ESTIMATING VISIBILITY OVER THE NORTH PACIFIC OCEAN USING MODEL OUTPUT STATISTICS

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ABSTRACT

The method of model output statistics (MOS) is used to develop multiple linear regression equations for forecasting the probability of marine visibility in five categories (0-.49, 0.5-1.9, 2-9.9, 10-19 and 20-50 km) at 24-h intervals to 48-h, for the summer season, North Pacific Ocean area. Further manipulation of the scheme yields categorical visibility forecasts for three (0-1.9, 2-9.9, 10-50 km) and two (0-9.9, 10-50 km) visibility categories. Dependent and independent tests are verified using percentage correct, bias, Heidke skill score and threat score. The experiment establishes the credibility of MOS applications over open ocean areas, with levels of skill commensurate to those for MOS visibility forecasts over land.

1. INTRODUCTION

Although fog and visibility forecast schemes abound for coastal locations, the open ocean has been largely ignored. These kinds of forecasts are of particular importance in order to safely execute maritime shipping and naval sea/air operations. Maritime casualties due to fog-related low visibility are highest in the summer months (Figure 1) when the combination of extent and density of fog is at a maximum (3,4). Since the ongoing computerized atmospheric prediction models do not output visibility directly, a reasonable approach to forecasting visibility is through the use of Model Output Statistics (MOS) (5). For the experiment reported on here, the North Pacific Ocean (30-60N, 145E-130W) was selected as the test basin, with various Fleet Numerical Oceanography Center (FNOC), Monterey, CA analysis and prediction models supplying the basic Model Output Parameters (MOP) from a 23x12 section of FNOC's Northern Hemisphere 63x63 polar stereographic grid. Verification of the developed MOS forecast scheme is compared to that using visibility climatology (3), visibility persistence, and a limited sample of National Weather Service MOS visibility forecasts for the continental United States (6).

2. DATA/PARAMETERS

The surface ship observational data from the North Pacific Ocean were obtained from the Naval Oceanography Center Detachment, Asheville NC, which is co-located with the National Climatic Data Center (NCDC). These data, Tape Data Family-11 (TDF-11), which are filtered to exclude duplications and erroneous reports, are a compilation of information from ships' logs, ships' weather reporting forms, published ship observations, automatic observing buoys, teletype reports and data purchased from foreign meteorological services. The quality varies from those observations taken by a deckhand to those of a trained observer. Data at 0000 GMT (local daylight) for the summer months July/August 1979 served as the dependent/independent data set. Over 4000 synoptic ship reports were available for each month.

The basic set of MOP's consists of 24 diagnostic-prognostic parameters generated from FNOC's Mass Structure Analysis Model and the Primitive Equation, Marine Wind and Ocean Wave Prediction Models. An additional 79 interactive and derived dynamic and thermal parameters, continuous and binary, were obtained from this set. Appendix (A) is a selected list of those model output and climatology parameters used in developing the MOS equations.

3. PROCESSING THE DATA AND DEVELOPMENT OF REGRESSION EQUATIONS

The first step consisted of interpolating the MOP's and derived parameters (via a curvilinear bi-cubic spline routine) from the FNOC grid to each ship position, where they were matched to the respective visibility code. These interpolated parameters (predictors) were then used in the stepwise multiple linear regression program BMDP2R (7) to derive five equations, the predictands of which are parameters indicating the five visibility ranges shown in Table I.

REGRESSION EQUATION (Visibility category)	VISIBILITY RANGE	SYNOPTIC OBSERVATION CODE
1	0.0- 0.49 km	90-92
2	0.5- 1.9 km	93-94
3	2.0- 9.9 km	95-96
4	10.0-19.0 km	97
5	20.0-50.0 km	98-99

Table I. Visibility categories

A comparison of open ocean visibility forecasting using MOS, in one case with a categorical predictand (8) and in the other case with a probabilistic predictand (9,10), indicated the desirability of the latter approach. The remainder of this paper will focus on the probabilistic visibility approach. Table II indicates the predictand values assigned to each ship observation as a function of reported visibility, for each of the five regression equations developed.

VISIBILITY FORECAST EQUATION (1)	(2)	(3)	(4)	(5)	SYNOPTIC OBSERVATION CODE
100	25	0	0	0	90
100	50	0	0	0	91
100	75	25	0	0	92
75	100	50	0	0	93
50	100	75	25	0	94
25	75	100	50	25	95
0	50	100	75	50	96
0	25	75	100	75	97
0	0	50	75	100	98
0	0	25	50	100	99

Table II. Visibility probability (%) (= predictand) assigned to each synoptic ship observation as a function of reported visibility, for each of the five regression equations developed.

For example, in deriving the equation for specifying visibility category 3 (see Table I), observations coded as 95 or 96 were assigned a predictand value of 100%, those with codes 94 and 97 a value of 75%, codes 93 and 98 a value of 50%, and so forth. Ideally, the predictand used in developing that equation should be 100% for all observations in codes 95 and 96 and 0% for all other visibility codes (i.e. 90 to 94 and 97 to 99). But, it is commonly accepted that visibility observations at sea are inexact at best (i.e. code 95 may be reported when in fact code 94 was observed, etc.). The ideal approach was tried first but it was not as successful as assigning to the predictand percentages other than 0% to visibility codes outside of the category to which the equation applies, in this case category (3). Several variations for predictand assignment were tried, such as 80% for code 94, 60% for code 93, 30% for code 92; and similarly for codes 97, 98 and 99. Considering all equations, it was most methodical and the success of the technique was best when using the quartile reduction approach, that is reducing the predictand value by 25% increments in either direction from the codes defining the category. Table II entries should not be viewed horizontally--only vertically, and, of course, the percentages should not add up to 100% or any other prescribed value. This is an experimental quantitative approach to an existing problem in working with visibility observations at sea.

Three sets of five equations each: a diagnostic set (tau 0 h) and two prognostic sets (tau 24 and 48 h), were derived (10) from the July 1979 data set (Tables III, IV and V). Only those predictors that contributed at least 0.5% to the explained variance of the predictand were retained. The evaporative heat flux (EHF) is prominent in all equations. The majority of explained variance was determined by this one parameter whenever it was the leading parameter. Negative (positive) EHF implies that the moisture flux is directed downward toward (upward from) the sea and is associated with low (high) visibility. It is evident that the visibility class 2-9.9 km is the most difficult to specify from the available FNOC predictor parameters.

VIS CODE GROUP	VISIBILITY PROBABILITY		R^2 (percent)
90-92	-35.1586		
(0-.49 km)	-0.9191	EHF	18.6
	43.9857	FTER	2.6
	0.0039	RASTDX	1.3
	0.0048	RHRSQ	1.0
	0.5606	BVISX	0.9
	0.0255	RASTDR	0.6
			25.0
93-94	356.8071		
(0.5-1.9 km)	-1.6095	EHF	19.0
	-1.1414	BVISR	6.2
	28.4439	FTER	1.2
	0.4441	BVISX	0.7
	0.0047	U925	0.5
	-0.3126	PS	0.5
			28.1
95-96	129.1194		
(2-9.9 km)	-0.9573	BVISX	5.0
	-0.6316	RHX	1.2
	-0.4581	ASTDRX	1.4
			7.6
97	75.6061		
(10-19 km)	0.5649	EHF	14.8
	-38.1213	FTER	2.2
	-0.9247	BVISX	1.7
	0.7383	BVISR	1.4
	-0.0237	RASTDR	0.8
	0.0041	U925	0.5
			21.4
98-99	57.5600		
(20-50 km)	1.9054	EHF	22.8
	1.4265	BVISR	5.4
	-40.5343	FTER	1.6
	-0.6891	BVISX	1.2
	0.0056	U925	0.6
			31.6

Table III. Regression equations for estimating visibility probability, by visibility code-group for the North Pacific Ocean 30-60N 145E-130W, Tau 0 h (4079 observations, July 1979). Variables for initial time listed in order of selection. R^2 specifies variance explained by each predictor. See Appendix A for parameter description.

VIS CODE GROUP	VISIBILITY PROBABILITY		R^2 (percent)
90-92	18.6298		
(0-.49 km)	-1.9898	EHF 24	23.0
	0.0213	RASTDX 00	2.0
	19.9026	FTER 00	1.0
	-0.5685	VVWW 36	0.6
	17.9254	FTER 24	0.5
			27.1
93-94	32.5351		
(0.5-1.9 km)	-2.0482	EHF 24	23.2
	-0.5285	BVISR 00	2.2
	0.0204	RASTDX 00	1.3
	18.4725	FTER 24	0.7
			27.4
95-96	137.1898		
(2-9.9 km)	-1,2913	BVISX 00	3.0
	-19.4424	FTER 00	1.6
	-0.5658	RHX 00	1.2
	-5.8802	EHF 24	0.9
	-0.6511	VVWW 00	0.7
			7.4
97	61.9611		
(10-19 km)	1.5293	EHF 24	18.2
	-0.0210	RASTDX 00	2.2
	-14.9147	FTER 00	0.7
	0.5736	VVWW 36	0.7
	-16.5002	FTER 24	0.5
			22.3
98-99	63.5259		
(20-50 km)	2.8336	EHF 24	28.3
	-0.0245	RASTDX 00	1.8
	0.5113	BVISR 00	1.2
	-21.7912	FTER 24	0.7
			32.0

Table IV. Same as Table III except Tau 24 h (4095 observations). Number following parameter indicates initial time (00) or prediction interval (12, 24, 36, 48) in h.

VIS CODE GROUP	VISIBILITY PROBABILITY		R^2 (percent)
90-92	-428.6230		
(0-.49 km)	-1.8534	EHF 36	20.9
	27.3651	FTER 00	2.0
	25.8898	FTER 48	1.1
	-48.3218	GGTHTA 36	1.0
	0.4235	PS 36	1.0
	0.4132	MBVIS 48	0.6
			26.6
93-94	-353.1233		
(0.5-1.9 km)	-1.0305	EHF 36	19.3
	0.2561	CLIMO 00	1.7
	22.6730	FTER 48	1.3
	-0.4162	BVISR 00	0.9
	0.3658	PS 24	0.6
	0.0146	RASTDX 00	0.6
			24.4
95-96	145.7690		
(2-9.9 km)	-1.3323	BVISX 00	1.5
	-1.1001	VVWW 00	1.7
	-0.6430	RHX 00	2.0
	2.4041	SSANOM 00	0.8
	0.3604	VVWW 36	0.6
			6.6
97	497.9680		
(10-19 km)	1.5811	EHF 36	16.0
	-19.7227	FTER 00	1.2
	0.4588	UCOMP 48	1.0
	40.4127	GGTHTA 36	0.8
	-18.4243	FTER 48	0.7
	-0.4210	PS 48	0.6
	-0.1205	ASDXSQ 00	0.7
			21.0
98-99	560.3628		
(20-50 km)	0.8640	EHF 36	23.7
	-26.1329	FTER 00	1.6
	-21.1406	FTER 48	1.4
	5.0147	TSEA 00	1.2
	-3.7253	EX 48	1.2
	-0.4837	PS 36	0.8
			29.9

Table V. Same as Table IV except Tau 48 h (4102 observations).

The forecast goal is to identify the one most likely category of visibility at any location for tau 0, 24 and 48 h. However, a number of comparisons of the predictand probabilities (P) computed from each of the five regression equations indicated a less-than-desirable focusing of the most likely visibility category (i.e. the one category to be forecasted). For example, the highest computed P among the five categories did not necessarily exceed the optimal threshold probability (P_t) for that category. Here P_t (Table VI), is defined, for each visibility category and time interval, as that predictand probability which best separates forecasts of occurrence and nonoccurrence of the categorical visibility event. The P_t used here maximizes the threat score (Appendix B) for each category. These considerations led to the definition of a decision ratio as a function of P, P_t (Table VI) for each regression equation (visibility category). In the experimental form shown here, P^2/P_t acts to suitably identify the most likely visibility category when P $\geq P_t$;Const P_t in the denominator serves to finely tune the decision ratio for best verification.

1) For $P/Pt \geq 1$:

REGRESSION EQUATION (visibility category)	DECISION RATIO	THRESHOLD VALUE TAU O, 24, 48 h
1	P^2/Pt	57, 54, 62
2	$P^2/1.1$ Pt	59, 55, 60
3	$P^2/0.9$ Pt	45, 34, 33
4	$P^2/1.1$ Pt	42, 47, 39
5	P^2/Pt	49, 45, 42

2) For $P/Pt < 1$, use P/Pt.

Table VI. The most likely visibility category at a location is that one category which is identified by the maximum decision ratio.

Even with minor statistical adjustments to the threshold values (Pt), low verification scores indicate that the initial MOS scheme developed here, which is verified to differentiate between five visibility categories, is operationally unusable. Table VII illustrates this fact for 24 h MOS visibility forecasts.

From the perspective of using the MOS scheme to forecast Navy carrier flight operations, it appeared advisable to collapse the five categories into three. Such a scheme approximates the primary visibility conditions for the launch and recovery of fixed-wing aircraft over the open ocean (11). In carrying out this modification, the original five regression equations and decision ratio calculations were retained, but for estimation and verification purposes the visibility categories were recombined in the following manner:

CATEGORIES 1 and 2 ⟶ CATEGORY 1a (0-1.9 km)
CATEGORY 3 ⟶ CATEGORY 2a (2.0-9.9 km)
CATEGORIES 4 and 5 ⟶ CATEGORY 3a (10-50 km)

Visibility Category		ESTIMATED (1)	(2)	(3)	(4)	(5)	TOTAL
	(1)	219	206	3	49	64	541
	(2)	139	166	18	71	70	464
OBSERVED	(3)	83	130	71	186	118	588
	(4)	65	90	29	282	232	698
	(5)	104	145	9	595	951	1804
TOTAL		610	737	130	1183	1435	4095

BIAS 1.13; 1.59; 0.22; 1.69; 0.80
PERCENT CORRECT = 41
HEIDKE SKILL SCORE = 0.280; 0.160; 0.154; 0.109; 0.323 (overall 0.218)
THREAT SCORE = 0.235; 0.160; 0.110; 0.176; 0.416

Table VII. Verification matrix of visibility estimates using MOS, five categories. 24 h forecasts, July 1979 dependent data set, North Pacific Ocean 30-60N 145E-130W. (Pt), from Table VI, modified as follows: 54, 65, 24, 57, 45 for categories 1-5, respectively.

Three-category verification results for both the dependent (July 79) and independent (August 79) 24 h forecasts appear in Table VIII.

DEPENDENT TEST JULY 1979

VISIBILITY CATEGORY		ESTIMATED (1a)	(2a)	(3a)	TOTAL
	(1a)	651	48	280	979
OBSERVED	(2a)	183	83	299	565
	(3a)	329	60	2031	2420
	TOTAL	1163	191	2610	3964

BIAS = 1.19; 0.34; 1.08
PERCENT CORRECT = 70
HEIDKE SKILL SCORE = 0.464; 0.159; 0.475; (overall 0.417)
THREAT SCORE = 0.437; 0.123; 0.667

INDEPENDENT TEST AUGUST 1979

VISIBILITY CATEGORY		ESTIMATED (1a)	(2a)	(3a)	TOTAL
	(1a)	464	51	316	831
OBSERVED	(2a)	129	48	308	485
	(3a)	276	47	2644	2967
	TOTAL	869	146	3268	4283

BIAS = 1.05; 0.30; 1.10
PERCENT CORRECT = 74
HEIDKE SKILL SCORE = 0.434; 0.105; 0.445; (overall 0.385)
THREAT SCORE = 0.375; 0.082; 0.736

Table VIII. Verification matrices, 24 h forecasts, three-category visibility estimates, MOS scheme North Pacific Ocean 30-60N 145E-130W July 1979 dependent and August 1979 independent data sets.

Compared to the five-category verification, the biases for categories 1a and 3a are much nearer to the desired value of 1.0, and percent correct and skill score have increased markedly. While the results for categories 1a and 3a showed considerable improvement, biases in category 2a indicate that this middle category is considerably underforecasted. 48 h MOS forecasts behave similarly.

In view of the continued problem with the visibility range 2.0 to 9.9 km, there followed a further recombination of categories 1, 2 and 3. Forecast detail is reduced and verification scores enhanced.

CATEGORIES 1,2 and 3 → CATEGORY 1b (0-9.9km)
CATEGORIES 4 and 5 → CATEGORY 2b (10-50km)

DEPENDENT TEST JULY 1979 (24 h forecast)

VISIBILITY CATEGORY		ESTIMATED (1b)	(2b)	TOTAL
	(1b)	965	579	1544
OBSERVED	(2b)	389	2031	2420
	TOTAL	1354	2610	3964

BIAS = 0.88; 1.08
PERCENT CORRECT = 76
HEIDKE SKILL SCORE = 0.475
THREAT SCORE = 0.499; 0.677

INDEPENDENT TEST AUGUST 1979 (24 h forecast)

VISIBILITY CATEGORY		ESTIMATED (1b)	(2b)	TOTAL
	(1b)	692	624	1316
OBSERVED	(2b)	323	2644	2967
	TOTAL	1015	3268	4283

BIAS = 0.77; 1.10
PERCENT CORRECT = 78
HEIDKE SKILL SCORE = 0.445
THREAT SCORE = 0.422; 0.736

DEPENDENT TEST JULY 1979 (48 h forecast)

VISIBILITY CATEGORY		ESTIMATED (1b)	(2b)	TOTAL
	(1b)	885	634	1519
OBSERVED	(2b)	391	1924	2315
	TOTAL	1276	2558	3834

BIAS = 0.84; 1.10
PERCENT CORRECT = 73
HEIDKE SKILL SCORE = 0.425
THREAT SCORE = 0.463; 0.652

INDEPENDENT TEST AUGUST 1979 (48 h forecast)

VISIBILITY CATEGORY		ESTIMATED (1b)	(2b)	TOTAL
	(1b)	557	678	1235
OBSERVED	(2b)	322	2548	2870
	TOTAL	879	3226	4105

BIAS = 0.71; 1.12
PERCENT CORRECT = 76
HEIDKE SKILL SCORE = 0.369
THREAT SCORE = 0.358; 0.718

Table IX. Verification matrices, 24 and 48 h forecast; two-category visibility estimates, MOS scheme North Pacific Ocean 30-60N 145E-130W July 1979 dependent and August 1979 independent data sets.

A graphical measure of the utility and credibility of the two or three category scheme is shown by Figure 2, in which an analysis of the categorized visibility observations for 0000 GMT 18 July 1979 is compared to the 24 h MOS-estimated visibilities.

4. VISIBILITY PERSISTENCE AND CLIMATOLOGY

Persistence is an often used forecast comparison scheme. The visibility persistence parameter developed at NPS is dependent on the MOS diagnostic visibility parameter and the observed value of visibility. In particular, visibility values from the July MOS scheme were used to initialize the polar stereographic grid field on a daily basis for that month. This field was then modified by the current visibility observations of surrounding ships, using an objective analysis based upon an inverse-distance formula. These changed field values were then re-interpolated back to the original ship positions using a curvilinear bi-cubic spline routine. Table X indicates the skill of the persistence field for initial, 24 and 48 h forecast times.

	JULY	AUGUST
00 h	0.598	0.614
24 h	0.327	0.360
48 h	0.241	0.260

Table X. Heidke skill scores using a persistence parameter for visibility estimates at 00, 24 and 48h, July and August 1979.

The skill scores are less than desirable, in part because grid-point values are not good indicators of local visibility conditions whenever there are large variations in the reported visibility at ship locations surrounding a grid point. The larger the gross-mesh size, the greater the number of ship reports that are interpolated to each grid point and the greater the likelihood of large variations. Nevertheless, if the 'Persistence' parameter developed here is in any way descriptive of persistence, it does indicate that persistence is not useful for forecasting open-ocean visibility. As evidence, note the rapid decrease in skill score for the 24- and 48-h forecasts (Table X). A visibility climatology frequency parameter was also derived for each Marsden square (10 lat x 10 long) using data received from NCDC Asheville (3). Instead of using climatological average visibilities (since these averages are biased toward good visibility), weighted values, using a percentage of each visibility category, were tried. In either case, there is an overwhelming tendency for the climatology parameter to over-forecast good visibility and the results were of little use, either alone or in combination with persistence or the MOS scheme.

5. FINAL REMARKS

Model output statistics, as a forecast scheme, has been in use for nearly a decade in the National Weather Service (NWS). To date, applications have been exclusively over land. The subject experiment with marine visibility and another with marine fog (12) indicates the applicability of MOS over the open ocean, with verification scores comparable to those published by NWS for MOS over continental U.S. (See 6 for example.) At the time of this writing, the U.S. Navy is developing plans for the extensive use of MOS forecasting over its marine area of responsibility -- the oceans of the world.

Another measure of the operational skill of the MOS technique proposed here is to compare the machine generated objective MOS forecasts to their subjectively prepared counterparts. MOS forecasts can be archived readily for future study, as is done by the NWS for land areas. However, manually prepared forecasts for visibility at specified ocean locations have not been collected and processed in the past, but, of course, should be in the future. Published comparisons of the two types of forecasts will be necessary if the operational forecaster is to properly use the MOS guidance and, indeed, improve on it.

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APPENDIX A

MODEL OUTPUT PARAMETER (MOP) DESCRIPTIONS

Continuous and binary (limits), direct and derived, Fleet Numerical Oceanography Center MOP's and climatology used in the development of the multiple linear regression equations shown in Tables III, IV and V.

Legend: <u>Models</u> -- a) analysis model; b) Northern Hemisphere primitive equation and c) marine wind models (parameters available at 12-h intervals from initial time to 48 h).

<u>Descriptive Title of Each Parameter</u> --

A. <u>Direct Model Output Parameters</u>

EAIR;a	Surface Vapor Pressure
EHF;b	Evaporative Heat Flux
EX;b	Surface Vapor Pressure
FTER;b,c	Advective Fog Probability
GGTHETA;b	Front-Location Parameter
PS;a	Sea-Level Pressure
SSANOM;a	Sea-Surface Temperature Anomaly from Monthly Mean
TAIR;a	Surface Air Temperature
TSEA;a	Sea-Surface Temperature
TX;b	Surface Air Temperature
U925;b	Zonal Wind 925 mb
VVWW;c	Marine Wind Speed

B. <u>Dynamic/Thermal Parameters Derived from Model Output Parameters</u>

ASTDR;a	TAIR-TSEA
ASTDX;a,b	TX-TSEA
BVISR;a,c	Infrared Extinction Parameter
BVISX;b,c	Infrared Extinction Parameter
MBVIS;b,c	Modified IR Extinction Parameter
RHR;a	Relative Humidity from EAIR & TAIR
RHX;b	Relative Humidity from EX & TX
U(COMP);c	Zonal Wind Component

C. <u>Combination Model Output Parameters</u>

ASDXSQ	=	ASTDX	•	ASTDX
ASTDRX	=	ASTDR	•	ASTDX
RASTDR	=	RHR	•	ASTDR
RASTDX	=	RHR	•	ASTD
RHRSQ	=	RHR	•	RHR

D. <u>Climatology</u>

CLIMO	Marine Fog Frequency

APPENDIX B

VERIFICATION SCORE FORMULAE

Definitions of the verification score formulae used in the study follow. A 2x2 contingency table illustrates the observation/estimation data basic to the definitions.

		Estimated Category	
		1	2
Observed Category	1	A	B
	2	C	D

Total (T) = A + B + C + D

No. of Correct Forecasts (FC) = A + D

Heidke Skill Score (HSS) = $\frac{FC - EX}{T - EX}$,

Range of HSS: $\frac{-2BC}{B^2 + C^2} \leq HSS \leq 1$,

where correct number of estimates due to chance = (EX) = $\frac{(A+B)(A+C) + (D+B)(D+C)}{T}$

Threat Score (TS) = $\frac{A}{T - D} = \frac{A}{A + B + C}$

Range: $0 \leq TS \leq 1$

FIGURES

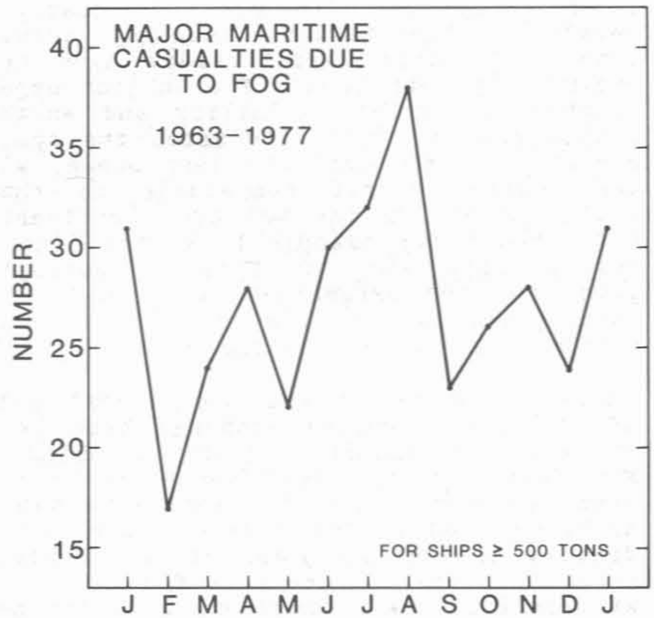

Figure 1. 323 major maritime casualties due to fog-associated low visibility for ships $\geq$500 tons (1963-77), derived from data furnished by the National Climatic Data Center, Asheville, N.C. Casualty data generally from ships operating in the Northern Hemisphere.

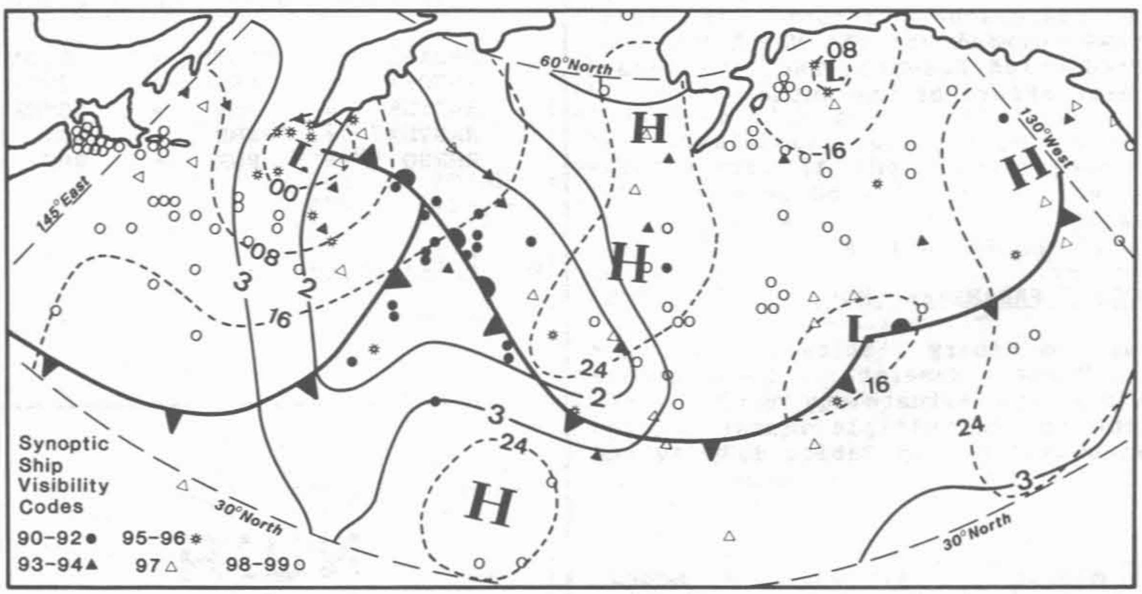

Figure 2. Objective analysis of regression-estimated visibility categories, three and two-category schemes, Tau 24 h, verifying at 0000 GMT 18 July 1979: Light solid lines (Area: < 2 = Category 1a (0-1.9 km); 2-3 = Category 2a (2-9.9 km); $\geq$3 = Category 3a ($\geq$10 km)). <3 = Category 1b = sum of Categories 1a and 2a (0-9.9 km). National Weather Service Sea-Level Pressure Analysis: dashed lines, 8 mb interval (16 = 1016 mb); Surface Fronts:

FOOTNOTES AND REFERENCES

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