The Icy Demise and Revamping of GFDL's ESM2G Earth System Model

R. Hallberg, A. Adcroft, J. Dunne, S. M. Griffies, and J. Krasting

NOAA/GFDL & Princeton University

GFDL’s IPCC AR5 Coupled Climate Models

	CM2G	CM2M	CM2.1	CM3
Atmosphere	AM2.1 (L24)	AM2.1 (L24)	AM2.1 (L24)	AM3 (L48)
Land	LM3	LM3	LM2	LM3
Sea ice	SIS	SIS	SIS	SIS
Ocean	GOLD 1° x L63 ρ	MOM4p1 “M configuration” 1° x L50 Z*	MOM4 1° x L50 Z	MOM4p1 “CM2.1-like” 1° x L50 Z*

ESM2G and ESM2M

New Models

Ocean Components of GFDL's AR5 Coupled Climate Models

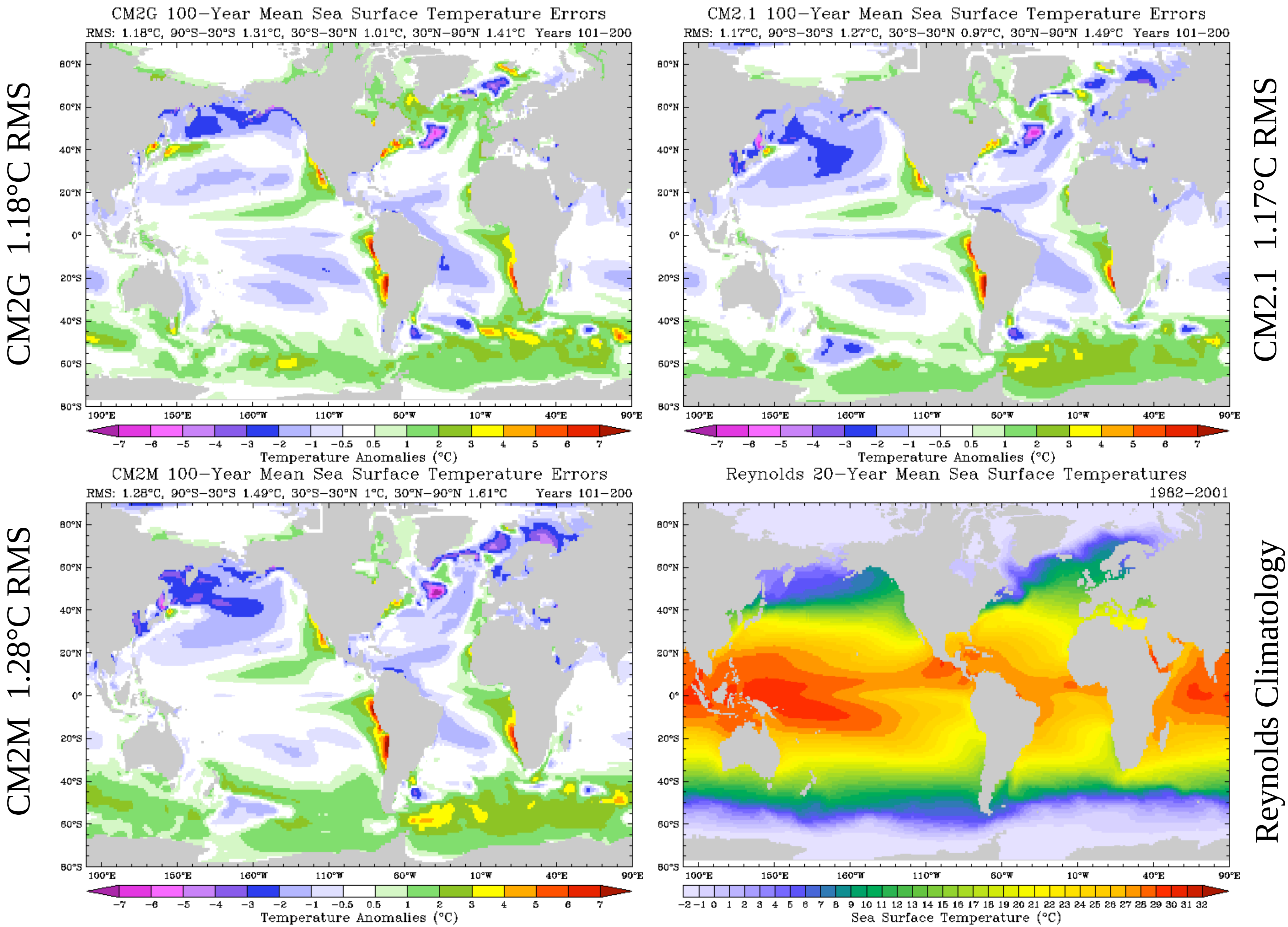
CM2G (GOLD)

- 1° res. (360x210), on tripolar grid.
- 59 **Isopycnal** interior layers + 4 in ML
- C-grid discretization
- Split explicit free surface ; fresh water fluxes as surface B.C.
- 2-layer refined bulk mixed layer with 2 buffer layers
- Full nonlinear equation of state except for coordinate definition
- Tracer diffusion rotated to σ_2 surfaces
- Partially open faces allow explicit exchanges with marginal seas.
- Legg et al. BBL mixing + Simmons et al. diapycnal diffusion + Vertically constant background diffusivity w/ Henyey structure.
- Visbeck variable thickness diffusivity.
- Biharmonic Smagorinsky + Resolution scaled Laplacian viscosity.
- Jackson et al (2008) shear-Richardson number dependent mixing.
- 1 hour baroclinic timestep, 2 hour tracer & coupling timesteps
- Continuously variable topography

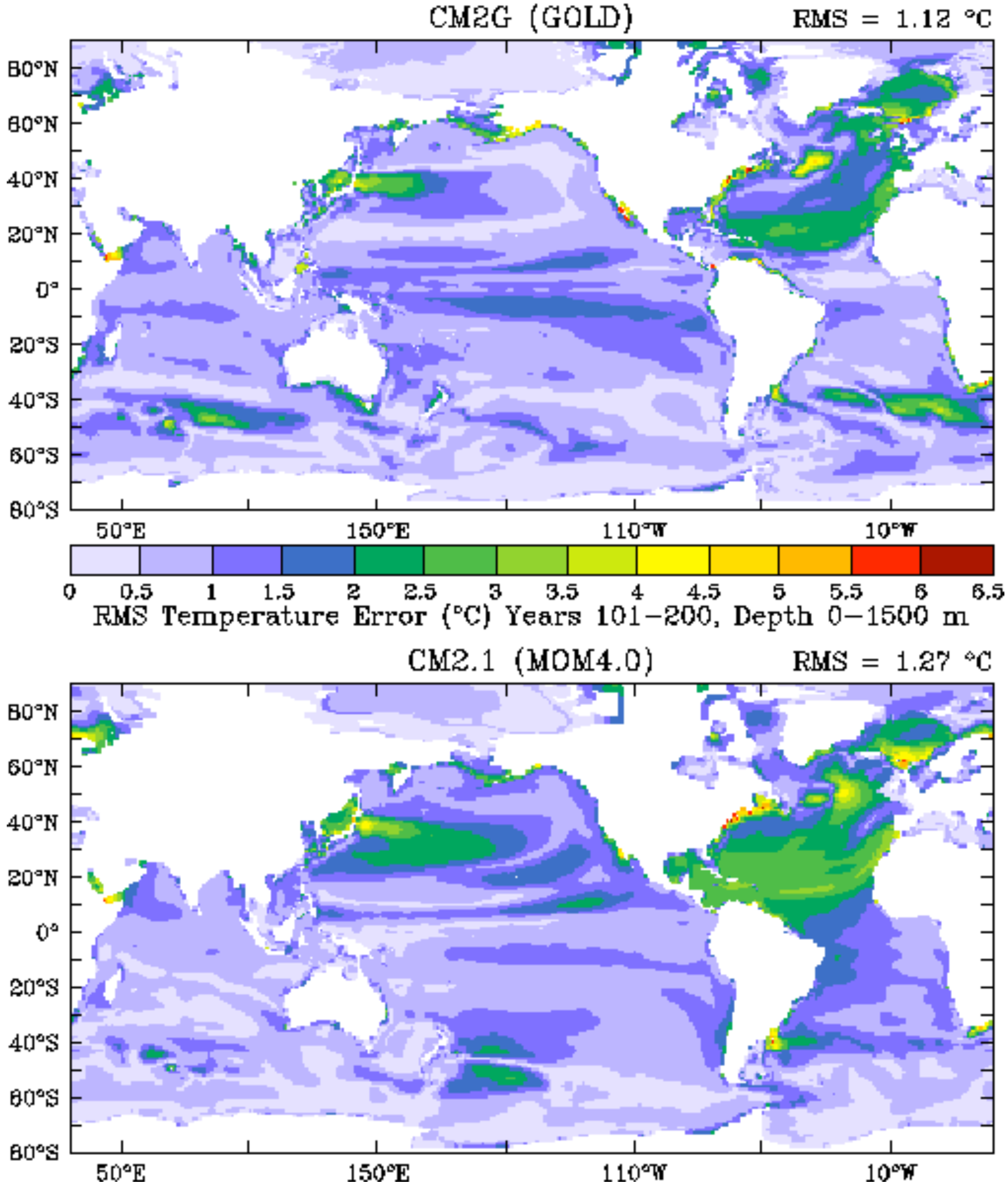
CM2M or CM2.1/CM3 (MOM4.0 & 4.1)

- 1° res. (360x200), on tripolar grid.
- 50 z- or **Z***-coordinate vertical levels
- B-grid discretization
- Split explicit free surface ; fresh water fluxes as surface B.C.
- KPP mixed layer with 10 m resolution down to 200 m
- Full nonlinear equation of state
- MDPPM tracer advection (CM2M)
- Tracer diffusion rotated to neutral directions
- Marginal sea exchanges specified via "cross-land mixing"
- Lee et al. BBL + Bryan-Lewis (CM2.1) or Simmons et al. (CM2M) diapycnal diffusion with vertically constant background w/tanh(θ).
- Baroclinicity-dependent GM diffusivity.
- Anisotropic Laplacian viscosity (CM2.1) or Biharmonic Smagorinsky + Resolution scaled Laplacian viscosity (CM2M)
- KPP specification of interior shear-Richardson number dependent mixing
- 2 hour baroclinic and coupling timesteps.
- Partial cell topography

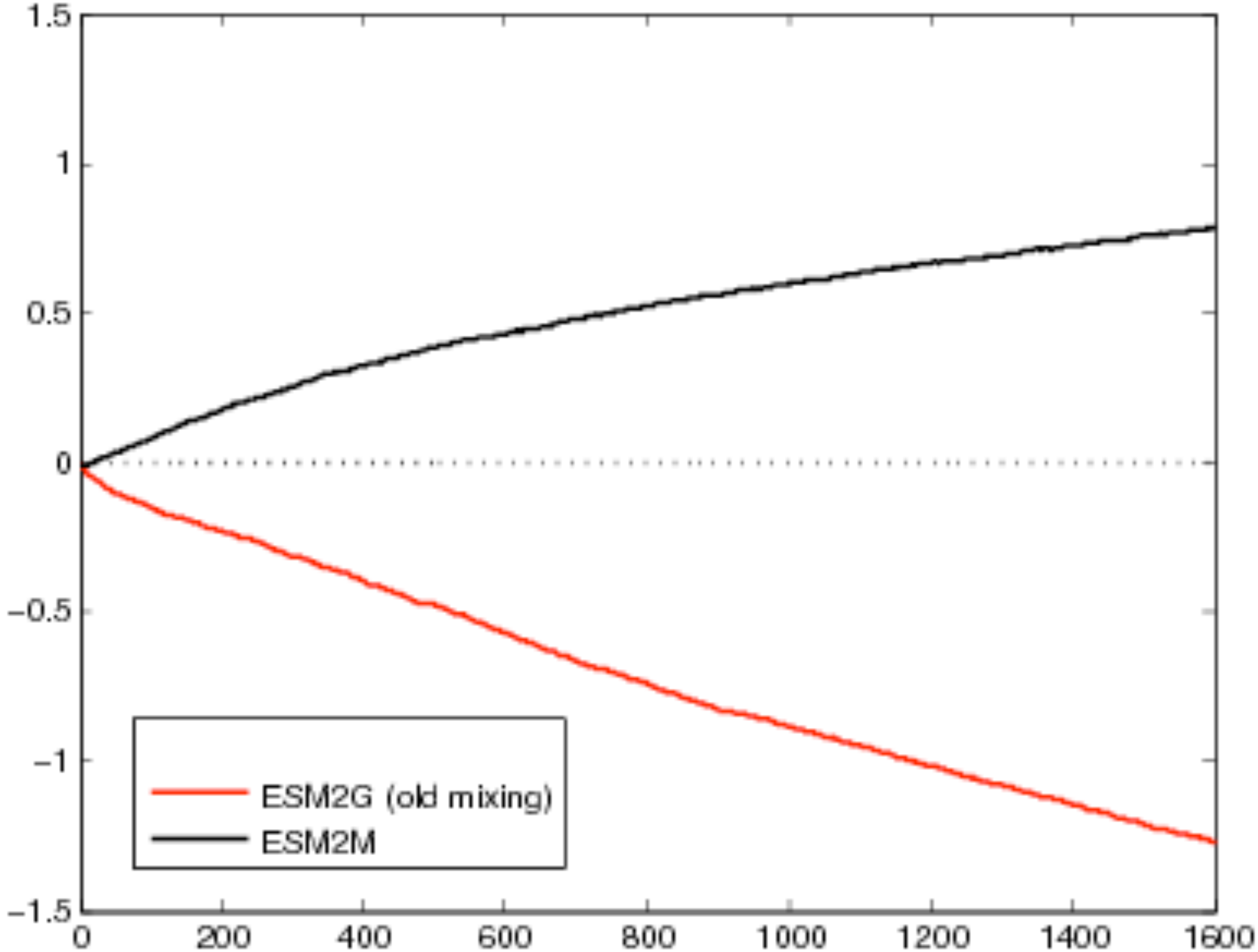
100-Year Annual Mean SST Errors – 1990 Radiative Forcing



RMS 0-1500 m Depth Temperature Errors, Years 101-200 with 1990 Forcing

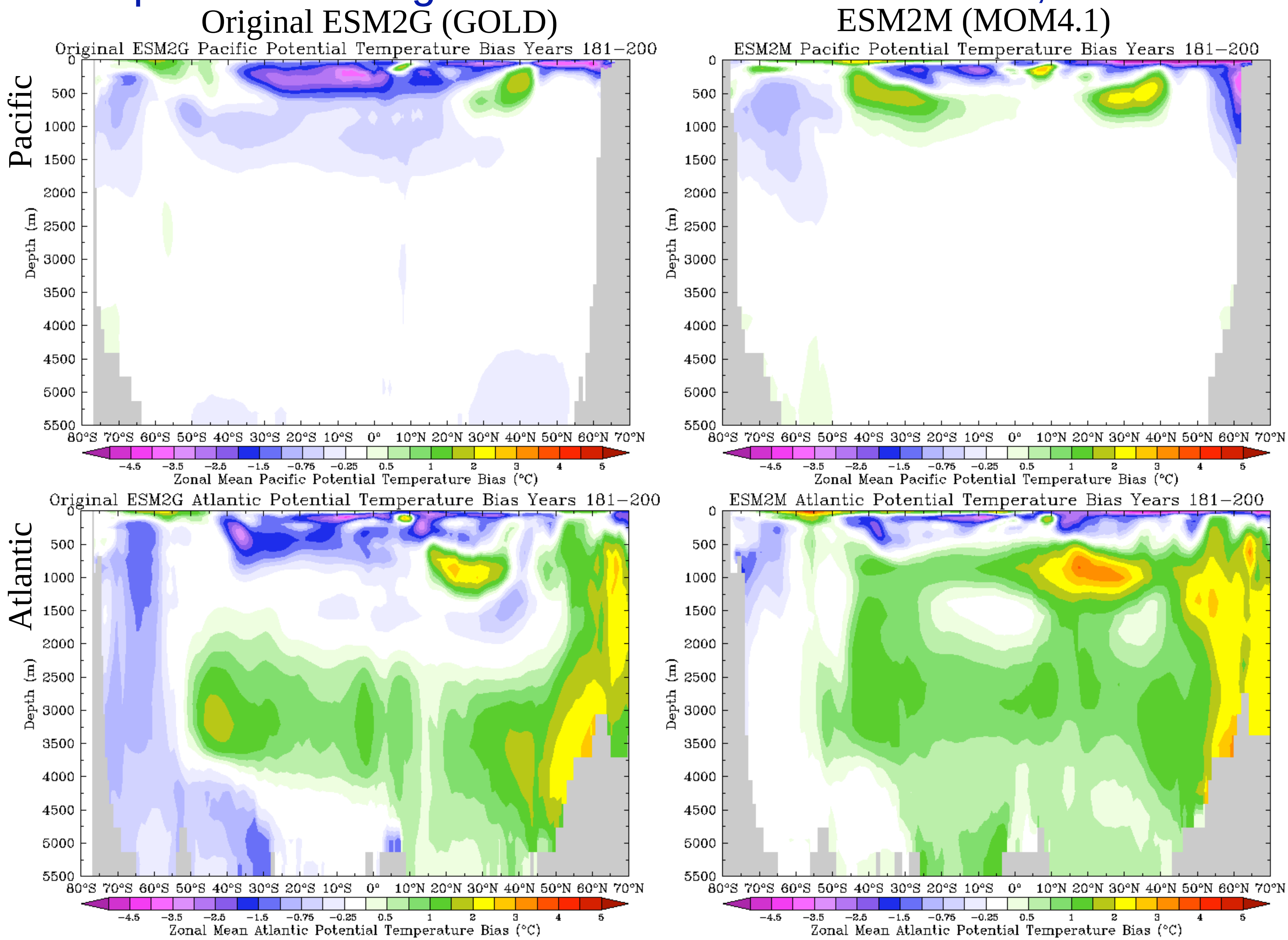


Global-mean Ocean Temperature in 1860 Spinups Starting from Climatological (~1990) Initial Conditions



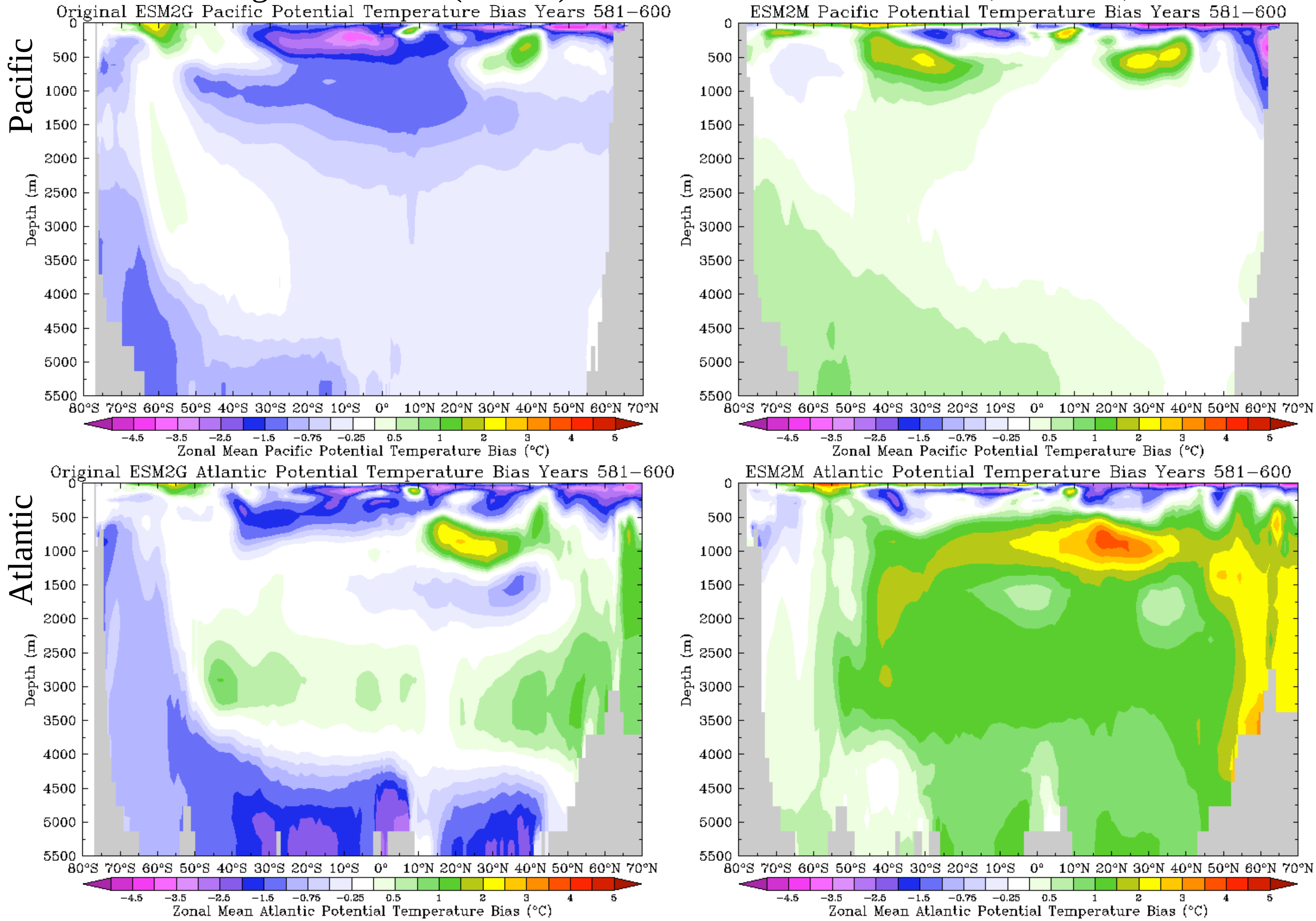
Time (Years)

Temperature change from 1990 ICs in 1860 Runs, Year 200



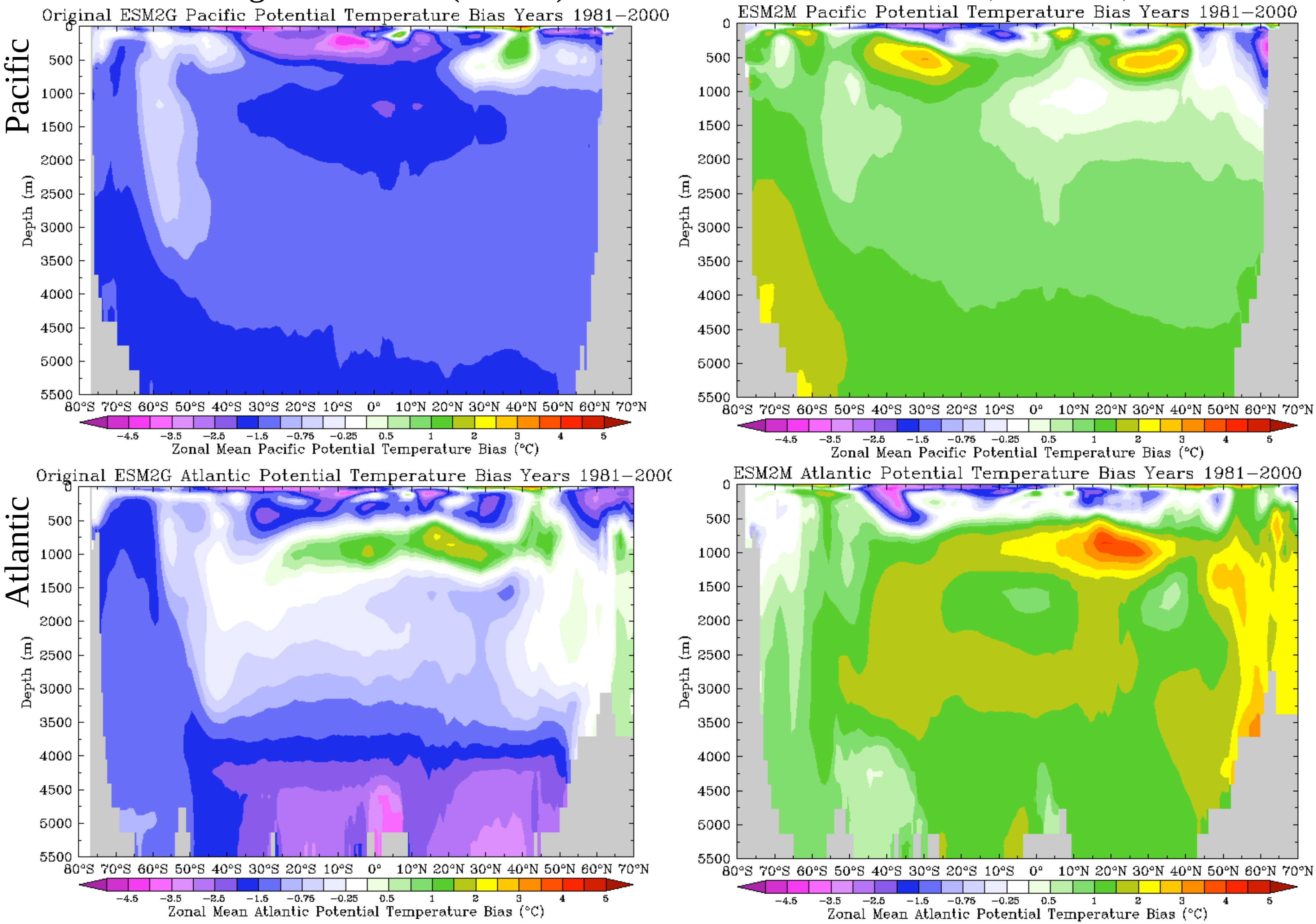
Temperature change from 1990 ICs in 1860 Runs, Year 600

Original ESM2G (GOLD) | ESM2M (MOM4.1)



Temperature change from 1990 ICs in 1860 Runs, Year 2000

Original ESM2G (GOLD) | ESM2M (MOM4.1)

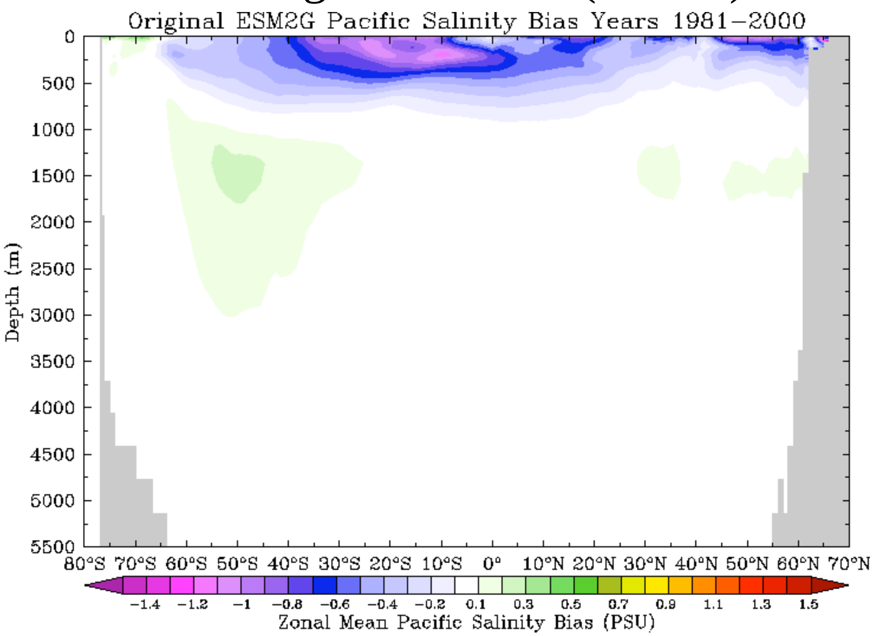


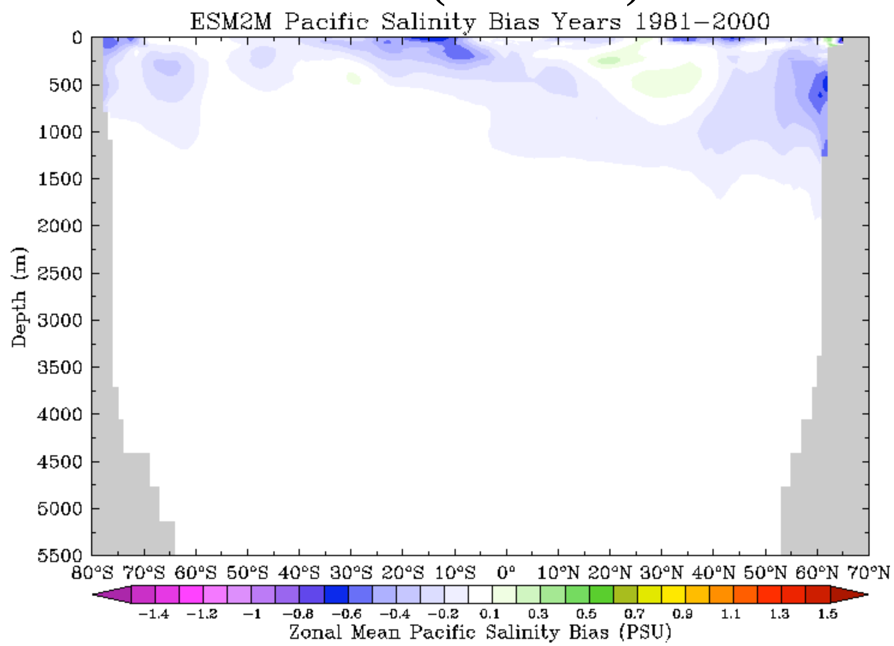
Salinity change from 1990 ICs in 1860 Runs, Year 2000

Original ESM2G (GOLD)

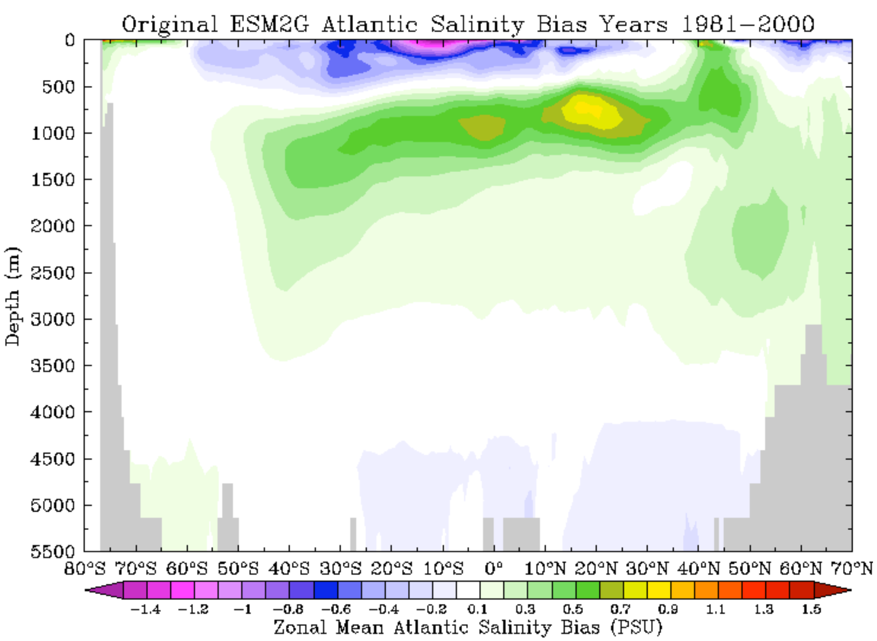
ESM2M (MOM4.1)

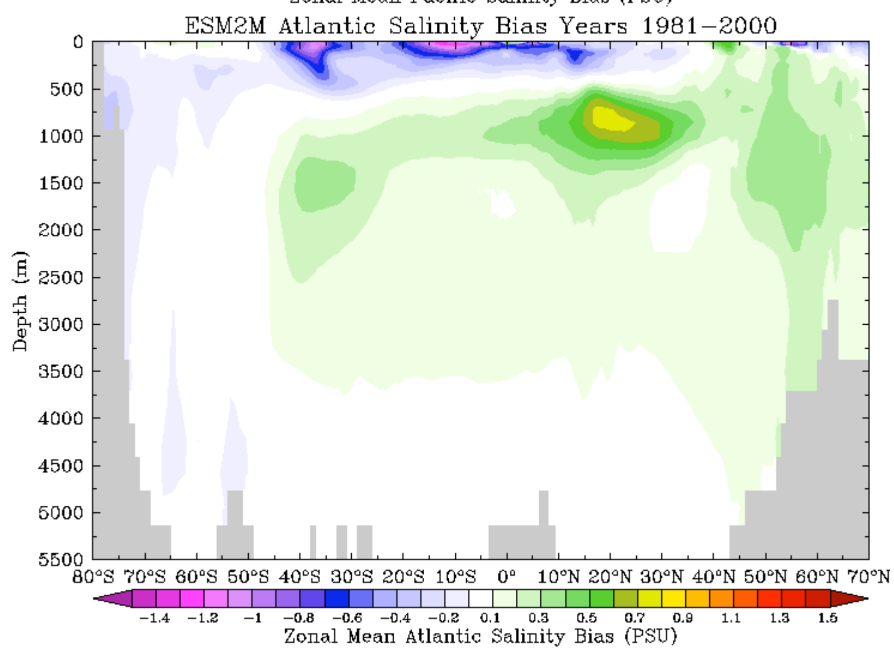
Pacific



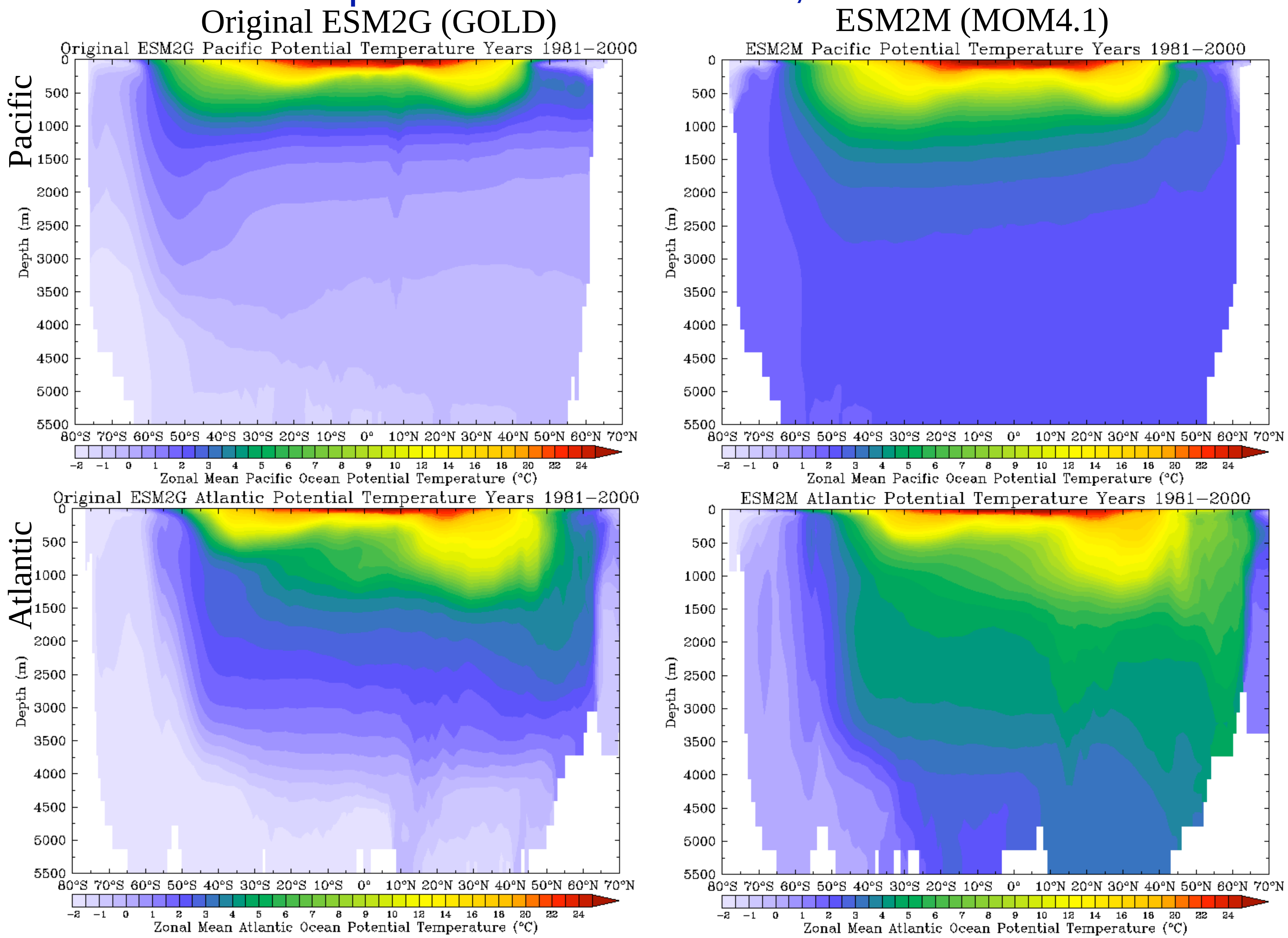


Atlantic





Temperature in 1860 Runs, Year 2000



Sea Surface Temperature in 1860 Runs, Year 1901-2000

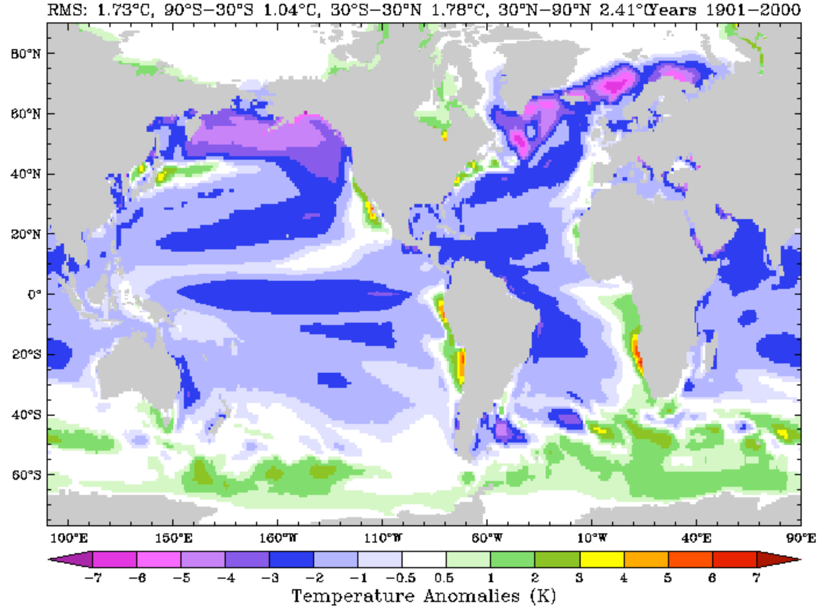
Original ESM2G (GOLD)

ESM2M (MOM4.1)

Pacific

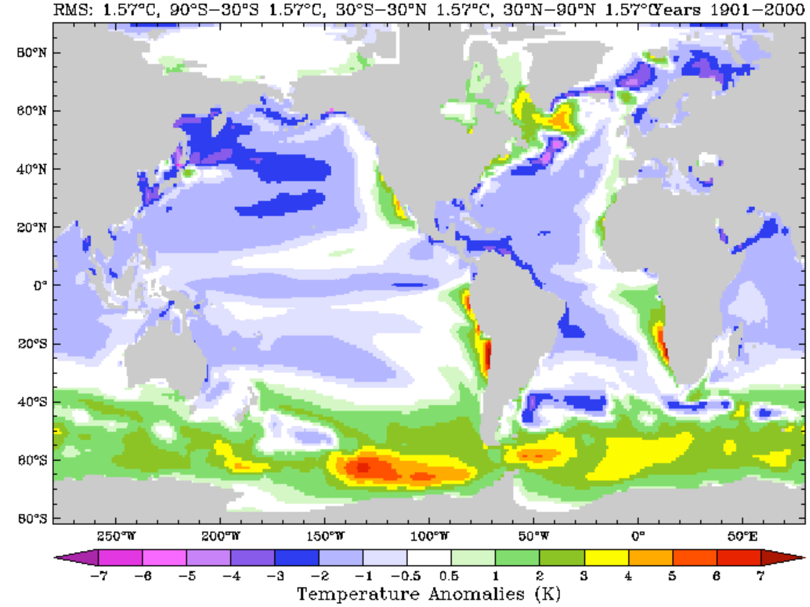
Original ESM2G 100−Year Mean Sea Surface Temperature Errors

RMS: 1.73°C, 90°S−30°S 1.04°C, 30°S−30°N 1.78°C, 30°N−90°N 2.41°C Years 1901−2000



ESM2M 100−Year Mean Sea Surface Temperature Errors

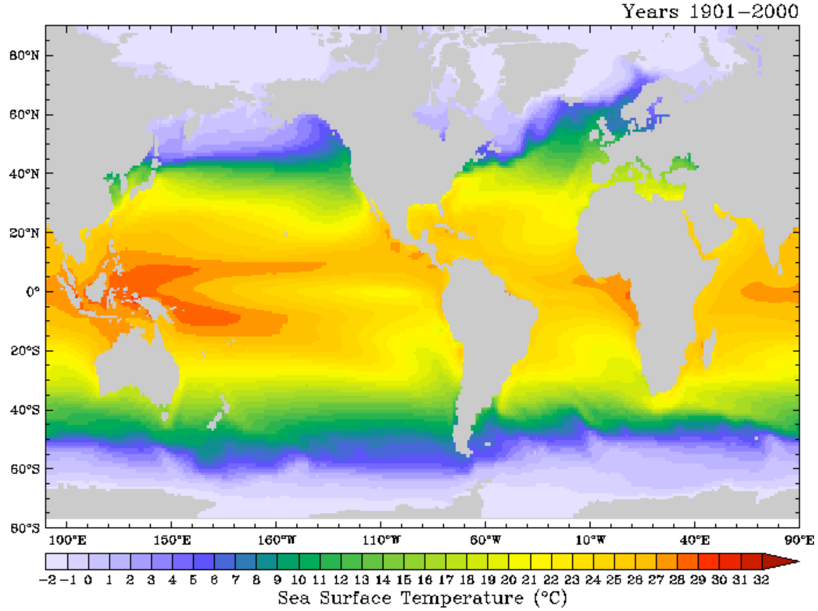
RMS: 1.57°C, 90°S−30°S 1.57°C, 30°S−30°N 1.57°C, 30°N−90°N 1.57°C Years 1901−2000



Atlantic

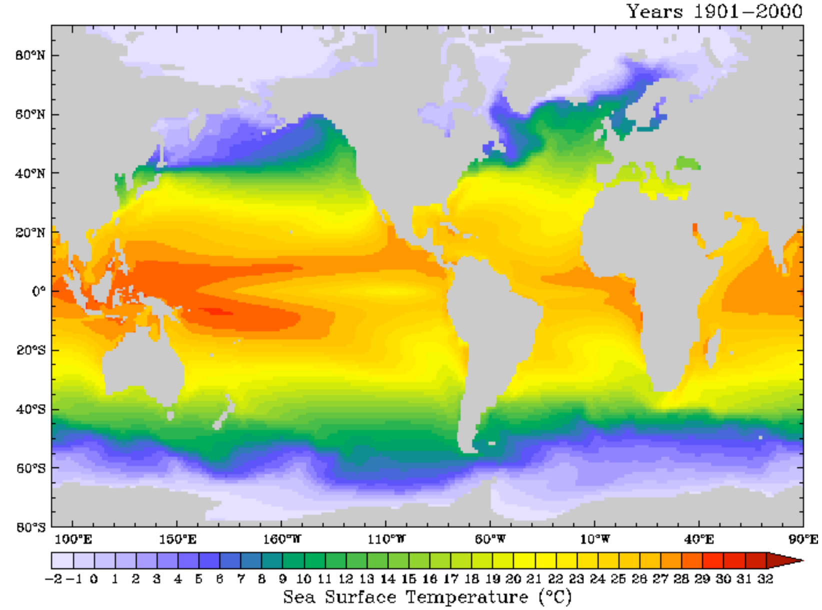
Original ESM2G 100−Year Mean Sea Surface Temperatures

Years 1901−2000



ESM2M 100−Year Mean Sea Surface Temperatures

Years 1901−2000



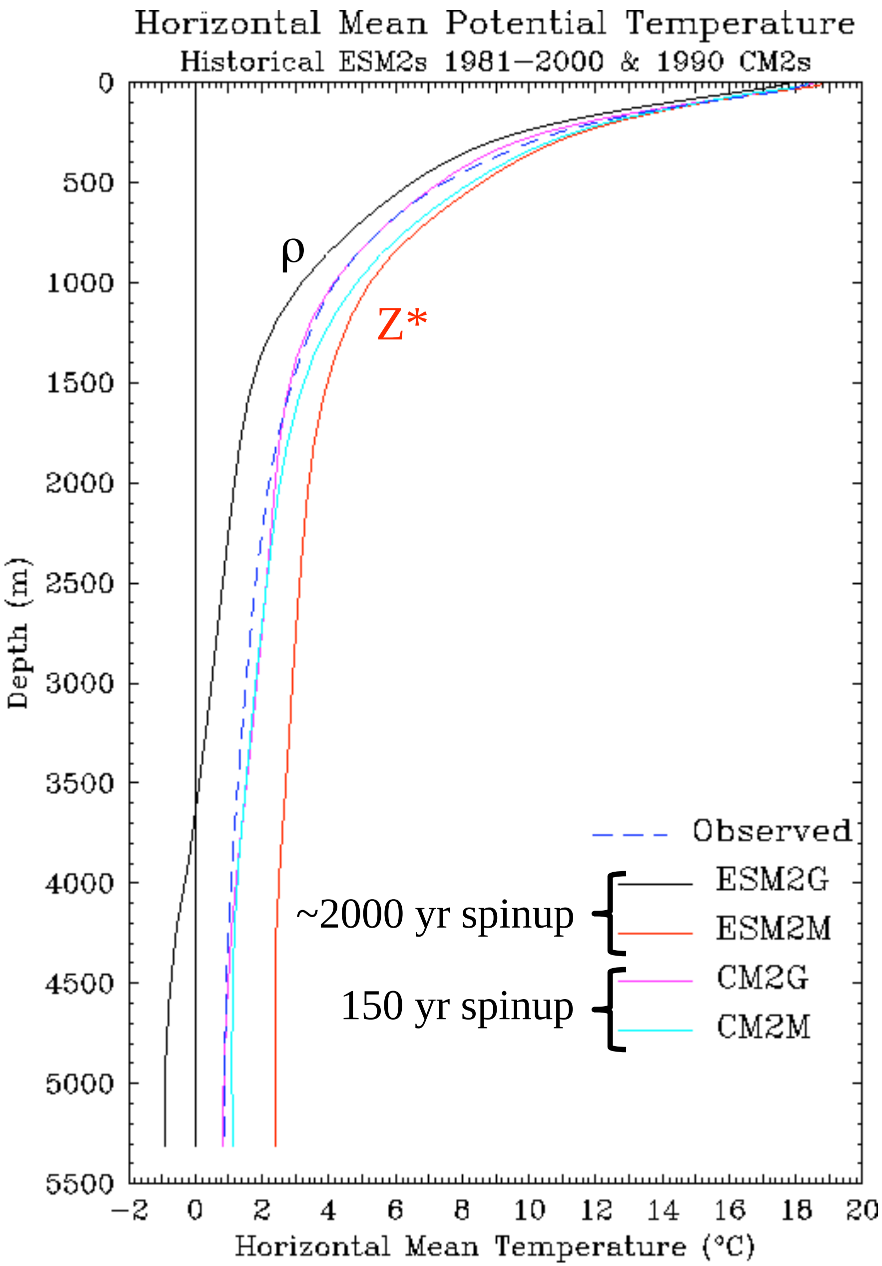
Differences in Physical Processes between ESM2M & ESM2G

What it does not appear to be:

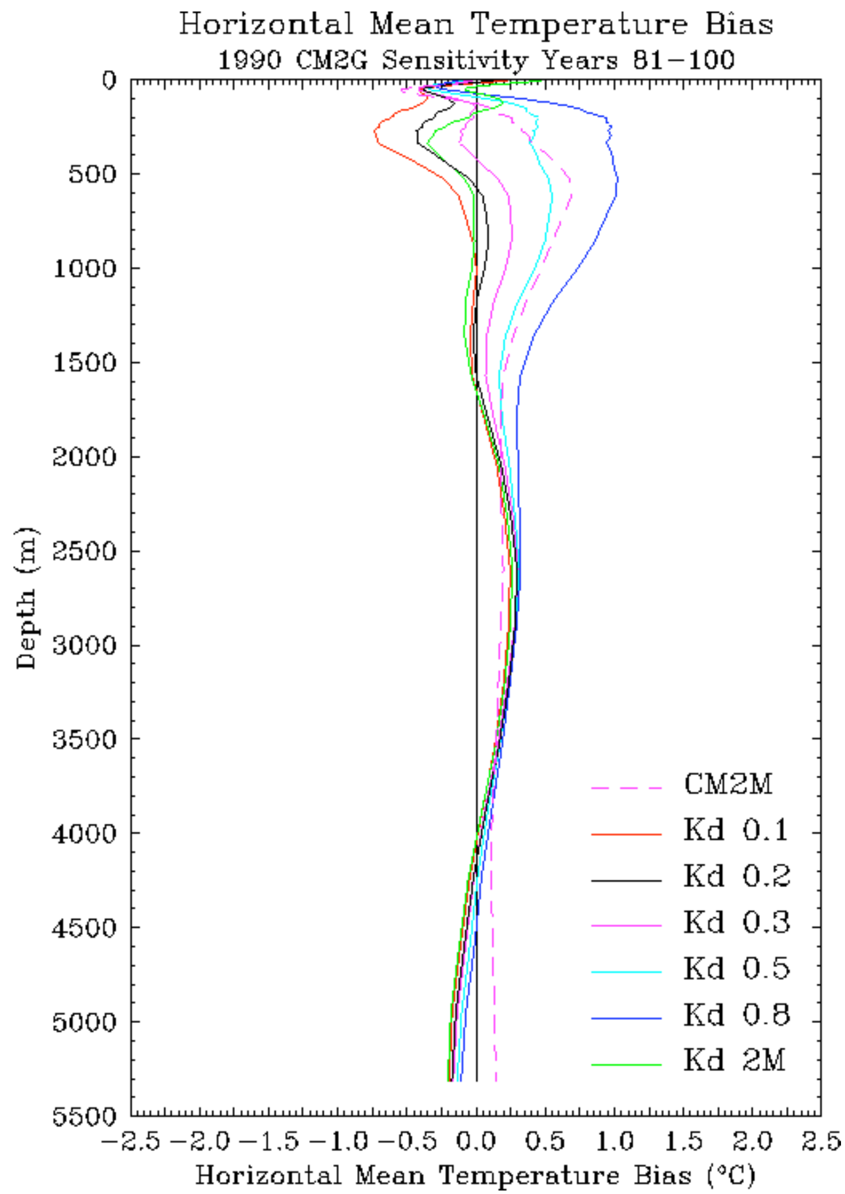
- Single-column mixed layer simulations give similar results.
- Specified levels of background mixing are similar.
- Abyssal internal tide mixing was originally calibrated to do similar amounts of work between ESM2M & ESM2G.

Plausible candidates:

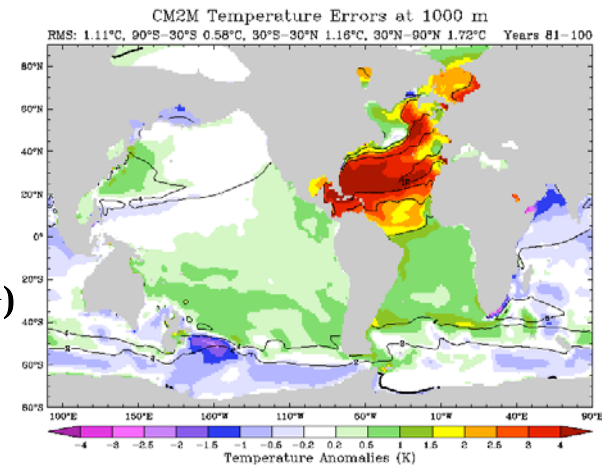
- Geothermal heating is present in ESM2M but missing in ESM2G
- Lee, Spellman, Rosati (2006) BBL mixing (unconstrained) vs. Legg, Hallberg, Girton (2004) BBL mixing (energetically consistent)
- No numerical mixing in ESM2G AABW overflows; maybe lots in ESM2M



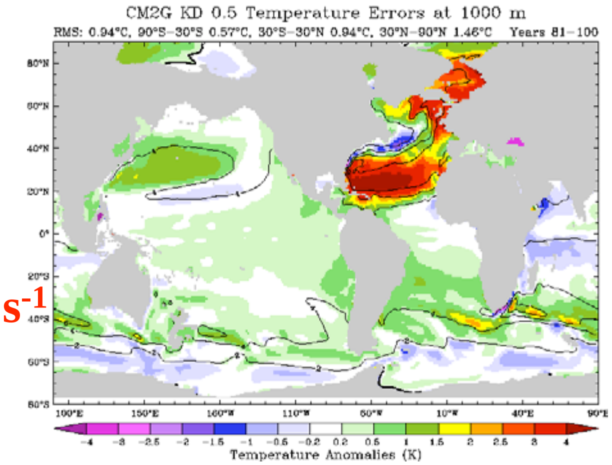
Thermocline Equivalence of CM2M to CM2G with Enhanced Diapycnal Diffusivity



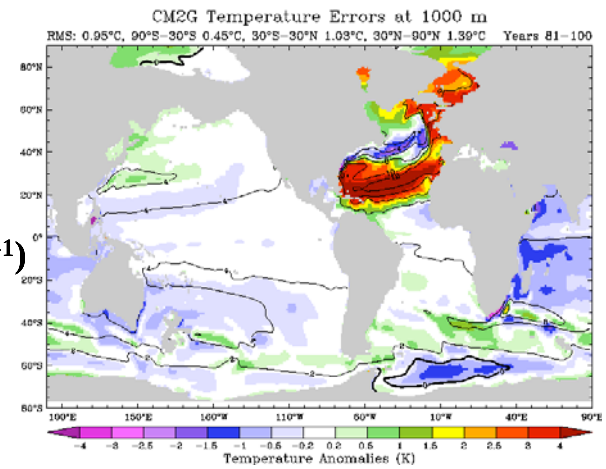
CM2M
(K_d 0.15 $cm^2\ s^{-1}$)



CM2G
with K_d 0.5 $cm^2\ s^{-1}$



CM2G
(K_d 0.2 $cm^2\ s^{-1}$)



Changes to ESM2G

1. Added geothermal heating similar to ESM2M

   (Reduced the abyssal cooling trend by ~20%)

2. Ensured that all internal tide energy is used or explicitly dissipated.

   (The bottommost layer cannot entrain.)

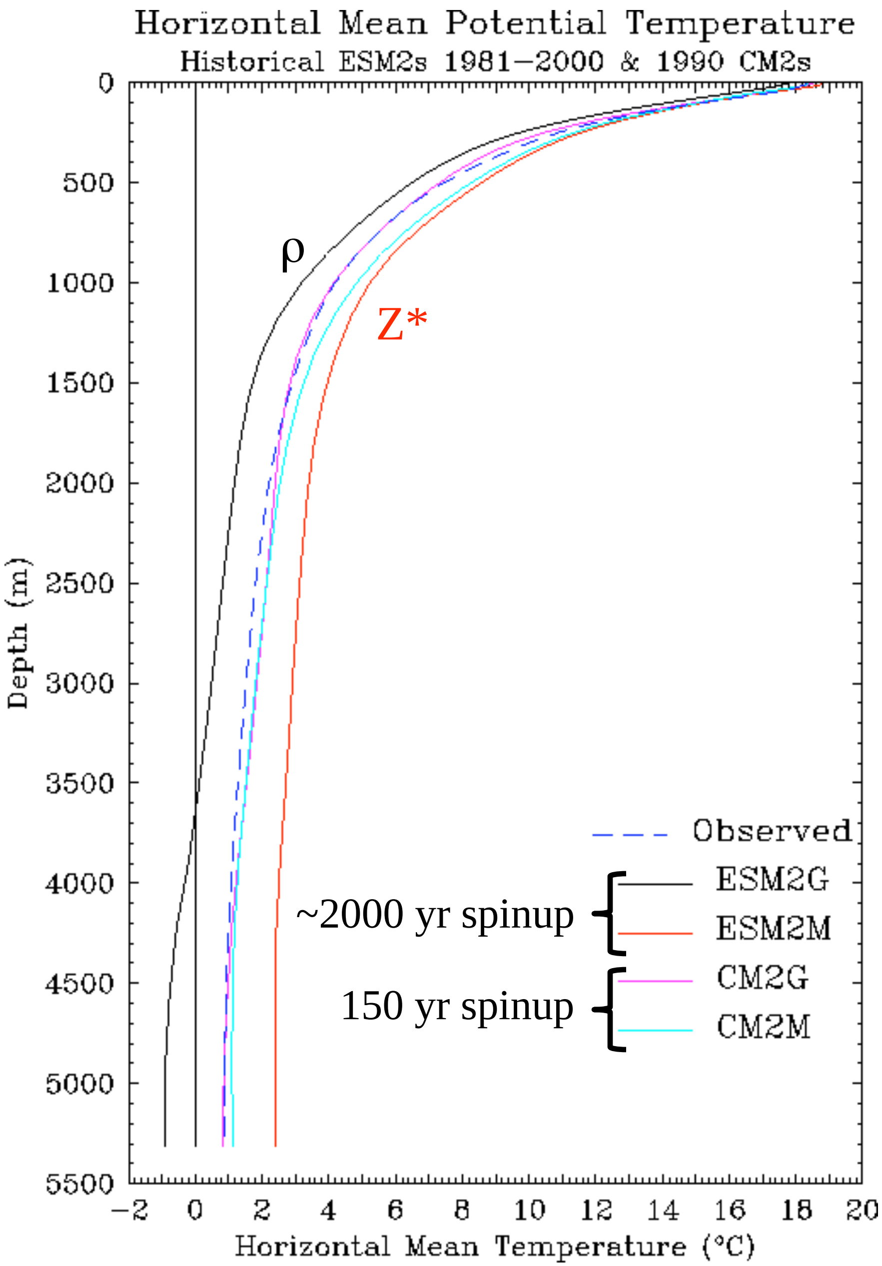
3. Added a floor to the diffusivity following the Gargett (1984) parameterization:

$$\varepsilon_{Min} = \varepsilon_0 + \varepsilon_N N \qquad \kappa \geq \frac{0.2\varepsilon_{Min}}{N^2 + \Omega^2}$$

   In choosing the parameters of the floor, we deliberately erred on the side of excess mixing:

$$\varepsilon_0 = 10^{-7}\ \mathrm{m^2\ s^{-3}} \ ; \ \varepsilon_N = 6\times10^{-4}\ \mathrm{m^2\ s^{-2}}$$

We are also trying a variant of ESM2M, where we eliminate some of the crazy mixing from the Lee et al BBL scheme; this seems to reduce ESM2M's warming bias by about 20%.



Lee, Rosati & Spellman Mixing in CM2.1 / CM2M

- Intended to model bottom boundary layer mixing due to barotropic tidal shears. (Ocean Modelling, 2006)
- Assumes that tidal shear is due to bottom drag and linearly varying over the depth of the ocean.

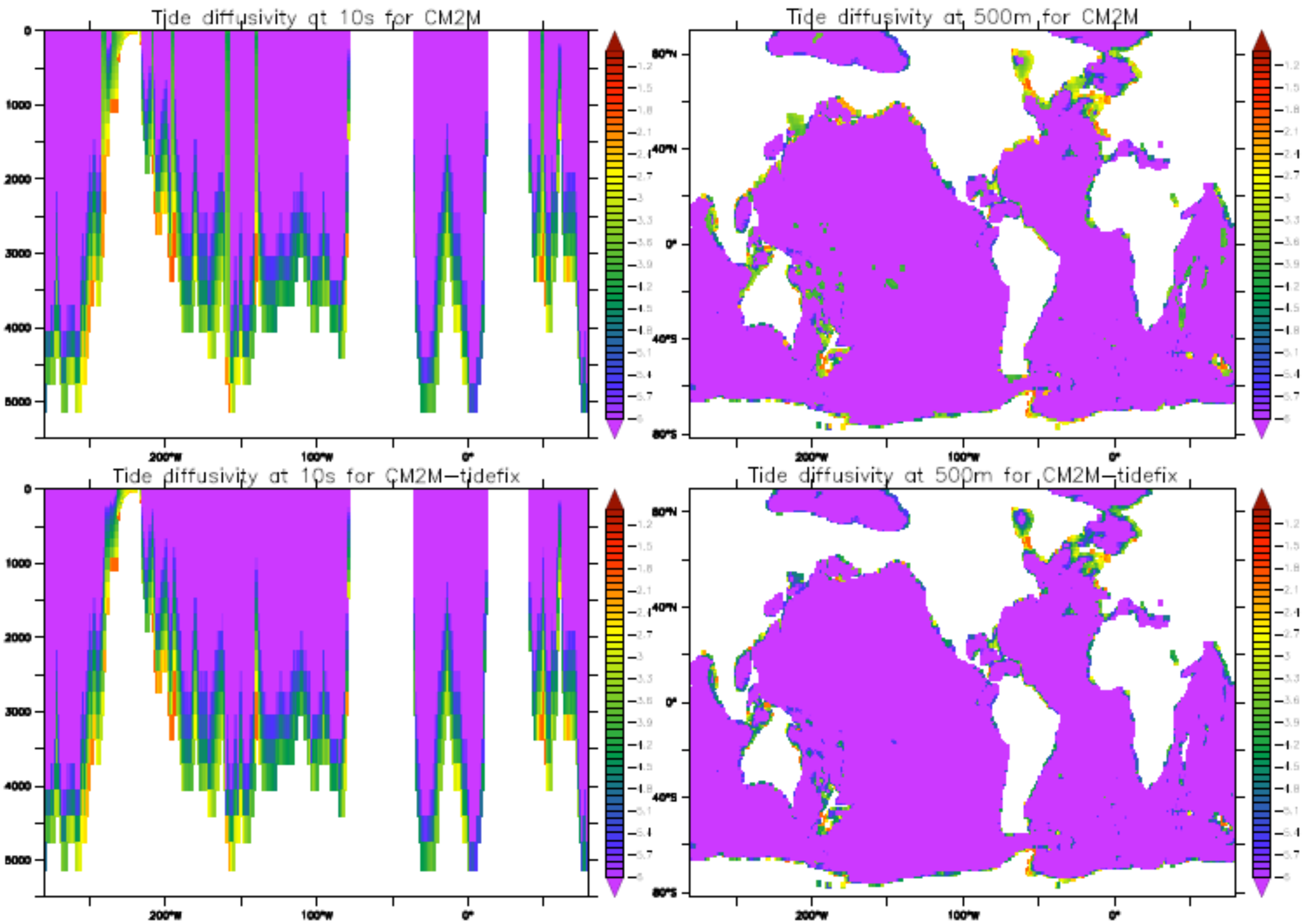
$$\kappa = 5\times10^{-3} m^2 s^{-1}\left(1+3Ri_{Lee}\right)^{-1/4}$$

$$Ri_{Lee} = 0.32N^2\frac{\left(z-D\right)^2}{c_d U_{Tide}^2}$$

- Problems with this scheme:
  - Dimensional "constant"
  - Very weak dependence on stratification
  - No limit on energy input

- (Not available in GOLD-based models.)

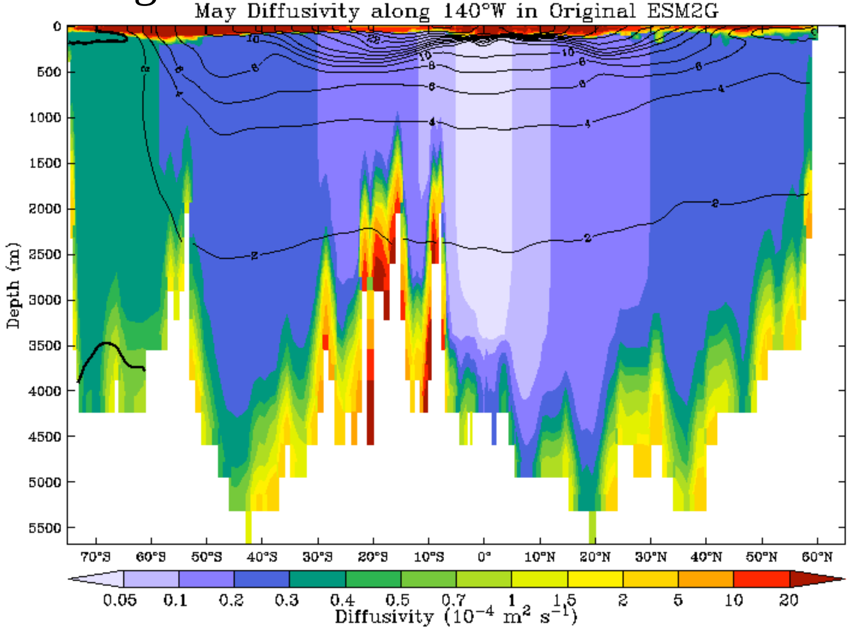
Simmons et al. + Lee et al. Tidal Mixing in ESM2M



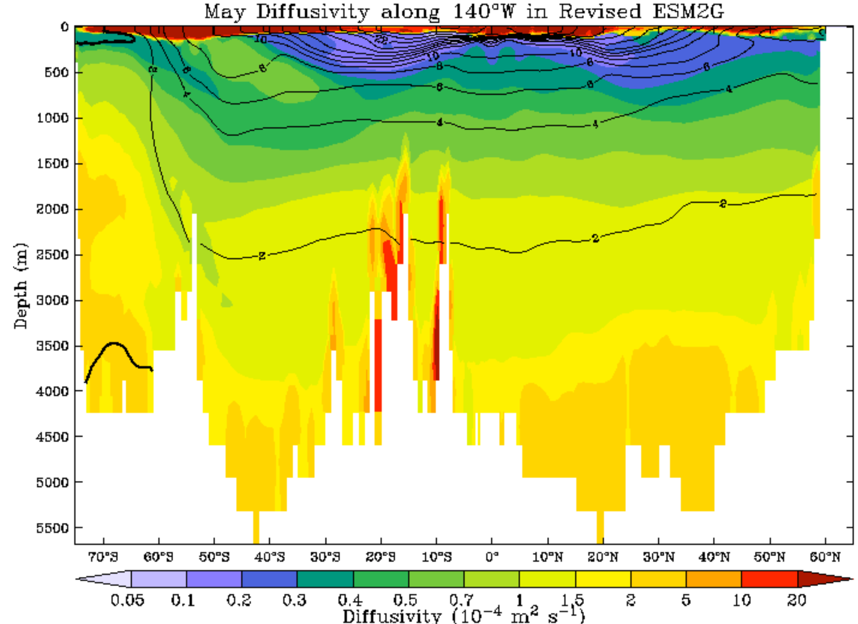
$$\kappa_{Lee}^{Fixed} = \kappa_{Lee} \exp\left[-(z-D)(\omega_{M2} / u_{Tide}^{*})\right]$$

Diffusivity Along 140° W

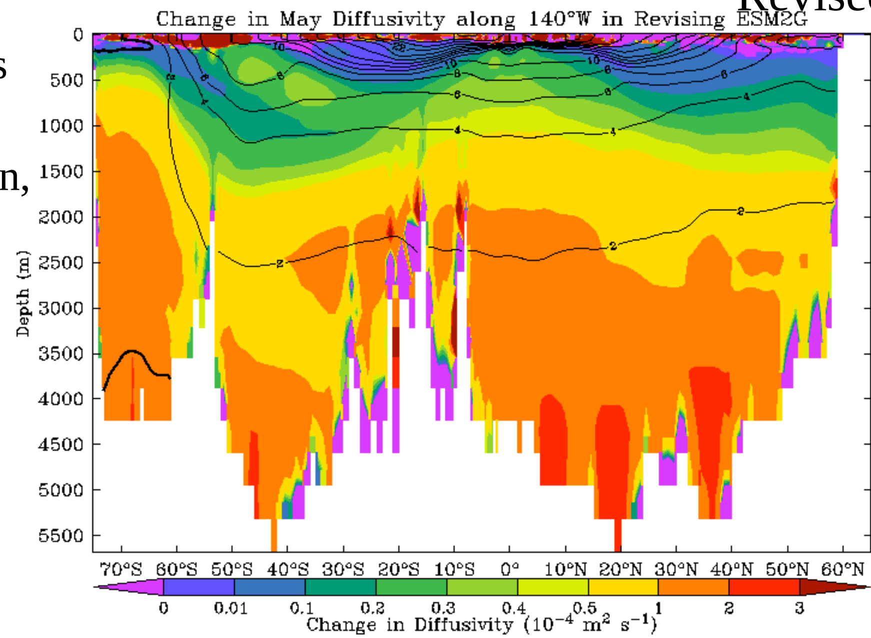
Original ESM2G



Revised ESM2G



Revised - Original



1. Ensured that all tidal mixing energy is used or explicitly dissipated.
   - The bottommost layer can not entrain, and hence can not use energy.
2. Added a Gargett-style mixing floor.

$$\varepsilon_{Min} = \varepsilon_0 + \varepsilon_N N \qquad \kappa \ge \frac{0.2\varepsilon_{Min}}{N^2 + \Omega^2}$$

   - This adds diffusion in the abyss, but not much in the upper thermocline

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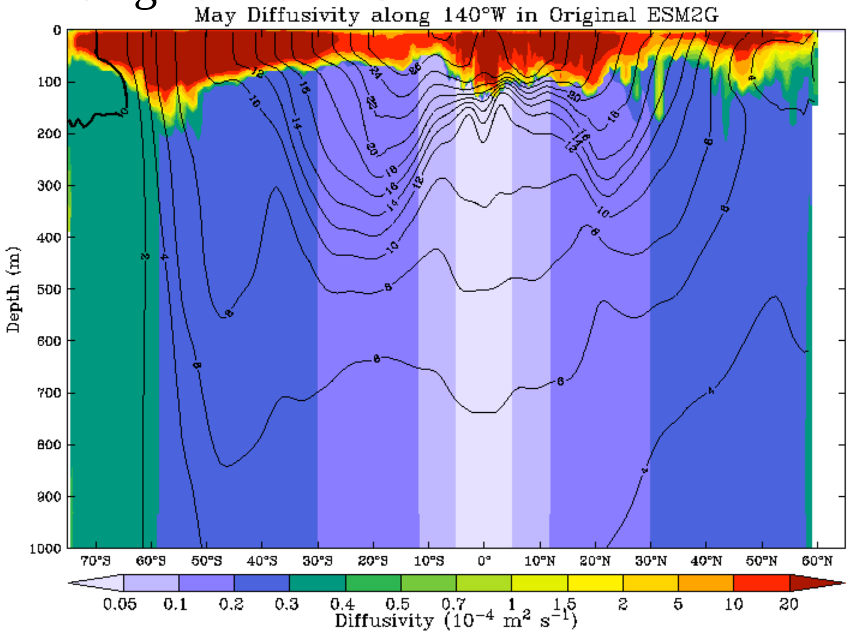
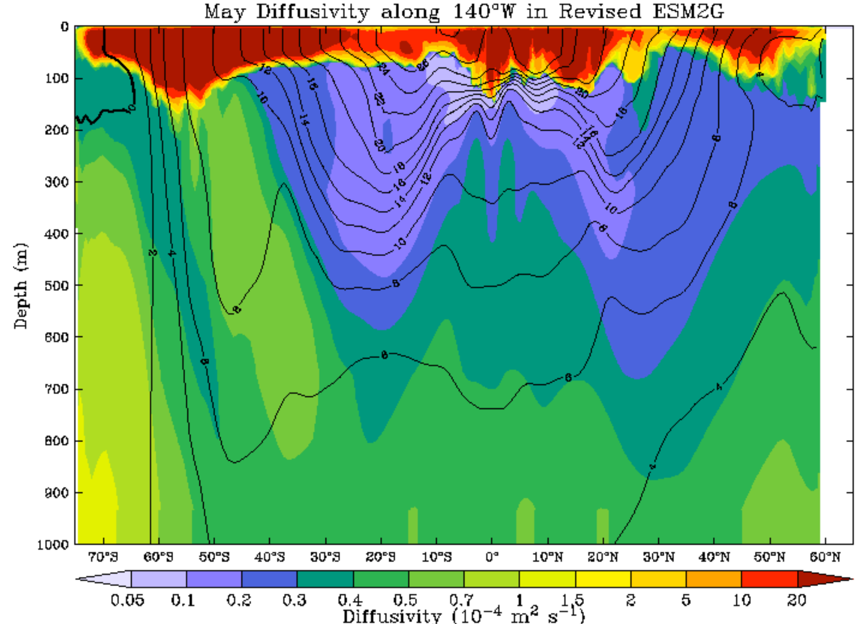


Revised ESM2G



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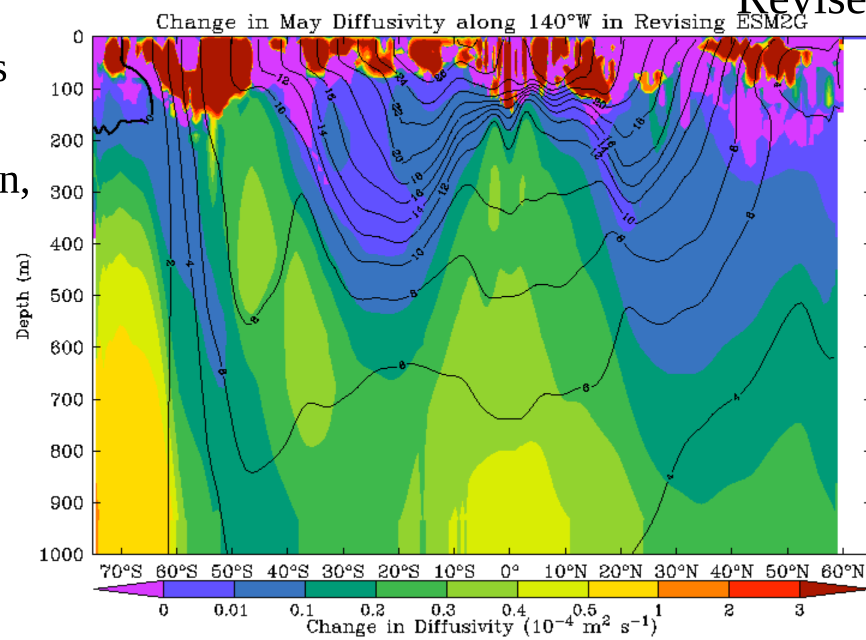
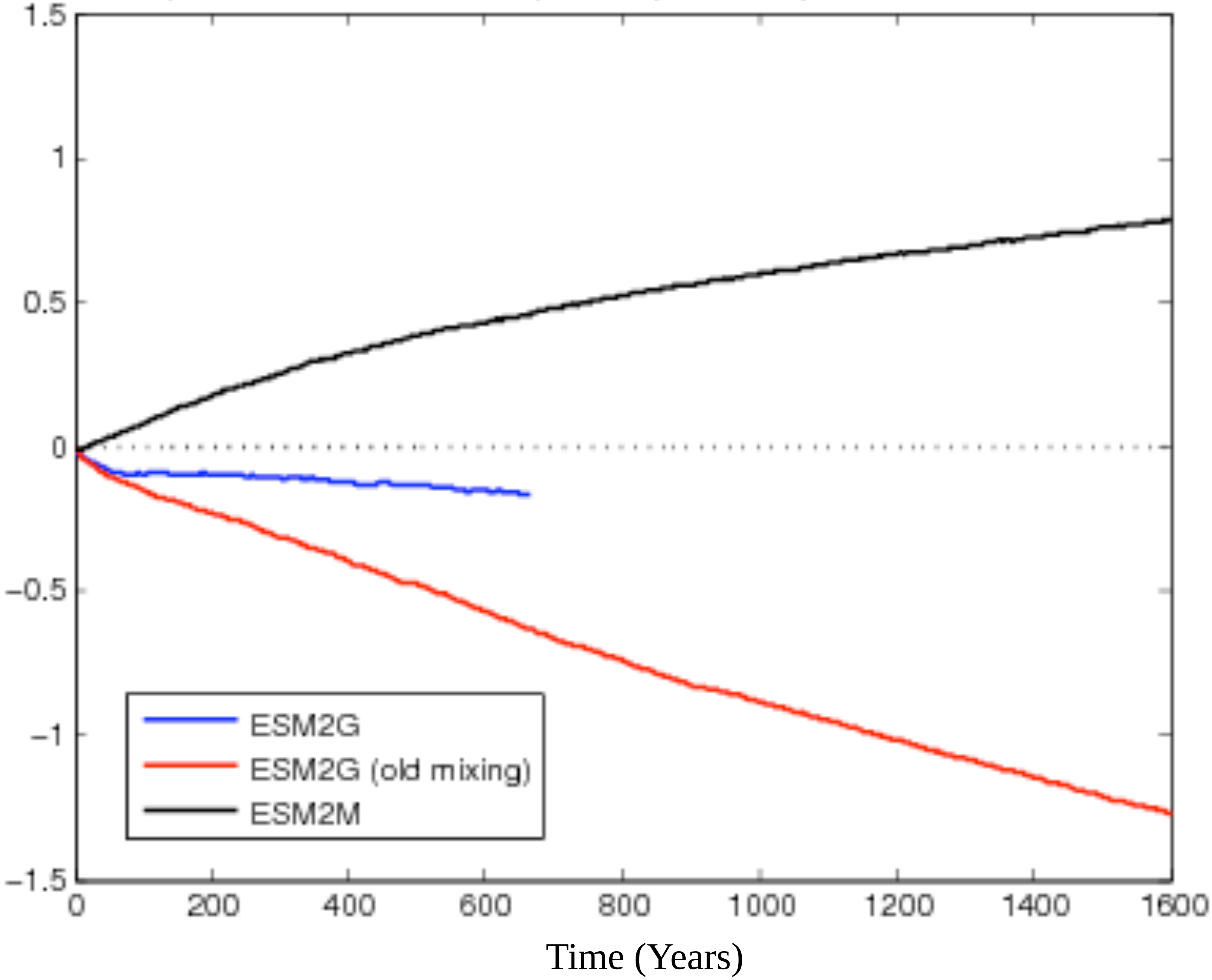
Revised - Original

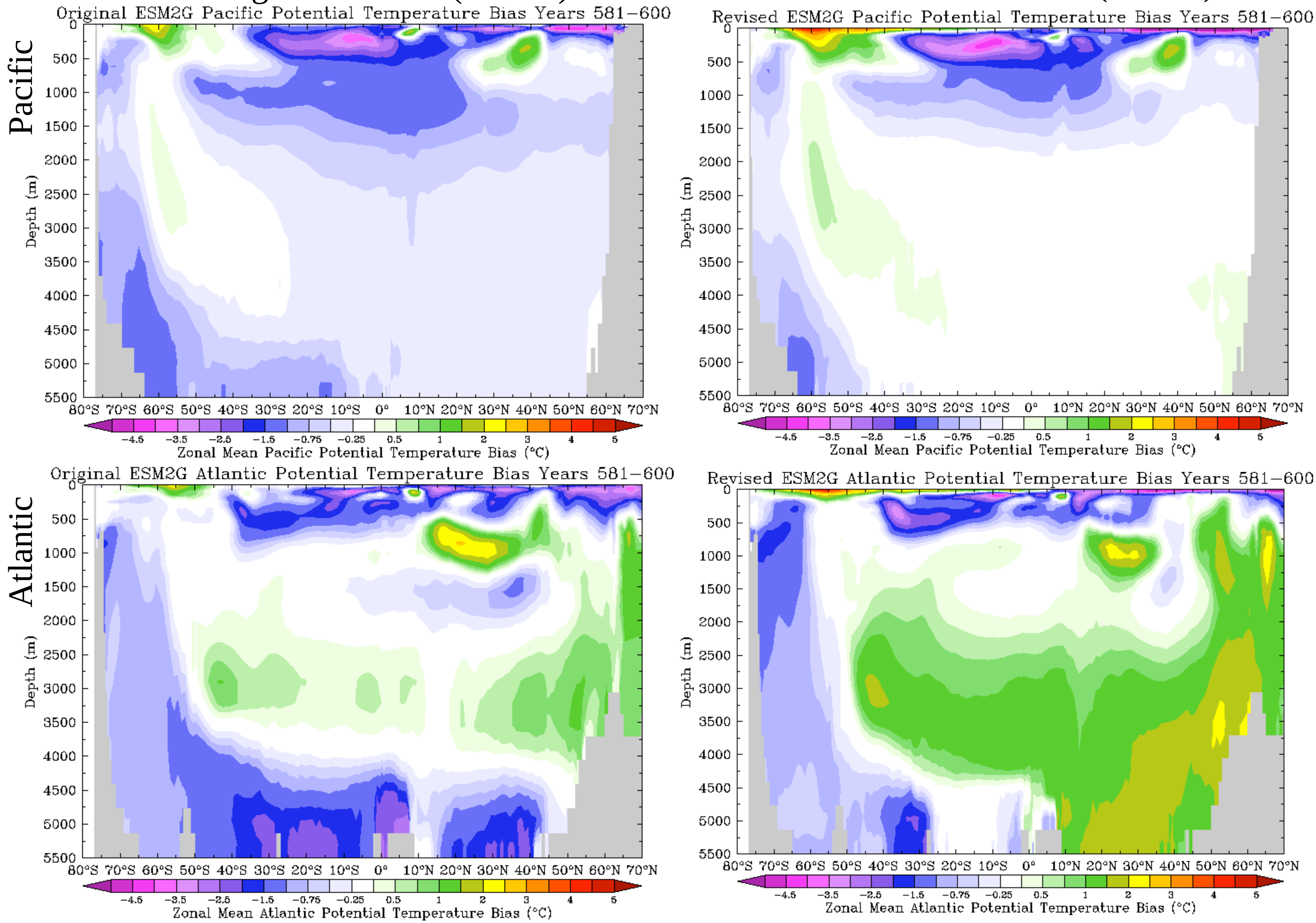


Global-mean Ocean Temperature in 1860 Spinups Starting from Climatological (~1990) Initial Conditions



Temperature change from 1990 ICs in 1860 Runs, Year 600

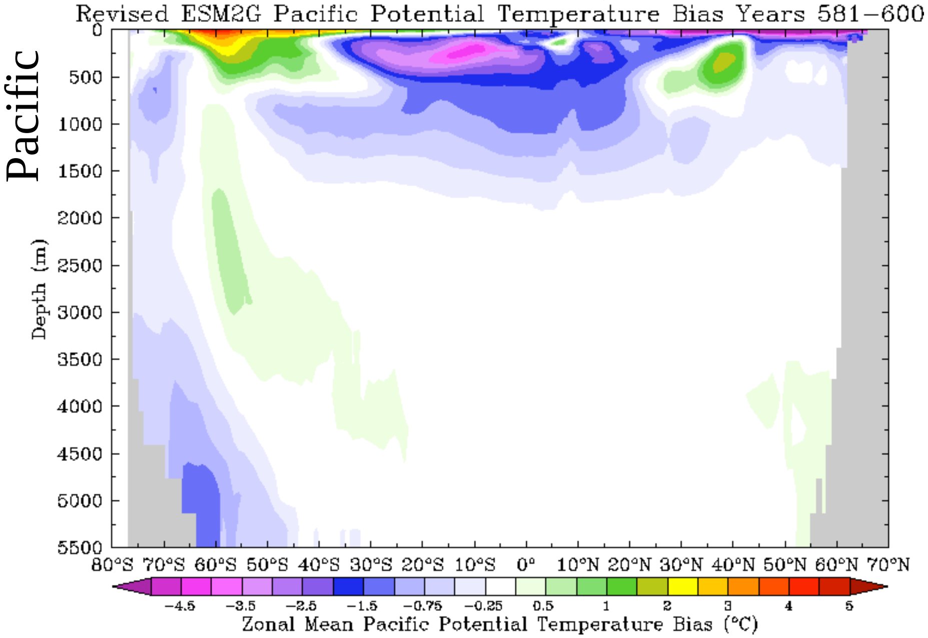
Original ESM2G (GOLD) | Revised ESM2G (GOLD)

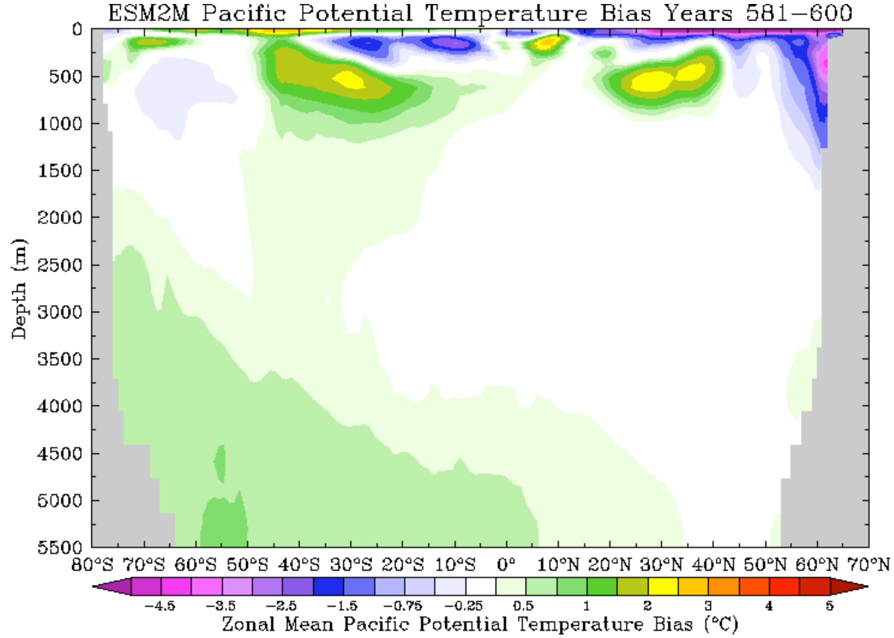


Temperature change from 1990 ICs in 1860 Runs, Year 600

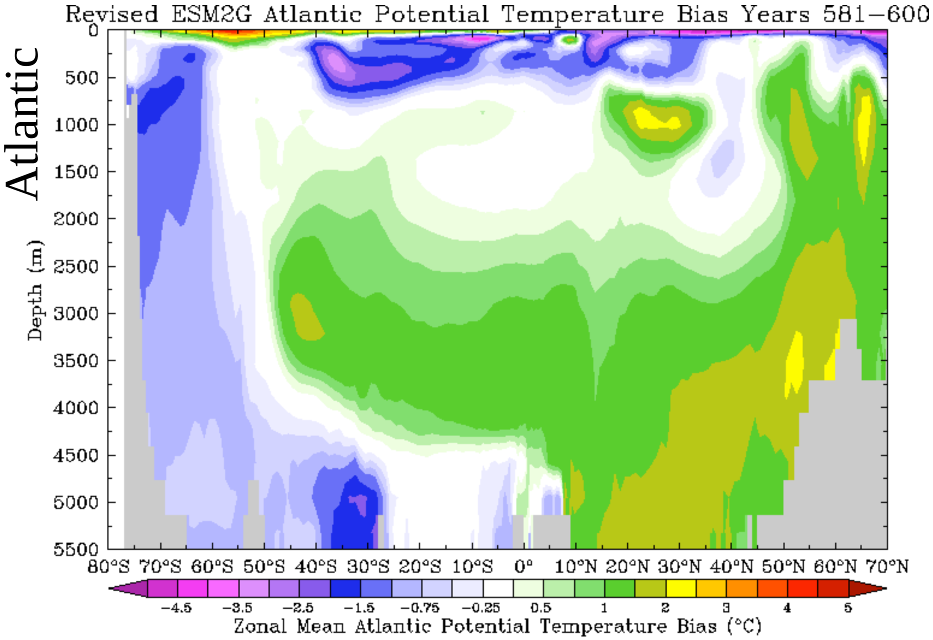
Revised ESM2G (GOLD) | ESM2M (MOM4.1)

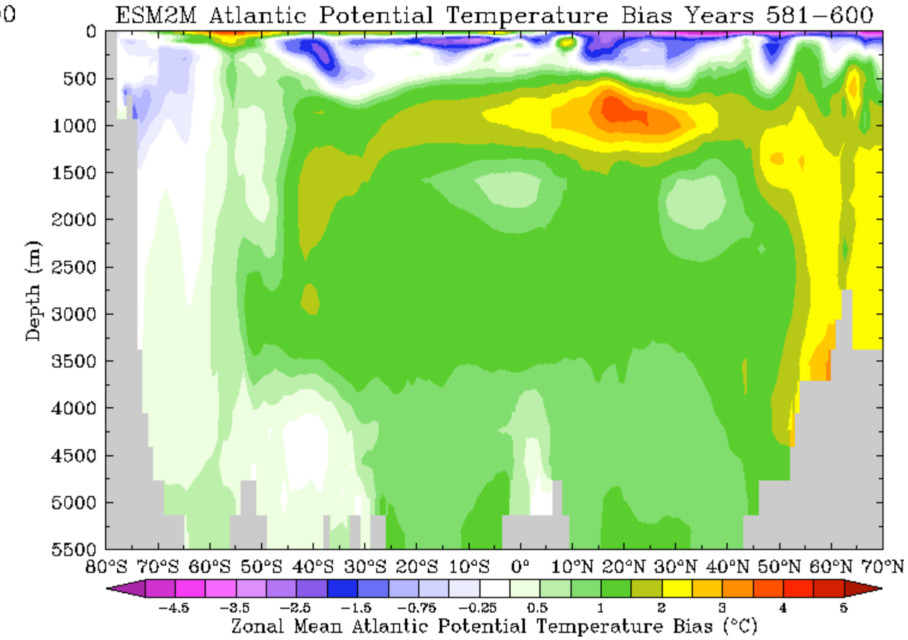
Pacific





Atlantic

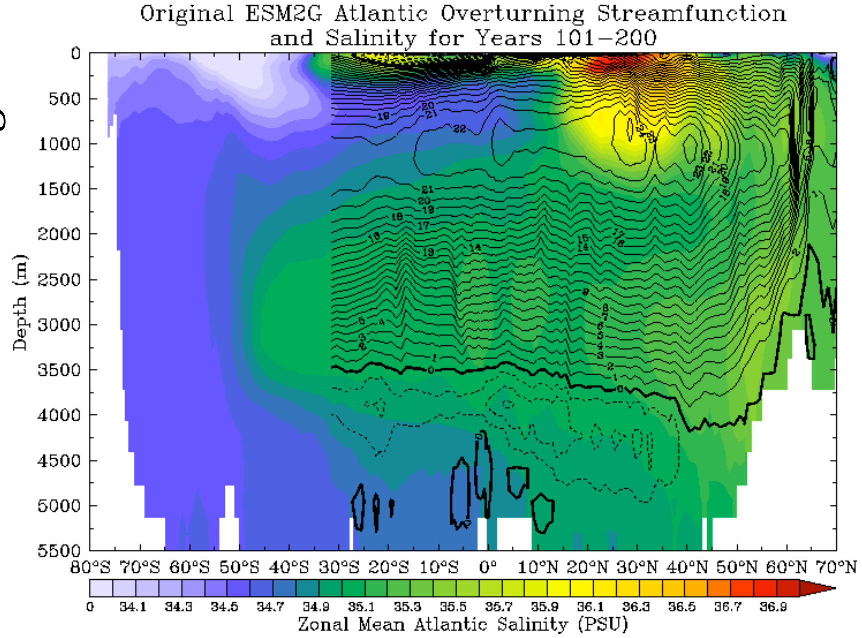




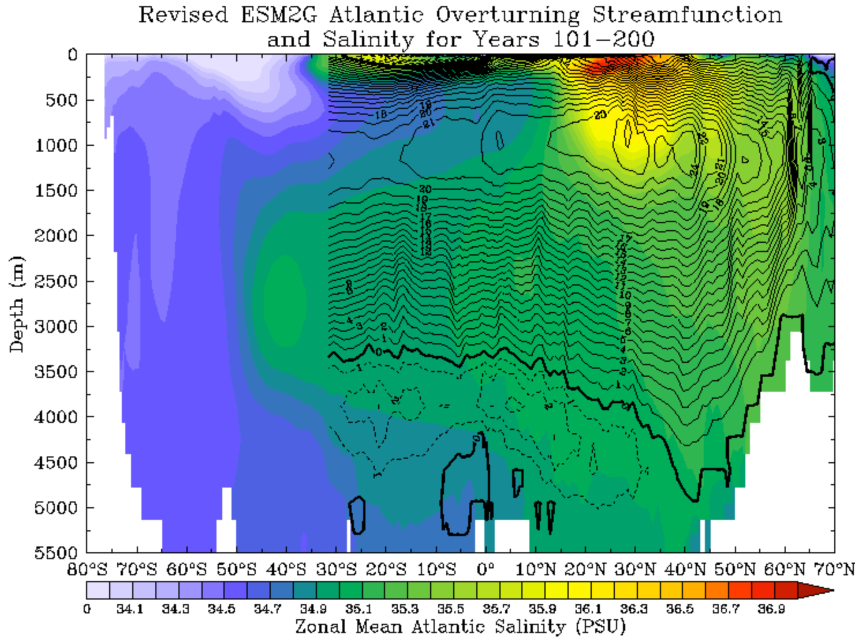
Atlantic Overturning Streamfunction and Salinity, Years 100-200

ESM2G (GOLD)

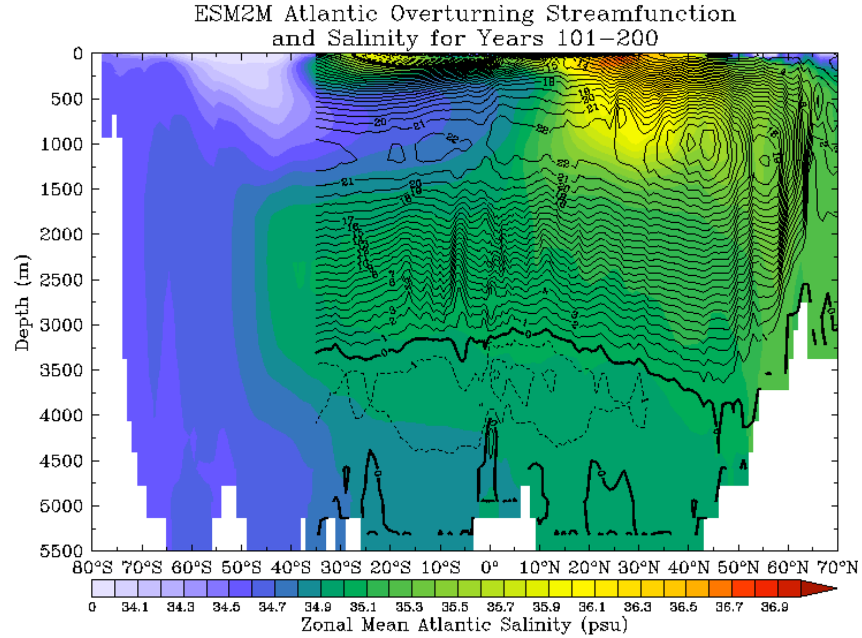
Original



Revised



ESM2M (MOM4.1)

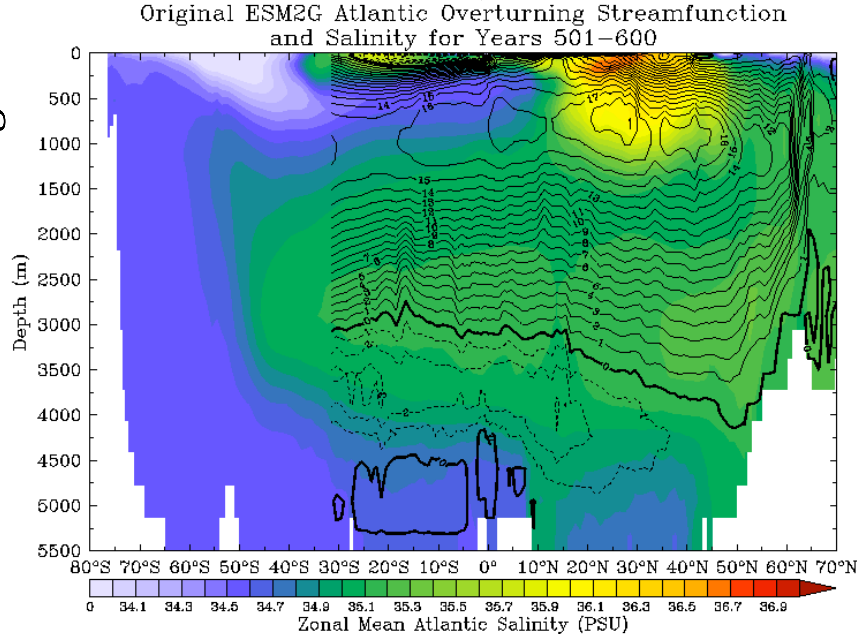


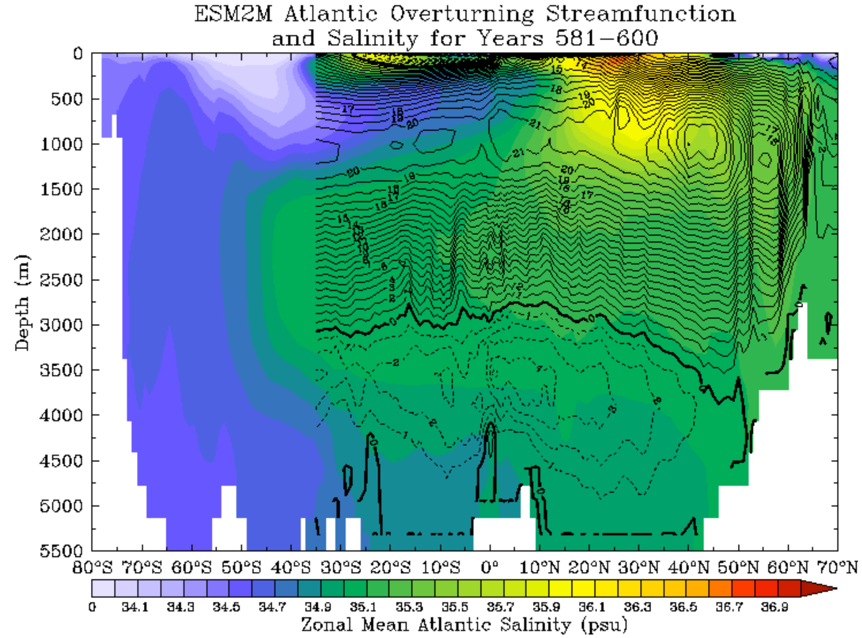
Atlantic Overturning Streamfunction and Salinity, Years 500-600

ESM2G (GOLD)

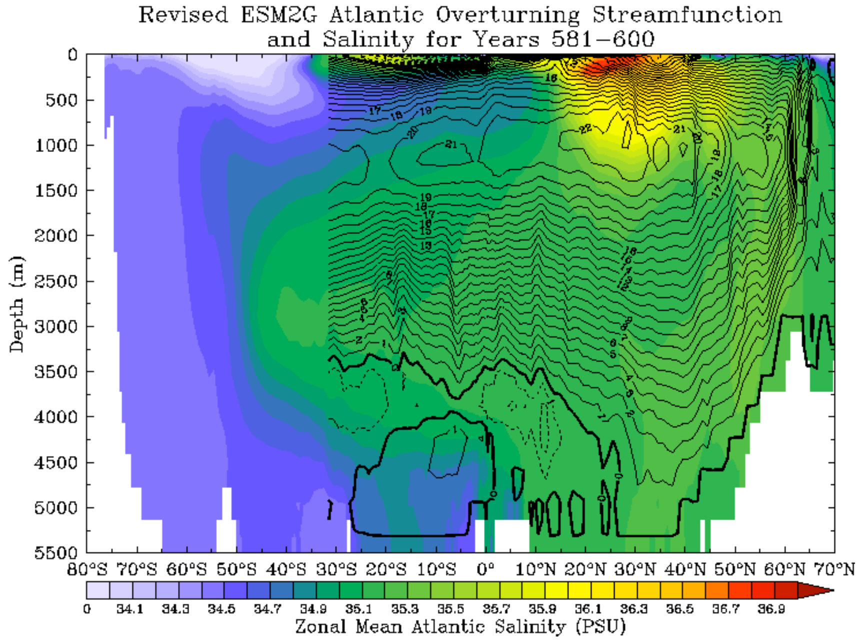
ESM2M (MOM4.1)

Original





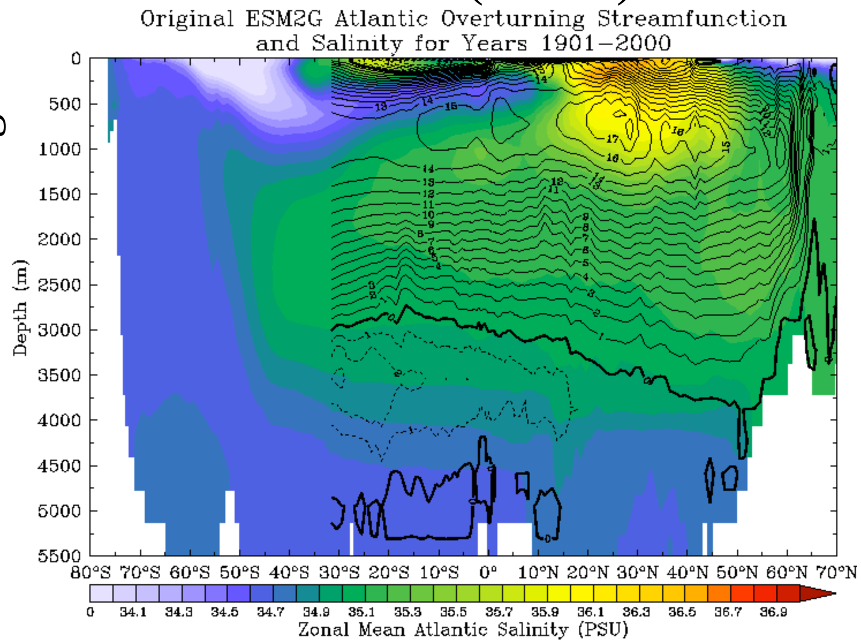
Revised



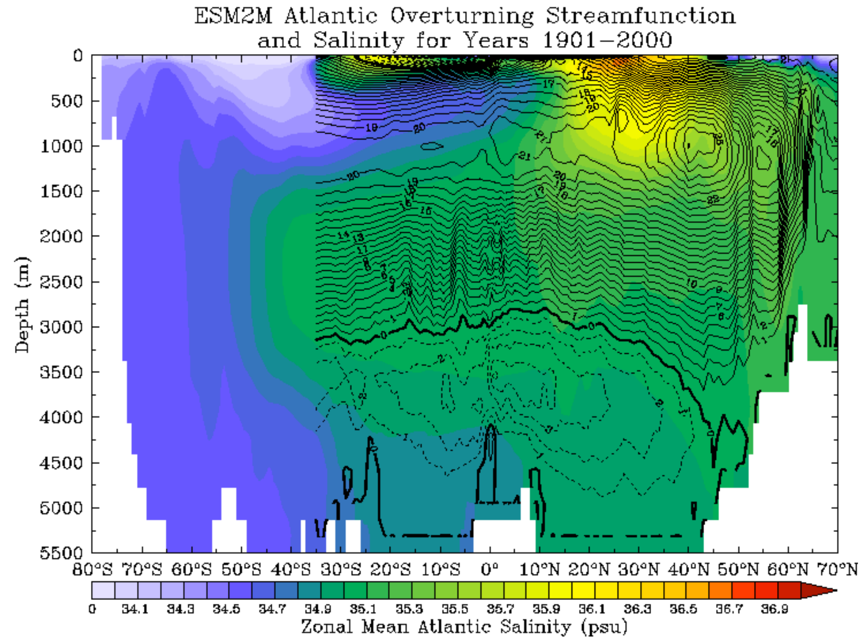
Atlantic Overturning Streamfunction and Salinity, Year 590

Original

ESM2G (GOLD)



ESM2M (MOM4.1)



What do these required changes mean?

There could be large amounts of abyssal and lower thermoclined mixing, beyond what is currently captured by mechanistic parameterizations.

Parameterizations (e.g., Jackson et al., 2008) that rely on resolved shears may be severely underestimating abyssal mixing.

ESM2G could simply be making far too much Antarctic Bottom Water.

The amount of AABW does not seem excessive in streamfunctions and sections.

Biogeochemical tracers also benefitted from the greatly enhanced mixing.

Where we are now with respect to the IPCC AR5 …

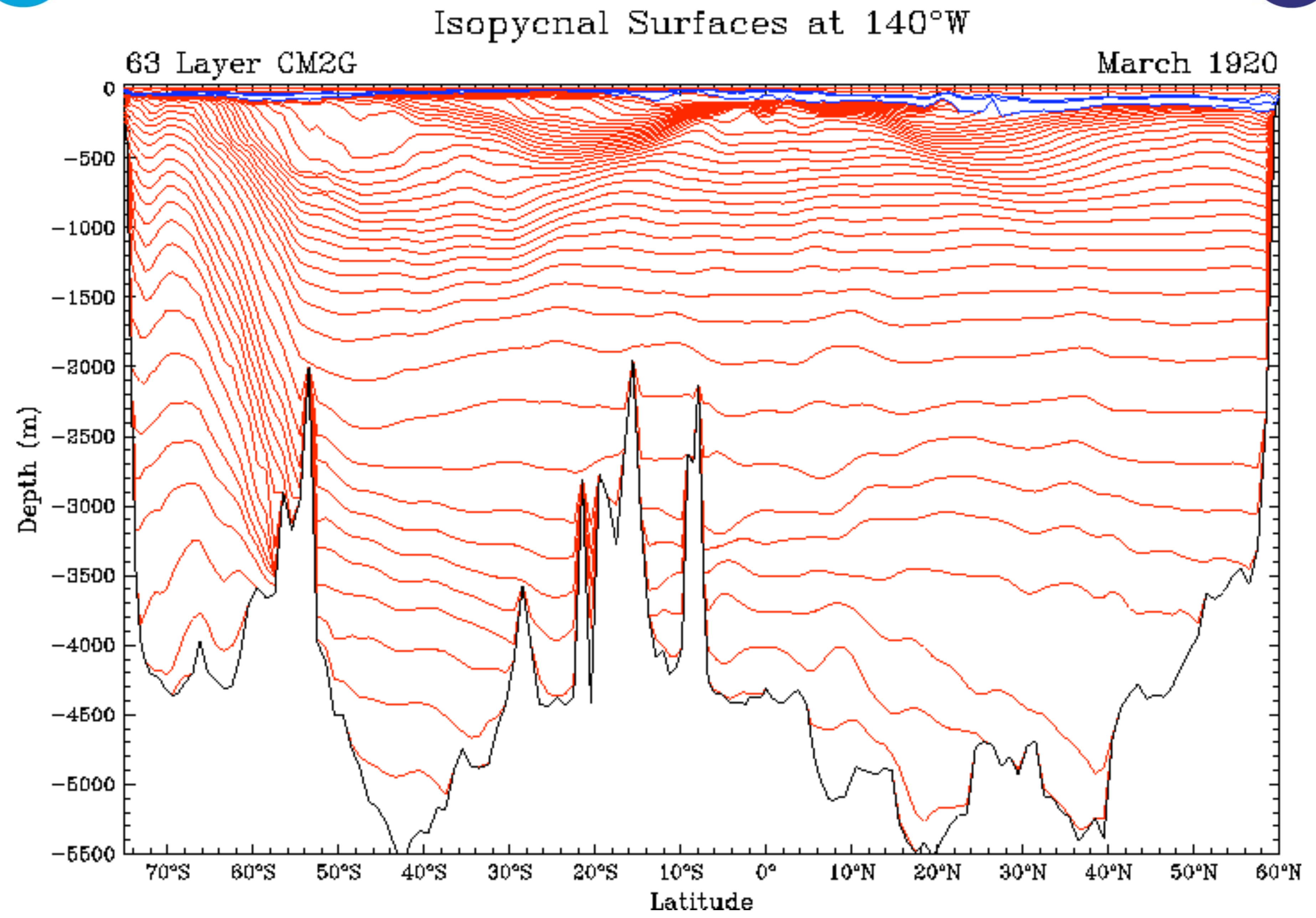
ESM2M completed its suite of runs for CMIP5 in December, and is being uploaded now.

GFDL has a large new computer that has slowed ESM2G from 17 years per day to 9 years per day.

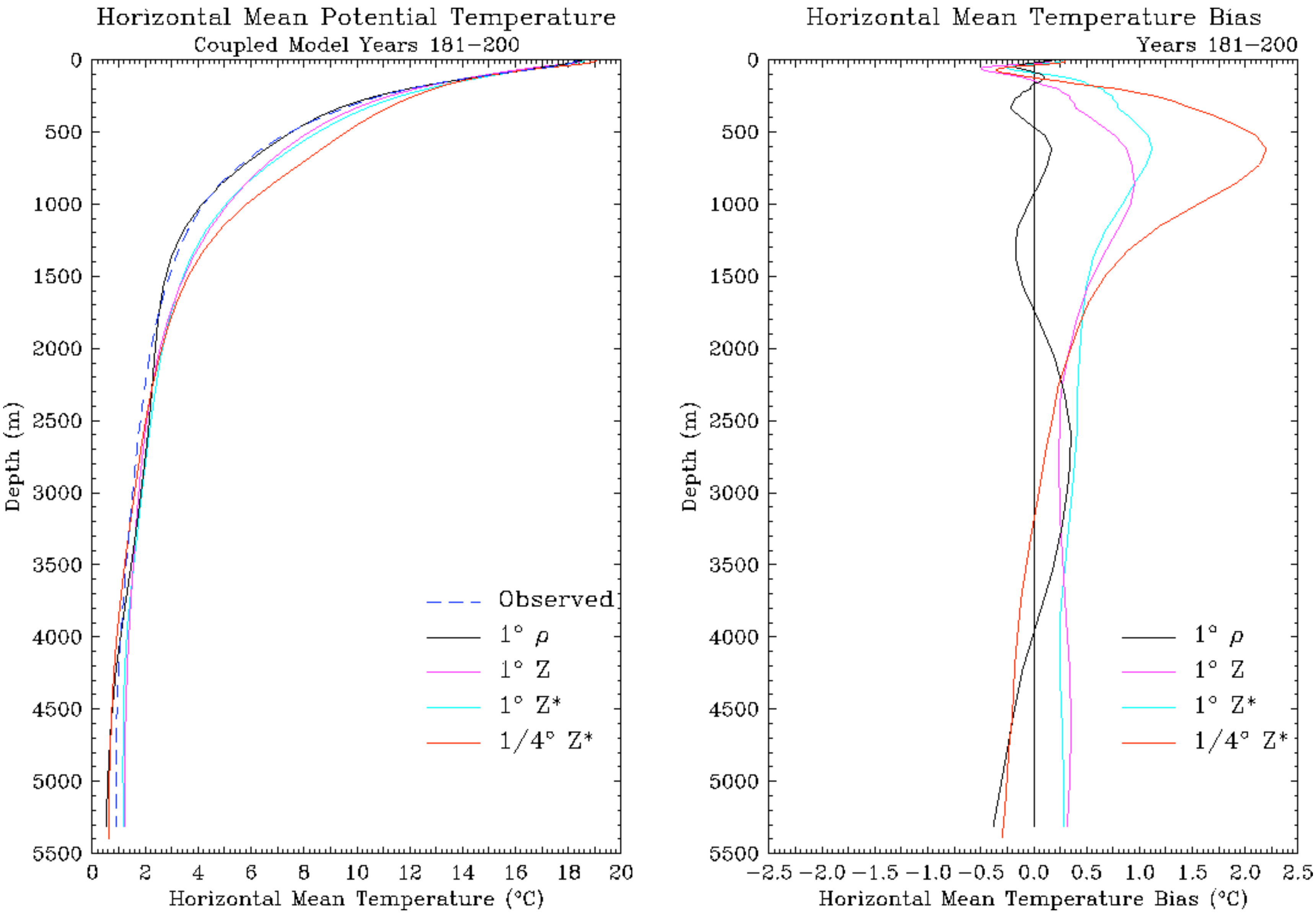
With the 666 years completed before the departure of our old computer on Jan 1st, we expect a 1500 year spinup to complete by May, and historical runs (1850-2100) sometime this summer.

GFDL will contribute ESM2G to the CMIP5 repository after all, but later and with fewer secondary scenarios than originally planned.

Pacific 2000 dbar Potential Density Surfaces from CM2G

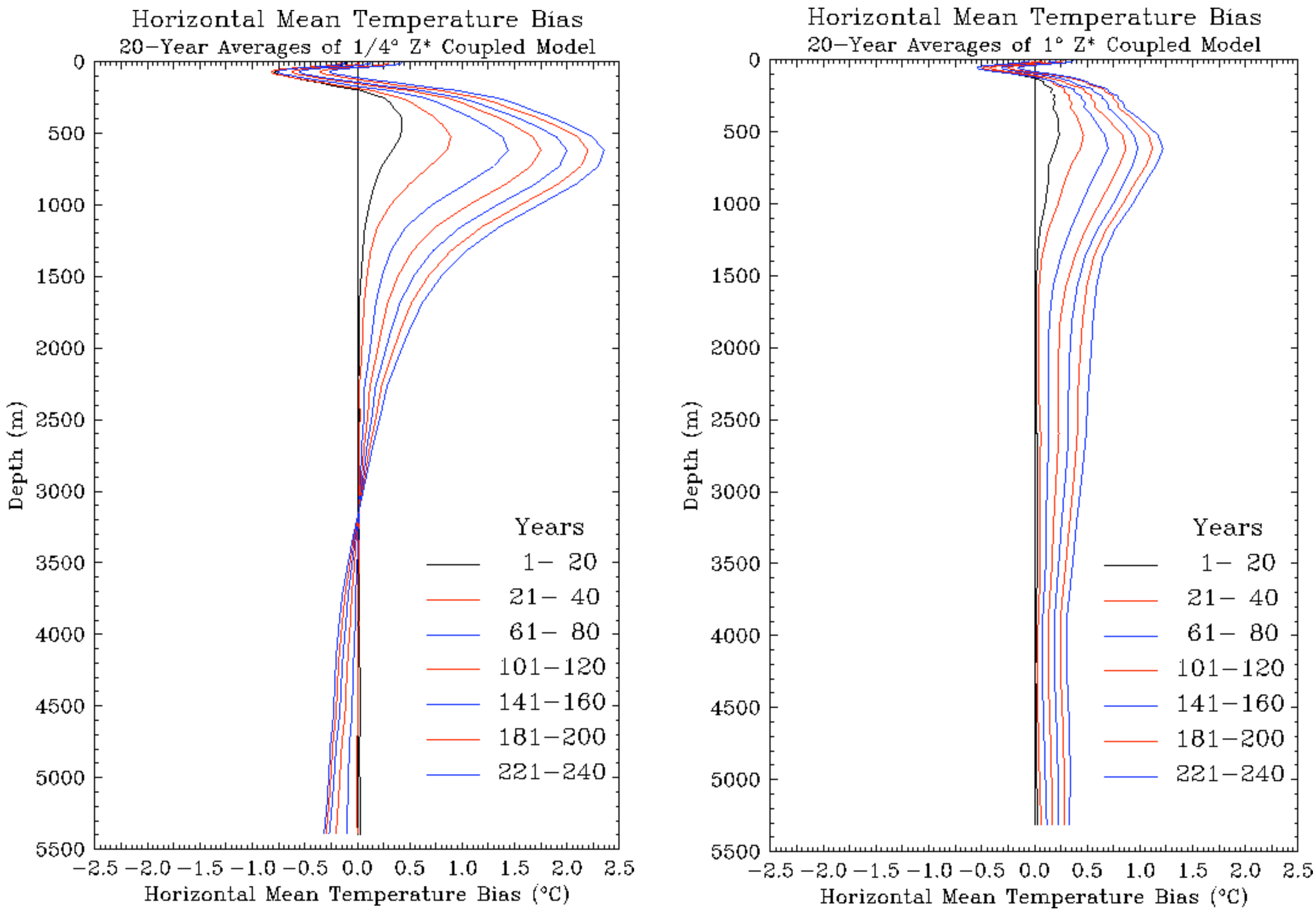


Spurious diapycnal mixing in coupled climate models?



All are 1990 control runs. ¼° Z* has turned off explicit diffusion.

Spurious diapycnal mixing increases with resolution?



1990 coupled control runs. ¼° Z* has turned off explicit diffusion.

Simmons et al. 2002 Mixing in GFDL Models.

- Based on Bell theory for internal tide radiation from topography.
- Energy input proportional to model's near-bottom stratification, and observed bathymetric roughness and barotropic tidal amplitudes.
- Simple vertical decay, λ = 300 m^{-1}.

$$\varepsilon = \lambda E_{Bot}(x, y)\exp\left[-\lambda(z - D)\right]$$

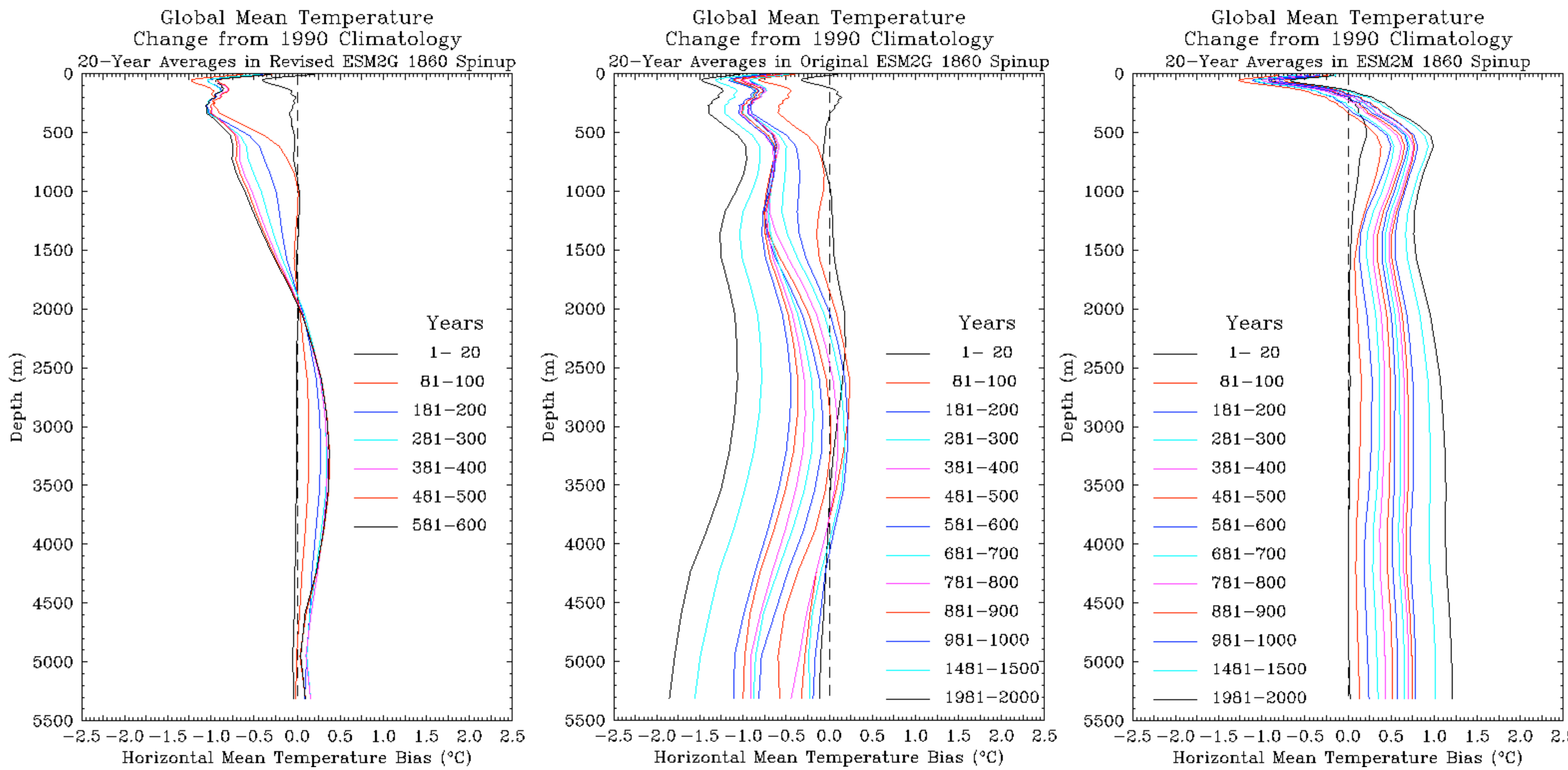
$$\kappa = \Gamma \frac{\varepsilon}{N^2}$$

- MOM implementation: Γ=0.2, but κ set to be monotonically decreasing upward.
- GOLD implementation: $\Gamma = \frac{0.2N^2}{N^2 + \Omega^2}$

- A better theory for the vertical distribution would be very desirable.

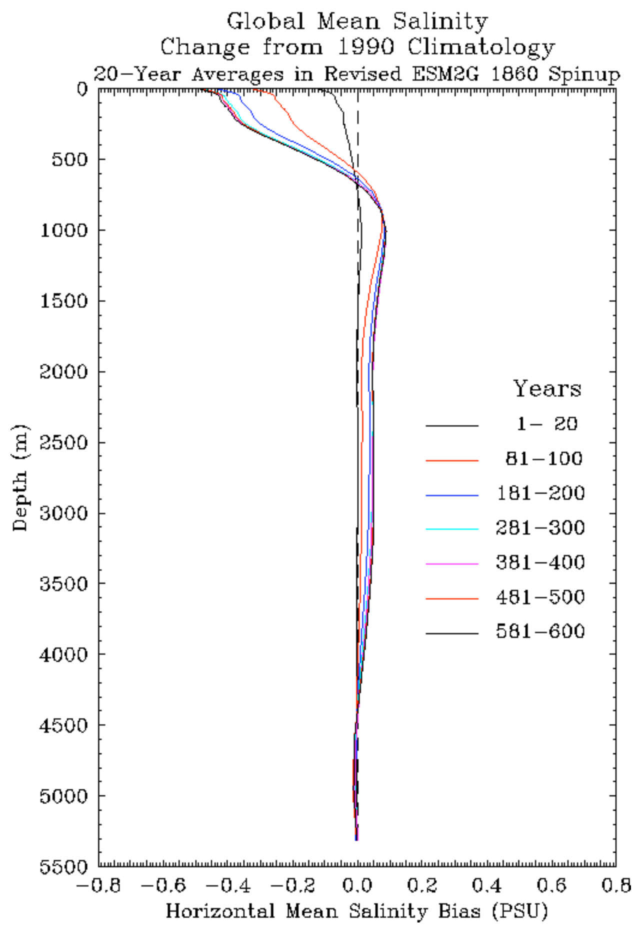
Global Mean Temperature Profile Evolution

Revised ESM2G | Original ESM2G | ESM2M

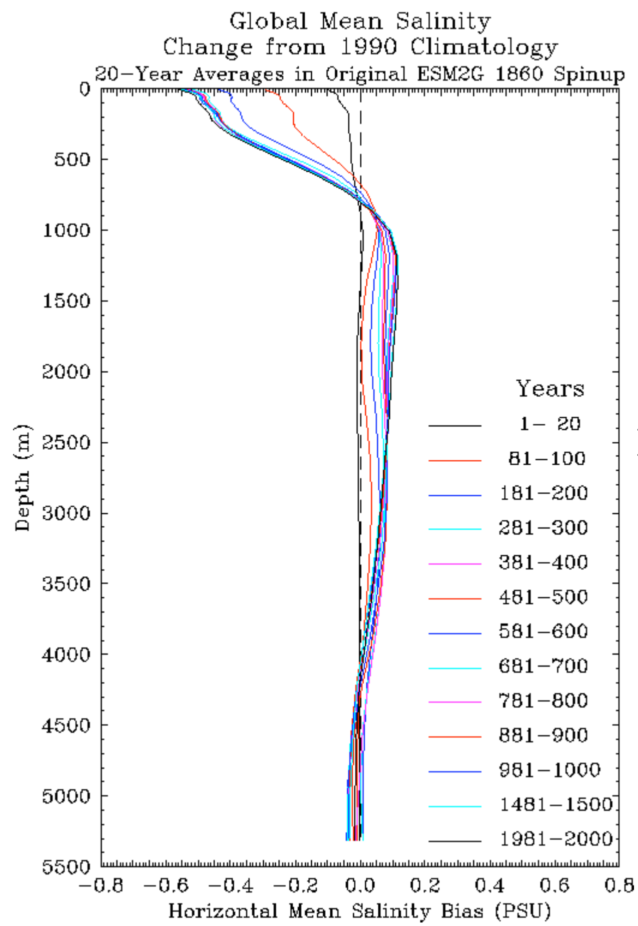


Global Mean Salinity Profile Evolution

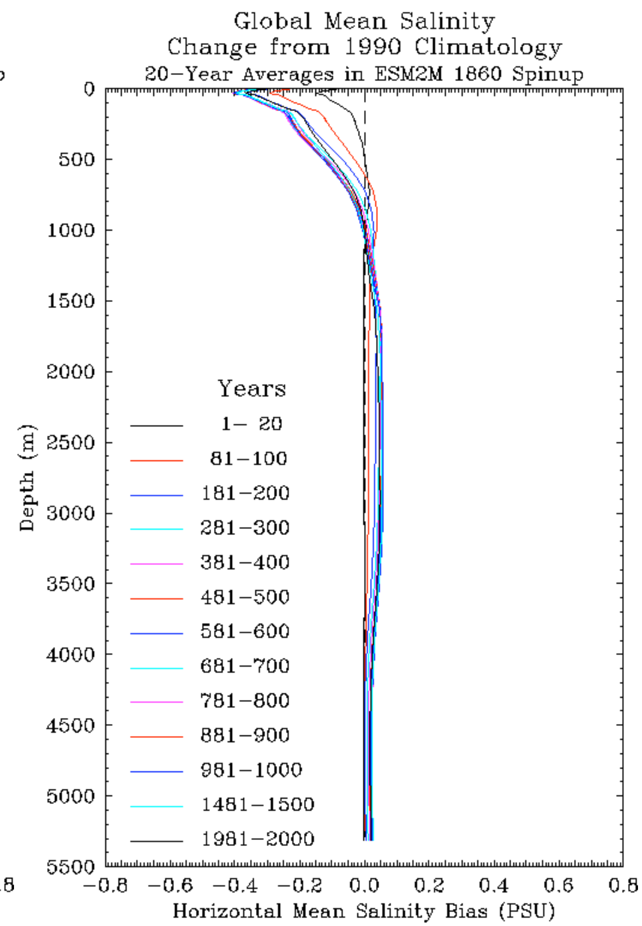
Revised ESM2G



Original ESM2G

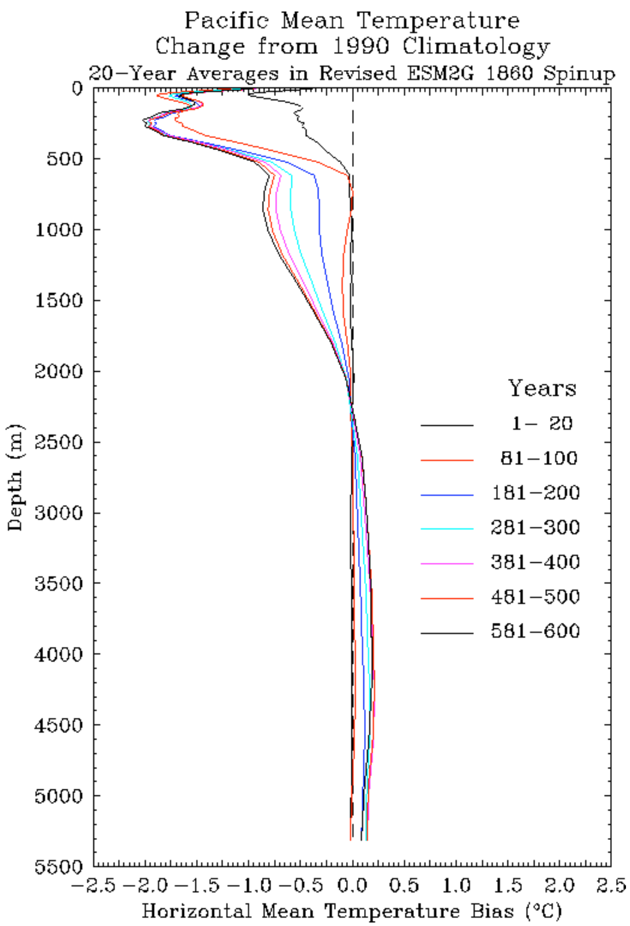


ESM2M

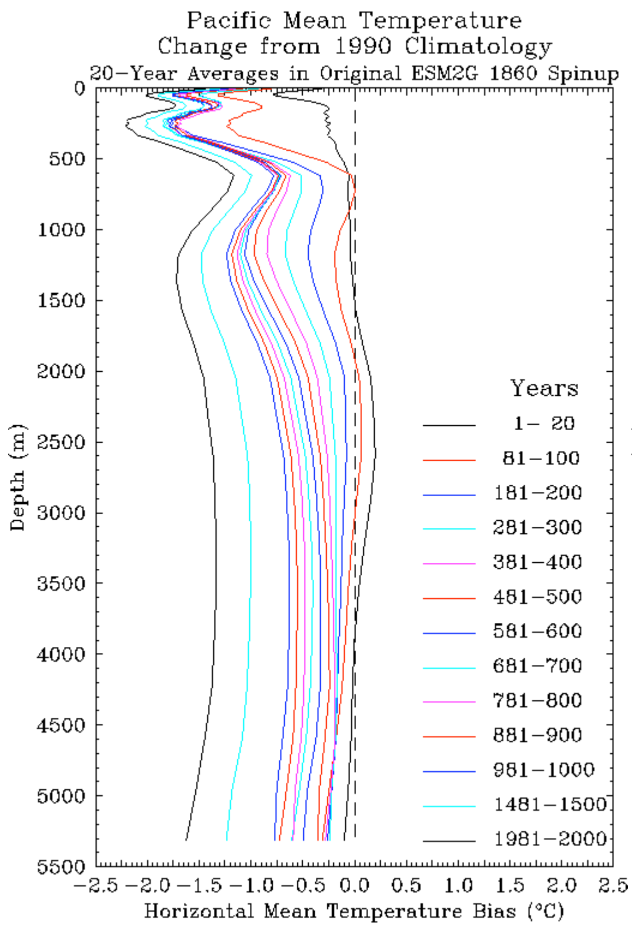


Pacific Temperature Profile Evolution

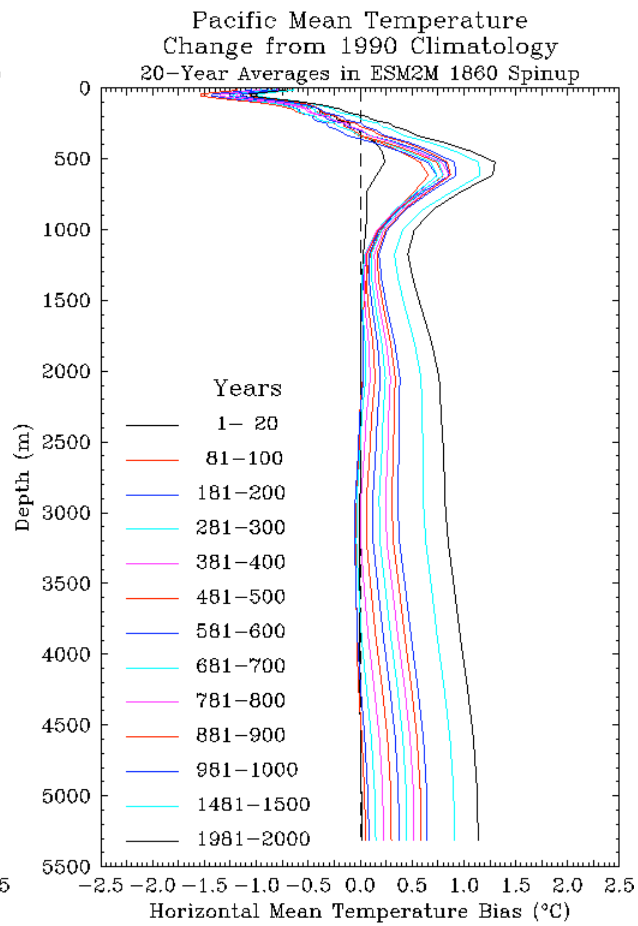
Revised ESM2G



Original ESM2G

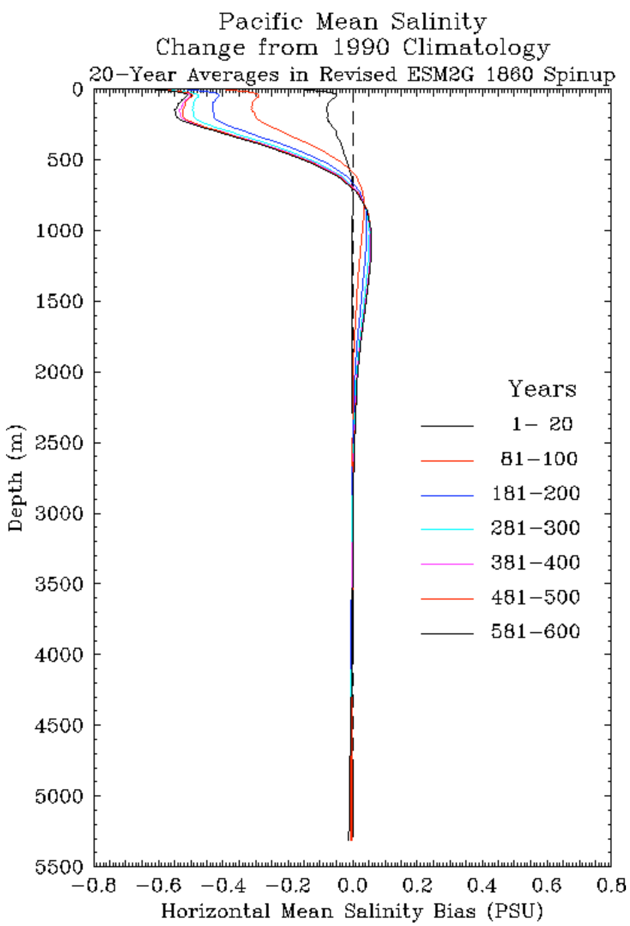


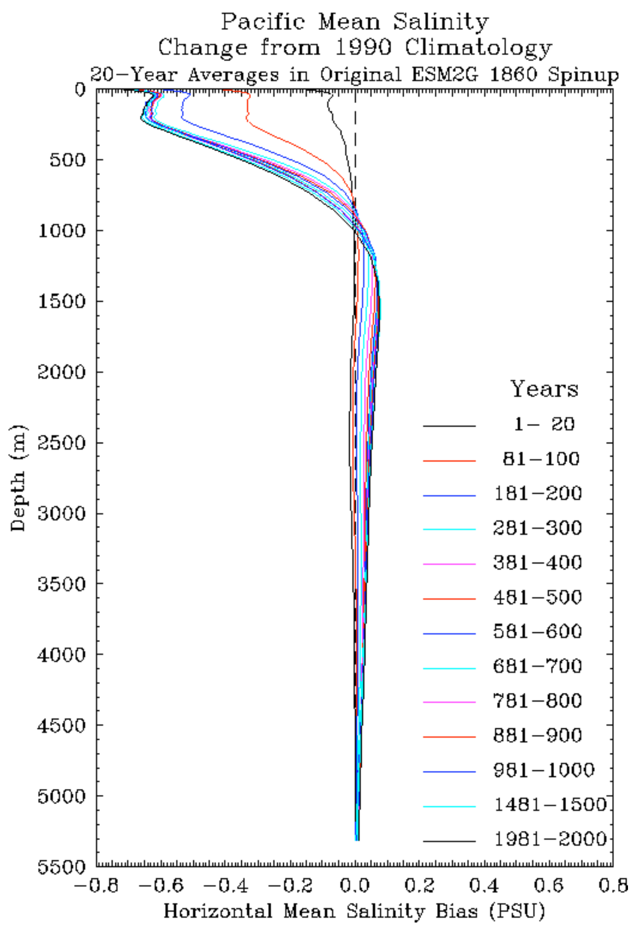
ESM2M

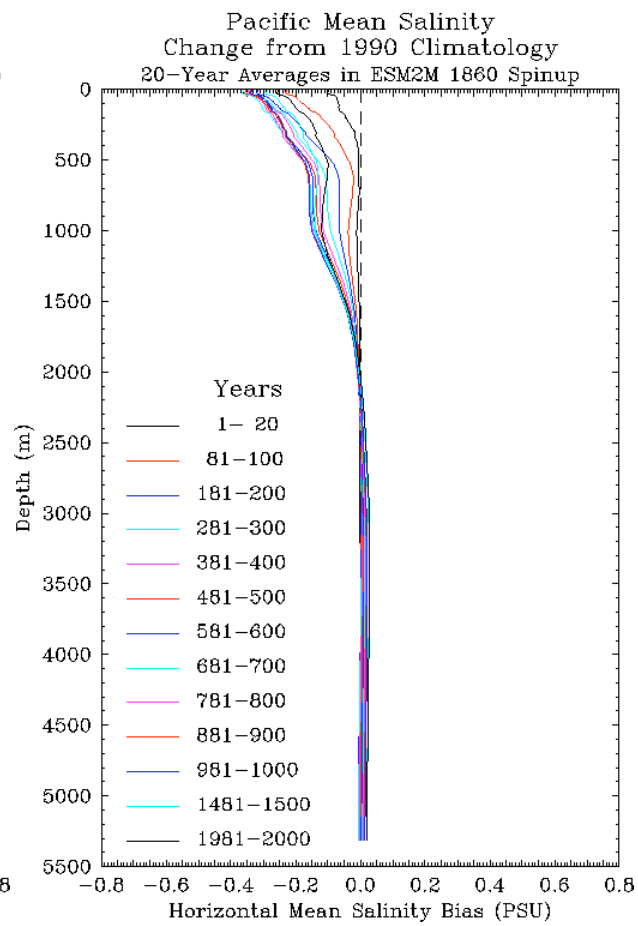


Pacific Salinity Profile Evolution

Revised ESM2G | Original ESM2G | ESM2M

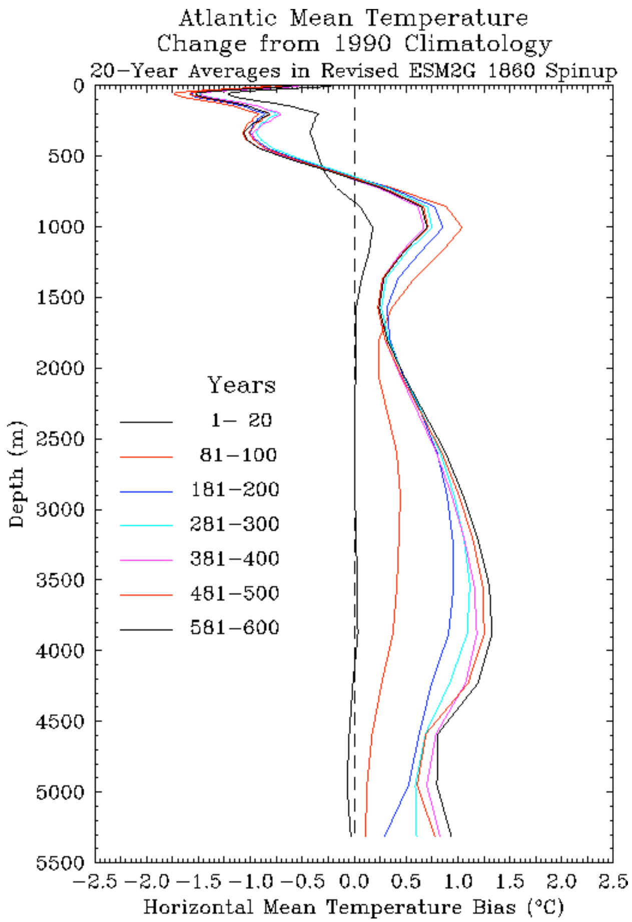




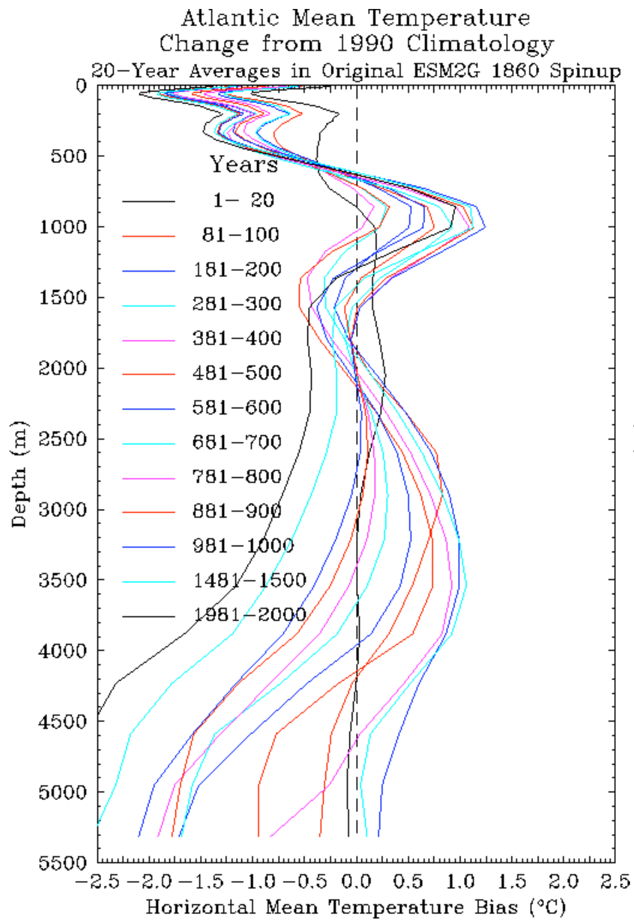


Atlantic Temperature Profile Evolution

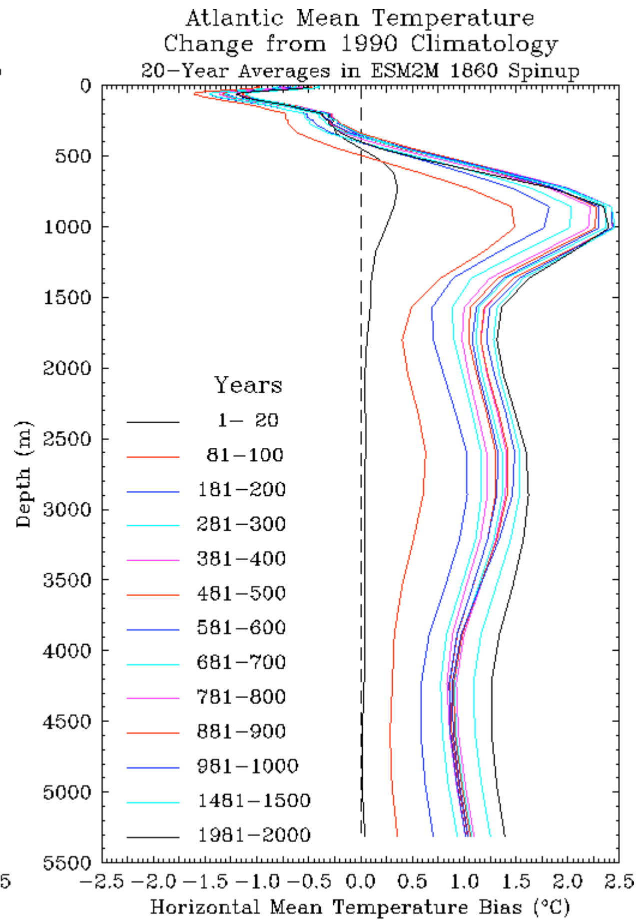
Revised ESM2G



Original ESM2G

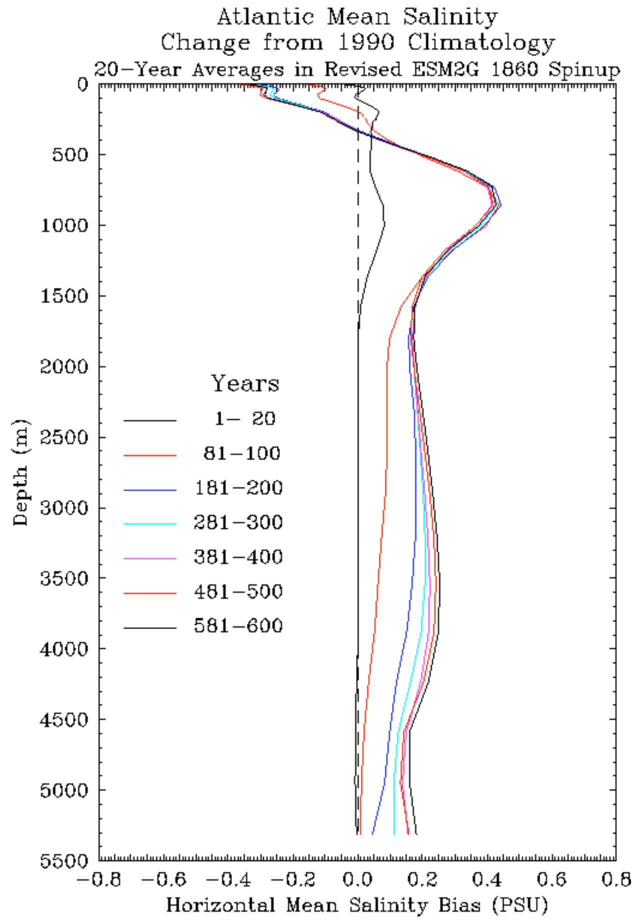


ESM2M

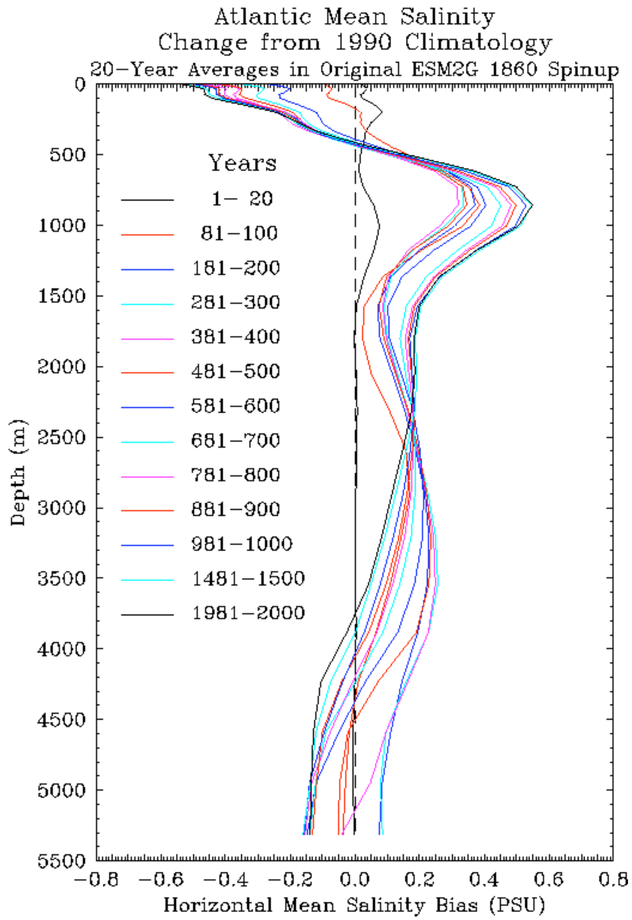


Atlantic Salinity Profile Evolution

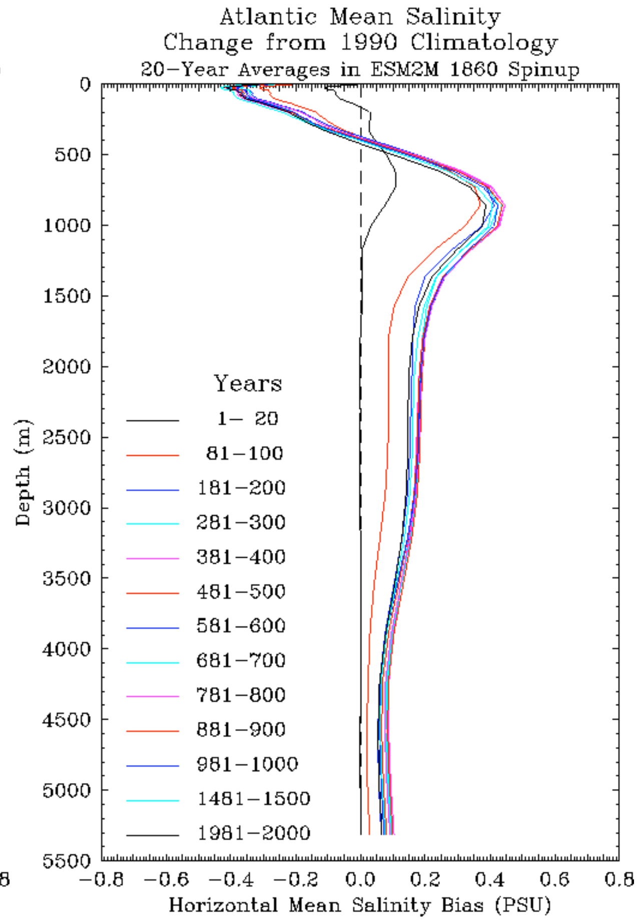
Revised ESM2G



Original ESM2G



ESM2M

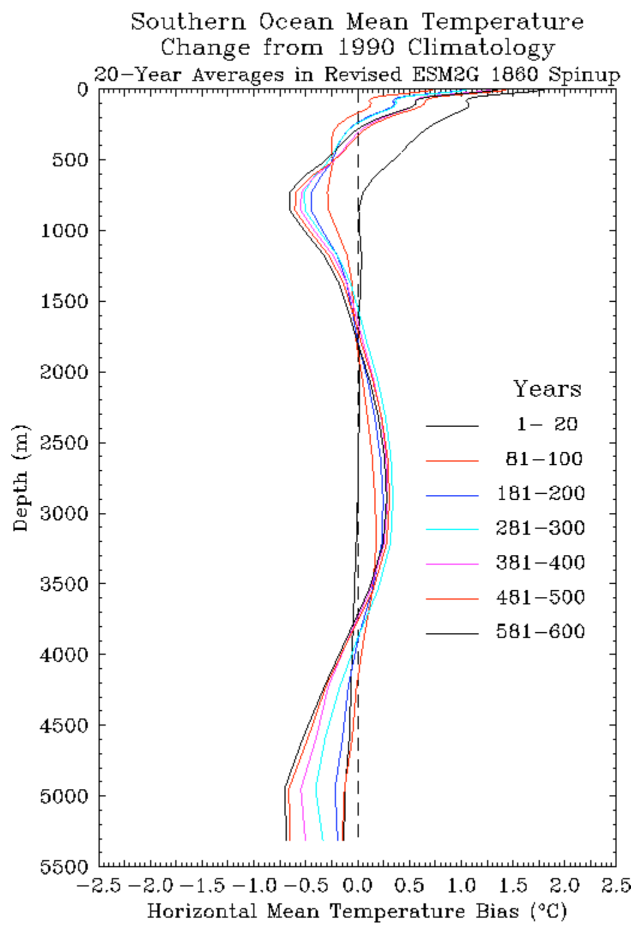


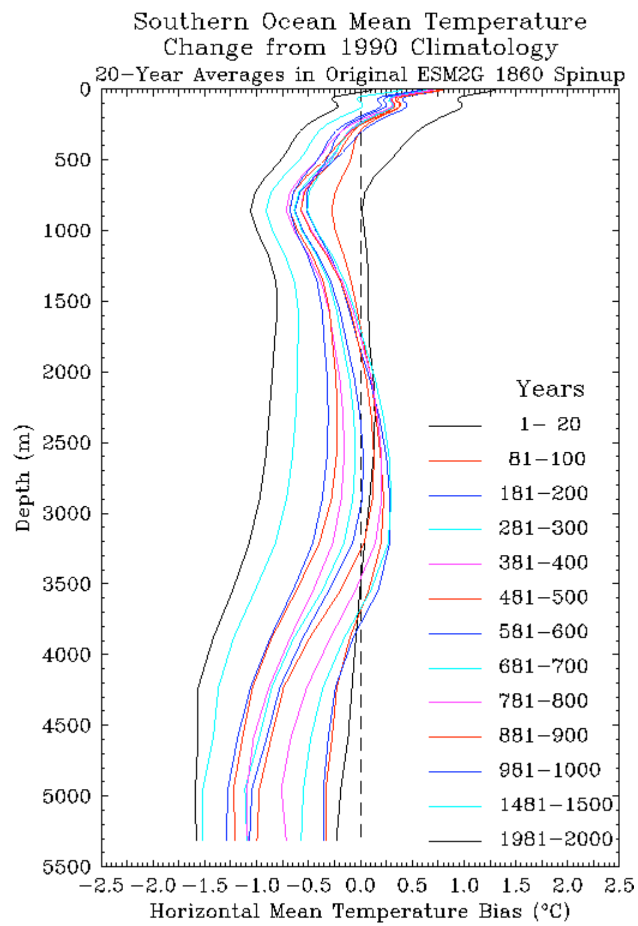
Southern Ocean Temperature Profile Evolution

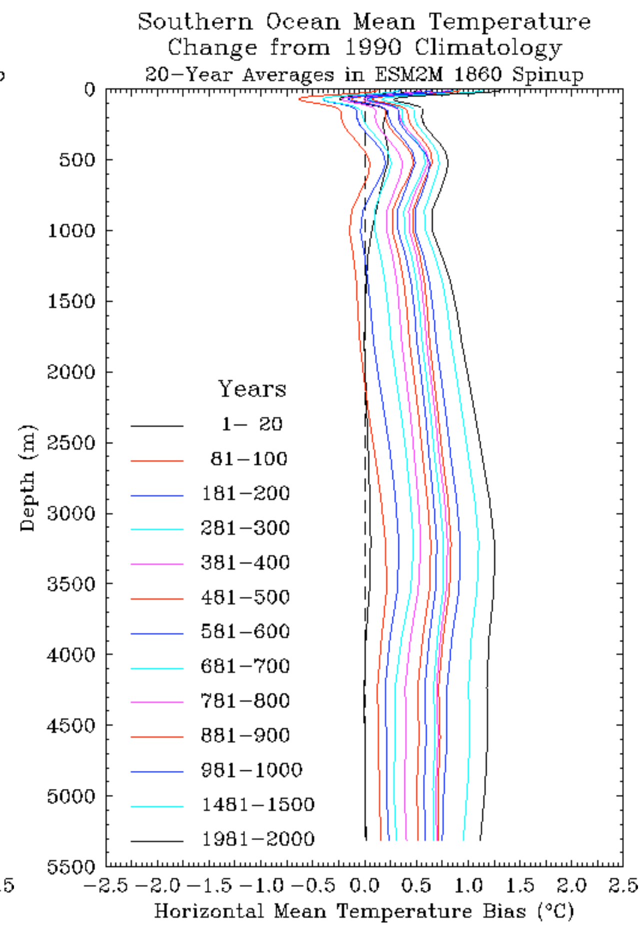
Revised ESM2G

Original ESM2G

ESM2M







Southern Ocean Salinity Profile Evolution

Revised ESM2G

Original ESM2G

ESM2M