NOTES AND CORRESPONDENCE

Isthmus of Tehuantepec Wind Climatology and ENSO Signal

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13 June 2002 and 14 February 2003

ABSTRACT

The statistical characteristics of the winds at the Isthmus of Tehuantepec and their seasonal and interannual variability are studied through the analysis of several datasets and a reconstruction of the winds for a 31-yr period. Observations show that the long-term monthly mean wind speeds and frequency of occurrence of northerly winds have a strong seasonal signal, with maximum values during December–January, minimum during May–June, and a relative maximum in July. The frequency distribution of wind speed is bimodal, a feature that is closely related to the wind direction, with northerly winds being stronger. Based on these results and the close relationship between the across-Isthmus pressure differences and the local winds, a statistical model is developed to get a reconstruction of 12-hourly winds through the Isthmus of Tehuantepec for 1964–95. The model reproduces fairly well the main characteristics of the observed winds: the bimodal distribution of the wind speed and the seasonal signal in the wind speed and frequency of occurrence of northerly winds. Reconstructed winds show that the high frequency of northerly winds in July is associated with weaker winds than those observed in winter. The summer maximum seems to be related with the westward displacement and strengthening of the Bermuda high during this time of the year. Based on the model results, the long-term monthly mean wind speeds show larger values during El Niño years compared with La Niña years. During La Niña years winds are significantly weaker than in neutral years for February–March, June–September, and November, and the percentage of occurrence of northerly winds is significantly lower than in neutral years from June to November. The larger occurrence of northerly winds during El Niño years compared with neutral years is statistically significant only for May and September.

1. Introduction

The Isthmus of Tehuantepec, located in southeast Mexico, is a narrow region that separates the Gulf of Mexico from the Pacific Ocean (Fig. 1). The mountain range Sierra Madre del Sur has a mean height of 2000 m above sea level, but at the central part of the Isthmus the mean height drastically drops to 250 m forming a gap of approximately 40-km width known as the Chivela Pass. In this region, strong gap winds are generated as a result of the combination of large-scale meteorological conditions and local topographic characteristics. These strong winds, known as Tehuantepecers (Hurd 1929; Parmenter 1970; Roden 1961), Tehuanos (Alvarez et al. 1989; Trasviña et al. 1995), or Nortes (Lavín et al. 1992; Magaña et al. 1999b; see Schultz et al. 1997 for a discussion of these names) spread hundreds of kilometers into the Pacific producing a considerable drop of the sea surface temperature in the Gulf of Tehuantepec (Roden 1961; Stumpf 1975; Barton et al. 1993), generating large oceanic eddies (Stumpf and Legeckis 1977; Clarke 1988; McCreary et al. 1989; Barton et al. 1993; Trasviña et al. 1995; Gallegos and Barberán 1998), and increasing the amount of nutrients and phytoplankton in the euphotic zone (Lluch-Cota et al. 1997; Müller-Karger and Fuentes-Yaco 2000).

Previous studies have shown that high pressure systems formed over the Great Plains of North America move southeastward crossing the United States, some

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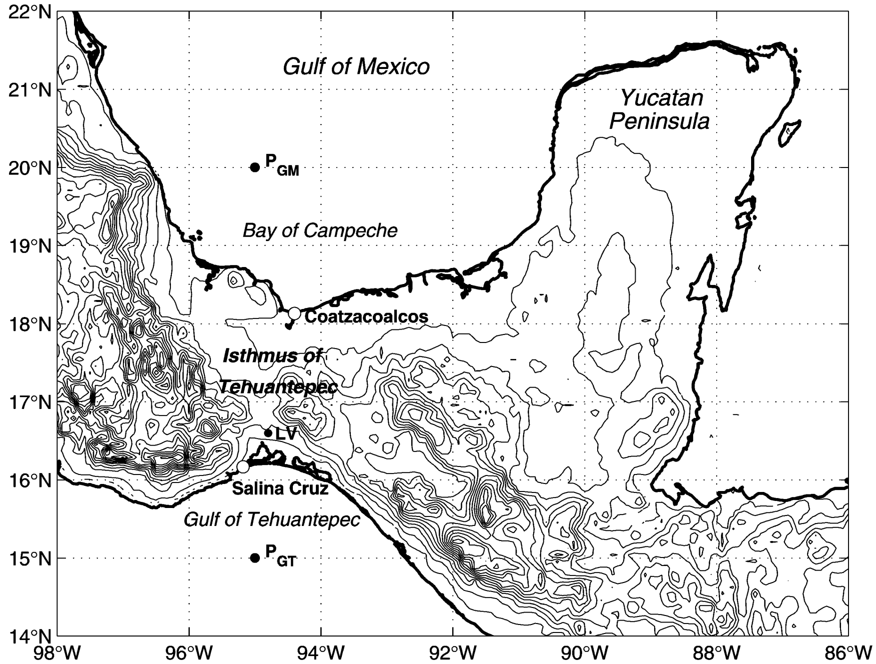

FIG. 1. Location of the Isthmus of Tehuantepec and sites of interest. The first two contour lines correspond to 50 and 200 m, respectively, and the following contours are every 250 m. Here, LV stands for La Venta station.

getting as far as the Bay of Campeche developing a large pressure difference between the Gulf of Mexico and the Gulf of Tehuantepec (Hurd 1929; Roden 1961; Stumpf and Legeckis 1977; DiMego et al. 1976; Lavín et al. 1992; Schultz et al. 1997, 1998; Chelton et al. 2000a,b). This pressure gradient produces strong northerly winds through the mountain gap that may last for several hours to a few days, with wind speeds often exceeding 20 m s^{-1} and gusts up to 30 m s^{-1}, typically followed by periods of light winds. Although Tehuanos are produced by a pressure gradient, they are not geostrophic winds because their direction is constrained by the topography. Once the winds flow out the mountain corridor, they are no longer influenced by the topography and predominantly follow an inertial trajectory, turning anticyclonically westward after leaving the coast (Clarke 1988; Bourassa et al. 1999; Schultz et al. 1997). Away from the head of the Gulf of Tehuantepec, a symmetric, fan-shaped pattern of the wind jet is observed (Barton et al. 1993; Trasviña et al. 1995; Steenburgh et al. 1998), becoming gradually more geostrophically balanced with increasing distance from the coast (Chelton et al. 2000b).

Several studies have characterized the seasonal and interannual variability of cold surges of midlatitude origin that penetrate southward (e.g., DiMego et al. 1976; Schultz et al. 1997 and references within; Schultz et al. 1998), some of which are responsible for the generation of the Tehuanos. In general, these studies conclude that there is considerable interannual variability in the frequency of cold frontal passages in Mexico and Central America, and that they are more frequent and intense during winter, with maxima in January and February.

In this study, we analyze the statistical characteristics of the winds at the Isthmus of Tehuantepec and review their seasonal and interannual variability. Based on the fact that there is a close relationship between the across-Isthmus pressure gradients and the local winds, a statistical model is developed to get a reconstruction of 12-hourly winds from sea level pressure fields for the period 1964–95. Model results are used to analyze the interseasonal and interannual variability of the winds and their relationship with the ENSO phases. Section 2 describes the data used for the study; in section 3, the main characteristics of the observed winds and their relationship with the pressure differences across the Isthmus are discussed. Section 4 describes the model used to estimate the winds from the observed pressure fields, and in section 5 the 30-yr wind climatology and ENSO signal are analyzed. A summary and conclusions are presented in section 6.

2. Data

Due to the unavailability of a continuous series of wind data at the Isthmus of Tehuantepec, different data sources are used for this study. Hourly wind and sea level pressure data at Salina Cruz and sea level pressure data at Coatzacoalcos observatories obtained from the Servicio Meteorológico Nacional (Mexican National

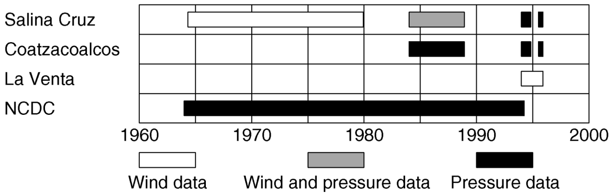

FIG. 2. Source and sampling periods of the data series.

Weather Service), high-quality wind data from La Venta station located at the southern end of the wind corridor, and 30 yr of mean sea level pressure records from the National Climatic Data Center (NCDC) are analyzed. The period of time covered by each data series is shown in Fig. 2. In addition, data from the National Centers for Environmental Prediction (NCEP) reanalysis provided by the National Oceanic and Atmospheric Administration–Cooperative Institute for Research in Environmental Sciences (NOAA–CIRES) Climate Diagnostics Center, Boulder, Colorado, from their Web site at http://www.cdc.noaa.gov/, are used to analyze the causes of the seasonal evolution of the pressure gradients in the Isthmus.

The observatory of Salina Cruz in Oaxaca is located at 16°10′15″N and 95°10′45″W, at an altitude of 6 m above mean sea level. This observatory is 300 m away from the Gulf of Tehuantepec shore and approximately 50 km SSW from the mountain gap (see Fig. 1). The wind data series extends from 1964 to 1988 with some periods of missing data due to instrument failure or maintenance (see Fig. 2). From 1964 to 1974 the series had three daily records (at 0300, 1300, and 2000 UTC), from 1975 to 1979 there were eight records (at 0000, 0300, 0600, 0900, 1200, 1500, 1800, and 2100 UTC), and from 1984 to 1988 there were hourly records. However, these records are not complete, having missing data

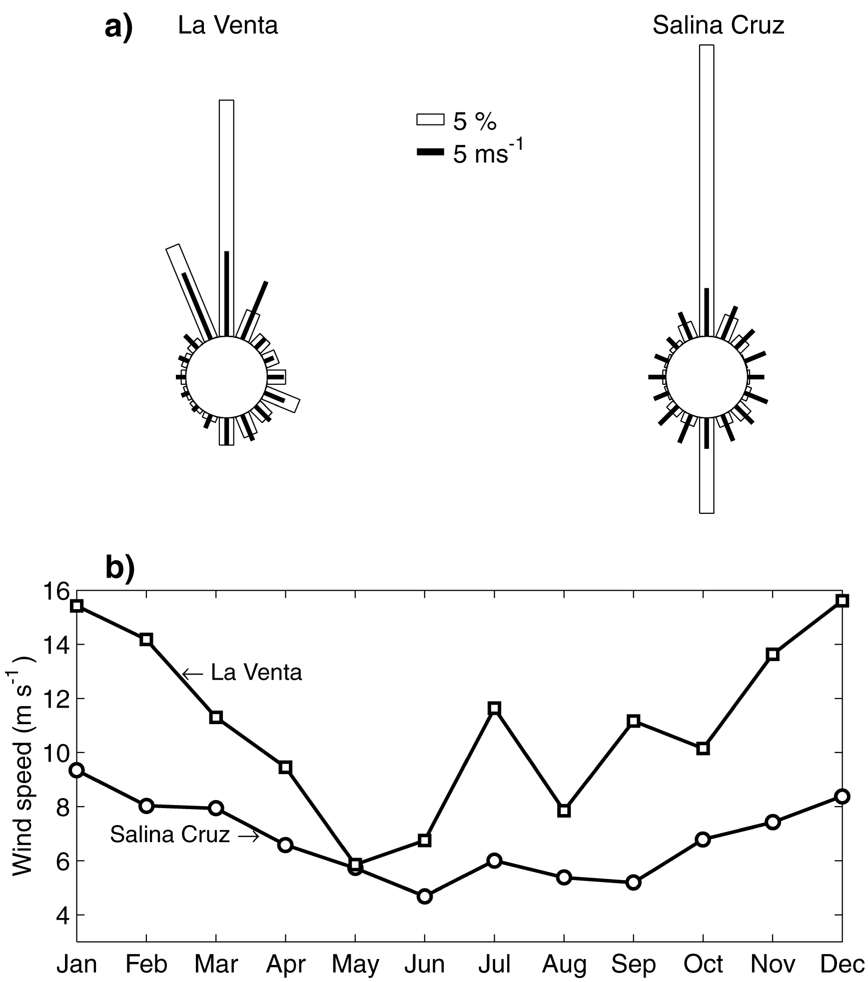

FIG. 3. (a) Frequency distributions of wind direction (every 22.5°) for La Venta (1994–95) and Salina Cruz (1984–88) from hourly data. Blank bars are proportional to the frequency of occurrence and thick lines are proportional to the mean speed of the corresponding wind direction. (b) Long-term monthly mean wind speeds from observations at La Venta (26.5 m) and Salina Cruz (10 m).

mostly between 0600 and 1200 UTC. The winds were measured 10 m above the ground using a conventional anemograph. The La Venta anemometric station was located over the Gulf of Tehuantepec coastal plain, close to the southern end of the mountain gap (see Fig. 1). Wind speed and direction were measured at 26.5 m above the ground, with complete hourly data records from January 1994 to December 1995.

Hourly records of atmospheric sea level pressure for the periods October 1983–December 1988, January–November 1994, and July–December 1995 from Salina Cruz and Coatzacoalcos observatories are used to compute the pressure differences across the Isthmus and to analyze their relationship with the winds. The observatory of Coatzacoalcos in Veracruz is located at 18°08′N and 94°24′W, at an altitude of 14 m above mean sea level (see Fig. 1). The sea level pressure fields from NCDC (Global Historical Fields, version 1.0) has twice-daily records, at 0000 and 1200 UTC, from January 1964 to April 1994 on a 5° × 5° latitude–longitude grid. The values at vertices 20°N, 95°W (P_{GM}) and 15°N, 95°W (P_{GT}) (see Fig. 1) are used to calculate 30 yr of pressure differences between the Gulf of Mexico and the Gulf of Tehuantepec.

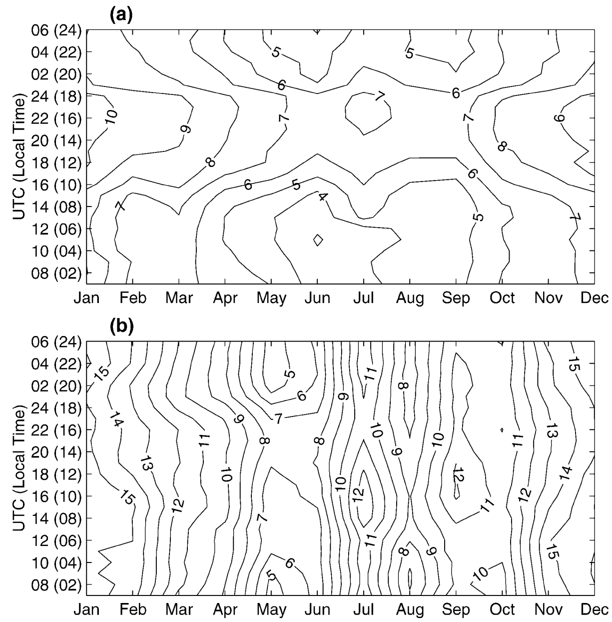

FIG. 4. Hourly mean wind speeds (m s^{-1}) throughout the year from observations at (a) Salina Cruz (1984–88), and (b) La Venta (1994–95).

3. Observations

a. The annual cycle

In order to determine the statistical characteristics of the winds once they have passed through the mountain gap, the observed wind speed and direction at La Venta and Salina Cruz are analyzed. The frequency distributions of wind direction show that northerly winds are dominant and stronger than winds from other directions (Fig. 3a), although the average intensity for each wind direction is more variable in La Venta than in Salina Cruz. Jointly, NNW, N, and NNE winds were recorded 61.3% of the time at Salina Cruz and 67.4% at La Venta. Remarkable differences between the two sites are the occurrence of southerly winds, 17.6% at Salina Cruz against 5.0% at La Venta, and the occurrence of calm winds (not shown), recorded 0.8% of the time at La Venta and 6.4% at Salina Cruz. The higher number of calm winds at Salina Cruz is due, in part, to the high threshold response of the measuring gauge used. The comparison has the limitation that the data do not correspond to the same sampling period.

The long-term monthly mean wind speeds show that the winds are stronger at La Venta than at Salina Cruz throughout the year (Fig. 3b). The annual mean wind speed at Salina Cruz is 6.9 m s^{-1} with a standard deviation of 4.0 m s^{-1}, and 11.2 m s^{-1} at La Venta with a standard deviation of 6.8 m s^{-1}. The seasonal variability of the wind speed at both sites shows more intense winds during winter, with maxima in December and January, and decreasing toward the summer, with a minimum in May at La Venta and in June at Salina Cruz. These results agree with those of Roden (1961) for Salina Cruz for 1928–47. An interesting feature of the annual cycle is the relative maximum of wind speed observed during July, which is discussed in section 5.

The differences between the wind fields at Salina Cruz and La Venta seems to be caused by the location of Salina Cruz, which is off the axis of the wind jet. Results from Steenburgh et al. (1998) show that, along the coastline of the Gulf of Tehuantepec, the wind magnitude decreases considerably a few tens of kilometers away from the axis of the jet. As a consequence, the winds are weaker at Salina Cruz than at La Venta, although both sites are strongly influenced by intense gap winds. Also, there is a variation of the wind speed with height (Justus and Mikhail 1976), so it is expected that winds measured at an altitude of 26.5 m in La Venta be more intense than the winds at 10 m. The wind speed difference between Salina Cruz and La Venta cannot be explained by a sea breeze because there is a maximum in the diurnal signal at Salina Cruz from 1800 to 0200 UTC (Fig. 4).

b. Wind speed and wind direction relationship

A characteristic of the wind speed at La Venta is that its frequency distribution is bimodal, with maxima around 4.0 m s^{-1} and 16.5 m s^{-1} (Fig. 5). This bimodality is strongly related to the wind direction, in that the more intense winds are those from the NNW, N, and NNE. These results suggest dividing the data according to their direction: winds from NNW, N, and NNE are combined into a group called the north-range, and winds

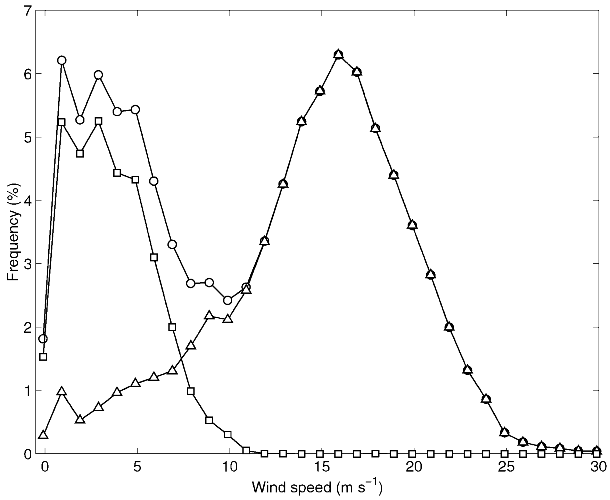

FIG. 5. Frequency distribution of obs wind speed at La Venta considering all winds (circles), winds from NNW, N, and NNE (triangles), and winds from other directions (squares).

from all other directions are combined into the non-north-range group. Observed mean wind speed during 1994 and 1995 show that north-range winds are considerably stronger than the non-north-range winds for every month (Table 1). From November to February the north-range winds occur more than 75% of the time, with maximum frequencies during November and December and with maximum intensity in January. From March, a substantial decrease in the occurrence of north-range winds is observed; however, their intensity remains high until April. During late spring and summer (May–September) the winds are less intense, but a relative maximum is observed in July showing an increase in the frequency and intensity of the north-range winds.

Nonetheless, it is important to note the large interannual variability. There is a remarkable difference between the frequency of occurrence of north-range winds during the summer of 1994 (71%) and 1995 (47%). This difference is more evident during May and August, showing considerably greater percentages of occurrence of north-range winds and associated mean wind speed in 1994 than in 1995.

c. Wind–pressure relationship

Previous studies have shown that strong northerly winds at the Isthmus of Tehuantepec are related with high pressure systems of midlatitude origin that penetrate into the Gulf of Mexico (e.g., DiMego et al. 1976; McCreary et al. 1989; Schultz et al. 1997, 1998; Chelton et al. 2000a,b). In this section, the relationship between

TABLE 1. Monthly, annual, and winter–summer mean wind speeds for La Venta (1994–95) considering all winds (mean) and winds grouped in north-range and non-north-range. The frequency of occurrence for each group of winds is in columns: % north and % non-north, respectively. Note: Winter includes months from Oct to Apr, and summer from May to Sep.

Yr	Period	Mean (m s^{-1})	% North	North (m s^{-1})	% Non-north	Non-north (m s^{-1})
1994	Jan	16.0	79	19.4	21	3.5
	Feb	14.1	80	17.2	20	3.5
	Mar	10.8	53	17.9	47	3.3
	Apr	9.4	52	15.2	48	3.4
	May	7.4	57	11.0	43	3.4
	Jun	6.3	45	11.6	55	2.6
	Jul	12.0	84	13.8	16	3.2
	Aug	10.4	80	12.5	20	2.6
	Sep	12.5	87	13.9	13	3.1
	Oct	9.8	65	13.6	35	3.2
	Nov	13.6	88	15.0	12	3.7
	Dec	16.2	94	16.9	6	4.3
	Annual	11.5	71	15.0	29	3.1
1995	Jan	14.8	76	18.4	24	3.6
	Feb	14.1	78	16.9	22	4.2
	Mar	11.8	57	16.7	43	5.1
	Apr	9.5	40	16.2	60	5.1
	May	4.3	5	6.1	95	4.3
	Jun	7.4	51	10.4	49	4.2
	Jul	11.3	76	13.9	24	3.4
	Aug	5.3	30	10.6	70	3.0
	Sep	9.9	77	11.7	23	3.7
	Oct	10.5	62	13.8	38	5.1
	Nov	14.0	82	16.3	18	3.0
	Dec	15.0	82	17.2	18	5.2
	Annual	10.6	59	15.0	41	4.2
	Summer 1994	9.4	71	12.8	29	3.0
	Winter 1994–95	12.5	71	16.3	29	4.4
	Summer 1995	7.5	47	11.9	53	3.8

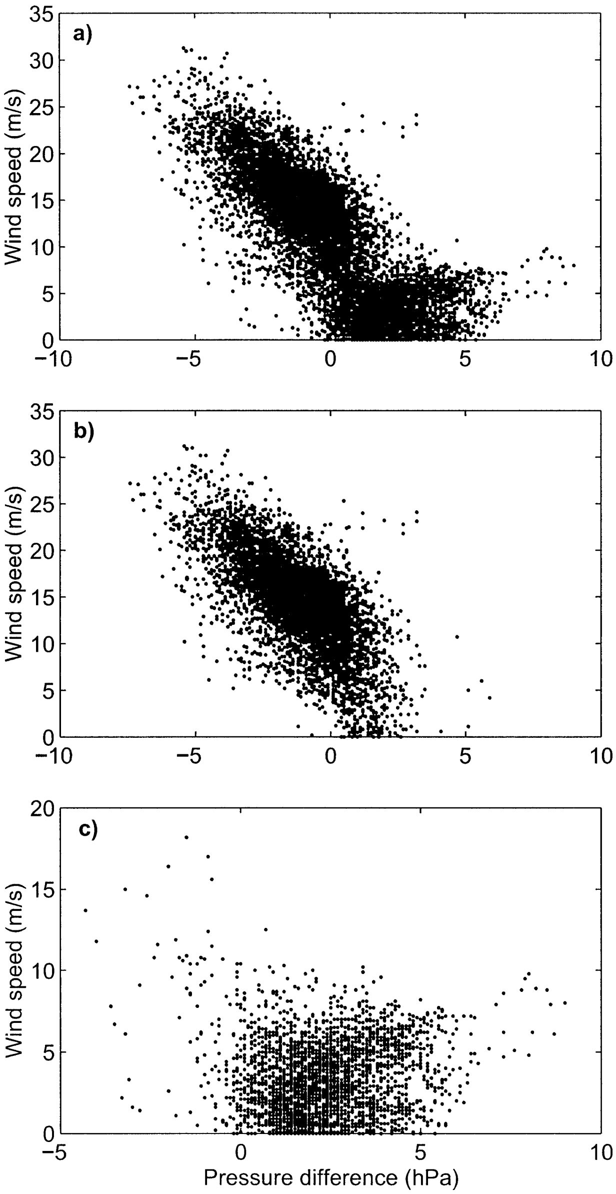

FIG. 6. Scatterplots of wind speed at La Venta and sea level pressure difference between Salina Cruz and Coatzacoalcos, considering (a) all winds, (b) north-range winds, and (c) non-north-range winds, as defined in the main text.

the winds at La Venta and the across-isthmus pressure gradients is analyzed using the pressure differences between the Salina Cruz and Coatzacoalcos observatories.

The data series of pressure differences between the observatories (hereafter $\Delta P_{\mathrm{SC-C}}$ = pressure at Salina Cruz minus pressure at Coatzacoalcos) has simultaneous records with the La Venta wind series over a period of 17 months: January–November 1994 and July–December 1995. The scatterplot of these two variables shows two clusters of points: one with points mostly associated with negative values of $\Delta P_{\mathrm{SC-C}}$, and the other with points mostly associated with positive values of $\Delta P_{\mathrm{SC-C}}$

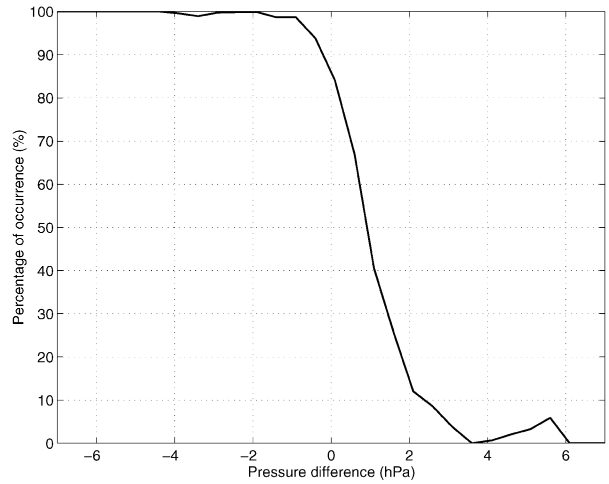

FIG. 7. Percentage of occurrence of north-range winds at La Venta as a function of the pressure difference between Salina Cruz and Coatzacoalcos.

(Fig. 6a). The scatterplot of wind speed at Salina Cruz and $\Delta P_{\mathrm{SC-C}}$ presents a similar behavior (not shown). These clusters of points are related to the wind direction, as can be seen when data are grouped by ranges. The scatterplot of the north-range wind speed and $\Delta P_{\mathrm{SC-C}}$ (Fig. 6b) shows strong winds mainly associated with large negative values of $\Delta P_{\mathrm{SC-C}}$, that is, when the pressure in Salina Cruz is considerably lower than in Coatzacoalcos, whereas the corresponding scatterplot for the non-north-range winds (Fig. 6c) shows that they are mostly associated with positive values of $\Delta P_{\mathrm{SC-C}}$. The correlation between $\Delta P_{\mathrm{SC-C}}$ and the meridional wind component is 0.84, similar to the value 0.83 obtained by Chelton et al. (2000b) for the correlation between the pressure gradient across the isthmus and the major-axis component of the gap outflow for October 1996–June 1997.

The percentage of occurrence of north-range winds as a function of the magnitude of $\Delta P_{\mathrm{SC-C}}$ is displayed in Fig. 7. This plot shows percentages above 90% for values of $\Delta P_{\mathrm{SC-C}}$ lower than -0.4 hPa, and below 10% for values greater than 2.2 hPa. Therefore, there is an interval of values of pressure difference, approximately from 0 to 2 hPa, for which winds from any direction can occur. Within this interval, the value of the pressure difference is not enough to determine if the wind comes from the north. However, in a probabilistic sense, wind direction can be estimated as a function of the pressure difference using the frequency distribution function shown in Fig. 7. These results are the basis to construct a simple model to estimate the wind speed from the pressure differences across the isthmus.

4. The model

The results obtained so far suggest grouping the winds in north-range (winds from the Gulf of Mexico through

TABLE 2. Linear regression parameters (m, b) and root-mean-square error (rmse) for the north-range and non-north-range winds.

Parameter	North-range	Non-north-range
m	−2.17	0.37
b	11.82	2.32
rmse (m s^{-1})	3.63	2.05

the isthmus) and non-north-range (winds from all other directions), and have shown that there is a clear relationship between the winds and the pressure gradients across the isthmus. Using a linear regression model, the wind speed for each range (WS_r) can be estimated from ΔP_{SC-C} as follows:

$$WS_r = m_r \Delta P_{SC-C} + b_r + A_r,$$

where m and b are the least squares linear regression parameters, A represents the error of the estimation, and the subindex r stands for the corresponding range of winds. It is assumed that A has a Gaussian distribution with zero mean and variance equal to the root-mean-square error between the observations (WS_o) and estimations (WS_r), and is given by

$$A_r = \mathrm{Rdn}\left[\frac{1}{n}\sum_{i=1}^{n}(WS_{o_i} - WS_{r_i})^2\right]^{1/2},$$

where n is the number of observations for each range of winds and Rdn is a normally distributed random number with zero mean and variance 1. The inclusion of the random term does not affect the mean of the wind speed, but does affect the variance and other parameters related to it, such as the kinetic energy. Table 2 shows the values of the linear regression parameters and the root-mean-square error for each range of winds.

In the model, the wind direction is determined by

$$\begin{aligned} &\text{north-range} && \text{if } F(\Delta P_{SC\text{-}C}) \geq \text{rand} \\ &\text{non-north-range} && \text{if } F(\Delta P_{SC\text{-}C}) < \text{rand}, \end{aligned}$$

where $F(\Delta P_{SC-C})$ is the frequency distribution function of the observed wind direction with regard to ΔP_{SC-C} (see Fig. 7), and rand is a uniformly distributed random number between zero and one.

Model results show that the mean, standard deviation, and bimodality of the distribution of the observed winds at La Venta are well reproduced (Fig. 8). The scatterplot of the monthly mean wind speeds from observations and model estimates (Fig. 9a), and that of the frequency of north-range winds from observations and model estimates (Fig. 9b), show a high correlation between the variables: 0.97 for the mean wind speeds and 0.95 for the frequency of north-range winds. The corresponding values for the square of the correlation are 0.94 and 0.90, respectively. These results show the goodness of the model.

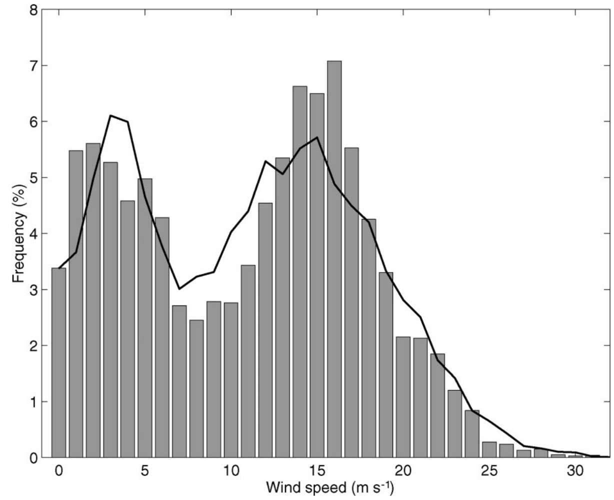

FIG. 8. Frequency distribution of wind speed at La Venta from observations (bars) and those estimated from ΔP_{SC-C} (line). The periods of simultaneous hourly data records for the wind data series at La Venta and the pressure differences between observatories are Jan–Nov 1994 and Jul–Dec 1995.

5. Wind climatology and ENSO signal

In order to obtain a 30-yr wind climatology for La Venta, the model described earlier and the sea level pressure data from NCDC for vertices P_{GM} and P_{GT} (see Fig. 1 for their location) are used. The time series of

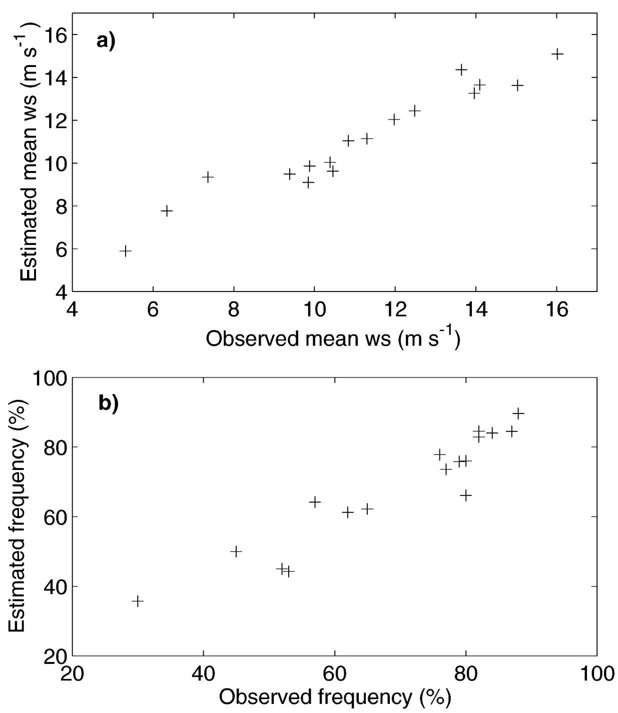

FIG. 9. Scatterplots of observations and model estimates from ΔP_{SC-C} for (a) monthly mean wind speeds, and (b) monthly mean frequencies of north-range winds, calculated from hourly data in Jan–Nov 1994 and Jul–Dec 1995.

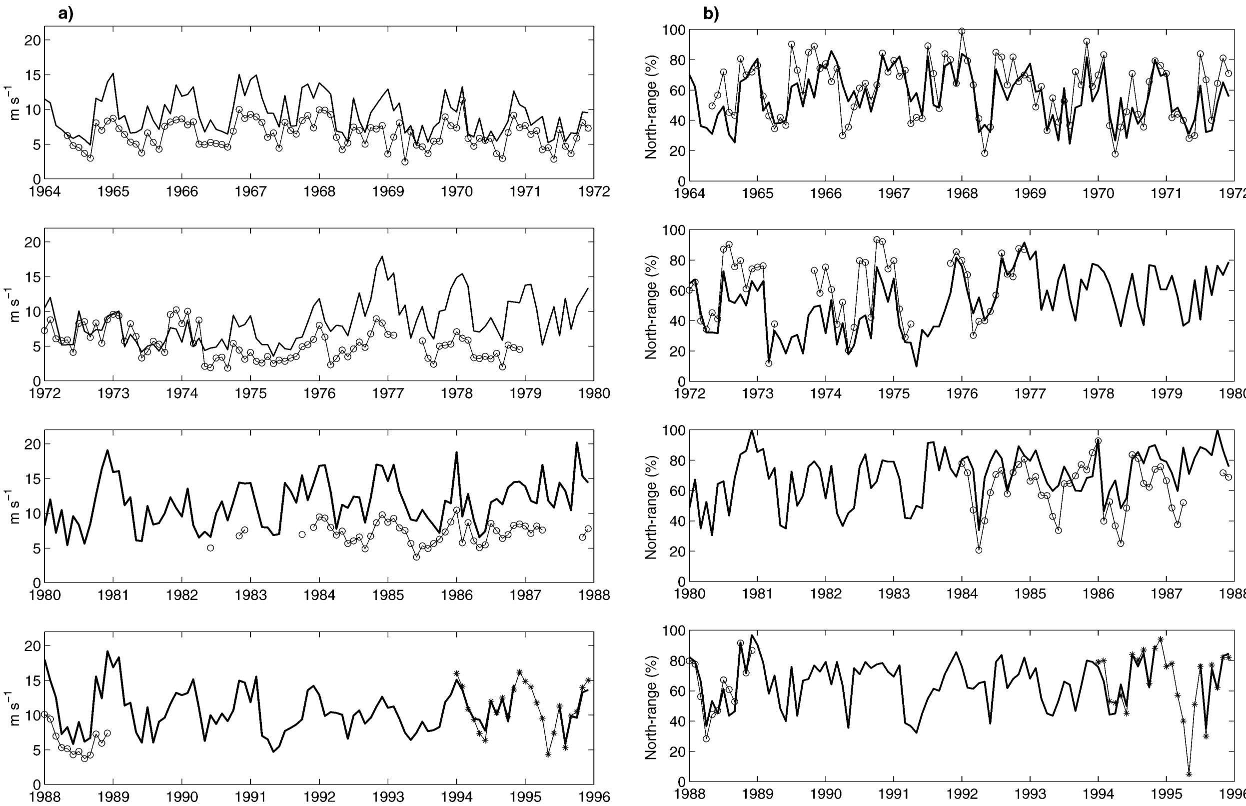

FIG. 10. Monthly means of (a) wind speed and (b) occurrence of north-range winds, from observations at Salina Cruz (circles), observations at La Venta (asterisks), and from model estimates for La Venta from $\Delta\hat{P}_{\mathrm{SC-C}}$ (NCDC adjusted pressure differences) (thick line). For the periods Jan–Nov 1994 and Jul–Dec 1995 the model estimates are from $\Delta P_{\mathrm{SC-C}}$ (pressure differences between observatories). There are no wind direction data at Salina Cruz for 1977–78.

pressure differences between P_{GM} and P_{GT} (hereafter $\Delta P_{\mathrm{NCDC}} = P_{\mathrm{GM}} - P_{\mathrm{GT}}$) is used instead of $\Delta P_{\mathrm{SC-C}}$ because the latter record is not long enough. The correlation between sea level pressure data at Salina Cruz and P_{GT} is 0.72, that for Coatzacoalcos and P_{GM} is 0.94, and between $\Delta P_{\mathrm{SC-C}}$ and ΔP_{NCDC} is 0.84. Although $\Delta P_{\mathrm{SC-C}}$ and ΔP_{NCDC} are highly correlated, their distributions have different mean and variance; thus, it was necessary to apply a scale transformation to ΔP_{NCDC} in order to obtain equivalent values to those of $\Delta P_{\mathrm{SC-C}}$. The scale transformation (Wilks 1995) is determined by the following equation:

$$\Delta\hat{P}_{\mathrm{SC\text{-}C}}(i) = \frac{\Delta P_{\mathrm{NCDC}}(i) - \overline{\Delta P_{\mathrm{NCDC}}}}{\sigma_{\mathrm{NCDC}}}\sigma_{\mathrm{SC\text{-}C}} + \overline{\Delta P_{\mathrm{SC\text{-}C}}},$$

where $\Delta\hat{P}_{\mathrm{SC-C}}$ is the transformed pressure difference, and the overbar indicates the mean and σ the standard deviation of the corresponding dataset.

Using the parameters obtained in the previous section, winds at La Venta are estimated from $\Delta\hat{P}_{\mathrm{SC-C}}$ for January 1964 to December 1993. The mean wind speed and frequency of north-range winds for La Venta from model estimates and observations at Salina Cruz and La Venta (Figs. 10a and 10b, respectively) show that there is a high correspondence in the magnitude of the variations and in the seasonal and interannual variability. The correlation between model estimates at La Venta and observations at Salina Cruz, for the periods with simultaneous data as shown in Fig. 10, is 0.70 for the wind speed and 0.72 for the frequency of north-range winds. The corresponding values for the square of the correlation are 0.49 and 0.52, respectively, which represent the proportion of the variability observed at Salina Cruz described by the estimated La Venta data. The model skill is good considering that differences are expected due to model limitations, differences between La Venta and Salina Cruz winds, and wind and pressure measurement errors. The correlation between observed and estimated winds at La Venta was discussed in section 4.

a. Seasonal variability

Long-term monthly mean wind speeds from model estimates (Fig. 11a) show stronger winds during winter, with maximum values in December and January (~12.9 m s^{-1}), and weaker winds during summer with minimum values in May and June (~7.0 m s^{-1}). A relative

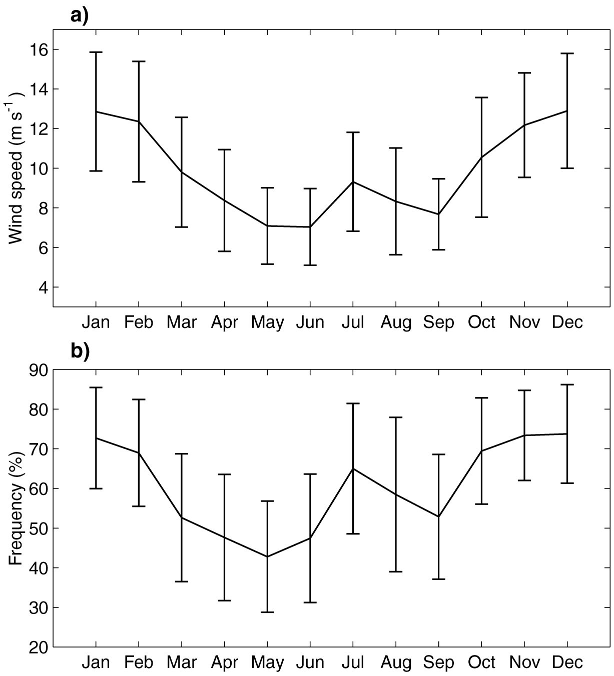

FIG. 11. (a) Long-term monthly mean wind speeds, and (b) long-term monthly mean frequencies of north-range winds from model estimates for La Venta. Error bars represent ±1 std dev from the mean.

maximum of wind speed in July, a feature that is observed in both La Venta and Salina Cruz measurements (see Fig. 3b), is also shown by the model estimates.

The percentage of occurrence of north-range winds from model estimates (Fig. 11b) also shows a strong seasonal signal, with larger values in winter and a significant relative maximum in July. An interesting characteristic is that, although the frequency of north-range winds is larger during the winter months, the interannual variability, that is, the standard deviation, is larger from May to September. The north-range winds occur during the whole year, but they are more frequent and stronger from October to February (Fig. 12). From March, an important decrease in north-range winds is observed, but strong events with wind speeds between 30 and 35 m s^{-1} still occur during April. In July, even though north-range winds are relatively frequent, they are weaker than during the winter season, with wind speeds generally between 10 and 15 m s^{-1}, while from December to February the speeds are generally between 15 and 20 m s^{-1} (Figs. 11b and 12).

Strong events, which produce winds attaining more than 30 m s^{-1}, are almost restricted to the fall-winter season and they have been the most studied. The origin and variability of the northerly winds during summer has not had the same attention. However, these winds may have a connection with the summer precipitation pattern over the southern part of Mexico, which shows a bimodal distribution with maxima in June and September–October and a relative minimum during July–August known as the midsummer drought (Magaña et al. 1999a). There is an increase in the pressure difference across the Isthmus of Tehuantepec in July that is caused by an increase of the sea level pressure in the Gulf of Mexico, instead of a decrease in the Gulf of Tehuantepec (Fig. 13). The analysis of the global climatological mean sea level pressure (SLP) fields from NCEP reanalysis data suggests that the increase of pressure in summer in the Gulf of Mexico is caused by the westward displacement and intensification of the Bermuda high (Fig. 14). The maximum mean SLP value of the center of the Bermuda high is around 1025 hPa in July and the minimum is around 1020 hPa in October–November; then, a relative maximum is reached in January of approximately 1023 hPa decreasing again to a relative minimum of 1021 hPa in April. At the same time, a westward shift of the center is observed from 23°W in January to around 35°W during May–August.

b. Interannual variability: El Niño and La Niña

The El Niño–Southern Oscillation (ENSO) impact on the interannual variability of the winds is studied through the analysis of the long-term monthly means and standard deviations of the modeled winds for 1964–95. The selection of ENSO phases is based on the Japan Meteorological Agency (JMA) index, which is a 5-month running mean of spatially averaged sea surface temperature anomalies over the tropical Pacific (from http://www.coaps.fsu.edu/research/jma_index1.shtml). If index values are 0.5°C (−0.5°C) or greater (lower) for six consecutive months, including October–November–December, the ENSO year from October through the following September is categorized as an El Niño (La Niña) year. For all other values of the index the year is categorized as neutral. In this study, however, it is assumed that El Niño (La Niña) years run from July through June of the next year because we found, after testing for different periods, that the winds have a clear ENSO signal for this period. Both periods agree with the results of Schultz et al. (1998) in the sense of including the winter months in the definition of the ENSO phase. There are eight years considered as El Niño from 1964 to 1995: 1965, 1969, 1972, 1976, 1982, 1986, 1987, and 1991; and seven years considered as La Niña: 1964, 1967, 1970, 1971, 1973, 1975, and 1988. The correlation between the JMA index and the frequency of north-range winds is maximum at zero lag with a value of 0.32, and the correlation between the JMA index and the monthly mean wind speeds is maximum at 1-month lag with a value of 0.27.

Long-term monthly mean wind speeds during La Niña years at La Venta are weaker than during neutral and El Niño (Fig. 15a). Comparison between means using the Student's t test shows that during La Niña years the mean wind speeds are significantly lower than in neutral years for February–March, June–September, and November at the 90% confidence level. During El Niño

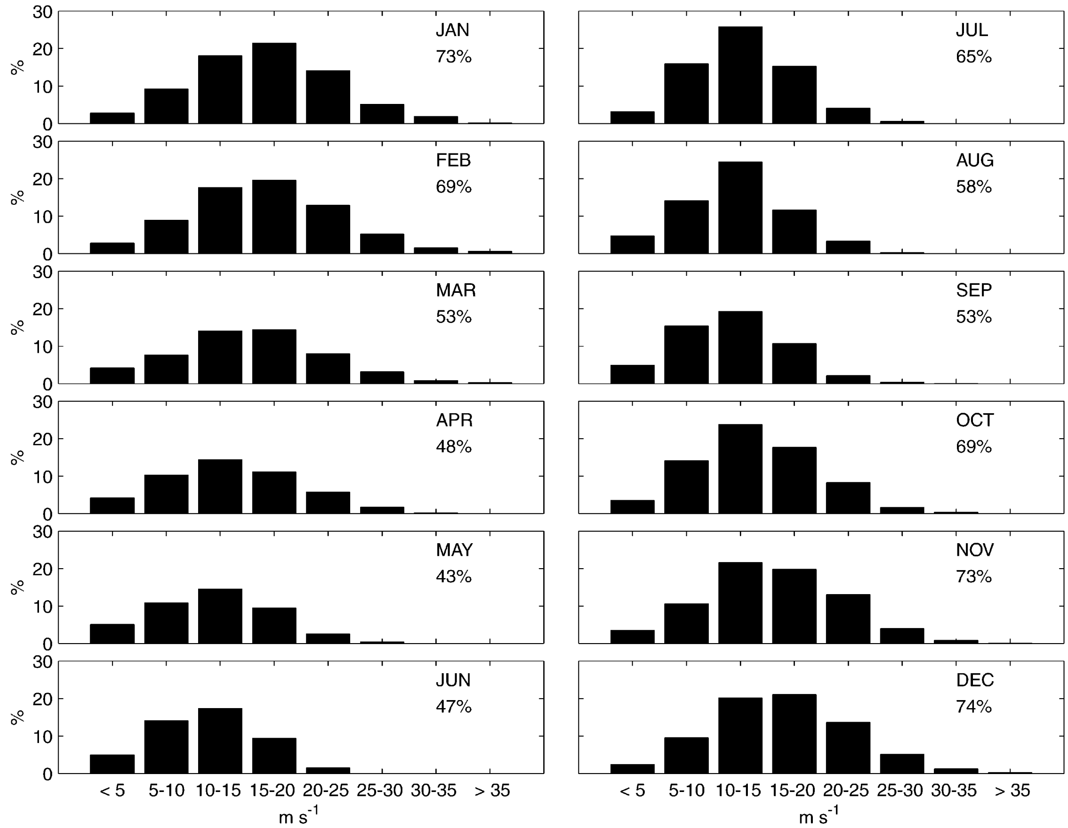

FIG. 12. Monthly frequency distributions of wind speed for the north-range winds at La Venta from model estimates. The percentage in each graph represents the cumulative frequency for each month.

years, the mean wind speeds for April–May and August–October are greater than during neutral years at the 80% confidence level. The percentages of occurrence of north-range winds (Fig. 15b) show that during La Niña years, north-range winds are less frequent than during El Niño and neutral years, presenting significantly lower values than in neutral years from June to November at the 96% confidence level. Occurrence of north-range winds during El Niño years does not show a significant difference compared to neutral years, except for May and September. In general, these results are consistent with Magaña et al. (1999b) that shows that the number of nortes increases during El Niño years in comparison to La Niña years, and with Schultz et al. (1998) who found that there are more cold frontal passages in southern Mexico during El Niño winters compared with La Niña winters. The interannual variability of strong events is tested by computing the frequency of winds stronger than 30 m s^{-1} at La Venta. These events occur from October to April, being larger during El Niño years than in La Niña years in all months but February. Results for the months between October and January are 0.82%, 1.26%, 2.77%, and 2.43% during El Niño years, and 0.46%, 0.74%, 0.71%, and 1.84% during La Niña years. These results suggest that the ENSO signal in the monthly mean wind speeds is due to both the frequency of northerly winds and their intensity.

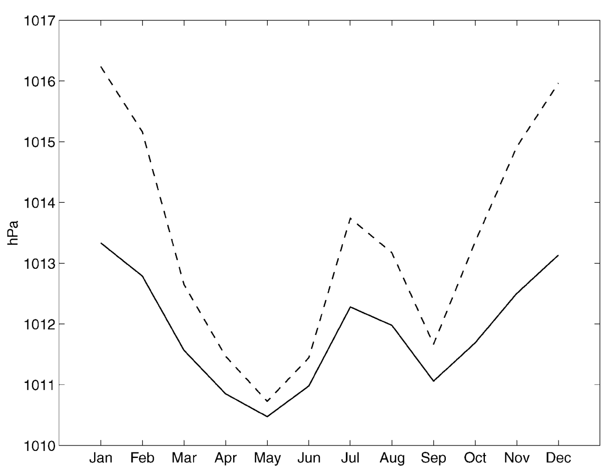

FIG. 13. Long-term monthly mean sea level pressure for P_{GT} (15°N, 95°W) in the Gulf of Tehuantepec (continuous line), and P_{GM} (20°N, 95°W) in the Gulf of Mexico (dashed line), from NCDC data.

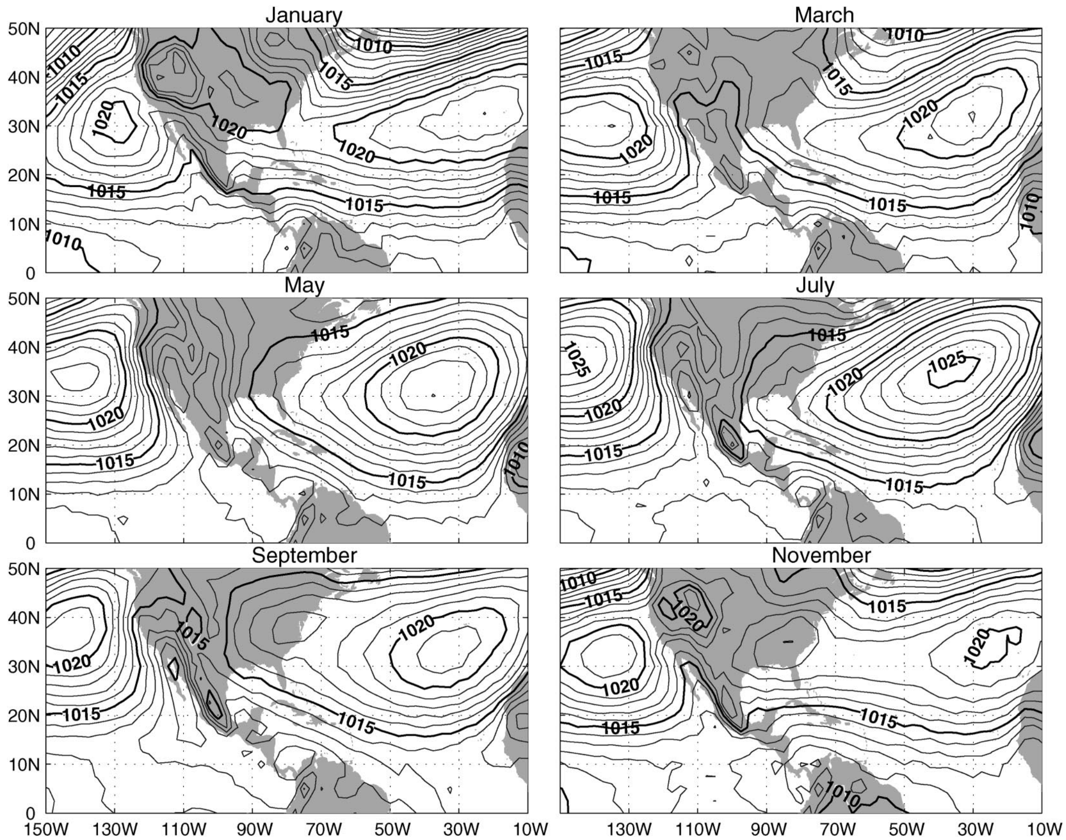

FIG. 14. Long-term monthly mean sea level pressure from NCEP reanalysis data for 1948–2001.

6. Summary and conclusions

The frequency distribution of wind speed at the coastal plain of the Gulf of Tehuantepec is bimodal and this special characteristic is associated with the wind direction. Decomposing the wind data series based upon wind direction, that is, winds from the north crossing the isthmus (north-range winds) and winds from other directions, the bimodality is removed. The direction of the wind can be established in a probabilistic sense from the across-isthmus pressure difference considering three cases: a range of pressure difference values where northerly winds through the gap are highly probable, another where they are very improbable, and a transition range where they can or cannot develop. When the gap winds develop, their intensity is directly proportional to the pressure difference.

Wind speed in the southern end of the Isthmus of Tehuantepec has a strong seasonal signal, with higher values during winter and lower in summer, but showing a relative maximum in July. The frequency of occurrence of north-range winds shows a similar seasonal pattern. Although the north-range winds are frequent in July, they are weaker than those observed in winter because the pressure differences across the isthmus are stronger during the winter months. In addition, the interannual variability of the frequency of northerly winds is larger in summer. The relative maximum of wind speed and occurrence of northerly winds in July is associated with an increase of sea level pressure in the Gulf of Mexico produced by the intensification and westward shift of the Bermuda high during this time of the year. This summer maximum coincides with the midsummer minimum of the annual cycle of precipitation over the southern part of Mexico, which has maximum values during June and September–October and a relative minimum during July and August (Magaña et al. 1999a). These results suggest that there is a relationship between the frequency of north-range winds in summer and the precipitation in southern Mexico and Central America, but more research must be done in order to explain the interannual variability of the precipitation cycle and the linkage of the pressure difference between the Gulf of Mexico and the Gulf of Tehuantepec with other meteorological variables.

The mean wind speed and the occurrence of north-range winds in the southern end of the Isthmus of Tehuantepec show an El Niño–La Niña signal, with larger values during El Niño years compared to La Niña years. This signal is consistent with Magaña et al. (1999b) that shows that the number of nortes reaching the Gulf of

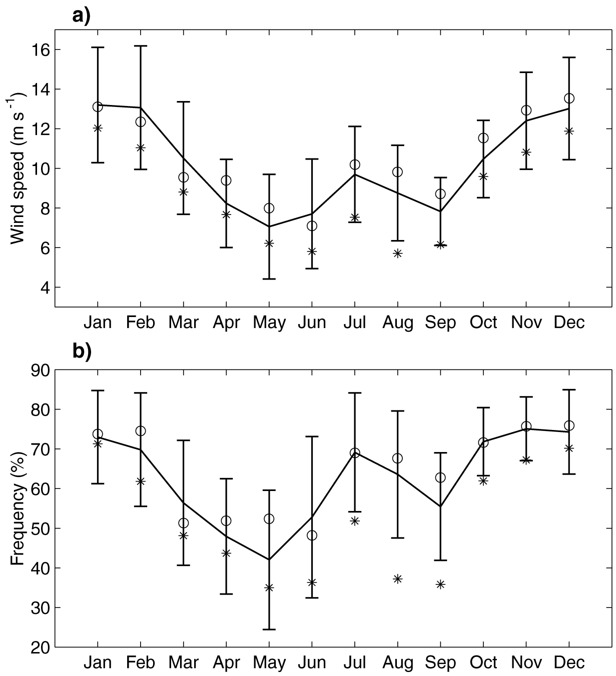

FIG. 15. (a) Long-term monthly mean wind speeds, and (b) long-term monthly mean frequencies of north-range winds from model estimates for La Venta considering neutral (line), El Niño (circles), and La Niña (asterisks) years. Error bars represent ± 1 std dev from the mean.

Mexico increases during El Niño years in comparison to La Niña years, and with Schultz et al. (1998) who found that the number of cold frontal passages in southern Mexico is larger during El Niño winters than during La Niña winters.

Acknowledgments. The authors wish to thank Deborah Hanley, Steven Morey, Shawn Smith, Nobuo Suginohara, Luis Zamudio, David Schultz, and one anonymous reviewer who made important suggestions that significantly improved the manuscript. We also want to thank Miguel Lavin from the Centro de Investigacion Cientifica y Educacion Superior de Ensenada (CICESE) for providing data from Salina Cruz, and to Ingeniería, Geofísica y Sistemas (IGS) for sharing with us some of the data used in this study. The Center for Ocean–Atmospheric Prediction Studies receives its base funding from the NOAA Office of Global Programs, and the NASA Physical Oceanography Program. J. Zavala-Hidalgo is funded by an ONR Secretary of the Navy Grant awarded to J. J. O'Brien.

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