NCEP Notes:

Virtual Floe Ice Drift Forecast Model Intercomparison*

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Abstract

Both sea ice forecast models and methods to measure their skill are needed for operational sea ice forecasting. Two simple sea ice models are described and tested here. Three different measures of skill are also tested. The forecasts from the newer sea ice model are found to perform better, regardless of the skill measure used. All three skill measures show essentially the same behavior, in terms of having no dependence on season and being roughly constant. All three measures also agree that there is no decline in skill with time through the 6 day period of forecast.

1 Introduction

Since at least the time of Nansen [1902], it has been common to think of sea ice drifting at some fraction of the wind speed, and at some angle to the wind. This is the drift rule. Nansen's values, based on observation of ice floe drift during the cross-polar drift of the Maud (1893-1896) were 1.8% and 28 degrees to the right of the wind. This included about 949 floe-days of observations (November 7, 1893 to June 27, 1896) from a single point.

In the time since then, two things have changed for drift models. It became the convention to use geostrophic winds rather than actual winds in deriving the drift law. And the number of observations has increased dramatically. Thorndike and Colony [1982] analyzed 7937 buoy-days of observations. Their simple drift law (0.8%, 8 degrees to the right of the geostrophic wind) was able to explain 70% of the variance in drift velocity in the central Arctic basin. In the Antarctic, Martinson and Wamser

[1990] derived a drift law of 3%, 23.4 degrees to the left of the geostrophic wind, from 3 points observed for 4-5 days each.

The US has been running operationally a drift law forecast model since about 1968 [Skiles, 1968], first at the Naval Oceanographic Office, then at the National Centers for Environmental Prediction (NCEP, formerly the National Meteorological Center). This drift law was based on about 1080 buoy-days of observations. The forecast is used by the National Ice Center (NIC) in making their 7 day forecasts of ice edge position. Their forecast is then used by shipping companies, fishermen, and oil companies. We present evidence that suggests that the forecast can be improved by using the more recent drift laws, and by adding the southern hemisphere (currently not forecast in the operational model, but forecast by the NIC.)

The sea ice literature includes relatively little in the way of quantitative model verification. For the most part, this has been because visual inspection of model output has been sufficiently unambiguous to determine which model or parameterization was better. Skill measurements which have been used have included ice drift distance correlation between forecast and observation [Ip, 1991; Flato, 1992] and index of agreement between forecast and observed ice drift [Preller and Posey, 1989]. Neither of these is a vector measure, so that forecasting the right distance in the wrong direction is still credited as a good forecast. In addition to these two, the vector correlation definition from Crosby et al. [1993] is tested. These three measures of skill will be examined by themselves, as well as used to determine which model is better.

Also to be examined is the dependence of forecast skill on length of forecast. Contrary to the more common differential models (c.f. weather, waves, sea surface temperature) where instantaneous values of variables governed by (partial) differential equations are desired, ice drift is an integral model (integrated drift over a period of time). Over the first 6 days of the forecast period (the maximum length run), there is no systematic decline of skill (by any of the three measures) with respect to time.

2 Ice Drift Models

The models discussed are based on a virtual floe concept. The prediction is how far and in what direction a floe would drift, if there were a floe at a given point to start with, and if it is assumed that it does not melt or encounter coasts. Forecasters must then temper the model output with their knowledge of meteorological, oceanographic, and coastal effects. For all the drift rules, the two constants to be determined are the ice drift speed and the drift direction relative to the geostrophic wind direction.

The currently operational model was developed by Frank Skiles [1968] for the Naval Oceanographic Office. The drift rule, based on an examination of buoy data [Skiles, 1968] is:

$$\vec{U}_i = (0.025 + 0.00772|\vec{U}_a|) \quad (1)$$

$$\theta_i = \theta_a + 31.3exp(-0.168|\vec{U}_a|) \quad (2)$$

where $\vec{U}_i$ is the ice velocity, $\vec{U}_a$ is the geostrophic wind velocity, velocities are in nautical miles per day, and θ_i represents the ice drift direction. The model implementation also includes a process to 'roughen' the pressure field prior to determining the geostrophic wind. The procedure is:

$$P'^j_i = D_0 P^j_i - D_1 * (P^j_{i+1} + P^j_{i-1} + P^{j+1}_i + P^{j-1}_i) + D_2 * (P^{j+1}_{i+1} + P^{j-1}_{i-1} + P^{j+1}_{i-1} + P^{j-1}_{i+1}) \quad (3)$$

where P'^j_i are the roughened winds, P^j_i are the model-derived pressures, and D_0, D_1, D_2 are assigned 16/9, 2/9, and 1/36, respectively. This is not, strictly speaking, a Laplacean operation as the metric terms of the polar stereographic grid are ignored in this step. The operational Skiles model uses the 2.5 degree gridded forecast pressure fields.

The newer model is based on the drift rule of Thorndike and Colony [1982] for the northern hemisphere, and Martinson and Wamser [1990] for the southern. In the northern hemisphere:

$$\vec{U_i} = 0.008\overline{\overline{R(\theta)}} * \vec{U_a} \quad (4)$$

where $\overline{\overline{R}}$ is the two dimensional rotation matrix: and θ is 8 degrees.

$$cos(\theta) \quad -sin(\theta) \quad (5)$$

$$sin(\theta) \; cos(\theta) \quad (6)$$

In the southern hemisphere, the rule is:

$$\vec{U_i} = 0.03\overline{\overline{R(\theta)}}\vec{U_a} \quad (7)$$

where θ is -23 degrees. The ice drifts more rapidly, and at a greater angle because Antarctic ice is generally thinner than Arctic. The newer model computes the geostrophic winds in the spectral domain, then interpolates them to a one degree mesh. No roughening procedure is used.

3 Model Intercomparison

The results of the two models' forecasts were compared by objective verification against observed buoy drifts in the poles, and subjectively by the Alaska forecast office and the NIC. The Alaskan office [Craig Bauer, personal communication] states that the revised model is indeed superior to the Skiles model. The differences are particularly notable for low drift conditions. The NIC [David Helms, personal communication] finds the Thorndike and Colony implementation to be superior in the Arctic generally. For the Antarctic this implementation is the only one available, and is considered helpful [David Helms, personal communication].

We take correct forecasting of the drift distance (and potentially, direction) integrated through the length of the forecast as the measure of success. This is the term that operational forecasters are concerned with. We also consider the skill as a function of time in the forecast model. In scoring the models, we also need to look for the scoring measure which differentiates most strongly between the models. Previous measures suffer from the problem that even large model differences can result in small forecast score differences [Ip et al, 1991; Flato, 1992; Preller and Posey, 1989].

The forecast ice drifts are verified against the observed buoy drift for each forecast day. The comparison point was the virtual floe point closest to the starting location of the buoy each day during the forecast period. The floe point and buoy were required to be within 55 km (1/2 degree) for comparisons to be made. No interpolation was done. The initial time (at which the forecast is started and the time that the buoy position is checked) is 00 UTC. The forecasts are every 12 hours to 6 days. If there were multiple buoy reports within 3 hours of 00 UTC, the average location was assigned to 00 UTC.

The three measures of skill are the correlation of distance, the index of agreement in distance [Willmott et al., 1985], and vector correlation after Crosby et al. [1993]. Correlation varies from -1 to 1, index of agreement from 0 to 1, and vector correlation from 0 to 2.

The index of agreement may be interpreted as a relative average error [Willmott et al., 1985]. It contrasts, then, with correlation in that index of agreement will penalize a 2 km forecast error more if the observation is one of 2 km than if the observation is for 20 km. Mathematically, the formulation is [Willmott et al., 1985]:

$$d_2 = 1 - [\Sigma\omega_j|\mathbf{e_j}|^2]/[\Sigma\omega_j(|\mathbf{p_j} - \mathbf{\bar{o}}| + |\mathbf{o_j} - \mathbf{\bar{o}}|)^2 \quad (8)$$

where d_2 is the index of agreement, summations are from 1 to N (the number of observations), ω are weights to correct $\mathbf{e_j}$ for being over- or underrepresentative, $\mathbf{e_j}$ is the error in the jth forecast, p is the prediction, o is the observation, and $\mathbf{\bar{o}}$ is the mean of the observations weighted by ω. In our case, the weights are taken to be unity. The index of agreement will be largest when the numerator is smallest (forecasts agree with observations), and when the denominator is largest (large natural variability - the o_j vary greatly from $\bar{o}$).

The vector correlation defined by Crosby et al. [1993] is a generalization of the scalar correlation. As such, it involves terms like the covariance between predictions and observations scaled by the standard deviation of the predictions and the standard deviation of the observations. It has the usual properties of scalar correlation, including that if the predictions are a linear function of the observations, the correlation will be perfect (1 in a 1 dimensional case, 2 in a two dimensional case). As for scalar correlation, a 2 km forecast error will be considered equally bad regardless of whether the observation is 2 km or 20 km. The definition for a sample is:

$$r^2 = Tr[\Sigma_{11}^{-1}\Sigma_{12}\Sigma_{22}^{-1}\Sigma_{21}] \tag{9}$$

where Tr denotes the trace of the matrix and Σ_{ij} is:

$$s(u_i, u_j) \quad s(u_i, v_j) \tag{10}$$

$$s(v_i, u_j) \quad s(v_i, v_j) \tag{11}$$

s() is the sample covariance, and i, j = 1 represent the observations and i, j = 2 are the forecasts.

Model forecasts from 14 April 1993 to 31 January 1995 are scored. July 1994 is missing due to an archive failure. Various other days are also missing due, typically, to a computer queueing failure. The models' skill as a function of forecast length and skill measure is shown in figure 1 for all forecasts. The line with circles represents the operational model, the cross-barred line is the test model. From figure 1, we clearly see that there is no noteable relation between forecast length and skill, for any of the measures. There no noticeable difference in character for any of the skill measures. All measures are essentially constants near the middle of their range. The new model appears to be consistently better than the old at all forecast intervals and for all scores (except day one in the vector correlation, where it is very slightly worse).

The model skills, for each of the three measures at day 6, per month from April 1993 through January 1995, is given in figure 2. As before, the Skiles model is the first line. The number in parentheses on the second line of each pair is the number of buoy-days for which there were observations. Again, there is little difference in character between the scoring methods. All are non-seasonal, though the vector correlation and linear correlation have substantial scatter.

The results of figure 2 suggest that the revised model is indeed superior to the Skiles model, and that there is no consistent difference in behavior between skill measures. The results of this drift model test agree with those found by [SAI, 1983] in comparing the Thorndike and Colony [1982] drift law with the Skiles model for the Navy.

The absence of skill degradation with time is puzzling at first glance, since the atmospheric model which is used does become less skilled with time. The forecast variable is net drift over time. To be correct in forecasting this, it is only necessary to be correct in inferring the average velocity over the period of integration. The atmospheric model error can be considered composed of a bias and a random component. An atmospheric bias contributes to drift forecast error uniformly through time. If the geostrophic wind is 10% too strong every day, then the forecast distances will be 10% too great for all lengths of forecast. This gives no loss of skill through time. If the random component were gaussian, the error in computing the mean velocity declines with an increase in time of integration. By the Central Limit Theorem, at least the tails of the distribution (of geostrophic wind speed errors) are gaussian. Consequently, we expect the errors in the forecast locations due to random errors to decline with time.

4 Conclusion

We have shown that the revised virtual floe model, based on the Thorndike and Colony [1982] model is superior to the Skiles [1968] drift law forecast model. We find no dependence of skill, by any measure, on forecast length out to day 6. All three measures of skill give essentially the same impression of model performance, so that ice modellers may continue to use whichever measure they prefer.

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