

Supplement of Geosci. Model Dev., 13, 3643–3708, 2020
<https://doi.org/10.5194/gmd-13-3643-2020-supplement>
© Author(s) 2020. This work is distributed under
the Creative Commons Attribution 4.0 License.



Supplement of

Evaluation of global ocean–sea-ice model simulations based on the experimental protocols of the Ocean Model Intercomparison Project phase 2 (OMIP-2)

Hiroyuki Tsujino et al.

Correspondence to: Hiroyuki Tsujino (htsujino@mri-jma.go.jp)

The copyright of individual parts of the supplement might differ from the CC BY 4.0 License.

S1 Introduction of supplement

This document contains supplemental materials of the paper by Tsujino et al. “Evaluation of global ocean–sea-ice model simulations based on the experimental protocols of the Ocean Model Intercomparison Project phase 2 (OMIP-2)” submitted for possible publication in Geoscientific Model Development.

5 References

- de Boyer-Montégut, C., Madec, G., Fischer A. S., Lazar, A., Iudicone, D.: Mixed layer depth over the global ocean: An examination of profile data and a profile-based climatology, *J. Geophys. Res.* 109, C12003, doi:10.1029/2004JC002378, 2004.
- Ishii, M., Y. Fukuda, H. Hirahara, S. Yasui, T. Suzuki, and K. Sato: Accuracy of Global Upper Ocean Heat Content Estimation Expected from Present Observational Data Sets. *SOLA*, 13, 163–167, doi:10.2151/sola.2017-030, 2017.
- 10 Hurrell, J. W., Hack, J. J., Shea D., Caron, J. M., Rosinski, J.: A new sea surface temperature and sea ice boundary dataset for the community atmospheric model, *J. Clim.*, 21, 5145–5153, <https://doi.org/10.1175/2008JCLI2292.1>, 2008.
- Locarnini, R., Mishonov, A., Antonov, J. I., Boyer, T. P., Garcia, H., Baranova, O., Zweng, M. M., Paver, C. R., Reagan, J. R., Hamilton, D. J., and Seidov, D.: World Ocean Atlas 2013, Volume 1: Temperature, NOAA Atlas NESDIS 73, 15 NOAA/NESDIS, U.S. Dept. of Commerce, Washington, D.C., 2013.
- Macdonald, A. and Baringer, M.: Ocean Heat Transport. *Ocean Circulation & Climate: A 21st Century Perspective*. International geophysics series 103. Academic Press, pp.759–785, 2013.
- McDonagh, E. L., King, B. A., Bryden, H. L., Courtois, P., Szuts, Z., Baringer, M., Cunningham, S. A., Atkinson, C., McCarthy, G.: Continuous estimate of Atlantic oceanic freshwater flux at 26.5°N, *J. Clim.* 28, 8888–8906. 20 <https://doi.org/10.1175/JCLI-D-14-00519.1>, 2015.
- Zweng, M., Reagan, J., Antonov, J., Locarnini, R., Mishonov, A., Boyer, T., Garcia, H., Baranova, O., Johnson, D., Seidov, D., and Biddle, M.: World Ocean Atlas 2013, Volume 2: Salinity, NOAA Atlas NESDIS 74, NOAA/NESDIS, U.S. Dept. of Commerce, Washington, D.C., 2013.

Vertically averaged temperature (OMIP-1)

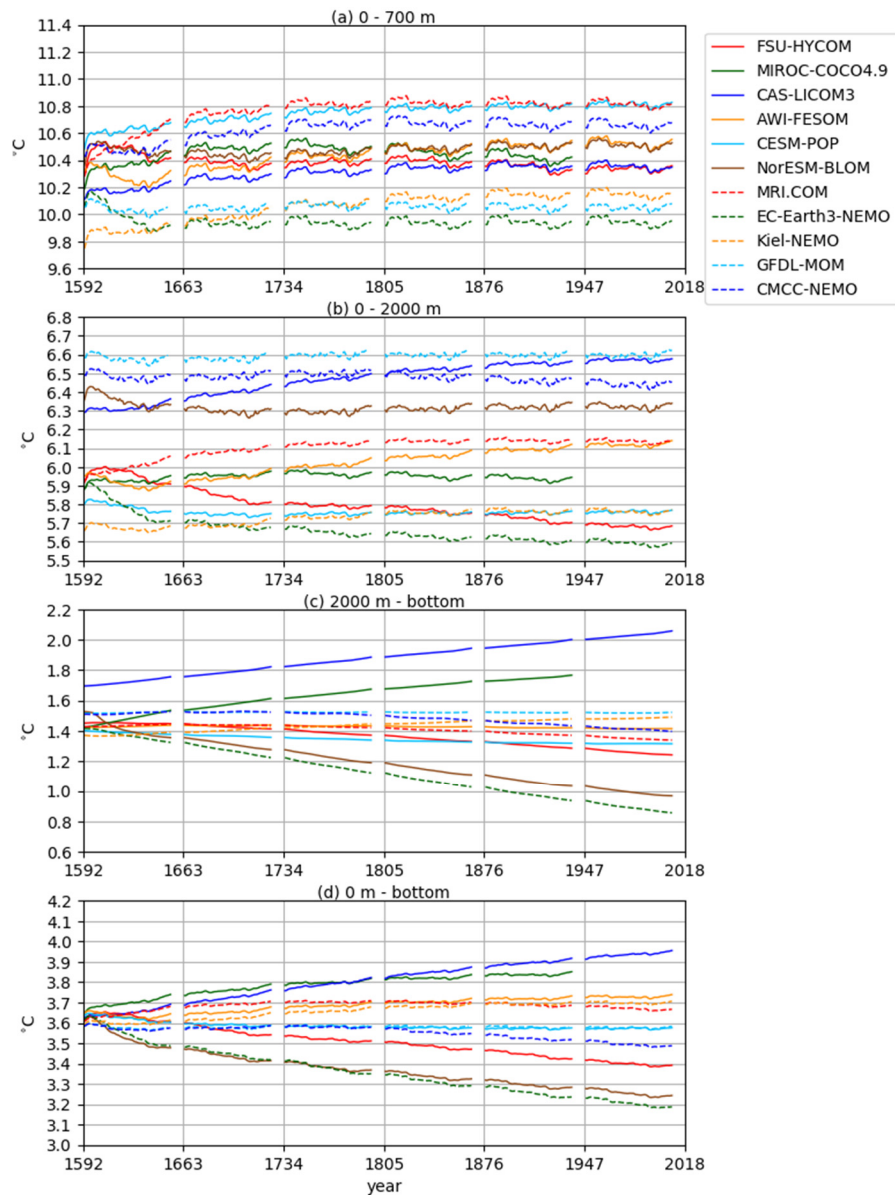
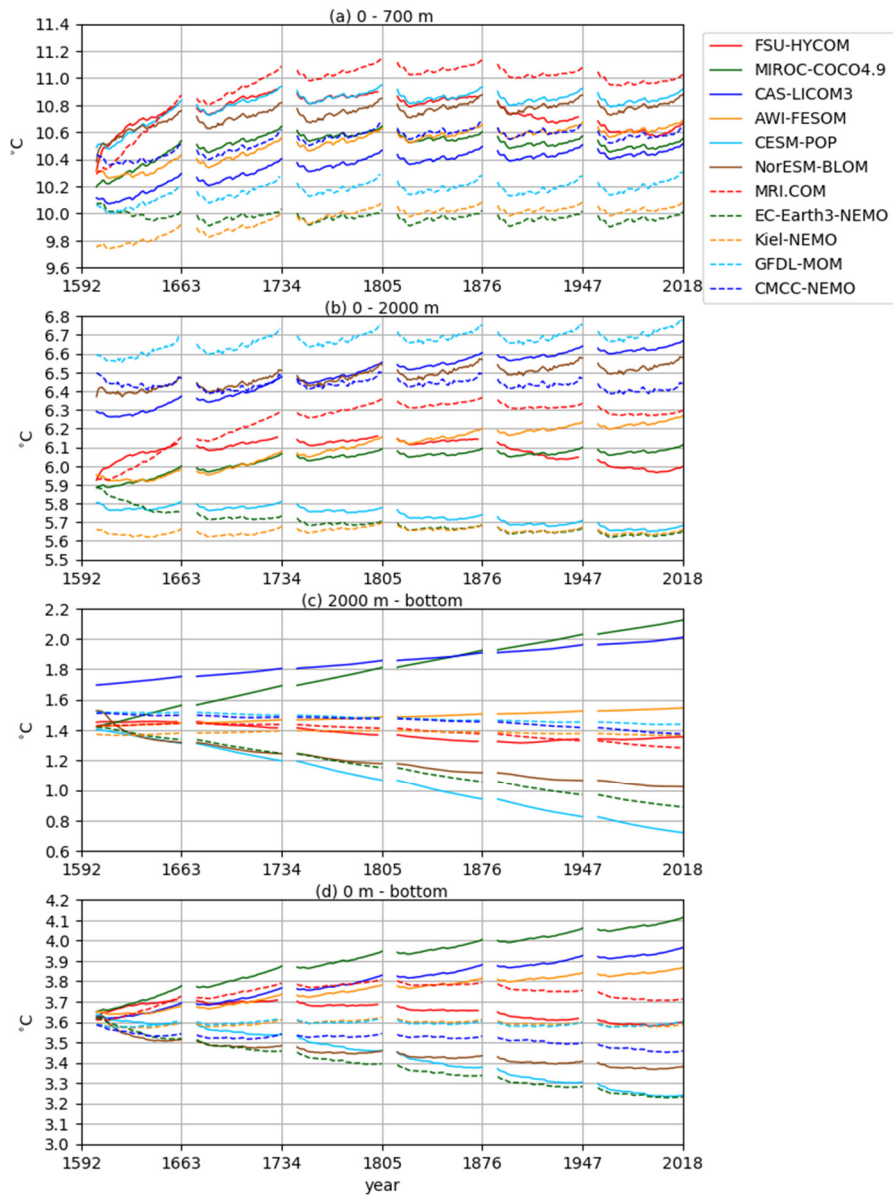


Figure S1: Drift of annual mean, global mean vertically averaged temperatures (°C) for four depth ranges of OMIP-1 simulations. (a) 0 – 700m, (b) 0 – 2000m, (c) 2000m – bottom, (d) 0 m – bottom.

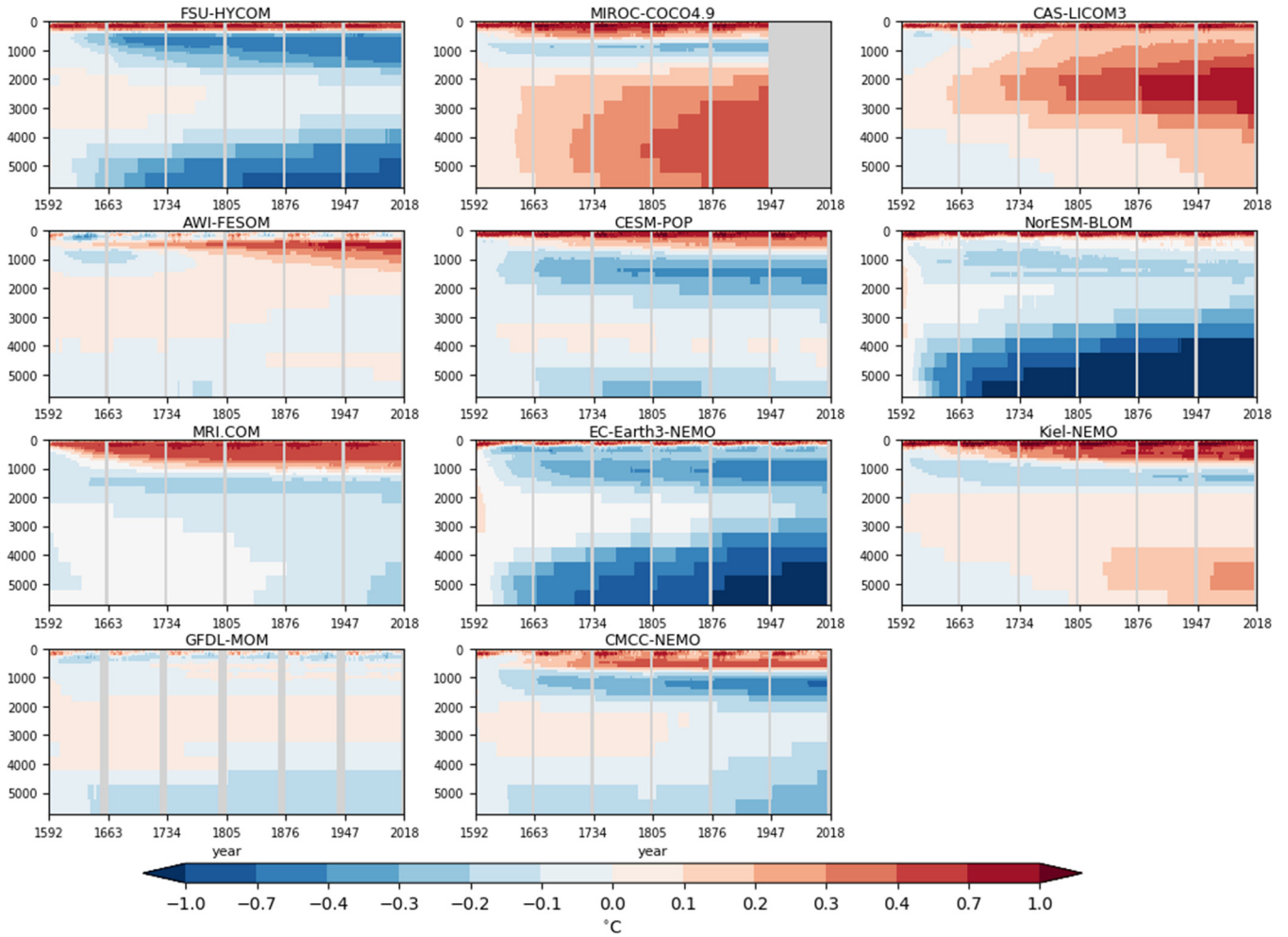
Vertically averaged temperature (OMIP-2)



30

Figure S2: Same as Fig. S1 but for OMIP-2 simulations.

OMIP-1 thetad



35 **Figure S3: Globally averaged drift of annual mean temperature (°C) as a function of depth and time for OMIP-1 simulations. The drift is defined as the deviation from the annual mean of the initial year of the simulation by each model.**

OMIP-2 theta0

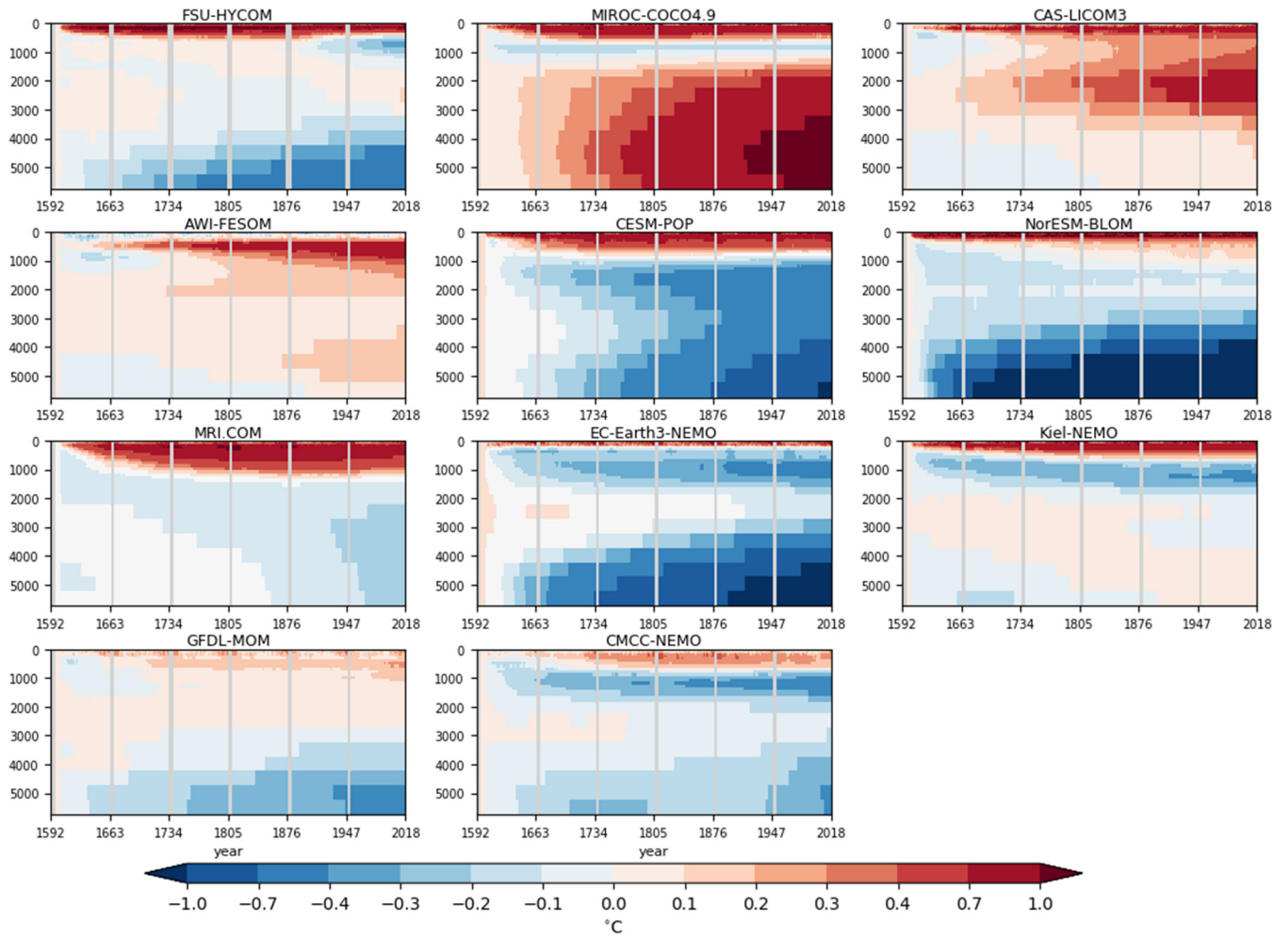
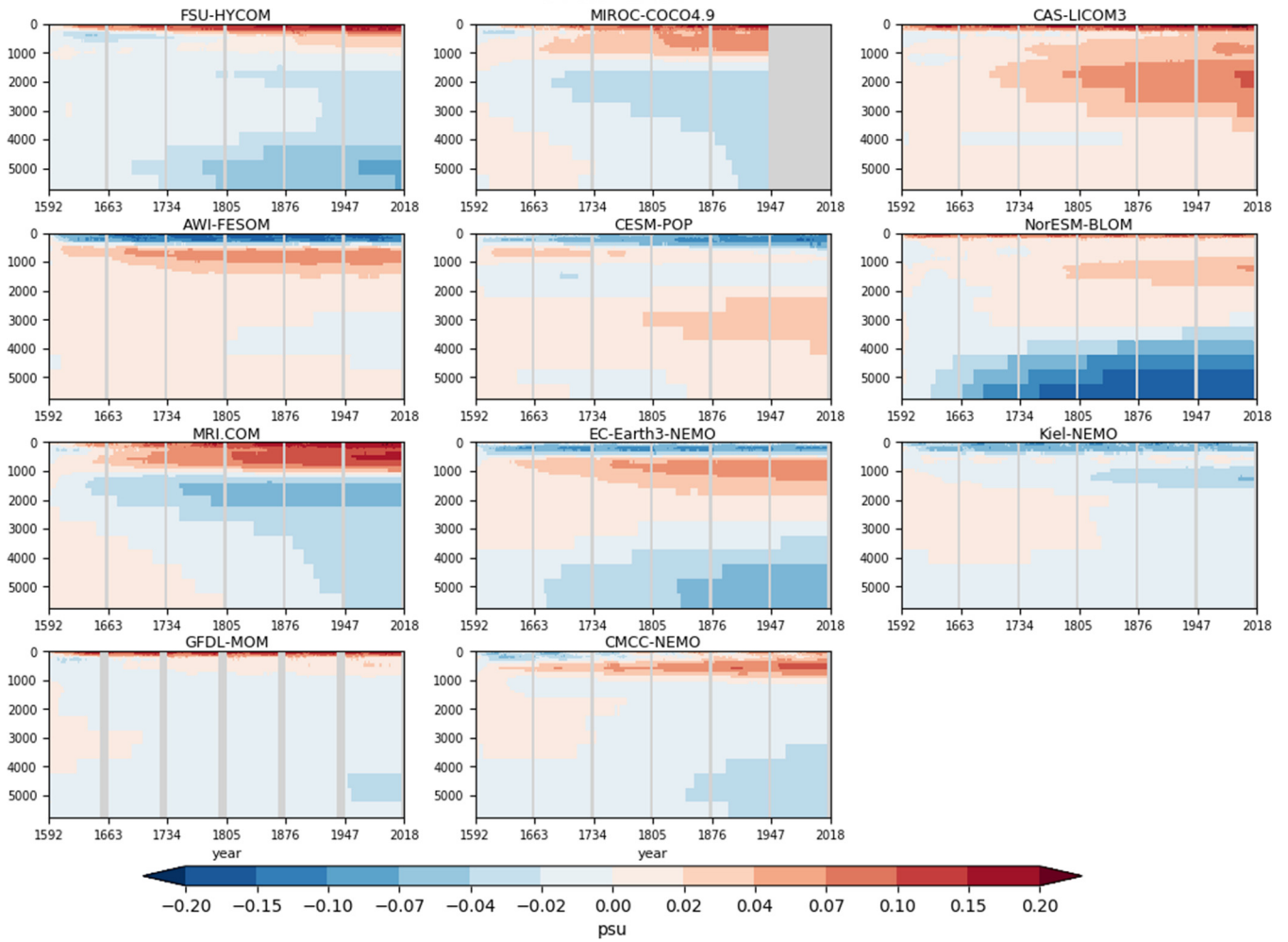


Figure S4: Same as Fig. S3 but for OMIP-2 simulations.

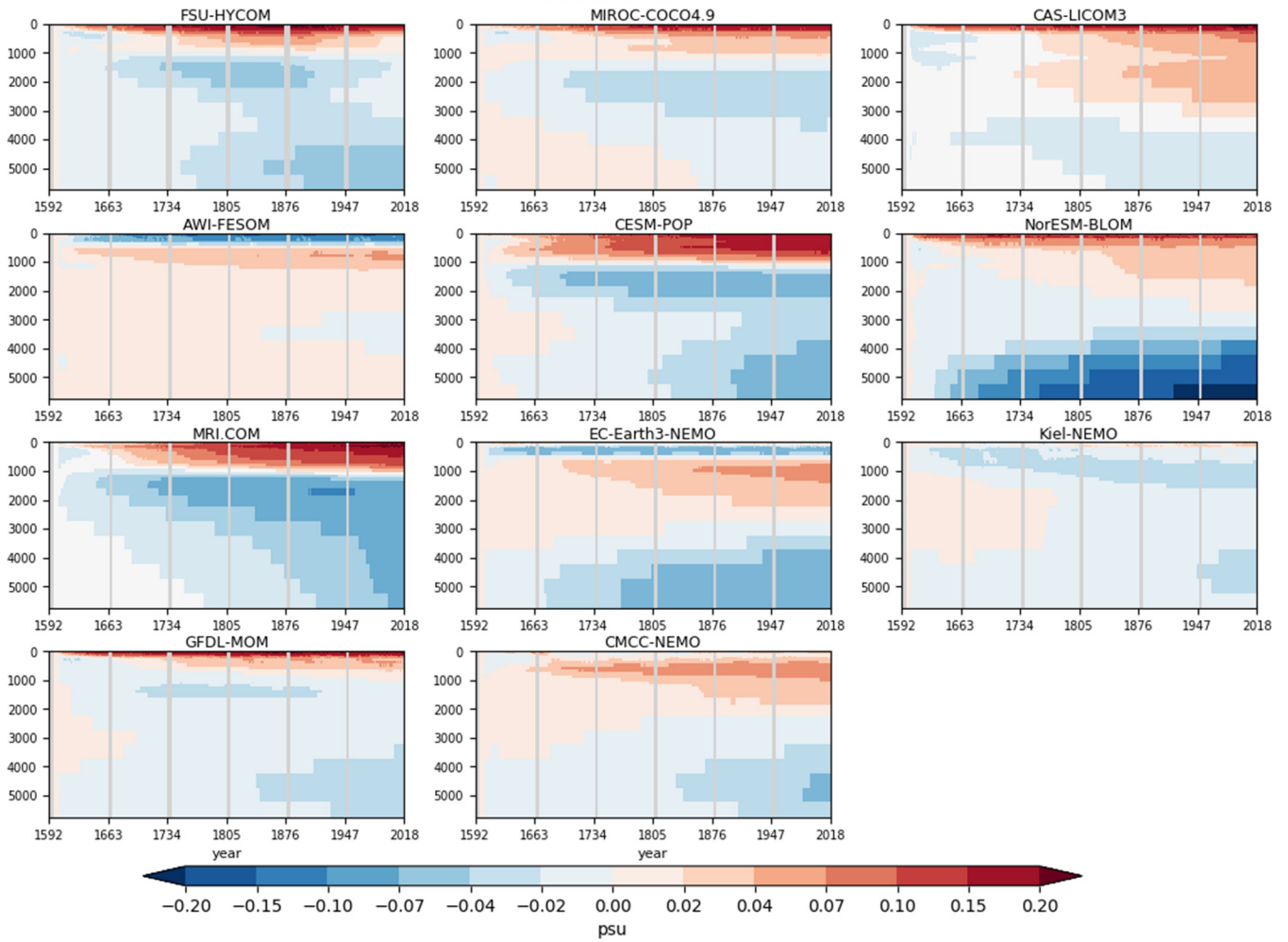
OMIP-1 so



40

Figure S5: Globally averaged drift of annual mean horizontal mean salinity (psu) as a function of depth and time for OMIP-1 simulations. The drift is defined as the deviation from the annual mean of the initial year of the simulation by each model.

OMIP-2 so



45 Figure S6: Same as Fig. S5 but for OMIP-2 simulations.

Sea ice volume (All models)

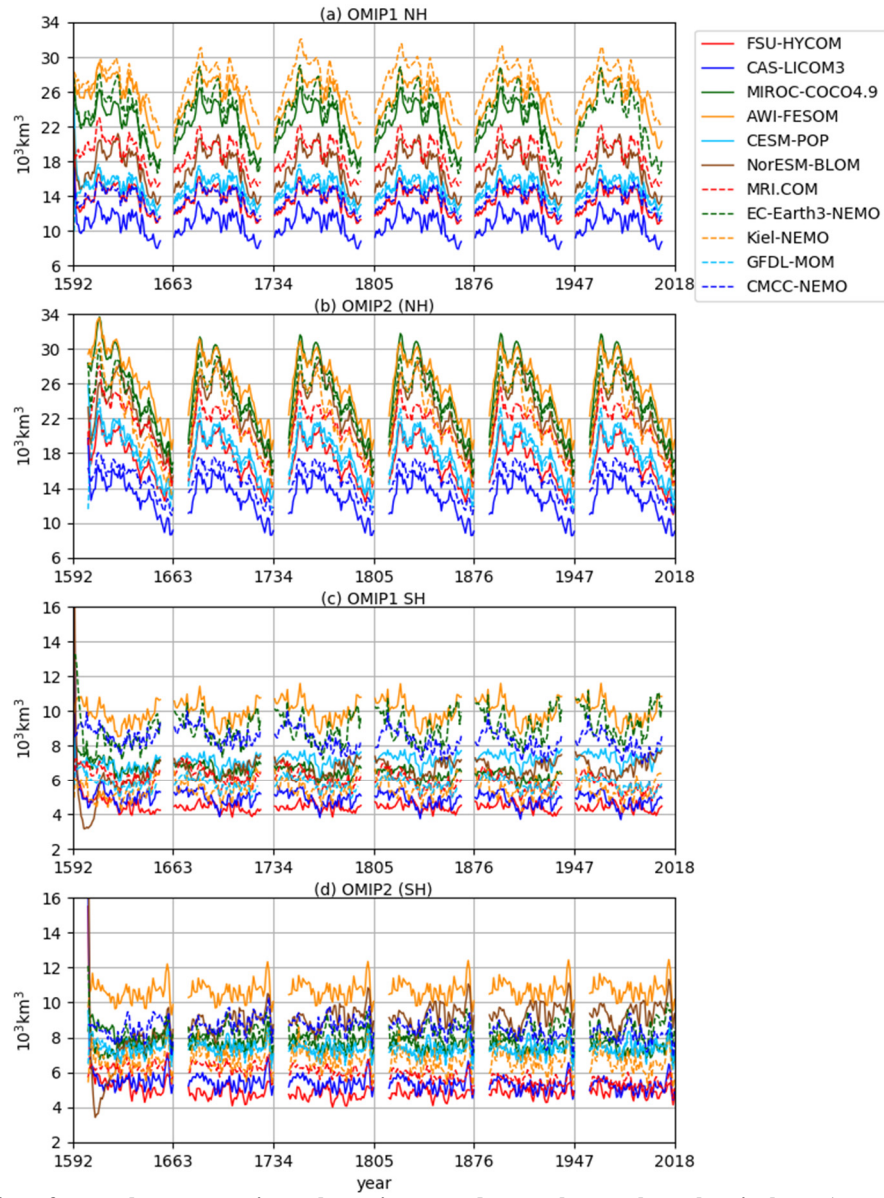
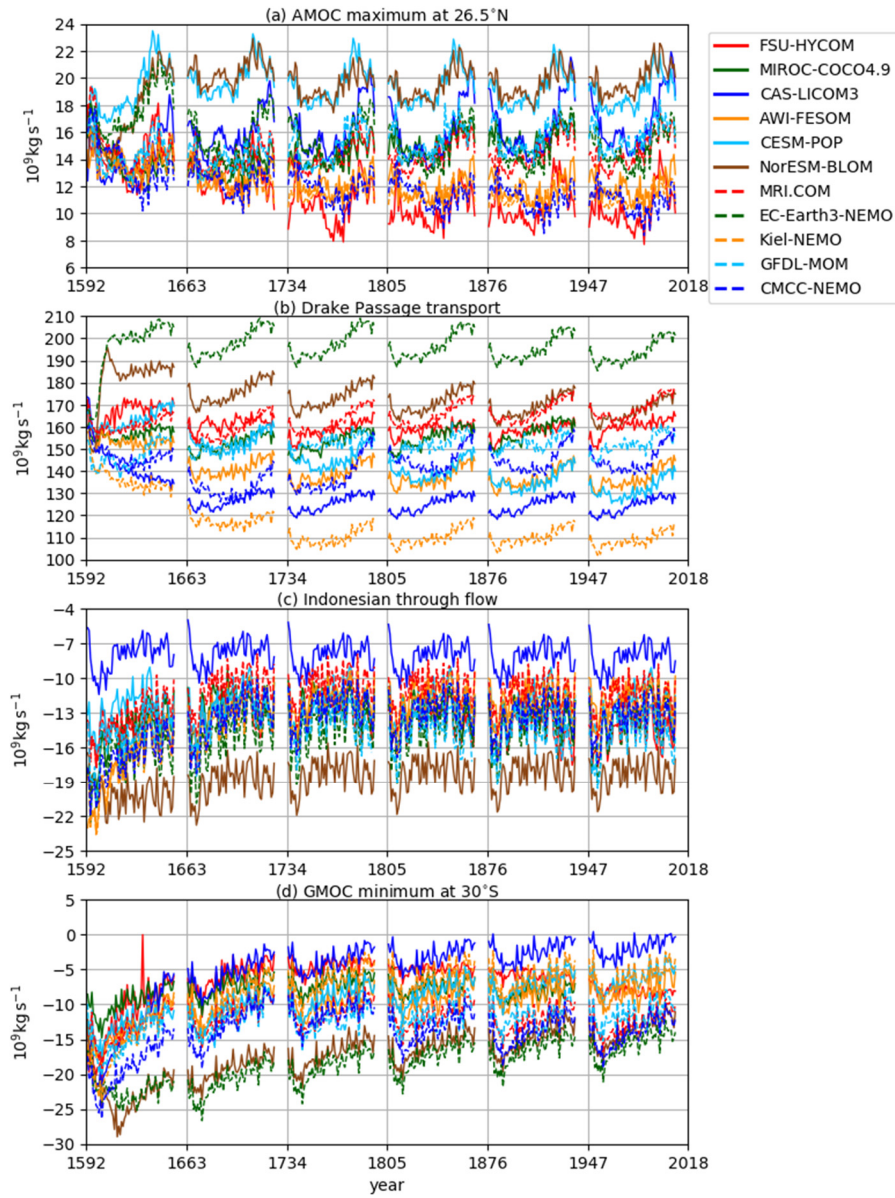


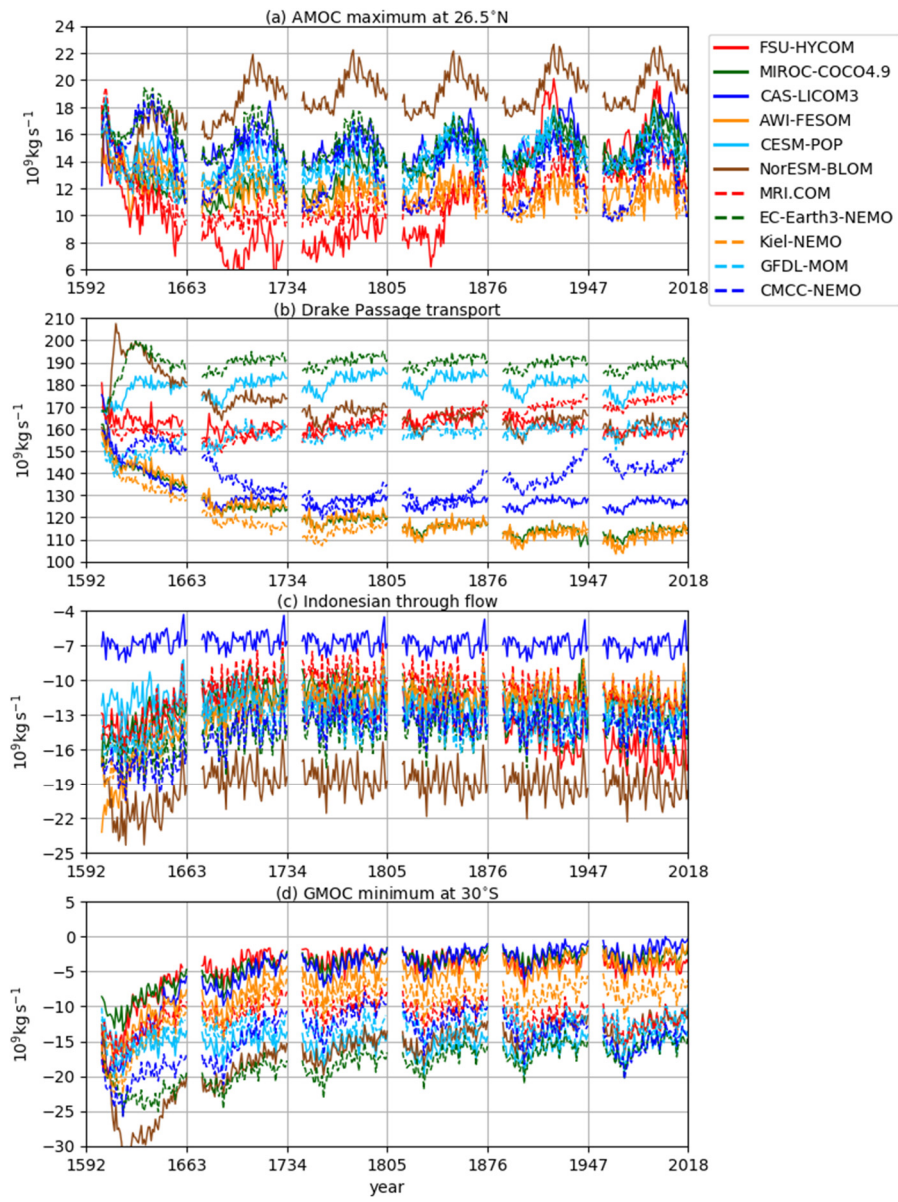
Figure S7: Time series of annual mean sea ice volume integrated over the northern hemisphere (upper two panels) and the southern hemisphere (lower two panels). Units are 10^3 km^3 . (a, c) OMIP-1 and (b, d) OMIP-2 simulations.

OMIP-1



55 **Figure S8: Time series of annual mean important ocean circulation metrics for OMIP-1 simulations. (a) Atlantic meridional overturning circulation (AMOC) maximum at 26.5°N, which represents the strength of AMOC associated with the North Atlantic Deep Water formation. (b) Drake passage transport (positive eastward), which represents the strength of Antarctic Circumpolar Current. (c) Indonesian Throughflow (negative into the Indian Ocean), which represents water exchange between the Pacific and Indian Ocean. (d) Global meridional overturning circulation (GMOC) minimum in 2000 m – bottom depths at 30°S, which represents the strength of deep to bottom layer GMOC associated with the Antarctic Bottom Water and Lower Circumpolar Deep Water formation. Units are 10^9 kg s^{-1} .**

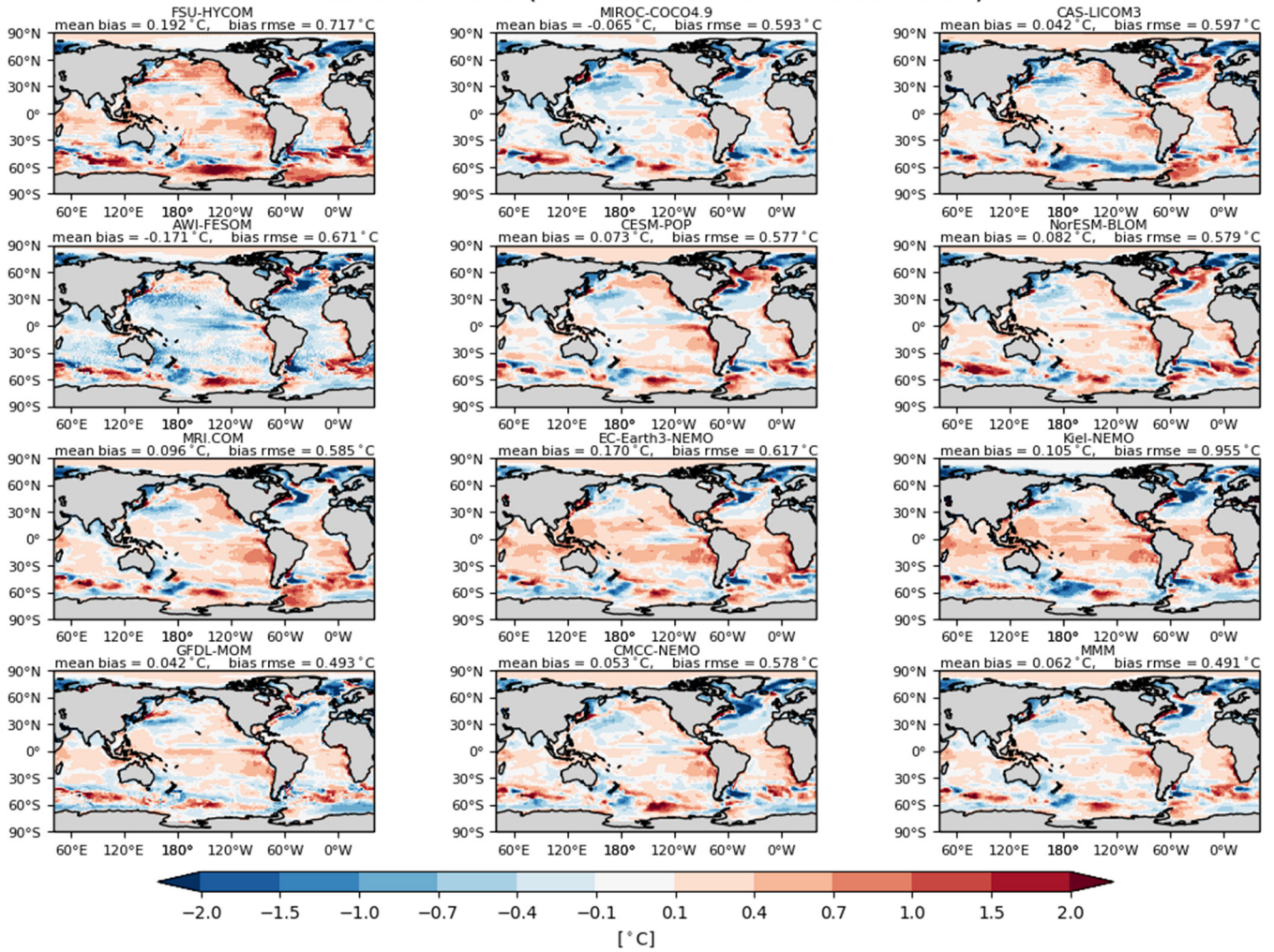
OMIP-2



60

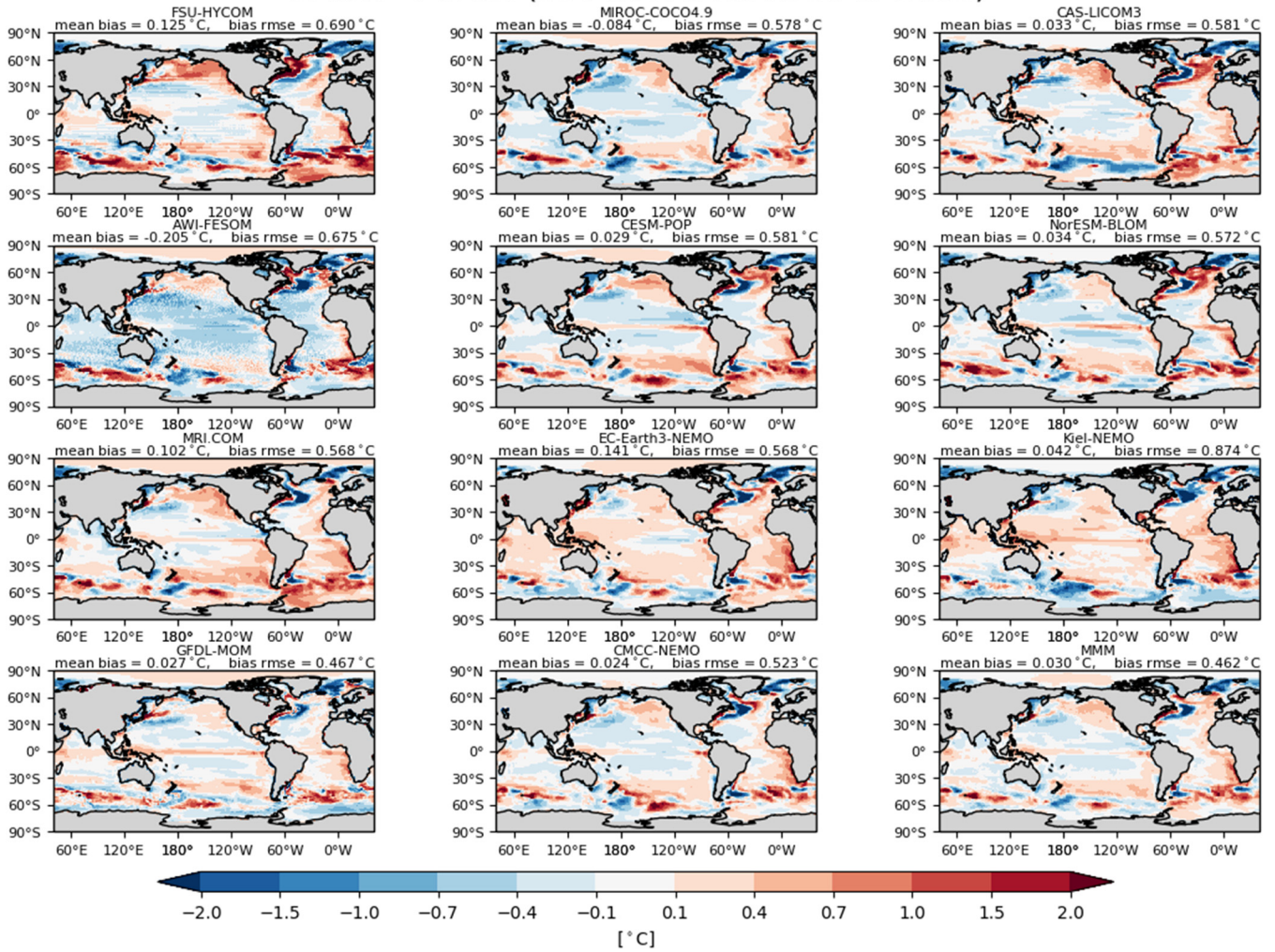
Figure S9: Same as Fig. S8 but for OMIP-2 simulations.

OMIP1 - PCMDI (SST ave. from 1980 to 2009)



65 **Figure S10:** Bias of 30-year (1980–2009) mean sea surface temperature (SST) of OMIP-1 simulations relative to an observational estimate provided and updated by Program for Climate Model Diagnosis and Intercomparison (PCMDI) following a procedure described by Hurrell et al. (2008) (hereafter referred to as PCMDI-SST). Units are °C. Global mean bias and global root-mean-square bias are depicted on the top of each panel.

OMIP2 - PCMDI (SST ave. from 1980 to 2009)



70 Figure S11: Same as Fig. S10 but for OMIP-2 simulations.

OMIP2 - OMIP1 (SST ave. from 1980 to 2009)

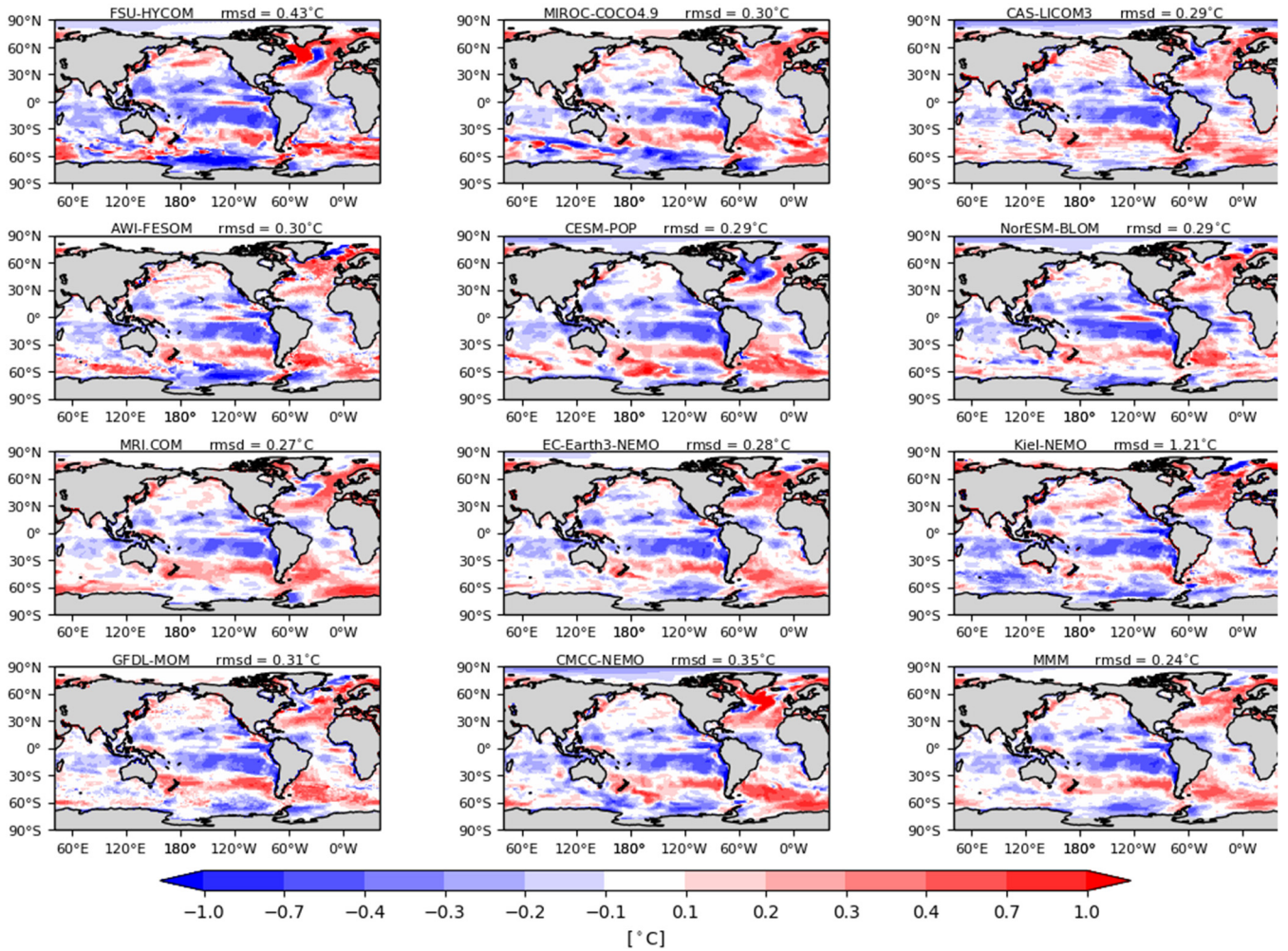


Figure S12: Difference of 30-year (1980–2009) mean SST between OMIP-1 and OMIP-2 simulations of individual models. Units are °C. Global root-mean-square difference is depicted on the top of each panel.

OMIP1 - WOA13v2 (SSS ave. from 1980 to 2009)

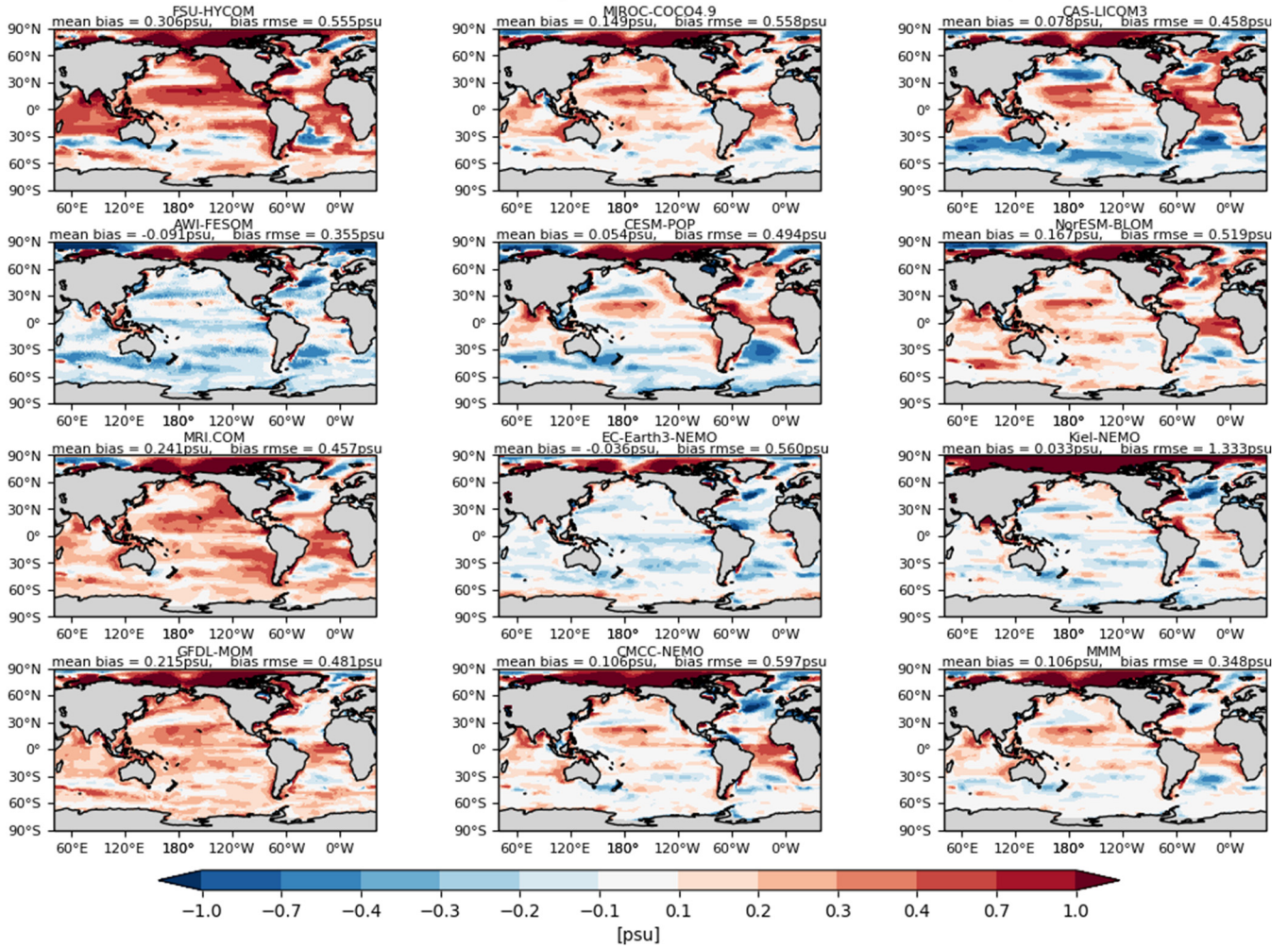
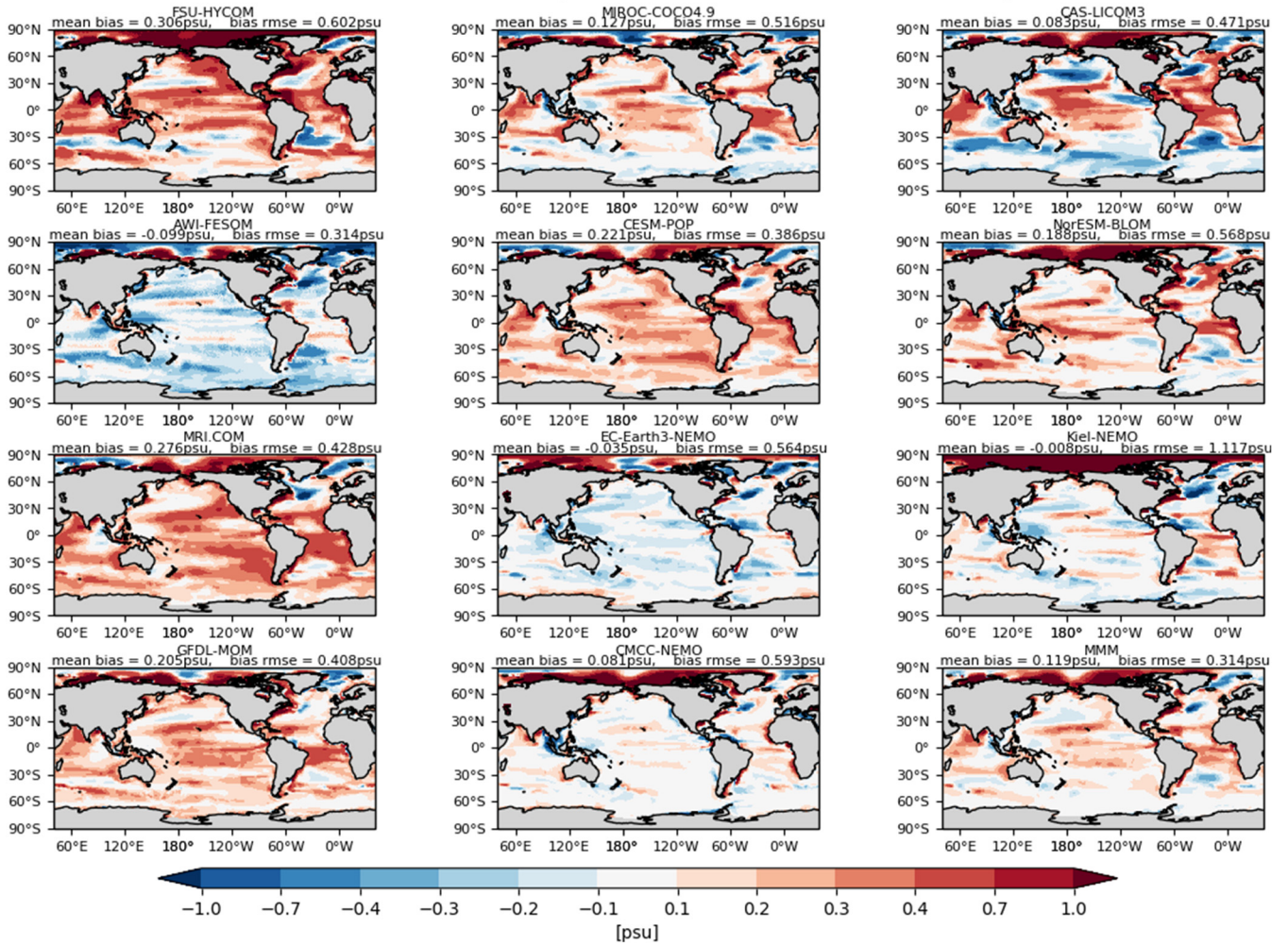


Figure S13: Bias of 30-year (1980–2009) mean sea surface salinity (SSS) of OMIP-1 simulations relative to WOA13v2 (Zweng et al. 2013). Units are psu. Global mean bias and global root-mean-square bias are depicted on the top of each panel.

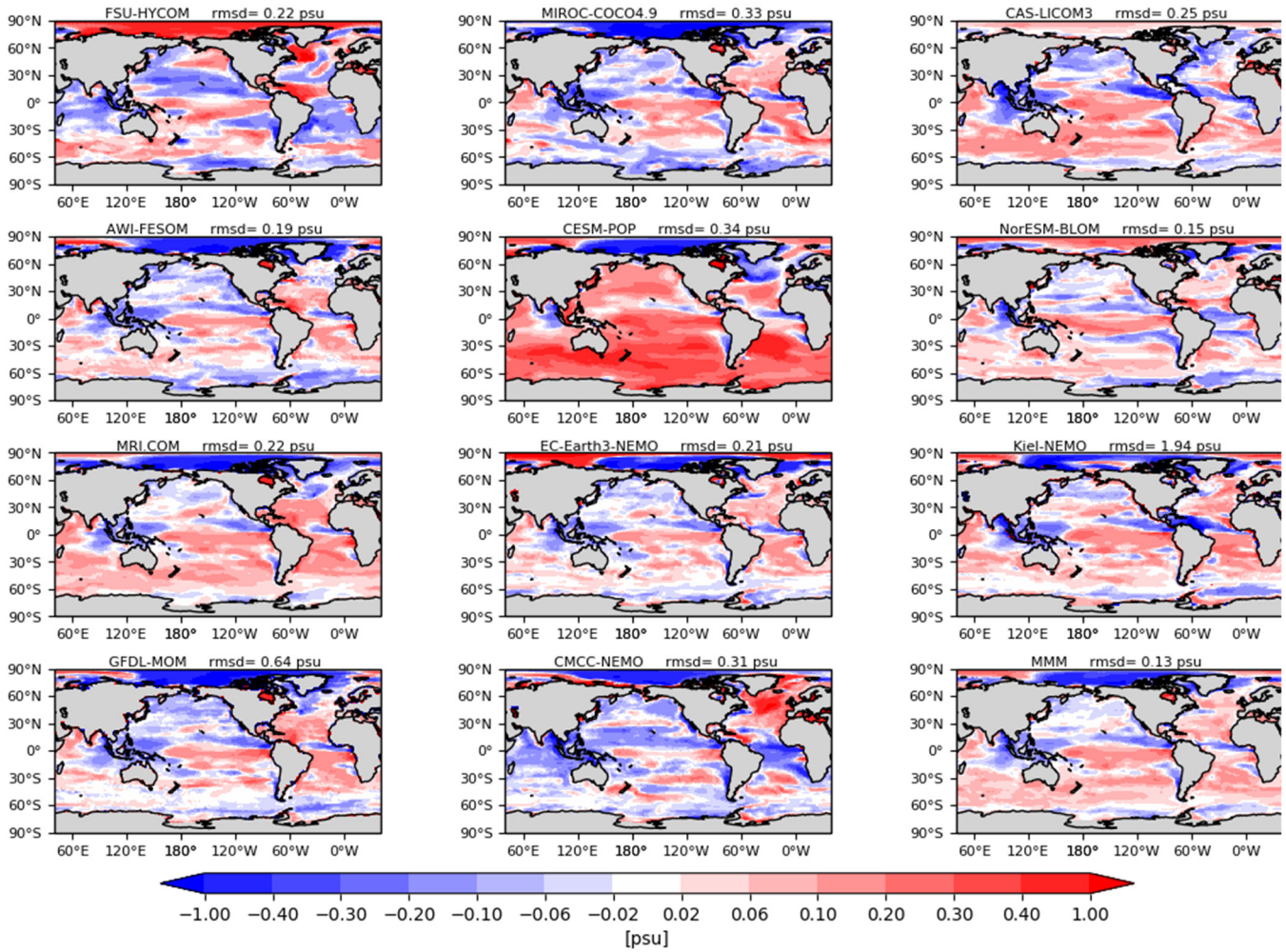
OMIP2 - WOA13v2 (SSS ave. from 1980 to 2009)



80

Figure S14: Same as Fig. S13 but for OMIP-2 simulations.

OMIP2 - OMIP1 (SSS ave. from 1980 to 2009)



85 **Figure S15: Difference of 30-year (1980–2009) mean SSS between OMIP-1 and OMIP-2 simulations of individual models. Units are psu. Global root-mean-square difference is depicted on the top of each panel.**

OMIP1 SICONC NH MAR (ave. from 1980 to 2009)



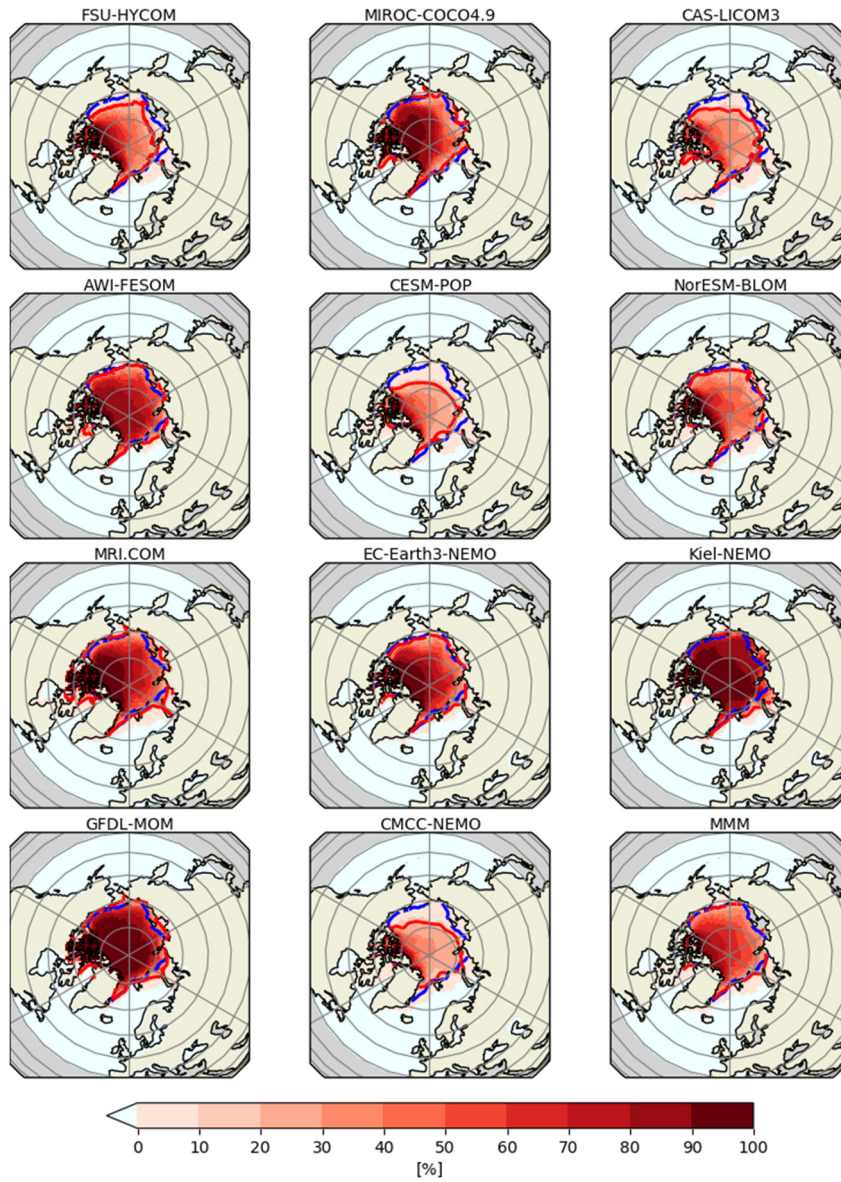
90 Figure S16: Thirty (30)-year (1980–2009) mean sea ice concentration (%) in March of northern hemisphere of OMIP-1 simulations. Blue lines are contours of 15 % concentration of an observational estimate from the PCMDI-SST dataset and red lines are those of the model.

OMIP2 SICONC NH MAR (ave. from 1980 to 2009)



Figure S17: Same as Fig. S16 but for OMIP-2 simulations. Blue and red lines as in Fig. S16.

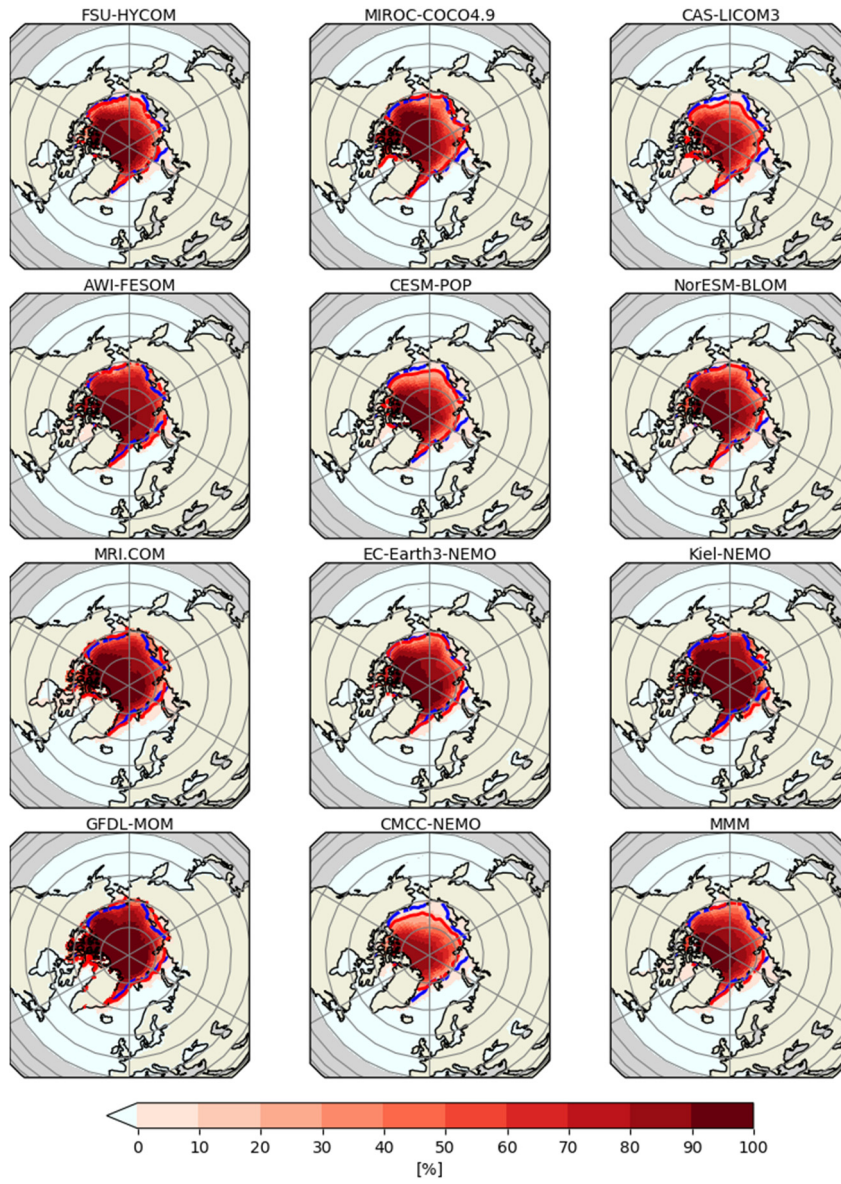
OMIP1 SICONC NH SEP (ave. from 1980 to 2009)



95

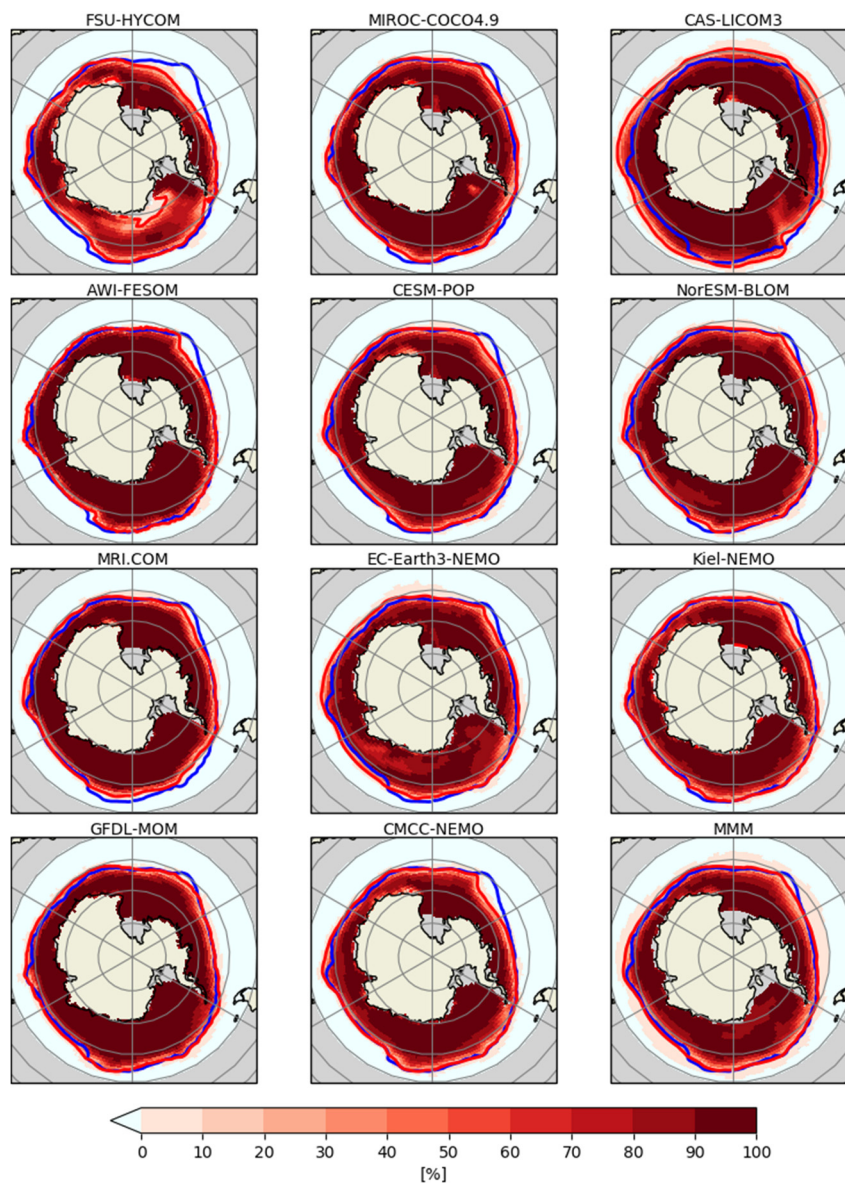
Figure S18: Thirty (30)-year (1980–2009) mean sea ice concentration (%) in September of northern hemisphere of OMIP-1 simulations. Blue and red lines as in Fig. S16.

OMIP2 SICONC NH SEP (ave. from 1980 to 2009)



100 Figure S19: Same as Fig. S18 but for OMIP-2 simulations. Blue and red lines as in Fig. S16.

OMIP1 SICONC SH SEP (ave. from 1980 to 2009)



105 **Figure S20: Thirty (30)-year (1980–2009) mean sea ice concentration (%) in September of southern hemisphere of OMIP-1 simulations. Blue lines are contours of 15 % concentration of an observational estimate from the PCMDI-SST dataset and red lines are those of the model.**

OMIP2 SICONC SH SEP (ave. from 1980 to 2009)

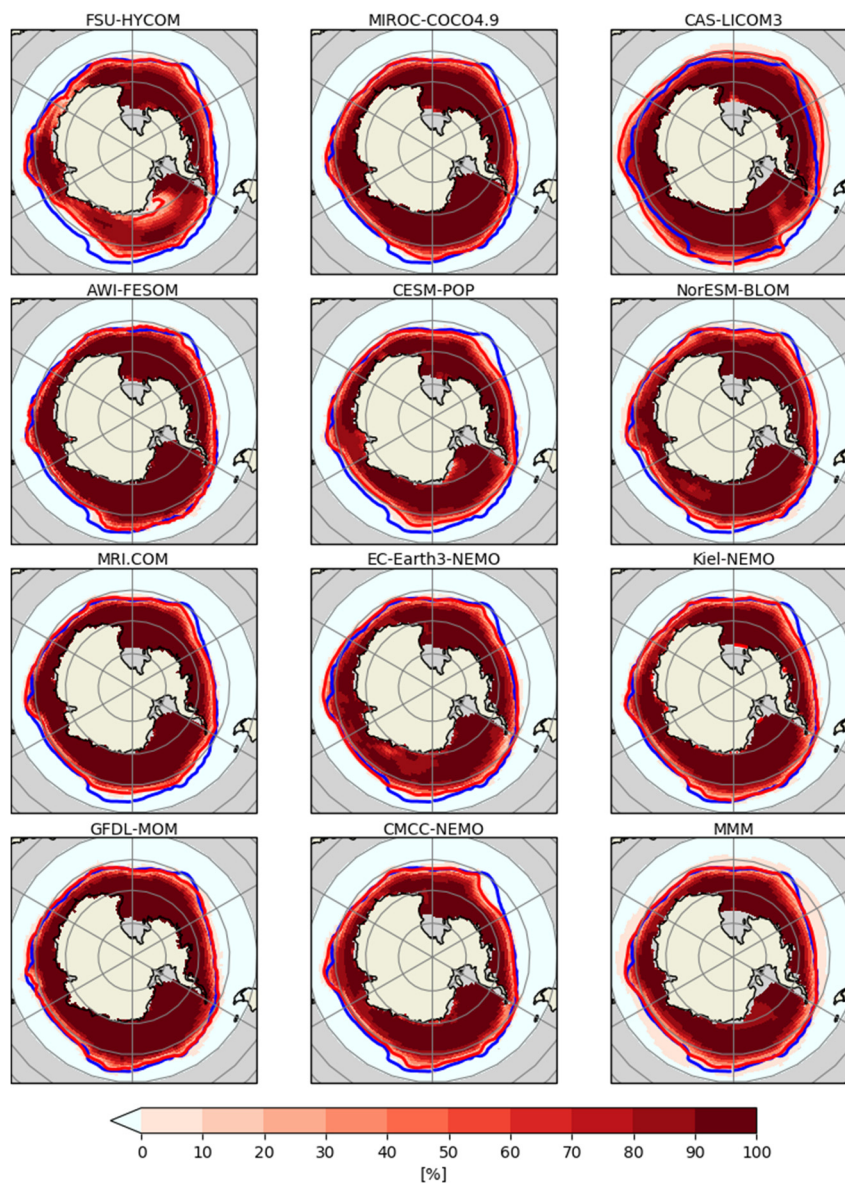


Figure S21: Same as Fig. S20 but for OMIP-2 simulations. Blue and red lines as in Fig. S20.

OMIP1 SICONC SH MAR (ave. from 1980 to 2009)

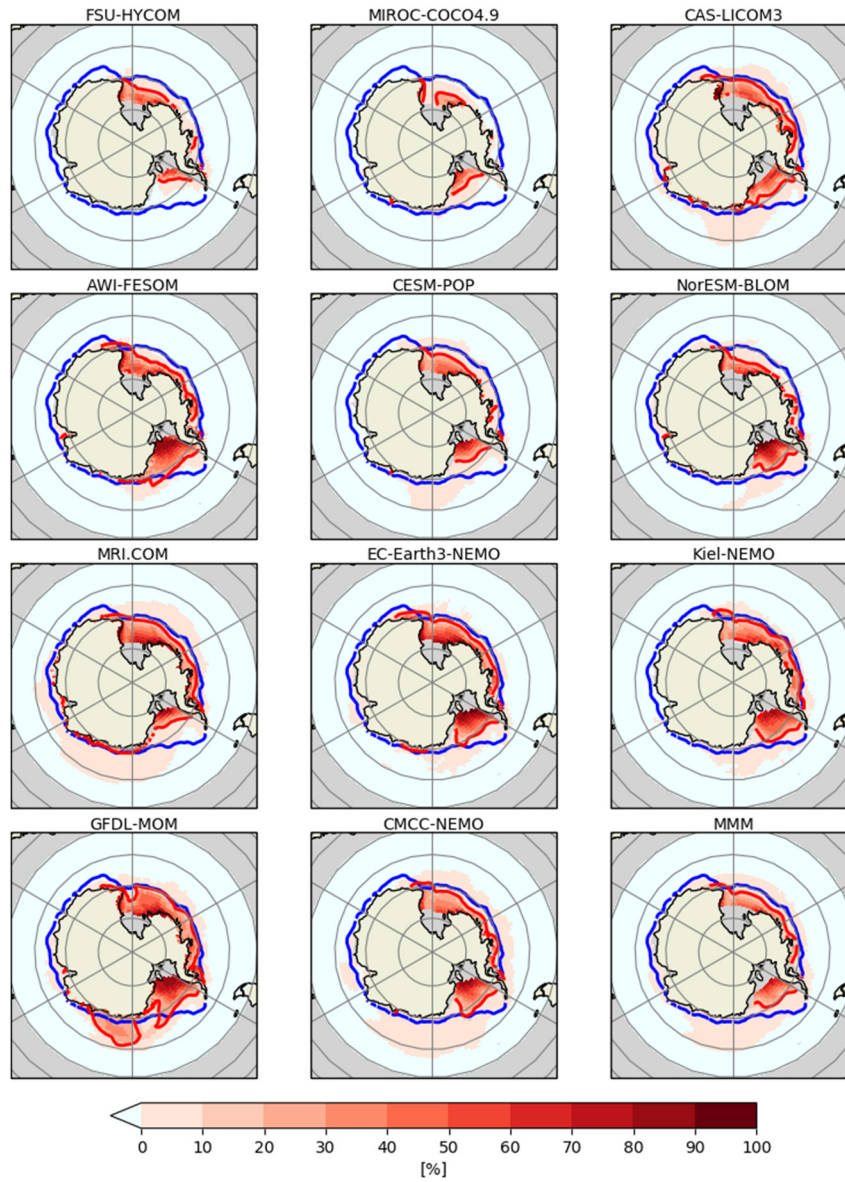
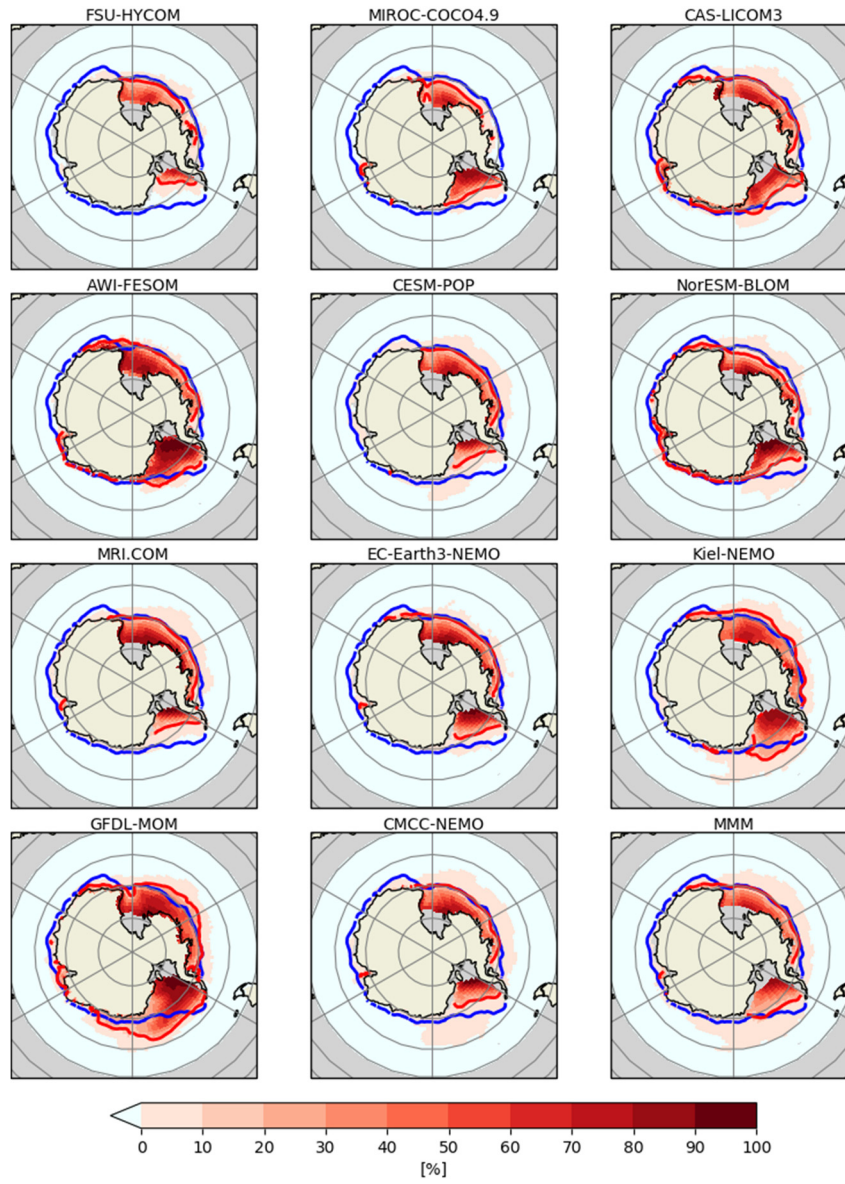


Figure S22: Thirty (30)-year (1980–2009) mean sea ice concentration (%) in March of southern hemisphere of OMIP-1 simulations. Blue and red lines as in Fig. S20.

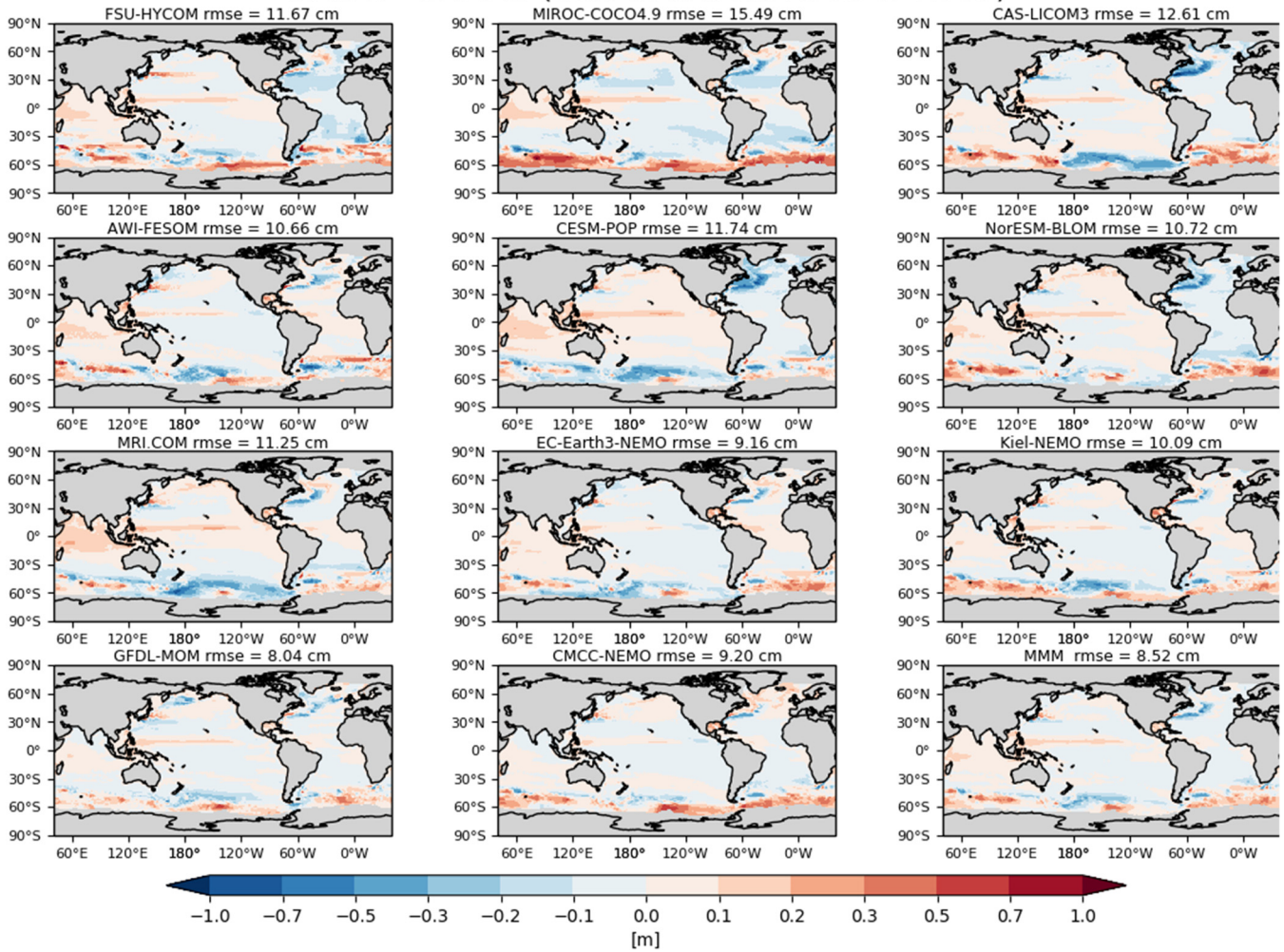
OMIP2 SICONC SH MAR (ave. from 1980 to 2009)



115

Figure S23: Same as Fig. S22 but for OMIP-2 simulations. Blue and red lines as in Fig. S20.

OMIP1 - CMEMS (SSH ave. from 1993 to 2009)



120 Figure S24: Bias of seventeen (17)-year (1993–2009) mean sea surface height (m) of OMIP-1 simulations relative to CMEMS. Global root-mean-square bias is depicted on the top of each panel.

OMIP2 - CMEMS (SSH ave. from 1993 to 2009)

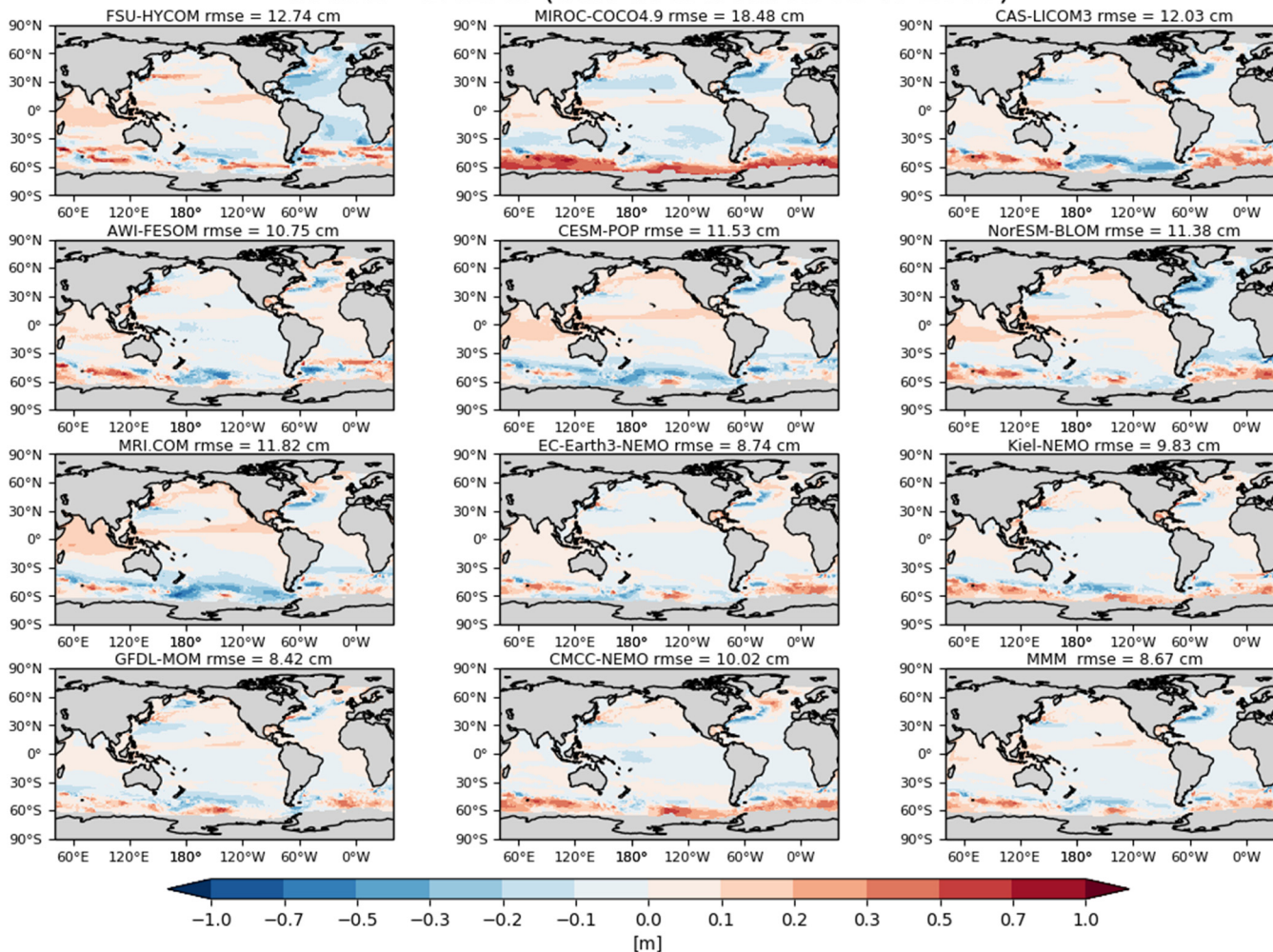
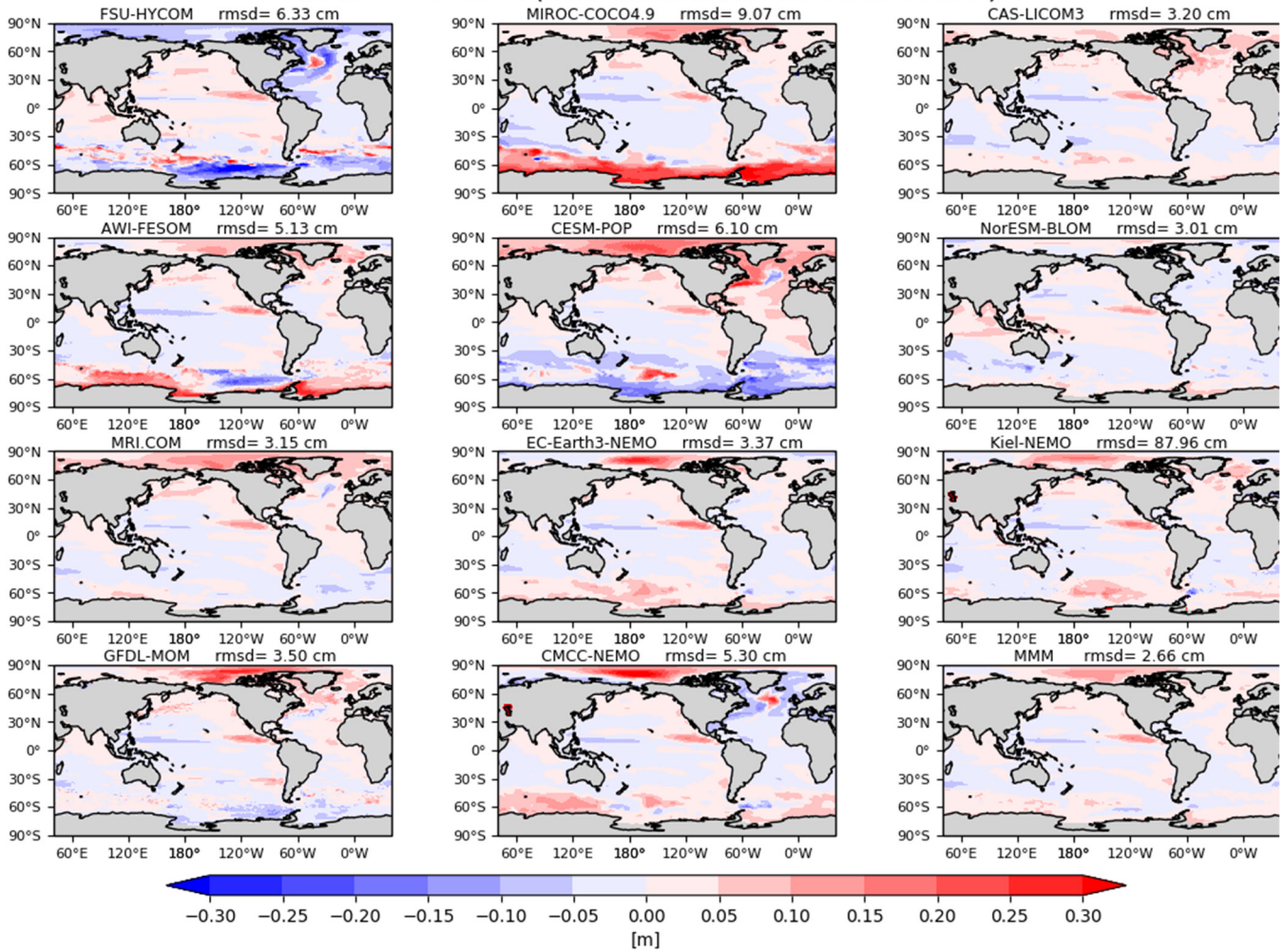


Figure S25: Same as Fig. S24 but for OMIP-2 simulations.

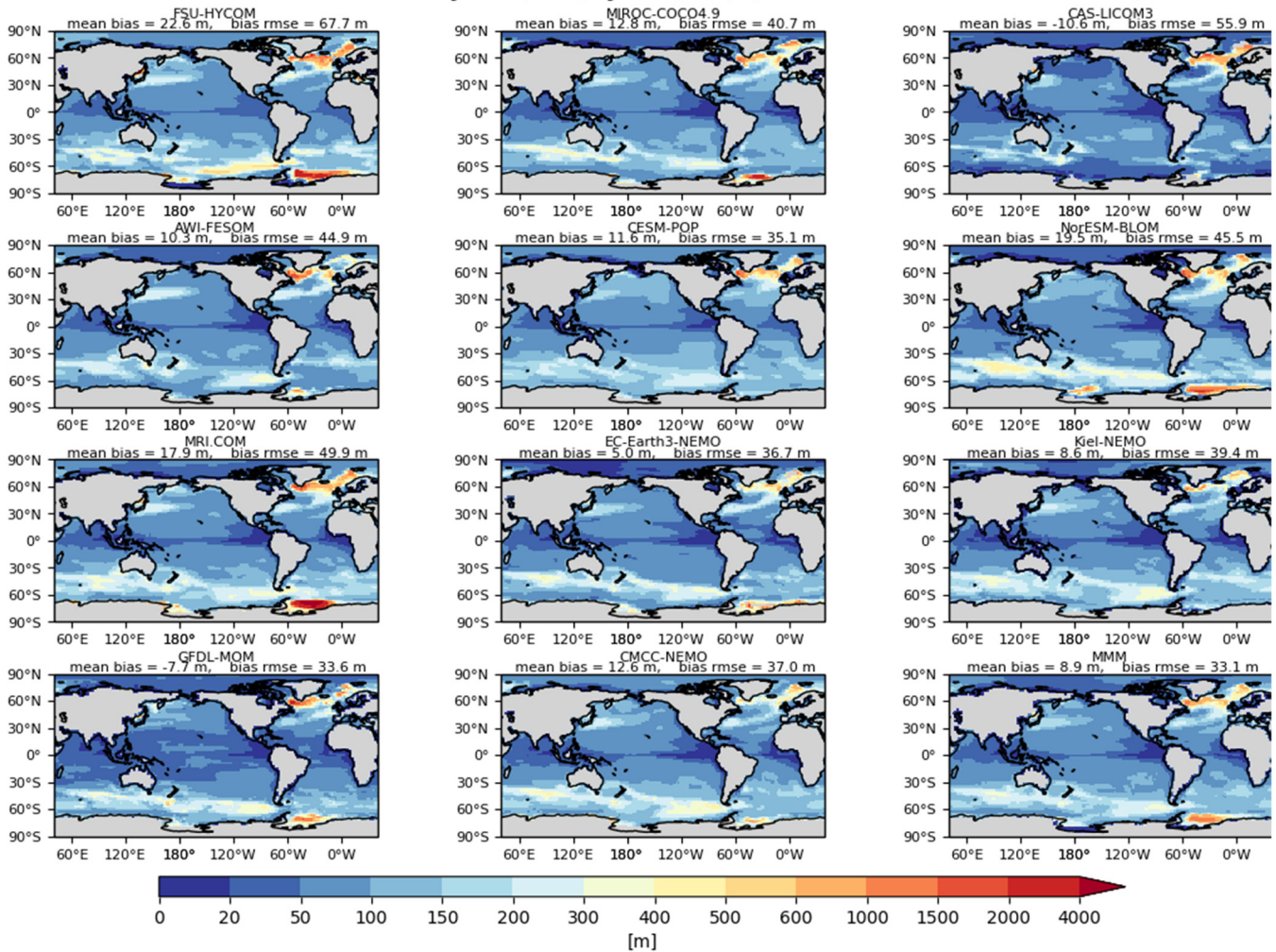
OMIP2 - OMIP1 (SSH ave. from 1993 to 2009)



125

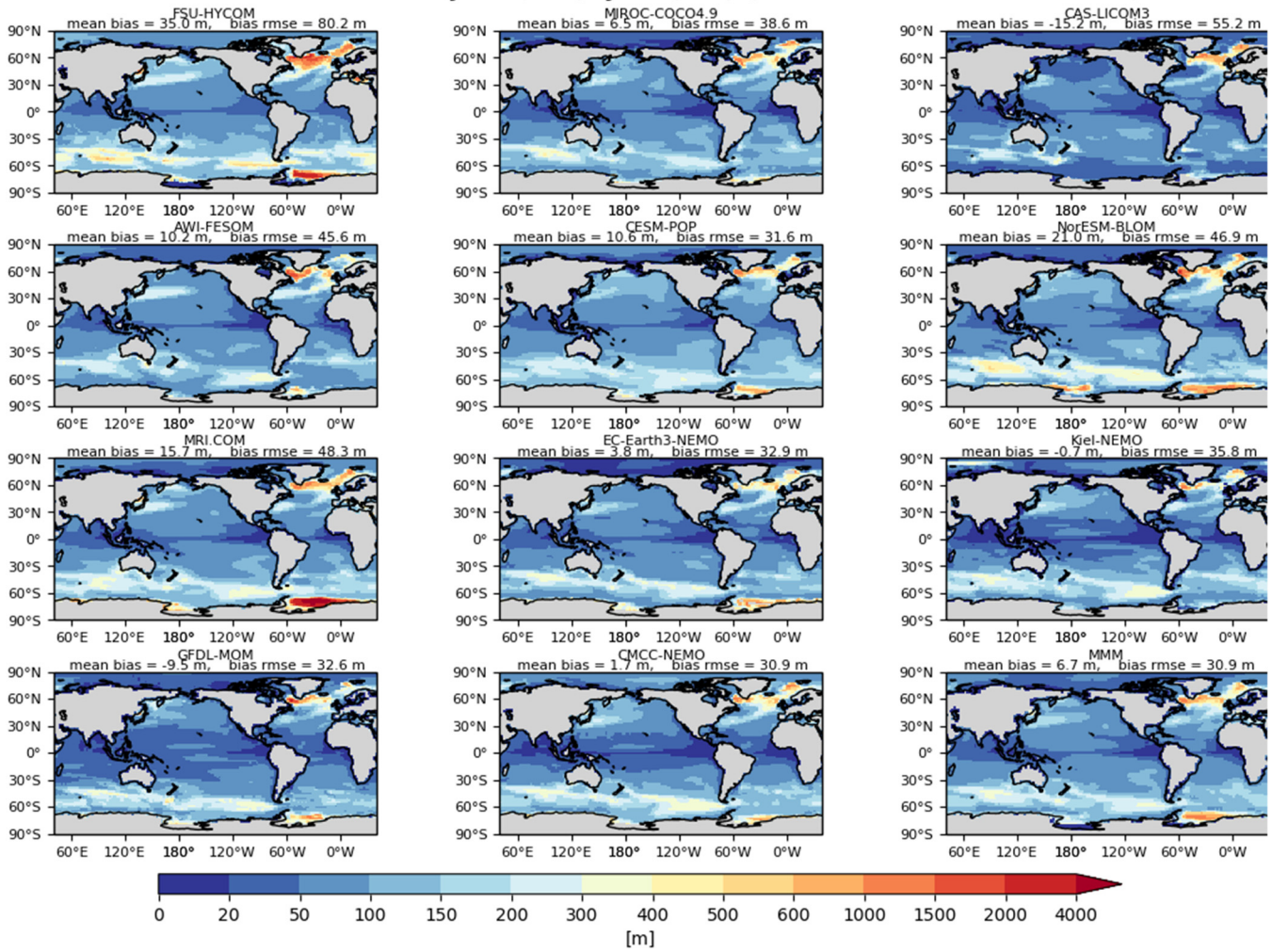
Figure S26: Difference of 17-year (1993–2009) mean sea surface height (m) between OMIP-1 and OMIP-2 simulations of individual models. Global root-mean-square difference is depicted on the top of each panel.

OMIP1 Winter MLD, JFM (NH), JAS (SH) (ave. from 1980 to 2009)



130 Figure S27: Thirty (30)-year (1980–2009) mean winter mixed layer depth (m) in both hemispheres of OMIP-1 simulations. January-February-March mean for the northern hemisphere and July-August-September mean for the southern hemisphere. On the top of each panel, global mean bias and global root-mean-square bias relative to observationally derived mixed layer depth data from de Boyer Montégut et al. (2004) are depicted.

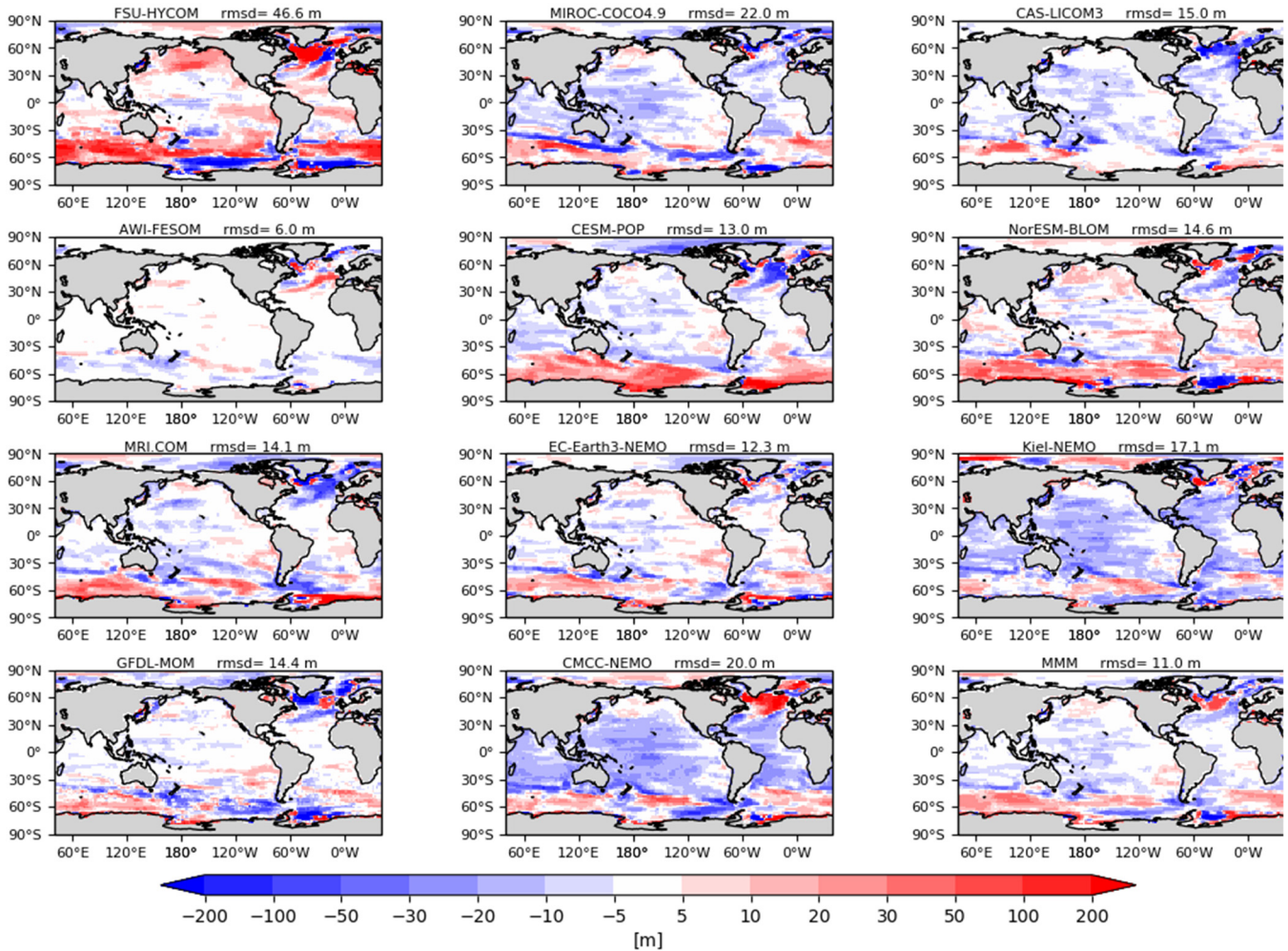
OMIP2 Winter MLD, JFM (NH), JAS (SH) (ave. from 1980 to 2009)



135

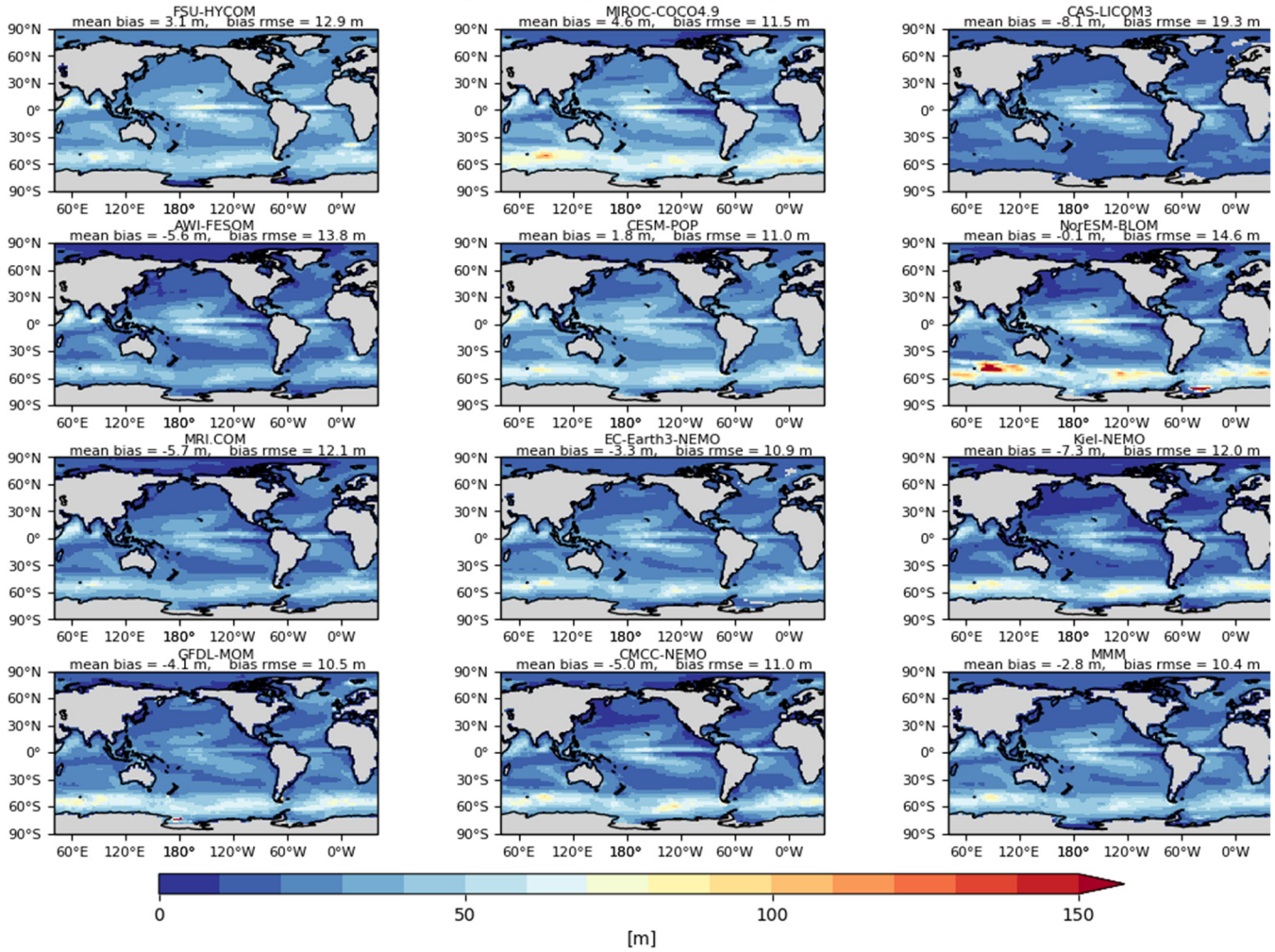
Figure S28: Same as Fig. S27 but for OMIP-2 simulations.

OMIP2 - OMIP1 Winter MLD, JFM (NH), JAS (SH) (ave. from 1980 to 2009)



140 Figure S29: Difference of 30-year (1980–2009) mean winter mixed layer depth (m) between OMIP-1 and OMIP-2 simulations (OMIP-2 minus OMIP-1) for individual models. Global root-mean-square difference is depicted on the top of each panel.

OMIP1 Summer MLD, JAS (NH), JFM (SH) (ave. from 1980 to 2009)



145 Figure S30: Thirty (30)-year (1980–2009) mean summer mixed layer depth (m) in both hemispheres of OMIP-1 simulations. July-August-September mean for the northern hemisphere and January-February-March mean for the southern hemisphere. On the top of each panel, global mean bias and global root-mean-square bias relative to observationally derived mixed layer depth data from de Boyer Montégut et al. (2004) are depicted.

OMIP2 Summer MLD, JAS (NH), JFM (SH) (ave. from 1980 to 2009)

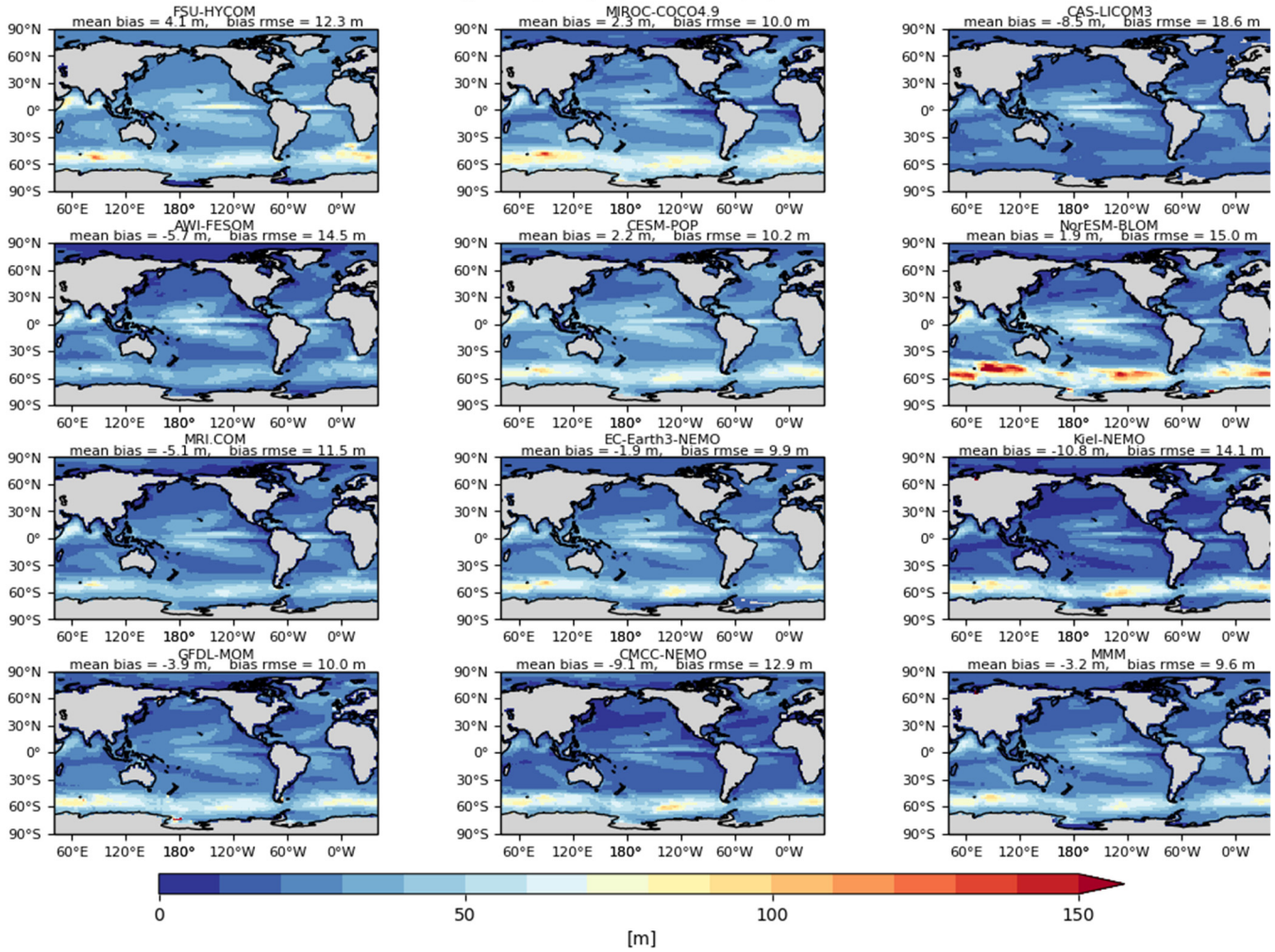


Figure S31: Same as Fig. S30 but for OMIP-2 simulations.

OMIP2 - OMIP1 Summer MLD, JAS (NH), JFM (SH) (ave. from 1980 to 2009)

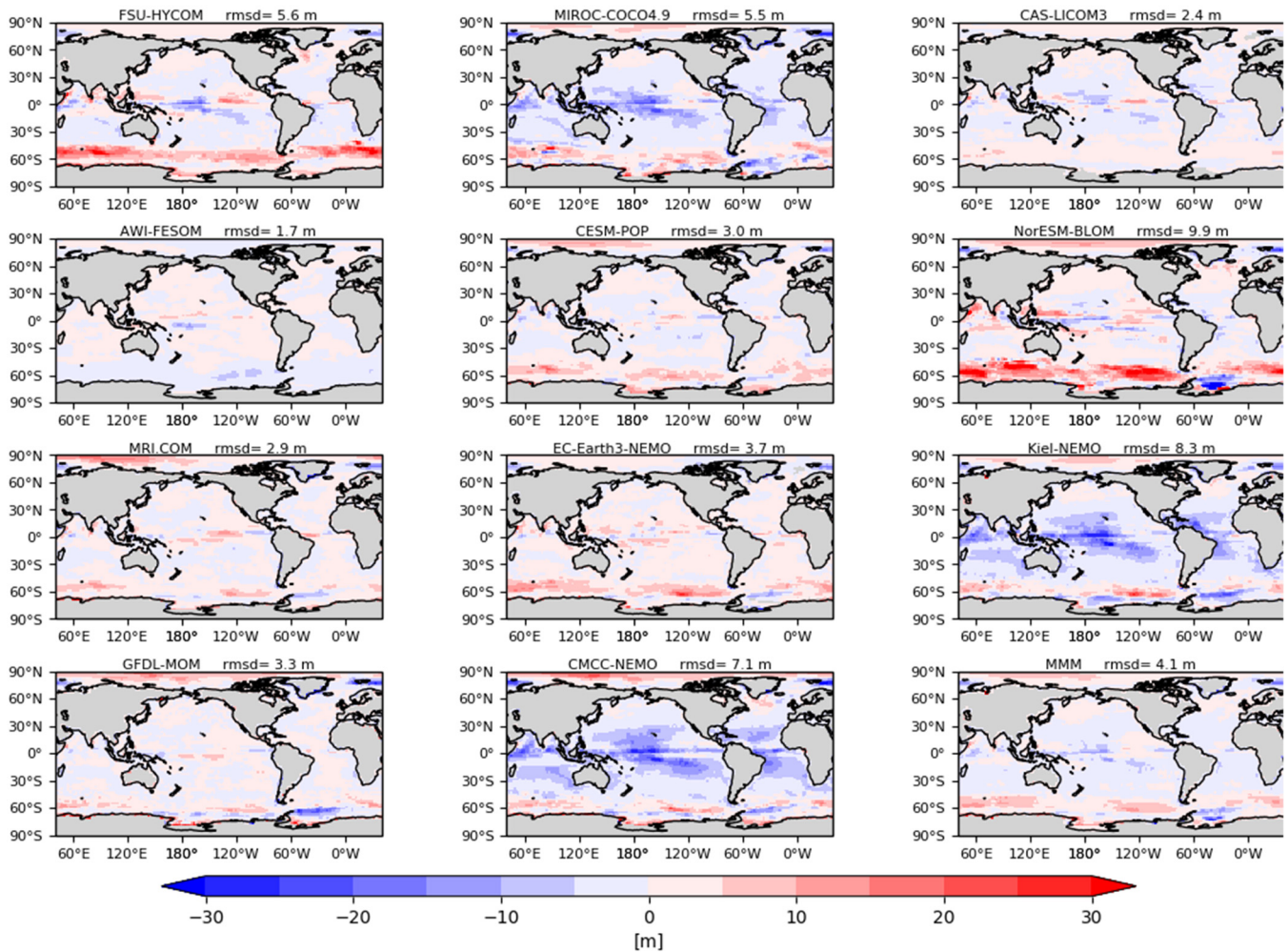
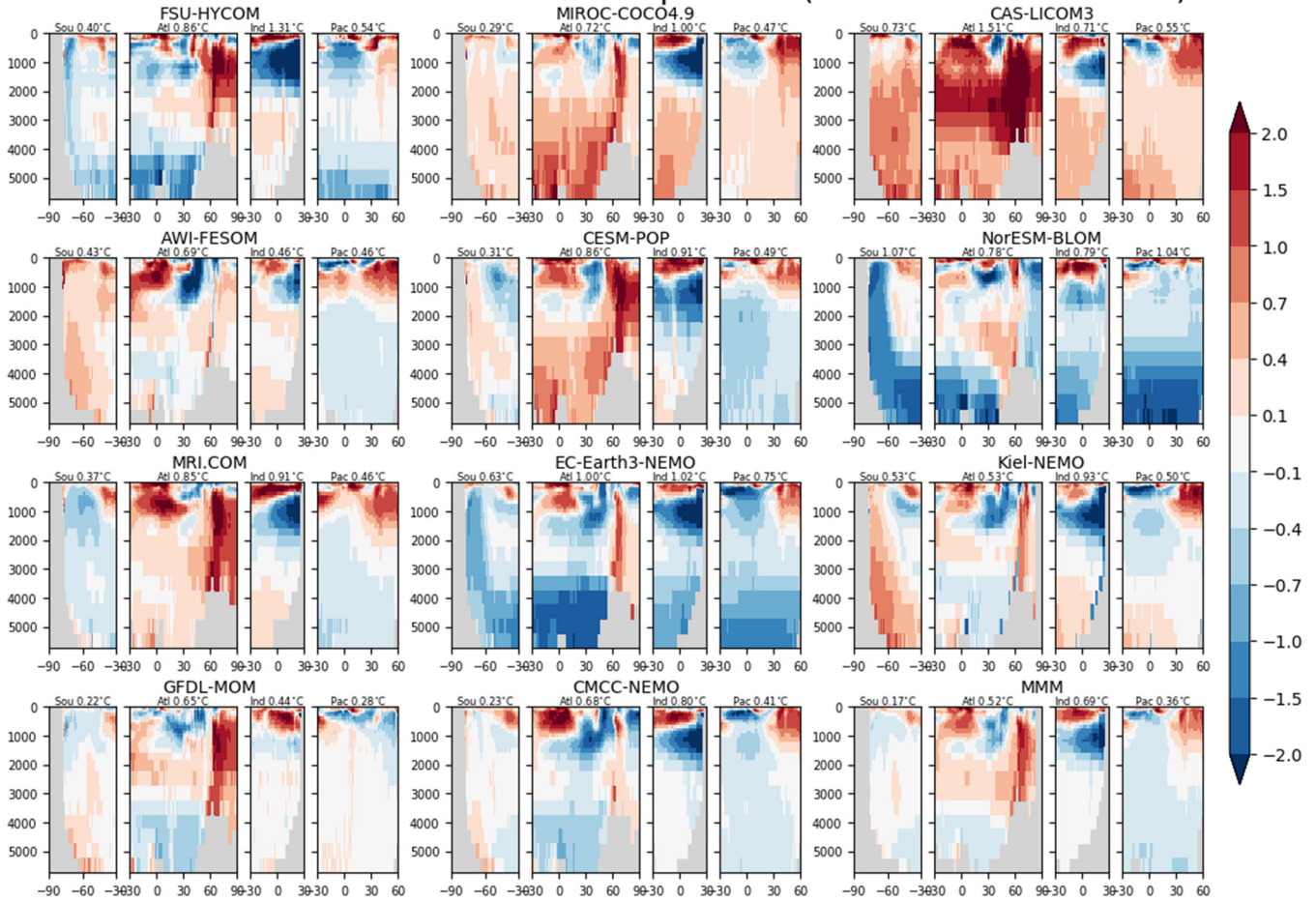


Figure S32: Difference of 30-year (1980–2009) mean summer mixed layer depth (m) between OMIP-1 and OMIP-2 simulations (OMIP-2 minus OMIP-1) for individual models. Global root-mean-square difference is depicted on the top of each panel.

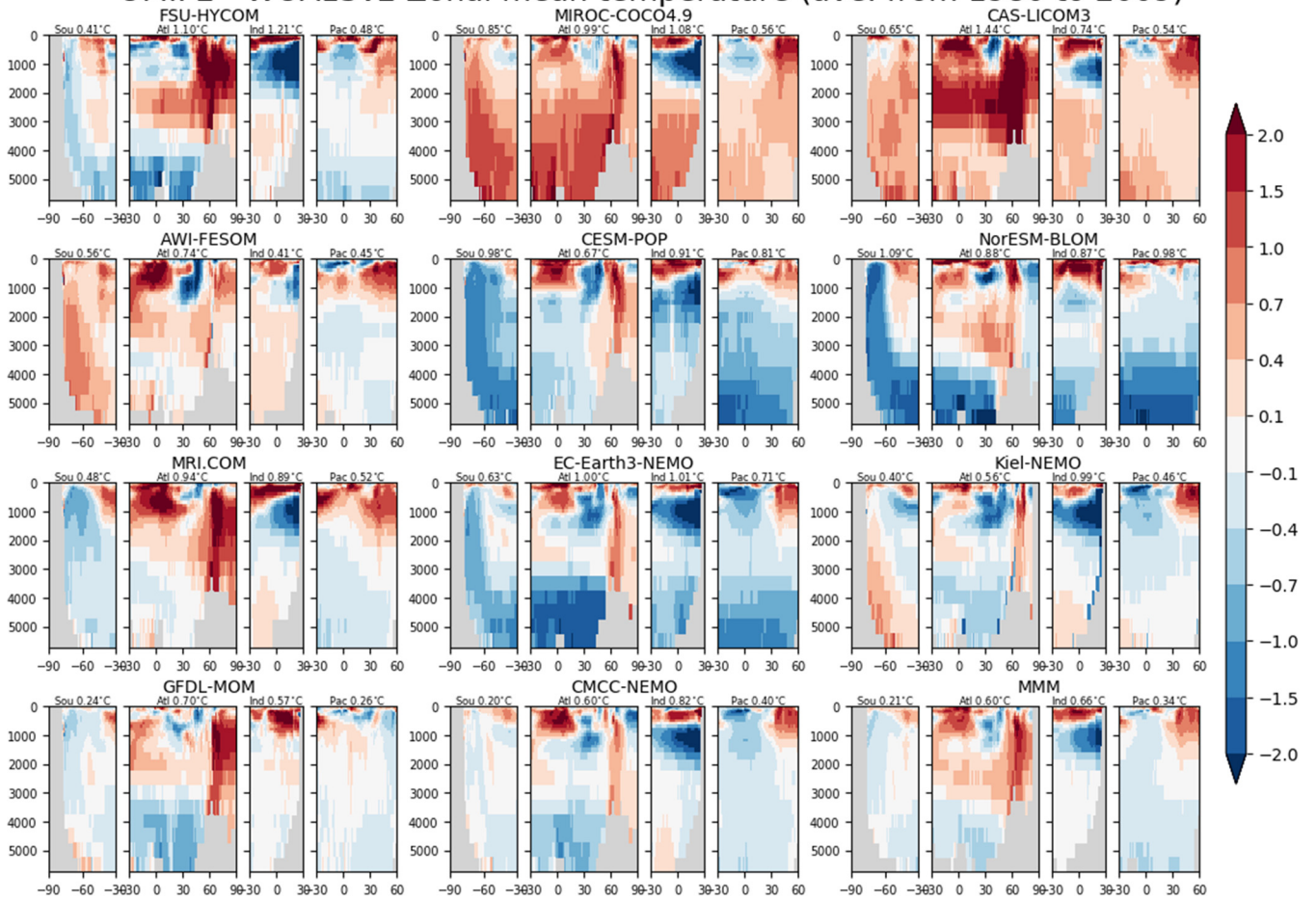
OMIP1 - WOA13v2 Zonal mean temperature (ave. from 1980 to 2009)



155

Figure S33: Bias of 30-year (1980–2009) mean basin-wide zonally averaged temperature (°C) of the last cycle of OMIP-1 simulations relative to WOA13v2 (Locarnini et al. 2013). Root-mean-square bias of each basin is depicted on the top of each panel.

OMIP2 - WOA13v2 Zonal mean temperature (ave. from 1980 to 2009)



160 Figure S34: Same as Fig. S33 but for OMIP-2 simulations.

OMIP2 - OMIP1 Zonal mean temperature (ave. from 1980 to 2009)

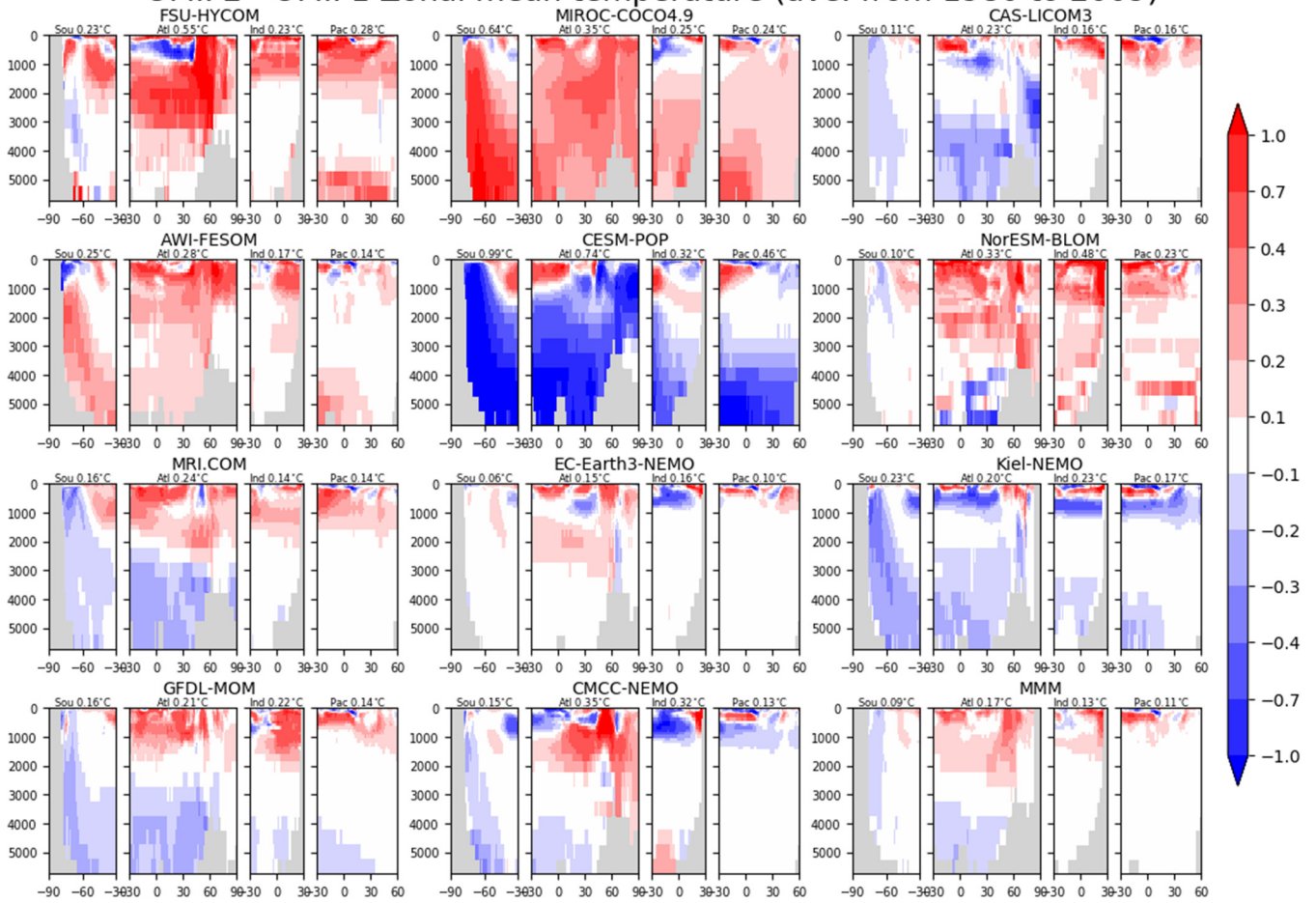


Figure S35: Difference of 30-year (1980–2009) mean basin-wide zonally averaged temperature (°C) of the last cycle between OMIP-1 and OMIP-2 simulations (OMIP-2 minus OMIP-1) for individual models. Root-mean-square difference of each basin is depicted on the top of each panel.

OMIP1 - WOA13v2 Zonal mean salinity (ave. from 1980 to 2009)

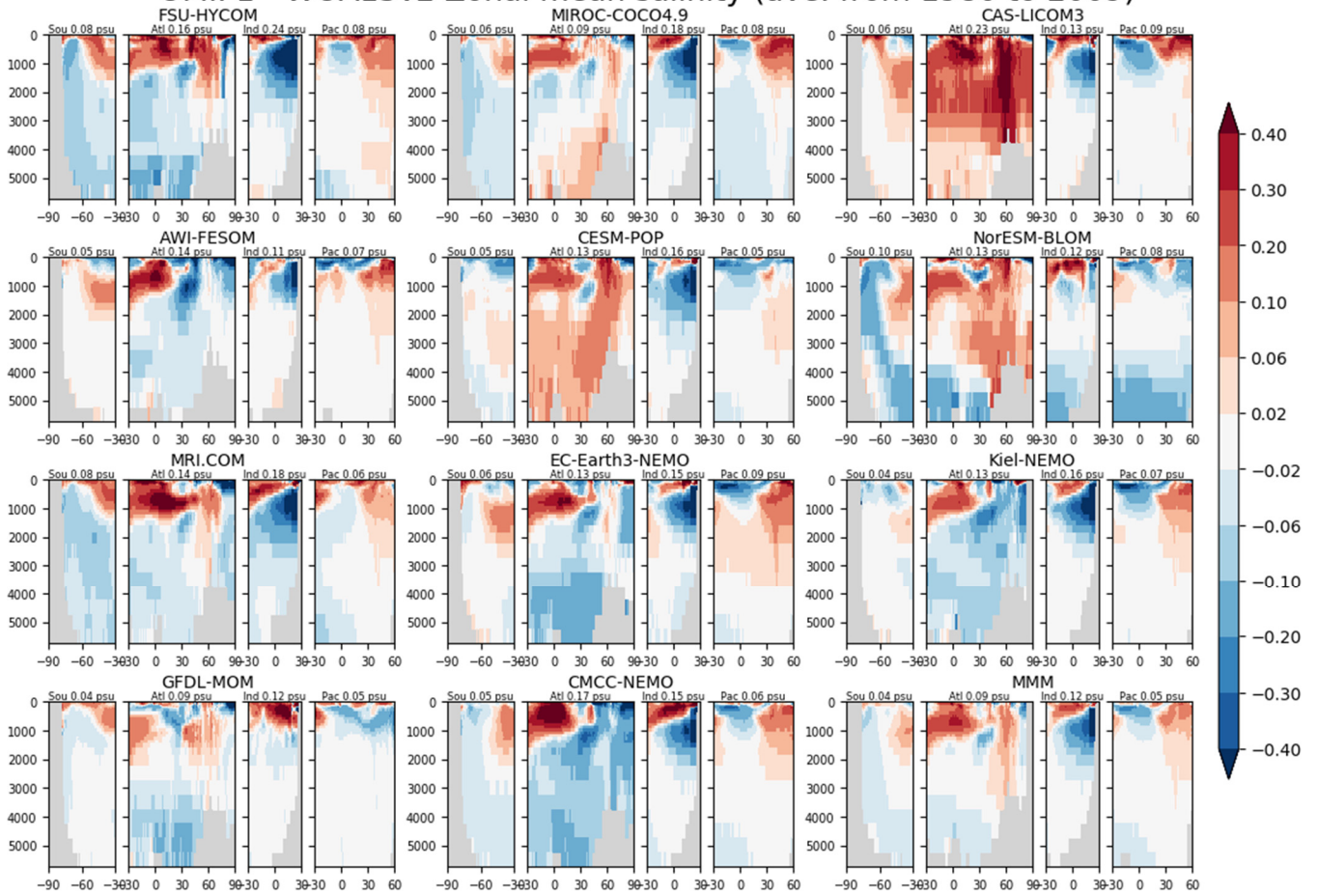


Figure S36: Bias of 30-year (1980–2009) mean basin-wide zonally averaged salinity (psu) of the last cycle of OMIP-1 simulations relative to WOA13v2 (Zweng et al. 2013). Root-mean-square bias of each basin is depicted on the top of each panel.

OMIP2 - WOA13v2 Zonal mean salinity (ave. from 1980 to 2009)

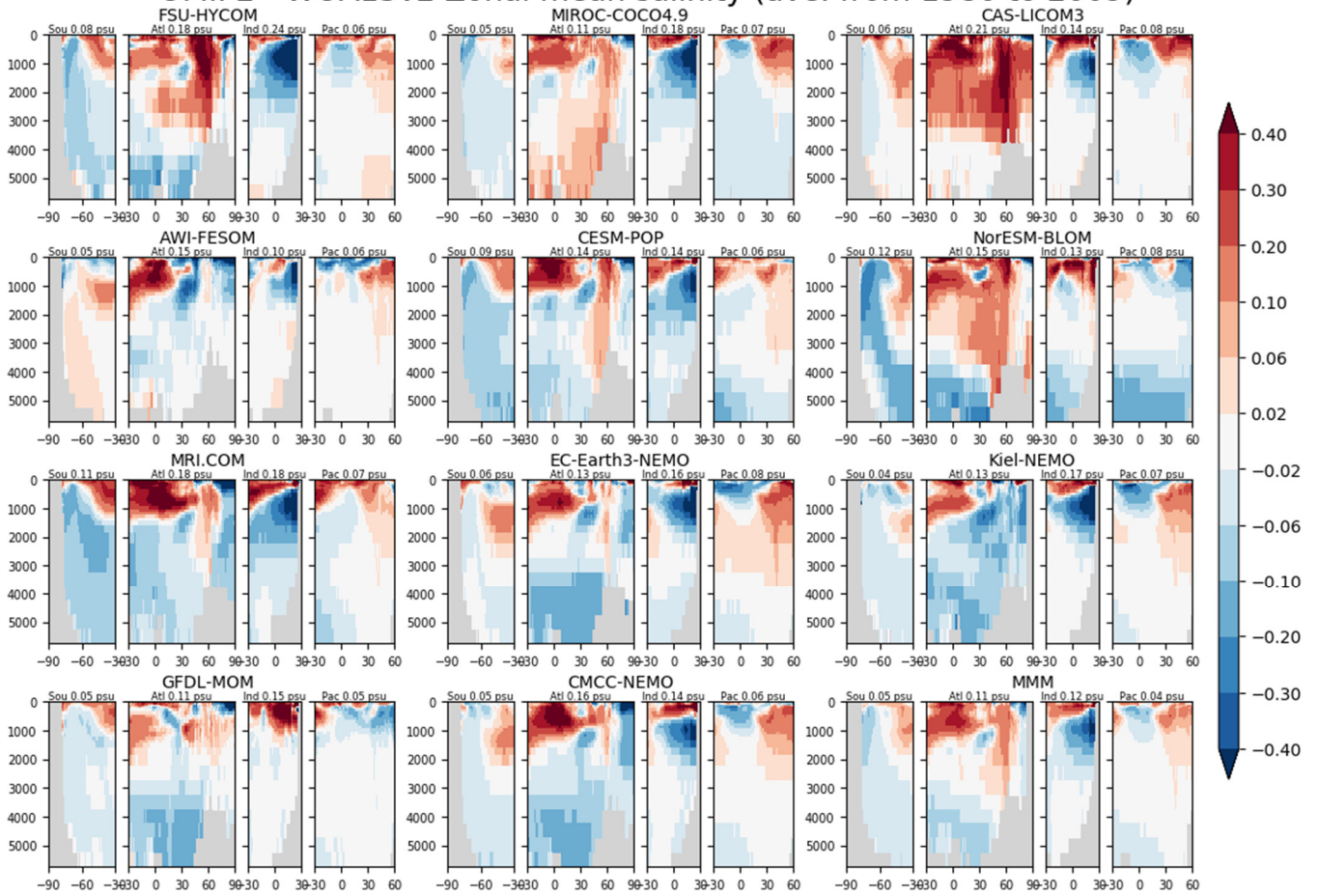
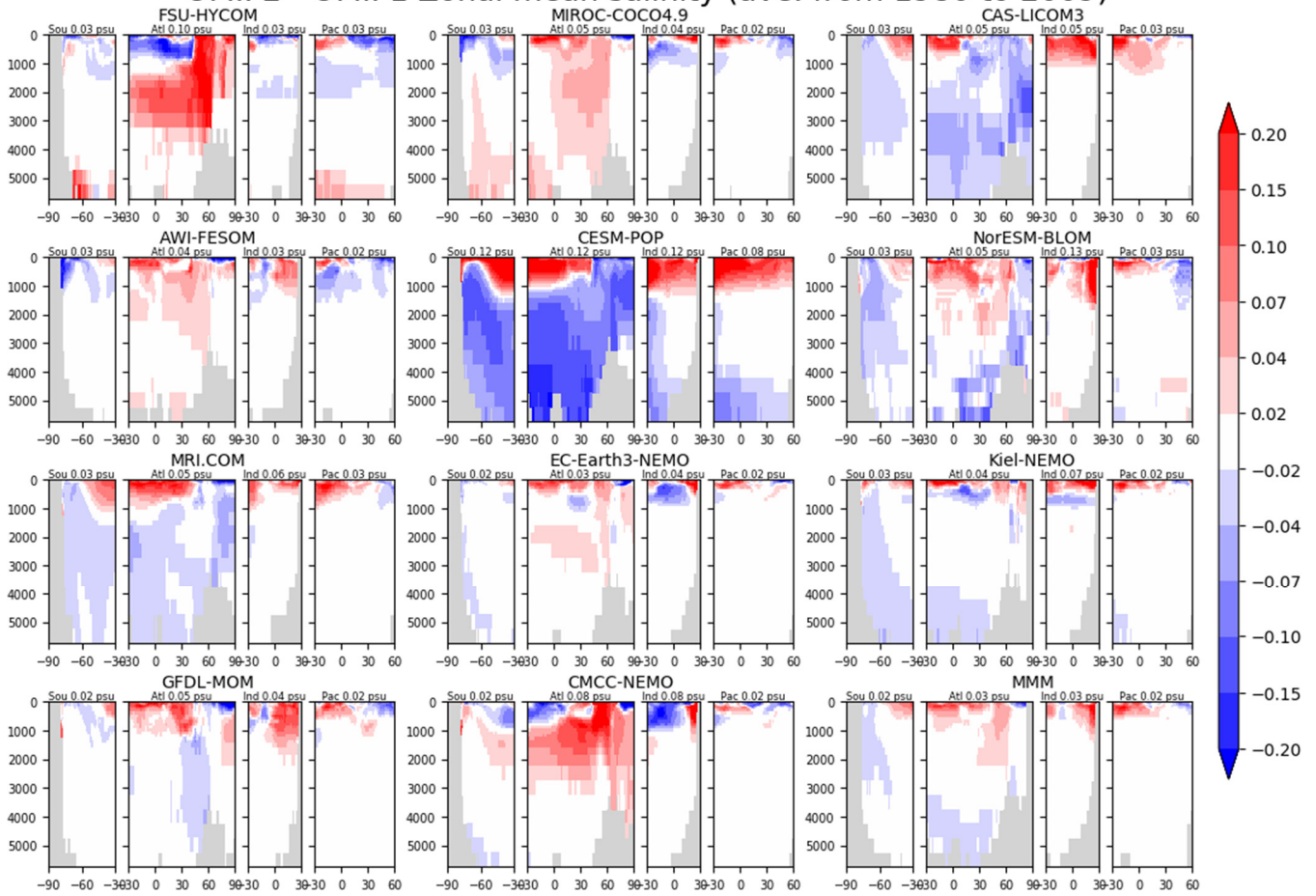


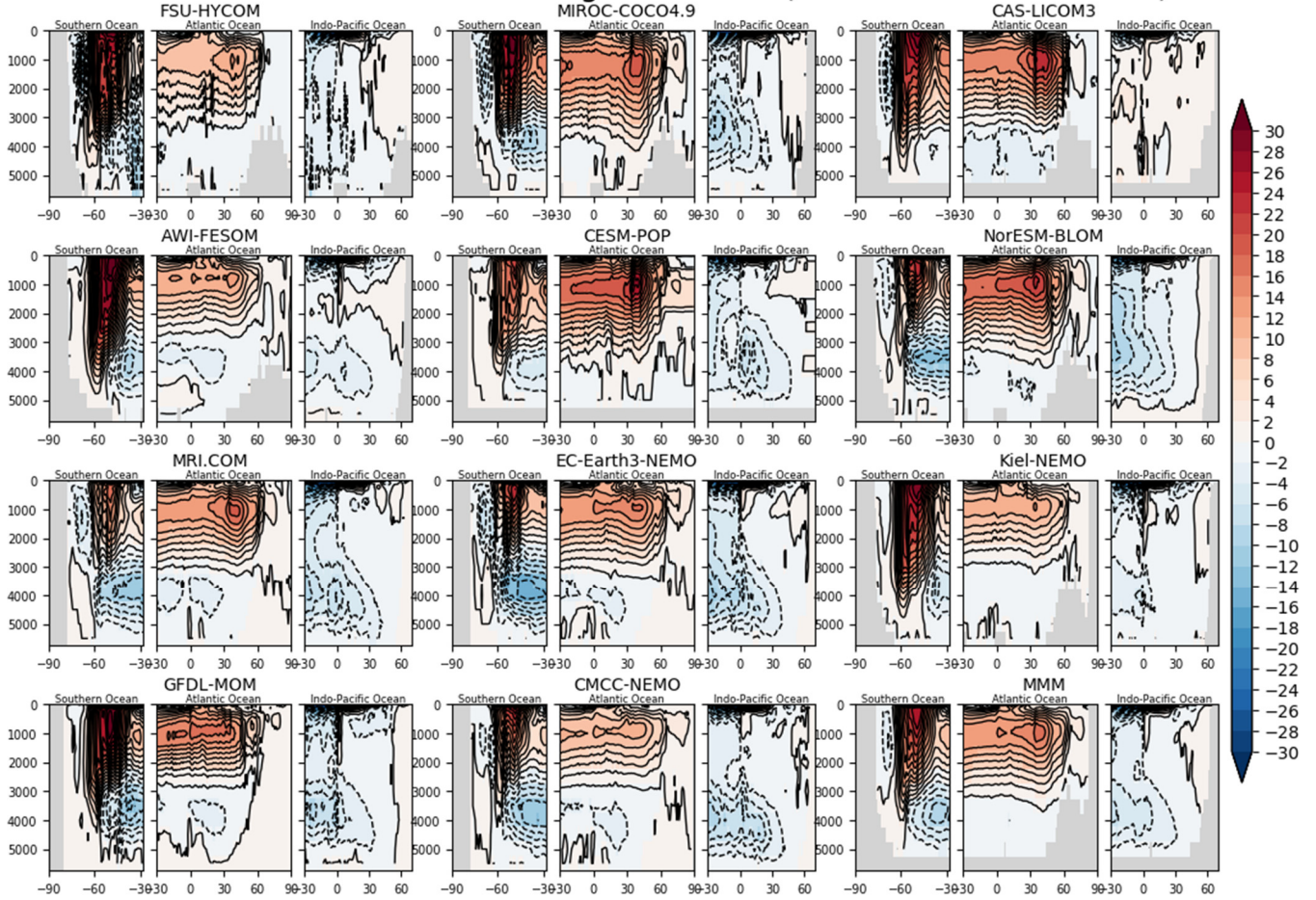
Figure S37: Same as Fig. S36 but for OMIP-2 simulations.

OMIP2 - OMIP1 Zonal mean salinity (ave. from 1980 to 2009)



175 **Figure S38: Difference of 30-year (1980–2009) mean basin-wide zonally averaged salinity (psu) of the last cycle between OMIP-1 and OMIP-2 simulations (OMIP-2 minus OMIP-1) for individual models. Root-mean-square difference of each basin is depicted on the top of each panel.**

OMIP1 Meridional Overturning Circulation (ave. from 1980 to 2009)



180 Figure S39: Thirty (30)-year (1980–2009) mean meridional overturning stream function in three oceanic basins of OMIP-1 simulations. Units are 10^9 kg s^{-1} . Clockwise circulations are implied around the positive extremes and vice versa.

OMIP2 Meridional Overturning Circulation (ave. from 1980 to 2009)

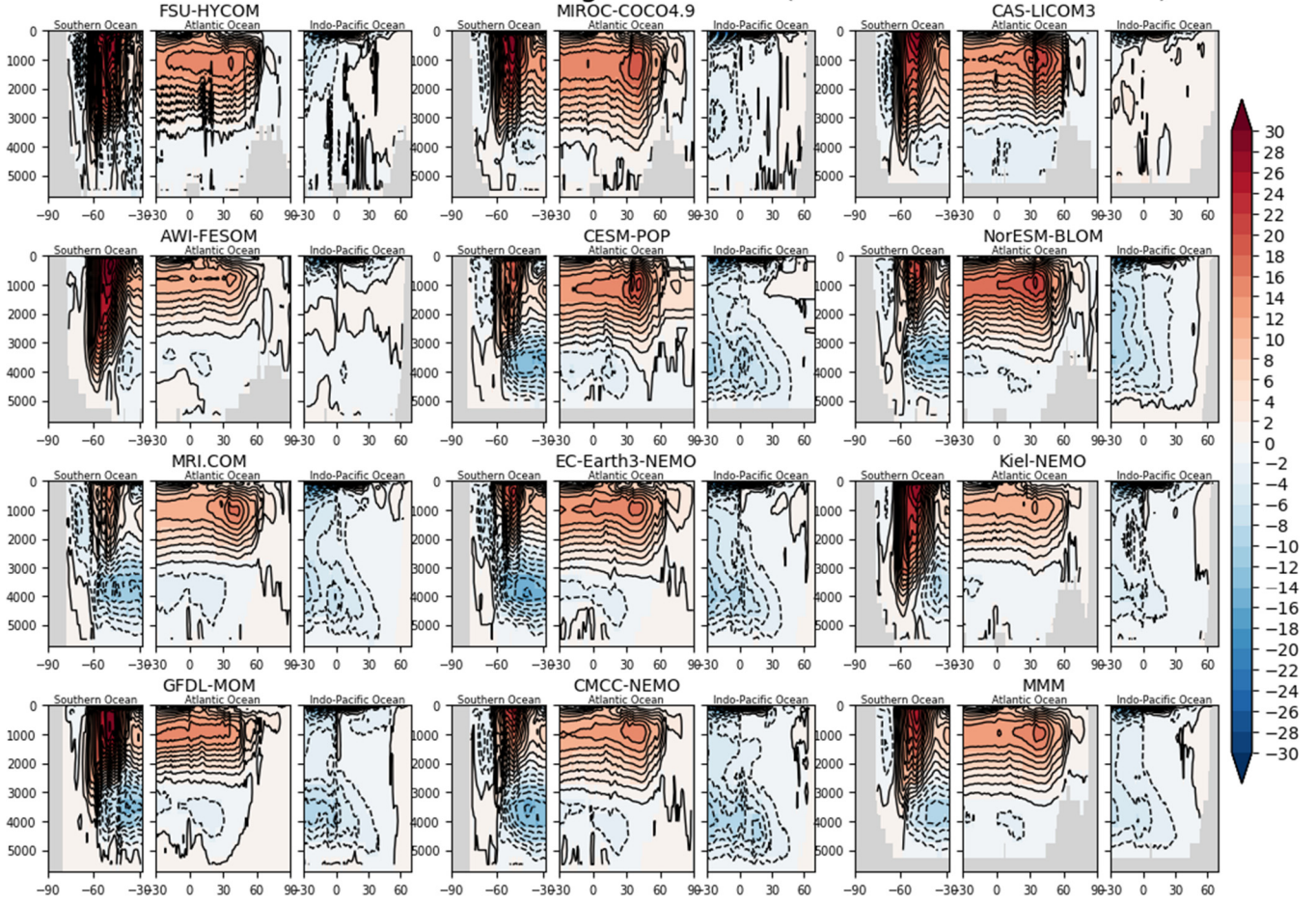


Figure S40: Same Fig. S39 but for OMIP-2 simulations.

OMIP2 - OMIP1 Meridional Overturning Circulation (ave. from 1980 to 2009)

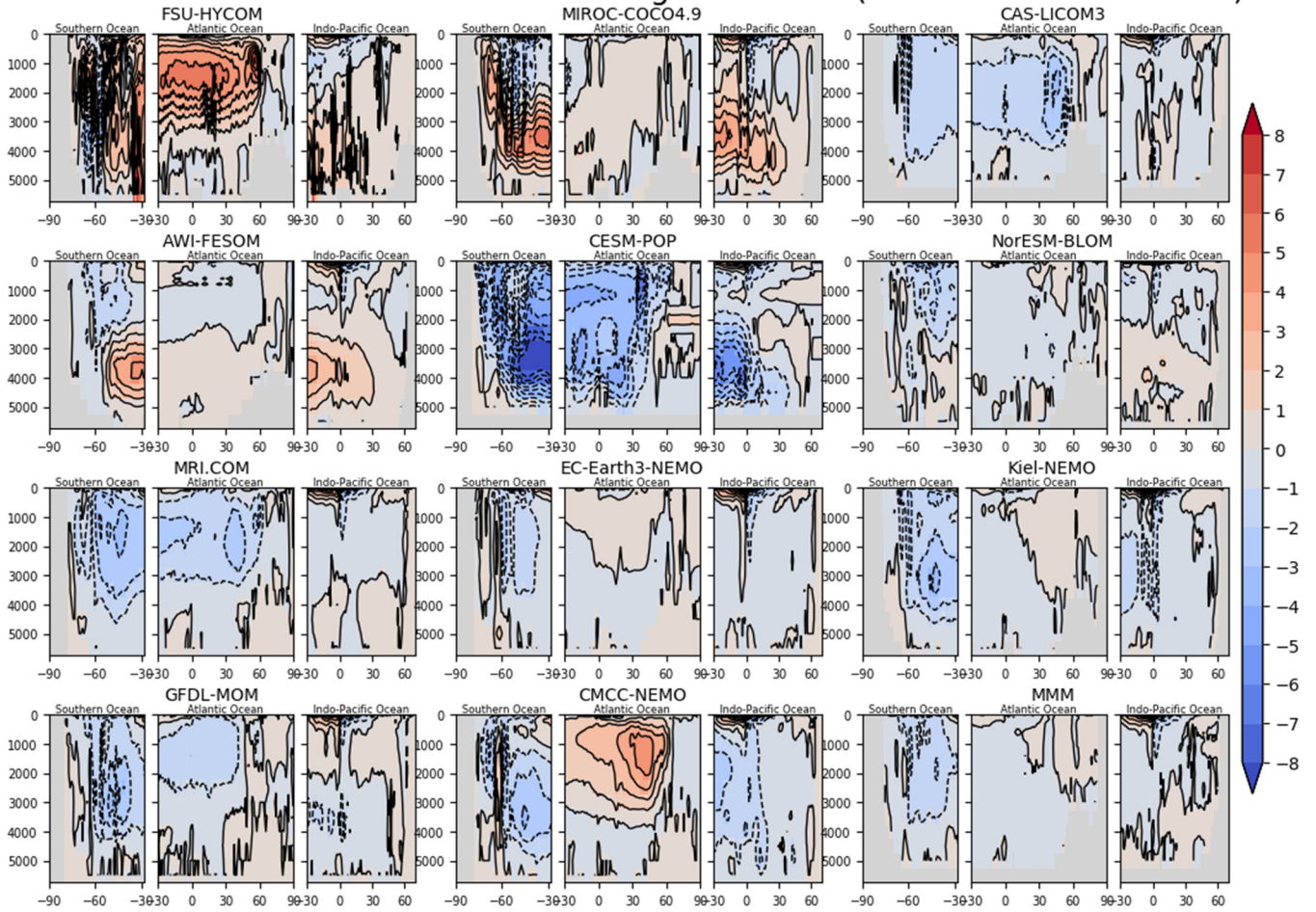
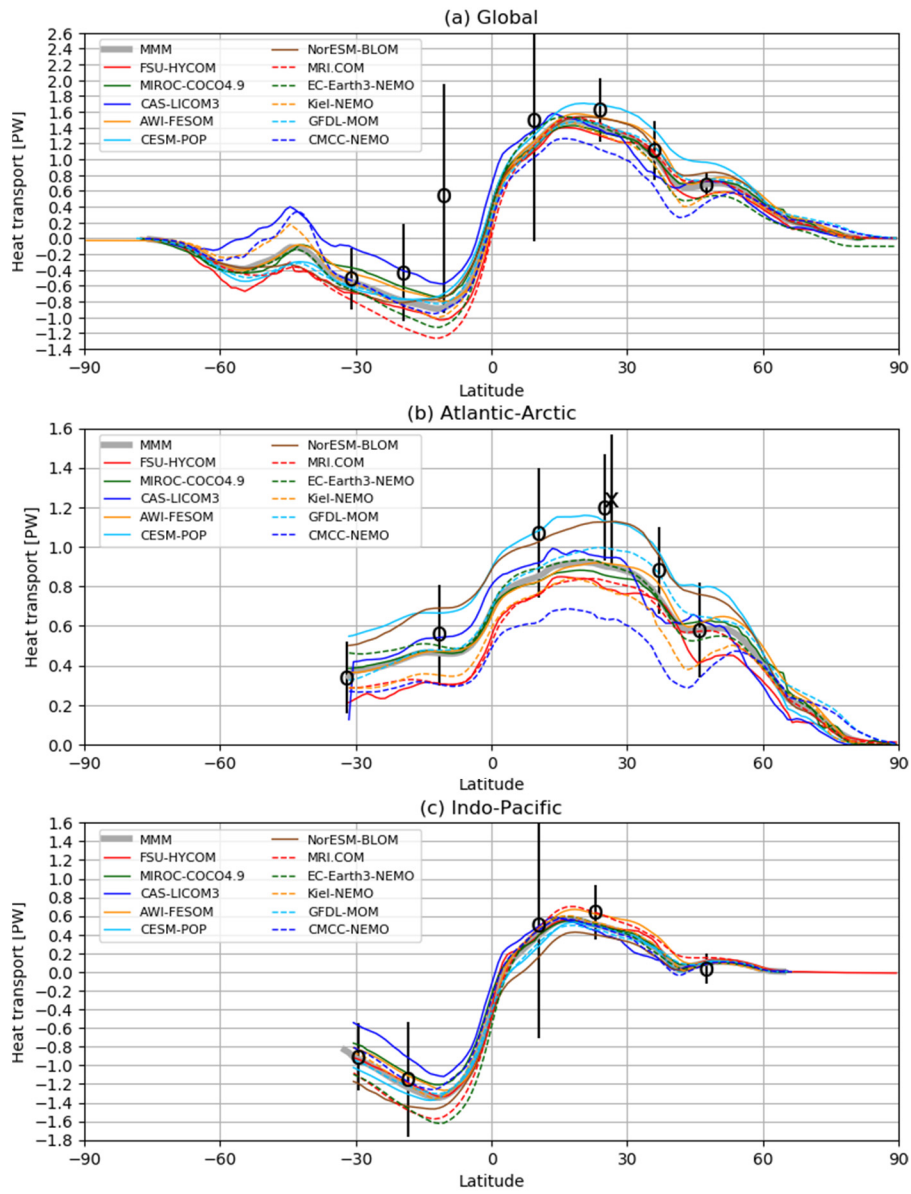


Figure S41: Difference of 30-year (1980–2009) mean meridional overturning stream function in three oceanic basins between OMIP-2 and OMIP-1 (OMIP-2 minus OMIP-1). Units are 10^9 kg s^{-1} .

OMIP1 (northward heat transport ave. from 1988 to 2007)



190

Figure S42: Twenty (20)-year (1988–2007) mean northward heat transport ($\text{PW} = 10^{15} \text{ W m}^{-2}$) in three oceanic basins of OMIP-1 simulations. (a) Global, (b) Atlantic-Arctic, and (c) Indo-Pacific Ocean basins. The open circles are estimates from observations and assimilations compiled by Macdonald and Baringer (2013). The cross at 26.5°N in the Atlantic is an estimation from RAPID transport array reported by McDonagh et al. (2015).

195

OMIP2 (northward heat transport ave. from 1988 to 2007)

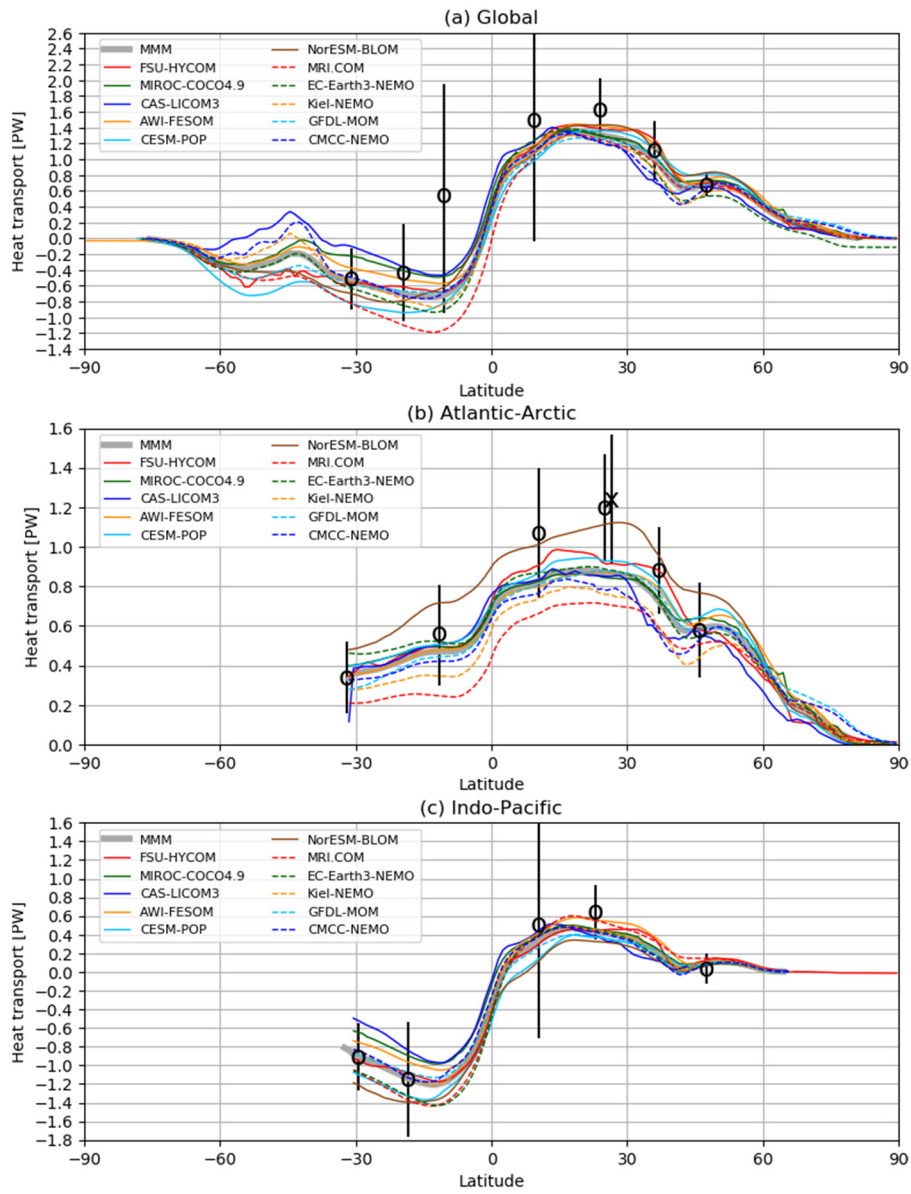
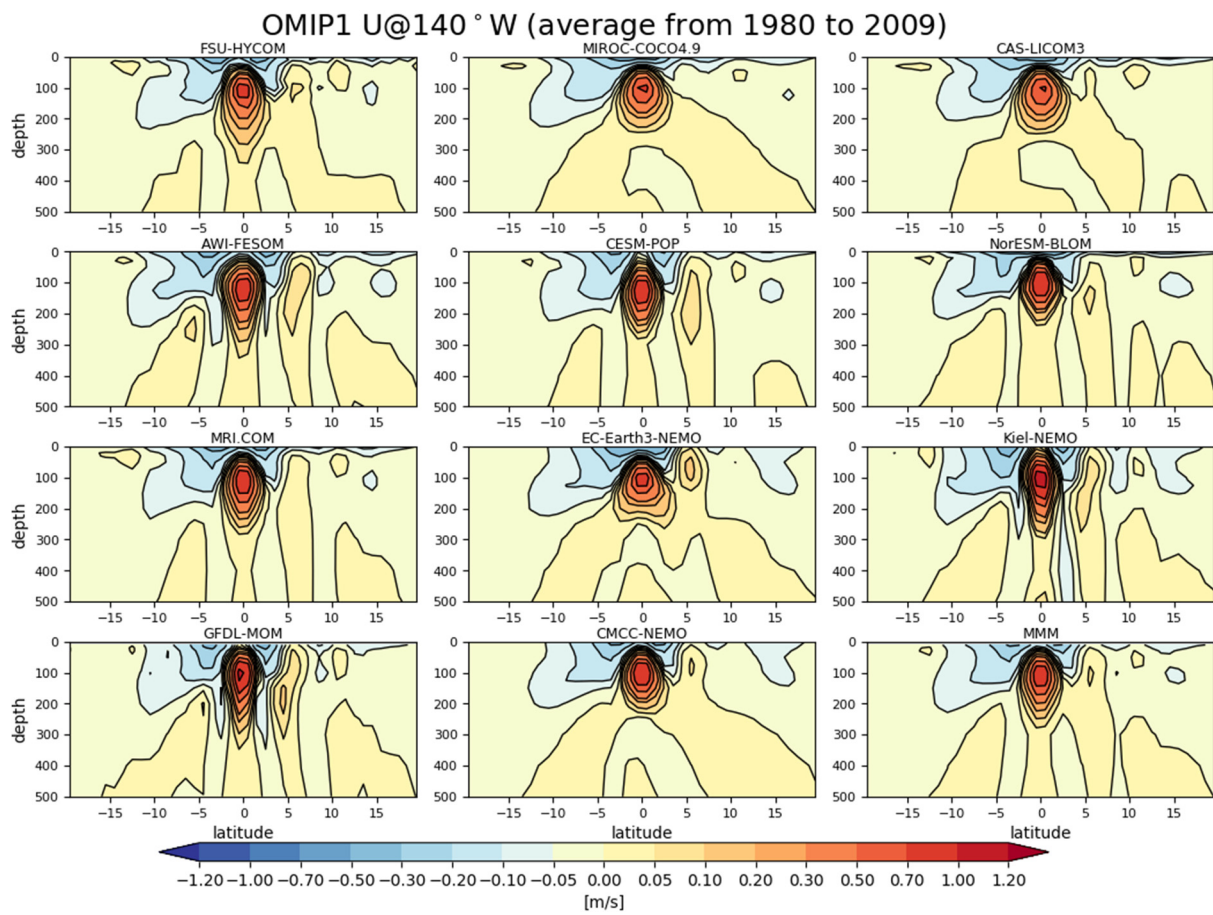


Figure S43: Same as Fig. S42 but for OMIP-2 simulations.



200 **Figure S44: Thirty (30)-year (1980–2009) mean zonal velocity (m s^{-1}) across 140°W in the eastern tropical Pacific for OMIP-1 simulations.**

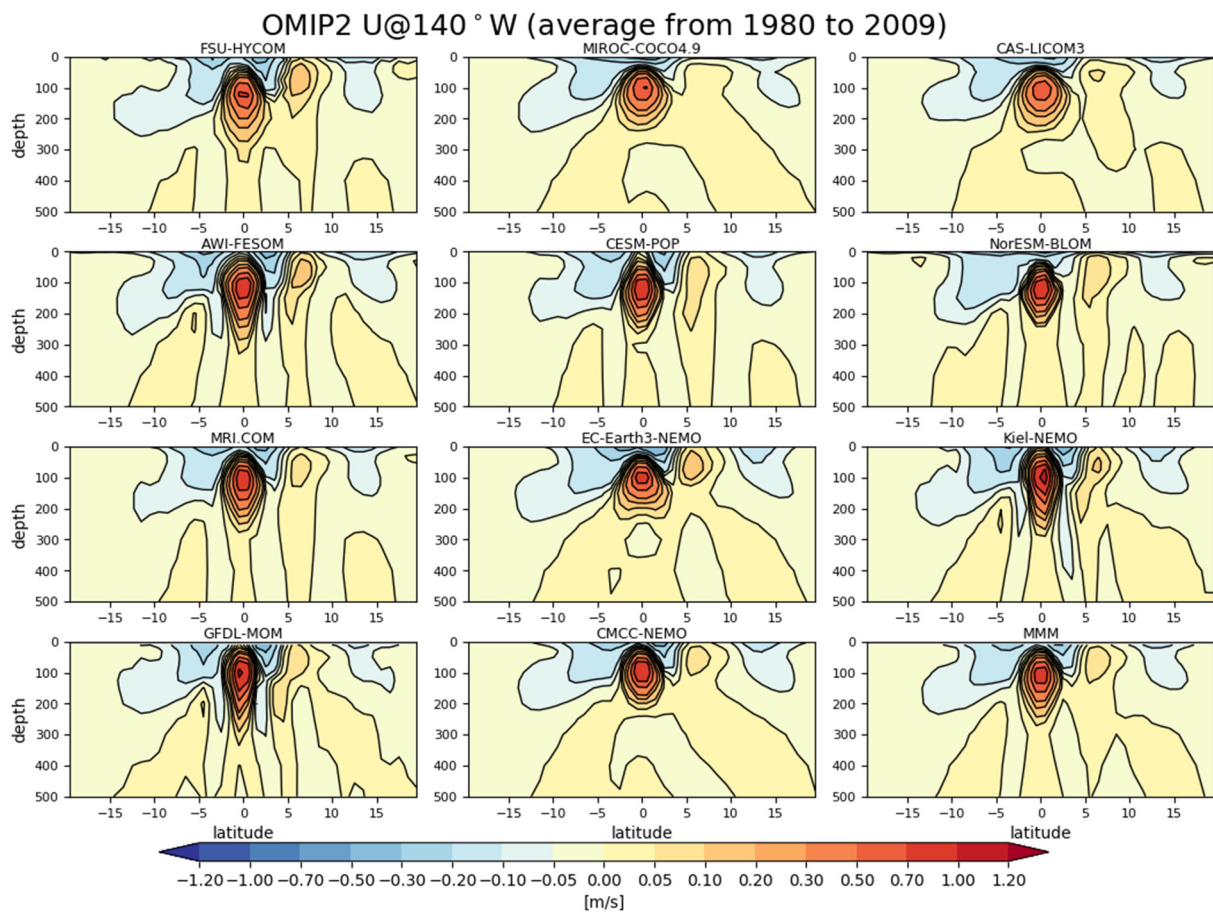


Figure S45: Same as Fig. S44 but for OMIP-2 simulations.

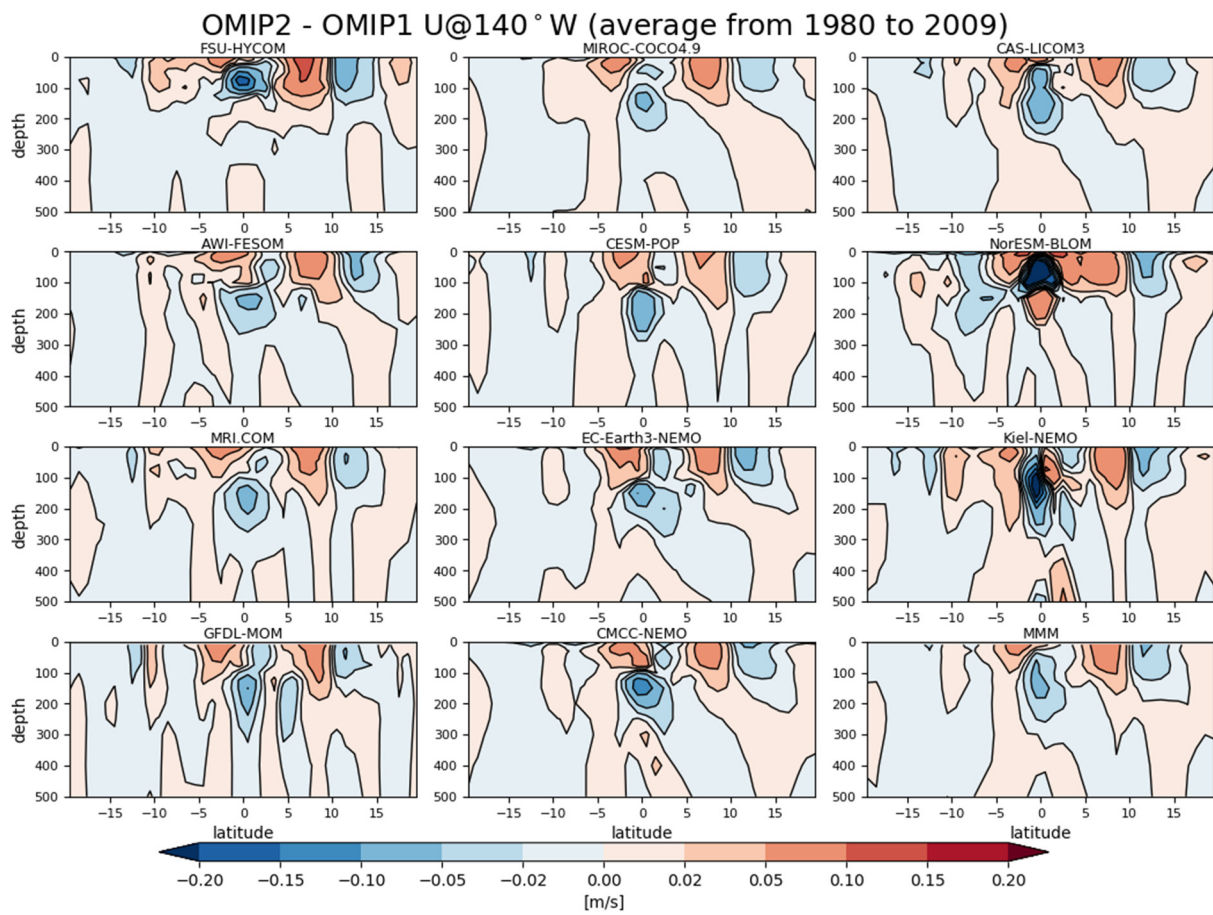
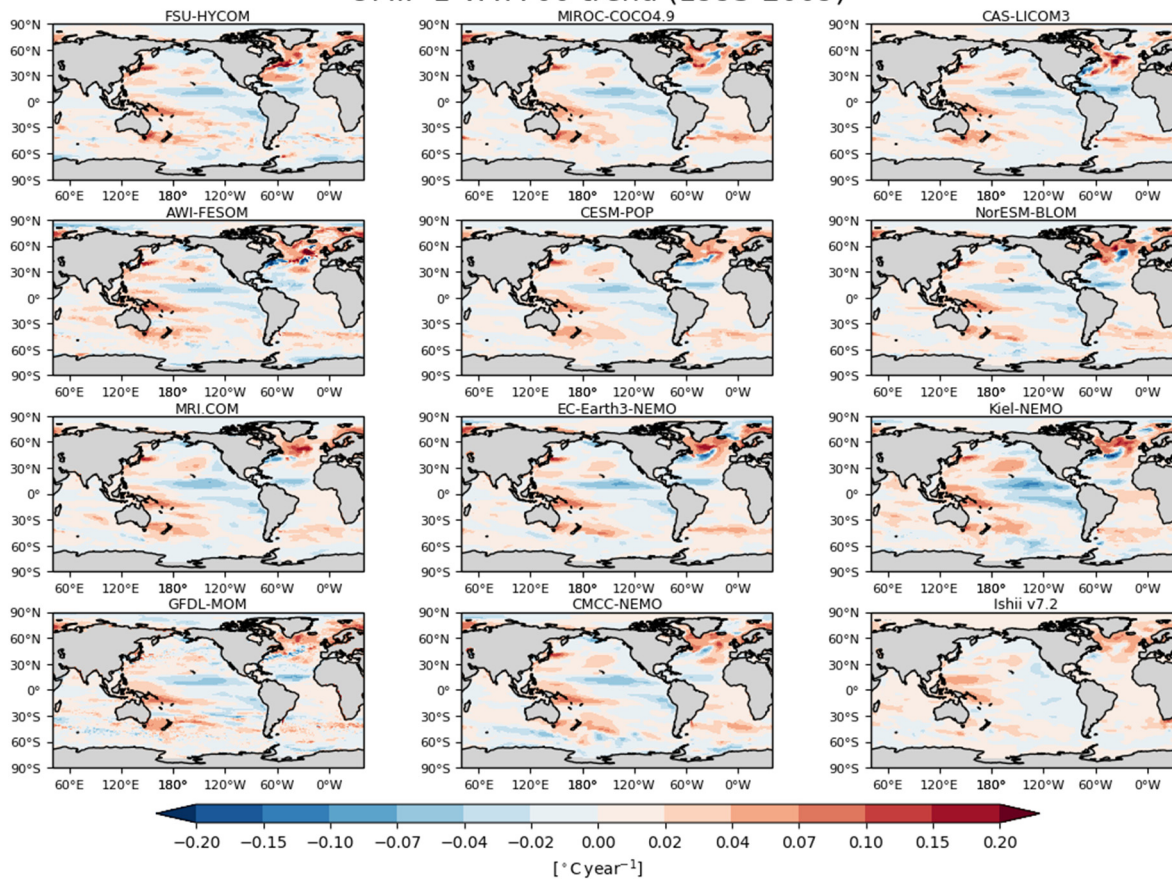


Figure S46: Difference of 30-year (1980–2009) mean zonal velocity (m s^{-1}) across 140°W in the eastern tropical Pacific between OMIP-1 and OMIP-2 simulations (OMIP-2 minus OMIP-1) for individual models.

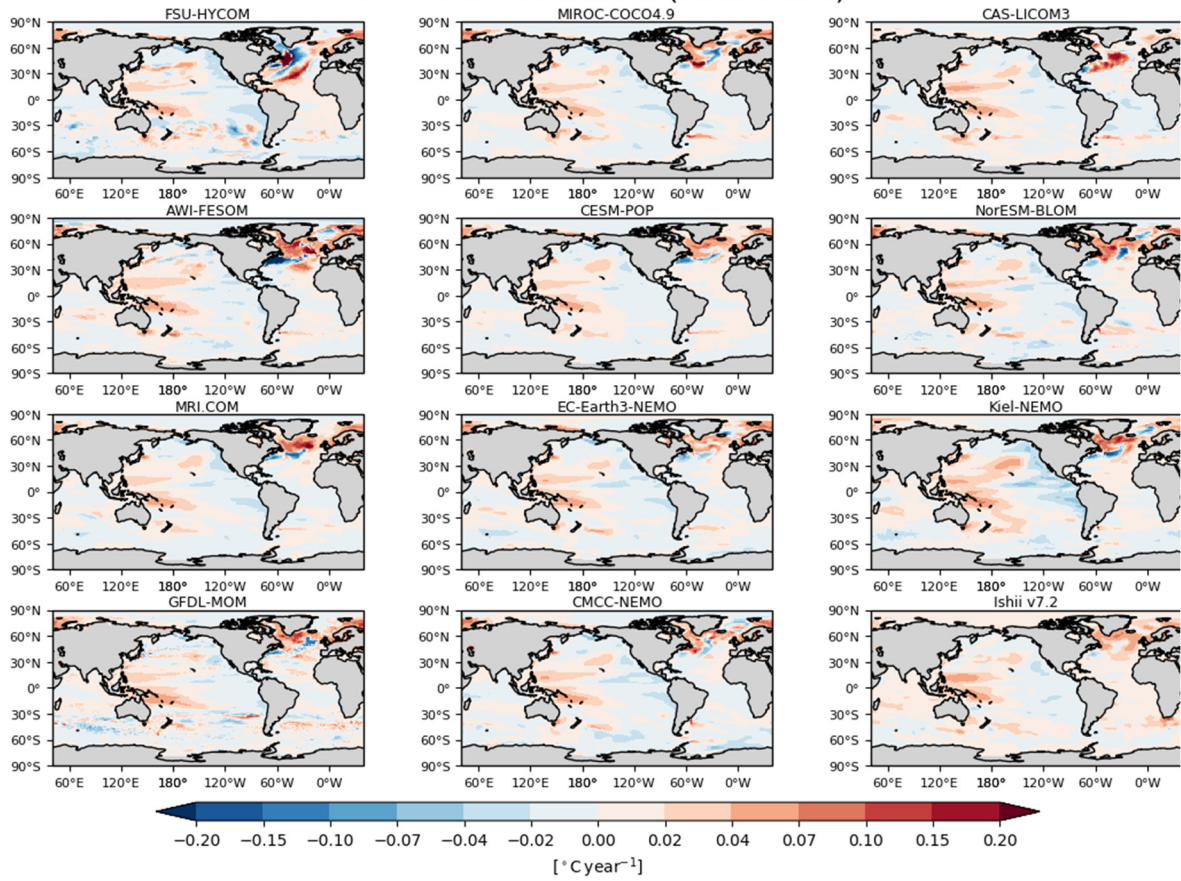
OMIP-1 VAT700 trend (1993-2009)



210

Figure S47: Seventeen (17)-year (1993–2009) trend of the upper 700 m temperature ($^{\circ}\text{C year}^{-1}$) of OMIP-1 simulations. The lower right panel is based on an observational estimate by Ishii et al. (2017).

OMIP-2 VAT700 trend (1993-2009)



215 Figure S48: Same as Fig. S47 but for OMIP-2 simulations.

OMIP1 Correlation of monthly climatology of SST from 1980 to 2009

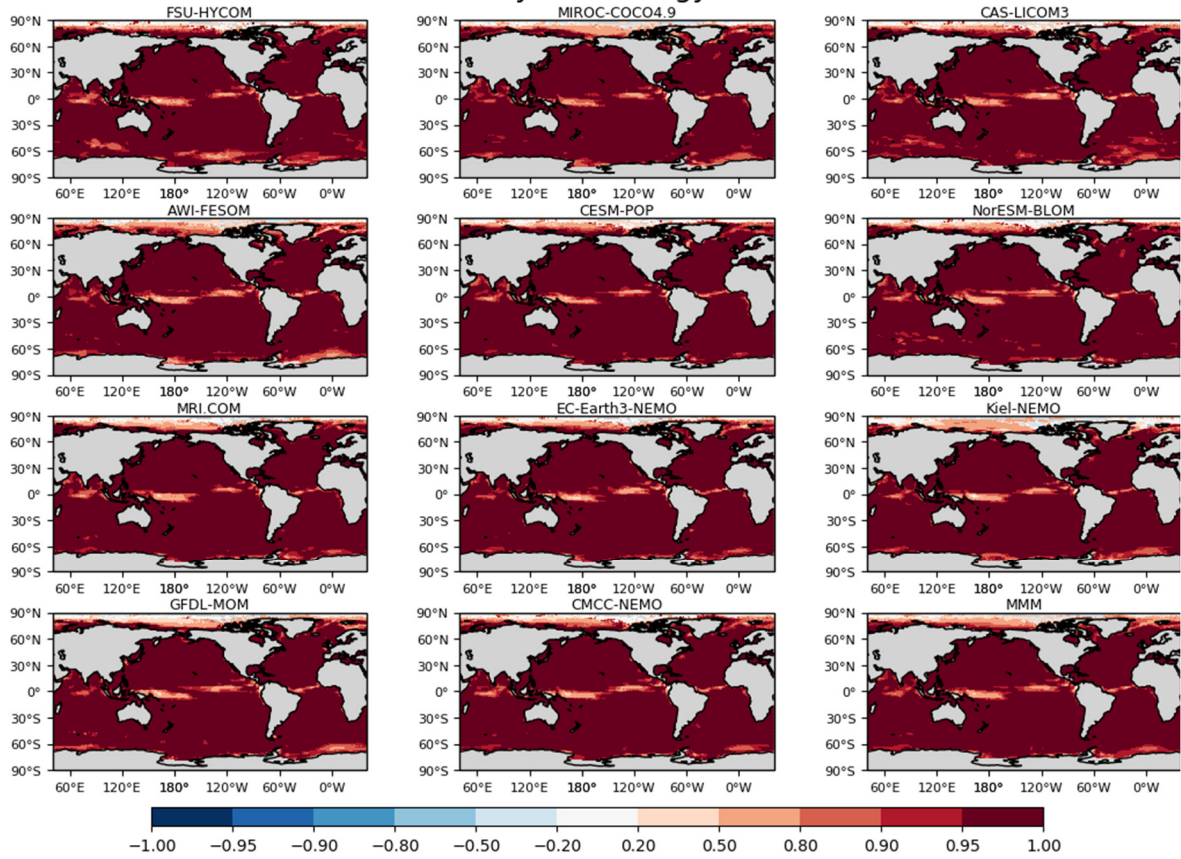


Figure S49: Correlation coefficients of monthly climatology of SST for the period 1980 – 2009 between OMIP-1 simulations and the PCMDI-SST dataset.

OMIP2 Correlation of monthly climatology of SST from 1980 to 2009

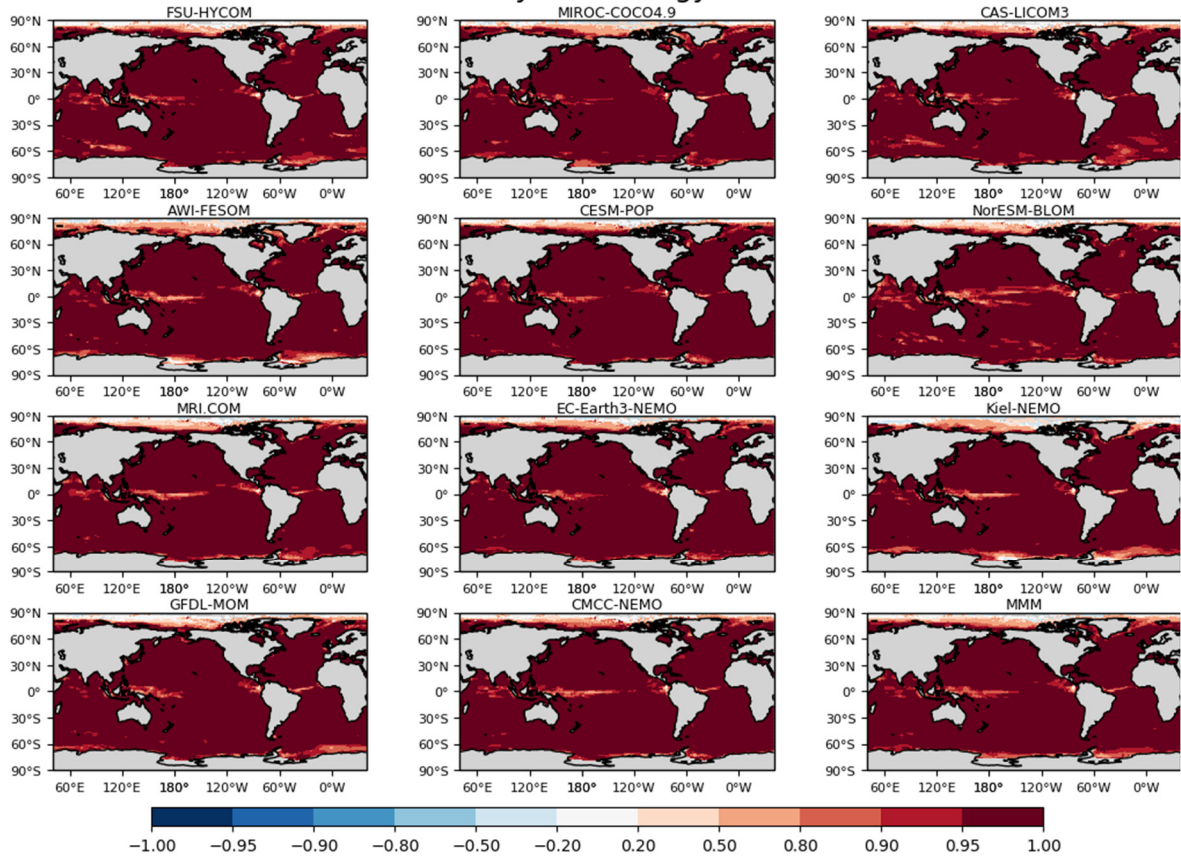
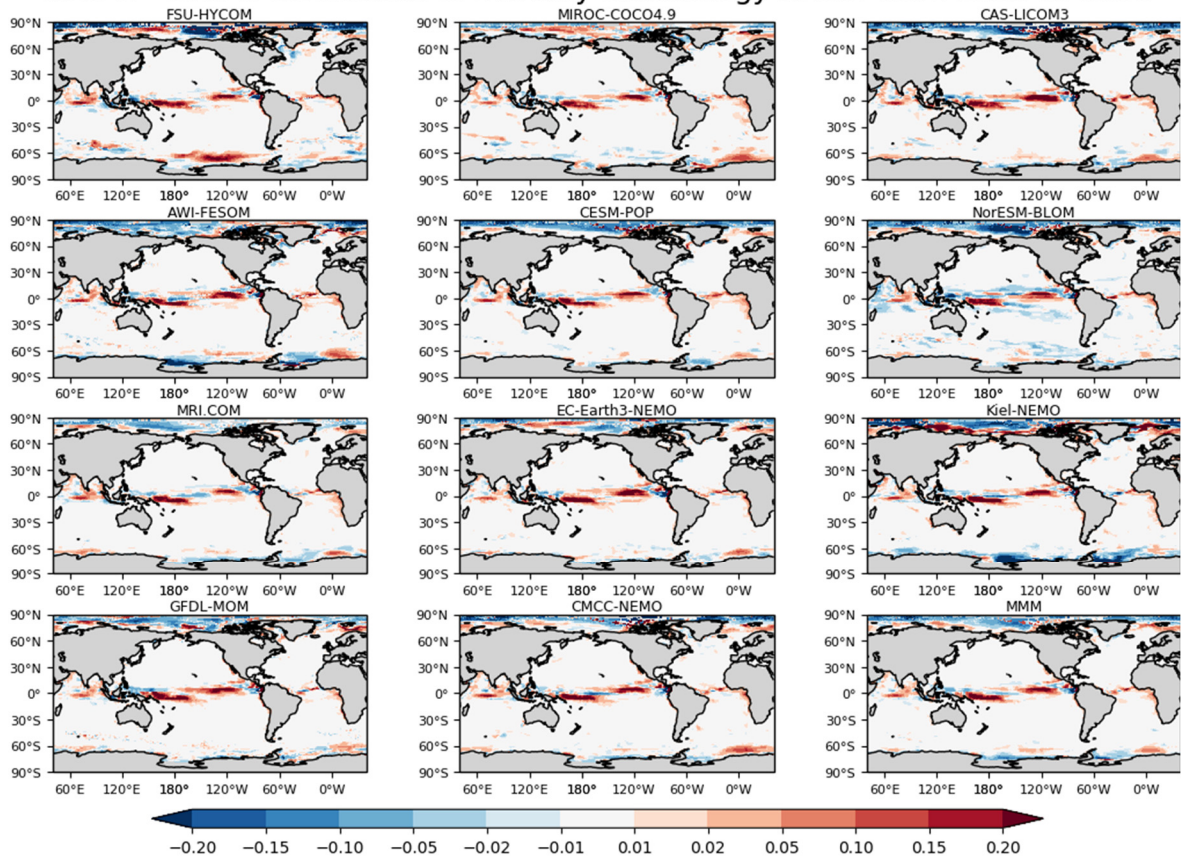


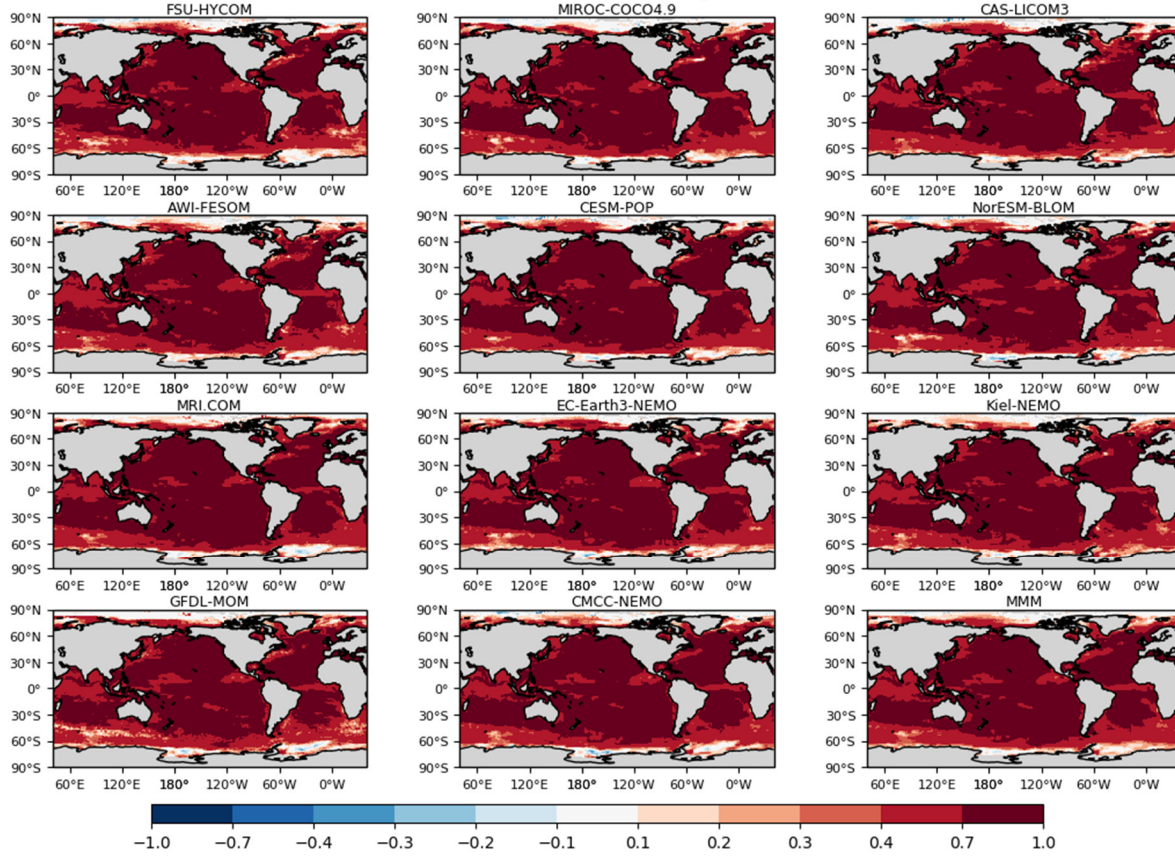
Figure S50: Same as Fig. S49 but for OMIP-2 simulations.

OMIP2 - OMIP1 Correlation of monthly climatology of SST from 1980 to 2009



225 **Figure S51: Difference between OMIP-1 and OMIP-2 simulations (OMIP-2 minus OMIP-1) of correlation coefficients of monthly climatology of SST for the period 1980 – 2009 between simulations and the PCMDI-SST dataset.**

OMIP1 (Correlation of interannual variability of SST from 1980 to 2009)



230 **Figure S52: Correlation coefficients of monthly SST anomaly relative to the monthly climatology for the period 1980 – 2009 between OMIP-1 simulations and the PCMDI-SST dataset.**

OMIP2 (Correlation of interannual variability of SST from 1980 to 2009)

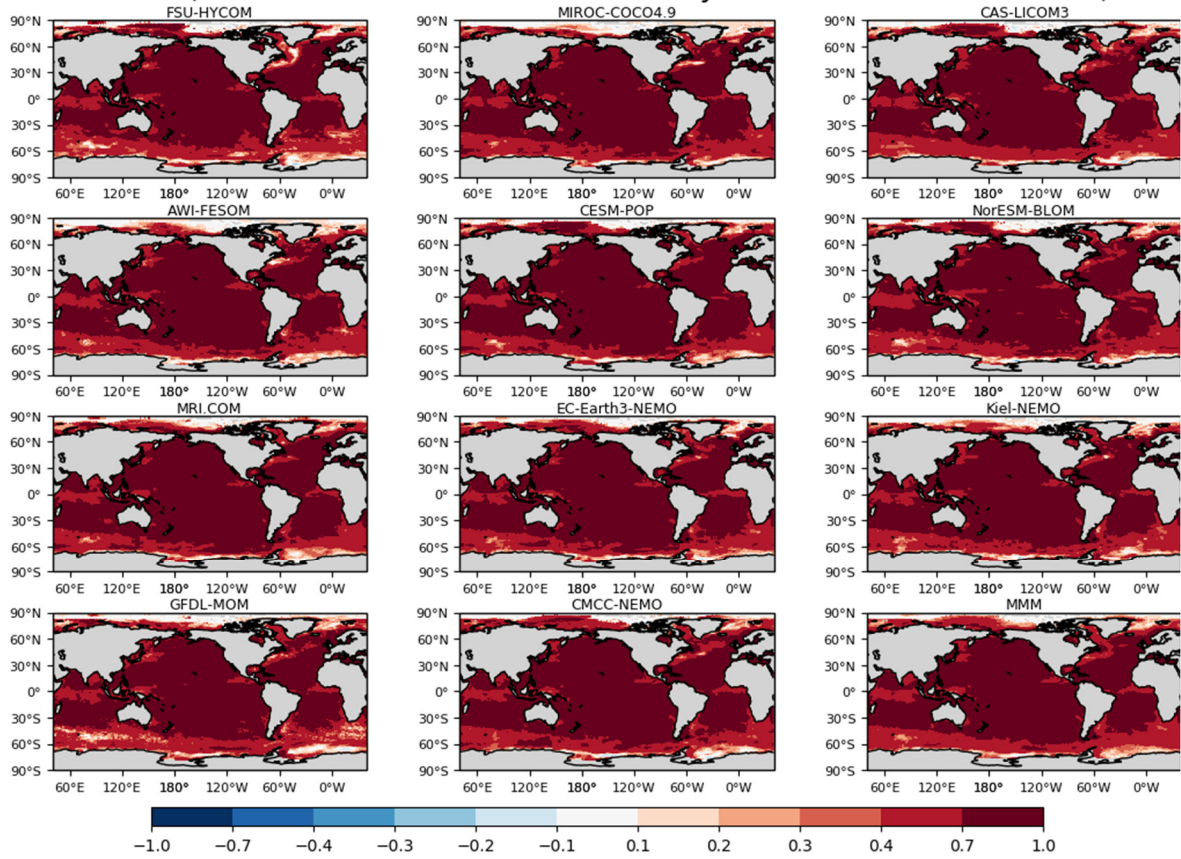
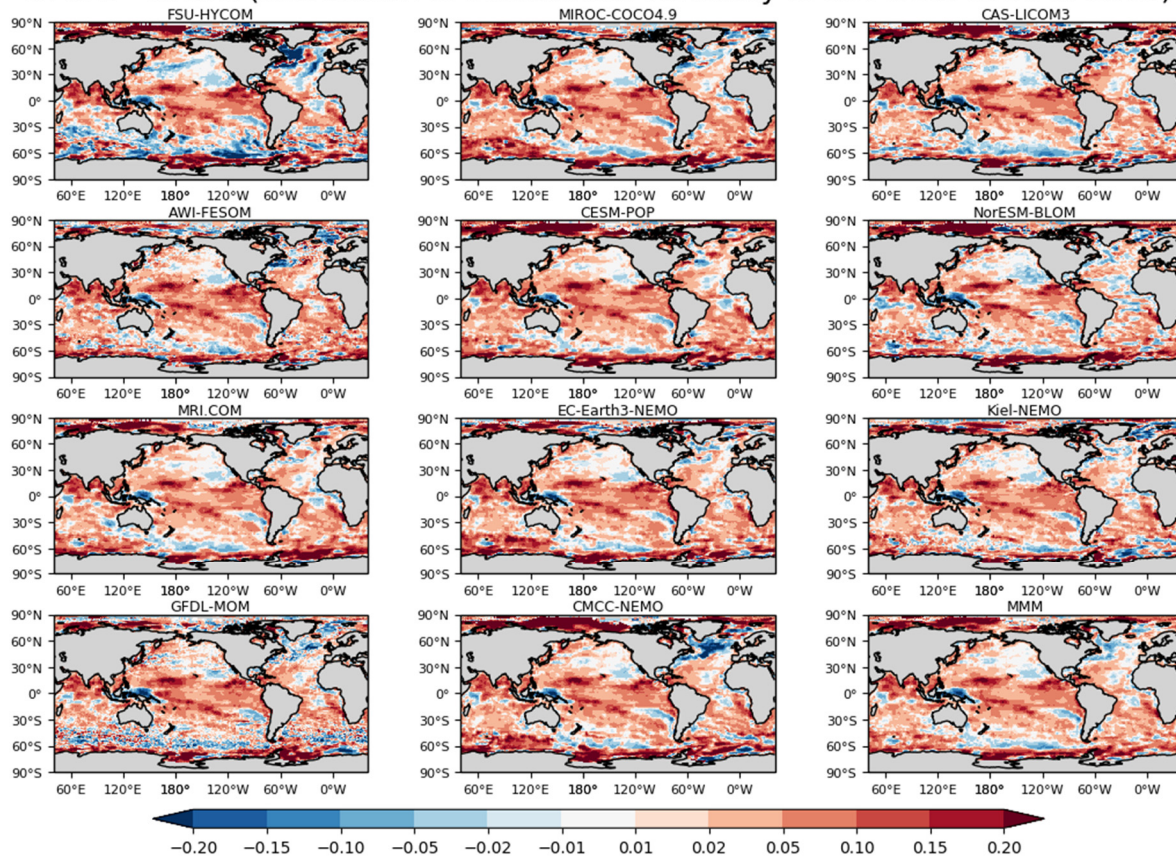


Figure S53: Same as Fig. S52 but for OMIP-2 simulations.

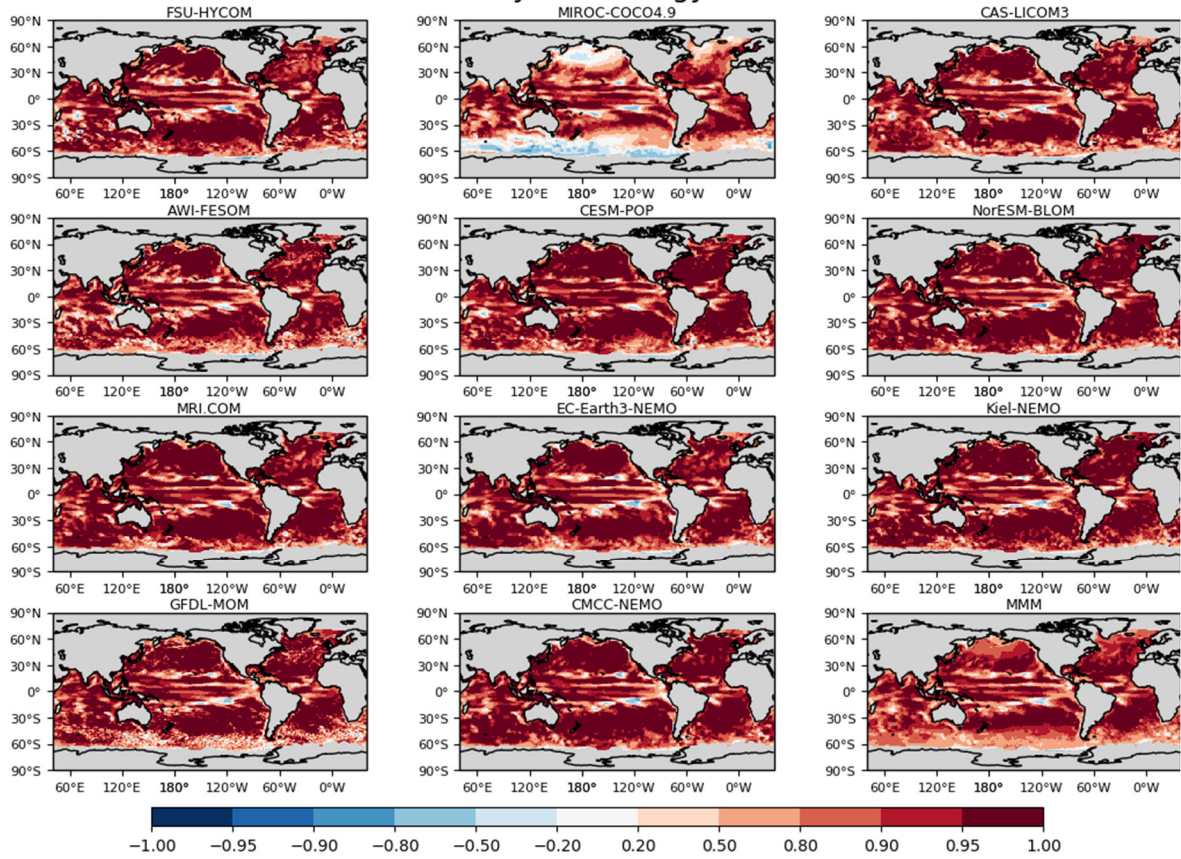
OMIP2 - OMIP1 (Correlation of interannual variability of SST from 1980 to 2009)



235

Figure S54: Difference between OMIP-1 and OMIP-2 simulations (OMIP-2 minus OMIP-1) of correlation coefficients of monthly anomaly relative to monthly climatology of SST for the period 1980 – 2009 between simulations and the PCMDI-SST dataset.

OMIP1 Correlation of monthly climatology of SSH from 1993 to 2009



240 **Figure S55:** Correlation coefficients of monthly climatology of SSH for the period 1993 – 2009 between OMIP-1 simulations and CMEMS.

OMIP2 Correlation of monthly climatology of SSH from 1993 to 2009

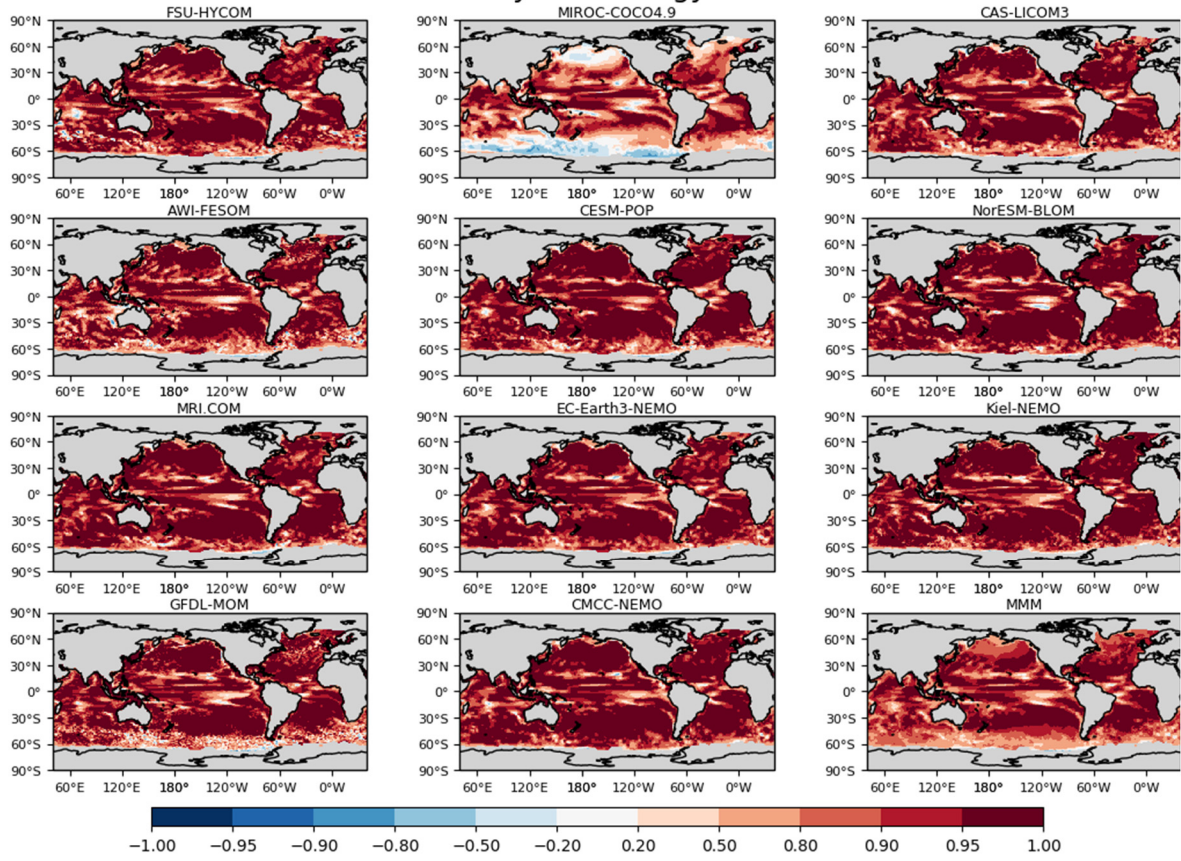


Figure S56: Same as Fig. S55 but for OMIP-2 simulations.

OMIP2 - OMIP1 Correlation of monthly climatology of SSH from 1993 to 2009

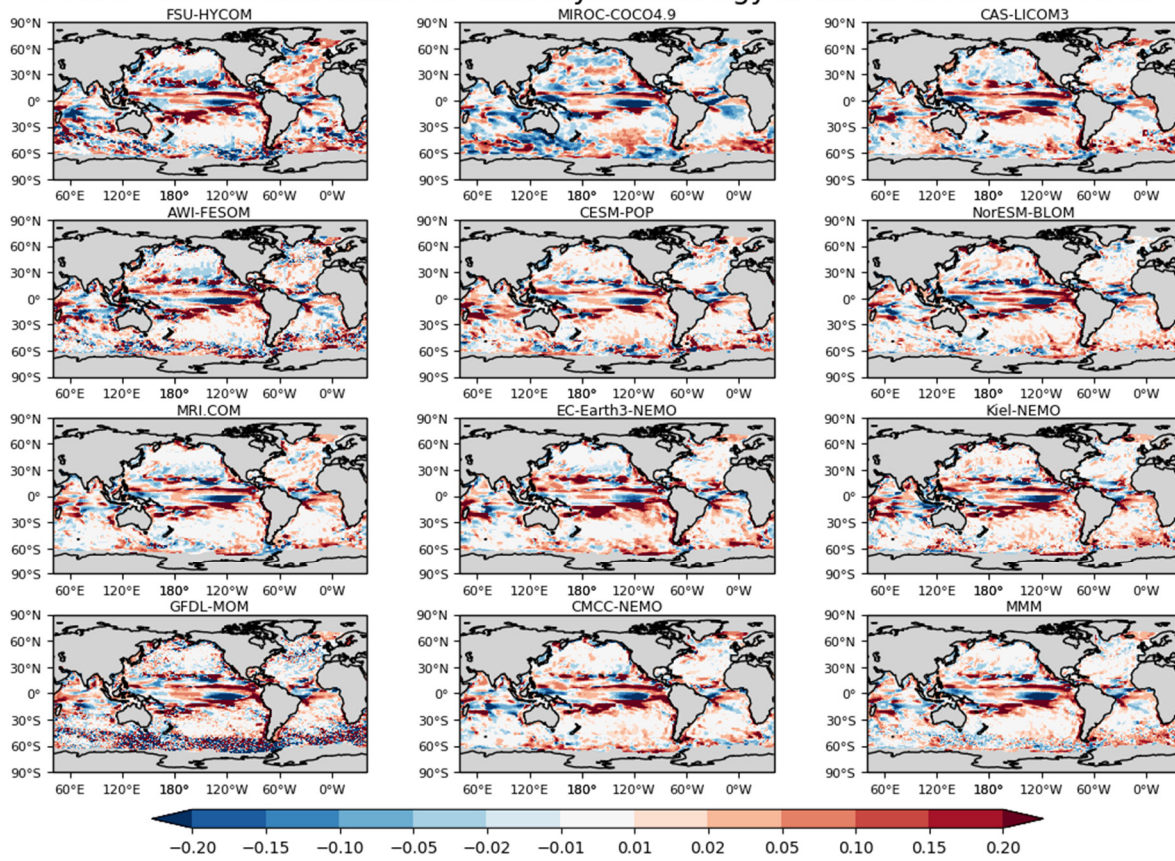
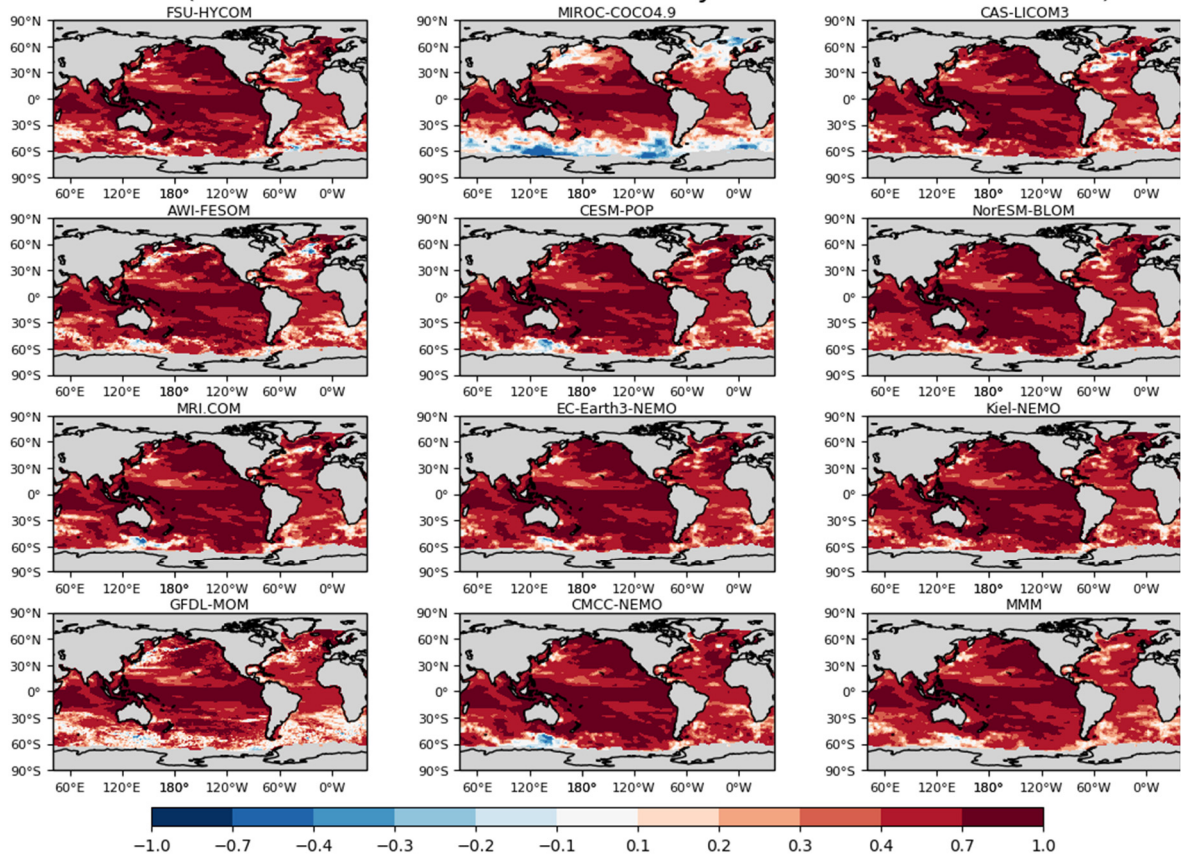


Figure S57: Difference between OMIP-1 and OMIP-2 simulations (OMIP-2 minus OMIP-1) of correlation coefficients of monthly climatology of SSH for the period 1993 – 2009 between simulations and CMEMS.

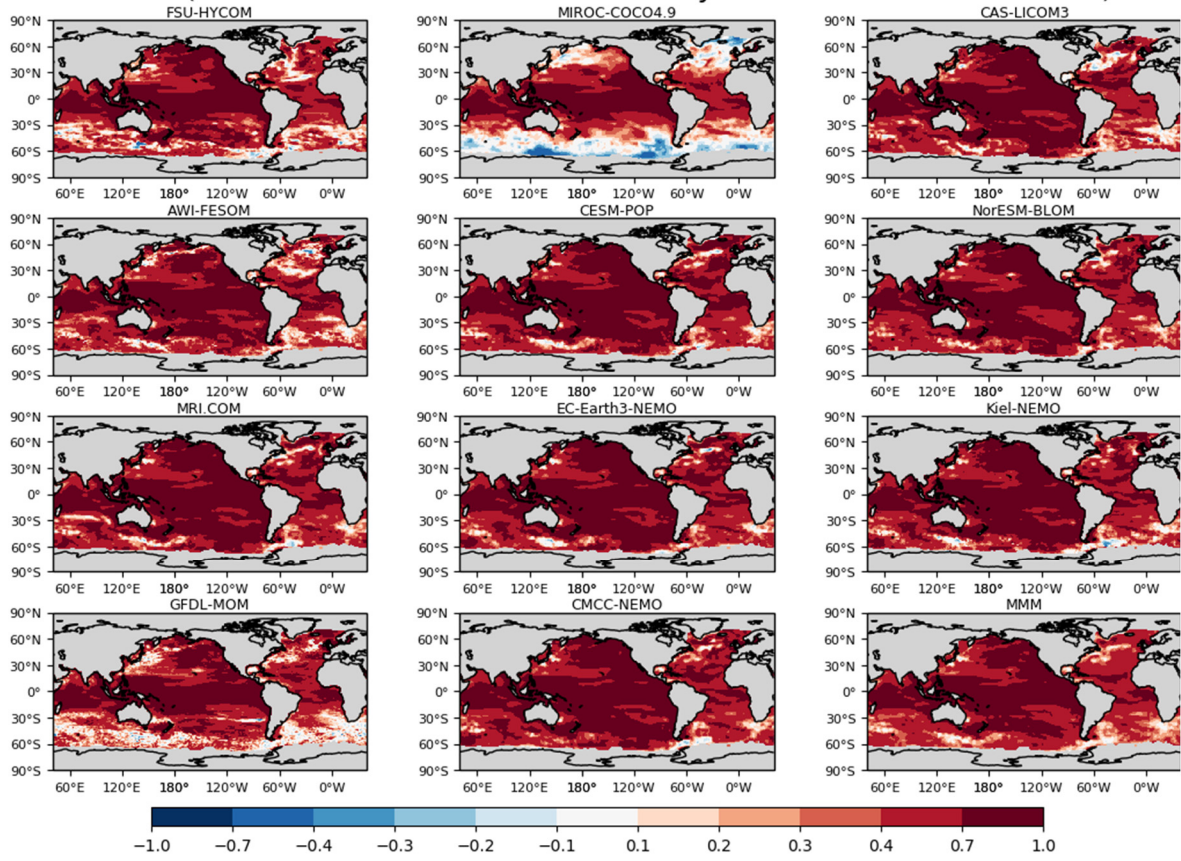
OMIP1 (Correlation of interannual variability of SSH from 1993 to 2009)



250

Figure S58: Correlation coefficients of monthly SSH anomaly relative to the monthly climatology for the period 1993 – 2009 between OMIP-1 simulations and CMEMS.

OMIP2 (Correlation of interannual variability of SSH from 1993 to 2009)



255 Figure S59: Same as Fig. S58 but for OMIP-2 simulations

OMIP2 - OMIP1 (Correlation of interannual variability of SSH from 1993 to 2009)

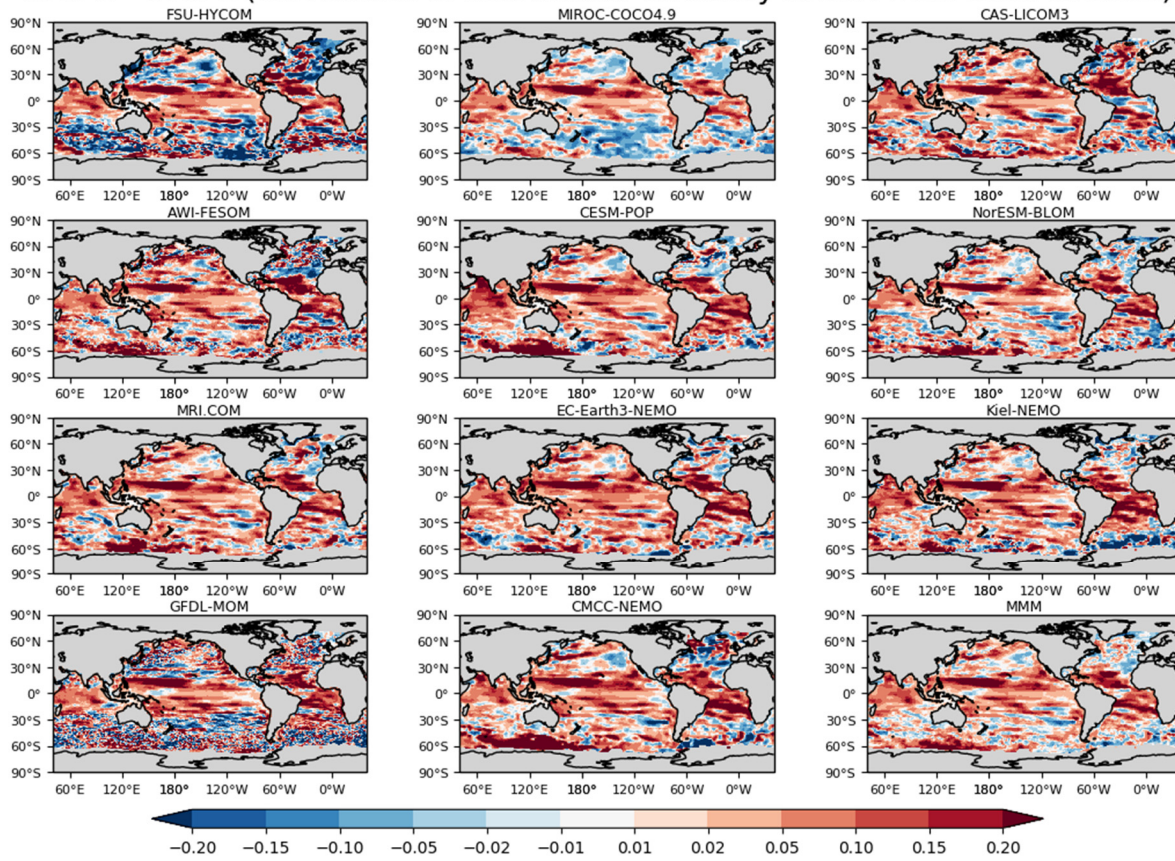


Figure S60: Difference between OMIP-1 and OMIP-2 simulations (OMIP-2 minus OMIP-1) of correlation coefficients of monthly anomaly relative to monthly climatology of SSH for the period 1993 – 2009 between simulations and CMEMS.

OMIP1 Correlation of monthly climatology of MLD from 1980 to 2009

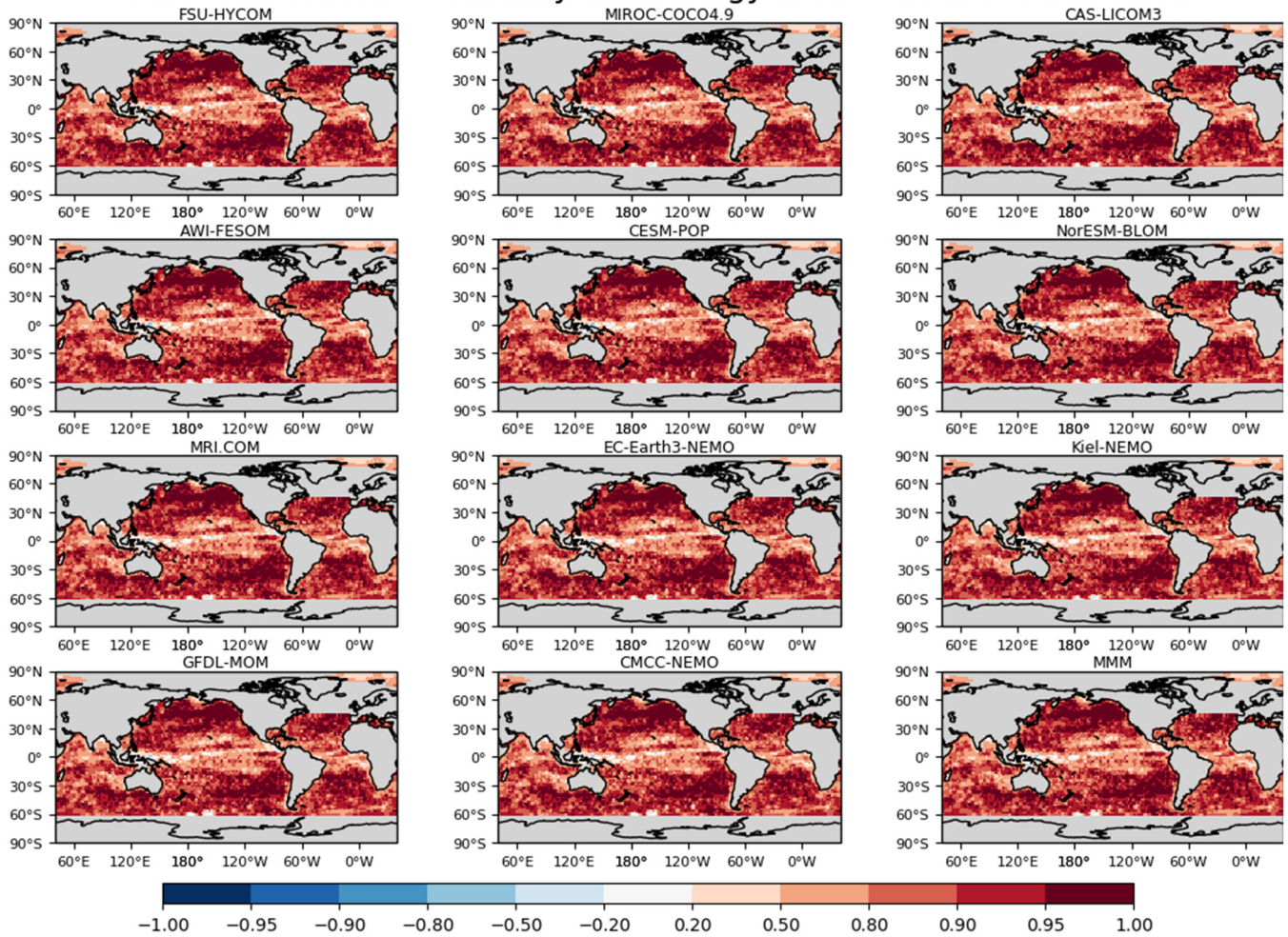


Figure S61: Correlation coefficients of monthly climatology of mixed layer depth (MLD) for the period 1980 – 2009 between OMIP-1 simulations and de Boyer Montégut et al. (2004).

OMIP2 Correlation of monthly climatology of MLD from 1980 to 2009

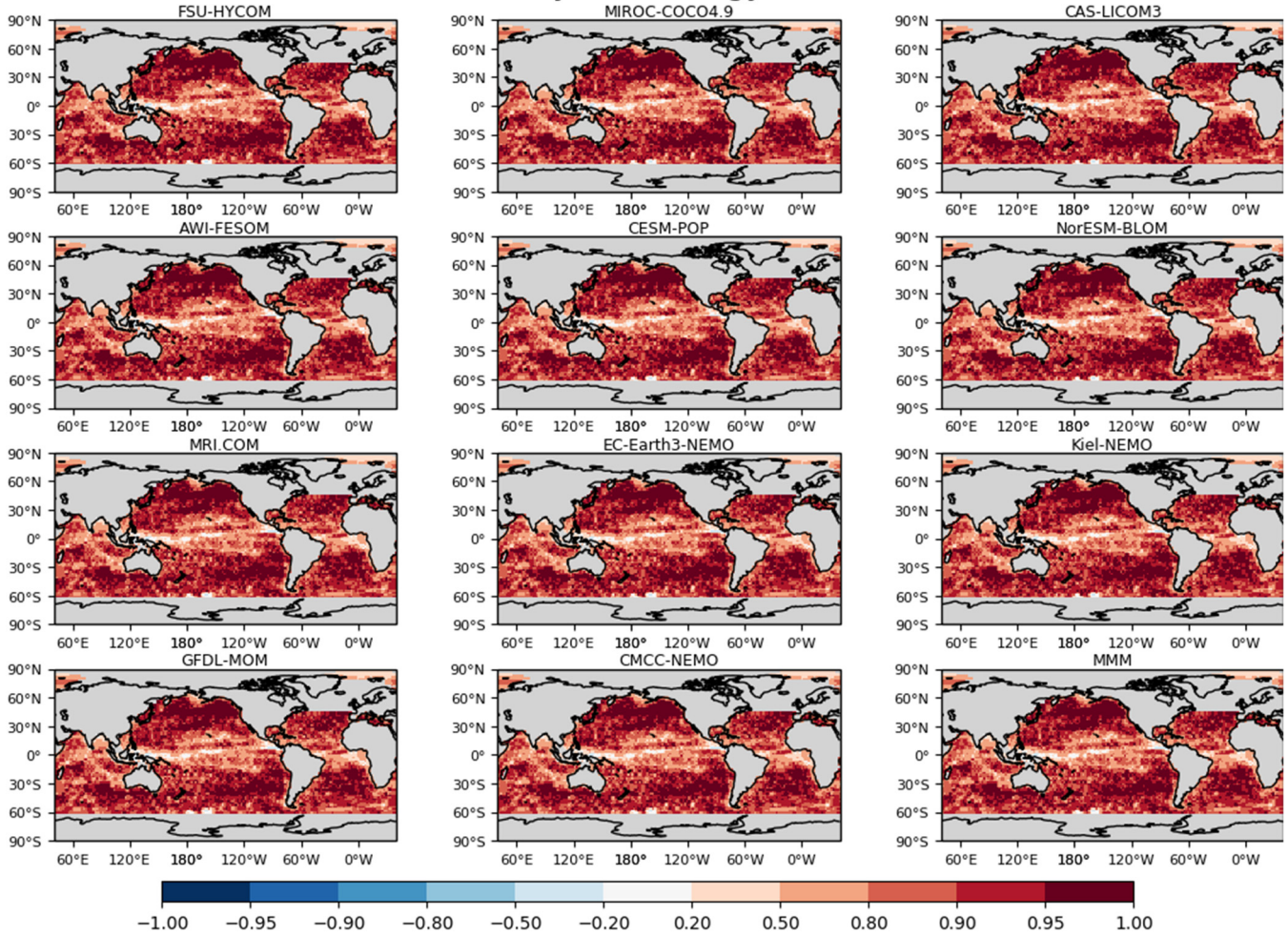
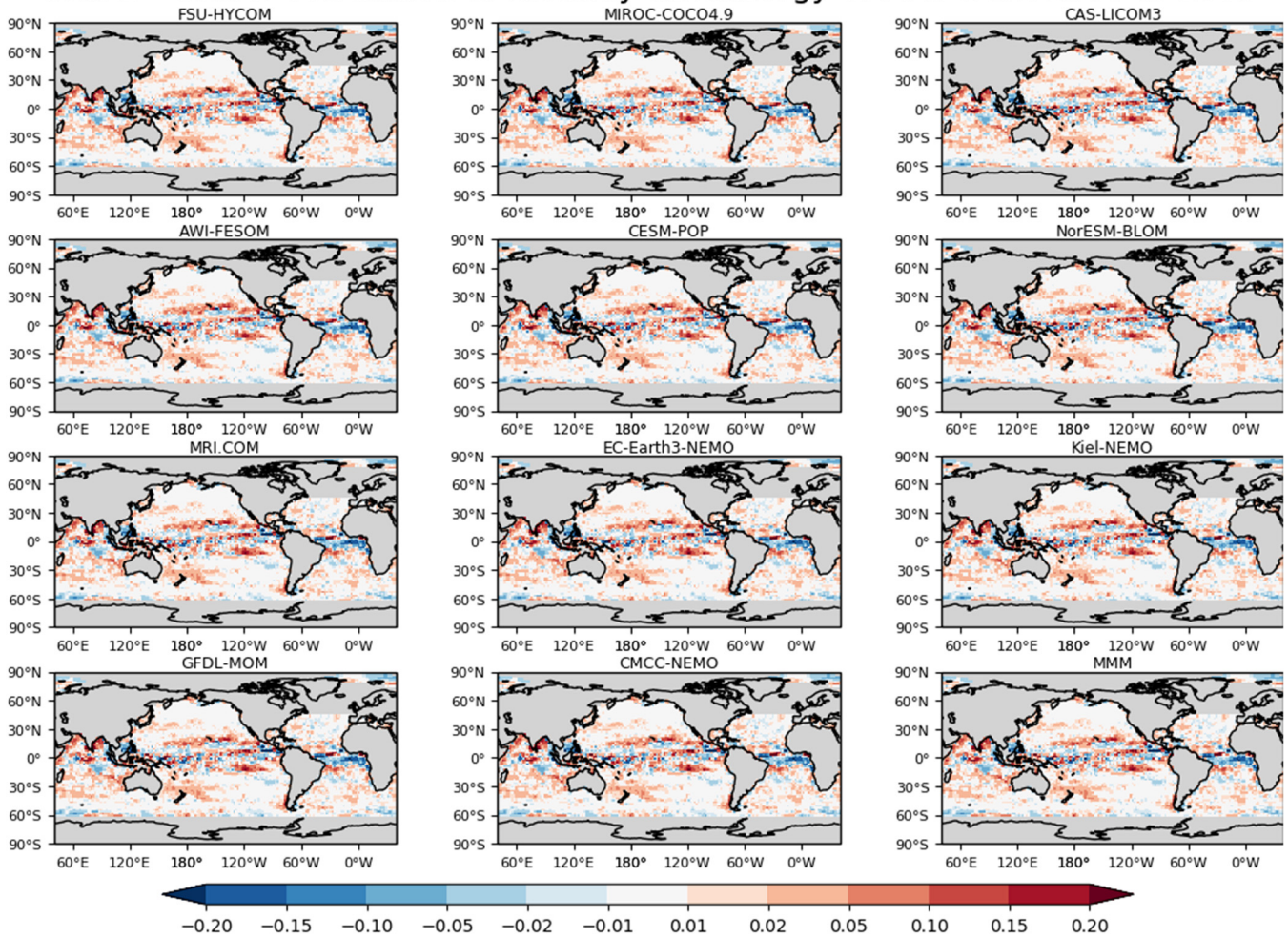


Figure S62: Same as Fig. S61 but for OMIP-2 simulations.

OMIP2 - OMIP1 Correlation of monthly climatology of MLD from 1980 to 2009



270 **Figure S63: Difference between OMIP-1 and OMIP-2 simulations (OMIP-2 minus OMIP-1) of correlation coefficients of monthly climatology of mixed layer depth for the period 1980 – 2009 between simulations and the dataset compiled by de Boyer Montégut et al. (2004).**