Variability of photosynthetic pigments in the Colombian Pacific Ocean and its relationship with the wind field using ADEOS-I data

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Variability of the oceanographic conditions in the Colombian Pacific Ocean, a part of the Panama Basin, is subjected to the variability of wind conditions in the equatorial part of the Pacific Ocean. Data of OCTS and NSCAT of ADEOS-I satellite provided as monthly averages for the period November 1996 – June 1997 by NASDA, were processed and manipulated. A meridional (N–S) component and a zonal (E–W) component were run in order to analyse the data variability and correlation. It is concluded that the variability of the oceanic surface chlorophyll and SST in the Colombian Pacific is a seasonal event related to the migration of the ITCZ and the generation of a wind jet at the Isthmus of Panama. Upwelling due to the wind rotor is present throughout the whole period, with variable spatial distribution and a tendency to be located towards the eastern part of the basin. In a similar way, high chlorophyll concentrations observed in March coincide with both the intensification of the vertical velocities during that month, and the maximal rise of the thermocline in the northern part of the Panama Basin. Picture series of surface chlorophyll, SST, wind stress and Ekman pumping are provided for the studied area.

1. Introduction

In the eastern tropical Pacific, seasonal upwelling events occur along the central American coast from December through March, associated with the polar anticyclones moving south from northeast Canada. They manifest as wind jets and cross the physiographic gaps of central America existing at the Gulf of Tehuantepec, Gulf of Papagayo and the Isthmus of Panama (Roden 1961). Preliminary studies carried out by Forsbergh (1969) and Ritter and Ruiz (1979) concluded that they largely depend on the position of the Inter-Tropical Convergence (ITCZ), the main trigger of the Gulf's productivity. Using NOAA/AVHRR, Legeckis (1986) studied the seasonal upwelling events occurring in the Panama Basin. He detected a strong upwelling front along the Colombian coast lasting from mid February to the end of March 1985. The upwelling front is characterized by a decrease in SST of at least 9° C. He later (1988) described this event as an apparently ageostrophic reply of the ocean to the wind jet at the Isthmus of Panama, pushing the water off the coast, producing a sea level descent and coastal upwelling which reduced the SST near 10° C in less than 24 hours. As the wind jet is projected beyond the coast, the advected surface water can be additionally cooled by entrainment and surface evaporation. The net result is the formation of long plumes of cold water parallel to the coast, different to those associated with the coastal upwelling (Roden 1961).

Data obtained during the active phase (1978–1986) of the Coastal Zone Color Scanner (CZCS) has allowed the study of seasonal and inter-annual variability of the concentration and distribution of phytoplanktonic pigments in the eastern tropical Pacific (Thomas *et al* 1994; Fiedler 1994;

Keywords. Colombia; Pacific; chlorophyll; wind jet; ADEOS-I.

Proc. Indian Acad. Sci. (Earth Planet. Sci.), **111**, No. 3, September 2002, pp. 227–236

Gaxiola-Castro and Muller-Kargen 1998). The authors, however, pointed out that in the extension of the ITCZ, namely in the Panama Basin and the Colombian Pacific, only sparse valid data are available. In particular, Fiedler (1994) relates the variability of the concentration of phytoplanktonic pigments with wind data stemming from the Comprehensive Ocean Atmosphere Data Set (COADS). This study, unfortunately, could not consider the Colombian Pacific owing to the lack of cloud free satellite data. But, the effect of the wind jet off the Gulf of Panama also seems to affect the Colombian Pacific in a seasonal and inter-annual scale suggesting the generation of areas rich in nutrients and photosynthetic pigments during the time of intensification of the northeast trade winds. This high concentration of pigments disappears at the time of wind relaxation due to the northward migration of the ITCZ. Thus, the wind jet crossing the Gulf of Panama is the most important physical factor controlling the seasonal and inter-annual variability of the concentration of photosynthetic pigments and sea-surface temperature in the Colombian Pacific.

To understand the seasonal dynamics of these events, we used monthly ADEOS-OCTS and ADEOS-NSCAT satellite data for the period November 1996 to June 1997. The ADEOS sensor configuration is advantageous over other satellites because it favors the temporary homogeneity of the data by simultaneously taking SST, chlorophyll and wind. One drawback in our study was the long cloudy coverage of the area related to the displacement of the ITCZ, limiting the use of satellite imagery in the visible spectrum.

2. Materials and methods

2.1 *Study area*

The Pacific Colombian Ocean, belongs to the Panama Bight described as part of the eastern tropical Pacific Ocean delimited by the Isthmus of Panama to the north (around 9°N), the Puntilla de Santa Elena to the south (around 2°S), the coasts of Panama, Colombia and Ecuador and extending to the West to the longitude of 81°W (figure 1).

2.2 *Oceanographic overview of the study area*

The variability of the oceanographic conditions in the Colombian Pacific Basin (CPB) is subject to the variability in wind conditions of the equatorial part of the Pacific Ocean, in turn connected with oscillations of the ITCZ. Cloudiness due to the northeast trade winds lasts from November through May (Tchantsev and Cabrera 1998).

The CPB oceanic waters are limited by the Cocos Ridge and Carnegie Ridge preventing the exchange of deep water with the central Pacific. Thus, the exchange of heat, salinity and water movements occur only in the upper 200 m. The general factors determining the hydrodynamic and thermohaline regimes are solar radiation, wind distribution, precipitation, freshwater run-off and the variations of the Humboldt Current and the Equatorial Countercurrent (Tchantsev and Cabrera 1998).

Circulation within the basin is generally cyclonic and includes the Colombian Current flowing north along the coast with velocities of about $1.0\,\mathrm{m\,s^{-1}}$ and extending 100–200 km offshore. A reverse, narrow flux along the central part of the basin presents a velocity of nearly $1.0\,\mathrm{m\,s^{-1}}$ in the surface, but widens and weakens with depth (Stevenson 1970).

Andrade (1992), calculated the geostrophic movement for the Colombian Pacific based on dynamic topography, finding geostrophic velocities of 0.95 to $2.00\,\mathrm{m\,s^{-1}}$ down to 250 m depth for the Colombian Current. He also observed upwelling events of subsurface waters in cyclonic cells during March 1976 and December 1978 at 6°N and 79°W, coinciding with similar findings by Stevenson (1970) during May – June 1965 and February – March 1966, located between 5°–6°N and 79°–80°W.

2.3 *Satellite data for color and SST (OCTS, August 1996 – June 1997)*

NASDA/ADEOS-I combines the advantage of a multispectral radiometer measuring ocean color and SST with high sensibility. We used OCTS monthly averaged processed data for chlorophyll and temperature distributed by NASDA. The digital number (DN) was converted to concentration of chlorophyll and temperature in °C using the following equation provided by NASDA (User's Guide 1999):

$$\begin{array}{l}\text{Chlorophyll}\\ \text{concentration}\end{array} - a(\mathrm{mg/m^3}) = 10^{(0.015^{*}\mathrm{DN}-2)},$$

$$\mathrm{SST}(^{\circ}\mathrm{C}) = [(0.15^{*}\mathrm{DN}) + (271.15)] - 273.15.$$

2.4 *Wind satellite data (NSCAT, August 1996 – June 1997)*

To describe the general wind field we used the monthly wind stress average ($\mathrm{N\,m^{-2}}$) for the

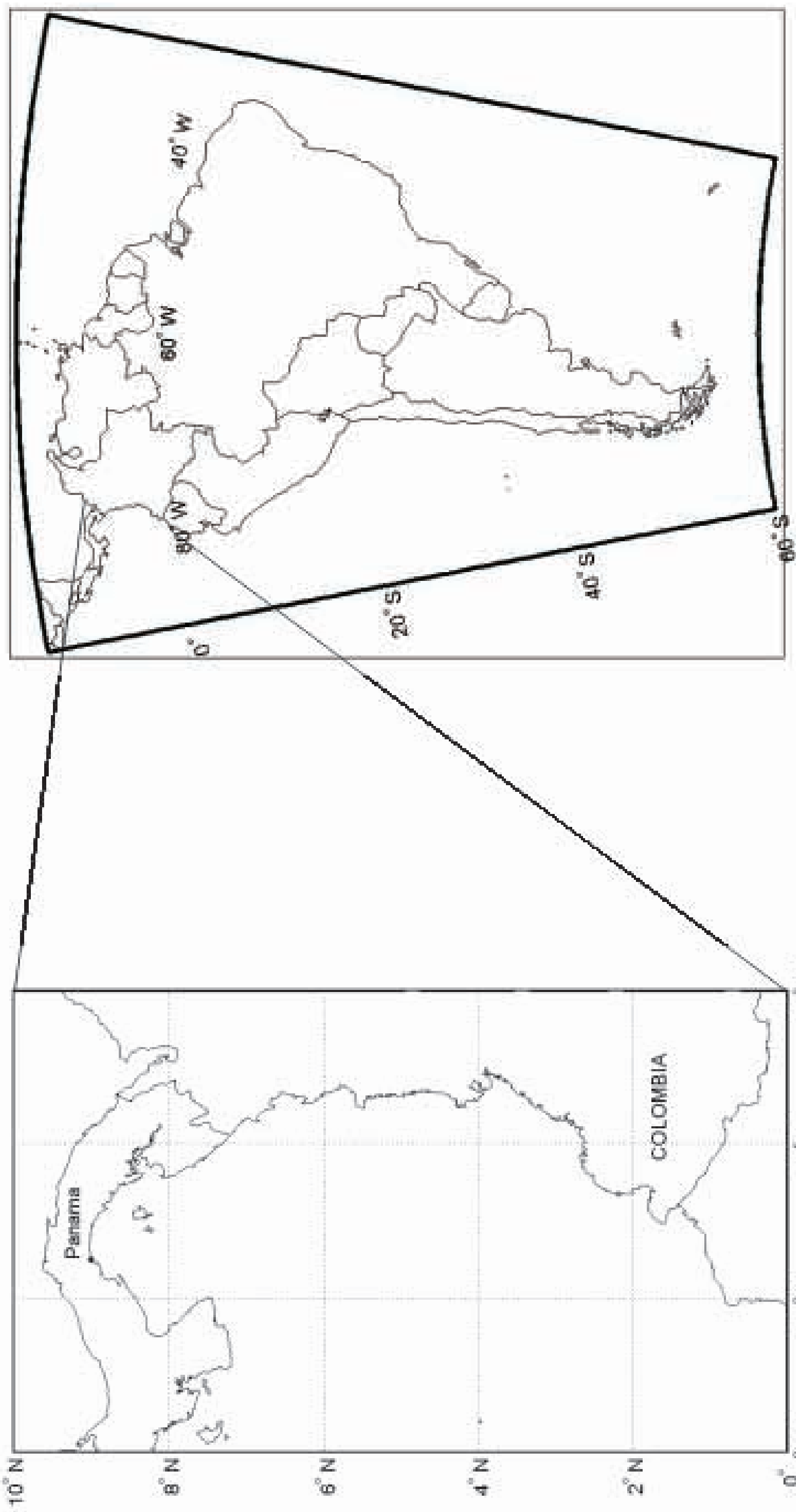

Figure 1. Localization of the Colombian Pacific Ocean, in the northern part of South America.

meridional and zonal component of the NSCAT provided by the COAPS/FS. These data with a spatial resolution of 0.5° × 0.5° were used for the calculation of Ekman pumping (We) using finite-differencing to obtain the space derivative.

3. Results

3.1 *Chlorophyll and temperature (OCTS)*

The concentration of surface chlorophyll (plate 1a) showed a low concentration in November in the central part of the basin (<0.05 mg m^{-3}). In March, a substantial increase is observed with similar values in two upwelling focuses located, one at the Gulf of Panama (which remained until April) and the other one in oceanic waters of the Colombian Pacific Basin around 5°N and 6°N, with values over 20 mg m^{-3}. None was observed in May and June. During June, values in the central part of the basin diminished to less than 0.04 mg m^{-3}.

A band of high pigment concentration (>40 mg m^{-3}) is observed in the coastal zone appearing from January to June at 5°N and extending southward up to the proximity of the equator; this band remained in spite of the appearance and disappearance of oceanic upwelling.

In the images of SST (plate 1b) a warm water mass of over 28°C is observed in the northern part of the basin during November; while waters relatively cold (< 26° C) predominate in the southern part establishing a well marked thermal front. Cooling of the northern part (Gulf of Panama) is observed starting in December and extending further south month by month, with temperatures decreasing to around 24° C. Thus, a well marked east–west delimited front appears in February moving southeast, apparently forming an anticyclonic gyre in the upper left part of the image. March is characterized by a strong reduction in temperature in the middle of the tongue resulting into two focuses of low temperature oscillating between 21° and 23° C, one in the Gulf of Panama and, the other, close to the shelf brake around 7°N. This plume of cold water turns towards the Galapagos Islands at 6°N. The approximate width of this plume is around 150 km close to the mouth of the Gulf of Panama, reaching about 250 km in the central part of the basin.

During April, the plume retreats, showing an increase in the SST in its central part, remaining relatively cold close to the Gulf and in the southern part of the basin. This plume has almost completely disappeared in May and June and a general warming is observed reaching temperatures up to 29° and 30° in June in the northern and central parts of the basin.

3.2 *Wind stress (NSCAT)*

During November the wind stress vectors (figure 2) pointed predominantly northeast, with highest stress-values in the southern part of the basin. A change of this pattern in the central part of the basin (5°N) was observed in December. Here, the direction of the wind stress is towards the Colombian coast, while in the northern part the winds blow towards the southeast. Similarly, the formation of a wind jet occurs in the meridional axis of the Panama Gulf pointing south, cyclonically gyring east and converging with the wind coming from the southeast between 5° and 6°N, in the direction of the Colombian coast.

During January an intensification of the wind jet from the Gulf of Panama moves the zone of convergence with the southeast winds down to 4°N, and in February pushes it down to 2°N; as a result the cyclonic gyre is gradually lost towards the east. The jet's maximal intensity was observed in March, reaching values of 0.09 N m^{-2} between 7° and 5°N and 81° and 79°W. The direction of the stress vectors was predominantly southwest between 84° and 80°W, and southeast between 79° − 78°W, almost parallel to the Colombian coast. The structure of the axis of this jet showed an anticyclonic gyre towards the west.

April marked the withdrawal of the wind jet in the meridional part of the Gulf of Panama, remaining its anticyclonic component. A relaxation and change in the general direction of the wind occurs in the remaining part of the basin, retaking its northern orientation. An intensification of the southeast wind is observed in May, generating a convergence zone around 4°N, marking the displacement of the ITCZ. The jet disappears from the Colombian basin and the Gulf of Panama in June due to a generalized wind relaxation.

3.3 *Correlation*

The relationship of wind stress with temperature and chlorophyll concentration was analysed for the meridional transect (79.5°W) and the zonal (5.5°N) transect with a confidence interval of 95%. During November, the behavior of the SST and stress in the meridional transect showed an inverse correlation ($R = -0.74$) at the mouth of the Gulf of Panama (7°N), gradually decreasing to the south. This transect evinces the presence of colder waters in the southern part of the basin (2°N) and warmer waters in the northern part adjacent to the Gulf of Panama. The wind stress also presented higher values in the southern part and lower values in the north, towards the Gulf.

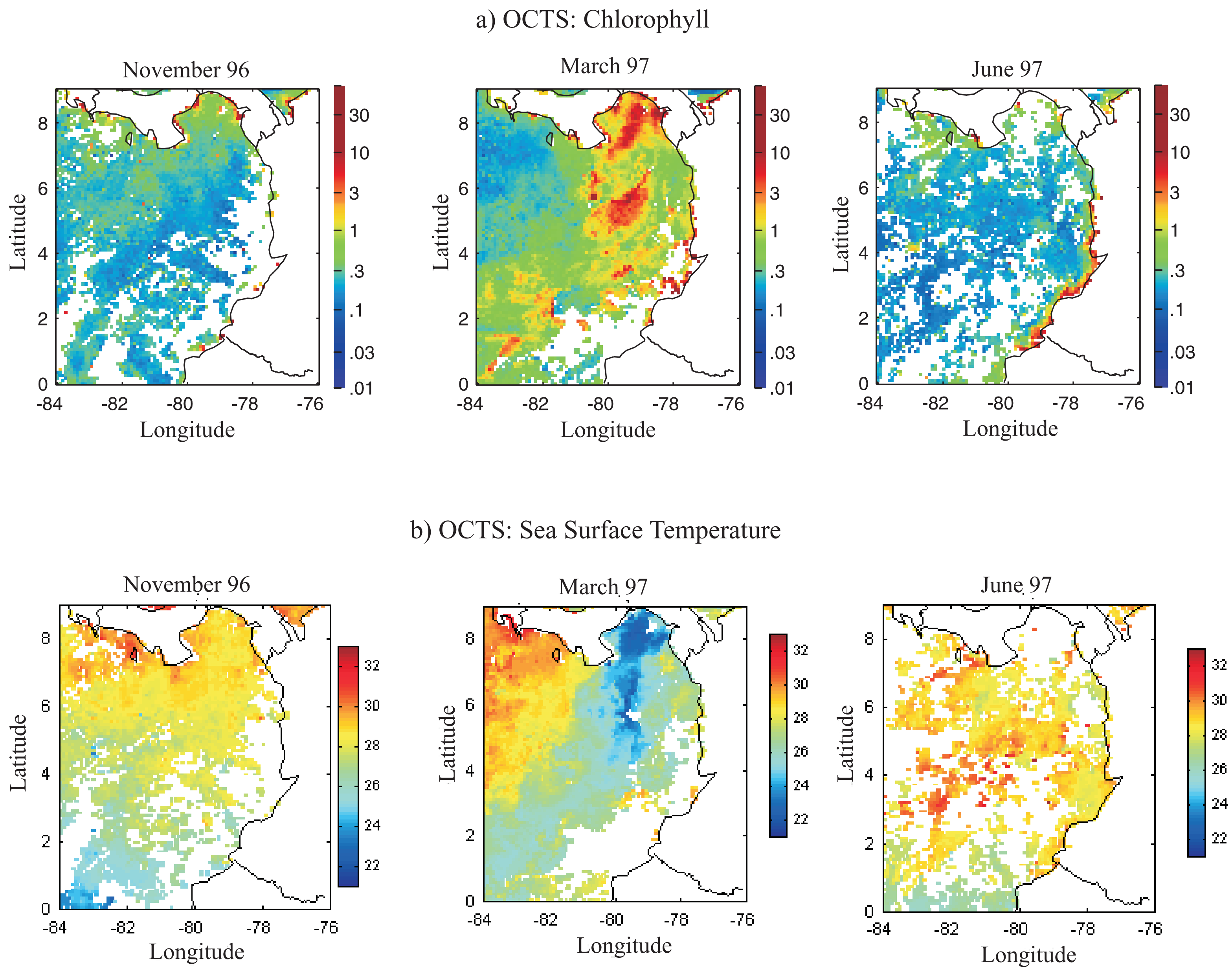

Plate 1. **(a)** Surface chlorophyll (mg m^{-3}) and **(b)** Sea Surface Temperature ($^{\circ}$ C), obtained from ADEOS/OCTS, November 1996 – June 1997 (see text for explanation).

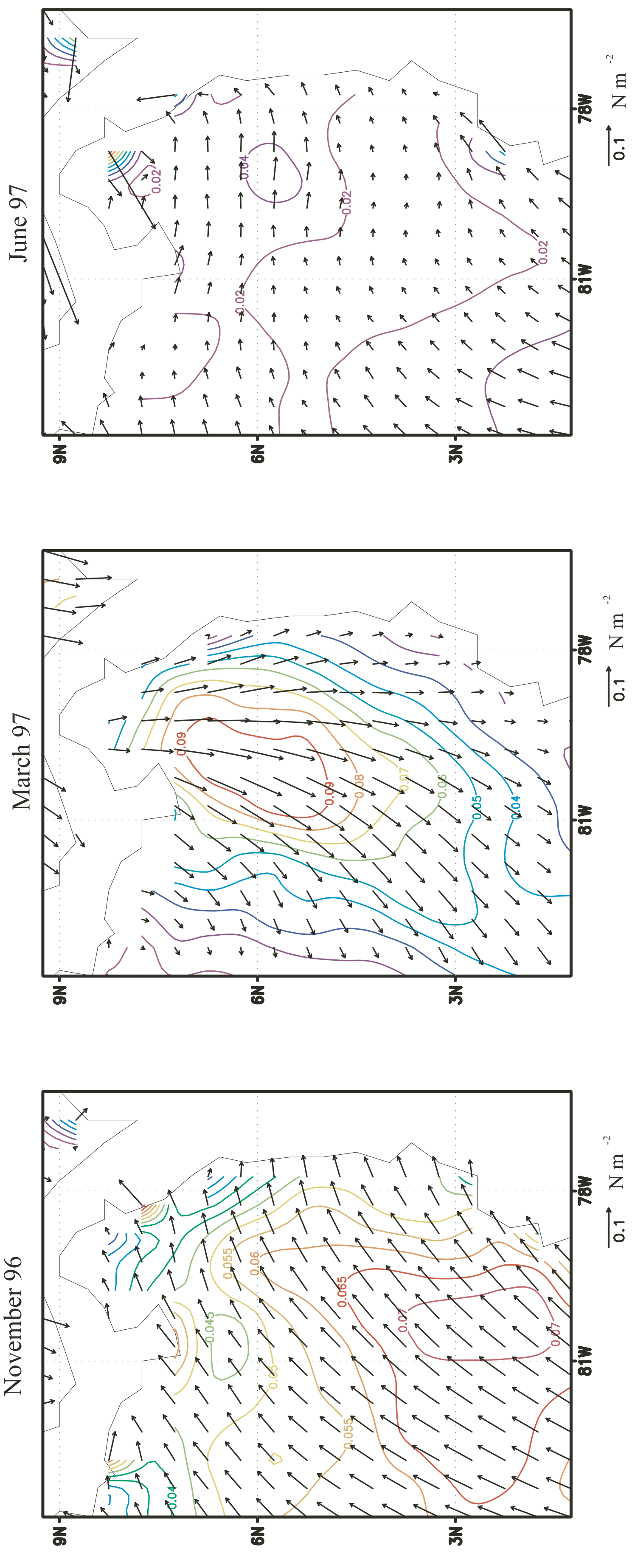

Figure 2. Monthly averages for wind stress (N m^{-2}) calculated for ADEOS/NSCAT data (see text for explanation).

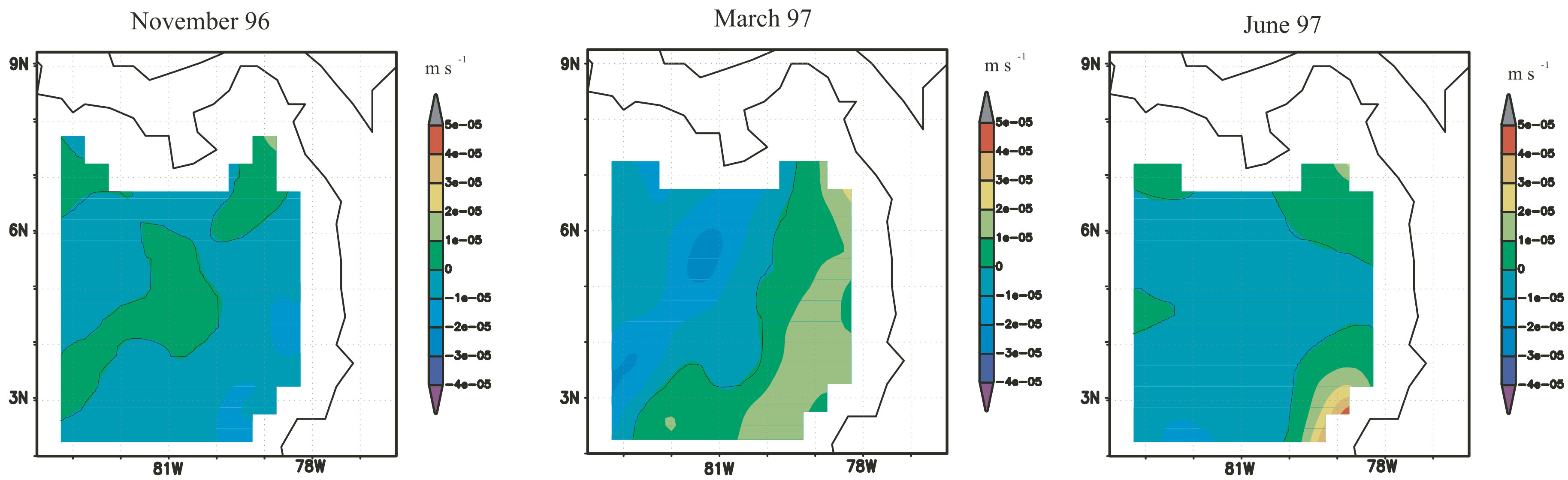

Figure 3. Monthly averages for Ekman pumping (We m s^{-1}) calculated for ADEOS/NSCAT data (see text for explanation).

During this period, the relationship between chlorophyll and wind stress showed an inverse but statistically significant correlation ($R = -0.78$). In March, the relationship between wind stress and SST variation was more marked along the whole transect, with a high correlation index ($R = -0.88$); that for chlorophyll and wind stress was not evident ($R = 0.065$). A high peak of chlorophyll concentration is observed at 5.5°N, concurrent with high wind stress, but another peak shown at 3.5°N coincides with a decrease of the wind stress towards the south. In June, the correlation between SST and chlorophyll is not significant.

For the zonal transect, a rather homogeneous SST and chlorophyll behavior is observed during November, with a low correlation regarding wind stress, presenting a light increase to the west between 79° and 80°W. During March, chlorophyll and SST present a significant negative correlation with wind stress, ($R = -60$), ($R = 0.93$), respectively.

The SST tendency showed a sudden decrease in temperature between 79° and 80°W coupled with a strong increase in wind stress at the same longitudinal range and a gradual increase in SST during wind stress relaxation. In turn, the chlorophyll concentration is high between 79° and 79.5°W, but lower compared to the maximal stress observed in March within the same range of longitude. In general, SST and chlorophyll remained homogeneously distributed along the longitudinal transect.

3.4 *Ekman pumping (We)*

We (figure 3) for the month of November shows an upwelling zone ($We = 1 \times 10^{-5}\,\mathrm{m\,s^{-1}}$) in the northern part of the basin close to the central part of the mouth of the Gulf of Panama. Another upwelling zone appears in the western part of the basin. In December, the upwelling region located in the northern part becomes a longitudinal fringe and spreads between 6.5° and 5°N. A downwelling region ($We = -1 \times 10^{-5}$ and $-2 \times 10^{-5}\,\mathrm{m\,s^{-1}}$) occurs in the middle part of the fringe facing the Azuero Peninsula of Panama.

In January, the basin was meridionally divided into two well defined zones ($We = 0\,\mathrm{m\,s^{-1}}$ at about 79°W): an upwelling and a downwelling zone with cyclonic and anticyclonic gyres, respectively. The upwelling is located in the eastern part of the basin along the Colombian coast, with *We* values between 1×10^{-5} and $2 \times 10^{-5}\,\mathrm{m\,s^{-1}}$ and a focus of greater intensity between 79°W and 5°–6.5°N; downwelling occurs at the western side of the basin being stronger off Azuero Peninsula. During February, two upwelling fronts are formed in the eastern and western part of the basin, respectively, with a downwelling front in between. Two more intense upwelling focuses appear in the north, close to the mouth of the Gulf, and one in the south at about 2.5°N ($We = 3 \times 10^{-5}\,\mathrm{m\,s^{-1}}$). In March, the basin has become meridionally divided (*ca.*80°W) into a large cyclonic and an anti-cyclonic gyre, and two upwelling zones are clearly defined in the eastern part, with increasing values of *We* towards the Colombian coast. The downwelling zone is found in the western part, depicting a very intense event ($We > -2 \times 10^{-5}\,\mathrm{m\,s^{-1}}$) originating in front of the Azuero Peninsula and running southeast up to 3°N.

During April and May the basin shows a decrease in the intensity and extent of the upwelling, although centers of different intensity remain towards the east. Downwelling, in spite of the decrease in intensity, is comparatively higher than the range of values observed from November to February. In June, the upwelling decreases everywhere in the basin.

4. Discussion

The tropical eastern Pacific is subjected to important atmospheric processes transferring momentum to the oceanic and coastal waters in the region and modifying the balance of the processes that maintain the mixed layer (Strub *et al* 1998; Chelton *et al* 2000). Further, this region has one of the most productive waters of the world oceans resulting from the equatorial upwelling and the various coastal and oceanic upwellings (Chavez *et al* 1996).

The OCTS imagery studied, showed a seasonal behavior for chlorophyll concentration in the Panama basin related to a strong upwelling event during March 1997 and April 1997. These events coincided with the seasonal changes of the upper thermal structure, resulting in strong descent of the SST in the meridional axis of the basin and in close relation to the intensification of the wind jet originated at the Gulf of Panama. This jet affected the Colombian coast due to a cyclonic circulation in the eastern part and an anti-cyclonic circulation in the western part.

The correlation between different parameters and wind stress for the meridional and zonal transects is significant only in March and November. Such behavior suggests the possible influence of another physical or biological factor on the circulation patterns responsible for the appearance of the second chlorophyll peak present in March.

The same could be implied in the division of the two focuses located to the north of the basin. Apparently, such division coincides with the zone where the shelf brakes and the oceanic realm begins, after the isobar of 1000 m outside the Gulf of Panama, suggesting either the strong influence of the bottom topography and bathymetry on the meridional development of the upwelling; or the return influence of the Colombian Current, or both. Muller-Karger and Fuentes-Yaco (2000), relate the high chlorophyll concentrations close to the mountain passes in the central American mountain range, first with coastal upwelling associated with the wind jets, and the offshore advected blooms in the large filaments created by the wind jet. These blooms are later increased or maintained by upwelling within the eddy structures. Their analysis, could also explain the appearance of the second chlorophyll bloom in the southern part of the basin, and other high chlorophyll concentration points in the area, as due to chlorophyll filaments advected from the Gulf of Panama or to the biggest chlorophyll bloom located in the half of the basin. The analysis of the vertical velocities for the Ekman layer in the Colombian Pacific Ocean indicated two upwelling zones during the whole period of study, particularly in the eastern part of the Panama Basin. A similar distribution was detected by Stevenson (1970) in his analysis of the ACENTO cruises, but as discussed above, the difference is due to the resolution of the wind data (all provided by ships) used in that study.

It is important to consider that the data obtained between 2° and 3°N close to the Equator, must be carefully taken as the Ekman calculation stops working close to the Equator. Accordingly, the high values of vertical velocity *We* found in June between 2° and 3°N must be taken with caution as the SST and chlorophyll data do not indicate the occurrence of such a strong event. In the same way, the upwelling zones calculated from the *We* which do not occur in March and April, 1997 do not show events of high chlorophyll concentration which might indicate that high level of nutrients originated in deeper water. As argued by Stevenson (1970) and Tchanstev and Cabrera (1998) for the Colombian Pacific, this could be explained by the seasonal change of the thermocline, which presents a maximal and homogeneous ascent in March reaching up to 10 m in the northern zone with little homogeneity in the south. A descent down to 90 m follows from June to December during the intensification of the trade winds from the southeast. For the Gulf of Tehuantepec, similar in dynamic behavior to the Panama Jet, Trasviña *et al* (1995), have shown that the upwelling of the thermocline due to Ekman pumping is not the main cause of the drastic lowering of the sea surface temperature. The intersection of the thermocline with the surface should occur (in the region of maximum wind curl) to the left of the axis in the eastern gulf, but they show that the lowest temperatures occur beneath the axis of the wind due to an entrainment. The same case is shown in the SST in the Colombian Pacific Ocean during March, the lowest temperatures being beneath the axis of the wind jet of the Gulf of Panama. Apparently, the vertical shear in the offshore jet penetrates deeper than elsewhere, producing vertical mixing and the intense minimum observed in the central basin.

Thus, we infer that the second chlorophyll bloom in the middle of the Colombian Basin is most probably due to the upwelling produced by the combined action of the positive wind stress curl, the entrainment beneath the axis of the jet, the cyclonic circulation in interaction with the return of the Colombia Current and the shelf break in the Gulf of Panama, forming an eddy, coupled with offshore chlorophyll advected from the Gulf of Panama. In order to understand the precise effects of the wind field in the Colombian Pacific Ocean and the mesoscale oceanic processes involved in the chlorophyll variability in the area, it becomes necessary to run *in situ* observations and take advantage of the new satellite tools offered by SeaWiFS or MODIS in ocean color studies, and QuickSCAT scatterometer.

We further conclude that the variability of the oceanic surface chlorophyll and SST in the Panama Basin and the Colombian Pacific Ocean is seasonal and related to the migration of the ITCZ and the generation of the wind jet known at the Isthmus of Panama. The upwelling events due to the wind rotor are present throughout the whole period, with variable spatial distribution and a tendency to be located towards the eastern part of the basin. In a similar way, high chlorophyll concentrations observed in March coincide with both the intensification of the vertical velocities during that month, and the maximal rise of the thermocline in the northern part of the Panama Basin. What remains unsolved is the process or processes determining the chlorophyll development of the oceanic focuses or patches, the temporal scales of some of the discussed events and the physical and biological dynamics in the vertical axis of the upwelling.

Acknowledgement

This work was supported by the German Academic Exchange Service (DAAD) scholarships.

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