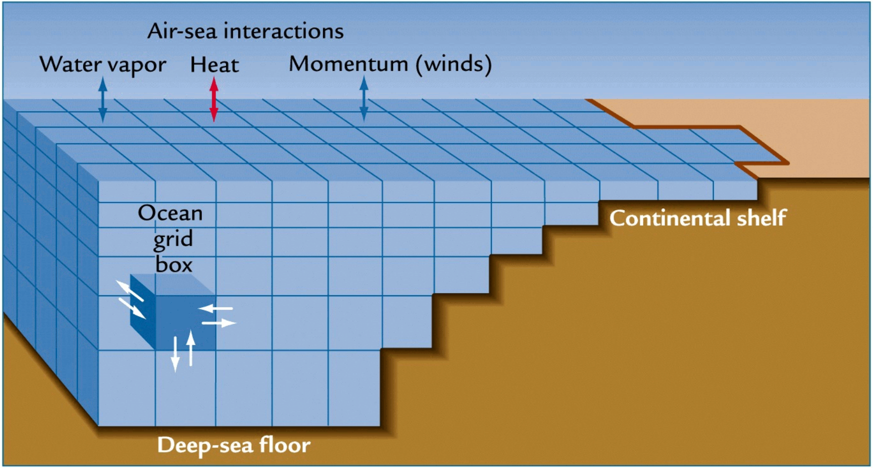
$$\begin{aligned} P_1(S,\theta,p) &= a_0 + a_1\theta + a_2\theta^2 + a_3\theta^3 + a_4 S \\ &\quad + a_5 S\theta + a_6 S^2 + a_7 p + a_8 p\theta^2 \\ &\quad + a_9 pS + a_{10} p^2 + a_{11} p^2\theta^2 \end{aligned} \tag{2}$$

$$\begin{aligned} P_2(S,\theta,p) &= b_0 + b_1\theta + b_2\theta^2 + b_3\theta^3 + b_4\theta^4 \\ &\quad + b_5 S + b_6 S\theta + b_7 S\theta^3 + b_8 S^{\frac{3}{2}} \\ &\quad + b_9 S^{\frac{3}{2}}\theta^2 + b_{10} p + b_{11} p^2\theta^3 + b_{12} p^3\theta \end{aligned} \tag{3}$$

Divides the Earth into discrete components



Divides the Earth into discrete components



Different types of models

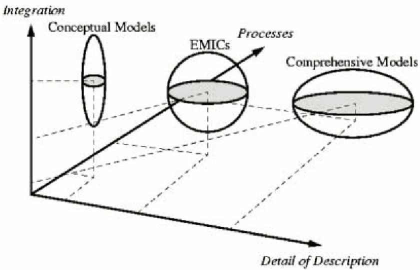


Fig. 1. Pictorial definition of EMICs. Adapted from Claussen (2000)

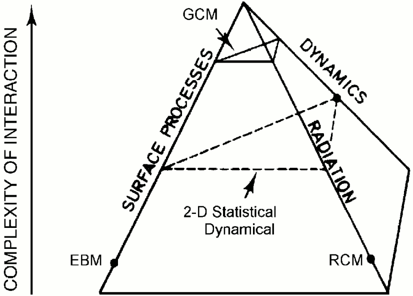
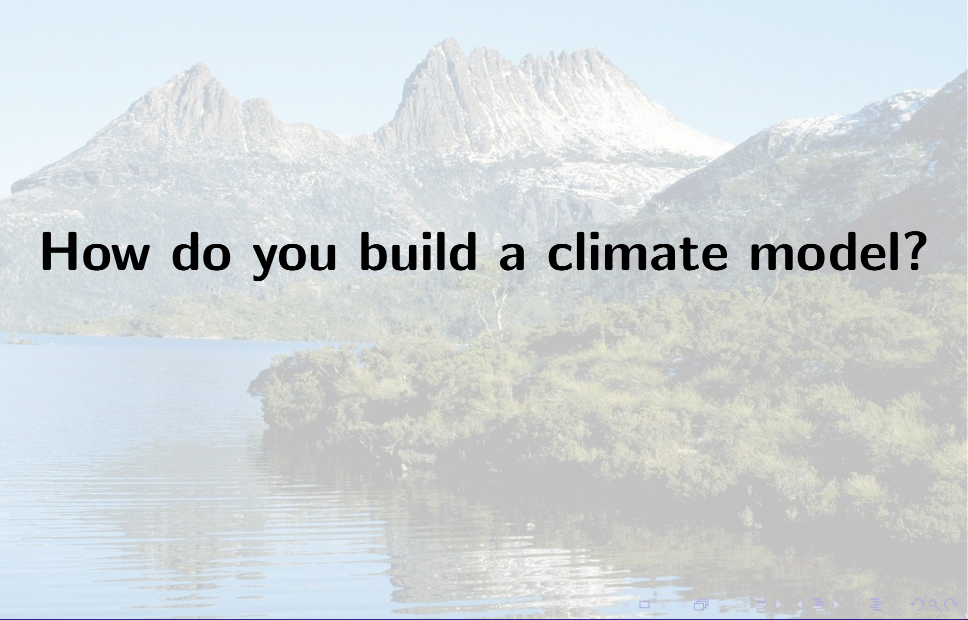


Fig. 2. The climate modeling pyramid. Adapted from Henderson-Sellers and McGuffie (1987)

Claussen et al. (2002)



How do you build a climate model?

Designing your climate 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.

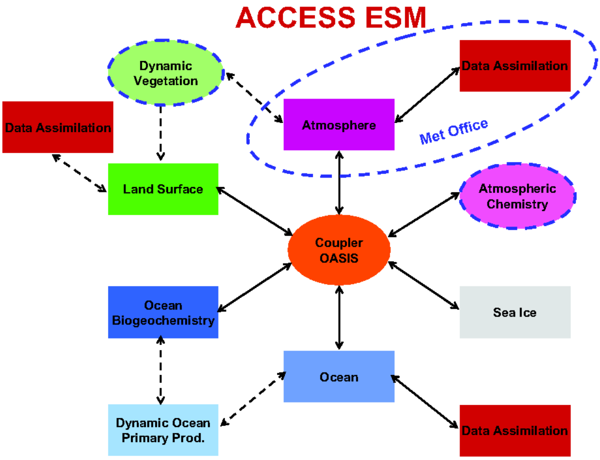
Building your climate model

- 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 climate model:
  - represents *hundreds* of person-years of work.
  - is an extremely large and complex piece of software.

Case study: ACCESS

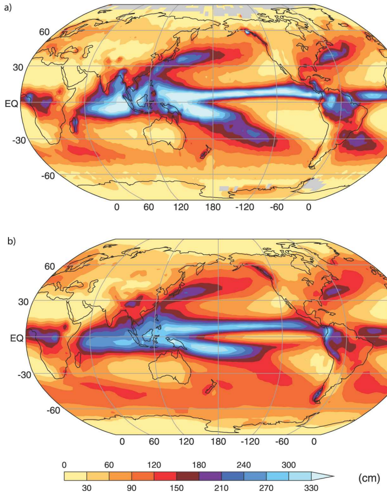
- Australian Community Climate and Earth System Simulator
- Atmosphere: Unified Model (UK)
- Ocean: MOM4 (USA)
- Sea ice: CICE (USA)
- Land surface: CABLE (Australia)
- Coupler: OASIS (France)
- Around one million lines of source code
- Can simulate around 2-3 years per day
- Generates up to 50 GB of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

Case study: ACCESS



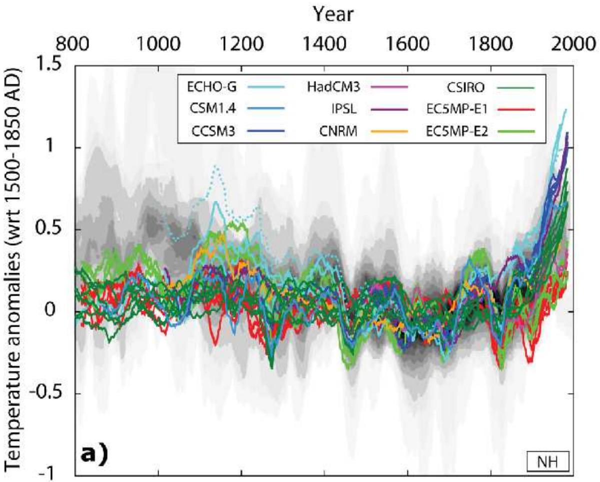
Climate modelling: Lego for adults?

Evaluation: present-day precipitation



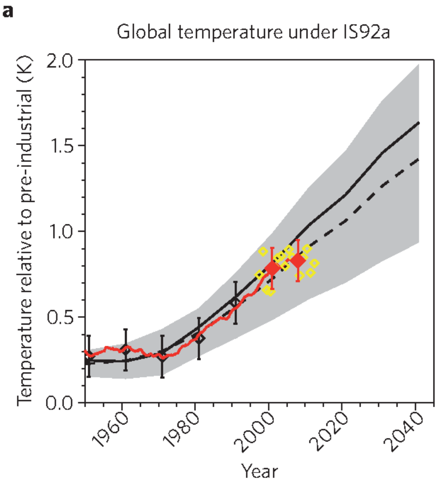
- The figures on the right show annual rainfall
- Which is observed and which is modelled?

Evaluation: past climatic changes



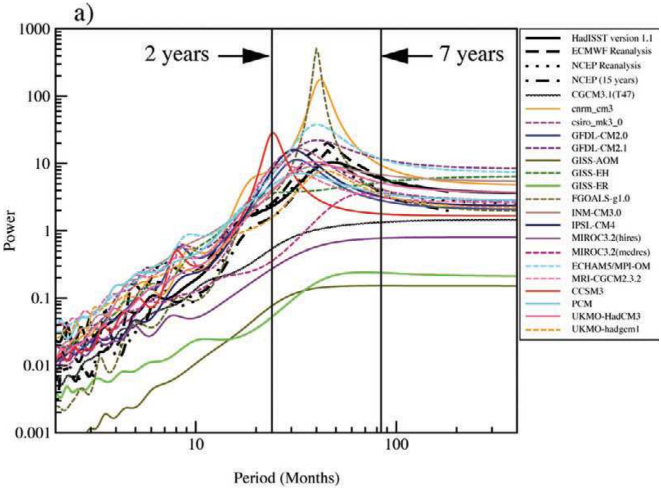
Fernández-Donado et al. (2013)

Evaluation: future climate?



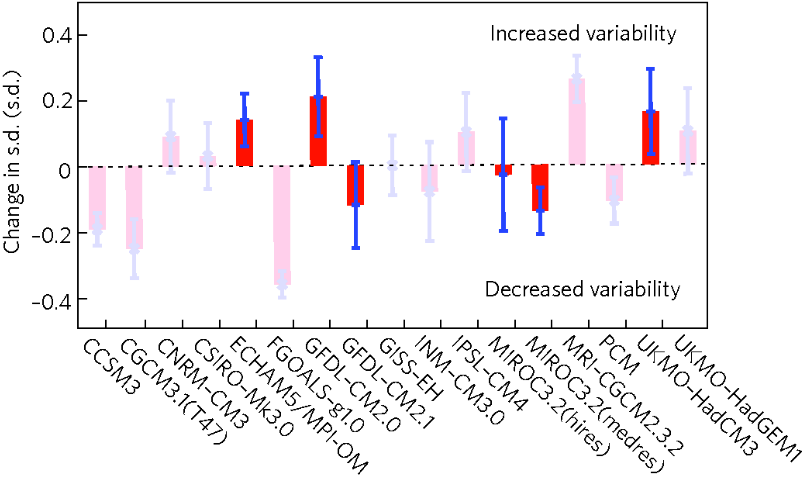
Allen et al. (2013)

Evaluation: El Niño–Southern Oscillation



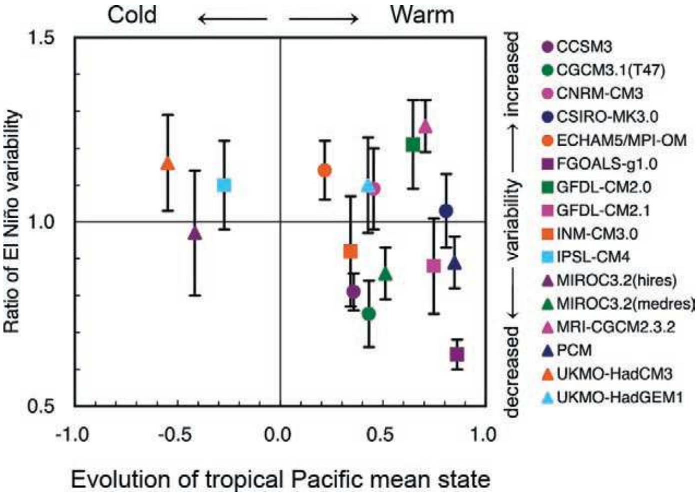
Guilyardi et al. (2009)

Model intercomparison: El Niño–Southern Oscillation



Collins et al. (2010)

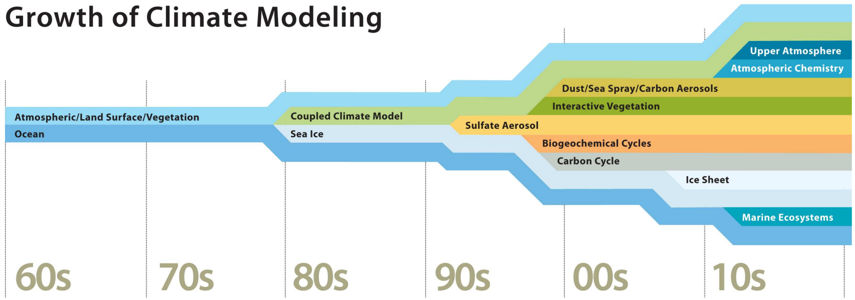
Model intercomparison: El Niño–Southern Oscillation



Guilyardi et al. (2009)

The development of climate models

The development of climate models



The first coupled atmosphere–ocean GCM

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Climate Calculations with a Combined Ocean-Atmosphere Model

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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 terrestial radiation is computed taking into consideration cloud and gaseous absorbers such as water vapor, carbon dioxide and

The first coupled atmosphere–ocean GCM

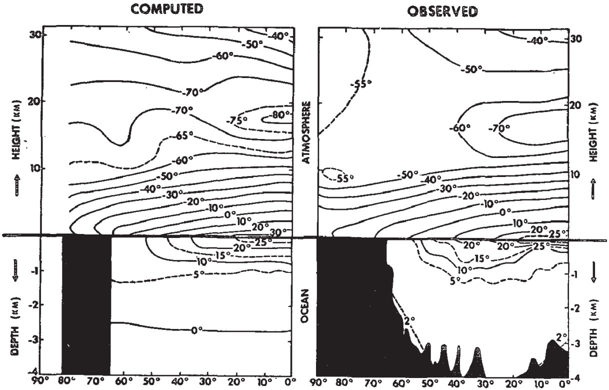

FIG. 2. Zonal mean temperature of the joint ocean-atmosphere system, left-hand side. This distribution, which is the average of two hemispheres, represents the time mean over two-sevenths of the period of the final stage of the time integration. The right-hand side shows the observed distribution in 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

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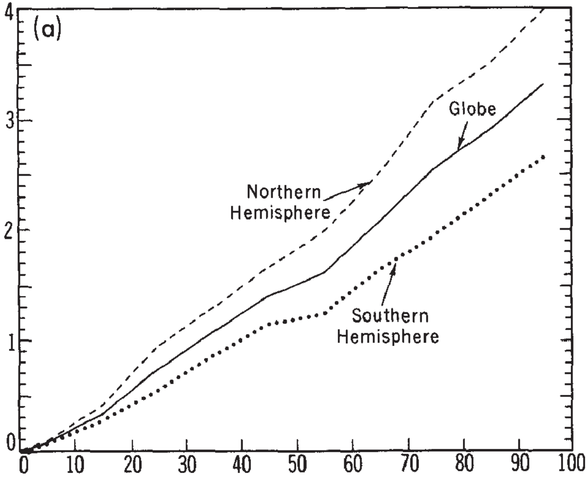
(Manuscript received 2 November 1990, in final form 4 March 1991)

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

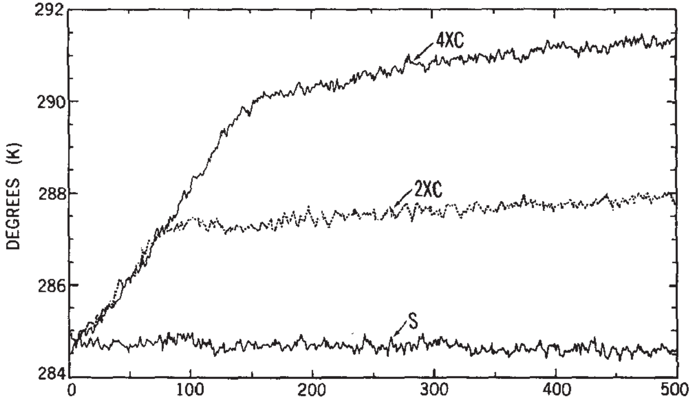


FIG. 2. Temporal variation of the global mean surface air temperature from the 4XC, 2XC, and S integrations. Units are in kelvin.

Manabe and Stouffer (1994)

Later coupled atmosphere–ocean modelling

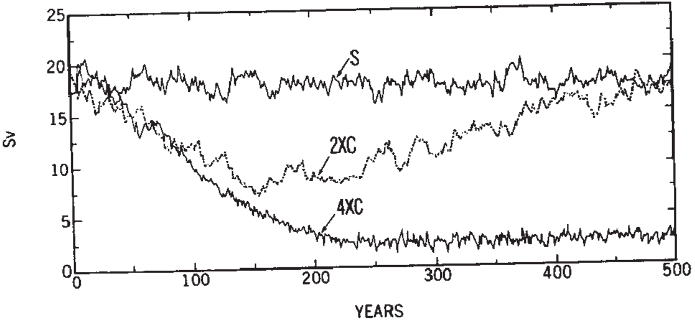
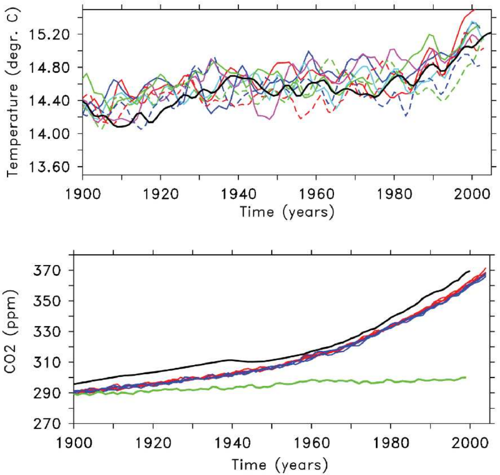


FIG. 4. Temporal variation of the intensity of the thermohaline circulation in the North Atlantic Ocean from the 4XC, 2XC, and S integrations. Here the intensity is defined as the maximum value of the streamfunction representing the meridional circulation in the North Atlantic Ocean (e.g., Fig. 5a).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

Manabe and Stouffer (1994)

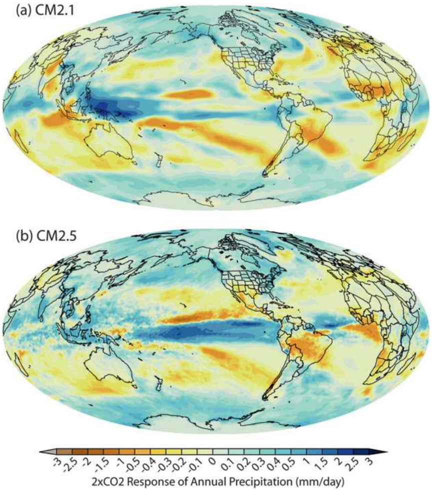
Rapid climate change?

Today: interactive carbon cycle



Jungclaus et al. (2010)

Today: increasing spatial resolution

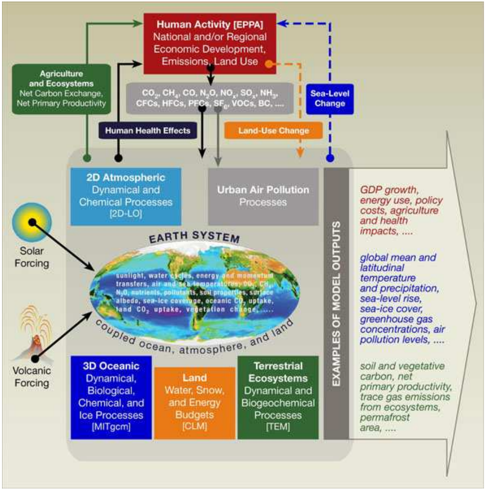


Delworth et al. (2012)

Future opportunities

Next steps: us

Coupling humans to the earth system



Conclusions

Conclusions

- Climate 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 climate 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 modeller.
- Think carefully when designing, building and using climate models; no model is perfect.

With great power, comes great responsibility

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