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Hydrology of winter–spring "red tides" in Bahía de Mazatlán, Sinaloa, México

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Abstract

"Red tide" events are frequent and periodical in Bahía de Mazatlán, Sinaloa, México. Yet, the ones observed from 4 February to 4 June 2000, showed some distinctive features: First, the dinoflagellates *Prorocentrum balticum* (85%), *P. mexicanum* (5%), and *Ceratium furca* (5%), dominated the composition of the blooms; Second, the average cell abundance by date was 1.3×10^6 cells l^{-1}, with a range of 3.5×10^3 to $24,500 \times 10^3$ cells l^{-1}, well above previous records; Third, the temperature registered at 10–20 m deep was unusually cold (19 °C), below the normal average of 21.5 °C observed over the last 10 years. Salinity was high (35.9 psu) and showed very little influence on the water density gradient. A mean thermal stratification index (TSI), of 3.4, with a maximum of 7 °C, was observed throughout the period, in spite of a weak upwelling activity and intermittent strong NW winds which were unable to break up water column stratification. Temperature fluctuations at the surface and at the bottom layers showed a 30-day periodicity, suggesting some association with the lunar cycle. To explain the characteristics of the "red tides" registered in Bahía de Mazatlán during the winter–spring period of year 2000, it is proposed that the temperature and density stratification, stabilized further by internal waves that compensated for the weak upwelling activity and provided the necessary nutrients to the surface layer, favored the persistence and intensity of the harmful algal bloom events then observed.
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1. Introduction

Bahía de Mazatlán is located in an area adjacent to the eastern coast of the Gulf of California, where winter upwelling occurs (Santamaría-del-Angel and Álvarez-Borrego, 1994; Fig. 1). Recorded observations of "red tide" phenomena in this area suggest that various factors appear to have favored an increase in their frequency, duration, and species variation during the last decades (Mee et al., 1984; Cortés-Altamirano et al., 1999). Besides the economic and environmental impact associated with these unpredictable events, the appearance of new toxic species brings a higher food-poisoning risk to this popular tourist resort area of Mexico (about 1 million visitors each year).

Dinoflagellate blooms are frequent in upwelling regions during the relaxation period, mainly in coastal upwelling fronts (Smayda, 2000). The seasonality of wind-driven upwelling confers variability to appearances of dinoflagellate blooms (Fraga, 1995), and seems also to be the primary force inducing upwelling events in Bahía de Mazatlán (Rosas-Cota, 1977). In Bahía de Mazatlán, upwelling pulses closely correlate with pigment concentration (Santamaría-del-Angel

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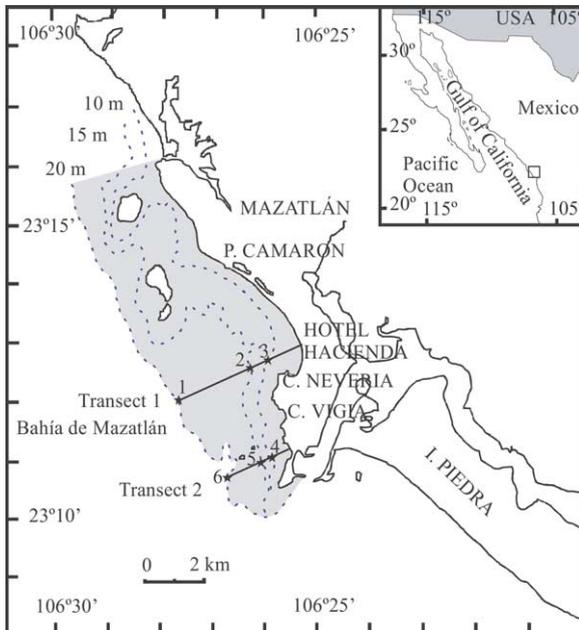*E-mail address:* jlochoa@cibnor.mx (J.L. Ochoa).

Fig. 1. Location of Bahía de Mazatlán and sampling stations within the study area.

and Álvarez-Borrego, 1994), and determine the thermal stratification-mixing cycles of the water, affecting phytoplankton dynamics. The presence of water masses of different salinity (Casas et al., 1997) may modify stratification of the water column, therefore influencing the duration of a bloom event. To understand the complexity of "red tide" events in Bahía de Mazatlán, it is important to account for its open, eutrophic, and shallow subtropical ecosystem character (Alonso-Rodríguez et al., 2000). These factors may also be important in determining the actual dynamics of a harmful algal bloom (HAB) in such an embayment.

Using remote sensing tools, Aguirre-Gómez et al. (1999) found that the massive proliferation of dinoflagellates that can occur in the winter–spring period in Bahía de Mazatlán is associated with the sudden cooling of sea surface. The events in 2000 seem to confirm this observation and, according to the present report, for a second year in a row the dominant species did not correspond to those reported for the past 18 years. This study attempts to understand the origin and behavior of HABs in Bahía de Mazatlán by analyzing the hydrologic processes

of the bay (Figueiras et al., 1995), and summarizing previous reports correlating dinoflagellate blooms to wind and currents (Pitcher et al., 1998). It was anticipated that such factors could determine the pattern of algal blooms in this area (Cortés-Altamirano et al., 1999) and explain its variability.

2. Materials and methods

2.1. Sampling

The study area is a $35 \, \text{km}^2$ zone in which previous reports have described "red tide" recurrences every winter–spring season (Cortés-Altamirano and Alonso-Rodríguez, 1997). Samples were collected with a 31 Van Dorn bottle every other day, from 4 February to 4 June 2000, from six paired stations (Fig. 1): at the surface (0.5 m), and at different depths (10, 15 and 20 m). An aliquot of each sample was used for phytoplankton analysis and fixed with Lugol's iodine (Throndsen, 1978), the rest was employed for organism identification and cell counting under a phase-contrast light microscope in a 1 ml Sedgwick-Rafter chamber (Sournia, 1978). The average abundance by date was calculated adding the values of abundance of each sampling and dividing by the number of samples (515) and by the number of collection dates (49): average cell density $= \sum \text{cell density/samples/date}$.

2.2. Physical data

Air temperature at time of collection was determined with an ambient thermometer. Water temperature and salinity were determined with a mercury thermometer and a salinometer (Beckman, Palo Alto, CA, USA). A thermal stratification index (TSI) was calculated from the difference between surface and the mean 10–20 m temperature. The density gradient sigma-*t* (σ_t), was estimated from the mean surface and at 10–20 m density values (Cox et al., 1970).

2.3. Meteorological data

Daily dominant wind data (velocity and direction) were plotted and the coastal upwelling index (CUI)

calculated from the resulting wind vector (at 6, 12, 18, and 24 h), using the Bakun equation (as modified by Lluch-Cota, 2000), and expressed as $m^3 s^{-1}$, 100 m off the coast. The periodicity of water temperature variation was determined with the aid of a formula in Mathlab (version 6), Release 12 software (The Mathworks, Inc., Natick, MA, USA) which takes into account the sampling frequency. Assuming a duplication rate of 1.5–4.0 days for harmful phytoplankton, and considering our sampling schedule, we used a frequency index (Nyquist frequency) of 48 h in the Mathlab formula to obtain a 24 h precision periodicity.

3. Results and discussion

Seventeen HAB events, with at least 3-day intervals, were detected in Bahía de Mazatlán between 4 February and 4 June 2000 (Table 1). In each case, bloom duration was from one to 20 continuous days, totaling 50 bloom days during the sampling period (Table 1). Distinguishing between "red tide" events is troublesome because some researchers consider an interval of a week between the manifestation of two different events (Cortés-Altamirano and Gómez-Aguirre, 2001) while others emphasize phytoplankton composition and cell density as better criterion because some blooms occur without water discoloration (Smayda, 1995). Using 1 week between events as reference, for the whole year 2000, only five "red tide" events, with a total of 95 days coverage, were reported by Cortés-Altamirano and Gómez-Aguirre (2001). Neither in this case is the phytoplankton composition known to allow further comparison.

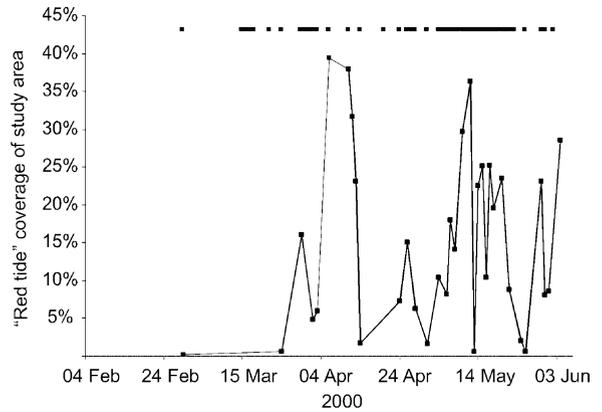The incidence of "red tides" in Bahía de Mazatlán seems to occur every year in two periods: winter–spring

Fig. 2. "Red tide" coverage of sea surface area in Bahía de Mazatlán from 4 February to 4 June 2000. Upper broken line indicates observations of "red tides".

and summer–fall (Ramírez-Camarena et al., 1999). During the present study, which corresponds to the winter–spring season, the average aereal extent of discolored sea surface within the bay, calculated with a computer assisted program (AUTOCAD version 2000) from aerial photographs, was 20%, with a maximum of about 40% on 6 April 2000 (Fig. 2). Fig. 2 shows at least 11 peaks, less than 17 "red tide" events listed in Table 1, and slightly less than the 13 cell density peaks depicted in Fig. 3. Most likely, the position of the observer (land, air, or sea), time of observation, intensity of sunlight, and reflection of light from the water surface, influence the detection of the phenomena and, as mentioned above, blooming does not necessarily involve discoloration of the water.
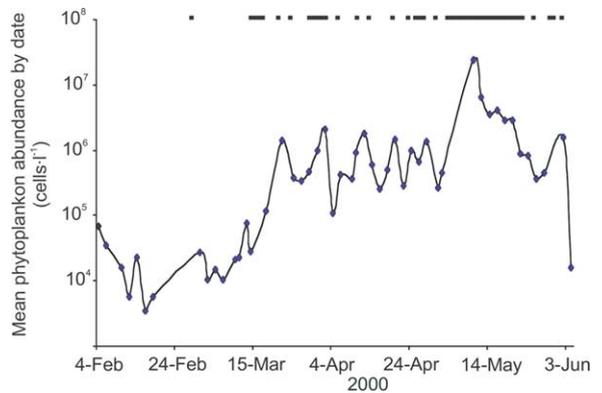
Table 1
"Red tides" observed in Bahía de Mazatlán (February–June 2000)

Month	Date	Days of occurrence	Number of events
February	29	1	1
March	15–18, 22, 25, 30–31	8	4
April	1–3, 6, 11–14, 20, 24, 26–28	13	6
May	1, 4–23, 26, 30–31	24	4
June	2, 7–8	4	2
Total		50	17

Fig. 3. Mean phytoplankton abundance at the surface in Bahía de Mazatlán from 4 February to 4 June 2000. Upper broken line indicates observations of "red tides".

Table 2

Dominant and co-dominant phytoplankton species in "red tide" events at Bahía de Mazatlán, México (1979–2000)

Species	Reported year	References
Amylax triacantha (Jörgensen) Sournia (=*Gonyaulax triacantha* Jörgensen) later identified as *Peridinium quinquecorne* Abé	1990	1–4, 20
Asterionellopsis glacialis (Castracane) round	1996, 1998, 1999	5, 6
Ceratium dens Ostenfeld and Schmidt	1985, 1997, 2000	6–8, 20
Ceratium furca var. *furca* Sournia	1989	1–3, 20
Ceratium tripos var. *ponticum* Jörgensen later identified as *C. dens*	1985, 1989	1, 3, 4, 10
Chaetoceros spp.	1998, 1999	5
Cochlodinium catenatum Okamura	2000	8, 20
Coscinodiscus centralis Ehrenberg	2000	8
Gymnodinium catenatum Graham	1979, 1985–1988, 1994, 1995–1998, 2000	1, 3, 7, 8, 10–13, 20
Gymnodinium mikimotoi Miyaka and Kominami (=*Karenia mikimotoi* Hansen and Moestrup)	1997	7
Gymnodinium sanguineum Hirasaka (=*G. splendens* = *Akashiwo sanguinea* Daugbjerg)	1985, 1994, 1997	1, 6–8, 20
Gyrodinium spirale (Bergh) Kofoid and Swezy	1997	7
Lauderia annulata Cleve (=*L. borealis* Gran)	1980	14
Leptocylindrus danicus Cleve	1980, 1997, 1999	5, 7, 14
Lioloma pacificum (Cupp) *Hasle* (=*Thalassiothrix mediterranea* v. *pacifica* Cupp)	1999	6
Mesodinium rubrum (Lohmann) Hamburger and Buddenbrock	1980–1982, 1984–1991, 1994–2000	1–3, 7, 8, 12, 15, 20
Nitzschia spp.	1992, 1999	5
Noctiluca scintillans (Macartney) Kofoid and Swezy	1986, 1991, 2000	1, 2, 8, 20
Peridinium spp. (=*Protoperidinium*)	1997	7
Proboscia alata Sundström (*Rhizosolenia alata*)	1997	7
Prorocentrum balticum (Lohman) Loeblich III	1999, 2000	2, 8, 16, 20
Prorocentrum dentatum Stein	1985, 1994, 1999, 2000	1, 8, 12, 16, 20
Prorocentrum mexicanum Tafall	1999, 2000	8, 9, 16, 19, 21
Prorocentrum micans Ehrenberg	1997, 1999	7, 16
Prorocentrum spp.	1998, 1999	1, 5, 21
Prorocentrum triestinum Shiller	1996, 2000	6, 8, 17, 18, 20, 21
Protoperidinium spp.	1989	3
Pseudo-nitzschia fraudulenta (Cleve) Hasle	1996, 1998	6
Pseudo-nitzschia. pungens (Grunow ex Cleve) Hasle	1996	6
Pseudo-nitzschia spp.	1997–1999	5, 7
Pseudo-nitzschia subfraudulenta (Hasle) Hasle	1988	6
Pyramimonas spp.	1996	15
Scrippsiella trochoidea (von Stein) Loeblich III (=*Peridinium trochoideum*, von Stein) Lemmermann	1980, 1985, 1989–1991, 1994–1997, 2000	1, 3, 6, 8, 11, 15, 20, 21
Skeletonema costatum (Greville) Cleve	1985, 1996–1999	5–7
Thalassionema nitzschioides Grunow ex Mereschkowsky	1998, 1999	5
Thalassiosira mala Takano	1996, 1998	6
Thalassiosira spp.	1998–2000	5, 9, 21
Thalassiotrix spp.	1998, 1999	6

References: 1, Cortés-Altamirano et al. (1995b); 2, Cortés-Altamirano et al. (1999); 3, Gómez-Aguirre (1998); 4, Cortés-Altamirano (2002); 5, Gómez-Aguirre (1998); 6, Licea et al. (1999); 7, Cortés-Altamirano and Alonso-Rodríguez (1997); 8, Cortés-Altamirano and Gómez-Aguirre (2001); 9, Alonso-Rodríguez and Ochoa (2002); 10, Cortés-Altamirano et al. (1996); 11, Aguirre-Gómez et al. (1999); 12, Cortés-Altamirano et al. (1995a); 13, Ramírez-Camarena et al. (1999); 14, Rojas-Trejo (1984); 15, Alonso-Rodríguez et al. (2000); 16, Cortés-Altamirano and Nuñez-Pastén (2000); 17, Cortés-Altamirano et al. (2000); 18, Hernández-Becerril et al. (2000); 19, Cortés-Altamirano and Sierra-Beltrán (2002); 20, Cortés-Altamirano et al. (2002); 21, this study.

The largest phytoplankton abundance was found in samples collected at the water surface. During the study period, armored dinoflagellates such as *Prorocentrum* (87%), *Ceratium* (5%), and the diatom *Thalassiosira* (1%), were the most diverse genera. *Prorocentrum balticum* (80%), *Prorocentrum mexicanum* (5%), and *Ceratium furca* (5%), considered common in upwelling systems during episodes of water column stabilization (Smayda, 2000), were the most abundant species. Table 2 lists the main phytoplankton organisms in "red tide" events in Bahía de Mazatlán observed during the last 23 years. It is noteworthy that species previously considered common, permanent residents of Bahía de Mazatlán, such as *Mesodinium rubrum* and *Gymnodinum catenatum*, were absent or sparsely detected in 2000 (see also Cortés-Altamirano and Gómez-Aguirre, 2001). Instead, *P. balticum* and *Cochlodinium polykrikoides* in the winter–spring season, and presumably *Cochlodinium catenatum* in the summer–fall (Cortés-Altamirano and Gómez-Aguirre, 2001), dominated the HAB events that year. Therefore, the 2000 "red tide" composition should be regarded unusual.

The average phytoplankton abundance during the study period was 1.3×10^6 cells l^{-1}, from a range of 3.5×10^3 to 24.5×10^6 cells l^{-1} in the different samplings (Fig. 3). On 18 May, *P. balticum* (Lohman) Loebich III cell density alone, peaked at 20.45×10^6 cells l^{-1}. Recent "red tides" dominated by *P. balticum* and *Cochlodinium polykrikoides*, have been observed along Costa Rica's shore (Víquez and Hargraves, 1995). Other *Cochlodinium* species have been observed also in the northern part of the Gulf of California since 1941 (Osorio-Tafall, 1943), and as far as Ensenada, B.C., on the Pacific coast of the Baja California Peninsula since 1985 (Venrick, 2000). The mean air temperature over Bahía de Mazatlán during the sampling season (February–June) was 24.4 °C (18.2–32 °C), which is normal for that period. Water temperature at the surface and at various depths (10–20 m) in contrast, showed significant differences (Fig. 4). Thermal stratification was always observed, which became more pronounced between 24 April and 3 June. Surface temperature during this period averaged 22.5 °C (17.9–29.2 °C), while near bottom temperature (10–20 m deep) averaged 19.0 °C (14.5–26.9 °C) and behaved quite uniformly, as a single water layer. Minimum water temperature at the
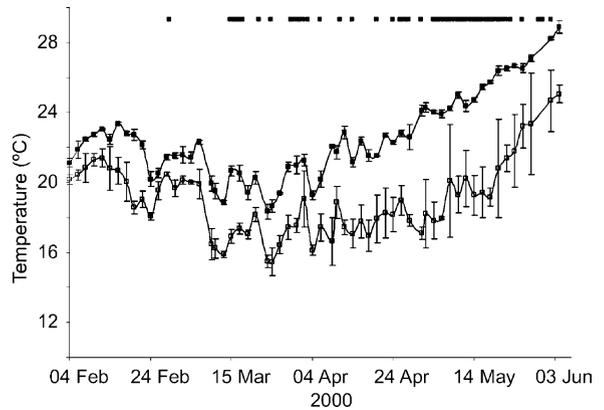

Fig. 4. Water temperature in Bahía de Mazatlán from 4 February to 4 June 2000: (■) surface temperature; (□) temperature at 10–20 m. Upper broken line indicates observations of "red tides" (S.D. in vertical bars).

bottom was 14.5 °C, an abnormally cold temperature in this area which has been also reported in 1960 (Secretaría de Marina, 1974), in 1989 by the Center for Fishery Research (Mazatlán Station), and more recently in 1999 by Ayón-Parente (2000; Fig. 5). This low temperature may be related to the start of a "La Niña" event in late 1999, as suggested by Behrenfeld et al. (2001).

Upwelling intensity during winter–spring 2000 generated a TSI variation in Bahía de Mazatlán that suggested periods of intermittent mixing before 9 April that became more intense after 12 April, for relatively
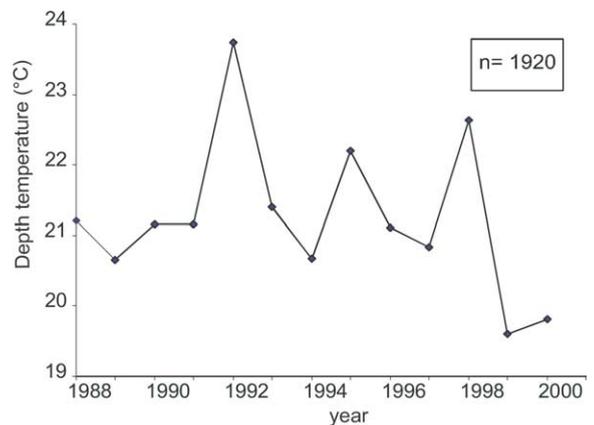

Fig. 5. Mean winter–spring (February–June) temperature, at 10–20 m, averaged from daily temperatures (1988–2000) in Bahía de Mazatlán. *Source*: Center for Fishery Research (CRIP).
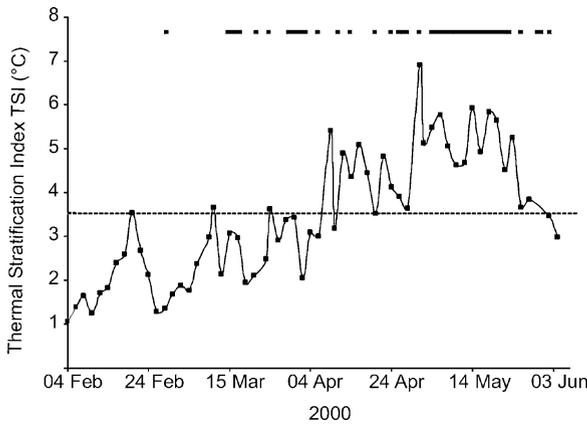
Fig. 6. Thermal stratification index (TSI) from 4 February to 4 June 2000 in Bahía de Mazatlán. The broken line is the mean TSI. Upper broken line indicates observation of "red tides".

short intervals. The TSI reached a maximum on 1 May (TSI = 7 °C), and decreased thereafter (Fig. 6). The average TSI value (3.4 °C) for this season has been exceeded only in 1981 (3.8 °C), when intense upwelling occurred (Mee et al., 1985). A summary of available data for water surface temperature and TSI values in Mazatlán Bay during the last 21 years is shown in Fig. 7. We conclude that the extent of thermal stratification generated in Bahía de Mazatlán during the year 2000 winter–spring season may have contributed to the "red tide" events then observed.

Water salinity, at the surface (34.9–36.8 psu) and at the bottom (35.5–36.7 psu) layers, was high compared to previous determinations (Rojas-Trejo, 1984;
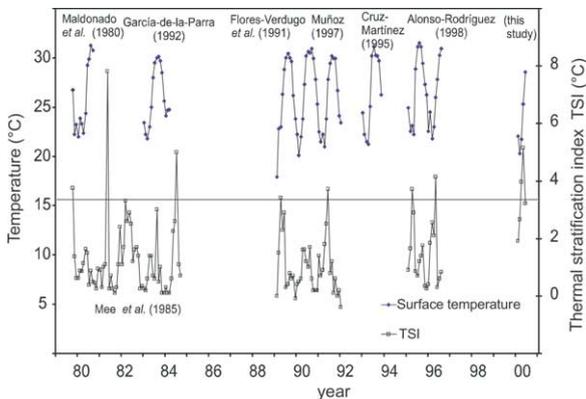

Fig. 7. Annual mean surface temperature and thermal stratification index (TSI) in Bahía de Mazatlán (1979–2000).
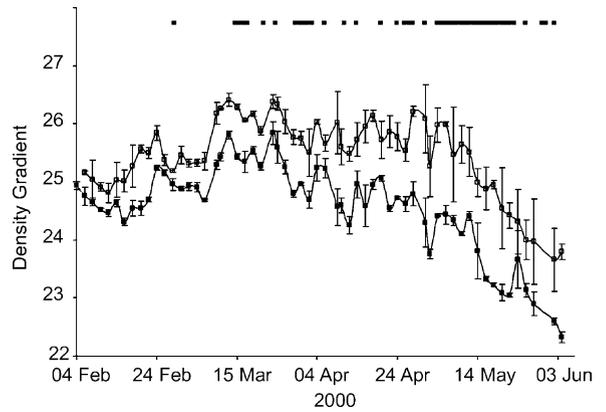

Fig. 8. Water column density gradient in Bahía de Mazatlán from 4 February to 4 June 2000: (■) surface σ_t; (□) σ_t at 10–20 m. Upper broken line indicates observations of "red tides". S.D. is indicated in the vertical bars.

Alonso-Rodríguez, 1998). These conditions may be a result of the dry weather that prevailed in the area during the study period. The density gradient between both layers was almost constant during the whole period (Fig. 8). The density, expressed as σ_t, showed few periods of mixing at the beginning of the study, when the difference between the surface and the bottom layer was only 0.5 units, but afterwards reached a maximum stratification, with differences of 1.8 units. This later condition has been previously observed during intense dinoflagellate blooms (Lechuga-Devéze and Morquecho-Escamilla, 1998).

Prevailing northwest winds during this study period were not able to promote mixing of the water column or abolish the "red tide" events at the sampling sites (Fig. 9). Possibly, internal waves, which normally contribute to the internal mixing helped to maintain separation of the different layers, compensating for the wind disruption effect. A situation like this is particularly feasible when the wind and the tidal current have the same direction and promote the accumulation of "red tide" forming organisms (Yoshida and Numata, 1982). Yet, and as observed in other regions (Rounsefell and Dragovich, 1966), mixing did occur in the shallow areas of Bahía de Mazatlán preventing algal blooming near the beach.

The CUI of Bahía de Mazatlán shows a frequency with values of less than 20 m³ s⁻¹, 100 m; this is lower than the those observed at similar latitudes in other regions of the Pacific (about 80 m³ s⁻¹, 100 m:
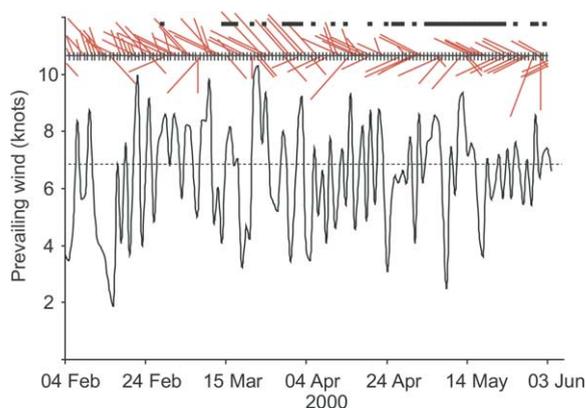
Fig. 9. Prevailing wind analysis in Bahía de Mazatlán from 4 February to 4 June 2000. Continuous line indicates wind velocity (knots). Pin diagram indicates the mean velocity and direction of the daily wind. Upper broken line indicates observations of "red tides".

http://www.pfeg.noaa.gov / products / PFEL / modeled/ indices/upwelling/NA/graphs_comp.html). This, we believe, may be a result imposed by the presence of the Baja California Peninsula which induces a weak upwelling that can drive the nutricline below the photic layer and allows a thermal stratification that favors the persistence of dinoflagellates (Figueiras and Ríos, 1993; Smayda, 2000).

Analysis of the periodicity of temperature variations at the surface and at the lower water layer (10–20 m) shows a 30-day frequency. This rhythm suggests a lunar cycle associated with the tidal currents and "red tide" outbreaks in Bahía de Mazatlán (de Bruyn and Meeuwing, 2001).

4. Conclusion

We conclude that during the winter–spring of 2000, weak upwelling, presence of unusually cold water, and strong stratification of the water column in Bahía de Mazatlán, combined to favor an increase in "red tide" activity and the change in species composition. Some evidence suggests that the lunar cycle, which promotes circulation in Bahía de Mazatlán, may also influence the extent and duration of a bloom. Wind, stronger than seven knots, was not able to disrupt the water column stratification or the phytoplankton con-

centration. Weak upwelling and the presence of internal waves, may have favored the persistence of dinoflagellate blooms during short relaxation episodes by promoting the interchange of nutrients between the bottom cold water and the surface layer. The wind and tidal currents, on the other hand, may have produced a stabilizing effect, further enhancing the dinoflagellate bloom intensity (Pond and Pickard, 1986). The "red tides" registered in the Bahía de Mazatlán year 2000 have been, so far, the most intense and persistent in historical times.

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