

Differences in eastern North Pacific stratification and their potential impact on the depth of winter mixing in CMIP5 models

P. Old¹, S. L. Hautala¹, and L. Thompson¹

¹School of Oceanography, University of Washington

Contents of this file

Tables S1 to S3
Figures S1 to S4

Introduction

Table S1 contains more information about the climate models, along with their bias in August buoyancy frequency (N) averaged over the upper 100 m and the subarctic/subtropical regions as defined in the text, relative to WOA six-decade average. Table S2 provides descriptive statistics for this group of models on average August stratification in upper 100 m and winter MLD predicted from the PWP model. Table S3 provides information about individual decadal averages and their estimated errors, along with estimates of error in the six-decade mean due to spatial and temporal sampling differences in each decade.

Figure S1 shows the time-evolution through winter of the PWP mixed layer depth where the mixed layer model is initialized with model and data profiles starting on Sep 1. Figure S2 shows additional upper ocean fields for each model, complementing Figure 1. Figure S3 provides more information on the number of observations and their distributions in each region. Figure S4 presents a case study illustrating the dependence of PWP-predicted winter MLD on the vertical structure of the stratification.

TAG <i>Institution</i>	Climate Model <i>(run r1i1p1)</i>	Ocean Model	$\overline{N}(100\text{m})$ bias Subarctic (10^{-3} s^{-1})	$\overline{N}(100\text{m})$ bias Subtropical (10^{-3} s^{-1})
BCC <i>Beijing Climate Center (China)</i>	CSM1-1	MOM4_L40	-0.2500	1.4701
BNU <i>Beijing Normal University (China)</i>	ESM	MOM4pq	2.2463	0.9658
CCCMA <i>Canadian Centre for Climate Modelling and Analysis (Canada)</i>	CanESM2	POP2	0.8720	-0.3044
CMCC <i>Centro Euro-Mediterraneo per I Cambiamenti Climatici (Italy)</i>	CESM	ORCA2	-0.3344	-0.5620
CNRM-CERFACS <i>Centre National de Recherches Météorologiques– Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (France)</i>	CNRM-CM5	NEMO3.2	0.1602	0.8705
CSIRO-BOM <i>Commonwealth Scientific and Industrial Research Organization – Bureau of Meteorology (Australia)</i>	ACCESS1-3	MOM4p1	1.7845	-3.1821
CSIRO-QCCCE <i>Commonwealth Scientific and Industrial Research Organization – Queensland Climate Change Centre of Excellence (Australia)</i>	CSIRO-Mk3.6.0	MOM2.2	-1.4097	-3.9840
FIO <i>First Institute of Oceanography (China)</i>	ESM	POP2.0	-2.1612	-0.1994
ICHEC <i>Irish Centre for High End Computing (Ireland)</i>	EC-EARTH	NEMO2.2	1.6254	1.9760
IPSL <i>Institut Pierre Simon Laplace (France)</i>	CM5A-LR	NEMO3.2	0.1081	0.8475
LASG-CESS <i>Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University (China)</i>	FGOALS-g2	LICOM2	0.9493	0.6875
MIROC <i>Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies</i>	ESM	COCO	-1.6003	0.3363
MOHC <i>Met Office Hadley Centre (UK)</i>	HadGEM2-ES	HadGOM	-4.0629	-1.6265
MPI-M <i>Max-Planck-Institut für Meteorologie (Germany)</i>	ESM-MR	MPIOM	-0.1195	0.5745
MRI <i>Meteorological Research Institute (South Korea)</i>	ESM1	MRI.COM3	2.0304	0.5727
NASA-GISS <i>National Aeronautics and Space Administration– Goddard Institute for Space Studies (USA)</i>	GISS-E2-H	HYCOM	0.4080	-0.1852
NCAR <i>National Center for Atmospheric Research (USA)</i>	CCSM4	POP2	-0.0081	-0.1785
NCC <i>Norwegian Climate Centre (Norway)</i>	NorESM1-M	MICOM	-4.4140	-3.1387
NIMR-KMA <i>National Institute of Meteorological Research – Korean Meteorological Administration (South Korea)</i>	HadGEM2-AO	HadGOM	0.1890	1.2456
NOAA-GFDL <i>National Oceanic and Atmospheric Administration – Geophysical Fluid Dynamics Laboratory (USA)</i>	ESM2M	MOM4p1	1.1884	0.8381
NSF-DOE-NCAR <i>National Science Foundation – Department of Energy – National Center for Atmospheric Research (USA)</i>	CESM1-CAM5	POP2	0.2831	-0.9126

Table S1. Individual model Information. Model stratification biases averaged over the upper 100 m (last 2 columns) are considered statistically significant at the 95% confidence level when they differ from the WOA values by more than $\pm 0.2 \times 10^{-3} \text{ s}^{-1}$ for the subarctic region, and by more than $\pm 0.8 \times 10^{-3} \text{ s}^{-1}$ for the subtropical region (see Table S3).

	Subarctic	Subtropical
\bar{N} (100 m) bias, August		
Median value % of WOA value	$0.16 \times 10^{-3} \text{ s}^{-1}$ 1 %	$0.34 \times 10^{-3} \text{ s}^{-1}$ 4 %
Standard deviation among models % of WOA value	$1.78 \times 10^{-3} \text{ s}^{-1}$ 15 %	$1.60 \times 10^{-3} \text{ s}^{-1}$ 17 %
Maximum positive value % of WOA value <i>MODEL TAG</i>	$2.25 \times 10^{-3} \text{ s}^{-1}$ 19 % <i>BNU</i>	$1.98 \times 10^{-3} \text{ s}^{-1}$ 22 % <i>ICHEC</i>
Maximum negative value % of WOA value <i>MODEL TAG</i>	$-4.41 \times 10^{-3} \text{ s}^{-1}$ 37 % <i>NCC</i>	$-3.98 \times 10^{-3} \text{ s}^{-1}$ 43 % <i>CSIRO-QCCCE</i>
Minimum absolute value % of WOA value <i>MODEL TAG</i>	$0.01 \times 10^{-3} \text{ s}^{-1}$ 0.07 % <i>NCAR</i>	$0.18 \times 10^{-3} \text{ s}^{-1}$ 2 % <i>NCAR</i>
PWP Mar MLD Model minus WOA		
Median value % of WOA value	-16 m 16 %	21 m 30 %
Standard deviation among models % of WOA value	34 m 38 %	28 m 24 %
Maximum positive (deep) % of WOA value <i>MODEL TAG</i>	161 m 181 % <i>NCC</i>	99 m 82.5 % <i>CSIRO-BOM</i>
Maximum negative (shallow) % of WOA value <i>MODEL TAG</i>	-35 m 39 % <i>BNU</i>	-32 m 27 % <i>ICHEC</i>
Minimum absolute value % of WOA value <i>MODEL TAG</i>	<0.5 m 0 % <i>NCAR-CCSM4</i>	1 m 1 % <i>IPSL</i>

Table S2. Descriptive statistics of model stratification and PWP predicted March mixed layer depth.

Decade	$\bar{N}(100\text{ m})$	$\bar{N}(100\text{ m})$
	Subarctic (10^{-3} s^{-1})	Subtropical (10^{-3} s^{-1})
1955-1964	13.02 ± 0.09	8.71 ± 0.14
1965-1974	12.83 ± 0.10	9.58 ± 0.21
1975-1984	13.02 ± 0.12	–
1985-1994	12.78 ± 0.11	–
1995-2004	13.15 ± 0.11	10.10 ± 0.28
2005-2012	13.35 ± 0.10	9.65 ± 0.14
Six decade mean	13.13 ± 0.19	9.19 ± 0.79

Table S3. Buoyancy frequency, computed from regionally averaged temperature and salinity profiles, and vertically averaged over 5 – 100 m depth for the WOA data. 95% confidence limit error bars on the decadal means are estimated by propagating WOA reported standard errors for each grid point, and the Student’s *t*-distribution based on a number of degrees of freedom equal to the number of grid points in the region with existing observations. 95% confidence limit error bars on the six-decade mean are estimated from the standard deviation of the decadal averages with the number of degrees of freedom equal to $(n-1)$ where n is the number of decades with observations of both temperature and salinity.

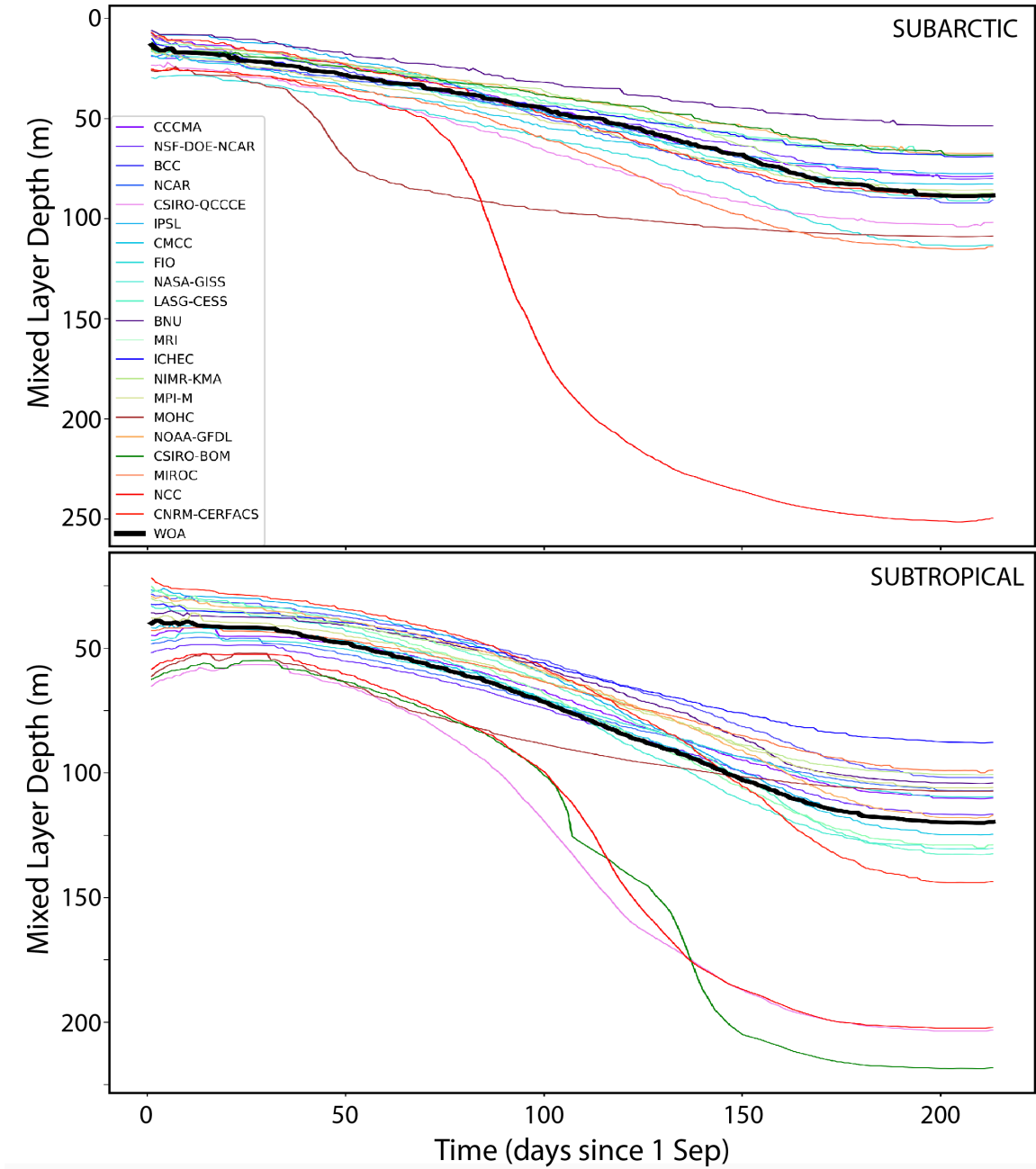
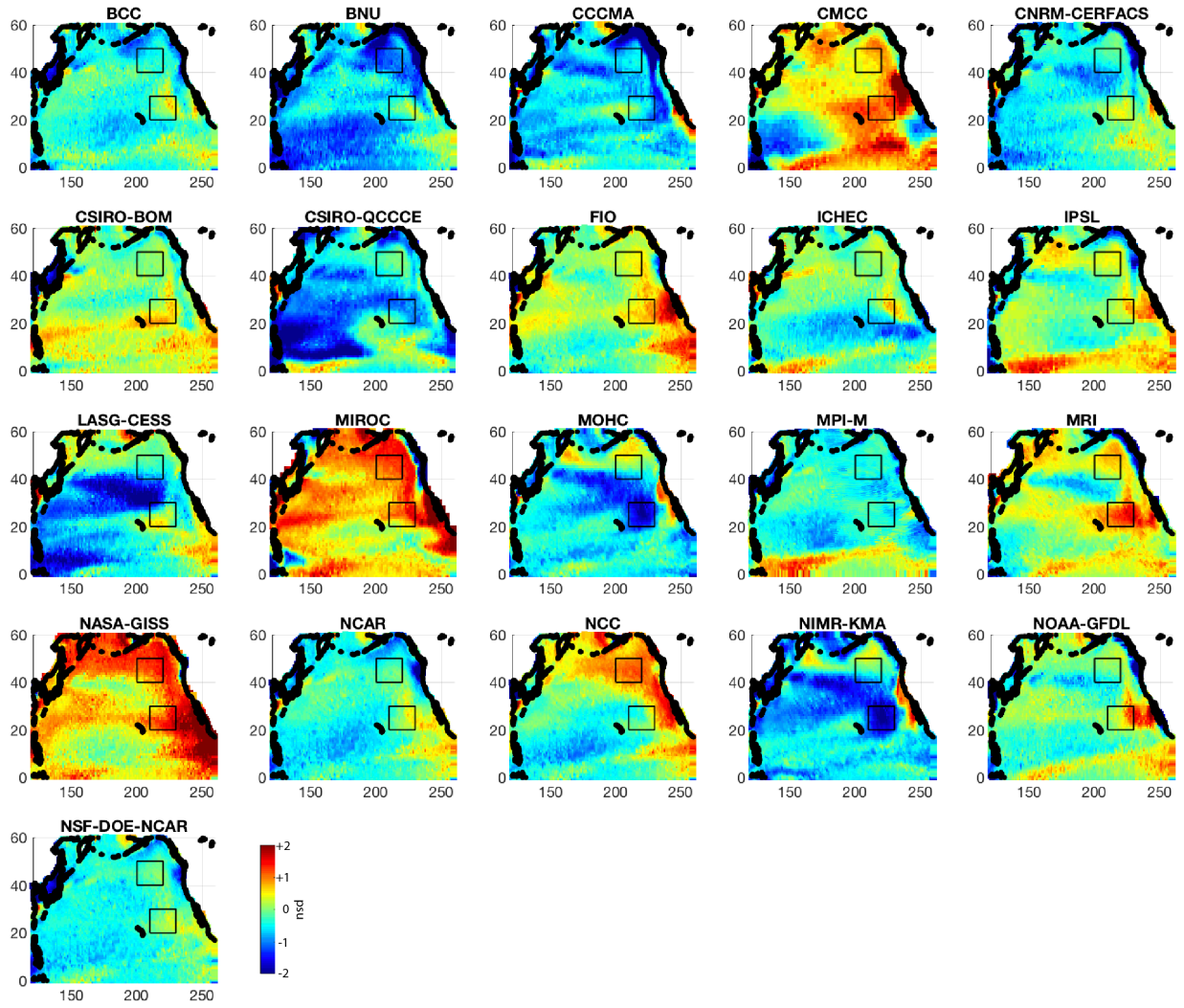
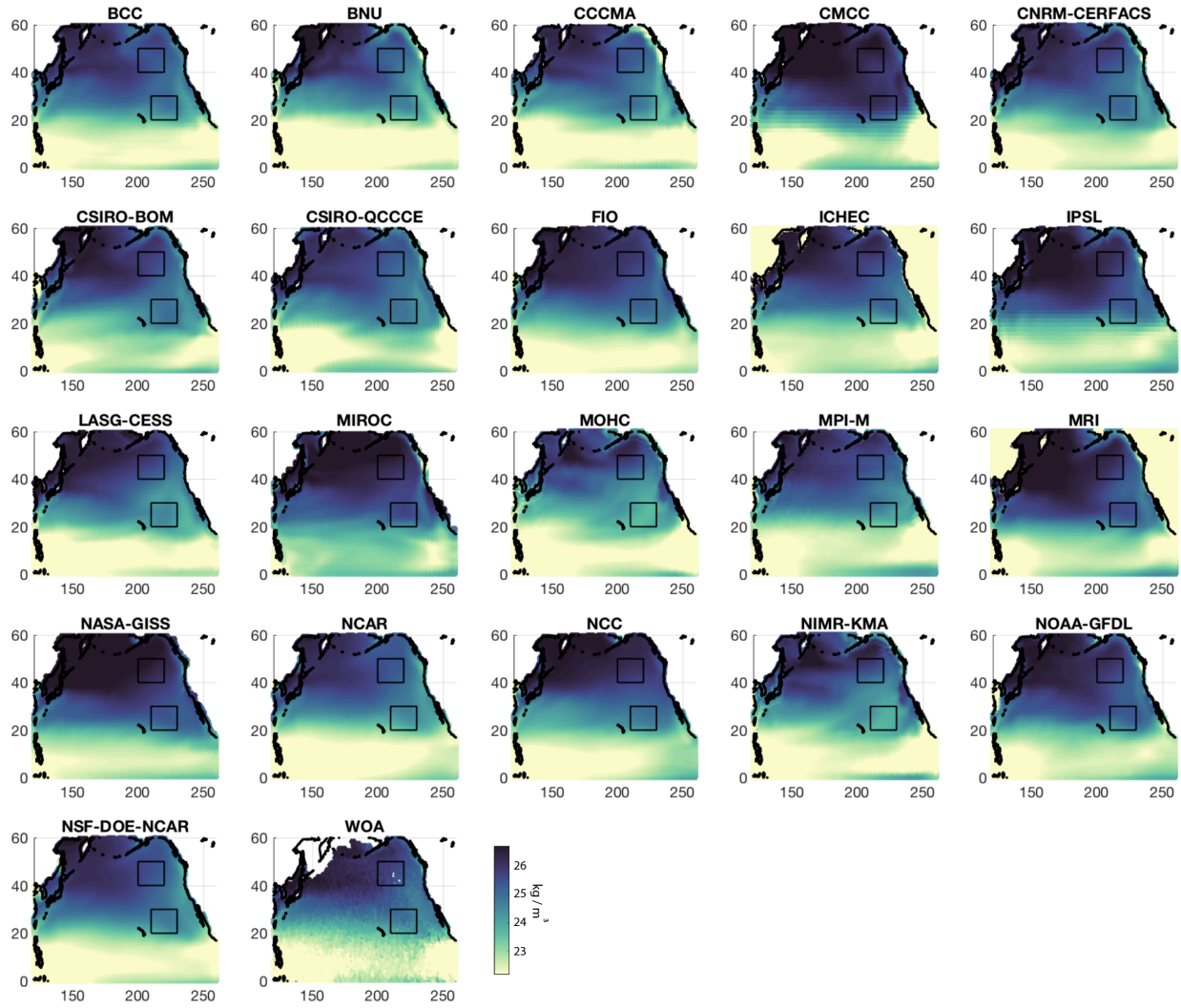


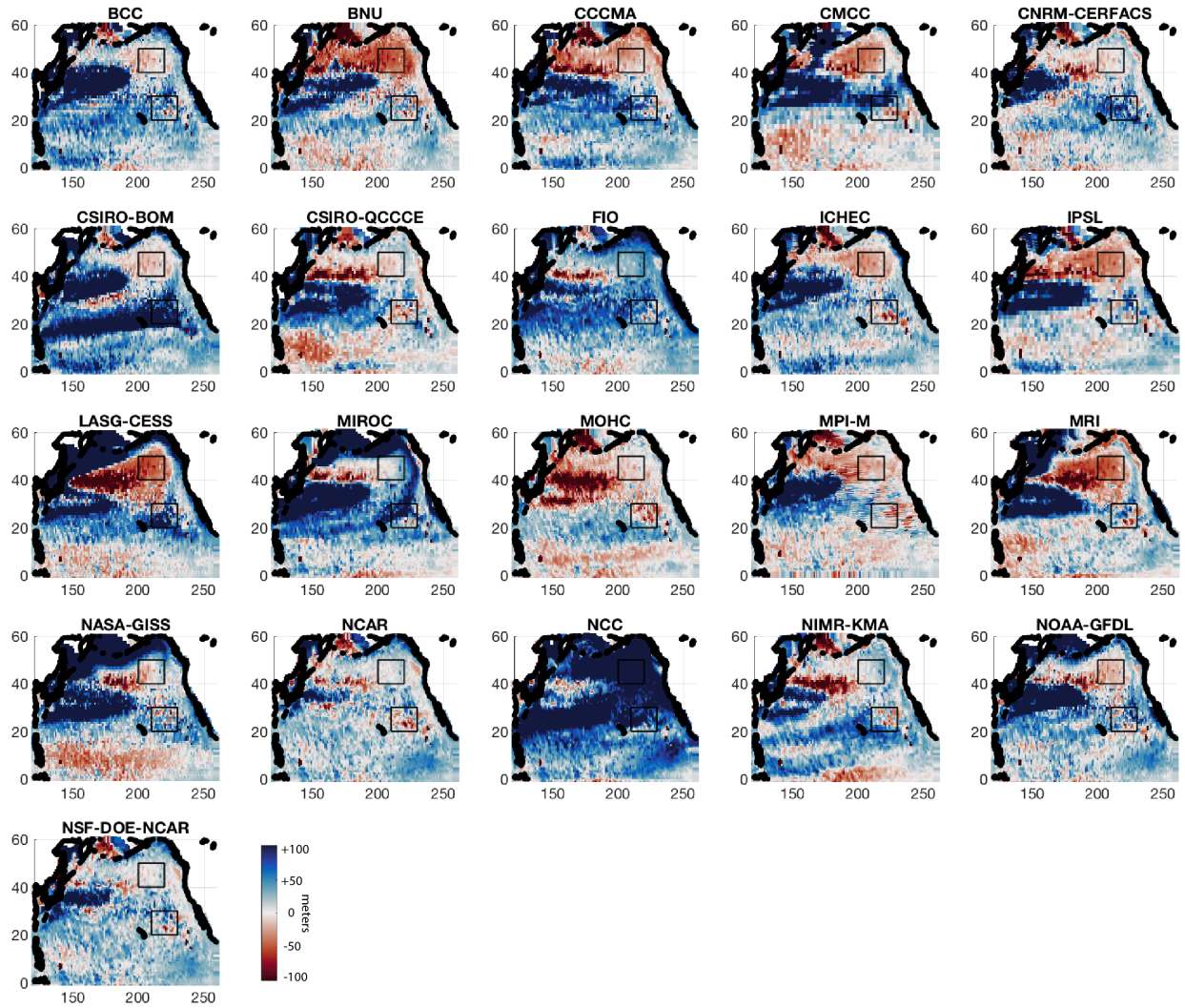
Figure S1. Winter-time evolution of the mixed layer in the PWP model as initialized with varying August model temperature and salinity profiles or WOA data (thicker black line).



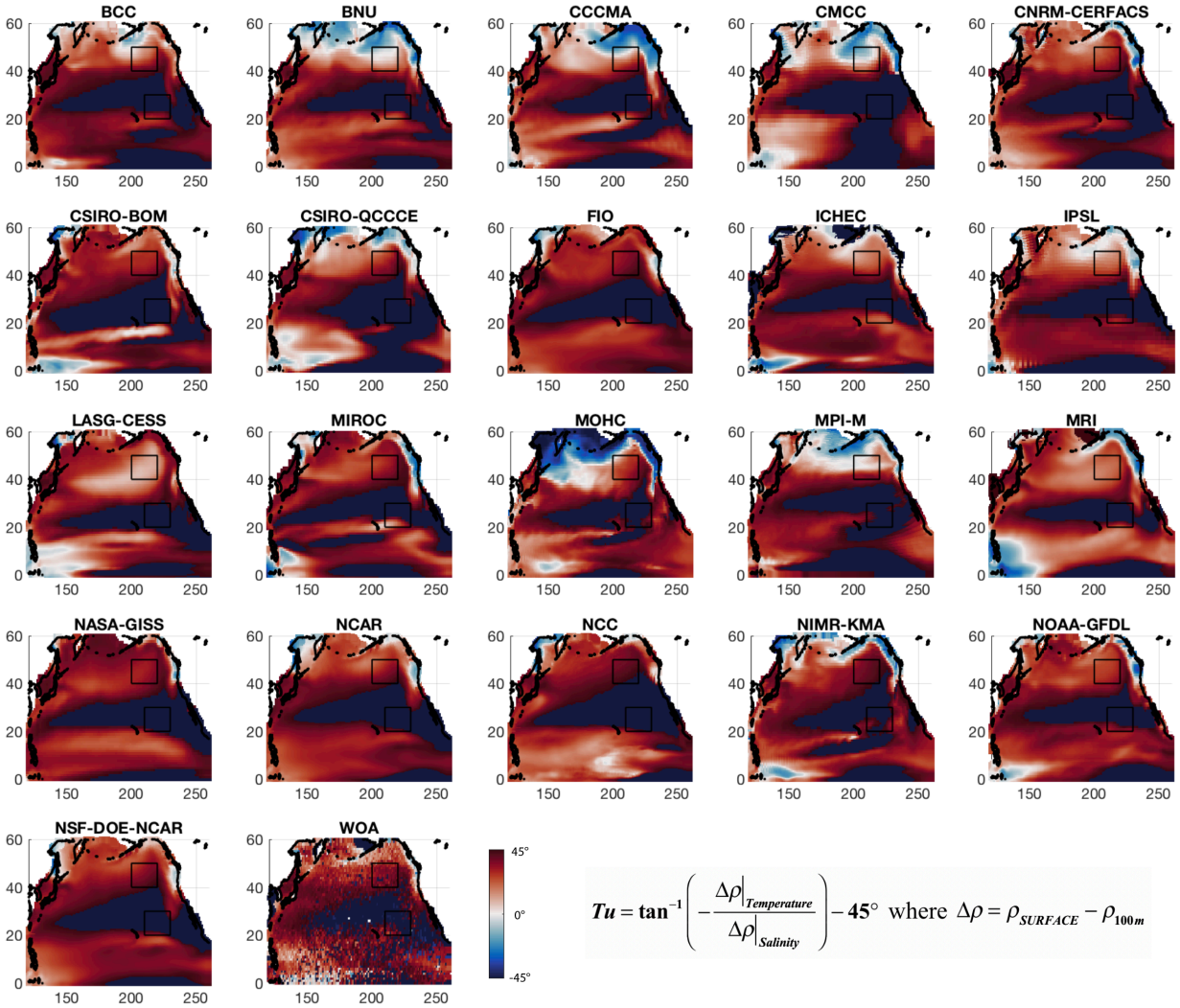
(a) August 10 m salinity bias (psu)



(b) March 10 m potential density (σ_θ minus 1000 kg m^{-3})



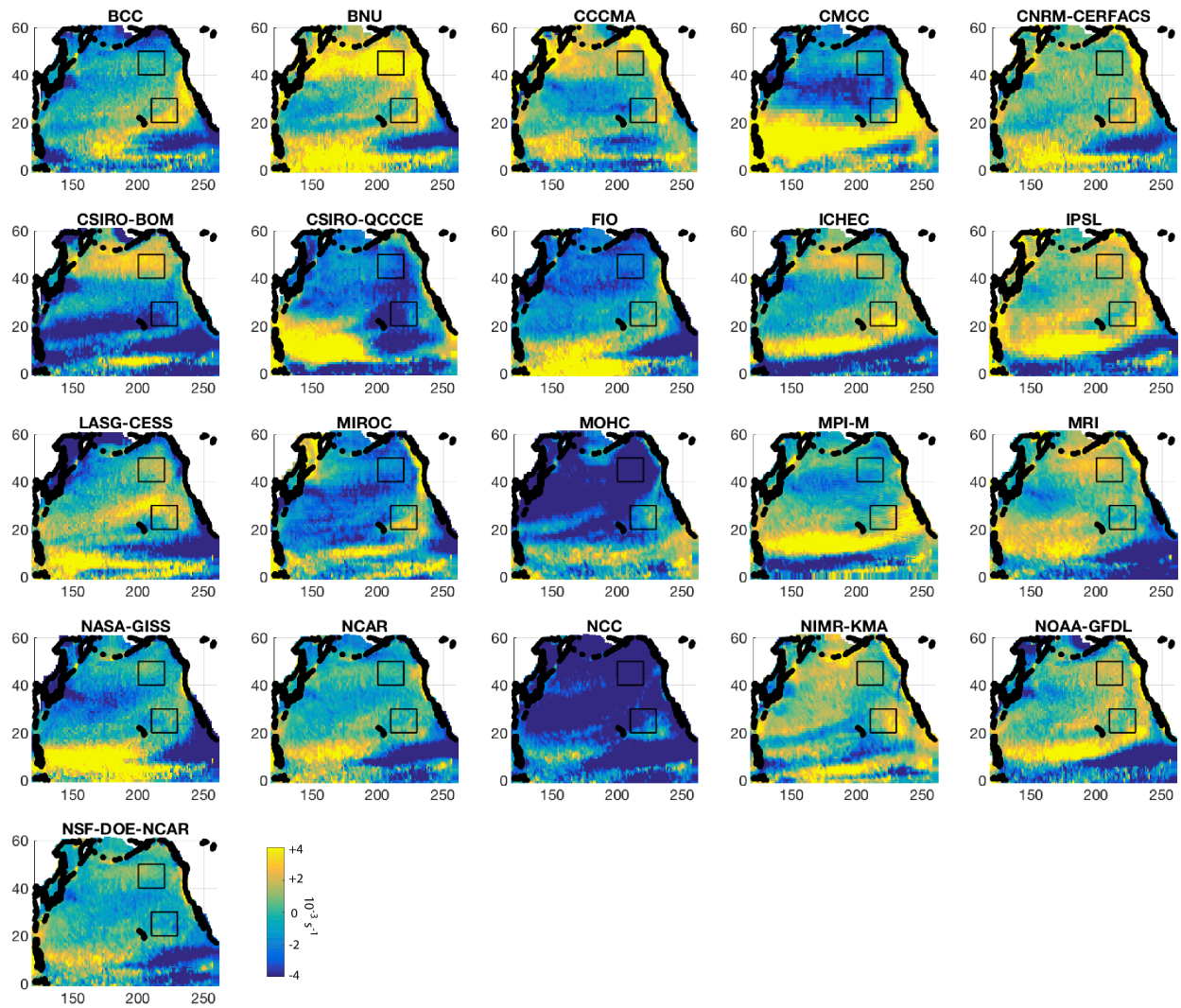
(c) March mixed layer depth bias (m)



(d) Upper ocean Turner angle, August

- Tu < -45
- 45 < Tu < 0
- Tu = 0
- 0 < Tu < 45
- Tu > 45

temperature is destabilizing
 salinity more important than temperature, both stabilizing
 salinity and temperature contribute equally to stable stratification
 temperature more important than salinity, both stabilizing
 salinity is destabilizing



(e) August buoyancy frequency bias, averaged over upper 100 m

Figure S2. Maps of selected upper ocean climatological average fields for the models and WOA data. The subarctic and subtropical Pacific regions are also shown. Bias fields are constructed by linearly interpolating WOA values to the model grid points.

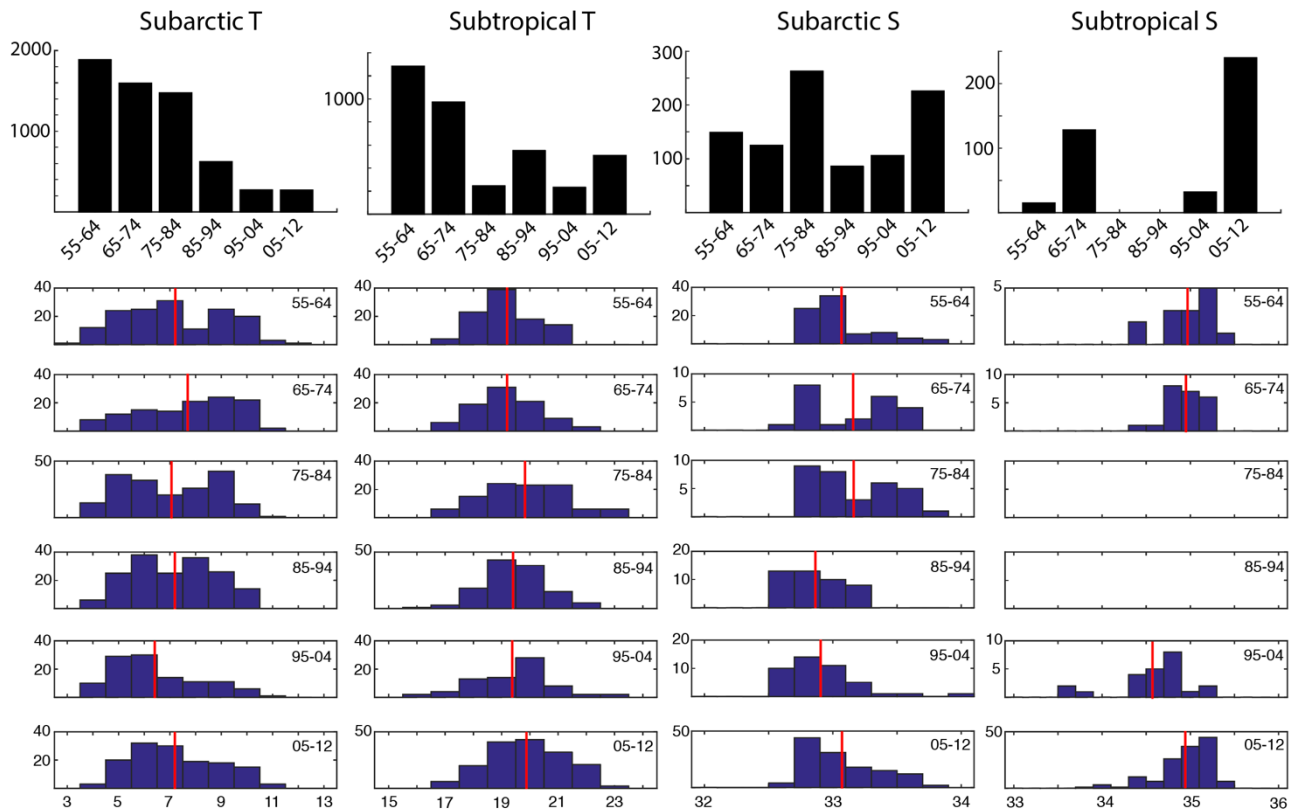


Figure S3. Number of August observations by decade in WOA at 100 m depth and histograms of 1° temperature values. Decadal mean values are marked with red lines.

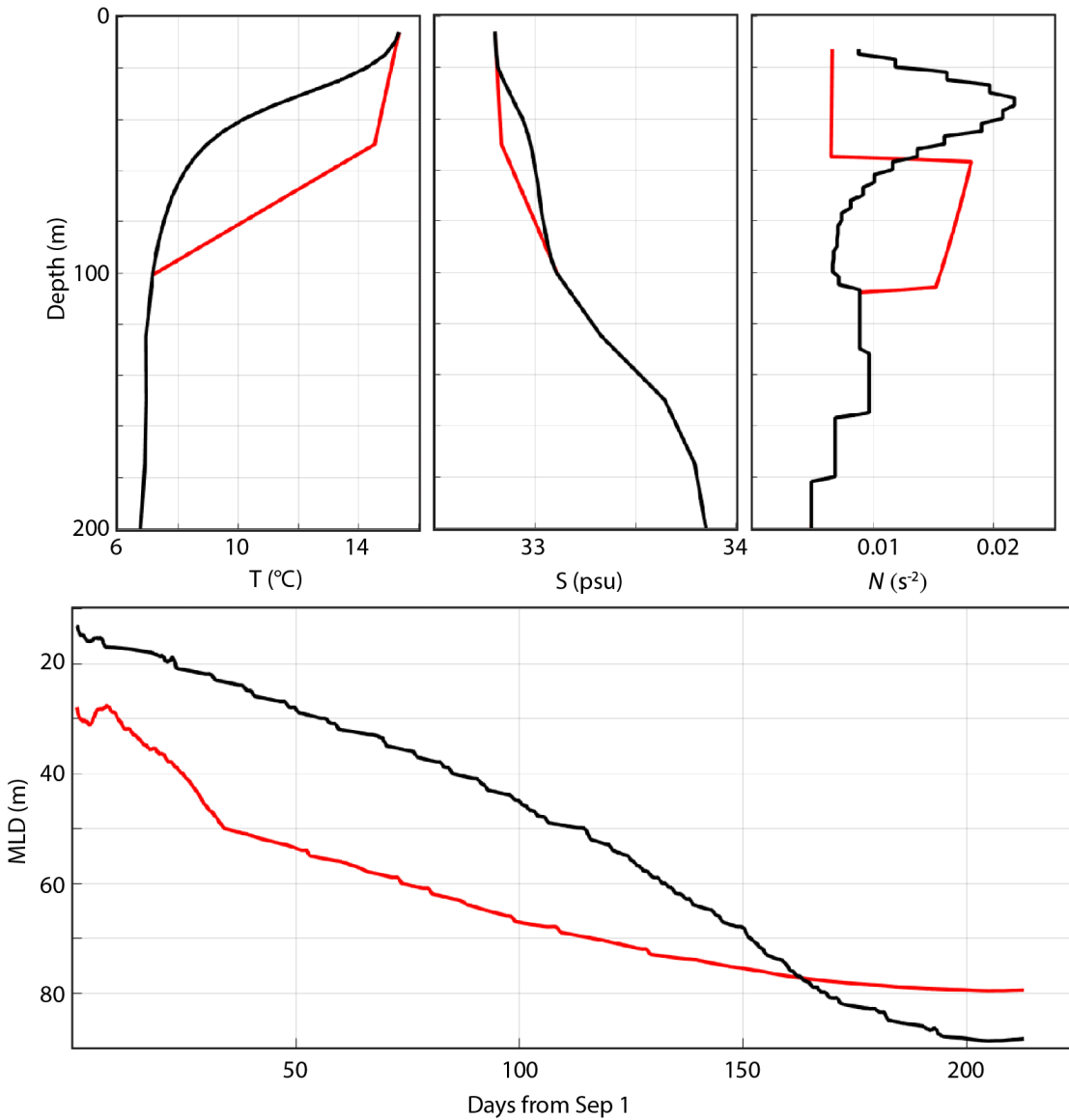


Figure S4. Idealized case study showing the response of the PWP model to the vertical structure of stratification. WOA (black) subarctic average profiles have had temperature and salinity redistributed within the upper 100 m (red) to produce a more layered stratification profile (top right). In both cases, the average value of buoyancy frequency (N) above 100 m is 0.013 s^{-1} . The bottom panel shows the time series of MLD from two PWP runs based on these profiles.