

Accuracy of Wind Measurements Performed on Buoys, Ship, and Island during the TOSCANE-2 Experiment

PIERRE QUEFFEULOU

Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), Centre de Brest, France

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ABSTRACT

In 1983 the project "Travaux d'Océanographie Spatiale: Capteurs Actifs dans l'Atlantique Nord-Est" (TOSCANE) was initiated in view of calibration, validation, and use of satelliteborne scatterometer and altimeter measurements in terms of wind and wave data, with special emphasis on the *ERS-1* satellite to be launched in 1991 by the European Space Agency. The wind measurements from an array of buoys and ship and land stations, deployed during the last experiment within the program, TOSCANE-2, are described, and a method is given to evaluate their accuracy. When comparing wind data from two measuring stations at sea, the averaging time has to be selected according to the separation distance between the two locations to filter out the space-induced wind variability. For buoy and ship comparisons, for distances less than 3 km, a 10-min averaging time was found to be a lower limit. For pairs of buoys separated by 25 or 35 km, the standard deviation of differences decreases with averaging time, in the same manner for speed and direction: by about 40% when passing from 10 min to 6 h averaging (from 1.3 to 0.8 m s⁻¹ for speed, and from 14° to 9° for direction) with a plateau value (50%) after 12 h. Data from the two independent wind systems on board *N/O Le Noroit* show a high consistency: mean values of differences for direction and speed are 5.9° and 0.29 m s⁻¹, with standard deviations of 4.5° and 0.40 m s⁻¹, the standard deviation of speed differences increasing (0.10 to 0.49 m s⁻¹) over the 1–30 m s⁻¹ speed range; 99.9% of data are within ±2 m s⁻¹. When calibrating anemometers with coefficients from wind tunnel tests, differences between buoy speeds are large, as much as 1.4 m s⁻¹ ± 0.8 m s⁻¹, resulting from, among other causes, the inability of sensors to correctly filter high-frequency fluctuations of wind speed. The buoys were then tuned independently, relative to ship data from dedicated runs, which allowed a reduction of differences to maximum values of 0.5 m s⁻¹ ± 0.8 m s⁻¹ and 4° ± 9°. These results are compatible with an assessment of the foreseen 2 m s⁻¹ and 20° accuracy of the *ERS-1* scatterometer wind data. In contrast, wind data from a 10-m mast on a flat island are shown not to be accurately representative of wind at sea, even for onshore wind.

1. Introduction

In 1983 the project "Travaux d'Océanographie Spatiale: Capteurs Actifs dans l'Atlantique Nord-Est" (TOSCANE) was initiated at Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), in view of calibration, validation, and use of satelliteborne scatterometer and altimeter measurements, in terms of wind and wave data. Special emphasis was put on the European Earth Remote Sensing Satellite (*ERS-1*), to be launched in 1991 by the European Space Agency (ESA). Radar sea-echo models for scatterometer, relating the backscatter coefficient to the wind vector, are at present essentially empirical, mainly because of the complexity of the physics of interaction among the wind stress, the various scales of sea surface roughness, and the incident radar electromagnetic

wave. Within this context, the TOSCANE group investigated two aspects. The first one was the development and test of wind and wave measuring devices at sea, and the evaluation of the accuracy of measurements. The second was the investigation of spatial and temporal scales of at-sea wind fluctuations in order to be able to use the classical in situ wind measurement, time-averaged data at a fixed location, to calibrate and validate the scatterometer backscatter coefficient measurement which is an average in space over the footprint (50 × 50 km² for the *ERS-1* scatterometer) and in time over a very short duration (less than about 2 min, depending on the subsatellite track range). These two ways were investigated through in situ experiments performed in collaboration with ESA and other teams involved in wind and wave measurement at sea and satellite or aircraft radar techniques.

This paper presents the TOSCANE-2 experiment performed in November and December 1987 and the subsequent effort to evaluate the data quality of wind measurements from an array of buoys and ship and land stations. This campaign was the third one per-

Corresponding author address: Dr. Pierre Queffeuou, Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), 29263 Plouzane, Centre de Brest, France.

formed within the project and it is worth recalling the previous steps.

The first experiment, TOSCANE-1-PROMESS (Penmarc'h Radar Oceanographic Experiment on Signature Study) in February 1984, allowed a test and evaluation of a wind measurement procedure on board a dedicated ship (Ezraty and Queffeuilou 1987). During the experiment, measurements were also collected from four airborne scatterometers flown by Max Plank Institut of Hamburg, Centre de Recherche de Physique de l'Environnement, Delft University of Technology, and Canada Centre for Remote Sensing, respectively. These data, together with ship data, allowed an estimation of the coefficients of an empirical model relating the C-band (frequency of the *ERS-1* scatterometer) backscatter coefficient to the surface wind vector (Long 1985). A third result from this experiment was an insight in the correlation between weather stability conditions and large wind fluctuations ranging in time from a few minutes to one hour (Lavanant et al. 1985).

A second step was achieved during the TOSCANE-T experiment in 1985 (Groupe Toscane 1986). Seven instrumented wind masts were deployed along the Baie d'Audierne coastal site in Brittany together with two buoys moored 6 km west of the site. Aircraft measurements were also performed. From a technical point of view, operations and monitoring of the land-based network were satisfactory; an IFREMER buoy was tested and improved for some construction errors in the radio transmitter. Comparison of masts, CMM (Centre de Meteorologie Marine, Meteorologie Nationale) buoy data, and aircraft data (Daniault et al. 1988) showed that the three types of measurements were in reasonable agreement and that most of the differences observed between buoys and masts came from the buoy data truncation (1 kt for speed and 10° for direction). Comparisons between aircraft and mast data were also shown to be delicate under meteorological conditions including convective clouds, as often found behind meteorological cold fronts over the North Atlantic Ocean. Furthermore, spectral analysis of the mast data showed (Champagne-Philippe 1989) that in such convective weather cases, the wind "spectral gap" in the transition region from turbulence to mesoscale disappeared. These situations are associated with cumulus and cumulonimbus clouds more or less organized in open mesoscale cells. The size of these cells is of the order of magnitude of the scatterometer footprint, which implies in such cases, for scatterometer calibration purpose, a careful choice of the averaging duration of surface data. The author also investigated the time and spatial structure of wind. The main result is that the averaged periods of decorrelation range from 10 to 20 min at distances from 1.5 to 8.5 km.

The next logical step was to deploy a wind measurement network at sea covering the 25–50-km spatial scales resolved by the *ERS-1* scatterometer. This was achieved during the TOSCANE-2 experiment. The aim

of this paper is to describe this experiment and to evaluate the quality of the wind measurements collected during this campaign from buoys, a ship, and an island-based station, taking into account the interdependence between separation distances and time averaging. First, the measuring network is described together with the operations within the experiment, data return, and meteorological conditions (section 2). General errors in wind measurements from the ship and buoys are discussed in section 3, as are particular characteristics relevant to the experiment (anemometers, ship speed, airflow distortion by ship superstructures, effect of buoy motion induced by waves, and adjustment of wind speed data to a reference level). The two wind-measuring systems mounted on board the ship allowed an evaluation of the consistency of ship wind measurements (section 4), and then the buoy measurements were tested against ship data with emphasis on the influence of time averaging and separation distances (section 5). The buoys were then calibrated against ship data and tested through intercomparisons (section 6). Section 7 is devoted to the analysis of the island wind measurements in terms of sensors and land effects.

2. Summary of surface experiment

The experiment was conducted in November and December 1987, in the North Atlantic Ocean, west of the southern Brittany coast (Fig. 1). The experimental setup involved eight wind- and two wave-measuring stations, supported by seven buoys at sea and one mast on Sein Island. Surveys of the network and monitoring of meteorological parameters were achieved on board *N/O Le Noroit*, during the intensive part of the campaign (19 November to 6 December).

a. At-sea in situ network

The major axis of the network M1–M0–M2, was selected along the prevailing wind direction anticipated during the experiment period. The buoy array was centered on location M0 ($47^\circ 51' 53''\text{N}$, $04^\circ 56' 30''\text{W}$) such that the second axis was perpendicular to the previous one, and the network used the Sein Island as a land-based measuring station. The sizes of the network were 25 km for M0–M1, M0–M2, and M0–M3, and 20 km for M0–Sein. Location M0 was heavily instrumented (see insert in Fig. 1) since one of the campaign goals was buoy wind data comparisons: Marisonde position refers to the CMM buoy, Tobis refers to the Norwegian Oceanor buoy, Spear-f is a wave spectrum buoy, and IFREMER is the position of buoy 5, a prototype instrumented with two independent wind-measuring systems. Buoys 6, 7, and 8, located at M3, M1, and M2, respectively, were practically identical wind-measuring buoys; unfortunately, buoy 8 (M2) broke its mooring line a few days after being deployed and returned no data.

1) IFREMER PROTOTYPE BUOY 5

This buoy (Fig. 2) was 12 m long and equipped with two independent wind measurement systems differing only by the wind sensors, mounted 5 m above sea level. The first one was the 05103 R. M. Young wind monitor: an integral horizontal axis propeller and vane. The second one was the three-cup anemometer and vane (Fig. 3) manufactured by Debucourt. The two Safare-Crouzet fluxgate compasses were mounted near the top of the mast in order to avoid as much as possible the magnetic perturbation of the buoy. Nevertheless, they were calibrated before the experiment, the buoy being fully equipped. More details about sensors and preexperiment calibration tests can be found in Queffeuou et al. (1988). Data sampling and processing were achieved by Cactus electronics (Nereides, France) including a two-way VHF radio link for internal programming and data transmission; these electronics were already used during the TOSCANE-T campaign (Groupe Toscane 1986).

The wind vector sampling is described next. Over a fixed time period T_o (3 s), the number of pulses produced by the anemometer is counted. For instance, the Debucourt anemometer output is two pulses per rotor

revolution. The passing wind distance between two pulses is a constant (l), of the order of 30 cm; its exact value is determined by calibration tests. For each pulse, the vane and compass information (compass data are averaged values over 3 s) are sampled and components ($l \cos \theta_i, l \sin \theta_i$) of the elementary covered distance are computed in the magnetic (east, north) reference frame, and then summed over the time period T_o . This information together with the number of pulses over T_o , expressed in frequency units (n/T_o), is used to compute the average wind vector "frequency" components over T_o . In the last step, according to the station setting, wind vector components are averaged over a time period T ($T = NT_o$). During the main phase of the TOSCANE-2 experiment, T was set to 1 min for buoys and mast station and to 30 s for N/O *Le Noroit* station; during the second part of the experiment (after day 340) T was set to 2 min 30 s.

Thus, the available data are the average frequency components (C_e, C_n) of the wind vector over T . Direction and speed of wind vector are then computed as:

$$\begin{aligned} \text{direction} &= \arctan(C_n/C_e) \\ \text{speed} &= A(C_e^2 + C_n^2)^{1/2} + B, \end{aligned}$$

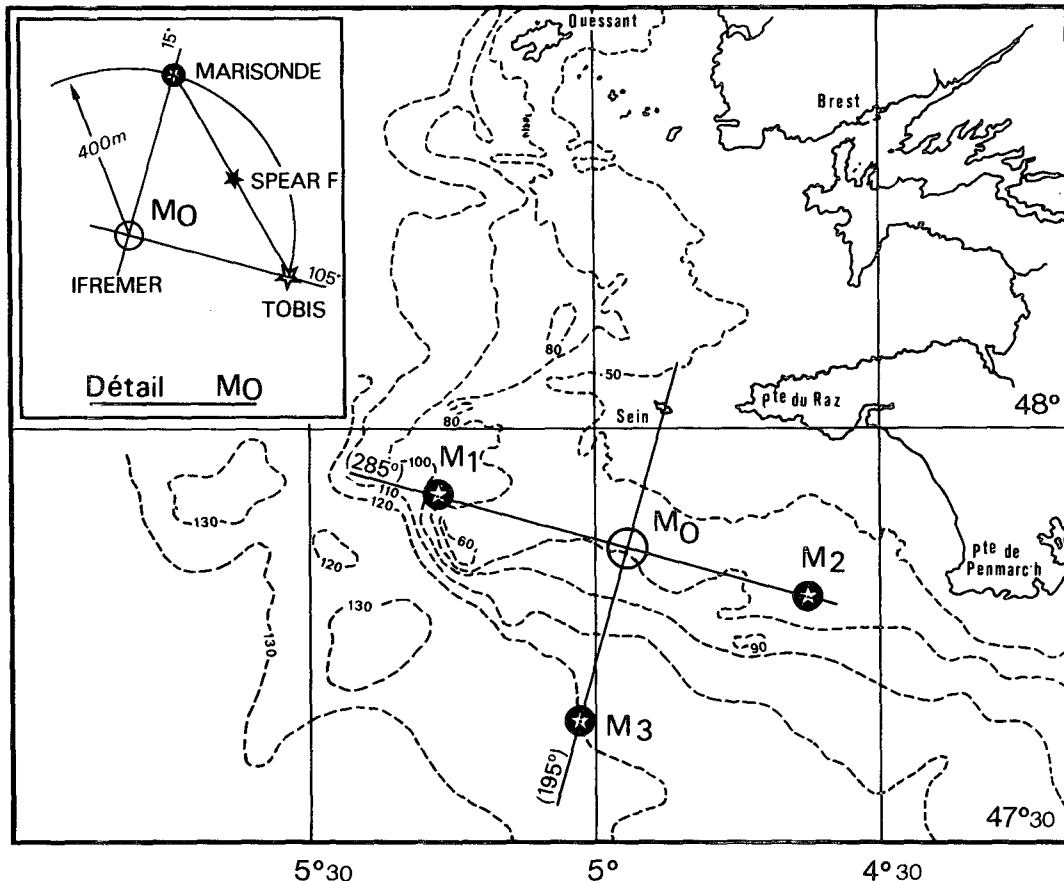


FIG. 1. TOSCANE-2 experimental area and moorings.

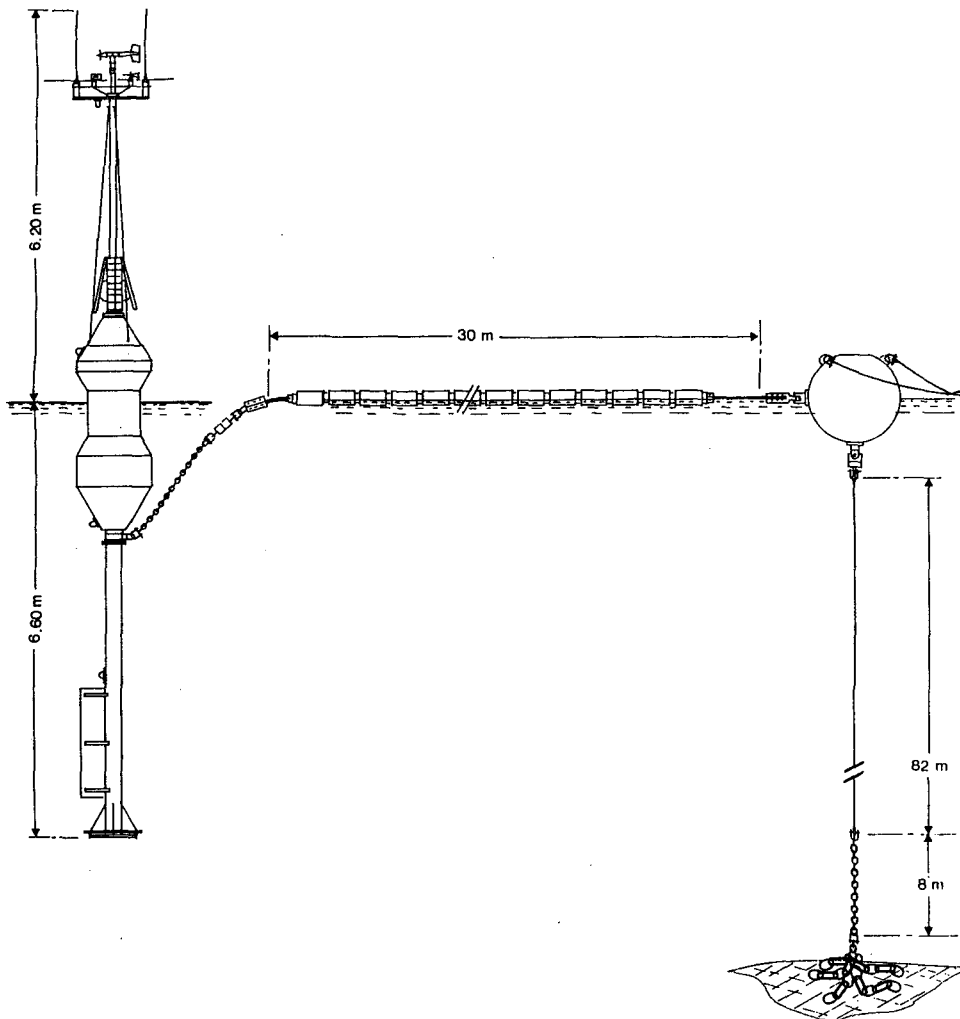


FIG. 2. The IFREMER prototype buoy and its mooring.

arctan being a four-quadrant function equal to the standard \tan^{-1} if C_e is greater than 0, and equal to $180 + \tan^{-1}$ otherwise. The A and B coefficients relating linearly the speed and the frequency output [$V(\text{m s}^{-1}) = AF(\text{Hz}) + B$] were obtained from calibration tests in a wind tunnel facility in Institut de Mecanique Statistique de la Turbulence (Marseille, France). Values of the coefficients are reported in Table 1, together with other buoy characteristics.

2) BUOY 6 AND BUOY 7

These two buoys were built on the Marisonde hull of CMM (Fig. 4), 7 m long (3 m above the sea surface) with a maximum diameter of 1.6 m. A three-cup Debucourt anemometer and vane, fluxgate compass, navigation light, and radio transmitter were installed at the top of the mast. The acquisition unit was a Cactus, identical to those of buoy 5.

3) CMM BUOY

The CMM Marisonde buoy, in M0, was equipped with the three-cup Debucourt anemometer and vane, a Digicourse magnetic compass, and a CEIS electronic package, using the Argos satellite system for data transmission. It was a modified version of the Marisonde RC described in Daniault et al. (1988): the wind vector was averaged over 10 min and available every 15 min, the data retrieval depending on Argos satellite passes and on the ship receiver location relative to the buoy (during the intensive part of the experiment). The buoy also measured, every 15 min, the sea surface and air temperatures, the atmospheric pressure, and pressure tendency.

4) SEIN ISLAND STATION

On Sein Island, wind measurements were performed from a 10-m mast deployed at the extreme west of the

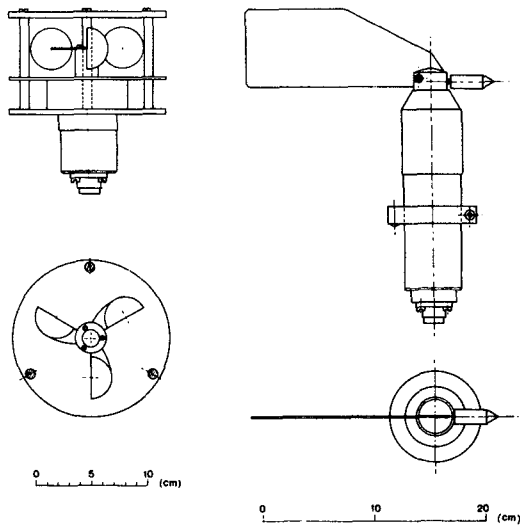


FIG. 3. Debucourt three-cup anemometer and vane.

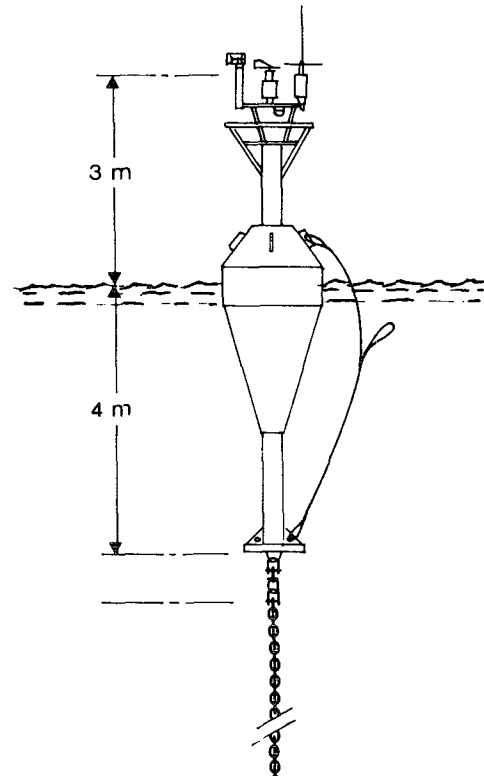


FIG. 4. The CMM Marisonde buoy hull.

island and equipped with Debucourt sensors and a Cactus unit. The mast was well exposed to winds blowing from directions outside of the range 30°–140°. The height of the anemometer above mean sea level was about 16 m.

5) WAVE BUOY

The Spear-f buoy, moored at location M0, is a modified Waverider from Datawell. A microprocessor computes, on board, the nondirectional sea-state spectrum and transmits the results via an Argos link, every hour. The duration of measurement is 34 min 8 s. Details on this buoy are given in Ezraty et al. (1987).

b. Ship measurement and operations

The research vessel N/O *Le Noroit* was instrumented with two independent wind measurement systems. One was similar to those of buoys 5, 6, and 7 (Cactus and Debucourt three-cup anemometer and vane). The sec-

TABLE 1. Characteristics of buoys and wind measurement systems. Variables *A* and *B* are the anemometer calibration coefficients and *H* is the height of the anemometer above the sea surface.

Buoy or support	Position lat (°N) long (°W)	Depth chart (m)	Anemometer		<i>H</i> (m)	Averaging time	Sampling rate
			<i>A</i>	<i>B</i>			
5 (<i>M</i> ₀)	47°51'53" 4°56'30"	65	0.401	-0.315	5.0	1 min/2 min 30 s*	continuous
6 (<i>M</i> ₃)	47°38'37" 5°01'43"	121	0.328	0.407	3.4		continuous
7 (<i>M</i> ₁)	47°55'15" 5°15'54"	80	0.358	0.236	4.0	1 min/2 min 30 s	continuous
<i>Le Noroit</i>			0.328 0.10	0.104 0.0	18 18	30 s	continuous
Sein Island	48°02'29" 4°52'09"		0.339	0.015	16	1 min/2 min 30 s	continuous
CMM (<i>M</i> ₀)	47°52'05" 4°56'24"	65	0.343	0.0	2.7	10 min	15 min**

*: change 1 min/2 min 30 s on day 340

** : rate of data retrieval depends on Argos satellite passes and on ship dedicated receiver location relative to the buoy

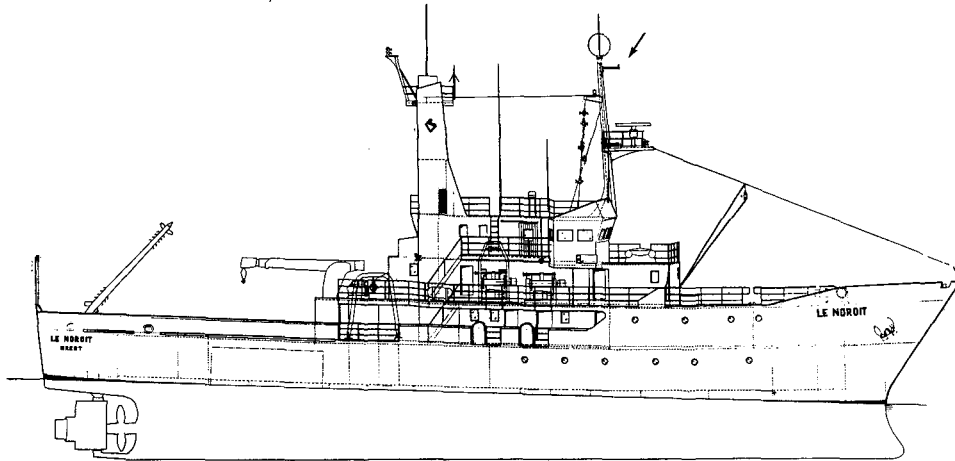


FIG. 5. N/O *Le Noroit* (50 m length); the arrow indicates the location of anemometers.

and one was a ship meteorological station (Pomar) using a Tavid three-cup anemometer and vane. Both pairs of sensors were installed, 18 m above sea level, above the main bridge on the forward mast of the ship. The anemometers were set 0.65 m to port and starboard of the mast and 0.70 m forward of it (Fig. 5). Dry- and wet-bulb air temperatures, atmospheric pressure, sea surface temperature, wave directions, ship heading, speed, and position were recorded. Sampling rates and averaging times are given in Table 2. During the intensive part of the campaign N/O *Le Noroit* achieved the following tasks: buoy data recovery through VHF radio link and first check of data consistency; survey of the network, consisting of changing and repairing buoy sensors or electronics when damaged; and calibration of buoy wind measurements through dedicated runs.

c. Data

A summary of the network data return is given in Fig. 6. The mooring of buoys was achieved on 5, 6, and 7 November by the service vessel *George De Joly*

operated by STPB (Service Technique des Phares et Balises). The N/O *Le Noroit* was in operation over the experiment area from 19 November until 6 December. The Sein Island data cover 130 days, from 5 November to 4 March with only two gaps: from 27–29 November, during which the wind direction is not available (vane incident), and during 5 min on 6 December. The wave Spear-f buoy had a 100% data return and measurements are available over 73 days, from 7 November to 19 January.

Time series plots of Figs. 7 and 8 show the 30-min-averaged wind speed and direction (from which the wind is blowing) from Sein Island measurements, the atmospheric surface pressure, the sea surface temperature (SST), the difference between air and SST from CMM buoy data at location M0, and the significant wave height from Spear-f buoy data. Meteorological conditions during TOSCAN-2 were governed by the relative locations and evolutions of low pressure systems over the northeast Atlantic Ocean and high pressure systems of Azores or over Europe. The atmospheric surface-pressure curves of Figs. 6 and 7 show the succession of lows and highs. The seasonal decrease

TABLE 2. Parameters measured on board N/O *Le Noroit*.

Parameter	Device	Acquisition sampling rate	Record-averaging time
Wind 1	Cactus	Averaged wind vector over 3 s	30 s
Wind 2	Pomar	0.5 s	3 s
Temperatures: dry-, wet-bulb air, and sea surface	Probes	0.5 s	30 s
Bucket temperature		1 h	no averaging
Pressure	Altimeter	1 h	no averaging
Wave direction	Radar/eyes	1 h	no averaging
Ship heading	Gyrocompass	3 s	no averaging
Ship speed	Loch	3 s	no averaging
Ship position	SYLEDIS	30 s	no averaging

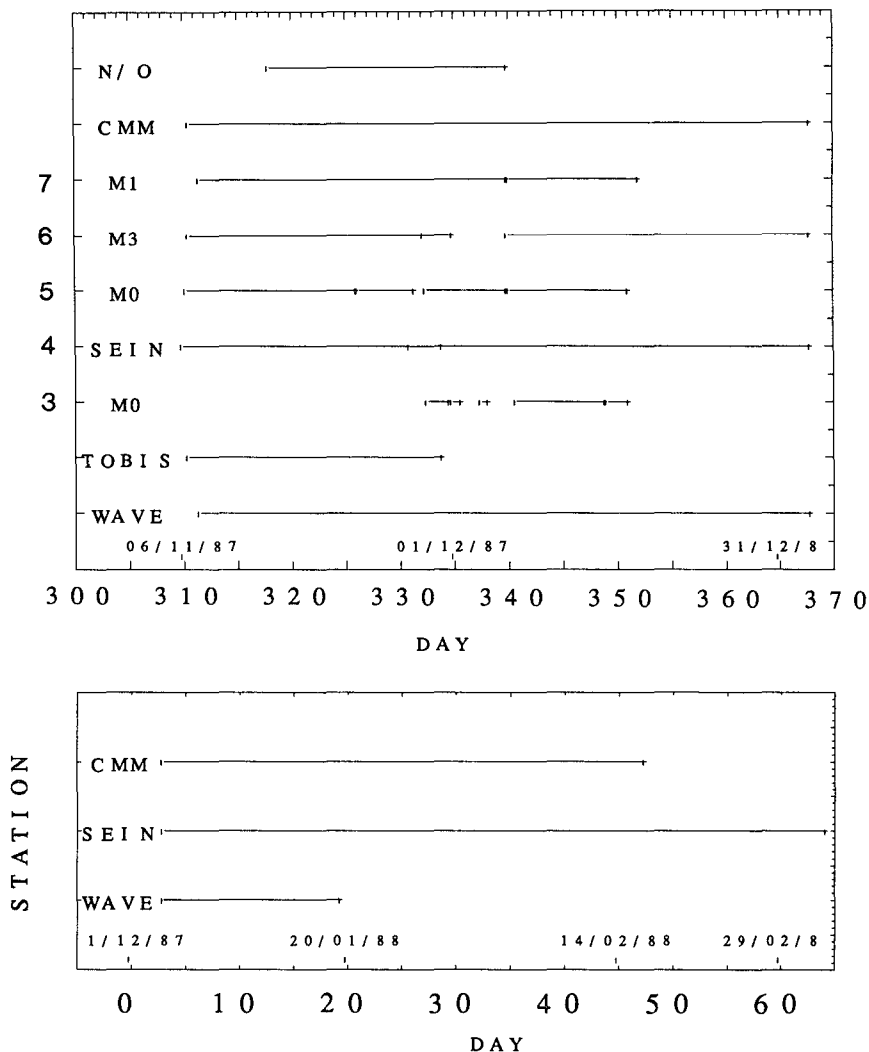


FIG. 6. TOSCANE-2 experiment data return.

of the SST is observed, from 14°C on day 310 to 10.5°C on day 47 of 1988. Some modulation appeared from time to time (day 345 to 350, for instance), due to tidal current (M. Tremant, CMM, personal communication). The air temperature was generally less than or equal to the SST, from day 310 to 348, with an exception on day 339. Between days 349 and 365, two periods of stable conditions occurred. After this date the conditions were unstable or near neutral. Wave height is roughly correlated to the wind speed for on-shore wind, days 3–4 and 316–317, for instance, but not for easterly wind (days 335–350) for which the sea state is lower, in spite of high wind speed, because of limited fetch.

3. Wind measurement errors and corrections

Calibration of anemometers in a wind tunnel facility leads to linear relations between the frequency output

of the sensors and the speed of the steady airflow, for speed above a few tens of centimeters per second. But the sensor responses differ significantly at sea, mainly because of the turbulent wind fluctuations and the wave-induced motions of buoy or ship. Furthermore, when wind measurements are performed on a ship, the data have to be corrected for the airflow distortion induced by the ship superstructures, for the speed of the ship, and for the altitude of the sensors above sea level. This is discussed in this section, together with particular characteristics of the Debucourt and Young anemometers.

a. Sensor response at sea

Three-cup anemometers generally overestimate the wind speed (values between 10% and 20% were reported in the literature), and propeller anemometers underestimate. A broad review of the subject is avail-

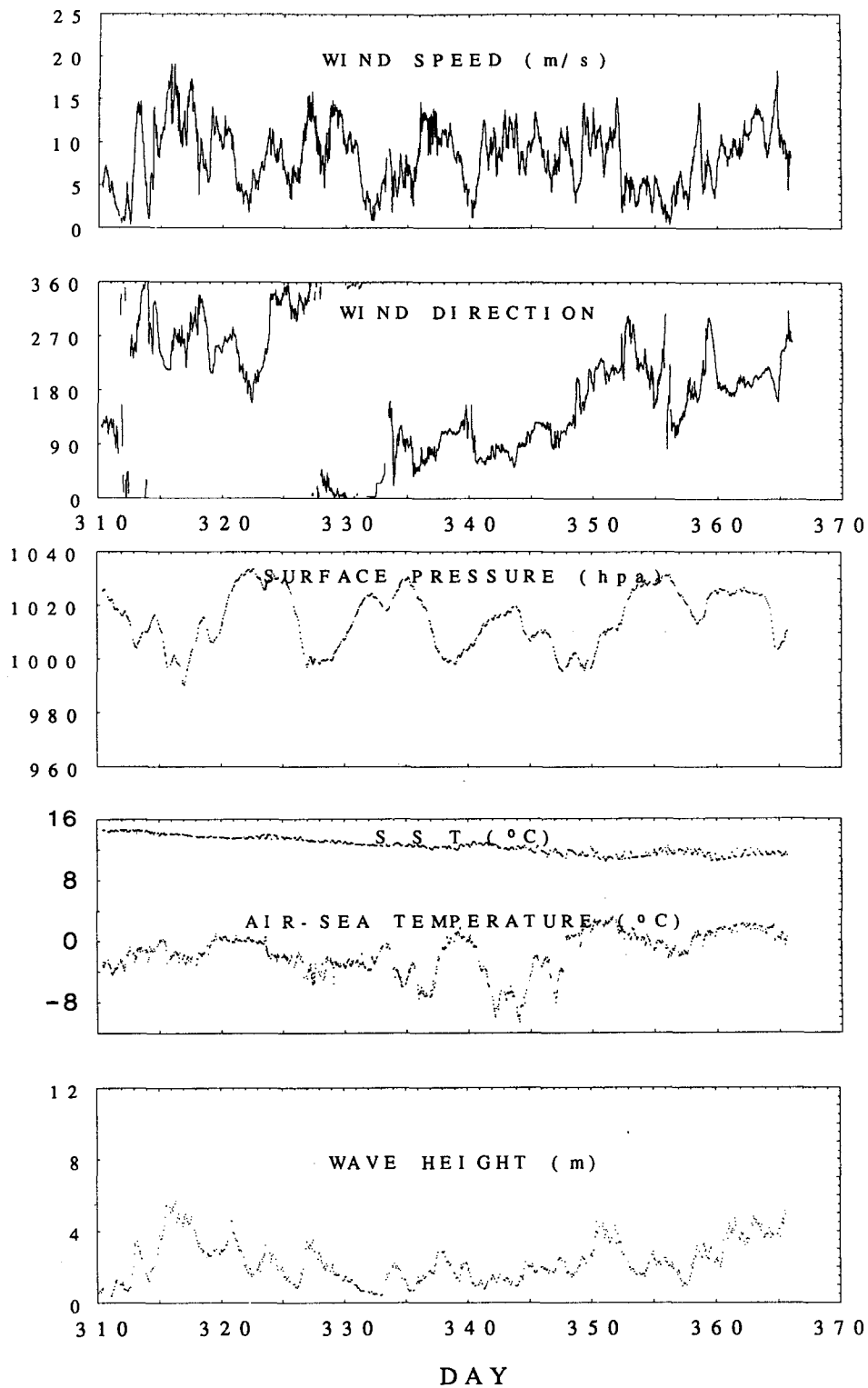


FIG. 7. Meteorological conditions experienced during the TOSCANE-2 campaign from day 310 to day 365 of 1987: wind speed and direction (mast on Sein Island), atmospheric surface pressure, sea surface temperature, difference between air and sea temperatures, and significant wave height.

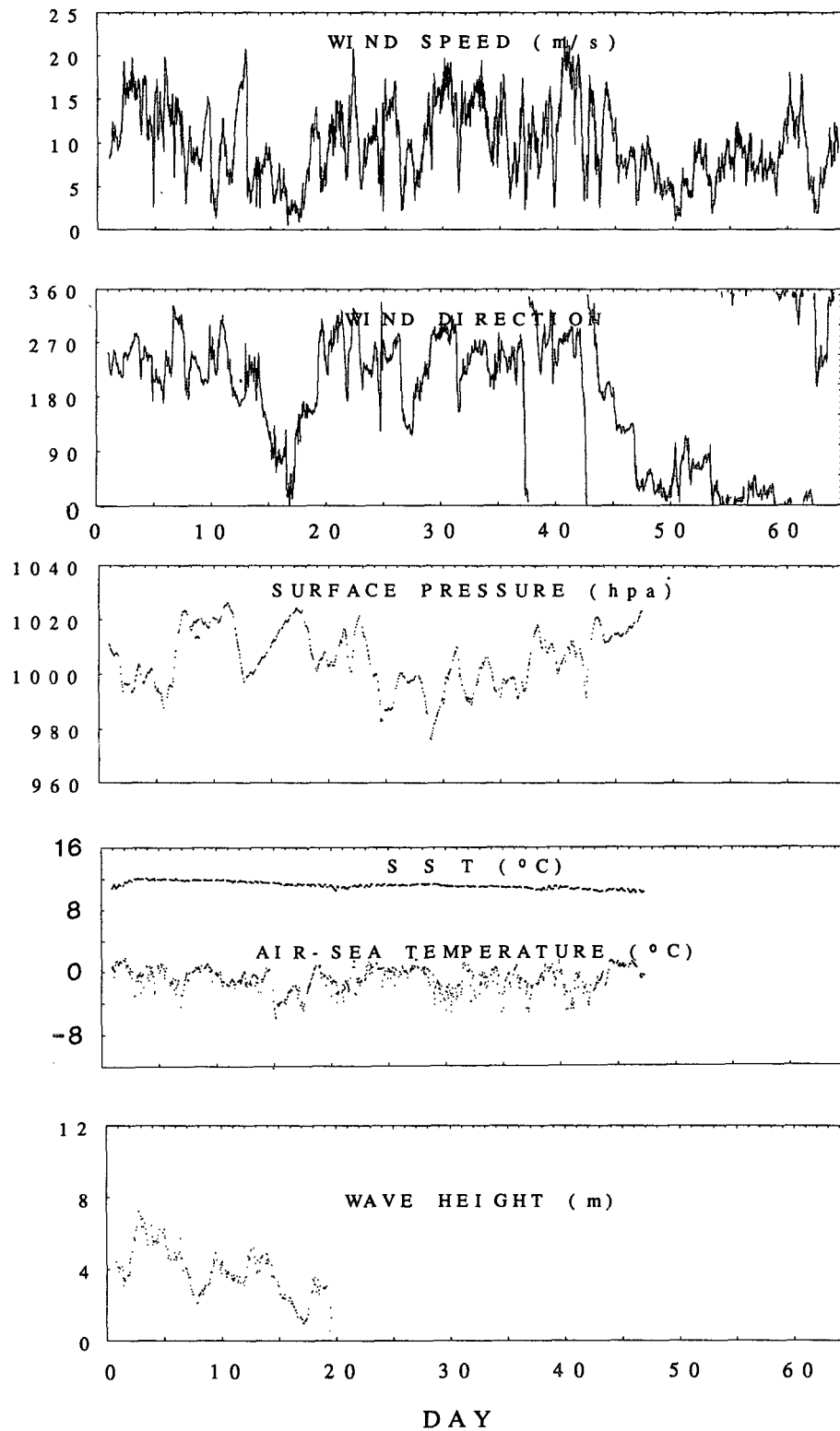


FIG. 8. Same as Fig. 7 for day 1 to day 65 of 1988.

able in Weller et al. (1983). The authors identified two particular sources of error for rotating anemometers, even when accurately calibrated in steady flow: "the inability of the sensors to follow high-frequency fluctuations in the wind vector," and "a lack of cosine angular response functions in either the horizontal or vertical." Cup anemometers are known to respond more quickly to rapid increases in wind speed than to rapid decreases, which results, on average, in a measured speed higher than the real one. Furthermore, this overspeeding effect may change from one anemometer to another according to the mechanical friction. The vertical response functions increase this difference between the two types of sensors: the responses are generally above the cosine curve for cup anemometers (resulting in overestimation of measured values) and below for propellers (underestimation). After the experiment, the off-axis response of the R. M. Young propeller was tested in a wind tunnel (Maresca and Favier 1988). The experimental dataset shows that the underestimation of speed is symmetrical relative to the off-axis angle and that it increases with wind speed: for angles below 15° the attenuation is less than 5% and for a 20° incidence angle the attenuation is 5% at 5 m s^{-1} , 10% at 10 m s^{-1} , and 14% at 15 m s^{-1} . For the extreme angle of 30° , it reaches 18%, 19%, and 21%, respectively. A performance analysis of the Frontal Air-Sea Interaction Experiment (FASINEX) meteorological buoys, performed by Weller et al. (1990), led to similar results from comparison of a three-cup anemometer and a Young propeller mounted on a similar buoy: an average 10% overestimation of the cup, with a strong correlation between overspeeding and atmospheric instability because of gusts. Therefore, the accuracy of the measurement is influenced by the geometry of the buoy hull and its response to sea waves. A spar buoy is more stable, and W. V. Burt (1975) reported an overestimation of 7% of wind speed measurements from a toroid buoy relative to a spar buoy equipped with the same type of three-cup anemometer.

A second effect of waves on a buoy is movement of the anemometer back and forth. For three-cup anemometers, the induced error will be large if wind speed and direction are averaged independently, particularly for light wind and swell conditions. If a quasi-sinusoidal motion is assumed, this error will be reduced in performing wind vector averaging at a high sampling rate (relative to wave periods). This was achieved by the acquisition system used on buoys and the ship (section 2).

In the case of the Debucourt anemometer, another error is due to the crossbars used to maintain the upper horizontal protecting disk (see Fig. 3). Postexperiment tests in a wind tunnel facility (Maresca and Favier 1988) have shown the influence of the bars: Fig. 9 presents the anemometer-sensed wind speed as a function of the horizontal azimuth for a nominal speed of 10 m s^{-1} in the tunnel. The zero origin of the azimuth is centered on one of the three bars, and three minima

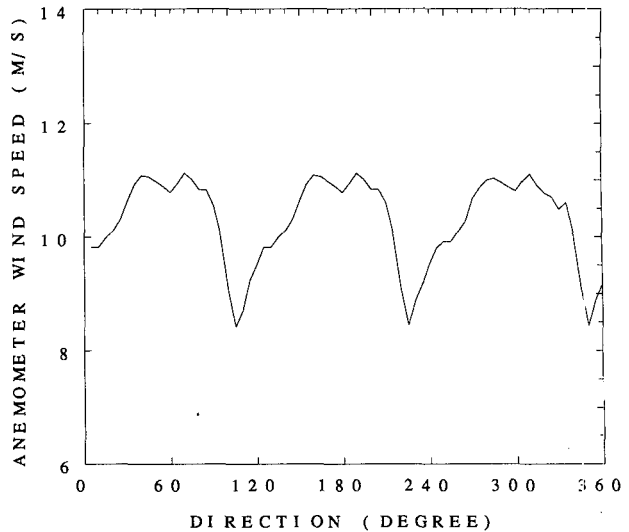


FIG. 9. Variation of the Debucourt anemometer-measured wind speed as a function of wind azimuth, for 10 m s^{-1} nominal wind speed, from tunnel experiment.

are observed, corresponding to each of the bars (the minima are in fact shifted about 10° relative to the bars). The difference between maximum and minimum values is 2.5 m s^{-1} for a 10 m s^{-1} nominal speed, but the width of the minimum being narrow, differences for in situ measurements would be smoother than those observed in the tunnel. Comparison of the wind speed data from the island mast (Debucourt anemometer) and the buoy 5 (Young anemometer, without crossbars) as a function of mast wind direction (Fig. 10) shows clearly the same shape (with a level change from west to east sectors). This is also observed for buoys 6 and 7, though equipped with the same type of crossbars: the perturbation effect of crossbars is smoothed because of the buoy motion. This large perturbation is certainly the main explanation for the modulation observed by Daniault et al. (1988) on wind speed differences between masts as a function of wind direction, during the TOSCANÉ-T experiment (their Fig. 8).

b. Ship airflow distortion

Wind speed and direction measurements on a ship can be seriously perturbed by the airflow distortion induced by superstructures, resulting in an acceleration of the flow above and around the ship. Induced errors are very sensitive to the location of the sensors and to the direction of the wind relative to the ship. From simulations in a wind tunnel on a 1:100-scale ship model (Blanc 1986), these errors were estimated and correction tables proposed for two standard anemometer locations on both sides of the forward mast. For wind speed measurements, the minimum error was observed near the upwind direction and estimated at 12% and 10% for starboard and port anemometer, re-

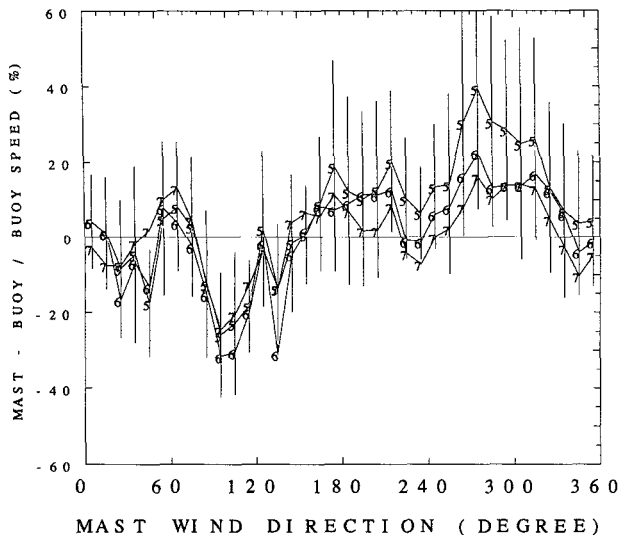


FIG. 10. Relative (to buoy) differences between mast and buoy wind speeds as a function of mast wind direction: 20-min-averaged data corrected to the mast altitude measurement and grouped within direction bins 10° wide, for buoys 5, 6, and 7. Vertical bars for buoy 5 indicate plus/minus one standard deviation computed within each direction class.

spectively. When the relative wind direction changes within $\pm 30^\circ$, the error ranges from 18% to 8% on starboard and from 11% to 13% on port, reflecting the asymmetrical configuration of the ship. For direction, errors are between -7° and 1° on starboard and between 0° and 6° on port, the minimum being slightly outside the upwind direction. These results were obtained in the assumption of neutral stability conditions and the author estimated the accuracy of the corrected values under other environmental conditions to be of the order of $\pm 5\%$ for speed and $\pm 5^\circ$ for direction. Other overspeeding values between 10% and 20% are reported by Blanc (1985) and Kahma and Lepparanta (1981).

This effect was roughly estimated during the TOSCANE-1-PROMESS campaign (Ezraty and Queffeuou 1987), on board N/O *Le Suroit*, from dedicated experiments consisting of measuring the relative wind speed during two following runs, the ship heading upwind in the first and downwind in the second, at a speed which must be greater than the wind speed (about 10 kt maximum). The ship speed relative to the bottom was computed from the positioning system data, and with the assumption that wind speed was steady over the two following runs, the overspeeding induced by the ship airflow distortion was estimated at about 8% of the measured speed. The reference quoted above gives a value of 12%, which includes a 4% difference due to anemometer calibration. This overspeeding value is less than those reported above, but the error on this estimation might be large because the assumption of constant wind speed, on average, over the two following runs (each about 20 min long) might not be verified. Nevertheless, this correction will be applied

to the data, but its questionable accuracy has to be kept in mind.

c. Correction for ship speed

Once the overspeeding correction is achieved, the relative wind speed is corrected for the ship speed, deduced from the SYLEDIS (Système Léger de mesure de Distance) data, at a 30-s sample rate. The SYLEDIS is a radio hyperbolic positioning system based on local transmitters of the Marine Nationale, and the position accuracy is better than 10 m over the experimental area. So, when vector averaging is performed over time duration longer than 10 min, the resulting speed accuracy is better than 0.03 m s^{-1} and the correction does not contribute significantly to the variance observed when comparing ship and buoy data.

d. Adjustment of wind to a reference level

In the following sections, ship, buoy, and mast data will be compared and for this purpose wind speed data have to be corrected for height shifts relative to the sea level. This is achieved through a stability-dependent model in the constant flux layer. The wind speed at z level is given by (1), u_* being the friction velocity, $k = 0.4$ the von Kármán constant, and z_0 the aerodynamic roughness length. The aerodynamic roughness length z_0 is related to the friction velocity (Wu 1982) by (2), $\mu = 14.10^{-6} \text{ m s}^{-1}$ being the kinematic viscosity of air and $g = 9.81 \text{ m s}^{-2}$ the gravity acceleration:

$$u(z) = \left(\frac{u_*}{k} \right) \left[\ln \left(\frac{z}{z_0} \right) - \psi_m \left(\frac{z}{L} \right) \right] \quad (1)$$

$$z_0 = \frac{0.0185 u_*^2}{g} + \left(\frac{\mu}{u_*} \right) \exp(-5.5k). \quad (2)$$

The parameter ψ_m is a stability-dependent function (Large and Pond 1981) equal to 0 for neutral conditions and given by (3) and (4) for stable and unstable conditions, respectively. The Monin-Obukhov stability length, estimated through the bulk formulas parameterization of turbulent fluxes is represented by L . The value of $u(z)$ is computed through an iterative method, using the software package developed by Ezraty and Ollitault (1985). Thus,

$$\psi_m \left(\frac{z}{L} \right) = \frac{-5z}{L} \quad (3)$$

$$\psi_m \left(\frac{z}{L} \right) = 2 \ln \left[\frac{(1+X)}{2} \right] + \ln \left[\frac{(1+X^2)}{2} \right] - 2 \tan^{-1} X + \frac{\pi}{2} \quad (4)$$

with $X = (1 - 16z/L)^{1/4}$.

4. Consistency of ship wind measurements

Data from the two independent wind measurement systems on board the ship were compared. The comparison was performed on relative wind data (as measured by the two wind systems and not corrected for ship speed and distortion). This information is directly available from the Cactus station (30-s average) using the Debucourt sensors and an internal compass. For the Pomar station (Tavid sensors) a wind vector is available at 3-s average; the direction of this wind vector refers to the ship axis and the transformation relative to north is performed using the ship gyrocompass data stored every 3 s. These two datasets are then synchronized and averaged over 30 s. Only data collected during calibration runs are compared, which represent 21 606 data points. Calibration runs are defined within the three following criteria: the ship-to-buoy distance is restricted to a maximum value of two nautical miles; the ship is heading upwind (difference between ship heading and wind direction being less than 30°) so that the airflow distortion induced by the ship superstructure is always the same; and the ship speed is as low as possible but high enough to maintain upwind (i.e., less than 3 kt).

a. Wind direction

The mean value of the differences between the two datasets is 5.9° and the standard deviation of the differences is 4.5°. The mean difference is small and compatible with possible asymmetrical deflection of wind direction as reported in section 3b. The distribution of the differences, shown in Fig. 11, is narrow: 47.9% of the data are within ±5°, and 85.8% within ±10°. When taking the mean value *m* into account, the following

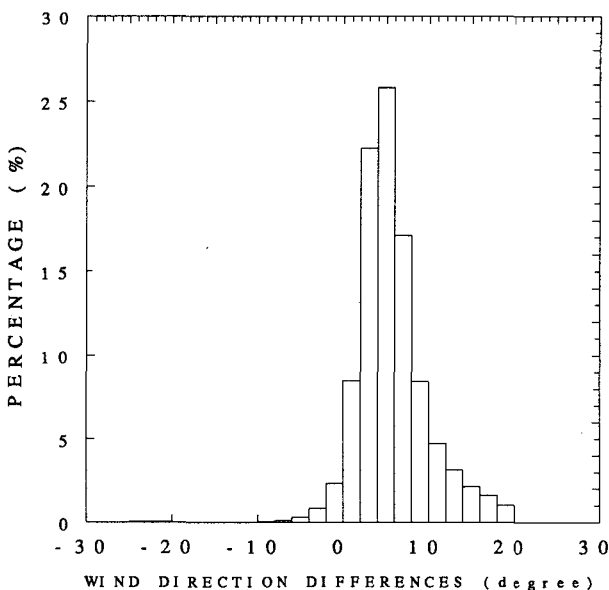


FIG. 11. Distribution of wind direction differences between the two measuring systems (Cactus and Pomar) on board N/O *Le Noroit*.

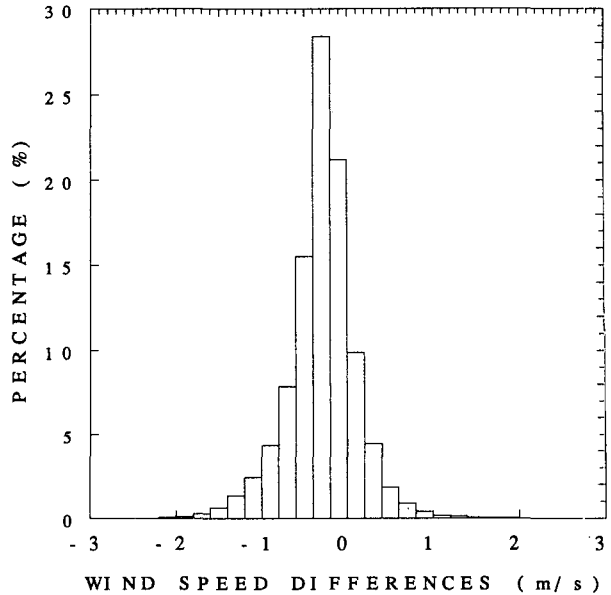


FIG. 12. Distribution of wind speed differences between the two measuring systems (Cactus and Pomar) on board N/O *Le Noroit*.

results are obtained: 82.1% within $m \pm 5^\circ$, and 95.3% within $m \pm 10^\circ$. These results are rather good, since the Tavid vane resolution is only 10°.

b. Wind speed

The distribution of the wind speed differences is shown in Fig. 12: the mean value is -0.29 m s^{-1} , Debucourt speed being lower, and standard deviation is 0.40 m s^{-1} ; 99.9% of data are within $\pm 2 \text{ m s}^{-1}$ and 94.8% of data within $\pm 1 \text{ m s}^{-1}$. After correcting for

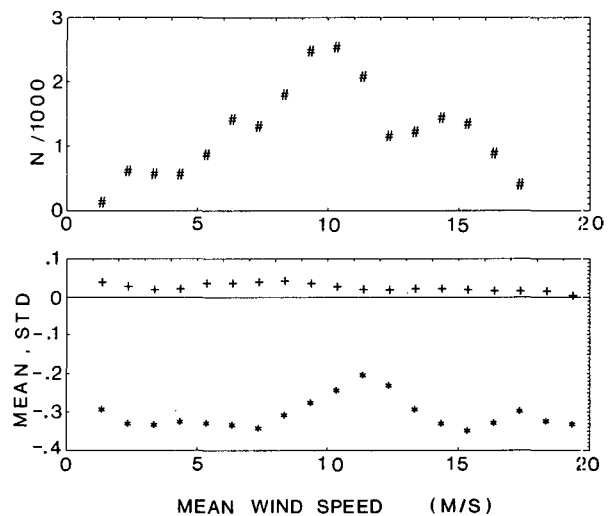


FIG. 13. Variation of mean value (*, m s^{-1}) and standard deviation (+, ratio to the speed) of speed differences between the two measuring systems (Cactus and Pomar) on board N/O *Le Noroit* as a function of the mean wind speed of the two systems. The upper curve (#) is the number of data for each speed bin.

the -0.29 m s^{-1} bias, 97.2% of data are within $\pm 1 \text{ m s}^{-1}$.

Figure 13 shows the evolution of the mean value and standard deviation of the speed differences as a function of the averaged wind speeds measured by Cactus and Pomar systems (bin width is 1 m s^{-1}): the mean is roughly constant; the standard deviation increases with wind speed, from 0.10 to 0.49 m s^{-1} , the ratio to the wind speed, shown on the figure, varying between 0.03 and 0.05 . When the mean value of the differences is taken into account, the analysis of the relative dispersion indicates that 94.3% of data are within $\pm 10\%$ of Cactus wind speed.

These results show that the wind measurements performed on board the ship by the two systems are in close agreement. The dataset obtained from the Cactus system (equipped with the Debucoart sensors, as most of the buoys) will be considered as a reference, although the 0.3 m s^{-1} mean difference is not explained and the absolute accuracy is questionable (section 3b). It is important to note that these results are obtained over a narrow range ($\pm 30^\circ$) of the wind azimuth relative to the anemometer (ship heading upwind), because in these conditions, the position of the Debucoart anemometer relative to the ship is such that no perturbation from the anemometer crossbars is expected.

5. Comparison of buoy and ship wind data

a. Time-distance influence

In order to compare buoy and ship wind measurements, the averaging time and the separation distance between the two platforms have to be chosen. An initial view of the time-distance influence is given in Fig. 14, showing the relative (to the ship) standard deviation of ship and buoy 5 wind speed differences according to averaging time and separation distance classes. The length of distance classes is not constant, but determined in order to obtain a constant number of data for each class (400, 200, 150, 60, 45, and 30 for the considered averaging times between 1 and 20 min, respectively). First, the standard deviation decreases rapidly from 1 to 5 min averaging time; then, no significant difference is observed between 10 and 20 min. So, in the following comparisons, the averaging duration will be set to 20 min. The shape of the curves is not interpretable as a function of separation distance because wind speed distribution is not the same over all distance classes, and the standard deviation is certainly speed dependent. As the length of the dataset is limited and as the distance effect cannot be estimated, the whole dataset for which the distance is less than or equal to 3000 m will be taken into account hereafter. Increasing this value does not significantly change the number of data.

b. Comparison of buoy and ship wind speed

Assuming the ship measurements can be considered as a reference, the goal of these comparisons is to cal-

ibrate measurements of buoys in order to get a homogeneous (as much as possible) wind dataset over the whole network.

The ship wind speed data have been reduced to the height of buoy sensors, using the boundary-layer model with, as input, the stability conditions inferred from ship measurements of atmospheric pressure, sea surface, and wet and dry air temperatures. Scatterplots of buoy and ship data are shown in Fig. 15. Each point corresponds to the value averaged over 20 min, and vertical and horizontal bars represent plus or minus one standard deviation of the 1-min elementary data relative to the 20-min-averaged value, for buoy (vertical) and ship (horizontal) data. This variability is shown in detail, in Fig. 16, for ship and buoy 6: the standard deviation is generally less for the ship than for the buoy but both variables increase with wind speed.

A straight line was fit to the dataset of Fig. 15 by minimizing the function $X^2(a, b)$ equal to the sum of the squares of the orthogonal distances d_i , between the data point (x_i, y_i) and the line $y = ax + b$, weighted by the "variability" of the data point, σ_i estimated as the square root of the sum of ship and buoy variances σ_{xi}^2 and σ_{yi}^2 . Uncertainties on a and b are functions of those on x_i and y_i , and standard deviations σ_a and σ_b have been estimated extending to two variables the propagation of errors used in Press et al. (1986).

Statistical results are summarized in Table 3. Mean values of differences between ship and buoy measurements range from -0.71 to 0.34 m s^{-1} . The standard deviation of the differences are significantly different among the buoys: the minimum value is 0.29 m s^{-1}

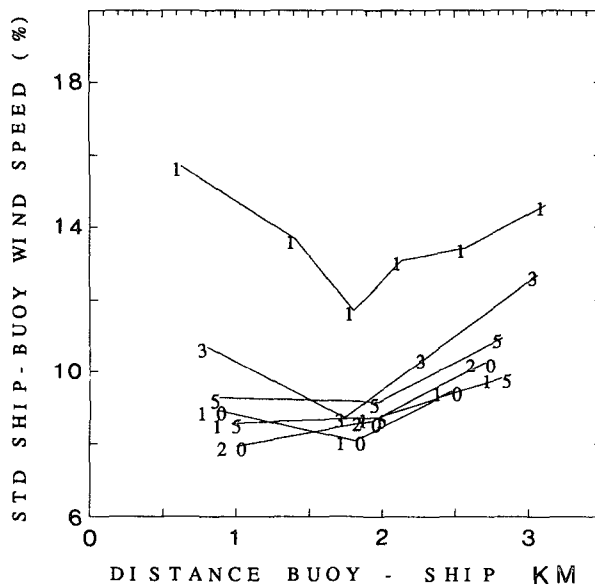


FIG. 14. Standard deviation of the relative (to the ship wind speed) differences between ship and buoy 5 wind speed as a function of separation distance, for 1, 3, 5, 10, 15, and 20 min averaging time (curve label is averaging time).

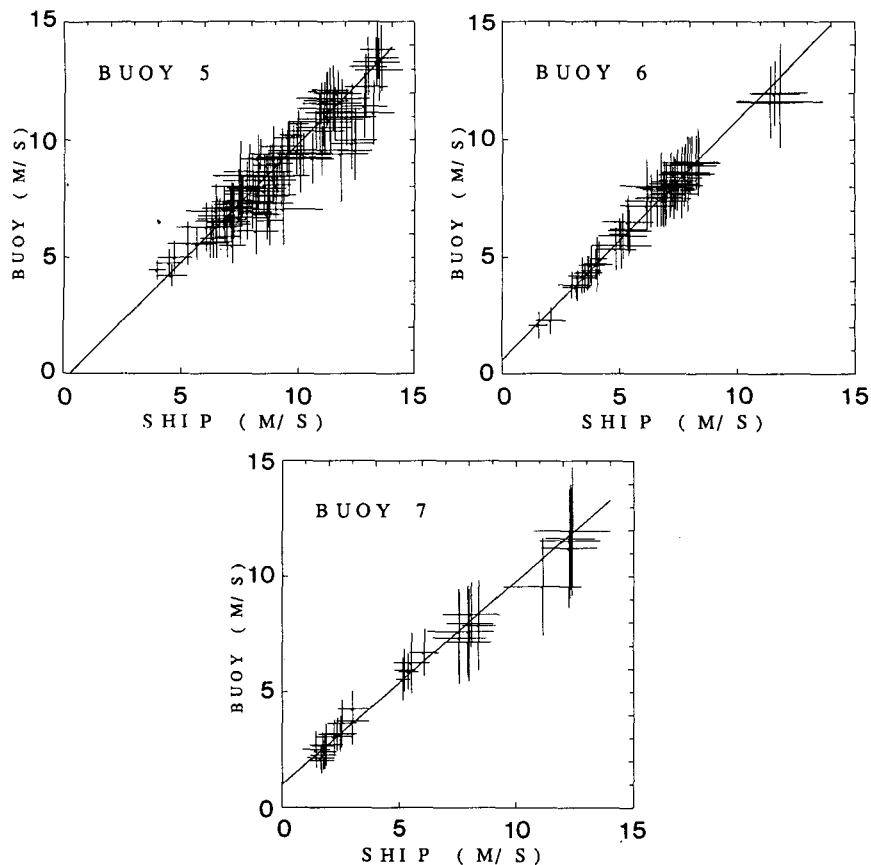


FIG. 15. Scatterplots comparing 20-min-averaged wind speeds from ship and buoys.

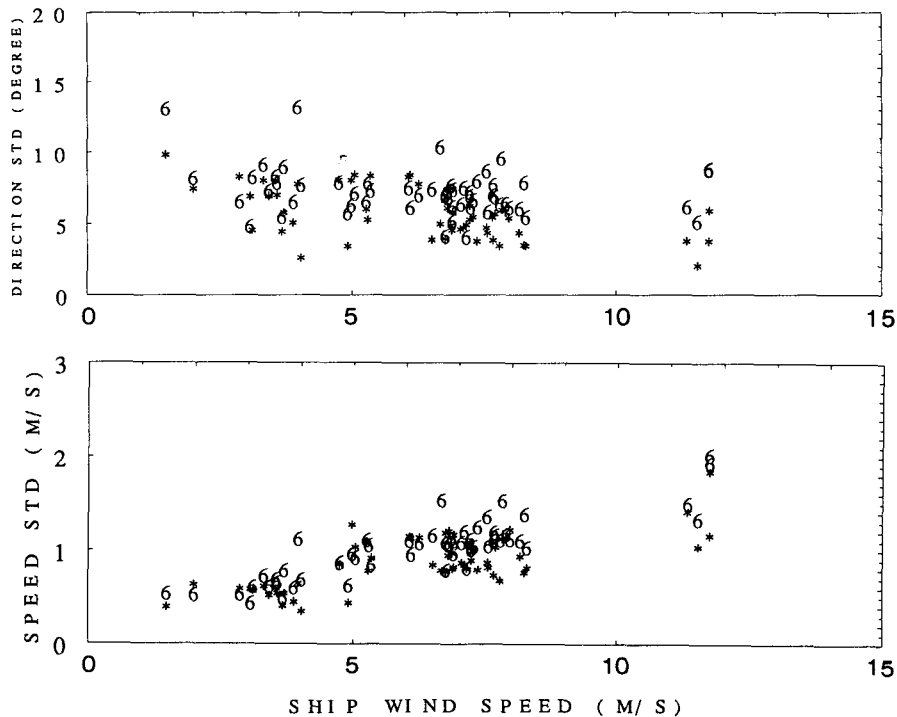


FIG. 16. Standard deviation of 1-min ship (*) and buoy 6 wind speed and direction measurements within 20 min averaging time.

TABLE 3. Statistical results for ship and buoy wind speed comparisons (m s^{-1}): data point number N , mean value, and standard deviation of differences between ship and buoy data, slope A and intercept B of the inertial axis with their estimated standard deviation σ_A and σ_B .

Buoy	N	Mean	Standard deviation	A	σ_A	B	σ_B
5	119	0.34	0.82	1.012	0.053	-0.269	0.46
6	58	-0.71	0.29	1.021	0.072	0.598	0.41
7	30	-0.22	0.71	0.879	0.083	0.993	0.35

for buoy 6 and the maximum 0.82 m s^{-1} for buoy 5. The slope of the regression lines is very close to unity for buoys 5 and 6 (about 1% and 2%, respectively), but is 12% for buoy 7. This buoy overestimates low wind speeds and underestimates high wind speeds ($> 10 \text{ m s}^{-1}$). Taking into account variances of ship and buoy measurements, the standard deviation of the slope coefficients is shown to range from 5% to 8%, the maximum value being observed for buoy 7. The values of the intercept range from -0.3 to 1.0 m s^{-1} (maximum for buoy 7) with standard deviation from 0.35 to 0.46 m s^{-1} .

The main conclusions from these results are that the wind speed measurement is biased, slightly low (0.34 m s^{-1}) for buoy 5, and high (0.71 m s^{-1}) for buoy 6, which is in agreement with the three-cup overspeeding described in section 3. A large slope coefficient is observed for buoy 7, which may indicate a miscalibration of the anemometer, though for this buoy the number of data is only 30, which is statistically insufficient.

c. Comparison of buoy and ship wind direction

Statistical results comparing the directions of the 20-min-averaged wind from buoys and the ship are given in Table 4. Mean value of differences is less than 1° for buoy 5, only -1.5° for buoy 7, and 5.5° for buoy 6. Standard deviation is less than 5° for buoys 5 and 6 and reaches 7.5° for buoy 7. The slopes are very close to unity and the intercepts are less than 5° . Standard deviations of the elementary 1-min wind direction relative to the 20-min average are given in Fig. 16 as a function of wind speed: as for the speed, the direction variability is less for the ship than for the buoys but it increases at low wind speed because of a higher variability of wind direction and a degraded response of vanes at light winds. In conclusion, results obtained for these direction comparisons may be considered very good.

6. Buoy calibration and test

Assuming the ship wind measurement is a reference, the regression coefficients (a , b) obtained earlier will be used to calibrate the buoy data as $x_c = (x - b)/a$, x being the buoy measurement (speed or direction) and x_c the calibrated value. To test the efficiency of this calibration, the resulting wind data of the three buoys will be compared (values corrected to the height of 5 m in neutral stability conditions), but before this step, the buoys being separated by 25–35 km, the averaging time has to be chosen long enough to filter out the effect of distance separation.

a. Averaging-time effect

The mean value and variance of the differences between calibrated wind directions from pairs of buoys were studied as a function of the averaging time, ranging from 10 min to 24 h. When analyzing the whole dataset, large spikes were obtained on curves relating the mean and the standard deviation to the averaging time. Inspection of the data revealed that these spikes were mainly induced by three sequences, of duration of the order of 12 h, for which directions measured by the two buoys are significantly different: discarding these time periods, the curves were smoother and the level of variance decreased. Two of the three perturbation sequences are illustrated in Fig. 17, showing 2.5-min-averaged wind speed and direction for buoys 5, 6, and 7 on days 345–349. The speed curves 6 and 7 have been shifted up by 8 m s^{-1} and 16 m s^{-1} , and the direction curves by 30° and 60° , respectively. A first anomaly is observed on day 345 when buoy 6's speed and direction are significantly different from those of buoys 5 and 7. The second perturbing sequence corresponds to a meteorological cold front propagating across the area at very low speed since the changes of wind direction are observed at 2140 UTC (day 347), 0110 UTC (day 348), and 0450 UTC on buoys 6, 7,

TABLE 4. Ship and buoy wind direction comparisons (deg).

Buoy	N	Mean	Standard deviation	A	σ_A	B	σ_B
5	119	-0.38	3.66	0.984	0.005	2.890	0.77
6	58	5.46	4.93	0.995	0.009	-4.071	2.05
7	30	-1.50	7.35	1.000	0.037	0.966	2.87

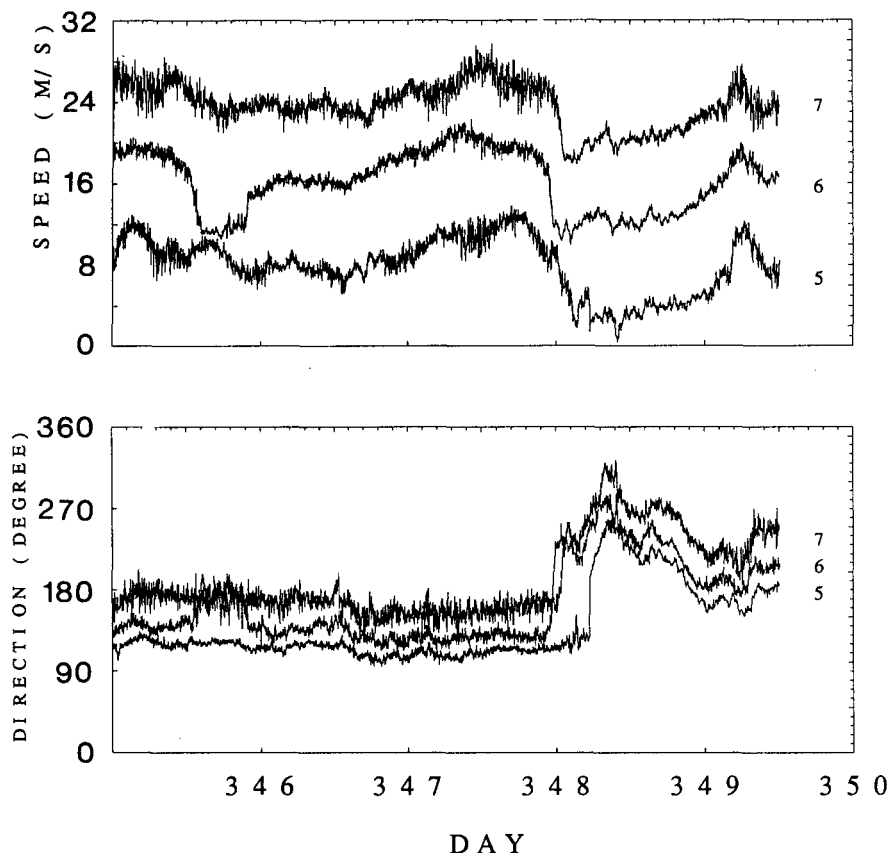


FIG. 17. 2.5-min-averaged buoy wind data for days 345–349. Curves are shifted by 8 m s^{-1} steps for speed and by 30° steps for direction.

and 5, respectively. There is a time lag about 7 h long between changes of direction at buoys 5 and 6, which are separated by 25 km only, and so when averaging, even over a duration as long as 12 h, and comparing directions of buoys 5 and 6, large differences may be observed depending on whether direction changes occurred on both buoys. The third perturbing sequence, not shown here, corresponds to low wind speed for which the direction is variable among buoys. In the following, these three sequences will be discarded, as also periods for which the speed is less than 1 m s^{-1} .

Within these conditions, evolution of mean and variance of measurement differences between buoys 5 and 6 is shown in Figs. 18 and 19 for wind direction and speed. The standard errors reported on the graphs were estimated as $\sigma n^{-1/2}$ for the mean and $(m_4 - m_2^2)^{1/2} n^{-1/2}$ for the variance, m_2 and m_4 being the second- and fourth-order central moments of the distribution. The curves obtained for the two remaining pairs of buoys, (5,7) and (6,7), have a similar shape. The variances decrease with averaging time, rapidly for the first 3 or 4 h, then more slowly, and reach a plateau value around 10–12 h. Some values of the standard deviation (absolute and relative to the 10-min observed one) are given in Tables 5 and 6 for

direction and speed. Orders of magnitude are roughly the same for the three pairs of buoys: for direction, the standard deviation decreases from 13° – 15° at 10 min to 6° – 8° at 12 h; for speed, the standard deviation ranges from 1.2 – 1.4 m s^{-1} at 10 min to 0.6 – 0.7 m s^{-1} at 12 h. From these results it appears that the standard deviation decreases by about 40% between 10 min and 6 h averaging durations, and only 10% between 6 and 12 h, and so it seems reasonable to select an averaging duration of 6 h for buoy measurement comparisons.

b. Results

Statistical results comparing calibrated wind speed from the three buoys are given in Table 7. The standard deviations of buoy wind speed differences are within 0.8 m s^{-1} . Buoys 6 and 7 are in good agreement since only a 0.11 m s^{-1} mean difference is observed, which is rather satisfying, considering the accuracy of a and b calibration coefficients (section 5). In spite of the calibration, the speed data of these two buoys, equipped with three-cup anemometers, are still slightly higher (biases of 0.40 and 0.50 m s^{-1}) than those of buoy 5 (propeller anemometer). An explanation might be that buoy 5 (Fig. 2) behaves much more like a spar buoy

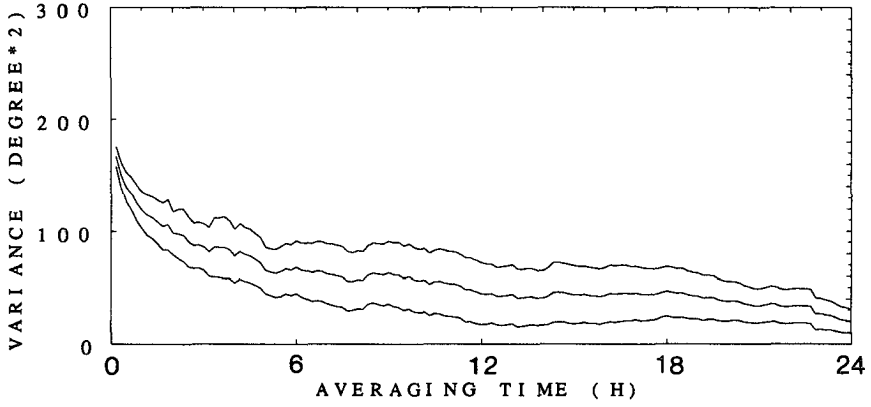
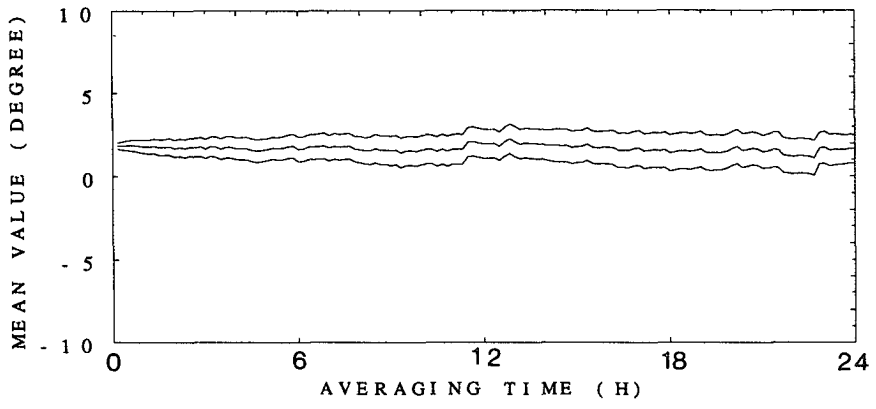


FIG. 18. Mean value and variance of wind direction differences between buoys 5 and 6, as a function of averaging time.

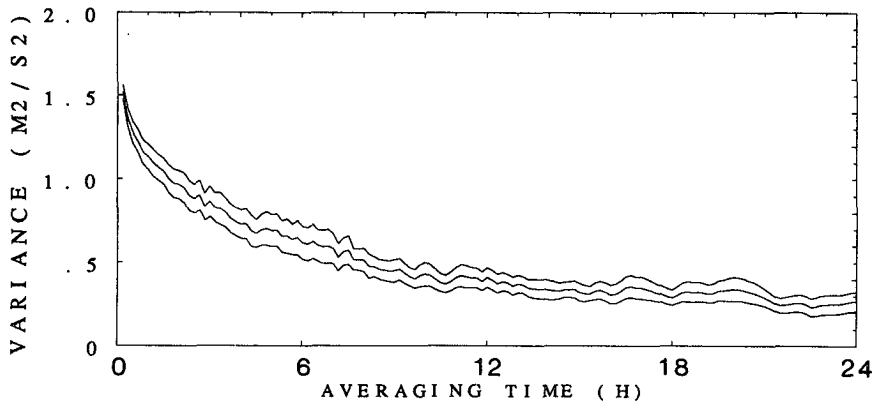
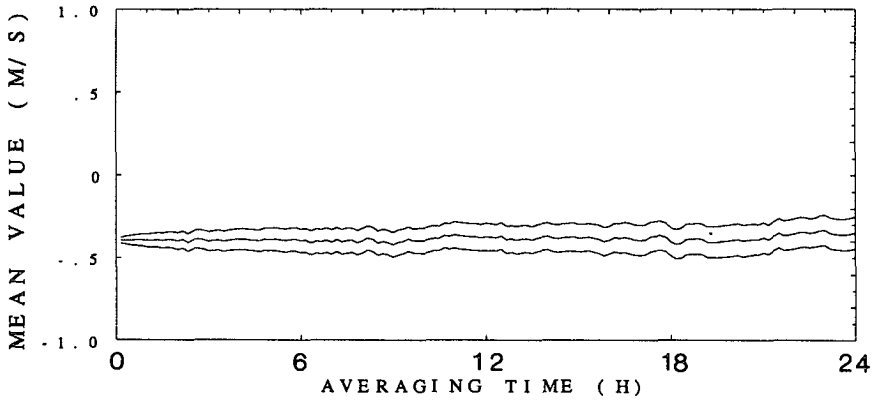


FIG. 19. Mean value and variance of wind speed differences between buoys 5 and 6, as a function of averaging time.

TABLE 5. Standard deviation of direction differences between buoys, expressed in degrees and in percentage of the standard deviation observed at 10 min, for various averaging times.

Buoys	5-6 [° (%)]	5-7 [° (%)]	6-7 [° (%)]
10 min	12.9 (100)	14.7 (100)	14.8 (100)
1 h	10.9 (84)	12.3 (84)	13.1 (88)
1 h	9.3 (72)	10.8 (73)	9.9 (67)
6 h	8.3 (64)	9.2 (62)	8.7 (59)
9 h	8.0 (62)	7.8 (53)	8.2 (56)
12 h	6.7 (52)	7.7 (52)	6.0 (40)
Average			
12-24 h	6.3 (49)	7.4 (50)	7.2 (49)

than buoys 6 and 7 (Fig. 4) and larger off-axis angles of these buoys result in overspeeding of the three-cup anemometer measurements, because of their vertical response (section 3). Nevertheless, the improvement due to the calibration is obvious, as shown by the results obtained without calibration, enclosed in parentheses in Table 7. Wind directions from all buoys are in good agreement with ship measurements (section 5) and the calibration correction is then very small. Mean values of calibrated direction differences between buoys are less than 5°, and standard deviations are less than 10°.

The above results on buoy performances are better than those reported by Weller et al. (1983), perhaps mainly because of a greater homogeneity among the TOSCANE-2 sensors and sampling schemes than for JASIN (Joint Air-Sea Interaction Program) 1978. Few comparisons between ship and buoy wind measurements are available. Reynolds (1982) compared the wind observations of the NOAA ship *Oceanographer* to measurements from a nearby buoy during the Storm Transfer and Response Experiment and obtained mean values of differences of 0.8 m s⁻¹ for wind speed and 3.5° for direction, with standard deviations of 1.2 m s⁻¹ and 11°, respectively. Pierson (1990) inspected pairs of ship reports and buoy data separated by 100 km or less and found a poor quality of ship reports, made on a routine basis, even for ships equipped with anemometers of known height. The U.S. National Data Buoy

TABLE 6. Standard deviation of wind speed differences between buoys, expressed in meters per second and in percentage of the standard deviation observed at 10 min, for various averaging times.

Buoys	5-6 [m s ⁻¹ (%)]	5-7 [m s ⁻¹ (%)]	6-7 [m s ⁻¹ (%)]
10 min	1.23 (100)	1.39 (100)	1.31 (100)
1 h	1.06 (86)	1.17 (84)	1.10 (84)
3 h	0.93 (75)	1.01 (73)	0.99 (76)
6 h	0.79 (64)	0.82 (59)	0.82 (63)
9 h	0.67 (64)	0.72 (52)	0.69 (53)
12 h	0.64 (52)	0.69 (50)	0.68 (52)
Average			
12-24 h	0.56 (45)	0.66 (47)	0.63 (48)

TABLE 7. Comparison of calibrated buoy wind speed measurements (m s⁻¹), values enclosed in parentheses are results for non-calibrated data.

Buoys	<i>N</i>	Mean	Standard deviation	<i>A</i>	<i>B</i>
5-6	122	-0.40 (-1.35)	0.79	1.08 (1.10)	-0.22 (0.65)
5-7	123	-0.50 (-0.72)	0.82	1.10 (0.95)	-0.22 (1.08)
6-7	123	-0.11 (0.62)	0.82	1.01 (0.86)	-0.01 (0.54)

Center performed an extensive amount of field comparisons in 1984 and 1985, to assess the performance of wind buoys. A comparison by Gilhousen (1985a) of several weeks (including storms events) of duplicate wind sensor data on a similar buoy (Bendix propeller anemometers) led to mean values of speed differences less than 0.2 m s⁻¹, with standard deviations between 0.4 and 0.5 m s⁻¹ (increasing with wind speed). For wind direction, the mean was less than 5° and the standard deviation about 10°. These results agree with those obtained from TOSCANE-2 ship wind measurements. One month of data from two buoys, anchored 3.3 km apart, was also analyzed (Gilhousen 1986b) and mean values of differences were less than 0.2 m s⁻¹ and 1.5°, with standard deviation of 0.78 m s⁻¹ and 9.2°. Finally the author compared the 10-m-level corrected data from a fixed platform and a buoy 1.3 km away: mean value of speed differences was 0.59 m s⁻¹, standard deviation 0.81 m s⁻¹ for speed and 10.4° for direction.

7. Validation of Sein Island wind measurements

For comparison, the mast data have been reduced to the measuring level of buoys. The height of the mast anemometer was estimated about 16 m above mean sea level and, for correction, the tidal variation of the sea level was also taken into account. Over the experiment area the tide is mainly semidiurnal and the maximum-level amplitude during the experiment was about 5.3 m. The variations of tidal level were computed by J. Garrett (personal communication). The data were also corrected for stability conditions, using the meteorological data of the CMM buoy at location M0.

A first comparison between mast and buoy wind speed data shows that the variances of measurement differences are much larger than those observed for buoy-to-buoy comparisons. For instance, for a 3-h averaging, variances are 2.4 m² s⁻² for mast-buoy 5 differences and 0.9 m² s⁻² for buoys 5 and 6 differences; these values become 1.8 and 0.4 m² s⁻² for a 12-h average. A land effect was suspected to be responsible for this variance increase. The mast being located at the extreme west side of the island, which is narrow and mainly orientated along the east-west direction, the wind data were separated into two groups according to the direction: the east sector for directions between

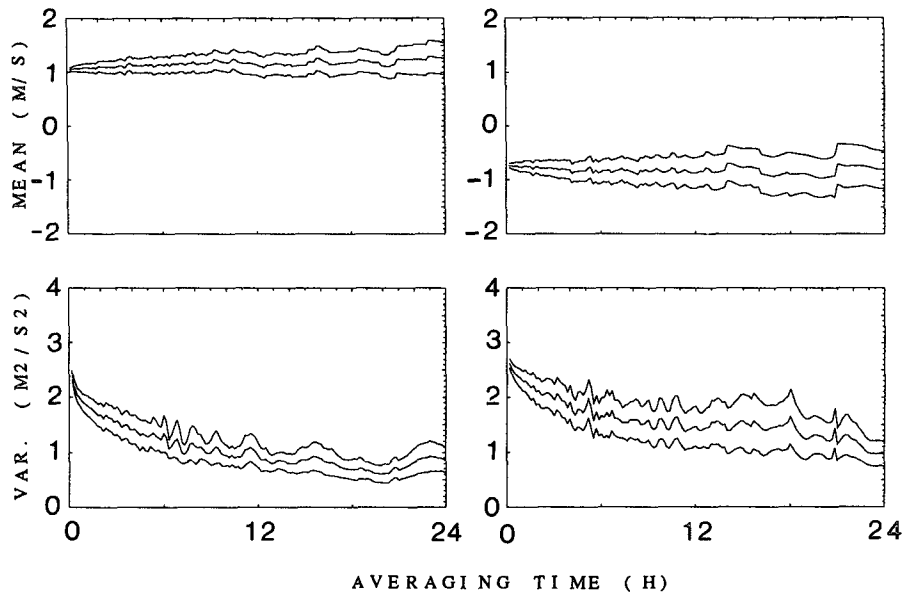


FIG. 20. Mean value and variance of wind speed differences between the mast and buoy 5 as a function of averaging time, for the west sector (left) and the east sector (right).

0° and 180°, and the west sector between 180° and 360°. The east sector includes all the offshore winds and the west one contains only onshore winds. Results of comparisons to buoy 5 are shown in Fig. 20, for the two sectors: the variance and standard errors are less for the west sector than for the east one and there is a difference of about 1.8 m s⁻¹ between mean values of buoy and mast wind speed differences relative to the two sectors. This means that for offshore winds (east sector) the variability increases and that the mast wind speed, relatively to the buoy, is less than for onshore winds (west sector). This is in agreement with a land effect: the surface roughness scale changes drastically from westerly winds (sea) to easterly winds (land) and this results in an increase of mast wind speed variance and in a decrease of mast wind speed due to friction increase. As shown in Table 8, comparing 6-h-averaged wind speed data, differences between east and west sectors are observed similarly for the three buoys.

When considering only the west sector, mean values of speed differences show that the mast wind speed measurements are larger than those of the buoys and that significant differences exist among the buoys, from 0.38 to 1.32 m s⁻¹, and so for standard deviation of differences, from 0.68 to 1.21 m s⁻¹, the larger value being relative to buoy 5. Daniault et al. (1988) reported mean values less than 0.7 m s⁻¹ and standard deviations between 0.8 and 1.3 m s⁻¹, for comparison between a buoy, 6 km offshore, and coastal masts wind data from the TOSCANE-T experiment; the sea winds sector they considered (110°) was much more narrow than in our case study (180°) and distances between buoy and masts were shorter.

Differences between Sein and buoy data are induced by several factors. The first one is that the Sein anemometer has been calibrated only in steady conditions (wind tunnel) and not adjusted to the ship reference, and, as already indicated, the response in nature may be different. Then the crossbar's effect on the fixed anemometer is not at all smoothed (relative to direction) as it can be on a moving buoy. Finally, local topography in the vicinity of mast may influence the measurement according to wind direction, even for sea winds. Influence of these factors, combined with possible "geophysical" effects, can be seen in Fig. 10. The crossbar's effect is associated with the three relative minima observed for directions about 100°, 230°, and 350°. The change of mean level between the two sectors 0°–180° and 180°–360° can be interpreted as the effect of friction over the island, resulting in a relatively lower mast wind speed. Local topography effect may perhaps explain the peak, for the three buoys, around 135°. But what is responsible for the difference of consistency among the data between the two direction sectors 40°–

TABLE 8. Mean values and standard deviations (m s⁻¹) of differences between 6-h-averaged mast and buoy wind speed data, for west (W) and east (E) wind direction sectors.

Buoys	5		6		7	
	W	E	W	E	W	E
Mean	1.32	-0.54	0.79	-0.88	0.38	-0.49
Standard deviation	1.21	1.30	0.68	1.48	0.88	1.26

90° and 220°–300°? For the first sector, comparisons to the three buoys give close results, when for the second sector buoy 5 (center location of the network) returns lower speed values than buoy 6 (south location) and buoy 7 (west location). As a result it does not seem feasible to calibrate accurately (better than 20%) the mast wind speed data.

Comparison of buoy and mast wind direction measurements gives better results than for wind speed. Mean values of differences range between 3.1° and 7.6°, and standard deviations between 7.7° and 10.7°; the slope coefficients are very close to unity (within 2%).

8. Conclusion

Analysis of ship, buoy, and island wind data of TOSCANE-2 experiment permits us to draw some conclusions about in situ wind data quality, which is useful for the calibration and validation of scatterometer data of the *ERS-1* satellite, planned to be launched soon.

First, for high-quality measurements, preexperiment calibration of anemometers in wind tunnels is necessary but not sufficient because of measurement errors induced by the sensor responses to high-frequency fluctuations of wind speed, which are difficult to assess through laboratory tests. Then, even if the accuracy of the measurement of the absolute wind at sea is questionable (and mainly for speed), measurements from an array of buoys will be more efficient (for scatterometer validation) if surface data are "calibrated" against a reference and through cross comparisons between buoys. A dedicated ship can be used as a reference. Results obtained from two independent systems on board *N/O Le Noroit* were close together: standard deviations of 0.4 m s⁻¹ and 5° were observed on speed and direction differences, respectively, accuracy in direction being mainly limited by the resolution of one of the vane sensors. Using ship wind measurements as a reference implies strong operational constraints to get high-quality data. In particular, the ship must be maintained upwind in order that the flow disturbance by the ship superstructure be always the same and able to be corrected through previous tests at sea. Meteorological parameters necessary to adjust wind speed measurements from the ship to buoy levels or to a reference level are also needed, as well as an accurate measurement of the ship speed for absolute wind vector computation. In these conditions, the buoy measurements were calibrated using 20-min-averaged ship data, for separation distances between ship and buoys less than 3 km. This permits us to significantly reduce errors on buoy measurements: maximum mean values of differences among the buoys were 0.5 m s⁻¹ for speed and 4.3° for direction, with corresponding standard deviations of 0.8 m s⁻¹ and 9.2°. Such a ship calibration implies a long enough at-sea campaign to get a suffi-

ciently wide range of measurements, but is neither realistic nor feasible for each buoy of the array (the need for an array of in situ measurements for scatterometer calibration is a consequence of the ground swath size, 500 km for *ERS-1*, and of the dependence of the backscatter coefficient on incidence angle). As a consequence, the consistency of the data among the whole array will have to be tested through buoy-to-buoy comparisons. For this, the time length of wind averaging has to be carefully selected in order to match the distance between buoys to be compared and to filter out space variability. Analysis of TOSCANE-2 data showed that an average over at least 6 h is needed for distances of 25–35 km and that, even for a time average as long as 12 h, particular events such as fronts or low wind speed situations (high variability of direction) have to be discarded from the dataset when testing the data consistency.

The above precision on wind measurements is compatible with the assessment of the 2 m s⁻¹ and 20° accuracy foreseen for the *ERS-1* scatterometer wind data. For the *ERS-1* calibration phase, it is planned to assess the quality of surface data using methods presented above. The surface array will consist of ten buoys developed by the Norwegian company Oceanor, to IFREMER design specifications. Each buoy will be instrumented with one wave sensor and two independent wind-measuring devices using R. M. Young propellers. The buoys will be separated by 50–150 km, covering an area 150 × 450 km², west of Norway. First tests of methods and instrumentations are performed on the data of the Rehearsal Experiment *ERS-1* validation, Northern Europe (RENE) campaign performed over the Norwegian site in February and March 1990.

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