An Assessment of IPCC 20th Century Climate Simulations Using the 15-year Sea Level Record from Altimetry

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ABSTRACT/RESUME

Recently, multiple ensemble climate simulations have been produced for the forthcoming Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Nearly two dozen coupled ocean-atmosphere models have contributed output for a variety of climate scenarios. One scenario, the climate of the 20th century experiment (20C3M), produces model output that can be compared to the long record of sea level provided by altimetry. Generally, the output from the 20C3M runs is used to initialize simulations of future climate scenarios. Hence, validation of the 20C3M experiment results is crucial to the goals of the IPCC. We present comparisons of global mean sea level (GMSL), global mean steric sea level change, and regional patterns of sea level change from these models to results from altimetry, tide gauge measurements, and reconstructions.

1. INTRODUCTION

Quantifying variations in sea level is important to policymakers because of the serious effects on human societies and the natural environment that can result from climate change. Estimates of the rate of globally averaged sea level change during the 20th century are in the range of 1 to 2 mm/yr [5]. This globally averaged rise in sea level is chiefly the result of both the thermal expansion of seawater and land-ice melt. Projections of sea level change using climate scenarios have been calculated using various coupled atmosphere–ocean general circulation models (CGCMs).

The geographical distribution of sea level change is largely determined by changes in the density structure and wind stress forcing, both of which affect ocean circulation [5, 6]. Reproducing ocean structures is important for estimating the distribution of future sea level changes. Unfortunately, the details of ocean structures, such as western boundary currents and fronts with pronounced horizontal gradients of water properties, were not well reproduced by coarse-resolution CGCMs. Consequently, many of the models analyzed for the Third Assessment Report of Intergovernmental Panel on Climate Change (IPCC) were not able to provide adequate geographical predictions for policymakers and stakeholders.

In this study, we review the sea level output from models contributed to the Coupled Model Intercomparison Project (CMIP) as part of the IPCC's Fourth Assessment Report (FAR). In particular, we compare results from CMIP's climate of the 20th century experiment (20C3M) to sea level metrics from the same time period. In Section 2, we review these metrics – tide gauge reconstructions, steric sea level analyses, and satellite altimetry. In Section 3, we present comparisons of model output to the metrics. Finally, in Section 4 we discuss our conclusions about the FAR's 20C3M results.

2. SEA LEVEL METRICS

2.1 Satellite altimetry

Estimates of sea level change for the period 1993–2003 have been estimated from TOPEX/Poseidon and Jason altimetry using the methods described in [8]. When the effects of glacial isostatic adjustment are included, the estimated trend in global mean sea level is 3.1 ± 0.4 mm/yr (Fig. 1). The geographical distribution of sea level change derived from these data is shown in Fig. 3.

2.2 Tide gauge reconstruction

A sea level reconstruction for the period 1930 to 2000 was constructed using methods similar to previous studies [3,4]. The method reconstructs low-frequency variability in global mean sea level by interpolating sparse tide gauge data to a global grid using empirical orthogonal functions (EOFs) of sea level variability determined from TOPEX/Poseidon (T/P) and Jason altimeter data. The altimetry data were gridded into monthly 1° grids. A seasonal signal was removed from the satellite altimetry data. Statistical tests suggest that only the first 20 EOFs are significant for the reconstruction. The tide gauges for the reconstruction used in this study are the same as those used in [3], the monthly revised local reference (RLR) tide gauges from the Permanent Service for Mean Sea Level (PSMSL) with a record length of at least 25 years and were more than 90% complete. For the years 1930-2000, 351 tide gauges meet these criteria. One tide gauge (Tribeni, India) was removed from the set due to its poor fit to the local reconstructed sea level. Insufficient tide gauge data were available to accurately extend the reconstruction earlier than 1930.

Table 1. Estimates of steric sea level changes

Reference	Steric sea level change (mm/year)	Period	Depth range (meters)	Data
Antonov *et al*. (2005)	0.40 ± 0.05	1955-1998	0-3000	Levitus *et al*. (2005b)
Antonov *et al*. (2005)	0.34 ± 0.04	1955-2003	0-700	Levitus *et al*. (2005b)
Ishii *et al*. (2005)	0.38 ± 0.04	1955-2003	0-700	Ishii *et al*. (2005)
Antonov *et al*. (2005)	1.23 ± 0.2	1993-2003	0-700	Levitus *et al*. (2005b)
Ishii *et al*. (2005)	1.8 ± 0.2	1993-2003	0-700	Ishii *et al*. (2005)
Willis *et al*. (2005)	1.6 ± 0.3	1993-2003	0-750	Willis *et al*. (2005)

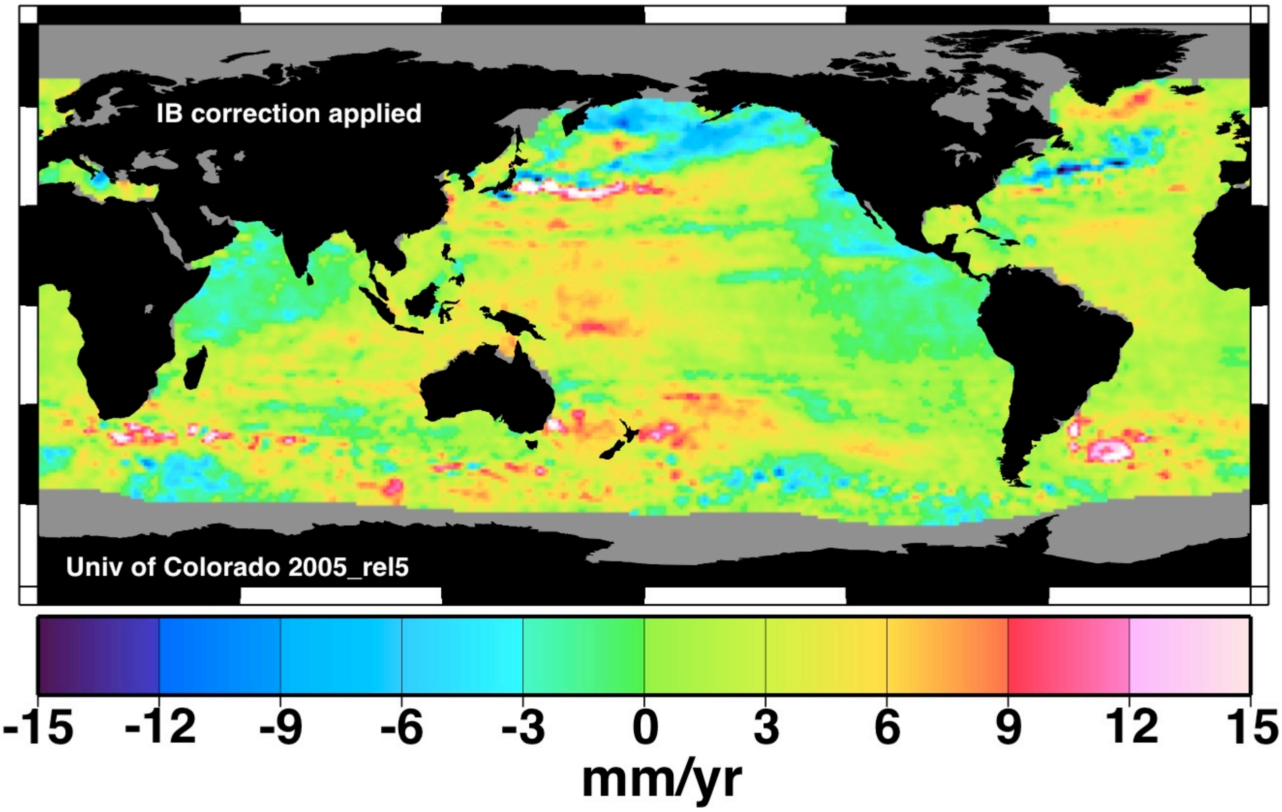

Figure 1. Local trends in global mean sea level from TOPEX/Poseidon and Jason altimetry data for the period 1993-2005.

Two separate reconstructions have been derived. The first method follows [4], which removes secular trends from the altimetry data before decomposing into EOFs and adds a uniform "EOF0" pattern (i.e. an ocean function). Reconstructed sea level using this method (Fig. 2) has a trend of 1.8 mm/yr over the study period. For the second method, EOFs are computed from the altimetry data with local trends intact. The trend in global mean sea level from this method (not shown) is 1.6 mm/yr for the same period.

2.3 Steric sea level change

Table 1 summarizes several recent studies [1, 7, 9, 10, 12] that have estimated global trends in steric sea level. Steric analyses can only be extended back to 1955, when sufficient in situ measurements of ocean temperatures and salinity became available for global estimates. Data availability in large regions, especially in the Southern Ocean, has been sparse until very recently. The trend during 1955–2003 in steric sea level variations in the upper 700 meters of the ocean is 0.34–0.38 mm/year, suggesting that 20–25% of sea level rise during this period can be attributed to density variations. For the T/P-Jason era (1993-2003), the estimated trend ranges from 1.23–1.8 mm/yr.

3. COMPARISON OF MODEL OUTPUT TO METRICS

A subset of models contributing to the CMIP report global mean sea level and global mean steric sea level as monthly time series for the 20C3M. Only models that output true total sea level, including glacier melt, were encouraged to report these time series. Results from these model have been adjusted for model drifts estimated from control runs. For models reporting multiple runs of output, an ensemble average is computed.

All models output sea level variations as monthly grids. The geographical distributions of sea level change have been computed by differencing 20-year averages of spatial variations.

3.1 20th century sea level change

Trends in global mean sea level from the 20C3M experiment output range from 0–1.74 mm/yr (Fig. 2 and Tab. 2). Most models underestimate the trend in GMSL, but overestimate the trends in steric sea level by a factor of 2 to 5. Models with significant trends in sea level show most (66–98%) of the rise is attributable to thermosteric sea level rise.

Table 2. 20th century average trends (1900-2000)

Model	GMSL (mm/yr)	Steric (mm/yr)	Ratio
CGCM3.1	–0.03	-0.09	3.00
GISS AOM	1.74	1.15	0.66
GISS E20/Russell	0.87	0.72	0.83
INMCM 3.0	1.28	1.25	0.98
MIROC 3.2 hires	1.04	0.98	0.94
MRI CGCM2 3.2	1.58	1.85	0.85

3.2 T/P-era sea level change

Sea level change estimated from the 20C3M experiment models for the TOPEX/Poseidon era ranges from 0.32–6.11 mm/year (Fig. 3 and Tab. 3), with one model (MIROC 3.2) within the error estimates from altimetry. The trends in steric sea level also range widely, from 0.79–5.69 mm/year.

Figs. 4-7 show the geographical distribution of sea level change from the 20C3M experiment model output for the years 1990–2000, which are coincident with the period with altimetry coverage. The GISS AOM (Fig. 4.) has the coarsest resolution (5° x 4°) and least reflects the observed pattern in sea level. The MIROC model (Fig. 7) has the highest resolution of the models, and the western boundary currents exhibit realistic variability. While there are notable differences with the observations (e.g. the Indian Ocean and the western equatorial Pacific), the spatial pattern shares major features with the altimetry map (Fig. 1). The models with intermediate resolution (Figs. 5 and 6) demonstrate that the ensemble of FAR models seem to show a wide range of predicted sea level variations under the same modeled scenario.

Table 3. T/P-era average trends (1990-2000)

Model	GMSL (mm/yr)	Steric (mm/yr)	Ratio
CGCM3.1	0.32	0.79	0.40
GISS AOM	6.11	3.51	0.57
GISS E20/Russell	1.99	0.72	0.36
INMCM 3.0	1.34	1.38	1.03
MIROC 3.2 hires	2.71	2.32	0.85
MRI CGCM2 3.2	3.98	5.69	1.42

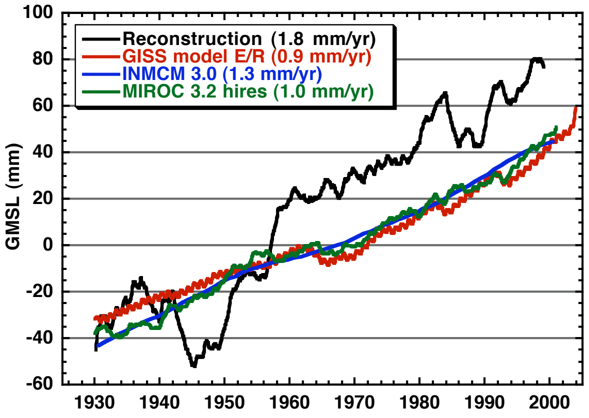

Figure 2. Global mean sea level estimates from selected 20C3M model output and sea level change from an EOF reconstruction of tide gauge data.

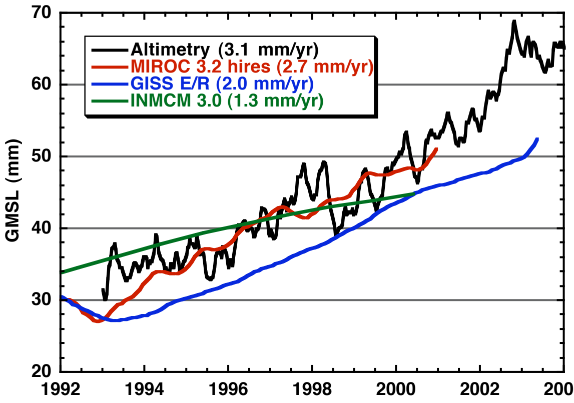

Figure 3. Global mean sea level estimates from selected 20C3M model output and observations from TOPEX/Poseidon and Jason altimetry.

4. CONCLUSIONS

IPCC FAR models generally underestimate 20th century sea level change compared to altimetry observations and tide gauge reconstructions. The models also overestimate the contribution from steric sea level change, presumably by overestimating the changes in ocean heat content over the century.

Given that coupled-climate models are limited in their ability to reproduce observed interannual variations, the high-resolution models of the 20C3M experiment (e.g. MIROC) appear to realistically reproduce the spatial pattern and magnitude of the trends as observed by altimetry.

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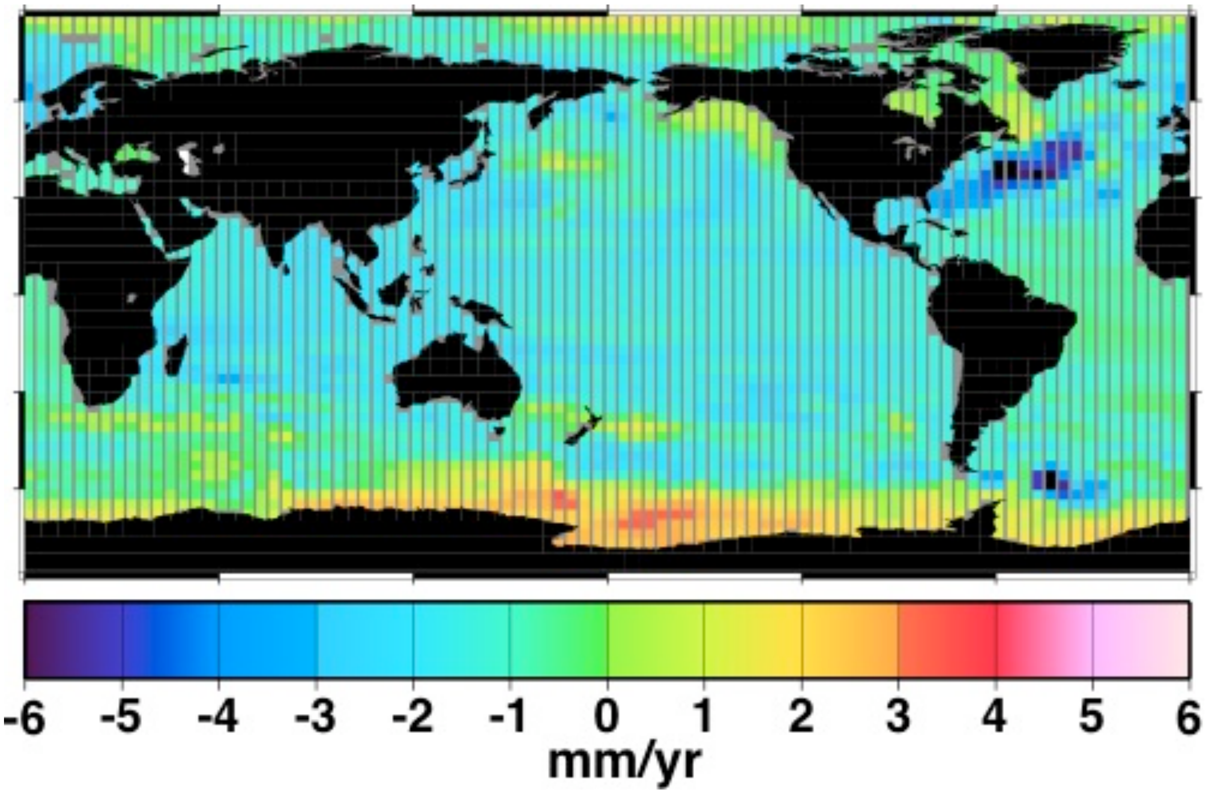

Figure 4. Local trends in global mean sea level from the GISS AOM model for the period 1990-2000.

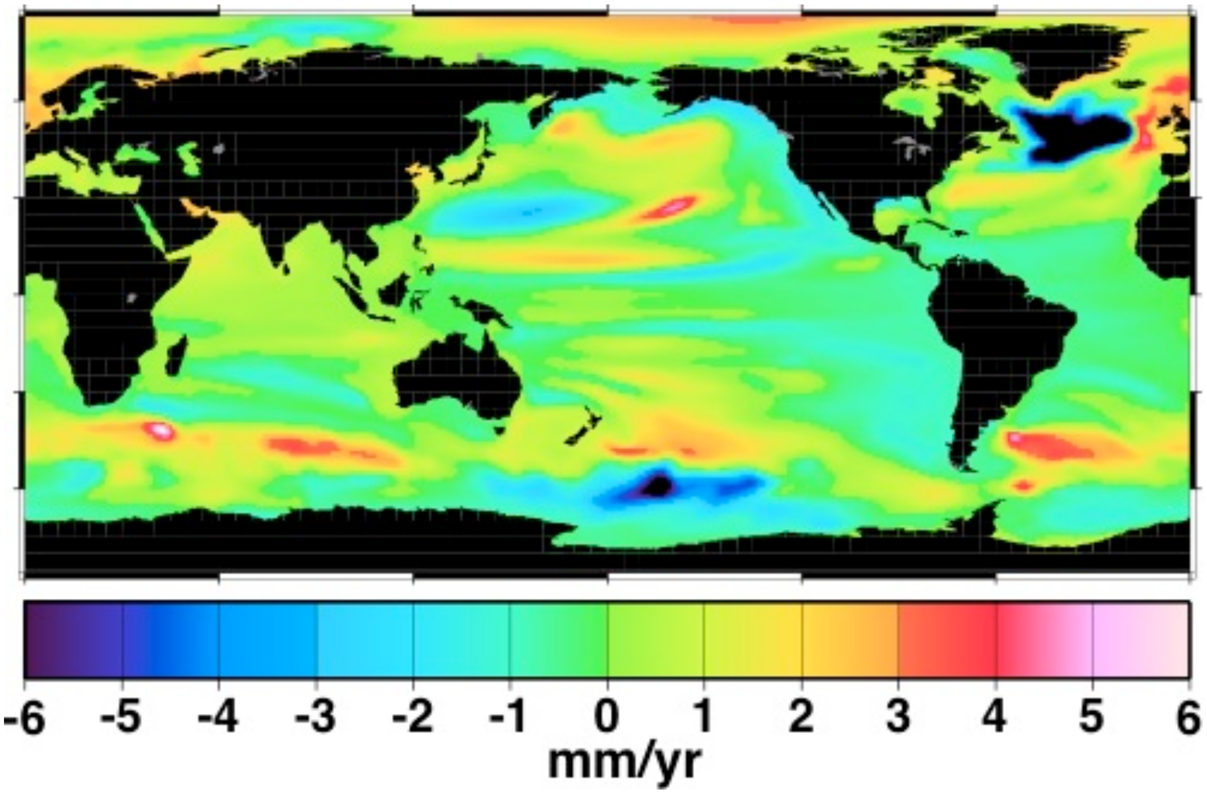

Figure 5. Same as Figure 4, except for the NCAR CCSM 3.0 model.

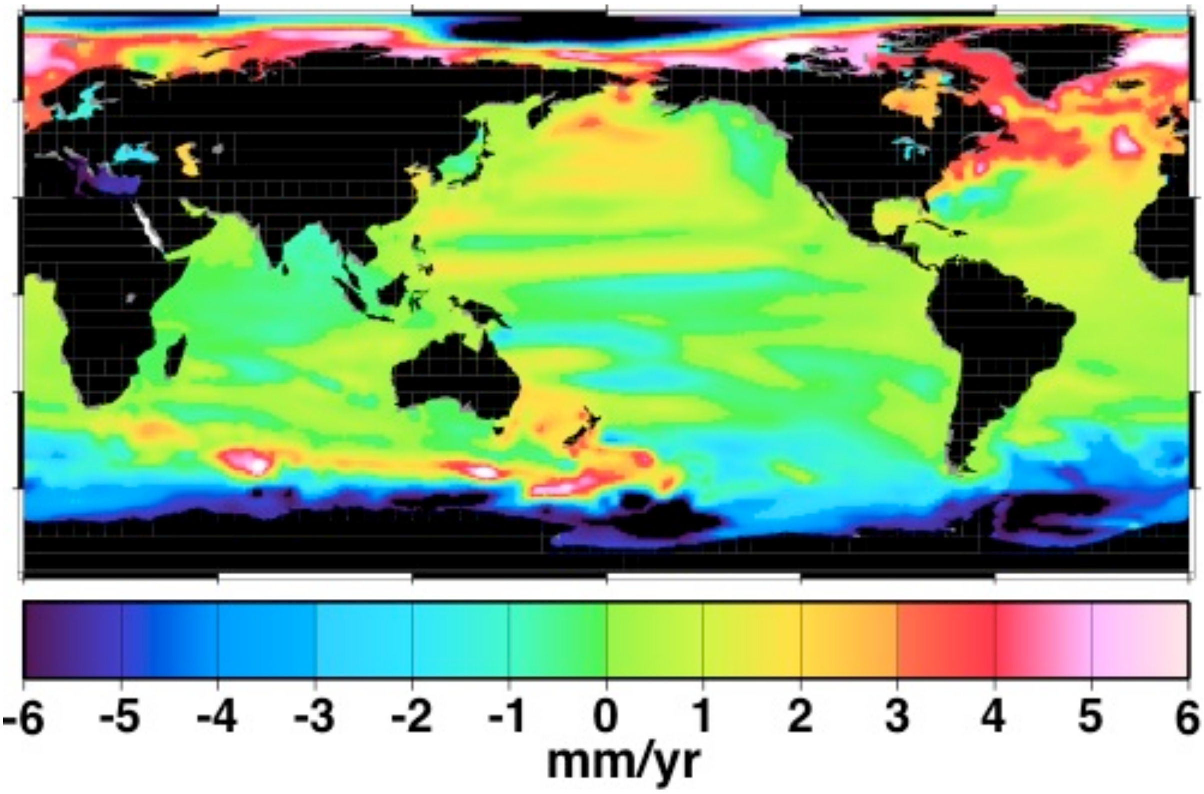

Figure 6. Same as Figure 4, except for the UKMO HADCM3 model.

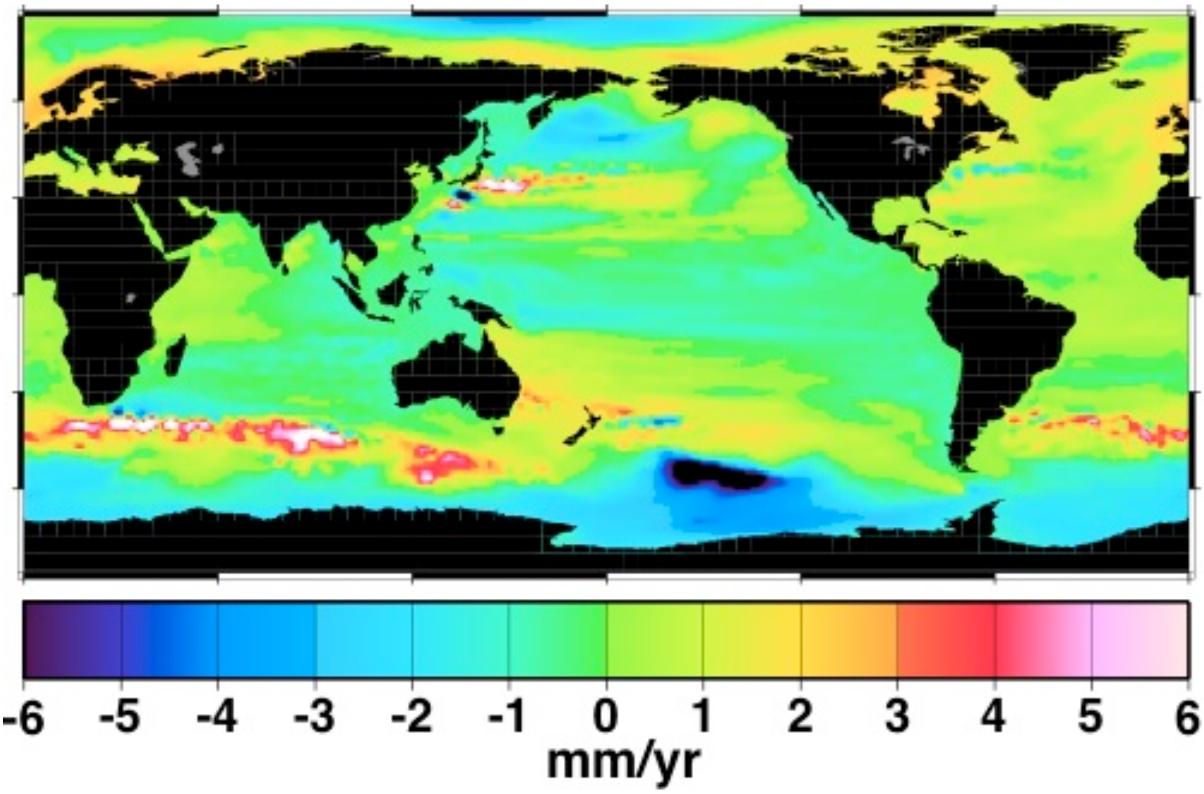

Figure 7. Same as Figure 4, except for the MIROC 3.2 model.