D-3.4 Study of Basin-scale Ocean Circulation Related to Global Chlorophyll Distribution

Contact Person Masahiro Endoh
Laboratory Head
Oceanographic Department, Meteorological Research Institute
Japan Meteorological Agency
Nagamine 1-1, Tsukuba, Ibaraki, 305 Japan
Tel: +81-298-53-8652 Fax: +81-298-55-1439
E-mail: endoh@mri-jma.go.jp

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Abstract To evaluate quantitatively cause/effect of global distribution of chlorophyll to physical environments such as ocean water circulation and surface mixed layer, a standard global circulation model is developed and employed. In the steady state of the model with annual surface forcing, equatorial and high latitudinal upwelling areas in the surface layer correspond to high primary productivity areas in the annual mean pigment distribution derived from the satellite ocean color data (CZCS data). Seasonal variations of surface mixed-layer depths (1) in the model and (2) in the in-situ observed temperature data (Levitus, 1982) are compared with seasonal variations of surface pigments from CZCS data. At mid- and high latitudes of the western North Pacific and the North Atlantic, shallowing of the mixed-layer depth from winter to spring largely explains basin-scale features of the spring bloom of phytoplankton in terms of the Sverdrup's (1953) critical depth theory. In the eastern North Pacific and the Southern Ocean the absence of a spring bloom is difficult to explain using the critical depth theory because Sverdrup's (1953) parameters are treated as constants, which in nature vary with physiological and ecological conditions. At northern latitudes the termination of fall bloom corresponds to a deepening in the mixed layer beyond the critical depth. Sverdrup's (1953) critical depth theory is found useful as a first step in examining the general pattern of phytoplankton seasonality. Based on these results, development of global oceanic chlorophyll model, where a numerical ecosystem model is embedded in the present ocean general circulation model, is encouraged for future studies.

Key Words Global Circulation Model, Surface Mixed Layer, Seasonal Variation, Chlorophyll Distribution, Bloom

1. Introduction

Recently, effects of human activity are expanding to the global ocean scale. Necessity of evaluating anthropogenic effects is increasing. Satellite ocean color data is an important indicator of ocean surface content of chlorophyll or phytoplankton as oceanic primary productivity, which is affected by the oceanic nutrient distribution related to the environmental deterioration.

In order to prepare useful satellite oceanic chlorophyll data for evaluation of the ocean environment, it is necessary to realize relationship between global chlorophyll distribution and global ocean circulation as a physical factor which affects biochemical environment of the ocean.

As the first step, we develop a global ocean circulation model which resolves processes influencing the chlorophyll distribution, such as circulation in the surface layer, depth of the surface mixed layer, upwelling of deep water and so on. Next, we compare horizontal structure of the surface mixed layer reproduced by this model, with the global satellite-derived chlorophyll distribution.

2. Research methods

A numerical model employed is a standard global ocean circulation model with realistic bottom and coastal topography and resolution of 2.5°x2°x21 levels (Endoh et al., 1994)(1). Embedded in the model is a turbulent mixed layer model which has a closure scheme of level 2 (Mellor and Yamada, 1982)(2) with 5 meters resolution in the upper 20 meters. It gives a set of turbulent mixing coefficients of temperature/salinity and momentum, which actually mixes water in the vertical direction and predicts new temperature/salinity and current. The model is driven by the monthly mean climatological wind stress (Hellerman and Rosenstein, 1983)(3), monthly mean surface temperature and seasonal mean surface salinity (Levitus, 1982)(4) after an equilibrium calculation with the annual mean climatology forcing as reported by Endoh et al. (1994).

In the steady state of the model with annual forcing for 1500 years, the vertical velocity distribution in the surface layer indicates downwelling in the middle latitudes and upwelling in the equatorial and high latitudinal areas (Figure 1), which are determined by the distribution of surface wind stress. The upwelling areas correspond to high primary productivity areas in the annual mean pigment distribution derived from the satellite ocean color data (CZCS data: Feldman et al., 1989(5); Ishizaka, 1993(6)) (Figure 2).

Using the supercomputer system of the Center for Global Environmental Research (CGER) of the National Institute for Environmental Studies, the calculation was carried out for 11 years until it reaches to a quasi-steady state with seasonal variation. We define the surface mixed-layer depth (hereafter referred to as MLD) as the depth where the downward temperature deviation in a vertical grid column reaches 0.5 °C from the surface, and investigate the global relationship between seasonal variations of MLD in our model and seasonal variations of the surface pigments from CZCS data. Comparison of these data is made in terms of the Sverdrup's (1953)(7) critical depth (CRD), which is defined as the depth where integrated phytoplankton production balances the integrated destruction in the surface mixed layer. In his analysis at a station in the North Atlantic, shallowing of the MLD to a depth less than the CRD (mostly in April to May) is coincident with the observed rapid growth of phytoplankton. A global distribution of optical water types of Jerlov (1976)(8) is used for visible light attenuation coefficients in deriving global critical depths.

3. Results

Global monthly changes of MLD in the model relative to CRD are mapped in Figure 3. Black areas indicate regions where MLD becomes shallower than CRD from the previous month to the current month. The black areas are referred to as euphotically conditioned areas where the euphotic condition for photosynthesis is satisfied by deepening of CRD with the spring increase of insolation and shallowing of MLD. Gray areas indicate regions where MLD becomes deeper than CRD or MLD remains deeper than CRD, which are referred to as aphotically conditioned areas.

Global monthly changes of surface phytoplankton pigments derived from CZCS data (Feldman et al., 1989; Ishizaka, 1993) are also mapped in Figure 4. Red areas indicate pigment increases of 100 % or more from the previous month, which can be regarded as regions where the blooms occur, and are referred to as CZCS blooms.

For the verification of the model, global monthly changes of MLD in the in-situ observed data (Levitus, 1982) relative to CRD are mapped in Figure 5 in the same way as Figure 3.

Now we compare global monthly changes of MLD (Figures 3 and 5) with phytoplankton pigments (Figure 4). In the northern hemisphere MLD becomes shallower than CRD (euphotic conditioning: black areas in Figures 3 and 5) from mid- to high latitudes from March to July in the model (Figure 3) and from March to May in the in-situ observed data (Figure 5), respectively. During these periods, the wind-driven shallow mixed layer develops with the increase of insolation at the sea surface. These periods are broadly consistent with the CZCS blooms (red areas in Figure 4), though the euphotic conditionings in the model (Figure 3) are later than the CZCS blooms by one/two months. Euphotic conditioning and the CZCS blooms are earlier in the eastern North Pacific than the western North Pacific and the North Atlantic.

The difference of basin-scale patterns of euphotic conditioning between the North Pacific and North Atlantic is related to the basin-scale patterns of MLD. At mid- and high latitudes in winter, MLD is deep in the western region of the North Pacific, while the deep mixed layer extends over the whole zonal scale of the North Atlantic (Endoh et al., 1994)[9]. The deep mixed layer is formed in winter where intensified winter convection occurs along the saline water advected by the Kuroshio or the Gulf Stream as the western boundary current of the subtropical gyre. The Kuroshio affects only the western region of the basin with its saline water, while the Gulf Stream advects the saline water to the whole zonal scale of the basin. Therefore the basin-scale patterns of the winter MLD lead to difference of the basin-scale patterns of euphotic conditioning between the basins. The one/two-months lag of euphotic conditioning in the model is related to the model biases that the Kuroshio path is not satisfactorily reproduced and the formation of winter mixed layer is delayed.

In the eastern North Pacific where the spring bloom has not been observed, the CZCS bloom observed in March at the coastal area of high latitudes (50-60°N) coincides with euphotic conditioning. However, the bloom is seen in the winter season earlier than the euphotic conditioning period for 30-50°N In the southern region where nutrients may be depleted during most of the year, the bloom in winter may be real; however, in the northern region where nutrients are abundant, the bloom is probably an error in the

CZCS data (Yoder et al., 1993)[10]. The small amount of data in this area also makes difficult the comparison between euphotic conditioning and the bloom. It is well known that the subarctic eastern North Pacific lacks a spring bloom, and the critical depth theory is not applicable for this area.

In the North Pacific and the North Atlantic the euphotic conditioning terminates in July, and the MLD is shallower than the CRD until October. The basin-scale CZCS blooms at the mid- and high latitudes are rare in July to September, and the fall blooms are seen in October to November. Then aphotic conditioned MLD (gray areas in Figures 3 and 5) extends to the south, which is consistent with the end of the fall blooms.

In the southern hemisphere the euphotic conditioning in the Antarctic Circumpolar Current (ACC) occurs generally later than that on both sides of the ACC, except the highest latitudes such as the Ross and the Weddell Seas. This is probably due to the deep MLD developed in the winter ACC in the Southern Ocean (Endoh et al., 1994)[9]. The CZCS blooms in the Southern Ocean are rare in spring and the critical depth theory cannot explain them, though the CZCS data are sparse in this area and it is difficult to examine the consistency between the bloom and euphotic conditioning of MLD.

In general, the critical depth theory of Sverdrup (1953) explains phytoplankton blooms in the western North Pacific and the North Atlantic, whereas it is difficult for this theory to explain the absence of spring bloom in the eastern North Pacific and the Southern Ocean. The deficiency of the critical depth theory is related to the constant parameters of Sverdrup (1953) which we have used in the present study. The parameters in nature vary with physiological and ecological conditions (Platt et al., 1991)[11], but we decided to use original Sverdrup's (1953) values since global distribution of those values is not clear.

4. Discussion

To evaluate quantitatively cause/effect of global distribution of chlorophyll to physical environments such as ocean water circulation and surface mixed layer, a standard global circulation model is developed and employed.

In the steady state of the model with annual surface forcing, equatorial and high latitudinal upwelling areas in the surface layer correspond to high primary productivity areas in the annual mean pigment distribution derived from the satellite ocean color data (CZCS data).

Seasonal variations of surface mixed-layer depths (1) in the model and (2) in the in-situ observed temperature data (Levitus, 1982) are compared with seasonal variations of surface pigments from CZCS data. At mid- and high latitudes of the western North Pacific and the North Atlantic, shallowing of the mixed-layer depth from winter to spring largely explains basin-scale features of the spring bloom of phytoplankton in terms of the Sverdrup's (1953) critical depth theory. In these areas the spring bloom occurs from mid- to high latitudes along with the increase of insolation from winter to spring. In the eastern North Pacific and the Southern Ocean the absence of a spring bloom is difficult to explain using the critical depth theory because Sverdrup's (1953) parameters are treated as constants, which in nature vary with physiological and ecological conditions. At northern latitudes the termination of fall bloom corresponds to a deepening in the mixed layer beyond the critical depth. Sverdrup's (1953) critical depth theory is found useful as a first step in examining the general pattern of phytoplankton seasonality.

Furthermore, interannual variation of the surface mixed-layer depth in the model with the forcing of climate variation will be compared with that of sea surface chlorophyll concentration derived from the satellite ocean color data and the in-situ observational data.

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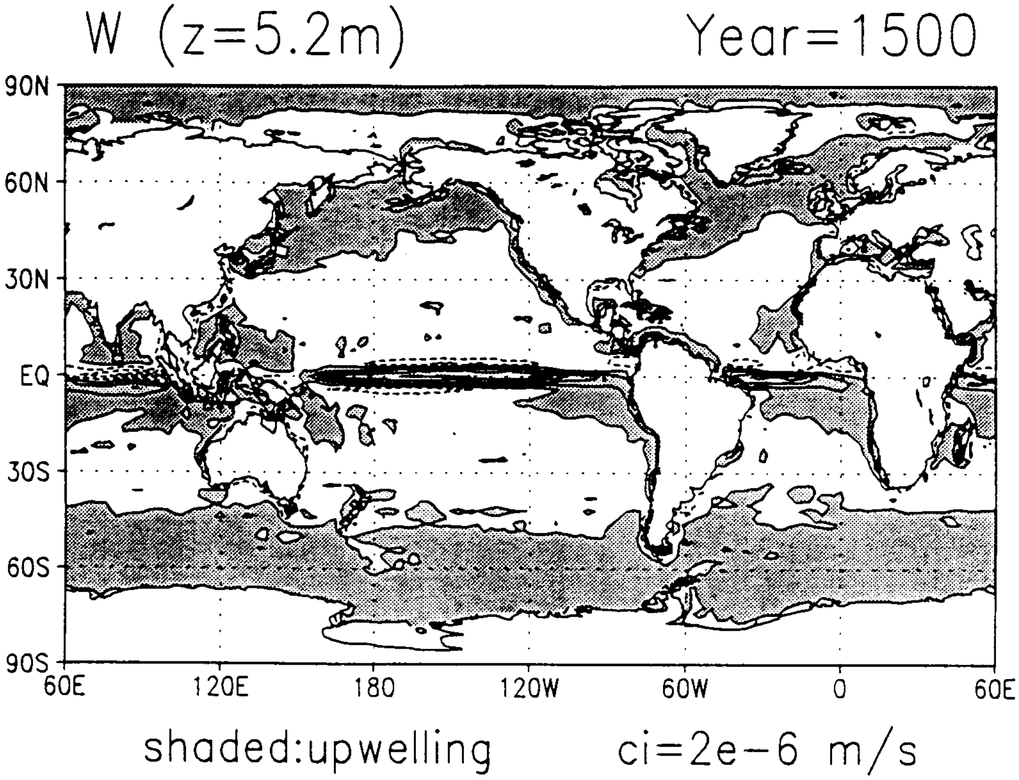

Figure 1. Vertical velocity in the surface layer in the model with annual surface forcing. Shaded areas indicate upwelling regions. The contour interval is 2×10^{-6} m s^{-1}.

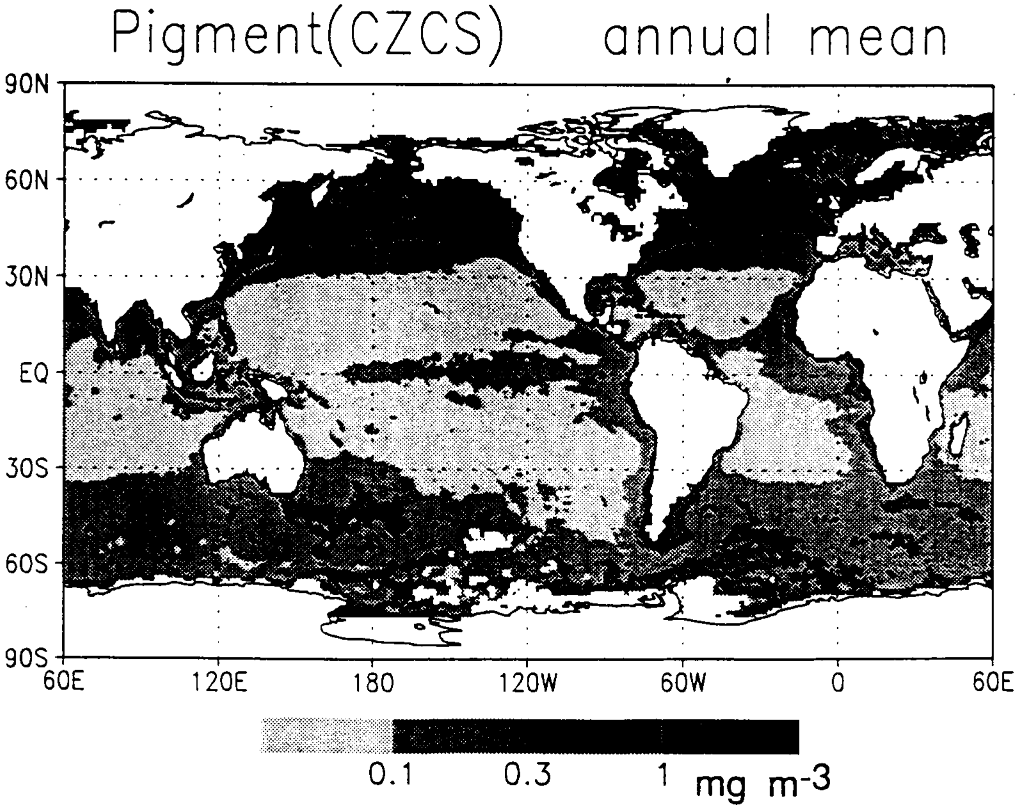

Figure 2. Annual surface pigments derived from satellite ocean color data (CZCS) (Feldman et al., 1989; Ishizaka, 1993). The unit is mg m^{-3}.

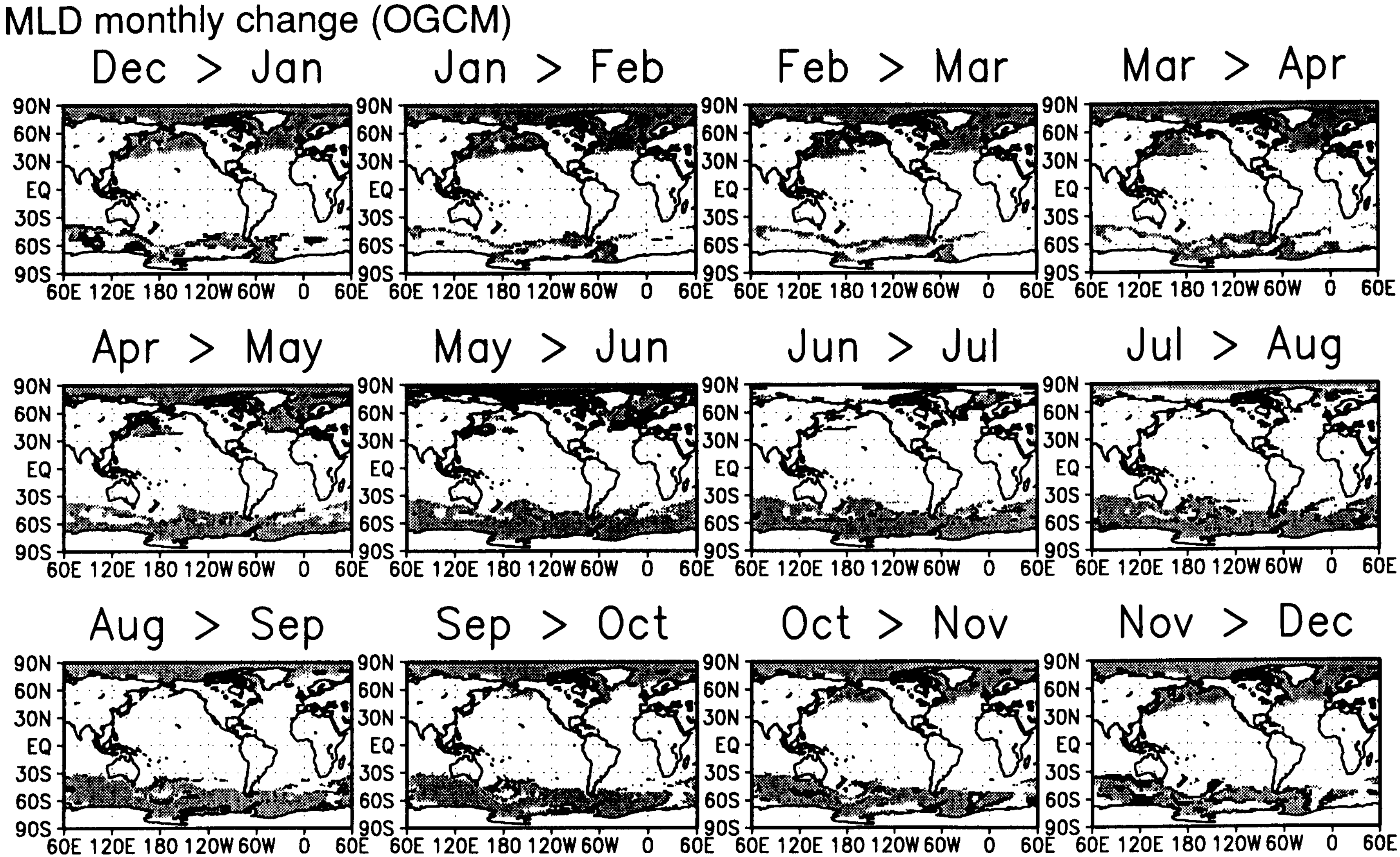

Figure 3. Monthly changes of the surface mixed-layer depths (MLD) in the global ocean circulation model compared with the Sverdrup's (1953) critical depths (CRD). Gray areas indicate *aphotically conditioned* regions where MLD becomes deeper than CRD or MLD remains deeper than CRD. Black areas indicate regions where MLD becomes shallower than CRD, referred to as *euphotically conditioned* for photosynthesis.

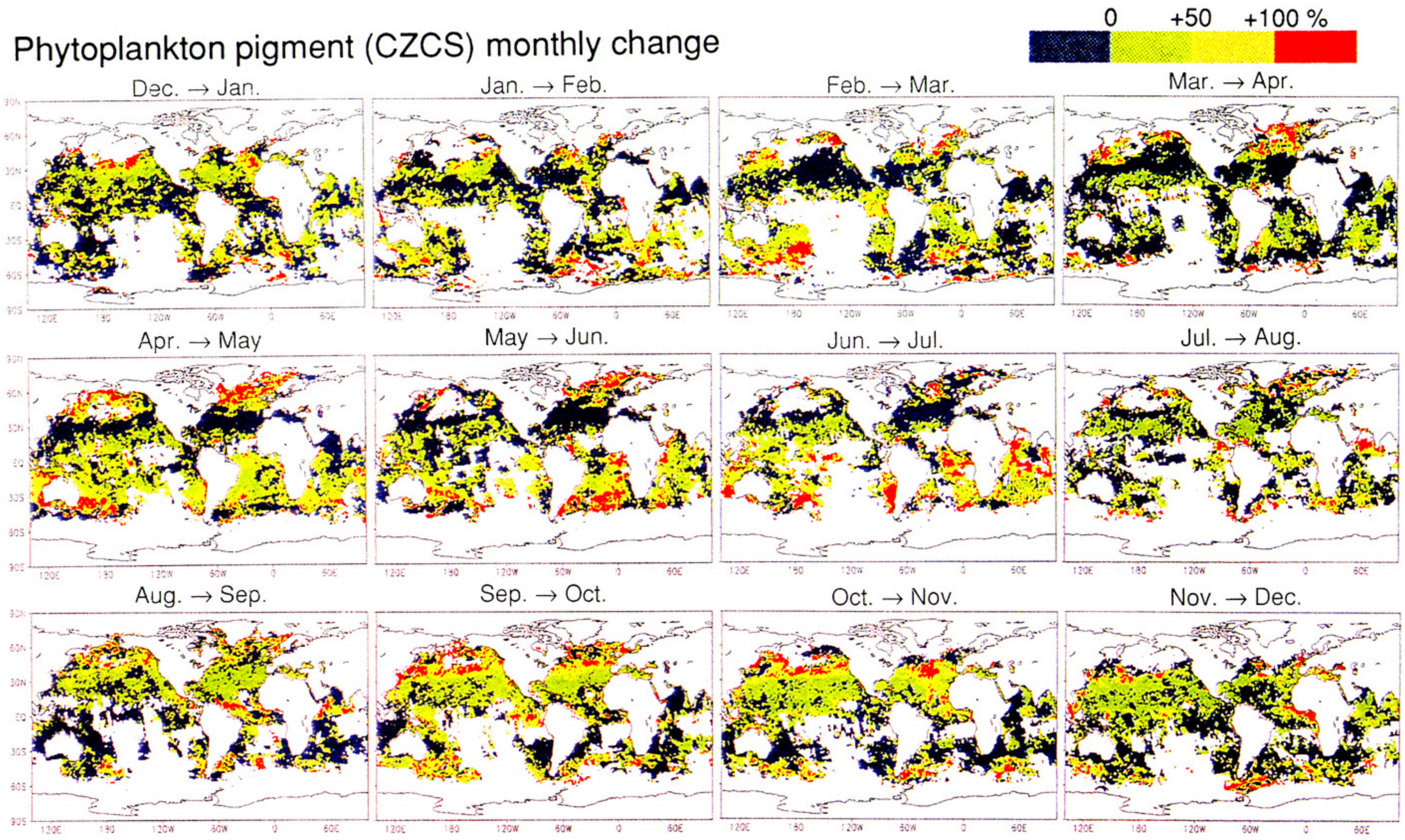

Figure 4. Monthly changes of surface phytoplankton pigments derived from the satellite ocean color data (CZCS) (Feldman et al., 1989; Ishizaka, 1993). Blue areas indicate pigment decreases from the previous month. Green areas show pigment increases of 0 ~ 50 % from the previous month, yellow areas show pigment increases of 50 ~ 100 %, and red areas increases of 100 % or more. The red areas can be regarded as regions where the blooms occur, and are referred to as *CZCS blooms*. White areas show no data.

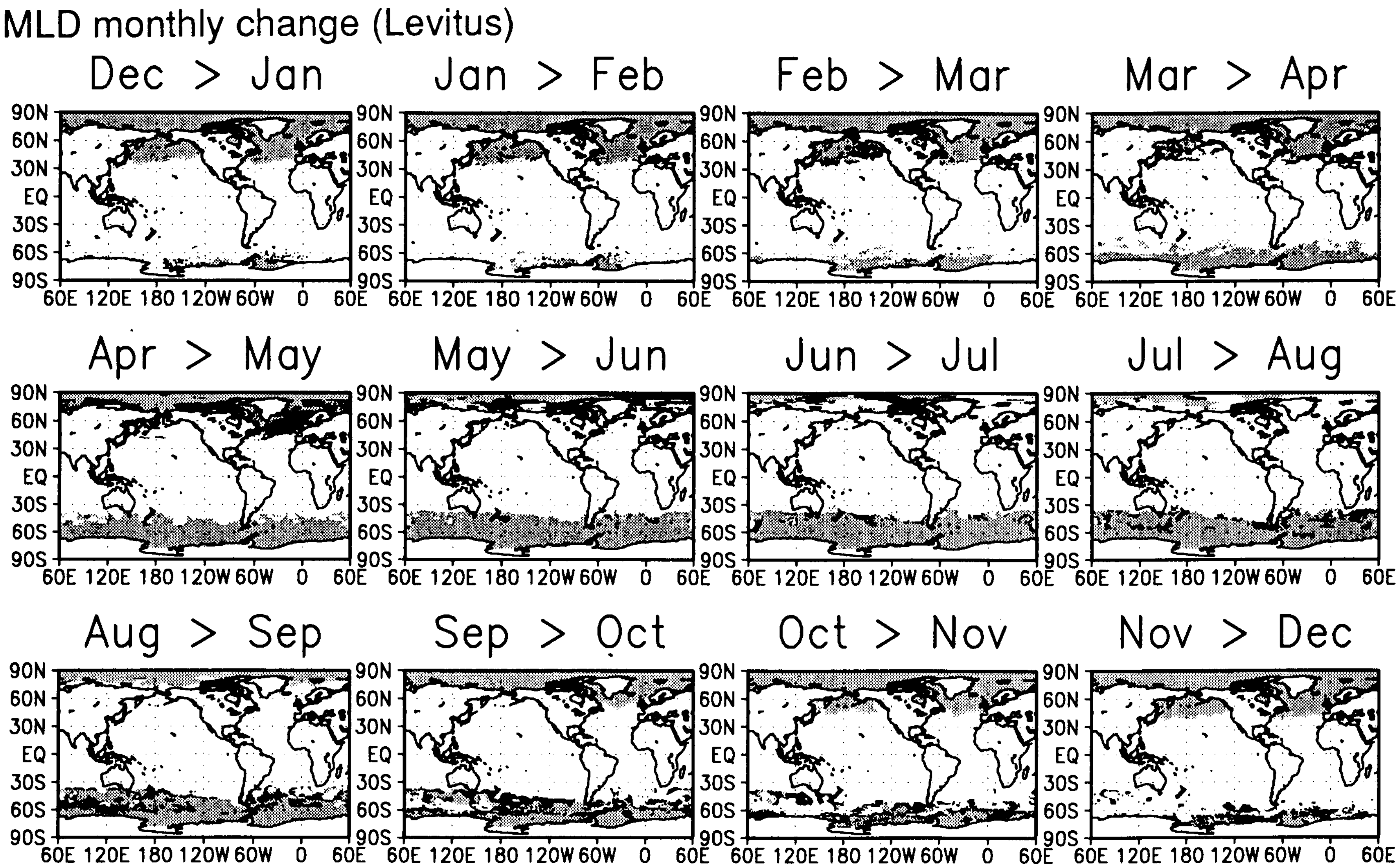

Figure 5. Monthly changes of the surface mixed-layer depths (MLD) in the in-situ observed temperature data (Levitus, 1982) compared with the Sverdrup's (1953) critical depths (CRD). Gray areas indicate *aphotically conditioned* regions where MLD becomes deeper than CRD or MLD remains deeper than CRD. Black areas indicate regions where MLD becomes shallower than CRD, referred to as *euphotically conditioned* for photosynthesis.