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Validation Test Report for a Navy Sea Ice Forecast System: The Polar Ice Prediction System 2.0

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Since 1987, the Fleet Numerical Meteorology and Oceanography Center (FNMOC) has been running sea ice forecasting systems in various regions of Navy interest (Central Arctic, the Barents Sea, and the Greenland Sea). The Polar Ice Prediction System 1.1 predicts sea ice conditions in the Arctic basin, the Barents Sea, and the Greenland Sea at a resolution of 127 km. Two regional sea ice forecast systems, the Polar Ice Prediction System – Barents Sea (RPIPS-B) and the Polar Ice Prediction System – Greenland Sea (RPIPS-G), also predict sea ice conditions in the Barents and Greenland Seas, respectively, at a higher resolution of 20–25 km. In 1995, the Naval Research Laboratory (NRL) delivered to FNMOC a coupled ice-ocean system, the Polar Ice Prediction System 2.0 (PIPS2.0), which predicts sea ice conditions of most of the ice-covered regions in the Northern Hemisphere. PIPS2.0 will replace the three existing operational forecast systems when it completes the final operational testing phase at FNMOC. PIPS2.0 uses as its basis the Hibler ice model and the Cox ocean model. PIPS2.0 has a resolution of approximately one-quarter of a degree, which is equivalent to the resolution of the operational regional systems (RPIPS-B and RPIPS-G). This report documents the validation of PIPS2.0 against both observational data and the results of the existing operational forecast systems.

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EXECUTIVE SUMMARY

The U.S. Navy requires accurate depictions of both the three-dimensional structure and the movement of sea ice in the Arctic Ocean and its marginal seas. Since 1987, the Fleet Numerical Meteorology and Oceanography Center (FNMOC) has used the Polar Ice Prediction System 1.1 (PIPS1.1) to predict sea ice conditions in the Arctic basin and in the Barents and Greenland Seas. Since 1989 and 1991, respectively, FNMOC has used the Regional Polar Ice Prediction System – Barents Sea (RPIPS-B) and the Regional Polar Ice Prediction System – Greenland Sea (RPIPS-G) to predict sea ice conditions in the Barents and Greenland Seas. These regional systems were defined at higher resolution than PIPS1.1 and, therefore, provided a more accurate description of the variability of the ice edge.

In the early 1990s, the National Ice Center (NIC), user of FNMOC's ice products, requested a sea ice forecasting system that could provide ice conditions for all sea ice-covered regions in the Northern Hemisphere. The Naval Research Laboratory (NRL) developed a coupled ice-ocean model that provided ice information over this large area. The coupled model consists of the Hibler ice model (Hibler 1979; 1980) coupled to the Cox (1984) ocean model. The purpose of the coupling was to provide daily, realistic heat exchanges between the ice and ocean, as well as realistic interfacial stresses. The Hibler ice model was converted into spherical coordinates to be consistent with the Cox ocean model. The resolution of the Polar Ice Prediction System 2.0 (PIPS2.0), approximately one-quarter of a degree (0.28°), is the equivalent of the resolution of the regional systems. PIPS2.0 was tested using daily and 3-hourly forcing from the Navy Operational Global Atmospheric Prediction System 3.2 (PIPS3.2). PIPS2.0 has been developed to replace PIPS1.1, RPIPS-B, and RPIPS-G.

This report documents the validation of PIPS2.0 against observational data in the form of satellite and buoy data, and against the results of the existing PIPS1.1 and RPIPS forecast systems using the year 1992 as the validation year.

VALIDATION TEST REPORT FOR A NAVY SEA ICE FORECAST SYSTEM THE POLAR ICE PREDICTION SYSTEM 2.0

1.0 INTRODUCTION

The Naval Research Laboratory (NRL) has been developing sea ice forecast systems, run operationally by the Fleet Numerical Meteorology and Oceanography Center (FNMOC), for the past 12 yrs. In the past, an emphasis was placed on the development of several high-resolution regional forecast systems in areas of specific Navy interest. This direction resulted in the development of the three existing sea ice forecast systems: the Polar Ice Prediction System 1.1 (PIPS1.1), the Regional Polar Ice Prediction System – Barents Sea (RPIPS-B), and the Regional Polar Ice Prediction System – Greenland Sea (RPIPS-G). The PIPS1.1 covers the central Arctic Ocean and the Barents and Greenland Seas using a horizontal grid resolution of 127 km. The two regional systems cover each individual region at a grid resolution of 20–25 km. All three forecast systems consist of the Hibler ice model, driven by atmospheric forcing from the Navy Operational Global Atmospheric Prediction System (NOGAPS) (Hogan et al. 1991) and by monthly mean climatological ocean currents and heat fluxes. Data in the form of an analysis of sea ice concentration, created by the National Ice Center (NIC), are used to initialize these forecast systems once each week.

Products derived from these forecast systems are ice thickness, ice drift, ice concentration (ice-edge location), ice convergence/divergence, and changes in these fields over the forecast period. In 1990, the NIC, user of the FNMOC ice products, made a request that the strategy be changed from the development of several high-resolution regional models to a single high-resolution model encompassing all of the sea ice-covered regions of the Northern Hemisphere. As a response to this request, NRL began development of a coupled ice-ocean model, the Polar Ice Prediction System 2.0 (PIPS2.0), that could provide the basis of such a large-scale, sea ice forecasting system. A coupled model was necessary to provide the ocean interaction that was both temporally and spatially adequate and accurate.

The coupled ice-ocean model was successfully developed and tested during 1993 and 1994 (Riedlinger and Preller 1991; Cheng and Preller 1992). Several upgrades to the coupled model were added, such as doubling the horizontal resolution and adding the effects of nine major rivers to the Arctic (Cheng and Preller 1996). The coupled model has also been successfully tested using ice concentration data from the NIC's analysis and from satellite passive microwave ice concentration as an initial condition. Once successfully implemented and tested at FNMOC, PIPS2.0 should serve as a replacement for the existing PIPS1.1 and RPIPS systems.

2.0 THE PIPS2.0 MODEL

The PIPS2.0 coupled ice-ocean model was developed to include all of the sea ice-covered regions of the Northern Hemisphere. The model domain extends from the north pole to 30° N (Fig. 1) and is designed to cover regions as far south as the Yellow Sea. The horizontal grid

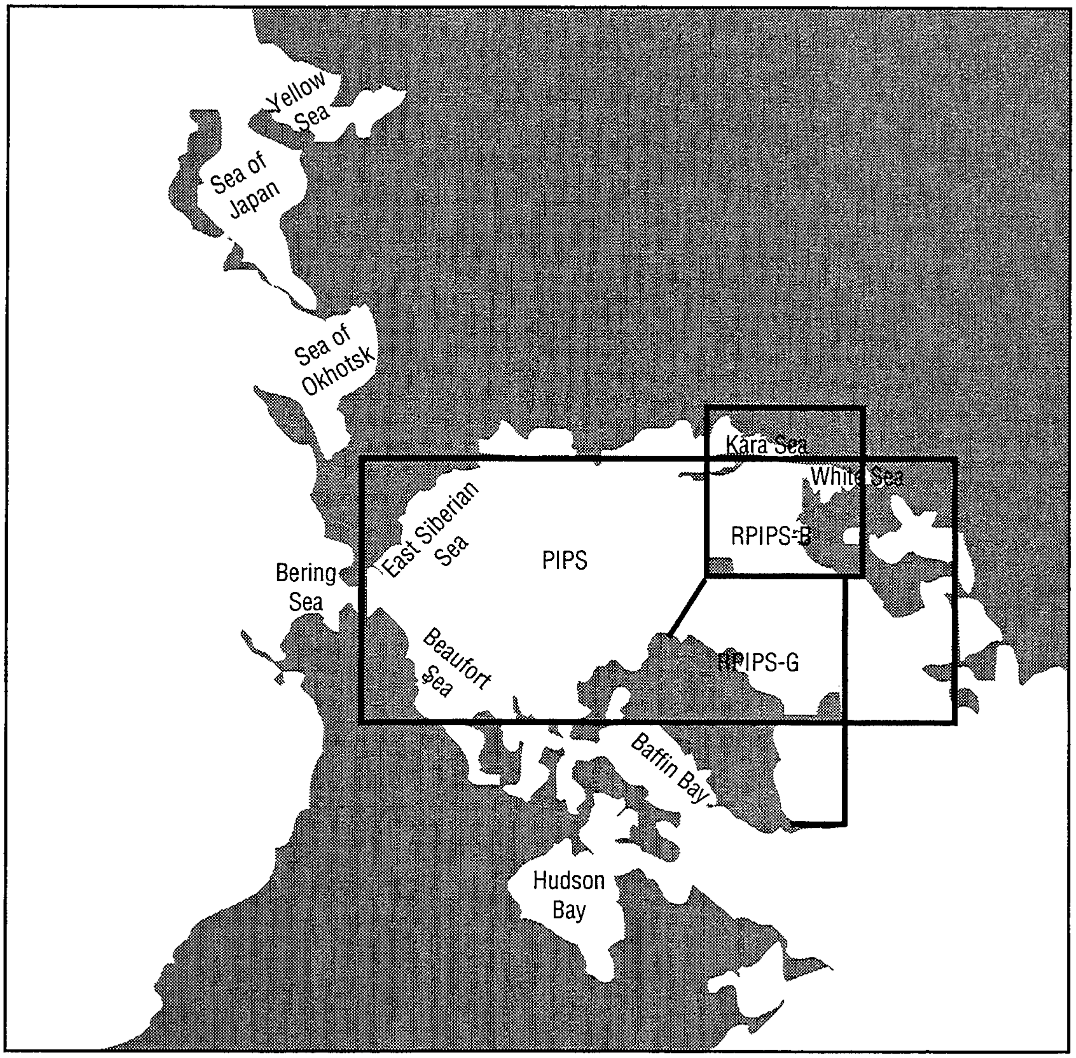

Fig. 1 — PIPS2.0 domain with regional models included (PIPS, RPIPS-B, and RPIPS-G)

resolution of the model is 0.28° (Fig. 2) and the ocean model uses 15 levels in the vertical direction. The top level is 30 m deep and the thickness of each level increases with depth. PIPS2.0 uses a 3-hr timestep for the ice model and a 30-min timestep for the ocean model. All boundaries in this model are solid walls. These walls are placed sufficiently far from the main forecast locations to minimize any boundary effect on the forecasts.

The PIPS2.0 model was tested using atmospheric forcing from NOGAPS, which will be used to drive the model when operational. This forcing consists of the following: surface pressure (used to calculate geostrophic winds), surface air temperature, surface vapor pressure (used in conjunction with surface pressure to calculate specific humidity at the ice surface), total heat flux, incoming solar radiation (short wave), and sensible plus latent heat fluxes. When implemented, PIPS2.0 will use NOGAPS surface stresses. The testing of PIPS2.0 used geostrophic winds to drive the model to reduce the number of forcing fields and, therefore, reducing the time spent with input/output (I/O) of the model.

The basis of the PIPS2.0 is the ice-ocean model, which is created from a coupling of the Hibler ice model, reformulated into spherical coordinates (Cheng and Preller 1996) to the Cox (1984)

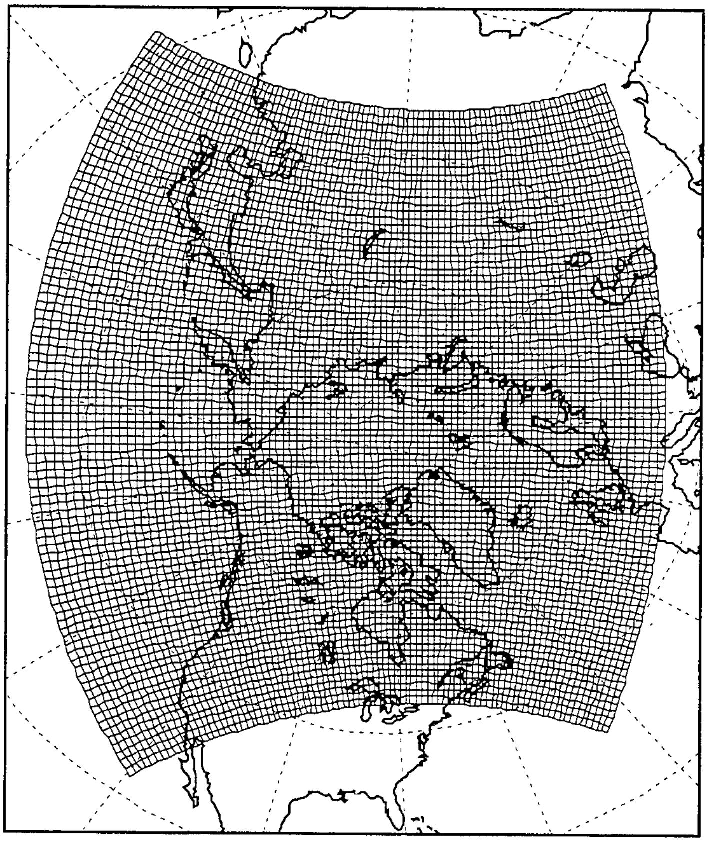

Fig. 2 — PIPS2.0 domain with the variable resolution grid overlaid. The hatched lines are drawn at every fourth gridpoint including land points.

ocean model, also in spherical coordinates. The models exchange necessary information by interfacing the top level of the ocean model with the ice model. The types of information exchanged at this interface are ice/ocean stresses, salinity fluxes, and heat fluxes. Two important equations for this exchange of information are the temperature and salinity equations, both from the Cox ocean model (Cheng and Preller 1996). The temperature equation is given by

$$\frac{\partial T}{\partial t} + \nabla \cdot (\mathbf{u} T) = K_H \nabla_H^2 T + K_z \frac{\partial^2 T}{\partial z^2} - \frac{f_A \delta(z) R_0 \theta(T - T_f)}{Z_{mix}} - R_t (T - T_0), \tag{1}$$

where T is the water temperature,

u is the ocean current,

K_H is the coefficient of the horizontal eddy diffusion,

∇_H^2 is the horizontal Laplacian operator,

K_z is the coefficient of the vertical eddy diffusion,

f_A is the ice growth/melting rate in open water due to atmospheric forcing only,

A is the ice concentration,

$\delta(z)$ is the delta function, i.e., 1 in the mixed layer and zero otherwise,

R_0 is a ratio of the latent heat of fusion of sea ice to the heat capacity of seawater,

$\theta(T - T_f)$ is 1 when the mixed-layer temperature T is greater than the freezing point T_f and zero otherwise,

R_t is the robust constraint for water temperature and salinity, and is set to 250 days for all levels in the ice-ocean coupled model,

T_0 is the Levitus monthly climatological temperature, and

Z_{mix} is the mixed-layer thickness.

The robust constraint R_t was used in the integration of the equation to keep the ocean temperature and salinity from dissipating due to eddy diffusion and lack of precipitation in the calculation. This is actually a very weak constraint on the equation.

The salinity equation used in the model is

$$\frac{\partial S}{\partial t} + \nabla \cdot (\mathbf{u}S) = K_H \nabla_H^2 S + K_z \frac{\partial^2 S}{\partial z^2} - \frac{0.035 S_f \delta(z)}{Z_{mix}} - R_t (S - S_0), \qquad (2)$$

where S is the salinity,

S_f is the total ice growth rate in open water, and

S_0 is the Levitus monthly climatology salinity.

The same robust constraint used in the temperature equation is applied to the salinity equation. The freezing temperature (°C) depends on the mixed-layer salinity and is defined as

$T_f = -54.4\ S$, where S is the salinity.

The "oceanic heat flux" into the top level of the ocean, a monthly mean value in earlier forecast systems, is calculated from the heat advected and diffused into each grid cell.

Sea ice is treated as a boundary layer blocking direct heat and momentum exchanges between the atmosphere and ocean. Surface wind stress passes momentum to the sea ice, some of which moves the sea ice, while the remainder is transferred into internal ice stress. Sea ice motion applies stress to the top level of the ocean model where there is ice cover. A variable drag coefficient, based on boundary layer theory (McPhee 1990), is used between the ice and ocean. Wind stress is applied directly to the top level of the ocean when there is open water.

Atmospheric heat fluxes and stresses are applied to the PIPS2.0 ice model following the techniques used by PIPS1.1 (Preller and Posey 1989). The combination of atmospheric and ocean fluxes are used by the ice model to determine the growth and decay of sea ice, while the combined effects of the air, ocean, and internal ice stress determine the ice drift.

3.0 MODEL RESULTS: SAMPLE FIELDS FROM PIPS1.1, RPIPS, AND PIPS2.0

The three operational forecast systems are run daily making a 72-hr forecast of ice drift, ice thickness, and ice concentration (ice edge). An example of the 24-hr forecast from each of these fields is shown in Figs. 3, 4, and 5. PIPS2.0 is capable of forecasting these fields at a resolution similar to, or better than, that of the operational systems.

In addition to forecasting over the regions covered by the operational systems, PIPS2.0 forecasts also include the lower-latitude ice-covered marginal seas, such as the Bering Sea, the Sea of

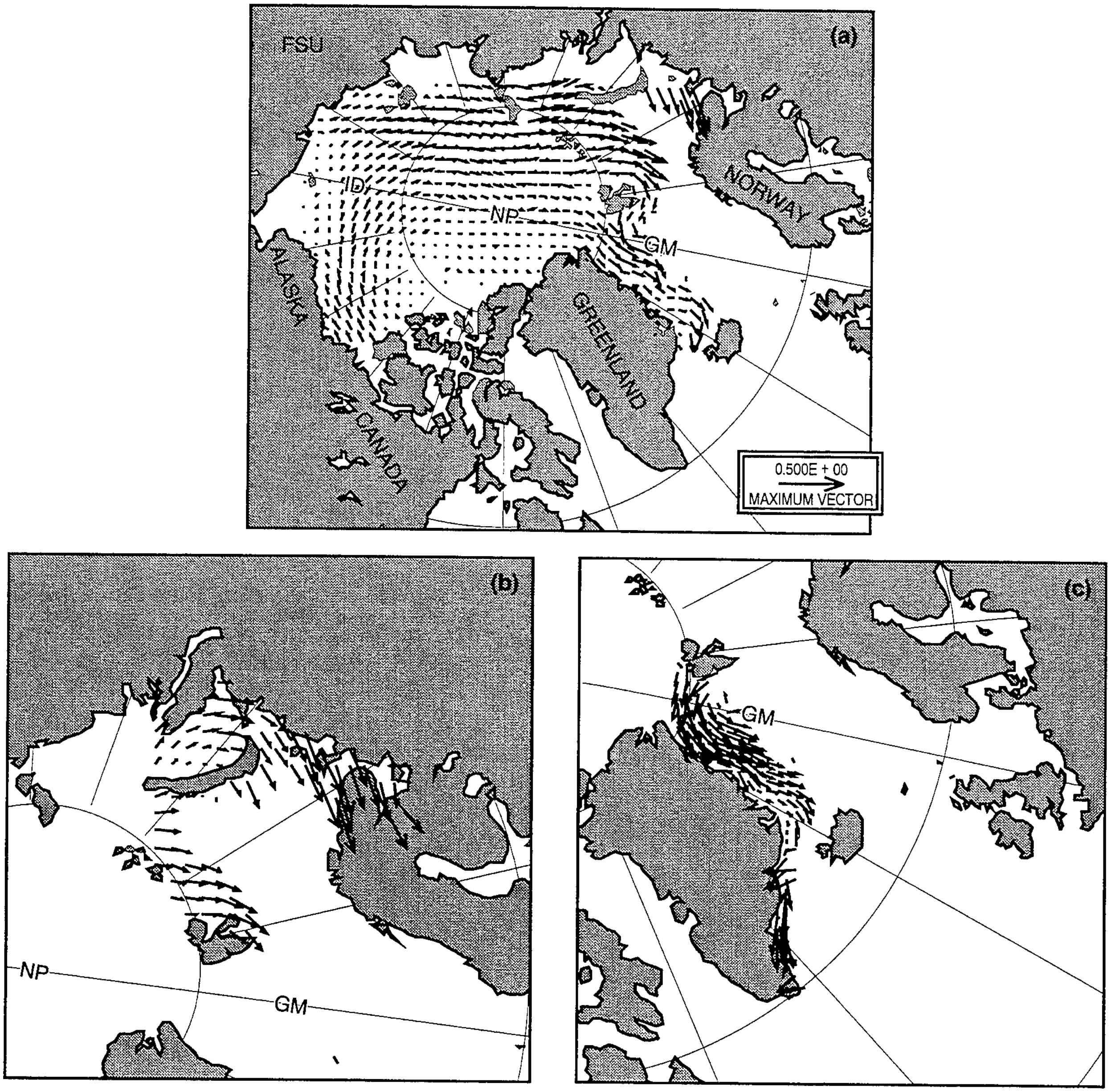

Fig. 3 — Sample 24-hr forecast of ice drift, valid Mar 30, 1992, from (a) PIPS1.1, (b) RPIPS-B, and (c) RPIPS-G. Maximum scaled drift vector is 50 cm/s.

Okhotsk, Baffin Bay, and the Labrador Sea. The PIPS2.0 ice-ocean model code has been rigorously tested using NOGAPS daily forcing. The model was run repeatedly for 3 yr using 1992 NOGAPS daily forcing. These model runs provided realistic simulations of ice drift, thickness, and concentrations, as well as ocean temperatures, salinities, and currents throughout the 3-yr run. Figures 6 and 7 show examples of model results for fall, winter, spring, and summer using 1992 NOGAPS forcing. It should be noted that for these simulations, the model was initialized from a model forecast for October, derived from 1986 NOGAPS forcing. There is no subsequent initialization from any type of data for the model forecast. Figure 6 shows the daily mean ice drift from PIPS2.0 representing the four seasons. For comparison, Fig. 7 shows surface pressure fields derived from Arctic buoy data (Colony and Rigor 1993) corresponding to each day in Fig. 6. The model ice drift clearly reflects the general features of the atmospheric circulation.

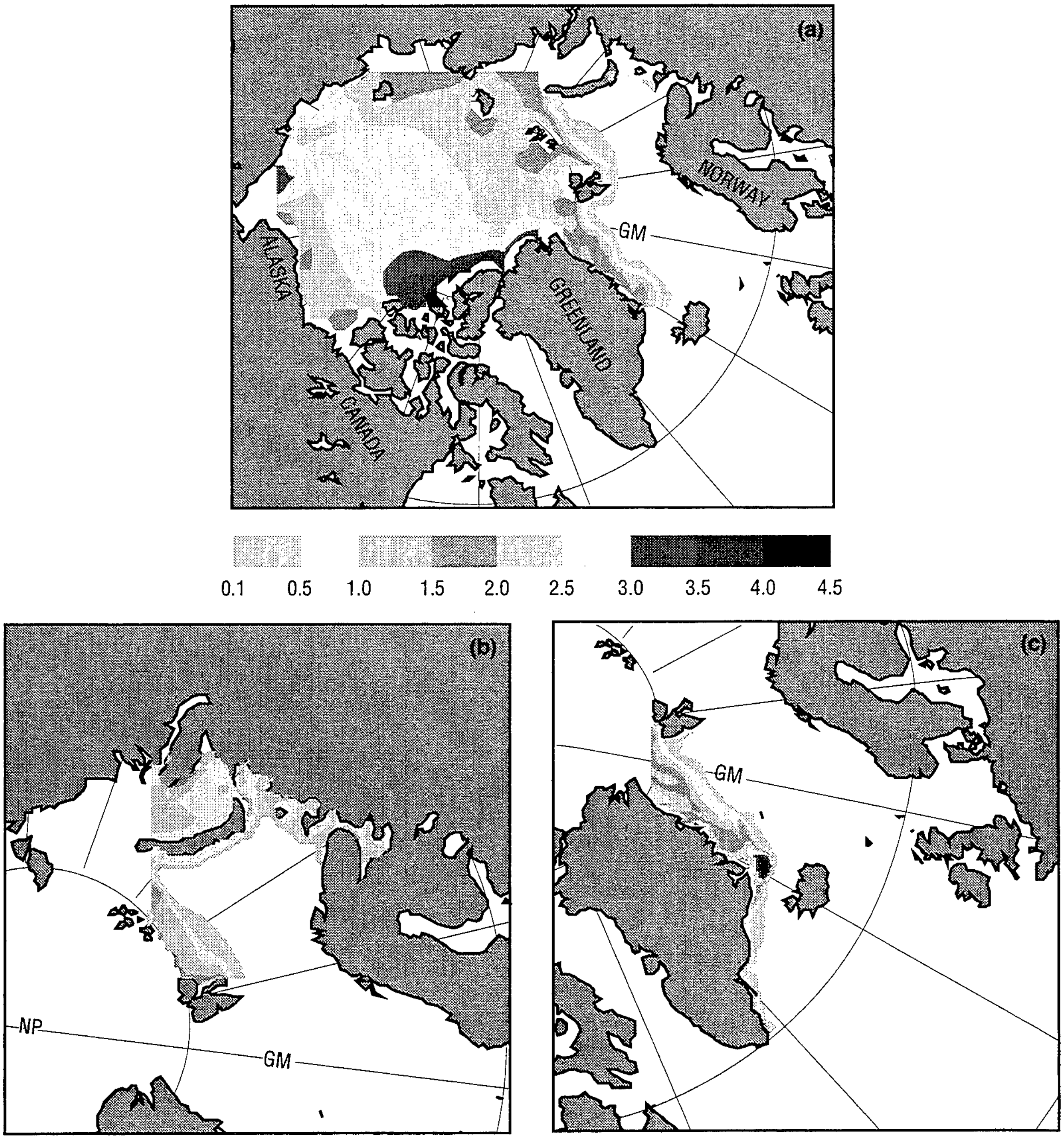

Fig. 4 — Sample 24-hr forecast of ice thickness (m), valid Mar 30, 1992, from (a) PIPS1.1, (b) RPIPS-B, and (c) RPIPS-G. Contour interval for ice thickness is 0.5 m.

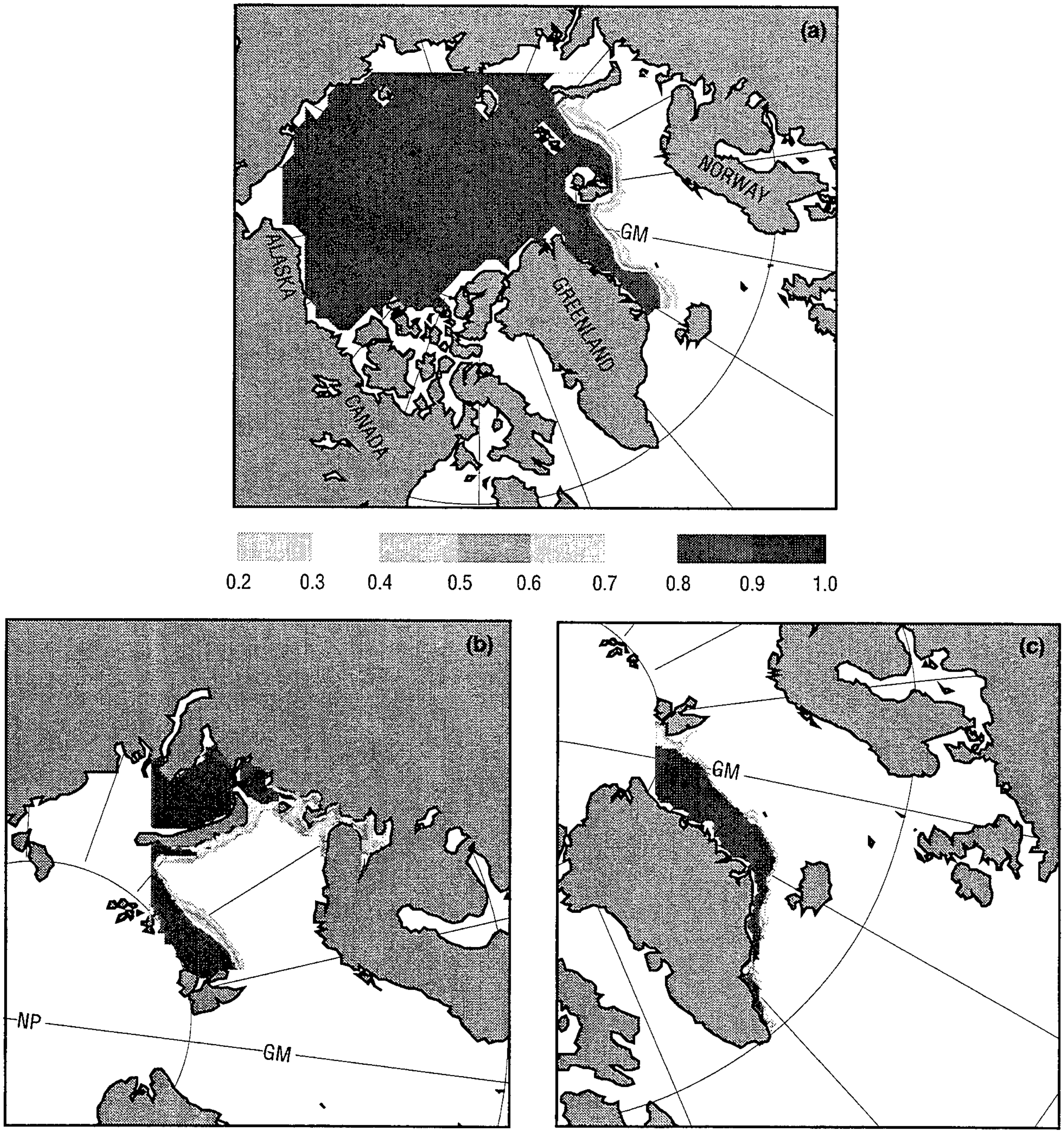

Fig. 5 — Sample 24-hr forecast of ice concentration (percent), valid Mar 30, 1992, from (a) PIPS1.1, (b) RPIPS-B, and (c) RPIPS-G. Contour interval for ice concentration is 10%.

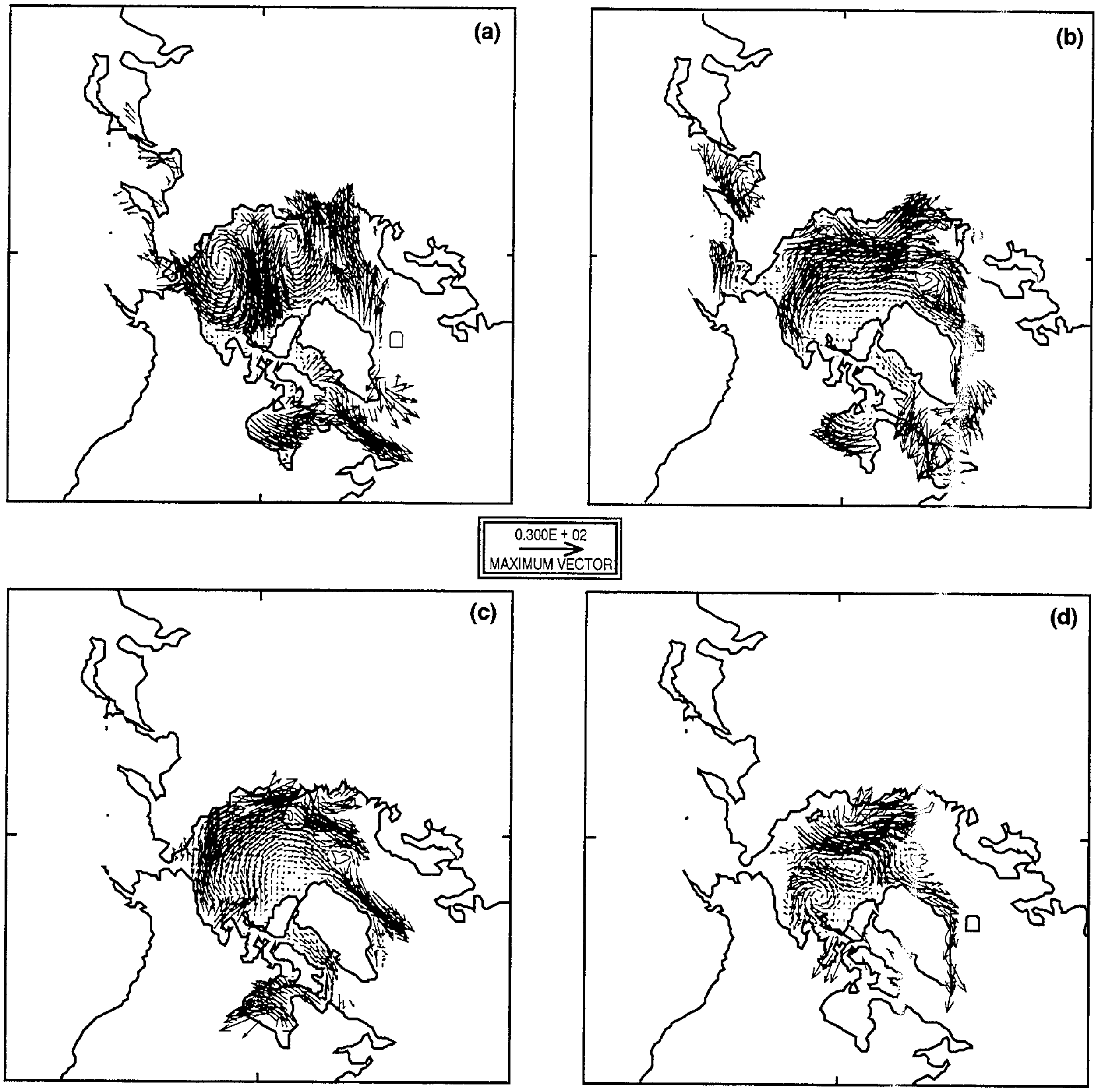

Fig. 6 — Daily ice-drift velocities (cm/s) from PIPS2.0 representing the four seasons: (a) fall, (b) winter, (c) spring, and (d) summer. Maximum scaled drift vector is 30 cm/s.

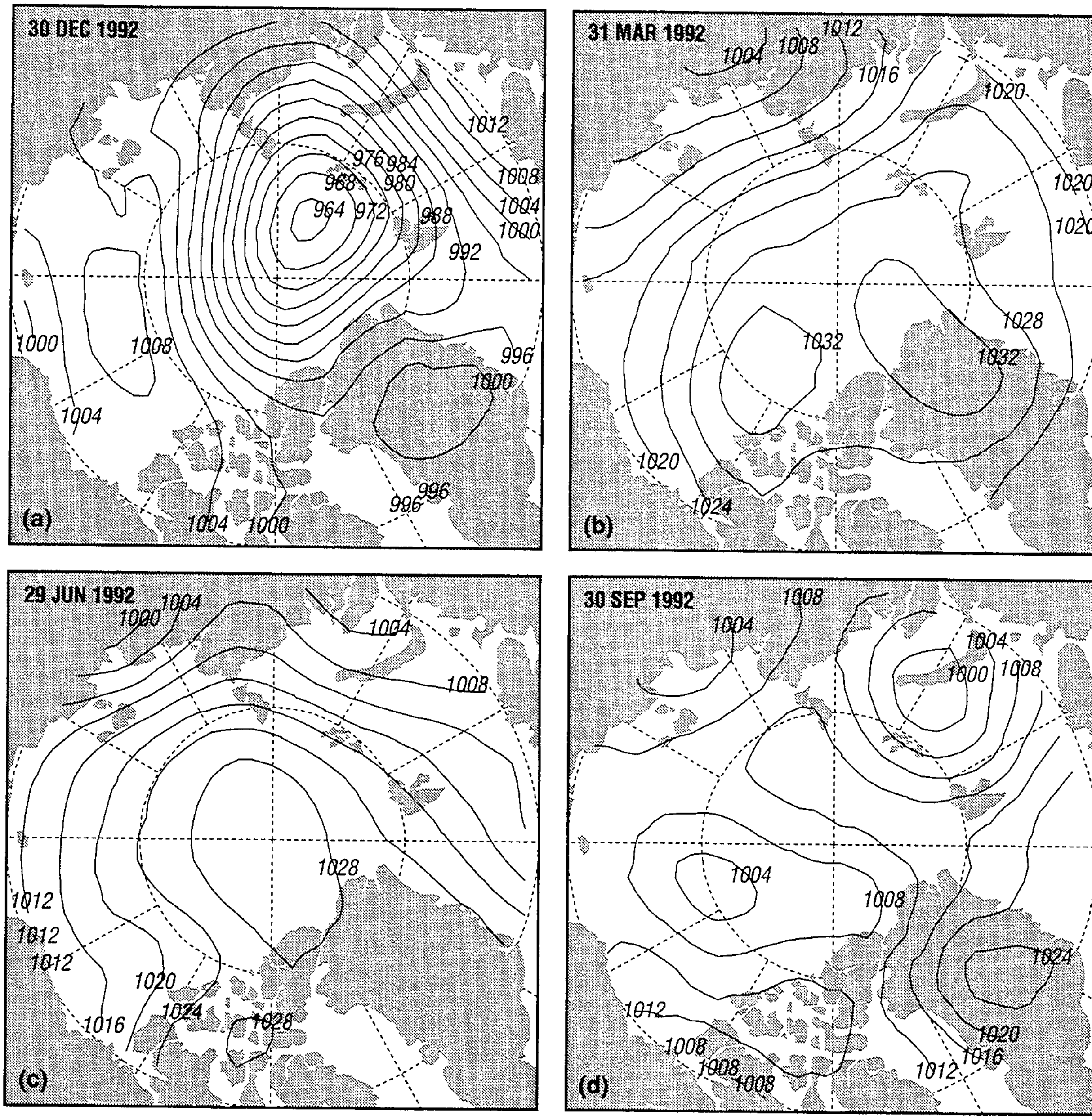

Fig. 7 — Daily surface pressures derived from Arctic buoys representing the four seasons: (a) fall, (b) winter, (c) spring, and (d) summer

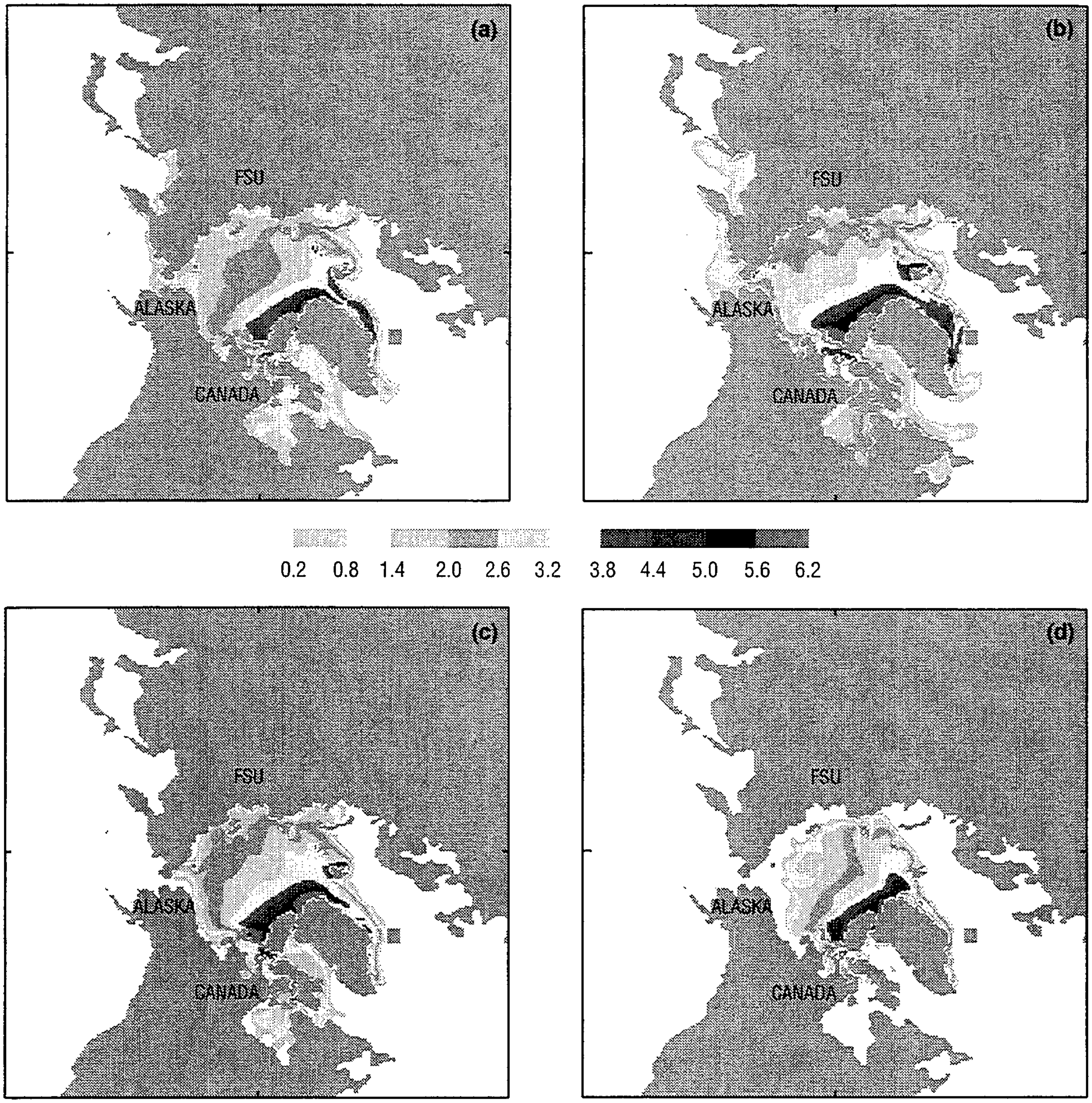

Fig. 8 — Daily ice thickness (m) from PIPS2.0 representing the four seasons: (a) fall, (b) winter, (c) spring, and (d) summer. Contour interval is 0.6 m.

Figure 8 shows the daily mean ice thickness from PIPS2.0 representing the four seasons. Figure 9 contains the daily mean ice concentration for the four seasons. The ice edge from the NIC analysis is drawn on this figure. Comparison of the modeled versus the observed ice edge indicates that the model does well in predicting the ice advance and retreat in the Pacific marginal seas, the Bering Sea, and the Sea of Okhotsk. The model also does well in Hudson Bay, Baffin Bay, and Davis Strait. However, the model has three inconsistencies: (1) in the Labrador Sea, the model underpredicts ice in the winter and fall; (2) in the marginal seas of the eastern Arctic Ocean, the Barents Sea, and the Greenland Sea, the model overpredicts the amount of sea ice in winter, spring, and summer in several different locations; and (3) the model underpredicts ice in the Beaufort Sea and parts of the Chukchi Sea and the East Siberian Sea in summer. Some of these inconsistencies

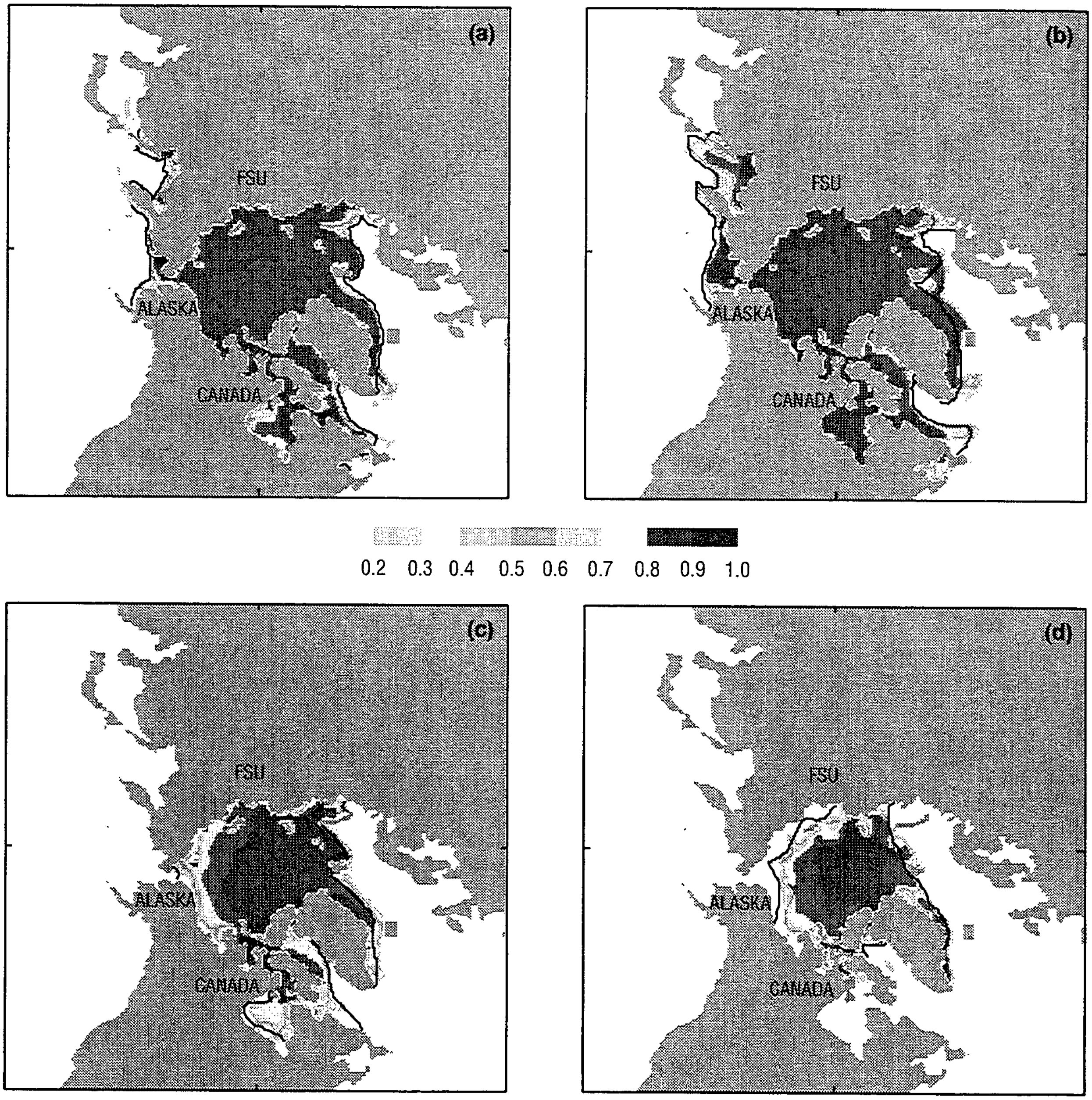

Fig. 9 — Daily ice concentration (percent) from PIPS2.0 representing the four seasons: (a) fall, (b) winter, (c) spring, and (d) summer. Solid black line represents ice edge from the NIC weekly analysis. Contour interval is 10%.

between model and observation are due to the fact that the ocean model was not specifically designed to handle coastal and shelf processes (shallow-water processes); some are due to the model's treatment of all ice as a continuum and not as separate floes; and some are due to inaccuracies in the atmospheric forcing. However, without benefit of any initialization of the PIPS2.0 model from observation, it still appears to have the capability to forecast ice conditions with a great deal of accuracy in many locations.

PIPS2.0 not only improves the existing forecast systems by providing ice products in new locations, it can also provide several completely new products. For example, Figs. 10 and 11 are

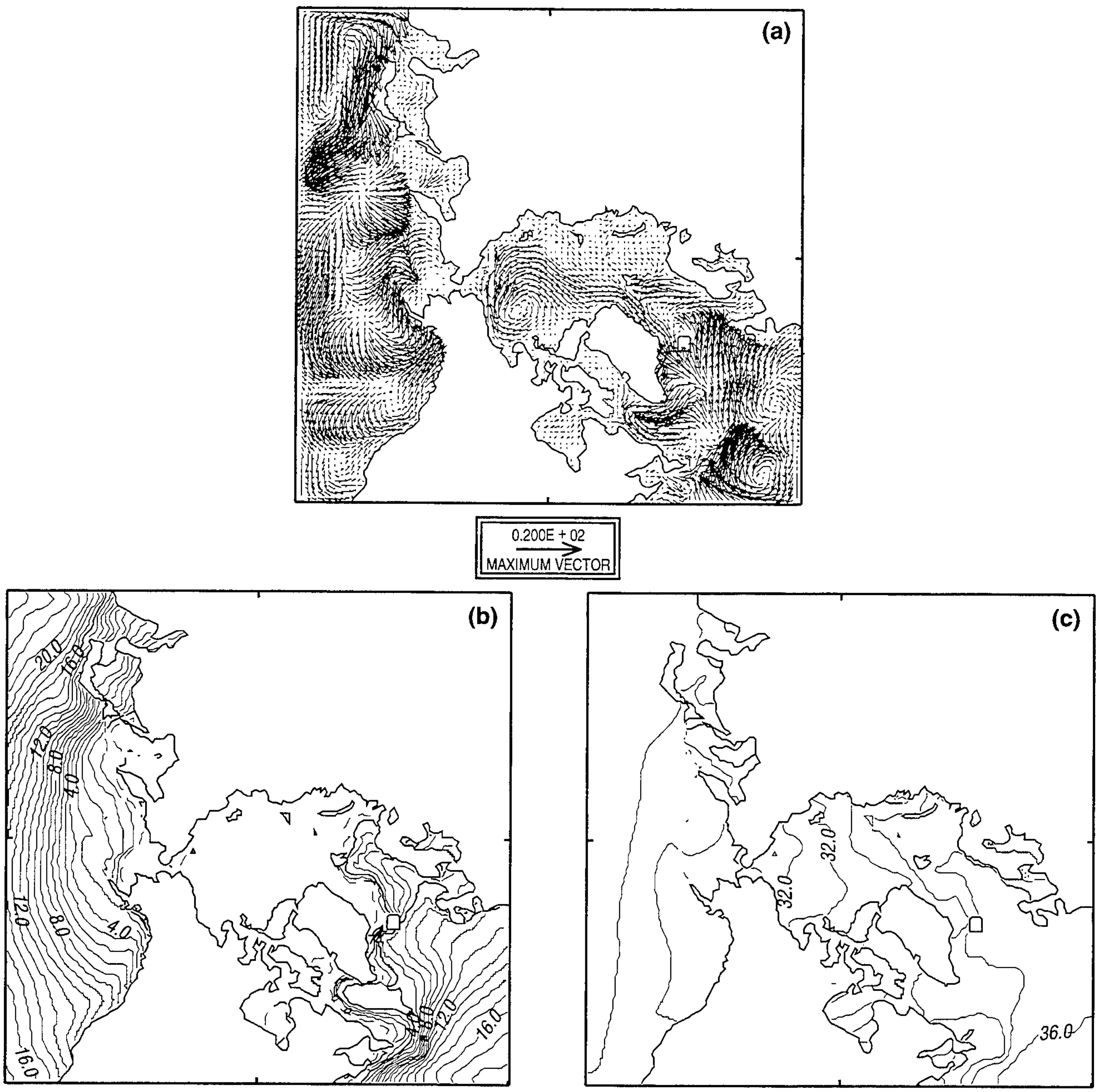

Fig. 10 — Sample 24-hr forecast, valid Mar 30, 1992, from PIPS2.0 of (a) ocean currents (cm/s) at 15 m, maximum scaled drift vector 20 cm/s; (b) ocean temperature (°C) at 15 m, contour interval range from −1°C to 24°C by 1°C; and (c) ocean salinity (ppt) at 15 m, contour interval range from 25 ppt to 40 ppt by 1 ppt

sample forecasts of these new products for ocean currents, ocean temperature, and salinity (for winter and summer, respectively). The weak constraint on the ocean temperature and salinity will not allow the model to forecast large anomalies like the Great Salt Anomaly; however, the model does allow realistic daily, monthly, and seasonal variability, as well as normal interannual variability. The surface ocean currents seem to be dominated by the surface stress and vary daily.

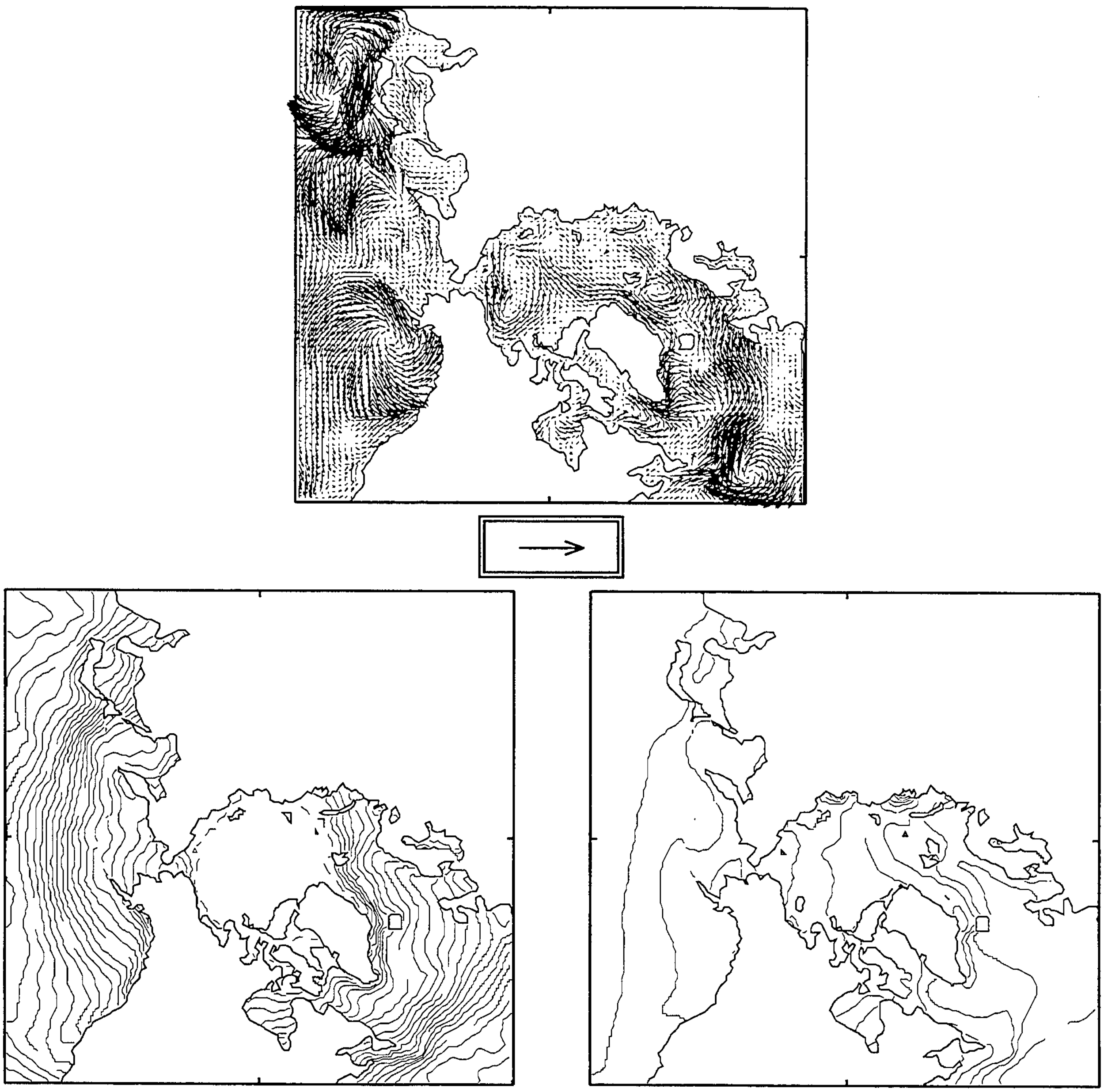

Fig. 11 — Sample 24-hr forecast, valid Sep 30, 1992, from PIPS2.0 of (a) ocean currents (cm/s) at 15 m, maximum scaled drift vector 20 cm/s; (b) ocean temperature (°C) at 15 m, contour interval range from -1°C to 27°C by 1°C; and (c) ocean salinity (ppt) at 15 m, contour interval range from 25 ppt to 40 ppt by 1 ppt

4.0 MODEL VERIFICATION: COMPARISON OF MODELED VERSUS OBSERVED ICE DRIFT

Ice motion is one of the few sea ice fields for which enough data exist to actually do a quantitative comparison between models and observation. Such a comparison was previously performed for the verification of PIPS1.1 ice drift (Preller and Posey 1989) and in an undocumented study comparing PIPS1.1 ice motion driven by geostrophic winds versus NOGAPS surface stresses. In this study, it was found that ice motion in the Arctic basin, derived using the surface stresses, gave results very similar to those using geostrophic winds. For that reason, each of the operational ice forecast systems was modified to use the surface stresses. In the case of PIPS2.0, although geostrophic winds could provide useful ice drift in the high Arctic, they might not be an accurate representation of winds at lower latitudes; therefore, the operational PIPS2.0 will use NOGAPS surface stresses.

The following discussion presents both a qualitative as well as a quantitative (statistical) comparison of the ice drift from PIPS2.0 versus the ice drift from PIPS1.1 and a comparison of both systems to observational data. Only PIPS1.1 was used in this comparison because the majority of the drifting buoys are in the central Arctic. In addition, all testing of PIPS2.0 used geostrophic winds derived from NOGAPS surface pressures. As stated previously, this was an attempt to keep the very large I/O requirements for testing this model down to a minimum. Use of the NOGAPS surface stresses would require an additional two fields for the model simulation. For this comparison of ice drift in the central Arctic, the use of geostrophic winds versus NOGAPS surface stresses has no impact on the results.

Starting and ending time and location for each drifter is shown in Table 1. Figure 12a and b shows the tracks for the eight *Argos* drifting buoys used in this comparison. Each of these buoys tracked through the Arctic in 1992 and were compared to model results driven by 1992 NOGAPS forcing.

Figure 13a and b shows the tracks of eight drifters started at the same location and time as the observed drifters shown in Fig. 12a and b. However, in this case, the drifter track is calculated based on the model-derived ice drift. Each day a new location is calculated based on the model-derived ice-drift velocity. The ice-drift velocity is determined by interpolating to the drifter's

Table 1 – *Argos* Buoy Locations

BUOY	STARTING DATE	ENDING DATE	STARTING LOCATION	ENDING LOCATION
11108	01/01/92	12/31/92	84.996° N, 74.040° E	80.850° N, 16.381° E
12800	01/01/92	08/09/92	75.959° N, 204.557° E	79.732° N, 195.139° E
12801	01/01/92	12/31/92	79.855° N, 222.181° E	72.243° N, 217.321° E
12802	01/01/92	12/31/92	85.791° N, 290.782° E	74.752° N, 349.720° E
12805	01/01/92	12/31/92	86.608° N, 327.827° E	71.241° N, 341.248° E
12806	01/01/92	12/31/92	72.326° N, 219.983° E	72.918° N, 175.332° E
12807	01/01/92	10/22/92	79.647° N, 192.552° E	80.595° N, 227.456° E
12808	01/01/92	12/31/92	76.170° N, 234.282° E	71.829° N, 209.405° E

location. Comparison of Figs. 12a and 13a shows good agreement between the model data and observed data for buoy 12805 drifting through the Fram Strait. The two buoys that are placed in the Beaufort Sea are initially on a course in agreement with real data, but they have a strong westward component pushing them toward the Chukchi Sea during the last half of their track. Buoy 12807 also seems to move with good agreement during the first half of its track, but then it veers southward while the observed drifter moves poleward.

Figures 12b and 13b indicate that buoy 12802, also exiting the Fram Strait, compares very well to the observed drifter's track. Buoy 11108, beginning north of the Barents Sea, tracks fairly close to the observed drifter along most of the pathway. Approximately two-thirds of the way through the track, however, it moves south instead of turning east and ends up farther east than the real buoy. Buoy 12800 tracks slightly farther north and west than the observed drifter, while Buoy 12801 gets caught in a relatively strong southerly flow not observed in the actual drifter's track. As a result, it is located closer to the Alaskan coast than the actual buoy.

The following statistical analysis compares the magnitude of the ice-drift velocity derived from the model and that derived from observed buoy motion. The mean magnitude ice drift is calculated from the observed daily change in the position of the buoys. The 3-hourly magnitude ice-drift velocities from the model are averaged into daily ice magnitude drift velocities. The daily ice magnitude drift velocities are then averaged into monthly means for each buoy. A comparison of the monthly means for each buoy is shown in Figs. 14 and 15. Although from month to month the comparison varies, overall the PIPS2.0 mean ice-drift magnitude is in slightly better agreement with the observed drift than the PIPS1.1 data. It was expected that the PIPS1.1 and PIPS2.0 values would be similar, since the wind forcing is similar and PIPS1.1 has always produced good forecasts for ice drift in the central Arctic. The slight improvement in the PIPS2.0 results is due to higher resolution and improved oceanic forcing. Figures 16 and 17 show the root-mean-squared (RMS) error between these two model-derived drifts and the observations. Again, these results are quite similar, with PIPS2.0 having a lower average RMS error for four of the eight buoys. Note that the largest number of RMS errors usually occurs during the summer when the buoy is observed to move substantially faster than the model-derived ice drift would indicate. Similar statistics calculated for the direction of the ice drift show the PIPS2.0 model to be a slight improvement over the PIPS1.1 model.

5.0 COMPARISON OF MODEL FORECASTS INITIALIZED FROM OBSERVATIONS

The operational forecast systems are initialized each day from their own 24-hr forecast. Once each week, the model's ice concentration field is initialized from the NIC analysis of ice concentration. This analysis uses several sources of remotely sensed data (AVHRR, SAR, and SSM/I). The model's ice thickness and ocean temperature fields are adjusted to agree with the ice concentration data when the system is initialized.

During the past several years (1993–1995), FNMOC has been obtaining SSM/I data that have been converted into ice concentration data and used by the NIC in a weekly analysis. Since these SSM/I data are now available in real time at FNMOC, the PIPS2.0 will use the NIC analysis for initialization once each week, and the SSM/I data several times during the week when the NIC analysis is not available.

A qualitative comparison was made between the 5-day forecast of the PIPS1.1 and RPIPS systems and the PIPS2.0 5-day forecast. In the case of PIPS1.1 and the regional forecast system's results, either a 5-, 6-, or 10-day forecast was used after the initialization from NIC concentration.

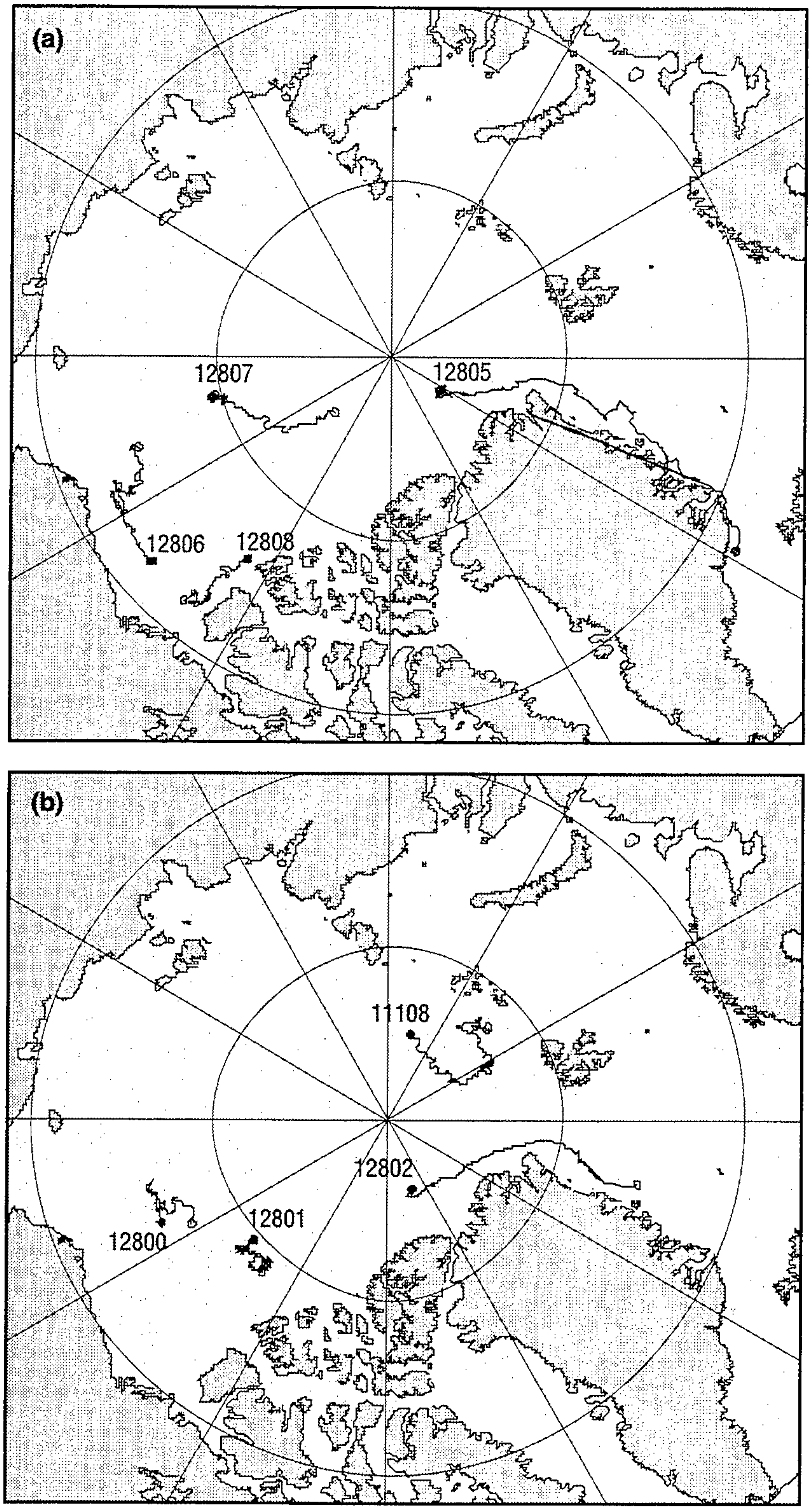

Fig. 12 — *Argos* drifter tracks from Jan 1, 1992 through Dec 31, 1992: (a) buoys 12805, 12806, 12807, and 12808 and (b) buoys 11108, 12800, 12801, and 12802

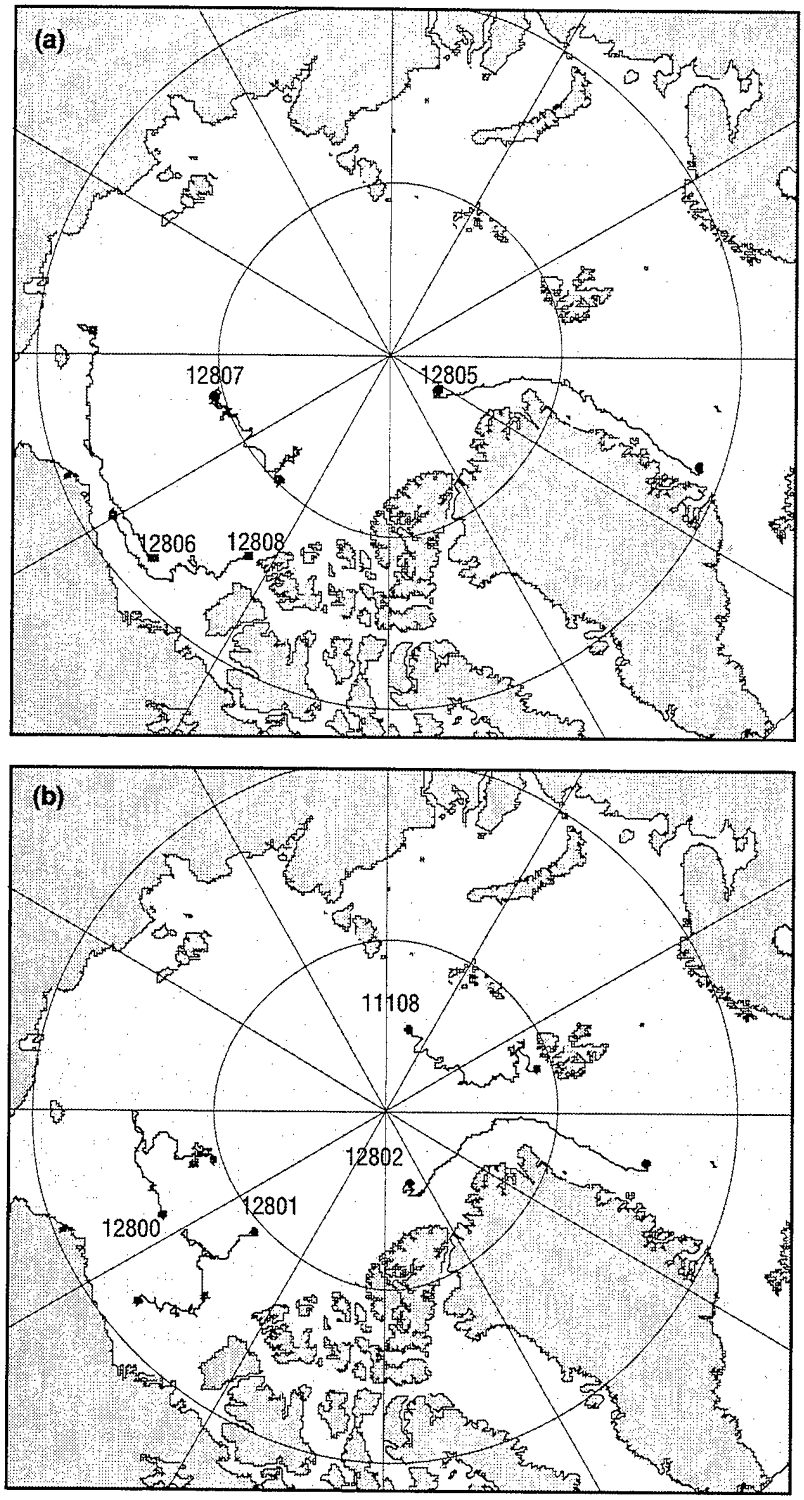

Fig. 13 — PIPS2.0 drifter tracks from Jan 1, 1992 through Dec 31, 1992: (a) buoys 12805, 12806, 12807, and 12808 and (b) buoys 11108, 12800, 12801, and 12802

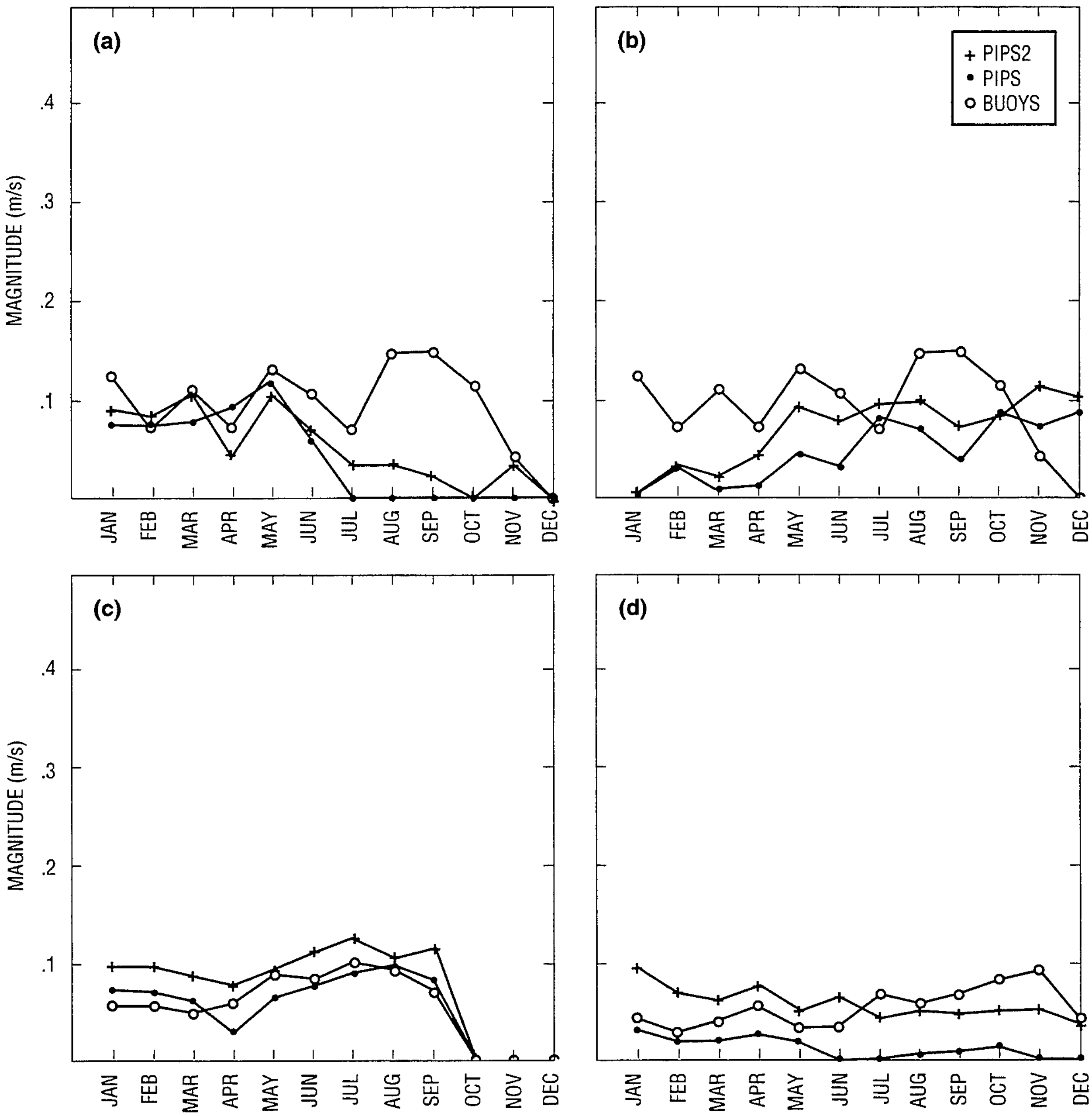

Fig. 14 — Mean ice-drift comparison of PIPS2.0 and PIPS1.1 against buoys (a) 12805, (b) 12806, (c) 12807, and (d) 12808

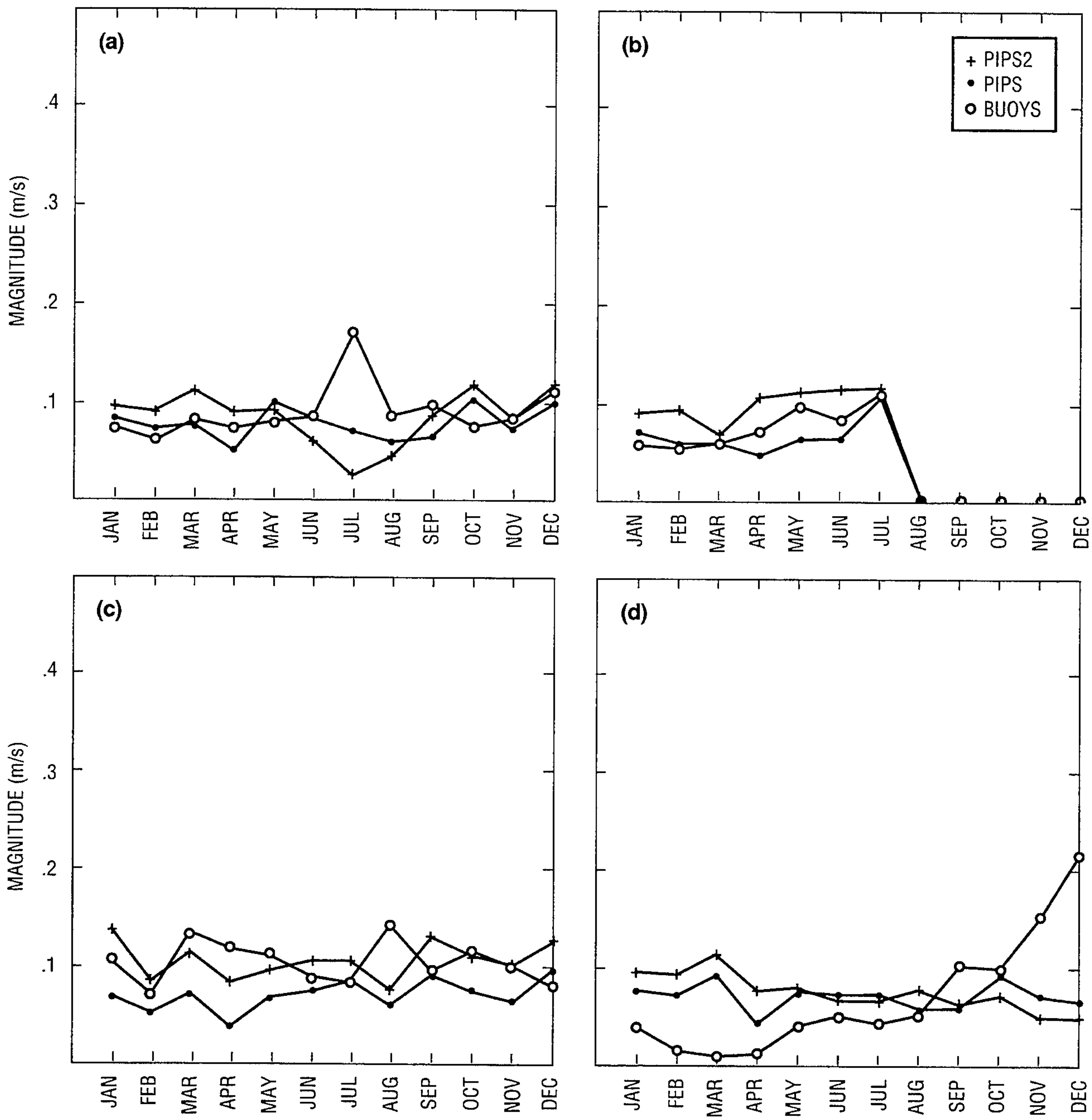

Fig. 15 — Mean ice-drift comparison of PIPS2.0 and PIPS1.1 against buoys (a) 11108, (b) 12800, (c) 12801, and (d) 12802

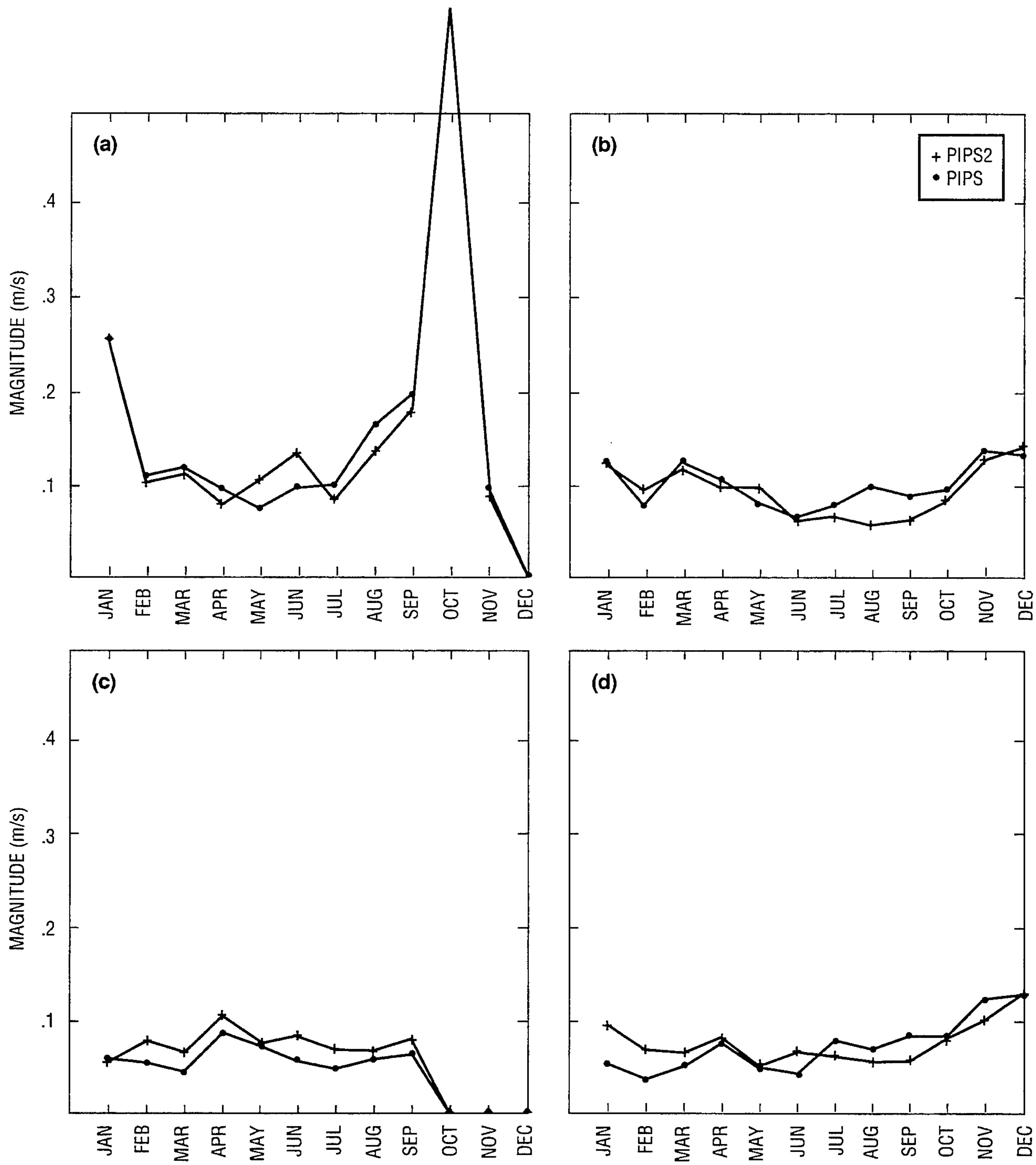

Fig. 16 — RMS error comparison of PIPS2.0 and PIPS1.1 against buoys (a) 12805, (b) 12806, (c) 12807, and (d) 12808

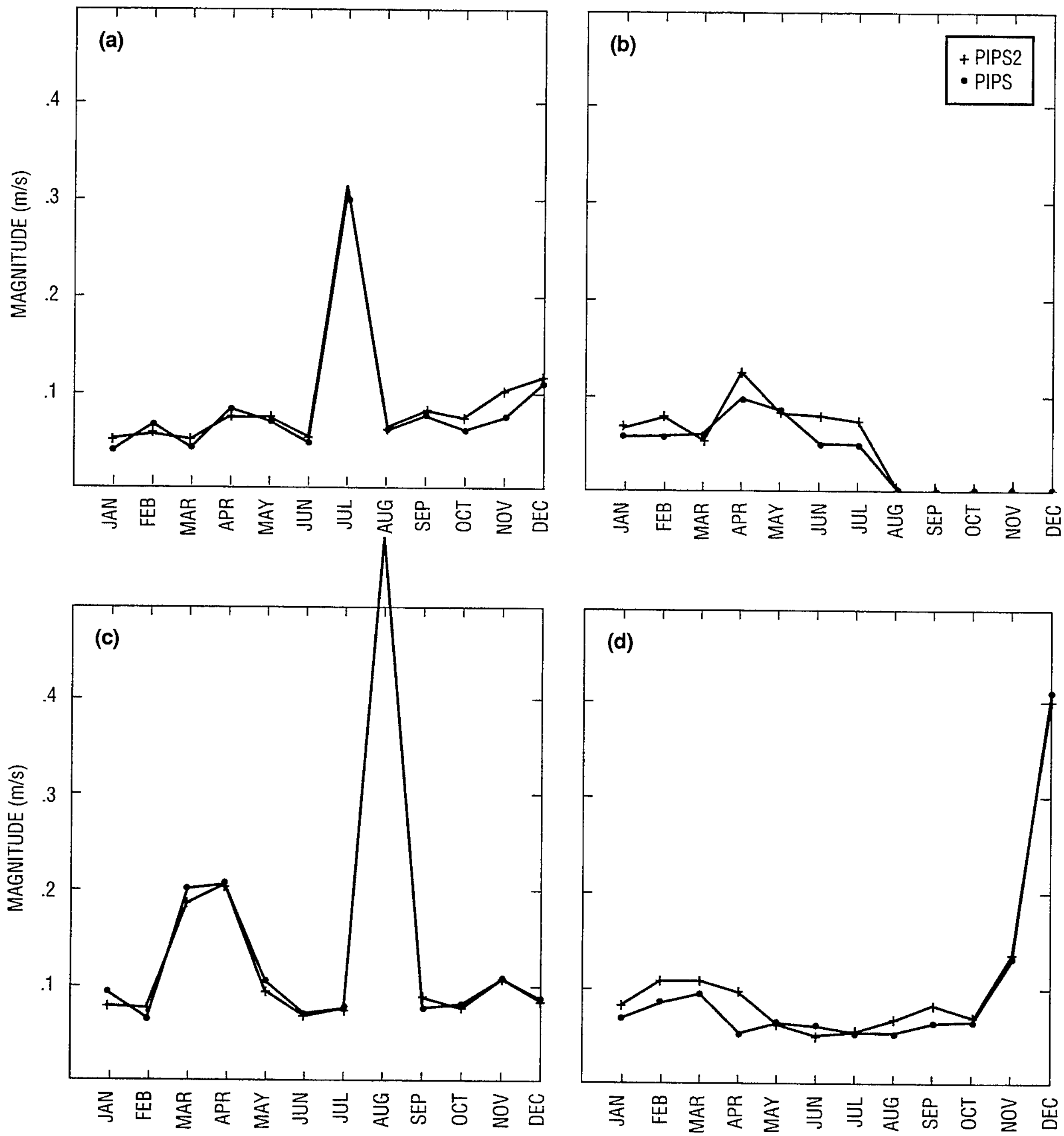

Fig. 17 — RMS error comparison of PIPS2.0 and PIPS1.1 against buoys (a) 11108, (b) 12800, (c) 12801, and (d) 12802

Varying the length of the forecast was due to data availability. The PIPS2.0 forecast was a 5-day forecast initializing from the SSM/I concentration data. The NIC data could not be used for the PIPS2.0 forecast because those data are not archived, and therefore, were not available for the PIPS2.0 initialization. The NIC data and the SSM/I data are very similar, though, since the NIC relies heavily on the SSM/I data in the analysis. Several examples from each season (fall, winter, spring, and summer) are shown in Figs. 18–21. For each case, the SSM/I concentration used for initialization, the SSM/I data from the final day of the forecast (used for verification), and the forecast ice concentration for PIPS1.1, RPIPS, and PIPS2.0 systems are shown.

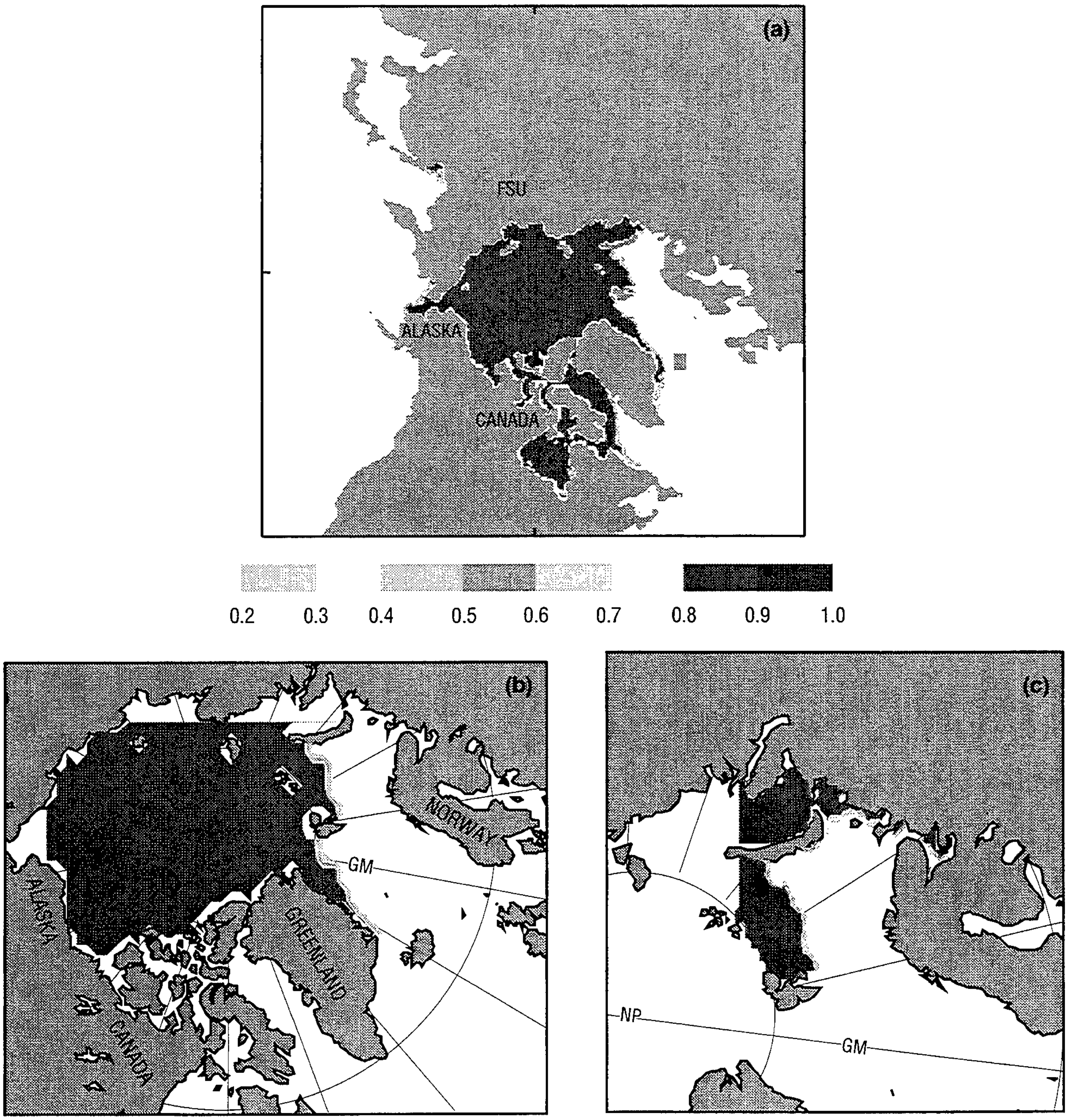

Fig. 18 — Forecast initialization field from (a) SSM/I data, valid Dec 5, 1992 and 5-day forecast of (b) PIPS1.1 ice concentration, valid Dec 10, 1992, and (c) RPIPS-B ice concentration, valid Dec 10, 1992. Contour interval for ice concentration is 10%.

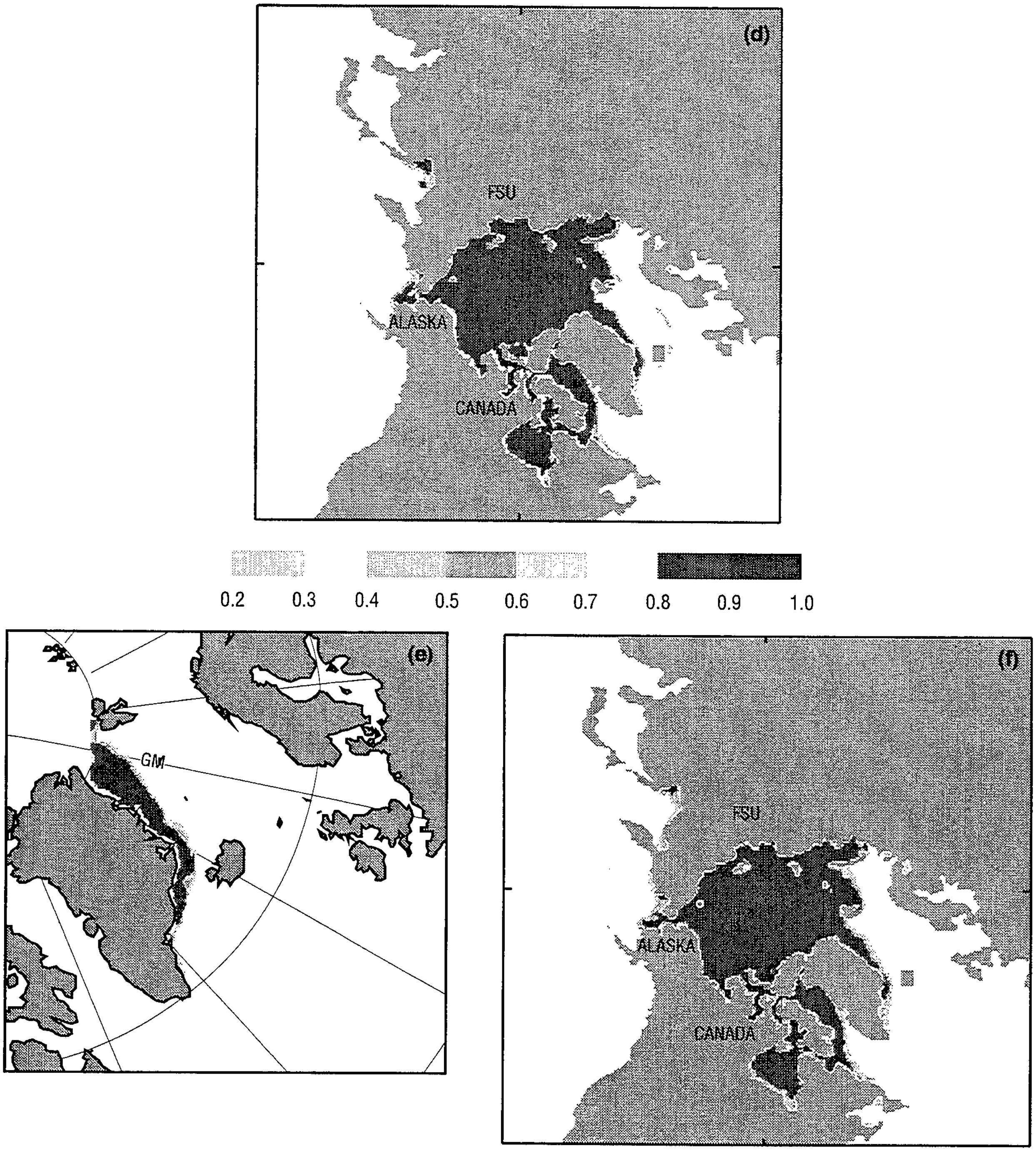

Fig. 18 (cont.) — (d) SSM/I ice concentration, valid Dec 10, 1992 and 5-day forecast of (e) RPIPS-G ice concentration, valid Dec 10, 1992, and (f) PIPS2.0 ice concentration, valid Dec 10, 1992. Contour interval for ice concentration is 10%.

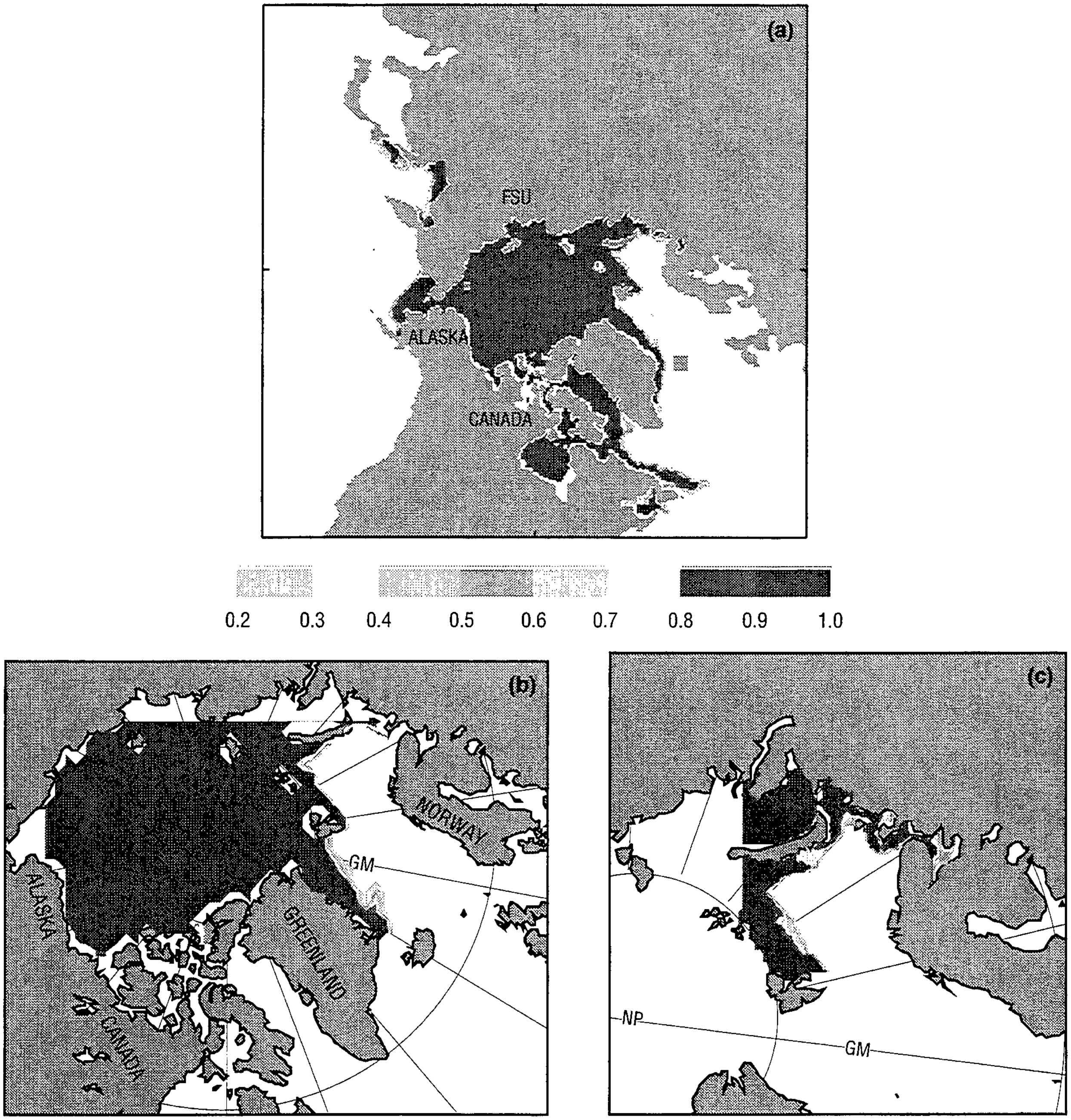

Fig. 19 — Forecast initialization field from (a) SSM/I data, valid Mar 3, 1992 and 10-day forecast of (b) PIPS1.1 ice concentration, valid Mar 13, 1992, and (c) RPIPS-B ice concentration, valid Mar 13, 1992. Contour interval for ice concentration is 10%.

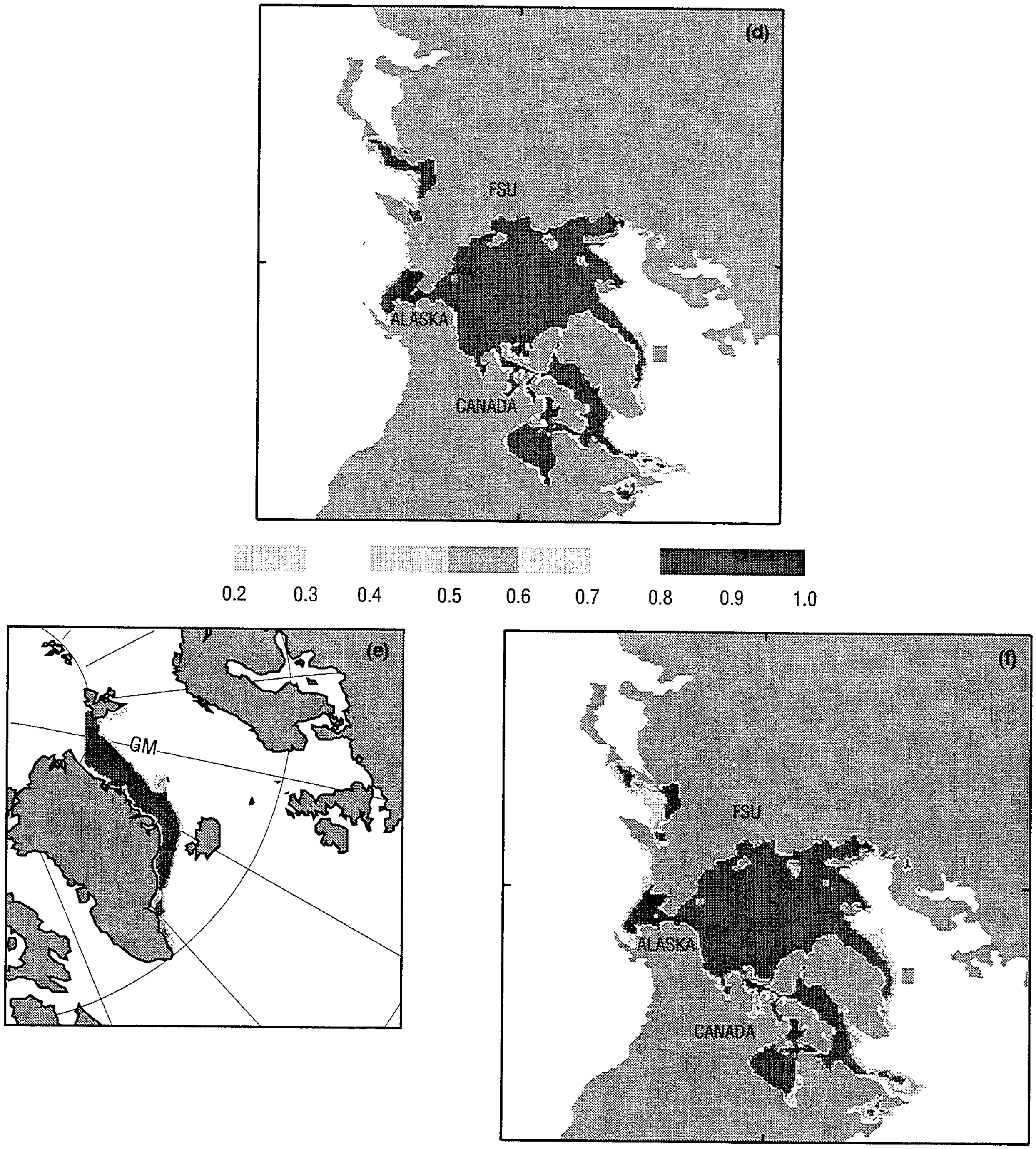

Fig. 19 (cont.) — (d) SSM/I ice concentration, valid Mar 13, 1992 and 10-day forecast of (e) RPIPS-G ice concentration, valid Mar 13, 1992, and (f) PIPS2.0 ice concentration, valid Mar 13, 1992. Contour interval for ice concentration is 10%.

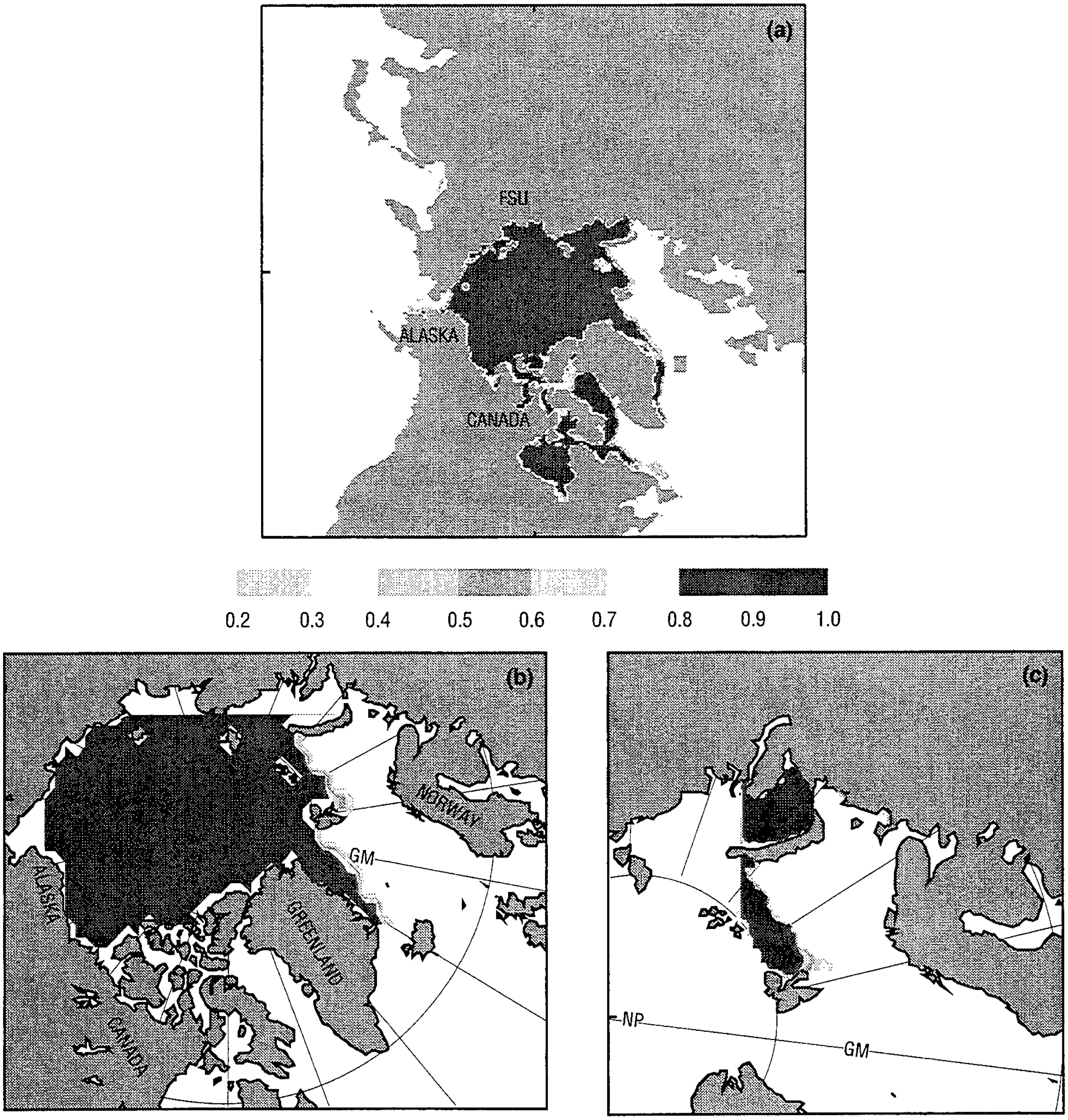

Fig. 20 — Forecast initialization field from (a) SSM/I data, valid Jun 6, 1992 and 5-day forecast of (b) PIPS1.1 ice concentration, valid Jun 11, 1992, and (c) RPIPS-B ice concentration, valid Jun 11, 1992. Contour interval for ice concentration is 10%.

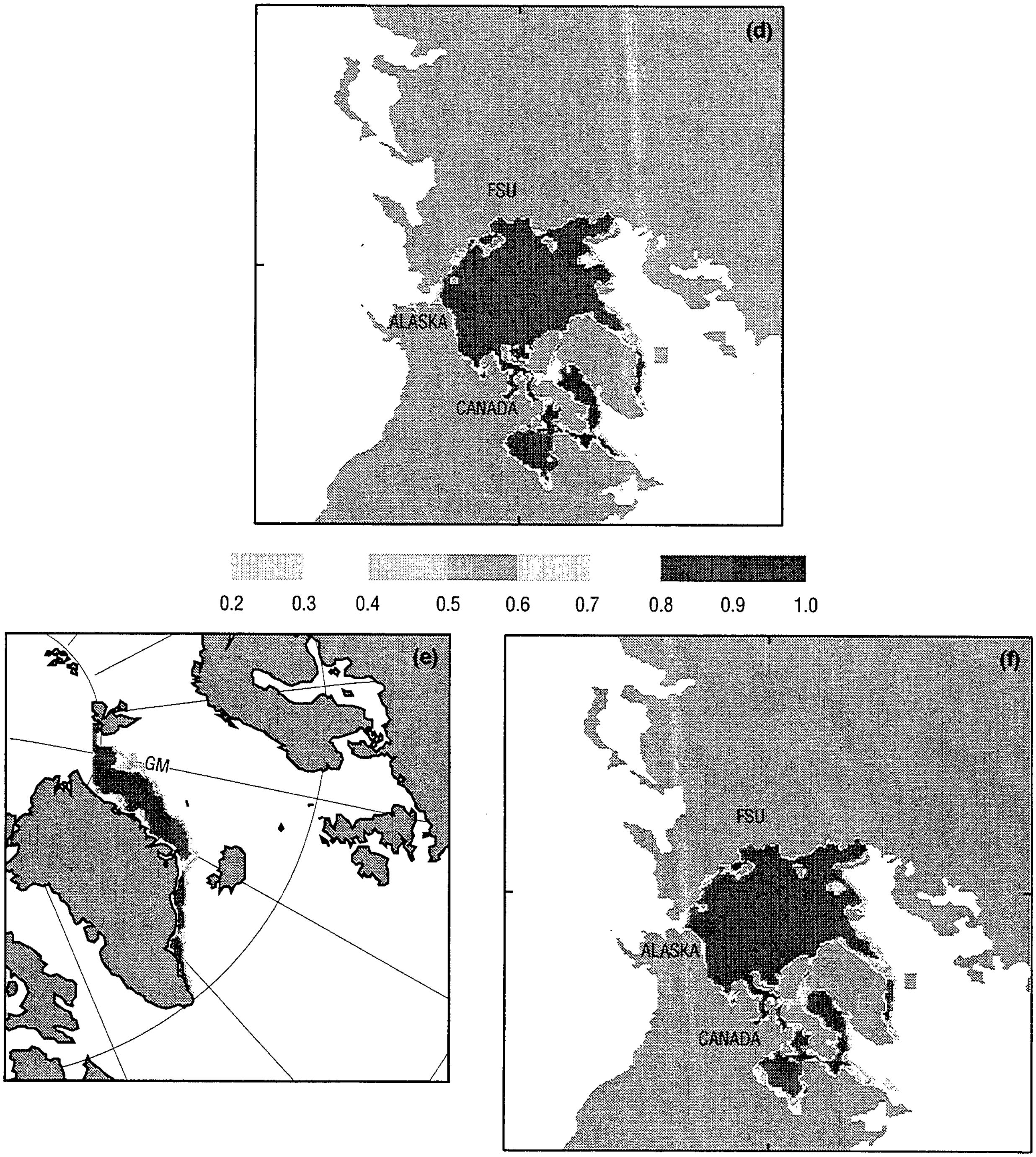

Fig. 20 (cont.) — (d) SSM/I ice concentration, valid Jun 11, 1992 and 5-day forecast of (e) RPIPS-G ice concentration, valid Jun 11, 1992, and (f) PIPS2.0 ice concentration, valid Jun 11, 1992. Contour interval for ice concentration is 10%.

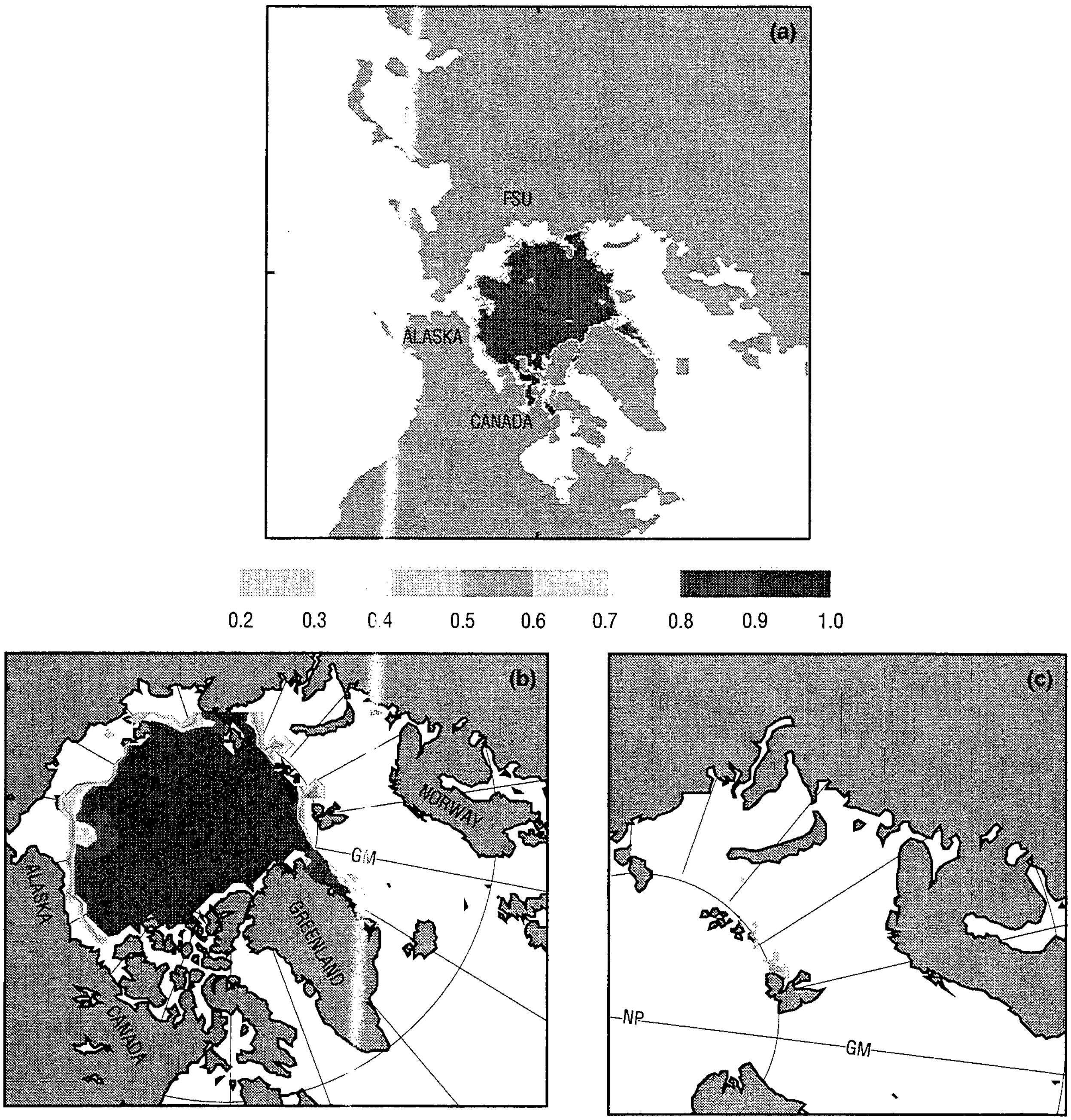

Fig. 21 — Forecast initialization field from (a) SSM/I data, valid Sep 4, 1992 and 6-day forecast of (b) PIPS1.1 ice concentration, valid Sep 10, 1992, and (c) RPIPS-B ice concentration, valid Sep 10, 1992. Contour interval for ice concentration is 10%.

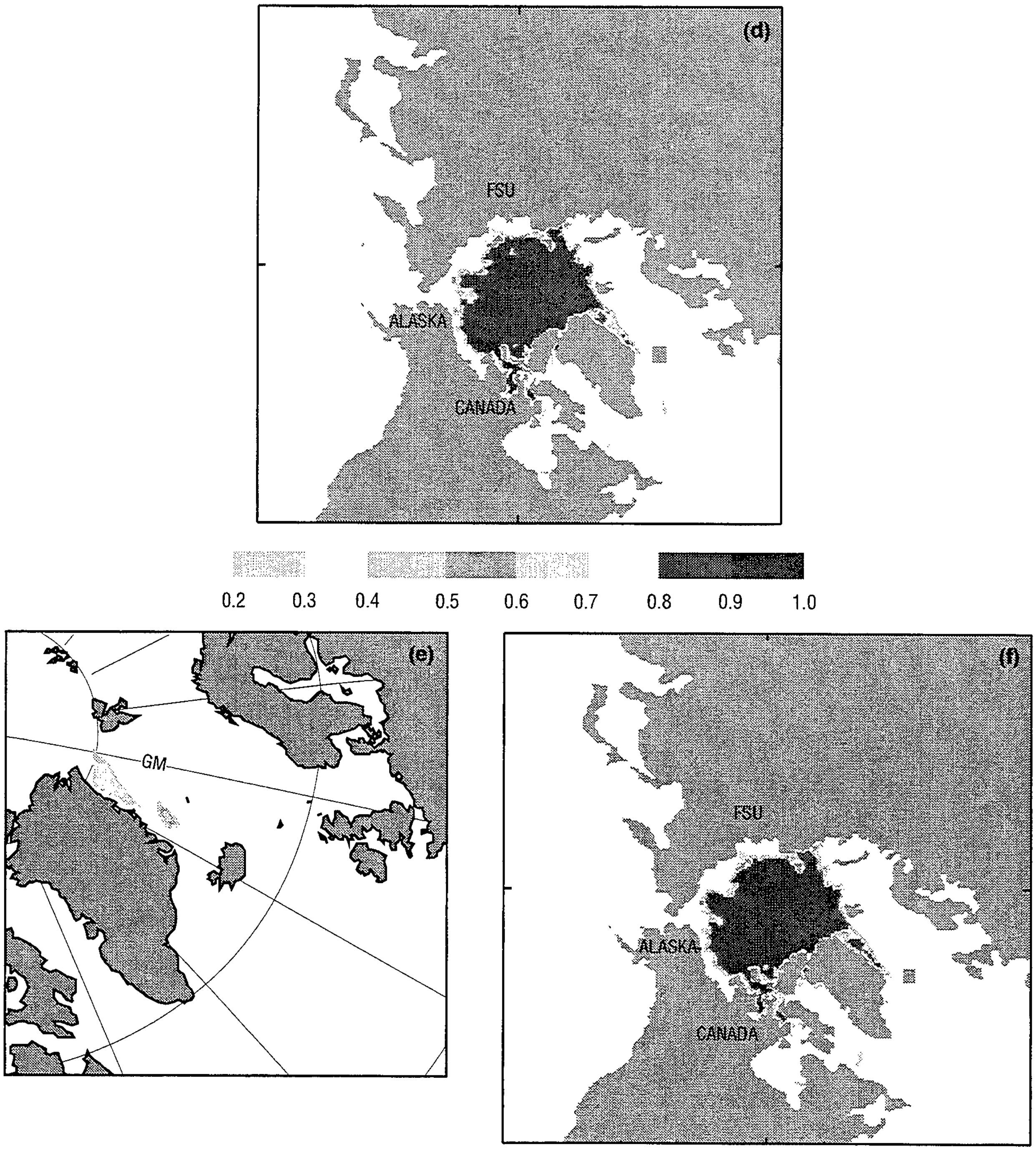

Fig. 21 (cont.) — (d) SSM/I ice concentration, valid Sep 10, 1992 and 6-day forecast of (e) RPIPS-G ice concentration, valid Sep 10, 1992, and (f) PIPS2.0 ice concentration, valid Sep 10, 1992. Contour interval for ice concentration is 10%.

In each case, the regional forecast systems and PIPS2.0 are better representations of the ice edge than PIPS1.1 because they provide higher resolution. In each case, the PIPS2.0 model produces at least as good a forecast as the two regional models and, in many cases, a forecast that agrees more closely with the SSM/I data. Finally, PIPS2.0 provides better areal coverage than any of the three existing forecast systems. PIPS2.0 forecasts of lower-latitude, ice-covered seas, such as the Bering Sea, the Sea of Okhotsk, Hudson Bay, Baffin Bay, and the Labrador Sea, seem reasonable over the 5-day period.

6.0 SUMMARY AND CONCLUSIONS

The PIPS2.0 ice-ocean model test results and forecasts discussed here present a major improvement over the capabilities of the existing forecast systems presently run by FNMOC. It has been shown that the PIPS2.0 forecasts of ice drift are at least as good as those provided by PIPS1.1. PIPS2.0 forecasts of ice thickness and ice concentration (ice edge) are at least as good as those of the high-resolution, regional forecast systems (RPIPS), and better than those of PIPS1.1. In addition, PIPS2.0 provides each of these products in regions of Navy interests that are not covered by the three existing forecast systems (i.e., the Bering Sea, the Sea of Okhotsk, Baffin Bay, Hudson Bay, and the Labrador Sea). PIPS2.0 also provides fields of ocean temperature, salinity, and ocean currents at each of its 15 vertical levels. Although these fields are weakly constrained to climatology, they should still provide the type of variability required of a forecast.

It is recommended that PIPS2.0 be considered as a replacement for all three forecast systems, PIPS1.1, RPIPS-B, and RPIPS-G. The existing PIPS2.0 code, before Cray optimization, required approximately 315 sec/day of CPU time. The newest code optimized for the Cray, using six processors, takes approximately 100 sec/day. Use of PIPS2.0 will provide a reduction in both the number of operational models run daily by FNMOC and the total operational run time for sea ice forecasts.

7.0 ACKNOWLEDGMENTS

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8.0 REFERENCES

Cheng, A. and R. H. Preller, "An Ice-Ocean Coupled Model for the Northern Hemisphere," *Geophysical Research Letters* **19**(9), 901–904 (1992).

Cheng, A. and R. H. Preller, "The Development of an Ice-Ocean Coupled Model in the Northern Hemisphere," NRL/FR/7322--95-9627, Naval Research Laboratory, Stennis Space Center, MS, 1996.

Colony, R. L. and I. G. Rigor, "International Arctic Buoy Program Data Report for 1 January 1992–31 December 1992," APL-UW Technical Memorandum TM29-93, Applied Physics Laboratory, Seattle, WA, 1993.

Cox, M., "A Primitive Equation, 3-Dimensional Model of the Ocean," GFDL Ocean Group Technical Report, 1141 pp., Geophysical Fluid Dynamics Laboratory, Princeton, NJ, 1984.

Hibler, W. D. III, "A Dynamic Thermodynamic Sea Ice Model," *Journal of Physical Oceanography* **9**, 815–864 (1979).

Hibler, W. D. III, "Modeling a Variable Thickness Sea Ice Cover," *Monthly Weather Review* **108**, 1943–1973 (1980).

Hogan, T. F., T. E. Rosmond, and R. Gelaro, "The Description of the Navy Operational Global Atmospheric Prediction System's Forecast Model," NOARL Report 13, Naval Research Laboratory, Stennis Space Center, MS, 1991.

McPhee, M. G., "Small-Scale Processes," in *Polar Oceanography, Part A: Physical Science*, W. Smith, ed. (Academic Press, Inc., San Diego, CA, 1990), pp. 287–333.

Preller, R. H. and P. G. Posey, "The Polar Ice Prediction System—A Sea Ice Forecasting System," NORDA Report 212, Naval Research Laboratory, Stennis Space Center, MS, 1989.

Riedlinger, S. H. and R. H. Preller, "The Development of a Coupled Ice-Ocean Model for Forecasting Ice Conditions in the Arctic," *Journal of Geophysical Research* **96**(C9), 16,955–16,977 (1991).