Spatial variation in satellite-based estimates of primary productivity across the Northeast Pacific subarctic-subtropical front

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Running Header: Satellite-based primary productivity

Non-technical summary

Photosynthesis by marine phytoplankton plays a critical role in Earth's carbon cycle by converting inorganic CO_2 into organic matter, which can be sequestered in the deep ocean. If there is a net flux of organic carbon out of the surface ocean and into the deep, the effect of marine photosynthesis is to remove CO_2 from the atmosphere, thus mollifying atmospheric CO_2 accumulation. Measurements of biological carbon uptake rates are therefore essential to calculations of global carbon fluxes, which are needed to accurately predict future climate change. Since ship-based measurements are limited in space and time by practical and financial constraints, satellite-based estimates of marine carbon uptake could potentially provide a source of continuous, global estimates of marine photosynthesis rates. This study uses one satellite-based algorithm to make discrete estimates of biological carbon uptake rates in the Northeast Pacific Ocean during a September 2008 cruise. The algorithm estimated relatively high rates of carbon fixation north of 40°N and low rates south of 40°N. This boundary roughly coincides with the interface of warm, nutrient-starved subtropical waters and cool, nutrient-rich subarctic waters. The trends observed in this study agree with historical algorithm-based estimates of carbon uptake rates, as well as estimates of carbon uptake rates from alternate methods employed during the 2008 cruise. Such discrete observations, however, cannot fully characterize biological carbon uptake rates in the whole region. Satellite-based algorithms are constantly evolving, and in the future may be accurate enough to make confident global estimates of marine biological carbon uptake.

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Abstract

Satellite data products and ship-based observations were used to estimate net primary productivity (NPP) along a transect in the Northeast Pacific Ocean in September 2008. NPP estimates were calculated according to the Vertically Generalized Productivity Model (VGPM), a widely used satellite-based productivity algorithm. One set of NPP estimates was made using only satellite data products and another using only ship-based observations of chlorophyll concentration, sea surface temperature, euphotic depth, and photosynthetically active radiation. Both sets of NPP estimates showed a trend of high productivity north of 40°N (930 ± 350 mg C m^{-2} d^{-1} satellite-based, 800 ± 480 mg C m^{-2} d^{-1} ship-based) and low productivity south of 40°N (310 ± 110 mg C m^{-2} d^{-1} satellite-based, 300 ± 250 mg C m^{-2} d^{-1} ship-based). This trend was also observed in September monthly mean NPP estimates calculated by the VGPM for the past six years and ^{17}O-based oxygen production measurements carried out during the September 2008 survey. Individual ship- and satellite-based NPP estimates, however, did not correlate well (r^2 = 0.39), particularly at higher latitudes. Ship- and satellite-based values of chlorophyll concentration exhibited the greatest variability and most significant effect on resulting NPP estimates. This study was limited primarily by the sampling frequency of the ship-based observations of algorithm input parameters. Continuous observations would be necessary to make a more complete comparison between discrete NPP estimates and time-averaged NPP estimates, and to extrapolate algorithm-based NPP estimates to a larger spatial scale in order to quantify regional biological carbon uptake rates.

In September 2008, a student cruise conducted by the University of Washington carried out a hydrographic survey of the Northeast Pacific. The purpose of this survey was to quantify the contribution of marine biota to the oceanic drawdown of atmospheric CO_2. To determine biological CO_2 uptake rates, multiple approaches were employed, including chemical proxies, on-deck productivity incubations, and remote sensing. By evaluating this array of methods, the survey aimed to generate a consensus view of the magnitude of photosynthesis rates in the surface ocean. The study described here assesses the accuracy with which remotely sensed estimates of primary productivity (PP), which could be used to extrapolate productivity to the scale of the entire study region, reflect direct measurements.

In a global analysis of sea-air CO_2 fluxes, Takahashi et al. (2002) emphasize the North Pacific between 14°N and 50°N as a region of strong atmospheric CO_2 drawdown with a net sea-air carbon flux of –0.64 Pg C yr^{-1}. The Northeast Pacific subarctic/subtropical front possesses unique environmental conditions prime for phytoplankton growth. At approximately 45°N, cold, nutrient-rich waters from the Alaskan Gyre meet warm, nutrient-starved waters from the North Pacific Subarctic Gyre. Takahashi et al. (2002) describe the combination of thermodynamic and biological factors that lead to strong CO_2 drawdown in frontal regions such as the Northeast Pacific. Cooler water possesses a greater CO_2 solubility, which favors penetration of more atmospheric CO_2 into the surface ocean; this thermodynamic effect enhances CO_2 drawdown in subarctic waters, particularly in the winter (Takahashi et al. 2002). Biological CO_2 drawdown at the subtropical/subarctic front, which dominates during the spring and summer, may be driven by the combination of warmer subtropical water and nutrient-rich subarctic water (and possibly the contribution of iron from subtropical waters).

Frequent measurements of PP (from ^{14}C incubations) have been made at subarctic Station P (50°N, 145°W) and subtropical station ALOHA (23°N, 152°W), providing a time-averaged estimate of both high- and low-productivity regimes. The mean net primary productivity at Station P, where nutrient levels are typically high, is 300 ± 30 mg C m^{-2} d^{-1} in the winter and 850 ± 85 mg C m^{-2} d^{-2} in the spring/summer (Boyd and Harrison 1999). Mean net primary productivity at Station ALOHA, where nutrient levels are extremely low, is 473 ± 123 mg C m^{-2} d^{-1} with little seasonality (Karl 1999). The present study looks at the spatial variability in PP between these subarctic and subtropical regimes.

The ability to accurately estimate PP using remotely sensed data acquired by satellites is a critical achievement for oceanographers wishing to quantify the contribution of marine biota to atmospheric CO_2 drawdown on a regional to global scale (Friedrichs et al. 2008). Since the launch of the Coastal Zone Color Scanner radiometer on the Nimbus-7 satellite in 1978, scientists have used measurements of water-leaving radiance to quantify biological, chemical, and physical processes at large spatial scales not practically possible through ship-based measurements. Over the last three decades, the sensors launched on subsequent missions have become more sensitive and the PP algorithms used to analyze their data have become more sophisticated (Minster et al. 2008).

Two approaches can be taken regarding PP algorithm development. An operational approach uses direct measurements of input variables to parameterize and calibrate the model so that it agrees with PP measurements. Alternatively, a theoretical approach attempts to model PP according to quantitative knowledge of the processes involved in photosynthesis (e.g. phytoplankton physiology, ocean circulation, light attenuation). Ideally, the latter method would be preferable, since it does not rely on prior knowledge of the system in order to predict productivity. However, the interactions between phytoplankton and their physical and chemical environment are highly complex and cannot at present be adequately parameterized with remotely sensed data without tuning and calibration from observations; hence many models are a hybrid of the two methods.

Algorithms in use today range from the very simple, such as that of Eppley (1985), where PP is modeled as the square-root of chlorophyll-*a* concentration, to the highly complex, in which many variables are resolved with depth and/or light wavelength (e.g. Morel 1991). In general, PP algorithms require sea surface temperature (SST), photosynthetically active radiation (PAR), surface chlorophyll-*a* concentration, and euphotic depth as input data (Carr et al. 2006). All of these parameters can all be derived to varying degrees of accuracy from satellite data products, with the exception of euphotic depth, which must be modeled as an operational function of water-leaving radiance. The output of an algorithm is typically calibrated to a set of ^{14}C incubation data. ^{14}C incubation measurements of PP are assumed to represent net primary productivity (NPP), defined as the gross photosynthesis rate minus autotrophic respiration, because 24-hour incubations allow ^{14}C-labeled CO_2 to cycle between phytoplankton and the water sample (Marra and Barber 2004).

A recent comparison among different satellite-based PP algorithms found agreement within a factor of two for global average NPP, with a mean of 51 Pg C yr^{-1} and a range of 32 Pg C yr^{-1} (Carr et al. 2006). This analysis also determined that models typically underestimate the variability of ^{14}C-based estimates of NPP by about a factor of two, and that the tropical Pacific Ocean and high nutrient-low chlorophyll regions (such as the subarctic North Pacific) are particularly challenging areas for most algorithms (Friedrichs et al. 2008). Friedrichs et al. (2008) also note the inability of the satellite-based PP algorithms tested to capture the shift in the

Pacific Decadal Oscillation from the late 1980s to the early 1990s, exhibited by circulation and temperature changes; these changes do not significantly affect the input variables to the algorithms, however they do affect primary productivity. The inherent difficulty for satellite-based algorithms to detect subtle climatic shifts indicates that these models are not presently capable of identifying interdecadal variability or the near-term impacts of global warming on marine productivity (Friedrichs et al. 2008). However, Friedrichs et al. (2008) note that model performance has improved since the previous comparison of Campbell et al. (2002) and speculate that at the current rate of model improvement, discrepancies between satellite-based estimates of NPP and direct measurements will be within the range of observational uncertainty in "a little more than a decade."

The Vertically Generalized Productivity Model (VGPM) is a popular satellite-based PP algorithm developed by Behrenfeld and Falkowski (1997). This model is widely used primarily because its data products, provided by the Ocean Productivity Group at Oregon State University, are easily accessible online (www.science.oregonstate.edu/ocean.productivity). The VGPM is a model of relatively low complexity, driven by SST, PAR, surface chlorophyll-*a* concentration, euphotic depth, and optimal photosynthetic rate (a photoadaptive parameter, modeled as a function of SST). The VGPM tends to estimate slightly lower NPP than other algorithms (Carr et al. 2006, Dunne et al. 2007). In this study, the VGPM was used to estimate NPP along the cruise track of the September 2008 hydrographic survey from Station P (50°N, 145°W) to near Hawaii (18°N, 152°W). This snapshot of PP will also be compared to monthly mean VGPM estimates of September NPP in the cruise region for the past six years. Input data were derived from both satellite data products (from the Moderate-Resolution Imaging Spectroradiometer, MODIS-Aqua) and ship-based measurements. The VGPM estimates of September 2008 NPP were then compared to estimates of PP from oxygen isotope measurements (Luz and Barkan 2000) performed during the cruise.

The comparison between VGPM estimates driven by satellite-derived and ship-based measurements provide an assessment of the efficacy of discrete observations of ship-based and satellite-based parameters in estimating spatial trends in PP in the Northeast Pacific Ocean. The final aspect of this study was to evaluate the water column light attenuation on a very fine scale. Through nearly continuous measurements of downwelling radiance throughout the euphotic zone during the cruise, the euphotic depth (1% light level) was determined for use as input data in estimating NPP from the productivity algorithm. This direct measurement allows for a comparison between observed and modeled euphotic depth, which will determine if an estimation of this parameter is a significant source of potential error for satellite-based algorithms. In addition, variation in the irradiance versus depth profile was used to evaluate discrepancies between satellite-based estimates and direct measurements of PP at different cruise stations.

Methods

Field Work

The hydrographic survey took place from 29 August to 17 September 2008 on the *R/V Thomas G. Thompson* (cruise TTN224). The cruise followed a southward track from Station P (50°N, 145°W) along 145°W to 38°N, then northwest to 48°N, 152°W, and finally south to 18°N, 152°W (Fig. 1). Field measurements of chlorophyll concentration, solar radiation, SST, and euphotic depth were collected at as many stations as possible during daylight hours (approximately every 3° latitude, 16 stations total).

On-deck measurements were made of PAR and solar radiation using HOBO sensors and data loggers (see Fig. 2 for sensitivity information). An in-water optical package included a full-spectrum upward-facing solar radiation sensor and an absolute pressure sensor. In-water pressure measurements were converted to water depth by the HOBO software based on the on-deck measurement of atmospheric pressure. The upward-facing in-water light sensor provided the calculation of euphotic depth (1% light level).

Chlorophyll-*a* concentrations were measured aboard the ship at each station for 3 – 6 depths throughout the euphotic zone. The extraction method described here is similar to that of Parsons et al. (1984). Briefly, water samples were filtered onto 0.2 µm glass fiber filters, from which chlorophyll was extracted in 10 mL of 90% acetone, and sonicated for 7 minutes. Chlorophyll concentrations were calculated from fluorescence measured with a Turner Designs 700 fluorometer (normalized to a solid standard for each station's samples) before and after acidification with 10% hydrochloric acid.

Satellite Primary Productivity Algorithm

The VGPM estimates NPP as a function of surface irradiance (E_0, mol quanta m^{-2} d^{-1}), euphotic zone depth (Z_{eu}, m), surface chlorophyll (C_0, mg m^{-3}), photoperiod (D_{irr}, h), and a photoadaptive parameter ($P^B{}_{opt}$, mg C (mg Chl)$^{-1}$ h^{-1}) (Behrenfeld and Falkowski 1997):

$$NPP = 0.66125 + P^B_{opt}\left(\frac{E_0}{E_0 + 4.1}\right) Z_{eu}\ C_0\ D_{irr} \quad (1)$$

The photoadaptive parameter is estimated as a polynomial function of SST:

$$P^B{}_{opt} = -3.27\times10^{-8}T^7 + 3.4132\times10^{-6}T^6 - 1.348\times10^{-4}T^5 + 2.462\times10^{-3}T^4 - 0.0205T^3 + 0.0617T^2 + 0.2749T + 1.2956 \quad (2)$$

Additionally, each of the variables needed to calculate NPP using the VGPM was measured directly at 16 stations throughout the cruise, and was also acquired from MODIS-Aqua online (http://oceancolor.gsfc.nasa.gov). Therefore, this study includes two separate estimates of NPP derived from the VGPM: one made with ship-based measurements and one made with satellite-based measurements.

Results

Historical NPP was estimated with the VGPM for the month of September between 2002 and 2007 in the Northeast Pacific (Fig. 3). The latitudinal trend in historic NPP along 152°W shows a sharp southward gradient from high to low productivity at approximately 40°N (Fig. 4). However, there is much variation between individual years. Overall, subarctic NPP is greater in some years than in others and areas of high NPP are often concentrated in large patches. Some years also exhibit patches of high NPP in subtropical waters.

NPP for the September 2008 hydrographic survey was estimated using the VGPM. Two different estimates were generated, first using only satellite data products ("sat-VGPM") and second using only ship-based measurements of the input parameters ("ship-VGPM"). There are significant discrepancies between the latitudinal trend in sat-VGPM and ship-VGPM estimates, particularly at higher latitudes (Fig. 5). These discrete values also suggest a more gradual gradient between the highly productive subarctic and less productive subtropics than the historical NPP estimates described above.

To determine the difference between the satellite- and ship-based estimates, the percent difference was calculated as:

$$\text{Difference} = \frac{(\text{sat - VGPM}) - (\text{ship - VGPM})}{(\text{ship - VGPM})} \times 100\% \qquad (3)$$

The percent difference between sat- and ship-VGPM estimates ranges from -50% to +500% (Fig. 6). There were many stations where sat-VGPM estimated significantly higher NPP than ship-

VGPM; however, at points where the sat-VGPM estimate is lower, the difference is less pronounced. Overall, ship-VGPM estimated lower NPP than did sat-VGPM (Table 1), however the difference between mean sat-VGPM and mean ship-VGPM for all stations is not statistically significant ($P >> 0.05$).

Discussion

Historical NPP as Estimated by the VGPM

The Northeast Pacific exhibits dramatic spatial and temporal variability in NPP from one year to the next (Fig. 3). During September over the past six years, it is evident that the subarctic region has higher and more variable NPP than the subtropics. However, even in the less productive subtropics, there are patches of higher productivity at irregular intervals across the region. Although the reasons for such variability are beyond the scope of this study, it is clear that a study which relies on a snapshot observations is likely to miss such fine-scale NPP variability. This difficulty could lead to errors when extrapolating discrete NPP estimate to large spatial scales, which underscores the importance of improving the accuracy with which NPP estimates can be derived from satellite data products.

In particular, ship-based measurements of VGPM input parameters were made at intervals of >100km during the September 2008 hydrographic survey, making the resulting discrete NPP estimates susceptible small-scale variability (i.e. patchiness in phytoplankton abundance and productivity). Nearly continuous measurements (whether for algorithm-based estimates or direct measurements such as ^{14}C incubations), an unpractical task for hydrographic surveys, would be necessary to provide an accurate picture of spatial variations in NPP along a particular transect. Furthermore, a region such as the subarctic/subtropical front is especially challenging, given the dynamic nature of the environmental conditions (including temperature and nutrient levels). NPP estimated by the VGPM for September along 152°W for the past six years (Fig. 4) shows the trend of high to low productivity moving southward from the subarctic to the subtropical region; wide fluctuations occur throughout this path, particularly at higher latitudes.

Sensitivity of VGPM NPP Estimates to Input Parameters

The agreement between satellite-based and ship-based estimates of each input parameter (PAR, chlorophyll concentration, euphotic depth, and SST) and NPP is shown in Figure 7, where the solid line represents a hypothetical 1:1 correlation while points represent the actual data. The first parameter, PAR, shows poor agreement between satellite- and ship-based estimates, with most ship-based PAR measurements being significantly greater than the corresponding satellite-based estimates. Agreement between satellite- and ship-based chlorophyll concentration estimates was generally good. Only one anomalously high ship-based value measured at Station 5 (46°N, 145°W) substantially exceeded the satellite-based chlorophyll values. Euphotic depth showed poor agreement between satellite- and ship-based values; there is no clear pattern to the discrepancy, however, satellite-based euphotic depth tended to be lower than ship-based. SST shows good agreement between satellite- and ship-based values.

The VGPM is notably insensitive to PAR, provided the value is sufficiently high (see Equation 1). For example, mean PAR from satellite data products, 45 mol quanta m^{-2} d^{-1} (which was lower than mean PAR measured from the ship, 80 mol quanta m^{-2} d^{-1}), multiples into the VGPM as 0.92; the higher the value of PAR, the closer this multiplier is to 1. Therefore, with the exception of the few points where both satellite- and ship-based PAR estimates were relatively low, any discrepancies between satellite- and ship-based estimates of PAR had a small-to-negligible effect on the difference between resulting NPP estimates.

A source of potential uncertainty in NPP estimates due to chlorophyll concentration estimates which is not shown is variability in the depth profile of chlorophyll throughout the euphotic zone. Subarctic stations (north of 40°N) exhibited well-mixed surface waters with relatively static chlorophyll profiles within the top ~30m. However, subtropical stations (south of 40°N) exhibited characteristic stratified surface waters with deep chlorophyll maxima (80 – 125m). Such a difference could lead to disparities in depth-integrated chlorophyll levels between ship-based and satellite-based estimates given that satellite chlorophyll estimates represent a surface value. This would lead to a significant underestimate in subtropical productivity by satellites if indeed a deep chlorophyll maximum contributes significantly to total euphotic zone NPP. Interestingly, in a much more comprehensive validation of satellite-based productivity algorithms, Friedrichs et al. (2008) find that deep chlorophyll maxima do not cause satellite-based algorithms to underestimate NPP, therefore this issue should not be considered a significant source of potential error in satellite-based estimates. This claim is reflected in the finding that, at subtropical station ALOHA (23°N, 152°W), ~75% of depth-integrated NPP occurs in the top 50m (Karl 1999); therefore, deep chlorophyll maxima at this location do not contribute significantly to total NPP. However, Carr et al. (2006) emphasize the importance of accurate surface chlorophyll estimates given that all models, including the VGPM, are particularly sensitive to chlorophyll concentration because this parameter is typically the driving factor in relating apparent optical properties to biological processes.

Estimates of ship- and satellite-based euphotic depth (defined as the 1% light level) did not agree well (Fig. 7C). A potential difficulty with the ship-based estimates is the fact that the in-water light sensors employed to create the light vs. depth profiles which were used to make the calculation of euphotic depth were only capable of recording to a depth of ~30m. In many cases, the euphotic depth was much deeper than 30m, and a power regression curve was needed to extrapolate the data to a sufficient depth (up to 170m at some stations). Two representative light attenuation profiles (Fig. 8) indicate that the light level at 30m is typically ~5% of surface irradiance. In addition, precise estimates of subsurface PAR (the 100% light level) proved elusive given the great variability in the measurements. Resulting NPP estimates were therefore very sensitive to small changes in the variables controlling euphotic depth. Satellite-based euphotic depth is also an uncertain quantity because it is estimated indirectly as a function of chlorophyll concentration (Morel et al. 2007):

$$\log(Z_{eu}) = 1.524 - 0.436X - 0.0145X^2 + 0.0186X^3 \quad (4)$$

where $X = \log_{10}(C_0)$. This parameterization increases the dependence of satellite-based NPP estimates on accurate surface chlorophyll concentration estimates.

Sea surface temperature (SST) estimates from the ship and the satellite were in very good agreement (Fig. 7D). This is expected given that SST has long been shown to be estimated to a high degree of accuracy from satellite measurements of infrared wavelengths (Minister et al. 2008).

In order to quatitatively assess the effects of parameter variability on algorithm-based NPP estimates, sat-VGPM and ship-VGPM were recalculated multiple times using equation 1, allowing each parameter to vary while the others were held constant. Each parameter does not exhibit the same amount of variability in the field. To yield a realistic estimate of actual parameter variability, each parameter was varied in proportion with the variability observed in this study. The mean value of each parameter and its uncertainty (±1s.d.) are shown in Figure 9.

All variables showed significant variation. Ship-based values were particularly variable, especially for chlorophyll, euphotic depth, and PAR. To quantify the effect of these variations on estimated NPP, NPP was recalculated using the original value of each parameter, plus and minus one standard deviation (Fig. 10). The significant variation in chlorophyll concentration also appears in NPP calculations as the strongest driver of variability. Variation in chlorophyll concentration as observed in this study has the strongest effect on the resulting NPP calculation. Variation in SST, euphotic depth, and PAR also caused some variation in calculated NPP.

The overall agreement between sat-VGPM and ship-VGPM NPP estimates was not especially good ($r^2 = 0.39$, Fig. 7E). Although both ship- and satellite-based estimates of NPP captured the general southward decrease in NPP, the individual NPP estimates did not correlate well. The two most important factors causing these discrepancies were chlorophyll concentration (due to the great variability in both ship- and satellite-based values) and euphotic depth (due to the difficulty in estimating this parameter from ship-based measurements of light attenuation). It is not clear from this study whether the ship-based or satellite-based euphotic depth estimates are more robust, but their disagreement lends a large degree of uncertainty to both NPP datasets.

The superimposition of sat-VGPM and ship-VGPM from the September 2008 hydrographic study on the September monthly mean VGPM-NPP for September 2002 – 2007 (Fig. 11) shows that many of the discrete 2008 NPP estimates lie well above and below the range of the past six averaged Septembers in the Northeast Pacific along 152°W. Many discrete NPP estimates from this study lie well above and below the maxima and minima of the past six averaged Septembers. This is not unexpected, since monthly averaged NPP estimates will likely suppress extreme high and low values, which may have existed on a day-to-day basis. Had the

2008 hydrographic survey included nearly continuous observations along the cruise track for the entire month, a spatial average of the highly variable discrete measurements might have approached a trend more similar to the historical averaged NPP estimates.

Comparison of the VGPM with Oxygen Isotope-Based PP Estimates

As part of the September 2008 TTN224 cruise effort, many other methods were used to estimate PP. One method used to measure biological oxygen production (and estimate the corresponding organic carbon fixation rate) is through the measurement of the ^{17}O isotope (Luz and Barkan 2000). Rather than NPP, ^{17}O measurements generate an estimate of gross primary productivity (GPP), which exceeds NPP by the rate of autotrophic respiration. A factor of 0.48x was used to convert GPP values to NPP equvalents (based on the mean relationship between GPP and NPP found by Bender et al. 1999). The GPP estimates derived from ^{17}O measurements (F. Janny pers. comm.) agree well with both sat- and ship-VGPM NPP estimates in predicting a gradient of high to low productivity moving from north to south (Fig. 12). On smaller spatial scales, however, ^{17}O-GPP estimates fluctuate widely, similar to the large variability observed in discrete VGPM NPP estimates from the September 2008 hydrographic survey. Because ^{17}O-GPP estimates and discrete NPP estimates were generated from discrete measurements rather than time-averaged values, this similarity is reasonable.

Conclusions

Estimates of NPP in the Northeast Pacific in September 2008 using the VGPM algorithm were derived from both ship-based measurements and satellite-based estimates of the required input parameters. Ship-based measurements of SST and chlorophyll concentration agreed well with their corresponding satellite-based estimates. Ship-based measurements of PAR and estimates of euphotic depth, however, showed significant deviations from satellite-based estimates. In general, chlorophyll concentration is the most significant source of variability in VGPM estimates of NPP due to the wide range of observed values. Uncertainty in ship-based euphotic depth estimates likely also contributed significantly to differences between sat-VGPM and ship-VGPM. Overall, VGPM estimates of NPP yielded a trend of high productivity at higher latitudes (mean >40°N = 870 ± 410 mg C m^{-2} d^{-1}) and low productivity (mean ≤40°N = 310 ± 190 mg C m^{-2} d^{-1}) at lower latitudes of the Northeast Pacific with the transition occurring at 38 – 42ºN, a trend also seen in GPP estimates derived from ^{17}O-based oxygen production measurements. Individual VGPM NPP estimates demonstrated high variablility compared to monthly mean VGPM NPP estimates in agreement with another “snapshot” PP estimate by the ^{17}O method. The most critical factor to improving a hydrographic study such as this in the future is to increase the sampling frequency of VGPM input parameters in order to better capture the significant, small-scale variability in PP in the Northeast Pacific Ocean. Also, comparison with ^{14}C-based NPP estimates from the September 2008 study (when these data become available) will shed further light on the ability of satellite-based productivity algorithms such as the VGPM to predict direct measurements of biological carbon uptake.

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Table 1. Mean values and standard deviations for sat- and ship-VGPM NPP estimates and the deviation of sat-VGPM from ship-VGPM for the September 2008 hydrographic survey. Overall, VGPM estimates calculated from satellite-derived input parameters estimated slightly higher NPP than those calculated from ship-based measurements, however the difference is not statistically significant (P >> 0.05). For both sat- and ship-VGPM estimates, NPP above 40°N was nearly three times as great as NPP below 40°N. The discrepancy between satellite- and ship-based NPP estimates was greater above 40°N. VGPM NPP means represent the mean of all NPP estimates derived from the VGPM from the 2008 study (both satellite- and ship-based).

	sat-VGPM (mg C m^{-2} d^{-2})	ship-VGPM (mg C m^{-2} d^{-2})	VGPM NPP (mg C m^{-2} d^{-2})	sat-VGPM Deviation from ship-VGPM (%)
Mean (s.d.)	620 (410)	550 (450)	590 (430)	77 (150)
Mean ≤40°N (s.d.)	310 (110)	300 (250)	310 (190)	59 (100)
Mean >40°N (s.d.)	930 (350)	800 (480)	870 (410)	95 (190)

Fig. 1. Cruise track for the September 2008 hydrographic survey. Individual stations are labeled by number.

Fig. 2. Sensitivities of the various HOBO sensors employed aboard the ship throughout the cruise, as reported by Onset Computer Corporation (www.onsetcomp.com). (A) Wavelength response curve for full-spectrum planar light intensity pendants, used for measurement of in-water light attenuation. (B) Quantum efficiency curve for planar PAR sensor. The vertical axis gives the percentage of total light measured by the sensor at a given wavelength. The solid red line represents the ideal response, and the solid black line is the actual response of the sensor. (C) Wavelength response curve for on-deck full-spectrum planar solar radiation sensor. Vertical axis gives the fraction of total light measured by the sensor at a given wavelength. The solid black line represents the relative intensity of sunlight at each wavelength, and the solid red line is the response of the sensor.

Fig. 3. Estimates of NPP for the month of September derived from the VGPM (Ocean Productivity Group, Oregon State University). Panels represent (A) 2002, (B) 2003, (C) 2004, (D) 2005, (E) 2006, and (F) 2007; solid black line indicates cruise track for the 2008 hydrographic survey. In each year, a regime of high productivity above and low productivity below ~40°N is apparent. Within these broad generalizations, many smaller-scale features exist, creating great spatial variability across north-south transects.

Fig. 4. Estimates of NPP for the month of September along 152°W derived from the VGPM. The variability seen in the maps of Fig. 3 are again present along this transect, as well as the general trend of decreasing NPP with decreasing latitude. Each year exhibits unique trends in NPP at small spatial intervals.

Fig. 5. Satellite- and ship-based estimates of NPP calculated using the VGPM ("sat-VGPM" and "ship-VGPM", respectively). There are great discrepancies between sat-VGPM and ship-VGPM at many individual stations; however, the overall difference between high and low productivity regimes evident for both datasets.

Fig. 6. Percent deviation of sat-VGPM from ship-VGPM. Satellite-based parameters estimate significantly higher NPP than ship-based parameters at many stations, while sat-VGPM underestimates are not nearly as pronounced.

Fig. 7. Comparison between satellite-based (x-axis) and ship-based (y-axis) input parameters for the VGPM. In each panel, the solid black line represents the hypothetical 1:1 correlation; individual points represent actual data. Linear regression equation and r^2 value for the observed ship-satellite correlation are shown in the bottom righthand corner of each panel. Parameters compared are (A) photosynthetically active radiation (PAR), (B) chlorophyll concentration (Chl), (C) euphotic depth, and (D) sea surface temperature (SST). (E) depicts the comparison of the resulting NPP estimates.

Fig. 8. Two representative light attenuation profiles at Station 9 (38°N, 145°W) and Station 37 (22°N, 152°W). For most stations, the depth limit of the light sensors (30m) was too shallow to reach the euphotic depth (1% light level); in these cases, a power regression model was used to extrapolate the data to a sufficient depth.

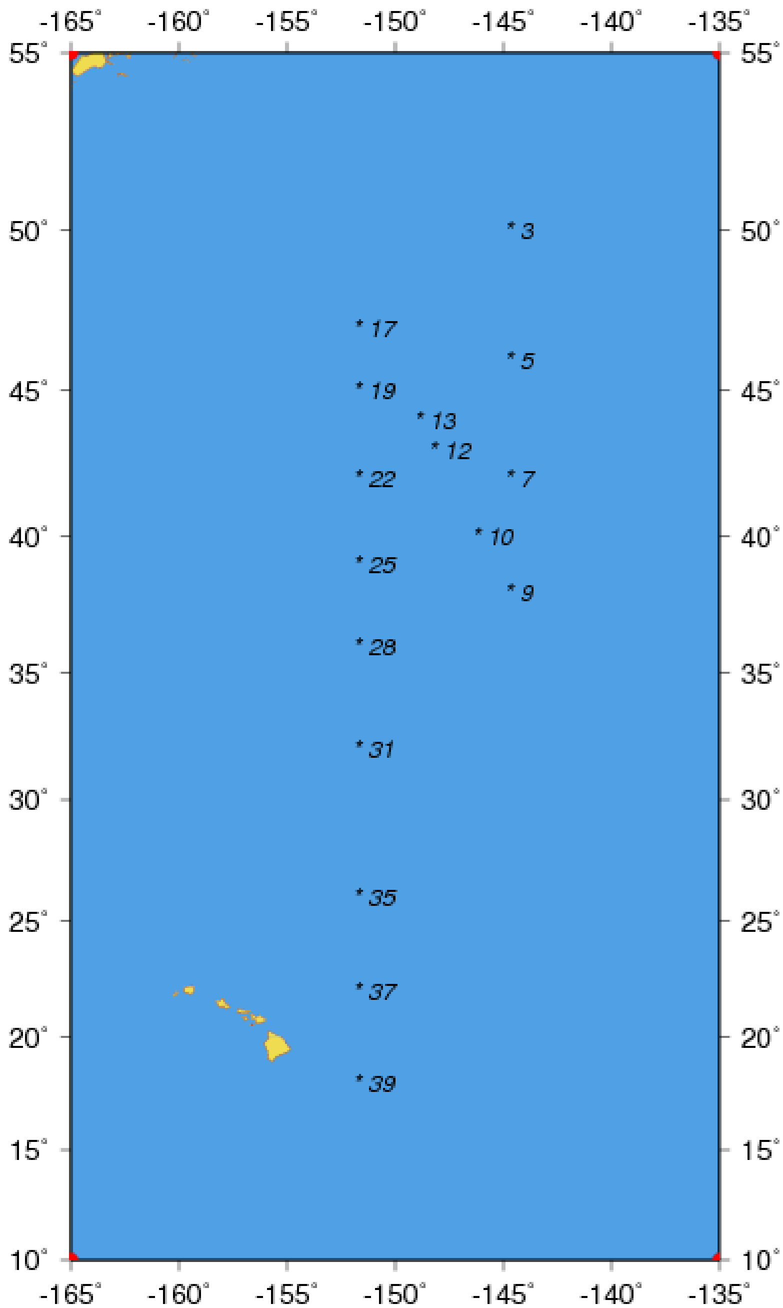
Fig. 9. Mean value (error bar represents ±1s.d.) of satellite- and ship-based observations of (A) chlorophyll concentration; (B) SST; (C) euphotic depth; and (D) PAR. All parameters showed significant variation. Ship-based values of chlorophyll, euphotic depth, and PAR were especially variable.

Fig. 10. Effect on observed variability of each input parameter on calculated NPP. For each parameter, NPP was recalculated by adding and subtracting one standard deviation. Variability in chlorophyll concentration caused the greatest effect on NPP estimates. The effect of other parameters was also significant (~100% in most cases).

Fig. 11. NPP estimates calculated along the September 2008 hydrographic survey overlain on mean September VGPM NPP estimates from previous years (i.e. Fig. 5 superimposed on Fig. 4). This comparison underscores the great variability of the discrete NPP estimates observed in this study. Historic NPP estimates represent a smoothed, average picture of an entire month, and are therefore less prone to wide fluctuations between maxima and minima that may occur on shorter time scales.

Fig. 12. Comparison between algorithm-based NPP estimates and ^{17}O-based GPP estimates (scaled to NPP equivalents using a factor of 0.48x from Bender et al. 1999). Both methods show a large-scale trend of high productivity at higher latitudes towards low productivity at lower latitudes. ^{17}O-based estimates resemble the discrete NPP estimates of the September 2008 hydrographic survey in that both exhibit much greater spatial variability than monthly averaged estimates. ^{17}O-GPP estimates provided by F. Janny (pers. comm.).

Fig. 1



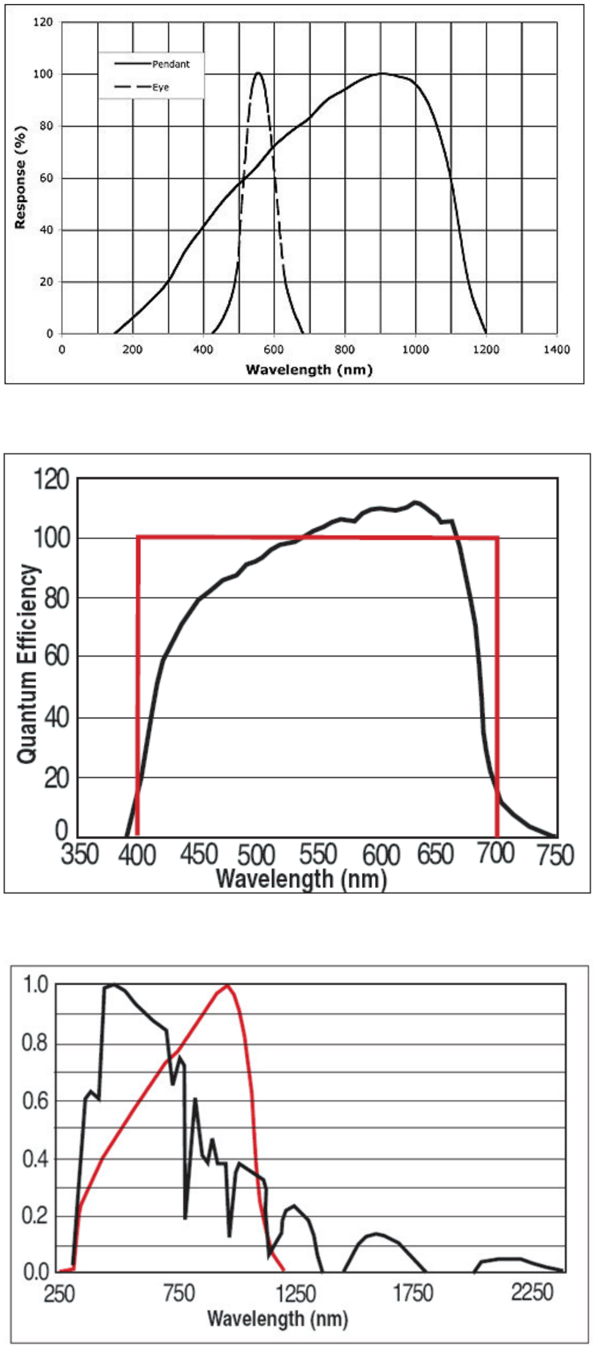
-165°
-160°
-155°
-150°
-145°
-140°
-135°
55°
50°
45°
40°
35°
30°
25°
20°
15°
10°
3
17
5
19
13
12
22
7
10
25
9
28
31
35
37
39

Fig. 2

(A)

(B)

(C)



Pendant
Eye
Response (%)
Wavelength (nm)
Quantum Efficiency
Wavelength (nm)
Wavelength (nm)

Fig. 3

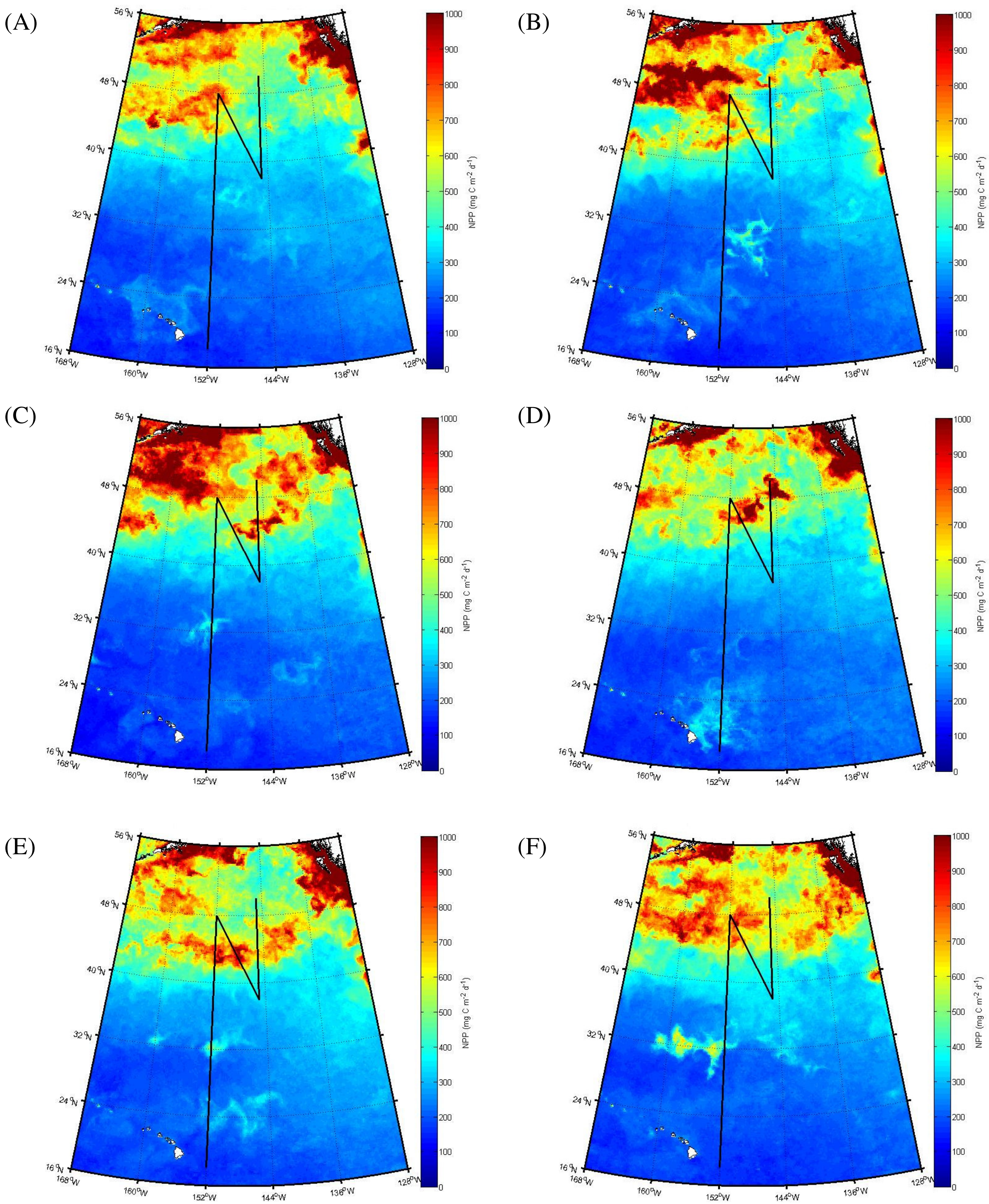

(A)
(B)
(C)
(D)
(E)
(F)
56°N
48°N
40°N
32°N
24°N
16°N
168°W
160°W
152°W
144°W
136°W
128°W
NPP (mg C m-2 d-1)
0
100
200
300
400
500
600
700
800
900
1000

Fig. 4

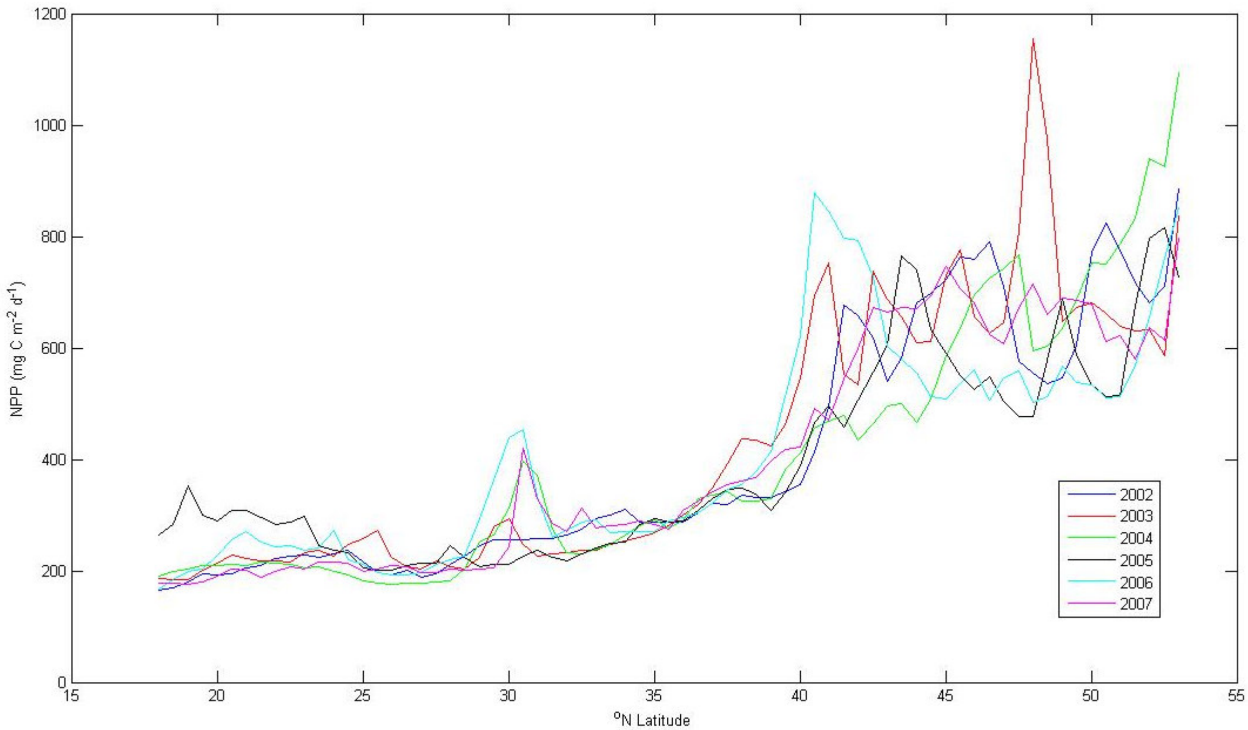

1200
1000
800
600
400
200
0
15
20
25
30
35
40
45
50
55
NPP (mg C m-2 d-1)
oN Latitude
2002
2003
2004
2005
2006
2007

Fig. 5

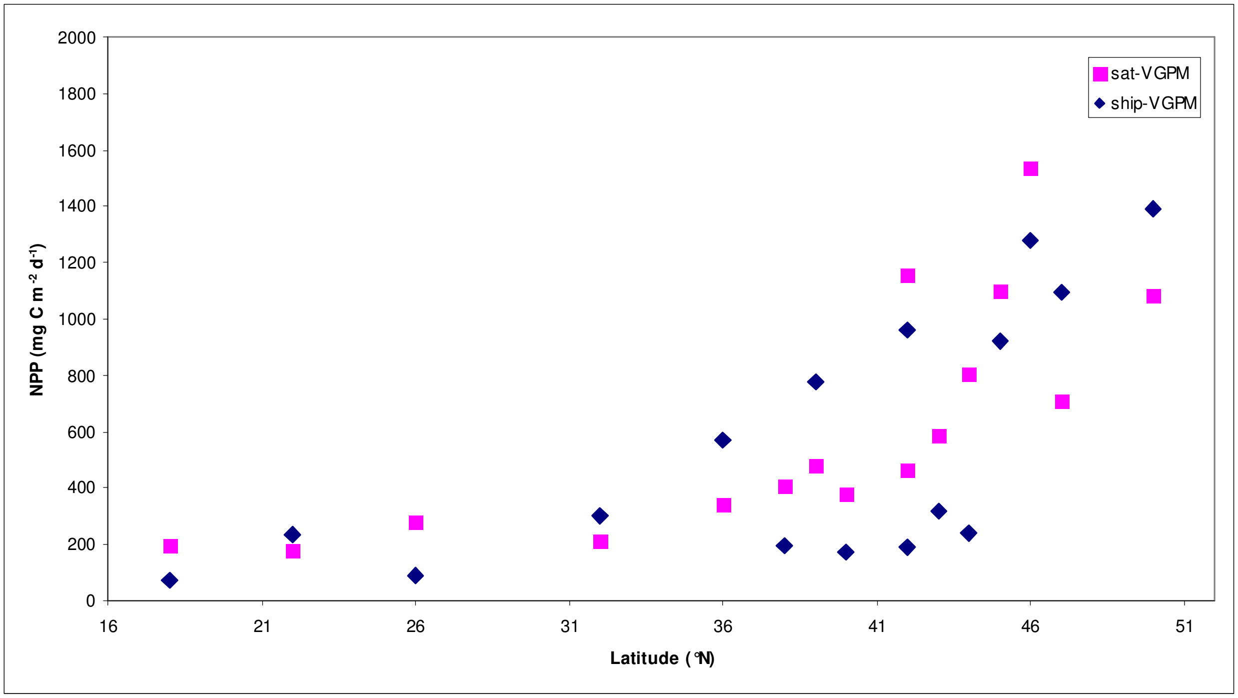

sat-VGPM
ship-VGPM
NPP (mg C m-2 d-1)
Latitude (°N)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
16
21
26
31
36
41
46
51

Fig. 6

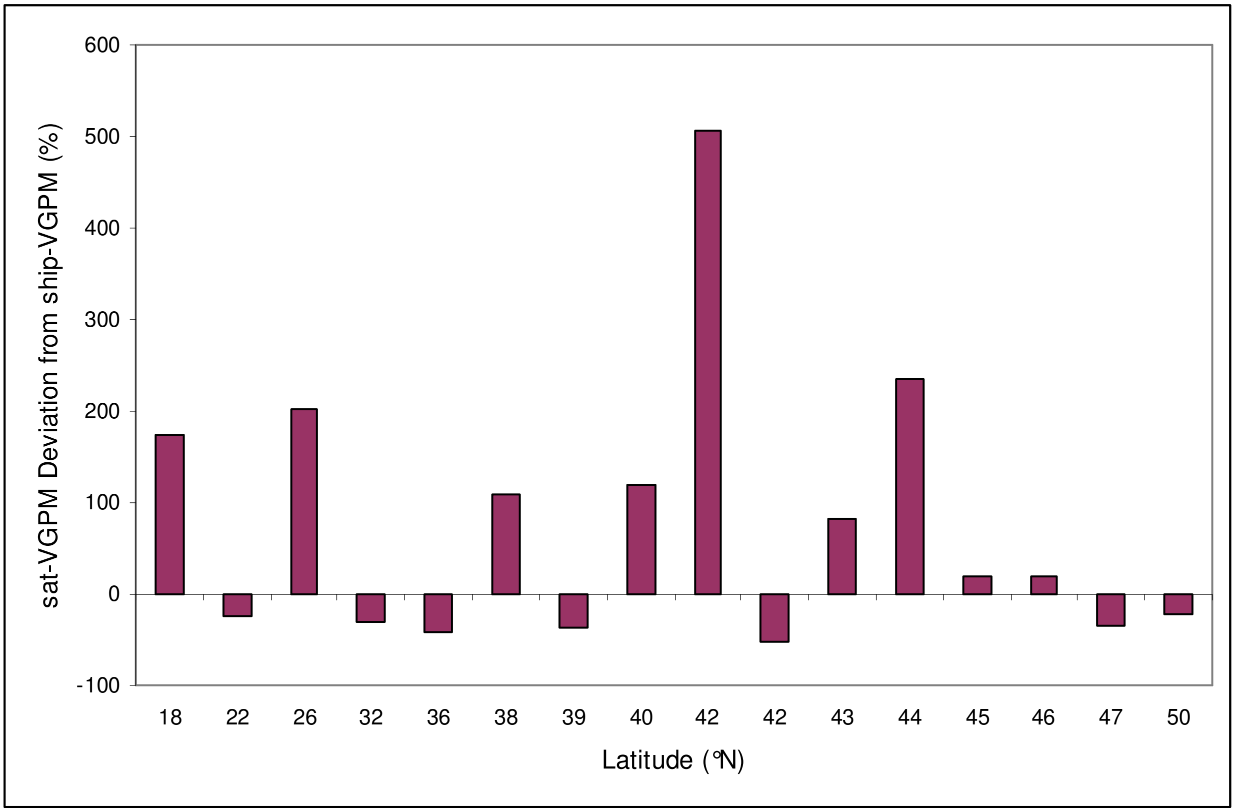

600
500
400
300
200
100
0
-100
sat-VGPM Deviation from ship-VGPM (%)
18
22
26
32
36
38
39
40
42
42
43
44
45
46
47
50
Latitude (°N)

Fig. 7

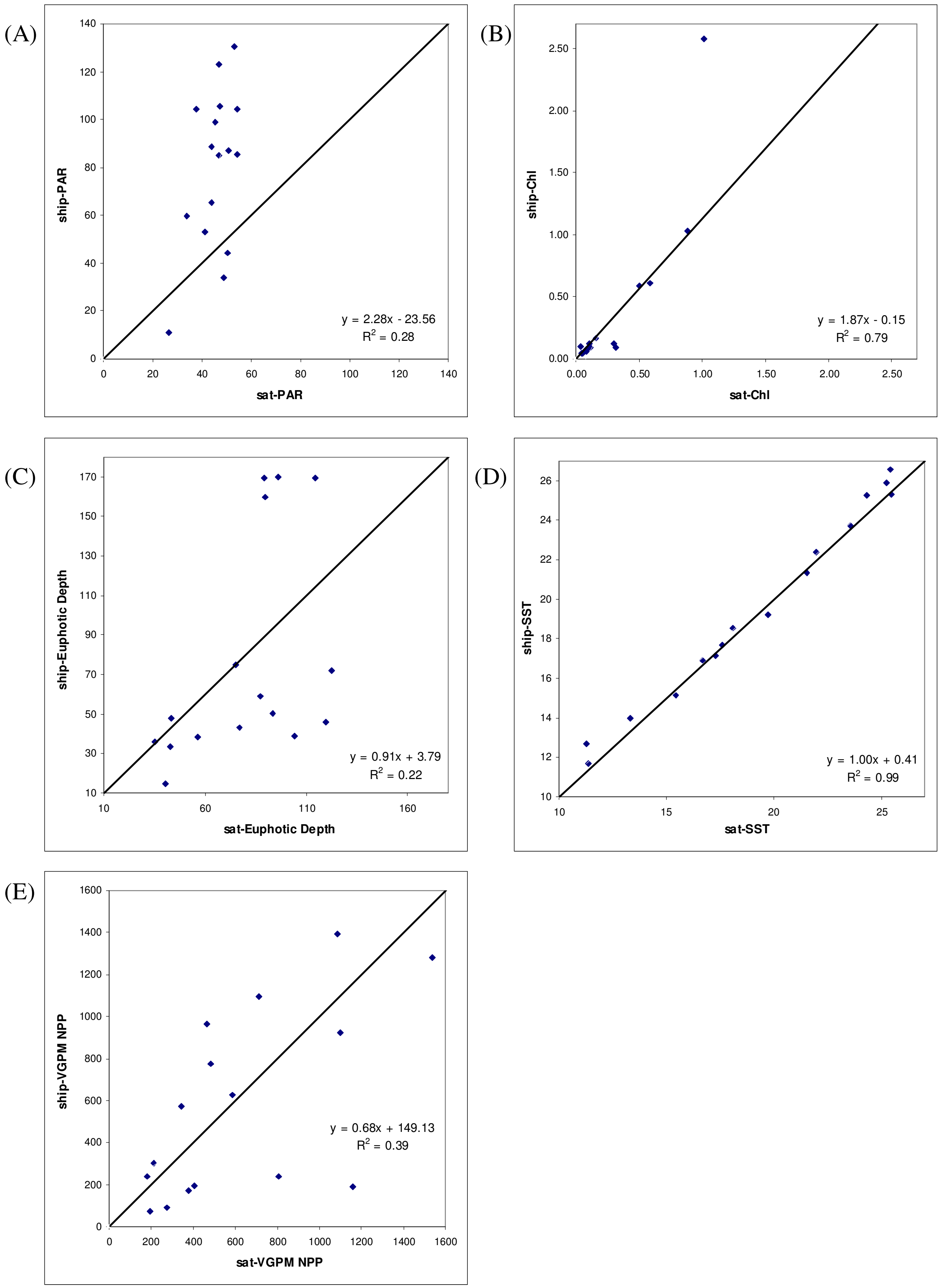

(A)
ship-PAR
sat-PAR
0
20
40
60
80
100
120
140
y = 2.28x - 23.56
R^2 = 0.28
(B)
ship-Chl
sat-Chl
0.00
0.50
1.00
1.50
2.00
2.50
y = 1.87x - 0.15
R^2 = 0.79
(C)
ship-Euphotic Depth
sat-Euphotic Depth
10
30
50
60
70
90
110
130
150
160
170
y = 0.91x + 3.79
R^2 = 0.22
(D)
ship-SST
sat-SST
10
12
14
15
16
18
20
22
24
25
26
y = 1.00x + 0.41
R^2 = 0.99
(E)
ship-VGPM NPP
sat-VGPM NPP
0
200
400
600
800
1000
1200
1400
1600
y = 0.68x + 149.13
R^2 = 0.39

Fig. 8

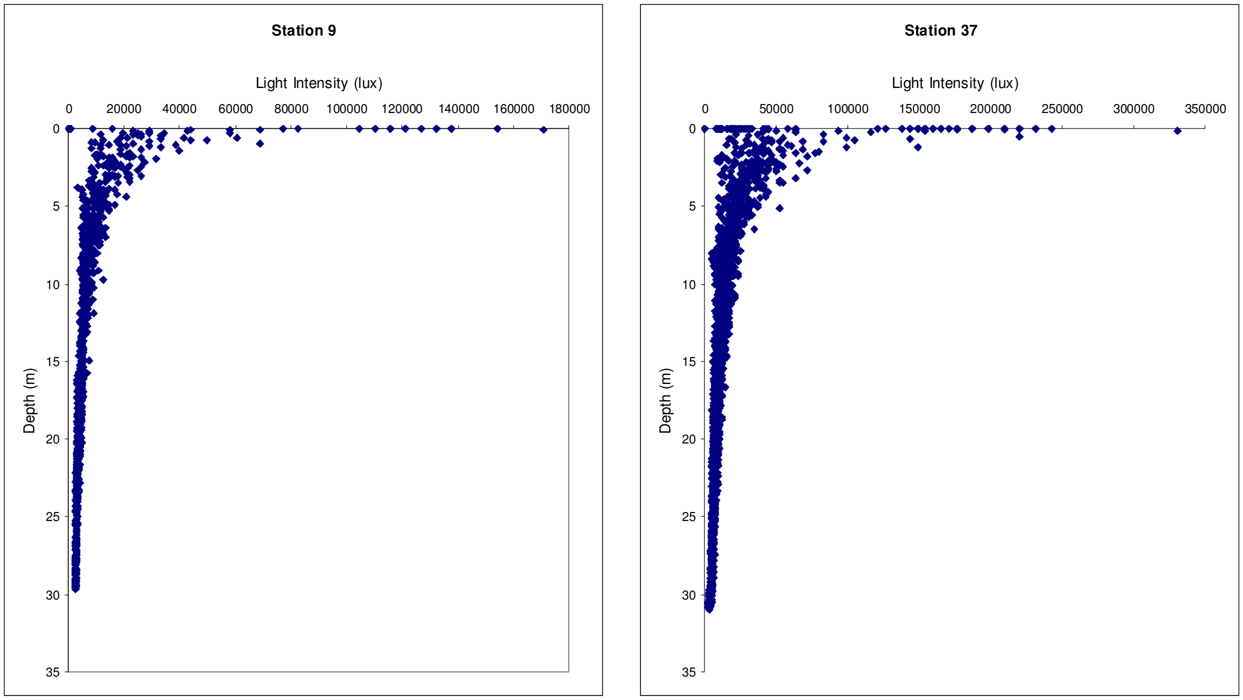

Station 9
Light Intensity (lux)
0 20000 40000 60000 80000 100000 120000 140000 160000 180000
Depth (m)
0 5 10 15 20 25 30 35
Station 37
Light Intensity (lux)
0 50000 100000 150000 200000 250000 300000 350000
Depth (m)
0 5 10 15 20 25 30 35

Fig. 9

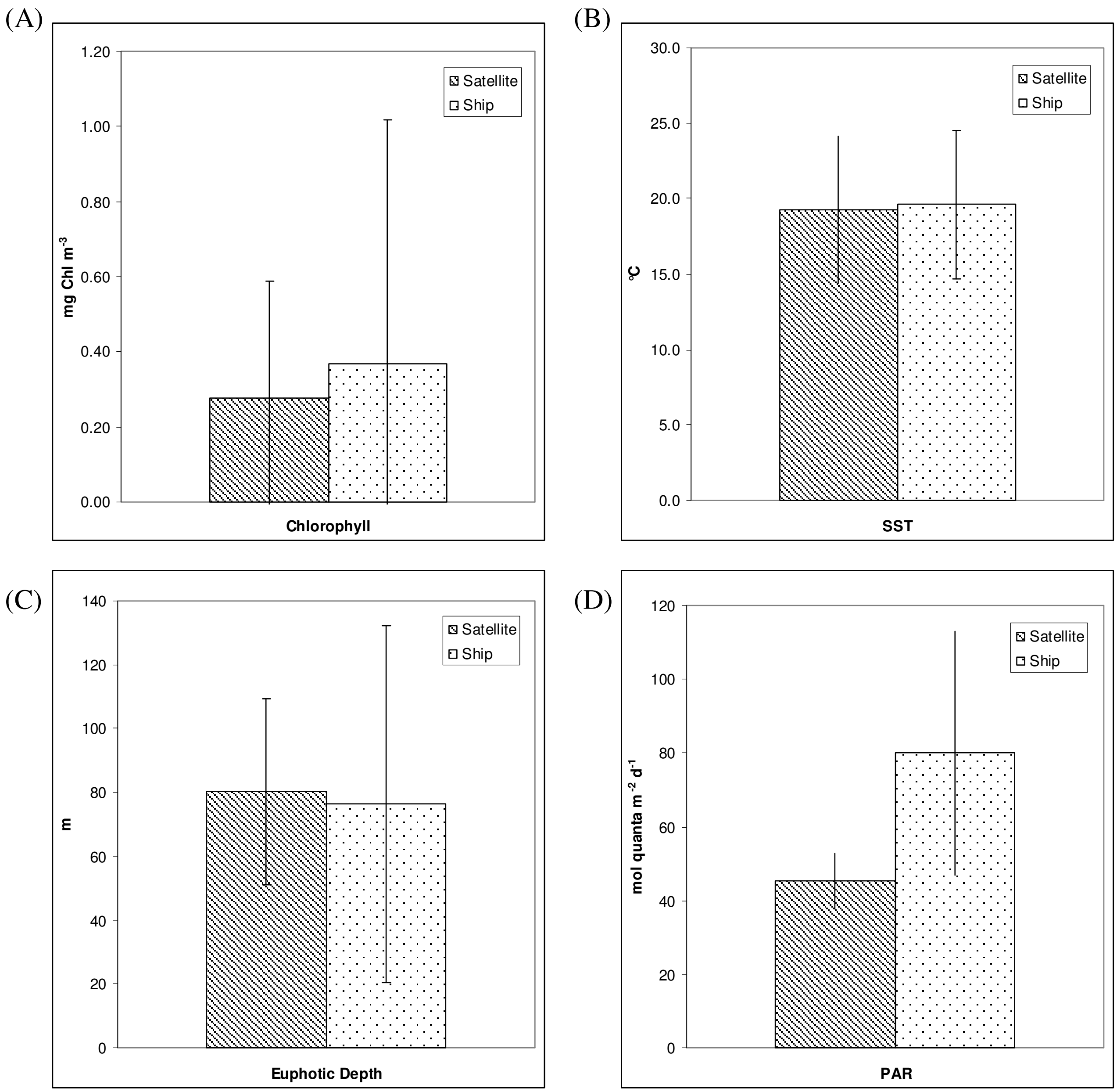

(A)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
mg Chl m-3
Satellite
Ship
Chlorophyll
(B)
30.0
25.0
20.0
15.0
10.0
5.0
0.0
°C
Satellite
Ship
SST
(C)
140
120
100
80
60
40
20
0
m
Satellite
Ship
Euphotic Depth
(D)
120
100
80
60
40
20
0
mol quanta m-2 d-1
Satellite
Ship
PAR

Fig. 10

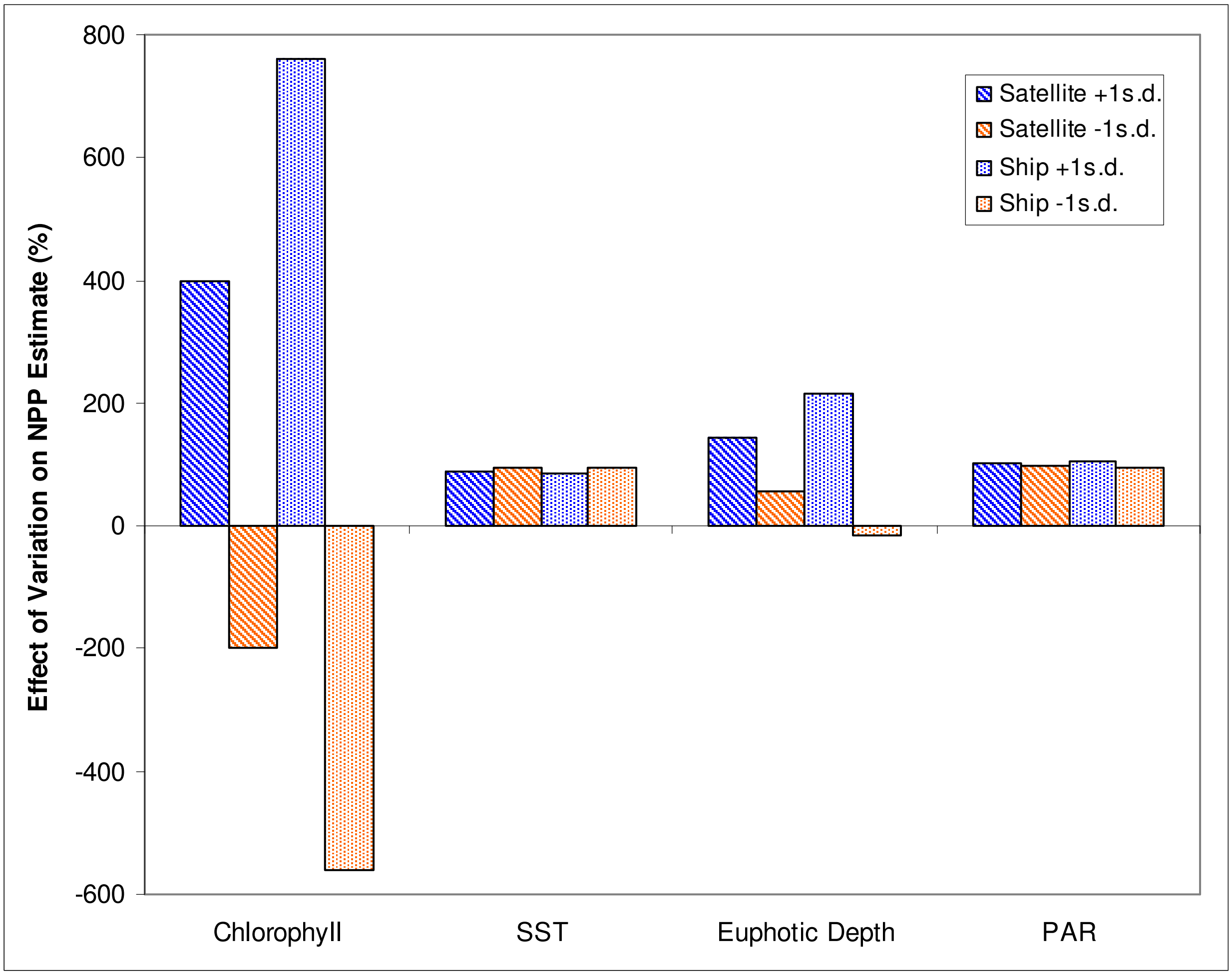

800
600
400
200
0
-200
-400
-600
Effect of Variation on NPP Estimate (%)
Satellite +1s.d.
Satellite -1s.d.
Ship +1s.d.
Ship -1s.d.
Chlorophyll
SST
Euphotic Depth
PAR

Fig. 11

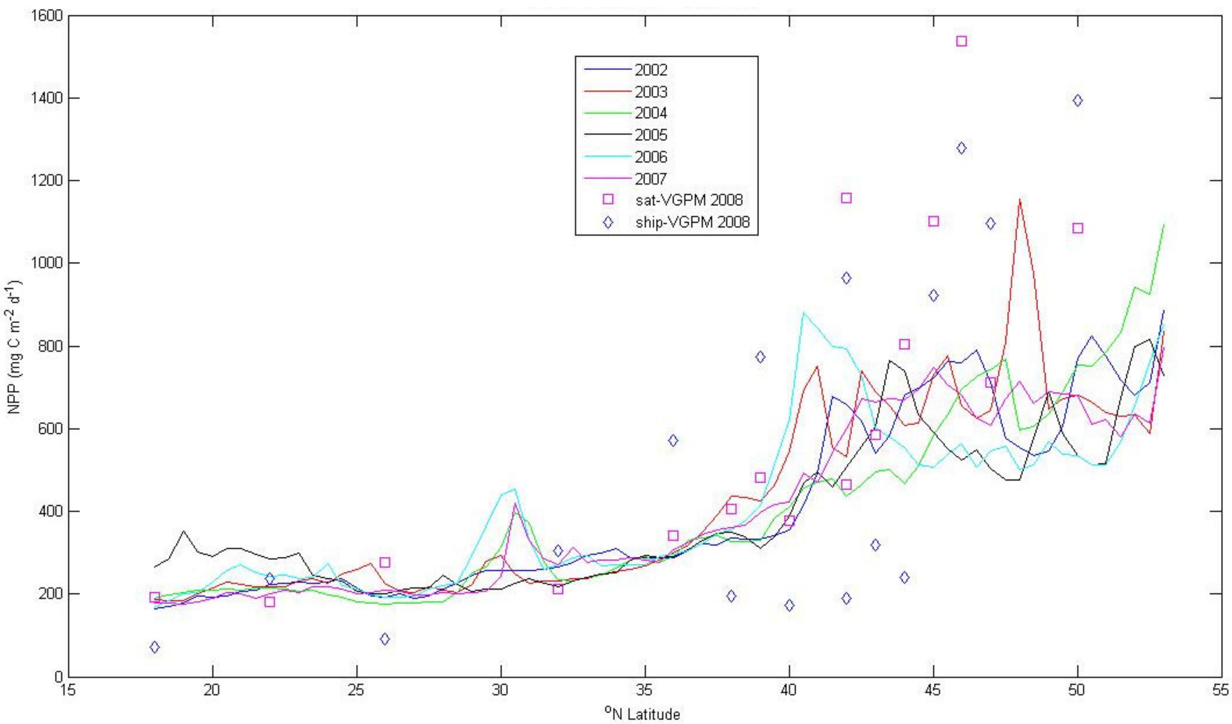
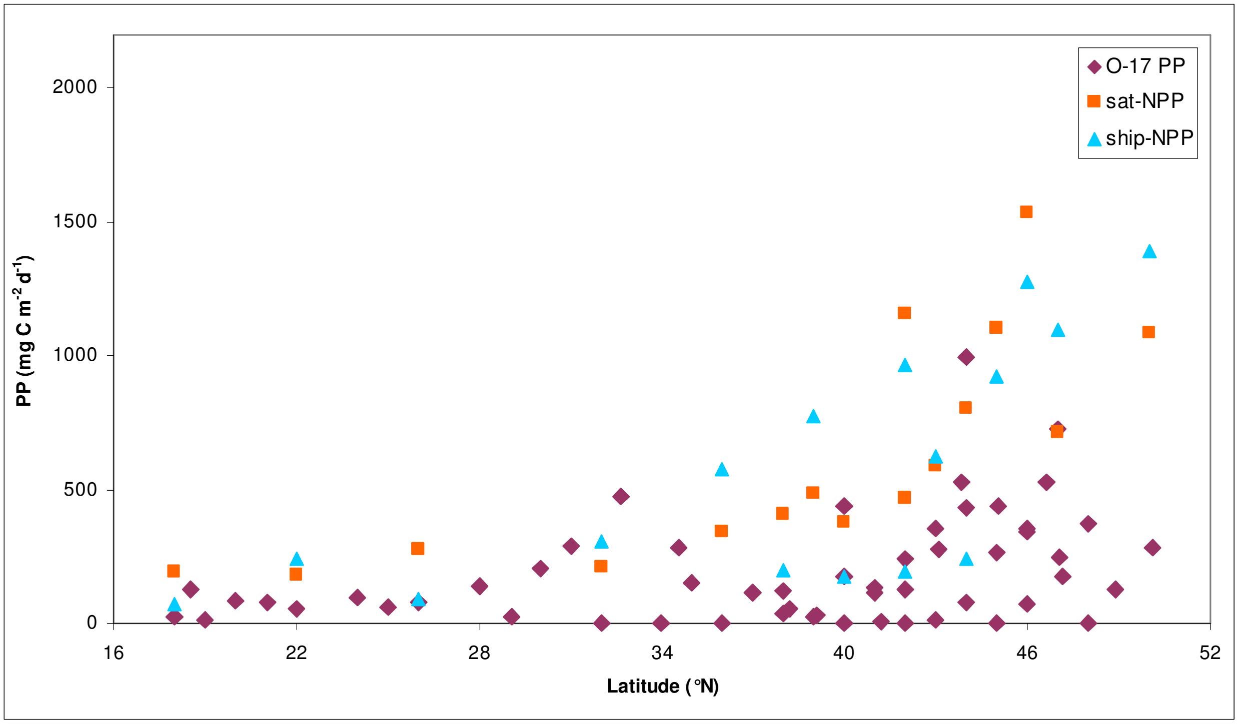

1600
1400
1200
1000
800
600
400
200
0
NPP (mg C m-2 d-1)
15
20
25
30
35
40
45
50
55
oN Latitude
2002
2003
2004
2005
2006
2007
sat-VGPM 2008
ship-VGPM 2008

Fig. 12


O-17 PP
sat-NPP
ship-NPP
2000
1500
1000
500
0
PP (mg C m^{-2} d^{-1})
16
22
28
34
40
46
52
Latitude (°N)