8A.4 OBSERVATIONS OF GULF OF TEHUANTEPEC GAP WIND EVENTS FROM QUIKSCAT: AN UPDATED EVENT CLIMATOLOGY AND OPERATIONAL MODEL EVALUATION

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1. INTRODUCTION

As part of the National Hurricane Center (NHC), the Tropical Analysis and Forecast Branch (TAFB) has marine analysis and forecast responsibility for portions of the eastern tropical Pacific Ocean (Fig. 1). Gap wind events in the Gulf of Tehuantepec are the most frequently observed storm-force (48 kt or greater) wind events that occur outside of tropical cyclones in this region.

The Gulf of Tehuantepec is situated south of the Isthmus of Tehuantepec, the narrowest area of land separating the Gulf of Mexico from the Pacific Ocean (Fig. 2). When cold-air outbreaks occur over the Gulf of Mexico, the Sierra Madre Mountains block the large-scale flow of cold air southward, resulting in the development of a strong north-south pressure gradient across the isthmus. Subsequently, northerly flow is funneled through the 40-km-wide Chivela Pass, a narrow break in the Sierra Madres. This gap flow often results in a narrow jet of winds that can reach gale (≥ 34 kt), storm (≥ 48 kt), and occasionally hurricane force (≥ 64 kt) in the Gulf of Tehuantepec (Fig. 3).

From previous case studies (e.g., Schultz et al. 1997; Steenburgh et al. 1998), and climatological studies (e.g., Schultz et al. 1998), the synoptic-scale features driving cold-air surges that result in gap wind events in the Gulf of Tehuantepec are relatively well-understood. The strongest cold surges into the region are associated with a confluent upper-level jet entrance region situated over the Gulf of Mexico and an upper-level ridge over the western United States, resulting in the equatorward movement of a surface anticyclone of arctic origin into the Gulf of Mexico (Schultz et al. 1998, their Fig. 14a).

Prior to the advent of satellite-based wind observations, sporadic ship observations provided the only information on the intensity of these gap wind events over the open waters of the Gulf of Tehuantepec, and little was known about the spatial distribution of the winds in these events. More recently, the availability of near-real-time (NRT) ocean surface vector wind (OSVW) retrievals from the SeaWinds scatterometer onboard the NASA QuikSCAT satellite, launched in 1999, has allowed consistent and unprecedented documentation of these events, including their frequency, duration and intensity (primarily gale vs. storm force).

NRT QuikSCAT retrievals have been available to forecasters at NHC since the fall of 1999, allowing for routine observation of these events and their intensity for the first time, the evaluation of operational model forecast performance in these events, and the development of a multi-year event climatology.

An initial climatology of Tehuantepec events was constructed by Cobb et al. (2002) based on the first three cold seasons of data (1999–2000 through 2001–2002) from the QuikSCAT mission. That study found an average of 15 gale-force and two storm-force events occurred each cold season. The first gale-force event of a season typically occurred in mid-October, with the final gale-force event occurring in late March or early April.

The goals of this study are (i) to utilize the long period of data from QuikSCAT to update the initial climatology of Cobb et al. (2002), and (ii) to examine the performance of real-time NWP model guidance available to TAFB forecasters for predicting these events during the 2006–2007 cold season.

A brief description of QuikSCAT will be provided in section 2, with the updated climatology presented in section 3. Section 4 contains an evaluation of operational NWP model guidance for the 2006–2007 cold season. Section 5 will discuss other potential sources of OSVW data for the detection of these events in the post-QuikSCAT era and section 6 will present a summary and conclusions.

2. QUIKSCAT DESCRIPTION

The SeaWinds scatterometer onboard QuikSCAT is a Ku-band scatterometer that estimates OSVW by measuring the backscatter due to centimeter-scale capillary waves on the ocean surface. QuikSCAT nominally provides wind retrievals with a horizontal resolution of 25-km, and since 2003 NRT 12.5-km retrievals have also been available. The NRT QuikSCAT retrievals available at NHC are processed at the National Oceanic and Atmospheric Administration/National Environmental Satellite, Data, and Information Service (NOAA/NESDIS) using the NRT retrieval process described by Hoffman and Leidner (2005). These data are displayed on the NOAA/National Centers for Environmental Prediction (NCEP) Advanced Weather Interactive Processing

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System (N-AWIPS) workstations used by NHC forecasters.

QuikSCAT provides wind retrievals in an 1800-km-wide swath, often twice per day near the Gulf of Tehuantepec. At 16°N (the approximate latitude of the Gulf of Tehuantepec), the gap between adjacent QuikSCAT swaths is approximately 930 km wide, resulting in occasional "misses" when the Gulf of Tehuantepec area falls in these gaps. Conveniently for synoptic analysis and comparison to NWP model output, QuikSCAT passes in the Gulf of Tehuantepec region generally occur within an hour of 00 UTC and 12 UTC.

Confidence in the accuracy of QuikSCAT OSVW retrievals is high for Tehuantepec events, especially since these wind events are rain-free, thus eliminating rain contamination as a source of error in the QuikSCAT retrievals. Recent measurements of hurricane-force winds in extratropical cyclones in non-raining conditions using the NOAA Stepped-Frequency Microwave Radiometer (SFMR) and GPS dropsondes were in close agreement with co-located QuikSCAT measurements (P. Chang, personal communication); confirming that QuikSCAT OSVW retrievals are accurate in the low end of the hurricane-force range in non-raining conditions.

3. TEHUANTEPEC EVENT CLIMATOLOGY

For each cold season from 1999–2000 through 2006–2007, all QuikSCAT passes showing winds of gale force or greater in the Gulf of Tehuantepec were cataloged. The classification of an event as gale- or storm-force is based on the peak QuikSCAT wind observed during the event from either 25-km or 12.5-km retrievals. Since 12.5-km QuikSCAT retrievals only became available in 2003, the number of storm events detected has increased substantially. Since the mean duration of a Tehuantepec event is 48 hours (Cobb et al. 2002), one or two QuikSCAT passes that "miss" during an event would not likely preclude detection of a gale-force event, but could result in missing a storm-force event, since those peak winds only occur during a short portion of the overall event.

During the 1999–2000 through 2006–2007 period, 99 gale- and 44 storm-force events have been observed; an average of 12.4 gale and 5.5 storm events per cold season. Since the advent of 12.5-km retrievals in 2003, the number of storm-force events detected has increased to an average of 7.4 per season from 2002–2003 through 2006–2007. The yearly count of gale- and storm-force events is shown in Figure 4. The 2003–2004 cold season had the largest number of events reach at least gale force (24), while the 2006–2007 cold season had the most storm-force events (12). This is nearly double the number of storm-force events observed in 2002–2003, the only other cold season with more than six storm-force events. The increased number of storm events during the 2006–2007 cold season occurred after the positive ENSO event in 2006. This is consistent with the findings of Romero-Centeno et al. (2003), who showed an increase in the frequency and strength of northerly winds in the southern Isthmus of Tehuantepec during ENSO years, and Schultz et al. (1998), who showed that Central American cold surges were more numerous after an El Nino year, due to a more prominent jet entrance region over the Gulf of Mexico.

The monthly distribution of Tehuantepec events shows the largest number of gale-force events occurring in December (Fig. 5). Storm-force events occur most often in January; with a secondary peak in November. Gale-force events have occurred as early as September and as late as May, however about 88% of the events occur between November and March.

4. OPERATIONAL MODEL EVALUATION

TAFB forecasters include forecasts and warnings for Tehuantepec events in a high seas forecast issued four times daily. NWP model guidance available in the region includes various global models, the NCEP Global Forecast System (GFS) being the most heavily used. For the first time in 2006–2007, the NCEP North American Mesoscale (NAM) model extended far enough south to include the Gulf of Tehuantepec region. Here operational model guidance for Tehuantepec events during the 2006–2007 cold season is evaluated.

At the time of this study, the GFS model was run with horizontal spectral truncation at wave number 382 (an effective horizontal grid spacing of approximately 40 km) and 64 vertical levels (T382/64) through the first 180 hours of the forecast, while the NAM model was run with 12-km horizontal grid spacing and 60 vertical levels. GFS output is delivered to TAFB forecasters on global 1° grids, and output from the NAM is provided on grids with approximate 90-km horizontal grid spacing.

For all times when QuikSCAT indicated at least gale-force winds in the Gulf of Tehuantepec, the maximum forecast wind speed from the GFS and NAM (to the closest 5 kt) was recorded at 12, 24, 36 and 48 h lead times. Table 1 summarizes the number of gale- and storm-force events, as observed by QuikSCAT, for which forecasts from each model were evaluated. The maximum QuikSCAT wind speed was obtained from gridded analyses with 1/4° (1/8°) grid spacing for the 25-km (12.5-km) retrievals [1] .The probability of detection (POD) of a gale-force or a storm-force event (as determined by QuikSCAT) from both the GFS and NAM was computed at 12-, 24-, 36- and 48-h lead

[1] At 15°N the spacing between individual points on the 1/4° (1/8°) grids correspond to 27 (13.5) km.

times. POD is defined in (1) as the number of hits (H) divided by the number of hits plus the number of misses (M) [2]:

$$POD=H/(M+H) \quad (1)$$

Model wind forecasts at the 10-m level were evaluated from the GFS and NAM, while winds from the lowest model sigma level in the GFS model (σ=0.9950), colloquially referred to as the "30-m wind", were also evaluated, since these data are often used by TAFB forecasters. POD results presented here have been verified against the 12.5-km QuikSCAT retrievals, since that data source is used by TAFB forecasters to verify the intensity of a Tehuantepec event.

Results indicate that 10-m wind forecasts from the GFS are unable to reliably predict the occurrence of storm-force Tehuantepec events, with a POD of 0.00 for all lead times (Fig. 6). The NAM 10-m wind shows some skill, with POD values of ~ 0.15 averaged over all lead times. The 30-m winds from the GFS have the highest POD, ~ 0.20 averaged over all lead times, but still miss about 80% of storm-force events.

Both models show considerably more skill in detecting gale-force events, with POD values of 0.84–0.88 for the NAM 10-m winds at 48-, 36-, and 24-h lead times, decreasing to 0.80 at 12-h (Fig. 7). POD scores are significantly lower for the 10-m GFS, between 0.49 and 0.58, while the 30-m GFS shows more skill, with POD values between 0.70 and 0.79.

Interestingly, for both gale- and storm-force events, relative to longer lead times, the POD scores for the NAM model decrease slightly at the 12-h lead time, while POD scores for the GFS generally increase at the 12-h lead time relative to longer lead time forecasts. The reasons for this loss of skill in the NAM as the event approaches are unclear; however this type of trend in short-term guidance can result in decreased forecaster confidence as an event approaches, and should be the focus of further study.

These verification results demonstrate a lack of reliable NWP low-level wind speed guidance available to TAFB forecasters, particularly for storm-force events. As a result, forecasters are forced to utilize pattern recognition and interrogate model wind forecasts at levels above the boundary layer (and assume that vertical mixing will transport these winds down to the surface) to accurately forecast and warn for storm-force Tehuantepec events.

The higher POD scores for the NAM 10-m winds suggest that the increased horizontal resolution of this model, which improves its ability to resolve the terrain features that help drive these events, may be important to improved detection of these events. However, differences in the planetary boundary layer and surface flux schemes between the NAM and GFS, and their impact on boundary layer stability and momentum transport, could be important factors in the accuracy of the 10-m wind forecasts. Additionally, the higher POD scores for the 30-m winds in the GFS relative to the 10-m winds suggest that an inability to properly mix higher winds down to the surface by the GFS model is partly responsible for its poor performance, particularly in storm-force events.

To examine the relationship between GFS model wind errors and errors in the larger-scale synoptic pattern, GFS model wind speed errors were compared to errors in the GFS model sea-level pressure difference across the Isthmus of Tehuantepec. The sea-level pressure difference was computed between Minatitlan (MMMT) and Ixtepec (MMIT, Fig. 2), and compared to observations. At the same approximate time, the GFS 10-m wind error was computed by comparison with the 25-km QuikSCAT maximum wind. This comparison was performed at 38 times for 36-, 24-, and 12-h GFS forecasts, and at 37 times for the 48-h GFS forecast.

Results indicate that in some cases, large errors in wind speed are associated with large model errors in the cross-isthmus SLP difference (Fig. 8), suggesting that errors in the overall synoptic pattern (e.g., position and intensity of the surface anticyclone) can cause large model wind forecast errors. However, large model forecast errors (under-forecasts) in wind speed are also seen when the model-forecasted pressure difference across the isthmus is accurate or even overestimated. This suggests that some large wind speed errors in the GFS are not a result of errors in the mass field forecast, further supporting the hypothesis that boundary layer processes such as vertical mixing, in addition to horizontal resolution deficiencies, play a role in accurate model forecasts of these events.

5. BEYOND QUIKSCAT

Without the benefit of QuikSCAT observations in the region, only 14 of 44 storm-force events (31.8%) that occurred since 1999 would have been identified by synoptic hour ship observations. Given that QuikSCAT has already exceeded its five-year life expectancy, an overview of other potential sources for OSVW in Tehuantepec events is provided. In general, NHC's ability to detect Tehuantepec events will likely be degraded once QuikSCAT data are no longer available.

Wind retrievals from the multi-frequency, polarized, passive microwave WindSat radiometer onboard the U.S. Navy/Air Force Coriolis satellite have been available in near real time at NHC for evaluation since

[2] A forecast of a gale-force event by a model at a time when QuikSCAT observed storm-force conditions would count as a "hit" in the gale category and a "miss" in the storm category.

June 2006. WindSat wind retrievals received at NHC are processed at NOAA/NESDIS using NOAA's WindSat Ocean EDR retrieval algorithm (Jelenak et al. 2004), with 50-km resolution.

During the 2006–2007 cold season, 22 WindSat passes occurred over active Tehuantepec events of at least gale force. Sixteen of the WindSat passes occurred in close proximity to QuikSCAT passes, allowing for a comparison of the retrievals (Fig. 9). WindSat showed gale-force conditions in seven passes, winds of less than gale force in nine passes, and did not retrieve any storm-force conditions. On average, the maximum WindSat retrieved wind speed was 7.6 kt less than the maximum 25-km QuikSCAT retrieved wind speed.

This difference is largely due to WindSat's resolution and land mask. The 50-km resolution of the WindSat retrievals is too coarse to resolve the strongest core of winds in Tehuantepec events, particularly those of storm force, which typically occur in a narrow swath. Additionally, the 100-km land mask for WindSat precludes retrievals in the region just offshore where the maximum wind in QuikSCAT retrievals is often observed. In fact, in 13 of the 16 co-located passes, a WindSat retrieval was not available at the point where the QuikSCAT wind maximum was seen.

These results suggest that WindSat will be unable to routinely identify storm-force Tehuantepec events, but can identify some gale-force events and detect the outer wind field of less than gale force. In addition to resolution issues, another limitation of operational use of WindSat for Tehuantepec event identification is the low number of passes compared to QuikSCAT passes, due to the relatively narrow swath (1000 km) of WindSat retrievals.

The Advanced Scatterometer (ASCAT) was launched onboard the European Space Agency's METOP satellite on 19 October 2006. NRT wind retrievals from ASCAT should become available later this year to NHC forecasters. The coverage of ASCAT is only about 60% of QuikSCAT, and ASCAT retrievals will be performed with 50-km resolution, with post-processing techniques resulting in the availability of 25-km retrievals as well. Therefore, relying on ASCAT alone will result in a reduction in the number of Tehuantepec events detected due to the decrease in resolution and coverage relative to QuikSCAT.

6. SUMMARY AND CONCLUSIONS

OSVW retrievals from QuikSCAT have become a critical tool used by TAFB forecasters at NHC to identify and warn for gale- and storm-force wind events in the Gulf of Tehuantepec. The long data record from QuikSCAT has allowed the development of a nine-year climatology of Tehuantepec events, indicating that, on average, 12.4 gale- and 5.5 storm-force events occur per cold season. Since the advent of 12.5-km QuikSCAT retrievals in 2003, the average number of storm-force events detected has increased to 7.4 per season. The great majority of Tehuantepec events occur from November through March, with some outlier events occurring as early as September and as late as May.

An evaluation of operational NWP model guidance in the region during the 2006–2007 cold season shows that the GFS and NAM models are unable to accurately forecast storm-force events in the region. Gale-force events are better identified in 10-m wind forecasts from the NAM relative to the GFS. Additionally, the use of the 30-m wind from the GFS by TAFB forecasters is justified (as a proxy), since winds at this level were shown to have considerably higher POD scores for gale- and storm-force events than the GFS 10-m wind. Large errors in GFS 10-m wind forecasts occurred even when GFS forecasts of sea-level pressure difference across the Isthmus of Tehuantepec were accurate, suggesting that while some GFS wind errors are associated with poor model forecasts of synoptic-scale features (e.g., surface anticyclones), some large wind speed errors occur even when the model synoptic-scale forecast is accurate. This combination of results suggests that both horizontal resolution and vertical mixing may play a role in the accuracy of operational NWP guidance for Tehuantepec events. Improvements in the resolution of model data received operationally at NHC would be beneficial to forecasters trying to predict these small-scale weather events.

An additional unexplored error mechanism in real time NWP model forecasts of Tehuantepec events is the impact of sea-surface temperature (SST) reduction due to strong mixing of the upper ocean after the onset of high winds. Previous work has shown that this cooling can be both rapid and extreme, exceeding 8°C in several hours (e.g., Schultz et al. 1993). Since current operational NWP model guidance in this region is not coupled with an ocean model, SST values remain fixed for the duration of the model run, likely resulting in an underestimation of boundary layer stabilization after the onset of high winds. The neglect of this factor should result in an *overestimation* of the winds in model guidance relative to observations; however, since large *underestimates* of wind speeds in this region are currently seen in operational model forecasts, it is possible that the lack of coupling is not currently the largest source of NWP model error in these events. Coupled model simulations of these events should be undertaken to quantify the impact of upper oceanic mixing on the transport of high momentum air to the surface.

As QuikSCAT moves into a fifth year of operation past its original life expectancy, the prospects for improving or even maintaining the current coverage and quality of ocean surface vector wind retrievals, that have revolutionized the analysis and forecasting of these gap wind events, are uncertain. Resolution and associated land-mask limitations of the WindSat passive radiometer preclude the satellite from providing wind retrievals in the region where the highest winds in Tehuantepec events are often observed with QuikSCAT. Wind retrievals from the ASCAT scatterometer will be performed with 50-km resolution, and enhanced resolution 25-km retrievals also expected to be available. Additionally, the coverage of the ASCAT wind retrievals will be reduced by 40% compared to QuikSCAT, resulting in decreased observations of these events.

Increasing the resolution of ocean vector wind retrievals into the 2.5-km range would provide for much more detailed observations of these events, and likely result in increased detection of storm- and hurricane-force Tehuantepec events. A multi-satellite platform, such as the extended ocean vector winds mission (XOVWM) recently recommended to NOAA by the National Academy of Sciences' *Decadal Survey* would provide a substantial increase in both the quality and quantity of remotely sensed ocean surface vector wind data for the real time observation of these and other extreme weather events.

7. ACKNOWLEDGEMENTS

Thanks to Mr. Greg McFadden of the Ocean Prediction Center for providing the original code to create gridded QuikSCAT files for GEMPAK.

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Table 1. Number of GFS and NAM forecasts evaluated for gale- and storm-force Tehuantepec events detected by 12.5-km QuikSCAT during 2006–2007 cold season.

	Forecast Hour							
	48h		*36h*		*24h*		*12h*	
Model Type	*Gale*	*Storm*	*Gale*	*Storm*	*Gale*	*Storm*	*Gale*	*Storm*
GFS 10 m	59	26	61	26	60	26	60	26
GFS 30 m	58	26	61	26	61	26	61	26
NAM	51	20	52	20	52	20	52	20

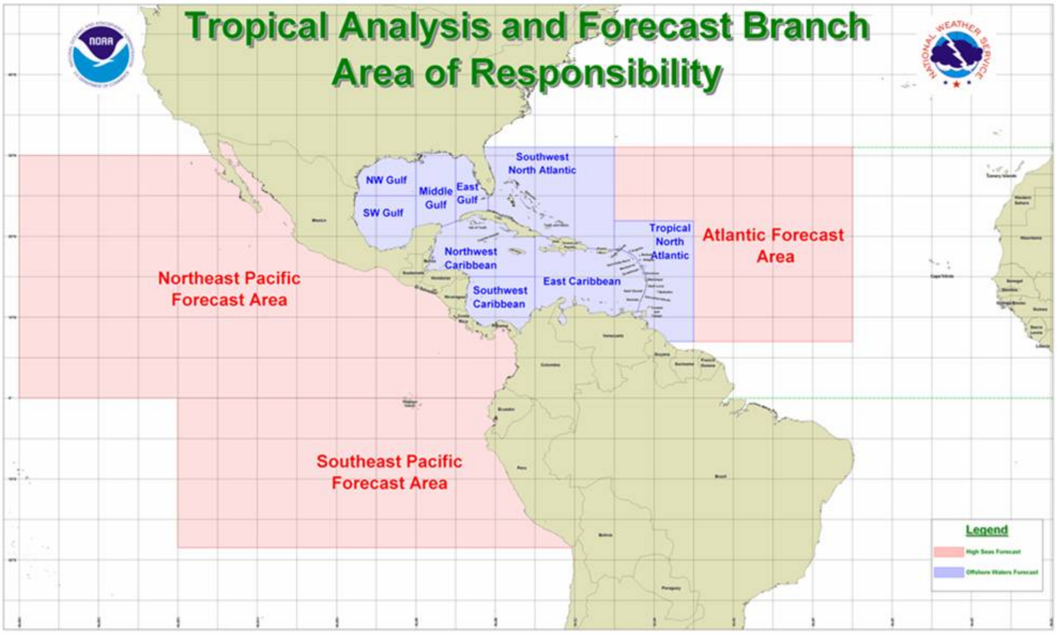

Figure 1. TAFB's area of marine forecast responsibility.

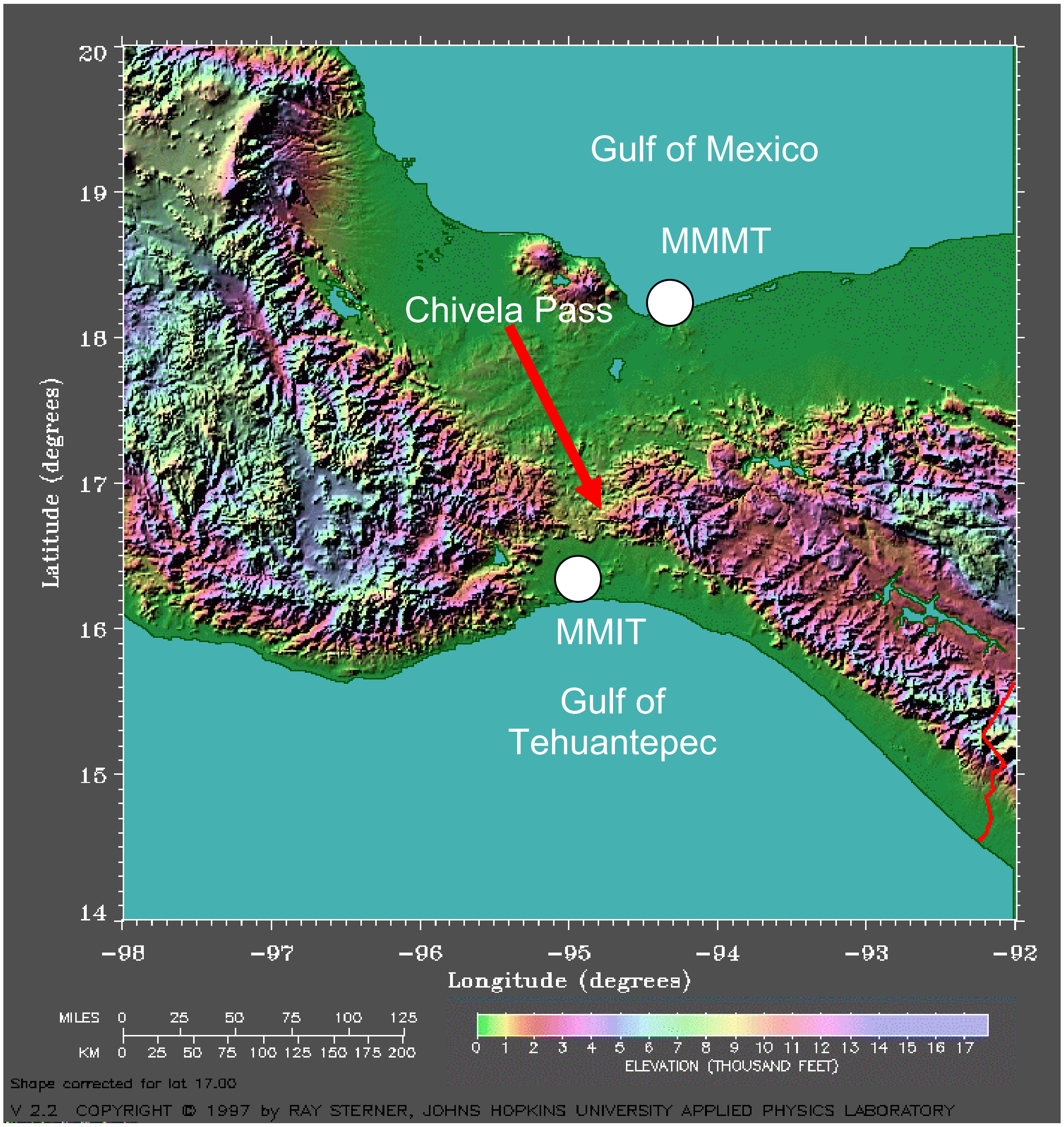

Figure 2. Topography of Isthmus of Tehuantepec. MMMT and MMIT mark the approximate locations of Minatitlan and Ixtepec, respectively. Image courtesy Johns Hopkins Applied Physics Laboratory.

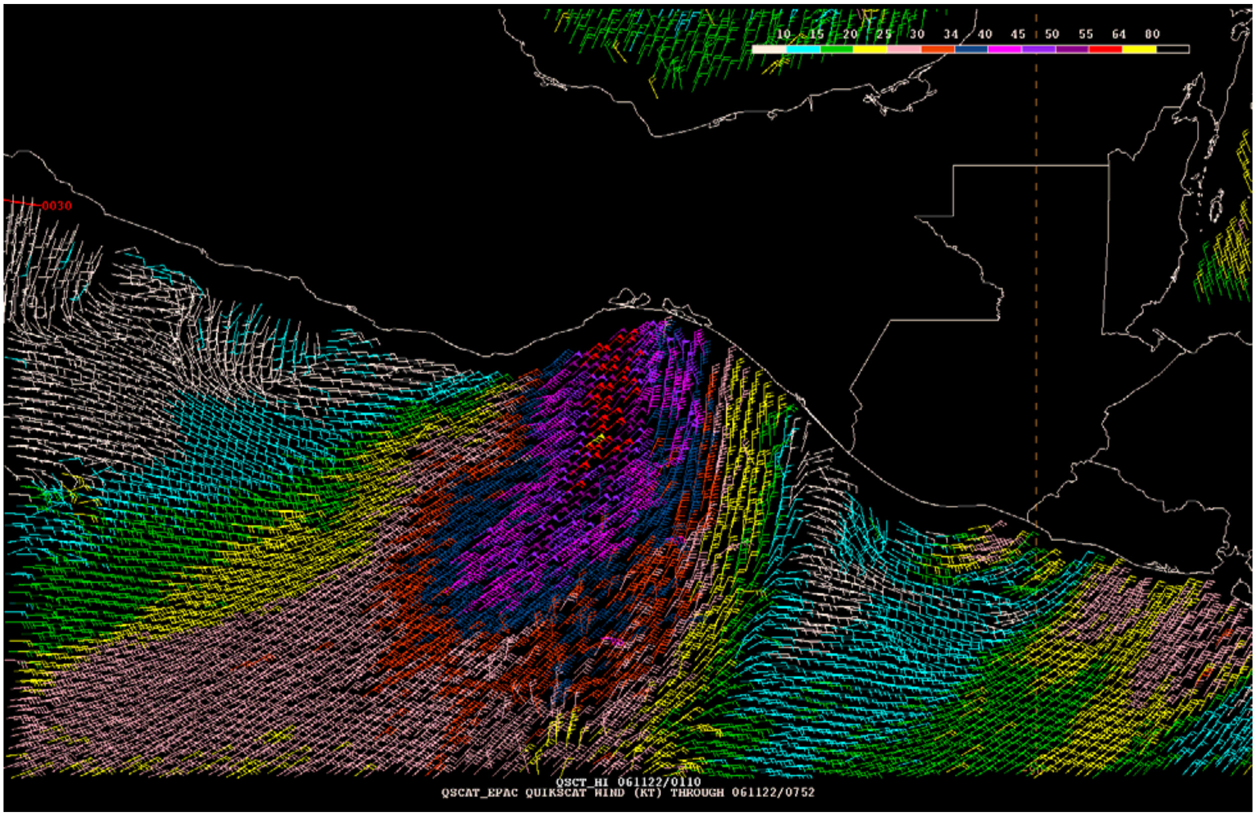

Figure 3. QuikSCAT pass over the Gulf of Tehuantepec showing 12.5-km wind retrievals (barbs, kt) at 0030 UTC 22 November 2006.

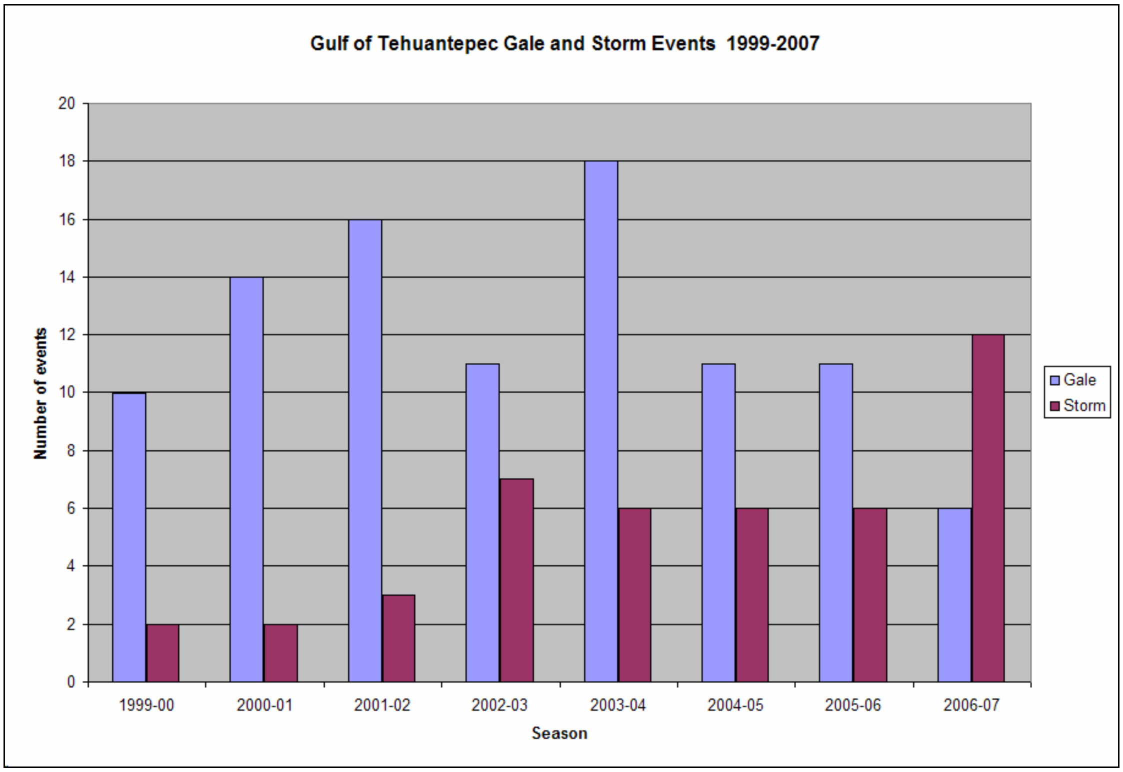

Figure 4. Annual count (by cold season) of gale- and storm-force Tehuantepec events in the QuikSCAT era through 2006–2007. Note that 12.5-km QuikSCAT retrievals became available in January 2003.

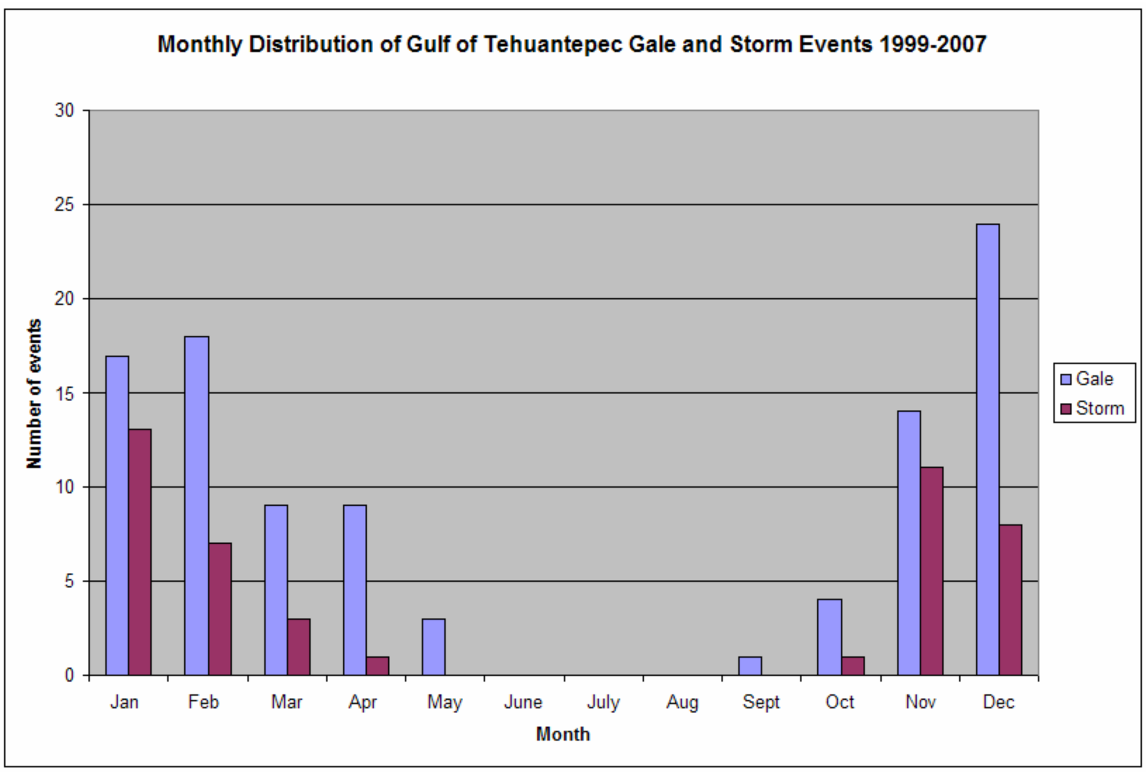

Figure 5. Monthly count of gale- and storm-force Tehuantepec events in the QuikSCAT era through 2006–2007.

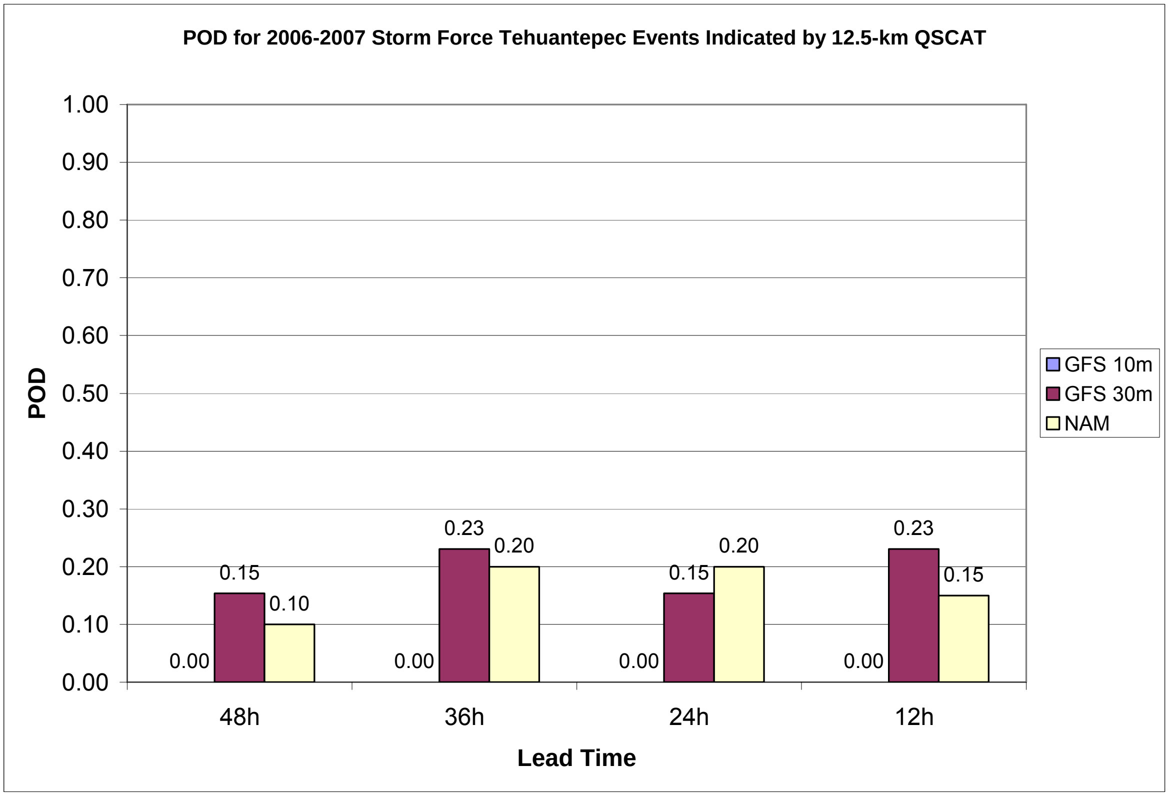

Figure 6. POD scores for GFS 10-m and 30-m winds, and NAM 10-m winds for 2006–2007 storm-force Tehuantepec events.

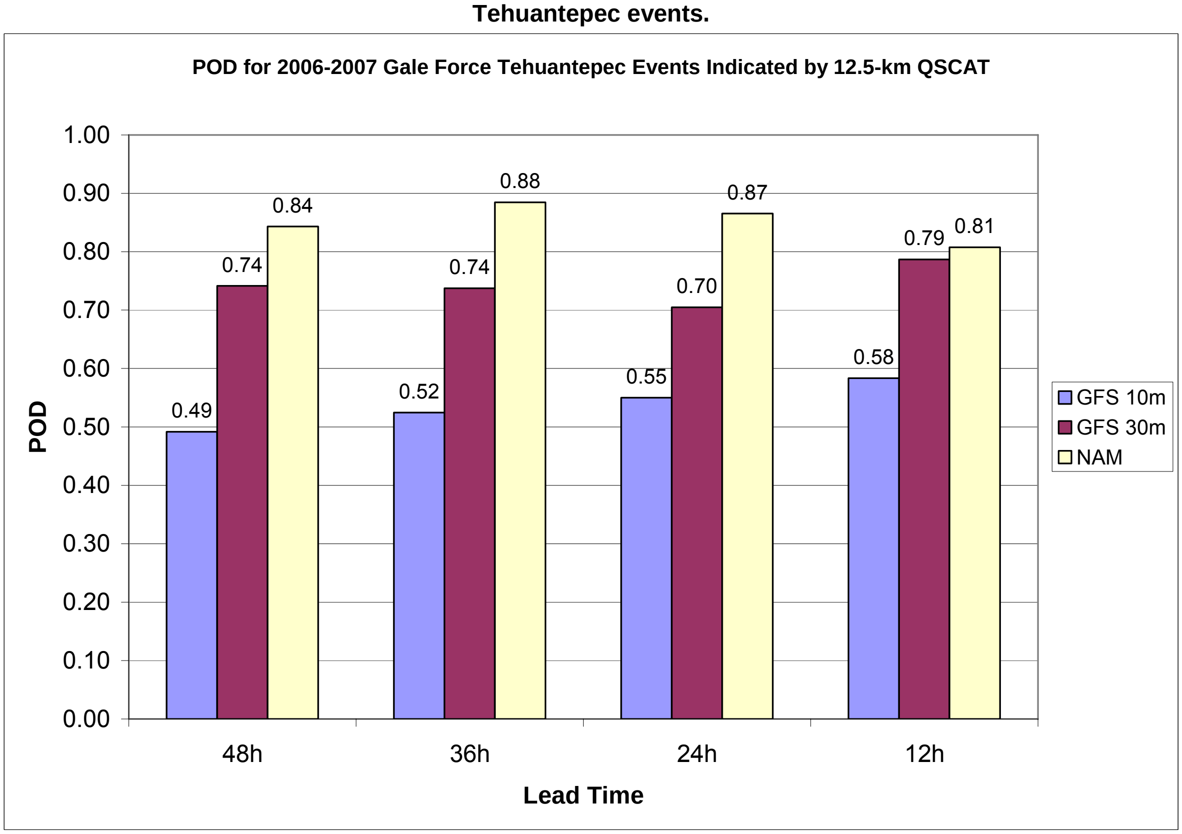

Figure 7. As in Fig. 6, except for gale-force events.

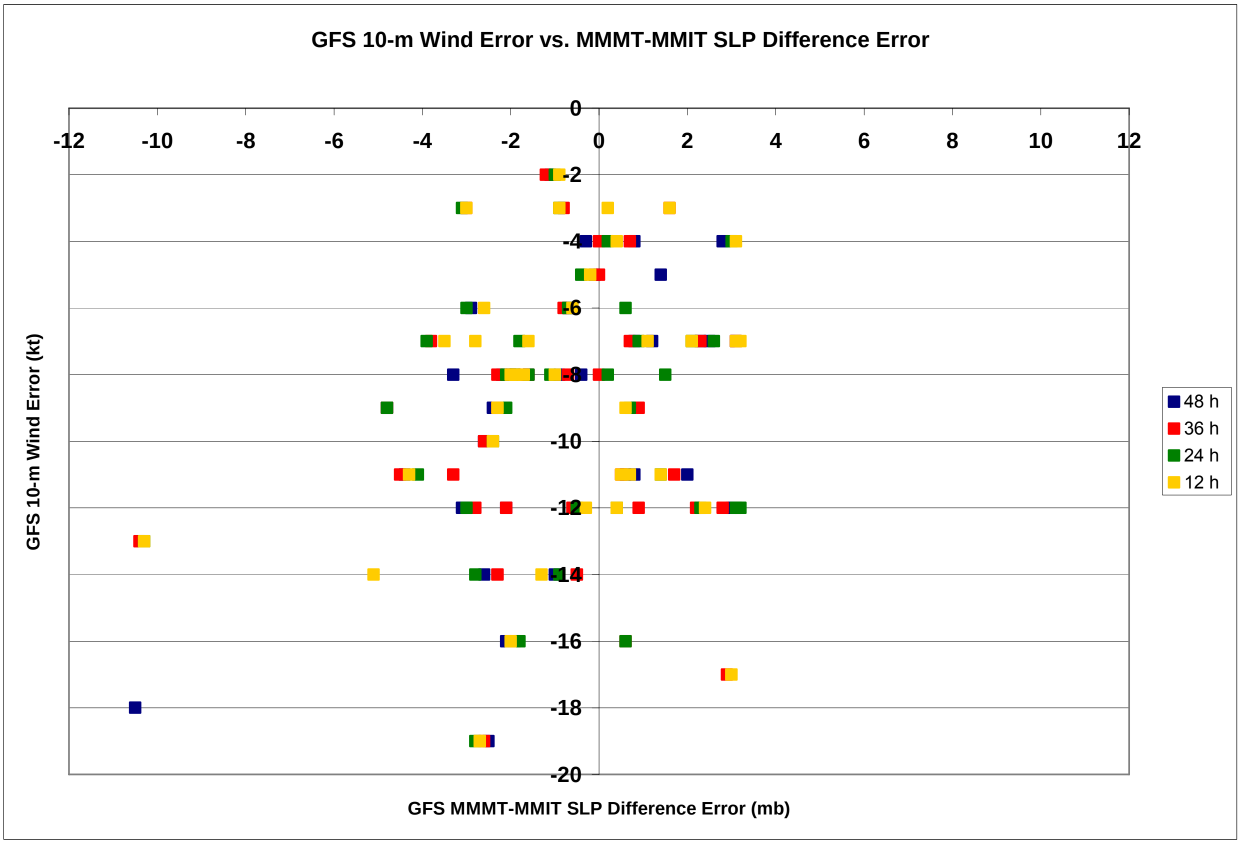

Figure 8. Scatterplot of GFS sea-level pressure difference errors across the Isthmus of Tehuantepec (hPa, x-axis) and model wind speed errors (kt, y-axis). Colors represent the forecast lead time.

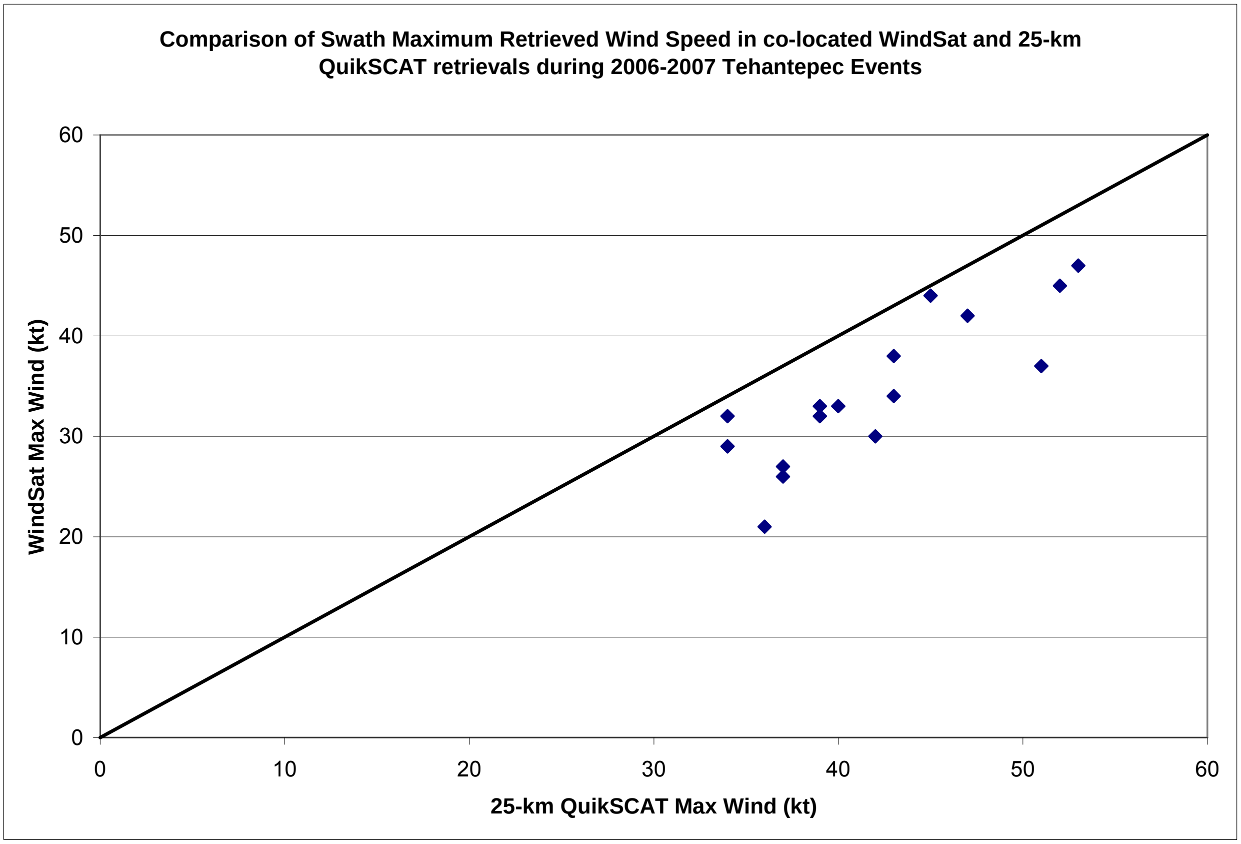

Figure 9. Scatterplot of maximum wind from WindSat and 25-km QuikSCAT in co-located passes during 2006–2007 Tehuantepec events.