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TECHNICAL NOTE*

OPEN OCEAN FOG AND VISIBILITY FORECAST GUIDANCE SYSTEM

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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, 4pp.

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. Ocean Products Center Technical Note, 23pp.

No. 3. Auer, S. J., 1986: Determination of Errors in LFM Forecasts Surface Lows Over the Northwest Atlantic Ocean. Ocean Products Center 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, 98pp.

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No. 7. Burroughs, L. D., 1986: Development of Open Fog Forecasting Regions. Ocean Products Center Technical Note/NMC Office Note. No. 323., 36pp.

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No. 14. Gemmill, W.H., D.M. Feit, T.W. Yu, 1987: Performance of Techniques Used to Derive Ocean Surface Winds. Ocean Products Center Technical Note/NMC Office Note No. 330, 34pp.

OPEN OCEAN FOG AND VISIBILITY FORECAST GUIDANCE SYSTEM

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ABSTRACT.

A guidance system to forecast open ocean fog and visibility has recently been implemented at NMC. The system, based on perfect prog statistics, forecasts fog and visibility over the open ocean during the months of April through September when these factors create significant hazards to navigation in the northern hemisphere.

Although the forecasts degrade in time, evaluation of the guidance shows it to have skill against climatology through 72 hours. In the Pacific, the fog equations tend to be unbiased, while in the Atlantic they tend to underforecast fog. The visibility equations in both oceans tend to overforecast the lowest category. In the Pacific the 1200 UTC equations tend to out perform the 0000 UTC equations. In the Atlantic the reverse is true, but not as noticeably as in the Pacific.

This forecast guidance is depicted on the Marine Significant Weather Chart during the months of April through September. Implementation of this system took place in September 1988.

INTRODUCTION

A large percentage of the accidents at sea occur with visibilities under one kilometer (Tremant, 1987). Although other obstructions may lower visibility below 1 km, the most prevalent obstruction is fog. Fog is only reported if the visibility is 1 km or less. Until now there has been no objective guidance available to National Weather Service forecasters for fog or lowered visibilities. The Open Ocean Fog and Visibility Forecast Guidance System was born out of a desire to fill this need. This system is designed to provide fog and visibility guidance over the North Pacific and North Atlantic during the prime season for fog and lowered visibilities (April - September). The guidance is not applicable to coastal areas.

DEVELOPMENT

The perfect prog technique (Klein *et al*, 1959) was used to develop the fog and visibility forecast equations. With this approach all data used in the development of relationships are analyzed or observed data. Usually, the predictor and predictand are concurrent in time. When the equations are used to predict, forecast values of the predictors must be obtained and substituted into the equations to give a forecast of the predictand. The name perfect prog comes from the fact that forecast data are entered into the equation as if it were equivalent to the analyzed data that were used to develop the equations (Wilson and Macdonald, 1985).

Predictand Data

The predictand data were taken from ship data for the years 1980 - 1983 at 12 hour intervals. Fog data included observed fog of any kind and observed drizzle when the past weather indicated fog and the visibility was less than 1 km. The fog was categorized as no fog or fog. Visibility data were corrected to be consistent with the observed weather and the WMO code and include poor visibility due to fog. Visibility is categorized to delineate areas with a visibility of less than or greater than 3 n mi.

Predictor Data

The predictor data came primarily from the analyzed fields of the Global Data Assimilation System (GDAS) (Kistler and Parrish, 1982 and Dey and Morone, 1985) or computations made by using the GDAS data. In addition a boundary layer diagnostic model was used to create air temperatures and equivalent potential temperatures at 19 m (the nominal height of most ship instrumentation). In all, 20 basic GDAS fields and 45 computed fields were used plus four climatological parameters and two location parameters. These potential predictors are shown in Tables 1 - 4. The data were interpolated to the location of the ship data to derive the forecast equations.

Regions

Burroughs (1987) describes the development of open ocean fog forecasting regions based on a National Climatic data Center fog climatology (Guttman, 1971), the frequency of fronts

Table 1: Basic GDAS fields used as predictors in the Open Ocean Fog and Visibility Forecast Guidance System equations.

Model Parameter	Surface	1000 mb	850 mb	700 mb	500 mb
Sea Level Pressure	X				
Height		X	X	X	X
Sea Temperature	X				
Air Temperature			X	X	
Relative Humidity		X	X	X	X
u-Wind Component		X	X	X	X
v-Wind Component		X	X	X	X

Table 2: Same as Table 1 except predictors are computed from GDAS fields or the boundary layer diagnostic model (BLDM). Only the 19 m fields come from the BLDM.

Computed Parameters	19 m	1000 mb	850 mb	700 mb	500 mb
Air Temperature	X				
Equivalent Potential Temperature	X		X	X	
Geostrophic u-Wind		X	X	X	X
Geostrophic v-Wind		X	X	X	X
Geostrophic Wind Speed		X	X	X	X
Relative Vorticity		X	X	X	X
Relative Vorticity Advection		X	X	X	X
Geostrophic Relative Vorticity		X	X	X	X
Geostrophic Relative Vorticity Advection		X	X	X	X

Table 3: Same as Table 1 except predictors are differences computed from fields listed in Tables 1 and 2.

19 m Air Temperature	-	Sea Surface Temperature
19 m Air Temperature	-	850 mb Air Temperature
19 m Air Temperature	-	700 mb Air Temperature
850 mb Air Temperature	-	700 mb Air Temperature
19 m Equivalent Potential Temperature	-	850 mb Equivalent Potential Temperature
19 m Equivalent Potential Temperature	-	700 mb Equivalent Potential Temperature
850 mb Equivalent Potential Temperature	-	700 mb Equivalent Potential Temperature
850 mb Height	-	1000 mb Height
700 mb Height	-	1000 mb Height
500 mb Height	-	1000 mb Height
700 mb Height	-	850 mb Height
500 mb Height	-	850 mb Height
500 mb Height	-	700 mb Height

Table 4: Same as Table 1 except predictors are for special purposes.

Predictor	Purpose
Latitude ($2.5X2.5^{\circ}$ grid: $j = 37, 73$)	Provides location adjustment
Longitude ($2.5X2.5^{\circ}$ grid: $i = 1, 145$)	Provides location adjustment
$\sin(\frac{2\pi(\text{day of the year (DOY)})}{365})$	Provides for climatological influences
$\cos(\frac{2\pi(\text{DOY})}{365})$	Provides for climatological influences
$\sin(\frac{4\pi(\text{DOY})}{365})$	Provides for climatological influences
$\cos(\frac{4\pi(\text{DOY})}{365})$	Provides for climatological influences

over the open ocean and the frequency of high and low centers over the open ocean. Thirteen warm and 13 cool season regions were delineated. These regions were then modified by the inclusion of drizzle and observed fog data for 1980 - 1984. The number of regions was reduced to those shown in Figs. 1 and 2 after test equations were derived and evaluated, and the results showed the equations for the regions excluded to be too unreliable to use. In general the regions with the highest probabilities of fog have been included.

Equation Development

Equations were developed for fog and visibility with discriminant techniques. A short discussion on these techniques, following Tatsuoka (1971), is given below. For additional information see Anderson (1958), Miller (1962), or Cooley and Lohnes (1971).

In meteorology, categorical events are often related to continuous predictors by the use of discriminant analysis. The categorical events are grouped by category. Then equations are developed by using the continuous predictors which best separate the groups.

Having developed the equations, the next question is how to classify a particular observation into a particular group. The objective is to minimize the number of misclassifications. The chi-squared statistic is used for this purpose. The smaller the value of chi-squared for a particular group the nearer the observation is to the average value for that group. Since the equations for each group differ only by the coefficients and constants used, the observation is categorized into the group whose equation has the smallest chi-squared value. This assumes that the groups have multivariate normal distributions with equal dispersion matrices, and, therefore, that a pooled covariance matrix can be used to compute chi-squared for each group. The equation is given by

$$\begin{aligned} \chi^2_{ik} &= \{X_{1i} - \overline{X}_{1k}, X_{2i} - \overline{X}_{2k}, \cdots, X_{pi} - \overline{X}_{pk}\} \, \mathbf{D}_w^{-1} \, \{X_{1i} - \overline{X}_{1k}, \cdots, X_{pi} - \overline{X}_{pk}\}^T \\ &= \mathbf{x}_{ik} \, \mathbf{D}_w^{-1} \, \mathbf{x}_{ik}^T \end{aligned} \tag{1}$$

where i is the observation index; p is the predictor index; k is the group index; $\mathbf{D}_w = \mathbf{S}_w/(N-K)$ is the pooled dispersion matrix; $\mathbf{S}_w$ is the pooled within-groups SSCP (sum of squares and crossproducts) matrix; $N = n_1 + n_2 + \cdots + n_k$, and K is the number of groups.

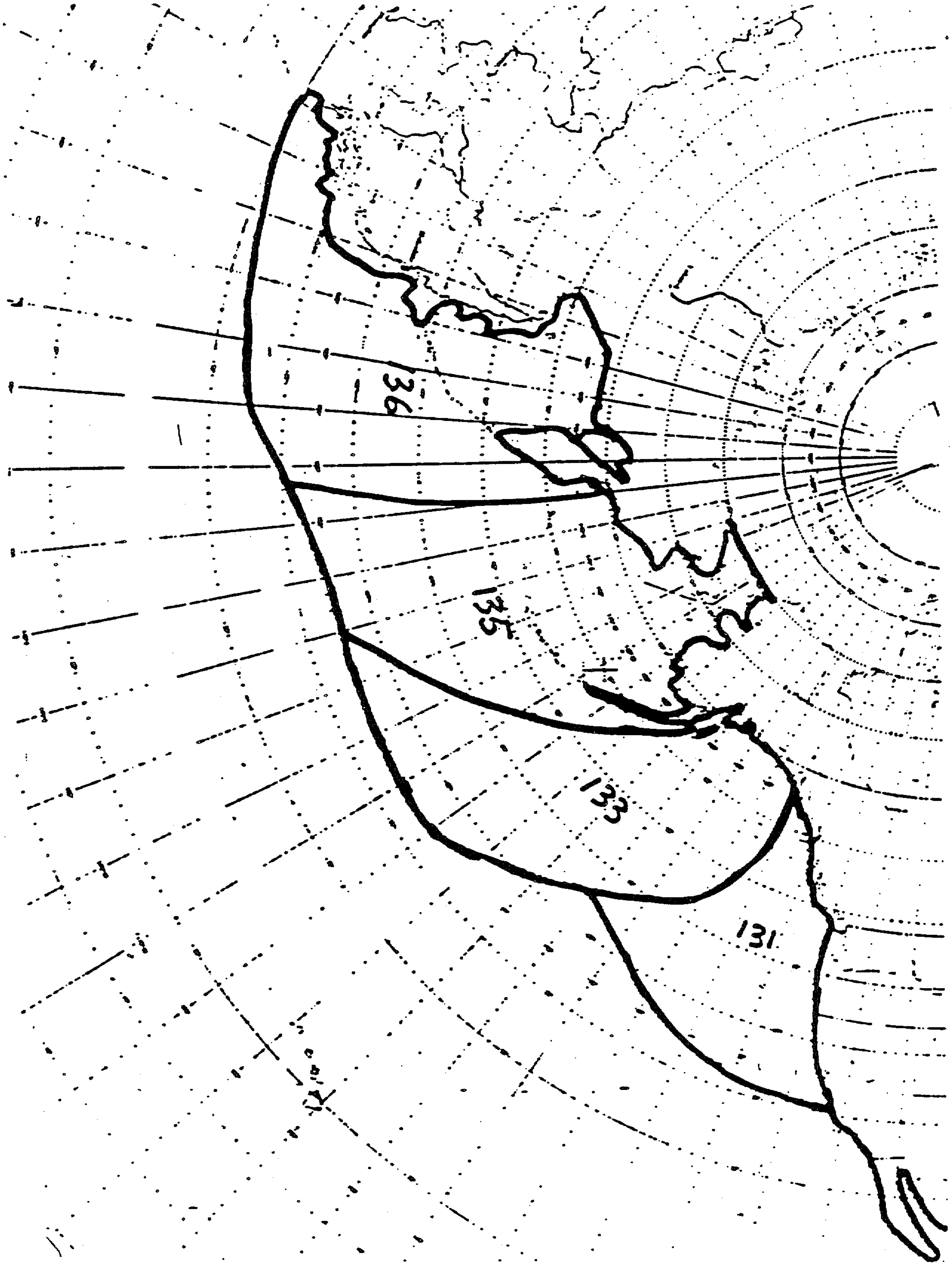

Figure 1: Warm season fog and visibility regions for the North Pacific.

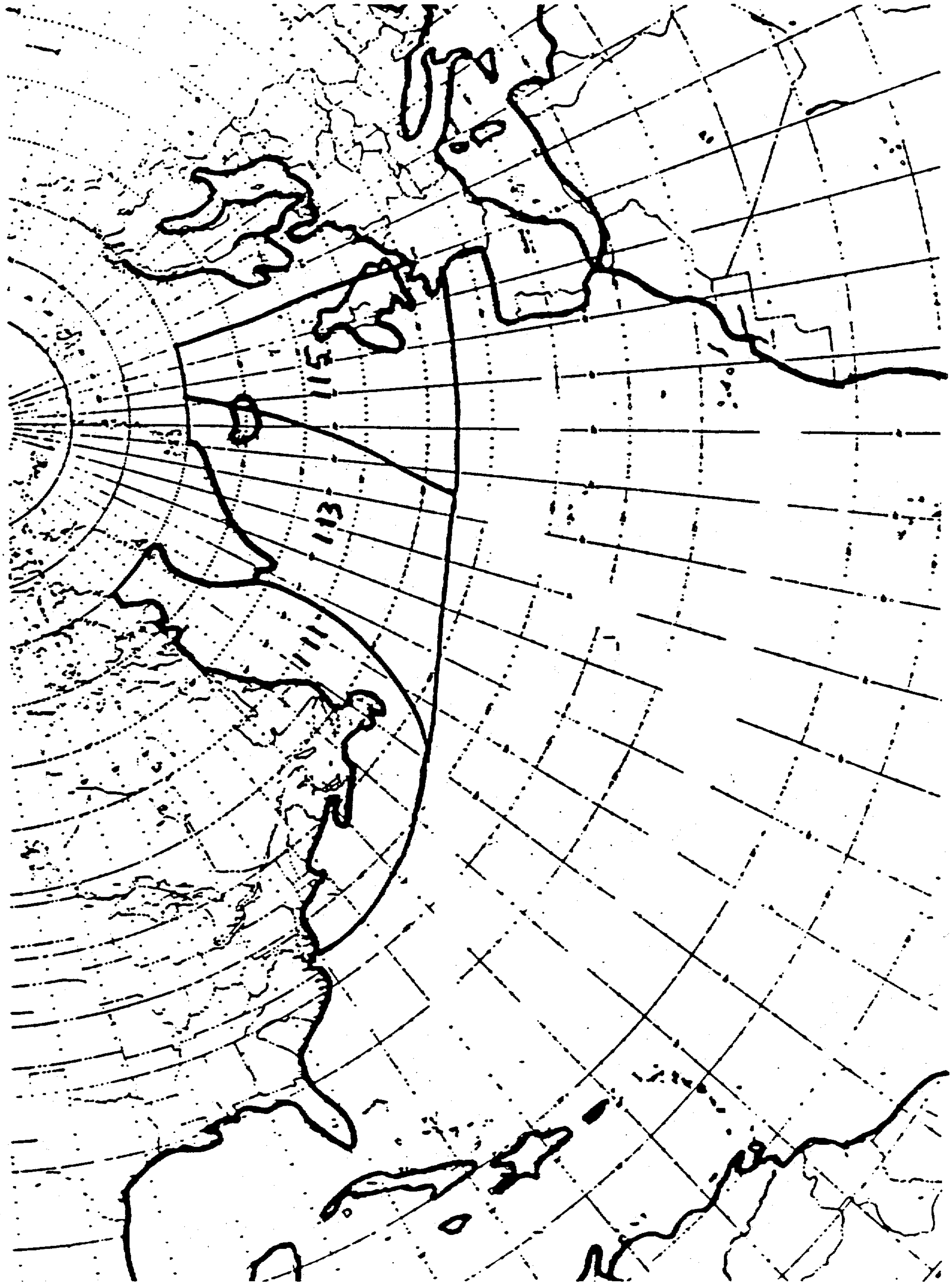

Figure 2: Warm season (April - September) fog and visibility regions for the North Atlantic.

When the covariance matrix cannot be pooled, the group equations are corrected for the differences in dispersion by using the individual group covariance matrices, and (1) becomes

$$\chi^2_{ik} = \mathbf{x}_{ik}\,\mathbf{D}_k^{-1}\,\mathbf{x}_{ik}^T \tag{2}$$

where $\mathbf{D}_k = \mathbf{S}_k/(N-1)$ is the dispersion matrix of the kth group; $\mathbf{S}_k$ is the within-groups SSCP matrix of the kth group; and $N = n_1 + n_2 + \cdots + n_k$. The classification rule is modified to be based on minimizing not χ^2 itself, but an adjusted quantity χ'^2 defined by

$$\chi'^2_{ik} = \chi^2_{ik} + \ln|D_k| \tag{3}$$

which is proportional to the natural logarithm of the multivariate normal density function $N(\overline{\mathbf{X}}_k, \mathbf{D}_k)$ evaluated at the point $\mathbf{X}_i' = [X_{1i}, X_{2i}, \cdots, X_{pi}]$. $|D_k|$ is the determinant of the dispersion matrix, $\mathbf{D}_k$.

Nowhere have the prior probabilities (relative frequencies) of group membership been taken into account. Thus far the assumption has been that the relative frequencies of all the groups are equal. For fog and visibility, this is not the case. χ'^2 can be further adjusted to take into account the prior probabilities which have been determined from the dependent predictand samples. With this adjustment (3) becomes

$$\chi''^2_{ik} = \chi'^2_{ik} - 2\ln p_k \tag{4}$$

where p_k is the prior probability, *ie* the probability that an observation selected at random from a mixed population comprising all K groups is a member of the kth group.

We have already assumed that the group dispersions are multivariate normal; if we further assume that an observation fits into one of the groups and does not fall outside the ensemble of groups, then χ''^2 can be related to the posterior probability that an observation belongs to a particular group. The equation for the posterior probability is given by

$$p(H_k|\mathbf{X}_i) \quad = \quad \frac{\exp(-\chi''^2_{ik}/2)}{\sum_{j=1}^{K}\exp(-\chi''^2_{ij}/2)} \qquad\qquad k = 1, 2, \cdots, K \tag{5}$$

where H_k is the hypothesis that the observation vector $\mathbf{X_i}$ belongs to group k. $\mathbf{X_i}$ is assigned to the group whose posterior probability is greatest.

If the discrimination was perfect, no further adjustments would be necessary. This, generally, is not the case, and two other procedures can be used to help minimize the number of misclassifications: inflation (Klein *et al*, 1959 and Miller 1988) and thresholding.

Inflation adjusts the forecasts so that the variance of the forecasts and the observations in the climatology are approximately equal. The inflated forecast is given by

$$\widehat{p}(H_k|\mathbf{X}_i) \quad = \quad \frac{p(H_k|\mathbf{X}_i) - p_k}{r} + p_k \tag{6}$$

where the $\wedge$ indicates the inflated probability; r is the canonical correlation or, for a two group case such as fog, the maximum correlation between a linear function of predictor variables and the criterion variable, and p_k is the prior probability for group k determined from the developmental sample and is an estimate of the group's climatological probability. This procedure is applied to the fog and visibility posterior probabilities prior to classification.

Thresholding means that a given category may not be chosen unless a certain predictand value is reached (in this case a given posterior probability). These values are normally determined empirically. This procedure is applied to the fog posterior probabilities after inflation.

To determine which variables to use as predictors, a stepwise discriminant analysis procedure was employed. The predictand was a classification variable which defined the groups with which the predictors were to be associated. Potential predictors were chosen to enter or stay in the discriminant model according to specified criteria for the squared partial correlation of the predictor with the classification variable, accounting for the effects of the predictors already selected.

The procedure began by selecting the variable that contributed most to the discriminatory power (group separation) of the equations and met the criterion to enter (a partial squared correlation of 0.0005). At each succeeding step, if a variable already selected failed to meet the criterion to stay (a partial squared correlation of 0.0025), it was removed. Otherwise, the variable, not already selected, that contributed most to the discriminatory power of the equations and met the criterion to enter was added. When all variables selected met the criterion to stay, and none of the remaining variables met the criterion to enter, the stepwise selection stopped (SAS, 1982). This procedure was used to determine which predictors to use in the final equations and provided the canonical correlation used in the inflation procedure. This procedure assumes that the variables are multivariate normal with equal dispersions.

Once the predictors for the fog and visibility equations were chosen, a second procedure was used. This procedure derived the final group equations which took into account the differences in dispersion matrices between the groups and the group prior probabilities. These equations produce the posterior probabilities for each group. The posterior probabilities are then inflated, and a threshold is applied to the fog equations.

There are two equation sets for fog and visibility in each region shown in Figs. 1 and 2: one for the 0000 UTC cycle and one for the 1200 UTC cycle. The reason for this is that the amount of predictand data and its quality varies between cycles. There is always less data available on the night cycle than the day cycle. The reason is that ships report fewer night observations than day observations. Also the day observations tend to be better than the night observations. In the Pacific the day observations occur on the 1200 UTC cycle, while the night observations occur on the 0000 UTC cycle. In the Atlantic the reverse is true although the number of observations per cycle are more balanced than in the Pacific.

Forecasts are made from the Aviation initialization and at 24-h intervals for projections from 24 through 72 hours from Aviation model output. At present only the 24- and 48-h forecasts on the 0000 UTC cycle are used on the Marine Significant Weather Chart (NWS, 1988). Eventually the 72-h forecast will be added and the 1200 UTC cycle forecasts. The initialization is used for verification studies only.

EVALUATION

Operational equations were derived for the warm season only. Several statistics may be used to evaluate the forecasts made with the equations. The ones which were used are described in the section below. The evaluation of the results is given following the description of the statistics.

Statistical Scores Used

All scores used in the evaluations are derived from the contingency table shown in Table 5. Each score can be expanded to include more terms depending on the number of categories in the contingency table.

Skill Score Against Climatology. The score is given by

$$SS = \frac{a+d-E}{a+b+c+d-E} \tag{7}$$

where $E = p_c(1)\cdot(a+c)+p_c(2)\cdot(b+d)$ and gives the number of correct forecasts that would have been predicted by climatology alone, $p_c(1)$ and $p_c(2)$ are the climatological probabilities of occurrence for each category, a and d are the number of correct forecasts in each category, and b and c are the number of incorrect forecasts in each category (Panofsky and Brier, 1963).

Bias. This score measures under or over forecasting in a given category and is given by

$$B(1) = \frac{a+b}{a+c} \quad \text{and} \quad B(2) = \frac{c+d}{b+d} \tag{8}$$

where $B(1)$ and $B(2)$ are the biases for each category. A bias of 1 means the number of observations and the number of forecasts in a given category are equal. It does not mean all the forecasts are correct. A bias of less than 1 means the category is being under forecast. A bias greater than 1 means the category is being over forecast.

Threat Score. The threat score is developed from the percent correct which is the total number of correct forecasts divided by the total number of forecasts, but which is not very useful if one is interested in how well a particular category is being forecast. This is particularly true of rare events. To determine how well an individual category is being forecast, the number of correct forecasts from the other categories is removed from the numerator and denominator of the percent correct to give categorical threat scores which are given by

$$TS(1) = \frac{a}{a+b+c} \quad \text{and} \quad TS(2) = \frac{d}{b+c+d} \tag{9}$$

where $TS(1)$ and $TS(2)$ are the categorical threat scores. In general the term threat score is applied only to rare events.

Fog and Visibility Evaluations

Evaluations were made with two months of data from the 1987 warm season (June and July). Tables 6 and 7 show the probabilities of occurrence for each category for the Atlantic and Pacific Oceans for fog and visibility respectively. Individual evaluations of fog and visibility were done for each region, but only the combined results are shown here. Tables 8 - 11 show the results of the evaluations of fog and visibility respectively.

In the Atlantic the fog is underforecast on both cycles. The results are better on the 1200 UTC forecasts than the 0000 forecasts. The equations have reasonable skill against climatology at all projections on both cycles. The visibility equations tend to overforecast the lowest category on both cycles and at all projections. Their skill is reasonable against climatology. The threat scores are less than hoped for, but can be improved by better optimization of the equations with different thresholds.

In the Pacific the fog results are better than the Atlantic. There is less underforecasting on both cycles, and the threat scores are better. The results are better on the 0000 UTC forecasts than the 1200. The differences between cycles is primarily due to the availability and quality of data on the respective cycles which is different in the two oceans as explained in Section 3. The visibility forecasts are worse in the Pacific than the Atlantic, but they still show skill against climatology at all projections. These scores can also be improved with

		FORECASTS		
OBSERVATIONS		1	2	TOTAL
	1	a	b	$a+b$
	2	c	d	$c+d$
	TOTAL	$a+c$	$b+d$	$a+b+c+d$

Table 5: Contingency table for two categories.

Region	fog	no fog
111	.19799	.80201
113	.19271	.80729
115	.05711	.94289
Atlantic	.14499	.85501
131	.06152	.93848
133	.16371	.83629
135	.30270	.69730
136	.26370	.73630
Pacific	.22593	.77407

Table 6: Fog climatology for the months of June and July. Probabilities were determined from data for the years 1980 through 1984.

Region	< 5.5 km	≥ 5.5 km
111	.35317	.64683
113	.35593	.64407
115	.19887	.80113
Atlantic	.29765	.70235
131	.15121	.84879
133	.33484	.66516
135	.51203	.48797
136	.45108	.54892
Pacific	.40232	.59768

Table 7: Visibility climatology for the months of June and July. Probabilities were determined from data for the years 1980 through 1984.

Table 8: Evaluation fog forecasts with independent data from June and July 1987 for the North Atlantic regions combined.

Projection	Sample Size	Skill Score	Bias		Threat Score	
			Fog	No Fog	Fog	No Fog
		0000 UTC				
00	2017	.194	0.52	1.08	.16	.83
24	2019	.288	0.58	1.06	.15	.86
48	2014	.228	0.54	1.07	.14	.85
72	2060	.223	0.55	1.07	.16	.84
		1200 UTC				
00	2261	.329	0.68	1.04	.16	.86
24	2167	.340	0.67	1.04	.16	.87
48	2034	.340	0.61	1.05	.15	.87
72	1757	.291	0.67	1.04	.14	.86

Table 9: Evaluation of fog forecasts with independent data from June and July 1987 for the North Pacific regions combined.

Projection	Sample Size	Skill Score	Bias		Threat Score	
			Fog	No Fog	Fog	No Fog
		0000 UTC				
00	4402	.312	1.06	0.99	.24	.75
24	4359	.313	0.96	1.01	.25	.76
48	4361	.300	0.92	1.02	.25	.75
72	4468	.261	0.94	1.01	.24	.73
		1200 UTC				
00	1402	.294	0.97	1.01	.19	.77
24	1343	.269	0.88	1.03	.19	.76
48	1266	.270	0.92	1.02	.21	.75
72	1163	.299	0.86	1.03	.22	.77

Table 10: Evaluation visibility forecasts with independent data from June and July 1987 for the North Atlantic regions combined.

Projection	Sample Size	Skill Score	Bias		Threat Score	
			< 5.5 km	≥ 5.5 km	< 5.5 km	≥ 5.5 km
			0000 UTC			
00	1750	.233	1.26	0.95	.22	.77
24	1801	.227	1.36	0.94	.19	.76
48	1773	.180	1.21	0.96	.17	.75
72	1790	.151	1.50	0.92	.16	.74
			1200 UTC			
00	2025	.246	1.14	0.98	.17	.79
24	1958	.262	1.19	0.97	.20	.79
48	1838	.249	1.06	0.99	.20	.79
72	1571	.252	1.26	0.96	.20	.77

Table 11: Evaluation of visibility forecasts with independent data from June and July 1987 for the North Pacific regions combined.

Projection	Sample Size	Skill Score	Bias		Threat Score	
			< 5.5 km	≥ 5.5 km	< 5.5 km	≥ 5.5 km
			0000 UTC			
00	3713	.094	1.91	0.78	.23	.61
24	3645	.097	1.84	0.80	.22	.62
48	3595	.098	1.72	0.82	.21	.61
72	3652	.106	1.70	0.83	.22	.62
			1200 UTC			
00	1193	.054	2.08	0.75	.21	.58
24	1128	.074	2.02	0.79	.20	.62
48	1049	.060	2.11	0.77	.20	.61
72	968	.019	2.20	0.78	.15	.61

different thresholding.

AVAILABILITY

Output from the Fog and Visibility Forecast Guidance System is depicted on the Marine Significant Weather Chart. Figure 3 shows a sample chart. The scalloped lines are where visibility decreases to 3 n mi or less and the hatched areas are where fog is predicted to occur.

OPERATIONAL CONSIDERATIONS

Since the system uses the perfect prog technique, forecasts tend to degrade in time; however, they have reasonable skill against climatology even at 72 hours. Because the forecast equations use model output, the forecasts from the guidance system depend on model performance; therefore, the forecaster needs to be aware of how the model is doing in his or her area of interest in order to make any necessary adjustments to the statistically derived forecast.

The forecaster should also keep in mind that system is designed for open ocean fog and visibility forecast guidance only. Its guidance should not be extrapolated into coastal areas. The system is also not designed to delineate lowered visibilities due to isolated mesoscale phenomena.

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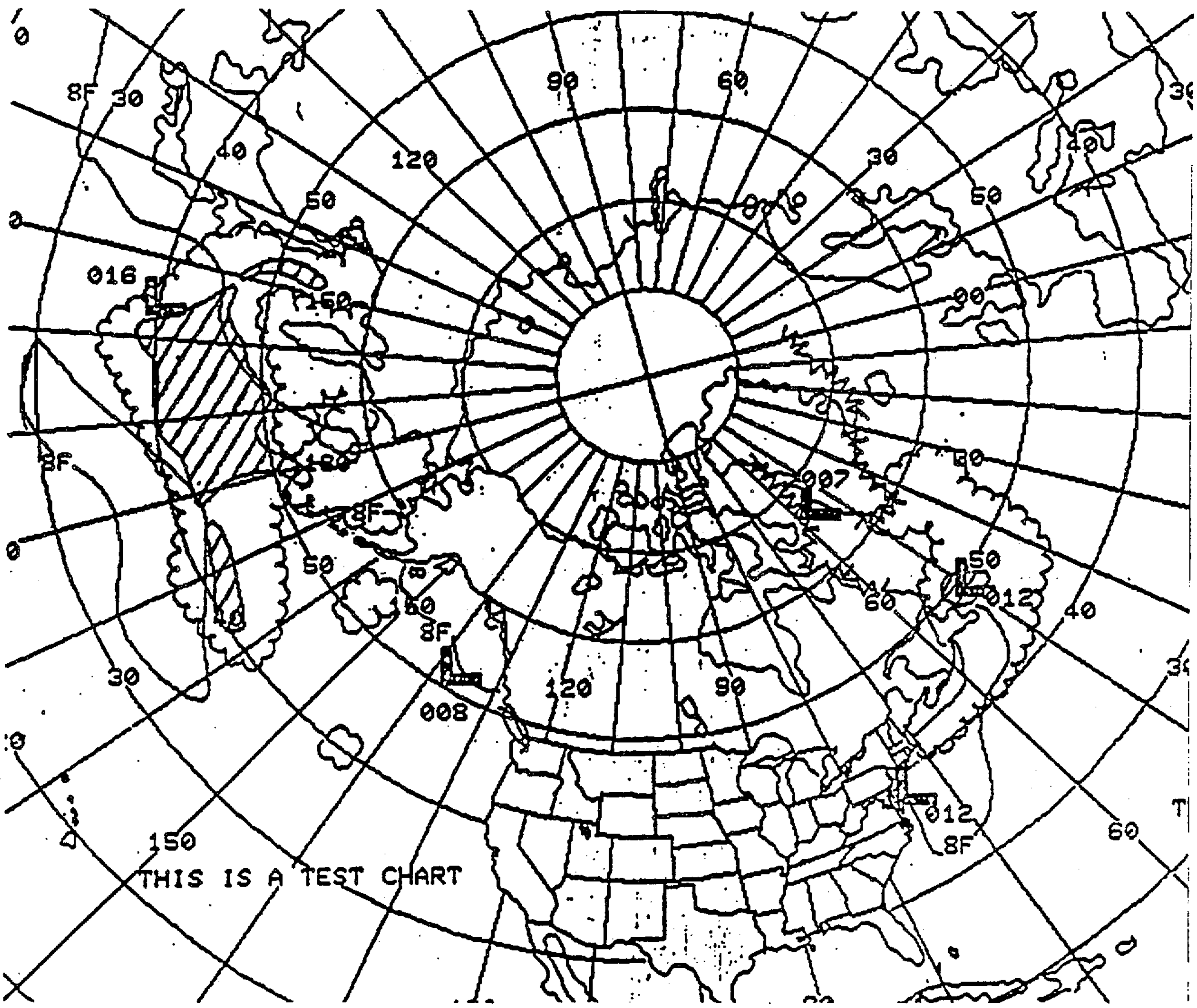

Figure 3: Sample Marine Significant Weather Chart. Scalloped lines indicate visibilities of 3 n mi or less. Hatching indicates fog.

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