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SAMMENDRAG

An operational sea ice border model (IBP-I) is presented. The model gives sea ice border forecasts based on input data from the LAM50/LAM150 atmospheric model and sea ice charts made at DNMI. Some thermodynamical calculations (freezing/melting) are included.

UNDERSKRIFT

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An operational model for ice border positions

by

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Det norske Meteorologiske Institutt
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Summary

The Norwegian Meteorological Institute has since 1970 produced and distributed weekly sea ice maps covering the Barents Sea, the ocean north of Svalbard and the Fram Strait. However, the institute regards forecasting of sea ice in the same regions as one of its responsibilities.

A manual sea ice border model was tested in late 1988. This model used the LAM 50/150 atmospheric model to obtain wind as well as background current to create input data. The sea ice border was forecasted using empirical relationships describing the ice drift. No thermodynamic effects were included.

A numerical sea ice border was developed i 1989. This work was partly funded by OKN. The aim was to develop this model to an operational level. The model includes some simple thermodynamics (freezing/melting).

The model, together with results from testing/simulation is presented in this report.

The report concludes that the model works satisfactory with an accuracy of 20 km, but may fail during situations with strong winds and long forecasting periods.

Background

Since early 1970 sea ice maps have been produced at Det Norske Meteorologiske Institutt (DNMI), between 1971 and 1981 two maps per week, and between 1981 and 1989 one map per week. The maps cover the Fram Strait, the Greenland Sea and the Barents Sea.

Information given on the maps are outer sea ice border, sea ice consentration borders (ice types) and sea surface temperatures. Maps of mean monthly as well as maximum and minimum sea ice extent (outer border only) have been produced since 1970.

Sea ice maps are produced using data from satellites (NOAA), ship observations (important for sea surface temperatures), and in some cases observations from land stations (Hopen, Bjørnøya, Jan Mayen).

A comprehensive sea ice border data set has been prepared by Norsk Polarinstitutt (NP) as a cooperation project between DNMI and NP (externally funded). Data sources for the data set are the sea ice maps produced by DNMI, maps from the British Meteorological Office (from 1963), also maps from the US Navy-NOAA Joint Ice Center (from 1972), ice surveys from the Icelandic Coast Guard aircraft, and finally, observations from the US Navy ice reconnaissance programme ("Birds Eye" 1962-1972). Satellite data used are IR images to estimate ice distribution as well as daylight pictures from ESSA (before 1971), NOAA, TIROS and METEOR (1972 - 1982). A series of 1196 ice maps have been produced from these data sources (the period is from 1966 - 1989) and digitized.

In november 1988 DNMI performed forecasting of ice border positions in the Barents Sea as an *ad hoc* project funded by Norsk Hydro. A simple analysis was used to forecast the movement of the sea ice border given on the sea ice map. New ice border positions were calculated based on wind forecasts from the DNMI atmospheric model LAM150 and the background current in the area described by Martinsen (1982 and 1985). No thermodynamic effects (freezing/melting of ice) were included. This manual forecasting of sea ice position gave satisfactory results in many of the forecasts (as compared with the sea ice maps drawn from satellite information), but it was also evident that the analysis in some forecasts gave ice border positions with unacceptably large errors. A full discussion of this manual forecast will not be given here, but it was concluded that

DNMI would develop a more sophisticated, numerical ice border position model with thermodynamical effects included. The aim of this work is to make available operational forecasts of ice border positions in the Barents sea.

In this report is presented the first version of the DNMI ice border position model (IBP-I).

Model description (IBP-I)

The ice border position model (IBP-I) is developed based on the same principles as the DNMI oil drift model (Martinsen, 1982, 1989). That is, a number of positions along the ´present´ sea ice border are moved by advection and freezing/melting to new positions which define the ´new´, or forecasted, ice border.

The geographical area covered by the model is shown in figure 1. It is a sub-area of the domain that is used for the calculation of oil drift statistics (Martinsen, 1985a). The area is divided into a 10 km by 10 km grid which also defines the resolution of the background current. The grid is defined on a polar-stereographic map projection where the grid distance is 10 km at 60^{o}N.

Input data to the model are background currents (figure 2), wind and radiation balance(figure3) at the ice/sea surface (sensible and latent heat) which are products from the LAM50/150 atmospheric model, sea ice border and sea surface temperatures (figure 3) which are products from digitized maps analyzed from satellite data and ship observations. A more detailed description of the input data is given in the next section.

The main program of the IBP-I model consists of two parts; initialization where input data are read into the model and prepared, and simulation where the new positions of the ice border are calculated. In the full model new positions are calculated in two steps, first assuming that the ice moves by advection, and then calculating an additional ice volume due to melting and/or freezing which is added to the outer position of the ice border.

Advection

The wind driven ice motion is determined from experimental field work and often presented as an expression of the type;

$$\underline{U}_W = a * \underline{k}^* \underline{v}_W$$

where $\underline{v}_W$ is input wind data for the 1000 hPa level from the LAM150 atmospheric model. a is an empirically determined constant of between 0.001 and 0.03 and $\underline{k}$ is a vector of unit length and direction 10 to 15° to the right of the wind direction. Both a and $\underline{k}$ can be varied in the model (see also test and simulation results). However, the above expression can also be written as;

$$\underline{U}_{ice} = \underline{U}_{bc} + \underline{U}_S + \underline{U}_E + \underline{U}_W$$

The ice advection velocity is $\underline{U}_{ice}$, $\underline{U}_{bc}$ is the velocity of the background current, $\underline{U}_S$ is the Stokes drift, $\underline{U}_E$ is the Ekman drift and $\underline{U}_W$ is the motion of ice due to the turbulent motion of the wind in a layer directly above the ice. In the present formulation of the model, $\underline{U}_W$ is zero. The Ekman current is given as 0.7% of the wind-speed and oriented 33% to the right of the wind vector, while the Stokes drift is given as 0.9% of the wind speed and in the same direction as the wind. This corresponds to a=1.4% and $\underline{k}$ makes an angle of 15° to the right of the wind direction. Values of a up to 3% have been tested, and it is evident that the best fit to observed data varies with wind speed and direction.

Thermodynamics

It is not possible to include a proper treatment of the thermodynamical processes in the ocean-ice-air interface for this simple model. Empirical formulae must be used and tuned to results from field work and observations (taken from the sea ice maps). In particular, since the model is an ice border model, we need to make some assumptions about the freezing/melting of ice that changes the position of the ice border. Thus, we do not concern ourselves with changes in concentration and ice thickness in the ice field behind the ice border.

We assume that the production/reduction of ice in the marginal ice zone leads to a change in ice position which is calculated from the volume of ice produced/reduced in the area of the ice margin;

$$\Delta Z = (M\Delta h\ u)/(hu)$$

where Δz is the change in ice border position, M is the width of the marginal ice zone (can be changed in the model, but 10 km is assumed here), Δh is the change in ice thickness due to melting/freezing (calculated in the model), u is a unit length along the ice border, and h is the ice thickness assumed to be 1 m (can be changed in the model).

A number of assumptions have been made to enable the calculation of freezing/melting;

- Melting may occur on the ice surface and at the bottom. Both types have been included in the model (see equations below).

- The melting (and also freezing) is assumed to be independent of wind speed and direction and of wave characteristics. This is not correct, but we assume that it gives an error below the resolution of the model (10 km) over 6 days.

- Waves induce lateral melting, but this is not included in the model.

- For freezing, we only look at slow bottom freezing. Processes involving the production of frazil ice are not included, although these processes will, under certain conditions, create large areas with thin newly frozen ice, pancake ice, etc.

The following expressions for freezing/melting have been used in the model (Lundquist and Omstedt, 1987, Doronin and Kheisin, 1975, Maykut and Untersteiner, 1969);

Bottom freezing;

$$h(t) = \sqrt{\frac{2\lambda}{L\rho_i}|T_s - T_f|\,\Delta t}\ \text{cm/s}$$

Bottom melting;

$$\frac{\Delta h}{\Delta t} = \frac{0.075}{3600}(T_s - T_f)\ \text{cm/s}$$

Surface freezing/melting;

$$\frac{\Delta h}{\Delta t} = 100\frac{\dot{Q}}{L\rho_i}(1 - \alpha)\ \text{cm/s}$$

where

α = albedo. Varies over the year; high in winter, low in summer
L = Latent heat. $L=0.8$ J/kg
ρ_i = density of ice, $\rho_i = 700$ kg/m^3
Q = heat exchange flux, from LAM50/150. J/m^{2}s
T_s = sea surface temperature
T_f = temperature at which sea water freezes (average), 1.5°C

The expression for the bottom freezing of sea ice cannot be used in this simple model, because the sea surface temperature is not accurate enough, and because the ice thickness which influence the bottom freezing, is not given in the model. Based on empirical field results (Kristensen, 1989), bottom freezing is assumed to be at a rate of

$$\frac{\Delta h}{\Delta t} = 2.315\text{x}10^{-4} \mid T_s - T_f \mid \text{cm/s}$$

A further simplification is that the sea surface temperature is set to -2°C during the freezing process, because of the resolution problems in the Cressman analysis for the sea surface temperature. Thus, when freezing conditions occur in the model, the freezing rate is, in the present formulation, constant. However, freezing calculated from the surface heat exchange varies.

Input data; ice border, current, wind

It is very important to note that the IBP-I model is ~~very~~ sensitive to the quality of the input data. Therefore, the quality of the forecasting could be improved first by improving the input data.

Ice border positions and sea surface temperatures

The sea ice border position is defined as input to the model for ice concentrations of 2/10 or higher. Thus, open ice fields (åpent vann, 1/10) are not included within the ice border. The following data sources are used to establish the position of the ice border.

NOAA satellite pictures:
Infrared pictures are being used during winter, and visual pictures are being used during summer. There are satellite passes every 90 minutes, thus the amount of data is satisfactory. All passes are used. Difficulties in

using this type of satellite data is in the classifification of sea ice and in the positioning of the sea ice border, particularly in cloudy conditions.

Ship observations:
Approximately 350 ship observations per day are relevant to the production of sea ice maps, in particular, the sea surface temperature lines.

Observations from land stations:
Sea ice is observed and reported from Jan Mayen, Bjørnøya og Hopen. These data are considered very useful by the observer. Weaknesses are connected with limited observation because of bad weather or local topography. In addition, the instruction scheme of local observers is not regular. Hopen and Bjørnøya could, to a larger extent than today, report on icebergs.

There is a high degree of subjectivity and skill involved in making use of the different data sources to obtain maps. To some extent the development of the ice and weather situation from previous maps is taken into account.

To obtain the sea surface temperatures in a smoothed field, a Cressman analysis has been run on the data (figure 2)

Currents

The background current used in this model is climatological in the sense that it is representative for a year mean of the current in the Barents Sea. Adjustments along the coast to take into account a stronger dependency on wind have been included similar to the DNMI oil drift model (Martinsen, 1982). However, current input into the model may be improved if seasonal changes in the background current could be given.

Wind

Wind at the 1000 hPa level is taken as input data to the IBP-I model from the LAM50/150 atmospheric model. Wind is interpolated bilinearly onto the 10 km grid from a grid of 50 km. Several other options to include other wind data into the model is available, but in most cases it is likely that the DNMI models will give the best input data for the Barents Sea area.

In many cases the empirical formulae for the wind-dependent ice motion have been obtained using the geostrophic wind or the 10m wind (above the ice surface). Tuning of the drift factors a and k (see above) is obviously dependent on the input wind field, and the drift factors are further discussed in the test section.

Tests and simulations

The IBP-I model is tested to ensure a consistent performance over the whole of the defined model area, and to tune the drift factors a and k. Simulations are then made for the period november/december in 1988 when the manual forecasting was performed. Model results are compared with the results from the manual forecasting, as well as the observed ice borders for the forecasted situations.

Tests

1) Constant current of 10 cm/s (in the -y direction), no wind, no freezing/melting.

Test shows consistent behaviour of ice border movement in the whole area. An example is shown in figure 4. In this and all following examples, a 50 km grid is plotted for convenience.

2) Constant wind of 100 cm/s (in the -y and x directions), no current, no freezing/melting

Test shows consistent behaviour of ice border movement in the whole area. Examples are shown in figures 5 and 6. Although ice border positions move to the right of the wind direction (because of Ekman drift), this will not show up in the figures, since each position on the ice border will be transported downwards and to the right, and will end up on a straight line.

3) Freezing/melting with no current and wind.

$Q = -200$ (H_L and H_S) and $T_S = -2^{o}C$ (freezing).

Results of the test are shown in figure 7. Freezing of the sea water moves the ice border with approximately 8 km over 6 days. This corresponds to an ice production in the marginal ice zone of 10 cm thickness over 10 km per day. Of course, this cannot in any way present the rapid changes of ice borders due to the freezing of frazil ice. Such changes may be in the order of 50 km per day.

$Q = 200$ (H_L and H_S) and $T_S = 2^{o}C$ (melting).
Rsults of the tests are shown in figure 8. Melting of the sea ice moves the ice border with approximately 10 km over 6 days. Again, this is a low value. Melting is dependent on the ice thickness, as well as a number of other factors (wave action, percolation of melt water, etc). Thus, in a spring/summer situation it is likely that large areas of melting, thin ice will disappear quickly. Such considerations cannot be taken into the model at the present stage, but must be treated with a field formulation.

Simulations

The simulations are all run on observations and prognoses from the period november/december 1988. Four test situations have been used; they are presented in figures 9 to 16.

Simulations have been run with varying drift factors. Best fits (compared with sea ice borders taken from the sea ice maps for the day which is forecasted) have been obtained with different a-values (between 1.4% and 3%), Indications are that the drift factor should be varied with wind speed and direction.

Best results are obtained when the forecasting period is short; 24 to 72 hours. The model then gives a better fit than the manual forecasting. (figure 17). This is arguably also the case for longer forecasts (up to 144 hours, figure 18). However, the longer forecasts tend to move the form of the ice border towards positive x-values in the grid. The reason may be a systematic error in the wind analysis, overestimating the easterly component.

Figure 19 shows the same pattern, in that the form of the ice border has been transported by the model (and the manual forecast) too far to the right in the figure. This is also a situation with freezing of sea ice over large areas, probably due to the formation of frazile ice (figure 20). Neither the model nor the manual forecast can present this situation accurately, however the inclusion of some freezing in the model makes it a better fit (than the manual forecast) to the observations.

Conclusions

The main conclusions from the testing and simulation of the IBP-I sea ice border model are the following;

1) The model simulates the motion of the sea ice border as well, or better, than a simple manual forecasting. The accuracy of the model varies between 10 km and 50 km for most cases, and the errors are larger for situations with rapid freezing or melting.

2) The model is extremely sensitive to the quality of input data and the quality of the model results can be significantly improved by improving the quality of input data. For example, the introduction of other, and more accurate, data sources will be an improvement. SAR and radar altimeter data may in the near future give valuable information on sea ice border positions in conditions with cloud cover.

3) Drift factors (a and k) varies with wind speed and direction. A next step in the development of the model is to implement such a variation, and it is likely that this will improve results in some cases.

4) The thermodynamical formulation within the model is very simple, and cannot accurately present melting/freezing. A semi-field representation will improve model results, but for a full thermodynamical analysis it is necessary to develop a field model. Considering the difficulties of initializing such a model, it may be more advantageous to use a manual forecasting of areas with rapidly melting/freezing ice for the situations where we have such conditions (spring/summer). From the point of view of climate research and also for input to the atmospheric model, it is valuable for DNMI to design and develop the full thermodynamical field model.

5) Less important adjustments can readily be made in the model. For example, a varying albedo with seasonal changes can be implemented. It is, however, necessary to have better field results before such corrections are attempted.

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Fig.1 Model area and 10x10 km grid

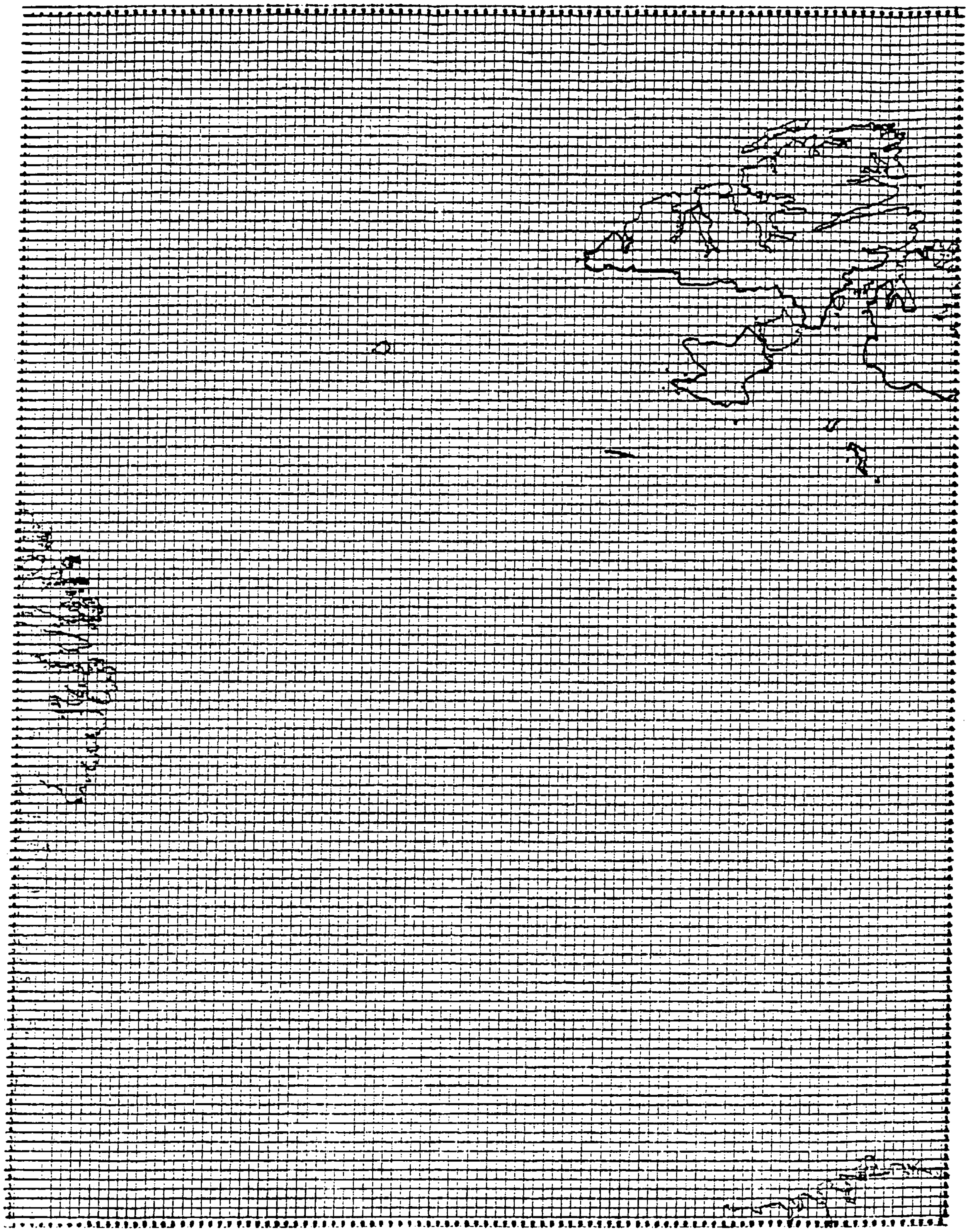


Fig. 2 Background current

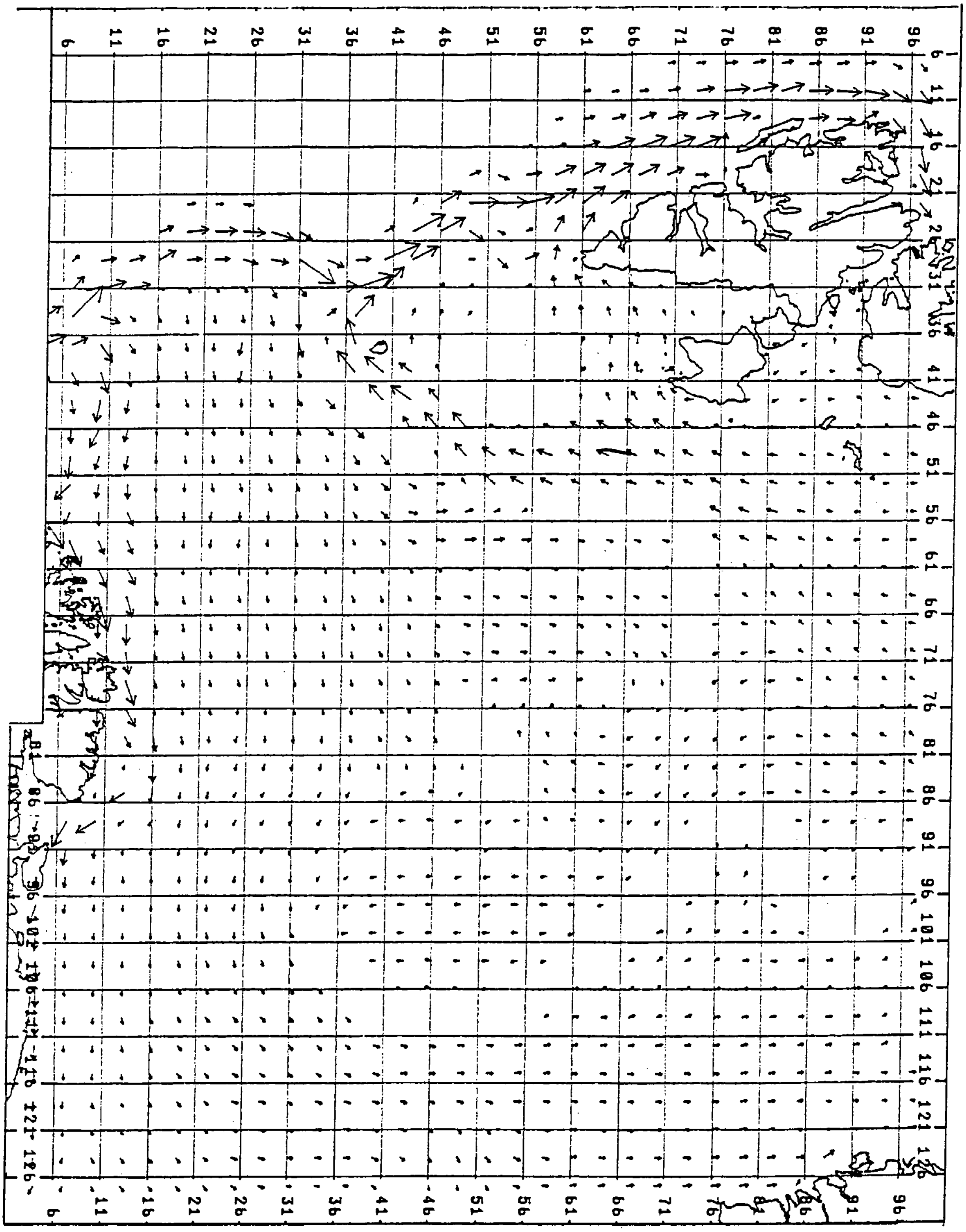


Fig. 3 Sea surface temperature (in degrees Celsius)

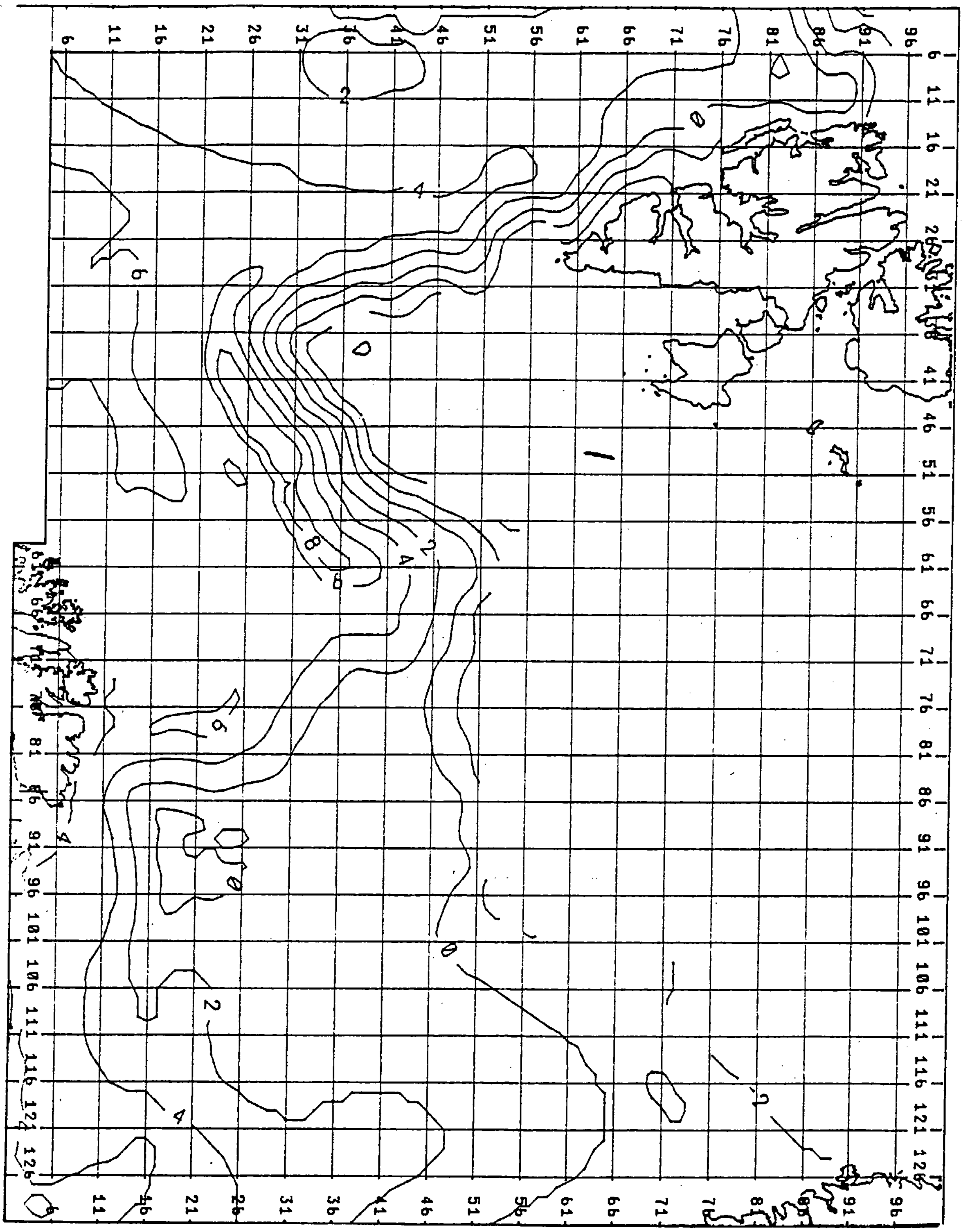


Fig. 4a Motion of ice line, constant current Cy= -10 cm/s

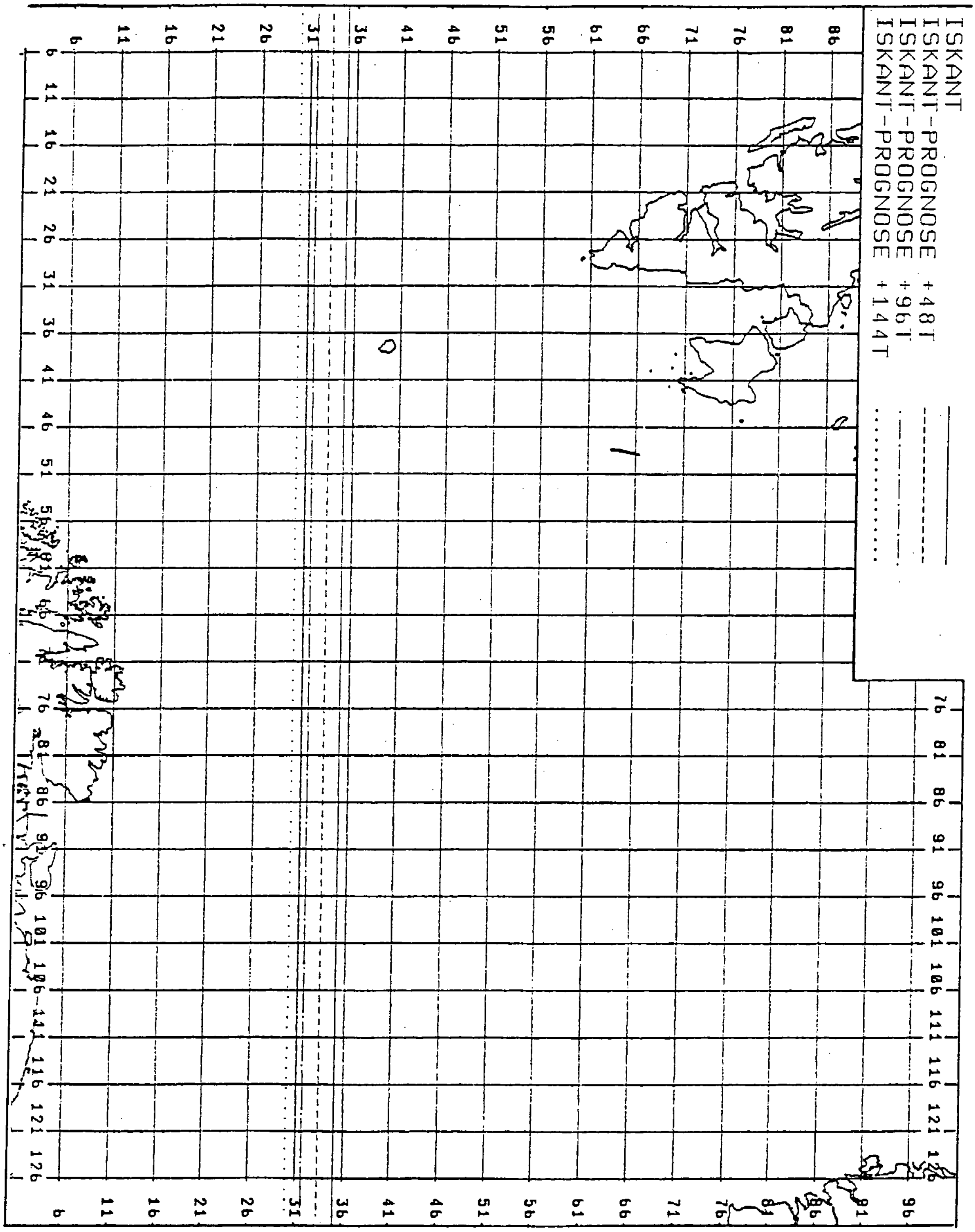
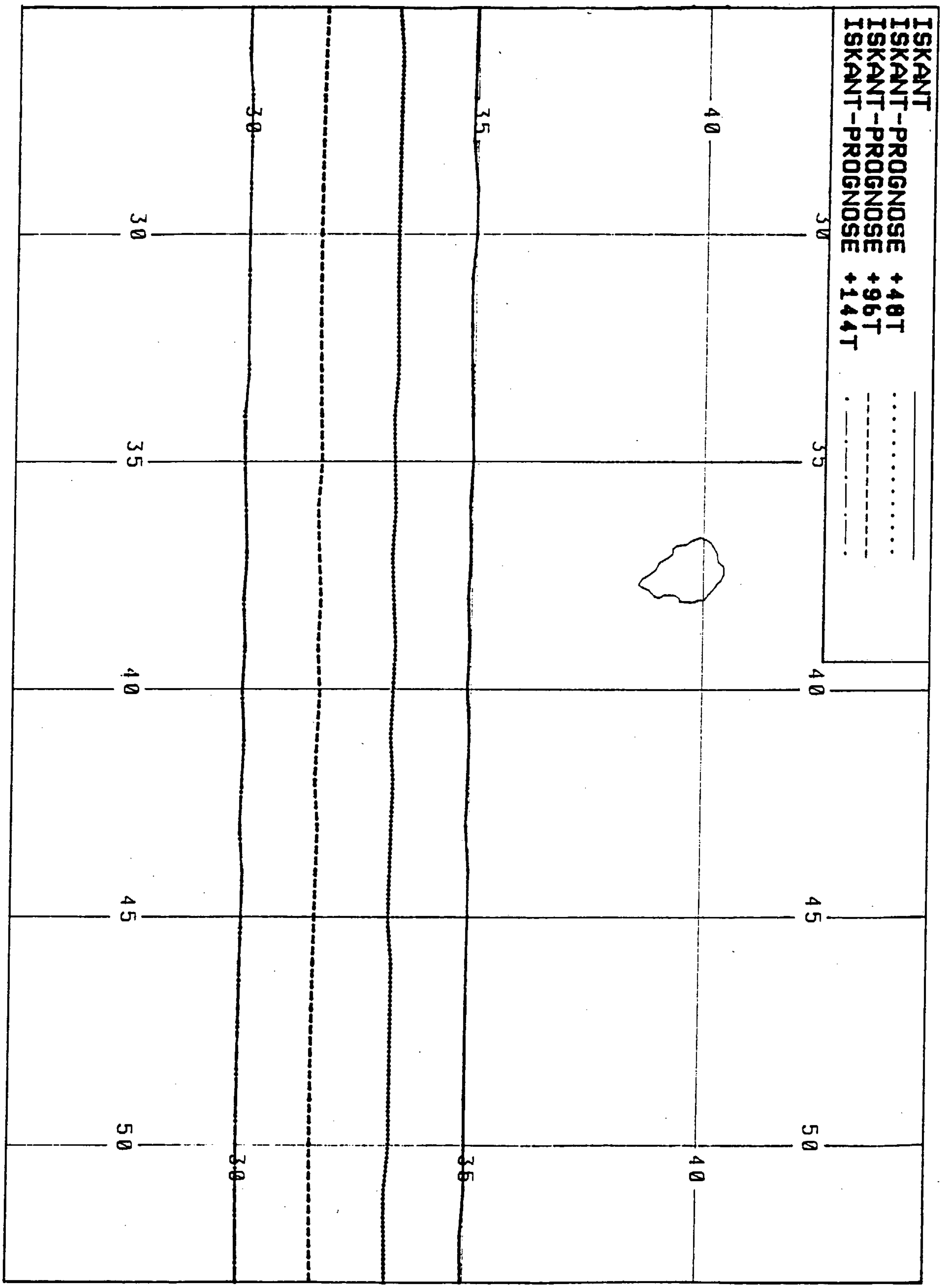


Fig. 4b Motion of ice line, constant current, Cy= -10 cm/s



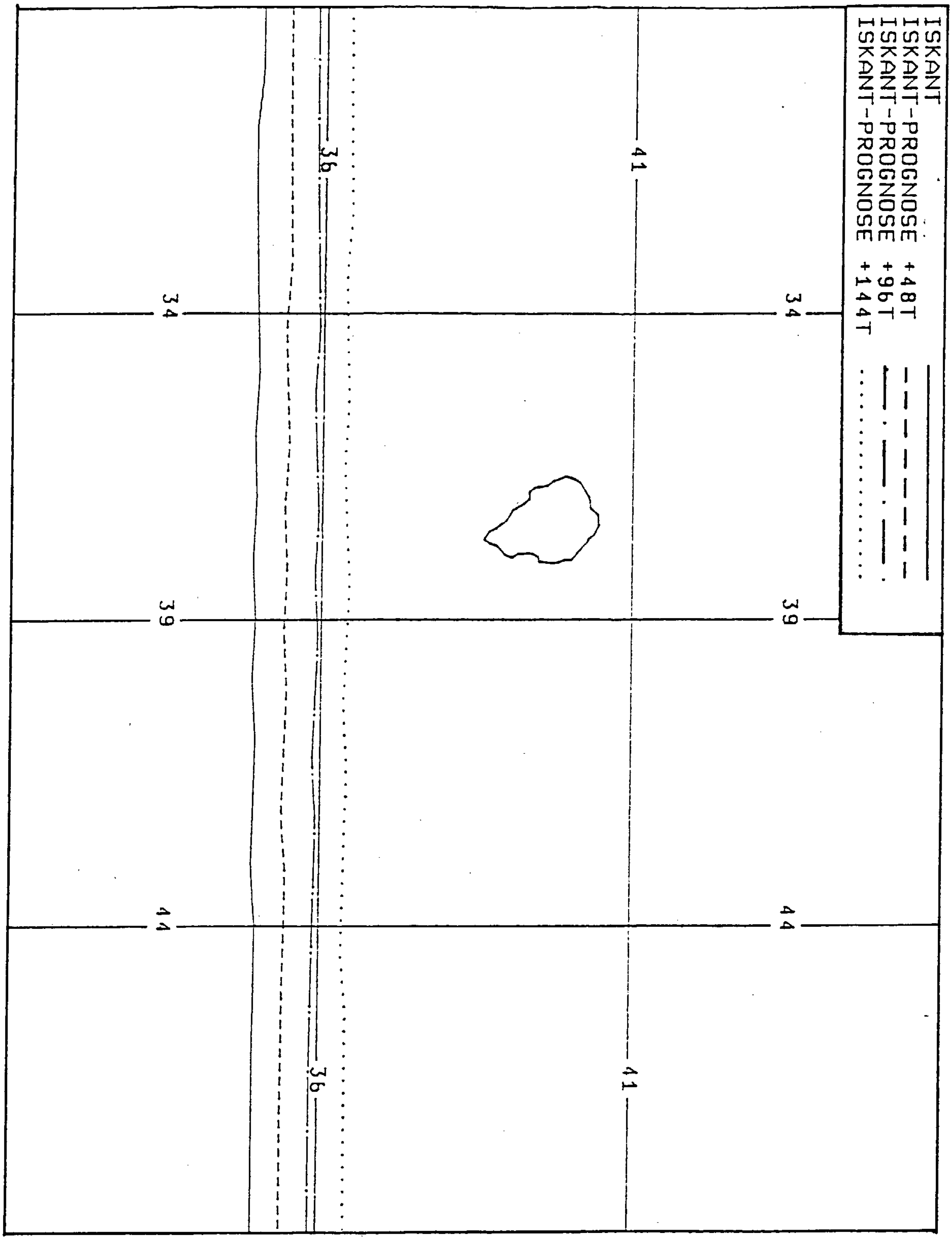


Fig. 5 motion of ice line, Constant Wind, Wy = -100 cm/s

Fig. 7 Freezing, Q = ÷200, Ts = Ts = ÷2°C, Wind and current zero

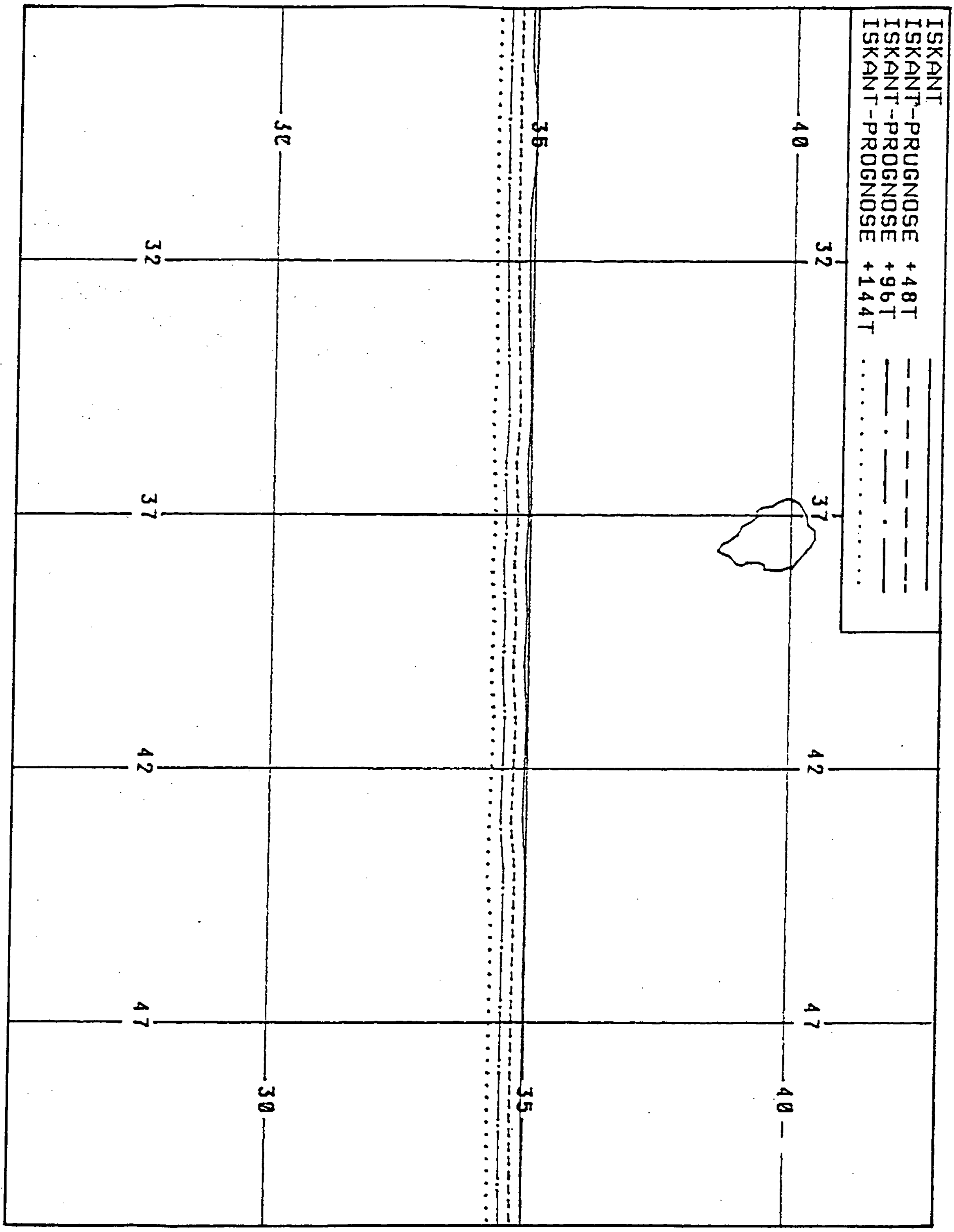


Fig. 8 Melting, Q= 200.Ts = 2°C, Wind and current zero

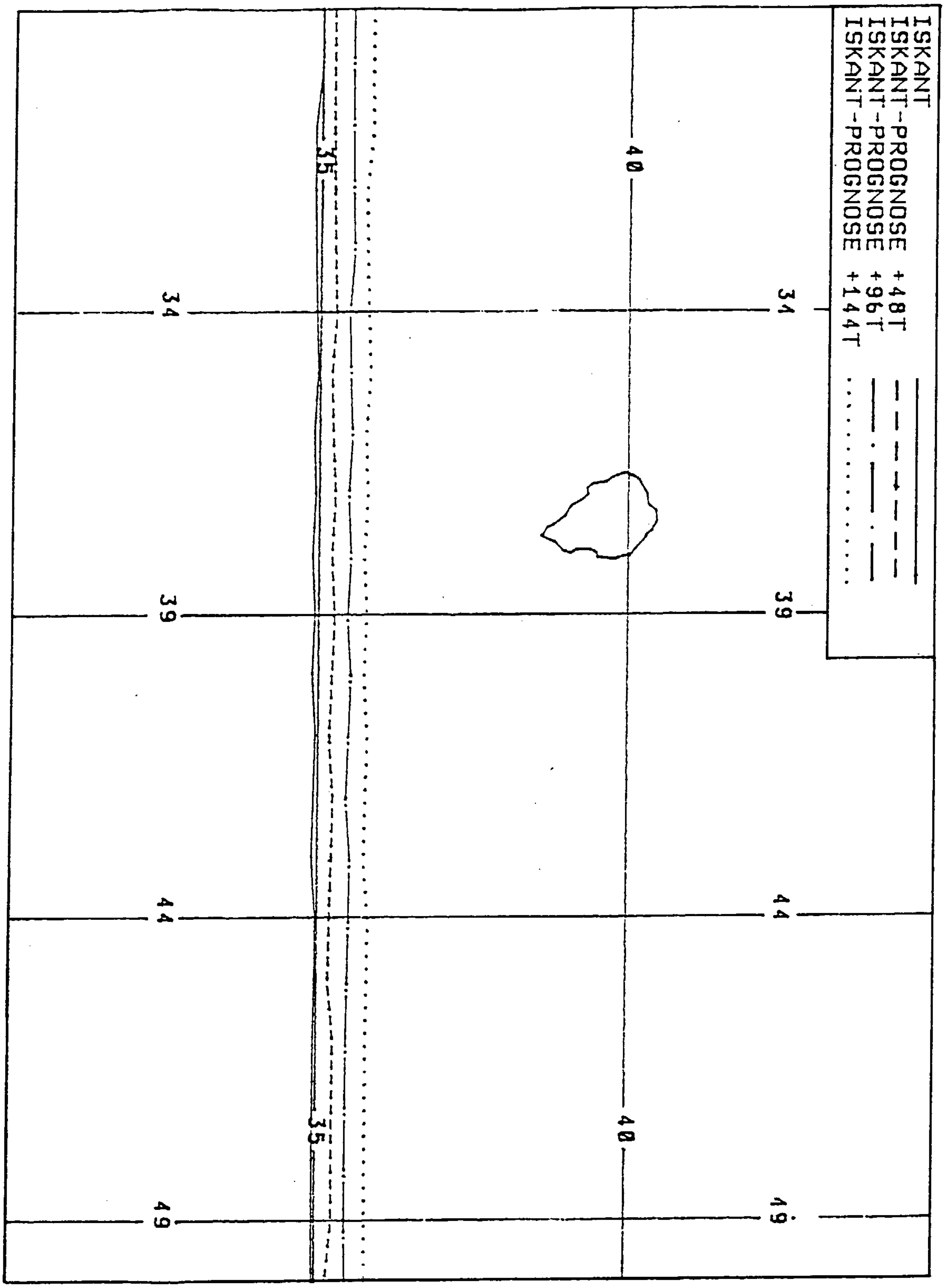


Fig. 9 Ice border positions and manual prognosis

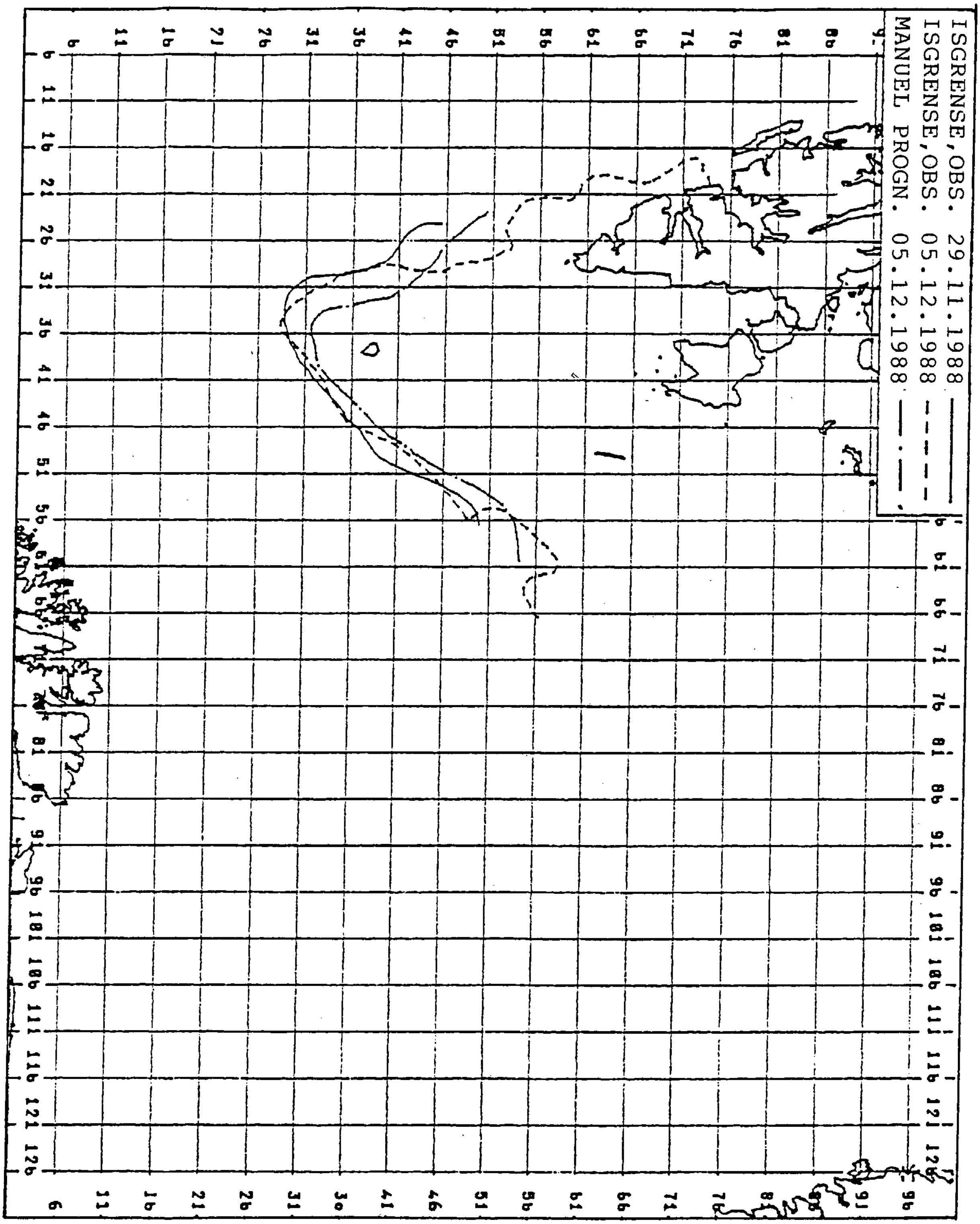


Fig. 10 Ice border positions and manual prognosis

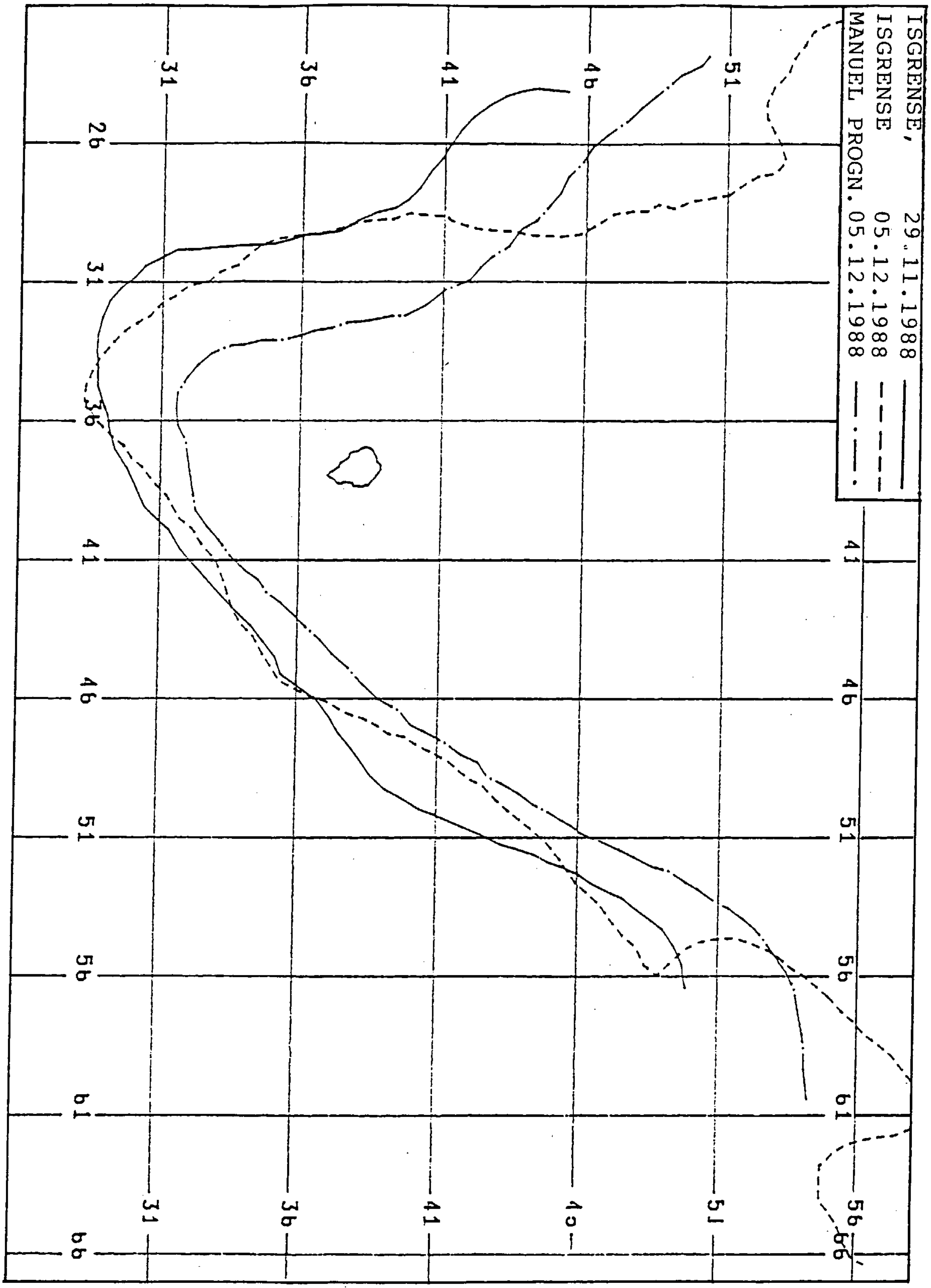


Fig. 11 Ice border positions and manual prognosis

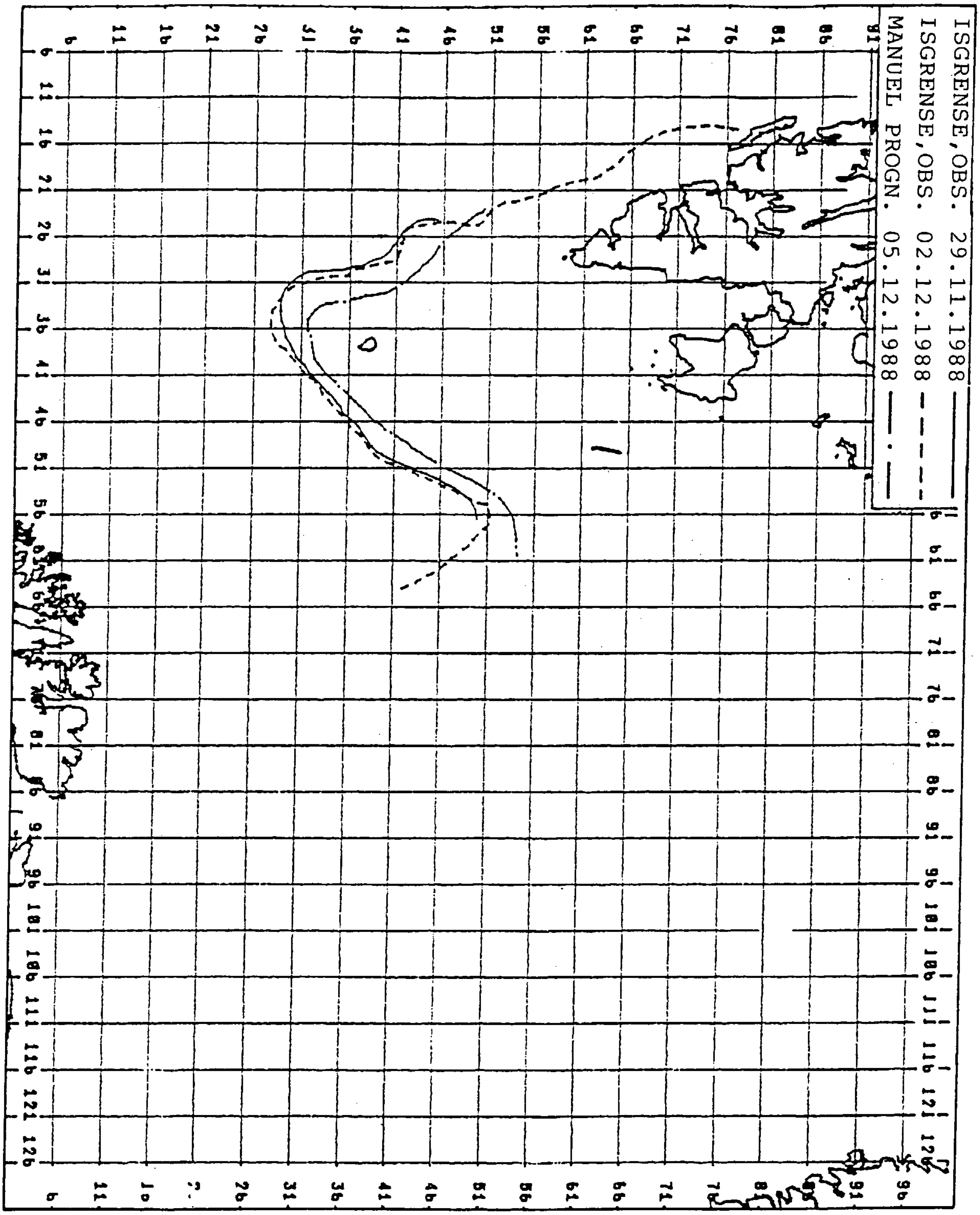


Fig.12 Ice border positions and manual prognosis

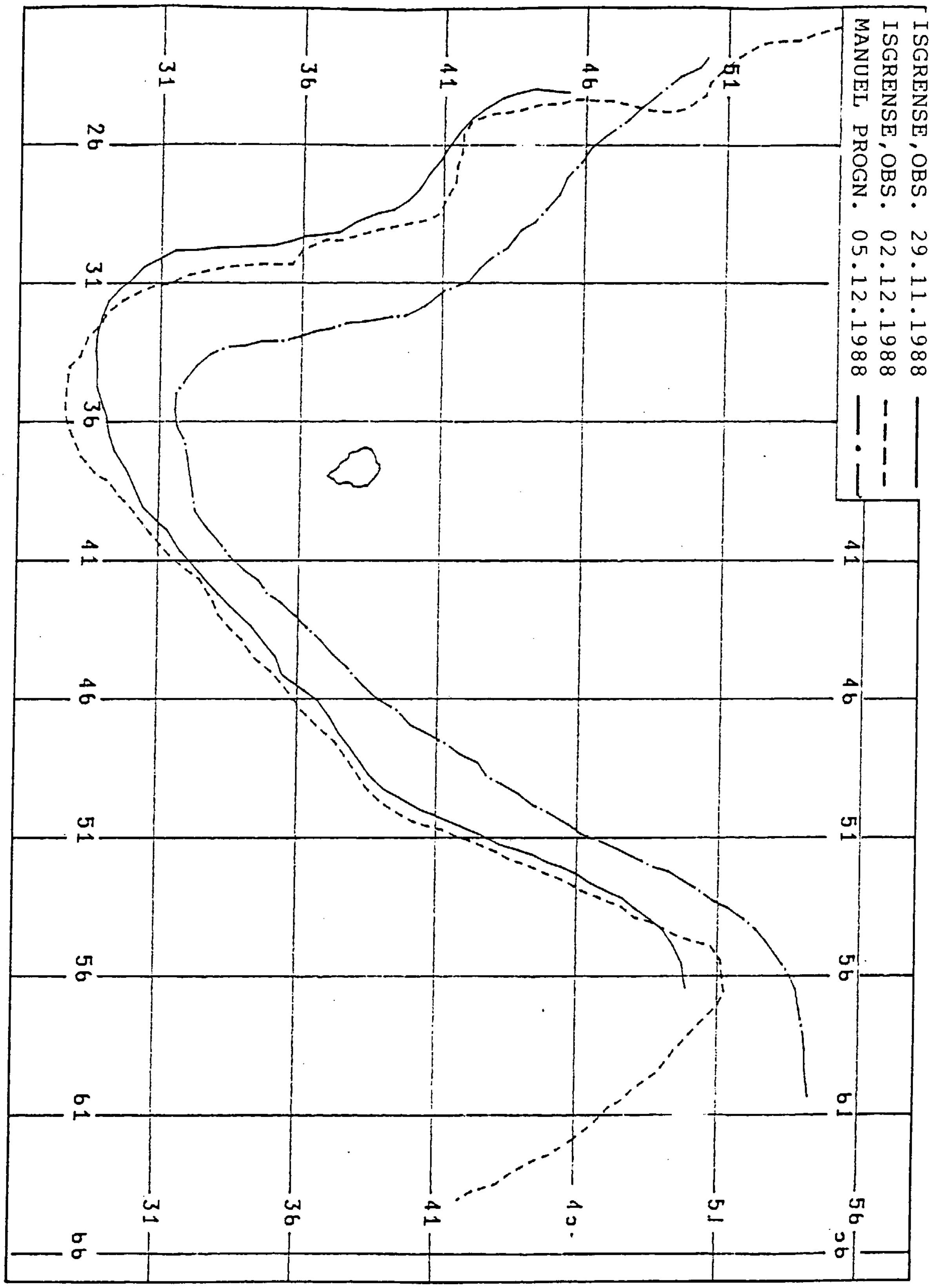


Fig. 13 Ice border positions and manual prognosis

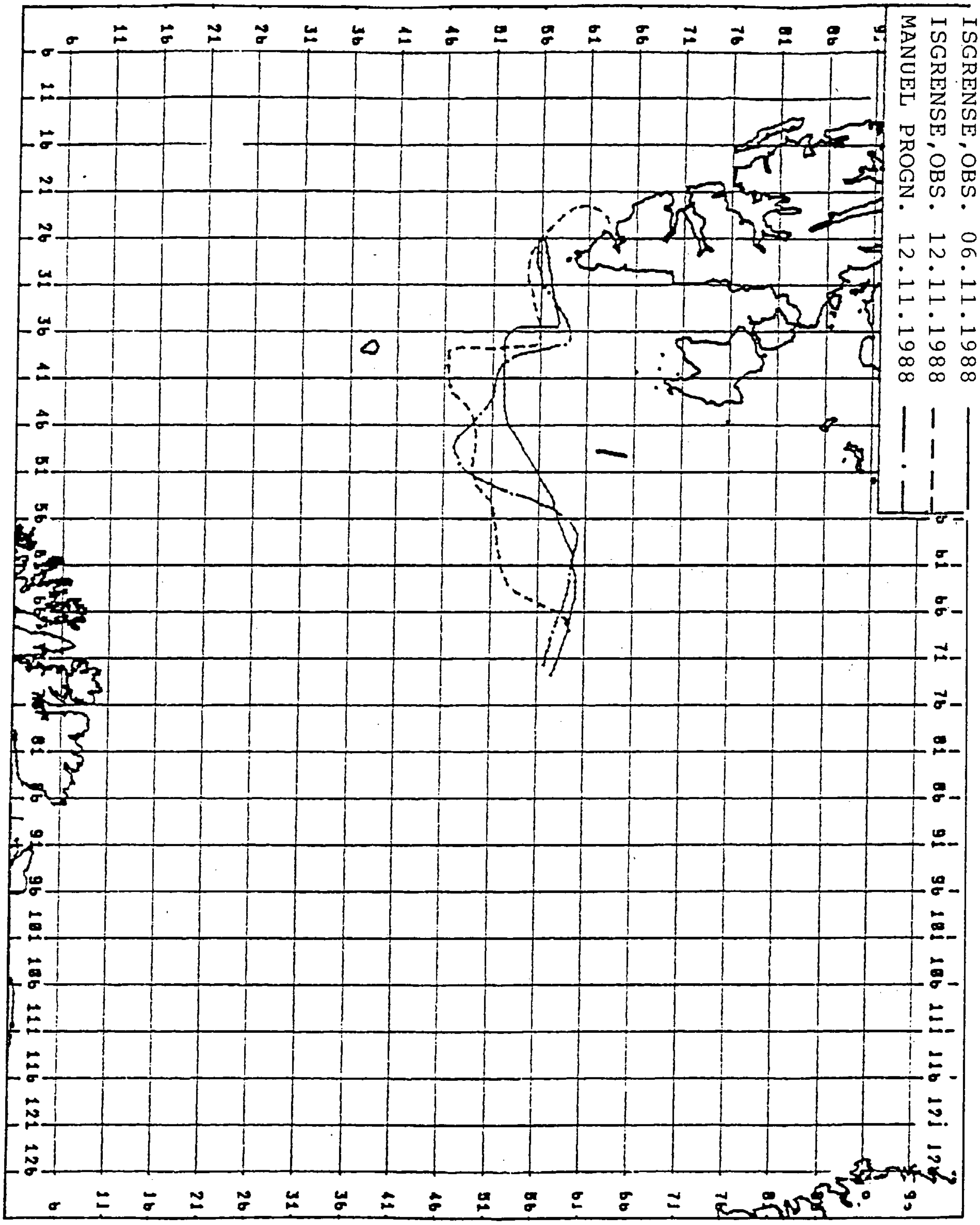


Fig. 14 Ice border positions and manual prognosis

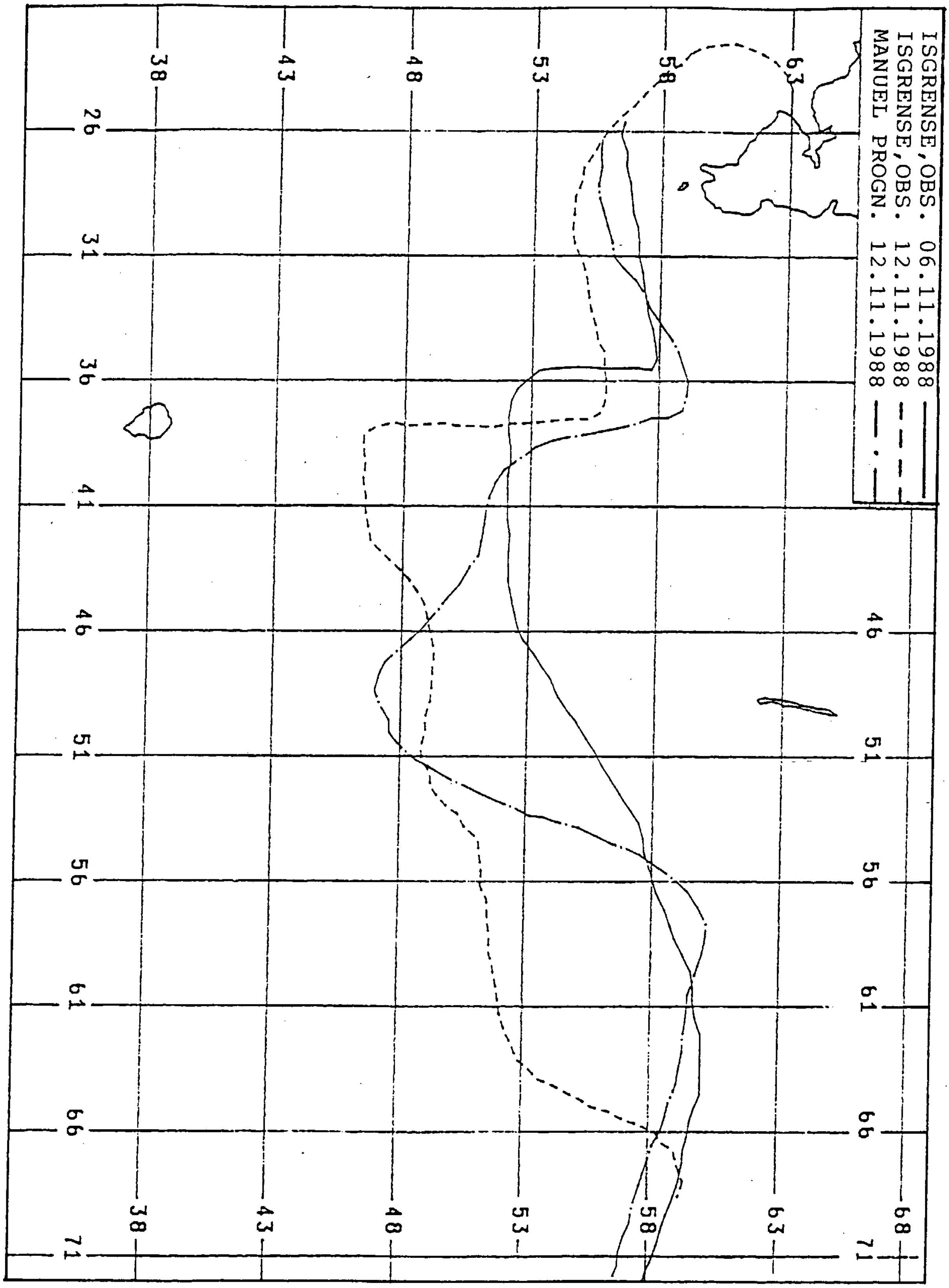


Fig. 15 Ice border postions and manual prognosis

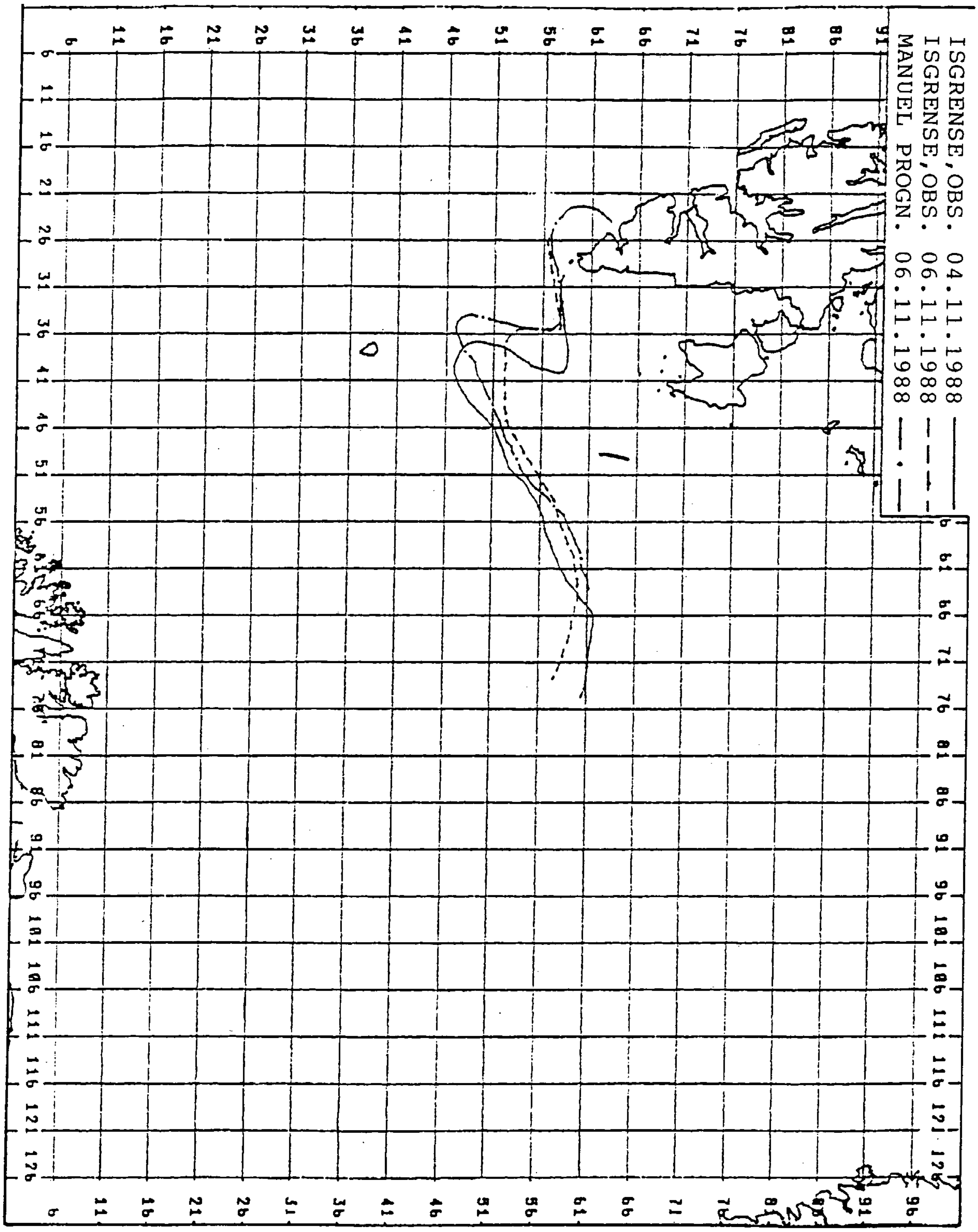


Fig. 16 Ice border positions and manual prognosis

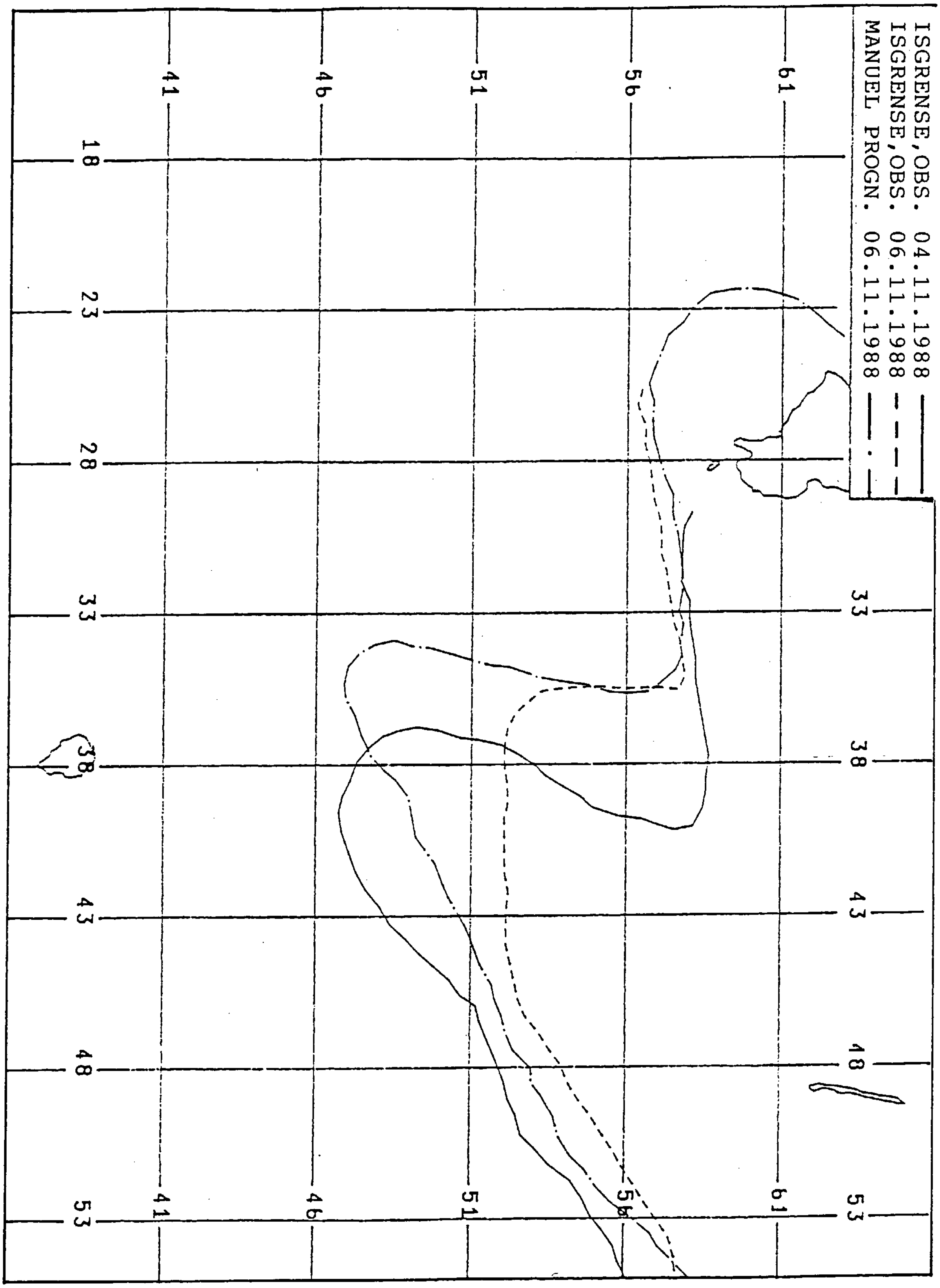


Fig.17 Ice border positions and manual and model forecasts

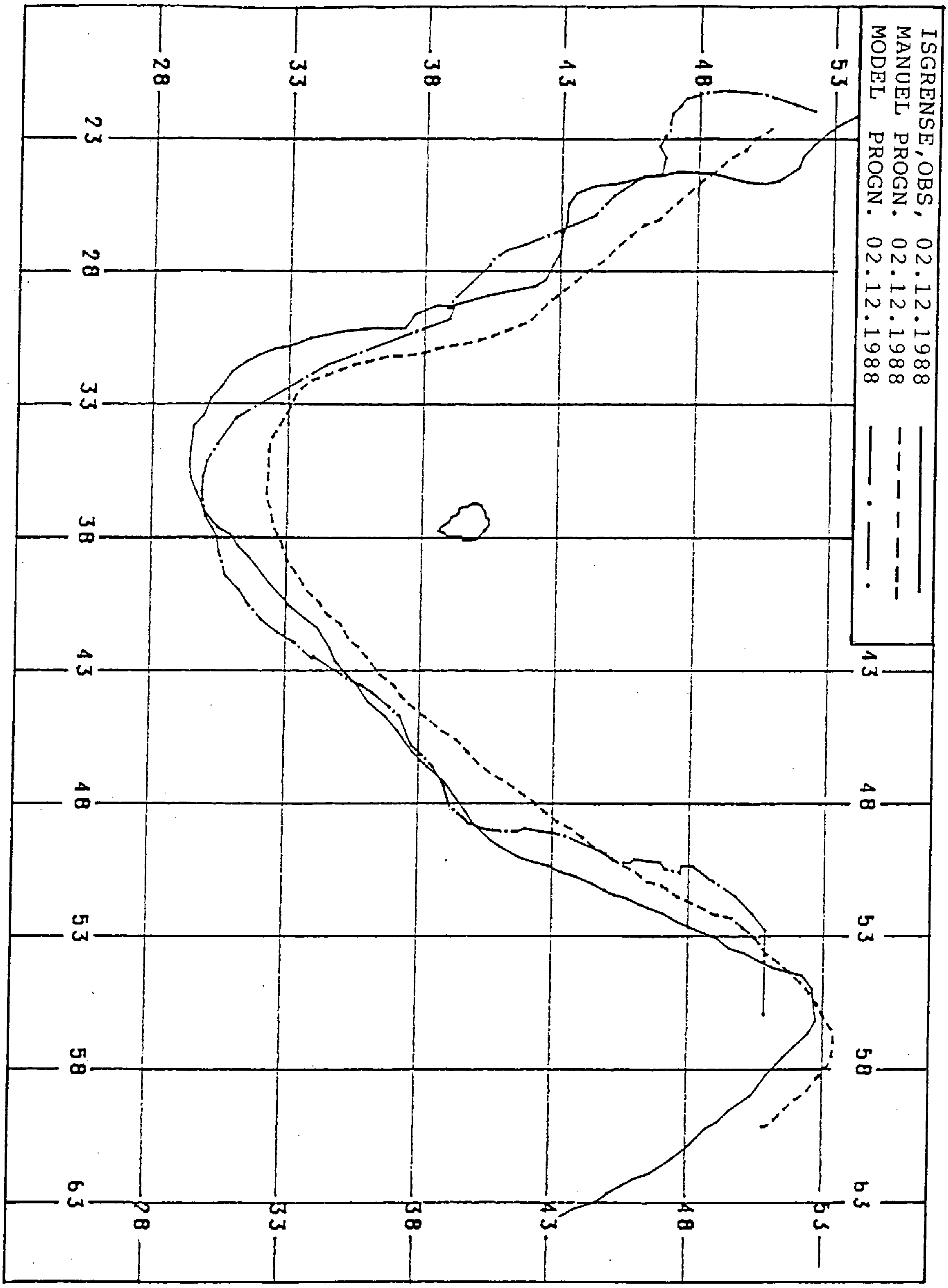


Fig. 18 Ice border positions. Manual and model forecasts

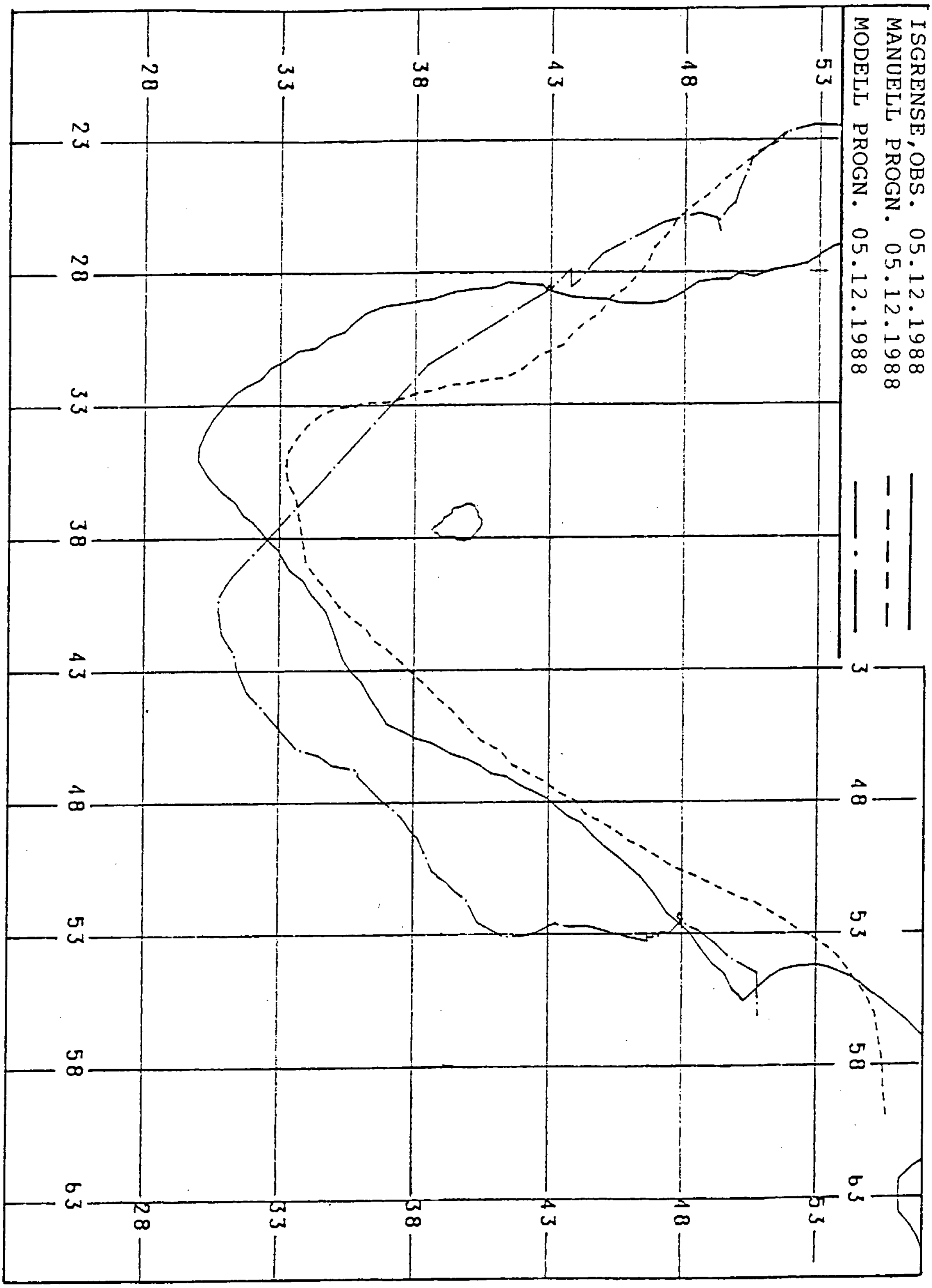


Fig.19 Ice border positions and manual and model forecasts