

# *The role of local atmospheric forcing on the modulation of the ocean mixed layer depth in reanalysis and a coupled single column ocean model*

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1 **The role of local atmospheric forcing on the modulation of the ocean mixed layer**  
2 **depth in reanalyses and a coupled single column ocean model**

3

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35 **Abstract**

36 The role of local atmospheric forcing on the ocean mixed layer depth (MLD) over the  
37 global oceans is studied using ocean reanalysis data products and a single-column  
38 ocean model coupled to an atmospheric general circulation model. The focus of this  
39 study is on how the annual mean and the seasonal cycle of the MLD relate to various  
40 forcing characteristics in different parts of the world's oceans, and how anomalous  
41 variations in the monthly mean MLD relate to anomalous atmospheric forcings. By  
42 analysing both ocean reanalysis data and the single-column ocean model, regions with  
43 different dominant forcings and different mean and variability characteristics of the  
44 MLD can be identified. Many of the global oceans' MLD characteristics appear to be  
45 directly linked to the different atmospheric forcing characteristics at different  
46 locations. Here, heating and wind-stress are identified as the main drivers; in some,  
47 mostly coastal, regions the atmospheric salinity forcing also contributes. The annual  
48 mean MLD is more closely related to the annual mean wind-stress and the MLD  
49 seasonality is more closely related to the seasonality in heating. The single-column  
50 ocean model, however, also points out that the MLD characteristics over most global  
51 ocean regions, and in particular in the tropics and subtropics, cannot be maintained by  
52 local atmospheric forcings only, but are also a result of ocean dynamics that are not  
53 simulated in a single-column ocean model. Thus, lateral ocean dynamics are essential  
54 in correctly simulating observed MLD.

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56 **Key words:** Ocean mixed layer depth; Atmospheric forcings; Coupled single column ocean  
57 model; Annual mean; Seasonal variability; Flux correction

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## 69 **1. Introduction**

70 The processes occurring in the upper ocean are predominantly forced by the atmosphere.  
71 Heating and cooling at daily to seasonal scales, wind-stress, evaporation and precipitation are  
72 the dominant physical processes that act on and interact with the upper layer of the ocean.  
73 Vigorous turbulent mixing near the surface by these forces results in a layer of homogeneous  
74 temperature and salinity (and thus density); its depth is defined as the ocean mixed layer  
75 depth (MLD).

76 Understanding the physics of the MLD is important for climate dynamics, because the  
77 thickness of the mixed layer (ML) modulates its heat capacity and hence its ability to store  
78 excess heat from the atmosphere (Godfrey and Lindstrom 1989; Maykut and McPhee 1995;  
79 Swenson and Hansen 1999; Peter et al. 2006; Dong et al. 2007; Montégut et al. 2007). In  
80 addition, MLD variations over the seasonal cycle or anomalies from it are one of the main  
81 processes for exchanging heat between the atmosphere and the deeper oceans. Proper  
82 quantification of the ML heat budget is important as it governs the evolution of the sea  
83 surface temperature (SST) (Chen et al. 1994; Alexander et al. 2000; Dommenges and Latif  
84 2002; Qui et al. 2004; Dong et al. 2008). In a study using a simple stochastic model,  
85 Dommenges and Latif (2008) showed that the low frequency (e.g., decadal) variability in SST  
86 is a result of the interaction of the heat stored in the layers below the MLD and the heat in the  
87 mixed layer. It thus suggests that decadal SST variability strongly depends on how the MLD  
88 varies and interacts with the subsurface layers. According to them the sensitivity of SST to  
89 MLD variability maximizes in the midlatitudes. Therefore, seasonal to interannual, and  
90 maybe even decadal, variability in SST can be simulated in terms of the local air-sea  
91 interactions and proper representation of MLD variability. Mixed-layer dynamics are also  
92 important for the ocean's biological productivity (Fasham 1995; Polovina et al. 1995;  
93 Narvekar and Kumar 2006) and acts as a medium for exchange of trace gases between the  
94 ocean and the atmosphere (Takahashi et al. 1997; Bates 2001; Sabine et al. 2004).

95 A number of studies have examined the mixed layer dynamics and demonstrated the variation  
96 in MLD at different spatial and temporal scales (Monterey and Levitus 1997; Kara et al. 2000;  
97 Cronin and Kessler 2002; Kara et al. 2003; Montégut et al. 2004; Halkides and Lee 2009).  
98 Most of these studies were limited to either a small region or at specific locations where in-  
99 situ data is available, and then extrapolated over a wider domain using some specific  
100 techniques. Since the advent of Argo data, reanalysis methods have produced a much more  
101 reliable source of representations of the state of the ocean at global scale. It has been shown  
102 that in summer the MLD is dominated by entrainment due to wind-induced mixing, whereas

103 in winter surface buoyancy forcing is the main driver (Alexander et al. 2000). These theories  
104 represent generalised concepts of MLD variability in the global ocean. However, the relative  
105 role of these forcings varies in time and space. This uneven distribution of MLD forcing on  
106 the seasonal time scale is not understood in detail over the global ocean. Lorbacher et al.  
107 (2006) and Carton et al. (2008) examined the variability in MLD at global scale from  
108 observations, but these are sparse over the Southern Ocean. Numerous attempts have been  
109 made to understand the ocean surface boundary layer and its sensitivity to atmospheric  
110 forcing (e.g., Adamec and Elsberry 1984; Large and Crawford 1995; Kantha and Clayson  
111 1994), but again they have mostly been limited to one location or in a small ocean basin.  
112 The focus of the present study is to examine the mean, seasonal cycle and variability of the  
113 MLD over the global ocean and how it relates to the different atmospheric forcings and the  
114 upper-ocean stratification. The aim is to understand the driving mechanisms of the MLD in  
115 different regions and to what extent these can be understood by the local air-sea interactions.  
116 In this we will focus on open ocean regions and do not discuss sea ice regions or shallow  
117 coastal ocean regions. Therefore, the MLD and the atmospheric forcing terms will be  
118 analysed in ocean reanalysis data and in a single-column mixed layer ocean model coupled to  
119 an atmospheric general circulation model (AGCM). The latter model simulation allows  
120 insight as to what extent the MLD characteristics can be simulated just by local air-sea  
121 interactions. It also allows us to diagnose the limitations of local air-sea interactions  
122 assumption by analysing the flux correction terms used in the model to maintain a density  
123 profile close to the observed mean profile.  
124 The paper is organized as follows: A detailed description of the reanalysis data used, the  
125 coupled model and the method to estimate the MLD is presented in the following section.  
126 Section 3 focuses on the observed characteristics of MLD estimated from reanalysis data. In  
127 section 4 most of the analysis is repeated for the single-column model simulation. Finally, the  
128 results are summarised and discussed in section 5.

129

## 130 **2. Data, Model and Methods**

131 Reanalyses and data from a single-column ocean model are used to understand the  
132 characteristics of the global ocean mixed layer depth and its relation to local atmospheric  
133 forcing. Details of the datasets and methods used in this study are described below.

134

### 135 *a. Reanalysis data sets*

136 The characteristics of the MLD presented here are partly based on vertical profiles of  
137 temperature and salinity from the German contribution to Estimating the Circulation and  
138 Climate of the Ocean system (GECCO2) for the period 1948-2011. The data has a spatial  
139 resolution of 1x1 degrees in longitude and latitude and comprises 50 vertical levels. The  
140 synthesis used model assimilation with available hydrographic and satellite data. A complete  
141 description of this data is given by Kohl (2014). Two other data assimilation products are  
142 also analysed in addition to GECCO2: The Global Ocean Data Assimilation System  
143 (GODAS) data (Behringer and Xue 2004) implemented at National Centers for  
144 Environmental Prediction (NCEP) for the period 1980-2013 and the Simple Ocean Data  
145 Assimilation (SODA v2.2.4) data for the period 1950-2010 (Carton and Giese 2008). In the  
146 following analysis we will focus all analyses on GECCO2, because it provides data for a  
147 longer time period than the NCEP-GODAS dataset and compared to the SODA dataset the  
148 results appear to be slightly less noisy. The reanalyses are a combination of model dynamics  
149 and sparse observational data, therefore one can expect biases between the products that arise  
150 from different assimilation procedures (Kröger et al. 2012). Overall the results we present in  
151 this study are qualitatively the same in all three datasets. Any significant differences are  
152 pointed out in the text.

153

#### 154 ***b. The coupled single column ocean model (ACCESS-KPP)***

155 A 50-year simulation of a coupled atmosphere-ocean single-column model is used to study  
156 the MLD variability over the global ocean. The atmospheric component of the coupled model  
157 consists of the Australian Community Climate and Earth-System Simulator (ACCESS)  
158 version 1.3 atmospheric GCM, which is similar to the UK Met Office's Global Atmosphere  
159 version 1.0 with the addition of some modifications included by the Centre for Australian  
160 Weather and Climate Research (CAWCR). A horizontal resolution of 3.75° longitude by 2.5°  
161 latitude (referred to as N48) and 38 vertical levels are applied in this model setup. A detailed  
162 description of the atmospheric model is given in Bi et al. (2013).

163 The ocean component of the coupled model consists of a single-column first-order nonlocal  
164 K-Profile Parameterisation (KPP) mixed layer model, which uses the vertical mixing scheme  
165 of Large et al. (1994). It comprises 40 vertical levels with the layer thickness increasing  
166 exponentially from the surface to 1000m deep. The single-column ocean model is coupled to  
167 the atmospheric model at every ocean grid point of the atmospheric model, and at the time  
168 step of both atmosphere and oceanic models (30min), following Klingaman and Woolnough  
169 (2014) and Hirons et al. (2015). The KPP model is very adaptable and flexible; it can be

170 applied to AGCM of any resolution. The atmospheric model provides the surface heat flux,  
171 wind-stress and freshwater flux (evaporation minus precipitation or E-P) to the ocean at each  
172 time step. The mixed layer model does not represent processes such as horizontal advection  
173 or upwelling from below the limited vertical domain. Mixing in the interior (layer below the  
174 surface) is governed by shear instability, which is modelled as a function of the local gradient  
175 Richardson number. A boundary layer depth is determined at each grid point, based on the  
176 critical value of the turbulent processes parameterised by a bulk Richardson number. Vertical  
177 diffusivity coefficients due to turbulent shear are estimated in the diagnosed boundary layer  
178 depth. Mixing is strongly enhanced in the boundary layer in both convective and wind driven  
179 situations enabling boundary layer properties to penetrate well into the thermocline. A  
180 detailed description of the first order nonlocal KPP fundamentals is given in Large et al.  
181 (1994). The ocean model is embedded with varying sea-ice concentration at the higher  
182 latitudes. The sea ice variability is simulated by a simple thermodynamical model of melting  
183 and freezing of sea ice by local forcings. However, regions with sea ice will not be discussed  
184 in this study. A flux correction is applied to the ocean temperature and salinity tendency in  
185 order to reduce the climate drift, which is described in the following sub-section.

186

### 187 **c. Flux corrections**

188 The ACCESS-KPP model computes the diffusivity profiles at each grid point and then  
189 estimates the temperature and salinity profiles. Since ocean dynamics (mainly advection) are  
190 absent in the model the temperature and salinity drifts away from the observed reference  
191 values for a longer run (many decades). So it is necessary to add flux corrections in order to  
192 prevent climate drift. The flux correction values are computed such that the mean seasonal  
193 cycle of temperature and salinity closely follow the climatology from WOA09 (Antonov et  
194 al. 2010; Locarnini et al. 2010). The temperature and salinity flux corrections are obtained in  
195 a number of iterations with the ACCESS-KPP model, where temperature and salinity are free  
196 to evolve. In each iteration biases between the model variables and the climatological values  
197 are then computed and added as an additional forcing to the model's tendency equation in the  
198 next iteration. This process is repeated until the biases between the model variables and the  
199 climatological reference values are sufficiently small. The flux corrections vary at each grid  
200 point and for each month of year but are state independent and remain the same from one  
201 year to the next. Characteristics of the flux correction terms are discussed in the analysis  
202 section (see section 4.4).

203



#### 204 *d. Method for MLD estimation*

205 A wide range of criteria exists for defining MLD from the vertical profiles of temperature,  
206 salinity or density. Generally, these criteria fall into two categories: the difference criteria and  
207 the gradient criteria. The difference criteria define the MLD as the depth where the oceanic  
208 property has changed by a critical value from a reference depth near to the surface (Kara et  
209 al. 2000; Montégut et al. 2004). The gradient criteria detect the shallowest depth where the  
210 vertical gradient of the oceanic tracers exceeds a given value (Brainerd and Gregg 1995;  
211 Lorbacher et al. 2006). The difference criterion largely depends on the difference value  
212 chosen and produces misrepresentation of the MLD in regions of weakly stratified surface  
213 layers. The gradient criteria also depend on the threshold value chosen for the derivative, but  
214 since the gradient is expected to be large at the base of the MLD, it gives more accurate  
215 estimations of MLD. Lorbacher et al. (2006) further developed the gradient criteria by adding  
216 the standard deviation threshold to assume the shallowest extreme curvature. As a first guess,  
217 the nearest MLD is assumed at the local maximum/minimum of the second derivative of the  
218 gradient and where the gradient exceeds 0.25 of gradient maximum of the profile. As a  
219 secondary boundary condition, 30-m standard deviation ( $>0.02$ ) is included to distinguish the  
220 near-homogeneous region and a standard deviation of gradient over the upper level is then set  
221 ( $0.004 \text{ km}^{-1}$  for high and  $0.002 \text{ km}^{-1}$  for low resolution). A more accurate estimation of MLD  
222 is provided by an exponential interpolation method (for thick layers), and hence the  
223 Lorbacher et al. (2006) criteria is used to estimate the mixed layer from the density profiles  
224 for all the data in this study. The results in this paper also hold when difference criteria are  
225 used for estimating MLD. We checked with difference in density of  $0.03 \text{ kg/m}^3$  and variable  
226 density criteria (Montégut et al. 2004) that results shallower or deeper ML than that obtained  
227 by Lorbacher et al, (2006). However, the spatial pattern remain fairly similar for all the  
228 criteria.

229

#### 230 **3. Observed MLD**

231 As a starting point for the analysis the seasonal mean MLD estimated from GECCO2 are  
232 presented in Fig. 1 (left column). They are largely consistent with those found in previous  
233 studies (Kara et al. 2003; Montégut et al. 2004; Lorbacher et al. 2006). Fig. 2 simplifies the  
234 seasonal mean MLDs to the annual mean and the relative strength of the seasonal cycle. They  
235 show a number of well-known characteristics, such as the strong seasonal cycle in the extra-  
236 tropical regions or the shallow MLDs in the upwelling regions along coastlines and the  
237 equatorial Pacific. Overall the structure of the global ocean seasonal mean MLD is fairly

238 complex. To simplify the following discussions and analyses it is useful to define some basic  
239 MLD regimes, based on the annual mean MLD and the relative strength of the seasonal cycle  
240 (Fig. 2). The regime selection criteria were somewhat guided by a good presentation of the  
241 following analysis. In terms of MLD the global ocean can be split into the following three  
242 regimes:

- 243 • **Extra-tropical-seasonal:** Regions where the standard deviation of the seasonal cycle  
244 is larger than 60% of the annual mean MLD (Fig. 3a). The criteria (60%) cover the  
245 regions where significant seasonal variability occurs. These are regions with a very  
246 shallow warm-season MLD and a substantially deeper cold-season MLD. This is  
247 mostly found in a band along 30-40 degrees with some regions extending further to  
248 higher latitudes. The most extreme seasonality is seen in the Southern Ocean in the  
249 Indian and Pacific sections, which are within the Antarctic Circumpolar Current  
250 (ACC) (Sallée et al. 2006; Dong et al. 2008). The far northern Atlantic is also a region  
251 of extreme seasonality.
- 252 • **Constant-deep:** Regions with an annual mean MLD  $> 30\text{m}$  and a standard deviation  
253 of the seasonal cycle that is less than 60% of the annual mean MLD (Fig. 3b). The  
254 30m selection criteria roughly mark half-standard-deviation away from the global  
255 mean MLD. These are mostly the off-equatorial tropical and subtropical regions, but  
256 also large fractions of the Southern Ocean and parts of the far northern Pacific.
- 257 • **Constant-shallow:** Regions with an annual mean MLD  $< 30\text{m}$  and a standard  
258 deviation of the seasonal cycle that is less than 60% of the annual mean MLD (Fig.  
259 3c). These mark mostly coastal regions and in particular upwelling regions along  
260 major continents and equatorial regions, but also coastlines in the north-western North  
261 Atlantic and west of Australia. Most of the North Indian Ocean falls in this shallow  
262 regime. But in NCEP-GODAS much of the North Indian Ocean falls in the constant-  
263 deep regime. It should be noted that MLD in NCEP-GODAS (annual mean is  $\sim 52\text{m}$ )  
264 is deeper than the other two reanalyses data ( $\sim 41\text{m}$  in GECCO2 and SODA). The  
265 difference could be associated with different model assimilation procedures (Kröger  
266 et al. 2012).

267 The following analysis focuses on how these different mean MLD regimes relate to the local  
268 atmospheric forcing and the stratification of the upper ocean.

269

### 270 **3.1 The annual mean MLD and its relationship with local forcing**

271 The external forces that act on the MLD are the heat, momentum and evaporation-  
272 precipitation difference (E-P) fluxes. All these forces interact with and influence the upper-  
273 ocean stratification. Strongly stratified profiles require strong forcing to break the  
274 stratification and to promote deepening of the mixed layer (ML). A comparison of the annual  
275 mean values of the atmospheric forcings and the upper-ocean stratifications (Fig. 4) with the  
276 annual mean MLD (Fig. 2a) gives some idea of the relative importance of the different  
277 forcings. Note that the shading in Fig. 4 is coded in such a way that bluish colours indicate  
278 forcings or stratifications that would support deeper mixed layers, and reddish colours  
279 indicate forcings or stratifications that would support shallower MLD.

280 The annual mean net heat flux (NHF) in the higher latitudes ( $>40^\circ$ ) is mostly negative, which  
281 implies that the ocean is losing heat (Fig 4a). Heat loss at the surface makes the upper ocean  
282 statically unstable, which tends to deepen the ML. The upwelling regions along the coastlines  
283 and the equator and in the tropical Indian Ocean are marked by annual mean heat gain, which  
284 tends to support shallow MLD. Overall there is only a moderate match between the annual  
285 mean NHF forcing and the MLD (spatial correlation of -0.3). Most of the *constant-shallow*  
286 MLD regime seems to be associated with annual mean heat gain. Also many of the extra-  
287 tropical regions with deeper annual mean MLD are associated with corresponding heat loss.  
288 However, many regions with shallower than global mean MLD are associated with annual  
289 mean heat loss, which does not support the observed shallow MLD (e.g. coastal regions in  
290 the western North Pacific and Atlantic and southern subtropical regions in the Indian and  
291 Pacific Oceans). Also regions with deeper than global mean MLD are associated with annual  
292 mean heat gain, which does not support the observed deep ML (e.g. off-equatorial tropical  
293 Pacific and parts of the Southern Ocean).

294 The annual mean wind-stress forcing (Fig. 4b) shows a slightly better match to the annual  
295 mean MLD than NHF (spatial correlation of 0.4). In particular, higher-latitude regions with  
296 deep annual mean ML are associated with strong mean wind-stress and equatorial regions  
297 with shallow annual mean MLD are associated with weak mean wind-stress. However, there  
298 are also large regions where the annual mean MLD is deep despite fairly moderate annual  
299 mean wind-stress (e.g. latitude bands around 30 degrees in both hemispheres) and regions  
300 where the annual mean MLD is shallow despite fairly strong annual mean wind-stress (e.g.  
301 subtropical South Indian Ocean and the Arabian Sea). One can also notice that for most  
302 regions NHF and wind-stress have similar influences on the MLD, with both either  
303 supporting deeper ML (e.g. most extra-tropical regions) or supporting shallower ML (e.g.

304 equatorial regions). Notable exceptions here are parts of the subtropical regions, parts of the  
305 Southern Ocean, the far northern Pacific, the western North Atlantic and the Arabian Sea.  
306 The precipitation and evaporation (E-P) plays in general a minor role in mixing processes in  
307 the upper ocean by changing the density structure (Dong et al. 2009), which is also  
308 highlighted here by the mismatch of the annual mean E-P (Fig. 4d) with the annual mean  
309 MLD for most regions (spatial correlation of 0.0). The mean E-P forcing is also mostly  
310 unrelated to the NHF and wind-stress forcings. In some regions, however, where both NHF  
311 and wind-stress forcings do not match the MLD, the E-P forcing does indeed seem to match  
312 the MLD. These appear to be mostly smaller and coastal regions (e.g. coastal regions of  
313 Greenland and some parts of the western boundary of the North Pacific and Atlantic).  
314 Remarkable are the shallower MLD regions in the subtropical Indian and western Pacific  
315 Oceans. Here, all three atmospheric forcings would support deeper annual mean MLD. The  
316 shallower MLDs here seem to match the stronger upper-ocean stratifications, displayed in  
317 Fig. 4c (spatial correlation of -0.5) in terms of the density gradient between the surface and  
318 100m depth. Although, upper-ocean stratification is partly a reflection of the atmospheric  
319 forcings, it is also influenced by oceanic processes. Since the annual mean atmospheric  
320 forcings seem to mismatch the mean MLD in these regions, it suggests that oceanic processes  
321 independent of the local atmospheric forcing contribute to the stratification of the upper  
322 ocean and thus a shallower MLD.

323

### 324 **3.2 The MLD seasonal cycle and its relationship with local forcing**

325 The *extra-tropical-seasonal* MLD regime largely represents the world ocean regions with  
326 strong mean MLD seasonal cycle (Fig. 2b). These regions are fairly well matched with the  
327 strength of the NHF seasonal cycle (Fig. 5a) with a spatial correlation of  $\sim 0.6$ . Although the  
328 wind-stress forcings in the Northern Hemisphere support the *extra-tropical-seasonal* MLD  
329 regime, they do not show strong seasonality in the Southern Hemisphere (Fig. 5b). Thus it  
330 seems that the *extra-tropical-seasonal* MLD regime is mostly a result of seasonally varying  
331 tendencies of heating and cooling at the surface. This is consistent with previous findings  
332 (Monterey and Levitus, 1997; Kara et al. 2003; Montégut et al. 2004). Also, seasonal  
333 variability in density gradients (Fig 5c) and E-P (Fig 5d) shows only a moderate match  
334 (spatial correlation of 0.3 and -0.2 respectively) with the seasonality in MLD. However, again  
335 there are some regions where this simple picture is not supported. In particular, the western  
336 boundaries of the North Pacific and Atlantic have a very strong seasonal cycle in NHF, but

337 not in the MLD. Also the very strong seasonality in the Indian and Pacific Oceans' ACC  
338 regions are not directly matched by the seasonality in either of the atmospheric forcings.  
339 An interesting aspect of the combined effect of annual mean forcing and the strength of the  
340 seasonality in the forcings can be seen along the zonal bands in the northern midlatitudes  
341 (Fig. 6). In the zonal band at around 30°N in the North Pacific the MLD is deeper on the  
342 western side and it has a stronger seasonality. Both mean and seasonality decrease to the east.  
343 This is supported by the behaviour of the mean heat flux and its seasonality. In the west an  
344 annual mean cooling and strong seasonality support the MLD behaviour; to the east the mean  
345 cooling turns into a mean warming and the seasonality in NHF decreases, again supporting  
346 the MLD behaviour. This reflects the change in atmospheric forcing from having strong  
347 continental characteristics in the west (e.g. strong cooling in winter and strong seasonality)  
348 and being more in balance with the ocean state in the east, due to the preferred westerly wind  
349 conditions that tend to transport characteristics from the west to the east. This is somewhat  
350 similar in the North Atlantic, but the relationship breaks down near the western boundary  
351 region.

352

### 353 **3.3 Anomaly variability and its relationship with local forcing**

354 Next, it is interesting to regard the MLD variability beyond the seasonal cycle. The second  
355 column of Fig. 1 shows the standard deviation (stdv) of monthly mean MLD anomalies  
356 estimated for each season. The patterns of strong and weak MLD stdv match very well the  
357 patterns of deep and shallow mean MLD (first column in Fig. 1). Thus, MLD variability is  
358 stronger when the mean MLD is deep and MLD variability is weak when the mean MLD is  
359 shallow. This pattern even holds when we consider the coefficient of variance (CV; the ratio  
360 of stdv over the mean) as shown in the last column of Fig. 1. The equatorial Pacific and  
361 Atlantic, however, mark regions where the MLD variability is strong even though the mean  
362 MLD is fairly shallow, which is consistent with the study by Lorbacher et al. (2006). In these  
363 regions the concept of MLD may not be so useful, as they are more dominated by lateral  
364 ocean wave dynamics in the thermocline. It is also remarkable to note that a CV > 100% is  
365 observed in the spring and winter seasons in the higher latitudes of North Atlantic and Pacific  
366 and in the Southern Ocean. This suggests a substantial amount of MLD variability. For most  
367 other regions the CV values are larger than 30%, indicating significant MLD variability for  
368 most regions in most seasons. Keerthi et al. (2012) have also shown large CV values (>40%)  
369 in the western and eastern equatorial Indian Ocean during boreal summer.

370 Fig. 7 shows the cross-correlation between monthly mean MLD and NHF anomalies in-phase  
371 and with one-month lead-time for the NHF for different seasons. Negative in-phase  
372 correlations dominate in all seasons and most regions, consistent with cooling (negative NHF  
373 anomalies) at the surface ocean leading to increased convective mixing and, hence, a deeper  
374 ML; and vice versa for positive NHF anomalies. Equatorial regions in the central Pacific and  
375 western Atlantic, however, show negligible correlation between NHF and MLD anomalies.  
376 Further, the in-phase correlation in both hemispheres (in the midlatitudes) is stronger in fall  
377 and winter and fairly weak in spring and summer. The one-month MLD lag cross-correlation  
378 with NHF is largest in the fall season and weakest in the spring season in both hemispheres.  
379 This relation is consistent with the idea that deeper MLDs evolve more slowly and therefore  
380 have a longer lag-time relation between forcing (NHF) and MLD anomaly.

381 The wind-stress forcing is in most regions positively correlated with MLD, consistent with  
382 stronger than normal wind-stress anomalies leading to deeper MLDs, and vice versa for  
383 negative wind-stress anomalies (Fig. 8). In the mid to higher latitudes this relationship tends  
384 to be stronger in spring and summer. The strongest correlations are essentially found in two  
385 regions: the off-equatorial tropical and subtropical regions with a tendency for stronger  
386 correlations in the warmer season, and the extra-tropical higher latitudes in the Southern  
387 Ocean and to a smaller extent in the far northern Pacific and Atlantic. The lag one-month  
388 correlation overall appears to be strongest in the subtropical regions and in the fall season in  
389 the Southern Ocean.

390 The cross-correlations of MLD with both NHF and wind-stress are mostly on a similar level,  
391 with some more widespread and clearer correlation for the NHF with MLD. Cross-  
392 correlations of MLD with E-P are in general weaker than those with NHF and wind-stress,  
393 but are mostly positive, which is consistent with increased evaporation (salinity forcing)  
394 leading to deeper MLs (see SFig. 1). This relationship is strongest in fall and winter seasons  
395 in both hemispheres.

396

#### 397 **4. The ACCESS-KPP model**

398 We now take a look at the MLD and its relation to the atmospheric forcings in the ACCESS-  
399 KPP model with a single-column ocean mixed layer model. Thus, in this model the simulated  
400 MLD is purely a result of local atmospheric forcing, vertical mixing and a heat and salinity  
401 flux correction, which is independent of the background state, to prevent the model from  
402 drifting away from the observed mean density profiles.

403 A comparison of the patterns of the seasonal mean MLDs and its variability between  
404 observations (Fig. 1) and the ACCESS-KPP model (Fig. 9) already illustrates that the model  
405 represents the mean MLD characteristics very well. In the following, the same MLD  
406 characteristics as above for observations will be analysed in the ACCESS-KPP model.  
407 Further the role of the flux corrections in maintaining the realistic upper-ocean density  
408 profiles will be investigated.

409

#### 410 **4.1 The annual MLD and its relationship with local forcing**

411 The figures 10 and 11 show the same atmospheric forcings and upper-ocean stratification  
412 fields as in figures 4 and 5, but for the ACCESS-KPP model. First of all one can notice that  
413 the annual mean and seasonal cycle of the atmospheric forcings in the ACCESS-KPP model  
414 are very similar to the observed values (spatial correlations are greater than 0.7, see Table 1  
415 in the supplementary material). This suggests that the MLD characteristics in the ACCESS-  
416 KPP model can be analysed for similar atmospheric forcings conditions. Some mismatches  
417 exist in the annual mean NHF in the northern Indian Ocean and tropical north Atlantic, where  
418 the observed NHF is positive but the ACCESS-KPP model values are negative. However,  
419 there are also some differences in these characteristics among the ocean reanalysis products  
420 (see Table 2 in the supplementary material for spatial correlation between the ocean  
421 reanalysis products), suggesting that such differences are not necessarily an indication of a  
422 significant model bias.

423 The regional distribution of the annual mean MLD and the three main MLD regimes in the  
424 ACCESS-KPP model are fairly similar to the observed (compare Figs. 12 and 13 with 2 and  
425 3). The ACCESS-KPP model has a very similar regional distribution of the *extra-tropical-*  
426 *seasonal* MLD regime, it also simulates the *constant-deep* MLD regime with a subtropical  
427 and Southern Ocean region and it simulates parts of the *constant-shallow* MLD regime in the  
428 coastal upwelling regions. However, some significant differences between the ACCESS-KPP  
429 model and the observations can be noted: first, the overall mean MLD in the ACCESS-KPP  
430 model is deeper than observed (63m and 41m, respectively). Here it should be noted that  
431 annual mean in the other ocean reanalysis product NCEP-GODAS is ~52m and for SODA it  
432 is ~41m. It must however be kept in mind that MLD in the model is predominantly driven by  
433 the atmospheric forcing; the strong inclination of ML dynamics on atmospheric forcing could  
434 be a reason for relatively deeper ML in the model. The model also misses several regions  
435 within the *constant-shallow* MLD regime: the equatorial cold tongues, the tropical Indian  
436 Ocean and the northern oceans coastal regions. The model's *extra-tropical-seasonal* MLD

437 regime is also slightly more widespread in the northern oceans than observed. Further, the  
438 ACCESS-KPP model simulates fairly deep ML in the eastern subtropical Pacific and  
439 subtropical Indian Ocean, which is much shallower in the observations. The deeper ML in  
440 these regions seems to fit to fairly strong annual mean local atmospheric heat and wind  
441 forcings. It thus seem to indicate that the observed shallow ML in these regions does not  
442 result from the local forcing, but may involve interactive lateral ocean dynamics not  
443 represented in the single-column ACCESS-KPP model. The northern North Atlantic shows  
444 deeper MLs in the model despite weak wind forcing compared to the observed. In the model,  
445 stronger cooling (compared to the observed) as well as statically less stable upper-ocean  
446 (caused by relatively high surface salinity) results in overturning to great depth producing  
447 deeper MLs in this region.

448 The relationship between the atmospheric forcings and the MLD in the ACCESS-KPP model  
449 is also similar to the observed (compare Figs. 4 and 10). Again the wind-stress forcing tends  
450 to be more strongly related to the annual mean MLD than the heat flux forcing and again the  
451 E-P forcing has no relationship with the annual mean MLD.

452

#### 453 **4.2 The seasonal cycle of MLD and its relationship with local forcing**

454 As stated above, the model is able to reproduce the observed seasonal changes reasonably  
455 well (compare Figs 2b and 12b): it essentially captures the zonal bands of the strong *extra-*  
456 *tropical-seasonal* MLD regime in the midlatitudes. Seasonal amplitude is weaker in the  
457 tropics, subtropics and also in parts of the Southern Ocean. As already indicated in the  
458 previous section, the ACCESS-KPP model tends to overestimate the seasonality in the  
459 eastern North Pacific and the western coastal region in the North Atlantic. The model is good  
460 at representing the mean summer MLD, but overestimates MLD during fall and spring. This  
461 however, cannot be due to stronger seasonality in the atmospheric forcings, as they appear to  
462 be similar or weaker than observed. This suggests that the ACCESS-KPP model is missing  
463 some ocean dynamics necessary to capture these features.

464 The seasonal cycle of the atmospheric forcings is well captured by the ACCESS-KPP model  
465 and again the relationship between the heating and wind-stress forcings and the MLD are  
466 mostly as observed (compare Figs 5 and 11). Thus, the seasonality in the NHF is the main  
467 forcing for the seasonal cycle of the MLD in ACCESS-KPP model.

468

#### 469 **4.3 Anomaly variability and its relationship with local forcing**



470 The overall strength and seasonal distribution of the anomaly variability of the MLD in the  
471 ACCESS-KPP model is very similar to the observed (compare Figs. 1 and 9). The stdv of the  
472 MLD is mostly strong where the mean ML is deep, but it follows the mean MLD even more  
473 closely than observed. Thus, the coefficient of variance is more homogenous in the ACCESS-  
474 KPP model.

475 The correlation between heat flux and wind-stress forcings and the MLD in the model have  
476 similar signs as in observations in all seasons, but are overall much stronger (compare Figs. 7  
477 and 8 with 14 and 15). This could be related to both errors in the reanalysis dataset and to the  
478 simplified dynamics of the ACCESS-KPP model. The observations include atmospheric heat  
479 fluxes, ocean observations and the model simulation of the reanalysis model. Errors in these  
480 elements will lead to inconsistencies between the forcings and the MLD. Subsequently, one  
481 has to assume that the correlation between forcings and the MLD is decreased in the  
482 observations. On the other hand, the ACCESS-KPP model has simplified dynamics that only  
483 include local forcings and vertical mixing, neglecting all other lateral ocean dynamics.  
484 Subsequently, one has to assume that the correlation between local forcings and the MLD is  
485 artificially enhanced.

486 As in the observations the effect of the anomalous wind stress forcings is stronger in the  
487 warmer, shallower MLD seasons. The lag-1 correlation of the heat flux is also stronger in the  
488 cold, deep ML seasons as in the observations. The E-P also shows higher correlations with  
489 MLD (see SFig.1 and 2) than observed, but still much weaker than the correlations with heat  
490 flux and wind stress, suggesting that the E-P forcing is not as important.

491

#### 492 **4.4 Missing dynamics and the role of flux corrections**

493 Although the ACCESS-KPP model represents the seasonal mean MLD and its variability  
494 fairly well by only simulating the local atmospheric forcing and the vertical single column  
495 dynamics, it does also have substantial limitations. A key aspect of the ACCESS-KPP model  
496 is that additional heat and salt flux correction terms exist on all levels in the ocean model.  
497 These flux corrections are essential in many regions to maintain the overall stratification in  
498 the density profile of the ocean, see Fig. 16(a,b). Without in particular the heat flux  
499 corrections (salinity corrections not shown), the ocean stratification in the tropics and  
500 subtropics would collapse eventually (over periods longer than 10 years) and the warm  
501 surface waters would mix all the way to the bottom layer of the KPP model (1000m depth).  
502 This is indicated by the significant surface warming and subsurface cooling effect of the heat  
503 flux correction over wide spread regions in the tropics and subtropics. This effectively

504 stabilizes the density profile and thus maintains the ocean stratification. The flux correction  
505 shown in Fig 16a (upper 50m) are of comparable magnitude to the atmospheric heat flux  
506 forcing (in Fig 4a). Also, the seasonal variability of heat flux correction in the upper 50m  
507 (Fig 16c) is large (no seasonal variability in the subsurface levels, Fig 16d). Since the flux  
508 corrections mimic the mean effect of the missing ocean dynamics, it suggests that interactive  
509 lateral ocean dynamics not simulated in the ACCESS-KPP model are also important for  
510 simulating the main MLD characteristics.

511

## 512 **5. Summary and Discussion**

513 In this study, the spatial and temporal relationship between the local atmospheric forcing and  
514 the mean, seasonal cycle and variability of the MLD are analysed using a recent ocean  
515 reanalysis product (GECCO2) and a single-column ocean model (KPP) coupled to an  
516 atmospheric GCM (ACCESS1.3) over the global ocean. The aim of this study was to  
517 understand the driving mechanisms of the MLD in different regions and to what extent these  
518 can be understood in terms of local air-sea interactions. The focus was on the MLD  
519 characteristics of the annual mean, the relative seasonal cycle strength and the variability  
520 anomalous from the seasonal cycle. To further simplify the fairly complex characteristics  
521 three main regimes were introduced based on the characteristics of the annual mean and the  
522 relative seasonal cycle strength of the MLD.

523 First of all, the findings about the annual mean and the relative seasonal cycle strength of the  
524 MLD can be summarised as follows:

- 525 • The annual mean MLD over most open ocean regions (away from sea ice and shallow  
526 coastal regions) follows the wind and heat forcing. Regions with stronger mean wind  
527 forcing tend to have larger annual mean MLD and regions with annual mean net  
528 heating tend to have shallower annual mean MLD. The annual mean wind forcing  
529 strength appears to be most strongly related to the annual mean MLD and stronger  
530 than the net heat forcing. Both of these forcing, however, show spatial correlations  
531 less than  $\sim 0.5$  with the global pattern of the annual mean MLD, indicating that the  
532 relationship is more complex. The large flux correction needed to prevent model drift  
533 signifies that ocean dynamics are also important for simulating MLD.
- 534 • Remarkable are a few regions, in which neither of the atmospheric forcings seem to  
535 match the annual mean or seasonal cycle characteristics of the MLD. The shallower  
536 MLD regions in the subtropical Indian and western Pacific Oceans do not seem to

537 relate to any of the three atmospheric forcing. The western boundaries of the North  
538 Pacific and Atlantic have very strong seasonal cycle in NHF, but not in the MLD.  
539 Also, the very strong seasonality in the Indian and Pacific Oceans' ACC regions are  
540 not directly related to the seasonality in either of the atmospheric forcings. Since the  
541 atmospheric forcings seem to mismatch the MLD characteristics (in the reanalysis  
542 datasets) in these regions and the single-column ocean model is also not able to  
543 simulate these characteristics, it suggests that oceanic processes independent of the  
544 local atmospheric forcing contribute to the stratification of the upper ocean and thus  
545 the MLD in significant ways.

- 546 • The annual mean E-P forcing is for most regions not related to the annual mean MLD,  
547 suggesting it is not a dominating forcing. However, in some regions, where both  
548 annual mean NHF and wind-stress tendencies do not match the MLD, the E-P forcing  
549 does indeed seem to play a role for the annual mean MLD (e.g. coastal regions of  
550 Greenland and some parts of the western boundary of the North Pacific and Atlantic).
- 551 • The relative seasonal cycle strength of the MLD is also mostly related to the relative  
552 seasonal cycle strength of the net heating and wind stress, but here the relationship  
553 with the net heating is stronger than with the wind forcing. Thus, the relative seasonal  
554 cycle strength of the MLD mostly follows the strength of the seasonal cycle in the net  
555 heating.

556 Alternatively the processes that dominate the three different MLD regimes can be  
557 summarised:

- 558 • **Extra-tropical-seasonal:** This regime of the MLD in the midlatitudes is primarily a  
559 result of the strong seasonal cycle in the heating. The seasonal cycle in heating is  
560 indeed strongest in the midlatitudes and matches the strongest relative seasonal cycle  
561 strength of the MLD fairly well. In this regime, however, the atmospheric storm track  
562 positions also play a major role as well as oceanic fronts and strong boundary currents  
563 that are not simulated in the model.
- 564 • **Constant-deep:** The regime, where the ML is fairly deep (>30m) throughout the year  
565 with no strong seasonal cycle, is mostly found in the subtropics and some high  
566 latitudes. These are regions with no strong annual mean heating nor cooling, no strong  
567 seasonal cycle in heating and the winds tend to be slightly less than the global mean.
- 568 • **Constant-shallow:** Shallow MLDs without strong seasonal cycles are mostly found  
569 in coastal regions, equatorial regions and the tropical Indian Ocean. Some of these

570 regions are fairly well related to the local forcings, such as coastal and some  
571 equatorial upwelling regions. However, much of this *constant-shallow* MLD regime  
572 is not well matched with the local forcings and is not well simulated in the ACCESS-  
573 KPP simulation, suggesting that local forcings and processes are not sufficient to  
574 explain these MLD characteristics. In particular, in the higher latitudes coastal  
575 regions, the central ocean basin equatorial regions and in the Indian Ocean the  
576 *constant-shallow* MLD regimes are not matched to local forcings or processes.

577

578 The analysis of the anomalous variability of MLD and how it relates to the local forcing can  
579 be summarised by the following main points:

- 580 • The overall strength of the MLD variability is in general proportional to the mean  
581 MLD, with stronger variability associated with a deeper mean MLD (e.g. cold  
582 season). The MLD variability appears to be quite significant with values of 30% to  
583 more than 100% of the seasonal mean MLD values.
- 584 • Most of this is well captured by the ACCESS-KPP model, but in some regions this is  
585 not well simulated by the model, including the equatorial Pacific. In higher latitudes  
586 the model does not simulate as strong MLD variability relative to the seasonal mean  
587 MLD as observed.
- 588 • MLD variability is mostly negatively correlated with heat flux variability and  
589 positively with wind stress variability. In the mid to higher latitudes the relationship  
590 to heating tends to be stronger in the cold (deep ML) seasons and the relationship to  
591 wind forcing tends to be stronger in the shallower MLD (warm) seasons. In seasons  
592 with deeper mean MLD the relationship to the atmospheric forcings tends to become  
593 stronger when the atmospheric forcings lead by about one month, which seems to be  
594 consistent with a larger inertia of the MLD when it is deeper.
- 595 • The ACCESS-KPP model is consistent with these observed relationships between the  
596 local atmospheric forcings and the MLD, but the relationships are significantly  
597 stronger in the model simulations. This may to some part reflect the simplification of  
598 the model to only local vertical mixing processes and neglecting other ocean  
599 dynamics, which leads to an overestimate of the role of local forcings on the MLD  
600 variability. But it may also point to errors in the reanalysis datasets that lead to  
601 inconsistencies between atmospheric forcings and the ocean state that artificially  
602 degrade the relationship between local forcing and the MLD.

603 While overall the local forcing perspective provides a fairly good representation of most of  
604 the MLD characteristics in the global oceans, it does have some limitations as mentioned  
605 above. This is in particular highlighted by the fact that the ACCESS-KPP model does require  
606 significant flux correction in temperature (most importantly) and also in salinity. These are  
607 important to maintain upper-ocean stratification close to observations. Without such terms in  
608 the ACCESS-KPP model, the upper-ocean stratification in most subtropical regions would  
609 collapse after about 10 years and the MLD would deepen to the base of the ACCESS-KPP  
610 model (1000m). Thus, with the flux correction terms, the coupled single-column model  
611 allows to study the upper ocean-atmosphere interaction with higher near-surface vertical  
612 resolution incorporated with a better vertical mixing. This coupled framework is  
613 computationally less expensive and allows identification of the role of atmospheric forcings  
614 for the upper-ocean processes.

615 The analysis has shown that the MLD characteristics arise from complex interactions  
616 between the local forcings, ocean stratifications and potentially lateral ocean dynamics. Most  
617 of the results discussed here result from comparisons of the overall statistics of MLD and  
618 local forcings in observations and in the ACCESS-KPP simulation. To further untangle the  
619 interactions and the relative contribution of different forcings and different oceanic processes  
620 it would require sensitivity experiments with the ACCESS-KPP or similar model simulations,  
621 in which forcings or elements of the forcings are turned ‘off’ or in which processes are  
622 altered or turned ‘off’. However, this is beyond this study and is left for future analyses.

623

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792

793 **Figure Captions**

794

795 Fig 1: Seasonal statistics of MLD estimated from GECCO2 density profiles averaged over  
796 January-March (a,b,c), April-June (d,e,f), July-September (g,h,i) and October-December  
797 (j,k,l) for the period 1948-2011. The left column shows the seasonal mean MLD (a,d,g,j). The  
798 standard deviations of the MLD calculated for each calendar month and then seasonally  
799 averaged are shown in the middle column (b,e,h,k). The right column (c,f,i,l) shows the  
800 seasonal average of the monthly standard deviation relative to the corresponding monthly  
801 mean MLD (i.e., the coefficient of variance).

802

803 Fig 2: (a) Annual mean MLD estimated from GECCO2 density profiles (30m contour  
804 represents shallow mixed layer), and (b) Seasonal amplitude (computed as the standard  
805 deviation of the monthly climatology) of MLD relative to the annual mean MLD and the  
806 contour represents 60% variability.

807

808 Fig 3: Different MLD regimes based on GECCO2 dataset: (a) Extra-tropical-seasonal;  
809 regions where seasonal amplitude change is >60% of the annual mean MLD. (b) Constant-  
810 deep; regions where MLD >30m and seasonal change is <60%. (c) Constant-shallow; regions  
811 with <60% relative seasonal change and MLD <30m.

812

813 Fig 4: GECCO2 annual mean fields: (a) Net heat flux (NHF); positive/negative sign indicates  
814 the ocean is gaining/losing heat, (b) wind-stress, (c) density gradient ( $\text{kg/m}^4$ ) between the  
815 surface and 100m depth, and (d) evaporation minus Precipitation (E-P). Colour code is in  
816 such a way that blue shading represents favourable for deep MLD and red shading for  
817 shallow mixed layers. Spatial correlation ( $r$ ) between the forcing variable and the annual  
818 mean MLD (Fig 2a) is shown at the top left corner of the corresponding subplot.

819

820 Fig 5: Seasonal amplitude of GECCO2 variables (computed as the standard deviation of the  
821 monthly climatology): (a) Net heat flux (NHF), (b) wind-stress, (c) density gradient ( $\text{kg/m}^4$ )  
822 between the surface and 100m depth, and (d) evaporation minus Precipitation (E-P). Spatial  
823 correlation ( $r$ ) between the seasonal change of the forcing variable and the MLD (relative to  
824 the annual mean as in Fig 2b) is shown at the top left corner of the corresponding subplot.

825

826 Fig 6: The annual mean MLD, net heat flux (NHF) and wind-stress (from GECCO2)  
827 averaged along (a) 30°-32°N (North Pacific) and (b) 33°-35°N (North Atlantic). The  
828 positive/negative heat flux (NHF) values indicate that the ocean is losing/gaining heat. The  
829 coloured shading represents the corresponding seasonal amplitude change at each grid point  
830 (light red for NHF, light blue for MLD and light yellow is for wind-stress).

831

832 Fig 7: Cross correlation of net heat flux (NHF) and MLD anomalies in different seasons from  
833 GECCO2. Left column shows concurrent correlations and the right column represents the  
834 corresponding one-month lag correlations, where MLD lags the forcing by one month. The  
835 rows represent from top to bottom the different seasons: January-March (JFM), April-June  
836 (AMJ), July- September (JAS), and October-November (OND). Significant (95%) non-zero  
837 correlation value is  $\pm 0.1$ .

838

839 Fig 8: Cross correlation of wind stress (TAU) and MLD anomalies in different seasons from  
840 GECCO2. Left column shows concurrent correlations and the right column represents the  
841 corresponding one-month lag correlations, where MLD lags the forcing by one month. The  
842 rows represent from top to bottom the different seasons: January-March (JFM), April-June  
843 (AMJ), July- September (JAS), and October-November (OND). Significant (95%) non-zero  
844 correlation value is  $\pm 0.1$ .

845

846 Fig 9: Seasonal statistics of MLD as in Fig 1 but for the ACCESS-KPP coupled model.

847

848 Fig 10: ACCESS-KPP annual mean fields (same as in Fig 4). Spatial correlation ( $r$ ) between  
849 the forcing variable and the annual mean MLD (in Fig 12a) is shown at the top left corner of  
850 the corresponding subplot.

851

852 Fig 11: Seasonal amplitude of ACCESS-KPP forcing variables (same as in Fig 5). Spatial  
853 correlation ( $r$ ) between the seasonal change of the forcing variable and the MLD (relative to  
854 the annual mean as in Fig 12b) is shown at the top left corner of the corresponding figure.

855

856 Fig 12: (a) Annual mean MLD estimated from ACCESS-KPP simulated density profiles  
857 (30m contour represents the shallow mixed layer), and (b) Seasonal amplitude of MLD  
858 relative to the annual mean MLD, with contour of 60% variability (similar to Fig 2).

859

860 Fig 13: Different MLD regimes based on ACCESS-KPP simulation (same as in Fig 3)

861

862 Fig 14: Cross correlation of net heat flux (NHF) and MLD anomalies in different seasons as  
863 in Fig 7 but for the ACCESS-KPP model. Significant (95%) non-zero correlation value is  
864  $\pm 0.1$ .

865

866 Fig 15: Cross correlation of wind-stress (TAU) and MLD anomalies in different seasons as in  
867 Fig 8 but for the ACCESS-KPP model. Significant (95%) non-zero correlation value is  $\pm 0.1$ .

868

869 Fig 16: Annual mean (a, b) and seasonal cycle (c, d) of heat flux correction applied on the  
870 model levels (top) surface to 50m, and (bottom) 200-300m depth. The actual flux correction  
871 at each model level is in  $W/m^3$  and here we multiplied with the thickness of all the layers  
872 (50m and 100m, respectively) to show the values in units of  $W/m^2$ . Seasonal cycle  
873 corresponds to the standard deviation of monthly flux correction in  $W/m^2$ . The deeper levels  
874 have no seasonal cycle corrections.

875

## 876 **Supplementary Figure Captions**

877

878 SFig 1: Cross correlation of E-P and MLD anomalies in different seasons from GECCO2.

879 Left column shows concurrent correlations and the right column represents the corresponding  
880 one-month lag correlations, where MLD lags the forcing by one month. The rows represent  
881 from top to bottom the different seasons: January-March (JFM), April-June (AMJ), July-  
882 September (JAS), and October-November (OND). Significant (95%) non-zero correlation  
883 value is  $\pm 0.1$ .

884

885

886 SFig 2: Cross correlation of E-P and MLD anomalies as in SFig 1 but for the ACCESS-KPP  
887 coupled model. Significant (95%) non-zero correlation value is  $\pm 0.1$ .

888

889

## 890 **Supplementary Tables**

891

892 Table 1: Spatial correlation of variables in model and reanalyses data. The hyphen represents  
893 missing or no data.

894

895 Table 2: Spatial correlation of variables in GECCO2 and other reanalyses. (The values in  
896 brackets are the spatial correlation of GODAS and SODA data). The hyphen represents  
897 missing or no data.

898

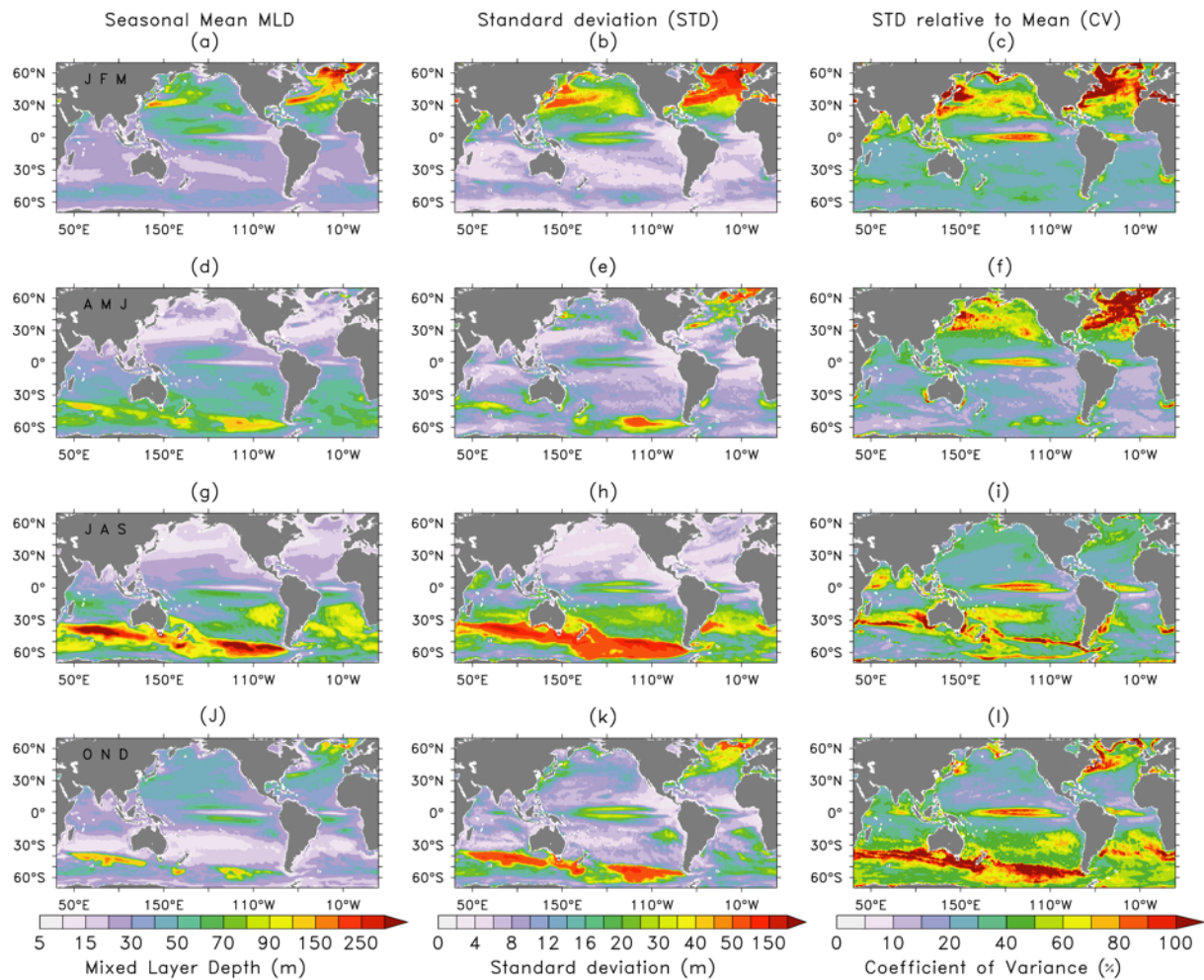


Fig 1: Seasonal statistics of MLD estimated from GECCO2 density profiles averaged over January-March (a,b,c), April-June (d,e,f), July-September (g,h,i) and October-December (j,k,l) for the period 1948-2011. The left column shows the seasonal mean MLD (a,d,g,j). The standard deviations of the MLD calculated for each calendar month and then seasonally averaged are shown in the middle column (b,e,h,k). The right column (c,f,i,l) shows the seasonal average of the monthly standard deviation relative to the corresponding monthly mean MLD (i.e., the coefficient of variance).

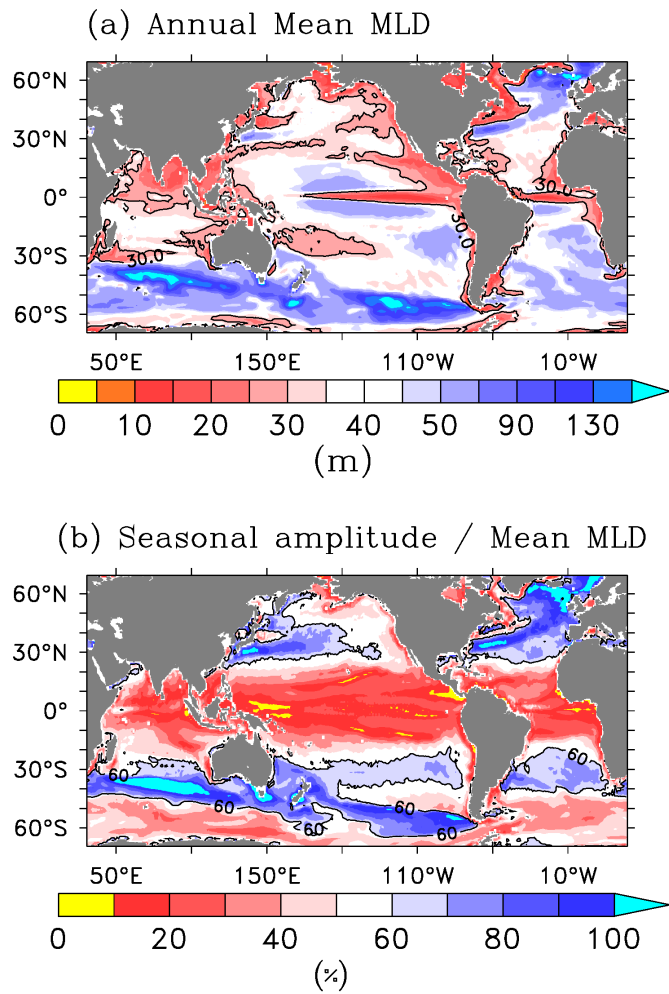


Fig 2: (a) Annual mean MLD estimated from GECCO2 density profiles (30m contour represents shallow mixed layer), and (b) Seasonal amplitude (computed as the standard deviation of the monthly climatology) of MLD relative to the annual mean MLD and the contour represents 60% variability.



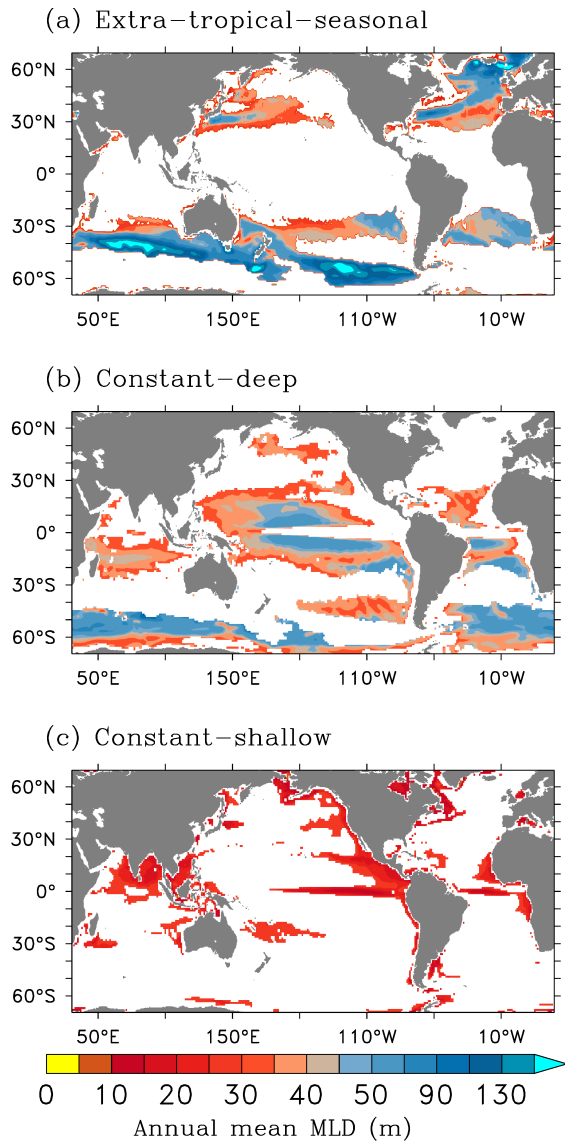


Fig 3: Different MLD regimes based on GECCO2 dataset: (a) Extra-tropical-seasonal; regions where seasonal amplitude change is  $>60\%$  of the annual mean MLD. (b) Constant-deep; regions where MLD  $>30\text{m}$  and seasonal change is  $<60\%$ . (c) Constant-shallow; regions with  $<60\%$  relative seasonal change and MLD  $<30\text{m}$ .

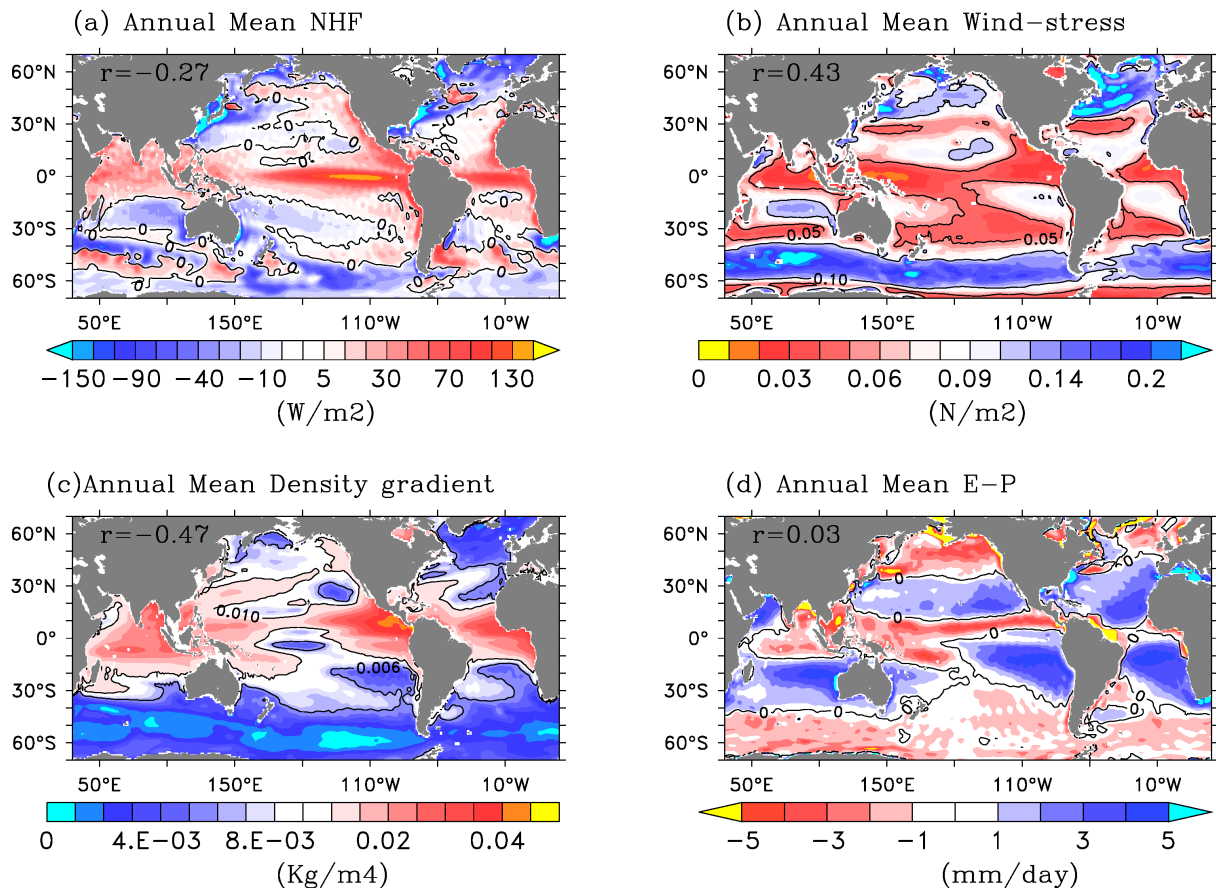


Fig 4: GECCO2 annual mean fields: (a) Net heat flux (NHF); positive/negative sign indicates the ocean is gaining/losing heat, (b) wind-stress, (c) density gradient ( $\text{kg/m}^4$ ) between the surface and 100m depth, and (d) evaporation minus Precipitation (E-P). Colour code is in such a way that blue shading represents favourable for deep MLD and red shading for shallow mixed layers. Spatial correlation ( $r$ ) between the forcing variable and the annual mean MLD (Fig 2a) is shown at the top left corner of the corresponding subplot.

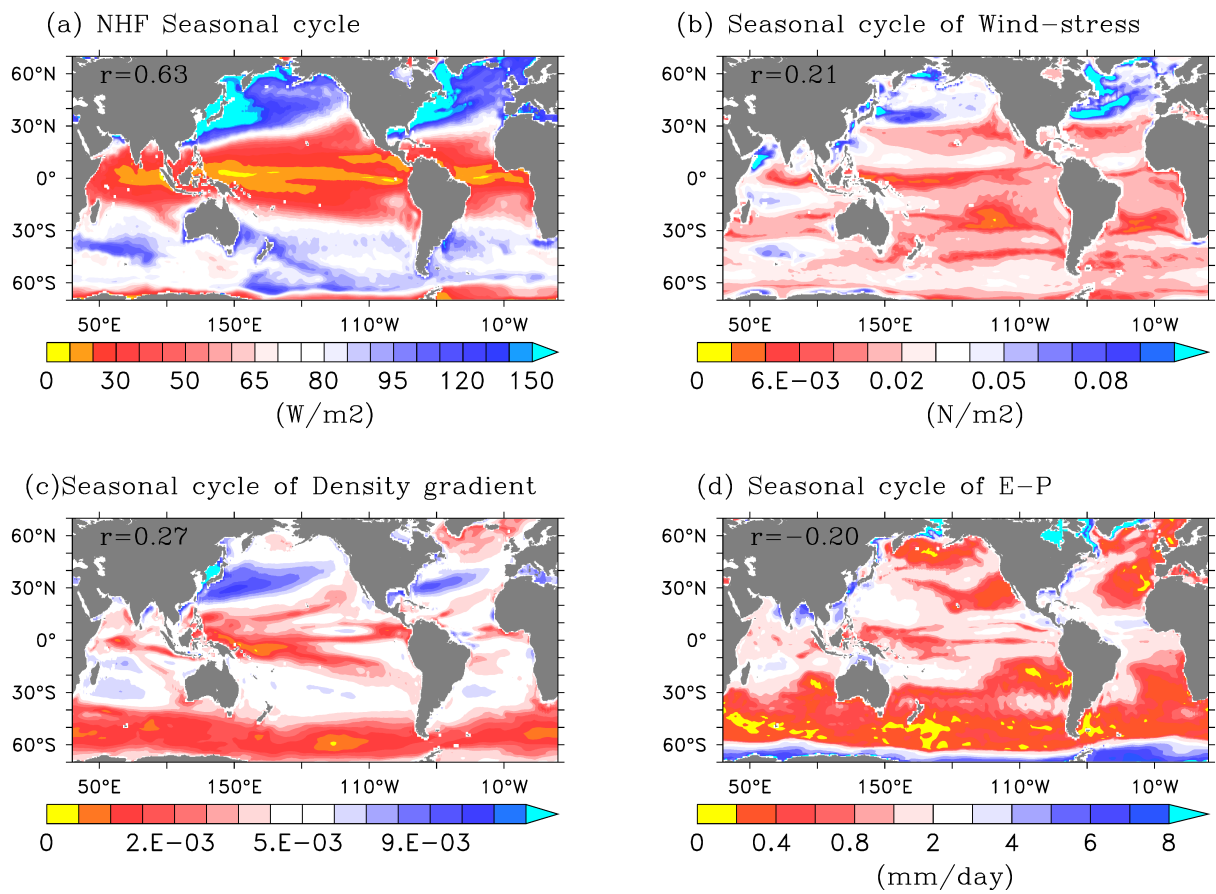


Fig 5: Seasonal amplitude of GECCO2 variables (computed as the standard deviation of the monthly climatology): (a) Net heat flux (NHF), (b) wind-stress, (c) density gradient ( $\text{kg/m}^4$ ) between the surface and 100m depth, and (d) evaporation minus Precipitation (E-P). Spatial correlation ( $r$ ) between the seasonal change of the forcing variable and the MLD (relative to the annual mean as in Fig 2b) is shown at the top left corner of the corresponding subplot.

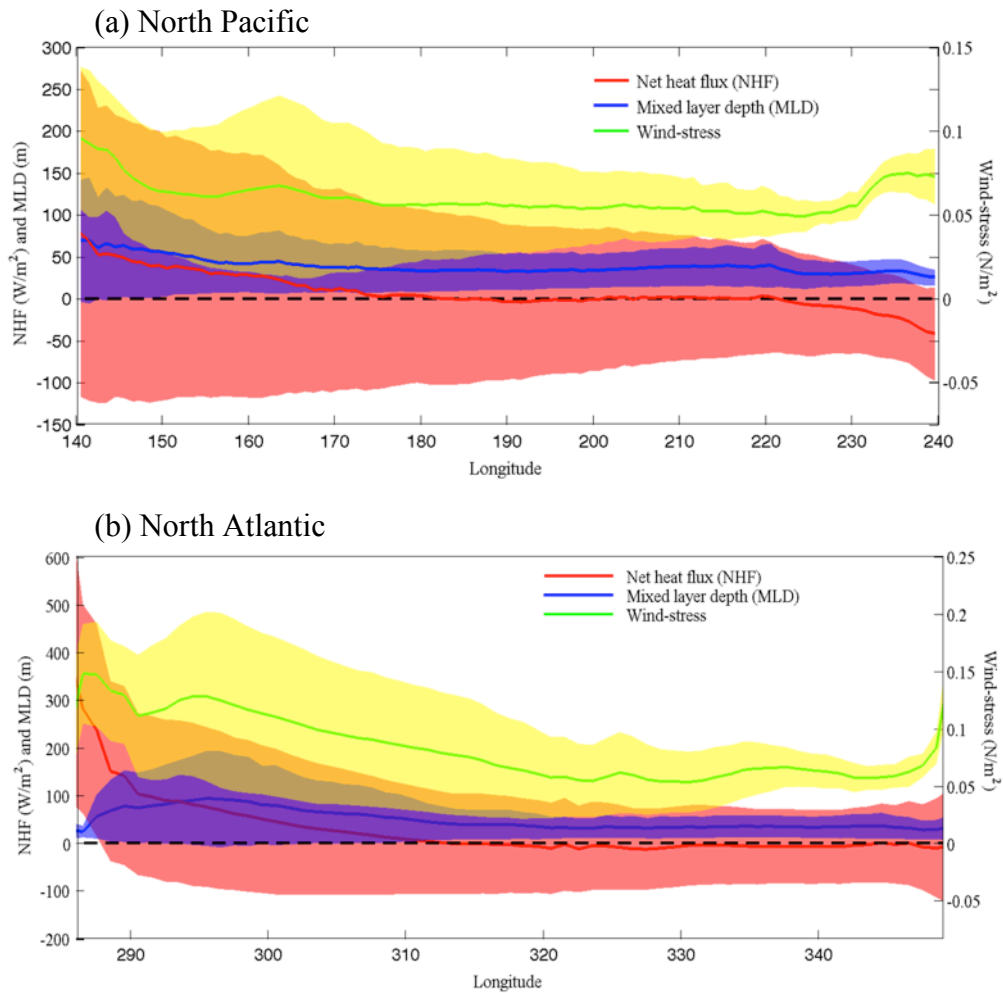


Fig 6: The annual mean MLD, net heat flux (NHF) and wind-stress (from GECCO2) averaged along (a)  $30^{\circ}$ - $32^{\circ}$ N (North Pacific) and (b)  $33^{\circ}$ - $35^{\circ}$ N (North Atlantic). The positive/negative heat flux (NHF) values indicate that the ocean is losing/gaining heat. The coloured shading represents the corresponding seasonal amplitude change at each grid point (light red for NHF, light blue for MLD and light yellow is for wind-stress).

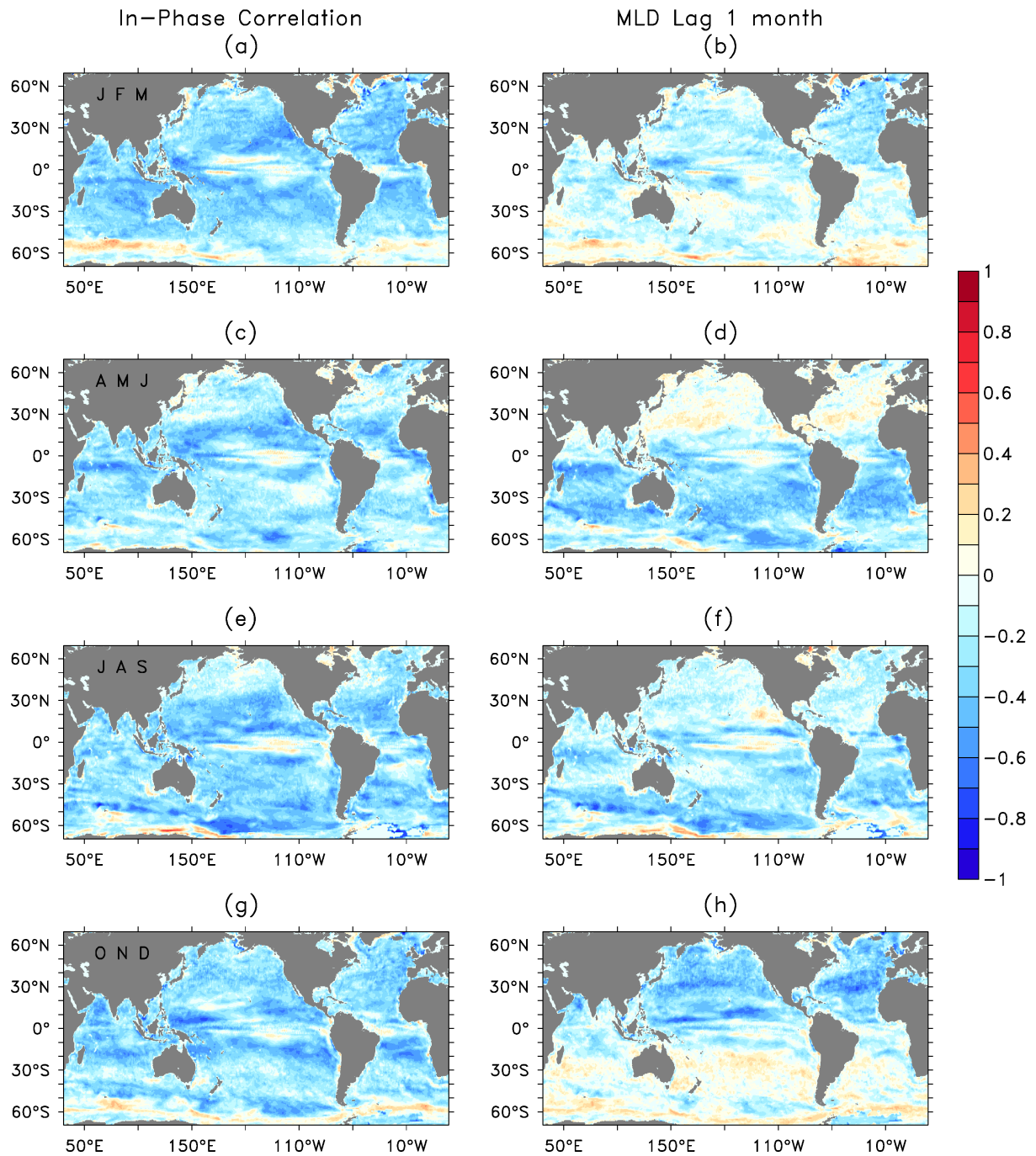


Fig 7: Cross correlation of net heat flux (NHF) and MLD anomalies in different seasons from GECCO2. Left column shows concurrent correlations and the right column represents the corresponding one-month lag correlations, where MLD lags the forcing by one month. The rows represent from top to bottom the different seasons: January-March (JFM), April-June (AMJ), July- September (JAS), and October-November (OND). Significant (95%) non-zero correlation value is  $\pm 0.1$ .

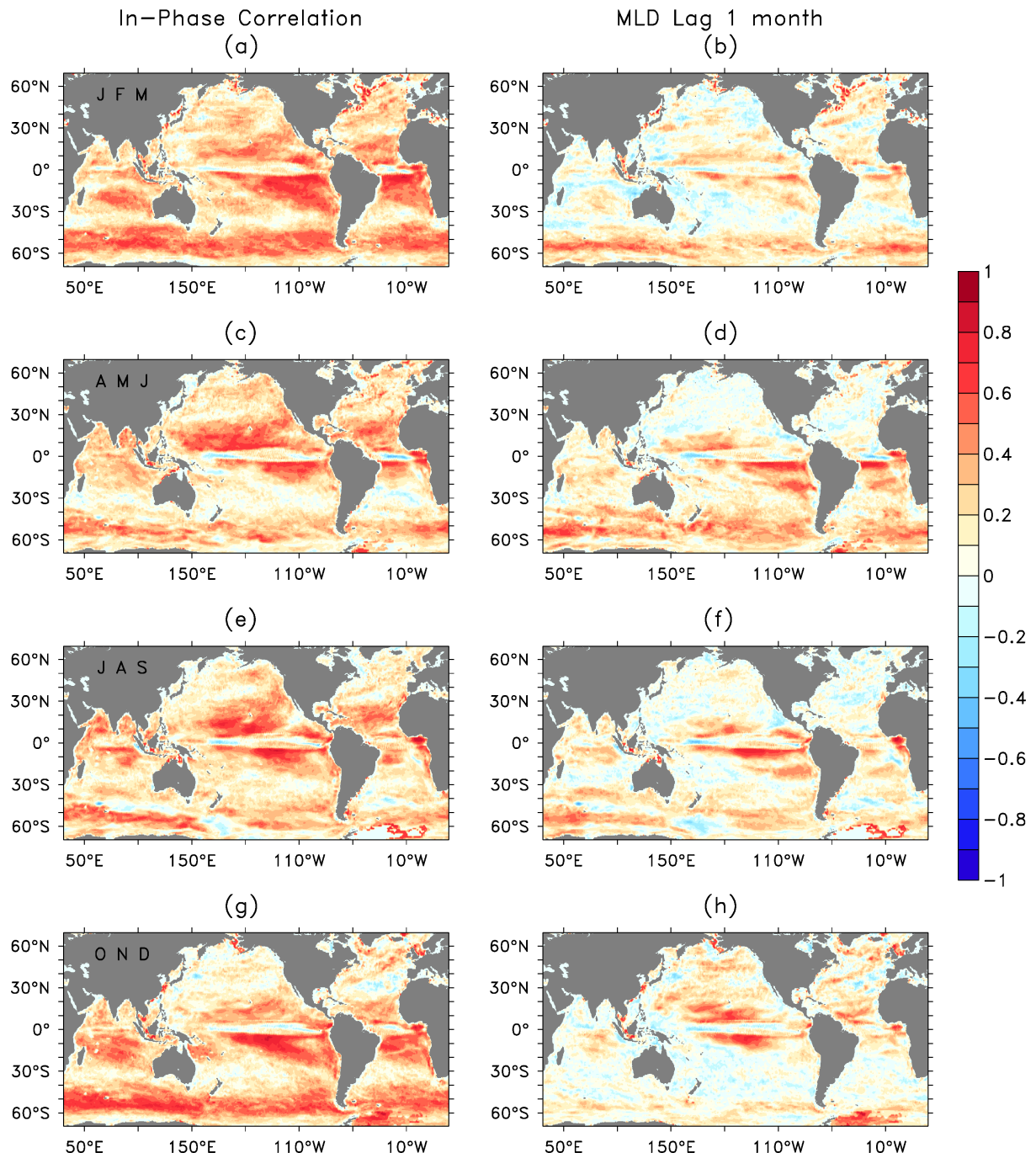


Fig 8: Cross correlation of wind stress (TAU) and MLD anomalies in different seasons from GECCO2. Left column shows concurrent correlations and the right column represents the corresponding one-month lag correlations, where MLD lags the forcing by one month. The rows represent from top to bottom the different seasons: January-March (JFM), April-June (AMJ), July-September (JAS), and October-November (OND). Significant (95%) non-zero correlation value is  $\pm 0.1$ .

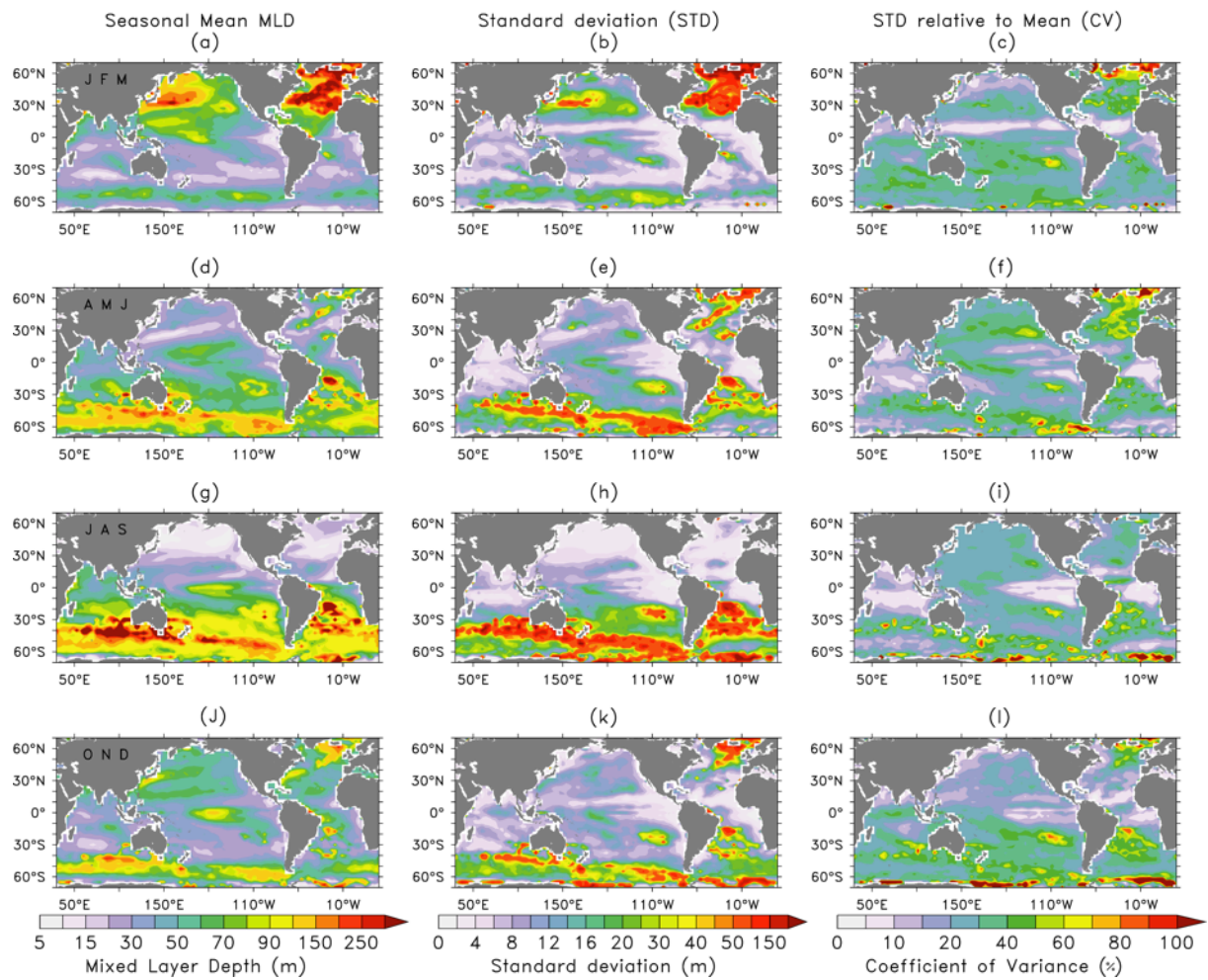


Fig 9: Seasonal statistics of MLD as in Fig 1 but for the ACCESS-KPP coupled model.

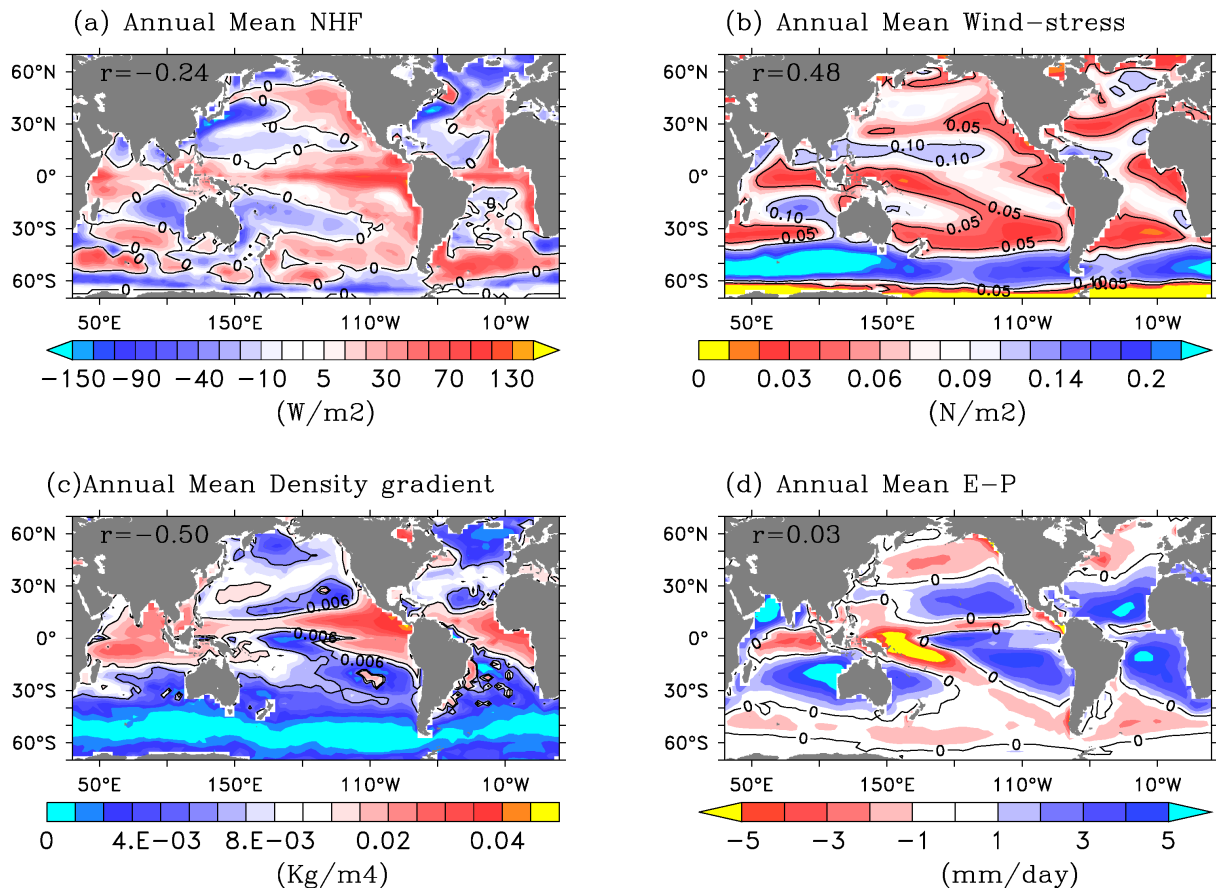


Fig 10: ACCESS-KPP annual mean fields (same as in Fig 4). Spatial correlation ( $r$ ) between the forcing variable and the annual mean MLD (in Fig 12a) is shown at the top left corner of the corresponding subplot.



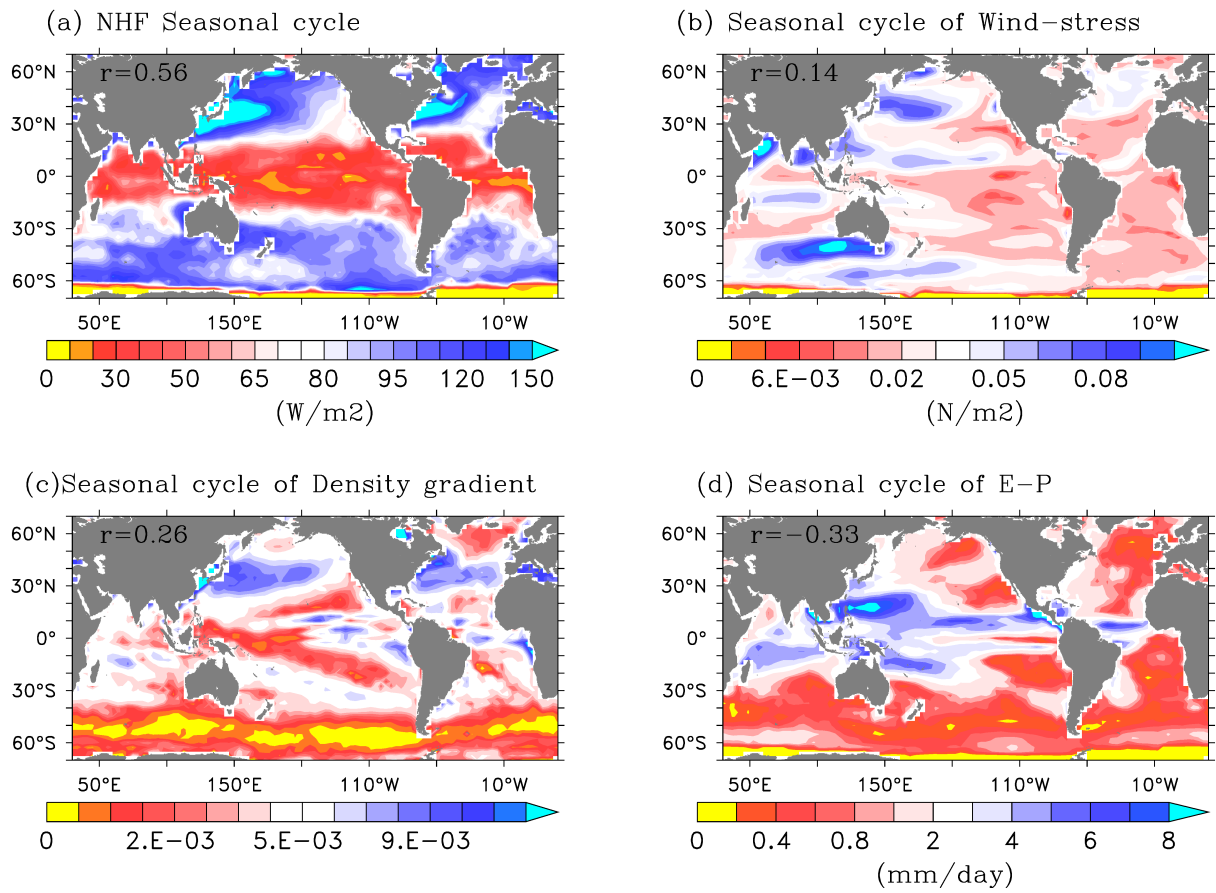
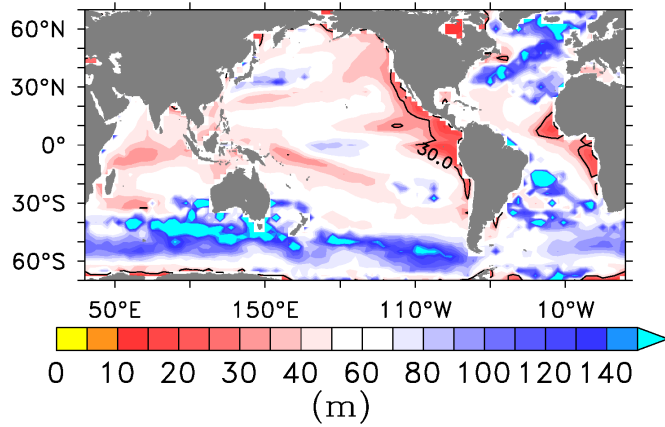


Fig 11: Seasonal amplitude of ACCESS-KPP forcing variables (same as in Fig 5). Spatial correlation ( $r$ ) between the seasonal change of the forcing variable and the MLD (relative to the annual mean as in Fig 12b) is shown at the top left corner of the corresponding figure.

(a) Annual Mean MLD



(b) Seasonal amplitude / Mean MLD

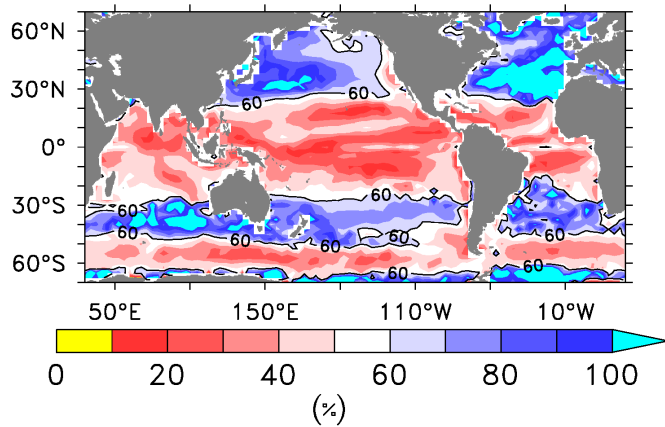


Fig 12: (a) Annual mean MLD estimated from ACCESS-KPP simulated density profiles (30m contour represents the shallow mixed layer), and (b) Seasonal amplitude of MLD relative to the annual mean MLD, with contour of 60% variability (similar to Fig 2).

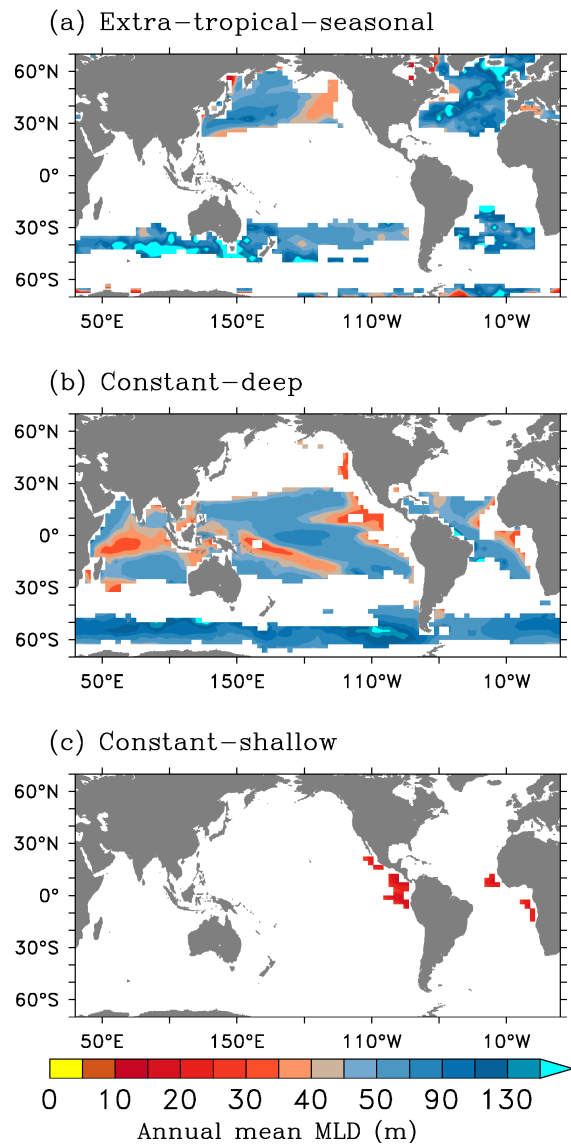


Fig 13: Different MLD regimes based on ACCESS-KPP simulation (same as in Fig 3)

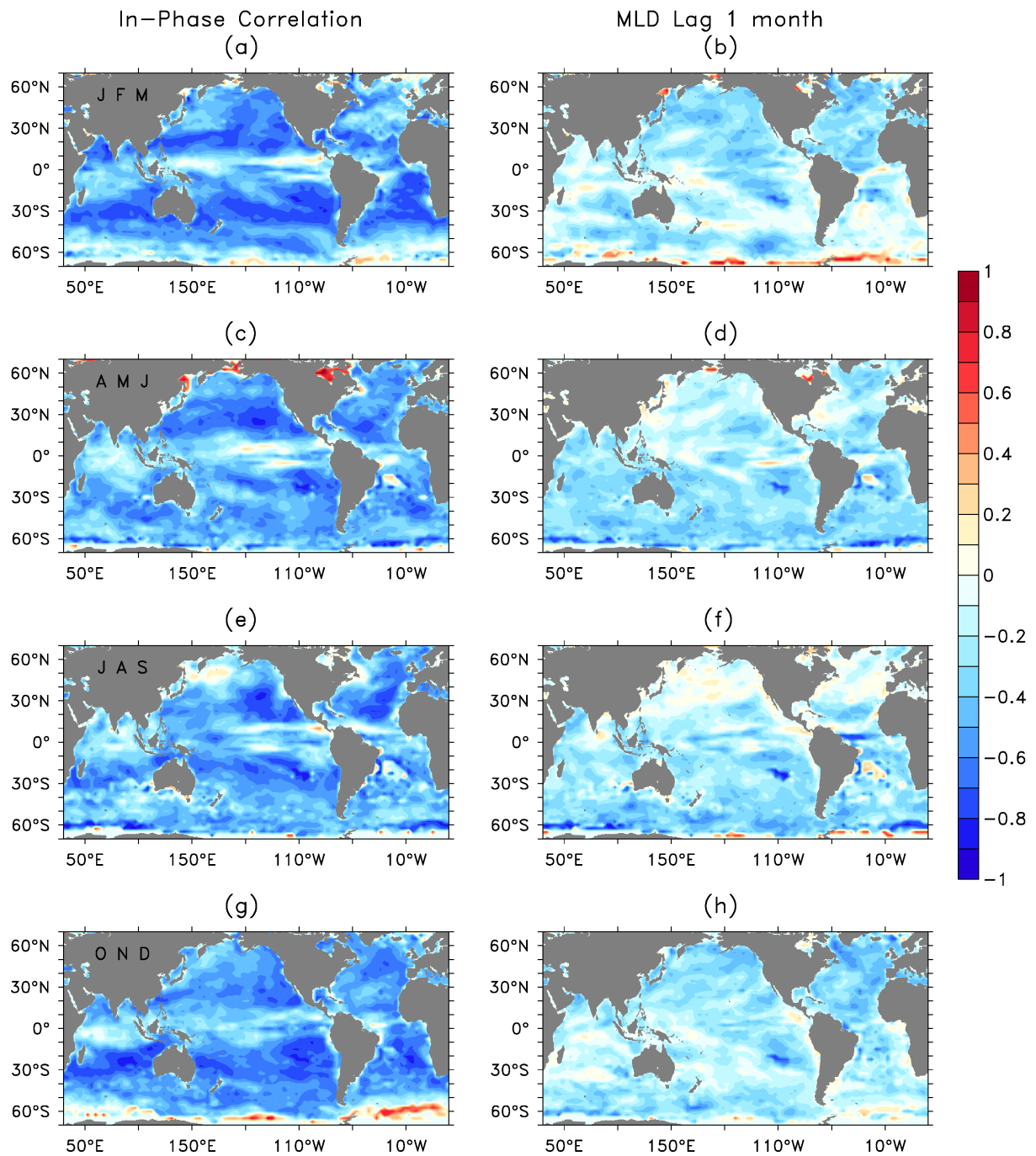


Fig 14: Cross correlation of net heat flux (NHF) and MLD anomalies in different seasons as in Fig 7 but for the ACCESS-KPP model. Significant (95%) non-zero correlation value is  $\pm 0.1$ .

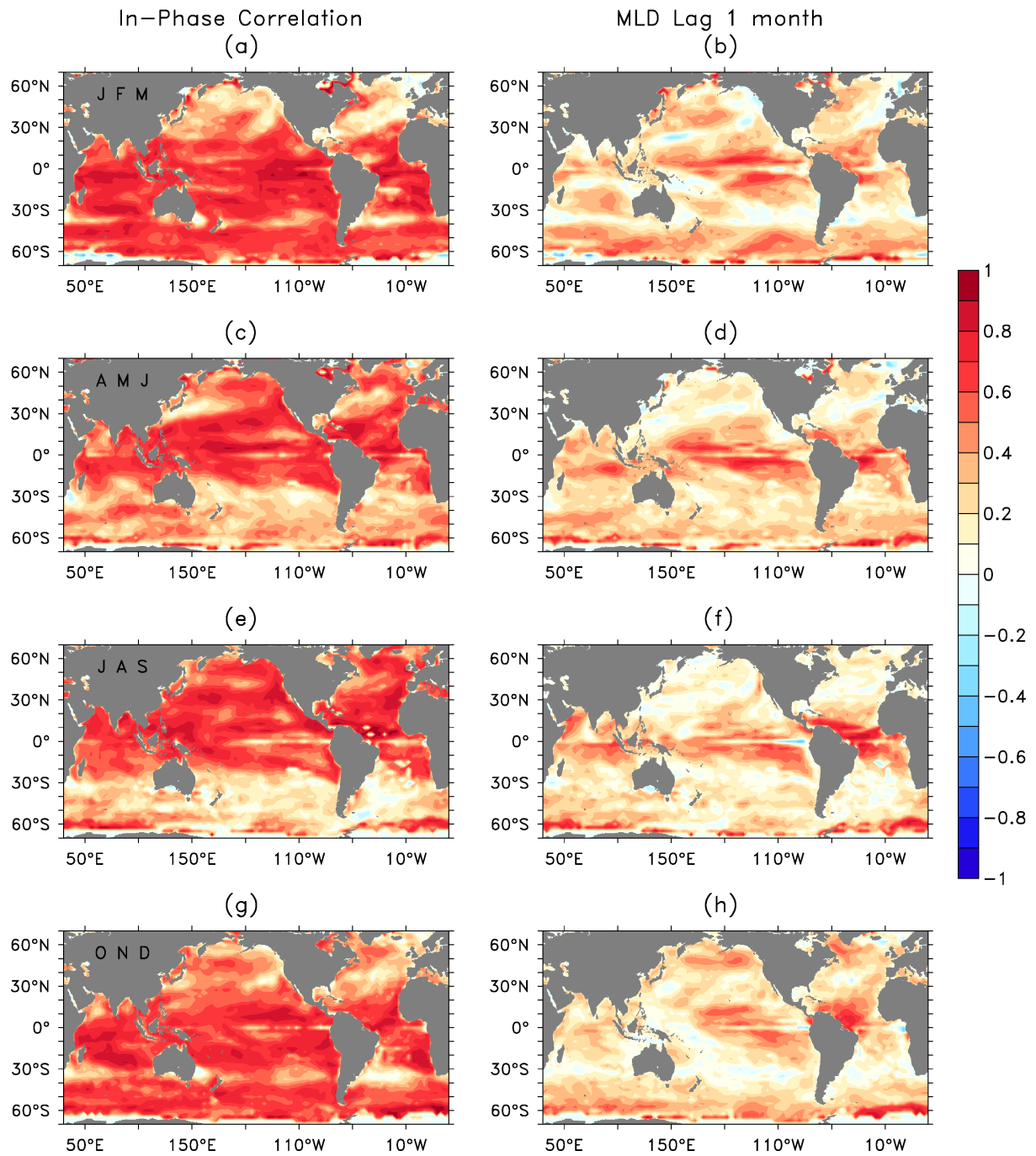


Fig 15: Cross correlation of wind-stress (TAU) and MLD anomalies in different seasons as in Fig 8 but for the ACCESS-KPP model. Significant (95%) non-zero correlation value is  $\pm 0.1$ .

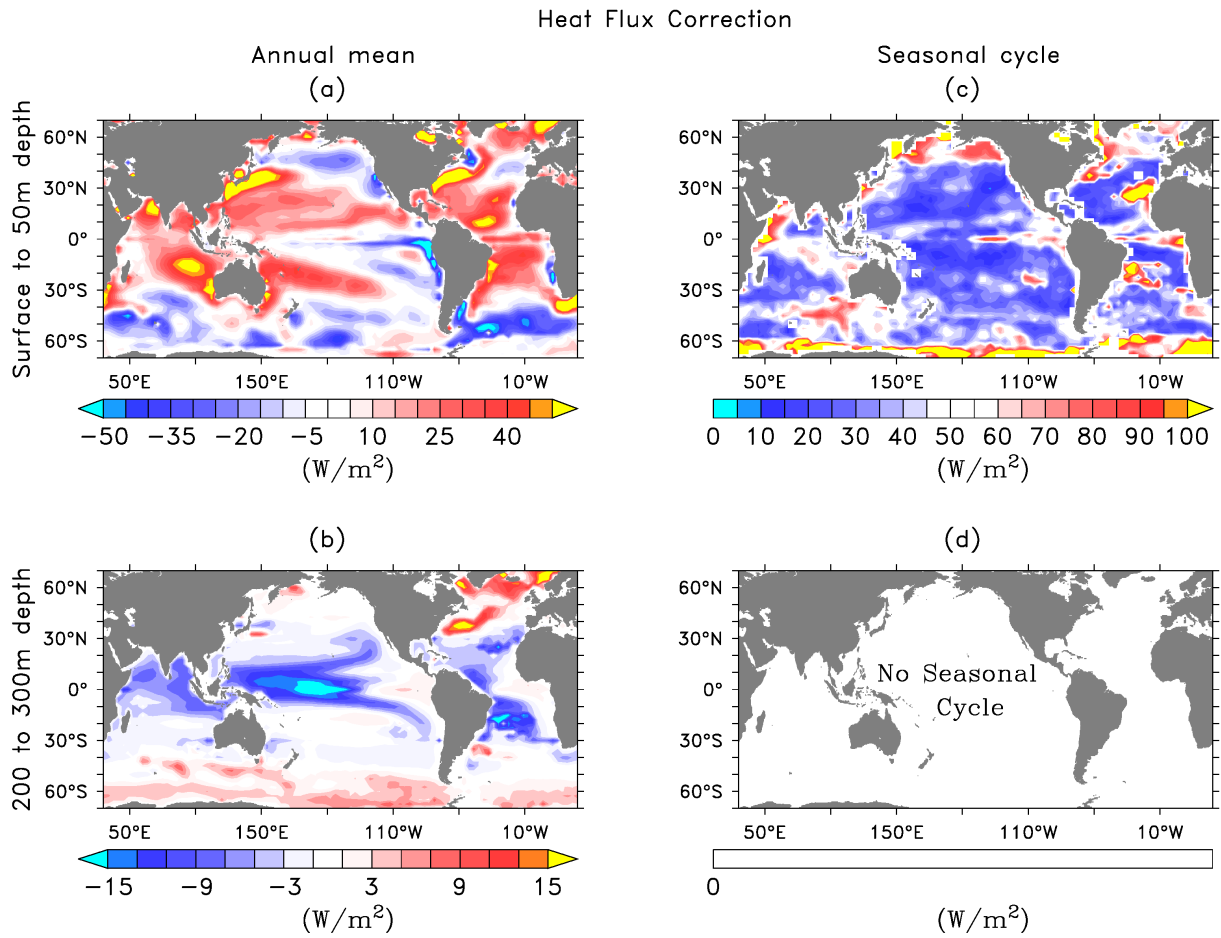
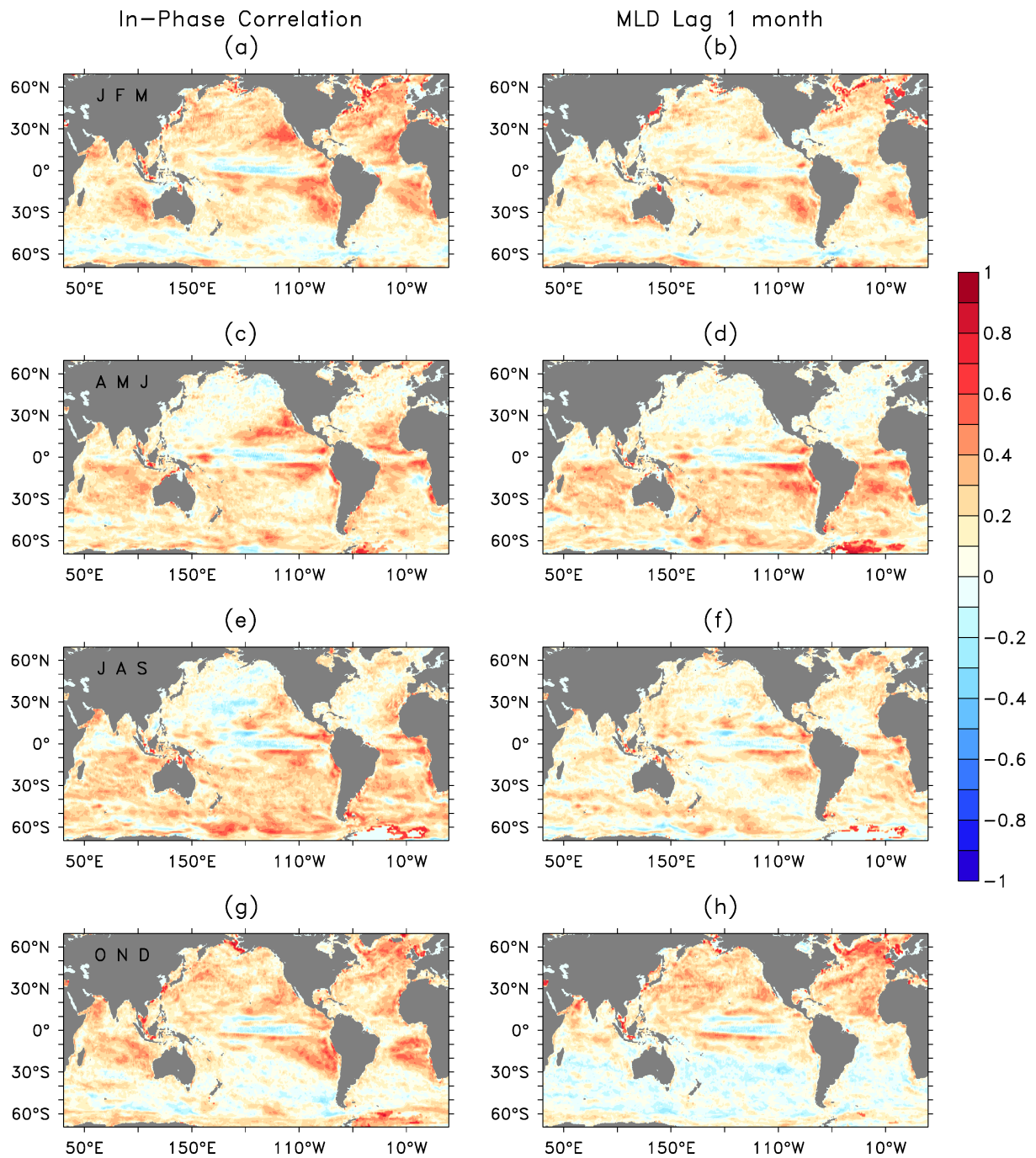
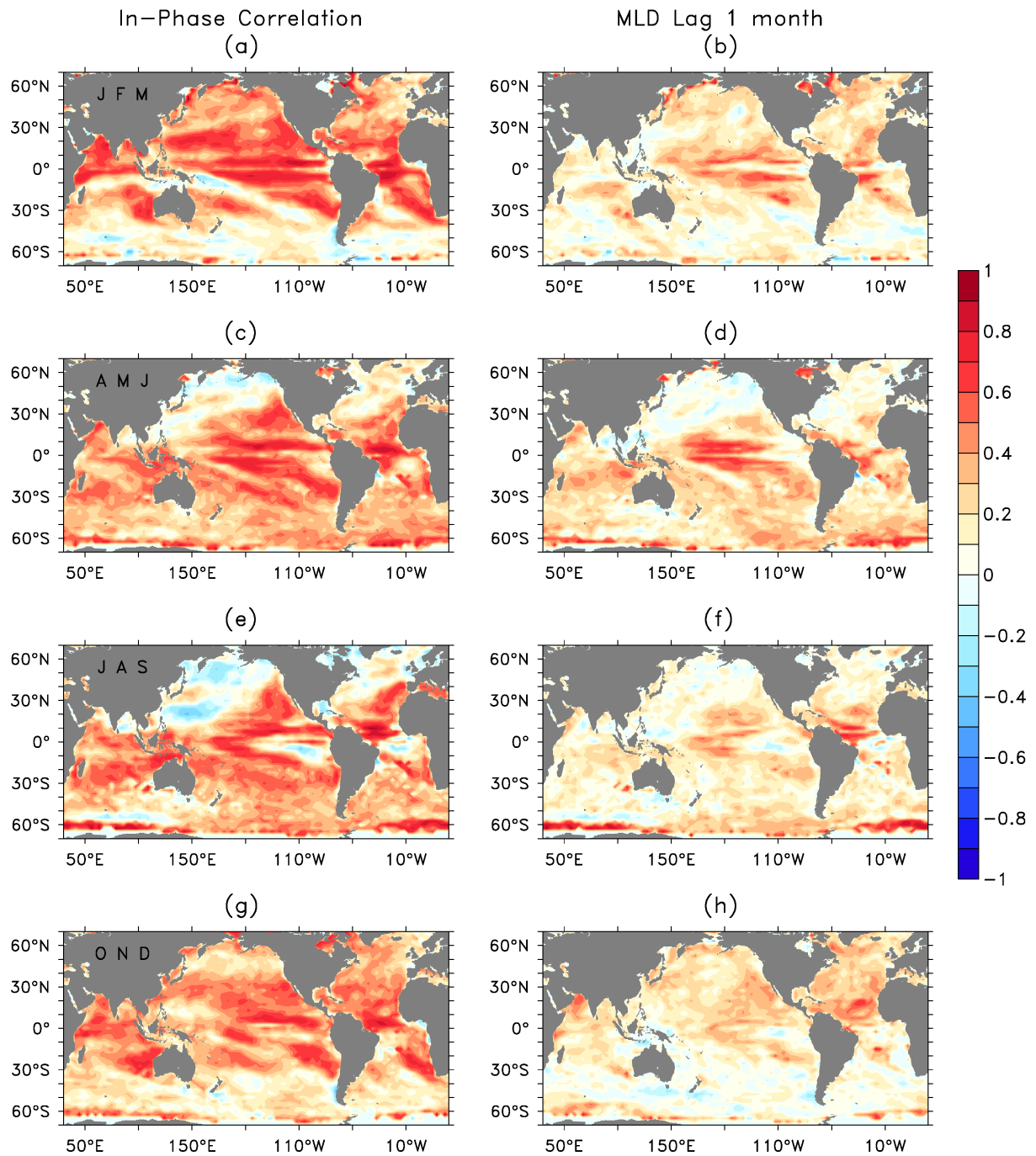


Fig 16: Annual mean (a, b) and seasonal cycle (c, d) of heat flux correction applied on the model levels (top) surface to 50m, and (bottom) 200-300m depth. The actual flux correction at each model level is in  $W/m^3$  and here we multiplied with the thickness of all the layers (50m and 100m, respectively) to show the values in units of  $W/m^2$ . Seasonal cycle corresponds to the standard deviation of monthly flux correction in  $W/m^2$ . The deeper levels have no seasonal cycle corrections.

## Supplementary figures



SFig 1: Cross correlation of E-P and MLD anomalies in different seasons from GECCO2. Left column shows concurrent correlations and the right column represents the corresponding one-month lag correlations, where MLD lags the forcing by one month. The rows represent from top to bottom the different seasons: January-March (JFM), April-June (AMJ), July-September (JAS), and October-November (OND). Significant (95%) non-zero correlation value is  $\pm 0.1$ .



SFig 2: Cross correlation of E-P and MLD anomalies as in SFig 1 but for the ACCESS-KPP coupled model. Significant (95%) non-zero correlation value is  $\pm 0.1$ .



Table 1: Spatial correlation of variables in model and reanalyses data. The hyphen represents missing or no data.

<b>ACCESS-KPP</b>		<b>GECCO2</b>	<b>NCEP-GODAS</b>	<b>SODA</b>
MLD	Mean	0.61	0.44	0.62
	Seasonal Cycle	0.57	0.44	0.58
NHF	Mean	0.71	0.68	–
	Seasonal Cycle	0.86	0.84	–
TAU	Mean	0.72	0.83	0.84
	Seasonal Cycle	0.53	0.54	0.62
E-P	Mean	0.65	0.83	–
	Seasonal Cycle	0.31	0.79	–

Table 2: Spatial correlation of variables in GECCO2 and other reanalyses. (The values in brackets are the spatial correlation of GODAS and SODA data). The hyphen represents missing or no data.

<b>GECCO2</b>		<b>NCEP-GODAS</b>	<b>SODA</b>
MLD	Mean	0.50	0.71 (0.57)
	Seasonal Cycle	0.54	0.72 (0.62)
NHF	Mean	0.75	–
	Seasonal Cycle	0.94	–
TAU	Mean	0.82	0.83 (0.96)
	Seasonal Cycle	0.65	0.80 (0.82)
E-P	Mean	0.76	–
	Seasonal Cycle	0.39	–