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Satellite remote sensing of primary production in the Bering Sea

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Introduction

The Bering Sea covers over 2 million square kilometres of the northernmost region of the Pacific Ocean (NPO, 2008), and is considered to be one of the most productive seas in the world (Walsh et al., 1989). Linking the Pacific and Arctic Oceans, the Bering Sea is almost entirely surrounded by the landmasses of Alaska and Russia. A steep continental slope divides this sea between the expansive continental shelf (<200 m depth) on its eastern waters and the deep basin (>2000 m depth) to the west (Brown et al., 2011).

Sustained with nutrient supplied from the warmer Pacific inflow (Grebmeier et al., 2006), rate of primary productivity in the region is controlled by sea-ice cover, ice-melt stratification, and light condition (Alexander and Niebauer, 1981). During sea-ice formation, brine rejection triggers convective mixing that restores nutrient to surface water (Stabeno et al., 2010). These nutrients are consumed by phytoplankton in spring when freshwater input from melting sea-ice stratifies the surface ocean, leading to higher than average mixed-layer light level and the start of the spring phytoplankton bloom in the marginal ice zone or at the ice edge (Niebauer et al., 2000).

However, sea ice loss also creates additional open water habitat for phytoplankton, whose growth is thought to be light-limited under the sea-ice cover (Hill and Cota, 2005). Rates of CO_2 fixation in the ice-free zone are generally far higher than in sea-ice habitats (Arrigo, 2003), therefore, sea-ice loss potentially leads to a more productive sea. Nevertheless, warming and sea ice loss are likely to affect patterns of primary productivity including the timing and magnitude of the spring bloom (ACIA, 2005). This can also remove the platform for the growth of sea-ice algae, which may act as a seed population for the phytoplankton bloom as the ice-edge moves north each spring (Spindler, 1994).

Satellite ocean colour remote sensing is potentially suitable for quantifying primary productivity in the ocean, worldwide (Hirawake et al., 2012). The simplest productivity model evaluates primary production integrated by depth and time, as a function of sea surface chlorophyll (e.g. Smith et al., 1982; Eppley et al., 1985) derived from satellite data. A more complex algorithm introduces surface irradiance as a second factor controlling productivity, where depth-integrated production is the product of depth-integrated chlorophyll, daily surface irradiance, and a constant, water-column averaged quantum yield (Ψ) for photosynthesis (Morel 1978; Falkowski 1981; Platt 1986; Morel 1991; Behrenfield and Falkowski, 1997).

Studies using satellite remote sensing have revealed an increase in satellite-detectable annual primary production in the Arctic due to the increase in open-water area (Arrigo et al., 2008; Pabi et al., 2008). Conversely satellite-based studies by Brown et al (2011), showed that the seasonal ice pack of the Bering Sea has not contracted since 1979 to 2009, hence the overall primary productivity hasn`t increased during those years. In fact the annual primary productivity of the Bering Sea (124 g C m^{-2} yr^{-1}) is below the global mean (140 g C m^{-2} yr^{-1})(Brown et al., 2011). Proxy records have also indicated a decline in the Bering Sea primary production this century (Schell 2000; Hirons et al., 2001). Similar studies also reported cooling rather than warming (Comiso, 2003) and no change or even an increase in Bering Sea ice extent (Liu et al., 2004; Moore and Laidre, 2006; Parkinson and Cavalieri, 2008; Brown et al., 2011; Brown and Arrigo, 2012). Using the algorithm developed by Pabi et al (2008), a study by Brown and Arrigo (2012) suggest that this phenomenon is caused by the Arctic winter wind bringing frigid air southwards over the past six decades.

Yet, a number of recent studies claim that the Bering Sea is rapidly warming and that its seasonal sea ice cover is retreating (Hunt et al., 2002; Overland and Stabeno, 2004; Grebmeier et al., 2006; Stabeno et al., 2007). According to Hirawake et al (2012) this is caused by the increase in temperature of the pacific summer water (Shimada et al., 2006) and heat flux in the Bering Strait over the past decade (Mizobata et al., 2010; Woodgate et al., 2010), which accelerates sea-ice reduction.

Discussion

Although it remains uncertain how primary production is affected by sea-ice loss and warming (Grebmeier et al., 2010), Loeng et al (2005) predict an association between an increase in Bering Sea productivity with a longer ice-free growing season, which has been observed and modelled in the adjacent Arctic Ocean. However, the increase of satellite-derived primary productivity in the Bering Sea has been questioned by Lee et al. (2012) because of the overestimation of chlorophyll-a concentration due to CDOM because it affects the absorption of short wavelength. Nonetheless this increase in primary productivity has been observed during summer 2002 to 2010, using absorption based approaches from satellite remote sensing (Hirawake et al., 2012).

Despite being a suitable tool to quantify primary production by deriving chlorophyll-a concentration, there is an unresolved problem associated with the subsurface chlorophyll maximum (SCM) detection. Investigation by Arrigo and van Dijken (2011) on the effect of the SCM on the estimation of annual primary production from satellite imagery showed that when neglecting the SCM a 7.6% underestimation of primary production results. In addition, a study by Pabi et al (2008) shows that an estimation of 10% error is found in the annual net primary production in the Arctic Ocean is present when neglecting the SCM.

Another drawback in the estimation of primary production using satellite ocean colour is the accuracy of chlorophyll-a estimation used in algorithms. Coloured dissolved organic matter (CDOM) from the terrestrial in the Arctic (Gue`guen et al., 2007) strongly affects the absorption of short wavelengths, about 400 nm, which results in an overestimation of chlorophyll-a concentration. This effect has pronounced seasonality as a consequence of photobleaching along with additional flow of Alaskan Coastal Waters towards the Bering Sea, and creation of CDOM from the degradation of phytoplankton (Matsuoka et al., 2011). Non-algal particles (NAP) and CDOM have similar effects on chlorophyll-a estimation and change seasonally (Matsuoka et al., 2011). Another error contribution comes from more highly package pigments related to large cells, such as diatoms (Cota et al., 2004).

As an improvement of the vertically generalised product model, (VGPM; Behrenfield and Falkowski, 1997), an absorption-based primary productivity model (ABPM) was developed for the southern ocean (Hirawake et al.,2011). The ABPM uses the light absorption coefficient of phytoplankton, determined from the optical density of particles from in-situ data, and applied to MODIS data by trapezoidal integration at the wavelength of MODIS bands (412-55nm) (Hirawake et al., 2012) thus it is possible to reduce inputs of uncertainties in satellite chlorophyll-a data from SCM, CDOM, and NAP, and photosynthetic rate as a SST. The VGPM model is a function of satellite-derived chlorophyll-a and SST:

$$PP_{eu} = P_{opt}^{b} \times \frac{0.66125 \times E_o}{E_o + 4.1} \times Z_{eu} \times C_{surf} \times D_{irr}$$

where C_{surf} is sea surface chlorophyll-a concentration, Z_{eu} is the euphotic depth, P_{opt}^{b} is the maximum photosynthetic rate at depth, and D_{irr} is the photoperiod. Marra et al. (2007) showed that near-surface primary productivity has a linear and invariant relationship with a phytoplankton absorption coefficient, $\bar{a}_{ph}(0-)$ rather than with chlorophyll-a concentration. Thus, $P_{opt}^{b} \times C_{surf}$ was replaced by:

$$PP_{eu} = f[\,\bar{a}_{ph}(0-)] \times \frac{0.66125 \times E_o}{E_o + 4.1} \times Z_{eu} \times D_{irr}$$

In this study, it is assumed that chlorophyll-a concentration is vertically homogenous, and similar to the C_{surf} in the context of this model (Hirawake et al., 2012). Hirawake et al. (2012) uses MODIS-Aqua daily averaged, with 4km resolution, from 2002-2010 to quantify the primary productivity. Using this model, the level of primary productivity obtained is less than half that of the estimation from VGPM. High productivity that is found in VGPM (>10 000 mg C m^{-2} day^{-1}) is not found using ABPM apart from in estuaries and river mouths, where in-situ data was not collected. The high difference between PP_{eu} in ABPM and VGPM might be caused by the overestimation of the chlorophyll-a concentration by VGPM, related to high absorption in blue wavelength by CDOM and NAP (Hirawake et al, 2012). However this study does not taken account of the sea-ice cover, winds, and the Bering Sea environment.

On the other hand, it can be assumed from the decline of benthic biomass and oxygen utilization (Grebmeier et al., 2006), as well as from a reduction in transport through the Aleutian Passes providing limited nutrients to the continental shelf (Schumaker and Alexander, 1999) that primary productivity at the Bering Sea has declined. Over decadal time-scales, such as from the 1970s-1990s, a decrease in primary productivity has also been suggested by Lee et al., (2007; 2012) The decline is also supported by the proxy record (Schell 2000; Hirons et al., 2001). Recent satellite-based studies by Brown and Arrigo (2012) shows that net primary productivity at the Bering Sea, apart from the Chirikov Basin, which due to sea ice loss has increased by 30% of its net primary productivity, has not increased.

The study by Brown and Arrigo (2012) used satellite reanalysis data of sea ice concentration, sea surface temperature (SST), atmospheric forcing, and ocean colour, coupled to the primary productivity algorithm of Arrigo et al. (2008) and modified by Pabi et al. (2008), to both characterise environmental change and quantify net primary production (NPP) in the Bering Sea. Although this primary production algorithm is adapted for the Southern Ocean, this algorithm calculates the rate of primary production as a function of diurnal changes in spectral downwelling irradiance, sea surface temperature, (°C) and chlorophyll-a concentration (mg m^{-3}). Horizontal distributions of chlorophyll-a were determined from satellite derived chlorophyll-a concentration. This algorithm assumes that within the upper mixed layer, chlorophyll a concentration is uniform and decreases exponentially with depths (Arrigo et al., 2008). The relationship between the chlorophyll-a, $Chl(0)$, on the surface, derived from satellite data, and its reduction is obtained from chlorophyll-a profiles from the Southern Ocean (Arrigo et al., 2000), where chlorophyll-a at depth, *z* is:

$$Chl(z) = Chl(0)\exp[(0.033(z - Mixed\ Layer\ Depth)]$$

To derive the daily primary productivity at 100m depth in time, t, hourly in 24 hours, net biomass-specific phytoplankton growth rate, G(z,t) along with phytoplankton chlorophyll-a to carbon ratio, C/Chl, is integrated with depth:

$$PP = \int_{z=0}^{100} \int_{t=0}^{t=24} Chl(z) \frac{C}{Chl} G(z,t)dt\, dz$$

The net biomass is calculated at each depth and each hour as a function of the temperature dependent upper limit to net growth and a light limitation term. This term is calculated using the Beer-Lambert Law and the ratio of photosynthetically usable radiation (PUR) and the spectral photoacclimation parameter (Arriogo and Sullivan, 1994; Arrigo et al.,2008; Pabi et al., 2008).

In this study, the near shore chlorophyll-a pixels were replaced by the daily mean of valid pixels within the same region of interest (Brown et al., 2011), which might cause an underestimate in the overall result. Nevertheless, this study relied upon primary production algorithms with inherited errors for SeaWiFS (Arrigo et al., 2008; Pabi et al., 2008; Brown and Arrigo, 2012) and does not taken account of the error from CDOM and SCM. Moreover, this algorithm was initially developed for the Southern Ocean rather than the Arctic Ocean, where the chlorophyll-a decreasing relationship equation is obtained from Southern Ocean dataset, not from the Arctic Ocean. The input data for the algorithm also has lower resolution, since it uses 9km resolution for both SeaWiFS and MODIS-Aqua. This will not capture better spatial variability in a very productive place, with varied topography. Additional errors may arise from the use of weekly averaging of the input chlorophyll datasets because time-scales of phytoplankton growth is short (less than 10 weeks) in high latitudes (Racault et al., 2012), as well as the use of baseline correction to join chlorophyll datasets from different sensors

(SeaWiFS and MODIS-Aqua). This is because SeaWiFS dataset is only available from the years 1998 through 2007, therefore to fill the data gap for the year 2008 to 2010, Brown and Arrigo (2012) join two different sensors, SeaWiFS and MODIS-Aqua. Furthermore, an analysis of the mean chlorophyll-a concentration in Arctic waters between 2003 and 2007 where these two datasets are available, shows that SeaWiFS-derived chlorophyll-a concentration exceeds those from MODIS-Aqua by ~ 2.6%.

The sum of studies to date suggests that a more accurate estimation of primary productivity would be obtained using ABPM along with physical oceanography data, such as sea-ice loss, wind speed, and temperature, and nutrient analysis. This could also establish whether the trends of increasing primary productivity and warming of the sea that are calculated using the model are real.

Conclusion

Two different models were used to estimate the primary productivity at the Bering Sea. The first model, by Hirawake et al. (2012) is an improvement on VGPM. This model utilised an absorption coefficient from in-situ phytoplankton samples and applied it to MODIS bands in order to calculate primary productivity, rather than just surface chlorophyll-a concentration. By applying this model, CDOM and NAP effect is minimised. This could be seen where using ABPM, the productivity estimated is less than half of the VGPM. Using this approach the net primary productivity at the Bering Sea has increased over the year of 2002 -2010. However, in this study, the authors do not provide any link between physical forcing and the Bering Sea environment. Conversely, using an algorithm by Arrigo et al (2008) then modified by Pabi et al. (2008), primary productivity has decreased at the Bering Sea from 1998-2010. However, the algorithm was initially developed for the Southern Ocean and uses two different sensors (SeaWiFS and MODIS-Aqua), which introduces baseline errors when joining two sensors together. Additional errors may also arise from weekly averaging of the input chlorophyll datasets, and they were derived at lower resolutions than the model by Hirawake et al. (2012). This primary productivity algorithm has also neglected the uncertainties contributed by CDOM, SCM, and NAP. Nonetheless, this result is coupled with sea ice loss, air temperature, and wind stress, and spans a longer time period. If the author uses ABPM, this study could produce more accurate results and confirm the trends between sea-ice loss and an increase in primary productivity.

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