GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L10109, doi:10.1029/2004GL020009, 2004

The low-level circulation of the North American Monsoon as revealed by QuikSCAT

Simona Bordoni,[1] Paul E. Ciesielski,[2] Richard H. Johnson,[2] Brian D. McNoldy,[2]
and Bjorn Stevens[1]

Received 16 March 2004; revised 15 April 2004; accepted 22 April 2004; published 29 May 2004.

[1] Five years (1999–2003) of near-surface QuikSCAT ocean winds over the Gulf of California and northeast Pacific Ocean are used to characterize the changes in the low-level circulation associated with the North American Monsoon. Our analysis shows that the onset of the summer season is accompanied by a seasonal reversal of the flow along the Gulf of California, with the establishment of a time-mean southerly wind throughout the gulf. This reversal, not evident in the global reanalysis products, occurs in late spring and precedes the onset of the monsoonal rains. In the core of the monsoon, the time-mean flow is found to be modulated by transient events, namely gulf surges, detected in the near-surface wind field as periods of enhanced southerly flow which typically originate at the southern end of the gulf and propagate northward. The histogram of the summertime along-shore winds identifies these surges as a distinct population of events, readily distinguishable from the background flow. *INDEX TERMS:* 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3329 Meteorology and Atmospheric Dynamics: Mesoscale meteorology; 3360 Meteorology and Atmospheric Dynamics: Remote sensing. **Citation:** Bordoni, S., P. E. Ciesielski, R. H. Johnson, B. D. McNoldy, and B. Stevens (2004), The low-level circulation of the North American Monsoon as revealed by QuikSCAT, *Geophys. Res. Lett.*, *31*, L10109, doi:10.1029/2004GL020009.

1. Background

[2] The North American Monsoon (NAM) is a regional scale circulation that develops during the summer months over large areas of northwestern Mexico and the southwestern United States and is associated with a pronounced increase in rainfall over an otherwise very arid region. Although less impressive than its Asian counterpart, such a circulation is regarded as a monsoon circulation, based on seasonal reversal of pressure and wind patterns, energy and mass transfers, and typical regimes of rainfall and temperature [*Adams and Comrie*, 1997]. From an historical perspective, attention originally focused on the observed abrupt increase in rainfall between June and July over Arizona. As a result, the NAM literature has a strong geographical bias towards the southwestern United States (SW USA) and only recently has the increased summertime precipitation over the SW USA been recognized as the northernmost and most variable extremity of a much broader phenomenon, centered over northwestern Mexico [*Douglas et al.*, 1993]. Because of the lack of data with sufficient horizontal resolution to adequately sample the atmospheric conditions over the monsoon area and because of the original focus on marginal regions rather than on the core of the monsoon, there are still gaps in our basic understanding of the NAM, let alone its potential relation to other features in the regional circulation.

[3] Observations mainly collected during field studies as part of the SouthWest Area Monsoon Project (SWAMP) suggest the existence of a persistent time-mean southerly wind over the Gulf of California (GoC), believed to be the primary mode of moisture transport to the western flanks of the Sierra Madre Occidental and to the arid southwest deserts [*Douglas*, 1995]. Superimposed on this mean moisture flux, transient events, namely gulf surges, are observed. Gulf surges along the GoC are northward surges of relatively cool, moist maritime air from the Tropical Pacific into the southwestern desert region, which occur every summer during the NAM season. They were initially described in the early 1970s [*Hales*, 1972] and their anomalous northward moisture transport from the GoC is believed to support periods of monsoon bursts over the SW USA. Because of the sparsity of lower tropospheric observations over the GoC, a complete description and understanding of the surge phenomenon are still lacking. Most recent works have involved case studies, both from observational and modeling approaches, whereas studies aimed at determining their structure and frequency have been relatively few [*Douglas and Leal*, 2003].

[4] Modern scatterometry (QuikSCAT) provides nearly daily maps of the near-surface winds over the oceans at ~25-km spatial resolution and makes it possible for the first time to characterize with a high degree of accuracy the dynamical state of the lower troposphere over otherwise poorly sampled regions [*Liu*, 2002]. In this study, we use five summers of QuikSCAT wind data (1999–2003) to quantify the changes in the low-level circulation associated with the monsoon, with particular focus on the GoC region, now recognized as the dominant low-level moisture source for the monsoon convection [*Schmitz and Mullen*, 1996; *Berbery*, 2001]. Since the width of the GoC ranges from 150 to 300 km, the spatial resolution of QuikSCAT winds provides a considerable number of data points within the span of the Gulf, thus allowing unprecedented spatial and temporal resolution of the summertime low-level circulation.

[5] This study begins by constructing mean climatologies from QuikSCAT of the low-level winds over the GoC, to explore the time-mean structure of the flow associated with the onset of the summertime precipitation and its relationship to the larger scale circulation over the northeast Pacific

---

[1] Department of Atmospheric Sciences, University of California at Los Angeles, Los Angeles, California, USA.

[2] Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado, USA.

0094-8276/04/2004GL020009$05.00

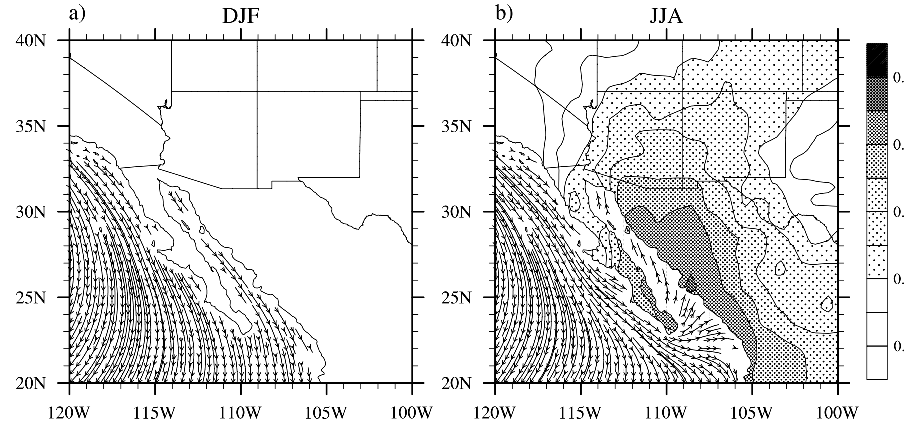

Figure 1. Mean streamlines of the 10m winds over the GoC as derived from all QuikSCAT observations for (a) DJF and (b) JJA. In (b) stippling over land areas shows the distribution of a Monsoon Index computed as the ratio of the JJA to the annual mean precipitation from the multi-year GPCP 1DD Precipitation Dataset [*Huffman et al.*, 2001].

in which it is embedded. The seasonal march of the monsoonal circulation is then examined by developing time series of the winds for the available years. Finally, histograms of the low-level winds are used to identify gulf surges. Hovmöller diagrams have been constructed to characterize their spatial and temporal structure and to detect their propagation speed up the GoC.

2. Analysis

[6] The QuikSCAT winds used in this study are obtained from the NASA/JPL Level 3 daily, gridded wind vectors with a horizontal grid spacing of 0.25°. In-situ studies [*Ebuchi et al.*, 2002; *Pickett et al.*, 2003; *Bourassa et al.*, 2003] have shown that QuikSCAT wind retrievals are accurate to better than the mission stated accuracy of 2 m s^{-1} in speed and 20° in direction. Data are available from late July 1999 to present. For each day, both ascending and descending pass measurements are provided. Typically these correspond to gulf-crossing times near 0500 and 1700 LST respectively. The exact crossing time and the degree of coverage varies with a four-day cycle, during which periods of “bursts” of closely spaced samples are separated by longer temporal gaps [*Schlax et al.*, 2001]. Over the GoC, sampling intervals are never longer than 24 hours, thus measurements are sufficiently frequent to allow resolution of synoptic-scale variability in the low-level circulation.

[7] Figure 1 shows mean streamlines constructed using all available QuikSCAT observations for a) boreal winter and b) boreal summer conditions. During the winter months, the low-level flow along the GoC appears to be an extension of the large-scale flow over the northeast Pacific Ocean, with northerly prevailing winds. In contrast, the onset of the summer monsoon season is accompanied by a seasonal reversal of the flow along the GoC, with the establishment of a time-mean southerly wind over the entire gulf. The existence of a strong seasonality in the low-level winds over the GoC had already been suggested by previous observational studies [*Badan-Dangon et al.*, 1991; *Douglas*, 1995]. In particular, mean streamlines of the lower-tropospheric flow derived from mesoscale observations during SWAMP-90 (35 days of pilot balloon soundings and several research aircraft flights in summer 1990) show a pattern similar to the JJA QuikSCAT streamlines in Figure 1b, with a mean southerly flow over and just east of the GoC extending into Arizona. Analysis of the SWAMP-90 winds at different heights indicates that this southerly flow possesses a low-level jet structure with maximum values in the lowest kilometer of the troposphere. The good agreement between the SWAMP-90 data and the five-year average surface winds from QuikSCAT increases our confidence in the use of the QuikSCAT product over the GoC, and suggests that the 35 days of pilot balloon soundings from SWAMP-90 are representative of the summertime mean circulation. It is worth emphasizing that this distinct summertime behavior of the low-level circulation over the GoC is not evident either in reanalysis products (e.g., NCEP), the spatial resolution of which does not resolve the dramatic topography of the monsoon region, or in the Seaflux wind product, which through an objective interpolation scheme initialized with ECMWF wind fields provides uniformly gridded maps of interpolated QuikSCAT winds on regular 0.5 × 0.5° grids at 12-hour intervals [*Tang and Liu*, 1996]. In Figure 2, a comparison plot of the coastal strip average of the JJAS flow along the GoC axis (along-shore wind) as derived from the three different datasets shows in fact that both NCEP and the Seaflux interpolated winds indicate northerly along-shore

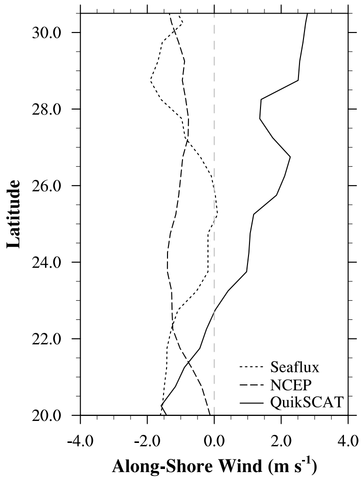

Figure 2. Coastal strip average of the JJAS along-shore winds over the GoC from QuikSCAT (solid), NCEP (dashed) and Seaflux winds (dotted).

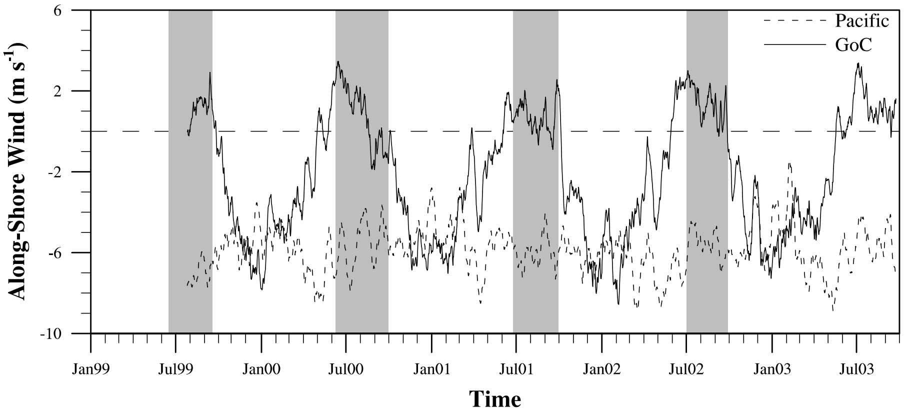

Figure 3. Time series of the 30-day running average of the along-shore winds composited over the GoC (solid line) and the northeast Pacific (dashed line). Shading roughly highlights periods of monsoonal precipitation larger than 3 mm day^{-1} over the core of the NAM as derived from the GPCP 1DD Precipitation Dataset (1999–2002).

flow. The large differences between the QuikSCAT and the Seaflux winds are somewhat surprising. One possible explanation is that the initialization of the interpolation process with ECMWF wind fields and/or the spatial size of the interpolating stencil, not critical over open-ocean regions, introduce biases in the interpolated fields over a region of complex topography such as the GoC. Such an explanation is consistent with the tendency (not shown) for the two wind products to agree better away from the GoC.

[8] To highlight the timing of the changes in the low-level circulation that lead to the summertime wind reversal, time series of the winds for the available years have been constructed for the GoC, by averaging over all points to the south of the midriff islands near 29°N, and for the Pacific Ocean, by averaging over all points in a box parallel and of the same longitudinal width of the GoC. From the zonal and meridional wind components, the along-shore (parallel to the GoC axis and positive for northward flow) and the cross-shore (perpendicular to the GoC axis and positive for on-shore flow) wind components have been computed. Evidence of distinct dynamical behavior in the northern GoC, influenced by the presence of the archipelago islands and by gap flow through the Peninsular mountain range of Baja California, complicates our analysis and motivates our focus on the southern GoC. Figure 3 shows the 30-day running average of the along-shore wind composited over the GoC (solid line) and the Pacific (dashed line). The summertime wind reversal over the GoC appears in the time series of the winds in that the along-shore wind over the GoC undergoes a strong seasonal cycle, which is not evident in the same component of the wind over the northeast Pacific. While the Pacific along-shore wind remains negative throughout the entire year, the along-shore wind over the GoC, whose negative values during the winter months are comparable to those over the Pacific, increases during the spring and becomes positive in the summer months, reaching a maximum in July. The time series of the cross-shore wind composited over the same two boxes (not shown) reveals a similar pattern with the GoC cross-shore flow undergoing a seasonal reversal from negative values during the winter to positive on-shore flow towards the western flanks of the Sierra Madre Occidental throughout the whole summer.

[9] The relatively high temporal resolution of the QuikSCAT time series allows us to address the question, first raised by the SWAMP-90 data, as to how transient disturbances contribute to the summertime climatology of the low-level flow over the GoC. Because of the implications for predictability studies, it is interesting to ask to what extent periods of strong southerly wind, or gulf surges, are identifiable as dynamical events readily distinguishable from the background flow. We begin to answer this question by constructing histograms of all available summertime along-shore wind observations as an approximation of the wind PDFs. The result is shown in Figure 4. A comparison of the Pacific (hatched) and the GoC (shaded) histograms reveals that, while the distribution of the winds over the Pacific appears to be monomodal, the GoC winds feature a bimodal distribution: although the most frequent along-shore wind value is negative and around 1.5 m s^{-1}, a secondary mode is found at positive values around 3 m s^{-1}, which represents pulses of southerly winds that are channeled into the GoC and propagate over its length. Kolmogorov-Smirnov tests performed on the observed GoC wind histogram allow us to reject at the 1% level the null hypothesis that the observed data are drawn from a single Gaussian. This motivates an alternative hypothesis, which such tests are not able to reject, that the data are drawn from a distribution composed of two Gaussians, with the second mode being associated with gulf surges. To further characterize the spatial and temporal properties of these periods of strong southerly flow, latitude-time Hovmöller diagrams have been constructed for the daily

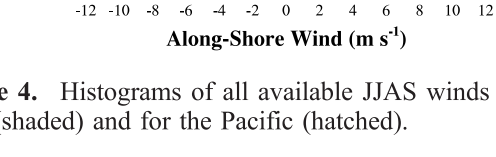

Figure 4. Histograms of all available JJAS winds for the GoC (shaded) and for the Pacific (hatched).

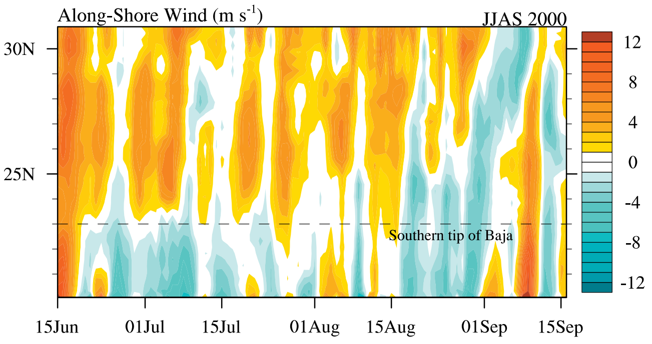

Figure 5. Latitude-Time Hovmöller diagram for the along-shore winds for JJAS 2000 averaged in longitude across an oceanic strip along the GoC from 20°N to 32°N.

along-shore winds averaged in longitude over an oceanic strip along and south of the GoC extending from 20°N to 32°N. In such diagrams (e.g., in Figure 5 for JJAS 2000) gulf surges appear as periodic, spatially coherent wind maxima up to 12 m s^{-1} usually confined to the length of the GoC. Most surges typically appear to originate at 23°N near the mouth of the GoC and propagate up the gulf with speeds of 5 to 10 m s^{-1}. Fewer events, associated with passages of tropical disturbances, are found to originate farther south from tropical latitudes.

[10] Overall, these results confirm the view of gulf surges as a distinct dynamical mode capable of transporting moisture from the GoC into the desert southwest. Furthermore, the bimodality of the GoC wind PDF provides a rational basis for identifying gulf surges, something which currently relies on surface observations at one single station [*Higgins et al.*, 2004]. This in turn can be used to examine the relationship between gulf surges and precipitation in the monsoon region.

3. Conclusions

[11] Past observations have hinted at the possibility that a low-level reversal in the flow over the GoC plays a role in the development of the North American Monsoon, particularly in connection with distinct events (surges) capable of providing anomalous moisture transport into marginal monsoon areas in the SW USA. Five summers of QuikSCAT winds, remarkable in both their temporal and spatial sampling over the GoC, resoundingly show that this seasonal reversal in the low-level flow is an integral component of the monsoon system itself. This reversal, in marked contrast to the rather tepid seasonality in the winds over the Pacific west of Baja, raises the question as to the role local topography plays in determining important features, such as the northward extent of the monsoon rains. In addition to demonstrating robust seasonality of the GoC winds, our analysis shows that this seasonal reversal happens rather abruptly in late spring, which precedes the rains and surface warming of the GoC. In the heart of the monsoon season, the southerly flow is found to be composed of distinct transients, or gulf surges, which are periods of enhanced southerly flow typically originating near the mouth of the GoC with a periodicity of 5–10 days. An analysis of the summertime wind histograms suggests that gulf surges are sampled from a distribution distinct from the background flow. This provides a rational basis for further studies which attempt to understand the relationships among (and predictability of) this type of transient activity, larger scale conditions, and precipitation events over marginal monsoon areas in the SW USA.

[12] These results demonstrate that QuikSCAT winds resolve with unprecedented resolution the low-level circulation over the oceanic NAM region. Used both in observation and modeling studies, such a dataset can make an important contribution to the current international effort to better understand and characterize the NAM, especially in view of the upcoming North American Monsoon Experiment (NAME) planned for summer 2004.

[13] **Acknowledgments.** The QuikSCAT Level 3 Ocean Wind Vector data were obtained from the Physical Oceanography Distributed Active Archive Center (PO.DAAC) at NASA JPL in Pasadena, CA. (http://podaac.jpl.nasa.gov). The interpolated Seaflux winds are obtained from the NASA/NOAA sponsored data system Seaflux, at JPL through the courtesy of W. Timothy Liu and Wenqing Tang. (http://airsea-www.jpl.nasa.gov/seaflux). This work was supported by NASA through Fellowship NGT530499 and Grant NAG512559 and by NOAA/PACS under Grant NA17RJ1228. We would also like to thank Rit Carbone and Hugo Berbery for their constructive reviews.

References

Adams, D. K., and A. C. Comrie (1997), The North American Monsoon, *Bull. Amer. Meteor. Soc.*, *78*, 2197–2213.

Badan-Dangon, A., C. E. Dorman, M. A. Merrifield, and C. D. Winant (1991), The lower atmosphere over the Gulf of California, *J. Geophys. Res.*, *96*(C9), 16,877–16,896.

Berbery, E. H. (2001), Mesoscale moisture analysis of the North American Monsoon, *J. Clim.*, *14*, 121–137.

Bourassa, M. A., D. M. Legler, J. J. O'Brien, and S. R. Smith (2003), SeaWinds Validation with research vessels, *J. Geophys. Res.*, *108*(C2), 3019, doi:10.1029/2001JC001028.

Douglas, M. W., R. A. Maddox, K. Howard, and S. Reyes (1993), The Mexican Monsoon, *J. Clim.*, *6*, 1665–1677.

Douglas, M. W. (1995), The summertime low-level jet over the Gulf of California, *Mon. Wea. Rev.*, *123*, 2334–2347.

Douglas, M. W., and J. C. Leal (2003), Summertime Surges over the Gulf of California: Aspects of Their Climatology, Mean Structure, and Evolution from Radiosonde, NCEP Reanalysis, and Rainfall Data, *Weather Forecasting*, *18*, 55–74.

Ebuchi, N., H. C. Graber, and M. J. Caruso (2002), Evaluation of wind vectors observed by QuikSCAT/SeaWinds using ocean buy data, *J. Atmos. Oceanic Technol.*, *19*, 2049–2062.

Hales, J. E. (1972), Surges of maritime tropical air northward over the Gulf of California, *Mon. Wea. Rev.*, *100*, 298–306.

Higgins, R. W., W. Shi, and C. Hain (2004), Relationships between Gulf of California Moisture Surges and Precipitation in the Southwestern United States, *J. Clim.*, in press.

Huffman, G. J., R. F. Adler, M. M. Morrissey, D. T. Bolvin, S. Curtis, R. Joyce, B. McGavock, and J. Susskind (2001), Global Precipitation at One-Degree Daily Resolution from Multisatellite Observations, *J. Hydrometeor.*, *2*, 36–50.

Liu, W. T. (2002), Progress in scatterometer application, *J. Oceanogr.*, *58*, 121–136.

Pickett, M. H., W. Tang, L. K. Rosenfeld, and C. H. Wash (2003), QuikSCAT satellite comparisons with nearshore buoy data off the U.S. west coast, *J. Atmos. Oceanic Technol.*, *20*, 1869–1879.

Schlax, M. G., D. B. Chelton, and M. F. Freilich (2001), Sampling Errors in Wind Fields Constructed from Single and Tandem Scatterometer Datasets, *J. Atmos. Oceanic Technol.*, *18*, 1014–1036.

Schmitz, J. T., and S. L. Mullen (1996), Water vapor transport associated with the summertime North American Monsoon as depicted by ECMWF analyses, *J. Clim.*, *9*, 1621–1634.

Tang, W., and W. T. Liu (1996), Objective interpolation of scatterometer winds, *Jet Propulsion Laboratory Publ.*, *96-19*, Pasadena, CA.

S. Bordoni and B. Stevens, Department of Atmospheric Sciences, University of California at Los Angeles, 405 Hilgard Ave, Box 951565, Los Angeles, CA 90095-1565, USA. (bordoni@atmos.ucla.edu)

P. E. Ciesielski, R. H. Johnson, and B. D. McNoldy, Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado, USA.