Comparison of GFDL's CM2G Coupled Climate Model with CM2.1 and CM2M

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Ocean Components of GFDL Coupled Climate Models

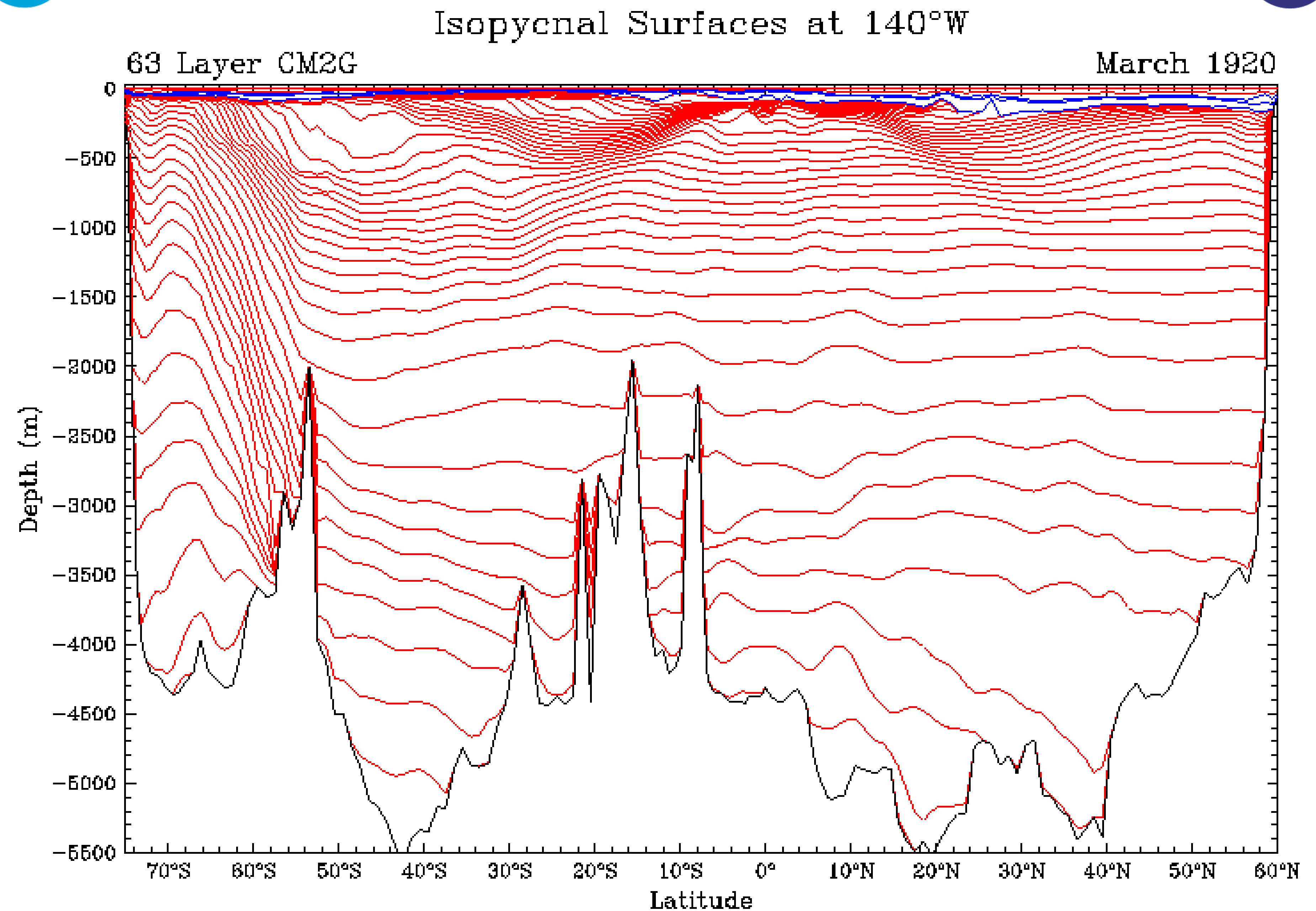
CM2G(63L)/GOLD

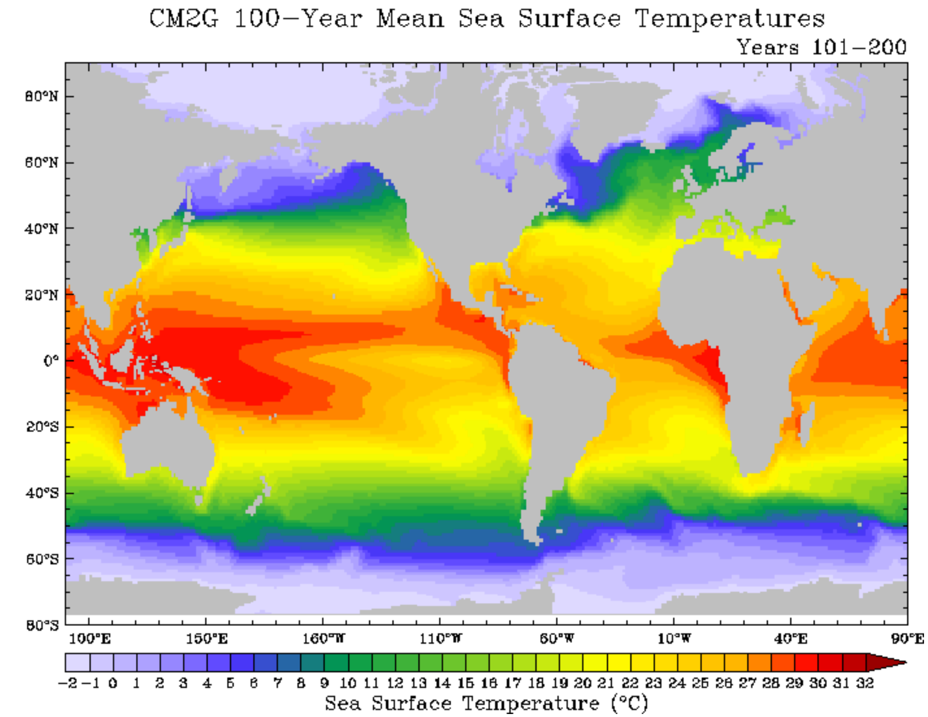
- 1° res. (360x210), on tripolar grid.
- 59 Isopycnal interior layers + 4 in ML
- C-grid discretization
- Split explicit free surface ; fresh water fluxes as surface B.C.
- 2-layer refined bulk mixed layer with 2 buffer layers
- Full nonlinear equation of state except for coordinate definition
- Tracer diffusion rotated to σ_2 surfaces
- Partially open faces allow explicit exchanges with marginal seas.
- Simmons et al. background diapycnal diffusion
- 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

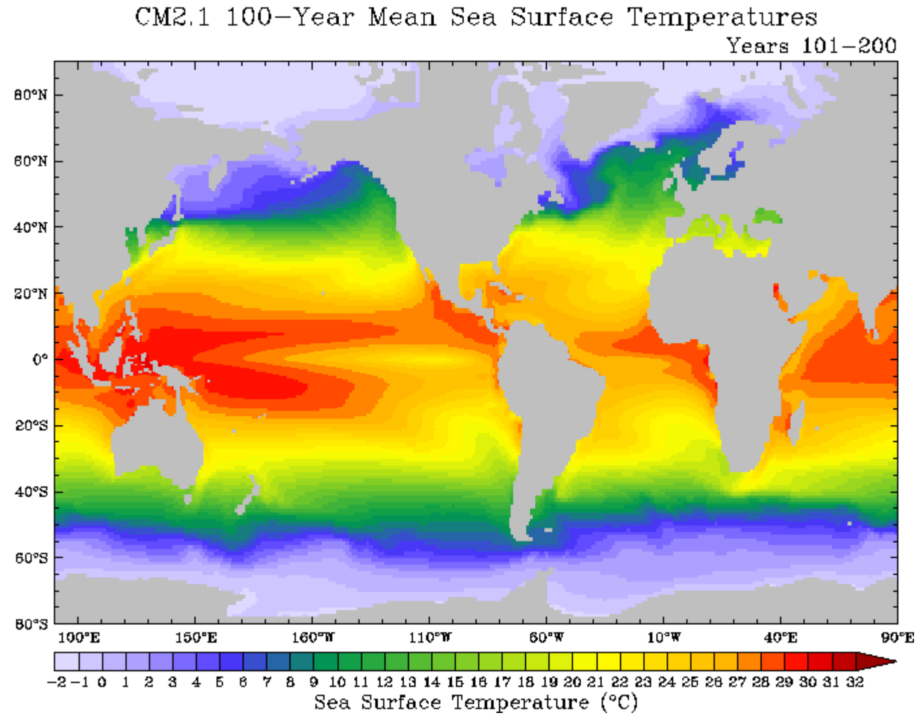
CM2.1/MOM4.0 or CM2M/MOM4.1

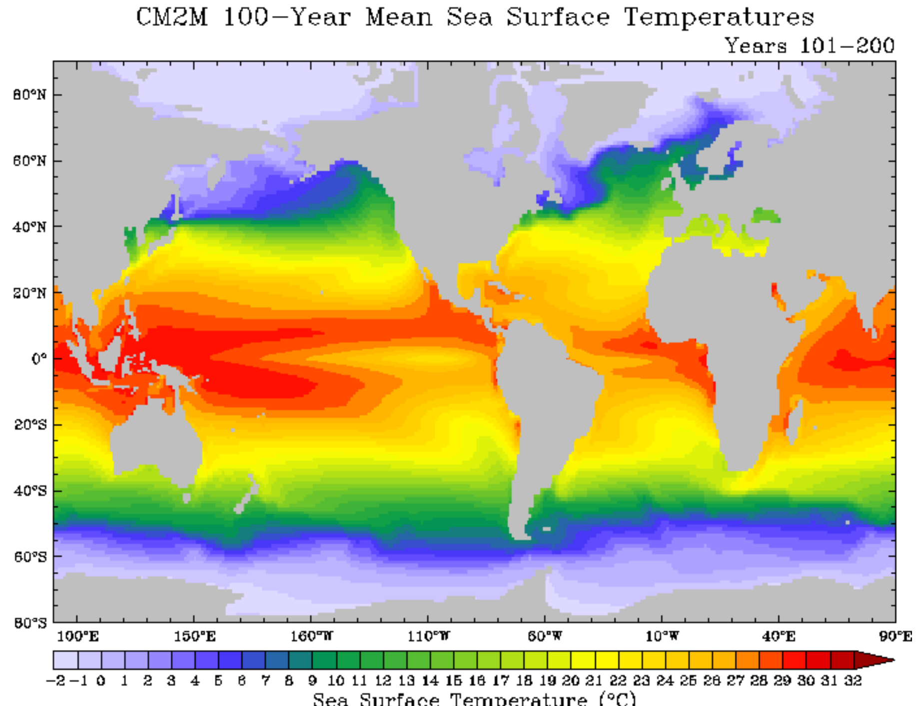
- 1° res. (360x200), on tripolar grid.
- 50 z- or z*-coordinate vertical levels
- B-grid discretization
- Split explicit free surface ; fresh water fluxes as surface B.C.
- KPP mixed layer with 10 m resolution down to 200 m
- Full nonlinear equation of state
- MDPPM tracer advection (CM2M)
- Tracer diffusion rotated to neutral directions
- Marginal sea exchanges specified via "cross-land mixing"
- Lee et al. + Bryan-Lewis background (CM2.1) or Simmons et al. (CM2M) diapycnal diffusion
- 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

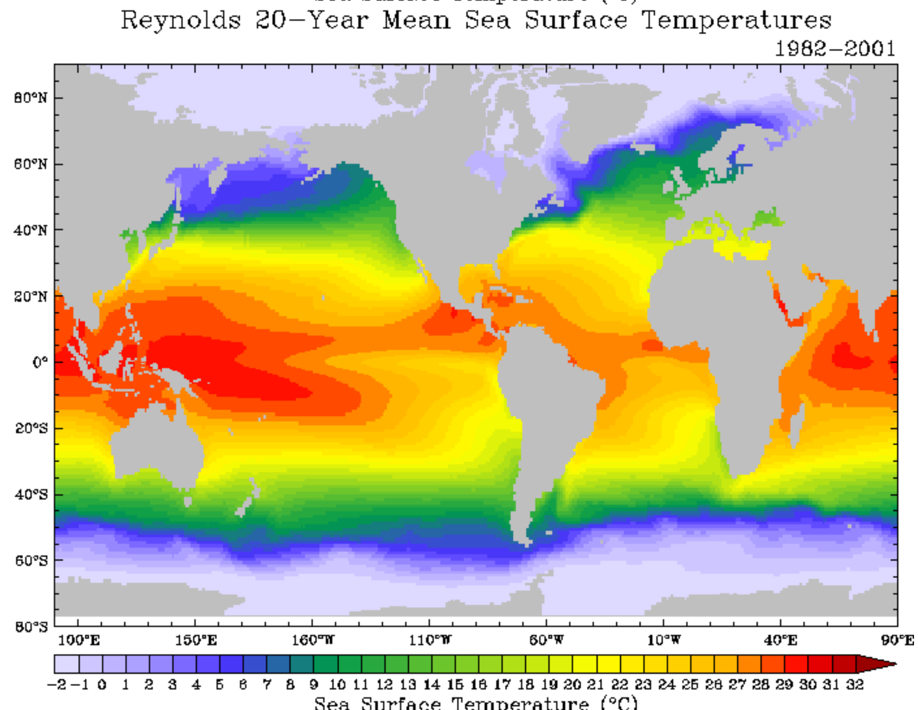
Pacific 2000 dbar Potential Density Surfaces from CM2G




CM2G 100-Year Mean Sea Surface Temperatures
Years 101-200
80°N 60°N 40°N 20°N 0° 20°S 40°S 60°S 80°S
100°E 150°E 160°W 110°W 60°W 10°W 40°E 90°E
-2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
Sea Surface Temperature (°C)

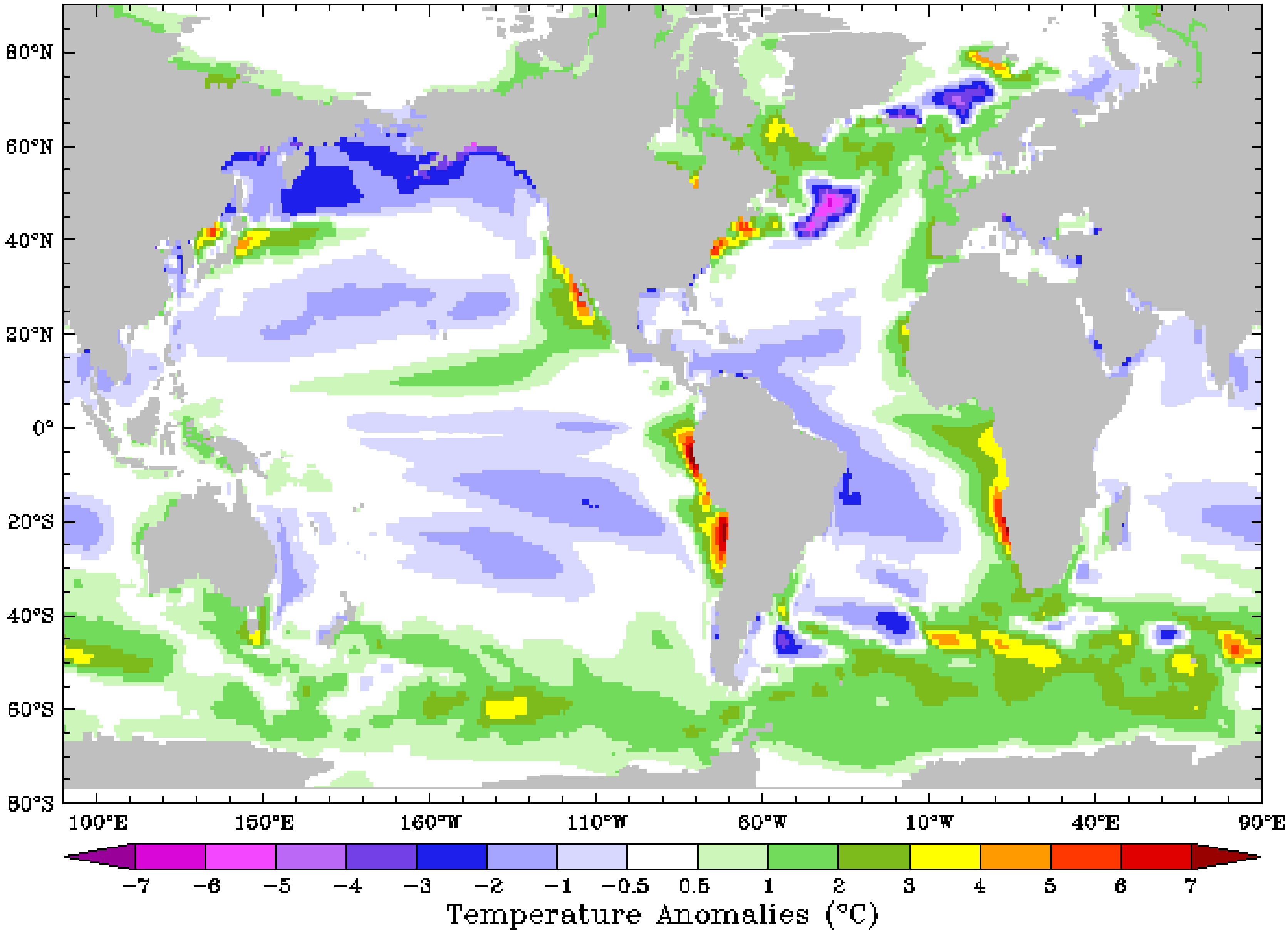

CM2.1 100-Year Mean Sea Surface Temperatures
Years 101-200
80°N 60°N 40°N 20°N 0° 20°S 40°S 60°S 80°S
100°E 150°E 160°W 110°W 60°W 10°W 40°E 90°E
-2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
Sea Surface Temperature (°C)

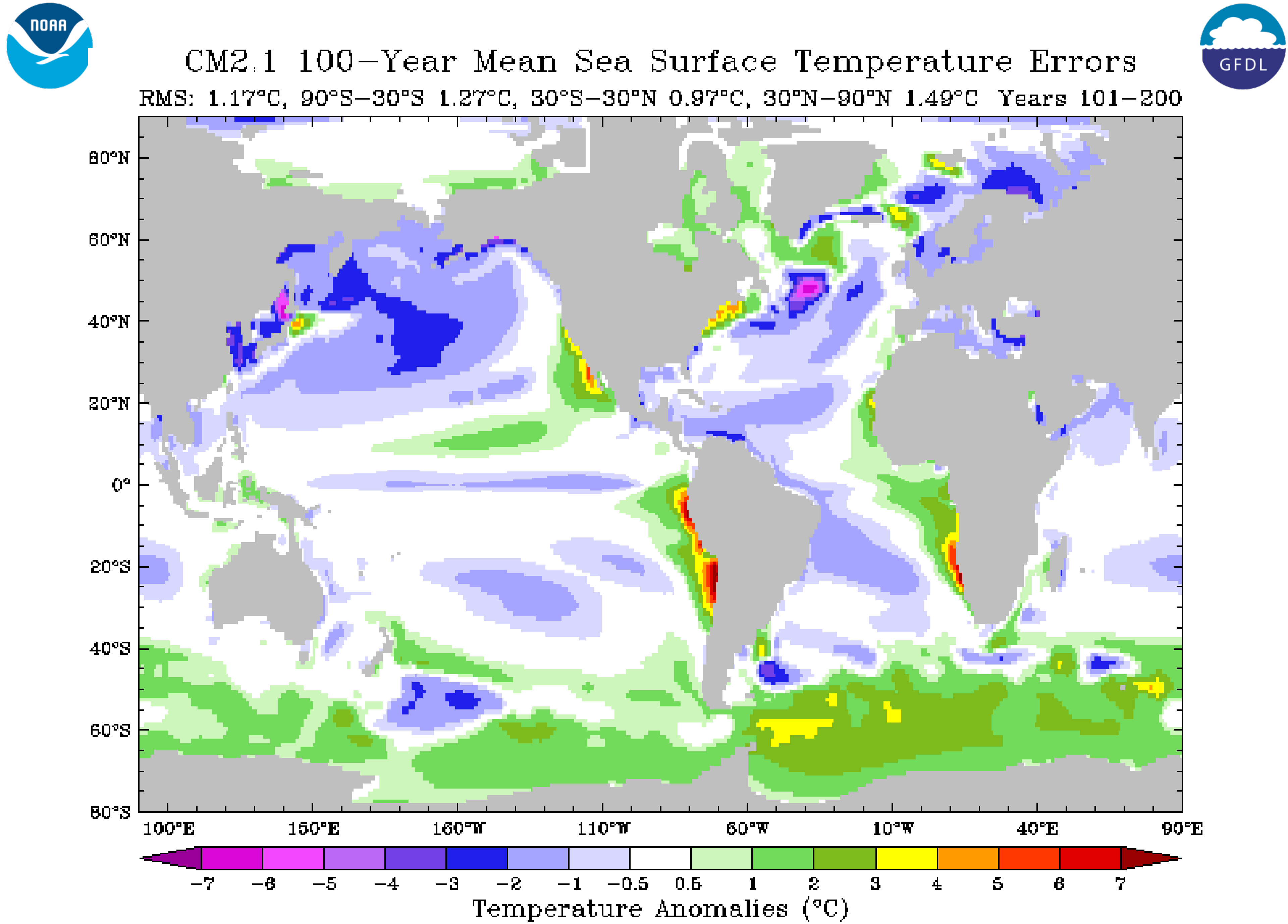

CM2M 100-Year Mean Sea Surface Temperatures
Years 101-200
80°N 60°N 40°N 20°N 0° 20°S 40°S 60°S 80°S
100°E 150°E 160°W 110°W 60°W 10°W 40°E 90°E
-2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
Sea Surface Temperature (°C)


Reynolds 20-Year Mean Sea Surface Temperatures
1982-2001
80°N 60°N 40°N 20°N 0° 20°S 40°S 60°S 80°S
100°E 150°E 160°W 110°W 60°W 10°W 40°E 90°E
-2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
Sea Surface Temperature (°C)

CM2G 100-Year Mean Sea Surface Temperature Errors

RMS: 1.18°C, 90°S–30°S 1.31°C, 30°S–30°N 1.01°C, 30°N–90°N 1.41°C Years 101–200





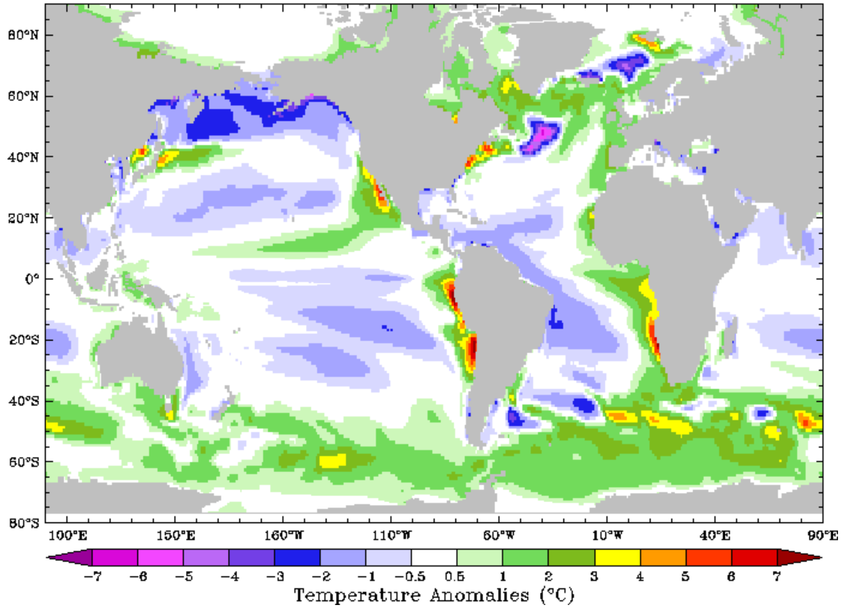
CM2.1 100-Year Mean Sea Surface Temperature Errors
RMS: 1.17°C, 90°S-30°S 1.27°C, 30°S-30°N 0.97°C, 30°N-90°N 1.49°C Years 101-200
80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
80°S
100°E
150°E
160°W
110°W
60°W
10°W
40°E
90°E
-7
-6
-5
-4
-3
-2
-1
-0.5
0.5
1
2
3
4
5
6
7
Temperature Anomalies (°C)
NOAA
GFDL

100-Year Annual Mean SST Errors

CM2G 1.18°C RMS

CM2G 100−Year Mean Sea Surface Temperature Errors

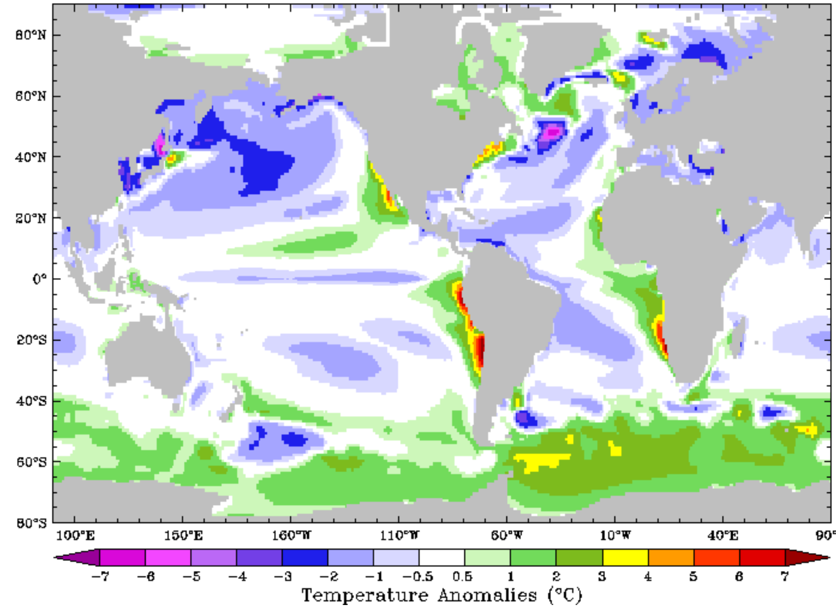
RMS: 1.18°C, 90°S−30°S 1.31°C, 30°S−30°N 1.01°C, 30°N−90°N 1.41°C Years 101−200



CM2.1 1.17°C RMS

CM2.1 100−Year Mean Sea Surface Temperature Errors

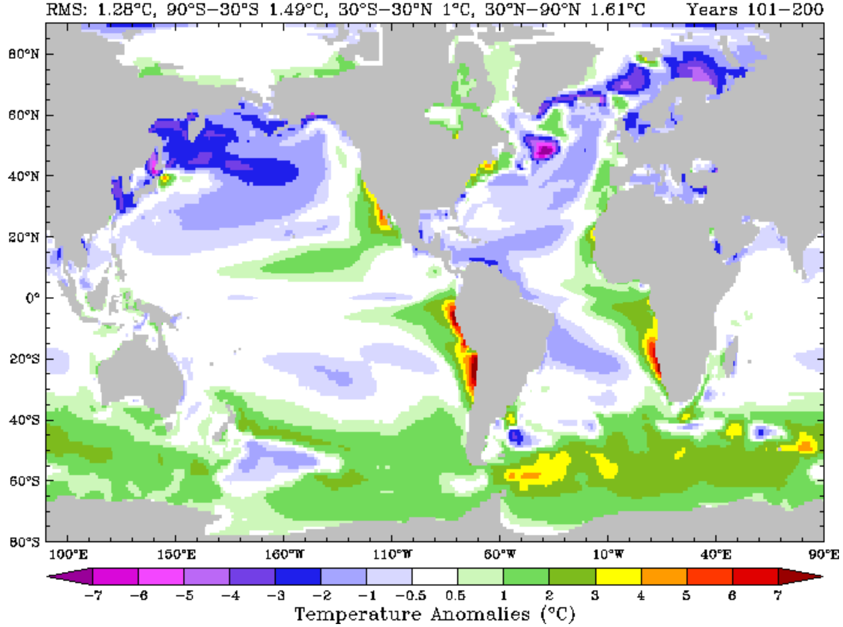
RMS: 1.17°C, 90°S−30°S 1.27°C, 30°S−30°N 0.97°C, 30°N−90°N 1.49°C Years 101−200



CM2M 1.28°C RMS

CM2M 100−Year Mean Sea Surface Temperature Errors

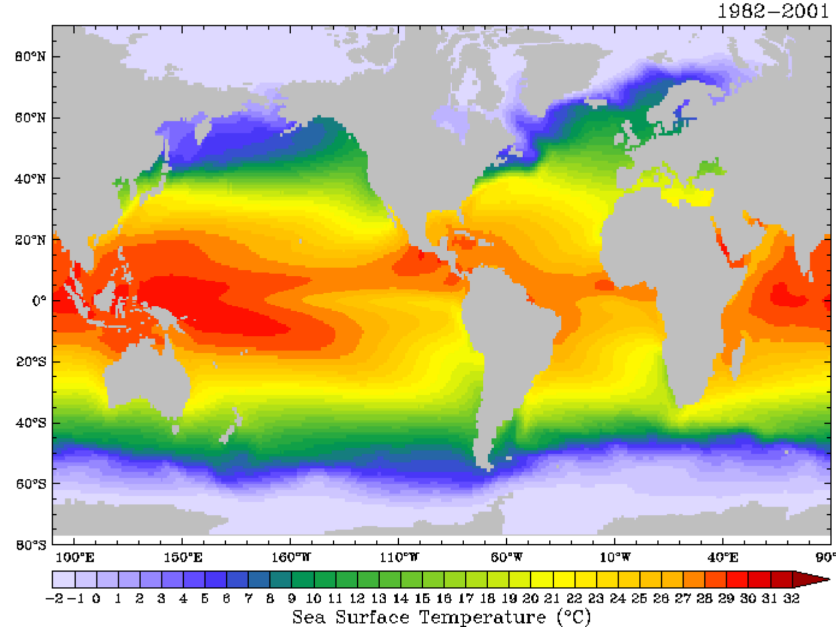
RMS: 1.28°C, 90°S−30°S 1.49°C, 30°S−30°N 1°C, 30°N−90°N 1.61°C Years 101−200



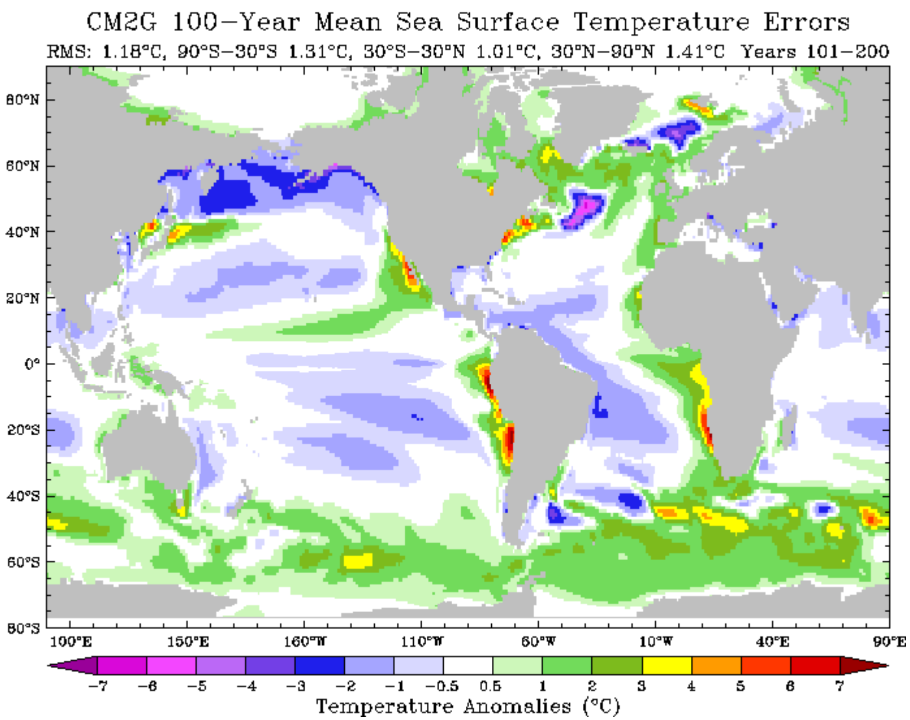
Reynolds Climatology

Reynolds 20−Year Mean Sea Surface Temperatures

1982−2001



Annual Average SST Errors



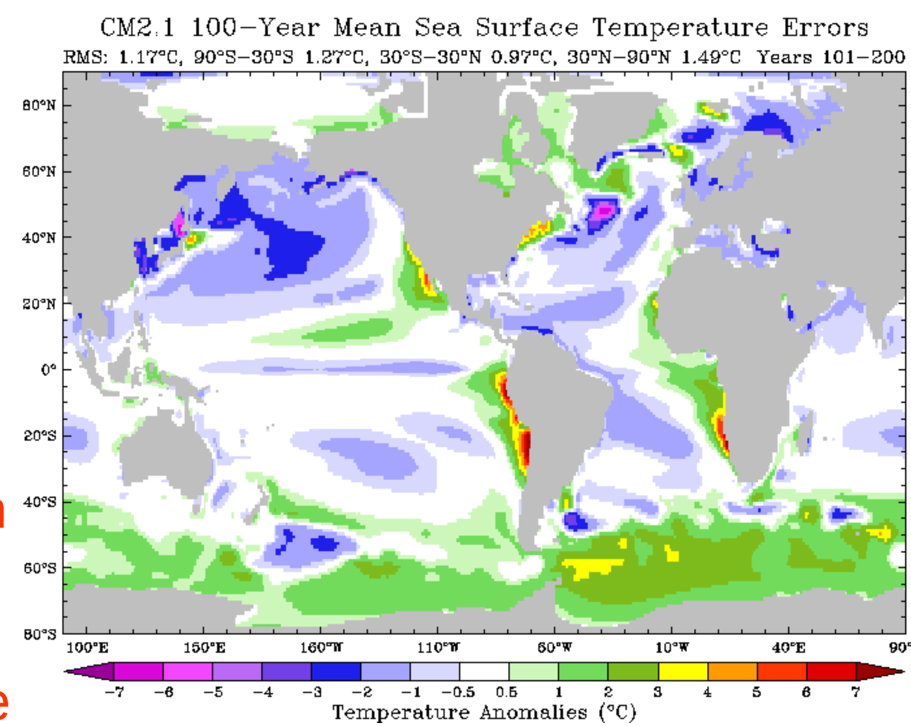
CM2G GOLD: RMS 1.18 K

Common biases:

- Almost no cooling in upwelling areas
- Warm Southern Ocean
- Equatorial cold tongue too cold.
- North Atlantic Current too zonal.
- Cold bias in N. Pacific subpolar gyre.
- Cold biases in southern subtropics

Differences in CM2G relative to CM2.1:

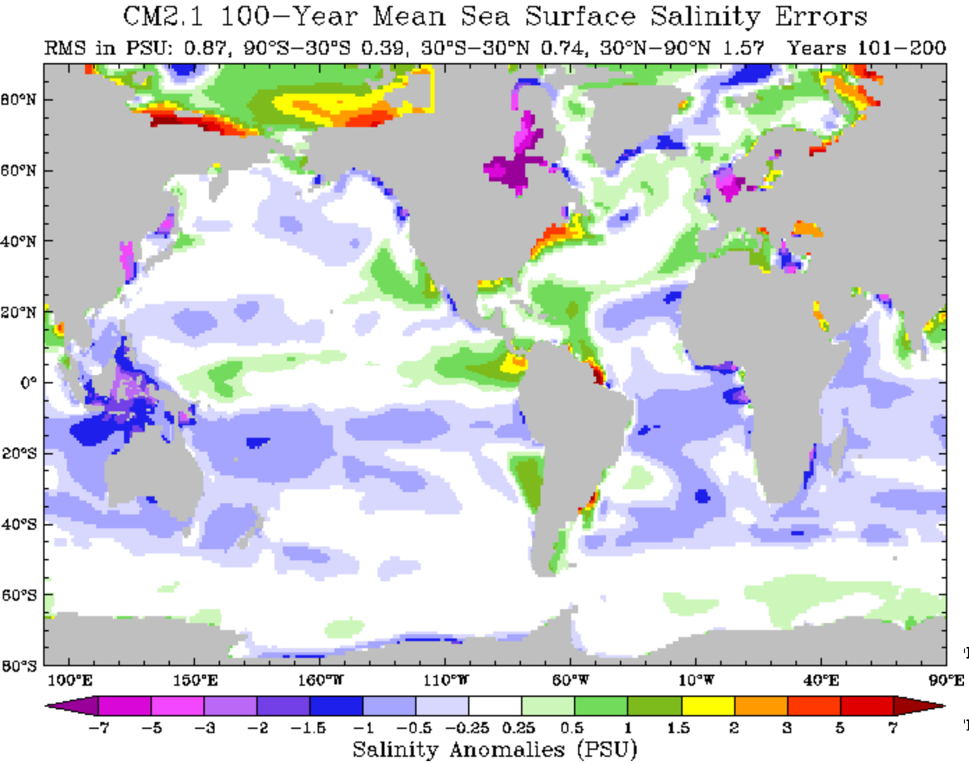
- Very different northern N. Atlantic
- Much better N. Pacific sea-ice pattern
- Smaller (summertime) Southern Ocean warm bias
- Larger cold biases in southern marine stratocumulus regions



CM2.1 MOM: RMS 1.17 K

CM2M MOM: RMS 1.28 K

Annual Average Sea Surface Salinity Errors



CM2.1 MOM: RMS 0.87 psu

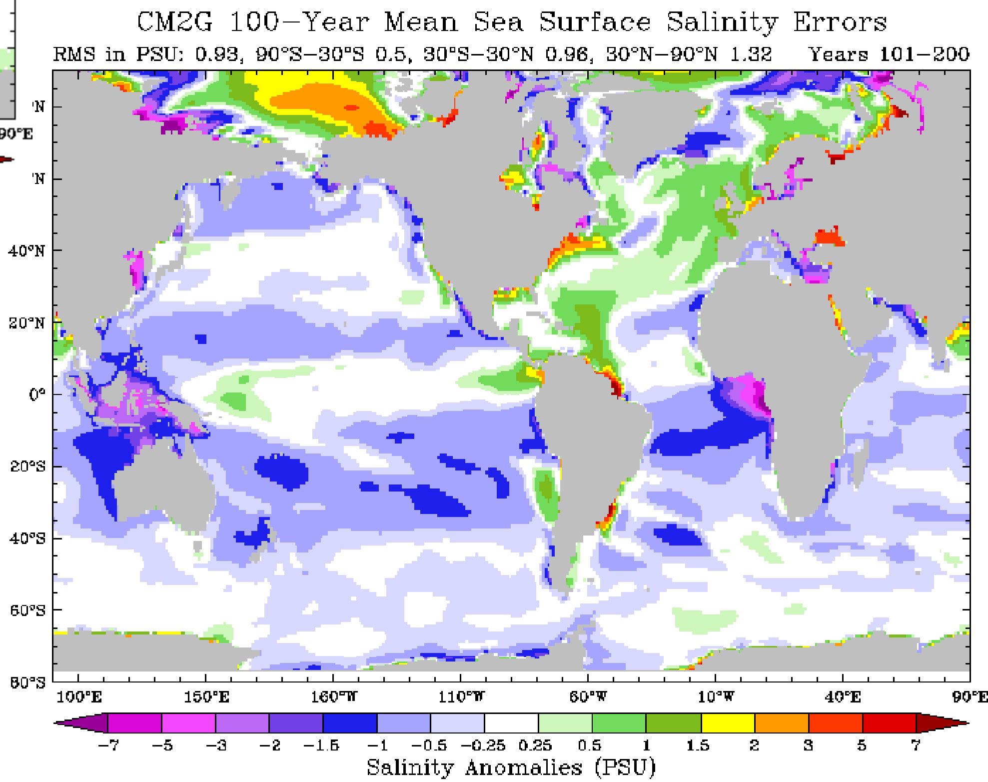
Common biases:

- Fresh subtropical southern gyres
  (Double ITCZ problem?)
- Weak Amazon plume; strong Congo
- Very fresh in Indonesia

CM2.1-specific biases:

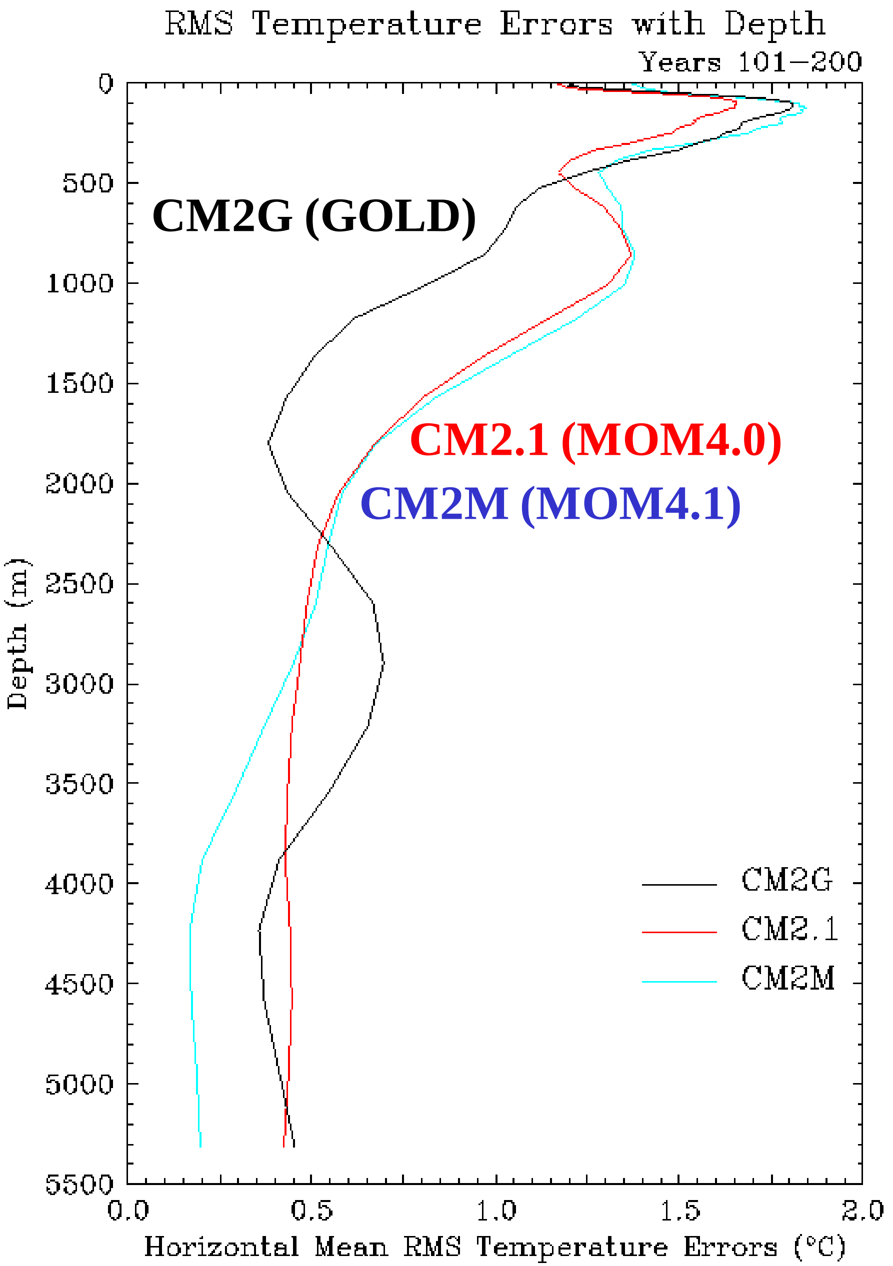
- Large fresh biases in marginal seas.

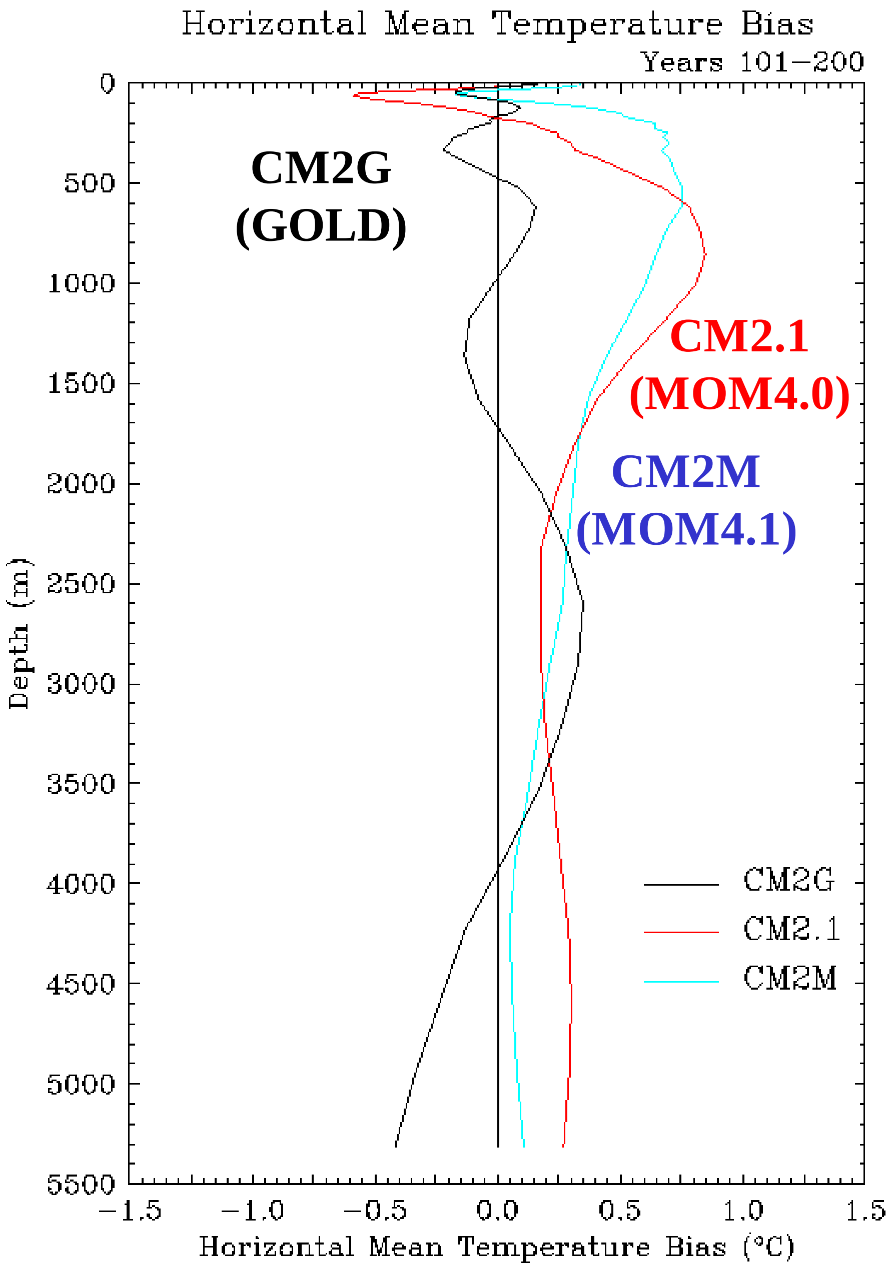
CM2G GOLD: RMS 0.93 psu



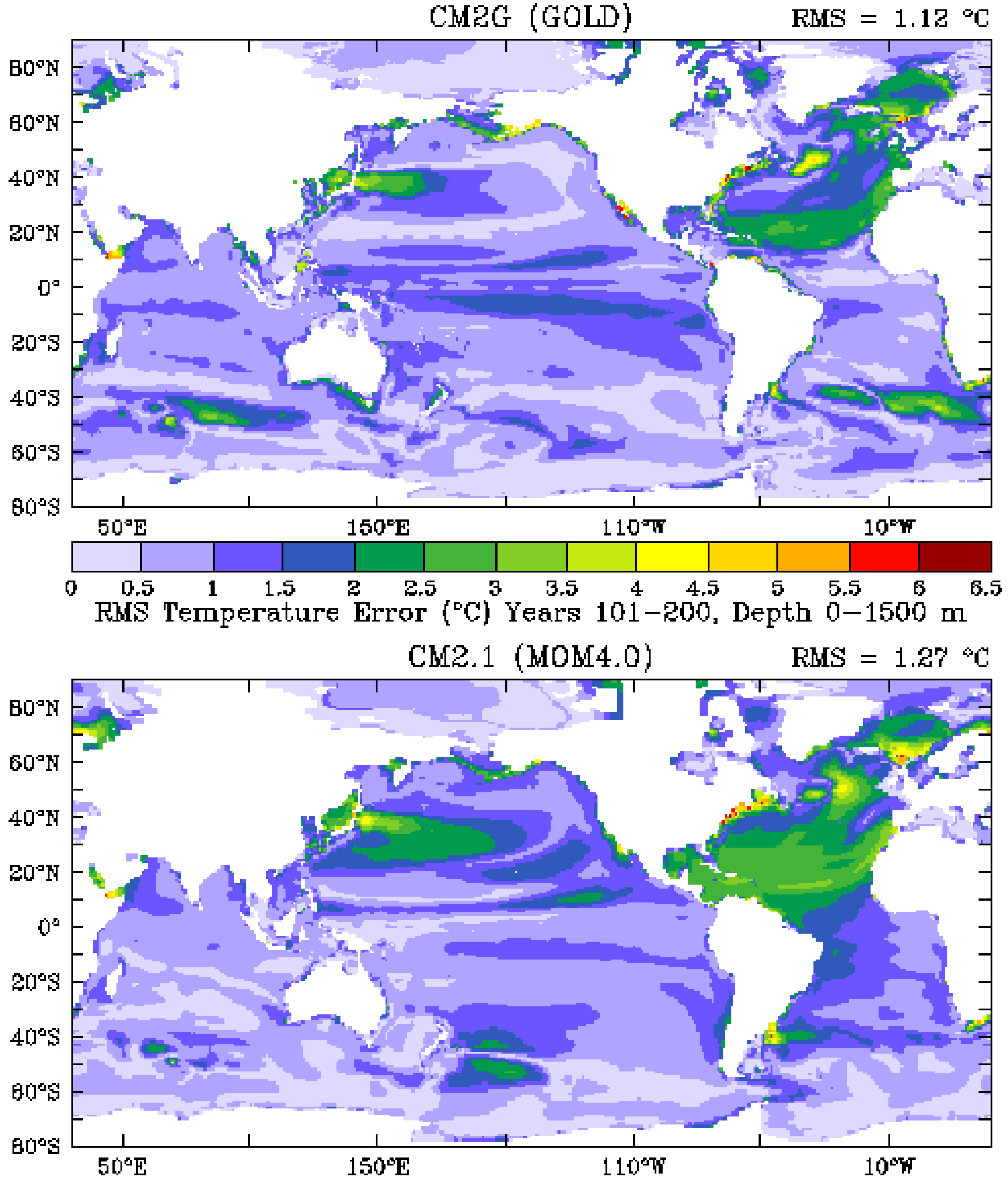
BROAD METRICS OF THE INTERIOR OCEAN STRUCTURE

Global Mean RMS Temperature Errors & Temperature Bias





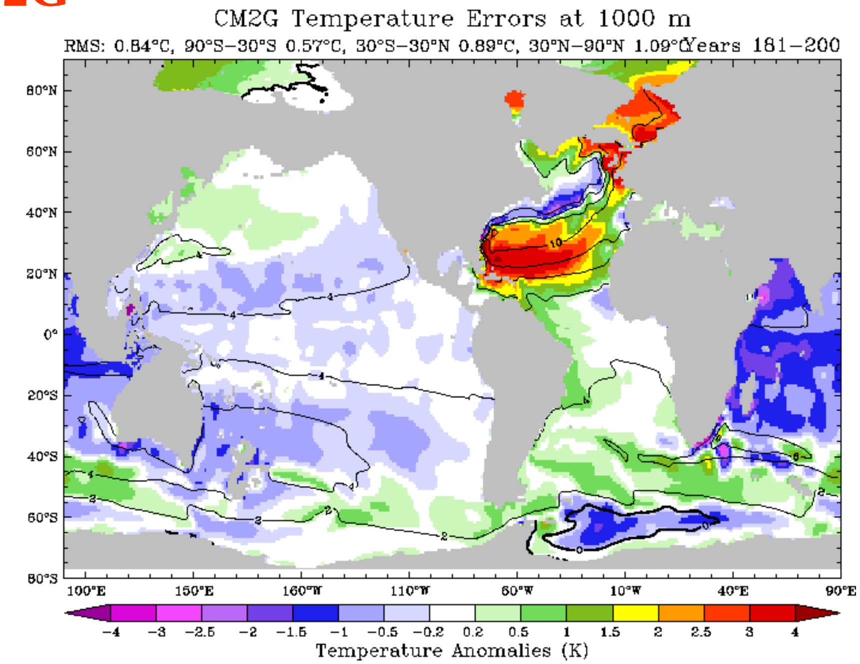
RMS 0-1500 m Depth Temperature Errors, Years 101-200

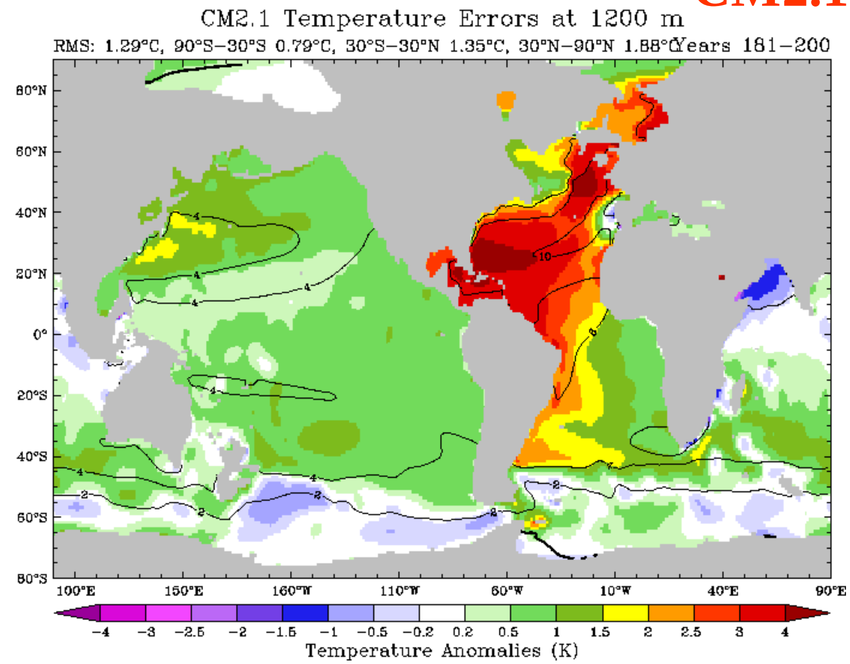


Year ~190 Temperature Errors at 1000 m Depth

CM2G

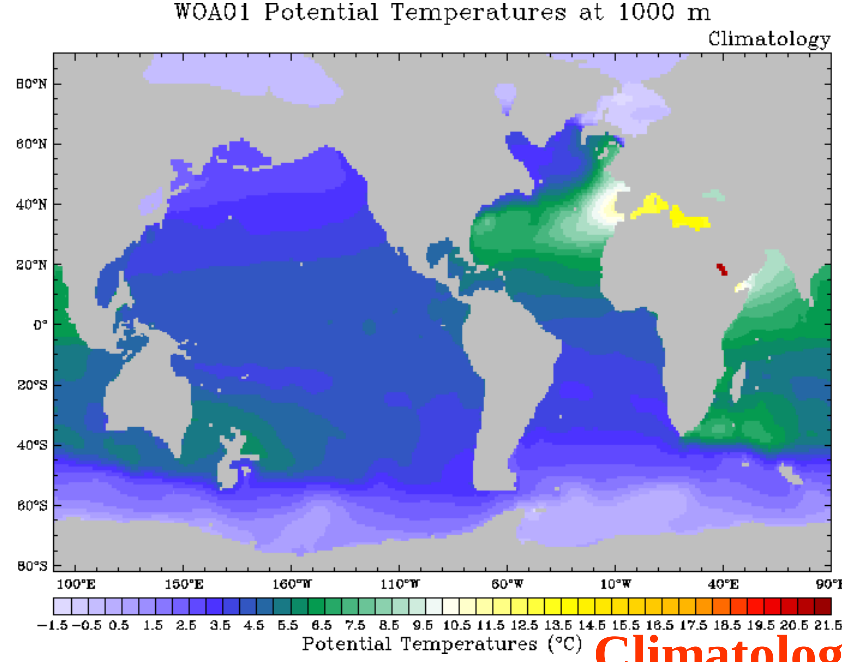
CM2.1





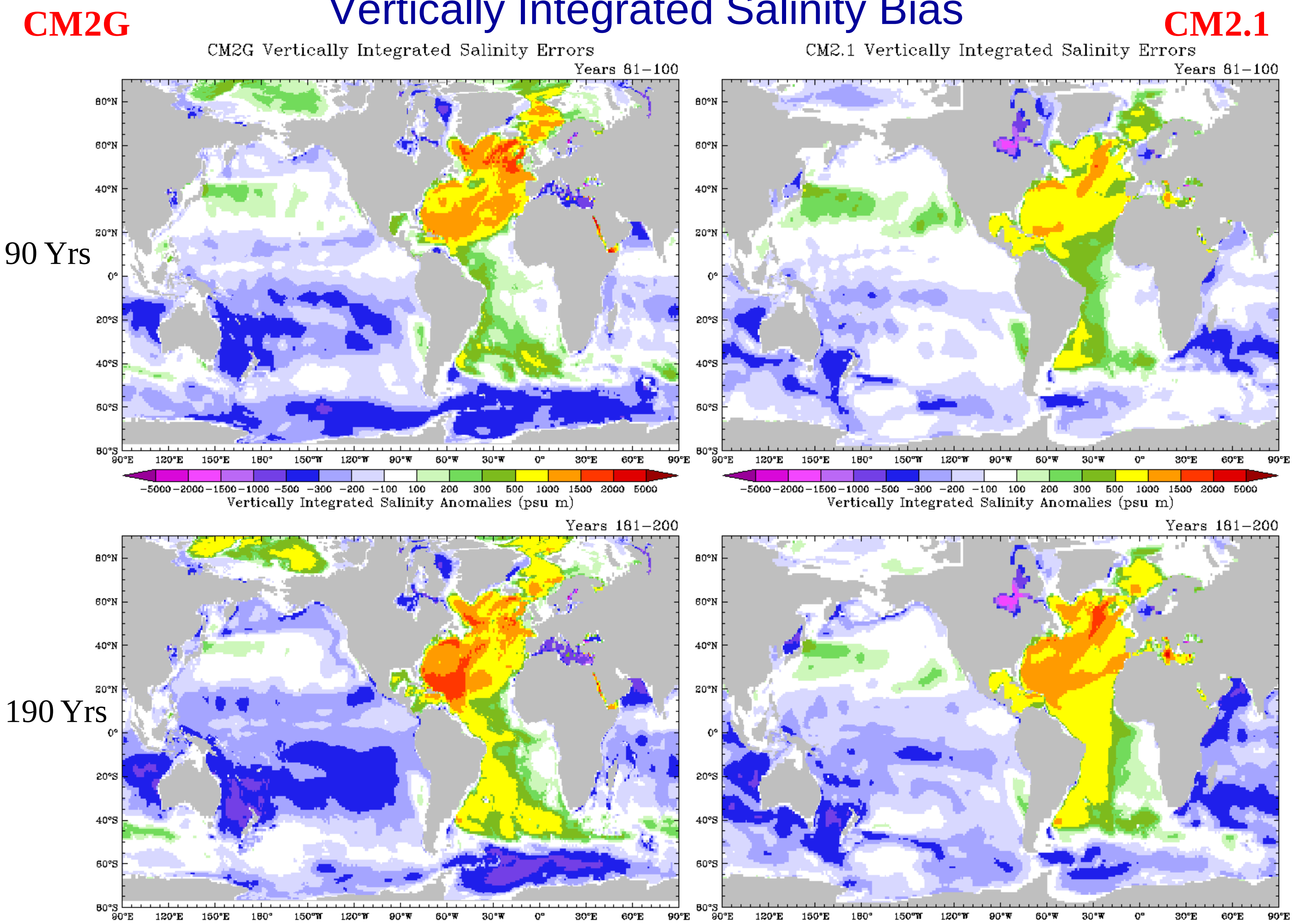
< 0.2 °C white

0.5 °C Contour interval



Climatology

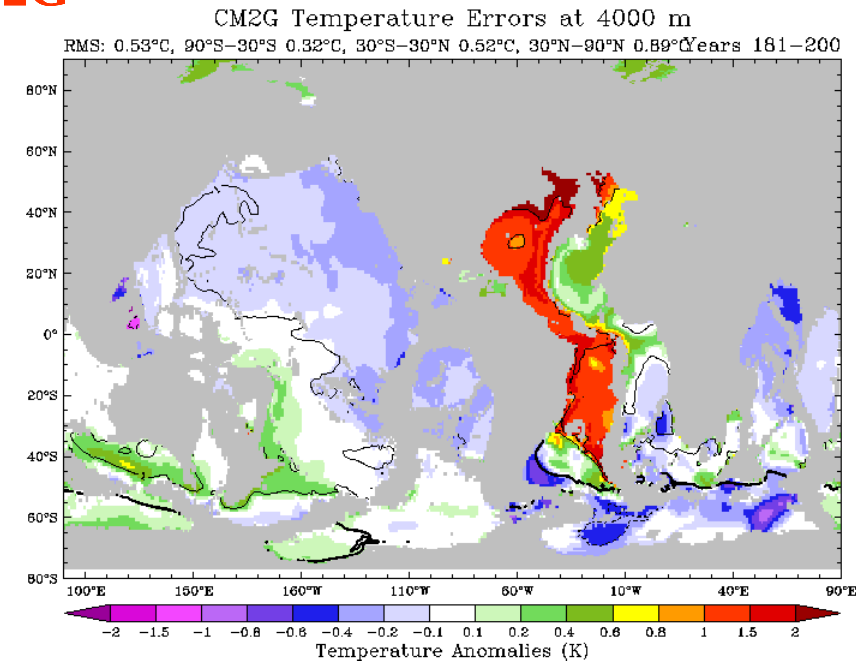
Vertically Integrated Salinity Bias

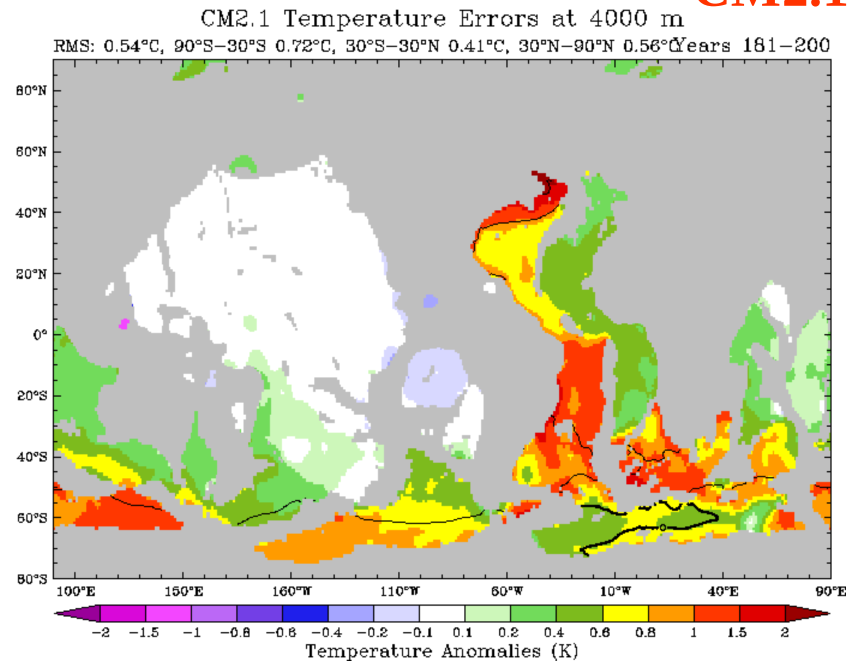


Year ~190 Temperature Errors at 4000 m Depth

CM2G

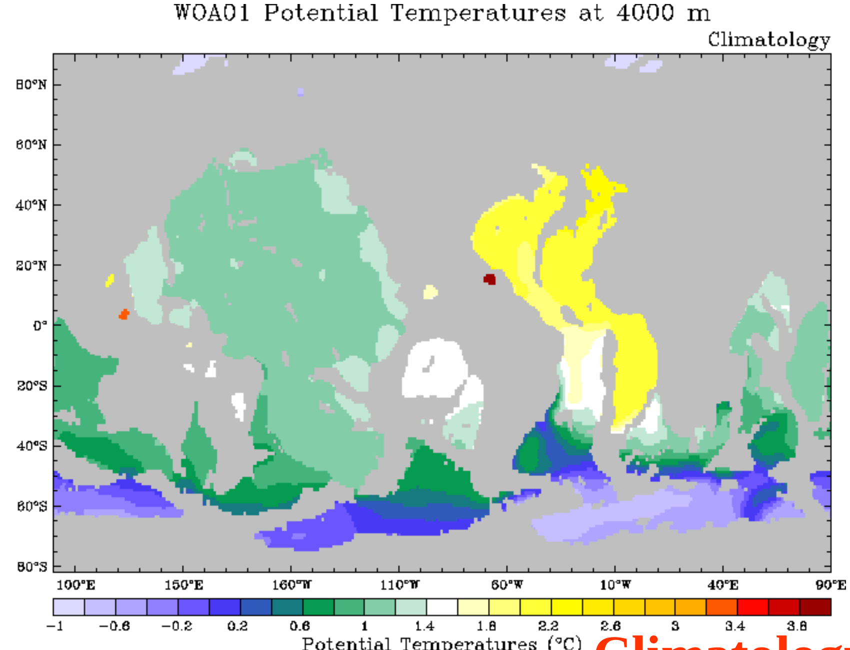
CM2.1





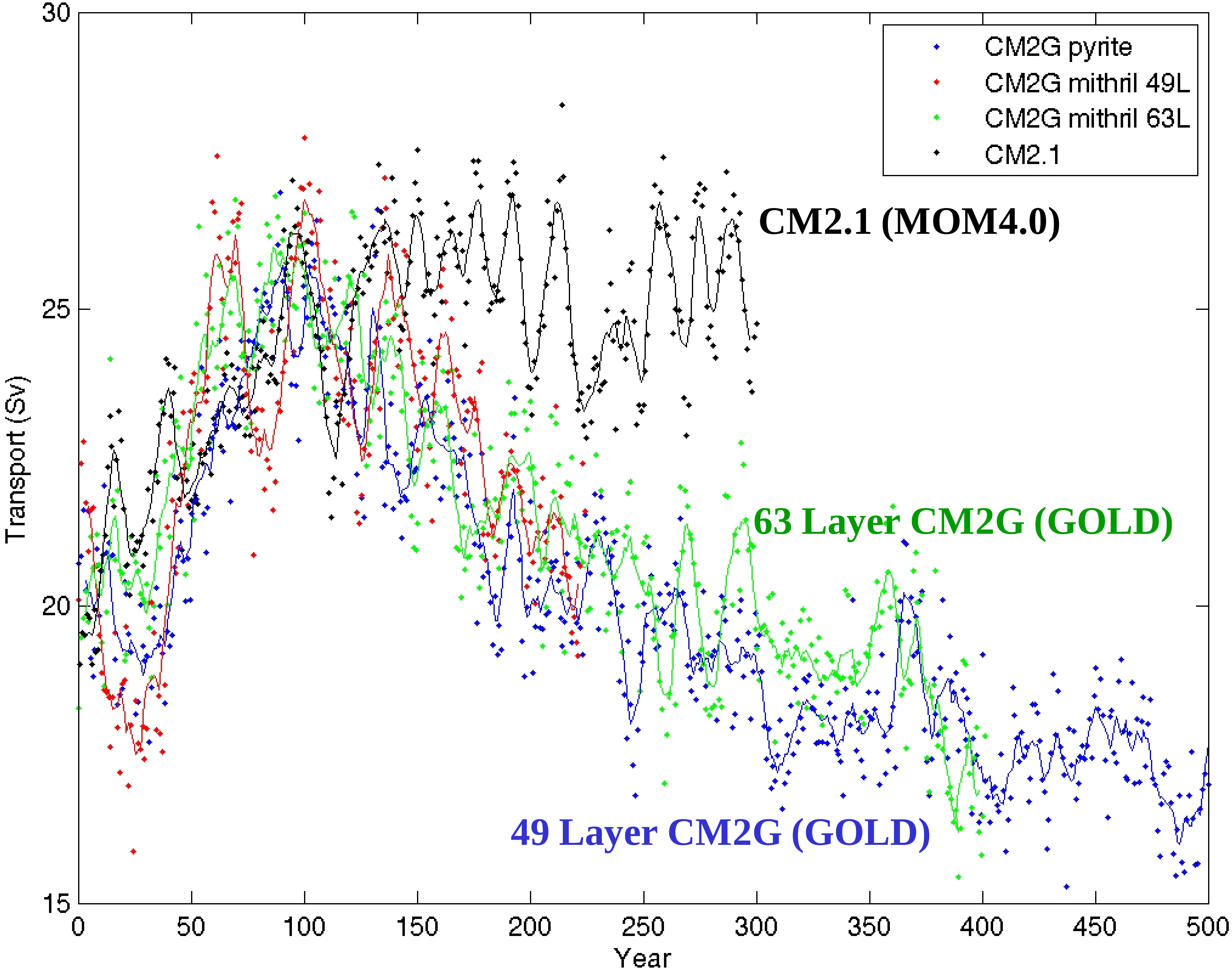
< 0.1 °C white

0.2 °C Contour interval



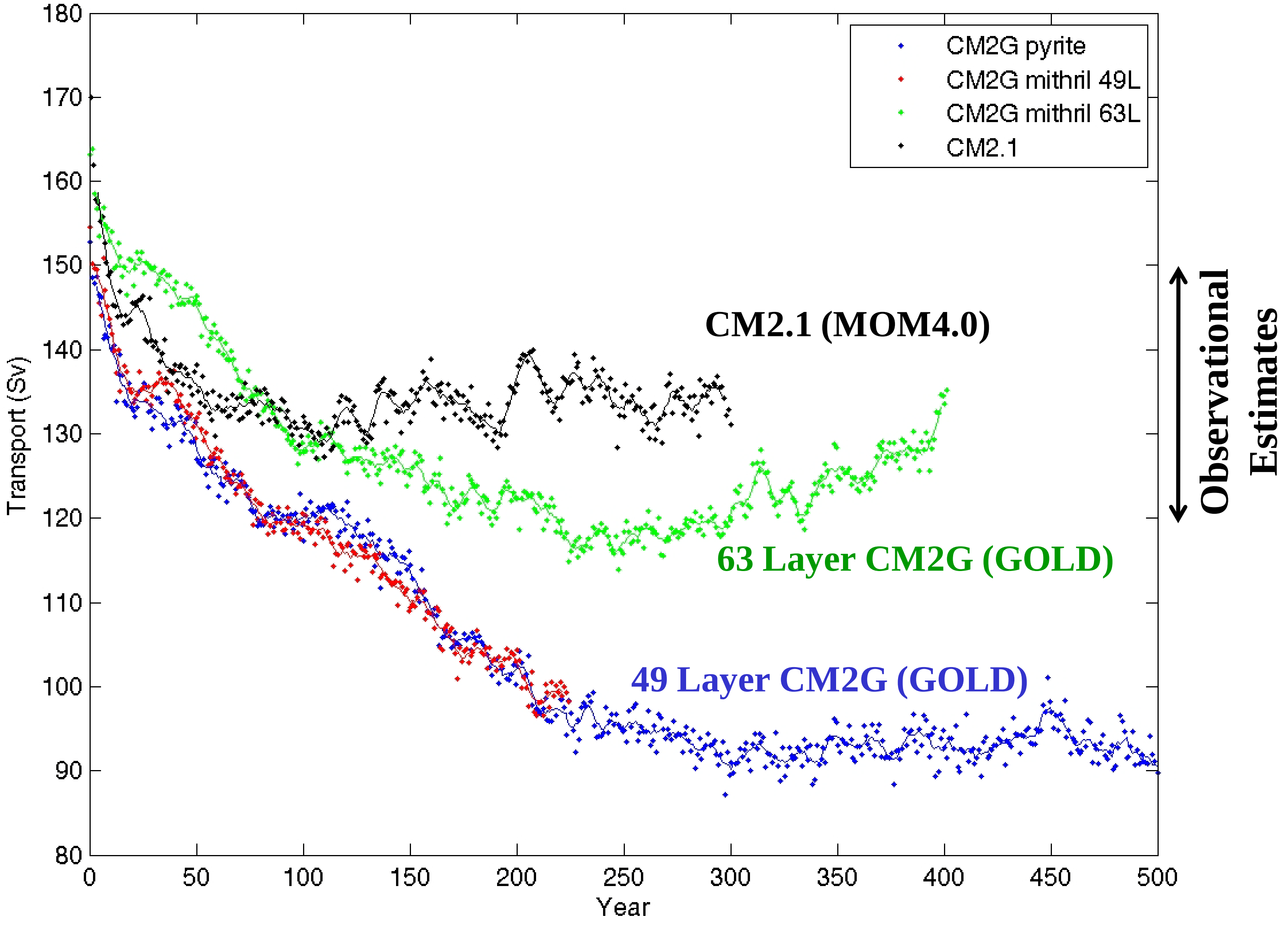
Climatology

The Strength of the Atlantic Meridional Overturning Circulation



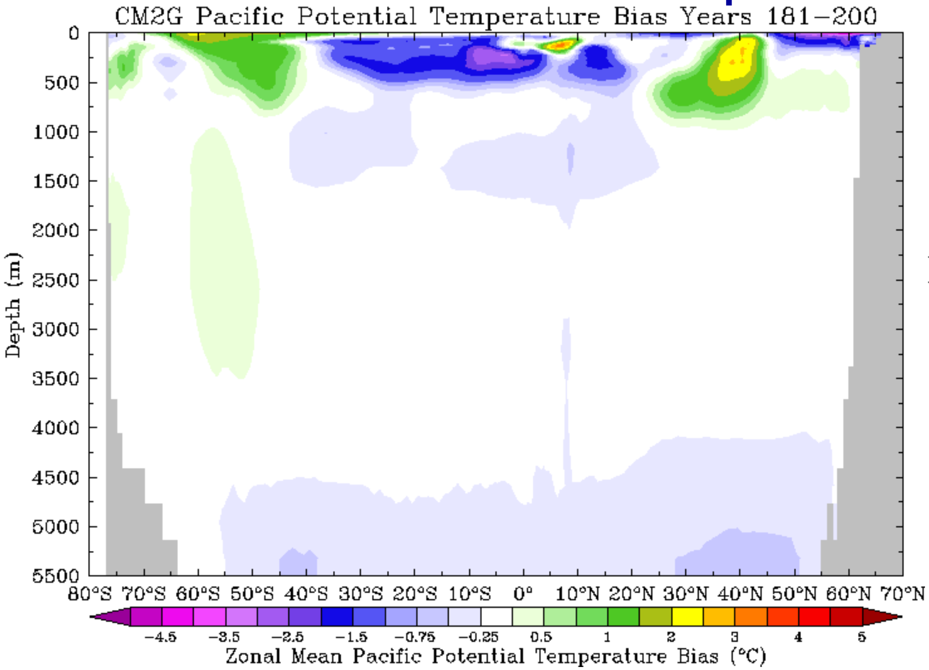
Depth-space overturning circulation. 63 Layer CM2G is in green.

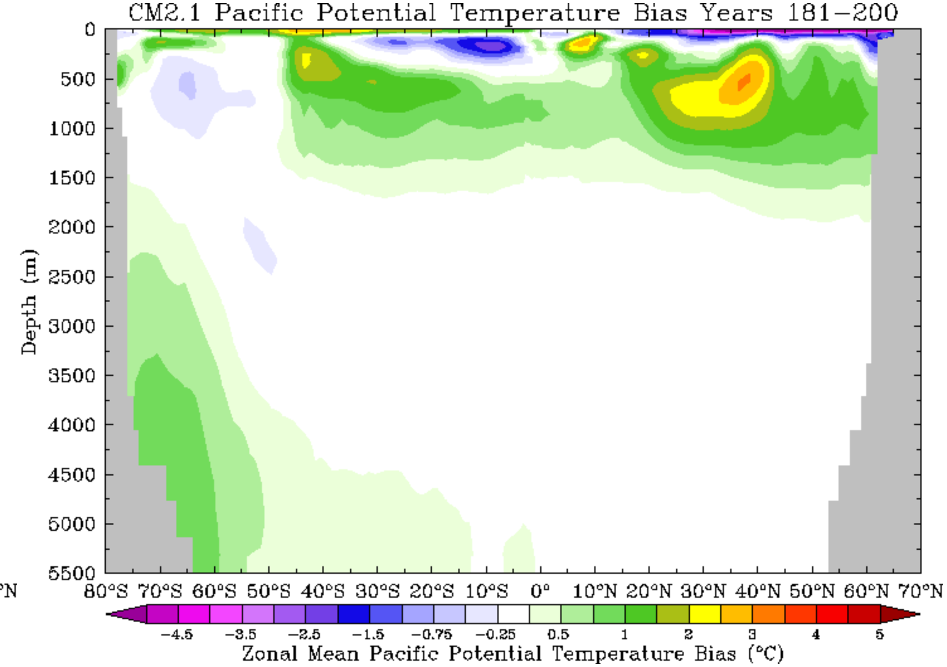
The Strength of the Drake Passage Transport



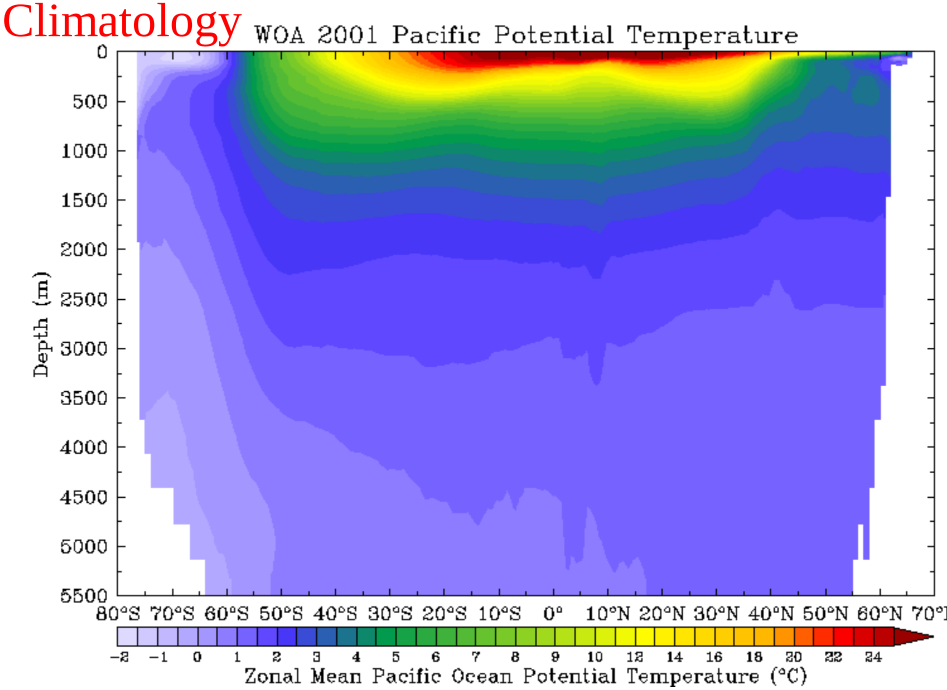
PACIFIC AND ATLANTIC OCEANS

CM2G Pacific Temperature Bias, ~190 Years CM2.1





Climatology



Possible causes of biases:

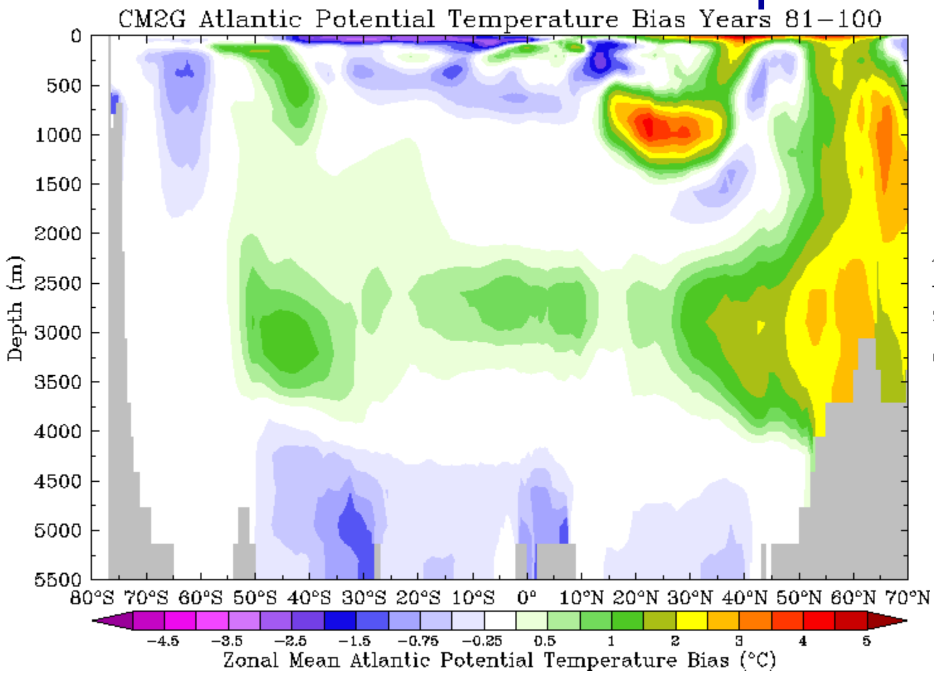
CM2.1: Excessive diffusion

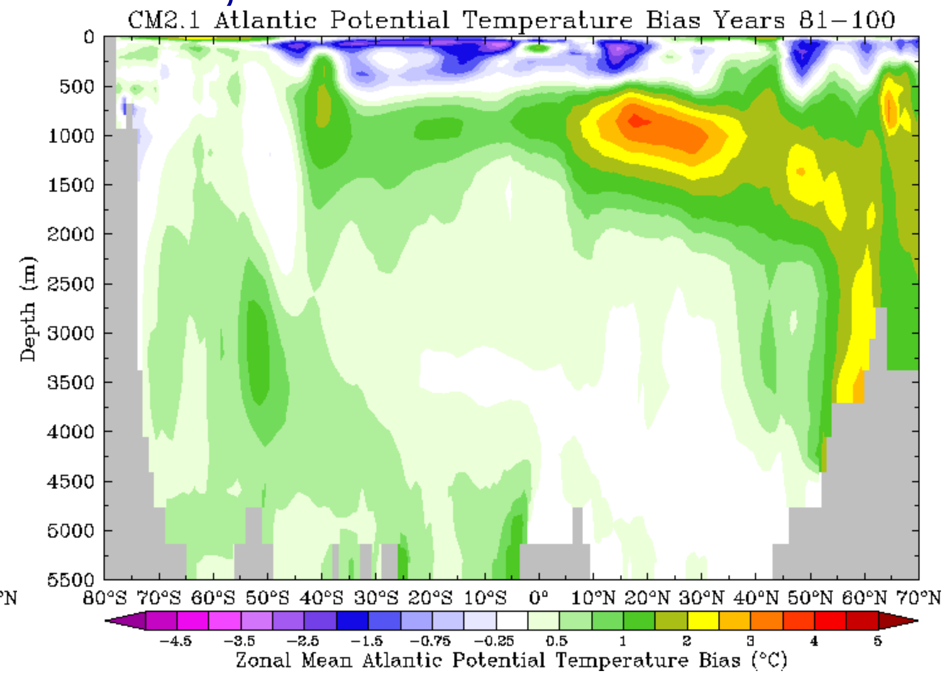
- Overly entraining overflows.
- Weak abyssal flow.

CM2G: Insufficient diffusion.

- Overly wide abyssal cateracts

CM2G Atlantic Temperature Bias, ~90 Years CM2.1



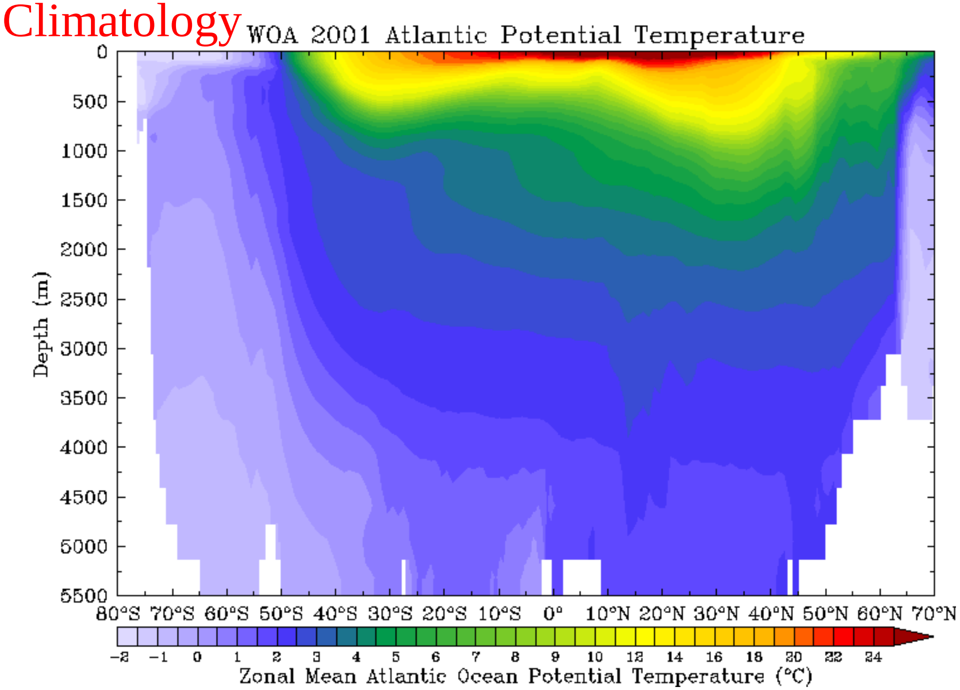


Zonal Mean Atlantic Ocean Potential Temperatures

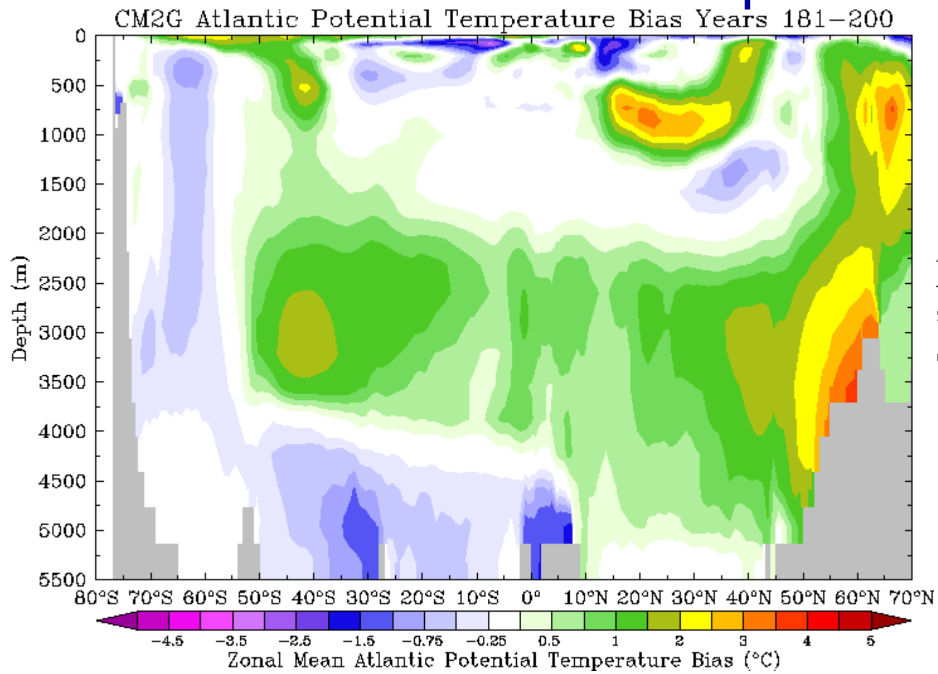
Average of Years 81-100

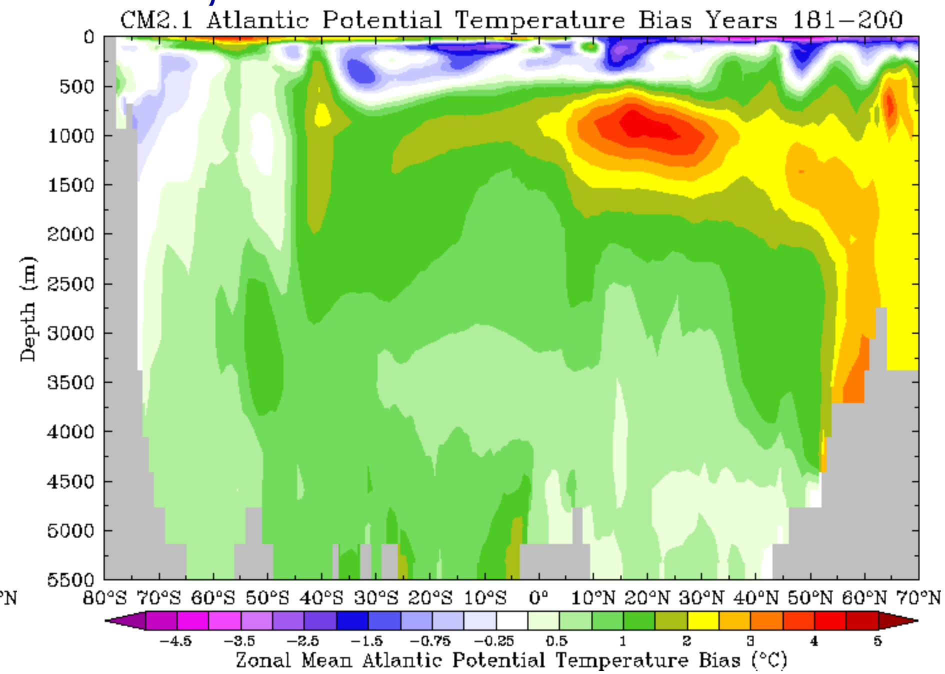
Excludes most marginal seas

Climatology

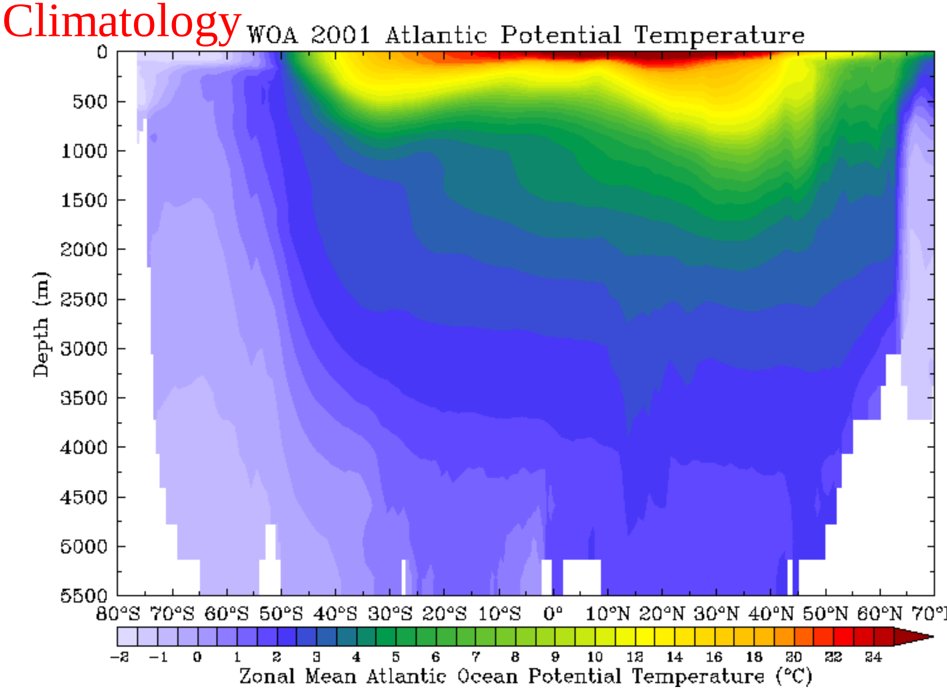


CM2G Atlantic Temperature Bias, ~190 Years CM2.1





Climatology

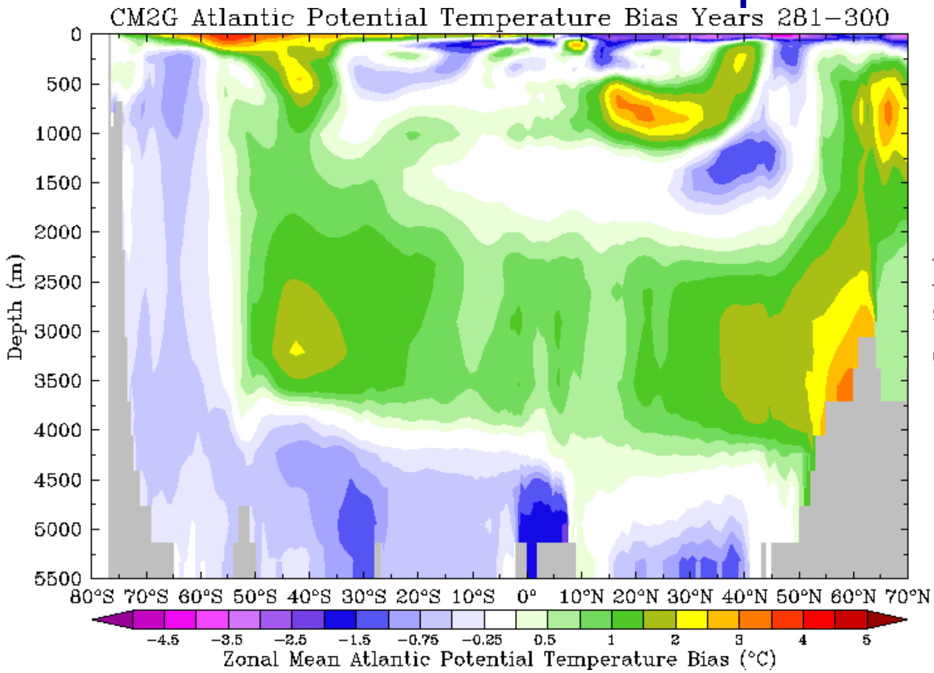


Possible causes of Atlantic bias:

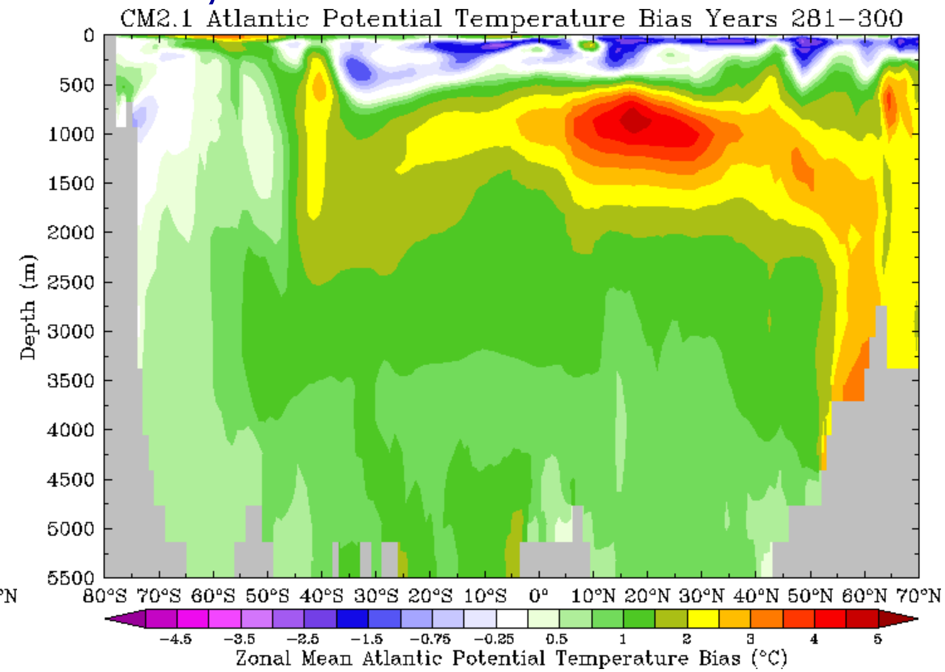
- Committed warming from 1990 forcing
- Circulation errors
- Excessive vertical diffusion
- Excessive exchange with Mediterranean
- Errors in NADW formation
- Salty bias from runoff + precip. - evap.

Atlantic Temperature Bias, ~290 Years

CM2G



CM2.1



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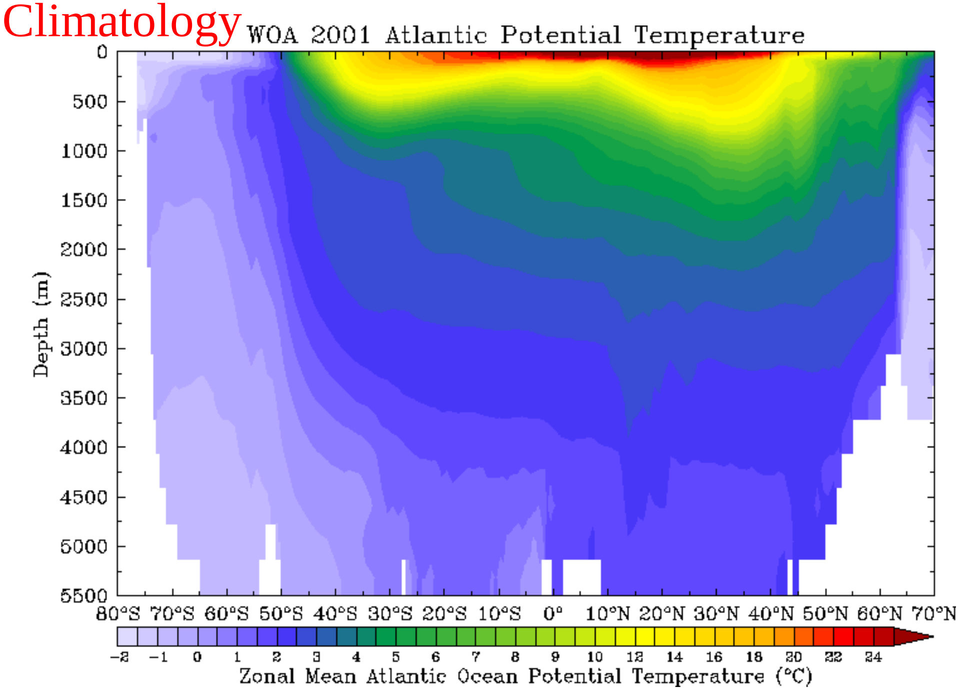
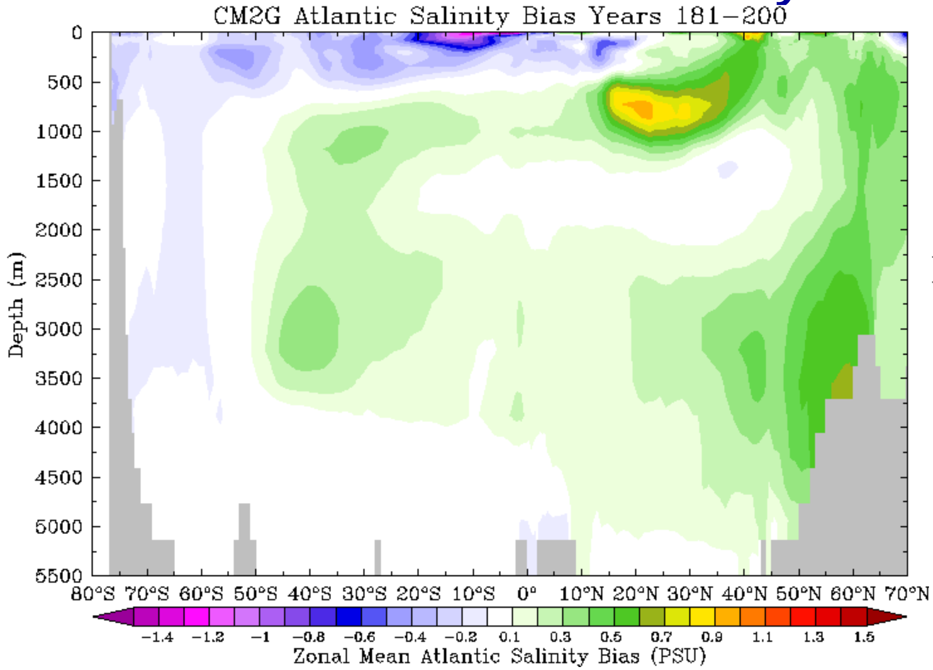
Climatology

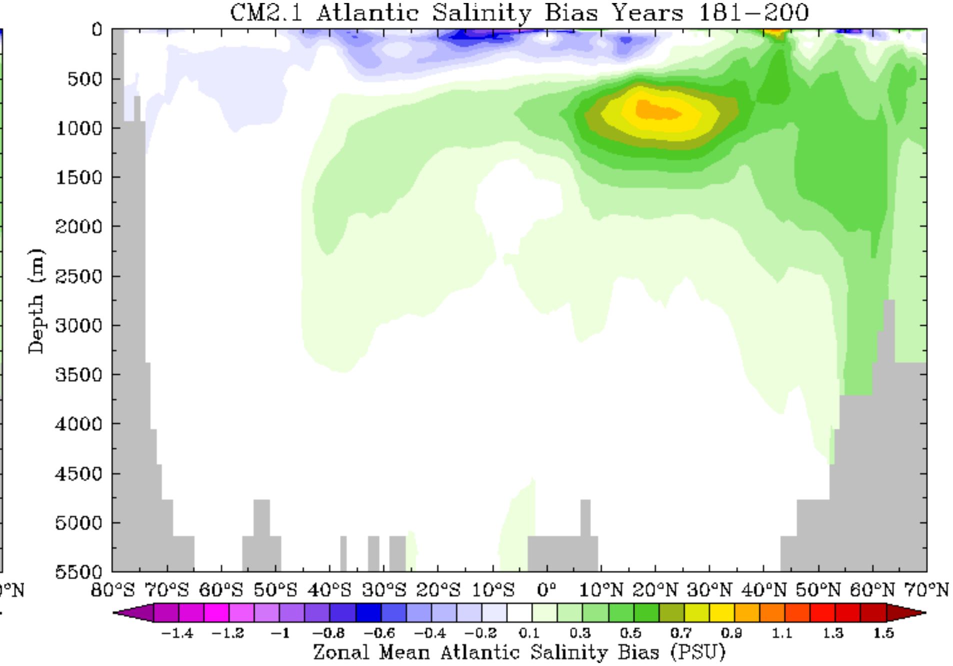


CM2G

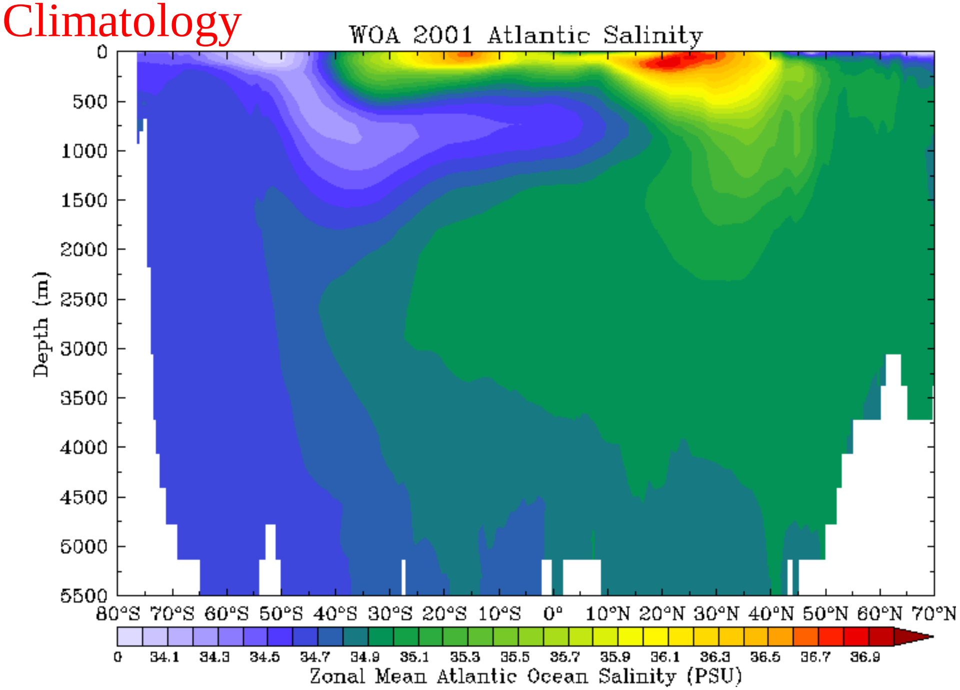
Atlantic Salinity Anomalies, ~190 Years

CM2.1





Climatology

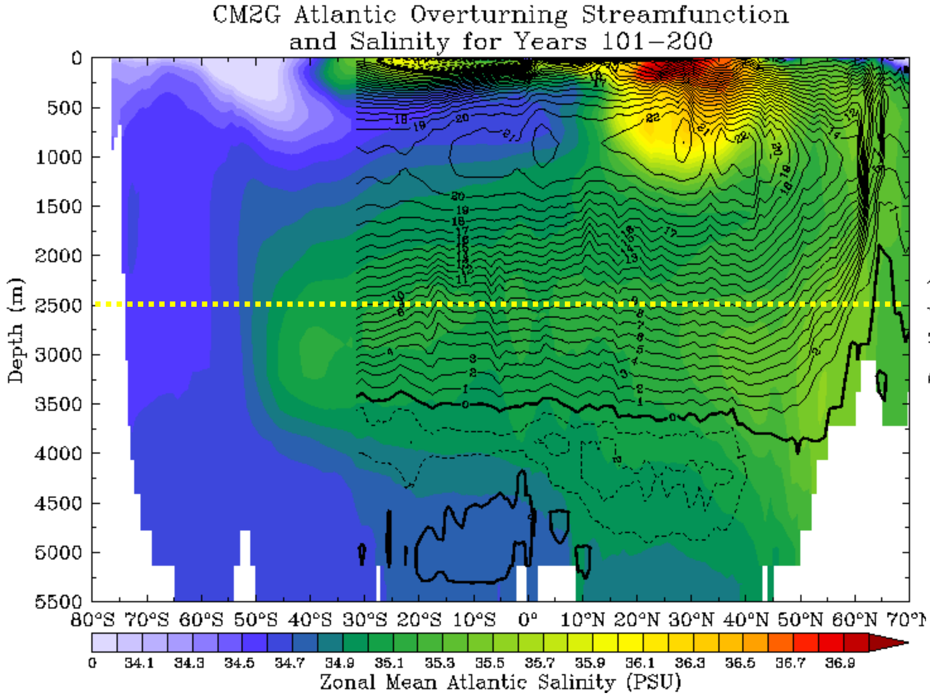


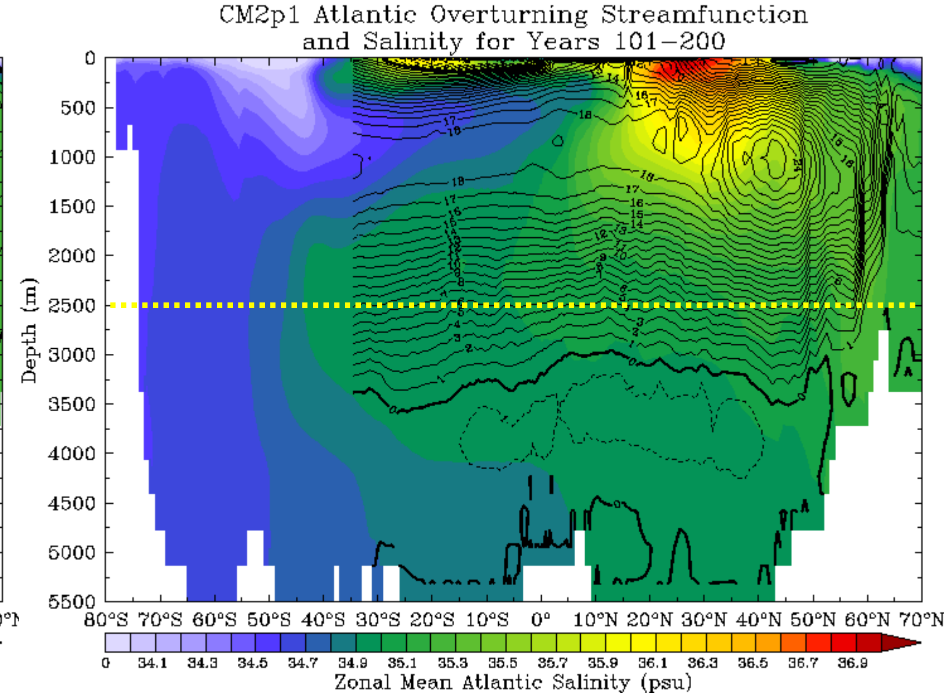
Zonal Mean Atlantic Ocean Salinity

Average of Years 181-200

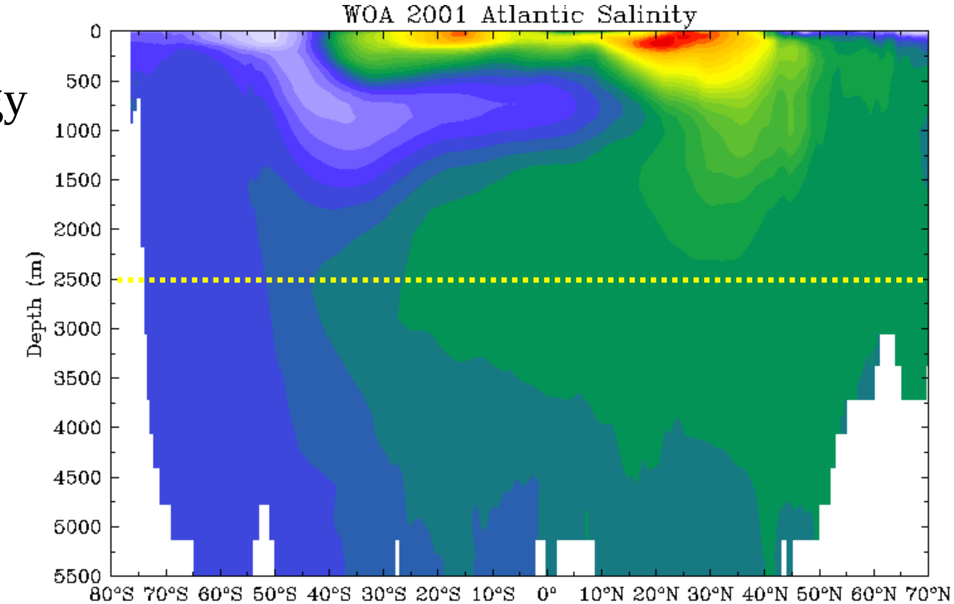
Excludes most marginal seas

CM2G Atlantic Salinities and Overturning Streamfunctions CM2.1

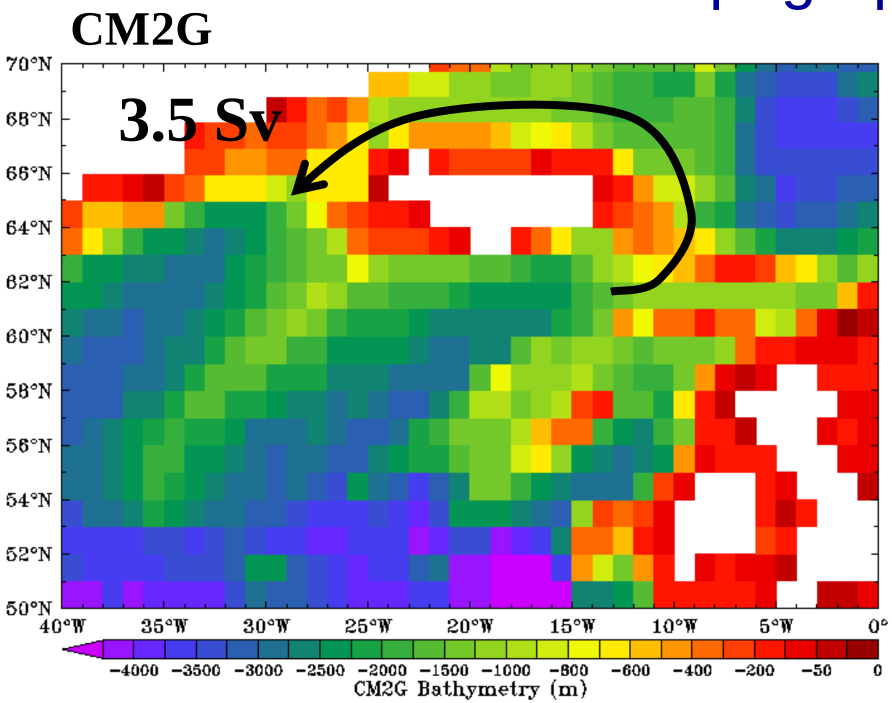


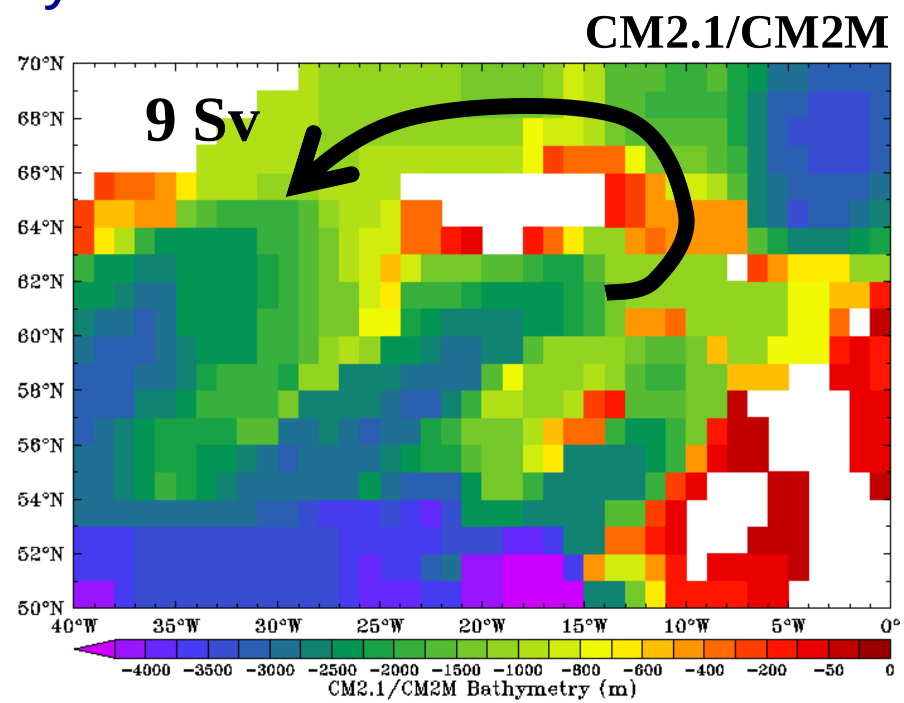


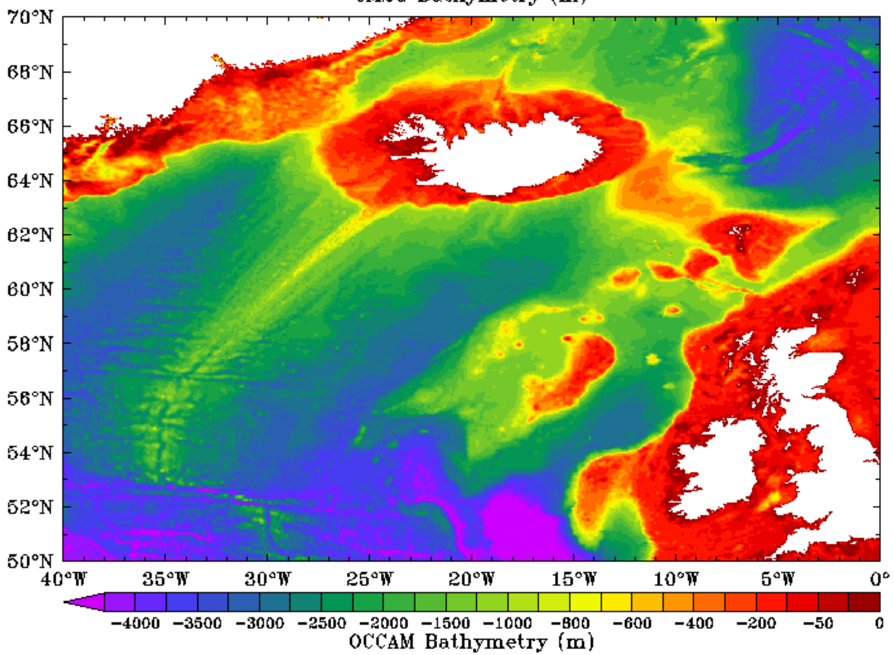
Climatology



Denmark Strait Topography in CM2.1 and CM2G







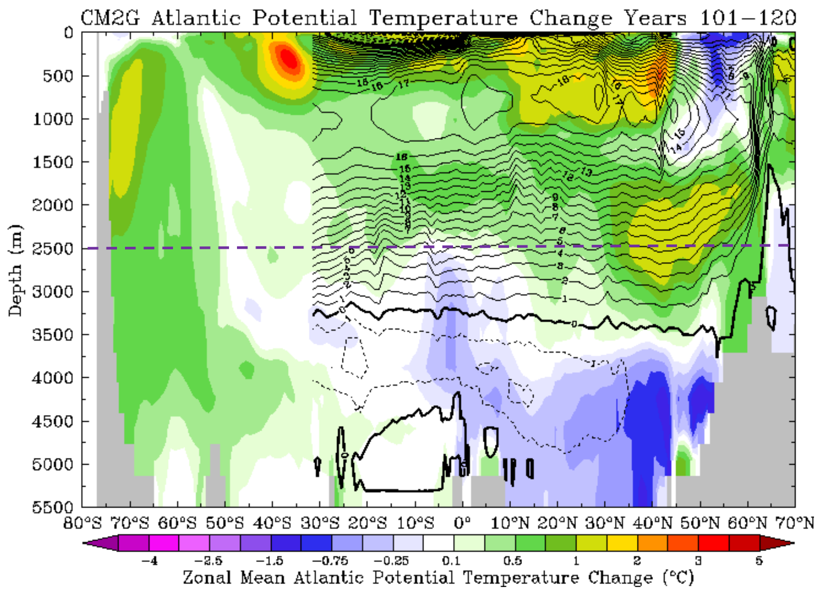
- An excessively deep Denmark Strait sill is ubiquitous in IPCC/AR4 models.
- In CM2G the Denmark Strait and Faroe Bank Channel sill depths are set to agree with observed, although the channels are too wide.

AN IDEALIZED GLOBAL WARMING SIMULATION

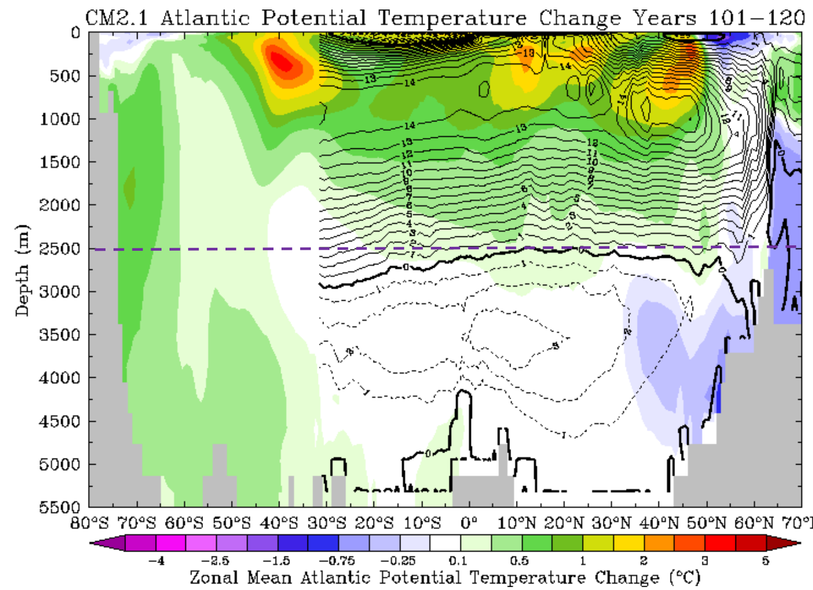
Changes after 110 Years in 1% per year CO_2 Runs

Atlantic Temperature Change & Overturning Streamfunction

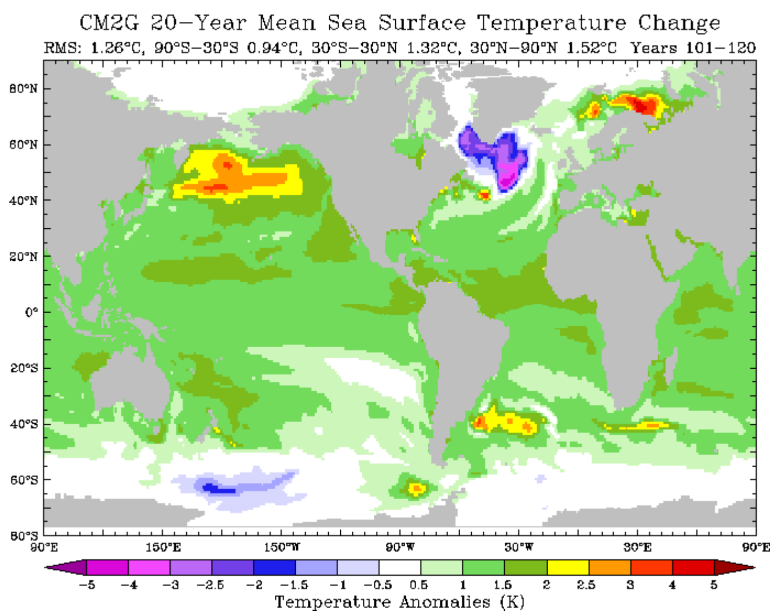
CM2G

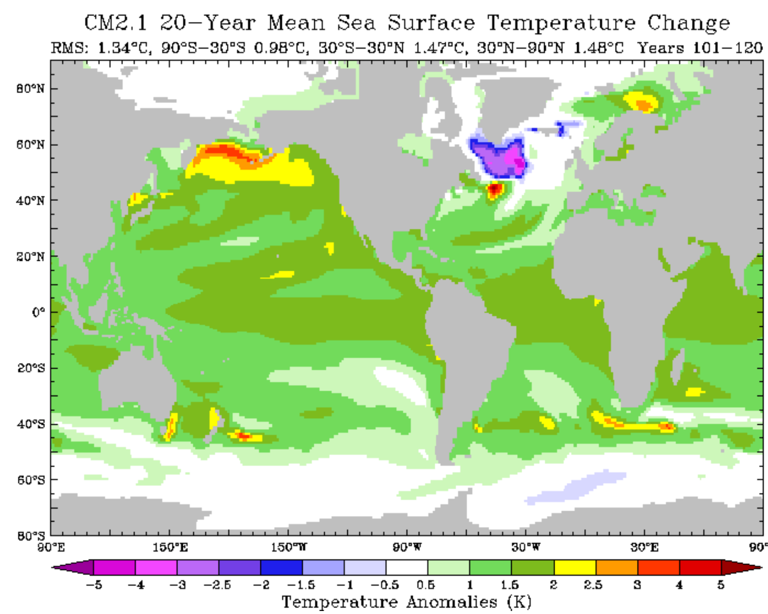


CM2.1



SST Change





Conclusions

CM2G and CM2M are both viable coupled climate models.

Mean climate:

- Both CM2M & CM2G exhibit similar long-term-mean SST biases to CM2.1 (mostly due to the atmosphere)
- CM2G has clearly superior interior watermass properties, thermocline structure, and AMOC structure.

Climate change:

- Surface warming patterns are similar between CM2G & CM2.1
- CM2G exhibits deeper Atlantic warming than CM2.1
  - Projected sea level rise is likely to be greater in CM2G than CM2.1.

Isopycnal coordinate ocean models have finally become the state-of-the-art for climate studies.

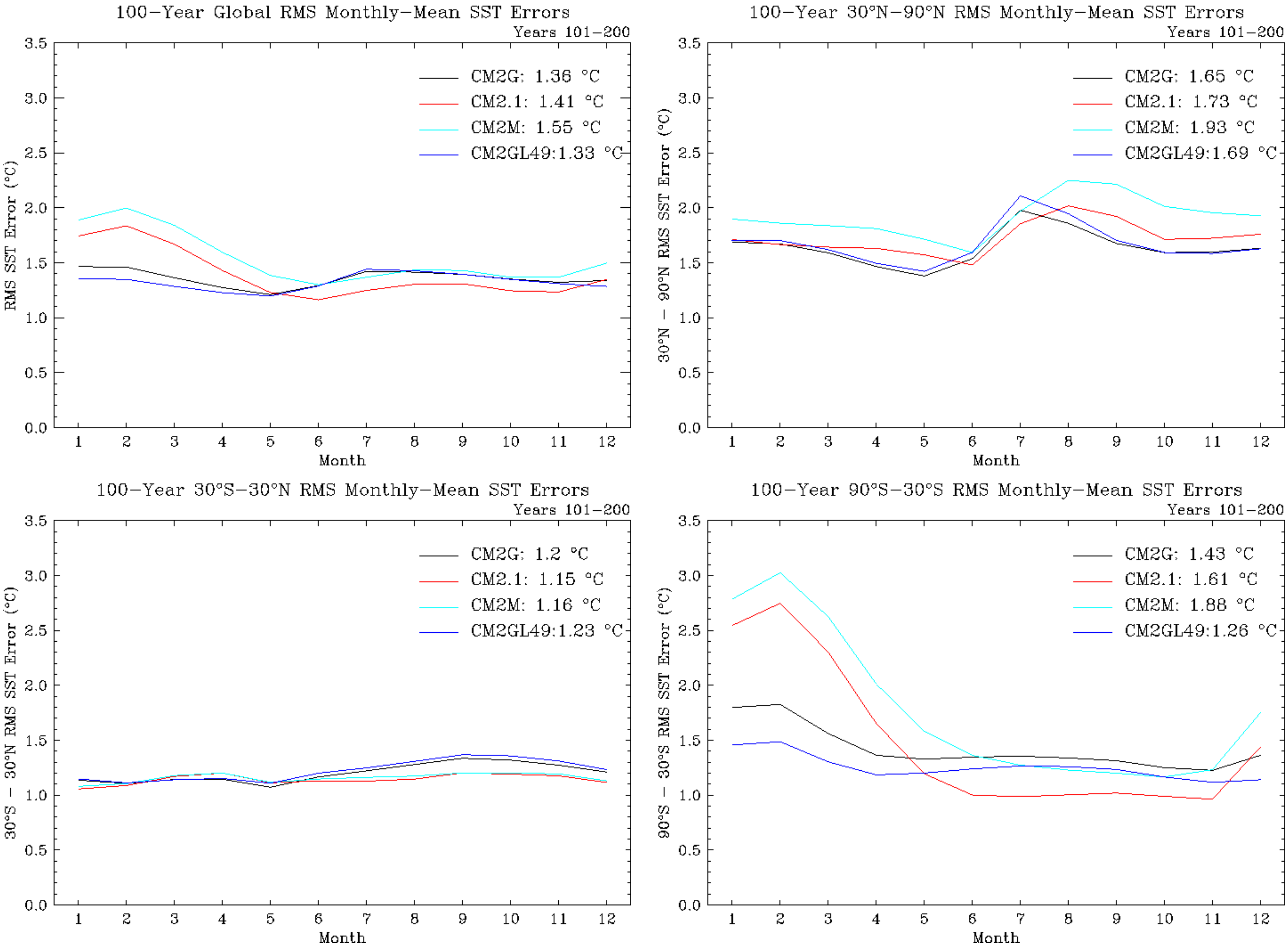
Why use 2 different ocean models to study climate?

- Z- and isopycnal models exhibit different inherent biases.
- The ocean observational record is short, sparse, aliased by eddies, and post-dates a statstically steady state.
- Great uncertainties exist in the ocean's long-term role.
- Biogeochemistry introduces even greater sensitivity to physical biases than does the physical state, along with even greater uncertainty about processes.

Using 2 ocean models gives the equivalent of binocular vision!

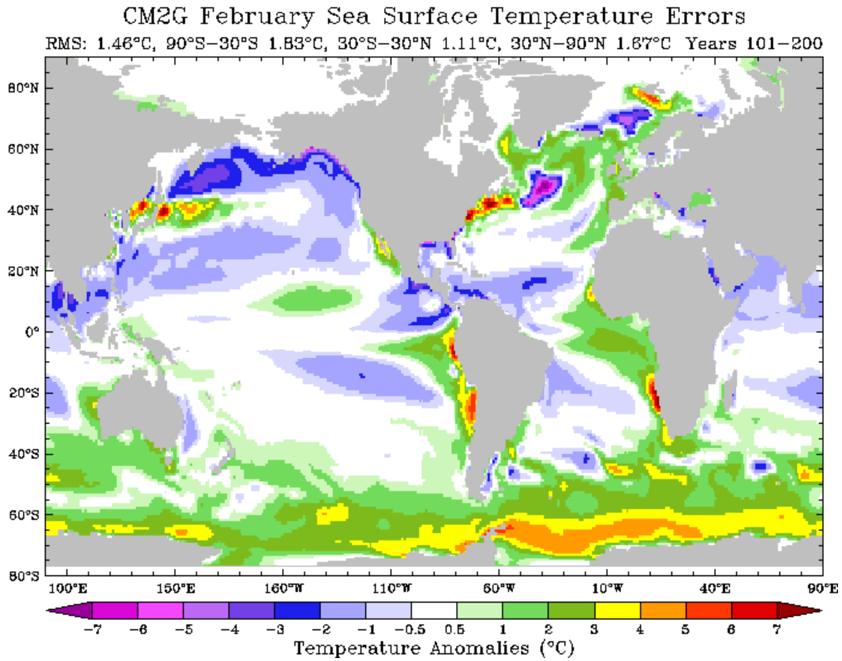
SURFACE PROPERTIES
SST, SSS, AND SEA-ICE

RMS Errors in Monthly SSTs

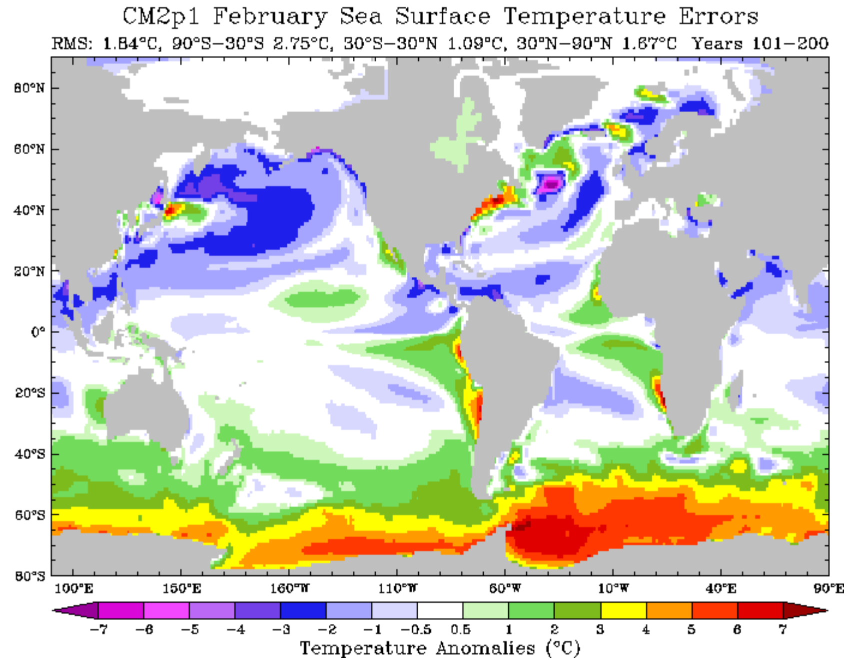


100-Year Mean February SST Errors

CM2G



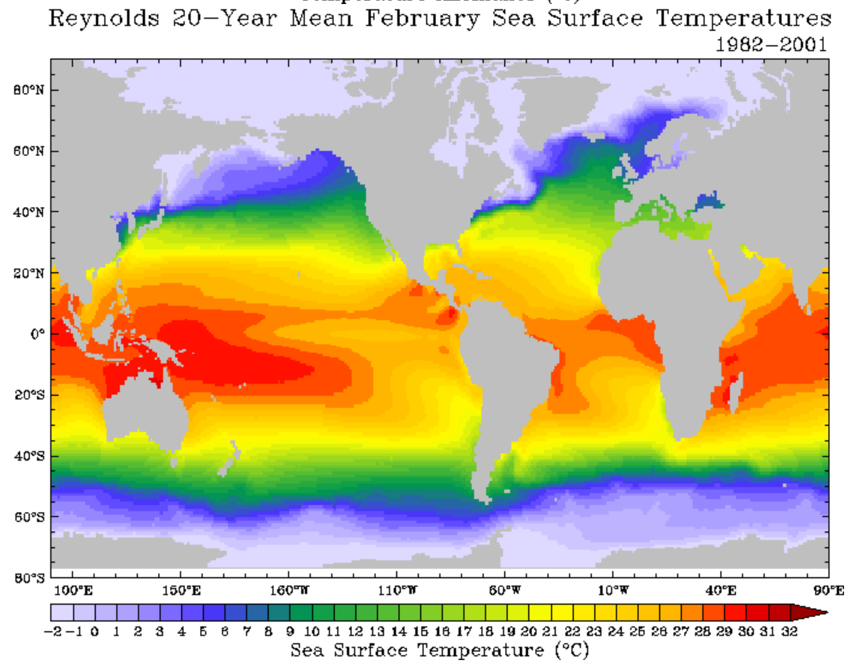
CM2.1



RMS February SST Errors:

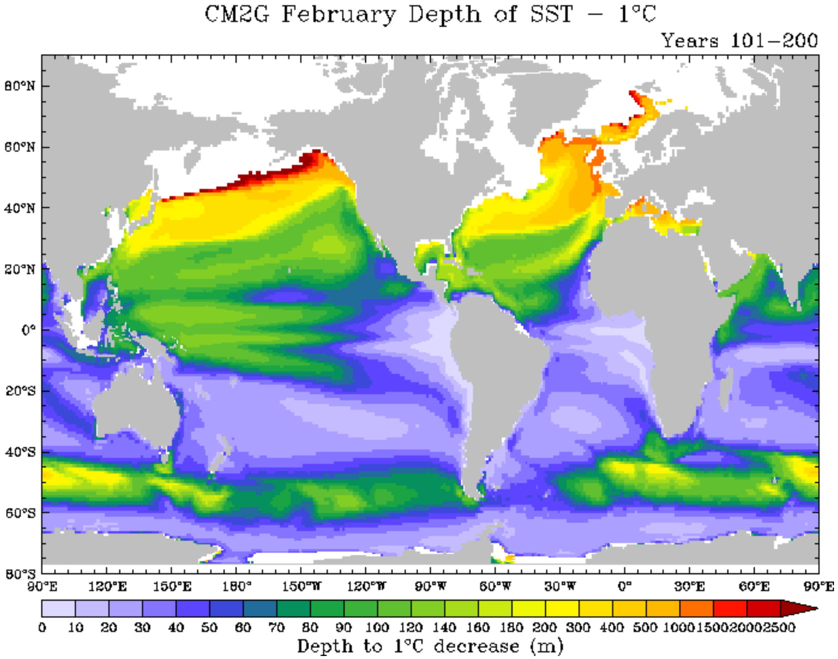
- CM2G 1.46°C
- CM2.1 1.84°C
- CM2M 2.00°C

Reynolds Climatology

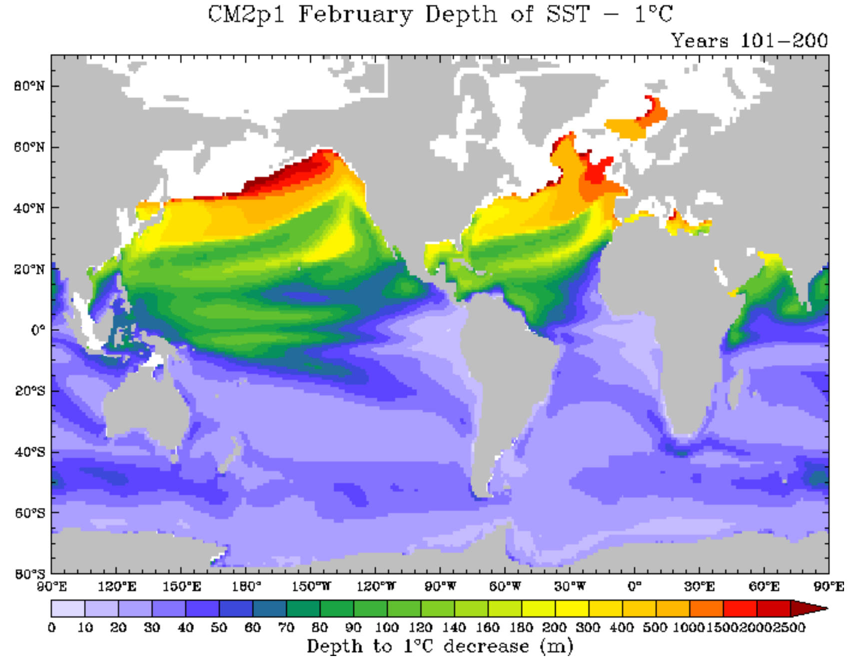


100-Year Mean February Depth to SST - 1°C

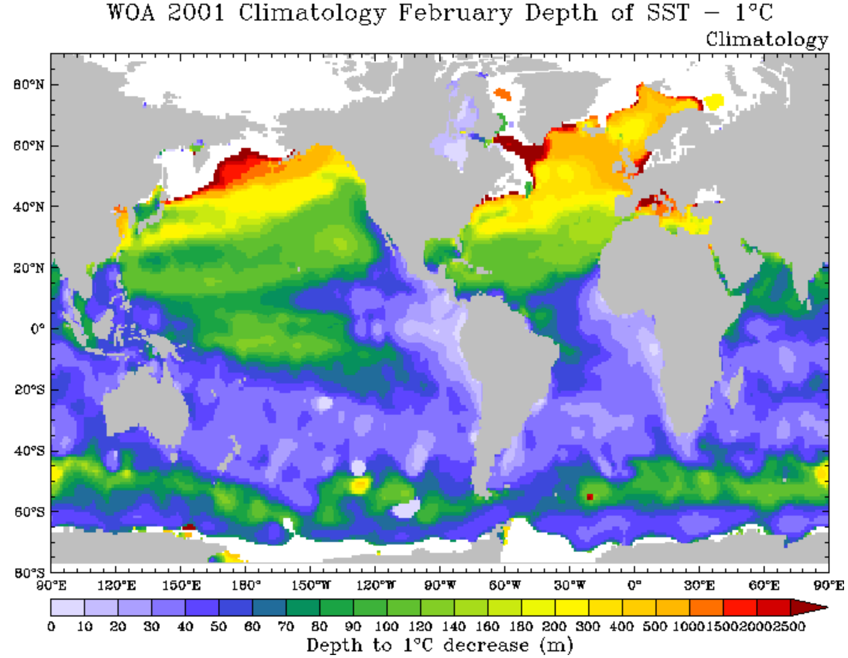
CM2G



CM2.1

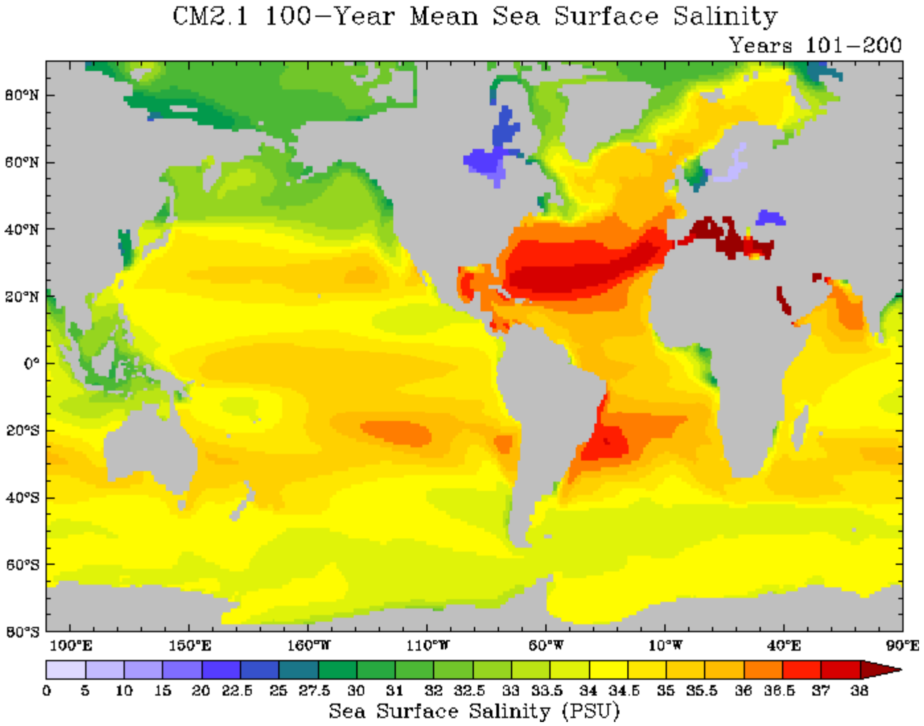


WOA2001 Climatology

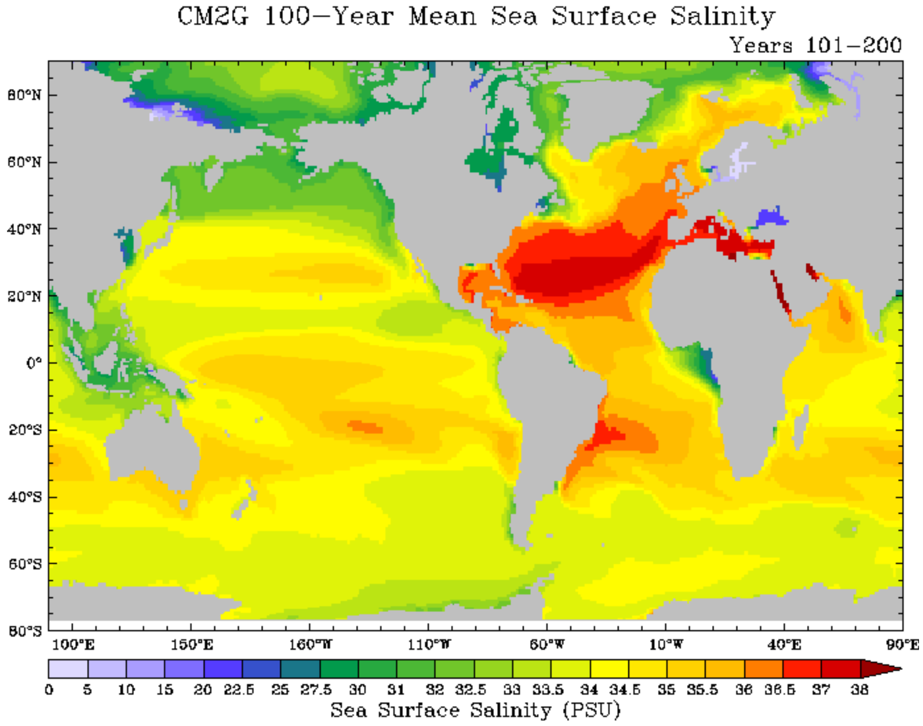


100-Year Mean Sea Surface Salinity

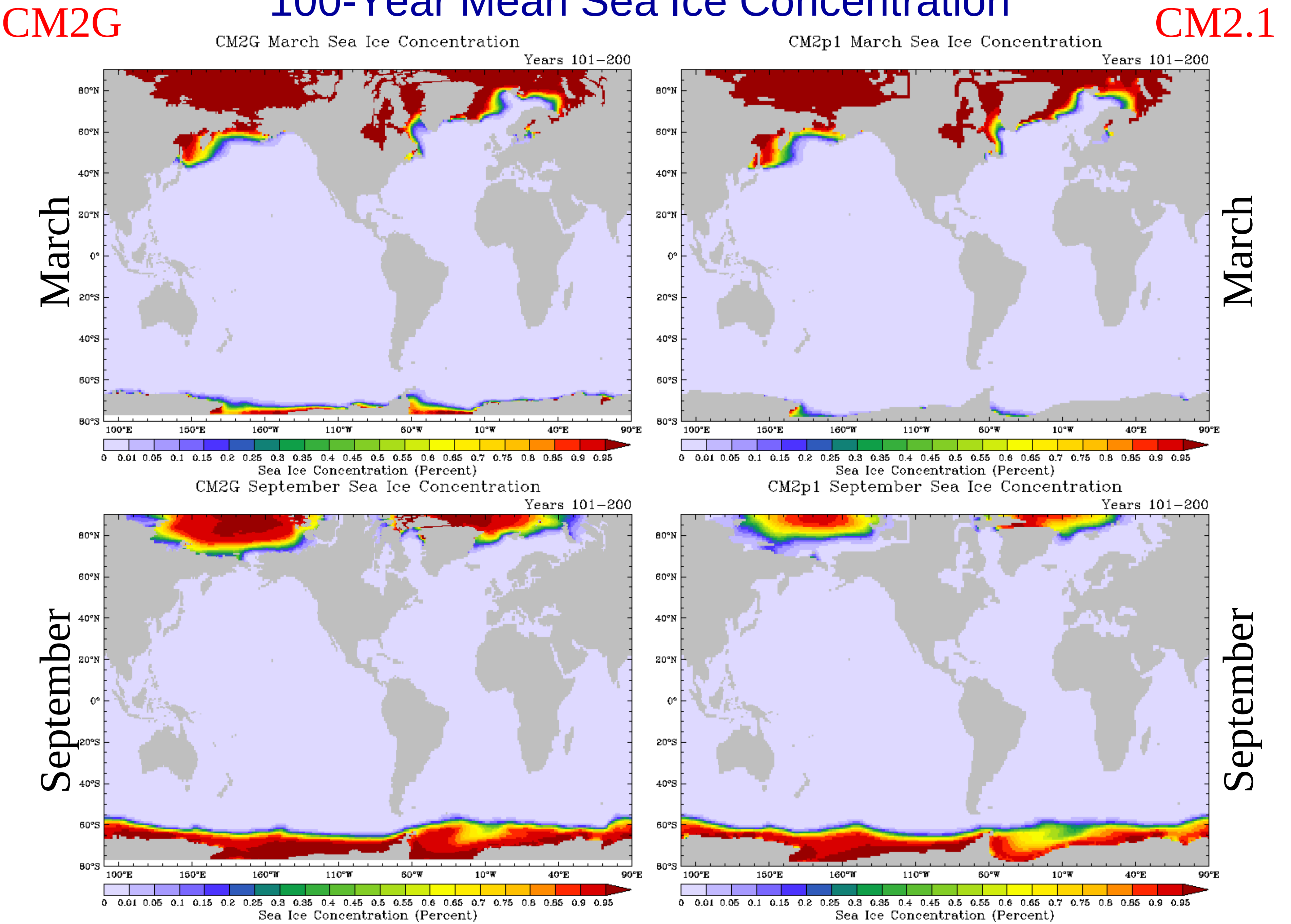
CM2.1



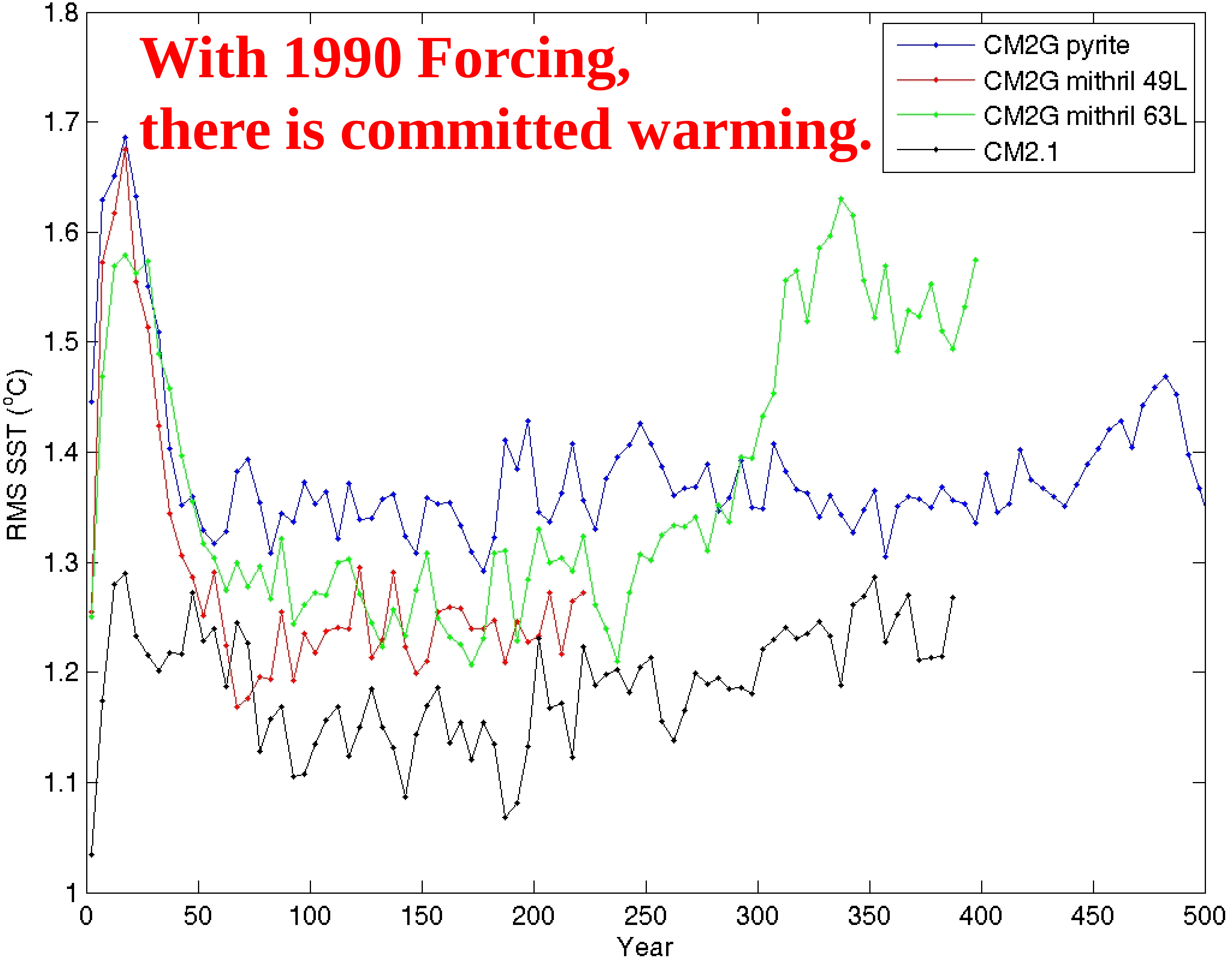
CM2G



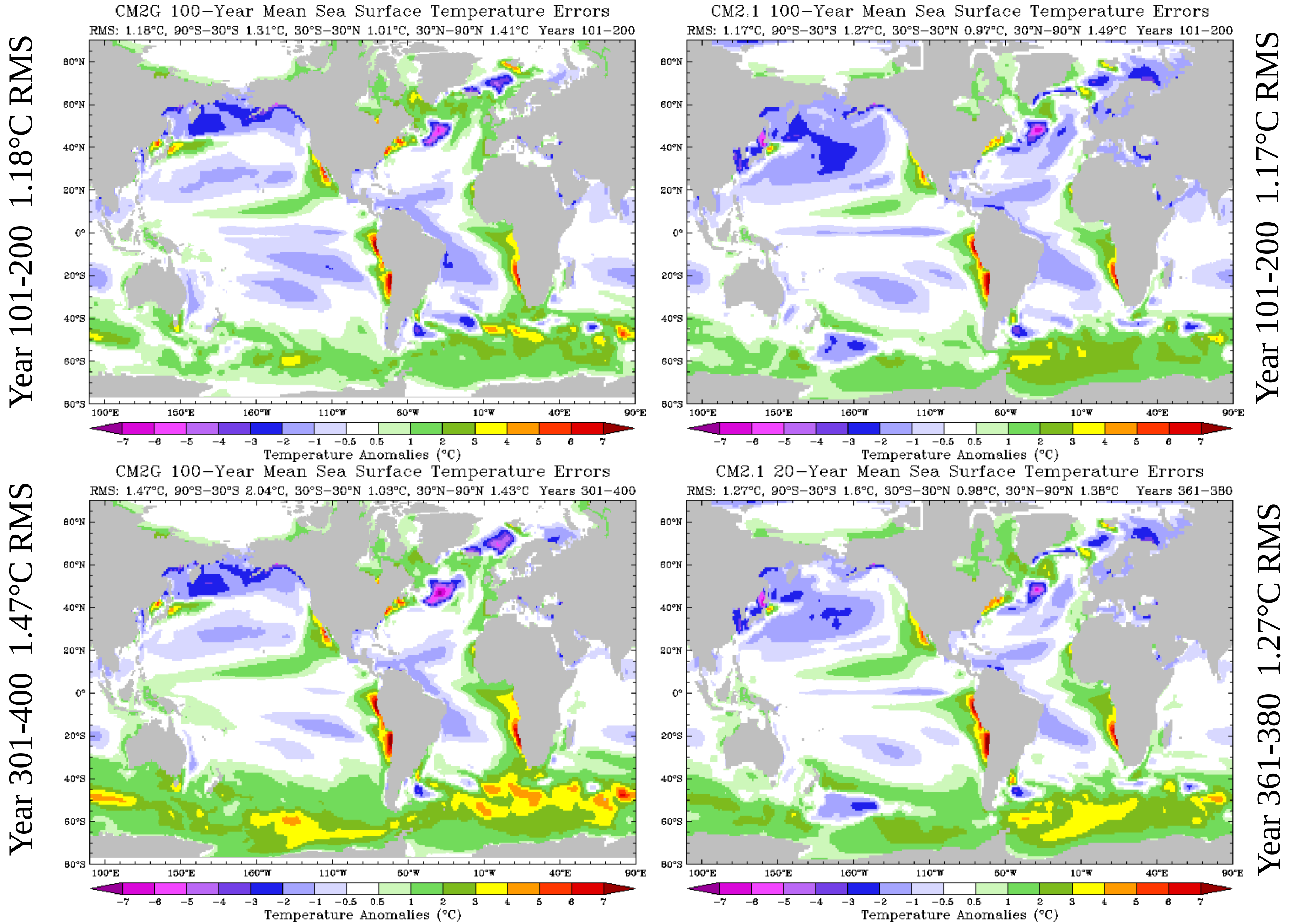
100-Year Mean Sea Ice Concentration



The RMS Annual-Mean SST Error



CM2G Long-term Evolution of Annual Mean SST Errors CM2.1

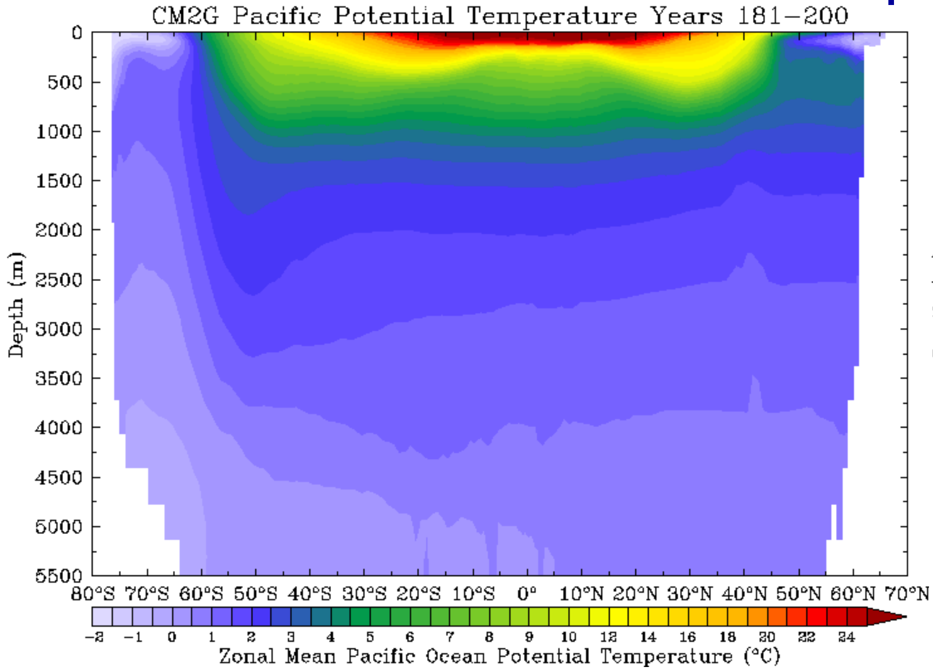


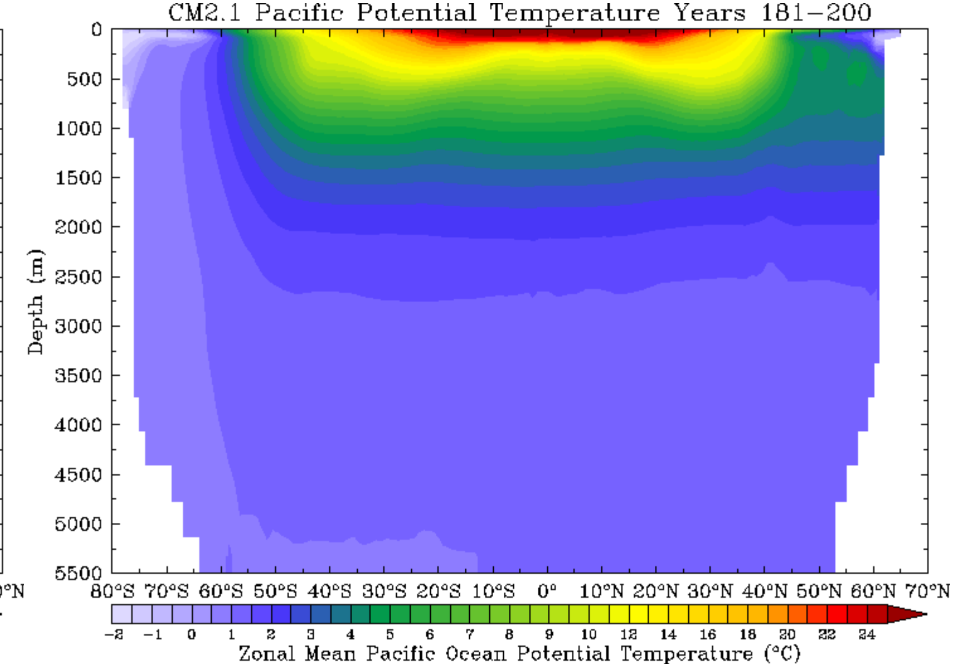
PACIFIC OCEAN

CM2G

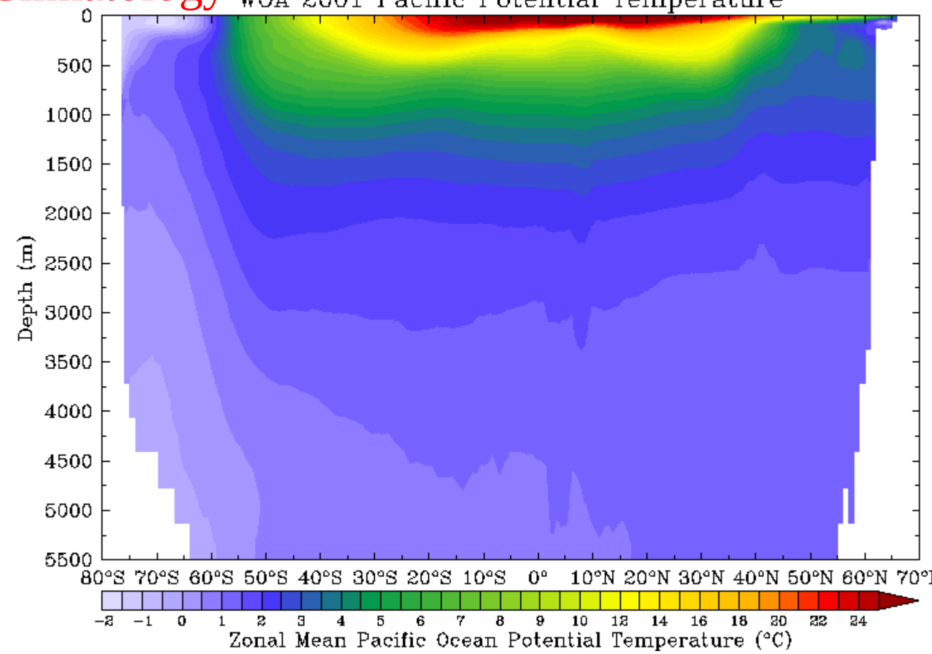
Pacific Ocean Temperatures, ~190 Years

CM2.1





Climatology

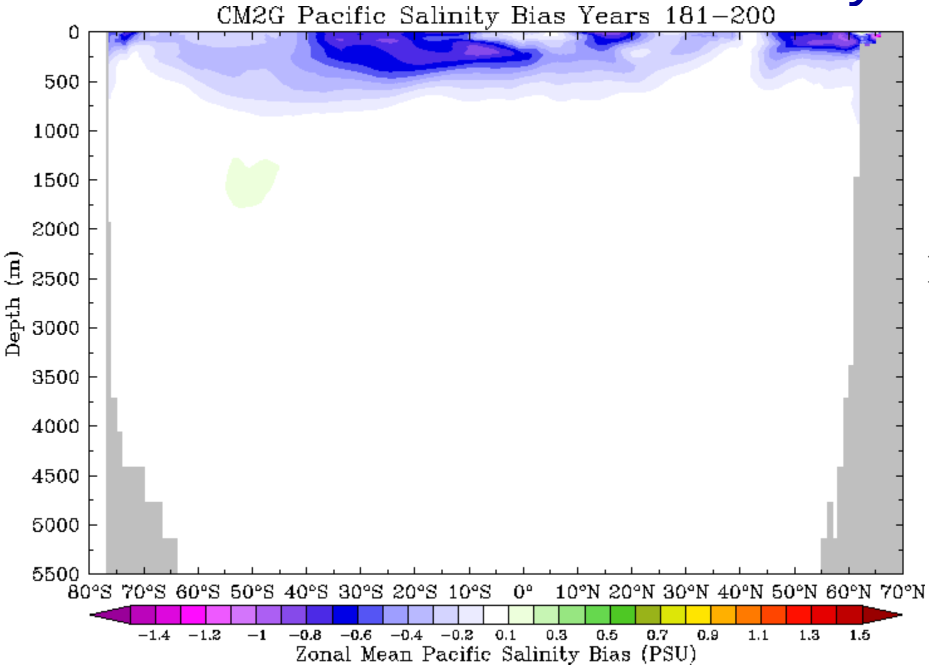


Zonal Mean Pacific Ocean Potential Temperatures

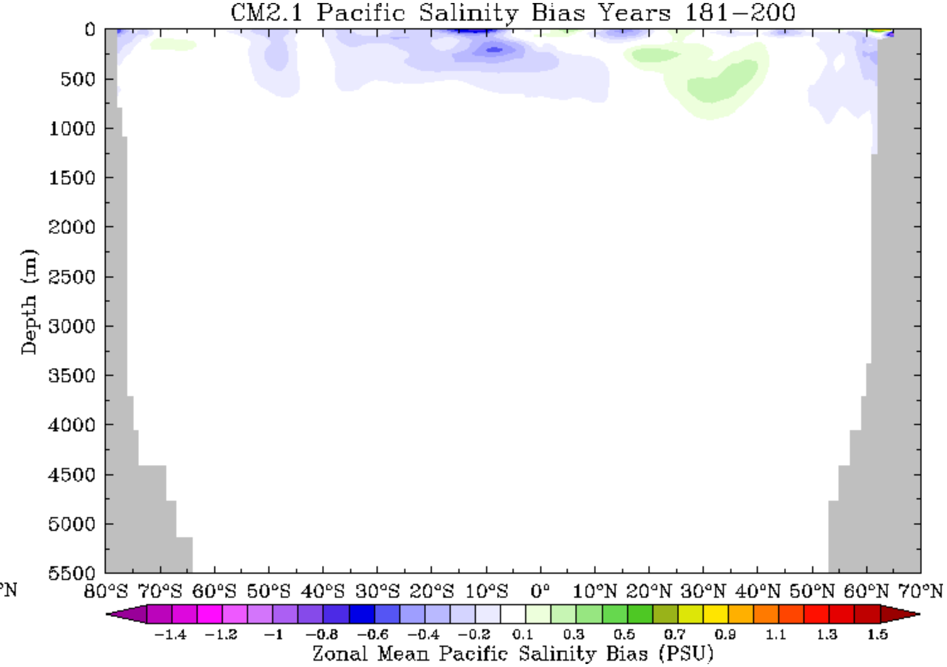
Average of Years 181-200

Pacific Salinity Bias, ~190 Years

CM2G63L



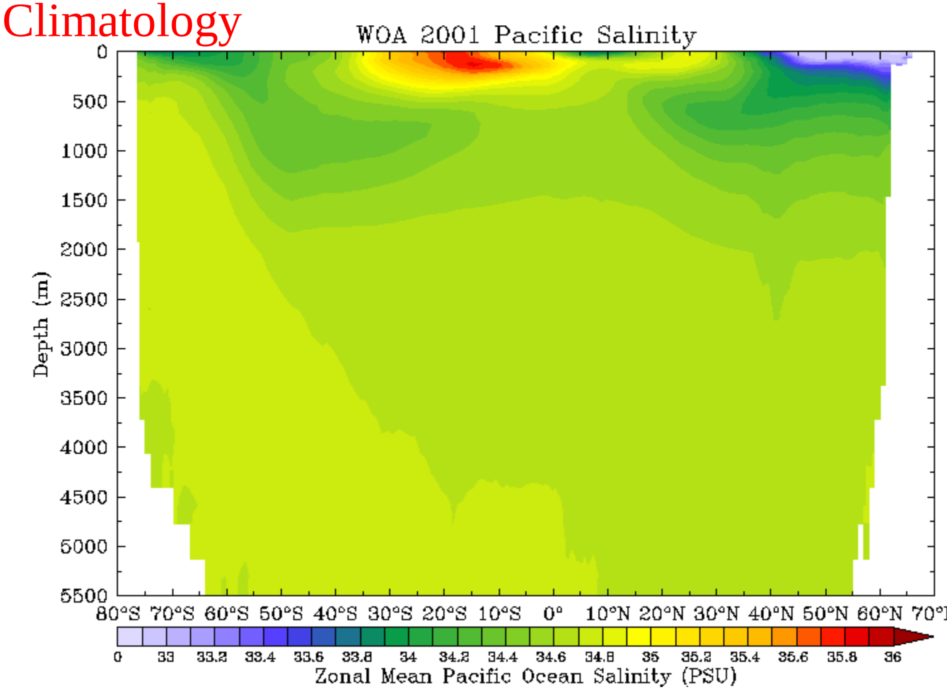
CM2.1



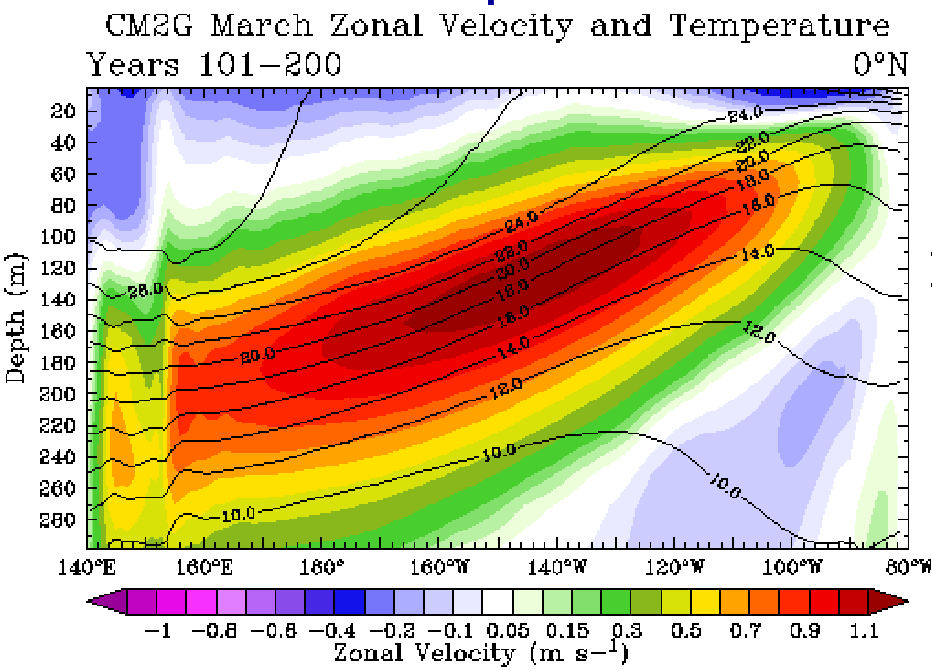
Zonal Mean Pacific Ocean Salinities

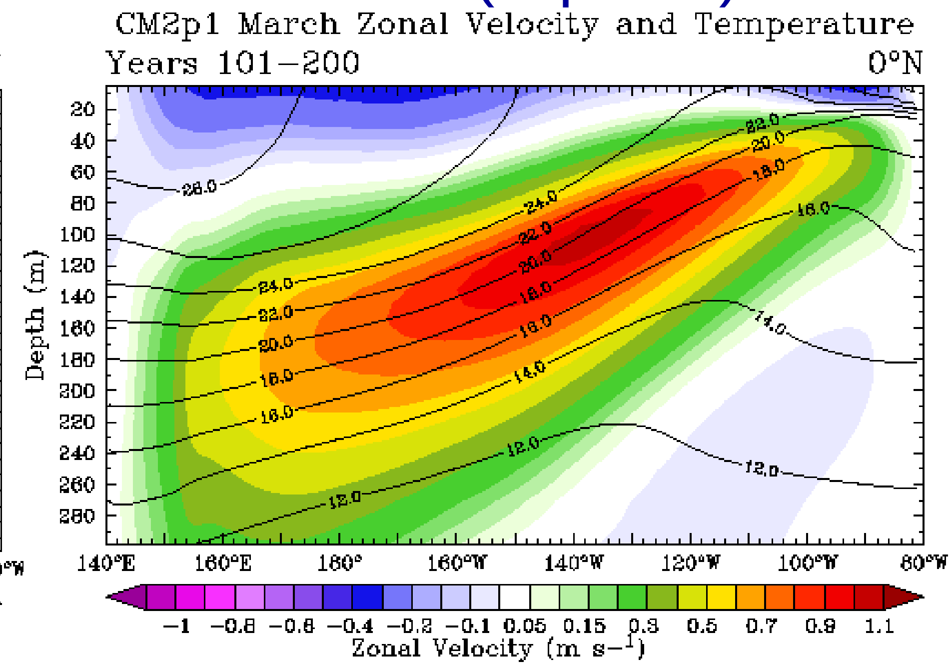
Average of Years 181-200

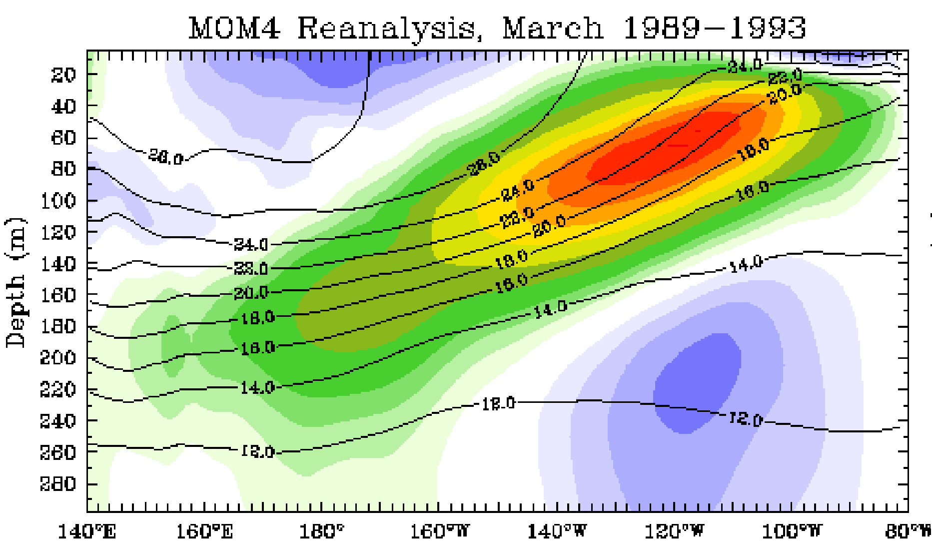
Climatology

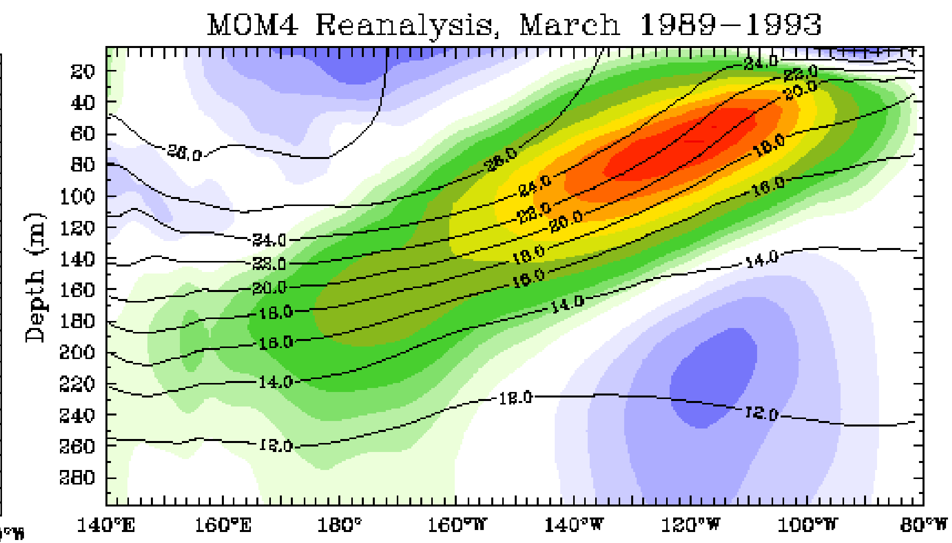


Pacific Equatorial Undercurrent in March (Equator)

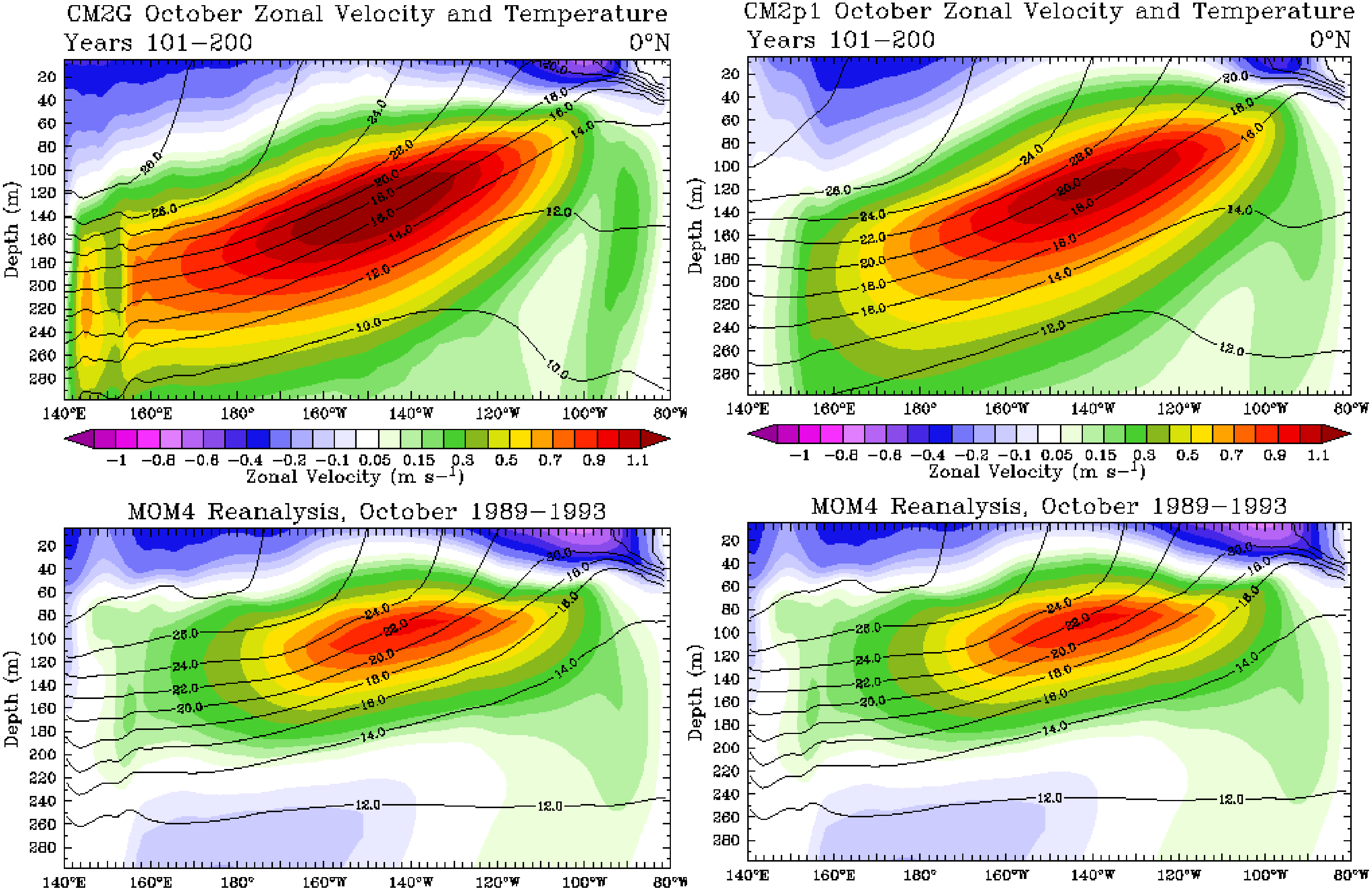




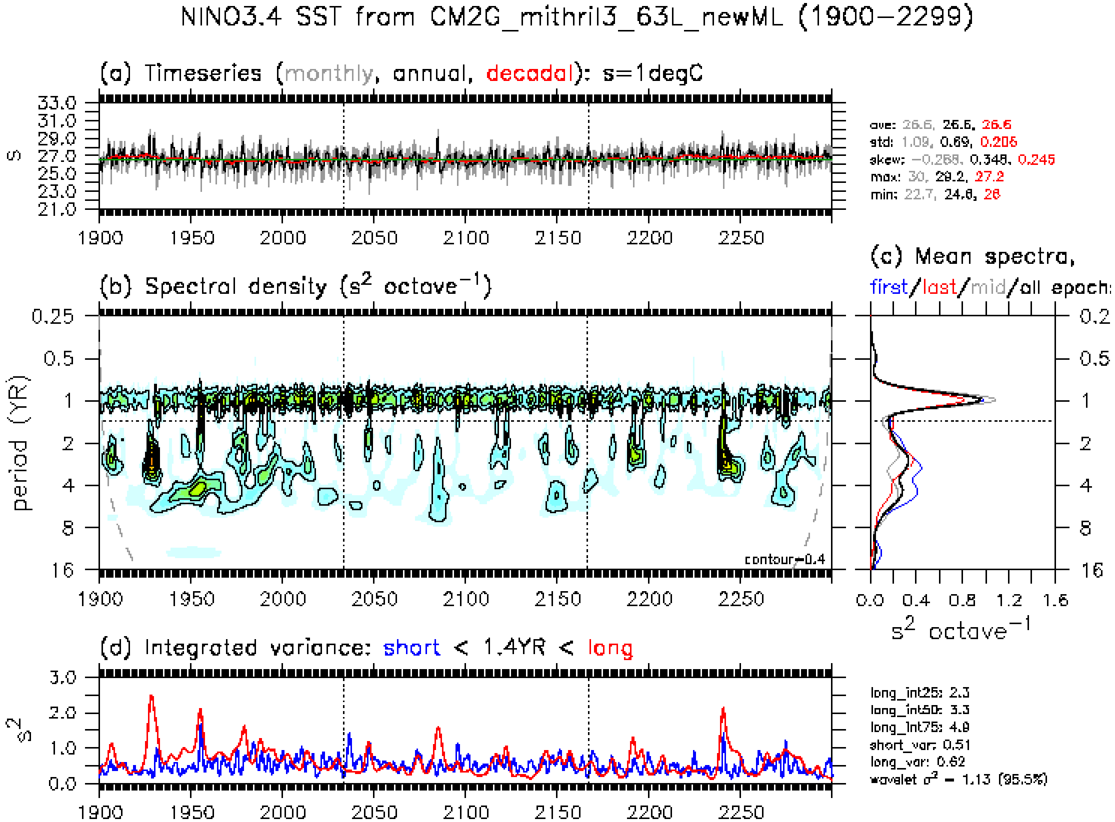


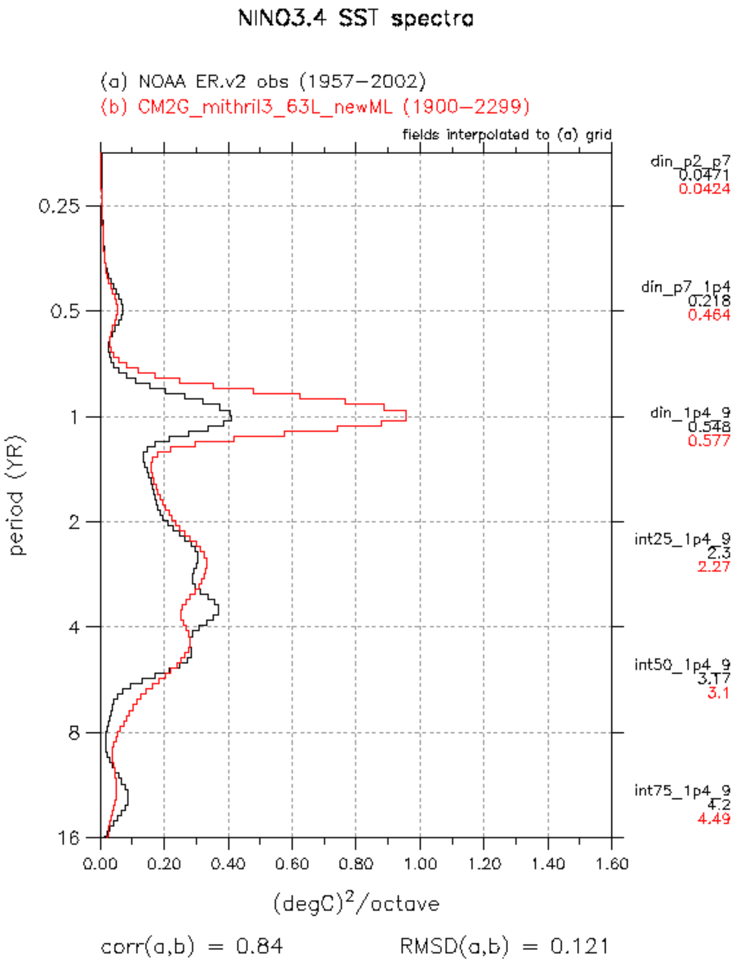


Pacific Equatorial Undercurrent in October (Equator)



ENSO Statistics for CM2G



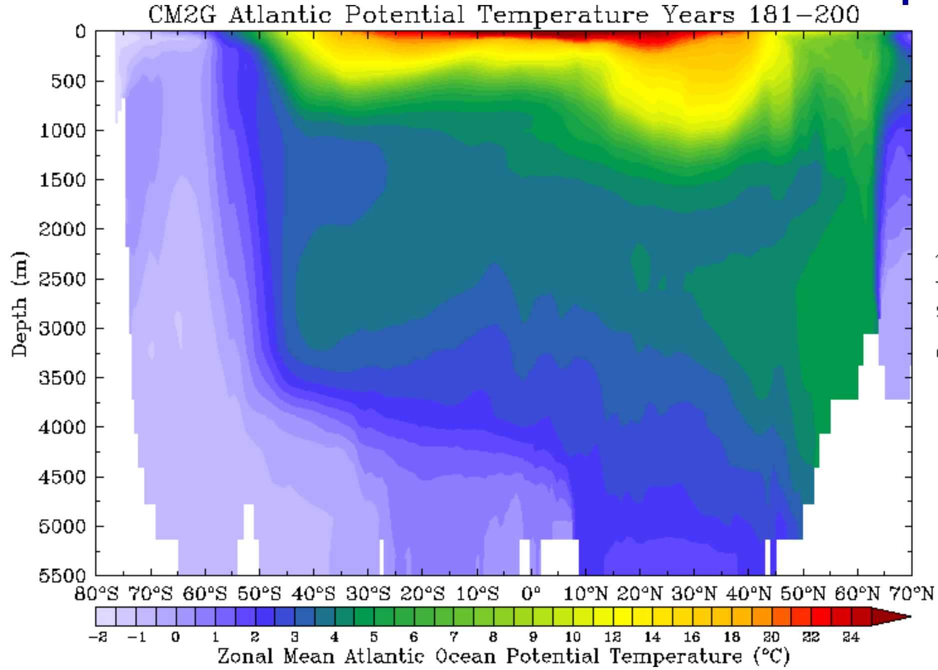


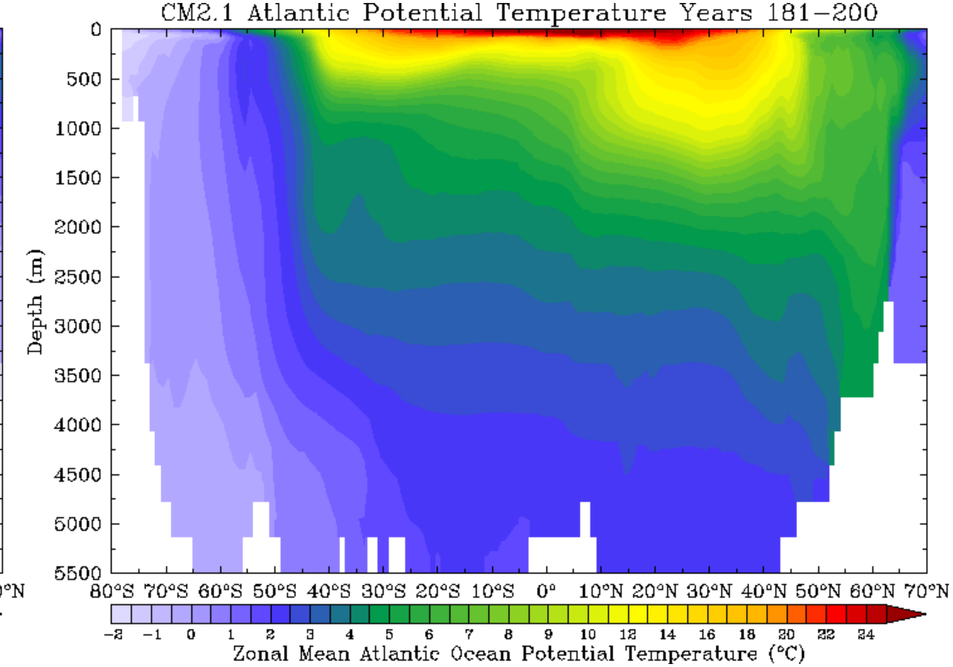
ATLANTIC OCEAN

CM2G

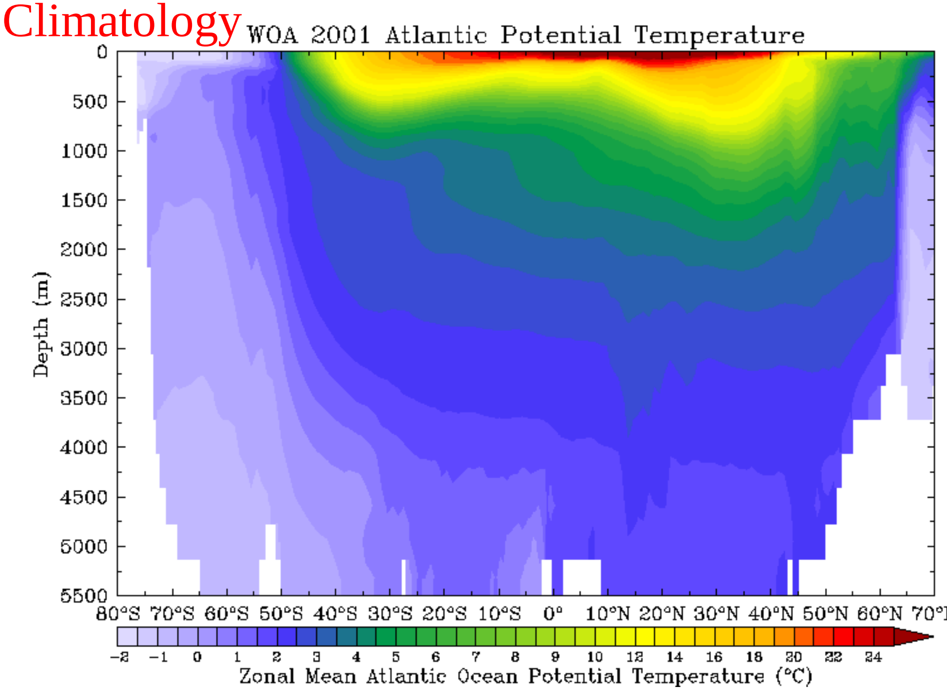
Atlantic Ocean Temperatures, ~190 Years

CM2.1





Climatology



Zonal Mean Atlantic Ocean Potential Temperatures

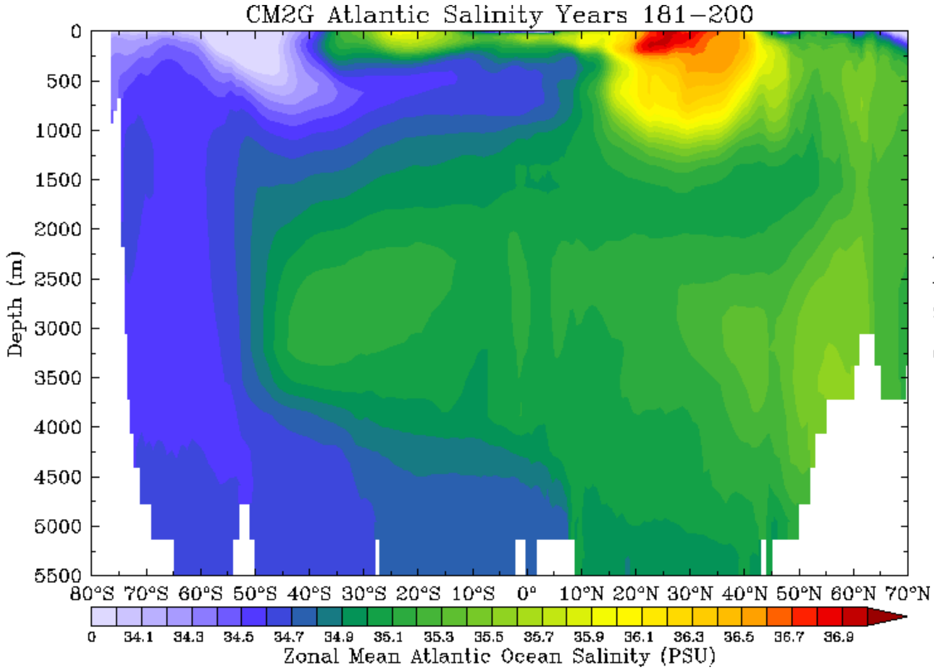
Average of Years 181-200

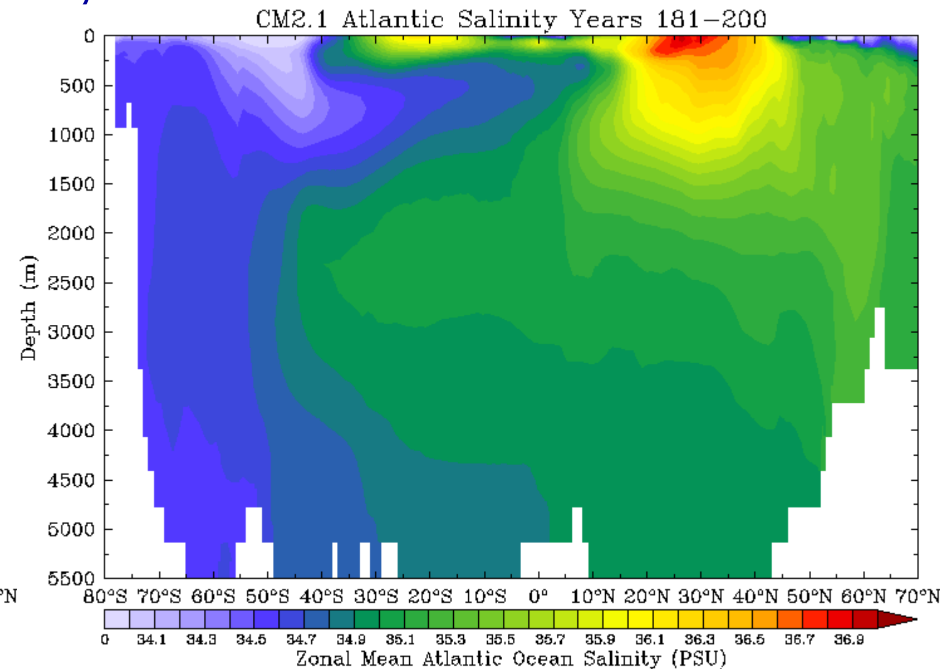
Excludes most marginal seas

CM2G

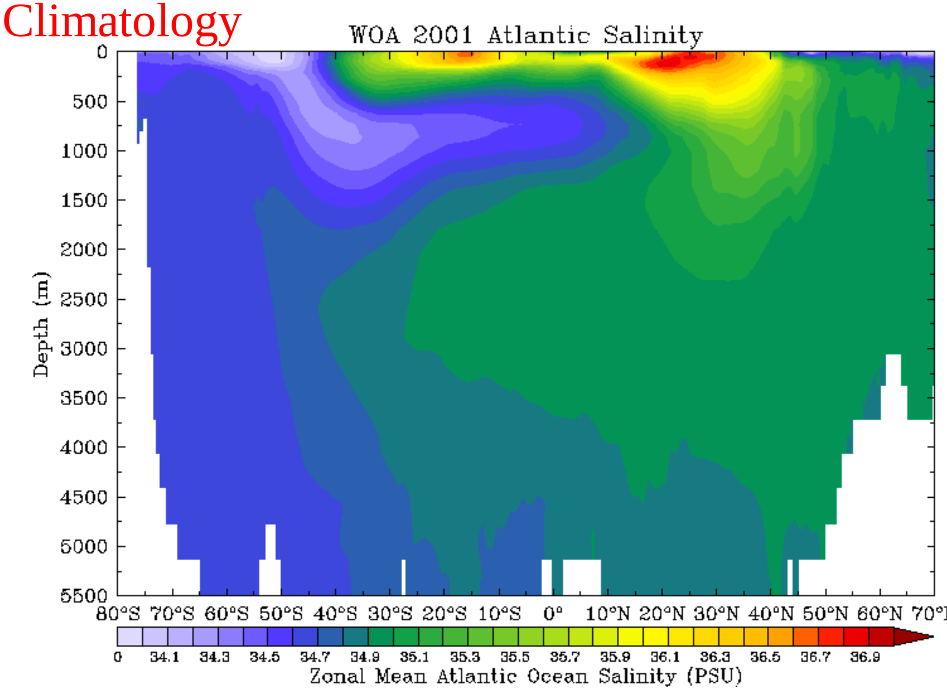
Atlantic Salinities, ~190 Years

CM2.1





Climatology



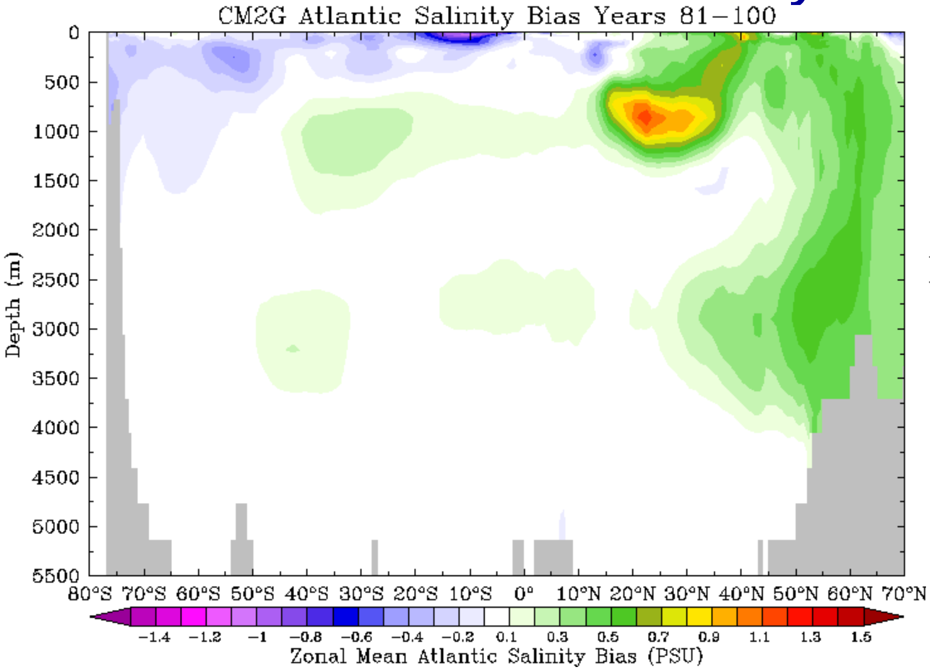
Zonal Mean Atlantic Ocean Salinity

Average of Years 181-200

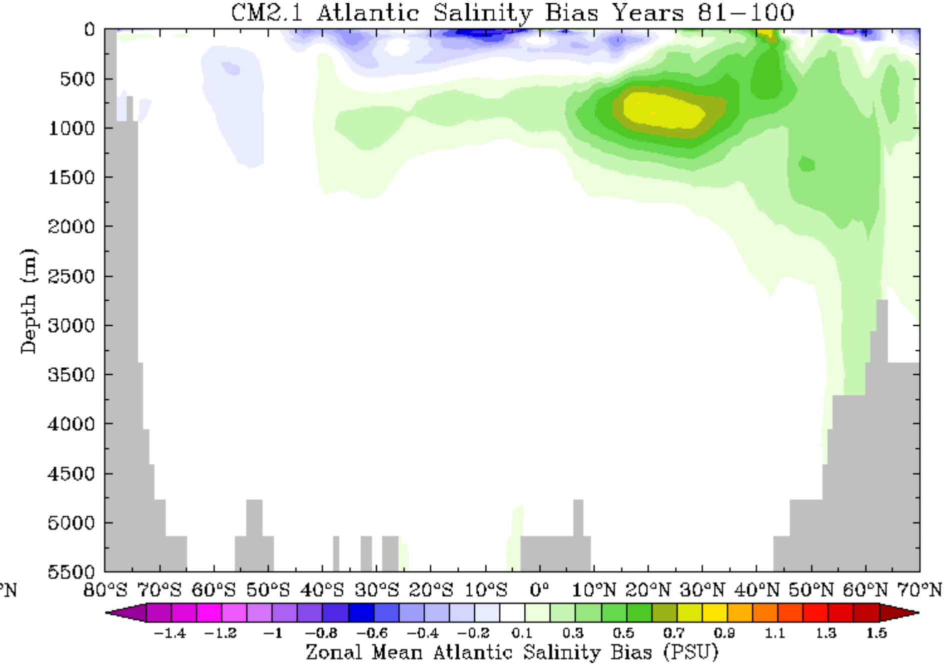
Excludes most marginal seas

Atlantic Salinity Anomalies, ~90 Years

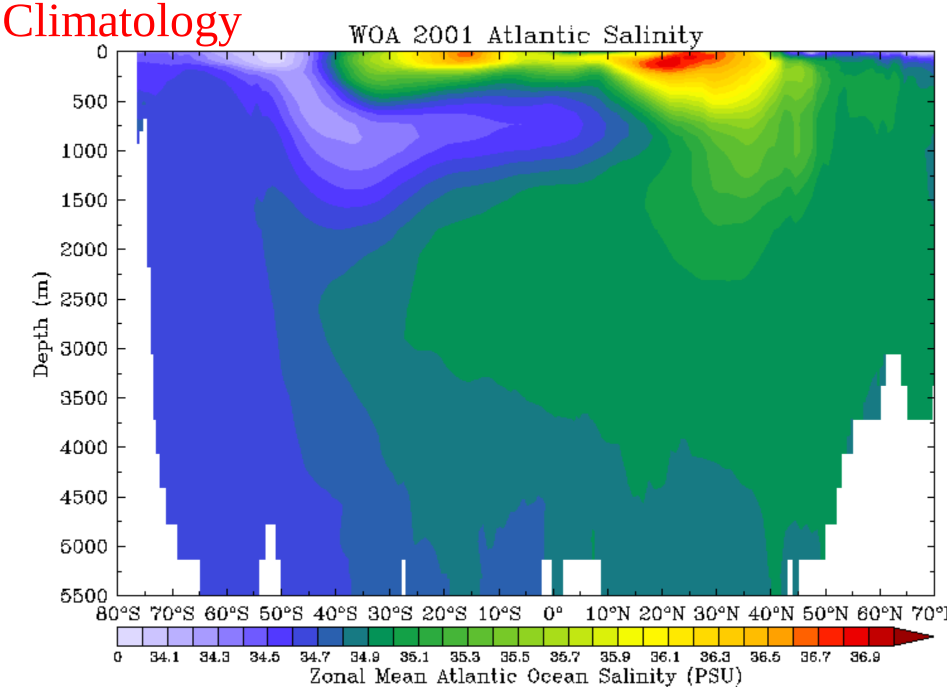
CM2G



CM2.1



Climatology



Zonal Mean Atlantic Ocean Salinity

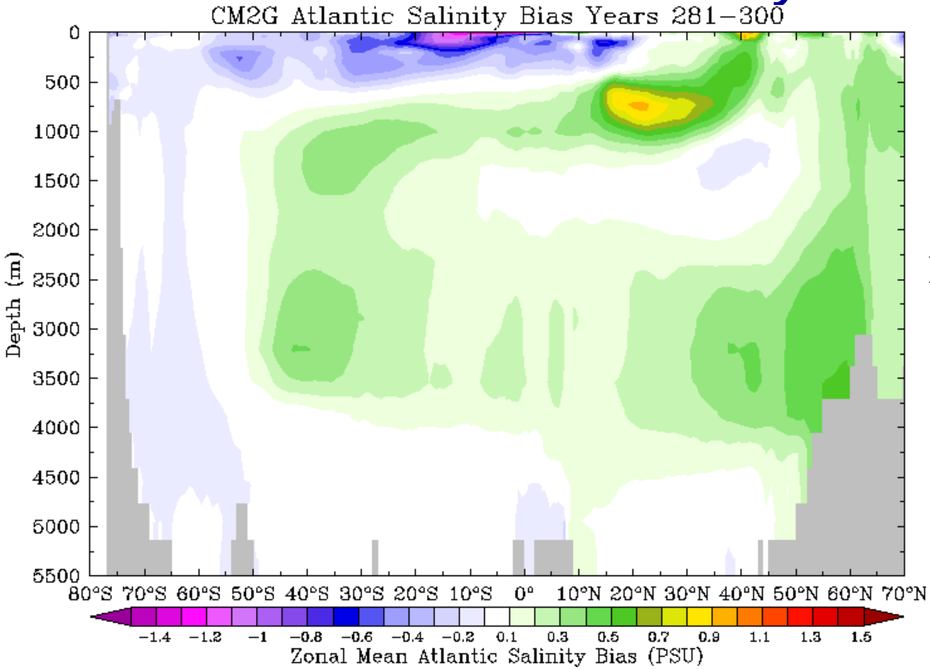
Average of Years 81-100

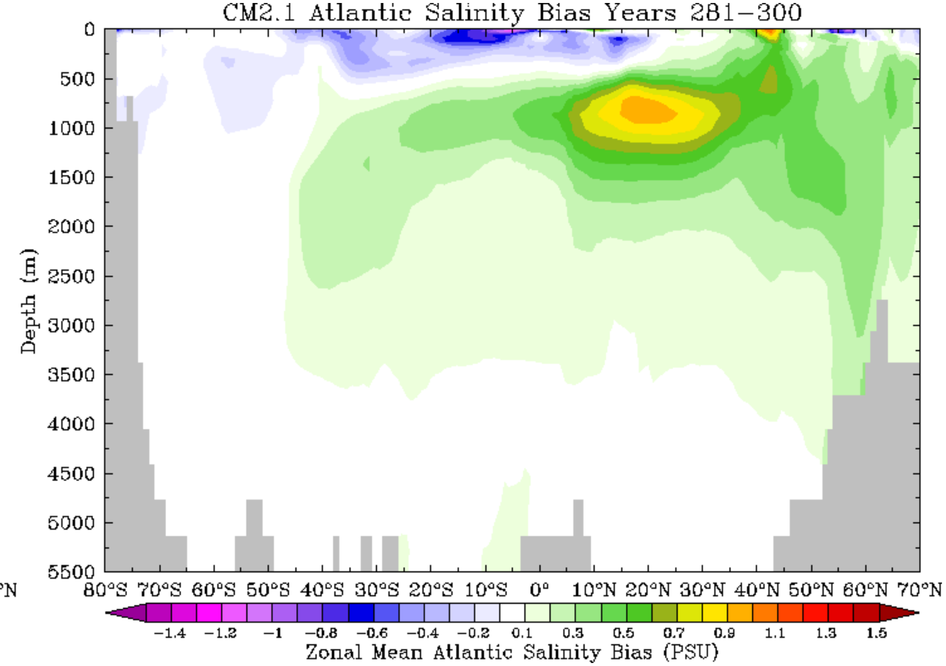
Excludes most marginal seas

CM2G

Atlantic Salinity Anomalies, ~290 Years

CM2.1





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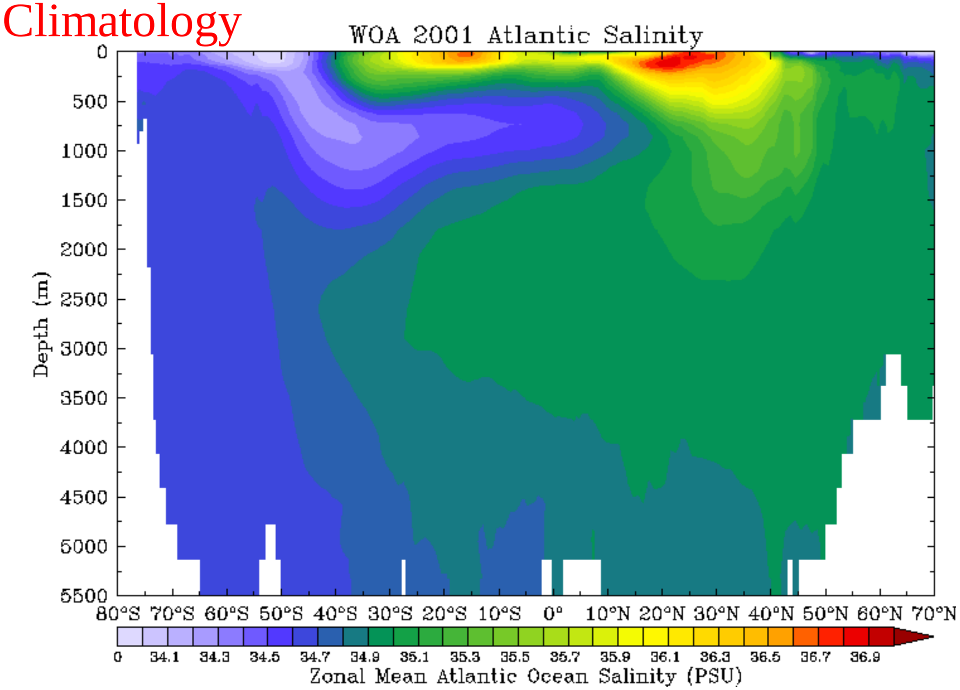


Zonal Mean Atlantic Ocean Salinity

Average of Years 281-300

Excludes most marginal seas

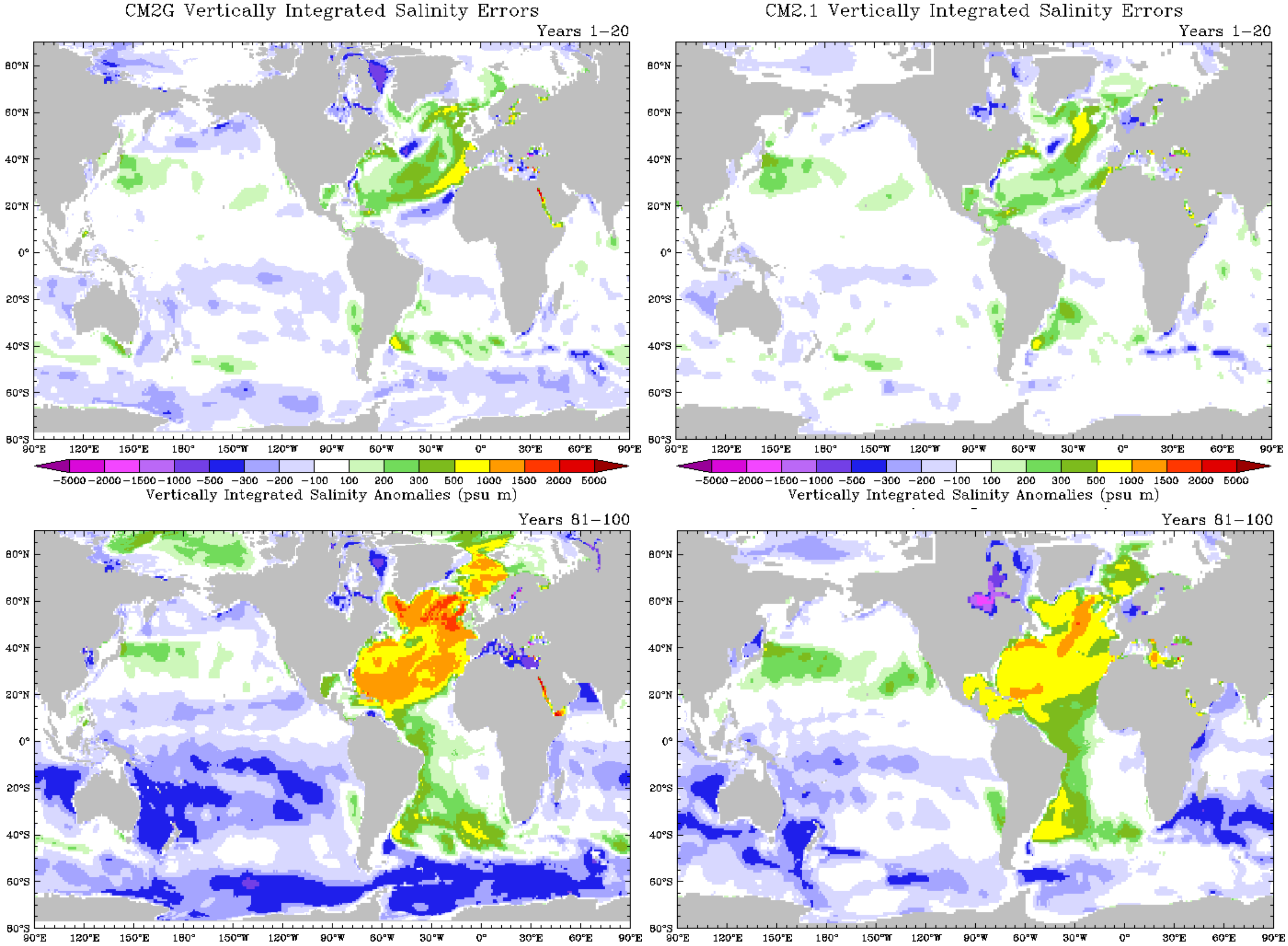
CM2G

Vertically Integrated Salinity Errors

CM2.1

10 Yrs

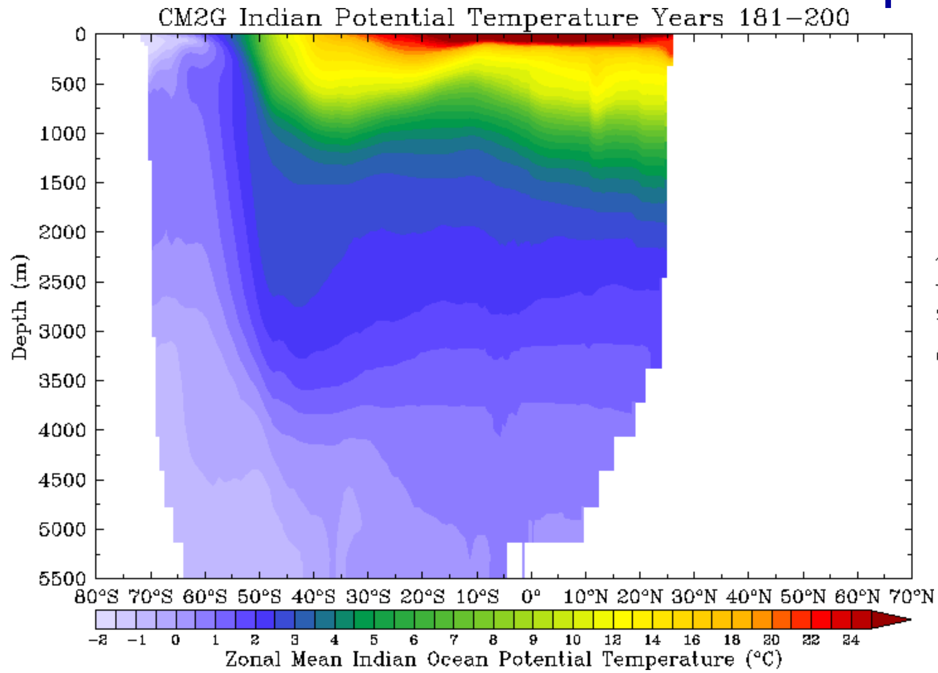
90 Yrs



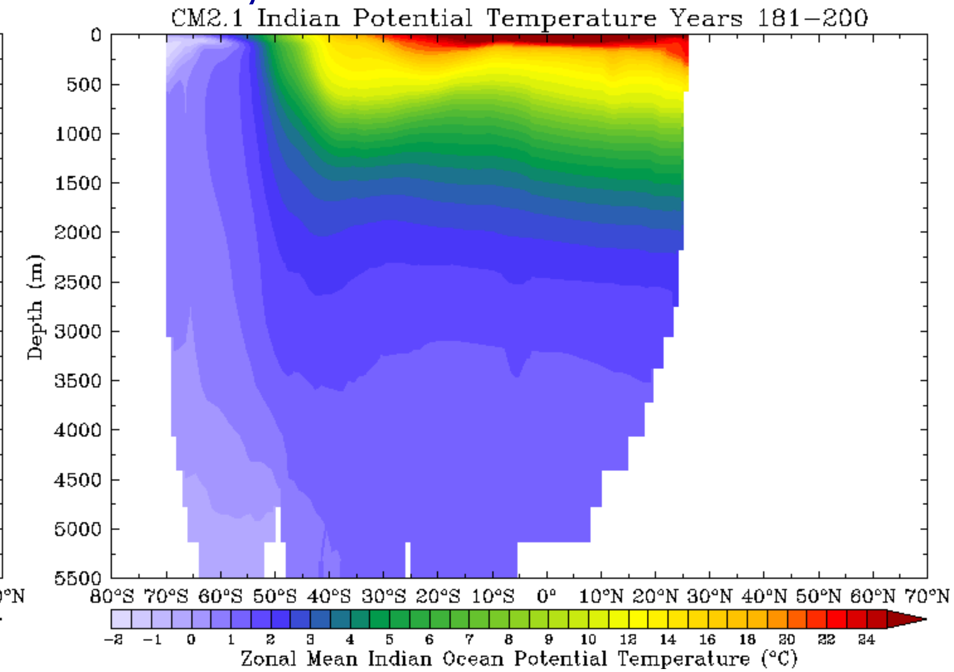
INDIAN OCEAN

Indian Ocean Temperatures, ~190 Years

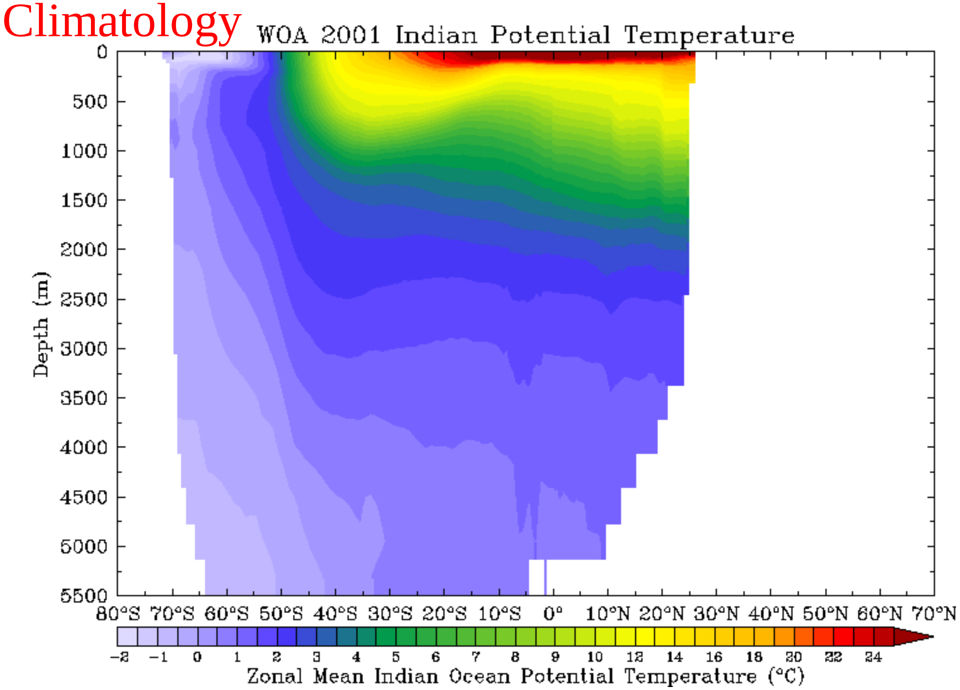
CM2G



CM2.1



Climatology

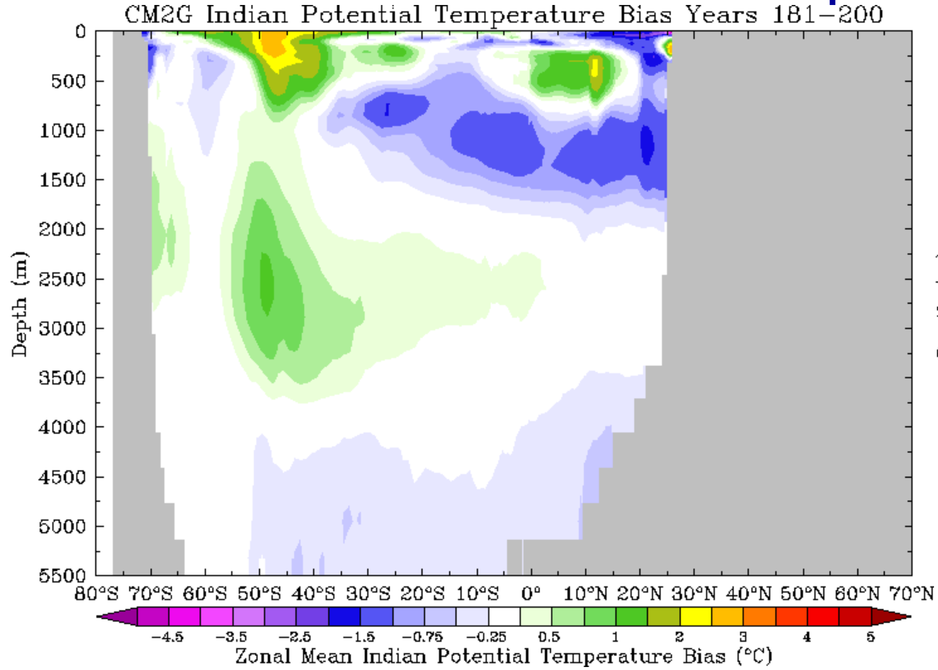


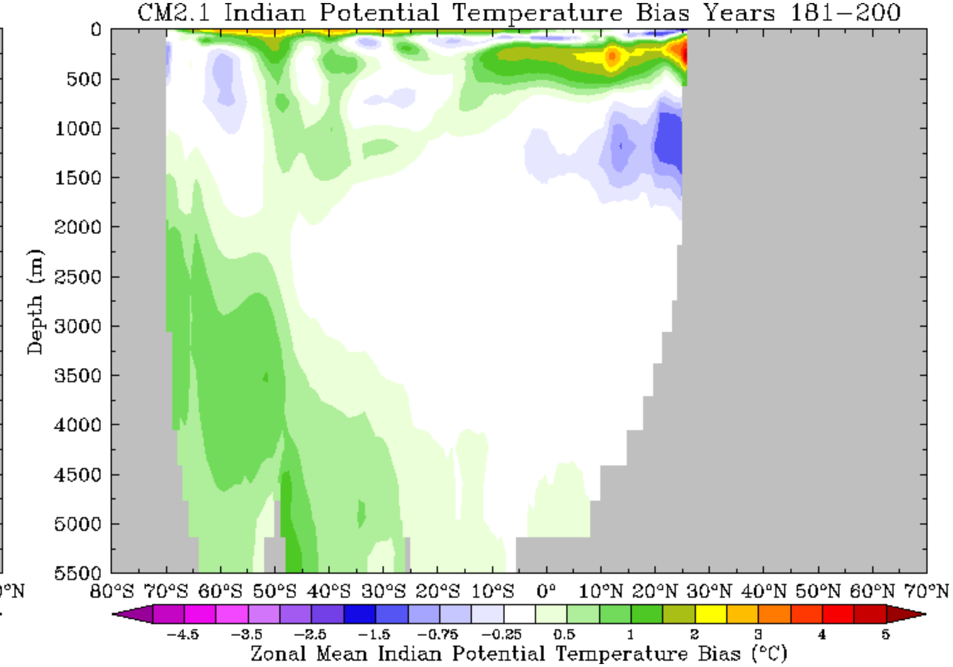
Zonal Mean Indian Ocean Potential Temperatures

Average of Years 181-200

Excludes most marginal seas

CM2G Indian Ocean Temperature Bias, ~190 Years CM2.1





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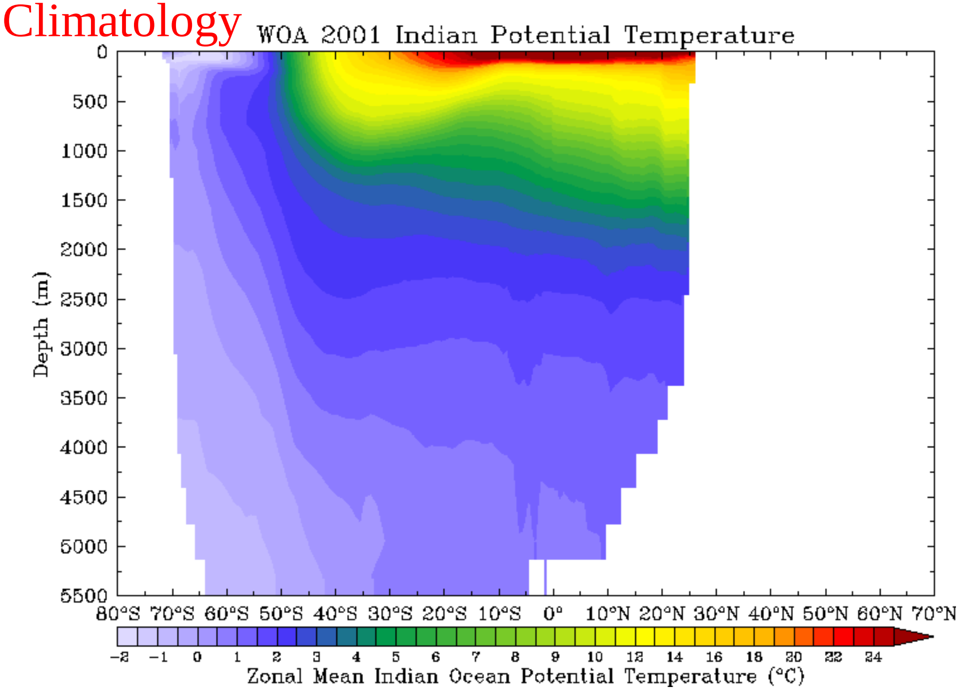


Zonal Mean Indian Ocean Potential Temperatures

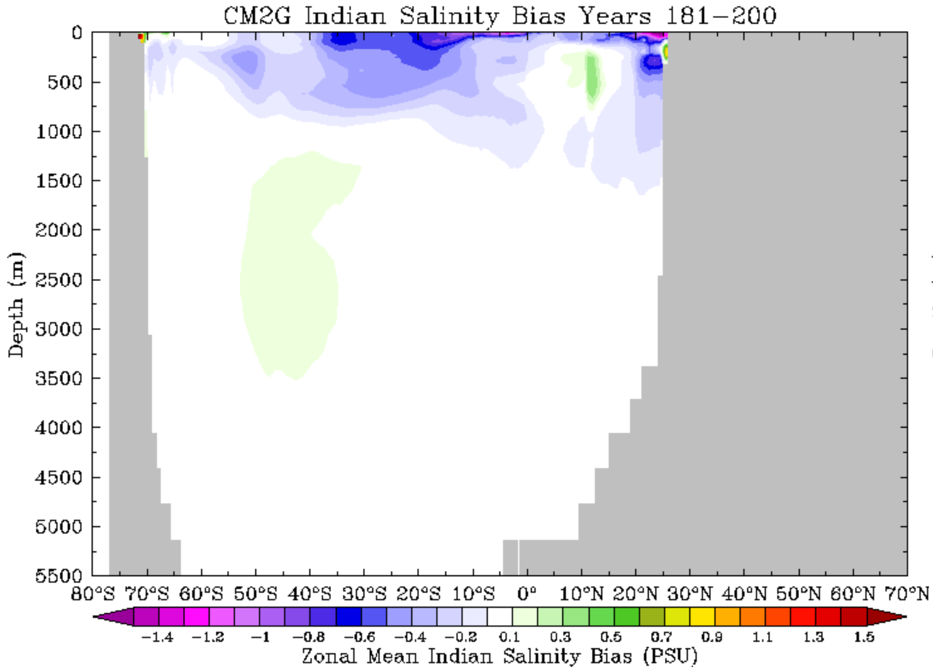
Average of Years 181-200

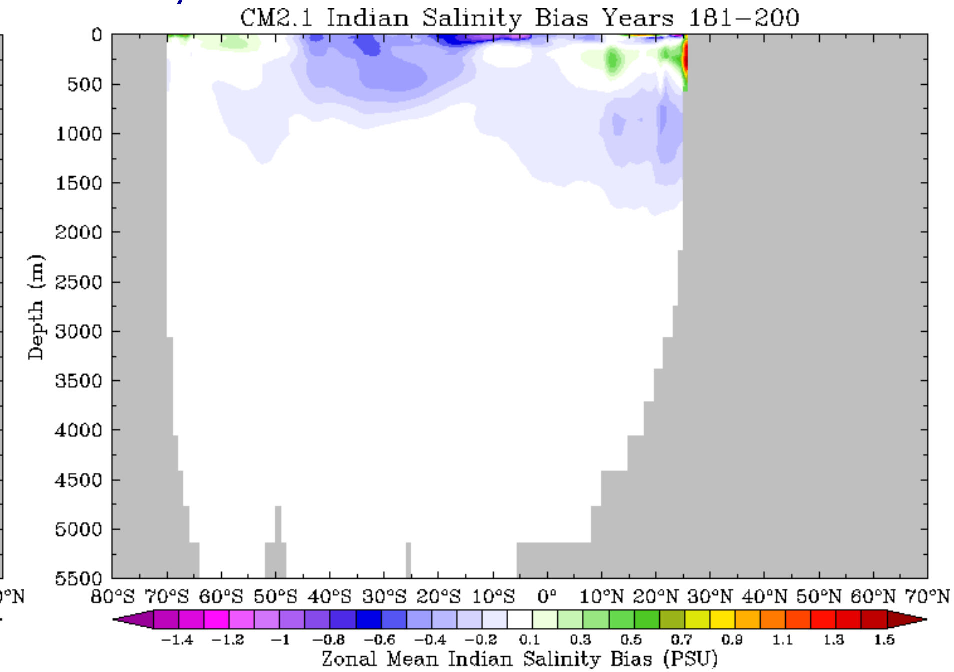
Excludes most marginal seas

CM2G

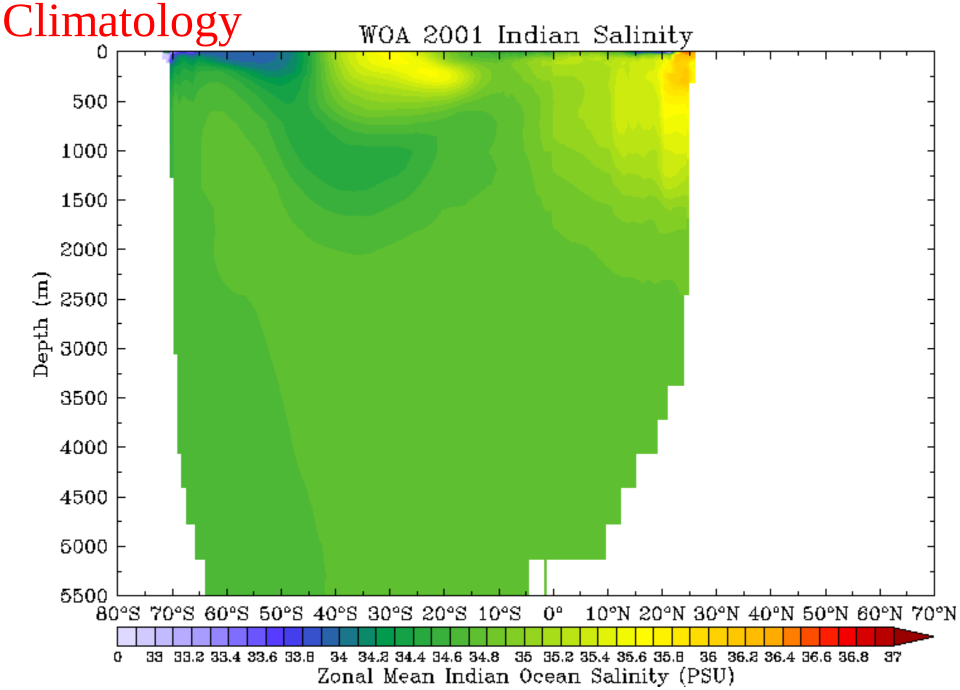
Indian Ocean Salinities, ~190 Years

CM2.1





Climatology



Zonal Mean Indian Ocean Salinity

Average of Years 181-200

Excludes most marginal seas

OVERFLOWS & EXCHANGES

Resolution requirements for avoiding numerical entrainment in descending gravity currents.

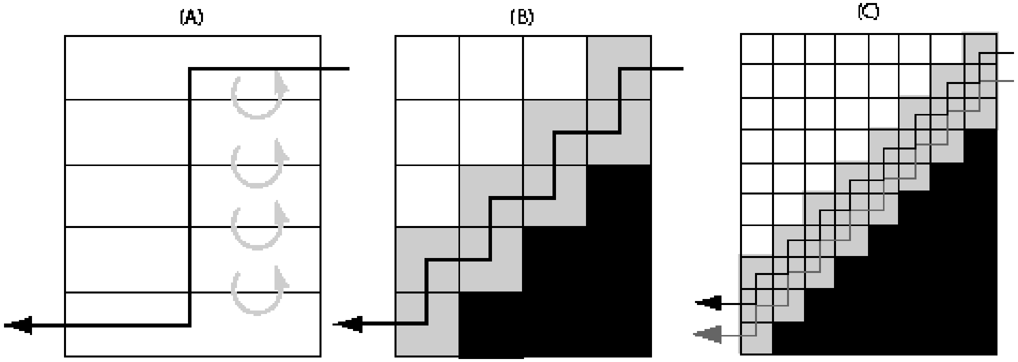
Z-coordinate:

Require that $(\Delta z < H_{BBL}/2 \approx 50m)$

AND $(\Delta x < H_{BBL}/2\alpha \approx 5km)$

to avoid numerical entrainment.

(Winton, et al., JPO 1998)



Many suggested solutions for Z-coordinate models:

- "Plumbing" parameterization of downslope flow:
  Beckman & Döscher (JPO 1997), Campin & Goose (Tellus 1999).
- Adding a separate, resolved, terrain-following boundary layer:
  Gnanadesikan (~1998), Killworth & Edwards (JPO 1999), Song & Chao (JAOT 2000).
- Add a nested high-resolution model in key locations?

Sigma-coordinate: Avoiding entrainment requires that $(\Delta\sigma D_{Ocean} < H_{BBL})$

But hydrostatic consistency requires $(\Delta x <\sim 3\Delta\sigma D_{Ocean}/\alpha)$ $(\Delta x <\sim 3H_{BBL}/\alpha \approx 30km)$

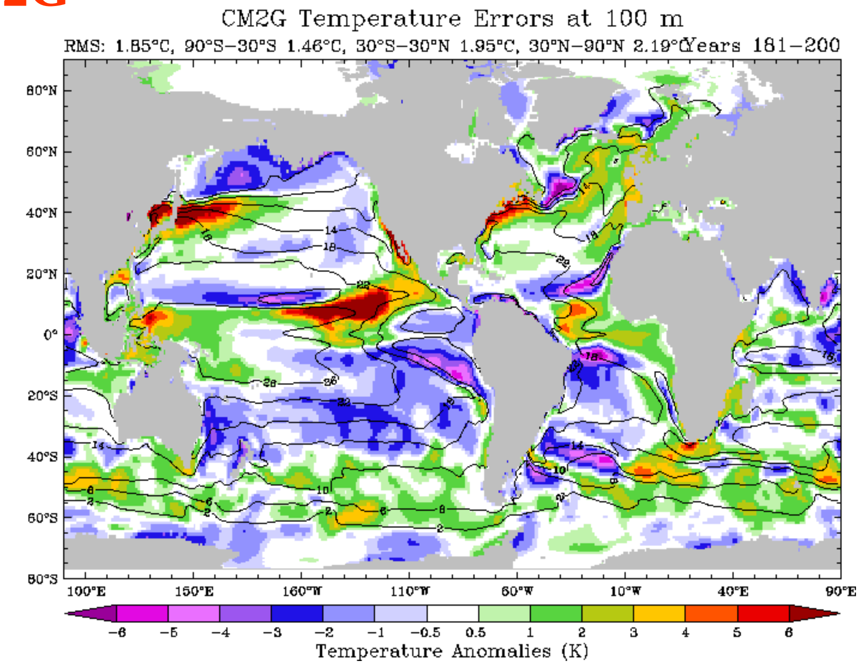
Isopycnal-coordinate: Numerical entrainment is not an issue - BUT

- If resolution is inadequate, no entrainment can occur. Need $\left(\Delta\rho < \frac{1}{2}\left(\rho_{Overflow} - \rho_{Ambient}\right)\right)$

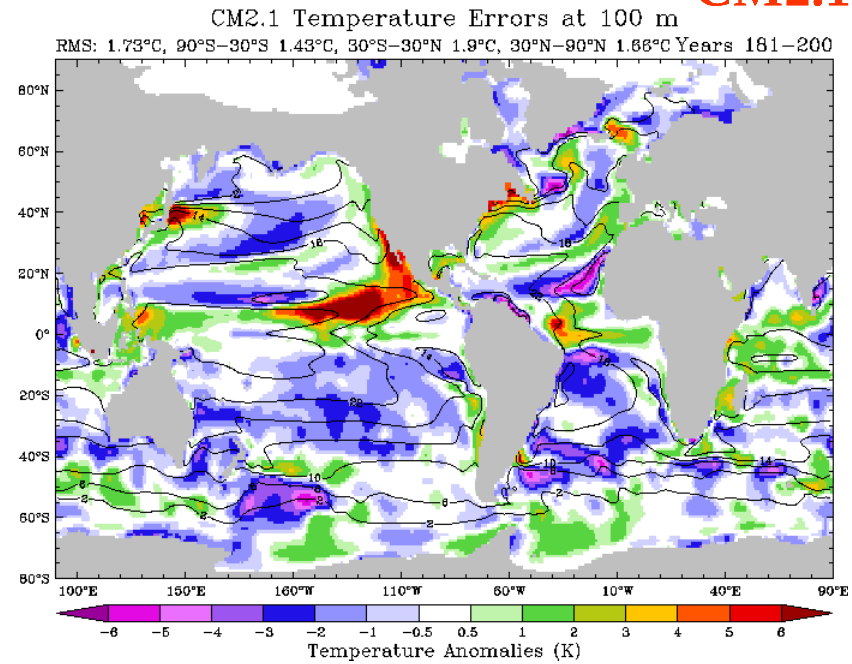
GLOBAL ANOMALY PATTERNS AT FIXED DEPTHS

Year ~190 Temperature Errors at 100 m Depth

CM2G

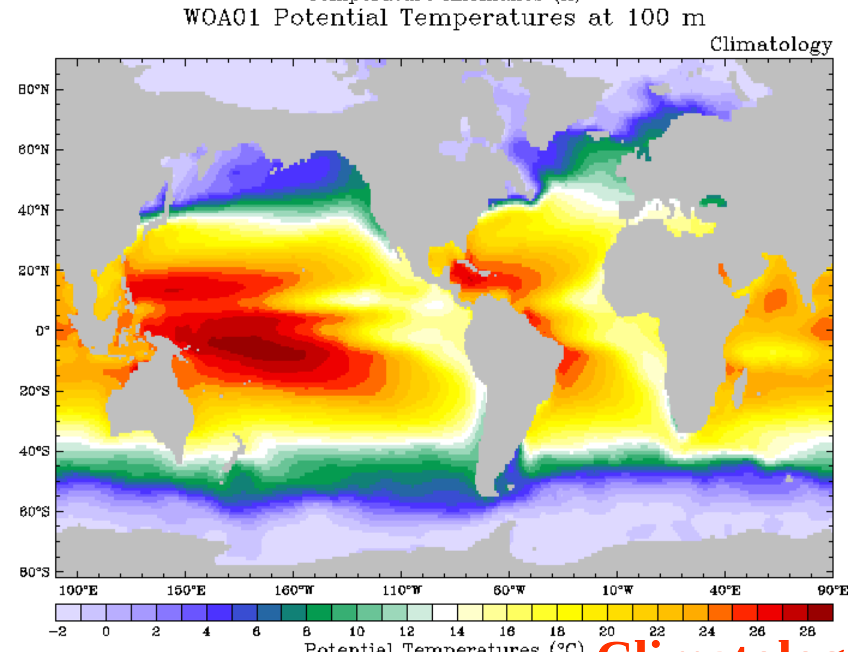


CM2.1



< 0.5 °C white

1 °C Contour interval

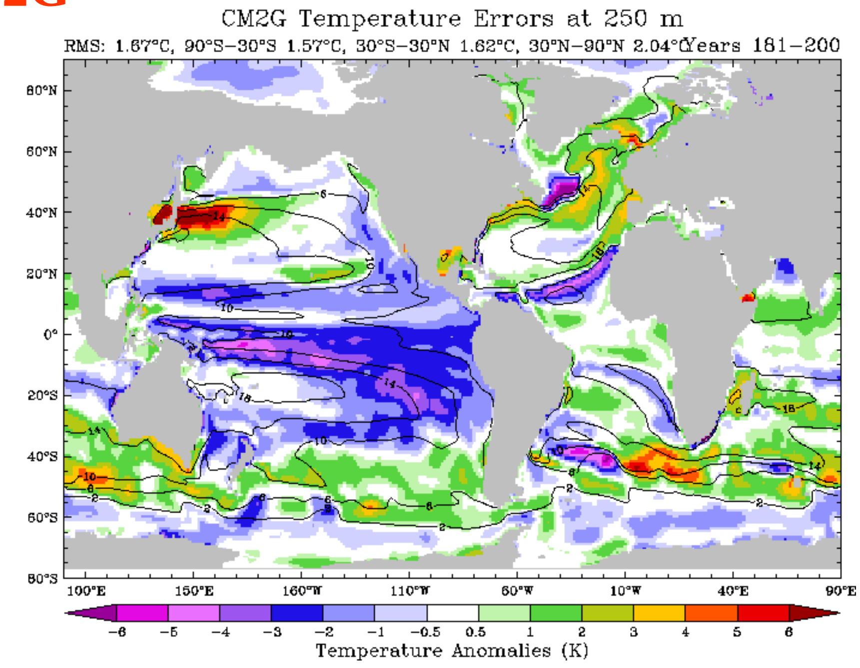


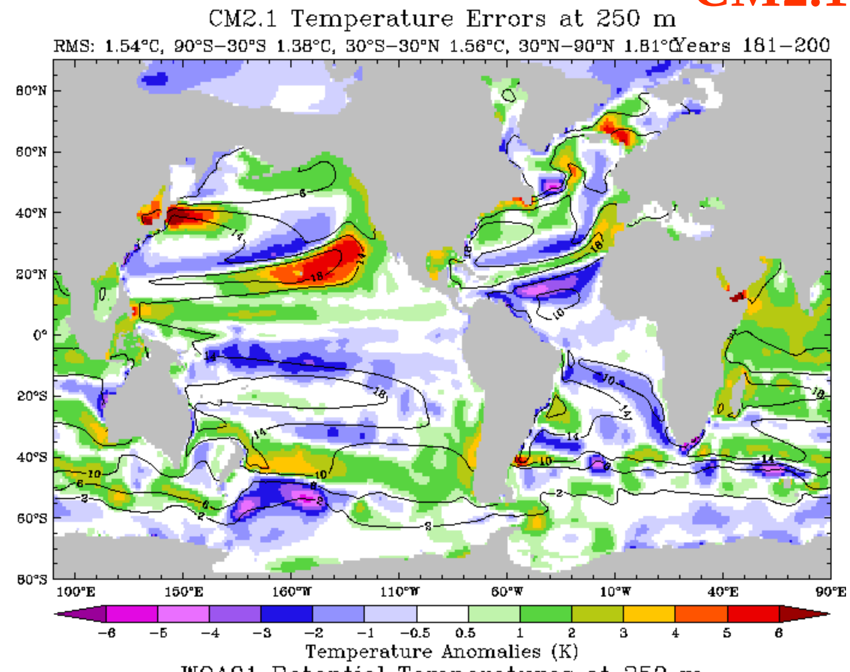
Climatology

Year ~190 Temperature Errors at 250 m Depth

CM2G

CM2.1





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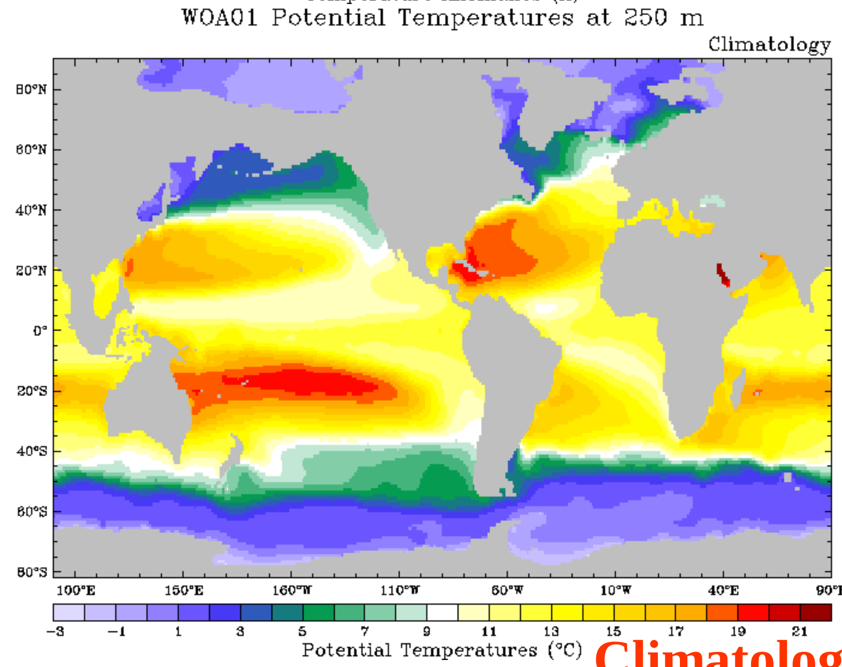
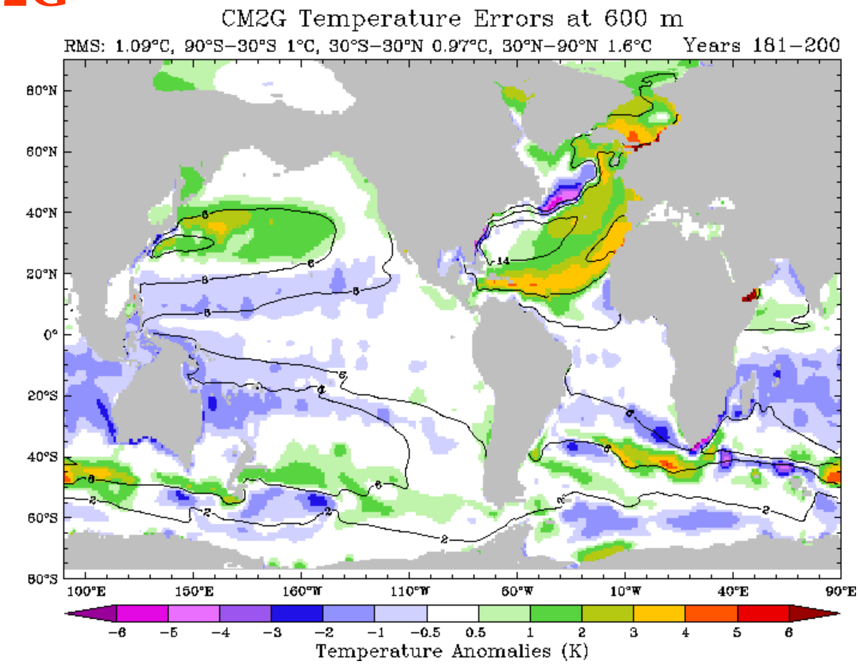
1 °C Contour interval



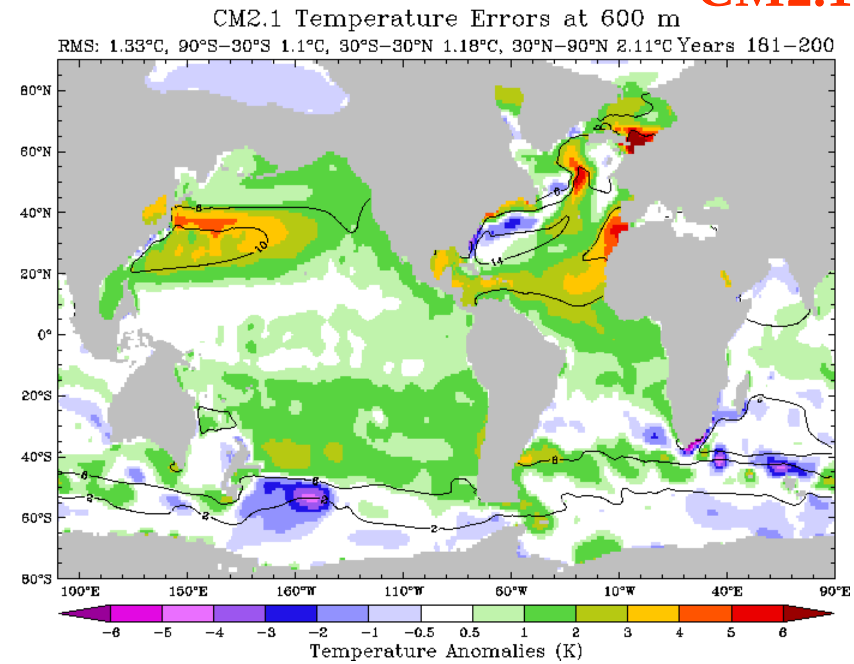
Climatology

Year ~190 Temperature Errors at 600 m Depth

CM2G

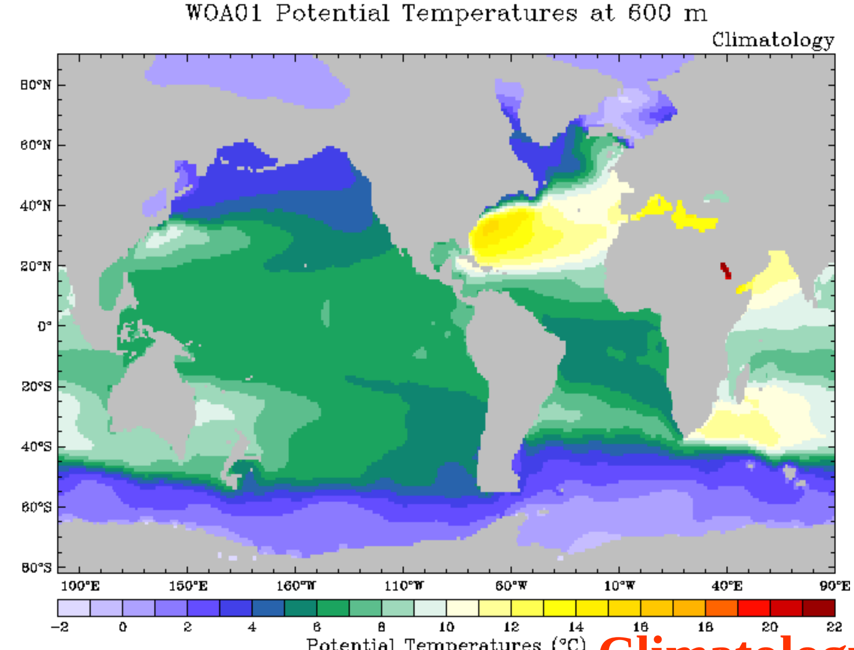


CM2.1



< 0.5 °C white

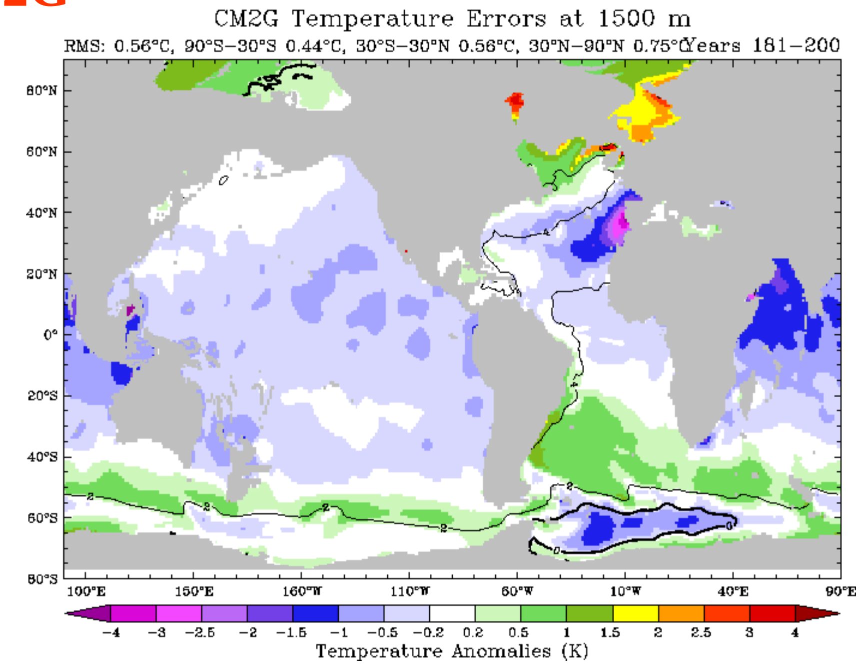
1 °C Contour interval



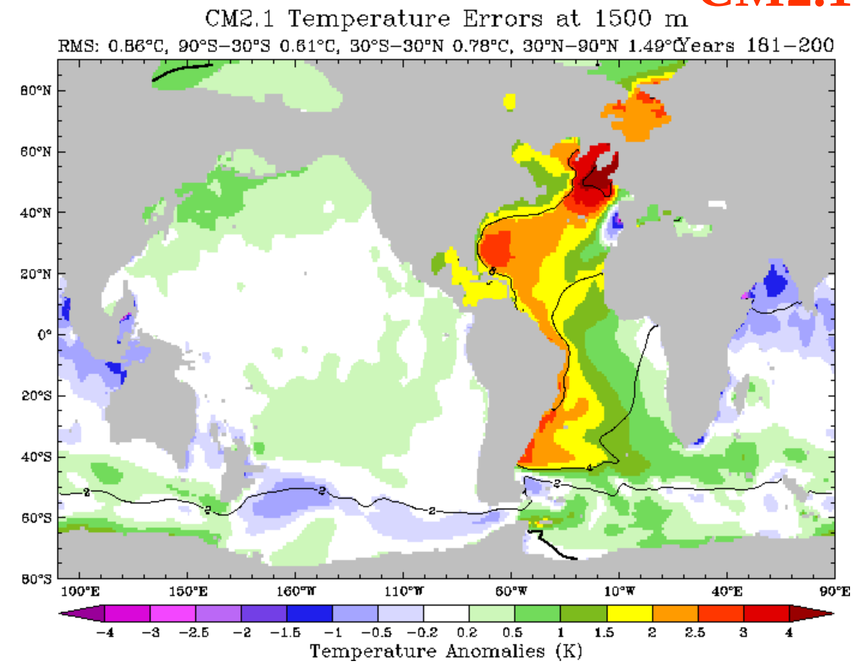
Climatology

Year ~190 Temperature Errors at 1500 m Depth

CM2G

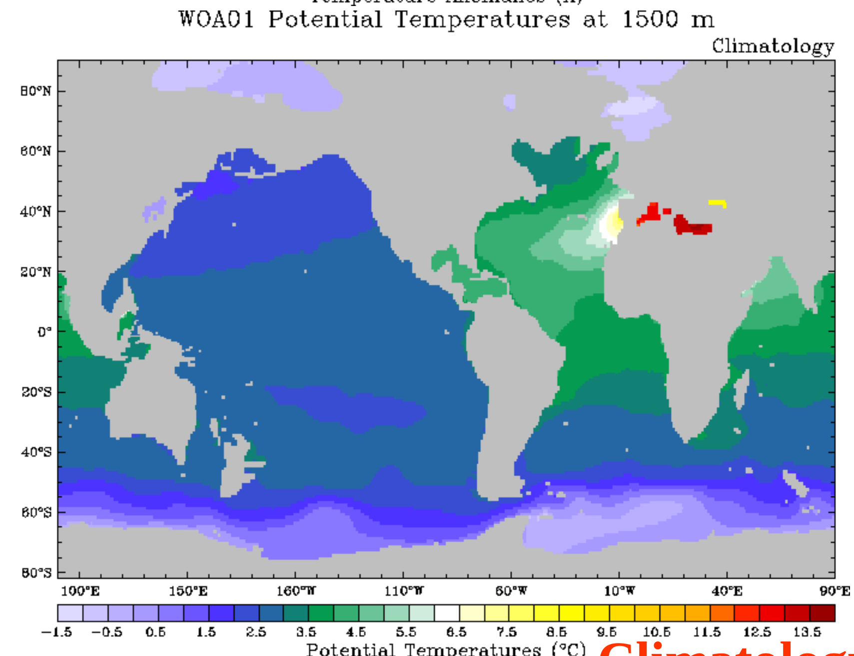


CM2.1



< 0.2 °C white

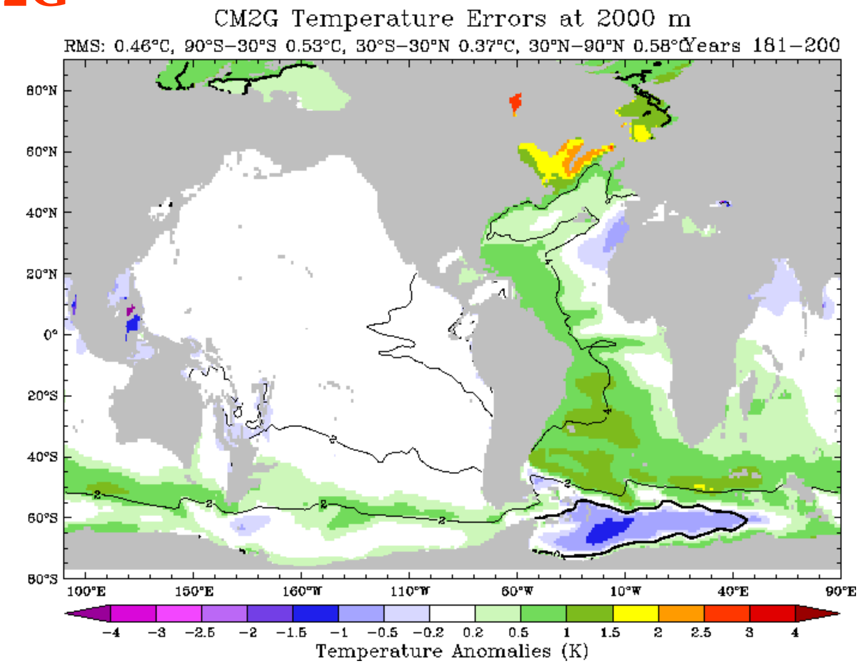
0.5 °C Contour interval



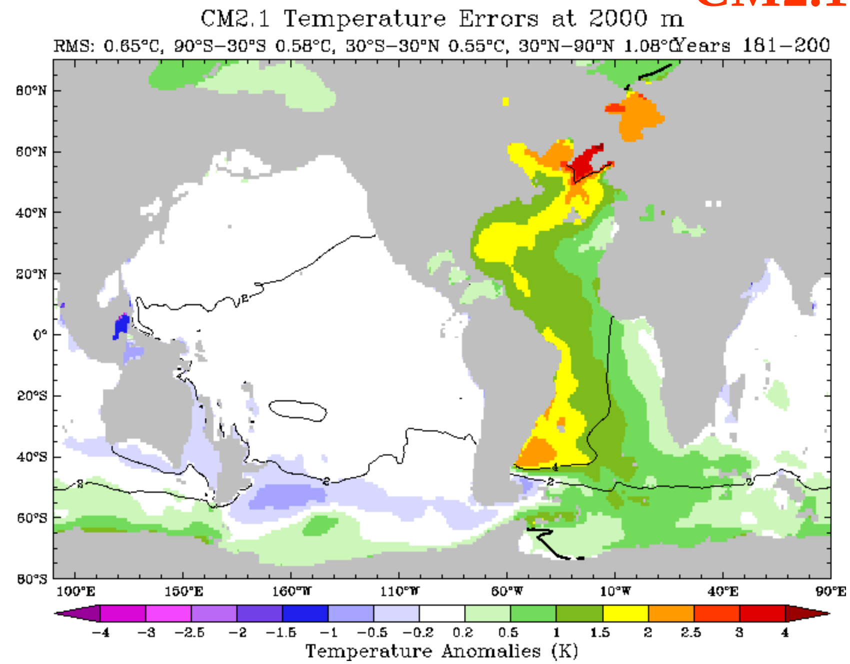
Climatology

Year ~190 Temperature Errors at 2000 m Depth

CM2G

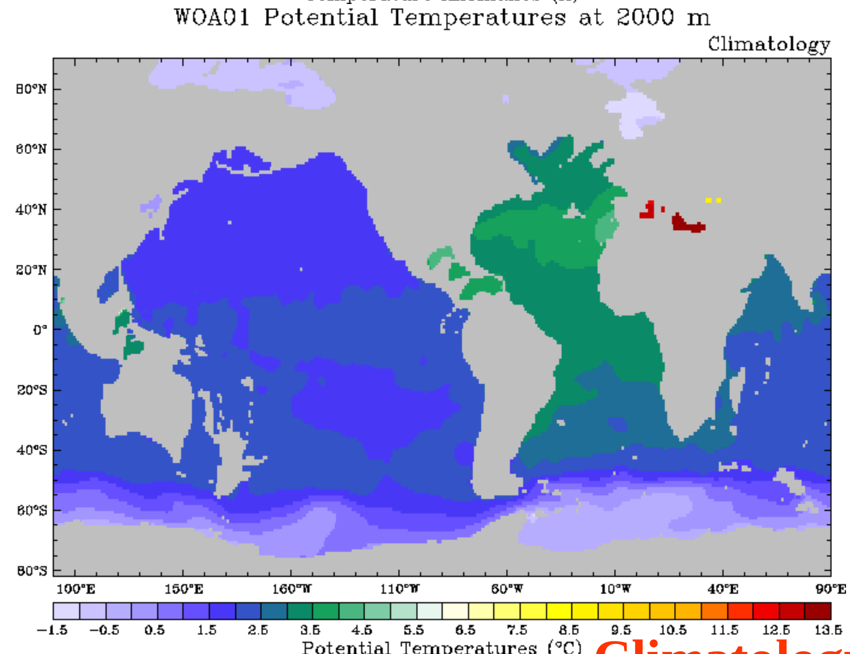


CM2.1



< 0.2 °C white

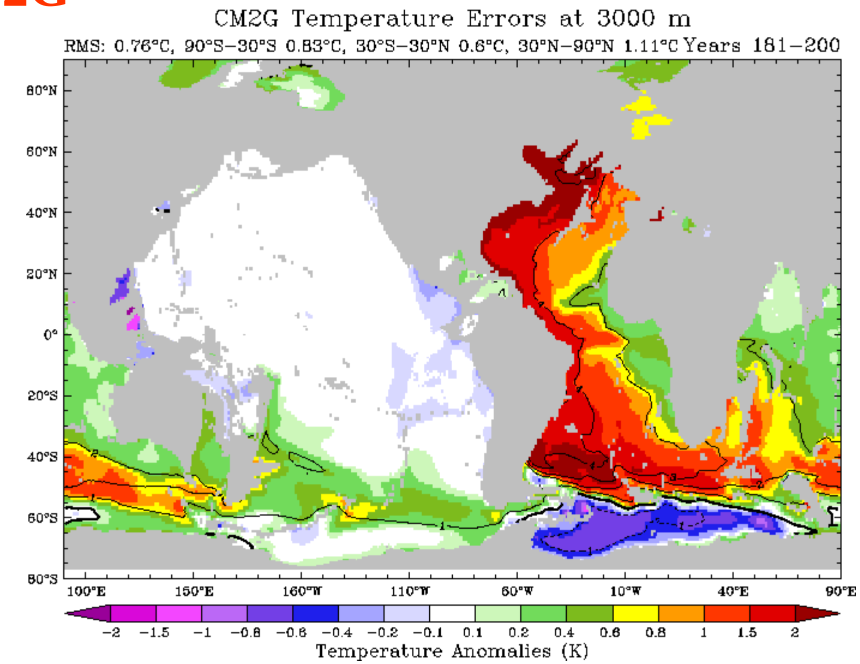
0.5 °C Contour interval



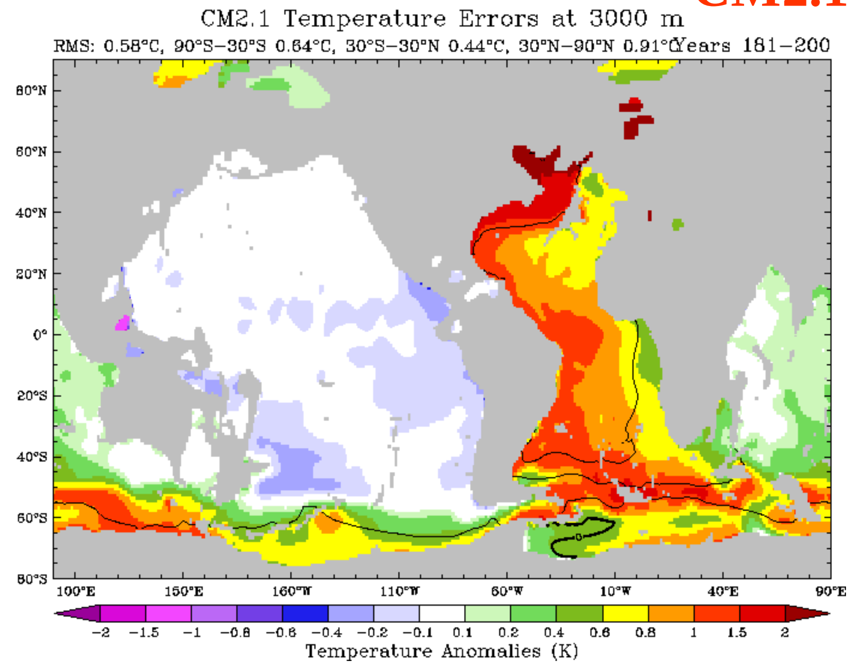
Climatology

Year ~190 Temperature Errors at 3000 m Depth

CM2G

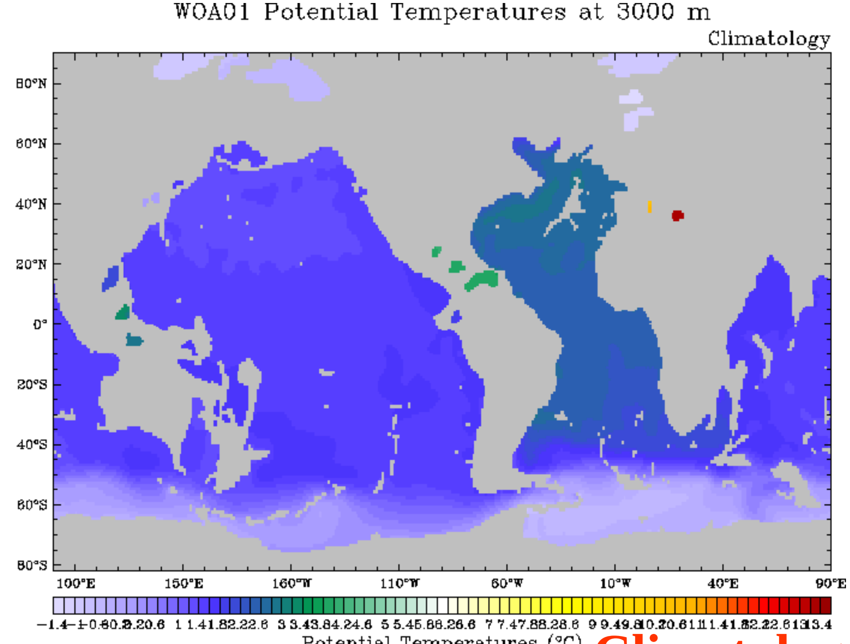


CM2.1



< 0.1 °C white

0.2 °C Contour interval



Climatology