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# Comparison of Surface Meteorological Observations from Ship and Toroid Buoy in the North Pacific During STREX[1]

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## ABSTRACT

Moored-buoy wind measurements were made at 20 min intervals at 3.4 m height at 50°8'N, 140°25'W in the North Pacific from 10 November to 12 December 1981. The measurements were part of the Storm Transfer and Response Experiment (STREX). The NOAA ship *Oceanographer* deployed the buoy and stood by within 25 km of it for an accumulated time of two weeks. The buoy measured wind by a vector averaging technique whereby the anemometer speed, compass angle and vane angle were combined at a 100 Hz rate. The averaging period was 640 s. The *Oceanographer* made standard ship observations with wind speed rounded to ±1 kt and direction rounded to the nearest 10°. Air and sea temperatures were used to correct all measurements to a standard height of 10 m with a diabatic surface layer model. The differences (ship − buoy) in wind speed and direction were compared. For wind speed, a mean difference of 0.8 m $s^{-1}$ and standard deviation of 1.2 m $s^{-1}$ was observed. For direction, a mean difference of 3.5° and standard deviation of 11° was observed. Differences were well correlated with ambient wind speed. The speed difference increased with increasing wind speed. This was particularly severe when the boundary layer was stratified, and could be related to streamline crowding over the ship. The absolute direction difference was less in higher winds, which is partly explained by increased variability in light-wind conditions.

## 1. Introduction

The Storm Transfer and Response Experiment (STREX) was a joint United States and Canadian program in the North Pacific to examine the response of the planetary boundary layer and upper ocean to frontal passage (Fleagle *et al.*, 1982). Scientists participated in STREX with research aircraft, drifting buoys, ships and moored buoys. A principal component was the NOAA ship *Oceanographer*, stationed 320 km east of Ocean Station PAPA (50°N, 145°W).

The ship provided atmospheric soundings, routine surface measurements and oceanographic profiles from which surface fluxes of momentum, vapor and heat would be estimated. The *Oceanographer* anchored a toroid buoy with meteorological instrumentation at 50°8'N and 140°25'W from 10 November to 12 December, and operated within 25 km of the buoy for much of that time (Fig. 1).

This paper compares buoy measurements with standard surface observations taken by the *Oceanographer*. To the author's knowledge, these observations represent the longest such comparison made between a ship and a buoy. The buoy was located in open ocean, well away from topographic influences. Wind and wave conditions varied from near calm to Beaufort scale 10 (whole gale), and included both stable and unstable atmospheric conditions. Systematic differences between buoy and ship observations are determined.

## 2. Instrumentation and data analysis

### *a. Buoy winds*

The buoy was a 2.4 m toroidal float in a taut-line mooring configuration (Berteaux, 1976, p. 200). The sensors were set 3.4 m above the ocean surface (Fig. 1). Wind speed was measured by a Young model 6101 3-cup anemometer. Relative direction was measured with a Young model 6301 vane assembly, and buoy orientation was measured with an ENDECO model 869 flux-gate compass. Air temperature and water temperature were measured with thermistors; their resistance was converted to a temperature-dependent frequency which was counted for 64 s. Temperatures were calibrated to ±0.01°C.

A vector average of the true wind was computed electronically, and is described in more detail by Reynolds (1981). The compass reading and vane position were digitized at a 100 Hz rate. The digital samples were added and entered into a read-only

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memory in which the sine and cosine tables were coded. The memory output was then combined with the cup voltage into two square waves whose frequencies were given by

$$f_x = Kv_c \sin(\phi_v + \phi_c), \qquad (1a)$$

$$f_y = Kv_c \cos(\phi_v + \phi_c), \qquad (1b)$$

where $v_c$ is the cup output (m $s^{-1}$), $\phi_v$ the vane angle, $\phi_c$ the compass angle, and $K$ a conversion factor. The frequencies were averaged for 640 s, and from these averages vector-mean wind velocities were determined. The cup was calibrated in the University of Washington wind tunnel, and the compass and vector-averaging system were calibrated in Lake Washington at the NOAA facility by surveying techniques. System accuracy is estimated to be ±0.4 m $s^{-1}$ in each vector component.

Burt (1975) found that motion of a toroid on the ocean surface produced a 7% higher wind speed than the same measurement from a stable spar buoy. Both scalar wind speed and vector-averaged wind speed were measured on the STREX toroid, and vector speeds were found to be ~6% less than scalar speed, in agreement with Burt.

A major improvement in this system was the inclusion of satellite telemetry. Data were sampled every 20 min and stored in the electronic memory. Every three hours, six samples were transmitted to the GOES (Geostationary Operational Environmental Satellite). Data were saved in the GOES computer and collected by telephone at PMEL and were then routinely available for STREX operations. Satellite transmission of data was most reliable; less than 2% of the data were lost due to transmission errors or telephone parity errors. The 20 min samples were block-averaged in groups of three to yield hourly measurements from the buoy, which were coincident with hourly ship observations.

### b. Ship winds

The *Oceanographer* wind measurements were collected routinely every hour and entered into the weather log with position. Speeds were rounded off to the nearest knot, and directions were rounded to the nearest 10°. Relative wind measurements were read subjectively by the quartermaster from one of two Bendix Aerovane anemometers located at a height of 36 m. Ship heading was taken from the gyroscope system and underway speed was estimated from propellor rotation rate. True wind speed was then calculated by graphically subtracting the estimated ship velocity from relative wind velocity. This technique is generally good when the ship is either holding station or on a continuous course, but becomes questionable when it is maneuvering. That, unfortunately, was generally the case here.

Godshall *et al.* (1976) compared wind measurements taken by the *Oceanographer* with a large buoy deployed by the Federal Republic of Germany ship *Meteor* during the GATE experiments. Their comparison was made with optimum conditions; the average winds were 6.3 m $s^{-1}$ or less and the seas were relatively calm. The ship took 15 min samples and carefully surveyed its position by radar fixes to the

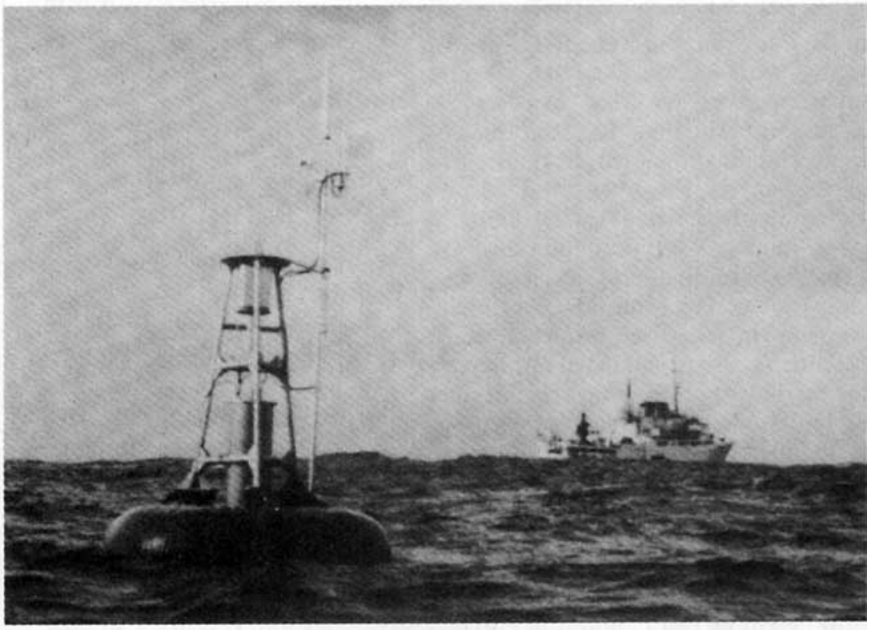

FIG. 1. Photo of toroid buoy with meteorological instrumentation and *Oceanographer* in background.

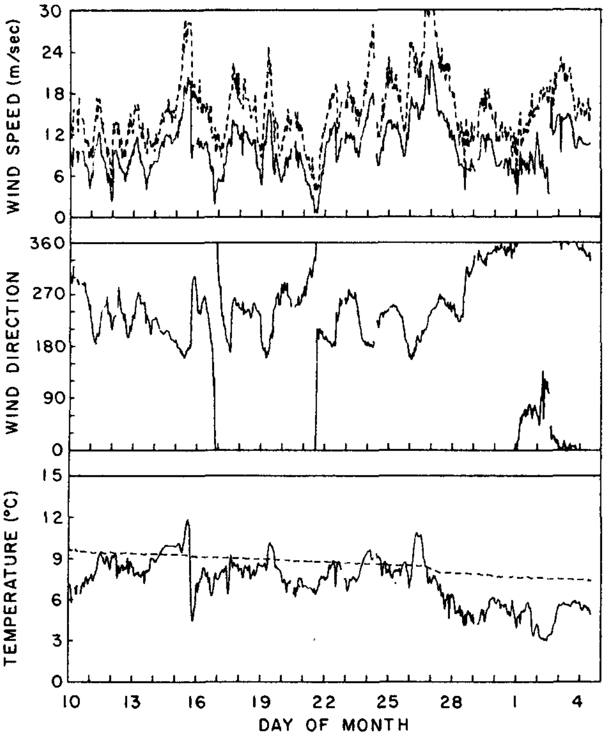

FIG. 2. Time series plot of meteorological data collected during the Storm Transfer Response Experiment (STREX) in the winter of 1980. The solid line for wind speed is the vector-mean speed, the dashed line is the gust. Mean speed is corrected from 3.4 to 10 m height. Wind direction is the true direction from which the wind comes. Water temperature is shown as a dashed line while air temperature is solid.

buoy. Since no surface-layer correction for height was made the ship-measured wind speeds were always greater than the buoy, but differences averaged less than 0.65 m $s^{-1}$ with standard deviations of $\sim \pm 1$ m $s^{-1}$. However, at higher wind speeds the differences increased dramatically. The ship-measured winds became significantly greater than the buoy. For example, when the ship measured 12 m $s^{-1}$, the buoy registered only 8.2 m $s^{-1}$. Godshall *et al.* suggest that ship motion is very difficult to ascertain, and severely contaminates the measurements. Also, modification of the wind flow over and around the ship results in increased winds at the mast. This effect is much more pronounced at higher wind speeds, and is dependent on the ship orientation in the wind. Apparently, even under extremely favorable conditions, ship measurements can exceed buoy measurements by as much as 4 m $s^{-1}$.

### c. *Data analysis*

Wind and temperature measurements were corrected to a standard height of 10 m before they were compared. The diabatic surface-layer profile proposed by Businger *et al.* (1971) was used to make these calculations. Input parameters for any sample were the wind speed $u$, potential temperature $\theta$, their respective sensor heights $z_u$, and $z_\theta$, and sea temperature $\theta_s$. To correct $u$ and $\theta$ to a standard height $Z$, an iteration procedure was used in which friction velocity $u_*$, scale temperature $\theta_*$, Obukhov length $L$ and roughness length $z_0$ were intermediate parameters. We began the iteration procedure by first setting at $z_0 = 5 \times 10^{-5}$ m, and setting the dimensionless height $\zeta = z/L$ equal to the bulk Richardson number

$$\zeta \approx \mathrm{Ri_B} \equiv \frac{g(\theta - \theta_s)(\bar{z} + z_0)}{Tu^2}, \tag{2}$$

where $T$ is absolute air temperature (K) and $\bar{z} = \frac{1}{2}(z_u + z_\theta)$. Humidity effects on buoyancy were not considered in this correction. With these parameters, following Businger (1973) we computed

$$u_* = \frac{ku}{\ln\left(\frac{z_u}{z_0}\right) + \psi_1(\zeta)}, \tag{3}$$

$$\theta_* = \frac{k(\theta - \theta_s)}{0.74 \ln\left(\frac{z_\theta}{z_0}\right) + \psi_2(\zeta)}, \tag{4}$$

where $k$ is the von Kármán constant, equal to 0.4. In the stable case ($\theta_s < \theta$),

$$\psi_1(\zeta) = \psi_2(\zeta) = 6\zeta; \quad \zeta > 0. \tag{5}$$

In the unstable case ($\theta_s > \theta$; $\zeta < 0$)

$$\psi_1(\zeta) = -2 \ln[(1 + x)/2] - \ln[(1 + x^2)/2] + 2 \tan^{-1}(x) - \tfrac{1}{2}\pi, \tag{6a}$$

$$\psi_2(\zeta) = -\ln[(1 + y)/2], \tag{6b}$$

where

$$\left.\begin{aligned} x &= (1 - 16\zeta)^{1/4} \\ y &= (1 - 16\zeta)^{1/2} \end{aligned}\right\}.$$

The iteration loop was closed by calculating $\zeta_0$ from $u_*$ with the equation proposed by Pierson (1978), i.e.,

$$z'_0 = \frac{3.905 \times 10^{-5}}{u_*} + 0.001604 u_*^2 - 1.7465 \times 10^{-4}, \tag{7}$$

in S.I. units. Charnock's relation (Garratt, 1977) or Cardone's (1969) could be used here also. By using (7), which is only applicable over the ocean, we can effect a solution without specifying $z_0$. The new value $z'_0$ was compared to $z_0$ and the loop was repeated at (3) with $\zeta$ computed as

$$\zeta = \frac{g\theta_* k(\bar{z} + z'_0)}{Tu_*^2}. \tag{8}$$

The solution was complete when $z'_0$ was within 5% of $z_0$. It can be shown that the error in $u_{10}$ at this point is less than 0.5%. The loop converged very quickly, usually requiring three iterations or less. Finally, $u_{10}$ and $\theta_{10}$ were computed by

$$u_{10} = \frac{u_*}{k}\ln\left(\frac{Z}{z'_0}\right) + \psi_1(\zeta), \qquad (9)$$

$$\theta_{10} = 0.74\frac{\theta_*}{k}\ln\left(\frac{Z}{z'_0}\right) + \psi_2(\zeta) + \theta_s. \qquad (10)$$

Inclusion of the diabatic correction is most important. For example, if the ship measured a 20 m $s^{-1}$ wind at 36 m, a neutral profile yields 17.9 m $s^{-1}$ at 10 m. For a −5°C air–sea temperature difference (unstable), the correction would yield 19.8 m $s^{-1}$, while for a +5°C difference (stable) the calculated value is 14.4 m $s^{-1}$.

In spite of open-ocean conditions, several mesoscale processes were apparent in the data. The frontal passage described later is only the most dramatic of these processes. Others were probably associated with cellular convection and sub-synoptic depressions. Their presence in the data was often detectable by a step change in wind speed and/or direction at one station followed by an equivalent change one or two hours later at the next. The direction and velocity of the discontinuity was ascertained since we knew both ship and buoy position at all times. The discontinuities in most cases moved westward at velocities of ~10 m $s^{-1}$. When such processes were present and obviously biased the comparison, those samples were removed manually. Approximately 1% of the samples were rejected by this editing procedure.

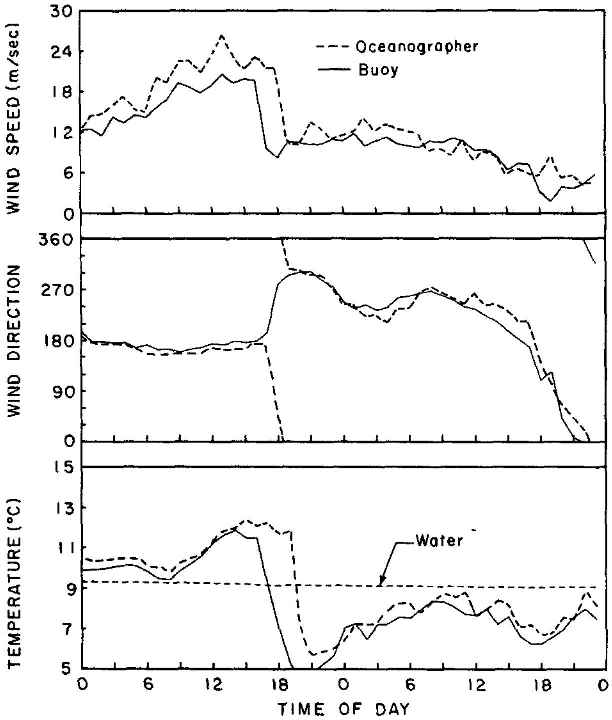

FIG. 3. A closer look at the frontal passage of 15 November 1980. Wind speed and temperature are corrected to a standard height of 10 m. The *Oceanographer* measurements are dashed lines, the buoy measurements are solid lines. The buoy-measured water temperature is shown as a dashed line.

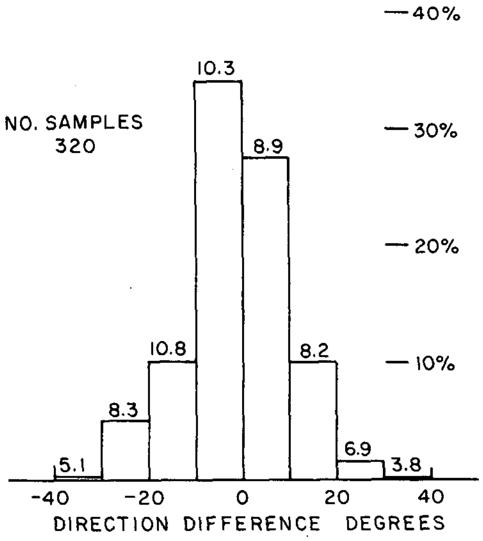

FIG. 4. Histogram of direction differences (ship − buoy). The mean difference is −3.5° and standard deviation 11°. The number above each column is average wind speed for each class and indicates improved agreement at greater wind speeds.

## 3. Results

The full time series of winds measured by the buoy is given in Fig. 2. Vector-mean wind speed remained relatively low; on only one occasion did it reach 20 m $s^{-1}$. However, the maximum wind, the "gust," was significantly higher. During most of the time period, wind directions varied from southerly to westerly in a regular manner. The mean speed oscillated from relatively low winds to stronger ones and increases appeared to lead westward shifts in direction by several hours. The above behavior suggests a series of low-pressure regions moving easterly on a trackline north of the buoy with strongest winds on the southeast portion of the depression. Around 1 December this pattern reversed with the wind shifting from northerly to easterly and back over a 2.5-day period. This shift was due to an outbreak of cold continental air from the northeast.

Ocean temperature gradually decreased from 9.5 to 7.5°C over the length of the experiment. The air temperature was usually colder than the water, even with southerly winds.

On 15 November, a dramatic front passed over the buoy. In only 2 h the wind speed changed from 20 m $s^{-1}$, 190° to 8 m $s^{-1}$, 290°. The temperature

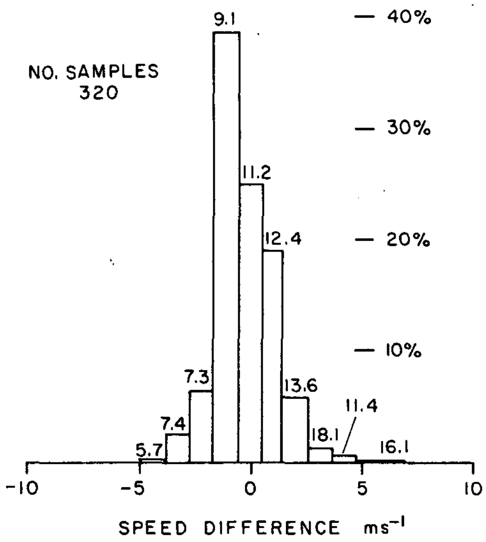

FIG. 5. Histogram of speed difference (ship − buoy). The mean difference is 0.8 m s$^{-1}$ and standard deviation 1.2 m s$^{-1}$. The numbers above the columns are the average wind speeds (m s$^{-1}$) for each class. It indicates that as wind speed increases, the ship measurement tends to exceed the buoy measurement.

dropped from 11.5 to 4.5°C. National Weather Service (NWS) maps showed no front or depression in this region for 0000 GMT 15 November, but by 1200 GMT that picture had been modified drastically; a 955 mb low was centered on the buoy with a frontal line running south from the buoy. By 0000 GMT on the 16th the front was well to the west moving at an apparent speed of 4.3 m s$^{-1}$ (Fleagle *et al.*, 1982).

A comparison of ship and buoy data for this time period (Fig. 3), indicates a frontal passage at ~1900 GMT; the NWS 1200 GMT analysis was apparently in error and should have positioned the front to the east of the buoy. The front passed the buoy first, then ~2 h later it passed the ship. The ship's location at this time suggests a frontal velocity of 6.6 m s$^{-1}$ if the front was oriented N–S.

The boundary layer was stable ($\theta > \theta_s$) before the front and unstable ($\theta < \theta_s$) after. The observed directions and temperatures agreed quite well, but interesting speed differences occurred. The speeds in Fig. 3 have been corrected to a standard height to 10 m. However, when the boundary layer was stable, the ship winds were significantly greater than the buoy winds. During the unstable period, the speeds were nearly equal. This result suggests that the body of the ship may be more effective in distorting the air flow within a stable surface layer than within an unstable one.

## 4. Discussion of ship and buoy measurements

A histogram from 320 samples of wind-direction differences, ship measurement minus buoy measurement, shows how well these two compare (Fig. 4). Even though the ship reports direction only to the nearest 10°, the mean difference was −3.5° and the standard deviation about the mean was only 11°. Absolute differences are correlated with wind speed, with better agreement at higher wind speeds. This result might not be intuitively obvious since the buoy undergoes more motion at higher winds. Apparently low persistence associated with weak winds is a more insidious source of noise.

A histogram from 320 samples of wind-speed difference also shows excellent agreement between ship and buoy measurements (Fig. 5). The mean speed difference is 0.8 m s$^{-1}$ and the standard deviation about the mean is 1.2 m s$^{-1}$. These numbers are comparable to those taken with extreme care during the GATE intercomparison. An interesting correlation exists between speed difference and speed. Apparently, with weak winds, the buoy measurement is greater than the ship. However, as the winds increase, ship measurements exceed buoy measurements.

An examination of Fig. 2 shows that the strongest winds were often associated with stable boundary-layer conditions. The blocking effect by the ship's body could explain the tendency of positive differences with higher winds. Also, higher winds are associated with higher waves, which could confuse the surface boundary layer flow and lead to a buoy-wind underestimate. Aside from calibration errors or frictional effects, no ready explanations are available for the clearcut correlation of negative difference and speed. This relation certainly must be considered in future intercomparisons.

To summarize the above research, winds measured by a vector-averaging anemometer from a toroid buoy compare well with those taken routinely by the *Oceanographer*. After the measurements were height corrected with a diabatic surface-layer model to a standard height of 10 m, a mean speed difference of 0.8 m s$^{-1}$ and standard deviation of 1.2 m s$^{-1}$ were observed. However, during periods of stable stratification, streamline crowding over the ship leads to overestimates of speed by several meters per second. During weak-wind conditions, the buoy tended to show higher speeds and there is no ready explanation for this effect. Measurements of direction were particularly close, and improve with higher winds; the mean difference was −3.5° and standard deviation 11°.

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