Classification of Well-Mixed and Stratified Waters in the Yellow Sea

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Abstract

Information on the vertical profile of phytoplankton biomass is important to estimate primary production using ocean color satellite data. As a first step, identification of well-mixed and stratified regions in the coastal ocean is needed. In this paper, the criterion of temperature difference between surface and bottom layer, $|\Delta T| < 0.8^\circ$C, and the Simpson-Hunter criterion, $\log (H/U^3) < 2$, (where $H$ is the water depth and $U$ is the depth-mean velocity of the tidal current), has been used to identify well-mixed waters in the Yellow Sea. A coupled ocean wave-circulation model and bathymetry data are used to derive the temperature difference between surface and bottom layer and $\log (H/U^3)$. Then model results were compared with remotely sensed sea surface temperature and water-leaving radiance at 667nm derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) to develop a method to differentiate stratified and well-mixed waters using remote sensing data.

From the model results, the criterion based on surface-bottom $\Delta T$ threshold ($\Delta T < 0.8$C) proved to be a better criterion. The $\log (H/U^3)$ criterion which applies only to mixing governed by tidal force is useful only during the summer season. In the winter, the Yellow Sea is vertically well mixed due to strong winds and surface cooling. Even in the summer, the $H/U^3$ criterion does not work in the Chinese coasts because the buoyancy of freshwater plume from the Changjiang River discharge creates a strong halocline in the surface layer. Three-year (2000 to 2002) monthly composite images of MODIS SST and nLw667 were compared with the model-based $\Delta T$ results in March to October to
investigate whether the satellite data can be used as the criterion. The nLw667 threshold could be used reasonably along the southwest coast of Korea during the warmer months. Maps of the well-mixed area were derived from MODIS nLw667 using the relationship between the nLw667 and the model $\Delta T$ in the southeastern Yellow Sea for the warmer months (April to September). The well-mixed area is located in the area where the nLw667 is higher than $2–4 \text{ W} \cdot \text{m}^{-2} \cdot \text{nm}^{-1} \cdot \text{sr}^{-1}$ depending on the month.

**Keywords**

Classification, Stratified waters, Well-mixed waters, Ocean color, MODIS, Yellow Sea

1. **Introduction**

The Yellow Sea is strongly affected by tidal forces as well as fresh water discharge from the Changjiang (Yangtze) River. Although the central part of the Yellow Sea is thermally stratified from spring through fall, the coastal areas of the Yellow Sea are vertically well-mixed due to tides throughout the year. Tidal fronts appear in April with surface heating by solar energy and become most clear in August. Then the fronts disappear in November with surface cooling (Seung et al., 1990). During winter months, most of the Yellow Sea is mixed due to surface cooling and strong winter winds. The southwestern part of the Yellow Sea is affected by the freshwater discharge from the
Changjiang River. The annual mean freshwater discharge from the Changjiang River is about $2.9 \times 10^4$ m$^3$ s$^{-1}$ with minimum of $0.9 \times 10^4$ m$^3$ s$^{-1}$ in January and maximum of $5.4 \times 10^4$ m$^3$ s$^{-1}$ in July (Riedlinger and Preller, 1995). The mid-western coast of Korea (Kyunggi Bay) is also affected by freshwater discharge from the Han River with the total annual mean is about $1.0 \times 10^3$ m$^3$ s$^{-1}$ (Schubel et al., 1984).

Information on the vertical profile of phytoplankton biomass plays an important role in algorithms used to estimate ocean primary production within water column using satellite-derived data. The biomass profile is generally dependent on the physical structure of the water column. Coastal and shelf seas are divided into stratified and well-mixed areas during the warmer months. The biomass profile in the tidally well-mixed area can be assumed as vertically uniform while there are deep chlorophyll maxima in the stratified areas. The vertically well-mixed area, caused by tidal forces has importance on phytoplankton growth and distribution. In addition, light limitation due to high turbidity caused by tidal mixing can inhibit the primary production. It has been reported that light transparency is an important factor governing primary production in the tidally mixed areas of the Yellow Sea (Kang, et al., 1992; Choi, 1991; Choi, et al., 1995; Yoo and Shin, 1995). Thus, it is important to identify well-mixed and stratified regions for estimation of primary production using the ocean color satellite data.

Simpson and Hunter (1974) proposed a criterion, based on $H/U^3$, where $H$ is the water depth and $U$ is the depth-mean velocity of the tidal current, to differentiate tidally mixed and stratified waters. They proposed a threshold value of $\log (H/U^3)$ less than 2 for vertically well-mixed areas and a value greater than 2 for stratified areas. Yentsch
and Garfield (1981) differentiated mixed and stratified waters in the Gulf of Maine using the criterion proposed by Simpson and Hunter (1974) in order to establish the magnitude of the productivity associated with well-mixed regions, and compared maps of log \((H/U^3)\) with infrared satellite imagery. They found a good agreement with the SST maps. Others have compared satellite infrared imagery and/or ship-measured temperature with this criterion in other regions (Pingree and Griffiths, 1978; Garrett et al. 1978; Bowman and Esaias, 1981; Baines and Fandry, 1983; Lie, 1989).

There were several attempts to predict the location of tidal fronts using the criterion, \(H/U^3\), in the Yellow Sea (Beardsley et al., 1983; Lie, 1989; Naimie et al., 2001). These authors demonstrated that tidal fronts were located along the mid-Chinese coast and in Kyunggi Bay and Seohan Bay, and that visual comparison with satellite SST was reasonably consistent. However, the log \((H/U^3)\) threshold varied with regions: it was between 2.0 and 2.4 over the shallow Yangtze Bank (Beardsley et al., 1983) and between 1.0 and 1.4 in the region off the southwest coast of Korea (Lie, 1989).

The upper mixed layer is generally defined as the surface layer where the temperature differs by less than 0.5°C from the sea surface temperature (Obata et al., 1996; Monterey and Levitus, 1997). Recently, Kara et al. (2000) defined an optimal mixed layer depth (MLD) as the depth at the temperature difference of 0.8°C. In this work, we regard the water column as vertically mixed if the temperature difference \((\Delta T)\) between surface and bottom is less than 0.8°C.

The main objectives of this study were to establish the stratified and well-mixed areas associated with monthly variations and to develop a method to differentiate those...
two areas using satellite observations. In the stratified water, there is commonly a deep chlorophyll maximum (DCM) at the base of the mixed layer that influences the vertical profile of productivity (Fig. 1). The primary production often peaks at the depth of DCM. In the mixed water where temperature and salinity are uniform, the chlorophyll profile is almost uniform and the primary production decreases exponentially with depth.

In this paper, the Yellow Sea was classified using the Simpson-Hunter criterion, \( \frac{H}{U^3} \), and also the criterion based on the temperature difference between surface and bottom. Both criteria were calculated from the results of the coupled ocean wave-circulation model developed by Moon (2004). The classifications were then compared with in-situ and remote sensing data to develop a method to differentiate stratified and well-mixed waters using remote sensing data.

2. Methods

2.1. Model data

A coupled ocean wave-circulation model for the Yellow and East China Seas was developed by Moon (2004), which considered the effects of tide, winds, heat flux, river discharge from the Changjiang River, and the Kuroshio Current. Monthly three-dimensional temperature data were derived from the model. The temperature difference between surface and bottom layer (\( \Delta T \)) was calculated from the model results to define the positions of the well-mixed and the stratified areas. The isoline \( \Delta T = 0.8^\circ C \) was then
drawn as the boundary between well-mixed and stratified waters based on the “optimal” MLD definition of Kara et al. (2000).

In addition, mean values of velocity (U) within the water column derived from the Moon (2004) model were used to compute the Simpson and Hunter’s criterion. The log (H/U^3) was calculated using the U-values and bathymetry data. The bathymetry (H) data were obtained from the National Geophysical Data Center.

The temporal resolution of the model results (temperature and U) is monthly and the spatial resolution is 1/6° × 1/6° degree (about 19.5×15 km). The vertical temperature from the model was divided into 11 layers. The spatial resolution of the bathymetry was the same as that of the temperature and U. Since the model was forced by climatological tide, winds, heat flux, river discharge, the model results represent average properties.

2.2. Satellite data

The Moderate Resolution Imaging Spectroradiometer (MODIS) products are available from the National Aeronautics and Space Administration (NASA) Goddard Distributed Active Archive Center (DAAC). Three-years (2000 to 2002) MODIS monthly Level-3 mapped products were obtained at a resolution of 4×4 km. From each MODIS product, data surrounding the Yellow Sea (32-42°N, 118-128°E) were extracted. The monthly MODIS data were averaged for each month. The water-leaving radiance at 667 nm (nLw667), SeaWiFS-analog chlorophyll concentration (Chla2), and the daytime sea surface temperature from the 11-12 µm band were used for this study.
2.3. Ship measurements

Geographical map of the Yellow Sea is shown in Fig. 2. Chlorophyll and suspended sediment data were measured from the Large Marine Ecosystem cruise in the Yellow Sea from June 14–21 in 2000. Temperature, salinity, and chlorophyll fluorescence profiles were also measured using CTD SBE25 as well. The spatial distributions and vertical profiles of the parameters obtained from the cruise were compared with log (H/U^3) and the difference of the model temperature between surface and bottom, and with the MODIS observations.

3. Results

3.1. Difference between surface and bottom temperature

The spatial distributions of well-mixed areas based on the ΔT < 0.8°C criterion are shown in Fig. 3. In the winter season (December, January, and February), most of the Yellow Sea is well mixed due to cooling at the surface and wind stirring. However, ΔT is greater than 0.8°C in a small area of the central and southeastern Yellow Sea in January and December. All of the Yellow Sea is well mixed in February except the southeastern Yellow Sea deeper than 100 m that is influenced by the warm Kuroshio current. Large areas of the Yellow Sea are still well mixed in March, but the northern Yellow Sea
(around 38.5°N and 121–124°E) is becoming stratified. In April, the area of the well-mixed regions decreased significantly compared with March. The vertically-mixed regions are restricted to the coastal regions of the Yellow Sea: along the west coast of Korea except for the middle coast between 36°N and 37°N, along the southeastern coast of China (near the Changjiang River), along the southern coast of the Shandong Peninsula, and in the northeastern and the southwestern Bohai Sea.

The spatial distribution of the mixed area is similar from May to August although further reduced in size compared with April. The mixed area is smallest in July and August. The mixed regions in May to August are located along the southwest coast of Korea, and around the Kyunggi Bay and the Seohan Bay, along the Chinese coast (33-35°N, 36-37°N), and in the northeastern and southwestern Bohai Sea. The mixed area around the Changjiang River in April disappeared, where there is a strong halocline caused by the input of freshwater from the Changjiang River. The amount of the freshwater discharge is biggest in summer (Riedlinger and Preller, 1995; Yang et al. 2002). The stratification is weakening in September as the surface cooling starts. The mixed areas are located along most of the coast of Korea and China, and the areas become larger. The water column in most of the Bohai Sea and around the Changjiang River becomes uniform in October. In November, the northern Yellow Sea above 37°N mixes and ΔT is greater than 0.8°C only in the middle of the Yellow Sea deeper than about 70m.

3.2. Simpson and Hunter’s criterion
The distributions of class intervals of the log \((H/U^3)\) criterion (values 1.5, 2.0 and 2.5) are shown for two summer months (June and August) and compared with the \(\Delta T = 0.8^\circ C\) isoline in Fig. 4. The distribution of log \((H/U^3)\) is similar in both months. Low values of the criterion less than 2.0 appeared around the southwest coast of Korea, the mid-west coast of Korea, the northeastern area of the Bohai Sea, and the mid-east coast of China, especially around the Changjiang River, whereas the values higher than 2.5 appeared in the central area of the Yellow Sea and the open seas of the East China Sea. The overall distribution is similar to the results of other studies (Lie, 1989; Naimie et al, 2001) although there are some discrepancies in the Bohai Sea.

The isoline line of \(\Delta T = 0.8^\circ C\) is also plotted on the map of log \((H/U^3)\). The distribution of \(\Delta T\) is coincident with the spatial pattern of log \((H/U^3)\), especially along the west coast of Korea and Bohai Sea where the isoline of \(\Delta T = 0.8^\circ C\) is between log \((H/U^3)\) = 1.5 and 2.0. The most notable difference between the \(H/U^3\) and \(\Delta T\) criteria is in the area of the Changjiang River plume where the \(\Delta T\) isoline is not present, but log \((H/U^3) < 2.5\). Clearly, the log \((H/U^3)\) criteria does not account for the effects of the freshwater discharge, since it is only based on tidal mixing.

### 3.3. Satellite observations

Three-year (2000 - 2002) averages of monthly composite images of MODIS SST and nLw667 in March to October are shown in Fig. 5 and 6, respectively. In March, the
SST is higher in the central area of the Yellow Sea and decreases toward the north (Fig. 5). All except the central areas of the Yellow Sea are well-mixed ($\Delta T < 0.8^\circ C$). The SST ranges from about $5^\circ C$ in the northern Yellow Sea and to less than $10^\circ C$ in the middle of the Yellow Sea. In April and May, cooler SST appears in the Bohai Sea and the northern (above 37N) and mid-eastern Yellow Sea. The spatial distribution of SST is similar in June to September although the temperature ranges vary with months. The distribution is approximately coincident with the result of $\Delta T$ and log ($H/U^3$) in the eastern part of the Yellow Sea. Lower temperatures along the western coasts of Korea are indicative of vertical mixing appear, but the actual SST values in the well-mixed areas vary with months and regions. The SST off the east coasts of China and in the Bohai Sea, where the distributions of $\Delta T$ indicate a vertically mixed water column, is not lower compared with adjacent offshore areas. Higher temperatures, $>19^\circ C$ in June and $>25^\circ C$ in August, were associated with the northeastern areas of Kyunggi Bay and Seohan Bay. These areas are regarded as well-mixed from the model results. These waters are warmer than the offshore waters due to their shallow depth and solar heating. In addition, lower SST appearing in the eastern area of the Bohai Sea differs from the model results. In October, the SST was decreased and more uniformly distributed spatially.

The MODIS nLw667 images show spatially similar patterns with months. While the nLw667 is comparatively low in the middle of the Yellow Sea, the value is much higher along the west coasts of Korea, Bohai Sea, and the east coast of China including the Changjiang River (Fig. 6). The images show a high nLw667 feature protruding offshore from near the Changjiang River (toward the east). However, nLw667 increases
and the areas spread more offshore in March, April, and October. In April to September, the higher value regions are coincident with the model results ($\Delta T = 0.8^\circ C$) in the western coast of Korea. In areas regarded as well-mixed along the Korean coasts, the seasonal variation of nLw667 was relatively small whereas that of the SST varied with months. The nLw667 values from April to September indicative of well-mixed waters were greater than 2–4 W·m$^{-2}$·nm$^{-1}$·sr$^{-1}$. Off the eastern coast of China, especially in the summer months (May to September), high values of nLw667 extended farther offshore compared to the lines of $\Delta T = 0.8^\circ C$ and $\log \left(\frac{H}{U^3}\right) = 1.5 – 2.0$. This may be caused by large amount of discharge from the Changjiang River in summer.

3.4. In situ measurements

The distribution of in situ temperature, chlorophyll-a, and suspended sediment at the surface in the eastern Yellow Sea, which were measured from the LME cruise in June 14–21, 2000, as well as the contour line of $\Delta T = 0.8^\circ C$, are shown on the monthly composite MODIS images of SST, chlorophyll-a concentration, and nLw667 for June, 2000 (Fig. 7). Lower values of ship-measured temperatures appeared in the southwest coastal area (around 34.5$^\circ$N and 125–126$^\circ$E) and mid-west coastal area (about 37$^\circ$N and 126$^\circ$E) of Korea. The overall distribution is similar both in in situ chlorophyll-a and suspended sediment: higher concentrations in the southwest coasts of Korea and Kyunggi Bay. However higher chlorophyll area is located slightly northerly in the southwest coast of Korea and higher suspended sediment appeared in the central area of the Yellow Sea.
as well. The stations of the *in situ* measurements were not located in the mixed area defined by $\Delta T < 0.8^\circ$C. However, the spatial patterns of *in situ* variables are approximately coincident with that of the criterion from the temperature difference in the southwest coast of Korea.

The spatial distribution of the MODIS images in June, 2000 is similar to that of the three-year composite MODIS images shown in Fig. 5 and 6. The overall distribution of *in situ* data was analogous to the satellite products although there is discrepancy in quantity and unit.

### 3.5. Comparison between model result and satellite data

As mentioned above, no significant horizontal gradient of MODIS SST was shown along the Chinese coast and some of the northwestern coast of Korea although the areas were well-mixed in the model result. This region seems to be homogeneous from bottom to surface due to the shallow bathymetry and solar heating. In addition, there is a large seasonal variability of the SST values. Thus satellite SST images are not as applicable as the criterion for the classification in the Yellow Sea. In the tidally well-mixed and shallow waters, the concentration of suspended sediment would be higher by re-suspension from the bottom. The nLw667 has been used in single-band algorithms for suspended sediment concentration (Salisbury, 2003). Seasonal variability of the MODIS nLw667 is relatively small compared with the SST in the Yellow Sea. However, high values of nLw667 may also be affected by suspended sediments from the river discharges.
The concentration of suspended sediments in the Chinese coasts would be affected not only by tidal mixing but also by fresh waters from the Changjiang River. Meanwhile, the Yellow Sea is totally well-mixed during the winter season due to strong winds and surface cooling. As stated, the satellite nLw667 provides a better criterion to differentiate the Yellow Sea into well-mixed and stratified areas, particularly on the Korean side and in warmer months.

To derive the threshold for the classification using satellite data, nLw667 and $\Delta T$ were compared off the Korean coasts in April to September (Fig. 8). Bin averages of the composite MODIS nLw667 (2000–2002) were plotted against the model $\Delta T$. The relationship varies with months but there is no seasonal trend. The nLw667 values at $\Delta T = 0.8^\circ C$, which are derived from these relationships, range from $2.1 - 4.1 \, W \cdot m^{-2} \cdot nm^{-1} \cdot sr^{-1}$ depending on the month. The maps of well-mixed area ($\Delta T < 0.8^\circ C$) were derived from the MODIS nLw667 images using the relationships between nLw667 and $\Delta T$ in the southeastern Yellow Sea (Fig. 9). The location of the well-mixed area derived from nLw667 agrees with the model result (isoline of $\Delta T = 0.8^\circ C$) in most of the months.

4. Discussion

In the results presented, temperature difference between surface and bottom layer ($\Delta T = 0.8^\circ C$) following Kara et al. (2000) was used as a criterion to differentiate the well-mixed and the stratified areas. The temperature differences were derived from the results
of the coupled ocean wave-circulation model (Moon, 2004). The $\Delta T$ criterion established well-mixed and stratified areas associated with monthly variations in the Yellow Sea. During the winter season, most of the Yellow Sea is totally well-mixed except for a small area in the middle of the Yellow Sea. The central part of the Yellow Sea is thermally stratified from spring through fall. The coastal areas of the Yellow Sea are vertically well-mixed year-around due to tidal force. This result is similar to that of Seung et al. (1990). However, the waters around the Changjiang River seem to be stratified during the warmer months (May to September) due to large input of freshwater from the Changjiang River. The amount of the freshwater discharge is biggest in summer (Riedlinger and Preller, 1995; Yang et al. 2002).

The Simpson and Hunter (1974) criterion, $\log (H/U^3)$, was compared with the distribution of $\Delta T$, where the $U$ values have been derived from the Moon’s model (Moon, 2004). The Simpson-Hunter criterion is based on the situation where tidal force is solely responsible for vertical mixing in shallow seas. Since tidal forces do not change appreciably with seasons in the Yellow Sea, the $\log (H/U^3)$ criterion for winter months was nearly identical to that in the summer months. Therefore, this criterion is useful only during the summer season, but is not useful in winter when mixing is governed largely by thermal convection and winds. Studies (Simpson and Hunter, 1974; Pingree and Griffiths, 1978; Bowman and Esaias, 1981) proposed a threshold value of $\log (H/U^3)$ of 1.5 or 2 to differentiate vertically well-mixed areas from stratified areas. From our result, the isoline of $\Delta T = 0.8^\circ C$, which divides well-mixed and stratified areas, is located approximately between $\log (H/U^3) = 1.5$ and 2.0 in the warmer months although it varies with regions.
However, there is discrepancy in the east coast of China, especially around the Changjiang River. It is inferred that the difference is caused by the buoyancy arising from freshwater discharge plume from the Changjiang River which makes the strong halocline in the surface layer as mentioned above.

In the result of Lie (1989), the boundary between stratified and well-mixed area was expected to be $\log \left( \frac{H}{U^3} \right) = 1.0 – 1.4$ in the southwest coastal water of Korea. This value was derived in a very small area and used observed tidal current data in a small island in the southwest of Korea. Thus the value may be different from our result due to the different temporal and spatial resolution. In addition, many small islands in that region were ignored in Moon’s model.

Ideally, one should use a time-dependent model forced by real winds and ambient conditions at the same time as the satellite data used for estimating primary production. In our case, we used a climatological model and therefore results are only general for the Yellow Sea. We do not have coincident in situ information about the stratification to compare with the MODIS satellite imagery. However, we have compared the isolines of $\Delta T = 0.8^\circ C$ with SST and normalized water-leaving radiance (nLw667) values from the monthly composite MODIS images averaged over three years (2000-2002). These composite images should be comparable to the climatological model results. We believe that it is possible to base a criterion either on the SST or normalized water-leaving radiance in the red region. Cool temperatures would generally indicate vertical mixing. Yentsch and Garfield (1981) compared the Simpson-Hunter criterion with SST maps for the Gulf of Maine and found a reasonable correspondence with their criterion.
The distribution of low inshore MODIS SST in summer months corresponded with the model results along the western coastal areas of Korea although the lower SST region extended more offshore compared with the results of ΔT. Although mixing zones can generally be identified with the appearance of lower temperature, the inshore SST values in the Bohai Sea, the mid-east coast of China, and the northeastern area of Kyunggi Bay and Seohan Bay were higher than offshore values. It is possible that the shallow bathymetry in the Bohai Sea, the eastern coast of China, and the northeastern area of Kyunggi Bay and Seohan Bay make the water temperature homogeneously high from bottom to the surface by solar heating even though these areas are well mixed by tidal force in summer. In addition, the surface stratification due to the fresh water discharge from the Changjiang River occurs over the areas adjacent to the Changjiang River.

The nLw667 has been used by others in single-band algorithms for suspended sediment concentration (Salisbury, 2003). High sediment or turbidity would indicate shallow well-mixed regions, and thus a threshold for nLw667 could be used. The mixed waters in the Yellow and East China Seas are strongly affected by re-suspended sediment due to the vertical mixing and shallow depths. The distribution of MODIS nLw667 is higher along most of the coastal areas whereas the values are comparatively low in the middle of the Yellow Sea. The visual comparison between the MODIS nLw667 image and the model results showed correlated patterns along the western coast of Korea. While SST values varied with months, seasonal variation of the nLw667 values in the areas regarded as well-mixed was relatively small in the Korean coasts. Therefore, it was
concluded that the nLw667 data would be used as a better criterion for differentiating well-mixed and stratified areas. Meanwhile, high values of nLw667 may also be influenced by suspended sediments from the river discharges such as the Changjiang river for the southwest Yellow Sea and the Yellow (Hwang He) River for Bohai Sea. Thus, if a high turbidity criterion were used as indicated by nLw667, the extent of well-mixed waters off the regions near the rivers, especially in the Changjiang River Bank, would be larger than the actual reality.

Similar pattern was shown in comparisons among the model results, the LME cruise data in 14–21 June, 2000, and the monthly composite MODIS images of June, 2000 in the southeastern Yellow Sea although in situ data were spatially limited compared with model results. The areas of lower temperature and higher nLw667 from MODIS deviated from the threshold line of the model results toward offshore. This discrepancy may be caused by temporal resolution. The model results were based on the climatological data, so the year-to-year variation is not considered in this model. The satellite images and in situ data vary with time and regions. Thus, satellite data can be better way to identify the mixed water.

The maps of well-mixed area were derived from the MODIS nLw667 images using relationships between nLw667 and $\Delta T$ in the southeastern Yellow Sea in warmer months. The location of the well-mixed area derived from the nLw667 images and the model result compared reasonably well although there was some discrepancy with regions and months. As mentioned, the discrepancy may be caused by the difference in temporal resolution. In addition, it should be pointed out that the model result has spatial
resolution of $1/6^\circ \times 1/6^\circ$ (about 19.5 $\times$ 15 km), but that of the MODIS images is 4 $\times$ 4 km and the _in situ_ data correspond to discrete stations. The model results are approximately 3.5 – 5 times coarser than the MODIS data. Lie (1989) reported that the discrepancy between SST and his model result was probably due to the coarse grid system of his model.

5. Conclusion

Using the model-based criterion of temperature difference between surface and bottom layer ($\Delta T = 0.8^\circ$C), we established well-mixed and stratified area associated with monthly variations in the Yellow Sea. This was a first step for estimating primary production using remote sensing data. Most of the Yellow Sea is vertically well-mixed during winter season. The middle of the Yellow Sea is thermally stratified from spring through fall. There is a rapid onset of stratification from March to April and breakdown of stratification from September to October. The coastal areas of the Yellow Sea remain vertically well-mixed year-around due to tidal forces. However, the area around the Changjiang River would be stratified in the surface layer due to strong halocline by the input of freshwaters from the Changjiang River during the summer season. The log ($H/U^3$) criterion for identifying tidally mixed areas is useful only during the summer season. However, this criterion does not work in the Chinese coasts because the
buoyancy of the freshwater discharge from the Changjiang River creates a strong halocline in the surface layer.

The satellite data could be used as a criterion to discover the position of the well-mixed and the stratified areas. High sediment or turbidity would indicate shallow well-mixed regions, and thus a threshold for nLw667 might be used. However, since the Chinese coast is strongly influenced by the large input of freshwaters from the Changjiang River, the nLw667 threshold would work more reasonably along the Korean coasts, especially in the southwest coast of Korea. Maps of the well-mixed area were derived from MODIS nLw667 using the relationship between the nLw667 and the model ΔT in the southeastern Yellow Sea for the warmer months (April to September). The well-mixed areas were located where nLw667 is higher than 2–4 W·m⁻²·nm⁻¹·sr⁻¹ depending on the month. These results provide the basis for modeling vertical biomass profiles in estimating primary production using satellite data in the Yellow Sea.

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