

MARINE WIND VARIABILITY: ILLUSTRATION AND COMMENTS

Sea-state modelers introduce a mean wind vector at each grid point of their models that varies only once every time step. Real winds often fluctuate at much shorter space and time scales. Some examples of these fluctuating wind fields are given, along with possible implications for modeling.

INTRODUCTION

Sea-state modelers and forecasters have always expressed the need for more and "better" winds either to develop or to initialize and run their models. Usually, winds are converted into wind stress estimates by using more-or-less controversial drag relations. It is not intended here to discuss these relations, but rather to stress how wind data should be handled to improve their use in modeling and predicting sea state.

Many wind vector measurements will be available soon from the European ERS-1 remote sensing satellite scatterometer, which will provide global coverage of the ocean. As pointed out by Janssen et al.,¹ however, the increase in data quantity is useless if the data quality is not sufficient. This statement is also true for conventional *in situ* measurements.

Much effort has been spent to improve the existing measurement techniques and to plan the calibration and validation of future satellite sensors. At sea, without an absolute reference, the performance of *in situ* systems can be stated only in terms of precision. As a result, we cannot trust a single isolated wind vector value. One way to increase our faith in wind measurements is to rely on space or time continuity, provided that the meteorological condition and its associated variability permit such an assumption.

Wind buoys that are designed and calibrated carefully can achieve precisions at sea of 0.8 m/s for speed and 5° for direction. Wind reports from ships without anemometers (as shown on most weather maps) are usually rounded to the nearest 5 kt and the nearest 10°. Moreover, neither the 10-min average recommended by the World Meteorological Organization (WMO) nor a standard reference height is used systematically. This situation induces added temporal variability, which impairs the spatial variability. (See the article by Pierson, in this issue, for even more cautions.)

The next section of this article will illustrate observed spatial and temporal wind variability. The following section will focus on the spectral description of the energy of wind fluctuations and their relations for various separation distances. The final section will describe an attempt to estimate, as a function of time, a spatial mean wind vector from point measurements averaged over time.

ILLUSTRATION OF WIND VARIABILITY

Figure 1 shows simultaneous wind estimates collected in the Mediterranean between France and Corsica in January 1986.² Five ships reported quite different wind speeds, ranging from 15 to 50 kt. Such a large number of at-sea reports, all within a 250-km span, is quite unusual. Wind speeds appear to have been erratic, but at least the measurements agree that a strong westerly component existed. Automatic data validation schemes would certainly reject such widely varying simultaneous reports. An untrained analyst might comment, "How unreliable the ship reports are!"

A closer look is more revealing. Two of the ships reported high winds (45 ± 5 kt), whereas the other three reported low values (20 ± 5 kt). Moreover, the two ships located between the two high wind speed reports both indicated similar low values. Allowing for reasonable ship measurement uncertainty, it is unlikely that any of the ships was completely wrong. It is more likely that the wind was highly variable in space or in time, since individual sets of comparisons have little chance to be exactly simultaneous and coincident.

Figure 2 shows a 17-h time series of wind measurements, averaged over 1-min intervals. This record was collected in 1984 during the Promess/Toscane 1 experiment on board N/O *Le Suroit*, in the northeast Atlantic,

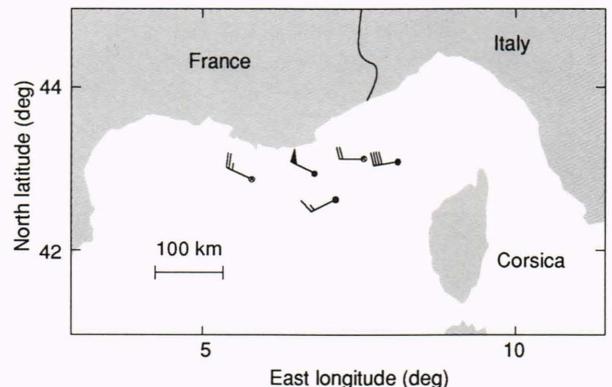


Figure 1. A sample of simultaneous ship reports in the Mediterranean on 23 January 1986 at 0000 UT, indicative of unusually high spatial variability. Each full barb indicates 10 kt, a half barb is 5 kt, and a triangle is 50 kt. (Adapted from Ref. 2.)

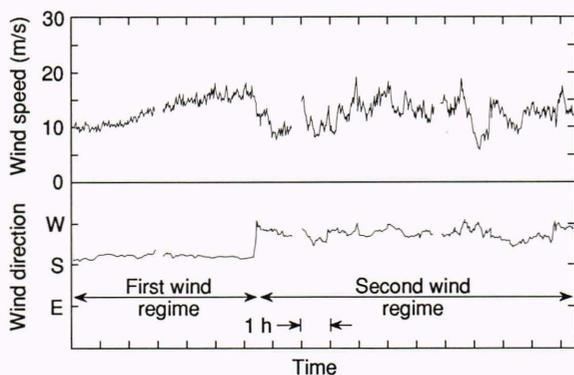


Figure 2. A time series of 1-min-averaged wind speed and direction collected at sea on board N/O *Le Suroit* (Toscane 1 data) from 1021 UT on 20 February to 0346 UT on 21 February 1984. Note the different signatures of wind fluctuations before and after the front.

southwest of Brittany. Two wind regimes separated by a cold front passage are clearly evident. The first regime corresponds to a stable atmosphere; wind direction is steady and wind speed fluctuations, at intervals of 10 to 15 min, are less than 1 m/s. The second regime corresponds to an unstable atmosphere and exhibits large wind speed variations (about 7 m/s) at intervals from 30 min up to 1 h, on top of which are the high-frequency components that are also present during the earlier stable regime. Directions also fluctuate by as much as 50° over the same intervals. These long-period oscillations persist for 12 h. Note the abrupt 12-m/s wind speed change during a time span of only 30 min that occurs about 4 h before the end of the record. For the 10-min averaging period recommended by WMO, the reported variation would have been only about 10 m/s.

In view of this time series example, the spatial wind pattern implied in Figure 1 seems likely to be real and not simply a measurement artifact. Taken together, these two examples show that representing the wind by a single mean vector, defined at a given reference level and for a given duration, may not capture its real variability over temporal scales of tens of minutes or spatial scales of a few kilometers.

THE SPECTRAL SIGNATURE OF MARINE WIND VARIABILITY

The time and space scales of concern here lie between the high frequencies, or short wavelengths, of the fine-grid meteorological models (typically 30 cycles/h and a few meters) and the lower part of the turbulent region (typically 1 cycle/h and 50 km), and thus may be influenced by both these scales. The justification for separating these two regimes is based on the well-known spectral gap of Van der Hoven³ for wind speed near the surface. This spectral energy gap, measured over land, has been used to justify a 3-h sampling interval and a 10-min averaging time for wind measurements.

At sea, evidence suggests that this spectral gap is not always present. For example, the two wind regimes of Figure 2 will each produce a different spectral shape in

the 1-h to 10-min band. The early regime will contain a spectral energy gap, but in the later regime, the spectral energy level at the gap location will be about the level of the turbulent peak, completely filling the gap.

Pierson⁴ reported overwater data from M. Donelan (personal communication), Klaus Hasselmann (personal communication), Pond et al.,⁵ and Miyake et al.⁶ He pointed out, specifically for the last two data sets (although the tendency could be detected in the others), that “the spectral estimates do not decrease toward lower values [of dimensionless frequency] as do the Kaimal et al. [see Ref. 7] overland spectra.” Then he modeled this part of the spectrum as the inverse of frequency, allowing the energy level to be an increasing function of wind speed. Corrections for this model are currently in progress (C. M. Tchen, personal communication, 1986).

During the Toscane T campaign in early 1985,^{8,9} a row of seven wind-instrumented masts was installed along the shore of the Bay d’Audierne (South of Brittany, France) at a site that was well exposed and nearly perpendicular to ocean winds. The nominal altitude of the measurement locations was 12 m above mean sea level, and the separation of locations ranged from 1.5 to 10.1 km. A meteorological buoy moored off the coast provided air and water temperatures. The experimental layout permitted the investigation of spectral signatures of the along- and cross-wind fluctuations (u and v , respectively) and also of their coherence and phase as a function of separation. The following results are extracted from Champagne-Philippe.¹⁰

Twenty-seven wind records were selected on the basis of synoptic weather stationarity. The measurement duration ranged from 6 to 20 h, and the mean speed varied from 6 to 15 m/s. Each record was sliced such that representative spectral estimates of the u and v components could be computed in the 1-h to 6-s band.

As anticipated, the spectra showed variable behavior in the gap region. No global estimate of the synoptic stability of the atmospheric boundary layer was available. To sort the spectra, we used the local stability parameter, z/L (where z is the height above sea level and L is the Monin-Obukov length), computed from the buoy temperature measurements. The hypothesis was that convective situations and the corresponding instability, which are related in this region to cold air masses, will be flagged by this local and low-altitude indicator. Only 5 situations out of the 27 selected did not fit into the “gap/no gap” spectral classifications anticipated by the *a priori* sorting into stable and unstable atmospheric conditions. The unstable spectra corresponded to z/L values between 0 and -0.03 . The stable spectra were further split into two subgroups, stable and stable/neutral, whose mean z/L values were, respectively, 0.065 and 0.023.

Figure 3 presents the average of the dimensionless spectra for each of the three aforementioned categories for both the along-wind and the cross-wind components, with Pierson’s 1983 model⁴ superimposed. For both components, the high-frequency parts of the spectra behave the same, regardless of the stability category, and decrease as $f^{-2/3}$, although the turbulence maximum is

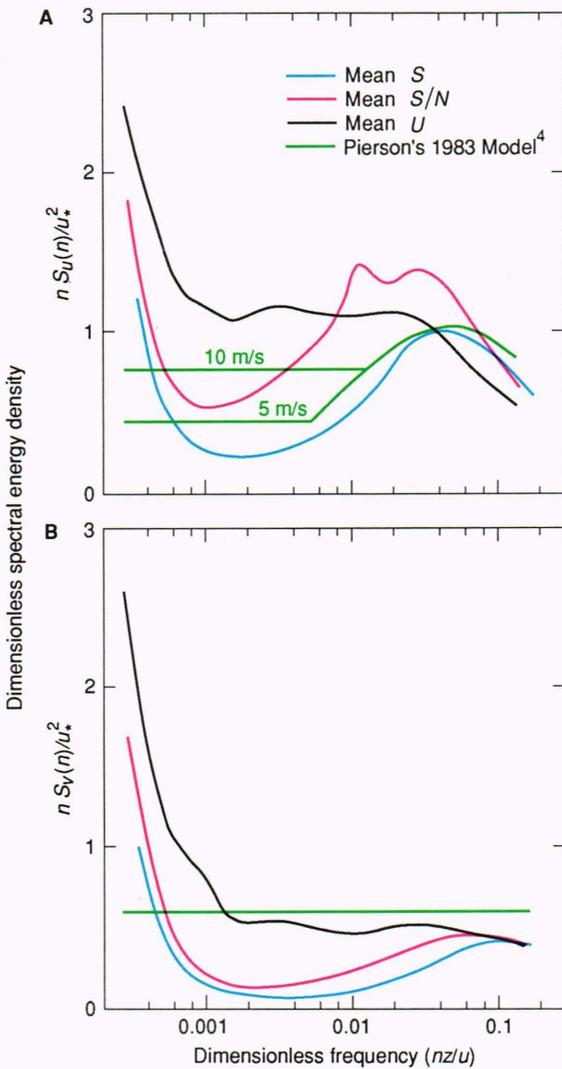


Figure 3. An averaged spectrum of wind fluctuations for the three stability regimes (S—stable, S/N—stable/neutral, U—unstable) **A.** Along-wind component. **B.** Cross-wind component. Note the energy-preserving form used to present spectral estimates; n is the natural frequency, z is the measurement altitude, u_* is friction velocity, $S_u(n)$ and $S_v(n)$ are the spectral energy densities, and u is the mean wind speed at z . (Adapted from Ref. 10.)

shifted to a lower dimensionless frequency. The striking feature is the shape change in the expected gap region. As local stability decreases, or convection increases, the gap fills up to about the energy level of the turbulent region. The plateau shape in this representation corresponds to a $1/f$ decrease, as modeled by Pierson,⁴ but does not seem to be a function of wind speed only, as he assumed. It is also related to the stability or instability of the upper layers of the atmospheric boundary layer. One might hypothesize that the spectral shape of wind fluctuations between mesoscale and turbulence is related to the profile of the Brunt–Väisälä frequency from the surface up to the first few kilometers.

Coherence and phase spectra of the u and v components were calculated for cases when winds blew either perpendicular to or along the row of masts for all separation distances.

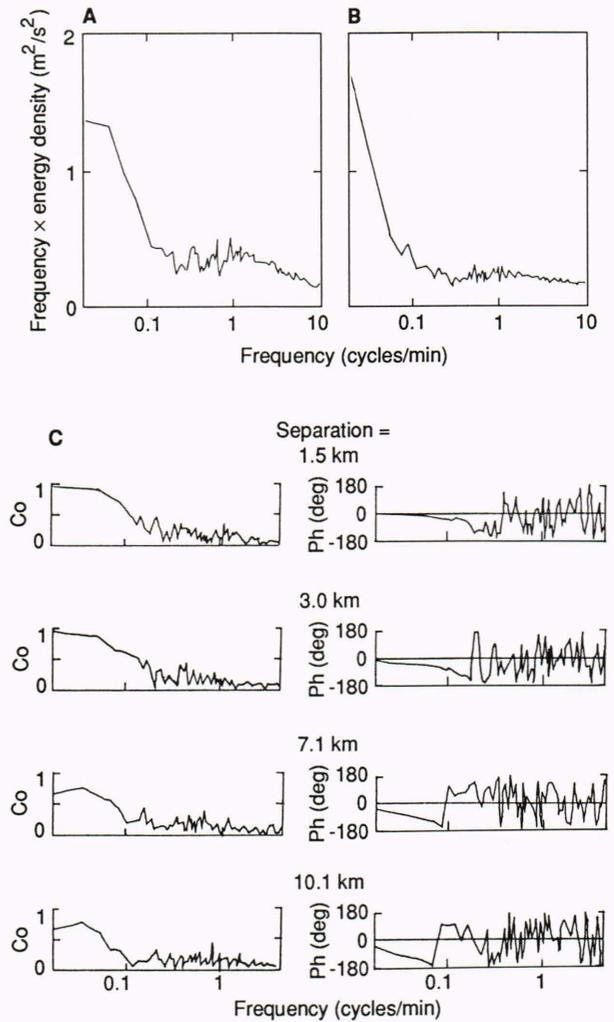


Figure 4. Spectra and cross-spectra of wind fluctuations representative of the meteorological situation: **A.** Along-wind component. **B.** Cross-wind component. **C.** Phases (Ph) and coherences (Co) of the along-wind component for separation distances of 1.5, 3.0, 7.1, and 10.1 km. (Adapted from Ref. 10.)

For both geometric configurations and for both components, the main result is that 10-min-average small wind fluctuations are not (or are very weakly) coherent, even at the shortest separation distance of 1.5 km. Such averages are therefore noisy estimates of the mean wind speed, even in the case of neutral or stable situations. Some coherence existed beyond periods of 20 min for 8.5-km separation.

Figure 4 presents, for the case of an unstable atmosphere, the coherence and phase of u and v wind fluctuations for the wind blowing directly along the row of masts. This geometric configuration permits one to test Taylor's hypothesis, which is often used to shift between time and space without considering the respective scales. For this highly convective case, the coherence diagrams confirm that 20-min fluctuations become significantly coherent at 10.1-km spacing. The linear phase variation as a function of frequency may reveal some advection of structures. The corresponding speed was estimated

to be 24 m/s, twice the wind speed at measuring level, and is about the wind speed measured by a radiosonde for convective clouds 1 to 3 km high.

For wave modeling and prediction, these results imply that wind estimates will be improved by time averages that are at least 20 min long. One must also account for the variability at time scales of about 1 h. Analysis of the meteorology can provide the necessary information to decide which kind of wind spectrum should be used and how to model the associated variability. For scientific applications, the proper averaging time can be determined after the fact from continuous recorded data.

THE SPATIAL EQUIVALENCE OF POINT MEASUREMENTS

By definition, a discontinuity prevents a spatial average from being physically meaningful; no one expects a wind vector point measurement on one side of a front to be representative of the other side. Nevertheless, sea-state modelers and forecasters must decide what confidence limits to apply to point measurements so that the data are representative of some geographic area. This problem is especially relevant for the calibration and validation of the ERS-1 scatterometer, scheduled to be launched soon. Typical scale sizes of interest are on the order of the scatterometer elementary footprint, about 25 km on a side.

During the Toscane 2 campaign, conducted during the winter of 1987–88, a network of three wind-instrumented buoys was moored in the Atlantic in an isosceles right triangle (area 1) with two sides of 25 km. An additional measuring station was implemented on the island of Sein to extend one side of the network to 50 km, such that the larger isosceles triangle (area 2) had two sides of 35 km.¹¹

By using the wind time series from that network, a method for defining an average spatial wind vector is being developed. One promising approach is to use vector empirical orthogonal functions that describe the common relative variability observed simultaneously at the borders of the area defined by the measuring points. The assumption is that this common variability affects the whole area. The analysis is performed jointly on the components of the wind vector at each measurement location. A time series of the spatially averaged wind vector is then computed. At each measurement location, the residual time series can be defined as the difference between the spatial average and the initial time series. This method requires carefully controlled and calibrated wind speed data but allows for wind direction offsets accounted for as a relative phase shift. In the data set analyzed, the maximum wind speed difference at any of the three buoys over the entire 30-day experiment was 20 cm/s, with a standard deviation of 5 cm/s. Figures 5A and 5C show, respectively, the 20-min-averaged wind speed and the direction of the initial time series at one location; the corresponding time series of the residuals are shown in Figures 5B and 5D.

Results indicate that the estimated spatial average performed over a 625-km² area recovers most of the ki-

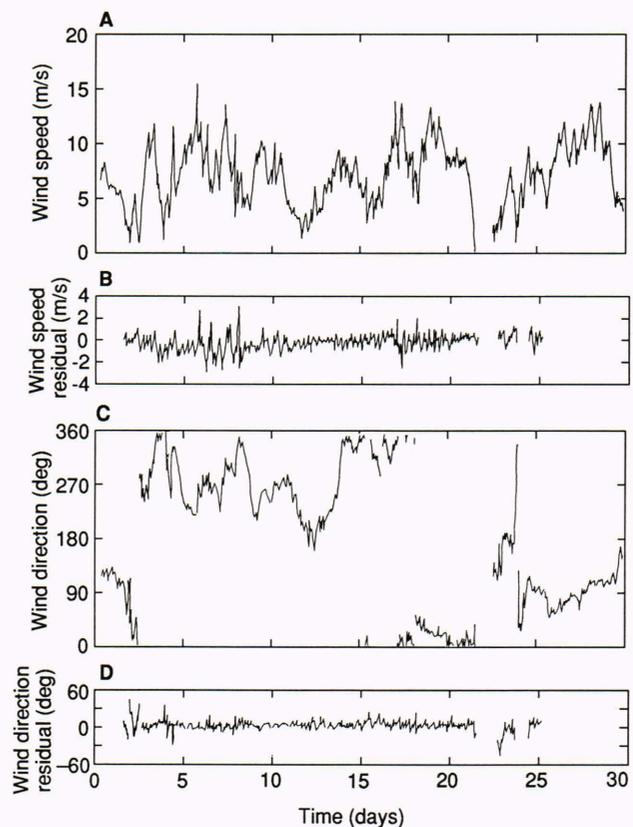


Figure 5. Twenty-minute-average time series of the wind vector at one location of the Toscane 2 network and related wind vector residuals between the spatial average and the point measurement. **A.** Wind speed. **B.** Wind speed residual. **C.** Wind direction. **D.** Wind direction residual.

netic energy from several weeks down to 50 min. Figures 6A and 6B present the standard deviations of wind speed and direction residuals at one buoy location as a function of the averaging time of the initial time series from 1 to 60 min. For the observed meteorological situations over area 1, after deleting transient events such as passing fronts and winds less than 1.5 m/s (since local thermal effects destroy the meaning of a spatial average), the standard deviation of wind speed at buoy level tends to a limit of about 0.6 m/s, and for wind direction, about 7°. The middle curve of Figure 6A is also for area 1 but is computed at a height of 10 m. The upper curve is obtained by using both the buoy array and the mast data and corresponds to area 2. To merge the two data sets at the same reference altitude, we used a logarithmic boundary layer for the mean wind profile, corrected for stability. For a given averaging time, differences in standard deviation within area 1 are the result of wind increasing with altitude, whereas the increase in standard deviation from area 1 to area 2 at the same height is simply the result of doubling the area.

For a given area, the lower limit of the residual variance can be interpreted as the minimum fluctuation energy introduced by both the measuring equipment and the geophysical wind variability (at the measuring level and for the wind conditions experienced). For a given aver-

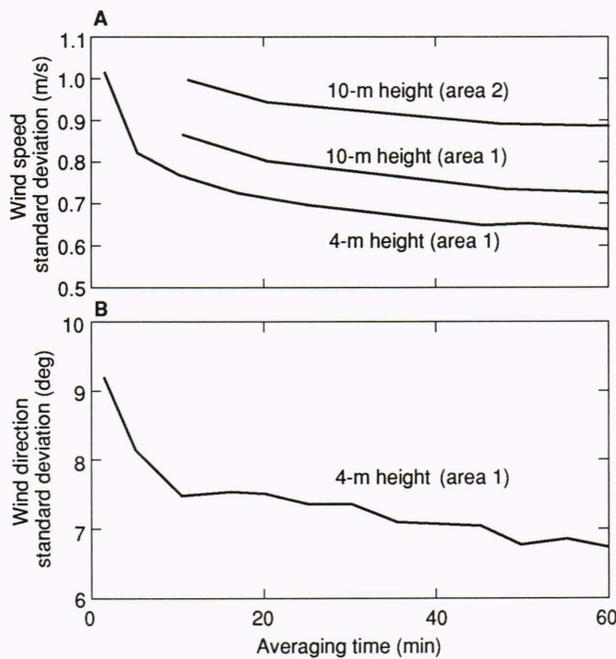


Figure 6. Standard deviation of the residual, at the same location of the Toscane 2 network, as a function of averaging time. **A.** Wind speed. **B.** Wind direction. Note the increases in the standard deviation of the wind speed residual as either the reference altitude or the averaging area increases.

aging time, assuming independence between the instrument and geophysical noise, the energy difference provides an estimate of the additional spatial variability at a given time scale.

CONCLUSIONS

We have shown that the mean wind vector fluctuates on time scales usually recommended to define the mean. The level of these fluctuations varies with meteorological conditions. Excessively short averaging times (about 10 min) will produce spurious estimates of the wind vector. For sea-state modeling and forecasting, it seems advisable to use a longer averaging time and to model the variability at shorter time scales. The estimate thus obtained still will not completely represent the wind vector over an area. Additional variability must be introduced to account for spatial effects. More research is needed to further quantify and model the real wind field variability.

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THE AUTHOR



ROBERT S. EZRATY is project leader at Institut Français de Recherche pour l'Exploitation de la Mer, Centre de Brest, BP 70, 29280 Plouzane, France.