Seasonal variability of the surface chlorophyll in the western tropical Pacific from SeaWiFS data

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Abstract

We used Sea-viewing Wide Field-of-view Sensor (SeaWiFS) to document the seasonal cycle of surface chlorophyll in the western tropical Pacific. Surface waters in this region can be divided into two ecosystems. The western end of the cold, salty waters of the cold tongue with high nutrient low chlorophyll (HNLC) characteristics occupies most of the eastern part of the region, while warm, fresh, and oligotrophic waters of the warm pool stand in the western part. Nevertheless, disruption of the oligotrophy may show up at different locations. We reconstructed the seasonal cycle of chlorophyll, sea surface temperature (SST), winds, and surface currents from satellite data and satellite-derived products by extracting the annual and semi-annual harmonics of the time series at each grid point. The calculation was done for the 1999–2004 years in order to exclude the consequences of the major 1997–1998 El Niño Southern Oscillation event. The variance explained by the seasonal cycle for this period highlights three regions with high seasonality: (1) The oligotrophy/HNLC transition zone undergoes meridional seasonal displacements. The cold tongue is at its northernmost (southernmost) position during boreal spring (fall). These displacements can be explained in terms of meridional advection of chlorophyll-rich waters and are consistent with the seasonal cycle of the north and south equatorial countercurrents that transport phytoplankton-poor waters. (2) Ocean-color images show seasonal enrichments in the far western north equatorial countercurrent (NECC) area, especially during boreal spring. The chlorophyll maximum coincides with the maximum NECC velocity, follows a SST minimum, and occurs during the upwelling-favorable phase of the wind stress curl. We attribute these enrichments to local upwelling associated with current meandering, horizontal advection from further west, and transport of nutrient-rich waters by the New Guinea coastal undercurrent. (3) Near the Solomon Archipelago, we observe enhancements of chlorophyll concentration southwest of the islands in austral winter, when both the southwestward surface currents and the southeasterly wind stress are strongest. This may be a combination of an island-mass effect and wind-driven upwelling. Horizontal advection from the Solomon area leads to an almost concurrent seasonal chlorophyll enrichment in the northern Coral Sea. In the Gulf of Papua, high chlorophyll concentrations at the same time can be explained by the presence of a strong cyclonic circulation. This study highlights the richness of the response of surface chlorophyll to physical processes at the seasonal time scale in a region usually acknowledged as oligotrophic.

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1. Introduction

The Pacific warm pool region has been investigated in numerous studies because of its significant role during the early stages of El Niño events and therefore its impact on the world climate. Because the knowledge of air–sea fluxes is critical in this region, Siegel et al. (1995) stressed that changes in phytoplankton concentration could induce variations of the heat content of the warm pool. In another field of research, abundant tuna catches in such an oligotrophic environment (Lehodey et al., 1997) motivated these studies. The ecosystem of the western tropical Pacific is mostly oligotrophic and is often likened to that of the warm pool alone. Actually, it is a complex region, in terms of both biology and dynamics (Fine et al., 1994). At least two ecosystems coexist: mesotrophic waters of the cold tongue in the east are surrounded by oligotrophic waters of the warm pool to the west and subtropical gyres poleward. These mesotrophic waters are cold and salty and have high nutrient low chlorophyll (HNLC) properties. Grazing and rapid exhaustion of iron lead to unused nitrate upwelled from the equatorial divergence, and to relatively low chlorophyll concentrations in the euphotic layer (Price et al., 1994; Landry et al., 1997), typically of the order of 0.2 mg m$^{-3}$. In contrast, the warm pool is characterized by sea-surface temperature (SST) higher than 29 °C, low surface salinity and oligotrophic conditions (exhausted surface nitrate and very low chlorophyll concentrations, less than 0.1 mg m$^{-3}$). The nitracline and a deep chlorophyll maximum are associated with the thermocline depth, around 100 m (Mackey et al., 1995). Primary production is controlled primarily by the availability of nitrate, but iron may be limiting too (Christian et al., 2002b).

Time scales of biological variability have been seldom studied in this region, probably because of a lack of comprehensive biogeochemical data sets. Yet, in situ observations of surface chlorophyll at different time scales are reported in a few studies. At the intraseasonal time scale, Siegel et al. (1995) showed that chlorophyll concentration in the surface layer could triple following a westerly wind burst. Transient nitrate or chlorophyll enrichments in the surface layer were observed at 10°S during repeated cruises along 165°E (Radenac and Rodier, 1996). A statistical analysis of surface chlorophyll measurements gathered during a ship-of-opportunity program (Dandonneau, 1992) showed an uncertain seasonal cycle along the western track north and south of the equator. Most of all, the interannual variability was emphasized: increase of new production in the warm pool during El Niño; and westward extent of chlorophyll-rich waters along the equator during La Niña years (Radenac and Rodier, 1996; Murtugudde et al., 1999; Radenac et al., 2001; Turk et al., 2001; Ryan et al., 2002; Le Borgne et al., 2002) as well as high-surface chlorophyll concentrations in the western part of the north equatorial countercurrent (NECC) region (Christian et al., 2004).

Ocean color sensors provide an opportunity to investigate variations of surface chlorophyll on a wide range of spatial and temporal scales. The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (Hooker and McClain, 2000) was launched in September 1997, so we now have 7 years of a continuous high-quality data set of surface chlorophyll concentrations. SeaWiFS imagery reveals chlorophyll-rich zones enclosed in the oligotrophic environment of the western tropical Pacific, which develop from intraseasonal to interannual time scales. The interannual scale, mainly related to the El Niño southern oscillation (ENSO), dominates chlorophyll variability in the tropical Pacific. However, the length of SeaWiFS time series is more appropriate to studying the weaker, but significant, seasonal variability, which is less known. During the 1980–1998 period, El Niño events were “phase-locked” to the seasonal cycle for both biological and physical parameters (Christian et al., 2002a), and getting new insights into the seasonal scale will help to better understand the interannual variability.

In this paper, we focus on the seasonal variability of surface chlorophyll in the western tropical Pacific (20°S–20°N, 120°E–160°W), which we describe and analyze from the SeaWiFS time series. Because nutrient inputs (mainly nitrate and iron) are essentially driven by physical dynamics, our goal is to relate the seasonal chlorophyll signal to the seasonal physical forcing, which is relatively well documented at least along the equator (Reverdin et al., 1994; Delcroix, 1998; Yu and McPhaden, 1999). Using complementary physical data such as sea level anomaly (SLA), temperature, wind and surface currents from other satellite sensors, we examine plausible physical processes responsible for surface chlorophyll changes in regions where the seasonal variability is significant.
2. Methods

2.1. Data

Surface chlorophyll concentrations were estimated from SeaWiFS data (Hooker and McClain, 2000) for the 1999–2004 period. SeaWiFS data have been available since September 1997, but we chose to exclude the 1997 and 1998 El Niño and La Niña years in order to avoid a strong interannual influence. We used Level 3 (9 km) 8-day composites from reprocessing #4, obtained from the Distributed Active Archive Center at NASA Goddard Space Flight Center.

SST data for the same period were derived from the tropical rainfall measuring mission (TRMM) microwave imager (TMI). TMI data are produced by remote sensing systems and are available at www.remss.com, as level 3a, 0.25° x 0.25° weekly maps.

Wind speed, wind stress and wind stress curl data were retrieved from NASA scatterometer SeaWinds, onboard QuickSCAT. We used level-3, 0.5° x 0.5° weekly maps provided by CERSAT, IFREMER. Since QuickSCAT data start on 1999, July 28, only the 2000–2004 years were considered to reconstruct the seasonal cycle.

Near-surface currents were ocean surface current analysis—real time (OSCAR) product, derived from satellite altimeter, scatterometer and SST (Bonjean and Lagerloef, 2002). The surface layer current is the sum of geostrophic and Ekman currents and of a buoyancy term. The mean geostrophic velocity field is derived from the Rio and Hernandez (2004) mean dynamic topography. We used the 5-day unfiltered data on a 1° x 1° grid available on-line at http://www.oscar.noaa.gov. Validations of this product in the western Pacific by direct comparison of OSCAR to drifter data are also available on-line. In particular, as explained in the OSCAR website, currents are obscured by a large eastward bias north of Papua New Guinea. Therefore, we applied a mask in this area.

SLA were TOPEX/Poseidon-ERS2 combined product delivered by Space Oceanography Division, CLS (Ducet et al., 2000). We used weekly data on a 1/3° x 1/3° grid for the 1999–2004 period.

Chlorophyll and physical data were interpolated on the same 1° x 1°, 8-day grid for comparison and calculation purposes. The SeaWiFS degraded product was obtained as follows: first, 0.25° x 0.25° maps were computed from the full-resolution product by using a geometric mean, and then they were smoothed to a 1° x 1° grid by taking the median of each box. SST, winds, surface currents and SLA fields were binned onto a 1° x 1° grid when needed, and fitted to 8-day SeaWiFS temporal intervals by linear interpolation.

2.2. Reconstruction of the seasonal cycle

The seasonal cycles of the different parameters were determined by a Fourier analysis, which requires that no gap remains in the temporal series. First of all, for each time series, data that were more than five standard deviations away from the mean were considered as false and treated as missing. Missing data were then spatially interpolated by an iterative method: gaps were filled by taking the weighted average of the first neighbors, if they existed. Applying once this method for the 1° x 1° products was enough to fill the gaps due to scattered clouds; if the gaps remaining in the time series were less than 1 month long, they were filled by a temporal linear interpolation. Otherwise, the corresponding pixel was considered as missing.

We performed a fast Fourier transform (FFT) to each resulting time series from January 1999 to December 2004 after removing its linear trend. Fourier power spectra (not shown) show that the annual and semi-annual harmonics are the main components of the seasonal cycle, and that the seasonal cycle, even if weaker than the interannual signal, is not negligible. Then an inverse FFT was performed on the corresponding Fourier coefficients in order to reconstruct the seasonal variations (typical year) for each parameter.

3. Seasonal variability of the surface chlorophyll

We define the variance explained by the seasonal cycle as the ratio of seasonal to total variance. The corresponding map for the 1° x 1° chlorophyll product on the 1999–2004 period (Fig. 1) reveals great disparities in the relative importance of the seasonal scale. In particular, three regions with seasonal variability higher than 30% are emphasized. The first region includes the meridional transition zones between the oligotrophic and HNLC ecosystems. The seasonal cycle accounts for 35% to 55% at the northern boundary and more than 30% at the southern boundary. The second region is the nascent NECC meanders (35%), and the third covers the South Solomon Sea and North...
Coral Sea (45%). Note that degrading the SeaWiFS data resolution to 1° × 1° enhances the contribution of the seasonal cycle. Nevertheless, the same patterns emerge from calculation using the full-resolution product, and the variance explained by the seasonal cycle remains greater than 25% in these three regions.

This map showing the importance of the seasonal scale in SeaWiFS chlorophyll signal mirrors the map of the relative contribution of the interannual variations presented by Dandonneau et al. (2004). Significant seasonal variations occur in regions with low to moderate interannual variations. Nevertheless, as we will see later, seasonal variations observed in these regions can be modulated by interannual variations.

The seasonal evolution of surface chlorophyll in the western Pacific is summarized in Fig. 2. The two ecosystems (mesotrophic and oligotrophic) are clearly visible. In the following, we will choose the 0.1 mg m⁻³ chlorophyll isoline as a boundary, and by extension, the “warm pool” (“cold tongue”) will refer to the oligotrophic (HNLC) ecosystem as well as to the dynamical region. Mesotrophic waters of the cold tongue are surrounded by oligotrophic waters of the warm pool to the west and by the northern and southern subtropical gyres. In January (Fig. 2a), the cold tongue is located east of 160°E in the 10°N–10°S latitude band and matches the extension of the westward south equatorial current (SEC). Very oligotrophic waters are observed in the northwestern part of the southern subtropical gyre as in McClain et al. (2004). During the very first part of the year, the cold tongue shifts northward and westward, as far west as 155°E in April (Fig. 2b), and remains circumscribed within the SEC area. A seasonal enrichment occurs in the nascent NECC meanders in early boreal spring. From April to August, the SEC weakens or reverses to an eastward current, while mesotrophic waters retire to 170°E. At the same time, chlorophyll concentration increases southwest of the Solomon Islands (Fig. 2c). During the last part of the year (Fig. 2d), the cold tongue shifts southward and again westward when the NECC and SEC are maximal. At that time, the oligotrophic southern
subtropical gyre reaches its southernmost extension (McClain et al., 2004). This rapid description shows that the seasonal variability of SeaWiFS chlorophyll appears to be strongly related to that of surface currents.

The seasonal cycle of the main tropical surface currents is in agreement with what is found in the literature (Reverdin et al., 1994; Donguy and Meyers, 1996; Johnson et al., 2002; Bonjean and Lagerloef, 2002; Chen and Qiu, 2004). North of 10°N, the westward north equatorial current (NEC) shows a weak maximum in boreal winter. To the south, the eastward NECC is maximum between October and January and minimum during boreal spring, except in its very western part, where it is strong from fall to spring. This seasonal phasing is consistent with that of NECC derived from expendable bathythermograph (XBT) data by Donguy and Meyers (1996) or modeled by Masumoto and Yamagata (1991). The weak eastward south equatorial countercurrent (SECC) around 10°S is maximum from January to April. The branch of westward SEC that flows between the NECC and SECC peaks during boreal winter (>0.5 m s\(^{-1}\)), weakens or reverses to an eastward current from May to July, and accelerates again in summer. This seasonal reversal is timely with the one observed at the 170°W equatorial Tropical Atmosphere Ocean/Triangle Trans-Ocean buoy Network (TAO/TRITON) mooring (Yu and McPhaden, 1999), but its amplitude is higher. The seasonal cycle of surface chlorophyll and currents will be detailed for each of the three regional studies.

4. The oligotrophy-HNLC transition zone

4.1. Results

Variations of the cold tongue westward expansion along the equator are mainly interannual. In particular, chlorophyll-rich surface waters have been observed in the western equatorial Pacific basin during La Niña years, especially during the long-lasting La Niña period between 1999 and 2001 (Radenac and Rodier, 1996; Murakami et al., 2000; Radenac et al., 2001; Ryan et al., 2002; Le Borgne et al., 2002). Therefore, this westward extension of
the cold tongue may be specific to the period we study.
In this section, we focus on seasonal meridional displacements of chlorophyll-rich waters. To the north, the region of shift is situated between the countercurrent trough and the equatorial ridge, where the eastward NECC flows (Wyrtki, 1974), and its displacement is annual (Fig. 3a). The northernmost position (12°N) of the 0.1 mg m⁻³ chlorophyll isoline is reached in June, just before the NECC return (Fig. 3b). Two months later, the chlorophyll front suddenly shifts southward. The NECC reaches its maximum speed in October (>0.4 m s⁻¹), when the chlorophyll front gets closest to the equator (5°N–6°N). Then the NECC decreases and disappears in March, while the cold tongue shifts northward.

To the south, meridional displacements of chlorophyll-rich waters are more intricate, only 2° broad with a bimodal variation and a weaker amplitude (Fig. 3a). The front is located around 7°S–8°S in April–May and 10°S in austral winter. The equatorward retreat of the front is slower with two phases: a 1° retreat in October and another one in March. The SECC appears in September around 10°S (Fig. 3b) and is present along the southern boundary until February; then it shifts poleward in March. Its zonal velocity remains weak (<0.1 m s⁻¹).

In these regions of surface chlorophyll gradients, horizontal advection is a likely candidate to explain observed chlorophyll changes. More precisely, the chlorophyll itself cannot be advected because phytoplankton lifetime is too short (because of division and grazing), so it is rather advection of water masses and as such of phytoplankton growth-favorable conditions. In the following, we will refer to “advection of water masses characteristics favorable to phytoplankton growth” when speaking about “chlorophyll advection”. We assess the contribution of horizontal advection to the surface chlorophyll temporal variations (∂[Chl]/∂t) along the north and south boundaries, by calculating the zonal (−u∂[Chl]/∂x) and meridional (−v∂[Chl]/∂y) advection of chlorophyll in the N (170°W–160°W, 6°N–8°N) and S (170°W–160°W, 9°S–11°S) boxes (Fig. 4). Positive (negative) chlorophyll changes occur when mesotrophic waters spread poleward (equatorward).

In the N box (Fig. 4a), the seasonal horizontal advection of chlorophyll follows the general tendency of chlorophyll changes. Meridional advection drives the horizontal advection of chlorophyll-rich waters from December to June, when the cold tongue spreads northward. Eastward advection of poor waters by the NECC is more important in
July–November during the abrupt southward retreat of mesotrophic waters. In the S box (Fig. 4b), horizontal advection is essentially driven by meridional advection and presents a strong maximum in August. The contribution of zonal advection almost counterbalances that of meridional advection when the SECC transports chlorophyll-poor waters from the west between November and February.

4.2. Discussion

In N and S boxes, horizontal advection does not totally explain the local temporal changes of chlorophyll, although their evolutions are similar. In particular, horizontal advection lags chlorophyll changes, which are smaller than expected from horizontal advection. One reason for that discrepancy is the accuracy of the estimated surface currents. Along the northern boundary, the satellite-derived NECC is underestimated (Bonjean and Lagerloef, 2002), leading to an underestimation of the eastward advection of chlorophyll-poor waters during boreal fall and winter. Besides, poleward surface velocity is overestimated in both regions (see Bonjean and Lagerloef, 2002; their Figs. 3 and 4): a few cm s$^{-1}$ in the 7°N–9°N latitude band, and about 5 cm s$^{-1}$ south of 5°S. Hence, another possible explanation could be an overestimation of meridional advection. This is consistent with the fact that the difference between local chlorophyll changes and horizontal advection is higher in the south than in the north. A stronger NECC and smaller poleward advection would increase the eastward advection of chlorophyll-poor waters by countercurrents, and would contribute to bringing horizontal advection closer to chlorophyll changes. Another reason is that vertical and biological processes are not considered even though they definitely contribute to the chlorophyll budget.

This study highlights the roles of meridional and zonal advections. Ekman drift is the dominant component at these latitudes (Bonjean and Lagerloef, 2002; their Fig. 4). A schematic scenario of the mechanisms at work along the northern boundary of chlorophyll-rich waters would be as follows. The southernmost position of the oligotrophy/mesotrophy limit happens in October shortly after the minimum northward velocity (Fig. 3c) and is consistent with a minimum Ekman transport in boreal fall as found by Wyrkki (1981). From November to March, northward advection of chlorophyll-rich waters from the equatorial region drives the chlorophyll increase. Until June, the same mechanism persists, lessened by vertical or
biological processes. Then a chlorophyll concentration drop starts in June and leads to a rapid southward shift of the oligotrophy/mesotrophy limit. It coincides with decreasing northward Ekman transport and the return of the NECC, which transports chlorophyll-poor waters from the west.

In the south, the limit is closest to the equator in April–May, when the southward component of the surface current is weak. Then, the Ekman drift increases during austral winter (as in Wyrtki, 1981) and conveys chlorophyll-rich waters that reach their southernmost expansion in September. The northward retreat of the boundary starts in October, when the SECC appears and carries chlorophyll-poor waters from the west, and continues when the southward velocity diminishes in March–April.

5. The western NECC area

5.1. Results

Chlorophyll blooms in the far western part of the NECC have been observed several times with SeaWiFS imagery, especially from February to June 1998 and during spring 2003. Christian et al. (2004) described the 1998 bloom and associated its intensity with the 1997–1998 El Niño event. They also reported chlorophyll enrichments in this region during other SeaWiFS years. The seasonal cycle explains more than 35% of surface chlorophyll variability for the 1999–2004 period around 5°N–9°N, 135°E–160°E, where the NECC emerges and meanders (Fig. 1). However, to avoid a possible influence of the cold tongue in the eastern part of this region, we restrict our study to the nascent NECC meanders region (NECC box, 135°E–149°E, 5°N–9°N).

The complex circulation of this region is detailed in Lukas et al. (1991), Fine et al. (1994, their Fig. 1a), and Christian et al. (2004). It is characterized by the presence of a cyclonic circulation, the Mindanao Dome (Masumoto and Yamagata, 1991), constituted of the westward NEC, southward Mindanao Current, eastward NECC, and a northward recirculation into the NEC. The NECC is also fed from the south by the shallow New Guinea Coastal Current (NGCC) and possibly by the subsurface New Guinea Coastal Undercurrent (NGCUC).

In the far western Pacific, the seasonal variations of the NECC closely follow that of the Mindanao Dome, which develops in late fall through spring and weak during boreal summer. These results are in agreement with direct current measurements (Kashino et al., 1999), model results (Masumoto and Yamagata, 1991), analytical study (Arruda and Nof, 2003) and geostrophic computation (Donguy and Meyers, 1996). The NECC meanders are visible in OSCAR data and also in the reconstructed seasonal cycle of surface currents in winter and spring (Fig. 5). However, their intensity is lesser in the reconstructed seasonal cycle than in surface current raw data because the extraction of seasonal components tends to smooth patterns. In ocean color images as well as in the reconstructed seasonal cycle (Fig. 5), NECC meanders appear as a high-chlorophyll ribbon (Christian et al., 2004), south of the very oligotrophic waters of the Mindanao Dome. In the reconstructed year, chlorophyll meanders appear at the end of the year, reach their greater extent in early spring and vanish in summer (Fig. 2).

Highest seasonal chlorophyll concentrations (0.09 mg m\(^{-3}\); Fig. 6a) are associated with high NECC velocity (0.35 m s\(^{-1}\); Fig. 6c) and low SST (28.8 °C; Fig. 6b). The seasonal cycle of wind stress curl (Fig. 6d), in agreement with the climatological field (Qiu and Lukas, 1996), precedes that of surface chlorophyll concentration by about 1 month. This phasing is consistent with a regional uplift of cold and nutrient-rich waters in boreal winter and a deepening of the thermocline and nutrient pool in summer and fall. Yet, it does not explain the confinement of high-chlorophyll waters to the NECC meanders.

5.2. Discussion

Christian et al. (2004) reviewed three processes that could contribute to the chlorophyll enrichment in the NECC meanders in 1998: local upwelling associated with current meandering, presence of nutrient-rich waters south of the NECC in the NGCUC, and advection of phytoplankton from the west. On a seasonal scale, these mechanisms remain suitable.

The upper part of the NGCUC carries the high-salinity South Pacific tropical waters (SPTW) with relatively high nutrient concentrations. Their northern limit matches the NECC axis (Kashino et al., 1996), and these authors propose that the NGCUC
is linked to the NECC. Such a pathway is confirmed by the Christian et al. (2004) model, which simulates a westward NGCUC transport in winter, and is consistent with the results of Ueki et al. (2003), who estimate a maximum northwestward transport in fall. Iron concentration in the NGCUC is relatively high and increases as the current flows northwestward along the coast of New Guinea (Mackey et al., 2002). Part of this water may transport iron as well as other nutrients to the NECC region. Therefore, the NGCUC possibly feeds the southern part of the NECC and strengthens the meridional front between nutrient-rich SPTW and nutrient-poor waters to the north.

The regional thermocline and nutrient pool are shallow in boreal winter because of the upwelling-favorable wind stress curl. Wang et al. (2000) mention an annual rise of the thermocline of more than 20 m in this region, with the shallowest depth in December–January. At that time, the NECC strengthens, and local upwelling associated with the meanders would be more efficient. Convergence and divergence alternate alongstream meanders (Bower, 1989; Flierl and Davies, 1993; Yoshimori, 1994). Upwelling on the anticyclonic side of meanders (Bower, 1989) would increase the biological production. Enrichment along the northward branch of meanders, as expected from the theory, is not clearly visible in satellite-derived chlorophyll images because of local horizontal advection, biological growth and loss processes. Nevertheless, alongstream discontinuity of chlorophyll in SeaWiFS images (Fig. 5a) suggests that local upwelling contributes to the formation and persistence of chlorophyll meanders. The study of water-leaving radiances at 412 nm (Christian et al., 2004; their Fig. 2) confirms that local upwelling effectively occurred, at least during the 1998 bloom. However, local upwelling alone cannot explain everything, especially remarkably high chlorophyll concentrations observed during the 1998 bloom. If the only involved mechanism was local upwelling, this could
be due: (1) to a stronger upwelling because of increased NECC speed, which did not seem to occur at the beginning of 1998 (Fig. 7b); (2) to a more efficient upwelling because of a shallow nutricline, but to a lesser extent, the nutricline is shallow during the 2002–03 El Niño too, whereas the bloom is not much stronger than usual (Fig. 7a).

Another possible explanation is horizontal advection of phytoplankton from the west. Several SeaWiFS images show northward intrusion of chlorophyll-rich waters from the Molucca Strait or from the Halmahera Sea, and at the seasonal scale they seem to originate from a region between Mindanao and Halmahera. This is in agreement with an overall northward transport simulated by Wannasingha et al. (2003) in the Molucca Strait and highly variable transport from the Halmahera Sea. In this region, chlorophyll concentrations are almost always higher than 0.1 mg m$^{-3}$. So, northward and eastward advection of phytoplankton-rich waters may contribute to the generation of the chlorophyll enrichment in the NECC, just as lateral advection of cold water from the west cools this region in winter (Masumoto and Yamagata, 1991). Study of single events supports this hypothesis: for instance, two peaks of high chlorophyll concentration (>0.35 mg m$^{-3}$ on average) occurred near Halmahera, on January 25 and March 3, 1998 (not shown). Two weeks later, similar peaks were observed in the NECC box (Fig. 7a). Timing of the bloom propagation as seen in SeaWiFS images (around 2–3° per week, not shown) is consistent with the speed of the NECC core (around 0.35 m s$^{-1}$ i.e. 210 km per week) at that time. More generally, when the averaged chlorophyll concentration near Halmahera exceeds 0.3 mg m$^{-3}$ (Fig. 7, dots), a chlorophyll peak is observed in the NECC box. Christian et al. (2004) did not retain the advection hypothesis, because of local chlorophyll maxima in the NECC meanders and because a monotonic decrease is expected in case of horizontal advection. Horizontal advection cannot explain alone the whole chlorophyll ribbon, which is around 2000 km long: at a surface velocity of 0.4 m s$^{-1}$, the transport time scale is about 60 days. So at a loss rate of 0.05 d$^{-1}$, if the initial concentration is 1 mg m$^{-3}$, no chlorophyll remains in the NECC after 20 days, which means that local upwelling is necessary to sustain the chlorophyll ribbon.

Nevertheless, eastward advection of chlorophyll-rich waters probably contributes to the generation of the NECC enrichment, acts as a “background process” during its existence, and finally drives the chlorophyll decrease. Local meander-induced upwelling is efficient to sustain the high chlorophyll pattern because the nutrient pool is shallow and
enriched by a high transport of macro- and micro-nutrients from the NGCUC at that time of the year. These seasonal variations can then be modulated by interannual influence such as El Niño events or high chlorophyll concentrations upstream.

6. The Solomon Islands and North Coral Sea zone

6.1. Results

The seasonal cycle represents more than 45% of the surface chlorophyll variance in a large area spanning the southern Solomon and northern Coral Seas (Fig. 1). This region, enclosed between Australia and Papua New Guinea coasts to the west, and an arc of islands to the east, is under the combined influences of monsoon and trade winds. Southeasterly trade winds that dominate the seasonal cycle are strongest during austral winter. At that time, the wind stress curl is strongly negative (upwelling favorable) over the Solomon Archipelago and much less upwelling favorable in the Coral Sea (Kessler and Taft, 1987). The surface large-scale current is southwestward (Fig. 2). At the beginning of austral summer, the warm pool reaches its southernmost extension (Wyrtki, 1989), and strong precipitation occurs during the 3 months of northwest monsoon (Vincent, 1994). Trade winds are replaced by northwest winds. A band of strong cyclonic wind stress curl extends eastward from the Gulf of Papua while it is weakly negative close to the Solomon Islands (Kessler and Taft, 1987).

Surface chlorophyll concentration increases between May and September in the region spanning the southern Solomon and northern Coral Seas (Fig. 2). We consider separately three sub-regions (Fig. 8): the region southwest of the Solomon Islands (SW box: 156°E–158°E, 11°S–9°S), the North Coral Sea (NCS box: 152°E–161°E, 15°S–12°S), and the Gulf of Papua (GP box: 146°E–149°E, 14°S–12°S). Although seasonal cycles of surface chlorophyll are in phase, different processes are involved to explain them.

Highest chlorophyll concentrations are observed southwest of Solomon Archipelago in austral winter (Fig. 8). In the following, the region southwest of
the islands (SW box) is compared to that east of the islands (E box, 162°E–164°E, 9°S–7°S), where the seasonal component of surface chlorophyll variability is weak (Fig. 1). Note that at the time of SW enrichment, conditions in E box are representative of the entire upstream zone (Fig. 8). Southwest of the islands, chlorophyll is at a background value of 0.10 mg m\(^{-3}\) during austral summer and reaches 0.20 mg m\(^{-3}\) in winter (Fig. 9a), whereas no noticeable seasonal enrichment is observed in E box. Seasonal cycles of chlorophyll are almost out of phase southwest and east of the islands. SLA is minimum in August and maximum in April–May in both boxes (Fig. 9d), and the amplitude of the seasonal signal reaches about 13 cm. Southeasterly trade winds are strongest in July–August (Fig. 9c), driving strong offshore Ekman transport southwest of the islands at the time of the chlorophyll maximum, while it inhibits upwelling on the northern side of the islands. The seasonal chlorophyll maximum southwest of the islands occurs in July–August, when the perpendicular component
of the surface current \( (u_\perp) \) flows southwestward (Fig. 9b), almost exactly when the perpendicular incident current \( (u_\perp in E \text{ box}) \) is the strongest. Note that the highest incident current speed \( (\|\hat{u}_\perp + \hat{u}_\parallel\|) \); Fig. 2) is reached in austral summer (near 0.16 m s\(^{-1}\) eastward in the SW box), whereas it remains weaker in austral winter (near 0.12 m s\(^{-1}\) southwestward in the E box). This point will be discussed further in Section 6.2.3.

Therefore, the seasonal chlorophyll enrichment observed southwest of the Solomon Islands could be the result of a wind-driven coastal upwelling amplified by an “island mass effect” (after Doty and Ogury, 1956), defined as an increase of chlorophyll concentration and phytoplankton productivity downstream of an oceanic island. This well-documented phenomenon was observed and studied in the wake of several islands such as Hawaii (Doty and Ogury, 1956; Flament, 1994), Gran Canaria (Aristegui et al., 1997; Barton et al., 2000), the Marquesas Islands (Signorini et al., 1999), and the Galapagos Archipelago (Palacios, 2002). The possible occurrence of an island mass effect in this region is discussed below.

In the NCS, strongest values are reached in winter \( (0.15 \text{ mg m}^{-3}) \), whereas very oligotrophic values are observed in February–March (less than 0.07 mg m\(^{-3}\)) (Figs. 2, 8). This region has strong oligotrophic characteristics (Furnas and Mitchell, 1996), and surface chlorophyll increase can be the result of horizontal advection. In the NCS box and between the Solomon Archipelago and Vanuatu, we obtain the highest correlation (higher than 0.4 locally) between horizontal advection and temporal changes of chlorophyll concentration for the 1999–2004 period (not shown), whereas no correlation exists in the SW box. From March to August, meridional advection (Fig. 10b) explains the chlorophyll increase observed in the North Coral Sea (Fig. 10a): surface currents north of the NCS box gradually rotate from eastward to southwestward and advect chlorophyll-rich waters from the enriched area south of the Solomon Islands. Then southward advection of chlorophyll-rich waters weakens (Fig. 10b), and the chlorophyll decrease in the NCS box may be the result of biological loss processes.

The surface chlorophyll seasonal cycle in the Gulf of Papua leads that in the North Coral Sea by 1 month (not shown): highest values \( (0.15 \text{ mg m}^{-3}) \) are reached in austral winter, whereas spring–summer values remain lower than 0.08 mg m\(^{-3}\). This seasonal phasing is consistent with cruise measurements presented by Furnas and Mitchell (1996), who also show a 20 m deepening of the nutricline from austral winter to spring. In this
region, in a two-layer system, the ratio between thermocline depth variation and SLA is about 200 (Rébert et al., 1985): a 20 m thermocline deepening would represent a 10 cm SLA rise. Although weaker (6 cm increase between August and December), the seasonal SLA signal is consistent with Furnas and Mitchell (1996) cruise measurements. The nutricline remains deep all year long, between 80 m and 100 m (Furnas and Mitchell, 1996), but while it matches the mixed layer depth in austral winter, it is 20 m deeper in austral summer. One reason could be strong summer stratification because of intense precipitation (Vincent, 1994; Yuan and Miller, 2002). The Gulf of Papua is characterized by a cyclonic circulation (Andrews and Clegg, 1989), with a maximum surface signature from April to August as calculated from surface current vorticity (not shown, see also Fig. 8). Therefore, surface chlorophyll is maximum in austral winter when the subsurface nutrient pool is shallowest (minimum SLA) and the cyclonic circulation is strongest (minimum current vorticity): high-surface chlorophyll values would be the result of favorable eddy pumping (McGillicuddy et al., 1998) and vertical mixing. In summer, these vertical processes become inefficient because of the cyclonic circulation weakening and nutrient pool deepening. SeaWiFS images sometimes show chlorophyll-rich filaments originating from Australia and New Guinea coasts and feeding the bloom in the Gulf of Papua in austral
winter. So horizontal advection of phytoplankton-rich or turbid waters from the coast probably enhances the chlorophyll signal (caution is required because turbid waters may induce artefacts in the SeaWiFS signal).

6.2. Discussion

Processes that drive the evolution of ocean color signal in the Gulf of Papua seem to be local and disconnected from those that prevail in the south Solomon Sea, whereas chlorophyll concentration in the North Coral Sea is seasonally influenced by the evolution of chlorophyll northward. Thus, here we focus on the possible mechanisms at work south of the Solomon Islands (SW box).

We attribute chlorophyll seasonal enrichments in the wake of Solomon Islands to a wind-driven upwelling and to an island mass effect, characterized by chlorophyll increase downstream of oceanic islands. In the case of isolated, deep ocean islands, several mechanisms can drive an island mass effect. The main ones are: (1) nutrient input from land drainage (Dandonneau and Charpy, 1985; Signorini et al., 1999); and (2) nutrient pumping and vertical uplifting of the deep chlorophyll maximum by lee cyclonic eddies, which are formed by flow disturbance or Ekman pumping (Heywood et al., 1990, 1996; Aristegui et al., 1997; Coutis and Middleton, 1999, 2002). The nature and strength of these eddies depend in turn on several factors, such as incident current speed, latitude and coastal geometry (Coutis and Middleton, 2002).

6.2.1. Context

The Solomon Islands Archipelago consists of a double chain of volcanic islands, mostly mountainous. The six main islands extend up to a length of about 200 km. Land drops steeply down into the sea, deeper than 4000 m southwest of the islands, whereas channels between the islands are often less than 100 m deep. The surface layer of the Coral Sea is nutrient-depleted (Mackey et al., 1987; Moutin et al., 2005). The lack of data prevents us from assessing the importance of land drainage in winter chlorophyll increase. However, island runoff is likely to occur in the Solomon Archipelago and to fertilize neighboring waters, mostly during strong precipitation of summer monsoon (Vincent, 1994; Yuan and Miller, 2002). Natural resources of Solomon Islands include phosphate (US Central Intelligence Agency, 2005), which is the major limiting nutrient in this region for Trichodesmium (Moutin et al., 2005). These nitrogen-fixing cyanobacteria contribute to the SeaWiFS chlorophyll concentration (Dupouy et al., 2000). Trichodesmium blooms occur during summer in stratified water (Moutin et al., 2005) coinciding with the supposed strongest land drainage. Dupouy et al. (2004) attributed the SeaWiFS chlorophyll winter bloom south of 5°S to seasonal cooling and claimed that even if Trichodesmium is present all year long in this region, it peaks only in austral summer. As such, Trichodesmium is not responsible for the seasonal chlorophyll increase we observe, so probably very little phosphate is brought to the sea in austral winter, and we assume that island runoff is a minor contributor to the island-mass effect.

In the following, we assess the possibility of upwelling in lee eddies. In order to evaluate the effect of variation of the background rotation, Boyer and Davies (1982) introduced the dimensionless parameter:

\[
\beta = \frac{\beta_0 L^2}{U}
\]

where \(\beta_0 = 2\Omega (\cos \phi_0) / R_E\) is the local change in the Coriolis parameter \((R_E, \Omega)\) the radius and rotation rate of the earth, respectively, and \(\phi_0\) the reference latitude, \(L\) is the characteristic dimension of an island, and \(U\) is the incident current speed. Local variations of the Coriolis parameter can be neglected \((f\text{-plane studies})\) if \(\beta \leq 1\). Otherwise, the \(\beta\)-effect enhances flow separation and increases the extent of the eddy region downstream of the obstacle in the case of westward flow; whereas it induces opposite consequences for eastward flows. So the corresponding impact on primary production is supposed to be stronger in the case of \(\beta\)-plane westward flows. Major enrichments are observed in the wake of New Georgia situated at 8.5°S, near the northern boundary of the SW box (Fig. 8). Its length is about 200 km and the incident speed varies between 0.06 and 0.16 m s\(^{-1}\) at the seasonal scale, so \(\beta\) ranges between 5.7 and 15.1. Essentially because of the size of the island, the \(\beta\)-effect is important. So, during the westward flow period (austral winter), chlorophyll increase downstream of the island is expected to be greater than calculated from the \(f\)-plane theory.

6.2.2. The upwelling mechanisms

Laboratory studies for non-rotating flows have shown that characteristics of the wake past an
obstacle can be predicted from the Reynolds number \( \text{Batchelor, 1967} \), \( Re = UL/\nu \) (\( \nu \) is the horizontal eddy viscosity), which stresses the importance of non-linearity relative to friction. In rotating cases, the numerical study of the island of Aldabra (Heywood et al., 1996) shows that wake regimes downstream of low-latitude islands can be determined according to the same thresholds. For \( \nu = 100 \text{m}^2\text{s}^{-1} \) (Heywood et al., 1990, 1996; Aristegui et al., 1997) and \( U = 0.1 \text{m} \text{s}^{-1} \) (seasonal incident speed in July), \( Re = 200 \), higher than the threshold value of 70, which is about the boundary for eddy shedding in the case of “thick” islands such as New Georgia (Heywood et al., 1996). So, a von Karman vortex street of eddies is expected to occur downstream of each major island of the archipelago. This effect should be enhanced by the \( \beta \)-effect since the zonal incident flow is westward (Boyer and Davies, 1982). Because cyclonic vortices are enhanced compared to anticyclonic ones on a rotating Earth (Boyer and Davies, 1982; Heywood et al., 1996), strong upwelling is expected in lee eddies formed by the flow disturbance. Note that the resolution of the OSCAR product is too low to resolve such eddies, and also that since the archipelago is constituted of several islands, there may be interactions between the different island mass effects that we cannot predict from the theory. However, these possible interactions are beyond the scope of this paper and are not discussed here.

In austral winter, strong southeasterly wind stress, parallel to the islands, induce an offshore Ekman transport southwest of the islands. This transport can be calculated as \( M = \tau_{||}/(\rho f) \) where \( \tau_{||} \) is the parallel wind stress (0.12 Pa in austral winter on a seasonal basis) and \( \rho \) the density of sea water; we obtain \( M = 5.4 \text{m}^2\text{s}^{-1} \). If this whole transport comes from deep waters that are brought upward, the corresponding vertical velocity can be calculated as \( w_z = M/r_o \), where \( r_o \) is a Rossby radius (Allen, 1973). In this region, the 100 km Rossby radius (Chelton et al., 1998) yields a vertical velocity \( w_z = 5.4 \times 10^{-5} \text{m} \text{s}^{-1} \) (4.7 \( \text{m day}^{-1} \)) which is to compare with typical upwelling velocities, around \( 10^{-4} \text{m} \text{s}^{-1} \) (8.6 \( \text{m day}^{-1} \)) along the west coast of North America (Pickett and Paduan, 2003). On a seasonal basis, the Ekman pumping velocity \( (w_E = (\text{curl} \tau)/(\rho f)) \) is \( 5.9 \times 10^{-6} \text{m} \text{s}^{-1} \) (0.51 \( \text{m day}^{-1} \)) in austral winter. Upwelling due to Ekman pumping is one order of magnitude smaller than wind-driven upwelling. Note that this estimation of vertical velocity due to wind-driven upwelling represents an upper limit. Since the Solomon Archipelago is not a continuous coast, horizontal transport through channels may contribute to the wind-driven offshore transport. However, channels between the islands of the eastern chain are less than 100 m deep, whereas surface currents are more than 300 m deep (Mackey et al., 1997). Since the archipelago presents a barrier to surface currents, we can suppose that a large part of the offshore transport comes from upwelling of deep waters.

Other mechanisms may also contribute to chlorophyll enrichments. A careful examination of some SeaWiFS weekly images (e.g. July–August 2000) reveals high chlorophyll concentrations not only in the wake of the major islands, but also between them, and especially downstream of New Georgia, itself constituted by smaller islands separated by shallow channels. Since these channels are very shallow compared to the ocean bottom, vertical flow separation and current acceleration occur between the islands, driving a positive vertical velocity and upwelling downstream of the channels. This would be almost the same mechanism as studied by Hasegawa et al. (2004) about horizontal and vertical flow separation on a shallow sea bed surrounding an island. Finally, in the case of high islands such as the Solomon Archipelago, mountains present obstacles to the trade winds. Wind shear on the flanks of Hawaii (e.g. Flament, 1994) and Gran Canaria (Aristegui et al., 1997; Barton et al., 2000) produces, or at least enhances, oceanic eddies because of perturbation of the wind stress and wind stress curl. In the case of the Solomon Archipelago, trade winds are parallel to the islands’ axis when chlorophyll enrichment takes place. So, the consequences of such a mechanism are unclear and are not investigated here.

6.2.3. Island mass effect at the seasonal scale

Upwelling occurs downstream of Solomon Islands in austral winter, mainly as a combination of upwelling in lee cyclonic eddies formed by the flow disturbance and wind-driven upwelling. The 13-cm amplitude of the SLA seasonal signal (Fig. 8b) represents a 26-m uplift of the thermocline, following Rébert et al. (1985). This uplift probably combines the effects of coastal upwelling driven by southeasterly trade winds, of the “dynamic uplift” downstream of the islands (Heywood et al., 1990), and of the doming of the thermocline in cyclonic vortices. Estimates of seasonal variations of the thermocline depth are consistent with cruise
measurements of the nitracline depth situated around 40 m in July and 70 m in October–November near 10°S (Mackey et al., 1997). In this oligotrophic system, the deep chlorophyll maximum observed between 50 and 80 m is close to the nitracline depth (Dandonneau, 1979; Furnas and Mitchell, 1996). So, in austral winter when the SLA is the lowest (Fig. 9d), nutrients are close to the surface. An efficient upwelling can bring nutrients to the euphotic zone and drive chlorophyll enhancement. Vertical uplift of the deep chlorophyll maximum is also supposed to occur (Aristegui et al., 1997), but the lack of vertical data prevents us from verifying this hypothesis.

We could wonder why chlorophyll increase occurs southwest of the islands in austral winter, when the currents are southwestward (hereafter the winter case), whereas in austral summer stronger eastward currents generate sporadic events but no seasonal enrichment (hereafter the summer case). Actually, the nutrient pool is deeper (Fig. 8d) and the parallel wind stress is weaker in summer (Fig. 8c), so wind-driven upwelling is much less efficient than in winter. Concerning the island mass effect, in winter the incident flow comes from the open ocean and is roughly perpendicular to the archipelago main axis; its maximum seasonal speed is 0.1 m s\(^{-1}\) (Fig. 9b). During the rest of the year, the incident flow comes from the other side of the islands and is embedded in a complex circulation caused by the coastal geometry of Papua New Guinea and the Solomon Islands. In summer, the surface current is almost parallel to the islands in the northern half of the archipelago (Fig. 2) and bifurcates eastward in the southern part: even if the incident current speed reaches 0.16 m s\(^{-1}\), the perpendicular component is only about 0.06 m s\(^{-1}\) (Fig. 9b), so weaker eddies are expected in summer. Moreover, in the case of weak incident currents, the capability of the wake to keep its biomass increases when the surface current speed decreases (Coutis and Middleton, 2002), which means that phytoplankton immediately downstream is more likely to be trapped close to the island in austral winter when the surface current is weaker for a sufficiently long time to respond to the increased availability of nutrients (Coutis and Middleton, 1999). Finally, since eastward flow is less favorable for eddy formation past an obstacle than westward flow (\(\beta\)-effect, Boyer and Davies, 1982), less efficient eddy formation is expected in the summer case.

7. Summary and conclusions

In this paper, we focused on the seasonal cycle of surface chlorophyll in the western tropical Pacific region. Three zones present seasonal variations that account for more than 30% of the 1999–2004 chlorophyll variability: the meridional boundaries of the cold tongue, the western NECC meanders, and the region southwest of the Solomon Islands. In these three areas, the seasonal variability of surface currents appears as a common key factor to explain seasonal evolutions of surface chlorophyll concentration, through horizontal advection, and local upwelling caused primarily by current meandering, cyclonic circulation, wind, or flow disturbance by oceanic islands.

The meridional displacements of the north and south boundaries of the cold tongue can be explained in terms of horizontal advection, linked to the seasonal cycle of the north and south equatorial countercurrents, and of the Ekman transport. Main mechanisms are poleward advection of chlorophyll-rich waters from the equator and eastward advection of chlorophyll-poor waters by the NECC in fall along the northern edge.

In the nascent NECC area, the wind stress curl becomes upwelling-favorable in October and intensifies in boreal winter. At that time, the thermocline is shallow, macro- and micro-nutrient inputs from the NGCUC increase, and the NECC speed is high. So, both horizontal advection and local upwelling associated with current meandering become more efficient and are plausible explanations for the seasonal chlorophyll increase in the NECC meanders.

Southwest of the Solomon Archipelago, chlorophyll concentrations increase in austral winter when the perpendicular component of surface currents and the parallel component of wind stress are strongest. This seasonal enrichment is attributable to an island mass effect (upwelling in cyclonic eddies formed by the flow disturbance) and to a wind-driven upwelling (offshore Ekman transport). In the North Coral Sea, horizontal advection from the Solomon area leads to a seasonal chlorophyll increase, while the cyclonic circulation present at the same time in the Gulf of Papua is responsible for the enrichment observed in the western part of the basin.

For this study, we used satellite data and a satellite-derived current product, which are valuable tools in a region where observations are scarce. We
should nevertheless keep in mind that chlorophyll as seen by ocean color sensors is only a proxy for phytoplankton biomass, since organic materials and other particles can also contribute to this signal. But despite this restriction, ocean color sensors give the best opportunity to study variations of surface chlorophyll on a wide range of spatial and temporal scales, as compared with coupled physical—biogeochemical models, which show some limitations in this very complex region, and with in situ data that remain localized in both time and space. Ocean color-based studies should also help to determine regions of interest, which require to be investigated through an integrated approach coupling multisensor satellite and in situ data with modeling systems.

This satellite study highlights the diversity of the chlorophyll response to physical forcing at the seasonal time scale and in different biological ecosystems. The warm pool, often considered as oligotrophic, exhibits a surface chlorophyll variability that is captured by SeaWiFS. At the seasonal time scale, chlorophyll variability is driven by the physical forcing at first order. SeaWiFS time series are too short to assess the dominant interannual variability except by focusing on specific case studies. As the ocean color time series grow longer, we should have better estimations of chlorophyll variability, from intraseasonal (largely modulated on an interannual time-scale) to interannual. The western tropical Pacific is a very complex region but offers rich possibilities to investigate the influence of a wide range of physical processes on biology, and as such deserves more study.

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