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TECHNICAL NOTE*

NATIONAL MARINE VERIFICATION PROGRAM - VERIFICATION STATISTICS

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OPC CONTRIBUTIONS

No. 1. Burroughs, L. D., 1986: Development of Forecast Guidance for Santa Ana Conditions. National Weather Digest, Vol. 12 No. 1, 8pp.

No. 2. Richardson, W. S., D. J. Schwab, Y. Y. Chao, and D. M. Wright, 1986: Lake Erie Wave Height Forecasts Generated by Empirical and Dynamical Methods -- Comparison and Verification. Technical Note, 23pp.

No. 3. Auer, S. J., 1986: Determination of Errors in LFM Forecasts Surface Lows Over the Northwest Atlantic Ocean. Technical Note/NMC Office Note No. 313, 17pp.

No. 4. Rao, D. B., S. D. Steenrod, and B. V. Sanchez, 1987: A Method of Calculating the Total Flow from A Given Sea Surface Topography. NASA Technical Memorandum 87799., 19pp.

No. 5. Feit, D. M., 1986: Compendium of Marine Meteorological and Oceanographic Products of the Ocean Products Center. NOAA Technical Memorandum NWS NMC 68, 93pp.

No. 6. Auer, S. J., 1986: A Comparison of the LFM, Spectral, and ECMWF Numerical Model Forecasts of Deepening Oceanic Cyclones During One Cool Season. Technical Note/NMC Office Note No. 312, 20pp.

No. 7. Burroughs, L. D., 1987: Development of Open Fog Forecasting Regions. Technical Note/NMC Office Note. No. 323., 36pp.

No. 8. Yu, T. W., 1987: A Technique of Deducing Wind Direction from Satellite Measurements of Wind Speed. Monthly Weather Review, 115, 1929-1939.

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No. 12. Feit, D. M., 1987: Forecasting Superstructure Icing for Alaskan Waters. National Weather Digest, 12, 5-10.

No. 13. Sanchez, B. V., D. B. Rao, S. D. Steenrod, 1987: Tidal Estimation in the Atlantic and Indian Oceans. Marine Geodesy, 10, 309-350.

No. 14. Gemmill, W.H., T.W. Yu, and D.M. Feit 1988: Performance of Techniques Used to Derive Ocean Surface Winds. Technical Note/NMC Office Note No. 330, 34pp.

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No. 16. Yu, T.W., 1988: A Method for Determining Equivalent Depths of the Atmospheric Boundary Layer Over the Oceans. Journal of Geophysical Research, 93, 3655-3661.

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NATIONAL MARINE VERIFICATION PROGRAM -

Verification Statistics

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Abstract. The Marine Prediction Branch of the National Meteorological Center has the responsibility to run the National Marine Verification Program. This note describes the forecast elements to be verified and the statistics used for the verification. Four elements are verified: Small Craft Advisories and warnings, wind direction, wind speed, and wave height. Periodic reports will be generated, and the data will be sent to the participating forecast offices to be used for local purposes.

Brief descriptions of the statistics used are given in the text, while full derivations are given in an appendix.

The application of the statistics to each element is described, and examples of the data sheets for each element are provided. Examples of comparitive statistics are also shown.

Future enhancements of the program are also described. Currently, only three forecast offices are included. Eventually all offices with marine responsibility will be included. More forecast elements will be added, and the High Seas forecasts as well as the Coastal and Offshore forecasts will be verified.

I. INTRODUCTION

The Marine Prediction Branch (MPB) of the National Meteorological Center (NMC) has taken the responsibility to run the National Marine Verification Program (NMVP). Burroughs and Nichols (1993) describes the concepts used in the program and the data management.

The NMVP is based on the comparison of WSFO operational and MPB guidance forecasts for selected data buoys and Coastal Marine Automated Network (C-MAN) stations with the observations from these stations. These "point" forecasts are derived from the operational and guidance forecasts with the assumption that they are fairly representative of wind, wave and warning conditions for the forecast area or subset thereof. A Marine Verification Matrix (MVM) is produced by MPB containing 2 coded forecasts per day issued by the WSFOs for the buoy and C-MAN stations; MPB guidance forecasts interpolated to these stations; and the observations. The MVM collates the forecast and observed elements for 2 verification times, 0600 UTC and 1800 UTC. The NMVP statistics are then produced from the MVMs.

The statistical derivations are based on a series of 5 hourly observations from the buoy and C-MAN stations centered on the two verification times. This approach makes the verification results more consistent with operational forecasts that predict conditions over a period of time and, thus, helps to measure performance from a user perspective.

This note describes the forecast elements to be verified in the NMVP and the statistics used to evaluate each element. Within the context of this note, forecast refers to the forecast bulletin issued by a WSFO, and element refers to the meteorological phenominon being forecast. Four forecast elements are verified: Small Craft Advisories (SCA) and warnings, wind direction, wind speed, and wave height. Periodic reports (currently semi-annually) will be made to show results for all WSFOs combined and for each coast or region. The data will also be sent to the participating WSFOs to be used for local purposes.

Section II gives a brief description of the statistics used in the NMVP.

The third section explains the statistics used to evaluate the verification of each element. Examples of the data sheets for each element are given, and some samples of the type of comparative statistics which can be derived from the data sheets are also provided. Data sheets are shown for both the WSFO forecasts and the MPB guidance.

The final section covers future enhancements of the NMVP. More WSFOs will be added in mid-1993. As a result of modernization and restructuring, more Weather Forecast Offices (WFO) will be added, and the NMVP will be redefined. Additional guidance products will be included for comparison with forecasts. The High Seas forecasts may be added, and more forecast elements may be included.

Definitions and abbreviations are given with the first mention in the text and are listed for convenience in Appendix A. Full derivations of the formulae used to compute the statistics are presented in Appendix B. This is done for those who wish to program the formulations for computing local statistics.

II. VERIFICATION STATISTICS

Two types of verification statistics are employed: the classic type of statistic which results in a single value and those which depend on contingency tables/performance matrices for their derivation. The first set of statistics include forecast and observed mean, mean error (ME) (sometimes referred to as the bias), root mean square error ($RMSE$), mean vector error (MVE), and the frequency distribution of errors (described in detail in the Section III). Although, these single valued statistics give numbers which are easy to display and compare, they provide little detail for further analysis.

All other evaluation statistics are computed from the information contained in performance matrices. For the wind speed and wave height, 7 x 7 performance matrices are used. The wind categories (in knots) are: < 8, 8-12, 13-17, 18-22, 23-27, 28-32, and > 32; while the wave height categories (in feet) are: < 3, 3-5, 6-8, 9-12, 13-16, 17-20, and > 20. For the wind direction, an 8 x 8 performance matrix is used since an 8 point compass is used, *i.e.,* North (N), Northeast (NE), East (E), Southeast (SE), South (S), Southwest (SW), West (W), and Northwest (NW). Warning category statistics have two performance matrices: one for coastal forecast points and another for offshore forecast points. Coastal points have 4 categories: None, SCA, Gale, Storm; or None, SCA, Tropical Storm, Hurricane. Offshore points have 3 categories: None, Gale, Storm; or None, Tropical Storm, Hurricane. In general, the tropical storm and hurricane performance matrices have too little data for statistical stability, so the forecasts and guidance are evaluated on a case by case basis.

In the evaluation procedure, we have replaced the conventional threat score with the Equitable Skill Score (ESS) (Gandin and Murphy, 1992). The Threat Score (Gilbert, 1884) is generally used to verify rare events. Murphy and Daan (1985) consider it to be a less satisfactory score than other skill scores because "two forecasters with exactly the same judgmental probability distribution might issue different forecasts (for the same situation) because they possess disparate 'forecasting histories'(backgrounds)." The Threat Score has also been called the Critical Success Index (Donaldson *et al.*, 1975). Another problem with the score is that it takes no account of correct forecasts of non-events (Doswell *et al.*, 1990), for example, correctly forecasting no fog. The advantages of the ESS are that it discourages hedging by penalizing forecasters who forecast the most likely event all the time and rewards forecasters who forecast rarer events when guidance and current analyses suggest they are likely to occur. The ESS operates in the interval $[0, 1]$ with 1 being the best score or representing the highest skill.

Several other evaluation statistics have also been included in this program. These include the probability of detection (POD), the probability of false detection ($POFD$) (Flueck, 1987), the probability of a hit (POH), the probability of a miss (POM), the risk difference (RD) (Murphy, 1990), and the likelihood difference (LD) (Murphy, 1990).

Each of the verification statistics will be described in this section; some discussion of their advantages and disadvantages will also be given. It is important to note that no single statistic should be used to judge a given set of forecasts or forecast guidance. A suite of statistics should be used, especially when comparing forecasts and guidance. Complete derivations are given in Appendix B for those who wish to write computer programs to compute verification scores.

Classical Statistical Measures

Only the ME, $RMSE$,and MVE are described here. See Willmott (1982) for more detail. The error distribution statistics are described in Section III.

ME is the average error between the forecasts and the observations. It gives the bias for a given set of forecast/observation pairs, and is used in the NMVP to show if there are any overall biases or categorical biases for a given forecast element. This statistic is used in conjunction with $RMSE$ to determine how much systematic error there is, and what may be contributing to it.

The $RMSE$ is the square root of the mean of the sum of the squares of the errors between the forecasts and observations. It may also be expressed in terms of the standard deviations of the forecasts and observations, the correlation of the forecasts to the observations, and ME (Barnston, 1992). $RMSE$ is a measure of the total error of an ensemble of operational forecasts or guidance forecasts with respect to the observations. One drawback to using $RMSE$ is that it can be hedged by forecasts in the middle range

(Panofsky and Brier, 1963). For example, if a forecaster believes the wind will average 40 kt over a given forecast period if a Gale continues to weaken at its current rate and 30 kt if the Gale weakens more rapidly than expected, he/she may forecast 35 kt in cases of doubt to minimize the $RMSE$.

The MVE is used to account for errors in the u and v components of the wind and, therefore, the wind vector. The $RMSE$ of the wind direction and the wind speed help to determine how errors in these variables contribute to the MVE.

Verification Statistics Based on Contingency Tables

Contingency tables/performance matrices contain the joint distribution of forecasts and observations and can be presented in the form of frequencies or relative frequencies. Most evaluation measures can be computed from the information contained in a performance matrix.

No forecast elements in the NMVP are currently verified with a 2 x 2 performance matrix, but the development of all performance based statistics can be illustrated with a 2 x 2 matrix. In general, the scores used for the higher order tables are expanded versions of scores used for the 2 x 2 matrices. The differences will be discussed as each score is described. For warning verification, a 3 x 3 matrix is required for offshore points, and a 4 x 4 matrix is used for coastal points. The scores for wind speed and wave height are derived from 7 x 7 performance matrices. While to verify wind direction, an 8 x 8 matrix is used.

The probability of detection (POD) is a measure of accuracy with respect to the observations; it shows the extent to which the forecasts give advanced warning of the occurrence of an event (Panofsky and Brier, 1963). This statistic has also been called the prefigurance (Brier and Allen, 1951). It takes values between 0 and 1.

The probability of false detection ($POFD$) (Flueck, 1987) is a measure of inaccuracy with respect to the observations; it gives the extent to which the forecasts provide a false warning for the occurence of an event and has values from 0 to 1. This measure is defined only for a 2 x 2 matrix. According to Murphy (1991), it is not clear how to generalize the $POFD$. For a k x k matrix, the score becomes a vector with $k-1$ elements. An approximation can be made by shrinking the $k-1$ elements into 1 element and making a 2 x 2 matrix for each category. When the approximation is used for higher order performance matrices, information is lost, but sufficient information is retained to be useful.

The probability of a hit (POH) is a measure of accuracy with respect to the forecasts which can have values from 0 to 1. It shows the extent to which subsequent observations confirm the prediction when a given event is forecast (Panofsky and Brier, 1963). This score has also been called the post agreement (Brier and Allen, 1951), hit rate (Murphy, 1990), and frequency of hits (Doswell *et al*, 1990); $1-POH$ is called the false alarm rate or ratio.

The probability of a miss (POM) is a measure of inaccuracy with respect to the forecasts which takes values from 0 to 1; it gives the extent to which the forecasts miss the occurence of an event. Like the $POFD$, it is not clear how to generalize the POM, but the same comments made about generalizing the $POFD$ apply.

The risk difference (RD) and likelihood difference (LD) are performance measures which were introduced by Murphy (1990). They are defined in terms of the difference between POH and POM and the difference between POD and $POFD$, respectively. These statistics were designed to measure performance of rare events; however, there is no restriction on their use for events that are not rare. They can have values from -1 to 1. In general, the magnitudes of RD and LD will differ, but the signs of both will be the same. The only time $RD = LD$ is when the number of forecasts and observations for a given category are the same. $LD > RD$ for the case of overforecasting, and $LD < RD$ for the case of underforecasting. For complete details, see Murphy (1990).

Bias can be defined in two ways: in terms of the difference between the average forecast value and the average observed value (ME), or the ratio of the frequency of forecasts of an event to the frequency of observations of the event (B). B is often computed from performance matrices, and has values from 0 to ∞[1]. When the number of forecasts equals the number of observations for a given category, $B = 1$, and the forecasts are said

[1]When the average observed value is very small or zero compared to the average forecast value, B is set to 9.99 on the data sheets.

to be unbiased. When $B > 1$, then the category is being overforecast; when $B < 1$, then the category is being underforecast.

The most common measure of accuracy is the number correct (NC) which is the total number of correct forecasts. It is computed from a performance matrix by adding the frequencies of the diagonal elements of the matrix. The percent correct is NC divided by the sample size and multiplied by 100.

Gandin and Murphy (1992) developed a method of formulating equitable skill scores (ESS) based on scoring matrices which assign scores to the joint probabilities of forecasts and observations for each cell of a performance matrix. The elements of the scoring matrix are scaled such that constant forecasts are given an expected score of zero and perfect forecasts are given an expected score of one. As a result of the constant forecasts being scaled to an expected score of zero, random forecasts are also zero. Except for a 2 x 2 performance matrix which has been shown to be unique by Gandin and Murphy (1992), these conditions are necessary, but not sufficient, to determine uniquely the elements of a scoring matrix. To obtain a unique scoring matrix, additional conditions are imposed, or some scores are specified.

Gerrity (1992) developed a specific formula for the general multiple-category scoring matrix that satisfies the necessary conditions for "equitability." It is not the only solution possible, but it is compatible with a logical condensation of the general k-category problem into a set of $k-1$ two-category problems, where each of the two-category problems is associated with one of the $k-1$ partitions defining the categories of the original problem. This method works for distributive variables, and it is used for the 3-category and 4-category verification matrices associated with warnings and SCAs and the 7-category matrices used for wind speed and wave height.

The wind direction verification matrix has eight categories. The direction has values from 0^o to 360^o, while the errors can have values from -180^o to 180^o. A negative (positive) error is interpreted to mean the forecast wind direction is counterclockwise (clockwise) of the observed wind direction. For a continuous, distributive variable (for example, wind speed) with an 8-category performance matrix, the maximum error can be 7; while for a periodic variable like wind direction, the maximum error can only be 4 categories. In this case, Gerrity's solution can not be used, and the off-diagonal elements of the scoring matrix are specified. Specific details showing how this is done is given in Appendix B.

III. EVALUATION OF FORECAST ELEMENTS

Four forecast elements are evaluated in the NMVP: warning category (broken into 2 sets of data: coastal and offshore), wind direction, wind speed, and wave height. The highest observed wind in a period encompassing the verification time ±2 hours is used to evaluate the warning category; the other elements are evaluated by using the average of the observed data over the same period [see Burroughs and Nichols (1993) for further details]. Each element is verified with some or all of the statistics described in the foregoing section. One statistic (error distribution) will be described in this section.

The forecasts verified are the 18-h and 30-h projections of the 0000 UTC and 1200 UTC NMC model cycles.[2].

Verification data are computed for all stations (AS) combined, Eastern Region (ER) stations, Southern Region (SR) stations, Western Region (WR) stations, Alaska Region (AR) stations, Pacific Region (PR) stations, each WSFO station set, and each station. When the Great Lakes are brought into the program, another station set will be added. Currently only three WSFOs are in the program: Washington, D. C., San Francisco, Calif., and Honolulu, Hawaii.

Specific details for each element are given below.

Separate statistics sheets are prepared for each element, cycle time, projection, WSFO forecast or guidance forecast, and station set, *i.e.*, for a given element and station set, there are eight sheets of verification data: four for the guidance and four for the WSFO forecasts. The national reports will contain 40 data sheets (for all elements including the breakdown into two sets for the warning category) times the number of station sets included in the report (currently AS, ER, WR, and PR). This means there will be a minimum of 160 data sheets excluding any interpretive material included in the reports. With this in mind, the

[2]The projections are several hours less for the operational forecasts although based on the same guidance (Burroughs and Nichols, 1993)

Table 1: Definitions for abbreviations used on statistical data sheets.

BIAS	(Number of forecasts/Sample size) for a given category
ESS	Equitable Skill Score
FCST	Forecast/Forecasts
FT	Feet
HT	Height
KT	knot/knots
LD	Likelihood Difference ($POD - POFD$)
MPB	Marine Prediction Branch
ME	Mean Error
MN	Mean of a given sample
MVE	Mean Vector Error
NC	Number Correct
OBS	Observations
OBSVD	Observed
PC	Percent Correct
POD	Probability of Detection
POFD	Probability of False Detection
POH	Probability of a Hit
POM	Probability of a Miss
RD	Risk Difference ($POH - POM$)
RMSE	Root Mean Square Error
SPD	Speed
SS	Sample Size

reports will be sent semi-annually. The interpretive material will include monthly statistics for ESS, overall ME and $RMSE$, and will highlight other statistics of interest from the semi-annual sample. The data sheets will be included as an appendix. Table 1 lists the terms and abreviations used on the data sheets.

The WSFOs in the program will get data sheets for their area and for each station within their area. These will be sent to them directly for their review without interpretation. It is left to the individual WSFOs to use the raw data sent to them on disk to determine the performance of the office and to make decisions or recommendations to improve their capabilities. See Burroughs and Nichols (1993) for a description of the concepts and goals of the NMVP.

Table 2: The Small Craft Advisory limits for wind speed (kt) and significant wave height (ft) for each NWS Region.

	REGIONS				
	Eastern	Southern	Western	Alaska	Pacific
Wind Speed	25	20	21	25	25
Significant Wave Height	*	7	10	8	S quad. 6 elsewhere 10

* SCAs not issued based solely on wave height.

Warning Category

Two performance matrices are required for this forecast element: 4 x 4 for coastal forecasts and 3 x 3 for offshore forecasts. Hurricane and Tropical Storm categories are reported, but their frequency is so small these situations will be evaluated on a case by case basis. Therefore, for the NMVP, the coastal categories evaluated are: No warning, SCA, Gale, and Storm, while the offshore categories are: No warning, Gale, and Storm. Limits for the SCAs are taken from Chapter D-51 of the NWS Operations Manual in the absence of any Regional limits. Table 2 gives the lower thresholds both for wind speed and wave height determined by the NWS Regions for issuance of SCAs. The wave criterion is used for SCA issuance when wind speed is below threshold (*e.g.*, high ocean swells with light winds).

From the performance matrices, several statistics are computed. These are NC, PC, ESS, B, POD, $POFD$, POH, POM, LD, and RD. The number of one, two, or three category misses is not computed, but is easily determined from the performance matrices.

Figures 1 and 2 give the coastal statistics for the warning element, for the months of June 1992 - May 1993, for the 0000 UTC cycle 18-h projection, and for all stations. Figure 1 gives the statistics for the "Field" (WSFO) forecasts, while Fig. 2 gives the results for the MPB guidance. Figures 3 and 4 are the same, except they are for the offshore statistics. Figure 5 shows a comparison of forecasts and guidance for all four forecast times for the ESSs (a) for all coastal stations and (b) for all offshore stations. Statistics for the offshore stations include only the PR and ER station sets. There are no offshore stations for the

99998 ALL STATIONS COMBINED
FIELD
CYCLE = 0 PROJECION = 18
ADVISORIES/WARNINGS

FCST

		NONE	SCA	GALE	STORM	TOTAL
	NONE	669	265	7	0	941
	SCA	22	75	6	0	103
OBS	GALE	0	0	0	0	0
	STORM	0	0	0	0	0
	TOTAL	691	340	13	0	1044

NC	PC	ESS
744	71.	0.16

	NONE	SCA	GALE	STORM
BIAS	0.73	3.30	9.99	0.00
POD	0.71	0.73	0.00	0.00
POFD	0.21	0.28	0.01	0.00
POH	0.97	0.22	0.00	0.00
POM	0.77	0.04	0.00	0.00
LD	0.50	0.45	-0.01	0.00
RD	0.20	0.18	0.00	0.00

Figure 1: 0000 UTC cycle, 18-h projection, WSFO Coastal Forecast statistics data sheet (Warnings Element) for all stations. The sample is from June 1992 through May 1993. See footnote 1 in the text for an explanation of the bias value in the gale category.

99998 ALL STATIONS COMBINED

MPB

CYCLE = 0 PROJECION = 18

ADVISORIES/WARNINGS

FCST

	NONE	SCA	GALE	STORM	TOTAL
NONE	920	21	0	0	941
SCA	78	25	0	0	103
OBS GALE	0	0	0	0	0
STORM	0	0	0	0	0
TOTAL	998	46	0	0	1044

NC	PC	ESS
945	91.	0.07

	NONE	SCA	GALE	STORM
BIAS	1.06	0.45	0.00	0.00
POD	0.98	0.24	0.00	0.00
POFD	0.76	0.02	0.00	0.00
POH	0.92	0.54	0.00	0.00
POM	0.46	0.08	0.00	0.00
LD	0.22	0.22	0.00	0.00
RD	0.47	0.47	0.00	0.00

Figure 2: Same as Fig. 1, for MPB guidance applied to Coastal forecasts.

```
99998            ALL STATIONS COMBINED
                   FIELD
       CYCLE =   0  PROJECTION = 18
                 WARNINGS

                   FCST

            NONE  GALE STORM TOTAL

     NONE   1706    57     2  1765

 OBS GALE      3     5     1     9

    STORM      0     0     1     1

    TOTAL   1709    62     4  1775

         NC          PC          ESS
       1712          96.         0.83

       NONE         GALE        STORM
                    BIAS
       0.97         6.89         4.00

                     POD
       0.97         0.56         1.00

                    POFD
       0.30         0.03         0.00

                     POH
       1.00         0.08         0.25

                     POM
       0.89         0.00         0.00

                     LD
       0.67         0.52         1.00

                     RD
       0.10         0.08         0.25
```

Figure 3: Same as Fig. 1, for Offshore Forecast statistics data sheet.

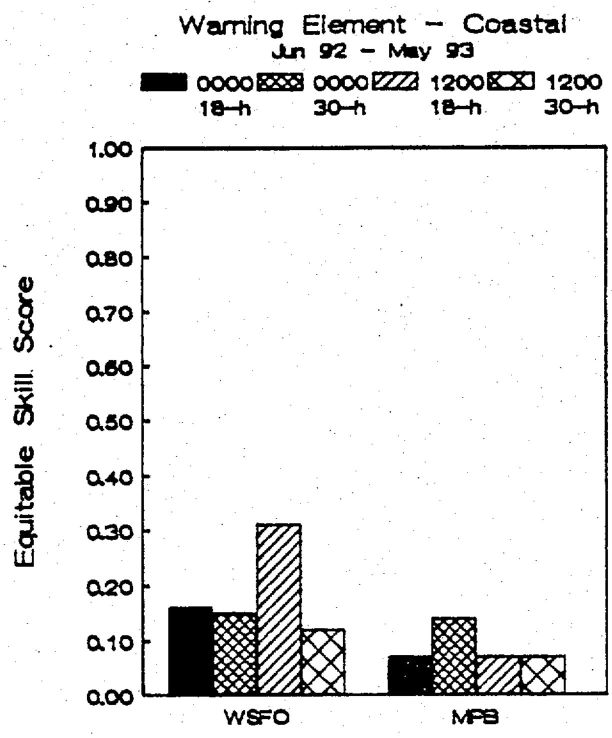
99998 ALL STATIONS COMBINED
MPB
CYCLE = 0 PROJECTION = 18
WARNINGS

		FCST			
		NONE	GALE	STORM	TOTAL
	NONE	1757	8	0	1765
OBS	GALE	3	6	0	9
	STORM	0	1	0	1
	TOTAL	1760	15	0	1775

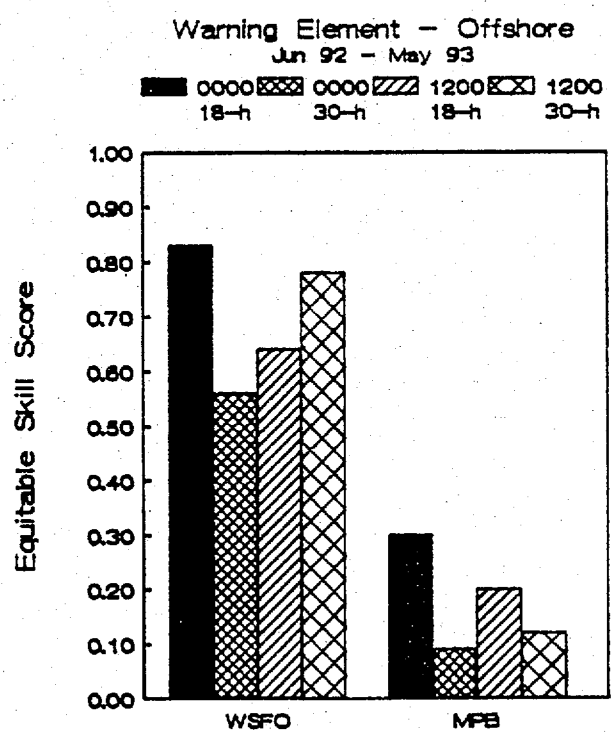
NC	PC	ESS
1763	99.	0.30

NONE	GALE	STORM
	BIAS	
1.00	1.67	0.00
	POD	
1.00	0.67	0.00
	POFD	
0.30	0.01	0.00
	POH	
1.00	0.40	0.00
	POM	
0.53	0.00	0.00
	LD	
0.70	0.66	0.00
	RD	
0.46	0.40	0.00

Figure 4: Same as Fig. 3, for MPB guidance applied to Offshore forecasts.



(a)



(b)

Figure 5: Comparison of Coastal Warnings and Guidance ESSs for a) all coastal stations and b) all offshore stations. The sample spans the same time as Figs. 1 - 4.

WR offshore forecast areas. Statistics for the coastal stations include only ER and WR station sets. There are no coastal stations for the PR coastal area yet. There will be in October 1993.

Wind Direction

Wind direction uses an eight-category performance matrix for some of the statistical measures used to evaluate it. The categories are: N, NE, E, SE, S, SW, W, and NW. The observed wind directions are the resultant of the reported directions in the period encompassing the verification time ±2 hours. No variable or calm wind forecasts are verified. Further, if the average observed wind is less than 8 kt, no verification is made. This is because winds of that strength are considered light and variable, and generally wind direction is not forecast. Table 3 shows the limits of each category in degrees.

$RMSE$, ME, and sample size (SS) overall and by category, NC, PC, ESS, observed mean, forecast mean, MVE, and the relative frequency distribution of errors from -180^o to 180^o are used to evaluate wind direction. The MVE is included here for convenience.

The relative frequency distribution of errors in the wind direction in percent are computed for the following categories in degrees: -180 to -158, -157 to -113, -112 to -68, -67 to -23, -22 to to 22, 23 to 67, 68 to 112, 113 to 157, 158 to 180. This gives an idea of how the errors are distributed to the counterclockwise or clockwise of the observed wind and what percentage of the forecasts are without any error.

Figures 6 and 7 give examples of the data sheets for WSFO forecasts and MPB guidance, respectively. Figure 8a shows a comparison of the $RMSE$ by category from Figs. 6 and 7. Figure 8b compares the relative frequency distributions from Figs. 6 and 7. Only the center point of each category is shown.

Table 3: The category limits for wind direction in degrees.

	WIND DIRECTION CATEGORIES							
	N	NE	E	SE	S	SW	W	NW
Limits	338 - 022	23 - 67	68 - 112	113 - 157	158 - 202	203 - 247	248 - 292	293 - 337

99998 ALL STATIONS COMBINED

MPB

CYCLE = 0 PROJECTION = 18

WIND DIRECTION

FCST

		N	NE	E	SE	S	SW	W	NW	T
	N	151	27	10	3	1	2	3	55	252
	NE	21	155	56	2	2	0	1	3	240
	E	2	108	295	36	3	2	0	0	446
	SE	0	3	20	67	41	4	0	0	135
OBS	S	1	0	0	20	127	58	2	0	208
	SW	0	1	0	3	12	80	24	2	122
	W	1	0	0	0	3	11	72	21	108
	NW	39	3	0	1	3	0	28	222	296
	T	215	297	381	132	192	157	130	303	1807

NC	PC	ESS
1169	65.	0.62

	N	NE	E	SE	S	SW	W	NW
MEAN ERROR BY CATEGORY	-3.	4.	-2.	5.	12.	7.	0.	-5.
RMSE BY CATEGORY	24.	26.	23.	29.	28.	30.	27.	25.
SAMPLE BY CATEGORY	252.	240.	446.	135.	208.	122.	108.	296.

WIND DIRECTION (DEGREES)

OBSVD--MN =	40.	FCST--MN =	39.	SS =	1807
ME =	1.	OVERALL RMSE =	27.	SS =	1807.
MVE =	5.9			SS =	1807.

ERRORS IN WIND DIRECTION (DEGREES)

	-180 TO -158	-157 TO -113	-112 TO -68	-67 TO -23	-22 TO 22
%	0.1	0.3	0.7	11.0	72.5

	23 TO 67	68 TO 112	113 TO 157	158 TO 180
%	13.8	1.2	0.2	0.2

Figure 6: 0000 UTC cycle, 18-h projection, WSFO Forecast statistics data sheet (Wind Direction Element) for all stations. The sample is from June 1992 through May 1993.

99998 ALL STATIONS COMBINED
FIELD
CYCLE = 0 PROJECTION = 18
WIND DIRECTION
FCST

		N	NE	E	SE	S	SW	W	NW	T
	N	141	32	6	1	5	2	6	59	252
	NE	34	117	76	5	0	0	1	7	240
	E	4	51	349	32	10	0	0	0	446
	SE	1	6	26	37	63	2	0	0	135
OBS	S	1	2	2	27	130	39	4	3	208
	SW	2	0	1	4	35	58	19	3	122
	W	6	0	0	1	8	17	57	19	108
	NW	48	0	0	2	5	4	34	203	296
	T	237	208	460	109	256	122	121	294	1807

NC	PC	ESS
1092	60.	0.52

	N	NE	E	SE	S	SW	W	NW
MEAN ERROR BY CATEGORY	-6.	2.	0.	6.	7.	1.	-2.	-5.
RMSE BY CATEGORY	31.	29.	22.	38.	37.	39.	40.	31.
SAMPLE BY CATEGORY	252.	240.	446.	135.	208.	122.	108.	296.

WIND DIRECTION (DEGREES)

OBSVD--MN = 40. FCST--MN = 33. SS = 1807
ME = 0. OVERALL RMSE = 33. SS = 1807.
MVE = 7.7 SS = 1807.

ERRORS IN WIND DIRECTION (DEGREES)

	-180 TO -158	-157 TO -113	-112 TO -68	-67 TO -23	-22 TO 22
%	0.3	0.7	2.1	11.7	68.3

	23 TO 67	68 TO 112	113 TO 157	158 TO 180
%	14.8	1.7	0.4	0.1

Figure 7: Same as Fig. 6, for MPB Guidance.

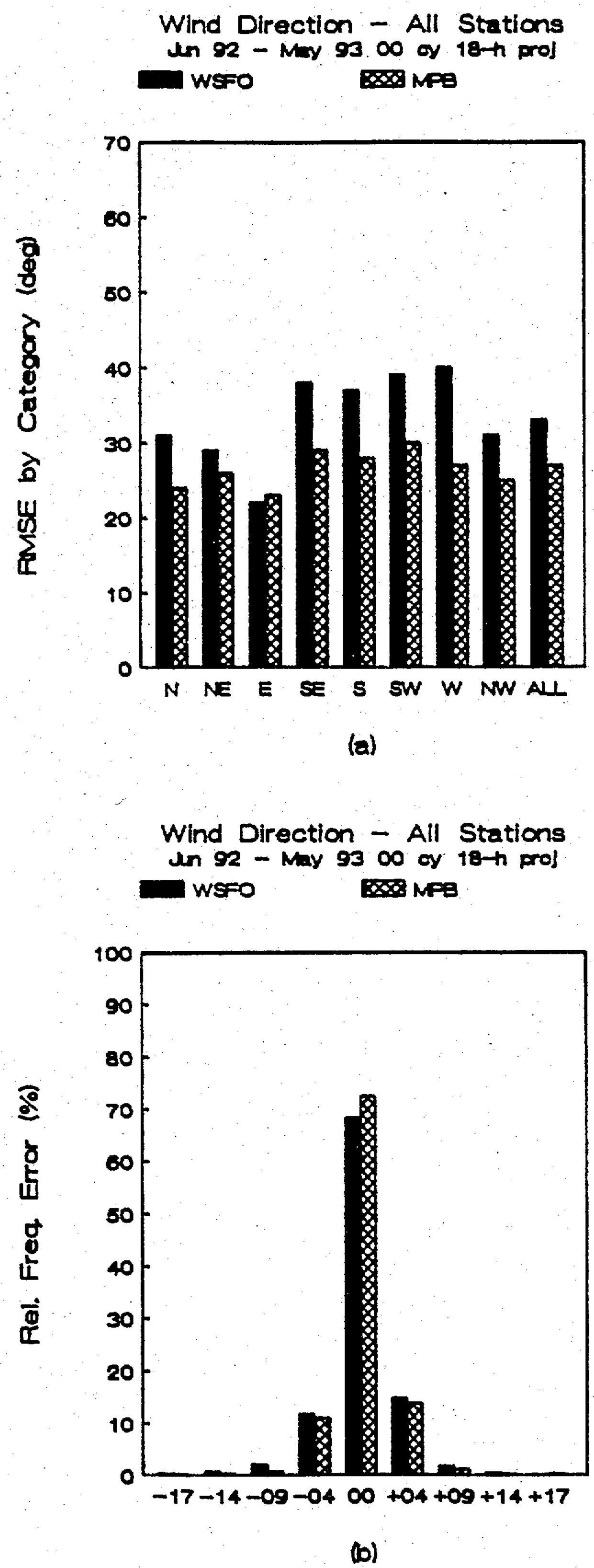


Figure 8: Comparison examples from data in Figs. 6 and 7 (a) $RMSE$ in degrees by category and (b) relative frequency error distribution in percent (centerpoint of error categories shown in tens of degrees).

Wind Speed

A seven-category performance matrix is used. Categories used are (in knots): < 8, 8-12, 13-17, 18-22, 23-27, 28-32, and > 32. The observed wind speeds are the average of the reported speeds in the period encompassing the verification time ±2 hours. The $RMSE$ and ME, overall and for each category, is given. The overall SS is given. The SS for each category is found in the performance matrix. The ESS, NC, PC, B, POD, $POFD$, POH, POM, LD, RD, the observed mean, and the forecast mean are also presented.

The relative frequency error distribution in percent is computed with the following categories in knots: < -22, -22 to -18, -17 to -13, -12 to -8, -7 to -3,-2 to 2, 3 to 7, 8 to 12, 13 to 17, 18 to 22, and > 20. These distributions help to show where biases may be located if any, and may help to explain some results that show up in the warnings evaluations.

Figures 9 and 10 present examples of statistical data sheets for WSFO forecasts and MPB guidance, respectively. Figure 11a gives a comparison of ESSs from Figs. 9 and 10, and Figure 11b delineates a comparison of relative frequency error distributions in percent from Figs. 9 and 10.

Significant Wave Height

A seven-category performance matrix is also used to evaluate the significant wave height (average height of highest 1/3 of the waves in the wave spectrum). The categories include (in feet): < 3, 3-5, 6-8, 9-12, 13-16, 17-20, and > 20. The observed wave heights are the average of the reported heights in the period encompassing the verification time ±2 hours. $RMSE$ and ME are computed for each category. Overall SS is given; the SS for each category is shown in the performance matrix. ESS, NC, PC, POD, $POFD$, POH, POM, LD, RD, observed mean, forecast mean, and relative frequency distribution of errors in percent are also presented.

The relative frequency of significant wave height errors in percent is given for the following categories in feet: < -8, -8 to -6, -5 to -3, -2 to 2, 3 to 5, 6 to 8, > 8. These distributions help to determine where biases exist and other information about the significant wave height errors.

99998 ALL STATIONS COMBINED
FIELD
CYCLE = 0 PROJECION = 18
WIND SPEED
FCST

		< 8	8-12	13-17	18-22	23-27	28-32	> 32	TOTAL
	< 8	159	283	93	30	3	0	1	569
	8-12	91	380	247	87	18	5	4	832
	13-17	33	234	359	257	49	10	5	947
OBS	18-22	4	32	77	128	61	18	5	325
	23-27	0	3	13	23	27	27	9	102
	28-32	0	2	0	3	8	13	9	35
	> 32	0	0	0	0	0	4	5	9
	TOTAL	287	934	789	528	166	77	38	2819

NC	PC	ESS
1071	38.	0.51

	LT 8	8 -12	13-17	18-22	22-27	28-32	GT 32
BIAS	0.50	1.12	0.83	1.62	1.63	2.20	4.22
POD	0.28	0.46	0.38	0.39	0.26	0.37	0.56
POFD	0.06	0.28	0.23	0.16	0.05	0.02	0.01
POH	0.55	0.41	0.46	0.24	0.16	0.17	0.13
POM	0.16	0.24	0.29	0.09	0.03	0.01	0.00
LD	0.22	0.18	0.15	0.23	0.21	0.35	0.54
RD	0.39	0.17	0.17	0.16	0.13	0.16	0.13
MEAN ERROR BY CATEGORY	4.8	2.6	0.8	0.0	-0.1	-0.7	1.4
RMSE BY CATEGORY	6.3	5.4	4.8	5.5	6.4	7.4	7.2

WIND SPEED (KT)
OBSVD--MN = 12.7 FCST--MN = 14.7 SS = 2819
ME = 2.0 OVERALL RMSE = 5.5 SS = 2819.

ERRORS IN WIND SPEED (KT)

	> 22 LO	22 - 18 LO	17 - 13 LO	12 - 8 LO	7 - 3 LO	2 LO - 2 HI
%	0.0	0.1	0.4	2.0	14.4	39.7

	3 TO 7 HI	8 - 12 HI	13 - 17 HI	18 - 22 HI	> 22 HI
%	31.6	9.0	2.2	0.5	0.2

Figure 9: 0000 UTC cycle, 18-h projection, WSFO Forecast statistics data (Wind Speed Element) for all stations. The sample is from June 1992 through May 1993.

99998 ALL STATIONS COMBINED
MPB
CYCLE = 0 PROJECION = 18
WIND SPEED

		FCST							
		< 8	8-12	13-17	18-22	23-27	28-32	> 32	TOTAL
	< 8	323	208	34	3	1	0	0	569
	8-12	221	399	170	37	5	0	0	832
	13-17	73	252	437	162	19	3	1	947
OBS	18-22	5	30	119	130	38	3	0	325
	23-27	0	7	14	25	43	9	4	102
	28-32	0	0	2	3	12	12	6	35
	> 32	0	1	0	0	0	0	8	9
	TOTAL	622	897	776	360	118	27	19	2819

NC	PC	ESS
1352	48.	0.61

	LT 8	8 -12	13-17	18-22	22-27	28-32	GT 32
BIAS	1.09	1.08	0.82	1.11	1.16	0.77	2.11
POD	0.57	0.48	0.46	0.40	0.42	0.34	0.89
POFD	0.13	0.25	0.18	0.09	0.03	0.01	0.00
POH	0.52	0.44	0.56	0.36	0.36	0.44	0.42
POM	0.11	0.23	0.25	0.08	0.02	0.01	0.00
LD	0.43	0.23	0.28	0.31	0.39	0.34	0.88
RD	0.41	0.22	0.31	0.28	0.34	0.44	0.42
MEAN ERROR BY CATEGORY	1.9	0.0	-0.9	-1.9	-2.2	-2.4	-1.4
RMSE BY CATEGORY	4.0	4.0	4.4	4.5	6.2	5.7	8.6

WIND SPEED (KT)

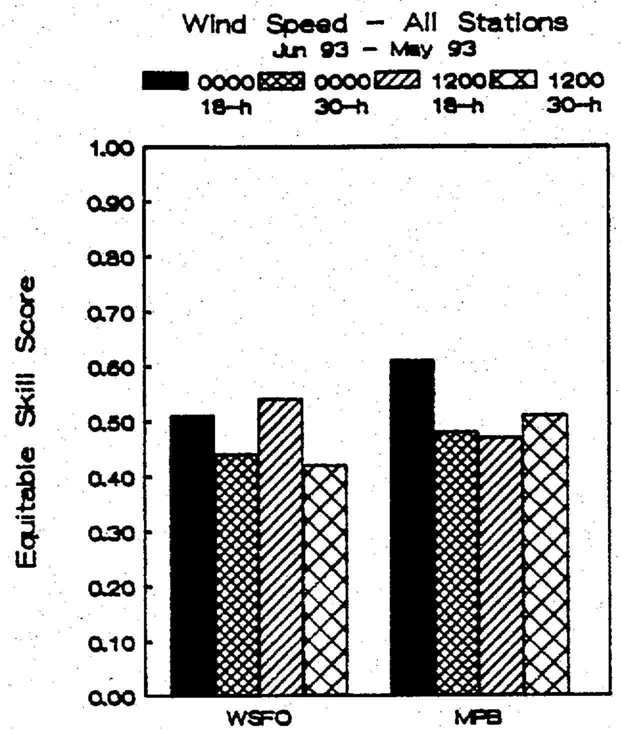
OBSVD--MN = 12.7 FCST--MN = 12.5 SS = 2819
ME = -0.3 OVERALL RMSE = 4.3 SS = 2819.

ERRORS IN WIND SPEED (KT)

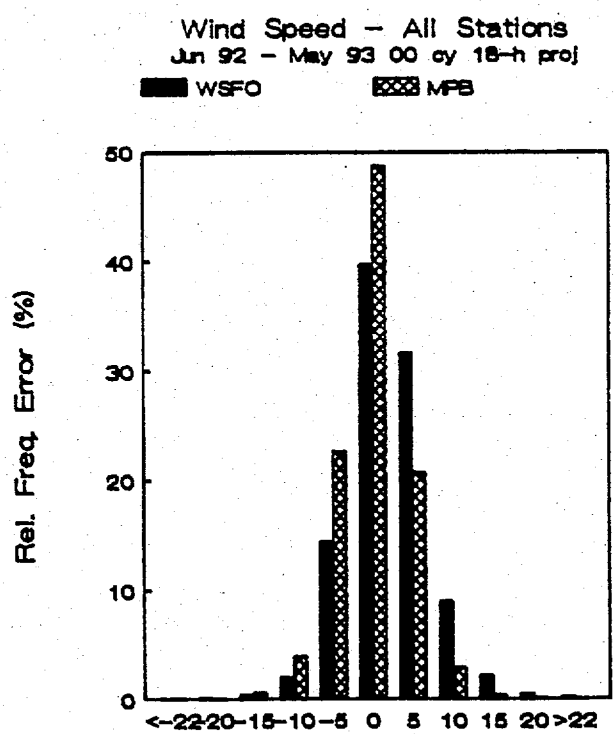
	> 22 LO	22 - 18 LO	17 - 13 LO	12 - 8 LO	7 - 3 LO	2 LO - 2 HI
%	0.0	0.0	0.6	3.9	22.6	48.7

	3 TO 7 HI	8 - 12 HI	13 - 17 HI	18 - 22 HI	> 22 HI
%	20.7	2.9	0.4	0.1	0.0

Figure 10: Same as Fig. 9, for MPB Guidance.



(a)



(b)

Figure 11: Comparison of (a) ESSs and (b) relative frequency error distribution in percent from data contained in Figs. 9 and 10 (centerpoint of error categories shown).

Figures 12 and 13 give example data sheets for significant wave height and show results for the WSFO forecasts and MPB guidance for all stations, respectively. The data are from March 11 through May 31, 1993. Figure 14a presents a comparison of ESSs and 14b compares the significant wave height error distributions in percent for data contained in Figs. 12 and 13.

IV. FUTURE ENHANCEMENTS

Currently, three WSFOs are in the program: Washington, D.C.; San Francisco, Calif.; and Honolulu, Hawaii. By the fall of 1993, all the WSFOs with marine responsibility, except those in the Great Lakes region, will be in the program (see Burroughs and Nichols, 1993 for details). Eventually, as the NWS modernization and restructuring takes place, the NMVP will be expanded and redefined to include all WFOs with marine responsibility including those in the Great Lakes region.

Regional guidance will also be added to the NMVP. This includes significant wave height from the Gulf of Mexico (Chao, 1991) and the Gulf of Alaska (in development) regional wave models, and wind direction and speed from the 30 km ETA Model. Other wind speed and direction guidance from the Coastal Wind Forecast System (Burroughs, 1991a) and the Santa Ana Forecast System (Burroughs, 1991b) will also be added.

Finally, in the distant future, High Seas Forecasts and their verification by ship data in specified areas will be added to the program. Also other verification data may be added to the Coastal and Offshore programs. Other forecast elements such as visibility, obstructions to visibility, and superstructure icing may be added if sufficient verification data exist.

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99998 ALL STATIONS COMBINED
FIELD
CYCLE = 0 PROJECION = 18
WAVE HEIGHT
FCST

		< 3	3-5	6-8	9-12	13-16	17-20	> 20	TOTAL
	< 3	1	15	0	0	0	0	0	16
	3-5	2	154	44	2	0	0	0	202
	6-8	0	57	136	29	1	0	0	223
OBS	9-12	0	8	36	61	11	0	0	116
	13-16	0	0	1	10	9	2	0	22
	17-20	0	0	0	1	3	0	0	4
	> 20	0	0	0	0	1	1	2	4
	TOTAL	3	234	217	103	25	3	2	587

NC	PC	ESS
363	62.	0.46

	LT 2	3 - 5	6 - 8	9 -12	13-16	17-20	GT 20
BIAS	0.19	1.16	0.97	0.89	1.14	0.75	0.50
POD	0.06	0.76	0.61	0.53	0.41	0.00	0.50
POFD	0.00	0.21	0.22	0.09	0.03	0.01	0.00
POH	0.33	0.66	0.63	0.59	0.36	0.00	1.00
POM	0.03	0.14	0.24	0.11	0.02	0.01	0.00
LD	0.06	0.55	0.39	0.44	0.38	-0.01	0.50
RD	0.31	0.52	0.39	0.48	0.34	-0.01	1.00
MEAN ERROR BY CATEGORY	1.3	0.6	-0.5	-0.8	-1.1	-3.3	-2.3
RMSE BY CATEGORY	1.6	1.6	1.9	2.7	3.0	3.9	6.0

WAVE HEIGHT (FT)

OBSVD--MN = 7.1 FCST--MN = 6.9 SS = 587
ME = -0.2 OVERALL RMSE = 2.1 SS = 587.

ERRORS IN WAVE HEIGHT (FT)

	> 8FT LO	6 - 8FT LO	3 - 5FT LO	-2 TO +2FT
%	0.0	1.2	11.9	80.1

	3 - 5FT HI	6 - 8FT HI	> 8FT HI
PERCENT	6.3	0.5	0.0

Figure 12: 0000 UTC cycle, 18-h projection, WSFO Forecast statistics data (Significant Wave Height Element) for all stations. The sample is from March 11 through May 31, 1993.

99998 ALL STATIONS COMBINED

MPB

CYCLE = 0 PROJECION = 18

WAVE HEIGHT

		FCST							
		< 3	3-5	6-8	9-12	13-16	17-20	> 20	TOTAL
	< 3	0	15	1	0	0	0	0	16
	3-5	1	143	56	2	0	0	0	202
	6-8	0	31	149	42	1	0	0	223
OBS	9-12	0	3	57	48	4	3	1	116
	13-16	0	0	3	12	4	3	0	22
	17-20	0	0	0	1	2	0	1	4
	> 20	0	0	0	2	0	0	2	4
	TOTAL	1	192	266	107	11	6	4	587

NC	PC	ESS
346	59.	0.39

	LT 2	3 - 5	6 - 8	9 -12	13-16	17-20	GT 20
BIAS	0.06	0.95	1.19	0.92	0.50	1.50	1.00
POD	0.00	0.71	0.67	0.41	0.18	0.00	0.50
POFD	0.00	0.13	0.32	0.13	0.01	0.01	0.00
POH	0.00	0.74	0.56	0.45	0.36	0.00	0.50
POM	0.03	0.15	0.23	0.14	0.03	0.01	0.00
LD	0.00	0.58	0.35	0.29	0.17	-0.01	0.50
RD	-0.03	0.60	0.33	0.31	0.33	-0.01	0.50
MEAN ERROR BY CATEGORY	2.1	0.9	-0.2	-1.2	-2.2	-3.0	-7.3
RMSE BY CATEGORY	2.4	1.4	1.6	2.7	4.4	5.3	9.1

WAVE HEIGHT (FT)

OBSVD--MN = 7.1 FCST--MN = 7.0 SS = 587

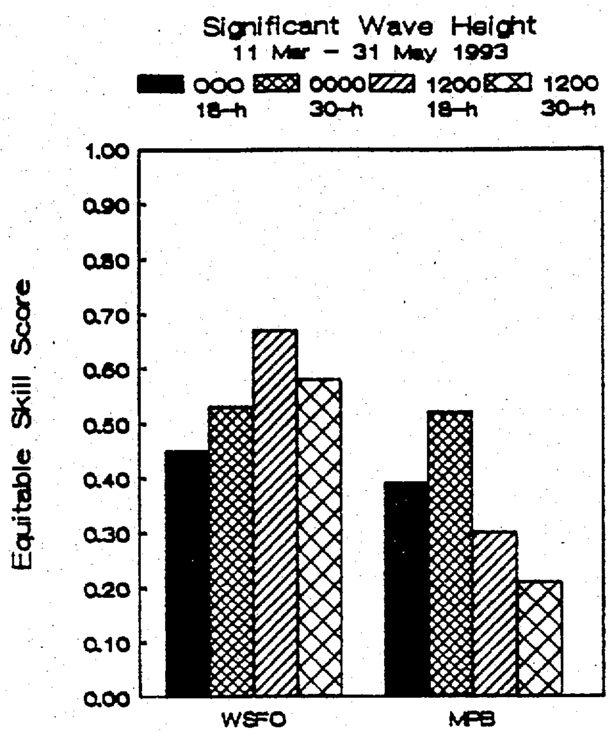
ME = -0.1 OVERALL RMSE = 2.2 SS = 587.

ERRORS IN WAVE HEIGHT (FT)

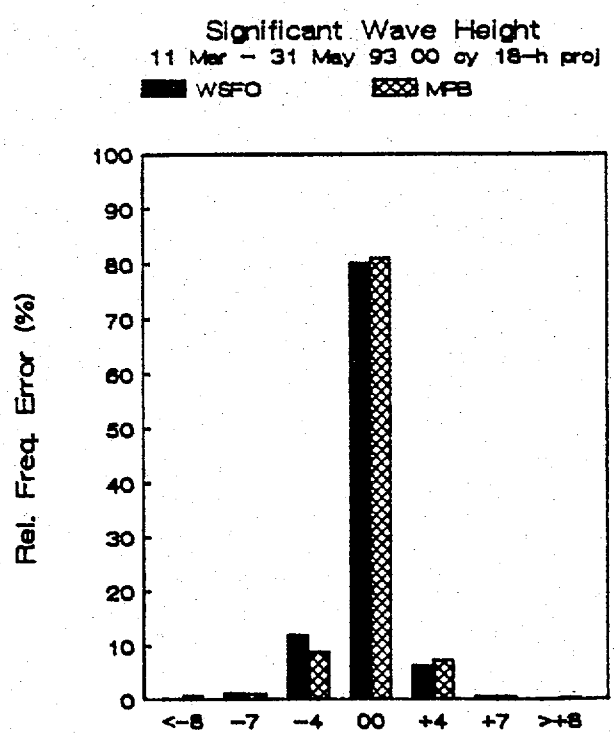
	> 8FT LO	6 - 8FT LO	3 - 5FT LO	-2 TO +2FT
%	0.7	1.0	8.8	81.0

	3 - 5FT HI	6 - 8FT HI	> 8FT HI
PERCENT	7.3	0.5	0.2

Figure 13: Same as Fig. 9, for MPB Guidance.



(a)



(b)

Figure 14: Comparison of (a) ESSs and (b) relative frequency error distribution in percent from data contained in Figs. 12 and 13 (centerpoint of error categories shown).

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APPENDIX A.

List of Definitions and Abbreviations

AR	NWS Alaska Region
AS	All Stations
B	Bias
C-MAN	Coastal Marine Automated Network
CR	Calibration-Refinement Factorization
E	East
ER	NWS Eastern Region
ESS	Equitable Skill Score
FCST	Forecast/Forecasts
ft/FT	Feet
h	Hour
HT	Height
LBR	Likelihood-Base Rate Factorization
kt/KT	knot/knots
LD	Likelihood Difference ($POD - POFD$)
ME	Mean Error
MN	Mean of a given sample
MPB	Marine Prediction Branch
MVE	Mean Vector Error
MVM	Marine Verification Matrix
N	North
NC	Number Correct
NE	Northeast, No Errors
NMC	National Meteorological Center
NMVP	National Marine Verification Program
NW	Northwest
OBS	Observations
OBSVD	Observed
OM	Office of Meteorology
PC	Percent Correct
POD	Probability of Detection
POFD	Probability of False Detection
POH	Probability of a Hit
POM	Probability of a Miss
PR	NWS Pacific Region
RD	Risk Difference ($POH - POM$)
RMSE	Root Mean Square Error
S	South
SCA	Small Craft Advisory
SE	Southeast
SPD	Speed
SR	NWS Southern Region
SS	Sample Size
SW	Southwest
W	West
WFO	Weather Forecast Office
WSFO	Weather Service Forecast Office
WR	NWS Western Region

APPENDIX B.
Derivation of Verification Statistics

a. Mean Error

The mean error is given by

$$ME = \frac{1}{n}\sum_{i=1}^{n}(f_i - o_i), \qquad (1)$$

where n is the number of observations, f_i is the ith forecast, and o_i is the ith observation.

b. Root Mean Square Error

The root mean square error is given by

$$RMSE = \left(\frac{\sum_{i=1}^{n}(f_i - o_i)^2}{n}\right)^{1/2}, \qquad (2)$$

where the variables are the same as in eq (1).

$RMSE$ may also be expressed in terms of the standard deviations of the forecasts and observations (s_f and s_o, respectively), the correlation of the forecasts to the observations (r_{fo}), and the mean error (ME) which is given in (1) (Barnston, 1992). Expressed in those terms

$$RMSE = (s_f^2 + s_o^2 - 2s_f s_o r_{fo} + ME^2)^{1/2}. \qquad (3)$$

c. The Mean Vector Error

The MVE is expressed as

$$MVE = \left(\frac{\sum_{i=1}^{n}(u_{fi} - u_{oi})^2 + (v_{fi} - v_{oi})^2}{n}\right)^{1/2}, \qquad (4)$$

where oi and fi are the ith observation and forecast, respectively; u and v are the westerly and northerly components of the wind, respectively, and n is the sample size.

Table 4: A 2 x 2 performance matrix with joint and marginal frequencies of forecasts and observations from the verification data set (after Murphy, 1990).

OBSERVATIONS		FORECASTS		
		$f = 1$	$f = 0$	Total
	$x = 1$	a	c	$a + c$
	$x = 0$	b	d	$b + d$
	TOTAL	$a + b$	$c + d$	n

d. Performance Matrix

Performance Matrices contain the joint distribution of forecasts and observations and can be presented in the form of frequencies or relative frequencies. Most evaluation measures can be computed from the information contained in a performance matrix. For purposes of discussion, a 2 x 2 performance matrix is given in Table 4.

No forecast elements in the NMVP are currently verified with a 2 x 2 matrix, but the development of all performance matrix based statistics can be illustrated with a 2 x 2 matrix. In general, the scores used for the higher order matrices are expanded versions of the scores used for a 2 x 2 matrix. The differences will be discussed as each score is derived. For warning verification, a 3 x 3 matrix is required for offshore points, and a 4 x 4 matrix is used for coastal points. The scores for wind speed and wave height use a 7 x 7 performance matrix. To verify wind direction, an 8 x 8 matrix is used.

Table 5 gives the basic joint, conditional, and marginal probabilities for the performance matrix given in Table 4 (following Murphy 1990). The conditional and marginal probabilities can be decomposed two ways. The first uses the forecasts, f, as the conditioning variable. This is referred to as the Calibration-Refinement (CR) factorization. The second decomposition uses the observations (x) as the conditioning variable and is called the likelihood-base rate (LBR) factorization. See Murphy and Winkler (1987) for complete details. Most of the scores described will make use of the joint, conditional, and marginal probabilities in some way.

Table 5: The joint, conditional, and marginal probabilities and their empirical estimates based on the verification data set from Table 5 following Murphy (1990).

(a) Joint Distribution: $p(f,x)$

$p(f=1,x=1)=p(1,1)=a/n, p(f=1,x=0)=p(1,0)=b/n,$
$p(f=0,x=1)=p(0,1)=c/n, p(f=0,x=0)=p(0,0)=d/n$
$p(1,1)+p(1,0)+p(0,1)+p(0,0)=1$

(b) CR Factorization: $p(x|f)$ and $p(f)$

$p(x=1|f=1)=p_f(1|1)=a/(a+b), p(x=0|f=1)=P_f(0|1)=b/(a+b)$
$p(x=1|f=0)=p_f(1,0)=c/(c+d), p(x=0|f=0)=p_f(0|0)=d/(c+d)$
$p_f(1|1)+p_f(0|1)=1, p_f(0,1)+p_f(0|0)=1$
$p(f=1)=p_f(1)=(a+b)/n, p(f=0)=p_f(0)=(c+d)/n$
$p_f(1)+p_f(0)=1$

(c) LBR Factorization: $p(f|x)$ and $p(x)$

$p(f=1|x=1)=p_x(1|1)=a/(a+c), p(f=0|x=1)=p_x(0|1)=c/(a+c)$
$p(f=1|x=0)=p_x(1,0)=b/(b+d), p(f=0|x=0)=p_x(0|0)=d/(b+d)$
$p_x(1|1)+p_x(0|1)=1, p_x(1|0)+p_x(0|0)=1$
$p(x=1)=p_x(1)=(a+c)/n, p(x=0)=p_x(0)=(b+d)/n$
$p_x(1)+p_x(0)=1$

e. Probability of Detection

For a 2 x 2 matrix, the POD is given by

$$POD_1 = p(f=1|x=1) = p_x(1|1) = \frac{a}{a+c}, \quad (5)$$

$$POD_0 = p(f=0|x=0) = p_x(0|0) = \frac{d}{b+d}, \quad (6)$$

where the subscripts 1 and 0 refer to the categories 1 and 0 of the performance matrix in Table 4.

The POD can be extended to any k x k performance matrix. The form of the equation is given by

$$POD_i = p(f=i|x=i) = p_x(i|i) = \frac{d_i}{n_{xi}}, \quad (i=1,\ldots,k), \quad (7)$$

where the subscript i refers to a given category; d is the element in the diagonal of the performance matrix for the ith category, and n_{xi} is the sample of observations falling into category i.

f. Probability of False Detection

For a 2 x 2 matrix, the $POFD$ is given by

$$POFD_1 = p(f = 1|x = 0) = p_x(1|0) = \frac{b}{b+d}, \tag{8}$$

$$POFD_0 = P(f = 0|x = 1) = p_x(0|1) = \frac{c}{a+c}, \tag{9}$$

where the subscripts 0 and 1 again refer to the categories in the performance matrix in Table 4.

According to Murphy (1991), it is not clear how to generalize the $POFD$. For a k x k matrix, the $POFD$ becomes a vector with $k-1$ elements. An approximation to the $POFD$ can be made by shrinking the $k-1$ elements into 1 element and making a 2 x 2 matrix for each category. The form of the equation becomes

$$POFD_i = p(f = i|x = [0,1,\ldots,k-1]) = p_x(i,[0,1,\ldots,k-1], x \neq i) \approx \frac{(n_{fi} - d_i)}{(n - n_{xi})}, \ (i = 1,\ldots,k), \tag{10}$$

where n_{fi} is the total number of forecasts for category i, n_{xi} is the total number of observations for category i, d_i is the element in the diagonal of the performance matrix for the ith category, and n is the sample size. When (10) is used, information is lost, but sufficient information is retained to be useful.

g. Probability of a Hit

For a 2 x 2 matrix, the POH is given by

$$POH_1 = p(x = 1|f = 1) = p_f(1|1) = \frac{a}{a+b}, \tag{11}$$

$$POH_0 = p(x = 0|f = 0) = p_f(0|0) = \frac{d}{c+d}, \tag{12}$$

where the subscripts 1 and 0 refer to the categories 1 and 0 of the performance matrix in Table 4.

The POH can also be extended to a k x k performance matrix like the POD was. The extended version is given by

$$POH_i = p(x = i|f = i) = p_f(i|i) = \frac{d_i}{n_{fi}}, \ (i = 1, \ldots, k), \tag{13}$$

where the subscript i refers to a given category; d is the element in the diagonal of the performance matrix for the ith category, and n_{fi} is the total number of forecasts made for category i.

h. Probability of a Miss

For a 2 x 2 matrix, the POM is given by

$$POM_1 = p(x = 1|f = 0) = p_f(1|0) = \frac{c}{c+d}, \tag{14}$$

$$POM_0 = p(x = 0|f = 1) = p_f(0|1) = \frac{b}{a+b}, \tag{15}$$

where the subscripts 1 and 0 refer to the categories 1 and 0 of the performance matrix in Table 4.

Again, it is not clear how to generalize the POM. For a k x k matrix, the POM also becomes a vector with $k-1$ elements. Like the $POFD$, an approximation to the POM can be made by shrinking the $k-1$ elements into 1 element and making a 2 x 2 matrix for each category. The form of the equation then becomes

$$POM_i = p(x = i|f = [0, 1, \ldots, k-1]) = p_f(i, [0, 1, \ldots, k-1], f \neq i) \approx \frac{(n_{xi} - d_i)}{(n - n_{fi})}, \ (i = 1, \ldots, k), \tag{16}$$

where n_{fi} is the total number of forecasts for category i, n_{xi} is the total number of observations for category i, d_i is the element in the diagonal of the performance matrix for the ith, and n is the sample size. When (16) is used, information is lost, but sufficient information is kept to be useful.

i. Risk Difference Performance Measure

RD is defined for a 2 x 2 performance matrix as follows

$$RD_1 = POH_1 - POM_1 = p_f(1|1) - p_f(1|0) = \frac{a}{a+b} - \frac{c}{c+d} = \frac{ad - bc}{(a+b)(c+d)}, \tag{17}$$

$$RD_0 = POH_0 - POM_0 = p_f(0|0) - p_f(0|1) = \frac{d}{c+d} - \frac{b}{a+b} = \frac{ad - bc}{(a+b)(c+d)}, \tag{18}$$

Note that the resulting equations are identical for both categories and that the numerator is the determinant of the performance matrix in Table 4. Only one equation need be used to measure performance with respect to the forecasts in a 2 x 2 matrix. If the two equations are averaged, the result is simply $\overline{RD} = (ad - bc)/[(a + b)(c + d)]$. For a k x k matrix, the approximate form of POM_i is used to give a categorical form of RD.

$$RD_i = POH_i - POM_i = \frac{d_i}{n_{fi}} - \frac{n_{xi} - d_i}{n - n_{fi}} = \frac{nd_i - n_{xi}n_{fi}}{n_{fi}(n - n_{fi})}, \ (i = 1, \ldots, k). \tag{19}$$

An overall risk difference can be computed by averaging RD_i over the number of categories that have observations and/or forecasts.

j. Likelihood Difference Performance Measure

LD is defined for a 2 x 2 performance matrix as follows

$$LD_1 = POD_1 - POFD_1 = p_x(1|1) - p_x(1|0) = \frac{a}{a+c} - \frac{b}{b+d} = \frac{ad - bc}{(a+c)(b+d)}, \tag{20}$$

$$LD_0 = POD_0 - POFD_0 = p_x(0|0) - p_x(0|1) = \frac{d}{b+d} - \frac{c}{a+c} = \frac{ad - bc}{(a+c)(b+d)}, \tag{21}$$

Again the resulting equations are identical for both categories and the numerator is the determinant of the performance matrix in Table 4. Only one equation need be used to measure performance with respect to the observations in a 2 x 2 matrix. If the two equations are averaged, the result is simply $\overline{LD} = (ad - bc)/[(a + c)(b + d)]$. For a k x k matrix, the approximate form of $POFD_i$ is used to give a categorical form of LD.

$$LD_i = POD_i - POFD_i = \frac{d_i}{n_{xi}} - \frac{n_{fi} - d_i}{n - n_{xi}} = \frac{nd_i - n_{xi}n_{fi}}{n_{xi}(n - n_{xi})}, \ (i = 1, \ldots, k). \tag{22}$$

An overall likelihood difference can be computed by averaging LD_i over the number of categories that have observations and/or forecasts.

k. Additional Information on RD and LD

RD and LD are similar except that the conditioning variables are different (forecasts and observations, respectively). In terms of the verification matrix (Table 4), the numerators are identical while the denominators differ. This means, in general, the magnitudes of RD and LD will differ, but the signs of both will be the same unless $a < bc/d$. The only time $RD = LD$ is when $b = c$. $LD > RD$ for the case of overforecasting, and $LD < RD$ for the case of underforecasting.

These arguments can be extended to k x k verification matrices even though information has been lost by collapsing $k-1$ elements to 1 element to determine POM_i and $POFD_i$.

l. Bias

For a 2 x 2 verification matrix B is given by

$$B_1 = \frac{p_f(1)}{p_x(1)} = \frac{a+b}{a+c}, \tag{23}$$

$$B_0 = \frac{p_f(0)}{p_x(0)} = \frac{c+d}{b+d}, \tag{24}$$

With this representation, B can take values from 0 to ∞. When $b = c, B = 1$, and the forecasts are said to be unbiased. The frequency of correct forecasts (a and d) can be any value from 0 to $b+d$ for B_0 or from 0 to $a+c$ for B_1. When $B > 1$, then the category is being overforecast; when $B < 1$, then the category is being underforecast.

B can be extended to a k x k verification matrix, and is given by

$$B_i = \frac{p_f(i)}{p_x(i)} = \frac{n_{fi}}{n_{xi}}, \ (i = 1, \ldots, k). \tag{25}$$

m. Number Correct and Percent Correct

The most common measure of accuracy is the Number Correct (NC) which is given by

$$NC = \sum_{i=1}^{k} d_i, \tag{26}$$

where d_i is the frequency of correct forecasts for each category i, and k is the number of categories. The Percent Correct (PC) is given by

$$PC = 100 \cdot \frac{NC}{n}, \tag{27}$$

where n is the sample size.

n. Equitable Skill Scores

(1) Basic definitions (following Gandin and Murphy, 1992)

The joint distribution of forecasts and observations for a k-event variable in terms of the verification sample is given by the *performance matrix* $\boldsymbol{P} = (p_{ij})$ $(p_{ij} \geq 0, \sum_i \sum_j p_{ij} = 1;\ i,j = 1,\cdots,k)$, where p_{ij} is the relative frequency of occasions on which the ith event is observed and the jth event is forecast. Let $\boldsymbol{p} = (p_i)$ represent the climatological probability vector, where $p_i = \sum_j p_{ij}$ $(j = 1,\cdots,k)$ is the sample climatological probability of the ith event, and let $\boldsymbol{q} = (q_j)$ be the predictive probability vector, where $q_j = \sum_i p_{ij}$ $(i = 1,\cdots,k)$ is the sample predictive probability of the jth forecast.

Let $\boldsymbol{S} = (s_{ij})$ be the k x k *scoring matrix*, where s_{ij} is the score assigned to a forecast of the jth event when the ith event occurs. Assume the elements of $\boldsymbol{S}$ are independent of the elements of $\boldsymbol{P}$. This assumption does not rule out the possibility that the elements of $\boldsymbol{S}$ may depend on the elements of the climatological probability vector $\boldsymbol{p}$.

The expected score S associated with $\boldsymbol{P}$ and $\boldsymbol{S}$ is given by

$$S = \sum_i \sum_j p_{ij} s_{ij}. \tag{28}$$

S represents a weighted average of the s_{ij}. The weights are the probabilities of the respective combinations of forecast and observed events.

The expected score for a constant forecast is set to zero; therefore, for a constant forecast

$$S_j = \sum_i p_i s_{ij} = 0, \ (j = 1,\cdots,k). \tag{29}$$

For a random forecast

$$S_r = \sum_j \sum_i q_j p_i s_{ij} = \sum_j q_j S_j = 0. \tag{30}$$

The expected score for perfect forecasts, S_p $(p_{ij} = p_i$ for all $i)$, is one; therefore,

$$S_p = \sum_i p_i s_{ij} = 1. \tag{31}$$

When (31) is added to the k relationships of (29) a total of $k+1$ relationships is available to determine the k^2 scores s_{ij}, $(i,j = 1,\cdots,k)$. If it is assumed $\boldsymbol{S}$ is symmetric, *i.e.*, $s_{ji} = s_{ij}$, $(i,j = 1,\cdots,k)$, then the number of scores to be determined is reduced to $k(k+1)/2$. $k(k+1)/2 \geq k+1$, except when $k = 2$.

Gerrity (1992) presented a solution for the k-class ESS. Let $p(r)$ be the relative frequency with which class r of the event is observed in a large sample of forecasts. Define the following:

$$D(n) \equiv \frac{1 - \sum_{r=1}^{n} p(r)}{\sum_{r=1}^{n} p(r)} \tag{32}$$

$$R(n) = \frac{1}{D(n)}. \tag{33}$$

Note that $D(n)$ is the ratio of the probability that an observation falls into a class with index greater than n to the probability that it falls into a class with index less than or equal to n; $R(n)$ is the reciprocal of this ratio of probabilities. In terms of D and R, the elements of a k-class equitable scoring matrix may be written

$$s_{n,n} = \kappa \left[\sum_{r=1}^{n-1} R(r) + \sum_{r=n}^{k-1} D(r) \right] ; \; n = (1, \cdots, k) \tag{34}$$

$$s_{m,n} = \kappa \left[\sum_{r=1}^{m-1} R(r) + \sum_{r=m}^{n-1} (-1) + \sum_{r=n}^{k-1} D(r) \right] ; \; 1 \leq m < k, \; m < n \leq k \tag{35}$$

$$s_{n,m} = s_{m,n}, \; 2 \leq n \leq k, \; 1 \leq m < n \tag{36}$$

$$\kappa \equiv \frac{1}{k-1}. \tag{37}$$

Equation (34) gives the elements on the diagonal of S. The remaining elements of the upper triangle are given by (35). The lower triangle elements (36) follow from the symmetry of S. These equations are used to develop ESSs for the 3- and 4-category performance matrices used in verification of the warning element and the 7-category matrices used to verify wind speed and wave height.

(2) The two-event ESS

This case is presented in the event verification of binary forecasts (for example, fog or superstructure icing) is desired, and for completeness since it is the only case to have an exact solution for the ESS. In two-event situations,

$$\boldsymbol{P} = \begin{pmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{pmatrix}, \tag{38}$$

$\boldsymbol{p} = (p_1, p_2)$; $\boldsymbol{q} = (q_1, q_2)$; the assumption of symmetry implies $s_{21} = s_{12}$, and

$$\boldsymbol{S} = \begin{pmatrix} s_{11} & s_{12} \\ s_{12} & s_{22} \end{pmatrix}; \tag{39}$$

The expected scores are given by

$$S_1 = p_1 s_{11} + p_2 s_{12} = 0, \tag{40}$$

$$S_2 = p_1 s_{12} + p_2 s_{22} = 0, \tag{41}$$

and

$$S_p = p_1 s_{11} + p_2 s_{22} = 1 \tag{42}$$

$(p_1 + p_2 = 1)$. There are three equations and three unknowns s_{11}, s_{12}, and s_{22}; therefore, there is a unique solution given by

$$s_{11} = p_2/p_1, \tag{43}$$

$$s_{12}(= s_{21}) = -1, \tag{44}$$

and

$$s_{22} = p_1/p_2. \tag{45}$$

The equitable skill score for $k = 2$, ESS_2, is given by

$$ESS_2 = p_{11}(p_2/p_1) + p_{12}(-1) + p_{21}(-1) + p_{22}(p_1/p_2), \tag{46}$$

or

$$ESS_2 = \frac{p_{11}p_{22} - p_{12}p_{21}}{p_1 p_2}. \tag{47}$$

Substituting from Tables 4 and 5 gives

$$ESS_2 = \frac{ad - bc}{(a+c)(b+d)}. \tag{48}$$

This version of ESS_2 is identical to the average likelihood difference performance score $\overline{LD}$ for the two-category case and can be used interchangeably with it. This does not imply that these performance measures are interchangeable for higher orders of k. The reason for using the approximate categorical form of LD in higher order performance matrices is to measure performance of the forecast guidance and/or the WSFO forecasts by category as well as overall.

(3) The three-event ESS

In three-event situations

$$\boldsymbol{P} = \begin{pmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & p_{22} & p_{23} \\ p_{31} & p_{32} & p_{33} \end{pmatrix}, \tag{49}$$

$\boldsymbol{p} = (p_1, p_2, p_3)$; $\boldsymbol{q} = (q_1, q_2, q_3)$; the assumption of symmetry implies $s_{21} = s_{12}$, $s_{31} = s_{13}$, and $s_{32} = s_{23}$, and

$$\boldsymbol{S} = \begin{pmatrix} s_{11} & s_{12} & s_{13} \\ s_{12} & s_{22} & s_{23} \\ s_{13} & s_{23} & s_{33} \end{pmatrix}; \tag{50}$$

The expected scores are given by

$$S_1 = p_1 s_{11} + p_2 s_{12} + p_3 s_{13} = 0, \tag{51}$$

$$S_2 = p_1 s_{12} + p_2 s_{22} + p_3 s_{23} = 0, \tag{52}$$

$$S_3 = p_1 s_{13} + p_2 s_{23} + p_3 s_{33} = 0, \tag{53}$$

and

$$S_p = p_1 s_{11} + p_2 s_{22} + p_3 s_{33} = 1 \tag{54}$$

$(p_1+p_2+p_3 = 1)$. There are four equations and six unknowns s_{11}, s_{12}, s_{13}, s_{22}, s_{23}, and s_{33}. Gandin and Murphy (1992) point out that a solution for this system of equations requires either imposing two additional relationships or specifying the values of two of the scores. Gerrity's solution for this case is given by

$$D_1 = \frac{1-p_1}{p_1}, \tag{55}$$

$$R_1 = \frac{p_1}{1-p_1}, \tag{56}$$

$$D_2 = \frac{1-(p_1+p_2)}{p_1+p_2}, \tag{57}$$

and

$$R_2 = \frac{p_1+p_2}{1-(p_1+p_2)}. \tag{58}$$

The solutions for the six unknowns are then given by

$$s_{11} = \frac{1}{2}\sum_{r=1}^{2} D_r, \tag{59}$$

$$s_{12} = \frac{1}{2}(D_2 - 1), \tag{60}$$

$$s_{13} = -1, \tag{61}$$

$$s_{22} = \frac{1}{2}(R_1 + D_2), \tag{62}$$

$$s_{23} = \frac{1}{2}(R_1 - 1), \tag{63}$$

and

$$s_{33} = \frac{1}{2}\sum_{r=1}^{2} R_r. \tag{64}$$

The associated score can be written

$$ESS_3 = \sum_{i=1}^{3}\sum_{j=1}^{3} p_{ij}s_{ij}. \tag{65}$$

(4) The four-event ESS

In four-event situations

$$\boldsymbol{P} = \begin{pmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \\ p_{41} & p_{42} & p_{43} & p_{44} \end{pmatrix}, \tag{66}$$

$\boldsymbol{p} = (p_1, p_2, p_3, p_4)$; $\boldsymbol{q} = (q_1, q_2, q_3, q_4)$; the assumption of symmetry implies $s_{21} = s_{12}$, $s_{31} = s_{13}$, $s_{41} = s_{14}$, $s_{32} = s_{23}$, $s_{42} = s_{24}$, and $s_{43} = s_{34}$, and

$$S = \begin{pmatrix} s_{11} & s_{12} & s_{13} & s_{14} \\ s_{12} & s_{22} & s_{23} & s_{24} \\ s_{13} & s_{23} & s_{33} & s_{34} \\ s_{14} & s_{24} & s_{34} & s_{44} \end{pmatrix}; \tag{67}$$

The expected scores are given by

$$S_1 = p_1 s_{11} + p_2 s_{12} + p_3 s_{13} + p_4 s_{14} = 0, \tag{68}$$

$$S_2 = p_1 s_{12} + p_2 s_{22} + p_3 s_{23} + p_4 s_{24} = 0, \tag{69}$$

$$S_3 = p_1 s_{13} + p_2 s_{23} + p_3 s_{33} + p_4 s_{34} = 0, \tag{70}$$

$$S_4 = p_1 s_{14} + p_2 s_{24} + p_3 s_{34} + p_4 s_{44} = 0, \tag{71}$$

and

$$S_p = p_1 s_{11} + p_2 s_{22} + p_3 s_{33} + p_4 s_{44} = 1 \tag{72}$$

$(p_1 + p_2 + p_3 + p_4 = 1)$. There are five equations and ten unknowns s_{11}, s_{12}, s_{13}, s_{14}, s_{22}, s_{23}, s_{24}, s_{33}, s_{34},and s_{44}. A solution for this system of equations requires either five additional relationships be imposed or values be specified for five of the scores.

Gerrity's solution for the 4 x 4 matrix is given by

$$D_1 = \frac{1 - p_1}{p_1}, \tag{73}$$

$$R_1 = \frac{1}{D_1}, \tag{74}$$

$$D_2 = \frac{1 - (p_1 + p_2)}{p_1 + p_2}, \tag{75}$$

$$R_2 = \frac{1}{D_2}, \tag{76}$$

$$D_3 = \frac{1 - (p_1 + p_2 + p_3)}{p_1 + p_2 + p_3}, \tag{77}$$

and

$$R_3 = \frac{1}{D_3}. \tag{78}$$

The solutions for the ten unknowns are then given by

$$s_{11} = \frac{1}{3}\sum_{r=1}^{3} D_r, \tag{79}$$

$$s_{12} = \frac{1}{3}\left(\sum_{r=2}^{3} D_r - 1\right), \tag{80}$$

$$s_{13} = \frac{1}{3}(D_3 - 2), \tag{81}$$

$$s_{14} = -1 \tag{82}$$

$$s_{22} = \frac{1}{3}\left(R_1 + \sum_{r=2}^{3} D_r\right), \tag{83}$$

$$s_{23} = \frac{1}{3}(R_1 + D_3 - 1), \tag{84}$$

$$s_{24} = \frac{1}{3}(R_1 - 2), \tag{85}$$

$$s_{33} = \frac{1}{3}\left(\sum_{r=1}^{2} R_r + D_3\right), \tag{86}$$

$$s_{34} = \frac{1}{3}\left(\sum_{r=1}^{2} R_r - 1\right), \tag{87}$$

and

$$s_{44} = \frac{1}{3}\sum_{r=1}^{3} R_r \tag{88}$$

The associated score can be written

$$ESS_4 = \sum_{i=1}^{4}\sum_{j=1}^{4} p_{ij}s_{ij}. \tag{89}$$

(5) The seven-event ESS

In seven-event situations

$$\boldsymbol{P} = \begin{pmatrix} p_{11} & p_{12} & p_{13} & p_{14} & p_{15} & p_{16} & p_{17} \\ p_{21} & p_{22} & p_{23} & p_{24} & p_{25} & p_{26} & p_{27} \\ p_{31} & p_{32} & p_{33} & p_{34} & p_{35} & p_{36} & p_{37} \\ p_{41} & p_{42} & p_{43} & p_{44} & p_{45} & p_{46} & p_{47} \\ p_{51} & p_{52} & p_{53} & p_{54} & p_{55} & p_{56} & p_{57} \\ p_{61} & p_{62} & p_{63} & p_{64} & p_{65} & p_{66} & p_{67} \\ p_{71} & p_{72} & p_{73} & p_{74} & p_{75} & p_{76} & p_{77} \end{pmatrix}, \tag{90}$$

$\boldsymbol{p} = (p_1, p_2, p_3, p_4, p_5, p_6, p_7)$; $\boldsymbol{q} = (q_1, q_2, q_3, q_4, q_5, q_6, q_7)$; the assumption of symmetry implies $s_{ji} = s_{ij}$, $(i, j = 1, \cdots, 7)$, and

$$\boldsymbol{S} = \begin{pmatrix} s_{11} & s_{12} & s_{13} & s_{14} & s_{15} & s_{16} & s_{17} \\ s_{12} & s_{22} & s_{23} & s_{24} & s_{25} & s_{26} & s_{27} \\ s_{13} & s_{23} & s_{33} & s_{34} & s_{35} & s_{36} & s_{37} \\ s_{14} & s_{24} & s_{34} & s_{44} & s_{45} & s_{46} & s_{47} \\ s_{15} & s_{25} & s_{35} & s_{45} & s_{55} & s_{56} & s_{57} \\ s_{16} & s_{26} & s_{36} & s_{46} & s_{56} & s_{66} & s_{67} \\ s_{17} & s_{27} & s_{37} & s_{47} & s_{57} & s_{67} & s_{77} \end{pmatrix}, \tag{91}$$

The expected scores are given by

$$S_j = \sum_{i=1}^{7} p_i s_{ji} = 0, \;\; (j = 1, \ldots, 7), \tag{92}$$

and

$$S_p = p_1 s_{11} + p_2 s_{22} + p_3 s_{33} + p_4 s_{44} + p_5 s_{55} + p_6 s_{66} + p_7 s_{77} = 1 \tag{93}$$

$\left(\sum_{i=1}^{7} p_i = 1\right)$. There are eight equations and 28 unknowns. A solution for this system of equations requires either 20 additional imposed relationships or specified scores.

Gerrity's solution for the 7 x 7 matrix is given by

$$D_1 = \frac{1 - p_1}{p_1}, \tag{94}$$

$$R_1 = \frac{1}{D_1}, \tag{95}$$

$$D_2 = \frac{1 - (p_1 + p_2)}{p_1 + p_2}, \tag{96}$$

$$R_2 = \frac{1}{D_2}, \tag{97}$$

$$D_3 = \frac{1 - (p_1 + p_2 + p_3)}{p_1 + p_2 + p_3}, \tag{98}$$

and

$$R_3 = \frac{1}{D_3}. \tag{99}$$

$$D_4 = \frac{1 - (p_1 + p_2 + p_3 + p_4)}{p_1 + p_2 + p_3 + p_4}, \tag{100}$$

and

$$R_4 = \frac{1}{D_4}. \tag{101}$$

$$D_5 = \frac{1 - (p_1 + p_2 + p_3 + p_4 + p_5)}{p_1 + p_2 + p_3 + p_4 + p_5}, \tag{102}$$

and

$$R_5 = \frac{1}{D_5}. \tag{103}$$

$$D_6 = \frac{1 - (p_1 + p_2 + p_3 + p_4 + p_5 + p_6)}{p_1 + p_2 + p_3 + p_4 + p_5 + p_6}, \tag{104}$$

and

$$R_6 = \frac{1}{D_6}. \tag{105}$$

The solutions for the 28 unknowns are then given by

$$s_{11} = \frac{1}{6} \sum_{r=1}^{6} D_r, \tag{106}$$

$$s_{12} = \frac{1}{6}\left(\sum_{r=2}^{6} D_r - 1\right), \tag{107}$$

$$s_{13} = \frac{1}{6}\left(\sum_{r=3}^{6} D_r - 2\right), \tag{108}$$

$$s_{14} = \frac{1}{6}\left(\sum_{r=4}^{6} D_r - 3\right), \tag{109}$$

$$s_{15} = \frac{1}{6}\left(\sum_{r=5}^{6} D_r - 4\right), \tag{110}$$

$$s_{16} = \frac{1}{6}(D_6 - 5), \tag{111}$$

$$s_{17} = -1 \tag{112}$$

$$s_{22} = \frac{1}{6}\left(R_1 + \sum_{r=2}^{6} D_r\right), \tag{113}$$

$$s_{23} = \frac{1}{6}\left(R_1 + \sum_{r=3}^{6} D_r - 1\right), \tag{114}$$

$$s_{24} = \frac{1}{6}\left(R_1 + \sum_{r=4}^{6} D_r - 2\right), \tag{115}$$

$$s_{25} = \frac{1}{6}\left(R_1 + \sum_{r=5}^{6} D_r - 3\right), \tag{116}$$

$$s_{26} = \frac{1}{6}(R_1 + D_6 - 4), \tag{117}$$

$$s_{27} = \frac{1}{6}(R_1 - 5), \tag{118}$$

$$s_{33} = \frac{1}{6}\left(\sum_{r=1}^{2} R_r + \sum_{r=3}^{6} D_r\right), \tag{119}$$

$$s_{34} = \frac{1}{6}\left(\sum_{r=1}^{2} R_r + \sum_{r=4}^{6} D_r - 1\right), \tag{120}$$

$$s_{35} = \frac{1}{6}\left(\sum_{r=1}^{2} R_r + \sum_{r=5}^{6} D_r - 2\right), \tag{121}$$

$$s_{36} = \frac{1}{6}\left(\sum_{r=1}^{2} R_r + D_6 - 3\right), \tag{122}$$

$$s_{37} = \frac{1}{6}\left(\sum_{r=1}^{2} R_r - 4\right), \tag{123}$$

$$s_{44} = \frac{1}{6}\left(\sum_{r=1}^{3} R_r + \sum_{r=4}^{6} D_r\right), \tag{124}$$

$$s_{45} = \frac{1}{6}\left(\sum_{r=1}^{3} R_r + \sum_{r=5}^{6} D_r - 1\right), \tag{125}$$

$$s_{46} = \frac{1}{6}\left(\sum_{r=1}^{3} R_r + D_6 - 2\right), \tag{126}$$

$$s_{47} = \frac{1}{6}\left(\sum_{r=1}^{3} R_r - 3\right), \tag{127}$$

$$s_{55} = \frac{1}{6}\left(\sum_{r=1}^{4} R_r + \sum_{r=5}^{6} D_r\right), \tag{128}$$

$$s_{56} = \frac{1}{6}\left(\sum_{r=1}^{4} R_r + D_6 - 1\right), \tag{129}$$

$$s_{57} = \frac{1}{6}\left(\sum_{r=1}^{4} R_r - 2\right), \tag{130}$$

$$s_{66} = \frac{1}{6}\left(\sum_{r=1}^{5} R_r + D_6\right), \tag{131}$$

$$s_{67} = \frac{1}{6}\left(\sum_{r=1}^{5} R_r + D_6 - 1\right), \tag{132}$$

and

$$s_{77} = \frac{1}{6}\sum_{r=1}^{6} R_r \tag{133}$$

The associated score can be written

$$ESS_7 = \sum_{i=1}^{7}\sum_{j=1}^{7} p_{ij} s_{ij}. \tag{134}$$

(6) The eight-event ESS

In eight-event situations

$$\boldsymbol{P} = \begin{pmatrix} p_{11} & p_{12} & p_{13} & p_{14} & p_{15} & p_{16} & p_{17} & p_{18} \\ p_{21} & p_{22} & p_{23} & p_{24} & p_{25} & p_{26} & p_{27} & p_{28} \\ p_{31} & p_{32} & p_{33} & p_{34} & p_{35} & p_{36} & p_{37} & p_{38} \\ p_{41} & p_{42} & p_{43} & p_{44} & p_{45} & p_{46} & p_{47} & p_{48} \\ p_{51} & p_{52} & p_{53} & p_{54} & p_{55} & p_{56} & p_{57} & p_{58} \\ p_{61} & p_{62} & p_{63} & p_{64} & p_{65} & p_{66} & p_{67} & p_{68} \\ p_{71} & p_{72} & p_{73} & p_{74} & p_{75} & p_{76} & p_{77} & p_{78} \\ p_{81} & p_{82} & p_{83} & p_{84} & p_{85} & p_{86} & p_{87} & p_{88} \end{pmatrix}, \tag{135}$$

$p = (p_1, p_2, p_3, p_4, p_5, p_6, p_7, p_8)$; $q = (q_1, q_2, q_3, q_4, q_5, q_6, q_7, q_8)$; the assumption of symmetry implies $s_{ji} = s_{ij}$, $(i, j = 1, \cdots, 8)$, and

$$S = \begin{pmatrix} s_{11} & s_{12} & s_{13} & s_{14} & s_{15} & s_{16} & s_{17} & s_{18} \\ s_{12} & s_{22} & s_{23} & s_{24} & s_{25} & s_{26} & s_{27} & s_{28} \\ s_{13} & s_{23} & s_{33} & s_{34} & s_{35} & s_{36} & s_{37} & s_{38} \\ s_{14} & s_{24} & s_{34} & s_{44} & s_{45} & s_{46} & s_{47} & s_{48} \\ s_{15} & s_{25} & s_{35} & s_{45} & s_{55} & s_{56} & s_{57} & s_{58} \\ s_{16} & s_{26} & s_{36} & s_{46} & s_{56} & s_{66} & s_{67} & s_{68} \\ s_{17} & s_{27} & s_{37} & s_{47} & s_{57} & s_{67} & s_{77} & s_{78} \\ s_{18} & s_{28} & s_{38} & s_{48} & s_{58} & s_{68} & s_{78} & s_{88} \end{pmatrix}, \tag{136}$$

The expected scores are given by

$$S_j = \sum_{i=1}^{8} p_i s_{ji} = 0, \; (j = 1, \ldots, 8), \tag{137}$$

and

$$S_p = p_1 s_{11} + p_2 s_{22} + p_3 s_{33} + p_4 s_{44} + p_5 s_{55} + p_6 s_{66} + p_7 s_{77} + p_8 s_{88} = 1 \tag{138}$$

$\left(\sum_{i=1}^{8} p_i = 1\right)$. There are nine equations and 36 unknowns. A solution for this system of equations requires either 27 additional imposed relationships or specified scores.

Ordinarily, Gerrity (1992) would be used to impose the added relationships, but this ESS is used to verify performance of wind direction guidance and forecasts. Wind direction is a periodic parameter with a range of values from 0° to 360°; the error in wind direction ranges from −180° to 180°. A negative (positive) error is interpreted to mean the forecast wind direction is counterclockwise (clockwise) of the observed wind direction. For a distributive variable (for example, wind speed) with an eight category performance matrix, the maximum error can be 7 categories different from the correct category. For the wind direction, the maximum error can only be 4 categories different, where the absolute difference in degrees is 23 - 67 degrees for 1 category, 68 - 112 degrees for 2 categories, 113 - 157 degrees for 3 categories, and 158 - 180 degrees for 4 categories.

The pattern of categorical errors for the performance matrix is given as

$$\begin{pmatrix} C & +1 & +2 & +3 & +4 & -3 & -2 & -1 \\ -1 & C & +1 & +2 & +3 & +4 & -3 & -2 \\ -2 & -1 & C & +1 & +2 & +3 & +4 & -3 \\ -3 & -2 & -1 & C & +1 & +2 & +3 & +4 \\ -4 & -3 & -2 & -1 & C & +1 & +2 & +3 \\ +3 & -4 & -3 & -2 & -1 & C & +1 & +2 \\ +2 & +3 & -4 & -3 & -2 & -1 & C & +1 \\ +1 & +2 & +3 & -4 & -3 & -2 & -1 & C \end{pmatrix},$$

where the Cs are the correct forecasts and the positive (negative) values indicate how many categories clockwise(counterclockwise) of the observations the forecasts are.

Assume a sample spans a year for a given station, or includes data from all stations in the NMVP for a given observation time, the distribution of wind directions will be about equal for each category. Let k_1, k_2, k_3, and k_4 be scores with specified values which are substituted into $\boldsymbol{S}$ in the same place as the categorical errors shown above so that

$$\boldsymbol{S} = \begin{pmatrix} s_{11} & k_1 & k_2 & k_3 & k_4 & k_3 & k_2 & k_1 \\ k_1 & s_{22} & k_1 & k_2 & k_3 & k_4 & k_3 & k_2 \\ k_2 & k_1 & s_{33} & k_1 & k_2 & k_3 & k_4 & k_3 \\ k_3 & k_2 & k_1 & s_{44} & k_1 & k_2 & k_3 & k_4 \\ k_4 & k_3 & k_2 & k_1 & s_{55} & k_1 & k_2 & k_3 \\ k_3 & k_4 & k_3 & k_2 & k_1 & s_{66} & k_1 & k_2 \\ k_2 & k_3 & k_4 & k_3 & k_2 & k_1 & s_{77} & k_1 \\ k_1 & k_2 & k_3 & k_4 & k_3 & k_2 & k_1 & s_{88} \end{pmatrix}.$$

This implies that $k_1 = s_{12} = s_{18} = s_{23} = s_{34} = s_{45} = s_{56} = s_{67} = s_{78}$; $k_2 = s_{13} = s_{17} = s_{24} = s_{28} = s_{35} = s_{46} = s_{57} = s_{68}$; $k_3 = s_{14} = s_{16} = s_{25} = s_{27} = s_{36} = s_{38} = s_{47} = s_{58}$, and $k_4 = s_{15} = s_{26} = s_{37} = s_{48}$ for the upper triangle of the matrix. Symmetry is also retained.

If the specified ks are substituted into (137), then there are eight equations and eight unknowns; however, (138) has not been taken into account. If the equations from (137) are added together, and the terms collected, then

$$[2(k_1 + k_2 + k_3) + k_4] \sum_{i=1}^{8} p_i + \sum_{i=1}^{8} p_i s_{ii} = 0$$

is the result. Recalling $\sum_{i=1}^{8} p_i = 1$ and substituting (138) into the foregoing gives

$$2(k_1 + k_2 + k_3) + k_4 + 1 = 0, \tag{139}$$

or

$$2(k_1 + k_2 + k_3) + k_4 = -1. \tag{140}$$

This relationship must hold in order for equitability to occur; therefore, the ks must be specified to satisfy (140). The equations for the unknowns are

$$s_{11} = -[k_1(p_2 + p_8) + k_2(p_3 + p_7) + k_3(p_4 + p_6) + k_4 p_5]/p_1, \tag{141}$$

$$s_{22} = -[k_1(p_1 + p_3) + k_2(p_4 + p_8) + k_3(p_5 + p_7) + k_4 p_6]/p_2, \tag{142}$$

$$s_{33} = -[k_1(p_2 + p_4) + k_2(p_1 + p_5) + k_3(p_6 + p_8) + k_4 p_7]/p_3, \tag{143}$$

$$s_{44} = -[k_1(p_3 + p_5) + k_2(p_2 + p_6) + k_3(p_1 + p_7) + k_4 p_8]/p_4, \tag{144}$$

$$s_{55} = -[k_1(p_4 + p_6) + k_2(p_3 + p_7) + k_3(p_2 + p_8) + k_4 p_1]/p_5, \tag{145}$$

$$s_{66} = -[k_1(p_5 + p_7) + k_2(p_4 + p_8) + k_3(p_1 + p_3) + k_4 p_2]/p_6, \tag{146}$$

$$s_{77} = -[k_1(p_6 + p_8) + k_2(p_1 + p_5) + k_3(p_2 + p_4) + k_4 p_3]/p_7, \tag{147}$$

and

$$s_{88} = -[k_1(p_1 + p_7) + k_2(p_2 + p_6) + k_3(p_3 + p_5) + k_4 p_4]/p_8. \tag{148}$$

In the NMVP, $k_1 = -0.025$, $k_2 = -0.075$, $k_3 = -0.15$, and $k_4 = -0.5$.

The associated score is given by

$$ESS_8 = \sum_{i=1}^{8} \sum_{j=1}^{8} p_{ij} s_{ij}. \tag{149}$$

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