Response of the ocean mixed layer depth to global warming and its impact on primary production: a case for the North Pacific Ocean

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This study investigates changes in the mixed layer depth (MLD) in the North Pacific Ocean in response to global warming and their impact on primary production by comparing outputs from 11 models of the coupled model intercomparison projects phase 3 (CMIP3). The ocean mixed layer defines a vertically quasi-homogeneous surface region of temperature, salinity, or density, which directly interacts with the overlying atmosphere. Atmosphere–ocean interaction, therefore, can be modulated by the ocean mixed layer, whose depth is determined by wind-driven mechanical stirring, surface buoyancy forcing, such as heat flux or freshwater flux, or ocean circulation changes. Changes in the MLD, for example, influence the variability of the sea surface temperature and oceanic uptake of atmospheric CO2 (Kraus and Businger, 1995). In addition to air–sea interaction, MLD also affects phytoplankton dynamics through controlling the availability of nutrients and light and hence biological productivity in the ocean (Sverdrup, 1953; Yentsch, 1990).

Significant changes in circulation in the ocean or the atmosphere have been projected by coupled climate models under global warming (Lu et al., 2007; Vecchi and Soden, 2007; Xie et al., 2010). Therefore, MLD would change in response to the circulation changes under global warming. For example, the deep mixed layers in the Southern Ocean are projected to shoal and shift south in response to intensified surface warming and a poleward shift in the windfield (Sen Gupta et al., 2009). The winter MLD is also projected to decrease (Merryfield and Kwon, 2007; Luo et al., 2009) in most of the North Pacific Ocean, resulting in a reduction in formation of mode waters in response to global warming (Luo et al., 2009). However, previous studies either focused on general circulation changes (Sen Gupta et al., 2009) or ensemble means, rather than individual model simulations (Luo et al., 2009). This study investigates both individual model projections and multimodel ensemble changes in the MLD in the North Pacific Ocean resulting from global warming, because multimodel means often hide biases from individual models through averaging procedures (Lefebvre and Goosse, 2008).

Biological consequences of MLD changes are also of interest, because MLD changes can affect primary production and the timing of spring phytoplankton blooms, by altering conditions of nutrients and light. The changes in primary production and timing of seasonal blooms will affect higher trophic levels further. However, it is not easy to predict the changes in primary production, which is controlled by many factors. Primary production consists of two components, regenerated production, and new production, fuelled by different sources of nutrient inputs (Eppley and Peterson, 1979). Because new production depends on the nutrient inputs from outside the surface layer, primary production largely depends on the change in new production. Sources of new production are diverse: seasonal vertical mixing, upwelling of deep waters, eddies, typhoons, nitrogen fixation, river run-offs, coastal current transportation, and aeolian

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...to name a few. Therefore, to account for all the changes in primary production in future, all of these factors have to be considered. Unfortunately, CMIP3 models do not provide all the information about the factors. In this study, we focus on the changes related to seasonal vertical mixing based on outputs from 11 CMIP3 models. Typical methods to estimate future changes in primary production use ecosystem models coupled with ocean circulation models (Nakata et al., 2004; Sarmiento et al., 2004; Popova et al., 2006; Hashioka and Yamanaka, 2007; Steinacher et al., 2010). However, ecosystem models with different structures behave differently. If we couple several ecosystem models to 11 CMIP3 models and compare future primary production, tremendous effort will be required, let alone the complexity needed to carry out the comparative analysis among models. Instead, we chose to use a simple approach of directly estimating primary production from seasonal vertical mixing. A similar approach was used by Yentsch (1990) to estimate new production in the North Atlantic. To estimate the shift in the timing of the spring phytoplankton bloom, we calculated the critical depth based on Sverdrup’s model (Sverdrup, 1953). The simple methods used here can facilitate a robust comparison of 11 model outputs using a minimal number of parameters and avoid the confounding effects of applying different ecosystem model structures and parametrizations.

Data and methods

CMIP3 models

This study examined the model outputs from CMIP3 as used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). The outputs from all the CMIP3 models are available from the Program for Climate Model Diagnosis and Intercomparison (PCMDI, archived at http://www-pcmdi.llnl.gov/about/index.php) at the Lawrence Livermore National Laboratory.

For the current climate, we used data from the 20th century climate simulation (20th Century Climate in Coupled Models, 20C3M) driven by both anthropogenic and natural forcing. Future projections are also assessed from the same models for the Special Report on Emissions Scenarios (SRES) A1B scenario, which assumes moderate future CO2 emissions. For the analysis, outputs from the past two decades were used for both 20C3M (1980~1999) and SRES A1B (2080~2999) experiments: a 20-year period is believed to be sufficient to account for interannual variability, giving a robust indication of climate (Sen Gupta et al., 2009).

The study analyzes as many models as possible to calculate MLD, because we aim to examine individual model simulations, as well as ensemble means, focusing on differences and similarities of model simulations. Table 1 lists 11 models used in this study from the initial set of 25 CMIP3 models, based on these criteria. First, we removed six models with which MLD estimation was not possible; two models (BCC-CM1 and INMCM3.0) were removed simply because temperature and salinity data were not available in the archives. Four models (CCM3-CGCM3T47, CCCMA-CGCM3T63, NCAR-PCM1, and UKMO-HadGEM1) were also excluded because their first vertical levels start below 10 m, the reference depth used for MLD estimation in this study; Second, we excluded four models (GISS-AOM, GISS-EH, GISS-EH, and IAP-GOALS-g1.0), because they have unrealistic 20th century MLD spatial patterns: the three GISS models display a large MLD bias (>400 m) in the northwestern area, and IAP-GOALS-g1.0 has an unrealistic uniform spatial pattern in MLD at high latitudes. Finally, we eliminated four models (BCCR-BCM2.0, CSIRO-MK3.0, GFDL-CM2.1, and INGV-ECHAM4) whose data were not available from the PCMDI archive for estimation of net heat flux or windstress.

Although ensemble runs initialized with slightly different conditions are available for some models, just one realization (mostly “run 1”) for each model was used for both the 20th and 21st centuries, focusing on multimodel comparison. All model results were interpolated to a common 2.5° longitude × 2.5° latitude grid where multimodel ensemble means and standard deviations were calculated. To assess model performance for the 20th century climate, the simulated MLD from each model was compared with observational estimates by de Boyer Montégut et al. (2004) (available from http://www.locean-ipsl.upmc.fr/~cdbleod/mld.html) that uses the same MLD definition, providing direct comparison between model MLDs and the observations.

This study used a Student’s t-test (von Storch and Zwiers, 1999) to evaluate the statistical significance of changes in each model and multimodel ensemble means. We evaluated statistical significance of the changes in average model projections of the 21st century MLD relative to those of the 20th century using a Student’s t-test with unequal variance. A paired t-test (also called a “repeated-measures” t-test; von Storch and Zwiers, 1999) was used to assess whether the multimodel ensemble average of MLD changes is significant or not.

Definition of MLD

Among various methods for MLD estimation, this study utilizes the variable density threshold method (Sprintall and Tomczak,
which considers salinity stratification that is not negligible at high latitudes, as well as the temperature effect on stratification. This method defines MLD as the depth where the density increase compared with density at 10 m depth equals an increase in density equivalent to a temperature decrease of 0.2 °C. This MLD estimation method has been widely used in various studies, including observational estimation (de Boyer Montégut et al., 2004) and veriﬁcation of simulated upper ocean density structures (Jang and Kang, 2009). Another common method for MLD estimation uses a ﬁxed density criterion, which deﬁnes MLD as the depth where the density increase compared with density at 10-m depth equals 0.03 kg m⁻³. Compared with the ﬁxed density criterion, the criterion used in this study tends to estimate deeper winter MLD by up to 30 m south of 40°N, but estimating shallower winter MLD north of 40°N by up to 30 m.

**Entrainment production**

After the MLD reaches its minimum in summer, gradual deepening of the upper mixed layer will entrain nutrients from below it. The entrained nutrients are consumed and transformed into organic matter during the course of the year. The amount of nutrients available for primary production in the sunlit surface layer will depend on the seasonal excursion of the mixed layer. Although seasonal entrainment of nutrients from the deep water might be a major source of new production in the middle latitudes (Yentsch, 1990), other sources of nutrients could also be altered under global warming. CMIP3 models do not provide enough information on other sources, such as typhoons, upon which predictions can be built. Therefore, we focus on seasonal entrainment of nutrients from the deep water and call this portion of new production “entrainment production” to distinguish it from productions resulting from other sources. Because entrainment production depends on the seasonal excursion of the mixed layer, it will decrease if the MLD becomes shallower. In this analysis, we assume the following. First, only the nutrient supply from entrainment of the deeper water resulting from a seasonal deepening of the surface layer is considered. Other processes, such as nitrogen fixation, upwelling related to eddies and typhoons, and atmospheric inputs, are not considered. Second, all the nutrients entrained into the surface layer are transformed to organic carbon during the year. Third, nitrogen is considered as the major limiting nutrient and only nitrate is considered in calculating primary production.

We calculate entrainment production at 4 × 10 grid cells in the KE region (Figure 1). The cells are spaced in 30.5–39.5°N and 151.5–178.5°E at an interval of 3°. The following equations are used to estimate entrainment production from the nitrogen entrained from deepening of mixed layer:

\[
PN(\text{mol m}^{-2} \text{year}^{-1}) = \int_{z=\text{MLD}_{\text{min}}}^{z=\text{MLD}_{\text{max}}} N(z) \, dz \quad \text{and} \quad PP(\text{g C m}^{-2} \text{year}^{-1}) = PN \frac{12}{N} \text{C.}
\]

Here, PN stands for the depth-integrated nitrogen entrained by deepening of the mixed layer (summer to winter). MLD\text{max} and MLD\text{min} are annual maximum and annual minimum of MLD, respectively. Note that depth integration is made from MLD\text{min} to MLD\text{max} not from the surface to MLD\text{max} because we calculate the entrained nitrate. In addition, note that the time unit of PN is per year, because the entrained nitrate is consumed during the course of an annual cycle. MLD\text{max} and MLD\text{min} values are determined from monthly density proﬁles from each CMIP3 model for every grid cell. N(z) is the vertical proﬁle of nitrate when the MLD is at its annual minimum (i.e. summer). PP is the annual entrainment production expressed in carbon and it is obtained from PN by multiplying by the Redfield atomic ratio and carbon atomic mass. To estimate N(z) at each grid cell, monthly climatologies (1° grid) of nitrate are derived from the online version of the World Ocean Atlas 2009 (Garcia et al., 2010; available at http://www.nodc.noaa.gov/OC5/WOA05/pr_woa09.html). At each grid cell, nitrate proﬁles are obtained from the standard depth levels (0, 10, 20, 30, 50, 75, 100, 125, 150, 200, 250, 300, 400, and 500 m). The density proﬁles from each grid cell are examined and the month of minimum MLD is chosen to select the nitrate profile. Figure 2 shows an example of nitrate proﬁles used for calculating the entrainment production for CSIRO-MK3.5. The proﬁles are from the months when the MLDs reach their minimum at

![Figure 1](http://icesjms.oxfordjournals.org/). Location of the grid cells (4 × 10 cells at an interval of 3°) where entrainment production and the spring bloom timing are calculated. The background image is the average daily primary production in 1999 estimated by Vertically Generalized Production Model (VGP; http://www.science.oregonstate.edu/ocean.productivity/).
each grid point. Because the time of minimum MLD can be different depending on the model and location, the pattern of nitrate profiles can be different for each model. The same climatology of nitrate profiles is used for future scenarios, assuming the changes in the profile would be relatively small when nitrate is integrated through depth.

**Timing of the spring bloom initiation**

The timing of spring bloom initiation is calculated at the same grid cells as with entrained production (Figure 1). As a proxy of the timing of the seasonal bloom initiation, we calculate the time when MLD becomes shallower than the critical depth according to the concept first proposed by Sverdrup (1953). The exact calculation is made following the formulation of Nelson and Smith (1991).

Here, \( Z_c \) is the critical depth, \( \Sigma I_\alpha \) is the daily-integrated PAR (photosynthetically active radiation) and \( K_{\text{PAR}} \) is the diffuse attenuation coefficient of PAR downwards in the water column. Above the surface, the PAR is calculated by multiplying 0.45 (Baker and Frouin, 1987) by the short-wave radiation data from each CMIP3 model. \( K_{\text{PAR}} \) is taken from Jerlov (1976). Although \( K_{\text{PAR}} \) can vary depending on chlorophyll \( a \) concentrations, we use a constant for \( K_{\text{PAR}} \) because chlorophyll \( a \) concentrations are generally low before spring blooms. To calculate the exact timing when MLD becomes equal to \( Z_c \), linear interpolation is done on the monthly time-series of MLD and critical depth and bloom timing is estimated in days. Figure 3 illustrates this procedure for two different cases. Here, case 1 (solid lines) represents a station from 30.5°N, whereas case 2 (broken lines) represents a station from 36.5°N. CRD indicates the critical depth. The intersections, T1 and T2, represent the timing of the spring bloom initiation.

**Results**

**Current winter MLD climate**

In the North Pacific, winter mixing of the surface layers controls the amount of nutrients entrained into the upper ocean, which support phytoplankton growth. In addition, the winter mixing is essential to the formation of the mode waters that determine the property of the thermocline water and connect the upper ocean to the deep ocean (Hanawa and Talley, 2001). Therefore, this study investigates the winter MLD averaged over January, February, and March.

The observed winter MLD presents significant spatial variations north of 25°N, whereas it is nearly uniform south of 25°N (Figure 4, bottom-right panel). The deepest MLDs exceeding 200 m are found between 25 and 40°N in the western North Pacific. Observed winter MLD features three local maxima exceeding 125 m: the first in the eastern subtropical Pacific centred at 140°W and 30°N and the second and third in the northwest Pacific. All three deep mixed layers are associated with mode water formation. The first local maximum corresponds to the region where eastern subtropical mode water (ESTMW) forms (Hosoda et al., 2001). The second, centred near 150°E and 32°N, is associated with subtropical mode water, and the third near 180° and 40°N is associated with central mode water.

Most models simulate the large MLD in the ESTMW region with slightly different values and locations, except MIUB-ECHO-G and MRI-CGCM2.3.2, which display no distinct local maximum. Conversely, the other two maxima tend to coalesce into one large region in the KE in most models, because of overshooting of the Kuroshio in the low-resolution models (Thompson and Cheng, 2008), whereas MIROC3.2 HIRES and MPI-ECHAM5 have a rather distinct signature for the two maxima with different locations. Moreover, the simulated deep mixed layers in the KE are overestimated by 50 m (CSIRO-MK3.5) ~380 m (GFDL-CM2.0) compared with the observation. This deep bias in the KE is probably because of underestimation of the Kuroshio Current, which carries less heat into the KE region, and therefore less stratification, giving the deep MLD bias there (Thompson and Cheng, 2008).
The multimodel mean MLD (Figure 5a) reflects the general features in individual models: a deep MLD in the KE and in the ESTMW formation region. It also carries the common MLD biases from individual models: a deep bias and one larger deep MLD region, rather than the observed two localized maxima in the KE, which is inherent because of the low resolution in most of the CMIP3 models.

Significant intermodel differences (>90 m) are observed in the mid-latitude between 160°E–160°W and 30°–40°N, with its maximum exceeding 110 m centred on 180°, 32°N (Figure 5b). The deep mixed layer (>300 m) extends to east of the 180° longitude in some models, including GFDL-CM2.0, whereas it is limited west of 180° longitude in the models, including NCAR-CCSM3.0 and UKMO-HadCM3, resulting in a dominant intermodel variability near the 180° longitude. The largest intermodel MLD difference corresponds roughly to the region of the largest intermodel variability of the windstress (not presented). This implies that a large component of the intermodel MLD difference results from different windstress in each model.

Future winter MLD changes
The MLD in the 21st century decreases in most regions of the North Pacific, whereas the spatial distribution of the MLD is nearly unchanged (Figures 6 and 7). The overall shoaling results largely from intensified upper-ocean stratification caused by amplified surface warming and freshening (Luo et al., 2009).

Significant MLD decreases (>30 m) are found in two regions: one in the KE and the other in the region centred on 140°W and 25°N. The consistent shoaling of the mixed layer in the KE matches roughly the region of significantly weakened windstress (Figure 8a), implying that the decreased MLD in the KE is attributable mainly to the weakened windstress over the KE. In association with reduced wind, latent cooling is reduced, resulting in diminished net surface cooling in the KE (Figure 8b). This additionally helps to reduce MLD in the KE.

Conversely, the MLD increases in the narrow-banded region between 40° and 45°N west of 160°W, just north of the KE front. This deepening is largely driven by a northward shift of the KE rather than by intensification of surface cooling or wind-mixing. In the multimodel means (Figure 8), the surface cooling is projected to be intensified and the wind intensifies slightly, which might not contribute significantly to the deepening.

Future primary production changes

Entrainment production
We estimate the annual entrainment production at each of 4 × 10 grid cells (Figure 1) for the 20th century and 21st century and calculate the percentage change of the annual entrainment production of 21st century to that of 20th century for each of the
11 CMIP3 models. In Figure 9, boxplots of the percentage changes from each model are illustrated along the four latitudes (see Figure 1 for locations). The overall trend is that the entrainment production will decrease more towards the south (Figure 9). This trend is particularly pronounced with models 5, 6, 7, 8, 9, and 11 (MIROC3.2 Hires, MIROC3.2 Medres, MIUB-Echo-G, MPI-ECHAM5, MRI-CGCM2.3.2, and UKMO-HadCM3). Model 7 (MIUB-ECHO-G) displays the greatest percentage change of decrease (median = 74.5%) along 30.5°N. Conversely, model 1 (CNRM-CM3) displays the largest decrease (median = 50.9%) in the middle latitudes. Models 2 and 10 (CSIRO-MK3.5 and NCAR-CCSM3) display small values of decrease (<15%) at all latitudes. Models 7 and 11 (MIUB-ECHO-G and UKMO-HadCM3) display large decreases at 30.5°N, but big increases (median = +55.5 and +118.3%, respectively) at 39.5°N. When all the grid cells are pooled, median values of the percentage...
change range from $-10.6\%$ (MRI-CGCM2.3.2) to $-40.6\%$ (GFDL-CM2.0). The greatest percentage decrease ranges from $-40.0\%$ (CSIRO-MK3.5) to $-92.2\%$ (MIUB-ECHO-G). The greatest percentage increase ranges from $4.0\%$ (IPSL-CM4) to $311.6\%$ (UKMO-HadCM3).

**Timing of spring blooms**

The estimated time of the spring bloom initiation, as approximated by crossing time of MLD and critical depth, displays a similar trend to entrainment production (Figure 10). Blooms initiate earlier towards the south with models 5–8 (MIROC3.2 HIRES, MIROC3.2 MEDRES, MIUB-ECHO-G, and MPI-ECHAM5). Conversely, blooms initiate earlier at 39.5°N with models 4 and 10 (IPSL-CM4 and NCAR-CCSM3). Models 7 and 11 (MIUB-ECHO-G and UKMO-HadCM3) display delayed spring blooms at 39.5°N. Hence, models 7 and 11 (MIUB-ECHO-G and UKMO-HadCM3) display a very wide range of bloom timing shift ($-24$ to $+18$ d in model 7 and $-13$ to $+22$ d in model 11; negative values indicate advancement of bloom timing, positive delay). For all the grid cells combined, median values of the timing shift range from 0 (MRI-CGCM2.3.2) to $-13$ d (CNRM-CM3). Minimum values range from $-6$ (NCAR-CCSM3) to $-43$ d (MIROC3.2 MEDRES). Maximum values range from $-3$ (CNRM-CM3) to $+38$ d (UKMO-HadCM3). To summarize, the overall trend is that the spring blooms initiate early, but actual values differ very much depending on the model and location. Similarly, with entrainment production changes, some models reveal advancement in spring bloom initiation in all the areas, whereas some models display mixed differences with differing magnitudes.

**Discussion**

Despite significant differences in model configurations (e.g. resolution or subgrid-scale parametrization), most of the CMIP3 models in this study project a consistent shoaling of the mixed
layer in the KE, mainly driven by a consistent weakening of the windfield over the KE. It might be argued that most of the CMIP3 models are not resolving mesoscale eddies, which could be crucial for simulating the Kuroshio and KE, and hence MLD, and their future changes. Noting that a consistent decrease in the KE is also projected in the MIROC3.2.HIRES model, with the highest model resolution among the CMIP3 models, it is not likely that model resolution would change the essential aspects of MLD projection in the KE, at least qualitatively.

We also note that under the SRES A1B scenario, the regions displaying the largest intermodel difference, remain nearly the same as in 20C3M, with a slightly decreased magnitude. The nearly unchanged pattern in the multimodel standard deviation implies that the performance of 20th century MLD simulation can affect MLD changes under global warming.

We have demonstrated that entrainment production (and hence primary production) decreases in the 21st century in most of the 11 CMIP3 models. We also examined whether the method used here to determine entrainment production from the seasonal changes in MLD is reasonable. We chose to use satellite-based primary production estimates as an independent example, an abrupt Arctic sea ice reduction occurs at different rates and different transition periods, depending on various emission scenarios (Holland et al., 2006). For MLD changes, the general patterns in the North Pacific Ocean MLD changes are not likely to differ much from those of the A2 scenario (SRES A2), which considers a worst-case scenario resulting in a four-to-fivefold increase in CO2 emissions over 2000–2009, whereas the changes in the MLD in the KE could be intensified for SRES A2. We do not expect a linear relationship between MLD and CO2 emissions, because atmospheric forcing and ocean circulation affecting MLD would not respond linearly to CO2 emissions.

Figure 10. Predicted shift in the spring bloom initiation by 11 CMIP3 models. Note that negative (positive) numbers on the y-axis represent advances (delay) in bloom timing. Model number represents: 1, CNRM-CM3; 2, CSIRO-MK3.5; 3, GFDL-CM2.0; 4, IPSL-CM4; 5, MIROC3.2 (HIRES); 6, MIROC3.2 (MEDRES); 7, MIUB-ECHO-G; 8, MPI-ESCHAM5; 9, MRI-CGCM2.3.2; 10, NCAR-CCSM3; and 11, UKMO-HadCM3 (Table 1). Dots in the circles represent the median and the boxes delimit the 25th and 75th percentiles. Plus signs represent outliers.
comparison. Because most of the CMIP3 models overestimate MLD compared with observed data, the resultant entrainment production will be overestimated accordingly. Therefore, we chose model 2 (CSIRO-MK3.5, Table 1), which displays the least overestimation, for comparison with the satellite-based estimates. The satellite-based primary production was obtained from Oregon State University (http://www.science.oregonstate.edu/ocean.productivity/). The satellite data were provided by SeaWiFS (Sea-viewing Wide Field-of-view Sensor), which are available only for 1997–2008. We compared the entrainment production calculated with MLD changes for 1998 (July 1998 to June 1999) and 1999 (July 1999 to June 2000) with satellite-based primary production in the same periods at the grid cells.

Yentsch (1990) estimated new production from monthly nitrate profiles and concluded that the estimates were reasonable compared with the observed values in the North Atlantic. Although the formulation for estimating entrainment production used by Yentsch is similar to ours in structure, time-scales are different. In our study, there is a good relationship between the total primary production and entrainment production estimated from annual changes in MLD in the study area (Figure 11). MLD-based estimates of entrainment production account for 81.8% of the variance in total primary production of the study region, which include oligotrophic to moderately productive areas. Note that the relationship is non-linear and valid only where primary production is > 100 g C m$^{-2}$ year$^{-1}$. We do not expect a quantitatively accurate relationship between the two, because of the uncertainties in MLD estimates, nitrate profiles, and satellite estimation of primary production. In Figure 11, new production is estimated by multiplying the $f$-ratio (Eppley and Peterson, 1979) with the satellite primary production, and it is denoted by a broken line. When primary production is below ca. 180 g C m$^{-2}$ year$^{-1}$, entrainment production estimates fall below the new production line. Above 180 g C m$^{-2}$ year$^{-1}$, there are more overestimates. The reason is that the MLD projected by model 2 (CSIRO-MK3.5) overestimates in the north and underestimates in the south. Despite this systematic difference, the coherent relationship between entrainment production and satellite primary production suggests that an MLD-based estimation of entrainment production gives reasonable results.

The results of this analysis indicate that 11 CMIP3 models give a wide range of differences. Despite the similar overall trends, the magnitude of changes in primary production and timing of spring blooms were quite different depending on models and latitudes. Hashioka and Yamanaka (2007) made projections on the ecosystem changes in the western North Pacific using a high-resolution, three-dimensional, ecosystem–biogeochemical model. Their results differed from the results of this study in that the change in the primary production was smaller. The smaller change in the primary production reported by Hashioka and Yamanaka (2007) seems to be caused by a smaller decrease in their MLD field, compared with the IPCC CGCMs analysed in this study. However, direct comparison of our results with those of Hashioka and Yamanaka (2007) is impossible, because they used a different global warming scenario (IS92a for IPCC AR3), as well as a different model, which was an earlier version (called CO-AGCM) of the MIROC models.

Although entrainment of deep nutrients might be the major source of primary production in KE, we recognize that other factors are also important, and we differentiate entrainment production from new production. In the KE region, eddies, typhoons, and nitrogen fixation might be important contributions to new production in addition to the changes in entrainment production. Increases in water temperature and dissolved carbon dioxide could change new production in future in the study area. We examined whether the increased temperature or dissolved carbon dioxide could enhance new production significantly. The first possibility is that increased temperature can enhance nitrogen fixation. Thus far, we only considered nitrate assimilation as sources of new production, but nitrogen fixation could be potentially important in the new production in the subtropical North Pacific (Karl et al., 1997; Dore et al., 2002; Capone et al., 2005; Kitajima et al., 2009). Nitrogen is fixed by diazotrophs, such as Trichodesmium, which are broadly distributed in oligotrophic, tropical, and subtropical oceans (Capone et al., 1997). Nitrogen fixation by Trichodesmium corresponds to half or more of the upward nitrate flux (at Station ALOHA; western subtropical and tropical North Atlantic) and accounts for up to 47% of the primary production in the tropical North Atlantic Ocean (Carpenter et al., 2004).

There are two questions to pose when considering the possibility of increase in nitrogen fixation in the 21st century. The first is whether the range of temperature increase projected by the models could enhance the new production significantly. Maximum specific growth rates of the axenic Trichodesmium IMS 101 strain were highest in the temperature range 24–30°C, with a peak at 27°C (Breitharth et al., 2007). Hence, if the temperature increases towards the optimal value, nitrogen fixation can increase. However, small changes in temperature (4°C) did not appear to affect gross nitrogen fixation in cultures of Trichodesmium IMS 101 (Mulholland and Bernhardt, 2005; Hutchins et al., 2007). The temperature increase from the models ranged from 2.2 to 3.3°C (annual means) and 1.9 to
4.0°C (annual maximum). Therefore, the projected temperature increases might not result in a significant increase in nitrogen fixation.

The second question is whether the temperature increase alone could enhance the new production significantly. Studies have demonstrated that nitrogen fixation can be limited by iron (Raven, 1988; Rueter et al., 1990; Falkowski, 1997) and phosphorus (Wu et al., 2000; Sañudo-Wilhelmy et al., 2001; Moutin et al., 2005; Mulholland and Bernhardt, 2005; Kitajima et al., 2009). Mahaffey et al. (2005) furthermore argued that nitrogen fixation activity is primarily regulated by iron and/or phosphorus availability. The study of Kitajima et al. (2009) in the western North Pacific supports this view. The whole-water nitrogen fixation was markedly elevated in winter throughout the study area compared with that in summer, probably because of the increased upward supply of phosphate resulting from a deeper mixed layer in winter (Kitajima et al., 2009). Similarly, the effects of increased carbon dioxide on nitrogen fixation can be evaluated. Hutchins et al. (2007) reported that chlorophyll a normalized nitrogen fixation rates of Pacific and Atlantic isolates increased by 35–100% at projected carbon dioxide levels of year 2100 (76 Pa, 750 ppm), even under severely phosphorus-limited steady-state growth conditions relative to current carbon dioxide conditions. Whether this can be extended to a longer time-scale (such as annual growth) is questionable, because nitrogen fixation will eventually be limited by iron and/or phosphorus availability.

Although CMIP3 models do not provide data to evaluate the impacts of future changes in typhoons and eddies on primary production, studies have indicated that eddies (Kimura et al., 2000) and typhoons (Siswanto et al., 2007) could contribute to the new production in the western North Pacific. Therefore, studies to evaluate the other sources of new production are desirable.

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