SEA ICE EDGE FORECAST VERIFICATION PROGRAM FOR THE BERING SEA

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Abstract

The Navy/NOAA Joint Ice Center issues 7-Day forecasts of changes in the position of the sea ice edge over the Bering Sea each week. These forecasts are used by marine interests, especially crab fishing fleets, to aid in safe and efficient operations. The Center undertook the verification of these forecasts, despite observational difficulties, in order to assess their merits and to explore ways to make them more accurate. Ice forecasts for the ice seasons of 1987–88 and 1988–89 were compared to climatologically derived changes in ice edge position and comparative statistics were developed. The mean error of the Center's 7-Day forecasts was about 23 n mi and 25 n mi for 1987–88 and 1988–89, respectively. The Center's forecasts outperformed climatology in both years by about 25%. Persistence forecasts proved poor since the ice edge rarely remained in the same location from week to week. A modified persistence forecast (using the prior week's ice edge motion) also proved far less accurate than climatological or Center forecasts. The Joint Ice Center's requirements for forecast accuracy were shown to be met, on average, but individual forecast errors highlight the Ice Center's dependence upon accurate medium range predictions by both NMC and the European Center for Medium Range Forecasting (ECMWF).

1. Introduction

The Navy/NOAA Joint Ice Center (JIC) is engaged in global sea ice analysis and forecasting. This paper describes a program to verify the accuracy of the JIC's routinely produced 7-Day ice edge forecasts for the Bering Sea. The ice edge changes in response to environmental conditions and is normally located using satellite remote sensing. Ice forecast user requirements are determined by the application and vary over a wide range. Fixed platform operations and some research applications call for accuracies exceeding the resolution of the best operational sensors, 0.6 n mi. At the other extreme, most operational Global Circulation Models call for ice edge accuracies of about ± 60 n mi. The majority of JIC's users are either commercial operators or Navy fleet elements who require ice edge information with an accuracy of between 10 and 60 n mi as an aid to navigation. As a compromise to the users and a concession to ice edge detection accuracy, the JIC ice forecasters established 7-Day forecast accuracy goals of ± 20 n mi under clear sky (good observation) conditions and ± 60 n mi under other, less favorable conditions.

Sea ice forecasting remains a subjective skill with few quantitative aids. State of the art sea ice models are incapable of accurately forecasting changes in the position of the ice edge, due in part, to our relatively poor knowledge of ice rheology (mechanical properties/interactions between ice floes) and the ocean environment. Empirical models relating ice drift and wind velocity often provide the best guidance.

Since many of the inputs are subject to substantial errors in the observation-sparse high latitudes and model outputs have their own errors, the ice forecaster's primary method to improve skill is to accumulate experience.

In the past JIC forecasters made little attempt to quantitatively verify their products. The accepted procedure called for the forecaster to subjectively compare last week's forecast with the current ice analysis. Little feedback was gathered from users because there was no mechanism to permit an exchange of information. Forecast accuracy was, and remains, dependent upon analysis accuracy. Unlike various meteorological and oceanographic measurements, sea ice edge location remains a subjectively determined parameter. Several data sources, with a wide range of resolutions, are blended in order to obtain the ice edge location. These data sources, discussed in more detail below, have improved in recent years, as have the JIC's tools for interpretation. In addition, the proliferation of marine satellite telefax communications has enabled the JIC to better serve the users and to solicit comments on the analyses and forecasts provided.

In producing ice edge forecasts, meteorological forecast products from the National Meteorological Center (NMC), the European Center for Medium Range Forecasting (ECMWF) and Fleet Numerical Oceanography Center (FNOC) are routinely employed by JIC ice forecasters. NMC and FNOC also provide specialized ice forecasting products requested by the JIC. NMC creates three special products; a Bering Sea model for the winter season (simple dynamics and thermodynamics), an empirical wind driven/ice drift model for selected locations and an alphanumeric listing of surface wind speed, wind direction and temperature for selected points in the Bering Sea derived from the Medium Range Forecast model. FNOC provides two special types of forecasts, a dynamic/thermodynamic model for the polar regions (north of the Bering Sea) and an empirical wind driven/ice drift model (different from NMC's) for selected locations. Ice forecasters at the JIC use common, empirically derived ice forecasting relationships, such as the 2% wind driven/ice drift relationship developed by Zubov (1945). They also make use of sea ice edge climatologies and climatological trends derived from an eleven year database of weekly ice analyses. Oceanographic parameters also strongly influence ice edge position but routine ocean products are limited to sea surface temperature charts whose resolution and accuracy are insufficient for most forecast situations. Forecasters use average ocean current data from several sources and derive some knowledge of sea surface temperatures from infrared satellite imagery when available.

A verification program was initiated at the JIC in order to obtain some degree of confidence in the accuracy of ice forecasts. Practical experience in supporting operations near the ice edge has shown that extreme and/or unusual changes in position are difficult but not impossible to forecast. This verification program was designed to establish a quantitative

measure of forecast accuracy and to identify those conditions leading to large forecast errors. The study area, in the Bering Sea, is shown in Figure 1.

2. JIC Sea Ice Analysis

An understanding of the analysis procedures employed at JIC is necessary in order to assess the forecast verification program, because forecasts are based upon current analyses and verified from the following week's analyses. Desired forecast accuracy and verification procedures are intimately related to analysis accuracy.

The JIC's weekly ice charts show the position of the ice edge and ice concentrations for ocean areas covered by ice. The accuracy of JIC's ice analyses is primarily dependent upon satellite sensors. Under clear sky conditions the Advanced Very High Resolution Radiometer (AVHRR) sensor aboard the NOAA polar orbiting satellites enables the

JIC ice edge analysis to be within about 10 n mi of its true position. However the AVHRR sensor does not image the surface through clouds. The JIC receives visual band images from the Defense Meteorological Satellite Program's (DMSP) Operational Linescan System (OLS) from the U.S. Air Force. The OLS resolution is only about 0.6 km but these images are delivered to JIC some 48 to 96 hours after imaging and are also cloud limited. Currently, the only all-weather sensor applicable to sea ice analysis is the Special Sensor Microwave Imager (SSMI) carried on board the DMSP "morning" satellite. SSMI brightness temperatures are entered into a sea ice algorithm developed by the Navy expressly for the JIC. Output consists of global sea ice concentration amounts for 50 km square "pixels." It is known that several sources of error exist in the SSMI data so that in practice the ice edge derived solely from SSMI data may be one to three pixels in error depending upon ice conditions. Through experience, including comparing SSMI data with
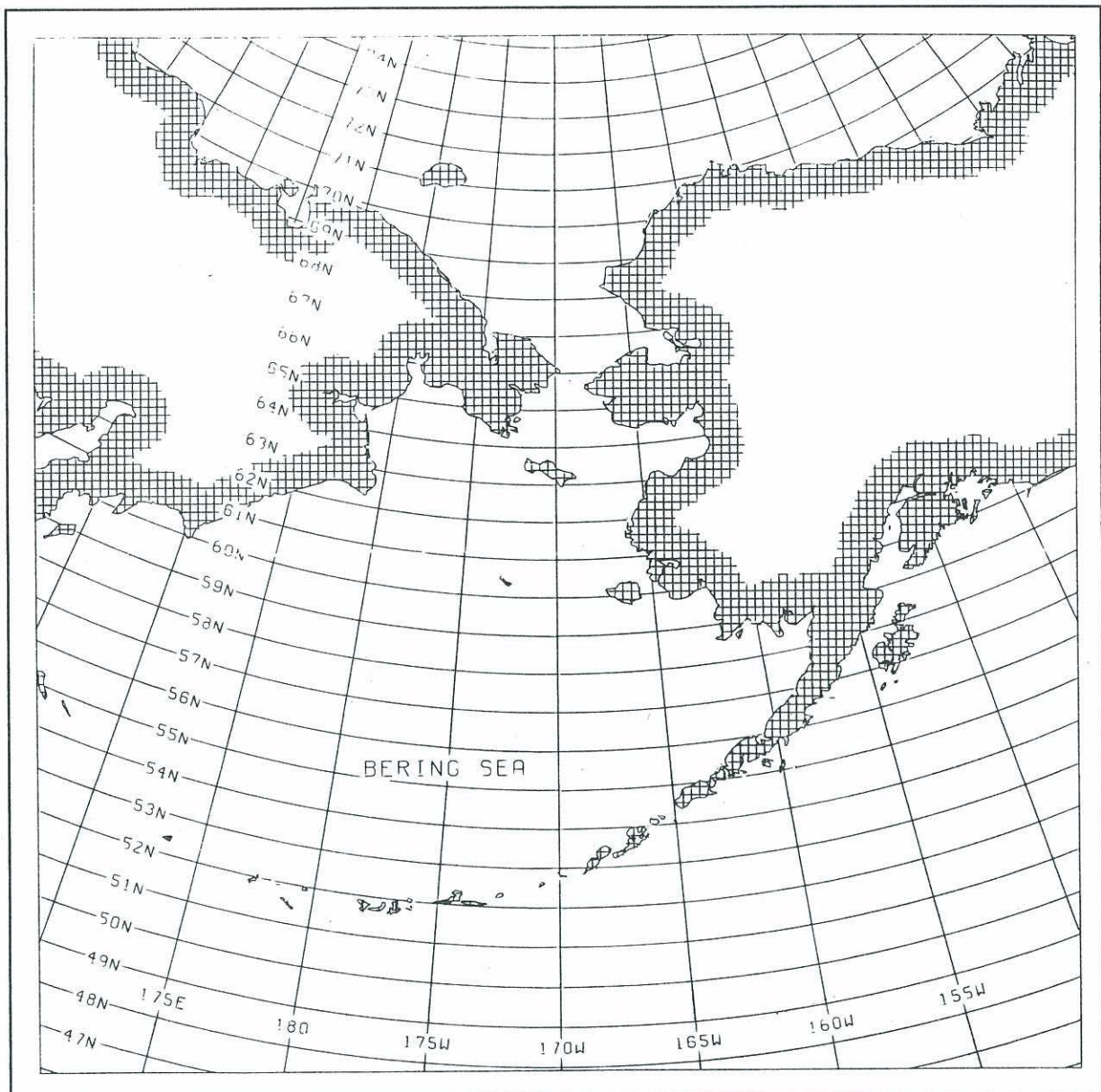

Fig. 1. Study Area.

other satellite sensor data, the JIC considers an SSMI derived ice edge to be an estimated ice edge accurate to about ± 30 n mi.

Whenever ice reconnaissance flights or ship observations are available these data are plotted on a "work chart" in addition to the satellite derived data. The analyst subjectively blends the data sources based upon their time of origination and relative accuracy. Final sea ice charts are hand drawn from work charts that contain all sources of information.

JIC sea ice analysts use two line types to depict the ice edge and ice concentration boundaries. A solid line indicates that portion of the ice edge that was observed on cloud free satellite imagery, a dashed line is used to indicate an estimated ice edge, usually based upon SSMI data. Each week the JIC issues an updated ice analysis and at the same time a 7-Day forecast of changes in ice edge position in message format. These forecasts were originally designed for Department of Defense units but are available upon request to any interested party. The JIC serves fishing fleets that have been operating closer and closer to the ice edge in the Bering and Labrador Seas. Each year the JIC supports at least one and usually several scientific endeavors that bring research ships adjacent to the ice edge. For these reasons the JIC has made an effort to improve its 7-Day ice forecasting capabilities.

3. Methodology

Ice forecasters at the JIC issue 7-Day sea ice forecasts on Tuesday of each week for the Western Arctic and Wednesday for the Eastern Arctic. An example is presented in Figure 2. Forecasts are issued in alpha/numeric format and delineate changes of the ice edge (expansion, recession or little change) for each sea containing an edge. These forecasts do not include information on changes in ice concentration or any other parameters. The forecast is a listing of the expected change, a distance in nautical miles of either expansion or recession, over some longitudinal range in a given region. Since the forecast is given in relative terms, it is not possible to interpret the forecast without knowledge of the location of the ice edge.

NAVY/NOAA Joint Ice Center: 7-Day Forecast

WEST ARCTIC

07 Day FCST: Yellow Sea: EXP Sea ice free conditions by end of FCST period; Sea of Japan: EXP 2–4 n mi recession in Vladivostok area, 5–10 n mi expansion in Tatarskiy Proliv; Sea of Okhotsk: EXP 3–6 n mi recession west of 14300E8, 25–30 n mi expansion FM 14300E8 to 15400E0, 10–15 n mi expansion east of 15400E0; Bering Sea: EXP 5–10 n mi recession FM 15800E4 to 16400E1, 15–20 n mi recession FM 16400E1 to 16900E6, 5–10 n mi recession FM 16900E6 to 17200E0, 10–15 n mi expansion FM 17200E0 to 17430E5, 25–30 n mi expansion FM 17430E5 to 17900E7, 10–15 n mi expansion FM 17900E7 to 1700W5, 5–10 n mi expansion FM 1700W5 to 17400W2, LTLCG FM 17400W2 to 17130W2, 5–10 n mi recession FM 17130W2 to 16700W4, 10–15 n mi recession FM 16700W4 to 15800W4; Cook Inlet: EXP 5–10 n mi recession thrut. 06MAR90 analysis date

Fig. 2. NAVY/NOAA Joint Ice Center: 7-Day Forecast.

In the past JIC forecasters have simply compared their 7-Day forecast to the following week's analysis. A more rigorous comparison was not attempted because the position of the analyzed ice edge was frequently thought to contain substantial errors. Recent improvements in remote sensing systems have made a more rigorous analysis possible. The forecast verification program required some standard measure to quantitatively assess the JIC 7-Day forecasts. A simple comparison with observations was unsatisfactory because of the ambiguity of the observations (detailed above). However the JIC has access to eleven years of digitized and statistically analyzed JIC weekly sea ice charts in atlas format (SEA ICE CLIMATIC ATLAS: VOLUME III ARCTIC WEST, June, 1986, Naval Oceanography Command, NAVAIR 50-1C-542). The atlas includes mean, maximum and minimum ice edge positions for all the polar regions.

Copies of these charts were overlaid on a light table and the changes between sequential charts were measured along predetermined lines of longitude. In the Bering Sea these were 175E, 180W, 175W, 170W, 165W and 160W (see Fig. 1). Data from the first half and second half of the month were provided in the atlas and the measured changes were divided in half to derive weekly distances. Measurements were taken as close to a perpendicular orientation to the ice edge as possible. In this manner a mean, maximum and minimum climatological forecast (or climatological trend) was established for the Northern Hemisphere. However, only the mean ice edge was derived from a statistical analysis (arithmetic mean). Both the maximum and minimum edges were simply derived from the extreme location found in the eleven year data base. The mean climatological forecasts established a baseline for comparison with the JIC's 7-Day forecasts. Note that there is an inherent uncertainty in mean ice edge positions due to the limitations noted in the description of ice analysis. The errors due to this uncertainty are assumed to be random and so cancel out over a period of time. Although this assumption may not be strictly correct, the actual bias should be small enough so as not to obscure the results of the verification program. We hope to show that subjectively derived ice forecasts are more skillful than simple climatological forecasts. This was accomplished by measuring the difference between weekly sea ice edge locations and comparing these distances with subjectively forecast changes and climatological forecasts. Using this methodology, comparisons can be made on a regional basis (eg. averaging over the Bering Sea) or for each line of longitude within a region (eg. along 170° West Longitude in the Bering Sea).

4. Results

The measurement of mean ice edge position change between sequential charts in the ice atlas yielded the data, ie. climatological forecasts, as shown in Table 1. Positive numbers indicate ice edge expansion (generally southward in the Northern Hemisphere) in nautical miles and negative numbers indicate recession. Values are weekly distances derived from the twice-monthly ice charts in the Atlas. These climatological forecasts are the basis for comparison to the JIC's 7-Day forecasts.

Bering Sea ice forecasts for two ice years, 1987–88 and 1988–89, were verified and compared to the mean climatological forecasts. Overall ice conditions were very different between these two years. The 1987–88 ice season was relatively normal whereas 1988–89 exhibited substantial swings

Table 1. Weekly Climatological Forecast: Bering Sea

Climatological forecast guidance, derived from SEA ICE CLIMATIC ATLAS: VOLUME III, ARCTIC WEST. The atlas contains two ice charts per month (1st and 15th) showing the mean position of the ice edge. Values below are the weekly change in the ice edge position, in nautical miles, found by dividing the bi-monthly values measured from the atlas by two. Climatological forecasts are applied during roughly two week intervals, first and second halves of each month.

Half Month		175E	180W	175W	170W	165W	160W
I	January	2	4	32	23	27	11
II	January	−2	0	13	4	−2	−4
I	February	−2	9	18	18	20	7
II	February	2	20	18	16	4	23
I	March	0	0	2	−4	−2	−18
II	March	18	16	6	−4	0	−13
I	April	−2	0	−11	0	−2	−9*
II	April	−14	13	14	−4	0	—
I	May	−36*	−21	−37	−57	−83*	—
II	May	—	−25	−23*	−20	—	—
I	June	—	−71*	—	−173*	—	—
II	June	—	—	—	—	—	—
I	July	—	—	—	—	—	—
II	July	—	—	—	—	—	—
I	August	—	—	—	—	—	—
II	August	—	—	—	—	—	—
I	September	—	—	—	—	—	—
II	September	—	—	—	—	—	—
I	October	—	—	—	—	—	—
II	October	—	—	—	—	—	—
I	November	9*	6*	0	—	—	—
II	November	6	2	9*	66*	16*	—
I	December	6	16	21	53	18	13*
II	December	2	13	14	13	2	0

*Indicates intersection with coastline.

in ice conditions. Very cold weather persisted over the region during much of January followed by record warm weather and strong southerly winds in February. More seasonable conditions returned in March 1989.

Forecast verification results are summarized in Tables 2 and 3. Table 2 contains the mean errors (algebraic) compiled from all forecasts, observed ice edges and estimated ice

edges. Table 3 lists forecast accuracy with respect to the direction of ice edge change. In these calculations forecasts were defined as the predicted change of ice edge position along each of the six lines of longitude that intersect the ice edge (Figure 1). Observed ice edge cases were limited to those in which the ice edge was observed two weeks in a row, the forecast week and the verification week. If one or

Table 2. Sea Ice Edge Verification Statistics: Mean Errors Bering Sea

1987–88

Forecast Error
Mean	:	22.5 n mi
Mean from observed ice edges	:	20.0 n mi
Mean from estimated ice edges	:	23.7 n mi

Climatological Error
Mean	:	28.2 n mi
Mean from observed ice edges	:	30.6 n mi
Mean from estimated ice edges	:	27.1 n mi

1988–89

Forecast Error
Mean	:	24.7 n mi
Mean from observed ice edges	:	19.3 n mi
Mean from estimated ice edges	:	26.9 n mi

Climatological Error
Mean	:	31.3 n mi
Mean from observed ice edges	:	24.6 n mi
Mean from estimated ice edges	:	34.2 n mi

Table 3. Sea Ice Edge Verification Statistics: Directional Bias Bering Sea

Mean forecast error categorized by analysis quality during expansion and recession phases of the ice edge.

1987–88

EXPANSION
Observed ice edges	:	17.3 n mi
Estimated ice edges	:	27.2 n mi

RECESSION
Observed ice edges	:	23.1 n mi
Estimated ice edges	:	20.0 n mi

1988–89

EXPANSION
Observed ice edges	:	18.4 n mi
Estimated ice edges	:	27.7 n mi

RECESSION
Observed ice edges	:	20.7 n mi
Estimated ice edges	:	26.3 n mi

both weeks were estimated then the forecast was classified as derived from estimated ice edges. Results in Table 2 show that the overall mean forecast from both years was more accurate than the climatological forecasts. Overall accuracy decreased during the more variable year (1988–89) as expected but only a slight improvement in forecast error as compared to climatological error was recorded, ie. a difference of 5.7 n mi in 1987–88 vs. 6.6 n mi in 1988–89. Table 2 shows that, on average, even in highly variable years JIC ice forecasters can do reasonably well given observed (accurate) sea ice edge positions. Errors were near 20 n mi for expansion and recession from observed ice edges during both years or about twice the resolution of the JIC's best analyses. Observed expansion and recession errors from the 1988–89 season were nearly comparable with 1987–88 despite more variable conditions. However, more opportunities for observed ice edges were recorded in 1988–89 (57 cases) than in 1987–88 (41 cases). In both years the standard deviation of the forecast error was close to the value of the mean.

Biases due to the direction of ice edge movement can be examined using Table 3, where expansion and recession were considered separately. These data should show any bias due to weather patterns since expansion is often brought about by clear, cold weather and recession commonly occurs during cloudy conditions. Data for 1987–88 are ambiguous, errors associated with observed expansion of the ice edge were nearly five nautical miles less than those associated with observed recession but estimated expansion (not observable on AVHRR) was considerably less well forecast (7.2 n mi) than estimated recession. During 1988–89 the situation was different, observed ice expansion was only slightly better forecast than observed ice recession and estimated changes were nearly equally well forecast. During 1987–88 observed expansion cases numbered 22 and recession 19. For 1988–89 the figures are 29 cases of observed expansion and 29 of recession. The standard deviation associated with these samples was generally the same magnitude as the mean except for observed expansion during 1988–89 in which the mean of 18.4 was associated with a standard deviation of 11.9. The data in this table show that for the two years of data, forecasts of ice edge expansion and to a lesser extent, observed recession, were of comparable accuracy despite the wide variation in ice conditions between the two years.

Table 3 implies that ice forecasters require high quality (clear sky) ice data during expansion or errors approach 30 n mi, which is comparable to the errors associated with recession, if not greater. Interpretation of these data are made difficult by the imprecise nature of the estimated ice edges. However, forecasters have noted that "sea smoke" and low clouds tend to obscure the sea surface immediately south of the supposed ice edge whenever cold air spreads over an existing ice field. First-hand observations indicate that there can be a considerable zone of new ice beneath the clouds. This "hidden" ice may contribute to the substantial errors associated with expansion forecasts when it becomes apparent under clearing conditions or when it becomes thick enough to register as an ice retrieval from the passive microwave algorithm. Recession forecasts apparently rely less upon the quality of ice data. In fact the 1987–88 statistics belie the reasoning that better ice data will yield more accurate forecasts. That year's data show a 3.1 n mi improvement in the forecasts based upon estimated rather than observed ice edges. The 1988–89 data indicate 5.6 n mi difference between observed and estimated recession, considerably less than the 9.3 n mi difference shown for expansion. Possible explanations are discussed in Section 6.

5. Application

Several benefits of this program have been realized. Initially, the creation of the forecast climatology has provided the JIC forecasters with a baseline forecast. The data have been printed in tabular format allowing the user to determine normal expansion and recession rates in any particular geographic area. Generally, a more experienced forecaster is less likely to use the climatological forecast during the preparation of the forecast. Rather, the climatology is consulted in a last step after all other guidance has been used and a forecast has been written. This final step allows the forecaster to assess the forecast in relation to historical ice conditions.

The climatology assumes more importance whenever the ice analysis is created from low resolution data sources (eg. SSMI) or simple estimates based upon observed weather and historical ice conditions. Under these conditions the forecaster has reduced confidence in the analysis and so cannot base decisions upon the exact position of the ice edge, ice thickness data or boundaries between areas of different ice concentration. Thus, a more generalized forecast may be appropriate, depending upon the forecast meteorological fields from the NMC or the ECMWF.

With only two years of data the JIC forecasters have not attempted to read more into the statistical data than exists. Clearly, interannual variability is important as well as forecaster skill but these factors were well known before this study. The quantification of forecast and climatological errors does add to the ice forecaster's confidence and demonstrates the likely result of inattention to the problem. Continued data collection and an expansion of the program to new regions will allow the JIC to identify more difficult forecasting regions or situations and so better allocate resources.

6. Discussion

During both years the mean forecast error was less than the mean climatological error. It is noteworthy that this difference did not change appreciably (5.7 n mi and 6.6 n mi) from one year to the next despite the considerable change in ice conditions. Generally, JIC ice forecasts were about 25% more accurate than climatology.

Table 3 shows that for both years, 1987–88 and 1988–89, ice forecast accuracy was difficult to relate to the direction of ice edge change. However, the difference between observed and estimated errors for expansion were considerably greater than those related to recession. This bias in favor of accurate forecasts of expansion under observed conditions is probably directly related to clear, cold conditions and well forecast movements of High Pressure systems. Under less favorable forecasting conditions accuracy suffers due, at least in part, to the obscured zone of new ice formation described in Section 4.

Ice edge recession was perceived to be the more difficult problem by JIC forecasters, in large part because of the tendency for recession to occur during storms. These storms can obscure the Bering Sea for days at a time, decreasing ice edge analysis accuracy. Forecasters expected to see large average errors associated with estimated versus observed ice edge forecasts for recession. However, the statistics indicate much less of a difference than anticipated. In fact, forecasted recession under estimated ice edge conditions in one year was three nautical miles more accurate than under observed conditions and only about six miles worse in the other year. Furthermore, despite record warmth and widespread cloudi-

ness during February 1989, when weekly changes in the position of the ice edge exceeded 50 n mi of recession for several weeks, the JIC forecasts for the 1988–89 season were nearly as accurate as in 1987–88 when conditions were much less extreme. Recession forecasts may appear to be less problematical, on average, due to the nature of the ice observing system used under cloudy conditions. Passive microwave data have been shown to be relatively insensitive to new ice formation on the ocean (Naval Research Laboratory, 1988). Therefore, these data consistently underestimate the rate of ice edge expansion. However, under "on-pack" wind conditions conducive to recession, the ice edge becomes compacted and is readily distinguishable by the same sensor. The result is a higher degree of accuracy of the recessed ice edge under cloudy conditions as opposed to the expanded ice edge under similar conditions. Additional differences associated with forecasting recession are illustrated in Figure 3. Large forecast errors were associated with two events, in April and May, when strong winds and low ice concentrations combined to produce large recessions. Between these events recession proceeded much more slowly and was easier to predict, hence reducing forecast errors.

The last step in this verification study was an analysis of persistence as a forecasting method. Strict persistence forecasting of sea ice edge location is nearly always incorrect as very few instances of no change in location were recorded. Better results may be obtained by a modified persistence technique in which the same change in ice edge position is forecast for the coming week as was measured for the prior week. Figure 3 shows the measured change in ice edge position along one line of longitude through the middle of the Bering Sea during 1988–89. The average forecaster's error was 37.5 n mi as compared to an error of 58.1 n mi for the modified persistence method. In a more stable year persistence should perform better but forecaster accuracy should also increase.

In order to improve ice forecasts the sources of error have to be identified. A primary input to any ice forecast is the forecast of meteorological conditions, since sea ice moves, as a first approximation, in response to surface winds and surface air temperature plays a major role in determining in-situ ice growth and decay. To determine the contribution of meteorological forecast error to sea ice forecast error the JIC obtained wind and temperature data for the Bering Sea region. These data were derived from the 0000 UTC Medium Range Forecast model run by the National Meteorological Center. Occasional ship observations and first-hand experience in the region by several JIC staff members indicated that wind speeds derived from the MRF surface pressure gradient associated with storms were generally underestimating wind speeds over the Bering Sea. JIC observations indicated that many storms were more intense than depicted on NMC charts and often storm systems were more complex with several centers of circulation apparent on satellite imagery. Also some orographic effects, especially near the Bering Strait, Anadyr Strait and through Norton Sound were not well modeled. Despite these shortcomings, JIC ice forecast-
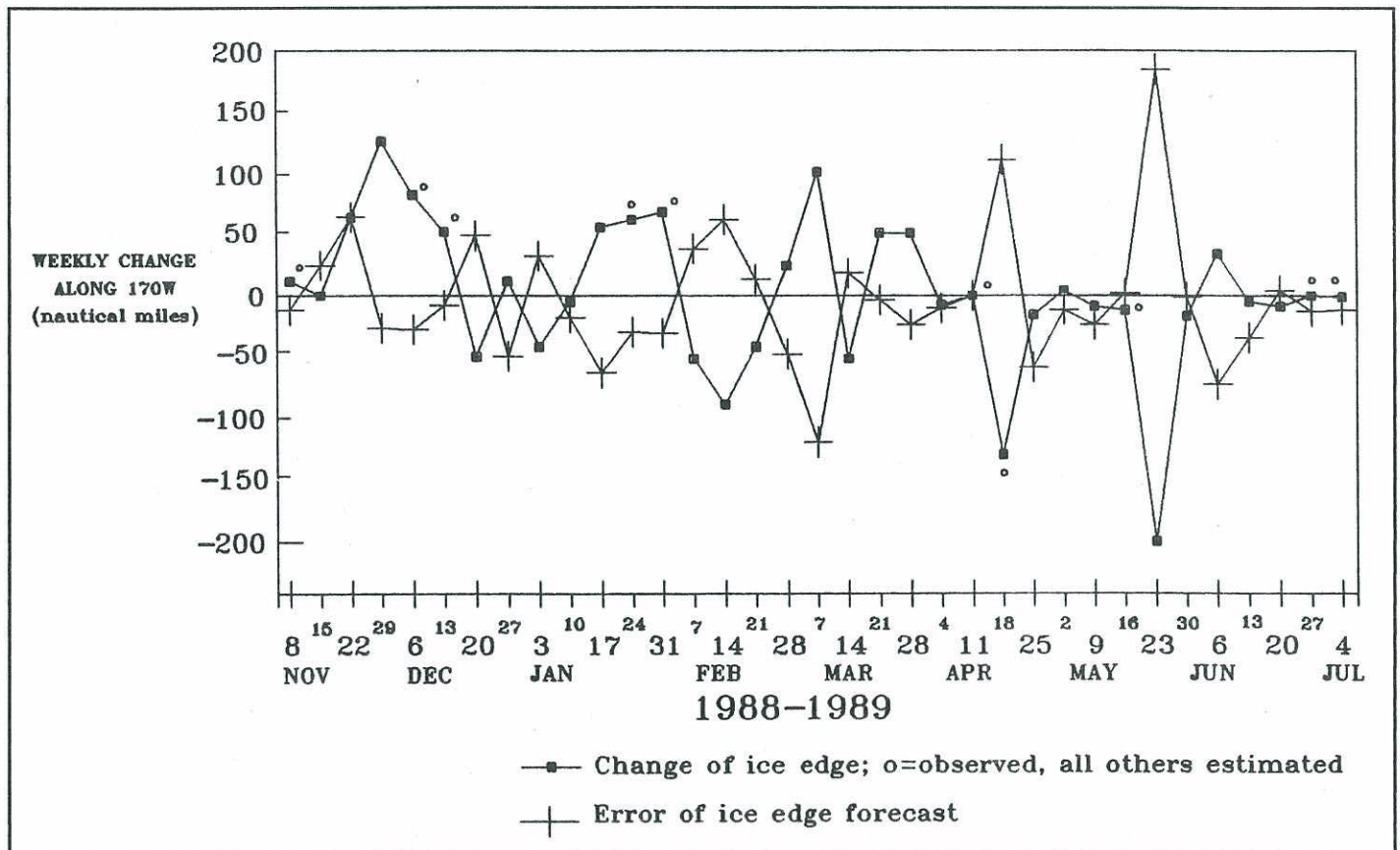

Fig. 3. Ice Edge Changes and Associated Forecast Errors, 170°W, 1988–89.

ers found the model guidance to be extremely useful in preparing ice forecasts.

Several sea ice forecasts that were in error by over 50 n mi were re-examined by referring to historical NMC analysis and forecast data. All these cases occurred in the 1988–89 season and are illustrated in Figure 3. In most cases the model guidance was accurate for two or three days with some significant errors in the four to seven day range. Wind direction errors were, at times, as high as 180 degrees and wind speed errors were often 10 to 15 kt, occasionally reaching as high as 30 to 40 kt. The periods of largest errors in the NMC model were also poorly handled by the other meteorological guidance sources used by the JIC (ECMWF and FNOC). These cases of greatest ice forecast errors were associated with major changes in weather patterns, several occurring in conjunction with the record setting cold wave, subsequent record warmth and then return to normal conditions recorded throughout much of Alaska during February–March 1989. None of the numerical guidance sources accurately predicted, seven days in advance, the formation of the remarkable cold air dome over Alaska or its shift eastward bringing strong southwesterly winds and warm air over the state. During April a large ice forecast error was recorded and was found to be due to a poorly forecast storm track that caused easterly winds rather than north to northwesterly winds. This problem was compounded by the storm's intensification and sustained wind speeds of over 30 kt over several days. Finally, the May case was one in which a large area of very low ice concentration (10% to 30%) was removed in the course of one week.

7. Conclusion

The Joint Ice Center is generally meeting its goals for 7-Day forecasts of ice edge position (20 to 60 n mi depending upon observing conditions) and its users' requirements for ice edge forecasting accuracy in the Bering Sea. This is being accomplished in spite of the fact that most medium range atmospheric forecasts do not have much skill beyond 120 hours. The reliability of medium range weather forecasts has been steadily improving (eg., Kalnay et al, 1990) and is likely to improve through better spatial resolution and improved treatment of physics. This improvement in the meteorological forecasts, combined with improved observational capabilities to be realized from future satellite missions (such as synthetic aperture radar on the ERS-1, JERS-1 and RADARSAT satellites) should considerably enhance the abilities of the JIC to produce higher quality forecasts of ice movement in the polar regions.

This verification program will be continued in the Bering Sea and will be extended to the Barents Sea, beginning in January 1990, to examine regional differences in forecasting accuracy.

Author

Gary Wohl has been involved with polar meteorology, sea ice research and applications since 1975 (after graduation from the City College of New York) when he joined the Arctic Ice Dynamics Joint Experiment team at the University of Washington. After spending ten months at ice camps performing meteorological experiments, forecasting and drilling holes he resumed graduate studies at the University of Colorado, Institute of Arctic and Alpine Research where he earned his Masters degree. He worked in private industry for about seven years performing applied meteorological, remote sensing and Arctic field programs mostly for Alaskan petroleum companies and the United States Department of Transportation. Since joining the National Weather Service in 1986, he has served as the Senior NOAA Ice Scientist at the Navy/NOAA Joint Ice Center and has been engaged in ice forecasting, passive microwave and Synthetic Aperture Radar remote sensing studies and computer workstation development programs.

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