Midsummer Gap Winds and Low-Level Circulation over the Eastern Tropical Pacific

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ABSTRACT

The low-level seasonal and intraseasonal wind variability over the northeastern tropical Pacific (NETP), its relationship with other variables, and the connection with large- and middle-scale atmospheric patterns are analyzed using a suite of datasets. Quick Scatterometer (QuikSCAT) wind data show that the low-level circulation over the NETP is mainly affected by the northerly trades, the southerly trades, and the wind jets crossing through the Tehuantepec, Papagayo, and Panama mountain gaps. The seasonal and intraseasonal evolution of these wind systems determines the circulation patterns over the NETP, showing predominant easterly winds in winter and early spring and wind direction reversals in summer over the central region of the NETP. During summer, when southerly trades are the strongest and reach their maximum northward penetration, weak westerlies are observed in June, easterlies in July–August, despite that strong southerlies tend to turn eastward, and again westerlies in September–October. This circulation pattern appears to be related to the Tehuantepec and Papagayo jets, which slightly strengthen during midsummer favored by the westward elongation and intensification of the Azores–Bermuda high (ABH). This ABH evolution induces an across-gap pressure gradient over the Isthmus of Tehuantepec favoring the generation of the jet and a meridional sea level pressure (SLP) gradient in the western Caribbean that favors the funneling of the trade winds through the Papagayo gap. The SLP pattern causing the gap winds in winter is different than in midsummer, being the southeastward intrusion of high pressure systems coming from the northwest, the main cause of the large meridional SLP gradients in Tehuantepec and the western Caribbean.

The westward low-level circulation observed over the central-eastern region of the NETP during midsummer induces westward moisture fluxes in the lower layers of the atmosphere, displaces convergence areas away from the coasts, and confines the relatively strong convergence in the easternmost NETP to the south of the area of influence of the wind jets and associated easterlies, contributing to the development of the midsummer drought observed in southern Mexico and Central America.

1. Introduction

The northeastern tropical Pacific (NETP), between 0° and 25°N and east of 120°W, is characterized by oceanic and atmospheric conditions leading to air–sea interaction processes in a wide range of spatial and temporal scales. Among them, those worth mentioning are the equatorial cold tongue, a region characterized by a sea surface temperature (SST) minimum that extends westward from the South American coast into the central Pacific, and the eastern Pacific warm pool, located off the west coast of southern Mexico and Central America and characterized by warm SSTs (mostly above 27°C) and relatively weak zonal winds. The eastern Pacific warm pool is separated from the equatorial cold tongue by a sharp SST front and is an important tropical cyclone development region. Another important feature is the intertropical convergence zone (ITCZ), a region of strong atmospheric convection and heavy precipitation where the southerly and northerly trades converge. Each one of these features has received special attention and research in a wide number of publications (e.g., Amador et al. 2006 and references within).

Besides the above-mentioned features of the NETP, the special orography of the continents on its eastern boundary, combined with the meteorological conditions, produces strong winds through the low-elevation gaps of the Sierra Madre del Sur in southern Mexico and the Central American cordillera (Fig. 1). The three major mountain gaps are located at the Isthmus of Tehuantepec, the lowlands of central Nicaragua, and
Panama, and the strong offshore winds in the lee of these mountain gaps are known as the Tehuantepec, Papagayo, and Panama jets, respectively. The influence of these wind jets on local processes over the adjacent Pacific waters, such as the generation of large warm oceanic eddies, intense offshore currents, increase in turbulent heat fluxes, considerable drop of the SST by upwelling and entrainment of subsurface water, and increase in biological activity, has motivated many studies, which have especially focused on the Gulf of Tehuantepec (e.g., Roden 1961; Stumpf 1975; Stumpf and Legeckis 1977; Alvarez et al. 1989; McCreary et al. 1989; Lavín et al. 1992; Barton et al. 1993; Trasvina et al. 1995; Lluch-Cota et al. 1997; Schultz et al. 1997; Steenburgh et al. 1998; Bourassa et al. 1999; Muller-Karger and Fuentes-Yaco 2000; Zamudio et al. 2006).

The generation mechanism of the Tehuantepec jet during boreal winter, when it is strongest and more frequent, has been widely documented: large sea level pressure differences between the Gulf of Mexico and the eastern Pacific, caused by the southeastward migration of high pressure systems associated with cold-air outbreaks coming from the northwestern United States, generate airflows that are blocked by the cordillera and then channeled through the mountain gap (e.g., Roden 1961; Parmenter 1970; Clarke 1988; Lavin et al. 1992; Schultz et al. 1997; Steenburgh et al. 1998). Frequently, as the high pressure system penetrates far to the south, the Tehuantepec jet is followed a few days later by the Papagayo and Panama jets. However, sometimes the Papagayo and Panama jets are influenced by trade wind fluctuations and tropical circulations that have little or no effect on the Tehuantepec jet (Chelton et al. 2000a). Also, there are differences among the three jets in intensity, orientation, time scales, and seasonality, which result in different oceanic and atmospheric responses (Chelton et al. 2000a,b; Kessler 2002; Xie et al. 2005). Chelton et al. (2000a) establish that the characteristic time scale of the highly energetic Tehuantepec jet is about 2 days and it is more variable and intense than the other two jets. They suggest that the Papagayo and Panama jets are predominantly controlled by a different mechanism than the across-gap pressure gradients associated with high pressure systems of midlatitude origin, being more likely to be coupled to variations in the Caribbean trades that are funneled through the Papagayo and Panama gaps.

At seasonal scale, the three jets weaken in late spring and summer, but there is a slight strengthening of the Tehuantepec and Papagayo jets during July–August whose origin, at least in the case of the Tehuantepec jet, has been attributed to a sea level pressure difference between the western Atlantic and the eastern Pacific that might be caused by the midsummer westward extension and intensification of the Azores–Bermuda high (Romero-Centeno et al. 2003). This strengthening
of the jets is in phase with the reduction of the tropical storm activity in the Caribbean and the far-eastern Pacific (Inoue et al. 2002; Curtis 2002) and with the midsummer drought in southern Mexico and Central America, a climatological phenomenon unique to the Western Hemisphere, where rainfall amounts reduce by roughly 40% in late July and early August compared to June and September (Magaña et al. 1999; Curtis 2004). Magaña et al. (1999) proposed that local air–sea interactions in the NETP lead to changes in the convection pattern. They suggest that the increase in cloudiness and reduction in solar radiation in June lead to a drop in SST over the eastern Pacific warm pool that inhibits rainfall in July–August. Cloudiness reduction in July–August allows a solar radiation increase reaching the surface that raises the SST and causes the return of precipitation by late August and September, establishing the essential role of solar radiation feedbacks in explaining the bimodal distribution in precipitation over central-southern Mexico, most of Central America, and parts of the Caribbean. The authors conclude that this seasonal SST fluctuation along with fluctuations in the low-level convergent flow and an intensification of the trade winds, which they suggest is part of the dynamical response to the intensity of the convective forcing of the ITCZ, produce the midsummer drought.

Recently, Magaña and Caetano (2005), based on observations of a field campaign conducted over the Americas warm pool in summer 2001, revealed the limitations of the Magaña et al. (1999) hypothesis and the necessity of an improved theory. Contrary to what they expected, solar radiation observations were higher during September than in July. They also observed an out-of-phase relationship in precipitable water between the NETP warm pool, off the coast of Central America, and the Caribbean coast of Central America and the western side of the NETP warm pool, where a maximum is observed during the midsummer drought period. They proposed a combined effect of SST changes and subsidence related to direct circulations as a better explanation of the convective activity observed during summer over the NETP.

At present, studies on the variability of the jets in boreal summer are scarce, and the influence and possible link between the midsummer Tehuantepec and Papagayo wind jets and the atmospheric circulation and convection patterns over the NETP still remains to be completely understood. In this study we discuss the midsummer strengthening of the Tehuantepec and Papagayo jets and its impact on the low-level circulation of the NETP, together with possible causes and implications. The near-surface wind analysis is performed by using the increasingly utilized National Aeronautics and Space Administration’s Quick Scatterometer (QuikSCAT)/SeaWinds scatterometer (QSCAT) winds. Recent studies have demonstrated that QSCAT winds represent the currently available product that best resolves the wind jets in different space–time scales and is an excellent tool to characterize the dynamical state of the lower troposphere with a high degree of accuracy (Chelton et al. 2004; Bordoni et al. 2004; McNoldy et al. 2004). The vertical structure of moisture fluxes, wind, and pressure fields is analyzed using data from the National Centers for Environmental Prediction–Department of Energy Atmospheric Model Intercomparison Project II (NCEP–DOE AMIP-II) reanalysis (NCEPR2; Kanamitsu et al. 2002). Precipitation rate data from the NCEPR2 and SST data from the National Oceanic and Atmospheric Administration (NOAA) are also used.

The paper is organized as follows. The following section describes the datasets used; section 3 details the results of the data analysis, and section 4 includes a discussion of the main results and the conclusions of the study.

2. Data

Previous studies have shown that scatterometers are unique among satellite remote sensors in their ability to measure wind speed and direction over the global surface waters. In particular, QSCAT provides wind measurements with a much greater spatial and temporal coverage than in situ observations or any previous scatterometer missions and a significantly higher resolution than what is currently provided by numerical weather prediction models or reanalysis wind products (Ebuchi et al. 2002; Bourassa et al. 2003; Chelton et al. 2004). QSCAT collects data within a 1600-km-wide swath, covering roughly 93% of the ice-free global oceanic surface in one day with a 25-km spatial resolution, and measures wind speed with an accuracy of ±2 m s⁻¹ and wind direction with an accuracy of ±20° or better (http://winds.jpl.nasa.gov/missions/QUIKSCAT). In the present study, daily near-surface vector winds are processed and analyzed for the period July 1999–December 2005 over the region 0°–33°N, 130°–75°W.

QSCAT winds were downloaded from the Center for Ocean–Atmospheric Prediction Studies Web site (http://coaps.fsu.edu/cgi-bin/qscat/wind-swath-ku2001), which consists of the Remote Sensing Systems Ku-2001 swath datasets. Winds are referenced to a height of 10 m, and the data files include wind speed, wind direction, time, latitude, and longitude. Zonal (u) and meridional (v) wind components are calculated from the wind speed and direction information and hourly averaged within 0.5° × 0.5° latitude–longitude boxes. Daily and monthly mean winds are calculated and long-term
monthly means for the analyzed period are then estimated from the monthly averages and used to analyze the seasonal and intraseasonal variations of the wind jets and the low-level circulation over the NETP. Monthly mean divergence fields, calculated using a centered difference scheme, are also analyzed.

Data flagged as rain contaminated were excluded. Heavy rain degrades the quality of surface wind retrievals from scatterometer observing systems due to the attenuation and backscatter of the emitted microwave pulse and the backscatter from the ocean surface (Milliff et al. 2004). Systematic biases in distributions of wind stress curl and divergence fields have been identified from scatterometer surface wind retrievals that are due to the observations missing from the QSCAT record, mostly due to rain (Milliff et al. 2004). The percentage of flagged data for the area and period of study is between 20% and 25% within the ITCZ region and up to 40% in small regions of highly divergent winds over the Gulf of Tehuantepec (not shown).

Derived NCEPR2 products (daily and monthly averages from 6-hourly values) for sea level pressure, wind components, geopotential height, specific humidity, and precipitation rate were provided by the NOAA/Office of Oceanic and Atmospheric Research/Earth System Research Laboratory Physical Sciences Division (OAR/ESRL PSD), Boulder, Colorado, from their Web site at http://www.cdc.noaa.gov/. The NCEPR2 is based on the NCEP–National Center for Atmospheric Research (NCAR) reanalysis (NCEPR1) and produces analyses of atmospheric fields using data from 1979 to the present. Improvements of the NCEPR2 project on the NCEPR1 are the fixing of processing problems and the updates of the forecast model, the data assimilation system, and the parameterizations of the physical processes. Surface and pressure level data are available on a 2.5° × 2.5° grid, and the data period used in this study is from July 1999 to December 2005. Monthly fields from the NOAA optimum interpolation SST V2 data on a one-degree grid for this same period are also used. The optimum interpolation V2 analysis uses in situ and satellite SSTs plus SSTs simulated by sea ice cover (http://www.cdc.noaa.gov/cdc/data.noaa.oiist.v2.html).

3. Results

a. Winds over the NETP

Long-term monthly mean wind vectors from the 6.5-yr QSCAT period from July 1999 through December 2005 show a strong seasonal signal in the NETP, the Gulf of Mexico, and the Caribbean regions (Fig. 2). One of the more outstanding features is the signal associated with the winds crossing through the low-elevation mountain gaps of the cordillera in southern Mexico and Central America (see Fig. 1 for location), which has been documented in previous works. The signal of the across-gap winds over the Gulf of Tehuantepec (Tehuantepec jet) is noticeable most of the year, being more evident during boreal winter (November–February) and showing a prevalent meridional orientation just off the coast (Figs. 2a, b, k, l). The southward-oriented winds over the Gulf of Papagayo (Papagayo jet) are weakly distinguishable in November and then become stronger reaching their maximum in January. During winter, the Tehuantepec jet extends far to the south, merging with the Papagayo jet and the Pacific northeast trades and turning westward. The Tehuantepec and Papagayo jets begin weakening in March (Fig. 2c) and they are barely visible in May (Fig. 2e). The January and February monthly averages also show evidence of the Panama crossing winds, which are north–south-oriented like the Tehuantepec jet, and they are still distinguishable as late as March and April (Figs. 2a–d). In general, the late spring and summer winds are very weak in the eastern region of the NETP north of the ITCZ, with the exception of a slight intensification of the Tehuantepec and Papagayo jets in July and August, though less intense in the latter.

During winter and spring months (from December through April), when the northerly trades are more intense, winds in the NETP are mainly easterlies blowing from the coast to the western Pacific (Figs. 2a–d, l). In May, this pattern begins changing: southerly trades start intensifying and slightly turn to the east around 3° to 7°N and east of ~110°W, while light westward winds cover the area north of ~8°N and east of ~110°W (Fig. 2e). In June, while the northerly trades are relatively weak, the southerly trades keep intensifying and penetrating northward and the light winds to the north (around 10°N) change direction, heading east from ~115°W (Fig. 2f). This circulation pattern favors moisture transport into the continent, coinciding with the first precipitation maximum observed in central-southern Mexico and Central America (see Fig. 3b).

However, in July and, though less intense, in August, when a slight strengthening of the Tehuantepec and Papagayo wind jets is observed, the low-level flow in the central region of the NETP (within box A in Fig. 1) shows again a westward orientation (Figs. 2g, h). This westward flow is not restricted to the area near the coast but is observed several hundred kilometers (~2200 km) offshore over the central NETP. This circulation pattern seems to inhibit the northward penetration of the southerly trades, mainly in the eastern region of the NETP, despite their strength and eastward orientation, and restricts the low-level moisture
transport into the continent coinciding with the midsummer drought observed in the region during July–August (see Fig. 3b).

The wind pattern changes abruptly in September (Fig. 2i), featuring imperceptible wind jets, the weakest northerly trades, the northernmost penetration of the southerly trades, and a low-level eastward flow that favors the moisture transport into the continent. During this month, the precipitation increases again in the region, when the second maximum is observed. In October, this wind circulation pattern begins weakening, giving rise to that observed during winter and spring.

b. Zonal winds and precipitation

The annual cycle of the zonal wind component averaged within box A (10°–15°N, 115°–95°W) (Fig. 3a; see Fig. 1 for its location) and that of the precipitation rates averaged within box B (10°–18°N, 100°–85°W) (Fig. 3b; see Fig. 1 for its location), both computed over the QSCAT observations period, summarize the results presented in the previous section. It is worth mentioning that box A is the region over the central NETP where changes in wind direction occur during the summer; this region is influenced by the gap winds but it is not much affected by the shift of the zonal wind component of the strong southerly trades during this time of the year. Box B covers part of southern Mexico and Central America, where the midsummer drought is observed. Plots in Fig. 3 show that easterlies are observed most of the year in box A; the strongest easterlies during the winter–spring months coincide with the lowest precipitation rates in box B, and the easterlies observed
in July–August coincide with the reduction in precipitation during this time of the year. The two precipitation maxima are observed in June and September, when westerlies are present in box A.

The 30-day running means of the zonal wind component averaged within box A and those of the precipitation rates averaged within box B are shown in Fig. 4. The correlation between these two variables is very high, with a determination coefficient of $r^2 = 0.71$. During the rainy season, from June through September, precipitation rates show fluctuations that correspond with changes in the zonal winds, like the clear correspondence between the precipitation peaks in June and September and the westerlies over the central NETP. Between these two peaks, precipitation variations also correspond with zonal wind changes most of the years in the 2000–05 time series.

c. Moisture fluxes

Monthly mean zonal moisture fluxes (kg kg$^{-1}$ m s$^{-1}$) at different atmospheric levels within box A are calculated from daily averages of the zonal wind component and specific humidity data from the NCEPR2 for the period July 1999–December 2005. The annual cycle of the zonal moisture fluxes at the 1000-mb level (Fig. 5a) shows westward fluxes from November to May, with maximum values in December–January and very small fluxes in May. In June, moisture fluxes reverse direction showing a small eastward component, while in July they reverse again heading westward and remain so in August, although they are very small. September is the month with the largest eastward moisture fluxes, remaining so in October but with a considerable smaller value. A similar behavior is observed at the 925-mb...
level, showing slightly smaller values year round, except in July–August when westward moisture fluxes show a slight increase (Fig. 5b). At the 850-mb level, westward moisture fluxes are observed in all months but September when eastward fluxes are still present (Fig. 5c). From December to March, a decrease in the intensity of the westward fluxes is observed compared with the lower levels. The 850-mb level is where maximum westward fluxes are observed during the midsummer.

There is a considerable decrease in the moisture fluxes in the upper levels, especially in the winter months (Figs. 5d–f). From the 700-mb level up, westward fluxes are observed along the whole year, with maximum values in July–August. Therefore, westward moisture fluxes are observed from the surface up to, at least, 500-mb in midsummer.

The above analysis reinforces the hypothesis that the strengthening of the wind jets and the associated reversal of the low-level circulation over the central NETP during midsummer are closely related with the reduction of precipitation in southern Mexico and Central America by means of a reduction of the moisture transport toward the continent, mainly at the lower levels of the atmosphere.

d. Wind divergence

Previous studies reveal that high-resolution QSCAT winds are capable of resolving important details of the wind field, which are undetected by the reanalyses, and improve our understanding of the surface circulation in the Atlantic and east Pacific regions (McNoldy et al. 2004; Chelton et al. 2004). For the present study, the monthly wind divergence fields derived from the QSCAT vector winds are an important tool to analyze the impact of the gap winds over the eastern Pacific ITCZ. These fields show the seasonal fluctuation of the ITCZ, which shifts to the south during the boreal winter months and to the north in summer (Fig. 6). The extent of the displacement appears more pronounced in the western region of the NETP. From November to January, when the northerly and southerly trades are both relatively intense, a band of strong convergence is observed, being slightly stronger and narrower in the eastern part of the NETP (Figs. 6a,k,l). From November to February the wind jets are very strong and their asso-

![Fig. 3. Long-term monthly means of (a) zonal winds from QSCAT data averaged within box A and (b) precipitation rate from NCEPR2 data averaged within box B. See Fig. 1 for location of boxes A and B.](image)

![Fig. 4. The 30-day running means of the zonal winds averaged within box A from QSCAT data (thick line) and those of the precipitation rates averaged within box B from NCEPR2 data (thin line). See Fig. 1 for location of boxes A and B.](image)
associated divergent winds are clearly observed. During this time of the year, when the ITCZ is shifting southward, the wind jets produce large divergence patches over relatively weak convergence areas just north of the band of stronger convergence, interrupting the ITCZ zonal continuity (Figs. 6a,b,k,l). In February, the southerly trades begin weakening and the convergence is less intense. March is the month with the maximum southward displacement of the ITCZ: the northerly trades are very strong, the southerly trades are weak, and the convergence is weak (Fig. 6c). The northward migration of the ITCZ begins in April, when the southerly trades begin strengthening (Fig. 6d).

From May onward, the southerly trades gradually intensify and the convergence strengthens and penetrates farther north, mainly over the western half of the NETP. In June, scattered convergence areas close to the continent and a relatively narrow convergence
zone in the western region of the NETP are observed (Fig. 6f). During July and August, the Tehuantepec and Papagayo wind jets strengthen and the low-level circulation over the central region of the NETP reverses (see Figs. 2g,h), shifting convergence areas west of \( \sim 107^\circ W \) where the ITCZ widens (Figs. 6g,h). Scarce convergence areas are observed close to the continent and the relatively strong convergence in the easternmost NETP is confined south of the area of influence of the wind jets. The abrupt change of the circulation pattern in September, when wind jets are imperceptible, causes convergence areas to be widely dispersed covering a large part of the NETP, next to the continent and up to \( \sim 22^\circ N \) (Fig. 6i). In this month, despite the ITCZ reaching its maximum northward penetration into the western NETP, the ITCZ is slightly narrower than in July–August in the westernmost NETP.

These divergence patterns agree with the analyses of the low-level circulation and the zonal moisture fluxes over the central NETP presented above. The zonal winds, moisture fluxes, and divergence analyses show that the midsummer drought observed in central-southern Mexico and Central America is closely related with the strengthening of the Tehuantepec and Papagayo wind jets, which induces a westward circulation over the central-eastern NETP that shifts convergence areas away from the continent, confines the relatively strong convergence in the eastern region of the NETP to the south of the wind jets, and reduces the moisture fluxes toward the continent, mainly north of \( \sim 10^\circ N \).

e. Sea surface temperature

SST gradients, along with surface winds, are very important elements in determining the structure and variability of the ITCZ. The eastern Pacific warm pool (EPWP), as mentioned in the introduction, is a relatively large area characterized by warm SSTs (mostly above 27°C) that is located off the west coast of southern Mexico and Central America, north of \( \sim 6^\circ N \) and east of \( \sim 120^\circ W \) (Wang and Enfield 2001; Xie et al.
2005). Although the warmest waters are located in the eastern NETP, next to the continent, the warm waters extend farther west bounded by cooler water on the north and by a sharp SST front on the south (Fig. 7). This strip of warm waters shows a northeast-to-southwest tilt; it varies in intensity (SST maximum) and has a meridional displacement along the year, being at its southermmost position in March (Fig. 7). From April onward, the strip displaces northward reaching its northernmost position in September. During July and August, while the strip of warm waters keeps migrating northward, the southerly winds and convergence seem to remain confined south of the area of influence of the wind jets and the associated easterlies in the central-eastern region of the NETP (see Figs. 2 and 6), when it might be expected that they continue penetrating northward following the strip of maximum SST. As mentioned above, this interruption of the northward intrusion of the convergence in the eastern region of the NETP occurs simultaneously with the intensification of the wind jets and the change in the low-level circulation over the NETP during midsummer. It is worth mentioning that the close relationship between the SST gradients and the surface winds in the NETP has been largely documented by Chelton et al. (2001), although on higher temporal frequencies.

f. Pressure and wind relationship

In this section, the seasonal and intraseasonal variations of the large-scale pressure systems involved in the generation of the Tehuantepec and Papagayo wind jets are analyzed, both in the lower and upper atmosphere.

1) Sea Level Pressure and Wind Variations

Long-term monthly mean sea level pressures (SLP) for the period July 1999–December 2005 over the region 0°–50°N, 150°–10°W from NCEPR2 data (Fig. 8) show the two permanent high pressure systems around 30°–35°N; over the subtropical Pacific [the North Pacific high, (NPH)] and the subtropical Atlantic [the Azores–Bermuda high (ABH)]. Also evident are a third nonpermanent system over the continental United States and a belt of low pressures dominating the tropical areas. The ABH and NPH show variations both in intensity and location along the year (Figs. 8 and 9). Both systems reach their absolute maximum intensity in July, although the ABH shows a relative maximum in January (Fig. 9a). In the monthly mean, the ABH is less intense by the end of the year (September–December), with a slight intensification in November, although it shows an absolute minimum in March. The NPH is less intense from October through February, showing an absolute minimum in February (Fig. 9a). The absolute maximum of the ABH intensity in July coincides with the maximum westward displacement of its center over the subtropical Atlantic, while in January its center is shifted far to the east (Fig. 9b). The center of the NPH also shows its maximum westward displacement over the subtropical Pacific in July, while in winter it is closer to the continent. A meridional migration is also observed on the annual course of both subtropical anticyclones (Figs. 8 and 9c); the maximum northward shift of the NPH is observed during July–September, while in winter its center is shifted southward. The center of the ABH is at its southernmost position in March when it reaches ~28°N, and the rest of the year it moves between 32.5° and 37.5°N, being at its northernmost position in February. These SLP variations determine, to a large extent, the monthly course of the circulation patterns over the region.

The forcing mechanisms and three-dimensional structure of the subtropical anticyclones in the Northern Hemisphere are not completely understood. There are several theories involving processes like upper-level planetary waves, monsoonal deep convective heating, midtropospheric subsidence, near-surface land–sea thermal contrasts across the west coasts of the subtropical continents, and topographic features, among others, as important mechanisms determining the structure and annual evolution of the subtropical highs (Chen et al. 2001; Liu and Wu 2004; Miyasaka and Nakamura 2005).

As was mentioned previously, the mechanism that generates the Tehuantepec jet is the across-gap pressure gradient through the Isthmus. The annual cycles of the SLP at 20°N–95°W in the southern Gulf of Mexico (GM) and that at 15°N–95°W in the Gulf of Tehuantepec (GT) (see Romero-Centeno et al. 2003, their Fig. 13) show that, on a monthly time scale, the SLP in the GM is larger than in the GT along the year and the pressure differences between them (GM – GT) are larger in the winter months (November–February), reaching ~3.5 hPa in January (Fig. 10). The monthly mean SLP conditions in winter (see Figs. 8a,b,k,l) show a high pressure system over the southeastern United States, which induces a large meridional pressure gradient over southern Mexico, Central America, and the Caribbean Sea, and the eastern NETP being affected by a relatively weak NPH. This pattern induces a large SLP difference between the GM and the GT, which favors the generation of the Tehuantepec jet. The SLP over the two gulfs decreases in the spring months as does the pressure difference between them, being around 0.82 hPa in June (Fig. 10). The SLP slightly increases in July–August at both gulfs, but the increase
Fig. 7. Long-term monthly mean sea surface temperatures (°C) from the NOAA optimum interpolation V2 data (contours are every 1°C; thick contours at 15°, 20°, 25°, and 30°C).
is larger over the GM than over the GT, enhancing the across-gap pressure difference ($\sim 2.0$ hPa in July) and inducing the strengthening of the Tehuantepec jet. The increase of SLP over the GM during midsummer is associated with the intensification and westward extent of the ABH, while the GT seems to be affected by a combined effect of the intensification of both subtropical highs, though the center of the NPH is shifted to the northwest (see Figs. 8g,h and 9b,c).

The annual cycle of the GM–GT SLP differences, from NCEPR2 data, and that of the meridional wind component averaged over the GT ($14^\circ$–$16^\circ$N, $94.5^\circ$–$95.5^\circ$W), from the QSCAT data, have a very high correlation ($r = -0.93, r^2 = 0.87$) (Fig. 10). The strengthening of the offshore winds in midsummer corresponds with the increase in SLP difference between the GM and the GT in this period. Consequently, the main physical mechanism that produces the intensification of the Tehuantepec jet in July–August is the same as that in winter: a large across-gap pressure gradient. However, in winter the main cause of the large SLP difference between the GM and the GT is the intrusion into the GM of high pressure systems coming from the north, while during midsummer it is the penetration of the ABH into the GM.

The annual evolution of the zonal wind component averaged over the Papagayo jet area ($10^\circ$–$13^\circ$N, $85^\circ$–$88^\circ$W) is very similar to that of the meridional wind component, with the zonal winds slightly predominating over the meridional winds most of the year (not shown). Zonal winds are westward most of the time except during September–October, and meridional winds are southward all year-round except in September. This annual evolution of the Papagayo winds is mainly related with the meridional SLP differences in the western Caribbean, calculated by the SLP differences between $15^\circ$N, $80^\circ$W (CBN) and $10^\circ$N, $80^\circ$W (CBS) (Fig. 11; see Fig. 1 for sites’ location), while it is less influenced by the across-gap pressure differences estimated by the zonal SLP differences between the
western Caribbean (12.5°N, 80°W) and the easternmost NETP (12.5°N, 90°W) (not shown). The correlation between the annual cycle of the zonal wind component averaged over the Papagayo jet area and that of the meridional SLP differences in the western Caribbean (CBN – CBS) is very high \((r = 0.93, r^2 = 0.86)\), in contrast with the very low correlation shown with the annual cycle of the across-gap pressure differences \((r = -0.24, r^2 = 0.06)\). In the monthly mean, the largest meridional SLP differences in the western Caribbean match with strong offshore Papagayo winds in winter and with relatively strong offshore winds in July–August, while the lowest meridional SLP differences in the western Caribbean match with onshore Papagayo winds during September–October (Fig. 11).

These results indicate that the monthly mean conditions favoring the generation of the Papagayo wind jet are associated with large-scale pressure systems that affect the tropical Atlantic and the Caribbean Sea, which induce a large meridional SLP gradient in the western Caribbean and the funneling of the trade winds through the cordillera gap. The funneling of the Caribbean trade winds is a mechanism for the generation of the Papagayo jet that was previously proposed by Chelton et al. (2000a).

2) Upper-level Pressure and Wind Variations

The midsummer strengthening and westward elongation of the ABH center is also observed at upper levels. Long-term monthly averages of geopotential height and vector winds from the NCEPR2 data for the 850-, 700-, 600-, and 500-mb surfaces over the region 0°–50°N, 150°–10°W show these ABH features during July–August (Fig. 12). At lower levels, up to ~850 mb, the distribution and location of the Atlantic and Pacific subtropical highs, separated by low pressures over the continent, establish relatively strong zonal pressure gradients north of ~15°N and relatively strong meridional pressure gradients between ~12° and 18°N. In the lower atmosphere, the pressure patterns determine complex wind fields that are also affected by the SST gradients and the topography. It has been proposed that the separated high pressure cells structure suggests

![Figure 9: Annual evolution of the (a) intensity, (b) zonal location, and (c) meridional location of the ABH (solid line) and the NPH (dashed line). The values were obtained from 0.5-hPa contour plots.](image-url)
Fig. 10. Annual cycle of the SLP differences between 20°N, 95°W in the southern GM and 15°N, 95°W in the GT from NCEPR2 data (dashed line) and that of the meridional wind component averaged over the GT from the QSCAT data (solid line).

Fig. 11. Annual cycle of the SLP differences between 15°N, 80°W (CBN) and 10°N, 80°W (CBS) in the western Caribbean (dashed line) (see Fig. 1 for sites’ location) and that of the zonal winds averaged over the Papagayo wind jet area (solid line). SLP data are from NCEPR2 and winds are from QSCAT.
that the dynamics of the subtropical highs is related to thermally forced planetary waves, rather than being part of a zonally symmetric circulation (Chen et al. 2001; Liu and Wu 2004; Miyasaka and Nakamura 2005). Studies on the formation of the subtropical anticyclones state that, near the surface, the strong alongshore northerlies over the eastern North Pacific and Atlantic basins, associated with the subtropical highs, keep cool SSTs locally by enhancing surface evaporation and coastal upwelling, which, in consequence, increase the land–sea thermal contrast during the summertime. In this context, the shallow continental heating and maritime cooling play major roles in the formation of the surface subtropical highs, which intensify from early to midsummer through local feedback processes (Miyasaka and Nakamura 2005 and references within).

In the upper atmosphere the large-scale pressure systems dominate the scene. At the 700-mb level and upward, the strong meridional component of the southerly winds vanishes; instead, easterlies dominate the region south of ∼20°N (Fig. 12). In the 600- and 500-mb geopotential height maps, the midsummer strengthening of the ABH is still evident and the anticyclonic circulation associated with the heating over the continental United States is clearly shown in July and August. At the 500-mb level the cell structure is more diffuse showing the merging of the two high pressure systems.

4. Discussion and conclusions

The low-level circulation in the NETP is affected by three main wind systems: the northerly and southerly trade winds and the wind jets coming through the Tehuantepec, Papagayo, and Panama mountain gaps. The seasonal and intraseasonal evolution of these wind systems determines the low-level circulation over the NETP on these time scales. QSCAT wind data (July 1999–December 2005) show that the low-level circulation over the central region of the NETP is mainly di-
rected westward from November to May and undergoes wind direction changes during summer, from weak westerlies in June to easterlies in July and August and changing back to westerlies in September–October (Fig. 2). This change in the circulation pattern during midsummer is associated with the strengthening of the Tehuantepec and Papagayo wind jets.

The wind jets are very intense during winter and, although much weaker, the Tehuantepec and Papagayo jets are also observed in July and August. The monthly mean SLP conditions in winter are characterized by the presence of a high pressure system over the southeastern United States that induces a large meridional pressure gradient over southern Mexico, Central America, and the Caribbean Sea (Figs. 8a,b,k,l). These conditions favor the generation of the Tehuantepec wind jet by increasing the SLP difference between the GM and the GT (Fig. 10) (i.e., by increasing the across-gap pressure gradient) and the generation of the Papagayo wind jet by increasing the meridional SLP difference over the western Caribbean (Fig. 11), which induces the funneling of the trade winds through the mountain gap. On the other hand, the monthly mean SLP conditions in midsummer are characterized by strong subtropical highs in the North Pacific (NPH) and Atlantic (ABH) basins, both shifted to the west (Figs. 8g,h). These mean SLP conditions in July–August increase the pressure difference between the GM and the GT due to the westward elongation of the ABH over the GM, favoring the generation of the Tehuantepec jet (Fig. 10), and strengthen the meridional pressure difference in the western Caribbean, favoring the generation of the Papagayo jet (Fig. 11). The very low correlation between the Papagayo winds and the across-gap pressure difference, estimated by the zonal SLP differences between the western Caribbean and the easternmost NETP, shows that the main mechanism of generation of the Tehuantepec and Papagayo wind jets is different, in accordance with Chelton et al. (2000a,b) results.

Results show that there is a high correlation among the Tehuantepec and Papagayo wind jets, the zonal winds and moisture fluxes over the central region of the NETP, and the precipitation rates in central-southern Mexico and Central America. The westward low-level circulation observed over the central-eastern region of the NETP during midsummer, which occurs simultaneously with the strengthening of the wind jets, induces westward moisture fluxes in the lower layers of the atmosphere (Fig. 5), displaces convergence areas away from the coasts (Fig. 6), and causes the relatively strong convergence in the easternmost NETP to remain confined south of the area of influence of the wind jets and associated westward winds (Fig. 6). This circulation pattern mostly determines the precipitation distribution in central-southern Mexico and Central America, where a reduction in precipitation rates is observed at the middle of the rainy season, known as the midsummer drought (Figs. 3 and 4). Time series for the July 1999–December 2005 period of the zonal winds averaged within box A and the precipitation rates averaged within box B (see Fig. 1 for their location) show that the two precipitation maxima that occur in June and September have a clear correspondence with eastward winds over the central-eastern NETP and that precipitation variations observed between these two peaks also correspond with zonal wind changes over that region.

Near-surface winds depend, among others factors, on SST gradients. The seasonal cycle of the SST over the NETP is closely related with the seasonal migration of the southerly trade winds and the ITCZ. The strip of warm waters, that is linked to the eastern Pacific warm pool and extends toward the west, intensifies and displaces northward during the summer, as the southerly trades do (Figs. 2 and 7). In this season, southerly trades show a strong meridional component and the intensified SST gradients induce southerlies to turn eastward, mainly in the eastern region of the NETP. This pattern has associated moisture transports toward the continent, but the northward penetration of the southerly winds and the ITCZ over the eastern NETP is restricted in July–August by the strengthening of the wind jets and the associated westward low-level circulation over the central-eastern NETP, despite that the strip of warm waters continues its northward migration (Fig. 7).

In conclusion, large-scale processes in the North Atlantic, like the ABH displacement and intensification, have a major contribution to the NETP seasonal and intraseasonal variabiity, affecting the gap winds, the zonal wind component over the NETP, the low-level moisture transports, and the precipitation in the region. Therefore, these processes contribute to the development of the midsummer drought observed in southern Mexico and Central America. The relationship of these large-scale processes with lower-scale processes, like local air–sea interactions and thermally direct circulations, has to be studied with more detail.

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