# A Statistical Comparison of Methods for Determining Ocean Surface Winds*

W. H. Gemmill, T. W. Yu and D. M. Feit

*National Meteorological Center, NWS, NOAA, Washington, DC*

(Manuscript received 15 November 1987, in final form 28 March 1988)

## ABSTRACT

The performance of various techniques which determine ocean surface winds using information from large-scale analyses and forecast models is discussed. The techniques evaluated are the geostrophic relation, a simple empirical law, National Meteorological Center (NMC) 1000-mb winds, a two-region analytically matched boundary layer, a two-region boundary layer based on Rossby number similarity theory, and the Fleet Numerical Oceanography Center (FNOC) marine winds. Statistical comparisons of the model winds were made with observed buoy and ship winds for wind speed, wind direction, and the vector wind. This study is based on analyses and 24-h forecasts made once a day at 0000 UTC from 3 December 1985 through 6 January 1986 on a 2.5 × 2.5 degree latitude, longitude grid.

The statistical results indicate that no one model was clearly the best. The absolute wind speed difference between all the models and observations is, on the average, about 3 m $s^{-1}$, and the RMS difference is about 4.0 m $s^{-1}$. However, the geostrophic relation was definitely the poorest, as would be expected. Model wind speeds and directions compared better with buoy data (lower RMS differences) than ship data. Furthermore, the study indicated that comparisons with buoys for wind speed were better over the northwest Atlantic than over the northwest Pacific, but the reverse was true for direction. For high wind speeds reported by ships (>22.5 m $s^{-1}$) all model winds were comparatively lower.

## 1. Introduction

Over the past 30 years, advances in operational numerical weather prediction have significantly improved the ability to forecast the large-scale synoptic features of the atmosphere. Because of computer limitations and time constraints within the operational environment, however, numerical weather prediction models must compromise horizontal and vertical resolutions as well as details of physics in order to produce timely predictions. Such atmospheric variables as wind, temperature, and moisture are computed at the midpoint of the model layers and boundary layer physics is parameterized so that depiction of the detailed structure of the atmospheric boundary layer is not possible. In order to obtain these variables at the sea surface, further considerations of boundary layer physics are necessary.

In practice, operational forecasts of surface variables use statistical regression techniques which relate the model forecast parameters to surface weather observations (Burroughs 1982). In order to apply the statistical approach, a continuous record of accurate observations at "fixed" weather stations is required. The resulting forecasts include the influence of local effects, as well as corrections for systematic forecast model errors. Unfortunately, the number of oceanic "fixed" observation platforms with sufficiently long records is limited and confined mostly to regions near the continents.

In order to develop products which provide forecasts of ocean waves, ice movement, upwelling, ocean mixing, fog, vessel icing, and boundary layer clouds, it is necessary to have accurate predictions of—among other parameters—ocean surface wind speed and direction. This study is based on statistical results for the period from 3 December 1985 to 6 January 1986 comparing observed ocean surface winds with those derived from NMC (National Meteorological Center) 1000-mb winds, FNOC (Fleet Numerical Oceanography Center) marine winds, and large-scale meteorological model fields using diagnostic methods. The term "diagnostic" is used here to categorize those methods which relate information from the large-scale meteorological analyses and forecasts to ocean surface wind speed and direction. The diagnostic models evaluated were a) the geostrophic wind, b) a simple wind law (Larson 1975), c) the boundary layer model of Cardone (1969), and d) the boundary layer model of Clarke and Hess (1975). Details of these techniques are summarized in section 2.

## 2. The techniques

The techniques used in this comparison are summarized in Table 1 and are presented below in order of complexity.

---

* Ocean Products Center contribution No. 27.

---

*Corresponding author address:* Mr. William H. Gemmill, Marine Products Branch, NOAA/NWS, World Weather Building, National Meteorological Center, Camp Springs, MD 20746.

### a. Geostrophic wind

Sea level geostrophic winds were determined from the gridded analyses and forecasts of sea level pressure and temperature.

### b. Simple law

Using a simple law, operational forecasters commonly determine ocean surface winds by simply reducing the geostrophic wind speed by a constant factor and rotating the direction toward low pressure by a constant angle. Larson (1975) proposed a slightly more complex empirical formulation in his study of time series of marine winds. In this study, the geostrophic wind was reduced to a surface wind, using a factor which is a function of latitude. The cross-isobaric angle (or inflow angle) of the wind is permitted to vary as a function of both wind speed and latitude.

TABLE 1. Summary of various diagnostic models.

| Model | Method | Theory |
|---|---|---|
| Geostrophic | Geostrophic wind | Geostrophic |
| Simple law | Geostrophic wind<br>Simple wind speed reduction<br>Simple wind direction turning | Empirical |
| NMC 1000 mb | Optimum interpolation<br>Analysis<br>Spectral model winds<br>Forecasts | OI, model |
| Cardone<br>Clarke and Hess<br>FNOC | Geostrophic wind<br>Corrected by:<br>• Air–sea temperature difference<br>• Thermal wind<br>• Friction | Two-region boundary layer<br>Constant flux<br>Ekman dynamics |

### c. NMC model 1000 mb winds

Forecasts of the 1000-mb winds were obtained from the NMC Medium Range Forecast model which was run once per day during the 0000 UTC operational cycle (Sela 1982). The initial analysis is obtained from the global data assimilation system. This model has 18 equal layers, each 28-mb thick (Dey and Monrone 1985) (Since October 1986, unequal sigma levels have been incorporated into the model, with the lowest layer having a thickness of 11 mb.) The 1000-mb winds were obtained from postprocessing the forecast model sigma-level winds to isobaric surfaces.

### d. Marine boundary layer model of Cardone

This model and the model that follows are similar in that they treat the atmospheric boundary layer as two regimes and include stability and baroclinic effects for application over the ocean. It has been shown that over the ocean the baroclinic effect (vertical wind shear) can be just as important as the stability effect (Nicholls and Reading 1979). Both models determine the surface-friction velocity and inflow angle from the surface geostrophic wind, air–sea temperature difference, and the thermal wind obtained from the large-scale numerical model. However, the mathematical approach of the two models is different.

Cardone (1969, 1978) developed a baroclinic, stability dependent, marine boundary layer model to specify ocean surface winds. The model separates the atmospheric boundary layer into a constant flux layer at the surface and an Ekman layer above. At the internal boundary between the two regions, the model requires that wind speed and direction, vertical wind shear, and stress be continuous. The governing equations are based on the equations for each region with the appropriate surface, internal and free atmosphere boundary conditions. For further details see Cardone.

### e. Marine boundary layer model of Clarke and Hess

The Clarke and Hess (1975) marine boundary layer model is based on similarity theory and has two distinct regions, an inner layer and an outer region which extends to the top of the boundary layer. The inner layer is a constant flux layer and the outer one is the Ekman layer. The equations for the two layers along with the boundary conditions are similar to the Cardone model. However, the mathematical basis of this technique is the asymptotic matching of wind from the constant flux layer to the Ekman layer through dynamic similarity scaling arguments. Full details may be found in Clarke and Hess.

Brown and Liu (1982) presented encouraging results with an operational model which essentially is also based on the Rossby similarity theory similar to Clarke and Hess but with the inclusion of secondary flow (Brown 1970). The addition of secondary flow did not result in major improvement in model performance and therefore was not used in this comparison.

### f. FNOC marine winds

The FNOC marine winds are analyzed at the ocean surface using a variational analysis method (Mihok and Kaitala 1976; L. Clark 1986, personal communication). Forecast marine winds were available directly from the Navy's global atmospheric operational forecast model.

The wind models described above were run daily for 0000 UTC from 3 December 1985 through 6 January 1986 to generate wind fields on a 2.5 by 2.5 latitude/longitude grid for analyses (meteorological variables obtained from the NMC global data assimilation system) and 24-h forecasts (obtained from the NMC spectral atmospheric forecast model). The comparison study covers 35 days of early winter conditions. During that period, 28 days of FNOC winds were available for comparison. Observations were matched with interpolated model winds for analyses and forecasts.

## 3. Sources of validation data

### a. *Ship weather reports*

Two types of observations were used as standards to measure the accuracy of the models—ship weather reports and data obtained from the NWS fixed buoy network. Meteorological observations from ships at sea are prepared by deck officers as part of their routine duties. These reports are disseminated worldwide in real time via the Global Telecommunications System (GTS).

Wind speed and direction are estimated either indirectly by the observer using the sea state and the feel of the wind or directly by anemometer if the vessel is so equipped. Estimated wind observations are subject to a wide variety of errors. Such reports are often made by the observer by first determining the wind speed parameter in terms of the Beaufort scale where each scale number represents a range of possible wind speeds. From this a single speed is chosen for reporting purposes. The scale is based, for the most part, on the appearance of the state of the sea. However, a substantial time lag may occur for the sea to reach a state that truly reflects the concurrent wind force conditions. In addition, it is obvious that nighttime wind reports based upon visual sea state observations are subject to great error. Generally less than 50% of ship reports (1980–83) from the Pacific and Atlantic oceans were from vessels without anemometers. However, Earle (1985) shows that quality of wind reports from ships with anemometers is not much better than those without. Dischel and Pierson (1986) also reported on the characteristics of ship wind observations made with and without anemometers and concluded that ship reports, with or without anemometers, are inferior to buoy measurements. Errors from anemometer measurements can be introduced by poor instrument exposure, improper reading of the wind speed and direction indicators, and vessel motion.

In spite of the fact that ship reports are not as accurate as buoy reports, they have oceanwide coverage. Therefore, ship reports are included in the comparisons. Ship wind observations were collected from reports transmitted over the GTS, which have been processed at NMC with only minimal quality control error checking. No distinction is made between estimated or measured reports. For measured winds there is no correction for varying anemometer heights.

### b. *Fixed buoy reports*

Since 1967 moored buoys, equipped with meteorological instruments, have provided surface atmospheric and oceanographic data. Buoys can be expected to provide improved data compared to those reported by ships for several reasons. First, each sensor location is carefully considered to avoid exposure problems. Second, measurement sampling frequencies and averaging periods are determined after accounting for buoy motion. Third, duplicate sensors are used and each is calibrated before deployment. Finally, all data are monitored in near-real time to detect instrument errors. Gilhousen (1987) reported that the buoys are presently providing measurements which are within the original accuracy specifications. The National Data Buoy Center stated system accuracy for winds, averaged for 8.5 min, requires the speed to be within a standard deviation of $\pm 1.0$ m s$^{-1}$ and the direction to be within $\pm 10$ deg.

## 4. Statistical procedures

The statistical comparisons are made for wind speed, wind direction, and vector wind for both analyses and 24-h forecasts with ship and buoy data. Standard statistical measures were used to compare and evaluate the models with observations. Willmott (1982) discussed the use of statistical difference measures to evaluate model performance and concluded that no one measure can be expected to provide complete information for evaluation. In this study we used statistical difference measures similar to the set described in his paper. However, since wind is a vector, additional vector statistical measures have been included.

The measures used for this study are given by the following definitions:

### a. *Wind speed and wind direction*

- Average absolute difference:

$$\sum |V_m - V_o|/N$$

- Average algebraic difference (bias):

$$\sum (V_m - V_o)/N$$

- and the root-mean-square difference:

$$[\sum (V_m - V_o)^2/N]^{1/2}$$

where

$V_o$ observed wind speed or direction
$V_m$ model wind speed or direction
$N$ number of comparisons

### b. *Vector wind*

- Average vector wind difference

$$\sum [(u_m - u_o)^2 + (v_m - v_o)^2]^{1/2}/N$$

- The root-mean-square vector wind difference:

$$\{\sum[(u_m - u_o)^2 + (v_m - v_o)^2]/N\}^{1/2}$$

where

$u$ the eastward component of the wind
$v$ the northward component
$m$ for model
$o$ for observed

A wind-vector correlation coefficient was calculated using the formulation developed by Court (1958). In this formulation, the correlation between two sets of wind vectors, $W_1$ and $W_2$, can be determined by a combination of expressions containing the scalar wind components. The wind vector $W_1$ is composed of a component ($u_1$) toward the east and ($v_1$) toward the north, and the wind vector $W_2$ is composed of similar components ($u_2$) and ($v_2$). The following expression has been used to determine the wind vector correlation coefficient ($RW_1W_2$):

$$RW_1W_2 = \{[Sv_2{}^2(Su_1{}^2u_2 + Sv_1{}^2u_2) + Su_2{}^2(Su_1{}^2v_2 + Sv_1{}^2v_2) - 2Su_2v_2(Su_1u_2Su_1v_2 + Sv_1u_2Sv_1v_2)]/[(Su_1{}^2 + Sv_1{}^2)(Su_2{}^2Sv_2{}^2 - Su_2{}^2v_2)]\}.$$

The terms in the above expression are defined as follows:

$$Su_1{}^2 = \sum(u_1 - \bar{u}_1)^2/N,$$

$$Su_1v_2 = \sum(u_1 - \bar{u}_1)(v_2 - \bar{v}_2)/N).$$

## 5. Discussion

This study considers wind reported from ships and buoys as two different datasets in order to understand characteristics of each. The ship data coverage is fairly uniform over the North Pacific and North Atlantic oceans especially above 20°N, and over the Gulf of Mexico. The mean wind speed for the ship data over the study period is 10.1 m s$^{-1}$. The buoy data coverage is limited to offshore areas adjacent to United States coastlines. The mean wind speed for the buoy data was 7.4 m s$^{-1}$. The distribution of wind speeds at 1 m s$^{-1}$ intervals is presented in Table 2. This table suggests that the buoys and ships are not necessarily in the same weather regimes as indicated by the difference in the distributions. The lower mean wind speeds at the buoys and the lack of high wind speeds over 22 m s$^{-1}$ strongly suggest that ships transiting the high seas were more likely to encounter high wind events than the fixed buoy network close to the North American continent.

Ships reporting high wind speeds were subjectively compared with the Northern Hemisphere surface analysis to determine whether the reports were reasonable. It was found that a few of the high wind speed reports (>22.5 m s$^{-1}$) were obviously erroneous when compared to synoptic analyses and should be rejected. Some other reports were located in regions of active small-scale meteorological events, such as frontal zones, squalls and extremely intense cyclones, which the large-scale analysis and forecast grid (2.5 × 2.5 degrees of latitude and longitude) cannot resolve. Since the purpose of this study was to investigate how well the various techniques produce ocean surface winds using large-scale models, and not how well the models handle subgrid meteorological systems, those wind reports were also eliminated.

Comparisons of model winds with observations are presented for wind speed (Table 3), wind direction (Table 4), and vector wind (Table 5), for both analyses

TABLE 2. Data distribution by ships and buoys at intervals of 1 m s$^{-1}$ such that the wind speed is the truncated speed (for example, 5 is the range 5 to <6 m s$^{-1}$, 6 is 6 to <7 m s$^{-1}$, etc.). Mean wind speed for ships is 10.1 m s$^{-1}$ with standard deviation of 5.4 m s$^{-1}$. Mean wind speed for buoys is 7.4 m s$^{-1}$ with standard deviation of 3.4 m s$^{-1}$.

| Wind speed | Ships (%) | Buoys (%) |
|---|---|---|
| Calm | 151 (1.1) | 14 (1.6) |
| >0 | 17 (0.1) | 3 (0.3) |
| >1 | 198 (1.4) | 22 (2.5) |
| 2 | 435 (3.1) | 33 (3.8) |
| 3 | 513 (3.7) | 47 (5.4) |
| 4 | 770 (5.6) | 56 (6.5) |
| 5 | 919 (6.6) | 95 (10.9) |
| 6 | 1081 (7.8) | 112 (12.9) |
| 7 | 1106 (8.0) | 99 (11.4) |
| 8 | 1324 (9.6) | 145 (16.7) |
| 9 | 1107 (8.0) | 77 (8.9) |
| 10 | 1049 (7.6) | 48 (5.5) |
| 11 | 769 (5.6) | 35 (4.8) |
| 12 | 943 (6.8) | 40 (4.6) |
| 13 | 626 (4.5) | 18 (2.1) |
| 14 | 479 (3.4) | 7 (0.8) |
| 15 | 659 (4.6) | 6 (0.7) |
| 16 | 180 (1.3) | 1 (0.1) |
| 17 | 322 (2.3) | 4 (0.5) |
| 18 | 346 (2.5) | 3 (0.3) |
| 19 | 218 (1.6) | 2 (0.2) |
| 20 | 224 (1.6) | 0 (0) |
| 21 | 85 (0.6) | 0 (0) |
| 22 | 69 (0.5) | 1 (0.1) |
| 23 | 95 (0.7) | — |
| 24 | 46 (0.3) | — |
| 25 | 36 (0.3) | — |
| 26 | 28 (0.2) | — |
| 27 | 19 (0.1) | — |
| 28 | 14 (0.1) | — |
| 29 | 16 (0.1) | — |
| 30 | 10 (0.1) | |
| 31 | 6 (<0.1) | |
| 32 | 4 (<0.1) | |
| 33 | 0 (0) | |
| 34 | 1 (<0.1) | |
| 35 | 3 (<0.1) | |
| 36 | 0 (0) | |
| 37 | 1 (<0.1) | |
| 38 | | |
| 39 | | |

TABLE 3. Ship/buoy vs model comparisons (model minus observation) for wind speed (m s$^{-1}$) for the Northern Hemisphere (NH), West Coast (WC), and East Coast (EC).

| | | Analyses | | | | | | | | | 24-h forecasts | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Avg. abs. diff.* | | | Avg. alg. diff.** | | | RMSD† | | | Avg. abs. diff. | | | Avg. alg. diff. | | | RMSD | | |
| Model | | NH | WC | EC | NH | WC | EC | NH | WC | EC | NH | WC | EC | NH | WC | EC | NH | WC | EC |
| Geostrophic: | Ship | 3.8 | 4.0 | 3.4 | 0.9 | 1.7 | −0.6 | 5.0 | 5.2 | 4.5 | 4.2 | 4.6 | 3.7 | 1.0 | 1.7 | 0.0 | 5.5 | 5.9 | 4.9 |
| | Buoy | 3.5 | 4.9 | 2.7 | 2.3 | 4.3 | 1.6 | 4.6 | 6.1 | 3.5 | 3.9 | 4.9 | 4.0 | 2.5 | 4.0 | 2.8 | 5.1 | 6.3 | 5.3 |
| Simple law: | Ship | 3.4 | 3.2 | 3.7 | −1.5 | −0.9 | −2.5 | 4.5 | 4.2 | 4.8 | 3.8 | 3.8 | 3.7 | −1.4 | −0.9 | −2.1 | 4.9 | 5.0 | 4.0 |
| | Buoy | 2.4 | 2.9 | 2.0 | 0.2 | −1.8 | −0.3 | 3.1 | 3.7 | 2.5 | 2.9 | 3.3 | 2.8 | 0.3 | 1.6 | 0.7 | 3.7 | 4.2 | 3.5 |
| NMC 1000 mb: | Ship | 3.4 | 3.5 | 3.4 | 0.6 | 1.4 | 0.0 | 4.5 | 4.6 | 4.0 | 3.6 | 3.9 | 3.3 | −0.0 | 0.6 | −0.2 | 4.8 | 5.1 | 4.4 |
| | Buoy | 3.1 | 4.0 | 2.5 | 2.1 | 3.6 | 1.5 | 4.0 | 5.0 | 3.2 | 3.3 | 4.2 | 3.4 | 2.1 | 3.2 | 2.6 | 4.3 | 5.3 | 4.5 |
| Cardone: | Ship | 3.7 | 3.6 | 3.9 | −2.1 | −2.0 | −2.9 | 4.8 | 4.7 | 5.1 | 3.8 | 3.7 | 3.7 | −2.2 | −2.1 | −2.5 | 4.9 | 4.9 | 4.8 |
| | Buoy | 2.5 | 2.9 | 2.2 | −0.2 | 0.6 | −0.1 | 3.2 | 3.2 | 2.9 | 2.6 | 2.5 | 2.4 | −0.3 | 0.3 | 0.6 | 3.3 | 3.1 | 3.0 |
| Clarke and Hess: | Ship | 3.3 | 3.0 | 3.4 | −1.0 | 0.6 | −1.6 | 4.3 | 4.0 | 4.1 | 3.6 | 3.5 | 3.4 | −1.3 | −1.0 | −0.9 | 4.7 | 4.9 | 4.4 |
| | Buoy | 2.5 | 3.1 | 1.9 | 0.6 | 2.3 | 0.6 | 3.2 | 3.9 | 2.5 | 2.6 | 2.8 | 2.6 | 0.4 | 1.4 | 1.1 | 3.4 | 3.6 | 3.2 |
| FNOC: | Ship | 3.1 | 3.0 | 2.9 | −0.5 | 0.0 | −1.6 | 4.1 | 4.0 | 4.0 | 3.8 | 3.8 | 4.2 | −1.3 | −1.0 | −2.2 | 4.9 | 4.9 | 5.4 |
| | Buoy | 2.3 | 3.1 | 1.8 | 0.9 | 2.3 | 0.5 | 3.2 | 4.2 | 2.6 | 3.1 | 3.3 | 3.3 | 0.3 | 1.4 | 0.2 | 3.9 | 4.1 | 3.9 |

* Average absolute difference
** Average algebraic difference
† Root mean square difference

TABLE 4. Ship/buoy vs model comparisons (model minus observation) for wind direction (degrees) for the Northern Hemisphere (NH), West Coast (WC), and East Coast (EC). The inflow angle is identified as the average algebraic difference under geostrophic model.

| | | Analyses | | | | | | | | | 24 h forecasts | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Avg. abs. diff.* | | | Avg. alg. diff.** | | | RMSD† | | | Avg. abs. diff. | | | Avg. alg. diff. | | | RMSD | | |
| Model | | NH | WC | EC | NH | WC | EC | NH | WC | EC | NH | WC | EC | NH | WC | EC | NH | WC | EC |
| Geostrophic: | Ship | 30 | 27 | 32 | 21 | 16 | 24 | 37 | 34 | 39 | 37 | 37 | 35 | 17 | 15 | 18 | 49 | 50 | 45 |
| | Buoy | 31 | 24 | 36 | 24 | 17 | 34 | 38 | 31 | 42 | 35 | 33 | 32 | 18 | 11 | 26 | 45 | 45 | 38 |
| Simple law: | Ship | 23 | 22 | 24 | 2 | −2 | 5 | 31 | 30 | 32 | 32 | 34 | 29 | −2 | 2 | −1 | 46 | 47 | 42 |
| | Buoy | 22 | 18 | 23 | 5 | 0 | 14 | 30 | 26 | 29 | 28 | 31 | 21 | −1 | −6 | 8 | 40 | 44 | 29 |
| NMC 1000 mb: | Ship | 21 | 21 | 24 | 4 | 3 | 3 | 29 | 29 | 32 | 32 | 33 | 30 | −4 | 0 | 2 | 46 | 48 | 42 |
| | Buoy | 19 | 17 | 17 | 4 | 5 | 6 | 27 | 25 | 22 | 28 | 31 | 21 | −3 | −1 | 3 | 40 | 44 | 29 |
| Cardone: | Ship | 23 | 22 | 24 | 5 | 2 | 8 | 30 | 30 | 24 | 32 | 34 | 29 | 2 | 0 | 2 | 46 | 47 | 41 |
| | Buoy | 21 | 18 | 21 | 6 | 3 | 15 | 29 | 26 | 26 | 28 | 30 | 20 | 1 | −4 | 0 | 40 | 44 | 28 |
| Clarke and Hess: | Ship | 23 | 22 | 24 | 2 | −3 | 6 | 31 | 30 | 32 | 32 | 33 | 29 | −2 | −5 | 1 | 45 | 48 | 41 |
| | Buoy | 21 | 19 | 17 | 2 | −2 | 14 | 29 | 26 | 24 | 28 | 31 | 21 | −3 | −11 | 7 | 41 | 45 | 28 |
| FNOC: | Ship | 21 | 20 | 21 | 1 | −1 | 5 | 29 | 29 | 31 | 37 | 38 | 40 | 3 | 0 | 9 | 52 | 54 | 54 |
| | Buoy | 18 | 16 | 17 | 3 | 0 | 12 | 26 | 23 | 24 | 40 | 37 | 43 | 6 | 0 | 19 | 55 | 53 | 59 |

* Average absolute difference
** Average algebraic diffference
† Root mean square difference

TABLE 5. Ship/buoy vs model comparisons (model minus observation) for wind vector (m s$^{-1}$) for the Northern Hemisphere (NH), West Coast (WC), and East Coast (EC).

| Model | | Analyses | | | | | | | | | 24-h forecasts | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Vector correlation | | | Vector diff. magn. | | | Vector diff. rms | | | Vector correlation | | | Vector diff. magn. | | | Vector diff. rms | | |
| | | NH | WC | EC | NH | WC | EC | NH | WC | EC | NH | WC | EC | NH | WC | EC | NH | WC | EC |
| Geostrophic: | Ship | 0.72 | 0.75 | 0.70 | 7.4 | 7.3 | 7.0 | 9.1 | 9.0 | 8.7 | 0.65 | 0.62 | 0.64 | 8.1 | 8.6 | 7.4 | 9.8 | 10.5 | 9.2 |
| | Buoy | 0.73 | 0.82 | 0.79 | 6.4 | 6.1 | 6.2 | 7.7 | 7.8 | 7.5 | 0.69 | 0.71 | 0.78 | 6.8 | 7.3 | 6.5 | 8.1 | 8.7 | 7.9 |
| Simple law: | Ship | 0.72 | 0.74 | 0.68 | 5.7 | 5.5 | 5.8 | 7.2 | 7.0 | 7.3 | 0.64 | 0.61 | 0.62 | 6.7 | 7.0 | 6.3 | 8.2 | 8.7 | 7.9 |
| | Buoy | 0.74 | 0.83 | 0.80 | 4.4 | 4.2 | 4.1 | 5.5 | 5.0 | 4.8 | 0.69 | 0.71 | 0.79 | 5.0 | 5.4 | 4.3 | 6.1 | 6.3 | 5.1 |
| NMC 1000 mb: | Ship | 0.76 | 0.77 | 0.73 | 5.8 | 5.9 | 5.4 | 7.4 | 7.5 | 7.1 | 0.66 | 0.62 | 0.65 | 6.8 | 7.4 | 6.3 | 8.4 | 9.1 | 8.0 |
| | Buoy | 0.79 | 0.84 | 0.83 | 4.7 | 5.3 | 3.9 | 5.8 | 6.1 | 4.6 | 0.70 | 0.70 | 0.78 | 5.6 | 6.4 | 5.1 | 6.8 | 7.4 | 6.0 |
| Cardone: | Ship | 0.70 | 0.72 | 0.67 | 5.8 | 5.6 | 5.7 | 7.1 | 7.0 | 7.1 | 0.64 | 0.61 | 0.62 | 6.5 | 6.7 | 6.1 | 7.9 | 8.2 | 7.7 |
| | Buoy | 0.73 | 0.81 | 0.79 | 4.2 | 3.7 | 3.8 | 5.3 | 4.4 | 4.6 | 0.69 | 0.71 | 0.80 | 4.6 | 4.5 | 3.8 | 5.6 | 5.4 | 4.4 |
| Clarke and Hess: | Ship | 0.72 | 0.74 | 0.70 | 5.7 | 5.6 | 5.5 | 7.2 | 7.1 | 7.0 | 0.64 | 0.62 | 0.63 | 6.5 | 6.8 | 6.1 | 8.0 | 8.4 | 7.8 |
| | Buoy | 0.74 | 0.82 | 0.80 | 4.4 | 4.5 | 3.6 | 5.5 | 5.3 | 4.2 | 0.69 | 0.72 | 0.78 | 4.9 | 5.0 | 4.1 | 5.9 | 5.9 | 4.7 |
| FNOC: | Ship | 0.75 | 0.76 | 0.72 | 5.3 | 5.2 | 5.0 | 6.9 | 6.9 | 6.8 | 0.60 | 0.59 | 0.49 | 7.1 | 7.3 | 7.5 | 8.6 | 8.9 | 8.9 |
| | Buoy | 0.78 | 0.84 | 0.85 | 3.9 | 4.3 | 3.3 | 5.3 | 5.3 | 4.3 | 0.59 | 0.62 | 0.62 | 5.9 | 5.9 | 6.0 | 6.9 | 6.8 | 6.7 |

and 24-h forecasts. The tables separate the data by type (ship and buoy) and by region [Northern Hemisphere (>17°N), East Coast (25°N to 50°N, the coast out to 55°W), and West Coast (20°N to 65°N, 180°W to the coast)]. The data used to produce these tables do not include reports within 50 km of land or data over lakes.

Inspection of the tables indicates that no one model is superior to the others in all respects. However, a few general comments can be made concerning the statistics. Three of the techniques, the simple law, the Cardone model and the Clarke and Hess model, are most consistently similar to one another for both analyses and forecasts. The models verify better against the buoys than ships. This is not unexpected; reports from fixed buoys are closely monitored and quality controlled in order to provide reliable data (Gilhousen 1987). Wind reports from ships are taken with a wide range of observing systems and the quality of those observations has been shown to be less than buoys (Dischell and Pierson 1986; Earle 1985).

The models verify better with the East Coast buoys than with West Coast buoys. This reflects a relatively poorer quality analysis from NMC's Global Data Analyses System over the northeast Pacific compared with the northwest Atlantic. This is not the case with ship reports which, if anything, are slightly poorer.

Comparisons of the analyses of model wind speeds with buoys (Table 3) shows that the geostrophic wind speeds are too high by 2.3 m s$^{-1}$ and have an RMS difference of 4.6 m s$^{-1}$. The 1000-mb wind speeds are also high by 2.1 m s$^{-1}$ with a RMS difference of 4.0 m s$^{-1}$. The diagnostic models do reduce the wind speed in agreement with theory, but the model performance statistics do not indicate which of the models is best.

When comparing the 24-h wind speed forecasts with buoys (Table 3), the model performances show a slight deterioration. Excluding the geostrophic wind, the analyses wind speed RMS differences ranged from 3.1 to 4.0 m s$^{-1}$, and the 24-h forecasts RMS differences ranged from 3.3 to 4.4 m s$^{-1}$.

Comparison of the wind directions indicates almost no difference between models (Table 4). The model wind directions show consistent improvement over the geostrophic wind direction when compared to buoys (and ships). The RMS difference between the geostrophic winds and buoys was 38 deg, whereas the models ranged from 26 to 31 deg. However, the models do not turn the winds enough, especially for the large inflow angles observed along the East Coast. The 24-h forecoast RMS differences range from 40 to 55 deg. Forecasts along the East Coast (RMS difference 29 deg) were better than for the West Coast (RMS difference 44 deg), excluding FNOC winds and geostrophic winds.

These statistics point out several problems concerning the evaluation of wind direction from the models. The turning of the ocean surface wind from geostrophic

TABLE 6. Ship/buoy vs model (analyses). Comparisons of biases (model minus observation) vs various wind speeds (m s$^{-1}$).

| Model | | Algebraic speed differences | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 0–45 | 0–5 | 5–10 | 10–15 | 15–22.5 | 22.5–30 | 30–45 |
| Geostrophic: | Ship | 0.9 | 2.6 | 1.3 | 0.7 | −0.4 | −3.8 | −16.1 |
| | Buoy | 2.3 | 2.0 | 2.1 | 3.6 | 0.7 | — | — |
| Simple law: | Ship | −1.5 | −1.4 | −0.6 | −2.1 | −4.1 | −8.4 | −19.3 |
| | Buoy | 0.2 | 1.0 | 0.0 | 0.2 | −3.4 | — | — |
| NMC 1000 mb: | Ship | 0.7 | 2.3 | 1.3 | 0.7 | −1.1 | −5.3 | −17.8 |
| | Buoy | 2.1 | 2.0 | 2.1 | 2.6 | −2.2 | — | — |
| Cardone: | Ship | −2.1 | 1.1 | −1.0 | −2.9 | −5.6 | −11.1 | −21.0 |
| | Buoy | −0.2 | 0.8 | −0.2 | −0.5 | −5.3 | — | — |
| Clarke and Hess: | Ship | −1.0 | 2.0 | 0.0 | −1.7 | −4.4 | −8.7 | −20.1 |
| | Buoy | 0.6 | 1.7 | 0.6 | 0.0 | −2.7 | — | — |
| FNOC: | Ship | −0.5 | 1.8 | 0.2 | −1.0 | −2.8 | −7.0 | −17.3 |
| | Buoy | 0.9 | 1.2 | 0.9 | 1.1 | −1.9 | — | — |

(the inflow angle) is on the order of 10 to 30 deg. This is small when compared with the natural variability of the wind and the errors in its reported value. Wind directions are reported to the nearest 10 deg and the fixed buoy sensor accuracy is ±10 deg. Although the absolute wind direction can be determined reasonably accurately, the inflow angle correction is small when compared with the uncertainty of the wind direction measurement. Therefore, it is difficult to differentiate model performance on the basis of wind direction errors. The statistics indicate that the model directions are a slight improvement over the geostrophic direction.

The comparison of the wind vector errors (Table 5) shows that the FNOC wind analyses provide slightly smaller errors when compared with buoys than the other models (vector RMS difference was 5.3 m s$^{-1}$). The vector RMS difference is largest for geostrophic winds when compared with buoys (RMS difference was 7.7 m s$^{-1}$), whereas the range for the other models was 5.5 to 6.3 m s$^{-1}$. For 24-h forecasts the vector RMS difference was 8.1 m s$^{-1}$ for geostrophic winds and ranged from 5.6 m s$^{-1}$ to 6.9 m s$^{-1}$ for the diagnostic models, with Cardone wind forecasts slightly better (vector RMS difference is 5.6 m s$^{-1}$, which is lowest) than the other models.

Table 6 identifies model performance in terms of whether the model is over- or underspecifying the wind speed as a function of wind speed. At high wind speeds (above 15 m s$^{-1}$) the mean model speeds begin to deviate from the mean buoy speeds, with Cardone underspecifying the wind the most. Although at speeds above 22.5 m s$^{-1}$ no buoy observations were available for comparison, ship speeds are much larger than the model wind speed. The large-scale models seem to be incapable of specifying the high wind speeds. The discrepancy between models and observations at those high speeds is related to the coarse resolution (2.5 × 2.5 deg grid) of the analyses and forecast fields on one hand, and the tendency for observers to overestimate high winds on the other. The extreme low model bias at high ship wind speeds (30 to 45 m s$^{-1}$) indicates that there is still a problem of identifying and eliminating erroneous ship reports in this study.

## 6. Concluding remarks

The statistical results in this study suggest that no one model is clearly the best. Absolute wind speed difference between all the models and observations is, on the average, about 3 m s$^{-1}$ with an RMS difference of near 4 m s$^{-1}$. On the other hand, the geostrophic relation was definitely poorest. Model wind speeds and directions compared better with buoy data (lower RMS differences) than ship data. The study indicated that comparisons with buoys for wind speed were better over the northwest Atlantic than over the northeast Pacific, but the reverse was true for direction. For high wind speeds observed by ships (>22.5 m s$^{-1}$) all model winds were too low.

The results of this study further point out the difficulty of specifying winds over the oceans using boundary layer models with limited physics and reduced vertical resolution and verifying those winds without accurate measurements at sea. The future lies in generating ocean surface wind fields using more complex boundary layer formulation schemes. At present, the lowest layer in the NMC model is only 11 mb thick. Future models will probably have even a thinner lowest layer, thereby eliminating the need for special boundary layer models. The data issue will have to wait for satellite measurements to provide a comprehensive coverage of the global oceans.

*Acknowledgments.* The authors are indebted to D. B. Rao for many helpful suggestions as well as his valuable critical review of the manuscript.

### REFERENCES

Brown, R. A., 1970: A secondary flow model for the planetary boundary layer. *J. Atmos. Sci.*, **27**, 742–757.

——, and W. T. Liu, 1982: An operational large-scale marine planetary boundary layer model. *J. Appl. Meteor.*, **21**, 261–269.

Burroughs, L. D., 1982: Great Lakes near shore wind predictions from Great Lakes MOS wind guidance. NOAA Tech. Memo., NWS TDL 74, 21 pp.

Cardone, V. J., 1969: Specification of the wind field distribution in the marine boundary layer for wave forecasting. Rep. TR-69-1, Geophysics Science Laboratory, New York University, 131 pp. [NTIS AD #702-490.]

——, 1978: Specification and prediction of the vector wind on United States continental shelf for applications to an oil slick trajectory forecast program. Final Rep., Contract T-35430, The City College of the City University of New York, 96 pp.

Clarke, R. H., and G. D. Hess, 1975: On the relation between surface wind and pressure gradient, especially in lower latitudes. *Bound.-Layer Meteor.* **9,** 325–339.

Court, A., 1958: Wind correlation and regression. Sci. Rep. 3, Contract Af19(604)-2060, AFCRC, Hanscom Field, Bedford, Mass., 16 pp.

Dey, C. H., and L. L. Morone, 1985: Evolution of the National Meteorological Center global data assimilation system: January 1982–December 1983. *Mon. Wea. Rev.,* **113,** 304–317.

by ships and data buoys. *Proc. MDS '86, Marine Data Systems Int. Symp.,* Marine Tech. Soc., New Orleans, 447–466.

Earle, M. D., 1985: Statistical comparisons of ship and buoy data marine observations. Rep. MEC-85-8, MEC Systems Corporation, Manassas, Virginia, 43 pp.

Gilhousen, D. B., 1987: A field evaluation of NDBC moored buoy winds. *J. Atmos. Oceanic Technol.* **4,** 94–104.

Larson, S. E., 1975: A 26-year time series of monthly mean winds over the ocean. Part 1: A statistical verification of computed surface winds over the North Pacific and North Atlantic. Tech. Pap. No. 8-75, Environmental Prediction Research Facility, Naval Postgraduate School, Monterey, 89 pp.

Mihok, W. F., and J. E. Kaitala, 1976: U.S. Navy Fleet Numerical Weather Central operational five-level global fourth-order primitive-equation model. *Mon. Wea. Rev.,* **104,** 1528–1550.

Nicholls, S., and C. J. Reading, 1979: Aircraft observations of the structure of the lower boundary layer over the sea. *Quart. J. Roy. Meteor. Soc.,* **105,** 785–802.

Sela, J. G., 1982: The NMC spectral model. NOAA Tech. Rep. NWS-30, U.S. Dept. of Commerce, NOAA, NWS, Washington DC.

Willmott, C. J., 1982: Some comments on the evaluation of model performance. *Bull. Amer. Meteor. Soc.,* **63,** 1309–1313.