

**Report of Large Scale Wind Patterns in the Tropical
Pacific via EOF and CCA Analysis of NSCAT and
TAO Array Data**

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Abstract

Wind measurements derived from the NASA Scatterometer (NSCAT) and measured by the Tropical Ocean Atmosphere (TAO) buoy array are used in a comparative analysis to examine the large-scale wind patterns in the tropical Pacific on 10-day and longer time scales. First, we addressed a possible aliasing of semidiurnal wind variability by the twice daily NSCAT sampling with a statistical analysis of averaged TAO hourly winds sampled at NSCAT crossing times versus 24-hour sampling. The aliasing was small ($-0.12 \pm 0.23 \text{ ms}^{-1}$ and $-0.03 \pm 0.24 \text{ ms}^{-1}$ for zonal and meridional winds, respectively) for 10-day and longer periods. A subset (34) of the TAO buoys with sufficiently complete time series was used for large-scale comparisons. These were located predominately in the central part of the TAO array. An EOF analysis over the period from October 1996 to June 1997 found the first two modes were very similar in both the TAO data and NSCAT data sampled at TAO locations. One mode represented an equatorial velocity jet associated with the onset of the 1997-1998 El Niño, the other an acceleration of the northeast Trade and Monsoon winds. The order of these modes was reversed in the EOF of the full spatial resolution NSCAT data. This is a result of the increased spatial coverage of the full NSCAT data in the region east of 95W where the trade wind mode is strongest. The strong agreement of the first two modes, together accounting for >65% of the total variance, shows that both measurement systems provide consistent observations of the large-scale wind field.

The two wind field data sets were very highly correlated ($r > 0.99$) as evidenced by results of a canonical correlation analysis (CCA). TAO buoy data were correlated with the NSCAT data subsampled at TAO buoy locations, as well as with the full spatial resolution NSCAT data with similar results. A directional offset was found with the NSCAT wind vector rotated 14° to the right, relative to the TAO data, averaged over all locations. This rotation was of the same sign in both hemispheres and on the equator, ruling out an Ekman planetary boundary layer effect. A small speed bias of 0.09 ms^{-1} was found, but it was not significantly different from zero at the 90% confidence level.

1. Introduction

The NASA Scatterometer (NSCAT) offers high-resolution measurements of the global surface marine wind field as described by Liu et al [1998a]. In this analysis, we address the applicability of these data for studying tropical Pacific wind forcing of climatic variability via comparison with the Tropical Atmosphere-Ocean (TAO) surface buoy wind measurements. Two kinds of errors can degrade the accuracy of NSCAT wind retrievals; one due to algorithms and the other due to sampling. Point validation studies are very important in estimating errors in the geophysical model functions that convert the NSCAT backscatter to wind velocity. Recent results show that the NSCAT vector wind retrieval accuracy was within the mission tolerances of 2 ms^{-1} speed and 20 degrees direction rms [Bourassa et al, 1997]. Nevertheless, such studies do not reveal certain problems, which may arise due to sampling and aliasing, and they do not address the spatial and temporal scales of variability. The key questions we address here are: what are the climatically important, large scale wind patterns in the tropical Pacific, and how do NSCAT and TAO data compare in representing these patterns? We consider what arises principally from differences in the sampling properties of the two observing systems. In the process, we also quantify direction and speed biases that are consistent with reports by other investigators.

Even with perfect wind retrievals from point measurements, there will remain errors in the derived wind fields over any space-time composite because real-time observing systems can not continuously sample all locations at all times. We consider first the effects of diurnal and semi-diurnal wind variability. Diurnal wind variability along the equator was evident in an early subset of the TAO array [Halpern, 1988]. More recently, Deser [1994] and Deser and Smith [1998] describe diurnal and semi-diurnal variations in a more extensive set of TAO winds in the eastern tropical Pacific where zonal winds had a distinct semi-diurnal component in the central and eastern basin. Peak easterly velocities occurred at approximately 1500 and 0300 local time. These peaks present an aliasing problem for NSCAT because the sun-synchronous satellite orbit permits measurements only at approximate local times: 1030 and 2230. The sampling would occur at the same phase of the semi-diurnal cycle, aliasing the mean downward if the minima are occurring at about 0900/2100. Meridional winds tended to be more diurnal, with peak northerly winds at night between latitudes 0-5N. Amplitudes were observed to vary seasonally, and can

be anticipated to vary interannually as well. For our study the degree of aliasing was determined objectively by analysis of TAO buoy hourly wind measurements. We found the differences to be small for 10-day winds and statistically negligible for monthly wind climatology.

We next address the large-scale space time variability of tropical winds on the scale of the Pacific basin. The objective here is to test whether NSCAT and TAO recover the same large scale modes which are important to ENSO and other tropical dynamics, and what the discrepancy patterns look like. It represents, in effect, a comparative evaluation of both the NSCAT and TAO wind observing systems.

Conventional EOF and canonical correlations (CCA) between TAO and NSCAT winds were used to determine how well the fields agree, to what extent they disagree, and what portions of the variance contribute to the dominant modes in each data set. This represents a space and time perspective that cannot be addressed with conventional point correlations. It is well known that EOFs often reduce, or filter, the space-time variability to a small number of statistically significant modes. CCA allows the description of orthogonal modes of covariance between two space-time distributed data sets. The canonical correlations are very high in this case, as would be expected of separate measurements of the same field. Significant differences were found, however, in the relative variance of highly correlated modes, partly related to sampling differences.

2. Data and Methods

As described by McPhaden et al [1998], the TAO array consists of approximately 70 buoys spaced fairly regularly across the tropical Pacific Ocean within 9 degrees north and south of the equator. This array measures upper-ocean properties and surface weather conditions, including wind speed and direction, thus providing a large-scale picture of the wind field over the Pacific. The winds are measured 4 meters above the ocean at a sample rate of 2 Hz, over period of 6 minutes centered at the top of each hour. Nominal wind speed and direction sample resolutions are 0.2 ms^{-1} and 1.4° , respectively. The TAO data used was obtained at two different sample

rates. Hourly data from 1990 through 1996 were used for the TAO/pseudo-NSCAT bias evaluation and 10-day averaged values derived from daily winds between September 1996 to June 1997 were used for the speed/direction bias estimates as well as the EOF/CCA analysis.

Ten-day averaged NSCAT winds, computed with the NSCAT-1 model function [NASA/JPL, 1997] and interpolated to a 1-degree grid, were provided by Wenqing Tang (NASA/JPL). Data from the tropical Pacific region within 10 degrees of the equator were extracted for this analysis.

3. Sample Aliasing

Because of the twice daily sampling of NSCAT and the evidence for semi-diurnal and higher frequency wind variability in the tropical Pacific [Deser, 1994], we tested the effect of aliasing these signals into the computation of the daily and longer-term means. The goal of this analysis was to quantify the potential for aliasing given the sampling regime, not necessarily to quantify aliasing during the limited period of NSCAT. Thus, it is not necessary that TAO and NSCAT data overlap in time for this analysis, so for more robust statistics, TAO records over several years (1990-96) were used. The hourly winds from the TAO buoy array (69 buoys) were subsampled at the NSCAT crossing times. The daily averages of these pseudo-NSCAT data were compared with daily averages computed using all the hourly wind data. For each TAO buoy location, the hourly wind components (u and v) before and after the local NSCAT crossing times (1030 and 2230) were averaged to produce a semi-diurnal time series that would simulate the NSCAT sampling protocol. Daily and 10-day means were calculated with both the TAO and pseudo-NSCAT data sets and the differences were analyzed. Ten-day averages were chosen for this analysis to be consistent with the 10-day averaged NSCAT data utilized in the EOF and CCA studies discussed below. A 10-day average was necessary to create the global coverage in the NSCAT data set and was not considered limiting since the emphasis in the study is on climatological response time scales.

A representative time series of the TAO daily mean and the pseudo-NSCAT daily mean for both zonal (Figure 1) and meridional (Figure 2) wind components, along with histograms of the daily

differences and the 10-day mean daily differences, over the entire data set, are presented. The time series track each other very well, with the general shape and character consistently represented by the pseudo-NSCAT daily means. The range of the distribution of the 10-day mean differences for both components is less than $\pm 1.0 \text{ ms}^{-1}$. The range of the mean daily differences for both computational methods was generally less than the NSCAT measurement threshold of 2 ms^{-1} . The means of these distributions showed very small biases (mean and SD were $-0.12 \pm 0.23 \text{ ms}^{-1}$ for zonal and $-0.03 \pm 0.24 \text{ ms}^{-1}$ for meridional components for the 10-day data), negative as expected. Our conclusion is that sampling interval aliasing of semi-diurnal signals in the NSCAT data is not a significant error source for daily and longer time scales.

4. Empirical Orthogonal Function Analysis

We compared large scale and low frequency modes in TAO buoy data with those from NSCAT data using Empirical Orthogonal Functions (EOF's) in order to evaluate the NSCAT measurement of the wind field. The NSCAT wind vectors were averaged to a 10-day, 1×1 degree global data set (courtesy of Wendy Tang, NASA/JPL), from which the tropical Pacific region of interest (10S to 10N and 160E to 100W) was extracted. A subset of this data, produced by linearly interpolating in 2-D to the locations of the TAO buoys, allowed as direct a comparison as possible with the more sparsely sampled TAO data set, thus adjusting for any spatial sampling bias. The TAO array data had gaps of various lengths in most of the buoy records during the operational period of NSCAT (September 1996 through June 1997). Daily wind data from the TAO array were averaged into 10-day intervals with no average calculated unless at least 5 of the 10 days had data. Continuous 10-day time series were recovered for 34 of the 69 TAO buoys. Their locations were clustered in the central basin between 140E and 110W (Figure 3). Both data sets were interpolated to a common 10-day time base and divided into three distinct sets for comparative analysis: 1) TAO winds, 2) NSCAT winds at TAO locations (NSCAT@TAO) and 3) $1^\circ \times 1^\circ$ resolution NSCAT winds. The EOFs of each were resolved for the first five modes (Table 1).

All five modes showed similar patterns among the respective data sets. The first two modes account for 58 to 68% of the total variance, while each of the subsequent modes are 10% or less

of the total variance. Accordingly, our comparisons are focused on the first two modes. The EOF amplitude and eigenvectors for modes 1 and 2 are shown in Figures 3 to 5 for each of the three data sets.

Table 1. - Percent Variance accounted for, by each EOF mode

EOF Mode	TAO Winds	NSCAT@TAO winds	NSCAT winds
1	41.2	34.9	32.8
2	26.6	27.8	24.8
3	10.2	8.9	9.0
4	5.0	7.0	6.5
5	4.1	4.7	5.2
Modes 1-2 total	67.8	62.7	57.6
Modes 1-5 total	87.1	83.3	78.3

The EOFs of the TAO array winds (Figure 3) illustrate the two distinct wind patterns. Mode 1 consists of an equatorial jet-like feature. Since the data have had the mean removed for this analysis, this represents a mode with enhanced eastward equatorial winds, or weakened westward winds, compared to the mean field. The amplitude function for this mode increases in March of 1997 and represents the equatorial, eastward wind anomaly pattern associated with the onset of the 1997-98 El Niño [Liu et al, 1998b]. The second mode indicates a strengthening of southwestward wind vectors, or equivalently, a strengthening of the northeast Trade Winds in the east-central basin. The seasonal cycle and the Monsoon patterns in the western Pacific are also evident in this mode, but the 9-month record length limits the resolution of these phenomena. The associated amplitude function shows the mode strengthening gradually from October 1996, reaching a maximum in March 1997 and subsequently decreasing in magnitude through early June 1997. The remaining EOF modes have much weaker amplitudes but do represent organized large scale geophysical signals. These patterns are represented in the CCA described in Section 4. The EOF analysis of the TAO array winds thus represents two dominant orthogonal modes of the

equatorial wind field during this time; the jet-like equatorial flow and the Trade Winds-Monsoon pattern.

The results of the EOF analysis using the subset of NSCAT wind vectors at the TAO buoy locations (NSCAT@TAO wind) are very similar (Figure 4). The first mode again represents the jet-like equatorial flow and the amplitude function is almost identical to the corresponding TAO data. The percentage of variance accounted for by the mode is slightly less than the TAO winds EOF mode 1 (35% as opposed to 41%), whereas, the respective mode 2 variances are nearly identical.

EOF analysis of the full resolution tropical Pacific NSCAT field (Figure 5) produces wind field modes similar to those from the less densely sampled data sets, except that the order of the two modes is reversed. The Trade Winds (mode 1) have a greater proportion of variance (33% vs. 25%) than the equatorial jet (mode 2). The reversal of the order of these modes is a result of the selection criteria for including TAO data in the analysis. NSCAT coverage extends well east of 125W, allowing the Trade Winds mode to represent a larger percentage of the variance since this variability is more prevalent in this region. Although the TAO array also extends into this region, gaps in the data at these locations precluded their inclusion. The resulting reversal of the order of the modes was tested by calculating the EOF using only the NSCAT data west of 95W (not shown), which resulted in the same order of modes seen in the TAO data. The full NSCAT wind fields show more detail in the structure due to the denser nature of the data set, which is a benefit of the NSCAT instrument¹. The amplitude functions for the high resolution modes are quite similar to the corresponding TAO located EOFs, demonstrating that the wind fields from these two disparate measurement systems represent the same large scale variability.

5. Canonical Correlation Analysis

The relationship between the two data sets can be further quantified using Canonical Correlation Analysis (CCA) [Barnett and Preisendorfer, 1987]. CCA modes represent ordered patterns of

¹ Note that the data are 1x1 degree resolution, but are sub-sampled 1x5 degree resolution for plotting.

correlation between the two arrays, which have the same time axis, but may have different spatial coordinates or may be different variables entirely. The first five EOF modes of the respective data sets were used as input to the CCA in the following discussions.

5.1 Large Scale Patterns

The CCA between the TAO wind field and the NSCAT@TAO winds had the highest correlation in a mode resembling the Trade Wind pattern (Figure 6a). This accounts for approximately the same amount of variance in both data sets (29.1% and 27.4%, respectively, Table 2). The CCA amplitude functions are nearly identical and are similar to those of the Trade Wind mode identified in the EOF analysis, increasing to a maximum near March 1997 and then decreasing with the onset of El Niño conditions. This mode reflects a pattern of increasing Trade Winds in the eastern central Pacific during late Northern Hemisphere winter and early spring, 1997, followed by a weakening trend in late spring. The second mode of the NSCAT@TAO CCA (Figure 6b) reflects the eastward equatorial jet with the TAO data accounting for slightly more variance than the NSCAT@TAO winds (35.3% versus 29.4%). Again, the amplitude functions track each other very well; showing a consistent increase after March 1997, reflecting strengthening, eastward equatorial winds during that period of time.

The remaining modes of the CCA (Figures 6c-6e) show that the correlations remain high, ($r > 0.91$) although much smaller percentages of the variance are explained (Table 2). These modes, which are less dominant for the large scales and probably reflect less climatically important variability, are nevertheless coherently represented in both the TAO and NSCAT observations. When the TAO winds are compared to the full resolution NSCAT wind field via CCA, the highest correlated mode remained the Trade Winds mode (Figure 7a). The data were highly correlated ($r = 1.00$ compared to 0.99), with almost an equal partition of variance between them (28.1% and 29.2%, Table 2). The spatial pattern also indicates a slightly greater influence of zonal winds along the equator than in the corresponding EOFs from the individual data sets. The second mode of the TAO and full resolution NSCAT (Figure 7b) represents a zonal equatorial flow to the east, or weakening of flow to the west. The TAO winds have significantly more variance attributed this mode than the NSCAT winds (34.8% vs. 21.6%). We attribute this difference to

the sampling distribution, since the TAO buoys are relatively more concentrated near the equator than the evenly distributed NSCAT data. The NSCAT winds also show a deflection of the axis of this flow to the south in the central portion of the field and a reduction of the core flow towards the east. The amplitudes of this mode in the two data sets are well correlated and indicate a stronger presence of this mode after March 1997.

Table 2. - Partition of variance in CCA analysis by mode and data set.

	TAO vs NSCAT@TAO				
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
r =	0.99	0.99	0.98	0.96	0.91
TAO	29.1	35.3	10.6	7.2	4.9
NSCAT@TAO	27.4	29.4	9.6	11.9	5.1
	TAO vs full NSCAT				
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
r =	1.00	0.99	0.98	0.95	0.85
TAO	28.1	34.8	13.5	5.1	5.6
full NSCAT	29.2	21.6	13.8	7.9	5.8
	NSCAT@TAO vs full NSCAT				
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
r =	1.00	1.00	0.98	0.96	0.93
NSCAT@TAO	27.3	34.1	9.2	6.4	6.4
full NSCAT	30.2	25.4	8.4	7.8	6.5

In order to quantify the effect of spatial sampling bias due to the equatorial concentration of TAO data we examined the results of CCA between the NSCAT data at TAO locations and the full NSCAT data. Since these sets originate from the same data, differences would be due to biases from the spatial subsampling of the NSCAT@ TAO locations. The CCA between NSCAT@TAO winds and the full NSCAT field (Table 2) finds a difference in the percent variance accounted for in mode 2 of 34.1% and 25.4% respectively. This is similar to the TAO/full NSCAT CCA, and is consistent with the conclusion that the buoy sampling locations enhance the percent variance accounted for by the TAO winds in this mode.

5.2 Speed and Direction Biases

Statistical differences between NSCAT and collocated direct wind measurements have been noted in other studies [Bourassa et al, 1997]. A direction difference is apparent in the CCA patterns in Figure 6 (see below). We thus examined the 10-day averaged NSCAT@TAO and TAO data sets for basic statistical differences in wind speed and direction. The distribution of the differences between the directions of the wind vectors in the input time series (NSCAT@TAO minus TAO) had a mean of +11.3 degrees, NSCAT to the right of TAO, with 90% confidence limits on the mean between 7.5 and 15.1 degrees (Figure 8). This interval encompasses the mean value from the CCA analysis (see below) and the rms difference (14°) determined by Bourassa et al [1997].

Differences in the wind vector magnitude (speed) were also estimated by Bourassa et al such that the NSCAT wind speed was less than the directly measured wind speed by a factor of 0.84. Applying the linear regression method of Bourassa et al to our data yielded a comparable scaling factor of 0.89. In our analysis, we found the mean wind speed bias to be slightly positive ($+0.09 \text{ ms}^{-1}$, NSCAT larger) but not statistically different from zero at the 90% confidence level (Figure 8) however, the mode of the distribution of this difference was negative, -0.2 ms^{-1} . In their study of NSCAT data and TAO buoy data, Caruso and Kelly (tech report, in preparation) found a speed bias of -0.54 ms^{-1} (NSCAT-TAO). The slight difference between this value and ours is a result of the concentration of our TAO data west of 125°W , where the bias is higher (M. Caruso, pers. comm.). From this we conclude that our results are consistent with Bourassa et al and Caruso and Kelly and that no systematic difference between 10-day average wind speed in the two data sets is discernable at the 90% confidence level.

The CCA spatial pattern, which represents the optimal vector relationship between the data sets, can also be used to test for directional bias. Examination of the NSCAT vectors in these patterns shows them to be directed slightly to the right of the TAO vectors (Figures 6a-e). The differences in direction of the CCA eigenvectors (in degrees) for all the modes are shown as a function of latitude in Figure 9. The data are clustered at specific lines of latitude and show a good deal of scatter. The lower window in Figure 9 compares the means and 90% confidence intervals for

each latitude cluster. The NSCAT vectors had a mean offset to the right of 14° (Std Dev= 28° with a 90% CI of $\pm 4^\circ$ over all data). This value is consistent with that found by other investigators [14° , Bourassa, et al, 1997, 9.8° , Caruso and Kelly, tech report, in preparation] for NSCAT wind vector comparison with direct surface measurements from ships and buoys. Only one cluster mean is different from 14° at the 90% confidence level. The lack of any significant trend or sign reversal in this offset across the equator eliminates the Ekman planetary boundary layer as a possible source. The magnitude of this directional error is smaller than the NSCAT mission requirement of $\pm 20^\circ$ rms error for individual measurements. Nevertheless, the bias is likely to influence climatological averages and users should consider a rotational correction, particularly if the data are to be applied to computing divergence and curl.

6. Summary

The NSCAT wind field is highly representative of the winds over the Tropical Pacific when compared to the wind fields measured by the TAO buoy array. Although the NSCAT sampling is twice daily, there is no significant aliasing effect resulting from the diurnal and semi-diurnal wind variability seen in the Tropical Pacific. An EOF analysis of the different data sets resulted in excellent agreement of the principal modes of variability. The first two modes reflect equatorial jet and Trade Wind variability, respectively, together attributing for 60-70% of the total variance in the wind field. The reversal of the order of the two modes for the full resolution NSCAT wind field is a result of the coverage of the NSCAT data compared to the subset of TAO locations used. CCA analysis quantifies the high correlation between the data sets and the reasonableness of the TAO buoy sampling to defining the first two modes of the wind field. A 14° clockwise rotation of the NSCAT winds relative to the TAO winds was found irrespective of hemisphere.

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