A History of Coupled Climate Modeling

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The first coupled ocean/atmosphere model with idealized continents was run at the GDFL: results published in JAS in 1969.

$5^\circ \times 5^\circ$ Horizontal grid: 9 levels in atm, 5 in ocean.
A Global Ocean-Atmosphere Climate Model.
Part I. The Atmospheric Circulation

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Fig. 2. The smoothed topography of the ocean model. Depth is given in kilometers.
Fig. 12. Heat transport by the ocean model in a northward direction compared to estimates based on heat balance calculations.

The conservation equations for potential temperature ($\theta$) and salinity ($S$) under conditions of stable stratification are

$$(\theta, S)_t + \nabla \nabla (\theta, S) + w(\theta, S)_z = \kappa(\theta, S)_z + A_H \nabla^2 (\theta, S).$$

(8)
In the control run, the global-average SST is reducing at a rate of 0.02°C/year.

If maintained, this means a 2°C SST fall in 100 year run.

Fig. 4. a Time evolution of globally averaged ocean surface temperature (°C) for 1×CO₂, 2×CO₂, and transient CO₂ experiments; b time evolution of ocean surface temperature differences from part (a) (°C)
Flux Corrections or Adjustments

- Atmosphere component run with SST obs.
- Ocean component run with observed wind stress and atmosphere surface variables.
- Fluxes of heat and fresh water in these runs subtracted to form the flux corrections.
- Or coupled run with very strong relaxation back to observed SST and surface salinity.
- These corrections are totally unphysical.
Sausen et al. (1988).

Ocean 3.5°x3.5° x 5 levels

Diagnostic atmosphere

Fig. 14. Temporal evolution of the global mean temperatures of the ocean in the coupled model, without flux correction (dashed line) and with flux correction (solid line)
Simulated Surface Currents Around Antarctica

Surface current speed in cm/s for October
The GM (1990) Parameterization

\[ \frac{\partial T}{\partial t} + (u + u^*).\nabla T = \nabla_\rho (\kappa \nabla_\rho T) \]

\[ w^* = -\nabla (\kappa \nabla \rho / \rho_z), \nabla .u^* = 0. \]

Assumes that eddies advect temperature and salinity and diffuse them along constant density surfaces. The advection represents the effects of unresolved baroclinic instability, because it ensures a global sink of mean potential energy.
$(u, v, w)$ is velocity in directions $(x, y, z)$

continuity equation $u_x + v_y + w_z = 0$.

Integrate over depth $\int u_x \, dz + \int v_y \, dz = 0$
form 2-D **barotropic streamfunction in Sverdrups** $(1 = 10^6 \, m^3/s)$.

Integrate over $x$ $\int v_y \, dx + \int w_z \, dx = 0$
form 2-D **overturning streamfunction**.
Original GM implementation in a very low resolution $4^\circ \times 3^\circ \times 20$ levels global ocean model; Danabasoglu et al. (1993).
Deep Water Formation $4^\circ \times 3^\circ$

Horizontal Mixing

GM 1990

Danabasoglu et al. (1993).
CSM 1 was the first climate model to produce a non-drifting control run without “flux corrections”
Components added to CCSM to make it into an Earth System Model (CESM)

- Carbon cycle components in the land, ocean & atm.
- A component that uses predictive chemistry.
- A whole atmosphere version of the atm (WACCM) that reaches up into the stratosphere and beyond.
- A land ice component that models the Greenland ice sheet, and will model the Antarctic ice sheet.
CO$_2$ in 20$^{th}$ Century Experiments

Modeled increase of CO$_2$ over 1850-2005 too large:

Observations: 94 ppmv

Prognostic CO$_2$: 114 ppmv

Diagnostic CO$_2$: 125 ppmv

Lindsay et al. (2013)
20th Century CO₂ Sinks from Atmosphere

Land Uptake

Ocean Uptake

Lindsay et al. (2013)
A community ice sheet model in CESM

CESM1 includes Glimmer, the Community Ice Sheet Model & a new surface mass balance scheme for ice sheets in CLM.

**Left:** Greenland SMB: CLM on 1° grid forced by CAM output, downscaled to 10 km  **Right:** Greenland SMB from a high-resolution regional climate model (Ettema et al. 2009).

Red = net accumulation

Blue = net ablation
Greenland ice sheet discharge and sea level rise over the 20th Century and 21st Century (RCP8.5)

C) Actual sea level rise (orange): Rise is 58mm over 2005 – 2100. Rise due to change in surface mass balance (blue): Fall due to change in Greenland ice dynamics (pink). Lipscomb et al. (2013).
# Climate Sensitivities

## Equilibrium
- Globally-averaged surface temperature increase due to a doubling of CO₂.
- Calculated using a slab upper ocean model, so the integration comes into equilibrium in about 30 yrs.
- CCSM4 -- 3.20°C
- CESM1 -- 4.10°C

## Transient
- Global surface temperature increase at doubling of CO₂ in a run where it increases at 1% per year: Average over years 60 -- 80.
- Calculated using the full depth ocean component.
- CCSM4 -- 1.73°C
- CESM1 -- 2.33°C

CESM1 includes secondary effects due to aerosols
Decadal Forecasts with the CESM

• Fully-coupled CESM1 simulations initialized from historical ocean and sea ice states for Jan 1\textsuperscript{st} of 1961, 1966, ..., 2006

• Ocean & sea ice initial conditions from an ocean/sea-ice simulation of 1948–2007 forced by atmospheric observations.

• Full-field initialization (with bias correction)

• 10-member ensembles for each of 10 start dates

• Case study of the mid-1990s warming in the subpolar gyre of the North Atlantic Ocean.
After bias correction, the CESM has significant skill in predicting SPG heat content & SST up to a decade in advance.

Yeager et al. (2012)
Conclusions

• The first coupled climate models were run in the early 1970s, and used very coarse resolution.

• These models had to use flux corrections in order to maintain the present climate in coupled runs.

• The CSM1 (run in 1996) was the first to maintain the present ocean temperatures in a coupled run.

• Earth System Models have interactive components for the carbon cycle, and possibly others, such as Chemistry, high-top Atmosphere and Land Ice.