Interaction between Coastal Upwelling and Local Winds at Cabo Frio, Brazil: An Observational Study

SERGIO H. FRANCHITO

Centro de Previsão de Tempo e Estudos Climáticos, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, Brazil

TANIA O. ODA

Instituto de Estudos do Mar Almirante Paulo Moreira, Arraial do Cabo, Brazil

V. BRAHMANANDA RAO AND MARY T. KAYANO

Centro de Previsão de Tempo e Estudos Climáticos, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, Brazil

(Manuscript received 6 December 2006, in final form 12 September 2007)

ABSTRACT

The relationships between coastal upwelling and local winds at Cabo Frio (Brazil) are studied using SST and time series of surface wind for a 10-yr period (1971–80). The results show that the seasonal variations of SST and local winds are closely related. Sea-breeze circulation is intensified by the enhancement of the land–sea temperature gradient due to cold water upwelling near the coast; coastal upwelling, in turn, is associated with strong northeasterlies. This result confirms the conclusions of earlier modeling studies. Interannual variability is also apparent in the results. During the period from 1971 to 1980, the highest SST values occur during the years 1972–73 (strong El Niño event) and the lowest occur in 1977 (moderate El Niño event). This suggests some possible effects of atmospheric teleconnections on South Atlantic SSTs. However, a record longer than 10 yr is needed to confirm the connection with El Niño and La Niña events. Time–frequency analyses of the SST and zonal wind series for 1975–77 are done using Morlet wavelet analysis. The global wavelet spectra for these variables show strong peaks at 24 and 157 h (approximately 6.6 days). These analyses also indicate that the sea breeze occurs at Cabo Frio almost year-round and confirm the relationships with the coastal upwelling in the region.

1. Introduction

The region near Cabo Frio (22°59′ S, 42°02′ W) is characterized by the occurrence of coastal upwelling. Strong negative anomalies of sea surface temperature (SST) are present during most of the year in this region (Valentin 1984). Figure 1 shows a *National Oceanic and Atmospheric Administration* (*NOAA*)*-12* Advanced Very High Resolution Radiometer (AVHRR) satellite image that illustrates the presence of coastal upwelling in this region. The upwelling is stronger in the austral spring and summer seasons and weaker during the other seasons (Stech et al. 1995). The seasonality of the upwelling at Cabo Frio seems to be related to the onshore/offshore seasonal migration of South Atlantic Central Water (SACW) at the continental slope. Several studies have shown that the SACW is the source of cold waters that crop up near the coast in this region (Campos et al. 1995; Valentin et al. 1987).

The upwelling at Cabo Frio is an uncommon case. Most of the regions of coastal upwelling in the world are located on the east coast of oceans: in Peru, Ecuador, California, and Oregon on the Pacific Ocean, and northwest Africa and southern Benguela on the Atlantic Ocean. However, the upwelling at Cabo Frio—which is of great importance for the biological enrichment of the water and the fishery activities in the region—occurs on the west coast of the Atlantic Ocean. Some efforts, therefore, have been made to identify, understand, and record the physical, chemical, hydro-

Corresponding author address: Sergio Franchito, Centro de Previsão de Tempo e Estudos Climáticos, Instituto Nacional de Pesquisas Espaciais, CP 515, São José dos Campos, SP 12245-970, Brazil.
E-mail: fran@cptec.inpe.br

DOI: 10.1175/2007JAMC1660.1

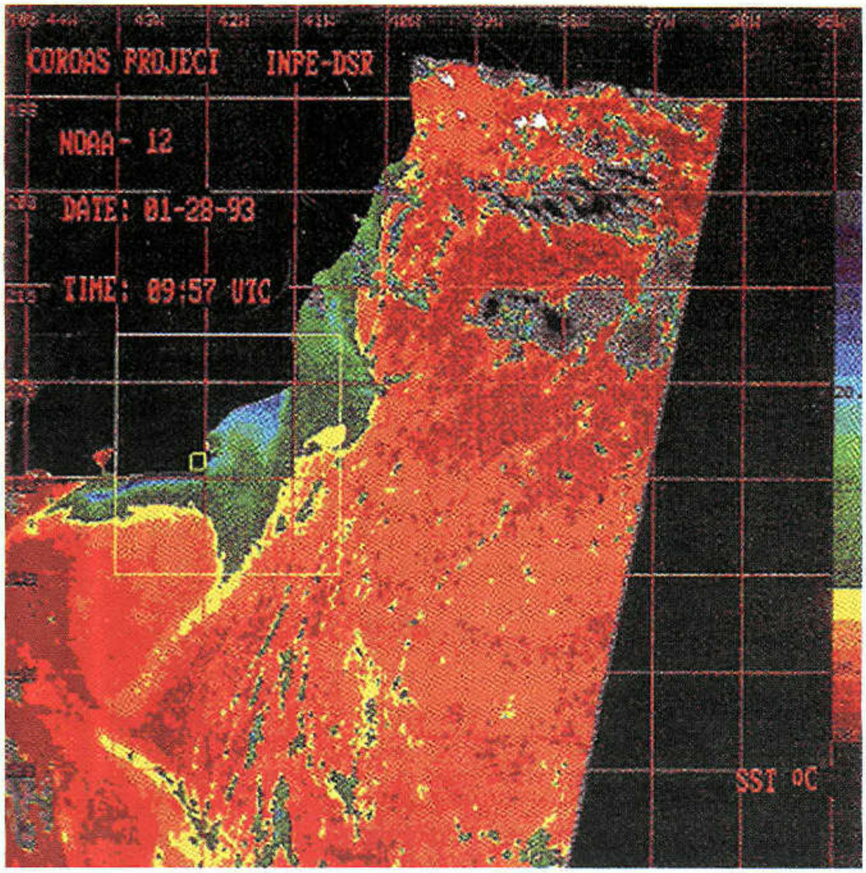

FIG. 1. Sea surface temperature satellite image showing the coastal upwelling in the Cabo Frio region (large yellow square) and the local region where the surface wind and SST data were obtained (small yellow square).

logical, biological, and geological processes involved in the coastal upwelling in this region (Matsuura 1996, 1998; Gaeta et al. 1994; Valentin 1984; Signorini 1978; Mascarenhas et al. 1971). However, only a few studies were devoted to investigating its climatic impact on the local circulation and most of them were done several years ago (Franchito et al. 1998; Dourado and Oliveira 2000).

The atmospheric circulation in the region near Cabo Frio is influenced by the South Atlantic subtropical high, which causes the prevailing surface wind to blow from the northeast along the coast (Stech and Lorenzzetti 1992). The prevailing large-scale northeasterly winds, together with the southwest–northeast and east–west orientation of the coastline in this region (see Fig. 1), are highly favorable for the development of a strong alongshore wind stress component, which is the main causal mechanism for the occurrence of the upwelling at Cabo Frio.

This atmospheric circulation pattern can be modified by the presence of a frontal system passage with its associated surface winds blowing from the southwest, south, and southeast (Gonzalez-Rodrigues et al. 1992). The large-scale winds also show a diurnal variation. Indeed, preliminary analysis of a surface wind time series observed near Cabo Frio indicates a sea-breeze signal [see, for example, Fig. 3 in Franchito et al. (1998), which shows northwesterly winds becoming more zonal during the afternoon because of the sea breeze]. Taking into account the coastline orientation in the region of Cabo Frio (Fig. 1) and the fact that the prevailing wind blows from the northeast when the upwelling occurs, the larger the inclination of the observed wind in the zonal direction is, the stronger the sea breeze will be. Because the sea-breeze circulation depends on the land–sea temperature difference, the circulation may be stronger when the upwelling occurs in the region. On the other hand, because coastal upwelling is forced by the surface wind, modifications in the surface wind field due to the local sea breeze may also affect the upwelling in the region. Results from model simulations indicate that there is a positive feedback between sea breeze and coastal upwelling at Cabo Frio: the sea breeze is intensified by the enhancement of the land–sea temperature gradient due to the upwelling of cold water, and the intensified sea breeze superimposed on the northeasterly winds in turn increases the upwelling in the region (Franchito et al. 1998).

However, the occurrence of a positive feedback between sea breeze and coastal upwelling at Cabo Frio as suggested by numerical model simulations (Franchito et al. 1998) should be confirmed by observational studies. Thus, the objective of the present paper is to study the relationship between coastal upwelling and local winds at the Cabo Frio region using hourly data of 10-yr SST and surface wind time series data for this region. We propose to analyze the seasonal and interannual variations of the local winds and SSTs and to determine the dominant high-frequency variability scales using a wavelet technique. Such a systematic quantative analysis has not been made earlier.

2. Data and methodology

We use in the present study 10-yr time series of SST and surface wind (magnitude and direction) for the period 1 January 1971 to 31 December 1980. These data correspond to hourly values for the 24 hours of the day. The surface wind (10 m above the surface) dataset is obtained from the Meteorological Station at Cabo Frio, and the SST data are obtained from the Institute of Marine Studies Almirante Paulo Moreira, which is located at the Cabo Frio coast (see Fig. 1).

The Morlet wavelet is used for the time–frequency analyses. This wavelet is a complex exponential modulated by a Gaussian, $e^{i\omega_0}\eta e^{-\eta^2/2}$, with $\eta = t/s$, where t is the time, s is the wavelet scale, and ω_0 is a nondimensional frequency. The computational procedure of the wavelet analysis as described by Torrence and Compo (1998) is used. It is worth mentioning that the wavelet function at each scale s is normalized by $s^{-1/2}$ to have unit energy, which ensures that the wavelet transforms at each scale s are comparable both to each other and to the transform of other time series (Torrence and Compo 1998).

The wavelet analysis is performed for zonal wind and SST time series of 1975–77, a period whose few missing data which have been filled with the climatological values.

To enable the study of the seasonal and interannual variations of the SST and surface wind magnitude data, hourly means for each calendar month and each year (from 1971 to 1980) are calculated.

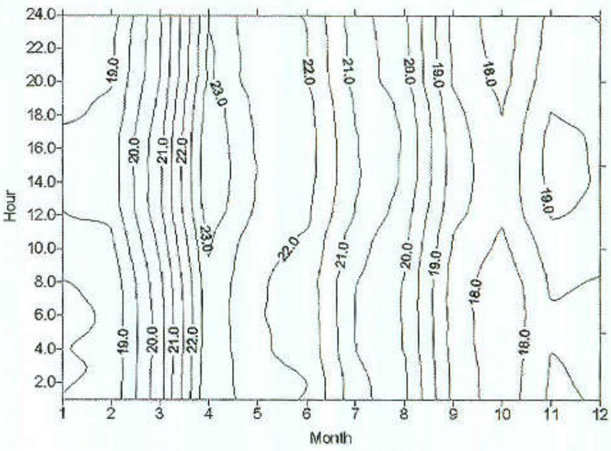

FIG. 2. Hourly mean SSTs (°C) for each month. The values of SST correspond to an average over a 10-yr period (1971–80) at each hour for each calendar month.

3. Results

a. Seasonal variation

As mentioned earlier, the coastal upwelling at Cabo Frio shows seasonal variations (Franchito et al. 1998; Stech et al. 1995). In this section, seasonal variations of SST and local surface winds and their relationships are investigated. Since the larger the inclination of the observed wind is in the zonal direction, the stronger the sea breeze will be, the surface zonal wind variations are focused.

Figure 2 shows the hourly mean SSTs for each month. The SST values are quite low (less than 19°C) from September to February; then they start to increase gradually, reaching the maximum values (between 22.8° and 23.4°C) in April. Figure 2 shows that the SST seasonal variation is strongly dependent on the occurrence of upwelling in the region, with high SST values occurring during the austral autumn and winter and low SST values in the austral spring and summer months. As shown in Fig. 2, from April through the austral summer months a gradual decrease of SST is observed. The minimum values of SST occur in October (between 17.6° and 18.2°C). The minimum SST values in October may be due to the higher frequency of coastal upwelling episodes during the austral spring in the region (Tanaka 1986). The period from April to August is much less favorable for the cold water upwelling because of the high frequency of frontal systems reaching this region during these months. Figure 2 illustrates a diurnal cycle of the SST, with the highest warming in the afternoon hours in all months. Because of the effect of upwelling in the austral spring and summer, the highest SSTs occur in the afternoon hours during the austral autumn

TABLE 1. Amplitude of the diurnal cycle of SST (°C) for each calendar month.

	January	February	March	April	May	June	July	August	September	October	November	December
ΔT	0.74	0.67	0.63	0.58	0.45	0.46	0.56	0.50	0.50	0.57	0.72	0.60

and winter. Table 1 shows the amplitude of the diurnal cycle for each month. The amplitude of the diurnal cycle of SST seems to be associated with the radiative heating because the higher amplitudes are found in the months where the incidence of solar radiation is also higher (Table 1). However, since the local SST is influenced by the local winds in the region, it is necessary to consider the processes of ocean coastal circulation that may be modulated by the diurnal cycle of the atmospheric circulation, as suggested by Rodrigues and Lorenzzetti (2001).

Figure 3 shows the hourly mean wind vector for each month. The prevailing wind is from the northeast in almost all months (except from April to June) because of the presence of the South Atlantic subtropical high. This figure also illustrates the interaction of the sea breeze with the synoptic flow. Because of the differential heating between land and sea, the winds become stronger and more zonal between 0900 and 1800 LT. The sea breeze is stronger from September to March. In these months, as a result of the low SST values (Fig. 2), the nocturnal radiative cooling is not strong enough to invert the land–sea temperature gradient. Thus, in these months, the coastal upwelling inhibits the land-breeze development. From April to June the winds are weaker than in the austral spring and summer months, so a weak land breeze can be noted in the early morning hours (0600–0800 LT). High values of SST and low radiative heating during the day cause a weak sea-breeze circulation from April to August.

Figures 4a and 4b show, respectively, the diurnal variations of the wind speed and zonal wind component for each month. Both the wind speed and zonal component show a well-defined diurnal cycle, with the highest values occurring during the afternoon and the lowest values occurring during the night and the early morning hours. This cycle again demonstrates the influence of the sea-breeze circulation. The wind speed is higher in the months when the upwelling is present. Two maxima of wind speed are noted: one in February and the other around September. As shown in Fig. 2, the SST values are lower in the austral summer and spring seasons. The minimum of wind speed occurs from April to July, when the SST values are higher. The diurnal variation of the zonal component is similar to that noted in the wind speed.

From the results above, it can be concluded that the seasonal variations of SST and surface local wind are closely related. Low values of SST (upwelling case) are associated with the northeasterly winds from Septem-

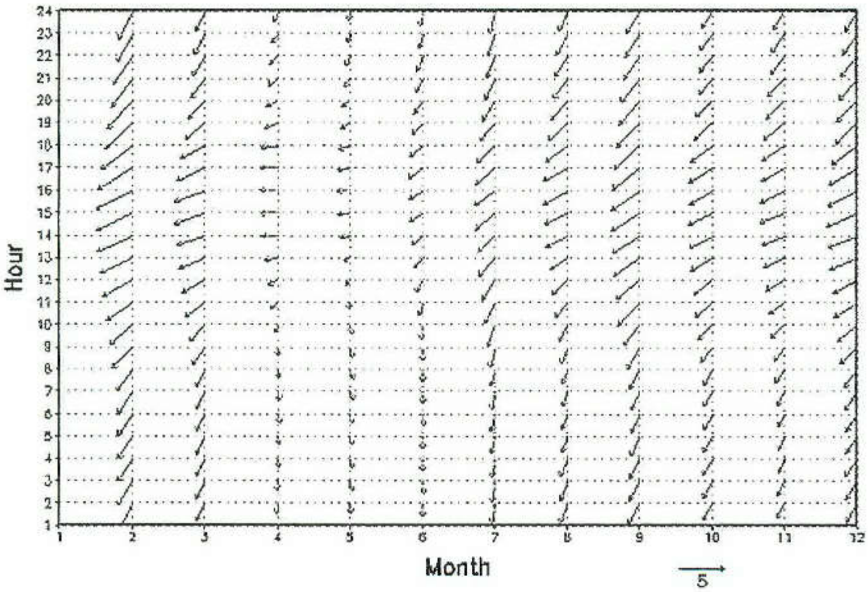

FIG. 3. Hourly mean wind vector for each month. The legend is as in Fig. 2 but for the wind vector. The magnitude of the wind vector (m s^{-1}) is given at the bottom-right of the figure.

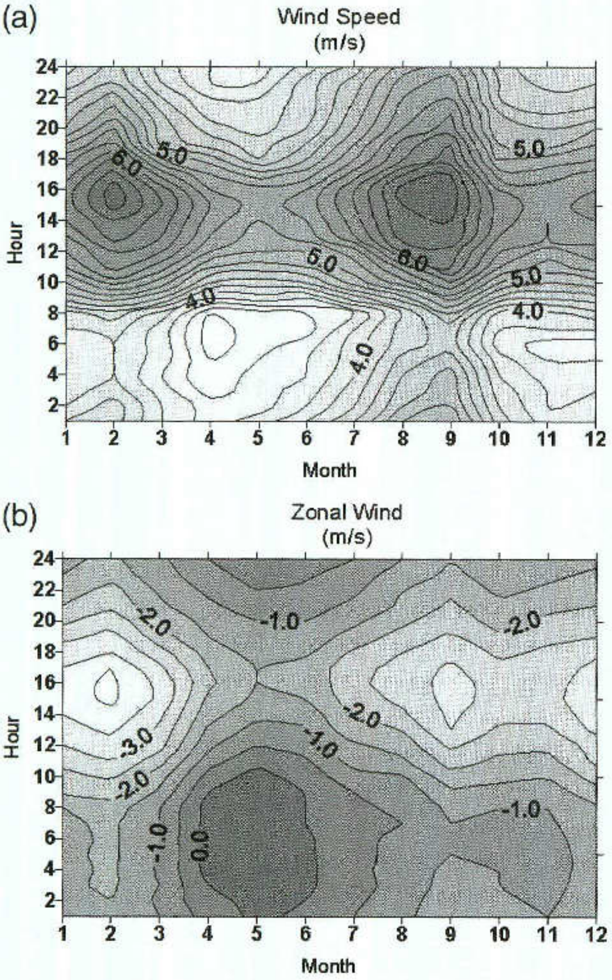

FIG. 4. Diurnal variation of (a) wind speed and (b) zonal wind component ($m\ s^{-1}$). Legends are as in Fig. 2 but for the wind speed and zonal wind component, respectively.

ber to March. The northeasterlies become stronger and more zonal in the afternoon hours, indicating an intensification of the sea breeze. The northeasterly winds (and the sea breeze) in turn are strong during the months when SSTs are low. This suggests a positive feedback between SST and local winds in Cabo Frio region.

b. Interannual variation

Figure 5a shows the hourly mean values of SST for each year. The SSTs are the highest (maximum around 21°C) in 1972–73. Two secondary maxima of SST are noted in 1980 and 1976. The SSTs are lowest in 1977 (minimum around 18°C), but two secondary minima are observed in 1975 and 1979. High values of SST are indicative of low frequency of upwelling in the region (and/or short period of occurrence of upwelling) while low values of SST indicate the opposite.

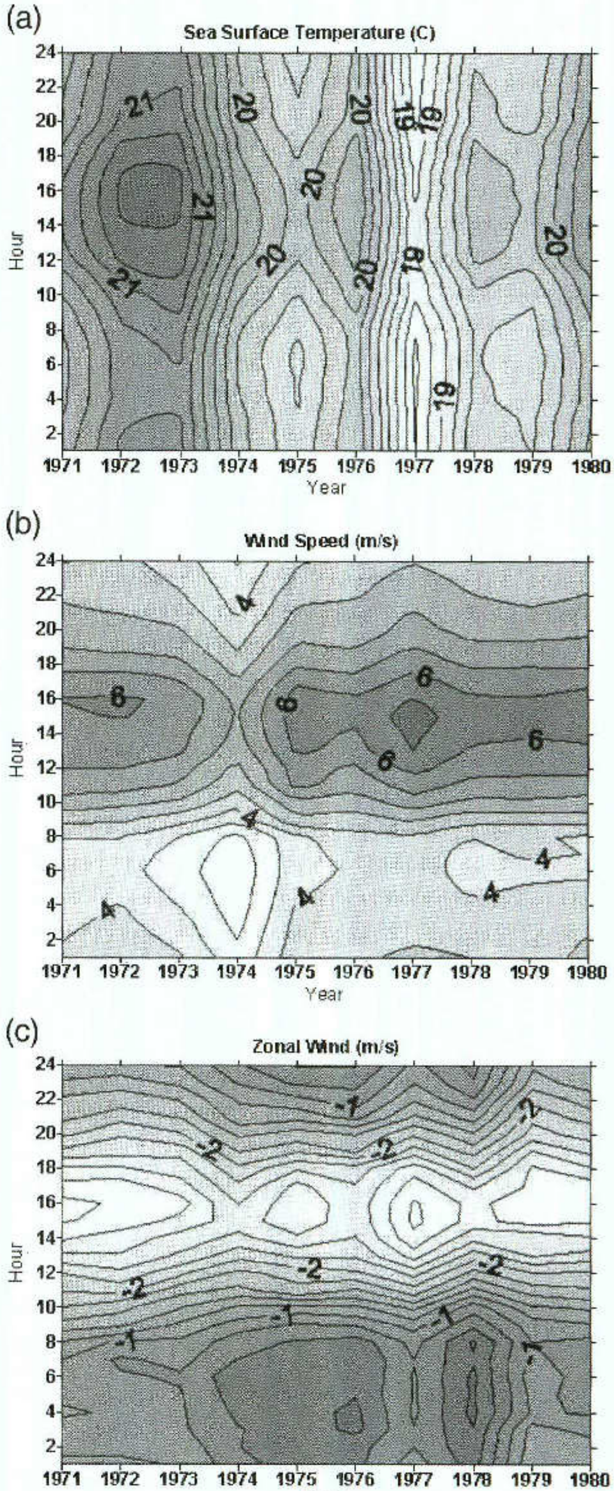

FIG. 5. Hourly mean values of (a) SST (°C), (b) wind speed, and (c) zonal wind component ($m\ s^{-1}$) for each year. The values of SST and wind correspond to an average over the 12 calendar months.

Since the onset and the duration of the upwelling phenomenon at Cabo Frio are associated mainly with the prevailing northeasterly winds in the region and with the passage of frontal systems, the interannual variation of local SST may be related to the large-scale atmospheric variation. The two extremes of SST (maximum and minimum values) in Fig. 5a occur in El Niño years. The years 1972–73 were marked by a strong El Niño event, while the El Niño event was moderate in 1977 (Quinn et al. 1987). The global-scale effects of the El Niño event were much less marked in 1977 than in 1972–73 (Deser and Wallace 1987). Also, the shift of the strong convection region (which is observed in strong El Niño events) was not noted in 1977 (Gage and Reid 1987), suggesting some possible effects of atmospheric teleconnections on South Atlantic SSTs.

Figures 5b and 5c show, respectively, the hourly mean values of the wind speed and the zonal wind component for each year. There are small differences from one year to another. As noted earlier, the wind speed and zonal wind component show a well-defined diurnal cycle. The wind speed shows a maximum in 1977 and a minimum in 1973–1974 (Fig. 5b). Thus, the wind speed seems to be high in the period when the SST is low (Fig. 5a). The maxima of easterly winds occur in 1971, 1975, and 1977 (Fig. 5c) and correspond to periods with low SSTs. The strongest easterlies in 1977 coincide with the lowest SSTs in this year. The meridional winds are weaker in 1972–1973 (figure not shown). Since the coastal upwelling at Cabo Frio depends on the prevailing northeasterly winds, it can be inferred that the large-scale circulation inhibited the upwelling of cold water near the coast in this period. This relationship explains the occurrence of maximum SST values in these years, as shown in Fig. 5a. In the case of 1977, the strong northerlies (figure not shown) are in agreement with the minimum SST values noted in this year.

The results shown in this section suggest that the studied record demonstrates some interannual variability. However, the length of the data record is insufficient to support conclusions regarding El Niño–Southern Oscillation (ENSO) relationships. Further studies with a record longer than 10 yr are needed to make a convincing connection with El Niño and La Niña events.

4. Wavelet analysis

The global wavelet power (GWP) of the zonal wind time series shows strong peaks at 24 and 157 h (approximately 6.6 days), which are significant at the 5% level (Fig. 6b). The corresponding wavelet power spectrum (power or variance) for this variable is displayed in the time–period plot in Fig. 6a. The strong 24-h peak in the GWP of zonal wind time series is due to the significant (at 5% level) 24-h variances observed during almost all months of the 1975–77 period, excluding the months from April to July in 1975 and 1976 and from April to August and again in October 1977. These results clearly illustrate that the sea breeze does occur at Cabo Frio almost year-round, and confirm that this phenomenon shows seasonal and interanual variarions. On the other hand, the significant (at 5% level) 6.6-day variances for zonal wind occur during relatively short time intervals scattered in the 3-yr period (Fig. 6a). The 6.6-day variances for this variable may be related to incursions of cold fronts from higher latitudes into the Cabo Frio region.

Scale-averaged wavelet power (SAP) time series of the zonal wind are constructed for 20–28 and 120–200 h (Fig. 6c). The SAP is obtained from Eq. (24) of Torrence and Compo (1998) and can be used to examine modulations of one time series by another or modulations of one scale by another within the same time series. The SAP series for 20–28 h shows significant amplitudes (in variance units) year-round that are related to the sea breeze in Cabo Frio. It is interesting to note some maximum SAP amplitudes occurring mainly during the austral spring.

The GWP of the SST time series shows a significant (at 5% level) peak at 157 h (approximately 6.6 days; see Fig. 7b), which is due to the significant 6.6 day variances for SST occurring during relatively short time intervals scattered in the 1975–1977 period (Fig. 7a). The SAP series for SST in the two analyzed frequency bands (corresponding to 20–28 and 120–200 h) show significant seasonal variations of the amplitudes, with the largest values occurring during summer and minimum values during winter (Fig. 7c). The variations for the two frequency bands are almost synchronous during the 1975–76 period. During 1977, the synchronous behavior of the SAP amplitudes is not noted. Figure 8 shows a closer detail of Fig. 7, namely, the local wavelet power spectrum and GWP for the period 2–64 h. The GWP of the SST time series shows a significant peak at 24 h (Fig. 8b), which is due to the significant 24-h variances during the summer and the beginning of the autumm months of the 1975–77 period (Fig. 8a).

The wavelet analyses above are in agreement with the results of section 3a, which showed that the upwelling strongly modulates the sea breeze at Cabo Frio. In the austral spring and summer the upwelling increases the sea-breeze circulation in the region, while from April to August the absence of the upwelling reduces the intensity of the local winds.

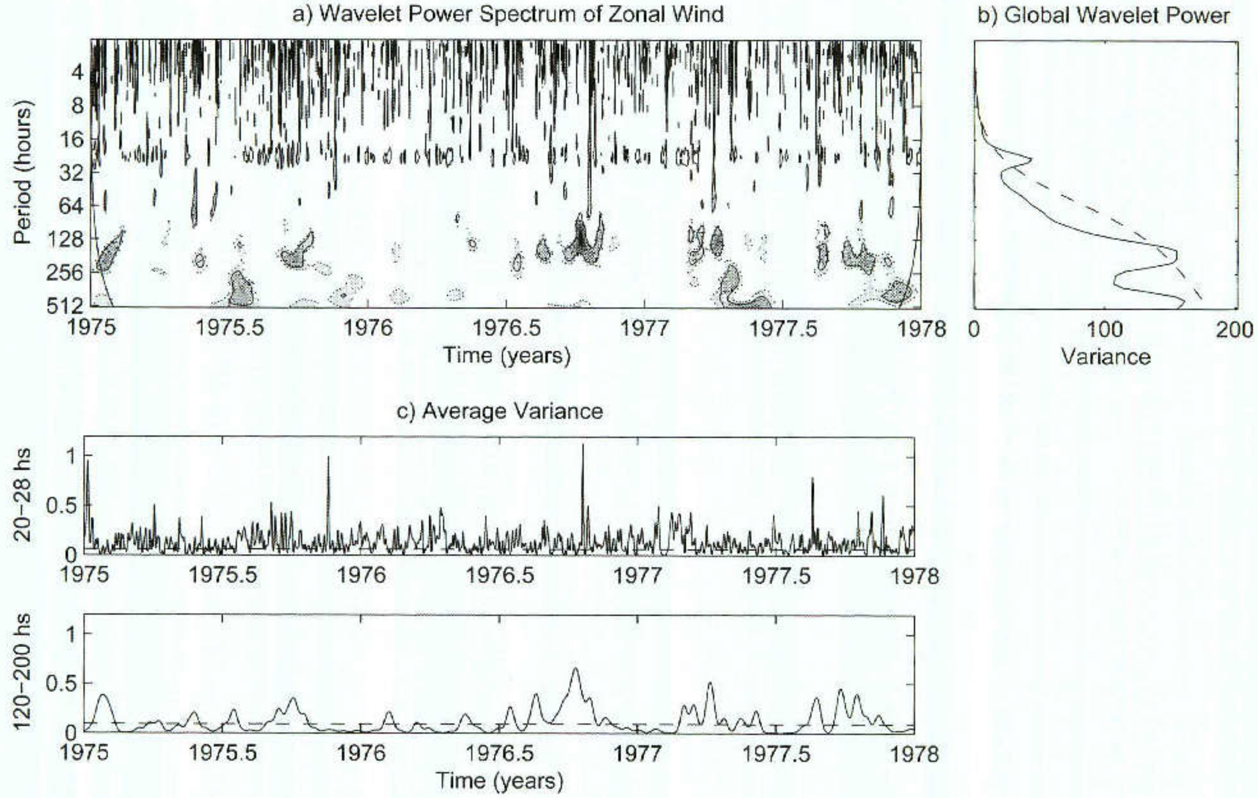

FIG. 6. (a) Local wavelet power spectrum of the surface zonal winds for the 1975–77 period normalized by $1/\sigma^2$ ($\sigma^2 = 7.7\ m^2\ s^{-2}$), (b) GWP (in variance units), and (c) SAP time series for 20–28 and 120–200-h scales. The shaded contours in (a) are at normalized variances varying from 30 to 90 with intervals of 30. The closed contours in (a) encompass significant variances at 95% confidence level and the two small regions where the edge effects are important are in the lower-left and lower-right corners in (a). The dashed curve in (b) is the significance at 5% level assuming a red-noise spectrum. The dashed line in (c) indicates the minimum significant value at the 95% confidence level.

5. Summary and conclusions

In this paper the relationships between the coastal upwelling and the local winds at Cabo Frio are studied. For this purpose, 10 yr of hourly SST and surface wind time series data are used. The seasonal variations of SST and surface local wind are closely related. Low values of SST (upwelling case) are associated with the northeasterly winds from September to March (values less than 20°C), with minimum in October. The SSTs gradually increase, reaching maximum values in April and exhibiting values higher than 22°C from April to June. The northeasterlies become stronger and more zonal in the afternoon hours, indicating an intensification of the sea breeze. Sea-breeze circulation occurs during the entire year in the region. The sea breeze is stronger from September to March and weaker from April to June. This variation shows the role of the upwelling in controlling the temperature difference between land and sea, and consequently, the sea-breeze circulation. From September to March, because of the low values of SST, the land-breeze circulation is inhibited in the region. Thus, the results indicate a positive feedback between SST and local winds in the region: northeasterly winds are highly favorable for the occurrence of the upwelling in the region, and consequently cause SST variations; low SSTs caused by upwelling enhance the sea-breeze circulation. These results are in agreement with earlier modeling studies (Franchito et al. 1998; Rodrigues and Lorenzzetti 2001).

The SST shows interannual variations with high values in 1972 and 1973 (strong El Niño event) and low values in 1977 (moderate El Niño event), suggesting some possible effect of atmospheric teleconnections on South Atlantic SSTs. The surface winds show high values during the years when the SSTs are low. Since the upwelling phenomenon at Cabo Frio is associated with the prevailing northeasterly winds, it can be inferred that the large-scale circulation inhibited the upwelling of cold water near the coast in 1972–1973. This event explains the maximum SST values noted in these years.

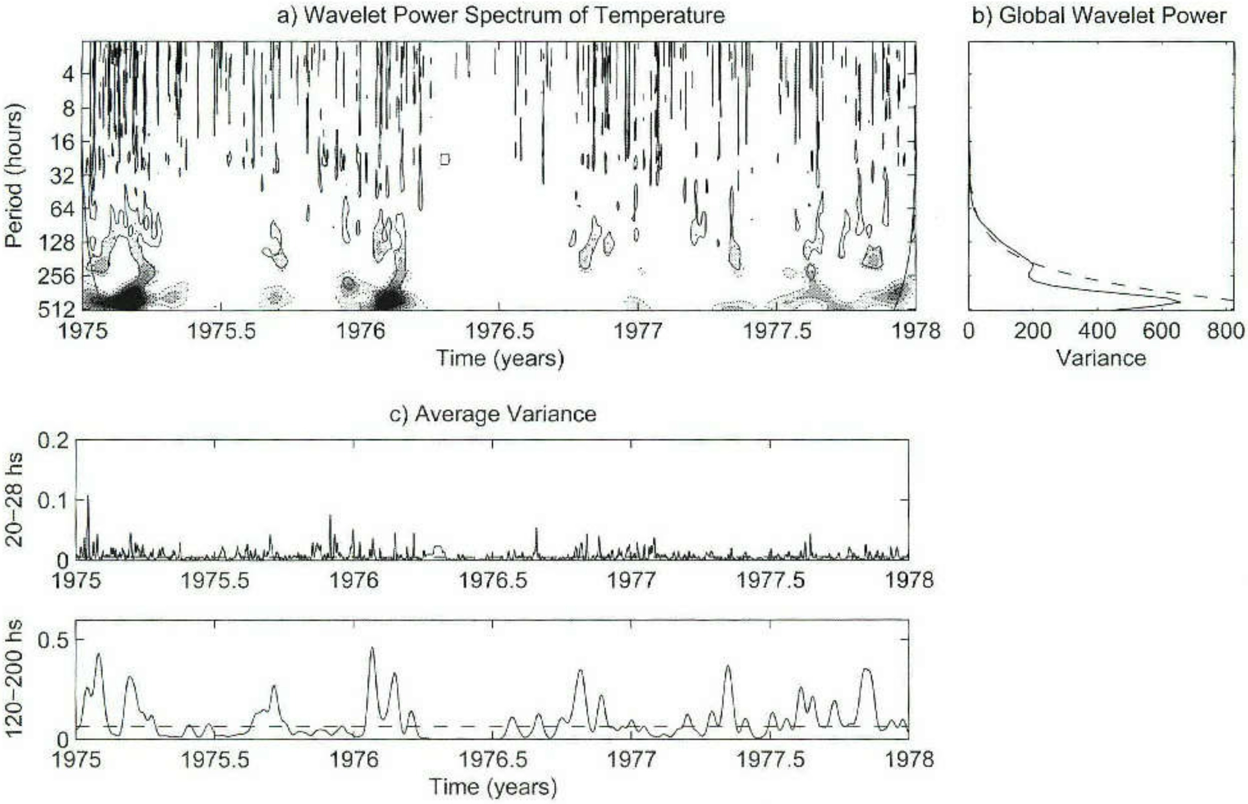

FIG. 7. As in Fig. 6 but for the SST time series (σ^2 = 10.4°C^2), with the shaded contours in (a) being at normalized variances varying from 40 to 120 with intervals of 40.

In the case of 1977, strong northerlies and associated minimum SST values are indicative of a feedback mechanism between the upwelling and the local winds in Cabo Frio. Although there is some interannual variability in the record, further studies with a record longer than 10 yr are needed to make a convincing connection with El Niño and La Niña events.

The wavelet analyses of the zonal wind and SST time series of the 1975–77 period show strong peaks at 24 and 157 h (approximately 6.6 days), which are related to the sea breeze and incursion of cold fronts, respectively. These analyses also indicate that the sea breeze occurs at Cabo Frio almost year-round, and confirm both the seasonal variations noted for this phenomenon in the climatological analysis and the relationships with the coastal upwelling in the region.

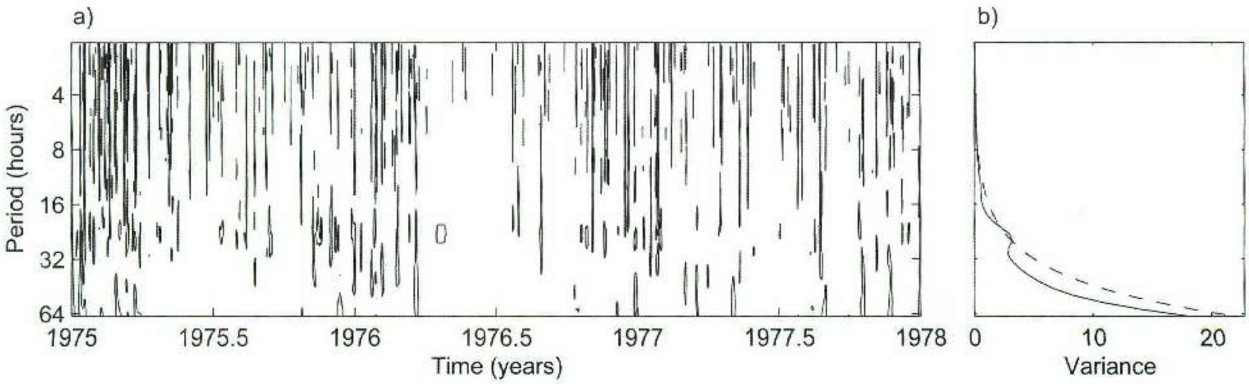

FIG. 8. Detail of the local wavelet power spectrum and GWP of Fig. 7 for the period 2–64 h. Display is the same as Fig. 7.

REFERENCES

Campos, E. D. J., J. E. Gonçalves, and Y. Ikeda, 1995: Water mass characteristics and geostrophic circulation in the South Brazil Bight: Summer of 1991. *J. Geophys. Res.*, **100** (C9), 18 537–18 550.

Deser, C., and J. M. Wallace, 1987: El Niño events and their relation to the Southern Oscillation 1925–1986. *J. Geophys. Res.*, **92** (C13), 14 189–14 196.

Dourado, M. S., and A. P. Oliveira, 2000: Observational study of the atmospheric and oceanic boundary layer over the Atlantic Ocean. *Rev. Bras. Oceanogr.*, **49**, 49–59.

Franchito, S. H., V. B. Rao, J. L. Stech, and J. A. Lorenzzetti, 1998: The effect of coastal upwelling on the sea-breeze circulation at Cabo Frio, Brazil: A numerical experiment. *Ann. Geophys.*, **16**, 866–881.

Gaeta, S. A., O. L. Brino, and S. M. M. S. Ribeiro, 1994: Distributions of nitrate, chlorophyll *a*, and primary productivity in the southwestern region of the South Atlantic during summer. *Southwestern Atlantic Physical Oceanography Workshop Report*, E. Campos, Ed., University of São Paulo, 57–60.

Gage, K. S., and G. C. Reid, 1987: Longitudinal variations in tropical tropopause properties in relation to tropical convection and El Niño–Southern Oscillation events. *J. Geophys. Res.*, **92** (C13), 14 197–14 203.

Gonzales-Rodrigues, E., J. L. Valentin, D. L. André, and S. A. Jacob, 1992: Upwelling and downwelling at Cabo Frio (Brazil): Comparison of biomass and primary production responses. *J. Plankton Res.*, **14**, 289–306.

Mascarenhas, A. S., Jr., L. B. Miranda, and N. J. Rock, 1971: A study of the oceanographic conditions in the region of Cabo Frio. *Fertility of the Sea*, J. D. Costlow, Ed., Gordon and Breach, 285–308.

Matsuura, Y., 1996: A probable cause of retruitment failure of Brazilian sardine (*Sardinella aurita*) population during the (1974/75) spawning season. *S. Afr. J. Mar. Sci.*, **17**, 29–35.

——, 1998: Brazilian sardine (*Sardinella aurita*) spawning in the southeast bight over the period 1976/93. *Rev. Bras. Oceanogr.*, **46**, 33–43.

Quinn, W. H., V. T. Neal, and S. E. Artunez de Mayolo, 1987: El Niño occurrences over the past four and half centuries. *J. Geophys. Res.*, **92** (C13), 14 449–14 461.

Rodrigues, R. R., and J. A. Lorenzzetti, 2001: A numerical study of the effects of bottom topography and coastline geometry on the southeast Brazilian coastal upwelling. *Cont. Shelf. Res.*, **21**, 371–394.

Signorini, S. R., 1978: On the circulation and volume transport of the Brazil current between the Cape of São Tomé and Guanabara Bay. *Deep-Sea Res.*, **25**, 481–490.

Stech, J. L., and J. A. Lorenzzetti, 1992: The response of the South Brazil Bight to the passage of wintertime cold fronts. *J. Geophys. Res.*, **97**, 9507–9520.

——, ——, and C. L. da Silva Jr., 1995: Observação por satélite da ressurgência de Cabo Frio. *Memórias do VII Simpósio Latinoamericano de Percepción Remota*, Puerto Vallarta, México, Sociedad Latinoamericana de Percepción Remota y Sistemas de Información Espacial, 269–275.

Tanaka, K., 1986: Analysis on 10-year time series data: Coastal upwelling in Cabo Frio (in Portuguese). INPE Rep. INPE-3812-RPE/502, Instituto Nacional de Pesquisas Espacias, 52 pp.

Torrence, C., and G. P. Compo, 1998: A practical guide to wavelet analysis. *Bull. Amer. Meteor. Soc.*, **79**, 61–78.

Valentin, J. L., 1984: Analyses des paramètres hydrobiologiques dans la remontée de Cabo Frio (Brésil). *Mar. Biol.*, **82**, 259–276.

——, D. L. André, and S. A. Jacob, 1987: Hydrobiology in the Cabo Frio (Brazil) upwelling: Two-dimensional structure and varibility during a wind cycle. *Cont. Shelf Res.*, **7**, 77–88.