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Performance review of the prototype FOAM system

by

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Abstract

This report describes the performance of the prototype Forecasting Ocean Atmosphere Model (FOAM) during the early winter of 1994/5. FOAM is designed to produce analyses of the upper layers of the open ocean using observations and a numerical model of the ocean that is driven by surface fluxes calculated by the Met. Office weather forecast models.

The numerical model is based on that used by the Met. Office for climate studies and includes a model of sea ice. Observations are assimilated using the analysis correction method that is used for the Met. Office weather forecasts. FOAM is run at 1° resolution for the whole globe. Each day an analysis for two days earlier is produced.

Comparison of the model analyses for December 1994 with independent observations shows the analyses to be a better representation of the ocean state than climatology. This is so for both the mean error and the standard deviation of the error. Partly because of the observation density the results were best in the tropics.

Synoptically the model represents those features it was expected to, such as deepening of the mixed layer in response to atmospheric disturbances. There were too few observations to allow these aspects to be judged objectively.

Although the report identifies several areas in which work is needed to improve the system, FOAM has reached a state where its analyses are close enough to reality that they can be used to help diagnose problems with both the model and the assimilation scheme.

Contents

1 Introduction

This report has been prepared to describe the Forecasting Ocean Atmosphere Model (FOAM) at the end of February 1995. It describes the performance of the prototype system both in terms of the results it produced and the method used to run it.

It is expected that this report will be of interest to the customers for the FOAM system and for managers within the Meteorological Office.

1.1 Background to FOAM

FOAM is being developed in response to the need of the Royal Navy for information about the temperature structure of the upper ocean for use in acoustic calculations. Originally the need was confined to the North East Atlantic, but following the end of the Cold War the Navy has asked for support for operations anywhere on the globe. Another change has been an increased emphasis on operations in shallow waters. FOAM is being developed to produce forecasts for deep waters, but its analyses and forecasts are expected to be used to create boundary conditions for models of the continental shelves.

FOAM consists of a numerical model of the ocean, driven by products from the Met. Office weather forecasts, and assimilates observations of the ocean temperature and salinity.

By the end of 1994 a global, coarse resolution version of FOAM had been implemented for experimental purposes and analyses were being run daily. This report assesses this version of the system.

1.2 Structure of report

The report is in six sections. Following this introduction, section 2 describes the models used in FOAM and other scientific aspects of the system. Details of the way the system is run are given in section 3. An overview of the performance of the system is in section 4. More detailed aspects of the system, such as its synoptic behaviour, are discussed in section 5. Section 6 suggests ways in which the system could be improved. Finally the results are summarised in section 7.

2 Description of models

This section of the report describes the FOAM model, assimilation scheme and other scientific issues describing how the system ran. Computational issues are discussed in the next section.

2.1 Specific aspects of the ocean model

2.1.1 Model formulation

At the heart of FOAM is the Met. Office ocean model. This is part of the Unified Model (Cullen, 1991). The ocean component is described in detail by Foreman (1993). Its use for FOAM data assimilation has been described by Foreman *et al.* (1994a). Only a brief summary of the main components of the model is given here.

The underlying model is that of Cox (1984). Several modifications have been made to the basic code. A mixed layer model following the method of Kraus and Turner (1967) is embedded into the main ocean model. This represents mixing by two mechanisms. The first of these is stirring by turbulence generated by the surface wind. The second is convective mixing that takes place when the surface water becomes denser than the underlying water. A form of vertical mixing that is dependent on the Richardson number (Pacanowski and Philander 1981) is used below the mixed layer for temperature and salinity, and throughout the water column for velocity. Lateral mixing of tracers favours mixing along isopycnal surfaces following the method proposed by Redi (1982). The formulation in the model limits the isopycnal slopes more than Redi's analysis would suggest to ensure numerical stability of the calculations. Details of the adjustable constants used in the model are given in table I

In the model, the Mediterranean and Black Seas are enclosed basins. Interaction between the ocean basins is allowed through a parametrization scheme. At each model time step the two neighbouring grid points either side of the boundary between the interacting seas are mixed at each level. This is a technique that has been successfully used in climate ocean models at the Met. Office.

Table I Constants used in the model.

Variable	**Value (SI units)**
Vertical diffusion	
Background diffusion coefficient for momentum (m^2s^{-1}) (*fnub_si*)	10^{-5}
Background coefficient for tracers (m^2s^{-1}) (*kappa0_si*)	10^{-5}
Vertical gradient of diffusivity (*dkappa_dz_si*)	0
Richardson number dependent coefficient (*fnu0_si*)	5.5×10^{-3}
Lateral diffusion	
Background horizontal tracer diffusion (m^2s^{-1}) (*ah_si*)	100
Base value of along-isopycnal diffusion for tracers (m^2s^{-1}) (*ahi_si*)	2000
Surface enhancement of along-isopycnal diffusion for tracers (m^2s^{-1}) (*ahi2_si*)	500
Maximum slope of isopycnal surfaces used to tilt diffusion.	1.0×10^{-3}
Depth by which isopycnal component decays by *e*. (m) (*ahi3_si*)	500
Horizontal diffusivity for momentum (m^2s^{-1}) (*am_si*)	6000
Mixed layer	
Proportion of wind mixing energy available for mixing ocean	0.7
Fraction of convectively released potential energy available for mixing.	0.15
Depth over which mixing energy decays by *e*. (m)	100
Relaxation coefficient for relaxation towards surface temperature (climate runs only). ($W\ m^{-2}\ K^{-1}$)	35

2.1.2 Topography

The model is global and the bottom topography it uses is shown in fig. 1. It has a horizontal resolution of 1° in both longitude and latitude. In the vertical it has 20 unevenly spaced layers, shown in table II. Vertical resolution is finest near the surface, where layers are 10 m thick. Resolution decreases with depth and the bottom layer is 615 m thick. The relatively low resolution at depth imposes a limit on how well the topography can be represented (fig. 1). Even so all the main large scale topographic features are present.

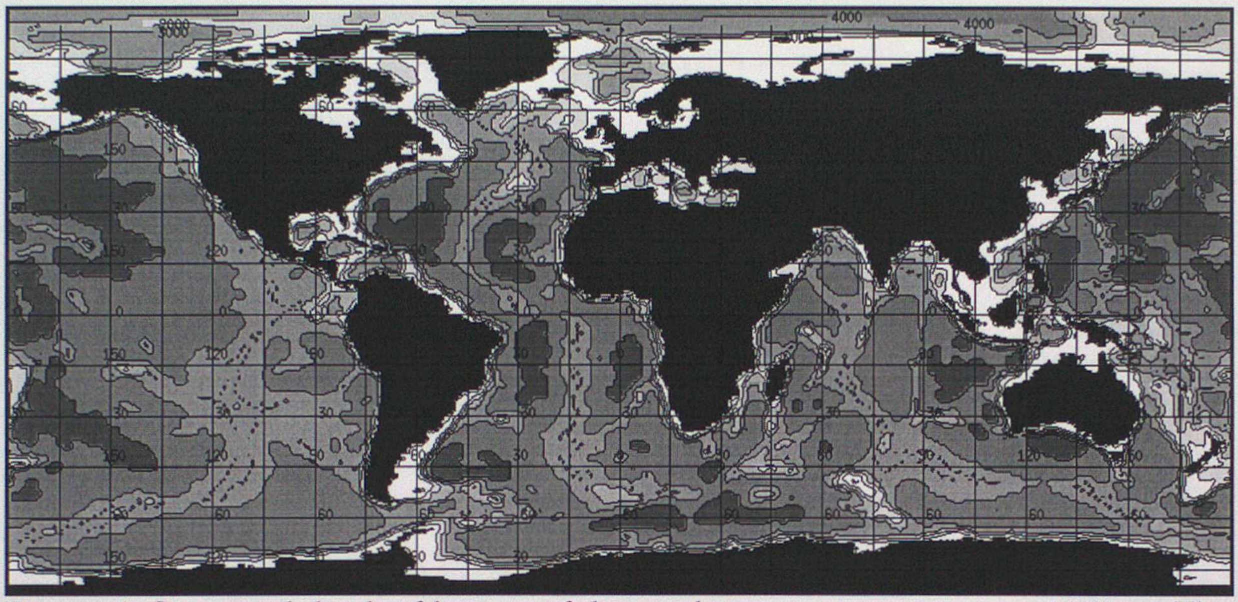

Figure 1 Contoured depth of bottom of deepest layer, contours are every 1000 m. This figure also shows the land/sea mask at the surface

Horizontal resolution of one degree allows a reasonable representation of the coast line. Thirty three islands are represented. In some areas the land sea mask has been simplified, for example the Canadian Archipelago, around the Indonesian islands and in the Caribbean. For numerical reasons there is an artificial island at the north pole. Several single velocity grid-point channels are also present, for example, the Florida Straits and channels around the Indonesian islands.

2.1.3 Initial state

An initial estimate of the ocean temperature, salinity and currents is needed before the analysis procedure can be started. Climatological values of temperature and salinity were taken from the Levitus (1982) climatology. Currents were set to zero. Climatological values of the ice thickness and concentration were not available. Instead these fields were taken from a 20 year average of the Met. Office coupled climate model. This initial state corresponded to climatology for 15 July. The model was run for sixteen days driven by climatological surface forcing and without data assimilation to create an initial state corresponding to 1 August. This calculated currents that were in geostrophic balance with the density. However, the spin up was short enough to prevent the model potential temperature and salinity drifting away from reality.

2.1.4 Sea ice model

FOAM models both dynamic and thermodynamic sea ice processes. The thermodynamic scheme is based upon the zero layer model of Semtner (1976). Ice velocity vectors are calculated using the cavitating fluid dynamics scheme of Flato and Hibler (1992). Heat flux between the open ocean and sea ice is proportional to the temperature gradient from the centre of the top layer of the ocean to the base of the ice. Initial ice formation can take place only if the grid box is at the freezing point of sea water; once formed, however, ice can exist and even grow, in warmer waters. The leads parametrization, which relates changes in total grid box ice content to changes in the proportion of the sea surface covered by ice (ice concentration), is based upon that of Hibler (1979).

Table II Levels used in the FOAM ocean model.

Model level	Layer thickness (m)	Depth of layer mid-point (m)
1	10.0	5.0
2	10.0	15.0
3	10.0	25.0
4	10.2	35.1
5	15.3	47.9
6	23.0	67.0
7	34.5	95.8
8	51.8	138.9
9	77.8	203.7
10	116.8	301.0
11	175.3	447.1
12	263.2	666.3
13	395.3	995.6
14	615.3	1500.9
15	615.3	2116.2
16	615.2	2731.4
17	615.3	3346.7
18	615.2	3961.9
19	615.3	4577.2
20	615.3	5192.5

FOAM assimilates ice observations in a very limited manner. Because climatological ice thickness fields were not available, twelve sets of monthly mean global ice thickness fields were prepared by taking twenty year averages of the output from the coupled climate model.

Every day, these fields are modified by the latest observations of Arctic and Antarctic ice edges (usually updated once per week); ice depth is set to zero for grid boxes outside the observed ice edge; any boxes within the observed ice edge for which the climate model gave an average thickness of less than 0.25m are set to 0.25m. The model ice depth is then relaxed towards these values with a timescale of 13 days.

2.2 Derivation of surface fluxes

The ocean model is driven by surface fluxes of heat, fresh water and momentum. These are applied over both the open ocean and leads within areas of sea ice. The full set of fluxes and other forcing fields required by the model is shown in table III. The two main sources of fluxes are climatology and weather forecast (NWP; numerical weather prediction) models. Not all fields are available from these sources. A third source was used to provide fields which were not available from the other two. This was a climatological 20 year integration of the Met. Office coupled climate model.

NWP fluxes were taken from the Met. Office global NWP model; this model is run twice a day. This model calculates six hour averages of surface fluxes. Fluxes from the first twelve hours of each forecast were used to drive the FOAM system. Climatological fluxes were available as monthly means. Climatological heat fluxes were taken from the climatology of Esbensen and Kushnir (1981) and wind stress and wind mixing fields were taken from the climatology of Hellerman and Rosenstein (1983). The climatological net fresh water flux was calculated using the precipitation climatology of Jaeger (1976) and evaporation from the Esbensen and Kushnir climatology. The coupled model fluxes were also available as monthly means (means of a 20 year run).

Two complete sets of forcing fields were available to drive the ocean model. The first, termed "NWP" fields consisted of NWP fluxes where they were available, climate fields where NWP ones were not available and coupled model fields where neither NWP nor climate fields were available. This was the ideal set for driving the ocean model as it used NWP fluxes as far as possible. The second set, termed the "climate" fields consisted of the climatological fields where they were available, otherwise it consisted of coupled model fields. This was used when NWP fields were not available.

Some processing of the flux fields was necessary. For each of the three sources, the respective land/sea mask did not always agree with that of the ocean model, due to differences in the horizontal grids. Points on the ocean model grid which did not have any data were filled by extrapolating the surrounding points.

2.3 Specific aspects of the data assimilation scheme

Pre-processing and assimilation of observations for use by FOAM is explained in some detail in Bell (1994a,b). This section gives a very brief overview of the system and then details the scientific differences from the system used in Bell (1994b). Section 3.2 describes how changes to the system were controlled during the period covered by this report, and details of the changes related to data assimilation are given later in this section.

Table III Forcing fields used by the ocean model

Field	NWP	Climate	Coupled Model
Momentum			
Wind stress- East/West component	✓	✓	✓
Wind stress - North/South component	✓	✓	✓
Wind mixing energy	✓	✓	✓
Heat			
Penetrative part of the net solar radiation	✓1	✓1	✓
Net non-penetrative heat flux (Latent, sensible, long-wave and non-penetrative part of solar)	✓1, 2	✓1	✓
Fresh water flux			
Net surface fresh water flux	✓	✓	✓
Ice forcing fields			
Snow fall	✓	×	✓
Sublimation from the ice surface	×	×	✓
Topmelt - represents the heat flux available to melt the top of ice or snow.	×	×	✓
Botmelt - diffusive heat flux through the ice	×	×	✓
Relaxation fields			
Reference sea surface temperature	✓3	✓	✓
Reference sea surface salinity	×	✓	✓
Reference ice depth	×	×	✓

Notes

1. These fields had no value for leads, ie. grid points with some ice. To obtain values they were filled in using a bi-linear interpolation from the surrounding four points.
2. The solar radiation had no values for leads, values over ice were used rather than filling in because a bi-linear interpolation technique does not take account of the latitude dependence of the solar radiation.
3. Under sea ice a climatological value was used.

Temperature profiles from BATHY (BATHYthermograph) and TESAC (TEmperature SAlinity and Current) messages and a range of *in situ* and AVHRR (satellite infra-red) surface temperature data are assimilated. In calculating the analysis for a given day, temperature profiles and surface temperatures received during the previous 5 days, on the day itself and on the next day are extracted. Thus, an analysis for 6 January uses observations received between 1st and 7th January.

Temperature profiles are quality controlled by comparing them against a "background" value which is either the model field from the previous day's analysis or the climate field. Observation values more than 2 climatological standard deviations from the "background" value are not used. Differences from the background are averaged onto the model level and spread vertically to fill gaps within the profiles (and just above or below them), and a profile of observation values and the weight to give to each value finally calculated.

Before each model time step, at each model level, the difference between each observation and the model field (the observational increment) is calculated and a suitably weighted fraction of these increments spread in the horizontal over an area with a radius of about 600 km. The model is nudged slowly towards each observation with the weight given to each observation decreasing linearly to zero at 5 days from the observation's time of validity. The weight given to each observation is about the same as that given to the model (so that a single observation in isolation would, over the period that it was used, halve the difference between the model and the observation).

Statistics of the differences between the observations and the analysis and climate fields are calculated each day. The observations which arrived in the previous 24 hours are compared with the analysis calculated the previous day (before the observations used in the statistics arrived) and the climate field interpolated to the same time of validity as that of the analysis field. The differences are calculated by interpolating the fields to the observations horizontally and vertically and averaging the differences within each model layer.

2.3.1 Version 1.0.0

Version 1.0.0 is the version of the system that was used between August 1994 and November 1994. Data assimilation in this system was the same as described in Bell (1994a) except for the aspects discussed in the following paragraphs.

Observations prepared for the operational NWP sea surface temperature (SST) analysis (Jones *et al*, 1994) were accessed and the *in situ* data (i.e. ships, fixed buoys, drifting buoys) used to make sea surface temperature increments (satellite observations were not used at this version). These increments were made to the model field in the surface layer only.

Coefficients used in the vertical interpolation of increments from profile data by Bell (1994a, page 6) were substantially altered: the new coefficients for the error correlation cut-off scale in the vertical ($S^2 = 0.5$ and $\gamma = 20$) result in observation values being interpolated over shorter distances.

2.3.2 Improvements made at version 1.0.1

Version 1.0.1 was run in parallel with the original version before it was used for the main run. Differences between it and version 1.0.0 are described below.

The error correlation scale in the east-west direction, s_{WE} in Bell (1994a), was increased by a factor of 2 within 4 degrees latitude of the equator:

$$s_{WE}=3.10^5\{1+\exp-\tfrac{1}{2}(\lambda/4)^2\}\ \ \textit{metres}$$

where λ is latitude in degrees. The north-south correlation scale was 300 km everywhere.

There has been much discussion about the depth calibration of XBTs (eXpendable BathyThermographs). Depth corrections, multiplying the depths of XBTs by a factor of 1.05 were introduced to allow for the error (N Smith, personal communication). BATHYs with call signs containing one or more letters (A-Z) were judged to be produced by XBTs and had the correction applied.

The quality control check against the background field was changed in two ways. Firstly the check which had been made against the analysis field for the previous day was made against a climate field which had been interpolated in time to the current day from the Levitus (1982) monthly mean fields. Secondly the r.m.s. difference from the background field was calculated from the Levitus (1982) estimate, for the appropriate season, of the standard deviation of observations from their monthly mean value.

Increments calculated for the surface by the SST analysis were applied at all depths within the model's mixed layer (this analysis excluded BATHY reports). The profile data still determined the depth of the mixed layer because increments from the profile data were calculated as a separate step within the analysis step.

AVHRR[1] satellite SST data were used with the *in situ* SST data . ATSR[2] data were not used.

For the statistical assessments and plots of observations, the following values were stored:

- monthly mean climate field interpolated to the observations in time and space
- r.m.s. field for appropriate season interpolated spatially.

Mainly to reduce the run time, the observation increments were projected to the nearest model grid points and spread by a grid point filter to model points within a few correlation scales (the filtered increment scheme, Lorenc 1992) rather than spread to all model points within a few correlation scales of each observation in turn. The effect on the results of doing this was small (though the region influenced by each observation is less circularly symmetric in the new system).

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[1]AVHRR is an infra red sensing instrument carried by the American civil polar orbiting satellites. Observations are calibrated to report bulk temperatures.

[2]ATSR is an infra red sensing instrument carried by the European ERS-1 satellite. It is capable of accurate measurements of skin sea surface temperature, but this can differ significantly from the bulk temperature needed by FOAM.

3 System for running

This section describes the way FOAM was implemented on the computers at the Met. Office and the controls that were used when making changes. It also discusses the computing cost of running FOAM.

3.1 Computer system for running FOAM

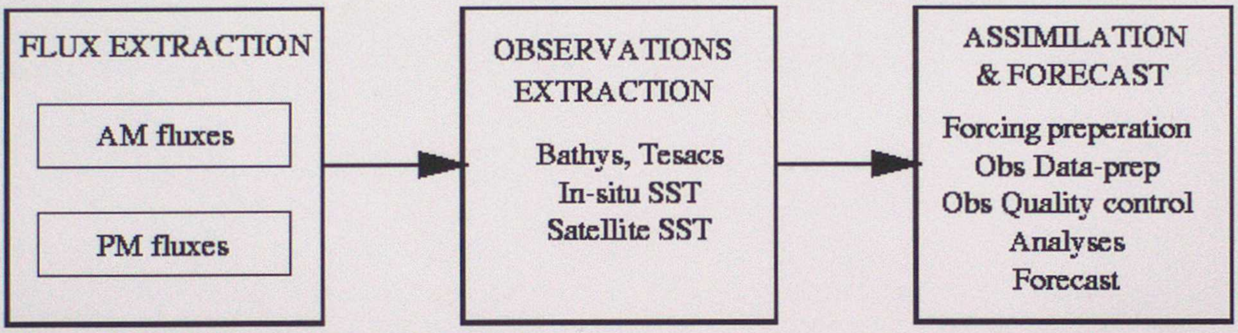

Figure 2 FOAM quasi-operational suite

A semi-operational suite was set up to run the FOAM system. This consisted of three basic sub-suites, shown in fig. 2. Each is described in turn below.

3.1.1 Flux extraction

The aim of the *flux extraction* sub-suite is to extract surface fluxes from the global NWP model and process the fields (for example, to calculate the non-penetrative heat flux from the individual components). It is run twice per day, after the midnight and midday global NWP runs. Fluxes from the first twelve hours of each NWP run are extracted. The end products of the AM and PM extractions are combined to form a set of six hourly fluxes for that day. This is then archived on cartridge so that it can be used by the *assimilation & forecast* sub-suite (section 3.1.3).

The *flux extraction* sub-suite must be run in real time as the NWP fluxes only remain available for a 12 hour period. Should something go wrong (for example, computational problems) and the suite not run as scheduled then the surface fluxes for that day will be lost. In the longer term there are plans for the NWP suite to archive all the fluxes required for FOAM. To increase the reliability of this sub-suite it can be run independently of the other two suites, and carries on running even if the other two suites fail.

3.1.2 Obs extraction

The aim of the *obs extraction* sub-suite is to extract the oceanographic observations required for the assimilation. Observations extracted are: BATHYs, TESACs, *in situ* SST observations and satellite SST observations. This sub-suite is run two days behind real time to allow observations that arrived up to two days late to be used. Like the *flux extraction* sub-suite it can run independently of any subsequent sub-suites. The observation files are archived on tape cartridge ready for the next sub-suite.

3.1.3 Assimilation & forecast

This sub-suite consists of five separate modules (fig. 3) and all are run on the Met. Office's

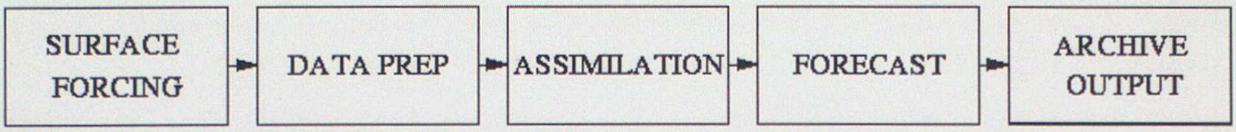

Figure 3 Modules in the *assimilation & forecast* sub-suite.

super computer, a Cray C90. This sub-suite is run two days behind real time to take advantage of the best set of surface forcing fields and observations available. Each module is discussed in turn below.

Surface forcing module

The *surface forcing module* retrieves the surface forcing data archived by the *flux extraction* sub-suite for a whole four day period and re-formats them for use by the ocean model. The middle two days correspond to the assimilation day and the forecast day. Fluxes are required either side of the two days of interest because the fluxes are interpolated from the six hourly means to the model time step. Should fluxes for one of the four days not be available (for example, because of computing problems during the *flux extraction* sub-suite), then climatological fluxes, as discussed in section 2.2, are automatically used for both assimilation and forecast. This ensures that the assimilation and forecast continues even when NWP fluxes are not available.

Data prep. module

Observations processed by the *obs extraction* sub-suite are reformatted and then passed through the quality control procedure. The selected observations are made into the final format ready for use by the assimilation scheme. Also produced is an observation diagnostics file that can be used by graphical or statistical packages to generate information about the model performance.

Assimilation module

A one day assimilation is run from the end of the last assimilation. This is done by running the ocean model for a day and nudging it towards the observations (see section 2.3).

Forecast module

There is an option to produce a one day forecast from the assimilation. This has not been used in the present study.

Archive output module

All output files produced by the *assimilation & forecast* sub-suite are automatically archived. This includes assimilation and forecast gridded fields valid at the end of each run and the observation diagnostics file produced by the *data prep. module*. Also archived is a re-start dump for each day so that the whole system can be re-run starting from any day along the assimilation.

3.2 Change control for FOAM

An essential aspect of the design is the strict version control of new releases. All aspects of the system from the model code to the data used comes under version control. This means that the system can only be changed through the release of a new version. This adds robustness to the system as there will always be a fully working version.

Another major feature of the design is that a new version can be very easily set up and run in parallel. Indeed, any number of versions can be set up by different users and run independently. This means that modifications can be easily and independently tested by each user. Furthermore, modifications can be tested for any period that has already been run in the past. For example, a modification could be tested for a winter month and a summer month, to fully test any seasonal dependence.

When a new release of the suite is due, a parallel suite is set up and run along-side the main suite. Results from the two suites can be compared to ensure that the new suite meets the *a priori* performance improvement criteria. Once the parallel suite has been fully accepted it becomes the main suite and the old main suite is switched off.

The initial implementation of the FOAM suite, version 1.0.0, began with an assimilation starting on 1 August 1994. On 13 November a parallel suite, corresponding to version 1.0.1, was started which contained several improvements to the assimilation (these are discussed in section 2.3). After a month of running in parallel the results from the parallel suite were compared with those from the main suite and were shown to be better. The parallel suite was then made the main suite and the old suite was stopped.

3.3 Monitoring day to day running

The FOAM quasi-operational run is monitored by a UNIX program that uses pattern matching to find and act on key output messages. This program runs automatically each morning and generates a summary of the output. If the output conforms to expectations then the monitor program takes no extra action. If output is missing or if an output value fails a test, then a message indicating the nature of the failure is sent to designated support staff. Tested output values include cpu time, change in model energy per time step, and number of observations used. Staff act on messages received from the monitor job and keep a log of incidents.

3.4 Computing costs

The FOAM suite requires a large amount of computing resources. The model assimilation and forecast modules (see 3.1.3) are the main users of the supercomputer CPU time. The *assimilation & forecast* sub-suite typically uses around 500 seconds of a Cray C90 cpu each day (this does not include a forecast). In order to run the suite 0.5 Gbytes of data are kept online on Cray disks.

The other main use of resources is associated with the front-end mainframe, which processes the data during the *flux extraction* and *obs extraction* sub-suites and archives all data used or produced by the suite. Currently about one cartridge (approx. 1 Gbyte capacity) is used every 5 days. This is a large storage requirement.

4 Overview of performance

Several problems with analyses from earlier versions of the FOAM system and remedies for them were reported in Bell (1994b). These included excitation of the stream function by temperature increments based on observations in the deep layers, and noise in the temperature field where the thermocline was steeply sloped. The drift of the model, when run freely without assimilation, away from the ocean's climatological potential temperature was also identified as a serious problem. This and the next section discuss how the characteristics of the system have changed from those described in the earlier reports. This section concentrates on looking at the broad scale features and the next examines more detailed aspects.

4.1 Objective statistics

Figure 4 presents the standard deviation of differences, and fig. 5 mean differences, between the BATHY and TESAC thermal observations and either the analyses or the climatology for 1 December 1994 to 31 December 1994. The statistics in these figures are calculated for 4 areas and 3 depth ranges. Area 1 covers the western basins of the northern hemisphere between 15°N and 60°N and area 2 the eastern basins (see fig. 6). Area 3 covers the equatorial belt between 15°S and 15°N. Area 4 covers the remainder of the globe. Observations between the surface and 10 metres fall in level group 1, those between 30 and 80 metres fall in group 2 and those between 170 and 370 metres fall in group 3. Only observations within two climatological standard deviations of both the climate field and the analysis field are included in the calculations.

Note first that the mean difference (bias) for the climate field is of the order of 0.8°C in level group 2 and up to 0.4°C in level group 3. Biases for the analysis fields are much smaller at less than 0.2°C. Analysis biases at the surface are also smaller than those of the climatology. The standard deviations of the analyses in the equatorial region (area 3) are also much smaller than those of the climatology, particularly in level groups 2 and 3. The standard deviations for the model in areas 1 and 2 are also generally smaller than climatology in all 3 level groups, but the margin of the difference is much less. The number of observations in area 2 is much less than that in area 1, and most observations are in area 3.

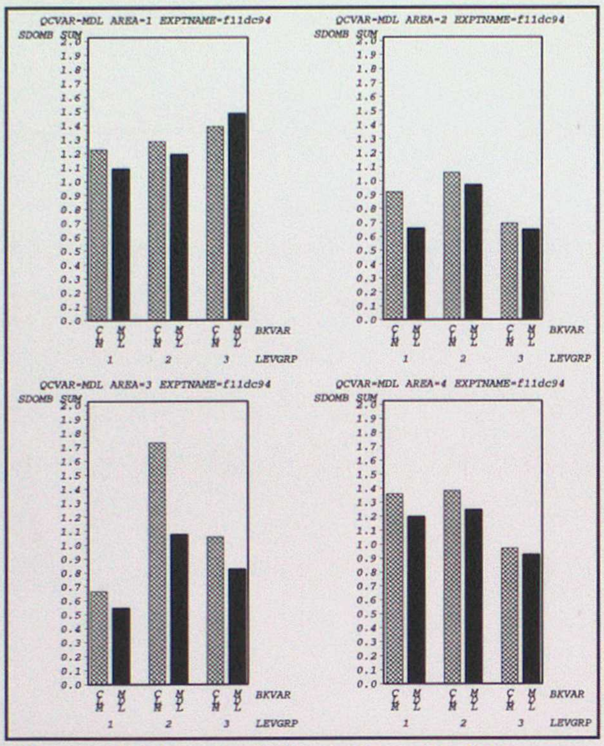

Figure 4 Standard deviation of differences from observations during December 1994. Light shading is for climatology and dark shading is for the FOAM analyses. Moving clockwise from the top left, the panels are in the order area 1, area 2, area 4, area 3. Areas are shown in fig. 6. Each panel shows three depth bands. These are (from left to right): 0 to 10 m, 30 to 80 m and 170 to 370 m. Units are degrees Celsius.

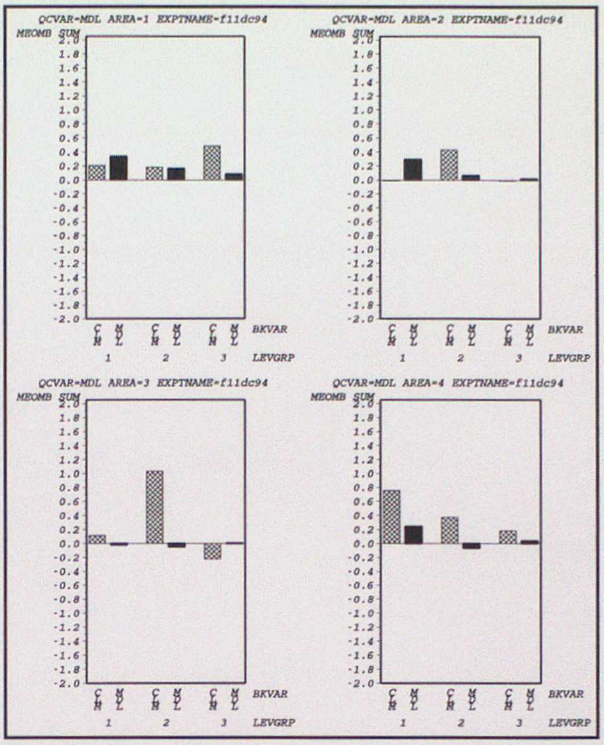

Figure 5 As fig. 4 but for mean errors.

Two alternative statistics are presented in figs 7 and 8: the mean of the absolute differences (fig. 7) and the normalised standard deviation (fig. 8). The latter is calculated by taking the standard deviation of observation minus background values (analysis or climate) which have been divided by the climatological standard deviation as estimated by Levitus (1982). With these measures the differences from the observations of the model analyses are again smaller than those of the climate field; the improvement being modest in areas 1 and 2 and substantial in area 3.

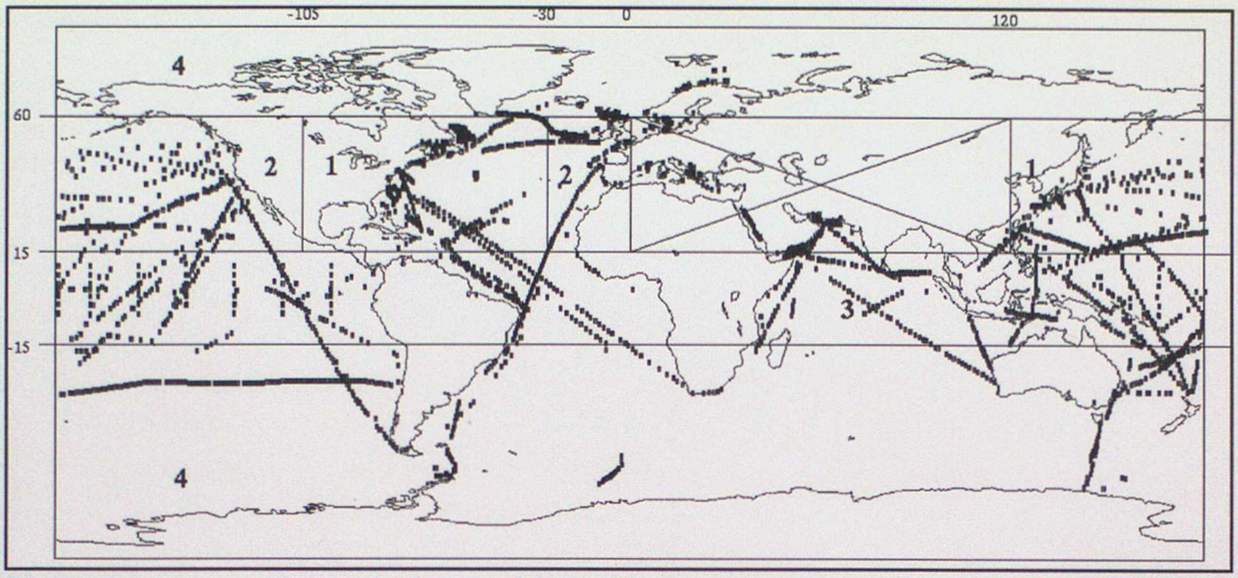

Figure 6 Areas used to calculate statistics. These are superimposed on the distribution of observations between 20 and 30 m during December 1994.

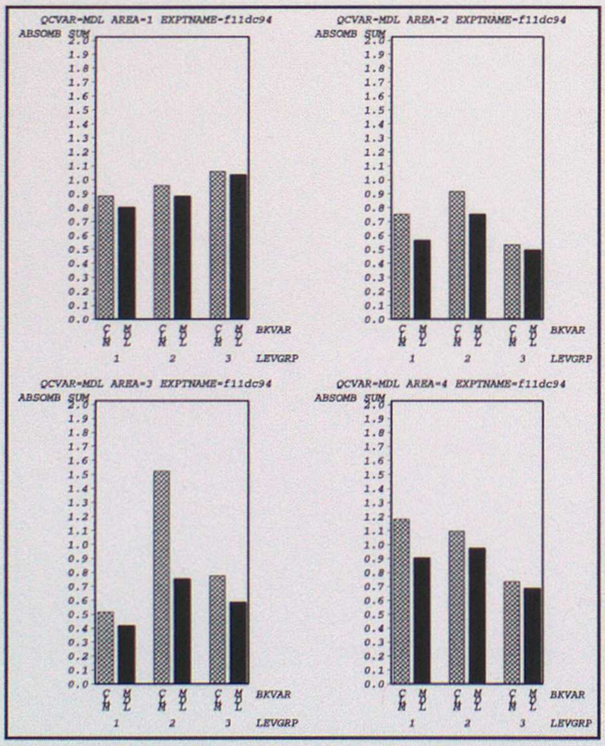

Figure 7 As fig. 4 but for absolute errors.

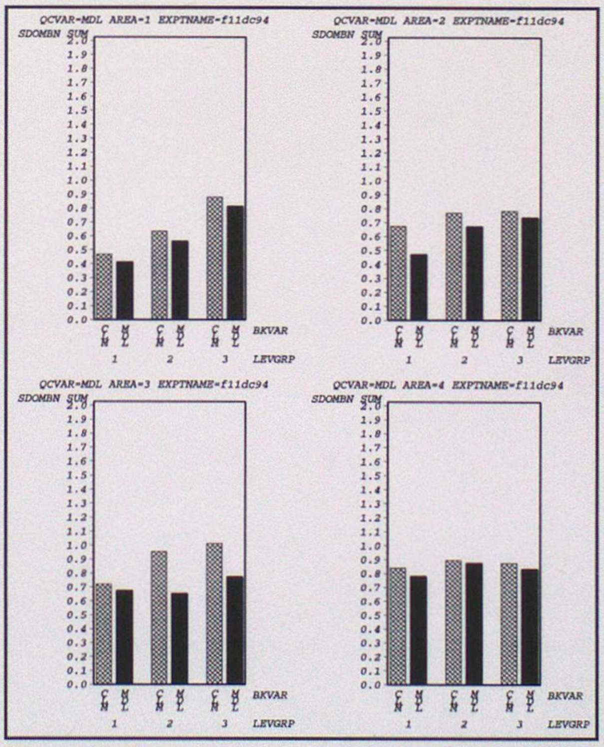

Figure 8 As fig. 4 but for normalised standard deviation.

Absolute differences have two advantages as statistics. They are less sensitive to the largest errors included in the statistics and hence less sensitive to the precise values of the ranges in quality control tests. Also they do not favour smooth fields in regions with large temperature gradients (such as western boundary currents). Like r.m.s. errors the absolute differences do not separate mean differences (biases) from variations (standard deviation).

Although the above statistics are "objective" they need to be interpreted with some care. The location of new observations is not independent of previous observations as they are produced by ships or moorings most of which report regularly and do not move outside the influence of an observation in a single day. Moorings which report frequently can dominate the statistics for an area. Hence the statistics favour the model analyses. It is worth noting that the assimilation scheme takes about five days to make full use of an observation. Statistics could be artificially improved by making full use of each observation on the day on which it is received.

It is interesting to note that the normalised standard deviations are much smaller than one. This suggests that, the model bias being small, the quality control check against the model field could be made significantly tighter than two standard deviations. This suggestion needs to be evaluated carefully in the light of the points made in the previous paragraph and the fact that the ocean model has a tendency to drift away from the ocean's mean climate in areas where no observations are received.

In previous reports (Bell 1994a,b) the climate field was found to be better than the analyses in most areas in level groups similar to 2 and 3. The statistics presented above reverse this for a combination of reasons.

- The statistical assessment previously used only the climate field in quality control checks. This had a major impact on the relative magnitudes of the standard deviations in area 1 for level group 3.
- Statistics for the Pacific are better than those for the Atlantic.
- In the equatorial regions, the increased correlation scale along the equator had a substantial impact. Previous statistics were calculated for 15°S to 30°N rather than 15°S to 15°N.
- Observations were assimilated from the start of the model run. This helped to prevent model biases developing.
- Use of SST observations improved the surface analysis, as did assimilation of these increments throughout the mixed layer (see section 5.2).

4.2 Assessment of global fields

A useful quantity to assess is the potential temperature anomaly. Figure 9 shows the SST (i.e. model top level) anomaly for the FOAM analyses averaged over January 1995, with respect to the Levitus climatology. Sea surface temperatures are also analyzed by the NWP suite to provide a lower boundary condition for the weather forecast models. The NWP SST anomaly (against the same climatology) is shown in fig. 10. The NWP anomaly can be thought of as the best estimate of reality. There is in general a very good agreement between the two throughout all the oceans. Of particular interest is a good agreement of large scale patterns in the North Atlantic. In the eastern equatorial Pacific there is a warm anomaly, present in both figures, characteristic of an El-Niño event.

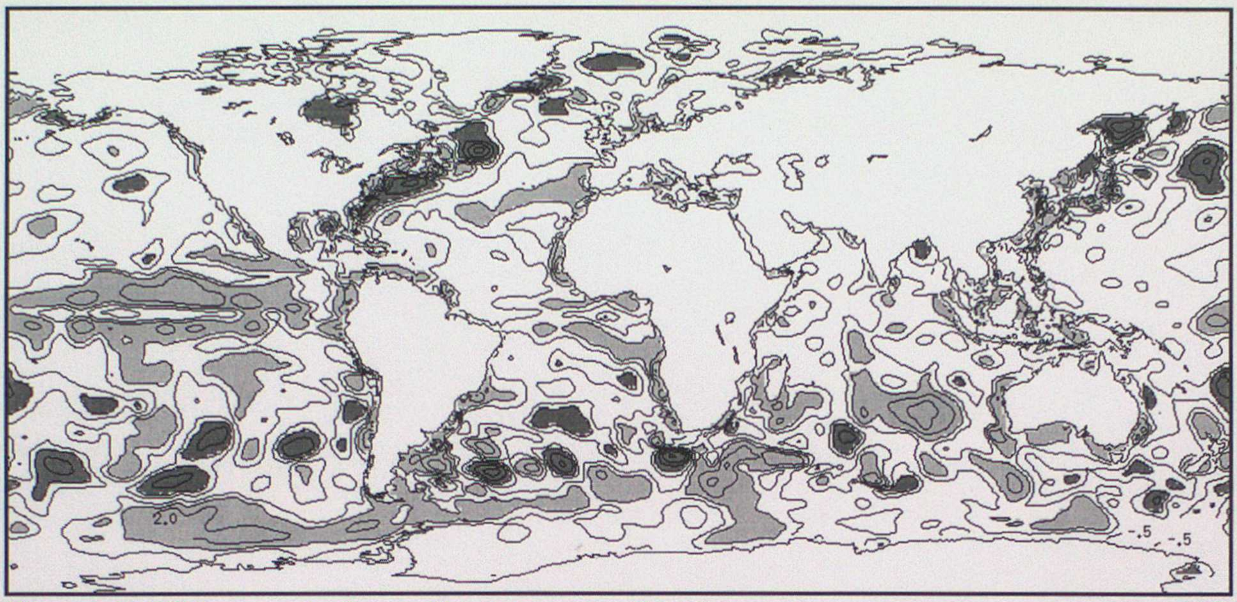

Figure 9 SST anomaly from climatology for FOAM analyses meaned over January 1995. Contours are at ±0.5,±1,±2,±3,±4 and ±5 °C. Light shading >1°C and dark shading <-1°C.

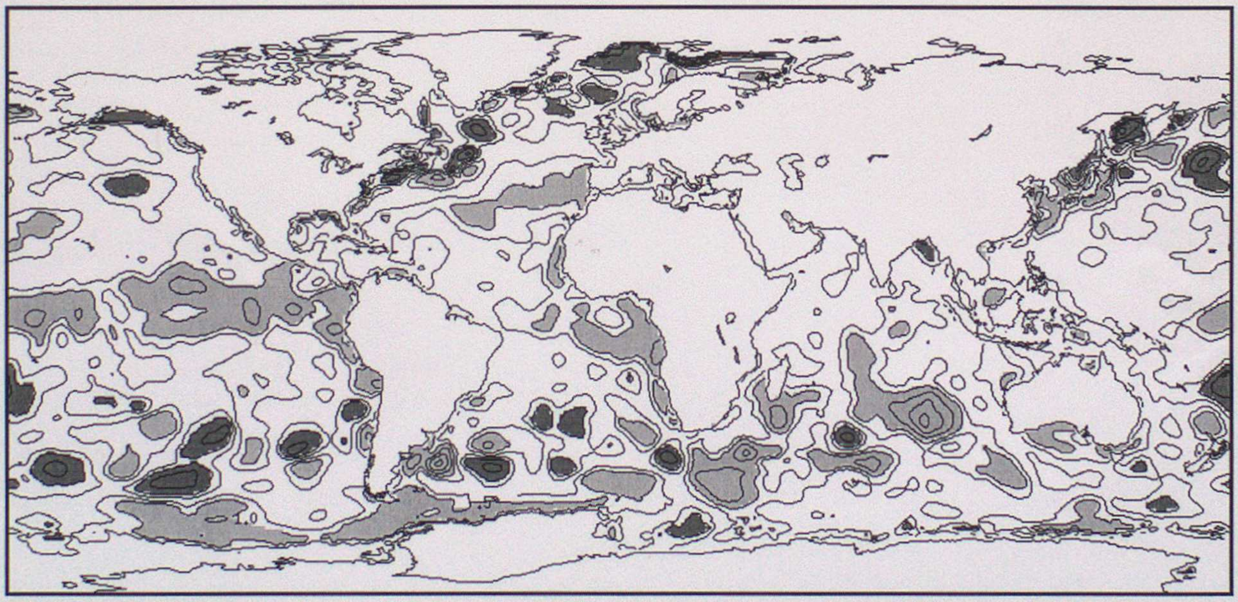

Figure 10 SST anomaly for NWP suite SST analyses averaged over January 1995. Contours are at ±0.5,±1,±2,±3,±4 and ±5 °C. Light shading >1°C and dark shading <-1°C.

Although there is a good general agreement there are differences. For example, the two differ significantly along the Gulf Stream path, in particular there is a cold anomaly greater than 3°C in the FOAM analyses off the Grand Banks which is not in the NWP analyses. Other differences are in the Kuroshio region and areas where there are strong horizontal temperature gradients. Models with the resolution of FOAM cannot represent the processes in such regions, so these errors had been anticipated. Differences can also be seen along the equator in the eastern Pacific. The FOAM analyses are relatively colder than the NWP analyses. This is an area where the surface temperature is dominated by upwelling; this depends strongly on the wind stress forcing and could be an indication of deficiencies in the wind stress or the model's ability to resolve the upwelling mechanism.

Despite the differences discussed above the model captures most of the observed anomalies. At the surface it clearly is better at predicting the observed SST patterns than climatology.

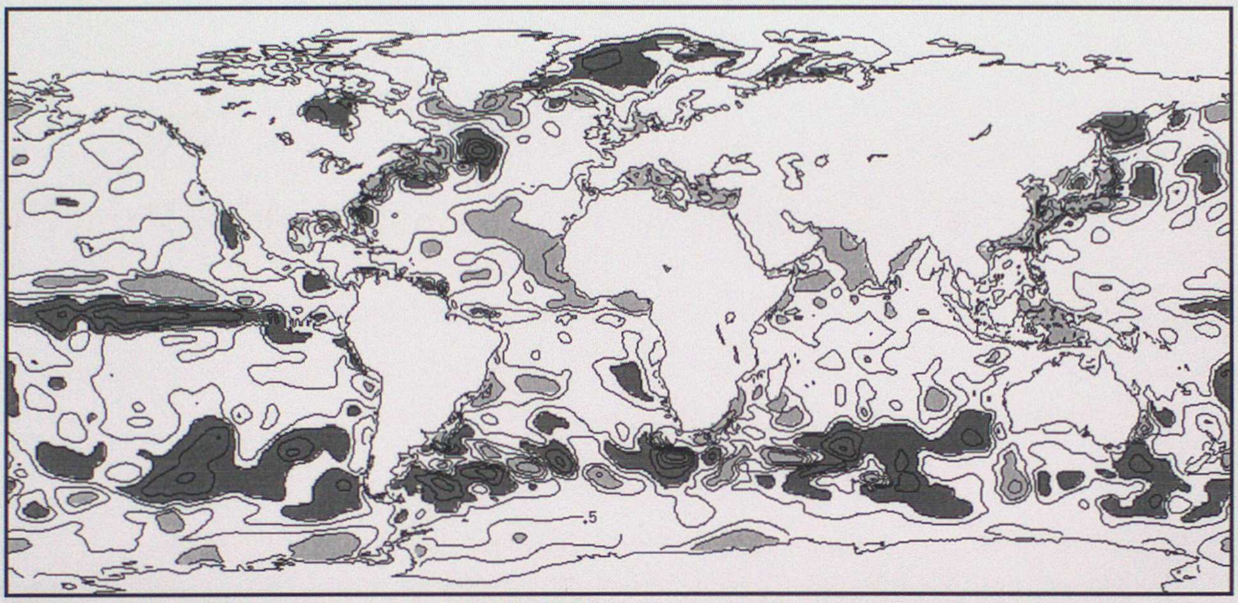

Figure 11 SST anomaly for CLIMATE run averaged over January. Contours are at ±0.5,±1,±2,±3,±4 and ±5 °C. Light shading >1°C and dark shading <-1°C.

A parallel run to the FOAM analyses was carried out for the whole period without any assimilation of observations or NWP surface fluxes. It was forced by the climate fluxes discussed in section 2, and will be referred to as the climate run. This parallel run allows the impact of the assimilation and NWP fluxes to be identified, and acts as a "control" integration for the assimilation. The SST anomaly from the climate run for January is shown in fig. 11. The anomalies for the climate run are in general very different from those of the NWP and the FOAM SST analyses. This confirms that the assimilation or NWP fluxes contribute to the good agreement between the FOAM analyses and NWP SST anomaly. The relatively large anomalies in the climate run are indications that, without the assimilation, the model can drift away from climatological estimates. In areas where the FOAM analyses disagree with the NWP analyses, for example, the strong cooling off the Grand Banks and the cool band along the eastern equatorial Pacific, the disagreement is much worse in the climate run. This means that in these areas the model is drifting away from reality and that using the assimilation reduces that drift.

Some of the anomalies shown by all three sources discussed above could be a result of errors in the climatology. Levitus and Boyer (1994) have deduced a new climatology. This new climatology will be referred to as the "new Levitus", and the one used in initialising the model and to create the anomalies will be referred to as the "old Levitus". Figure 12 shows the difference in temperature between new and old Levitus at the surface for January. The differences are remarkably large considering that Levitus is the most widely used estimate of climatology against which the models are assessed. Large differences, greater than 1°C occur around the Gulf Stream area (small compared with the model errors), Greenland Sea, Polar oceans, north-western Pacific and Southern Ocean. Clearly some care must be taken when comparing model results against the climatology. Even so, the climate run produces SST anomalies at least as large as and significantly greater in many areas than the differences between the Levitus climatologies.

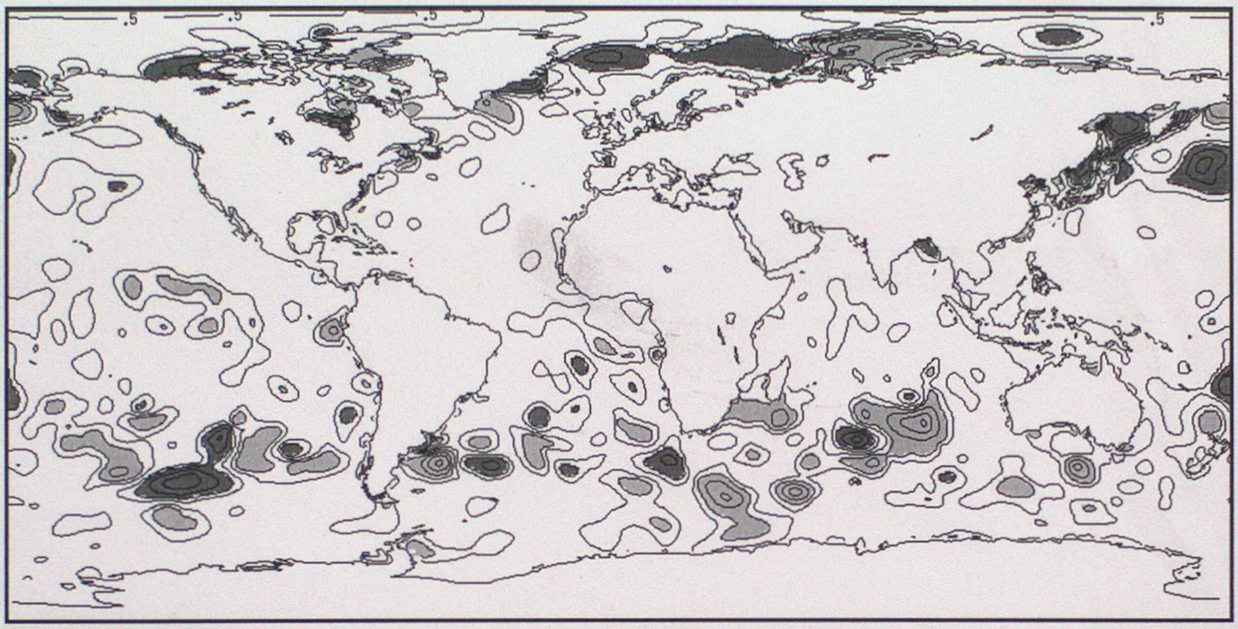

Figure 12 Surface temperatures for January from the new Levitus climatology minus those from the older one. Contours are at ±0.5,±1,±2,±3,±4 and ±5 °C. Light shading >1°C and dark shading <-1°C.

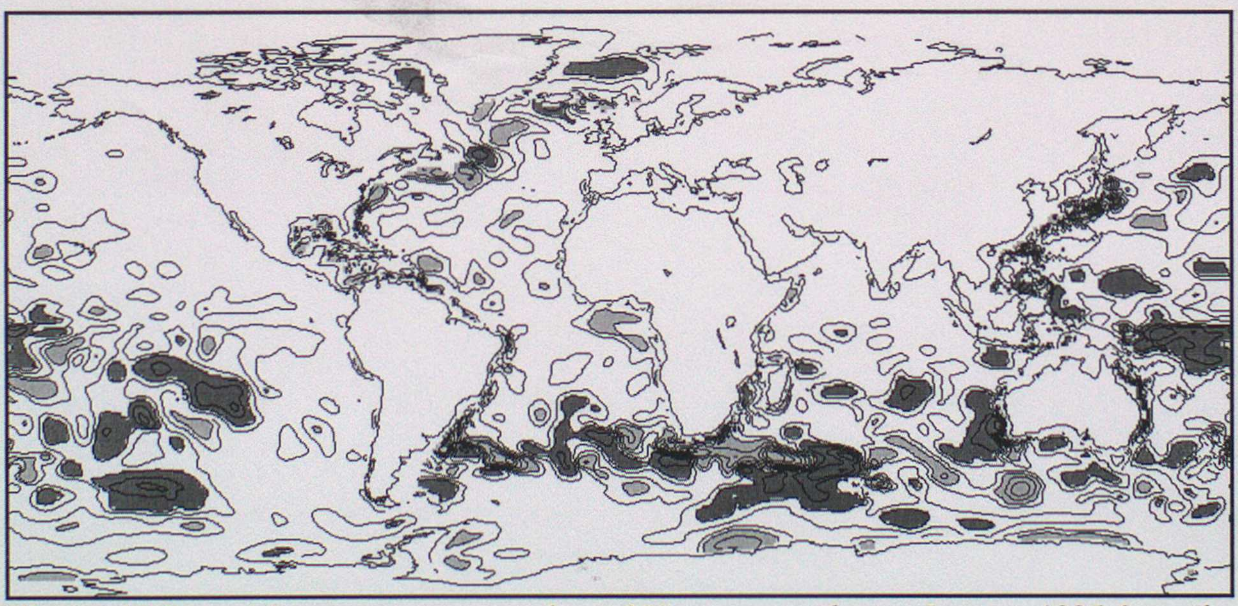

Figure 13 Potential temperature anomaly at 300 m averaged over January 1995 from the FOAM analyses. Contours are at ±0.5,±1,±2,±3,±4 and ±5 °C. Light shading >1°C and dark shading <-1°C.

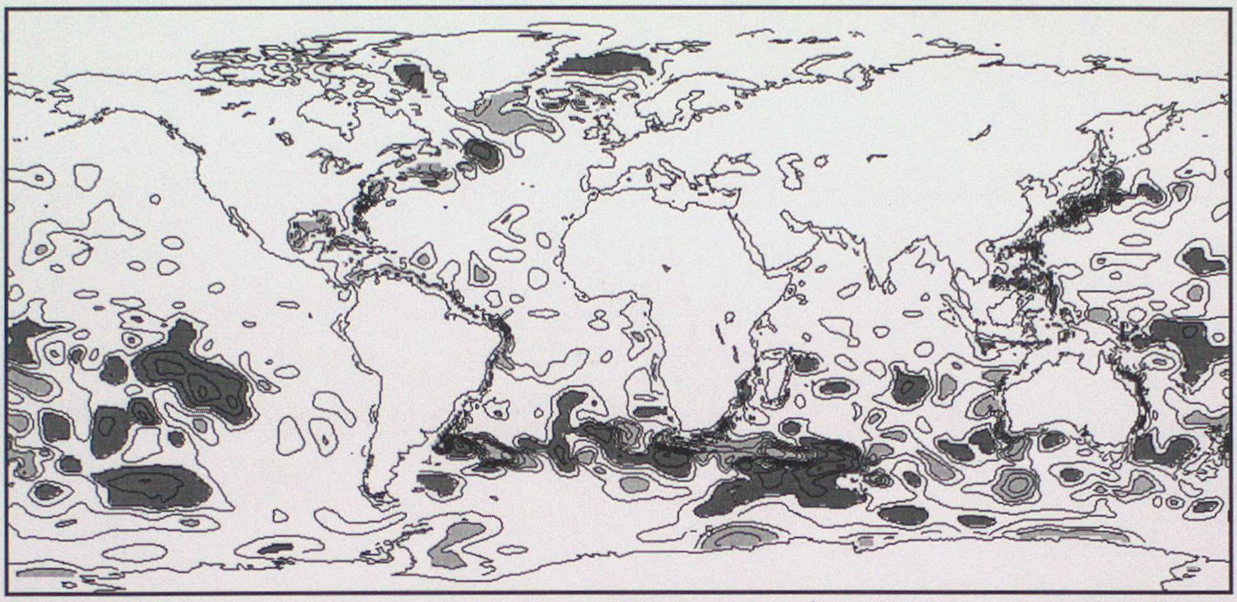

Figure 14 Potential temperature anomaly at 300 m averaged over January from the climate run. Contours at ±0.5,±1,±2,±3,±4 and ±5 °C. Light shading >1°C and dark shading <-1°C.

So far only the surface temperature from the model has been discussed. The anomalies in potential temperature from the old Levitus climatology at 300m depth are now presented. The potential temperature anomaly at 300m from the FOAM analyses is shown in fig. 13. There is no NWP equivalent to provide an independent estimate of reality. Figure 14 shows the potential temperature anomaly at 300m from the climate run. Patterns in the two anomalies are very similar in both spatial extent and magnitude. However, there are significant differences in many areas, for example in the Gulf Stream and Kuroshio areas and other parts of the North Atlantic and South Pacific. Relatively smaller numbers of observations reach this depth so that the assimilation has a smaller impact on the ocean model than near the surface, making the anomalies from the runs with and without the assimilation similar in many areas. This is particularly true in the Southern Ocean, where observations are sparse.

Anomalies shown for the climate run can be thought of as a model drift away from the climatological estimate. However, as for the surface, the reliability of the climatological estimates need to be understood. The new and old Levitus climatologies at 300 m are compared in fig. 15. Differences are relatively large. There are several areas where they exceed 1°C, although these are mainly in the Southern Ocean, South Pacific, Greenland Sea and polar oceans. In these areas observations to create the Levitus climatology were sparse. Several of the differences between the climatologies correlate well with the anomalies produced by the model. For example, a cold anomaly in the western tropical Pacific and the a cold anomaly in the Greenland Sea. Again care is needed when assessing the model against a climatology. Some of the differences have a small spatial scale, indicative of noise in the climatology.

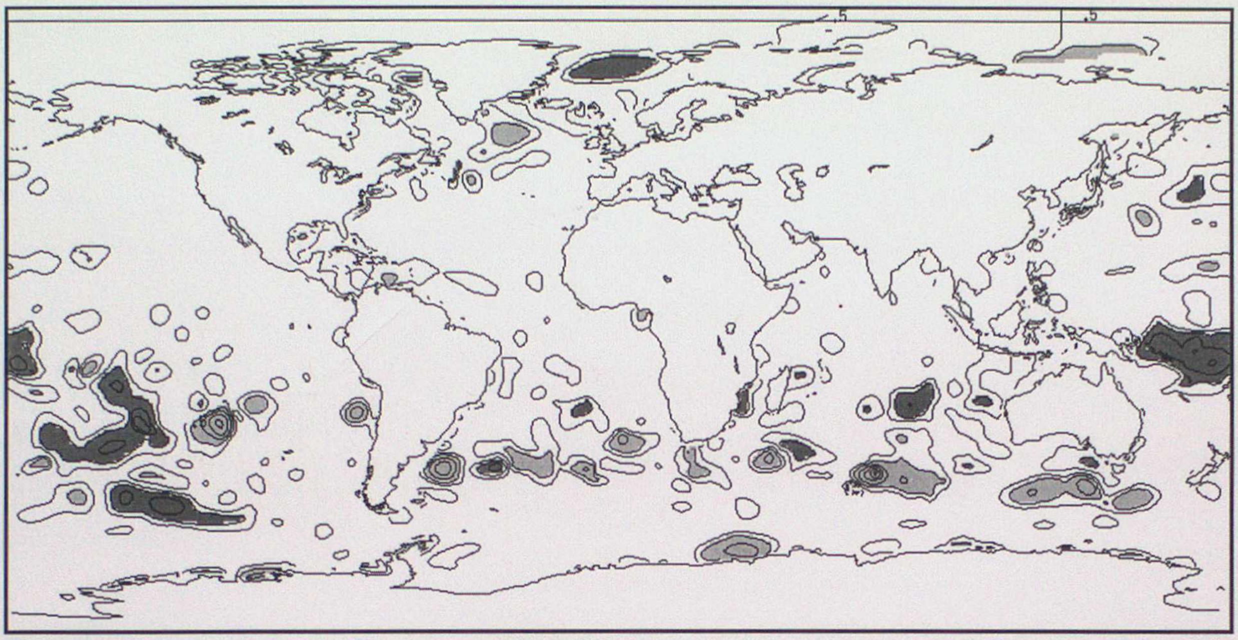

Figure 15 New minus old Levitus at 300m for January. Contours are at ±0.5,±1,±2,±3,±4 and ±5 °C. Light shading >1°C and dark shading <-1°C.

More work is needed to determine the reliability of the Levitus climatology. The results above have shown that there are significant differences between the new and old Levitus. The reliability of the seasonal variation in the Levitus climatology also needs to be investigated since this too could give larger biases in the model from one season to the next. In conjunction with this the performance of the model and any drifts need to be identified and understood. In particular the model's ability to represent the seasonal cycle and the dependence of errors of the model on the surface fluxes need to be investigated.

4.3 Sea ice fields

4.3.1 Ice depth and concentration: effectiveness of relaxation

As described in section 2, the model ice depth was relaxed towards an externally generated ice depth dataset. Observations of ice depth are sparse, so a climatology was generated by taking output from the coupled climate model and modifying it with an ice mask produced from US National Ice Center ice edge analyses.

The relaxation was a temporary measure intended to keep the model ice edges close to those observed, and to regulate the model ice depth, preventing totally unrealistic values due to poor quality fluxes over ice.

In spite of the relaxation, the January fields show too much model ice cover in both hemispheres. In the Antarctic, the NWP ice edge (the 10% ice concentration contour) is fairly close to that of the model, and generally passes through model ice concentrations of 30% or less. The model's Arctic ice, however, has progressed significantly further south than observations allow for; so that the NWP ice edge corresponds roughly to the model's 80% cover contour. Although inaccurate, the model's ice edge is not abnormal for the time of year (see fig. 16). It shows the observed general trends, with ice hugging the east coasts of Greenland and Canada, and penetrating into the Sea of Okhotsk (north of Japan). Moreover, the spurious ice cover is very thin, generally much less than 0.5m deep.

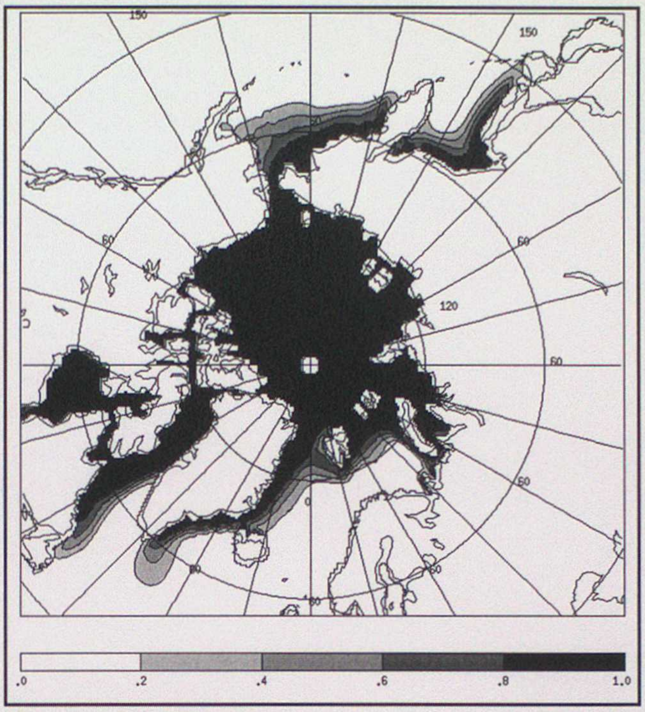

Figure 16 FOAM mean ice concentration for January 1995 in the Arctic.

The FOAM ice depth distribution (fig. 17) is generally very close to the distribution towards which it is relaxed. In the Arctic the overall shape is similar to a multi-year winter mean, with thick ice to the north of Greenland and the Canadian Archipelago, thinner ice to the north of Siberia and Alaska and to the east of Greenland. However, FOAM ice depths are much smaller than those observed in the winter: ice to the north of Greenland and Canada is generally 4m or more deep, and ice close to the east coast of Greenland reaches depths of over 2m (e.g. Bourke and Garrett, 1987). This shallow bias is a known characteristic of the ice model used in FOAM, and is probably compounded by the relaxation towards a depth distribution which has been generated by a similar ice model. The FOAM ice model gives the correct shape to its Antarctic ice distribution, with the thickest ice in the inner Weddell Sea; in the Antarctic, however, the FOAM ice is generally too thick.

In the Arctic, January means of the changes in ice depth due to model dynamics, thermodynamics and relaxation of ice depth are all of roughly the same magnitude. Away from the central ice pack there is a strong negative correlation between thermodynamic and relaxation effects as, in general, the model produces too much ice and the relaxation attempts to remove it. In a few small areas, such as to the east and south of Greenland, the

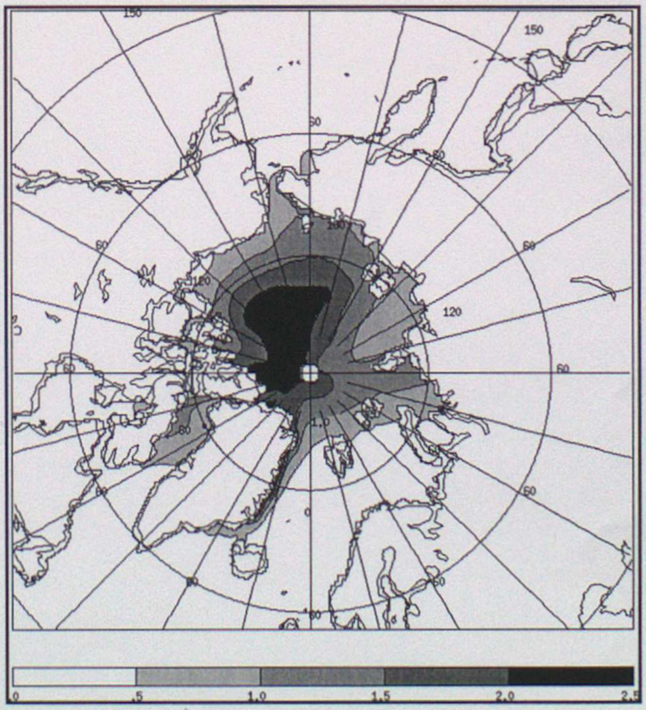

Figure 17 Average Arctic ice depths (in metres) in FOAM for January 1995.

relaxation counters the model dynamics. In the central Arctic there is no obvious correlation between the fields.

In the Antarctic, January mean thermodynamic increments are never very large and are uniformly negative as would be expected for summer melt. Increments sue to the dynamics and ice depth relaxation show mush more variability, both in sign and magnitude. There is a strong correlation between the extrema of the two fields. It appears that in the Antarctic in January ice movement, driven by winds from the atmosphere model, causes the ice depth to differ markedly from the climatology of the climate model.

An examination of the Antarctic ice depth distribution shows a region in the Ross Sea where the ice is significantly shallower than is to be expected. During the NWP processing, which produces the observational ice mask used by FOAM, this area is classed as land. Hence the relaxation ice depth data set contains no ice and a 'low depth' bias is passed to the model. Technically the region is ocean, but contains extremely thick ice shelves, which neither the ice nor ocean models are designed to handle. Future versions of FOAM should treat this region as land.

4.3.2 Circulation compared with schematic flows

The January mean of FOAM Arctic ice velocities (fig. 18) shows most of the features generally observed in the Arctic circulation. Ice tends to flow quickly down the east coast of Greenland, and into the N. Atlantic; also through the Bering Strait and into the Pacific. The model also reproduces the tendency for ice to leave Baffin Bay on the Canadian side of the Davis Straits. Furthermore, the January means exhibit a transpolar ice drift from the Alaskan/Siberian Arctic to the W. European side.

There is no model gyre in the Beaufort Sea (north of Canada); the flow here may be inhibited by the model's spurious polar island (section 2.1.1), or there may (in reality) have been no such circulation in January, as the gyre is not a permanent feature of the Arctic.

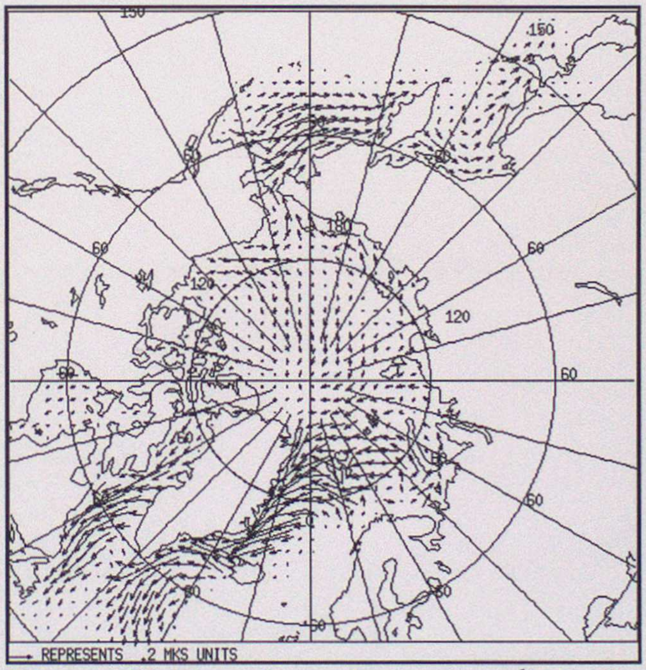

Figure 18 Mean ice velocity (m s^{-1}) in the Arctic during January 1995 from the FOAM analyses.

5 Examples of performance

5.1 Mixed layer depth evolution

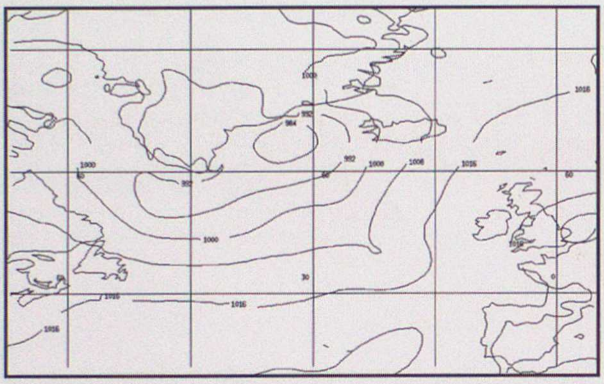

Figure 19 Mean sea level pressure (contours every 8 mb) 1 September 1994

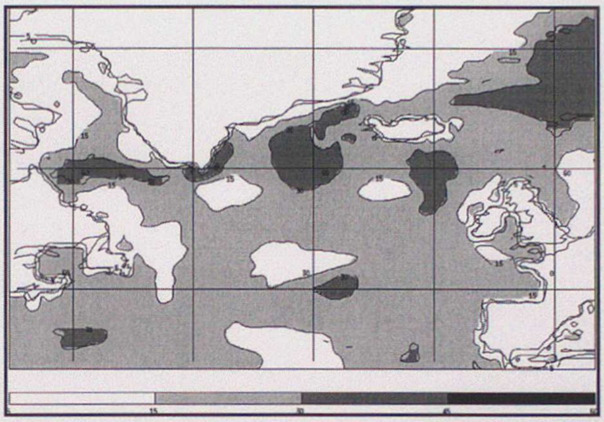

Figure 20 Daily maximum mixed layer depth (contours every 15 m) 1 September 1994

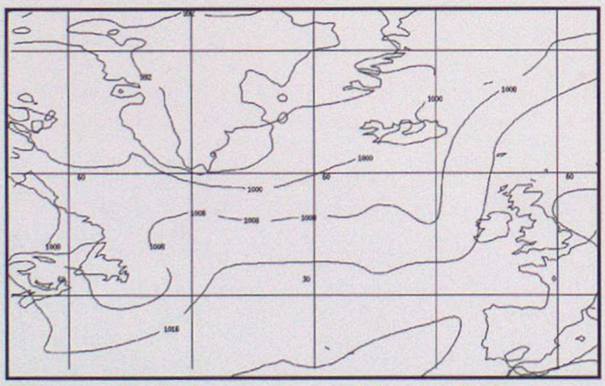

Figure 21 2 September 1994. MSLP

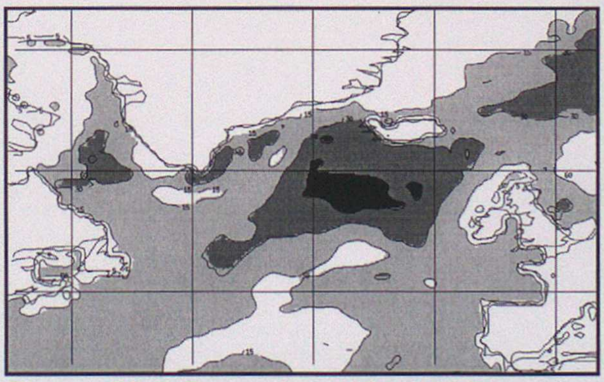

Figure 22 2 September 1994. MLD

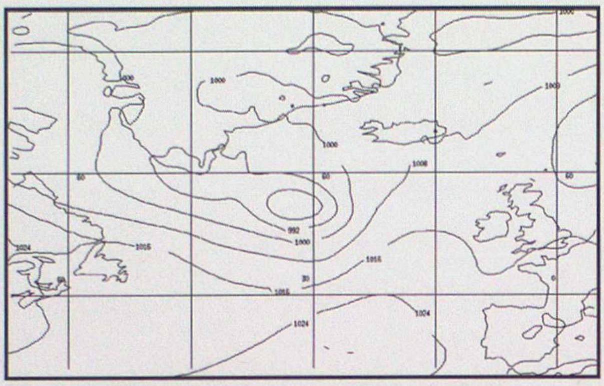

Figure 23 3 September 1994. MSLP

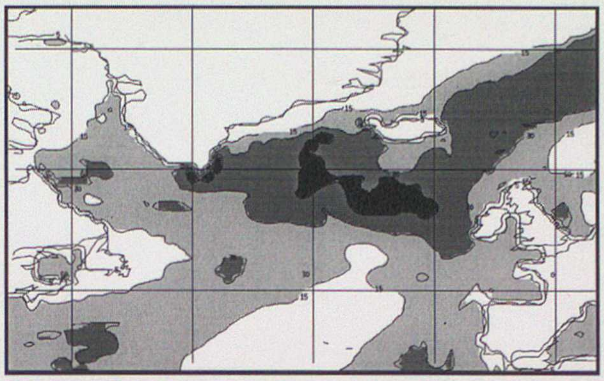

Figure 24 3 September 1994. MLD

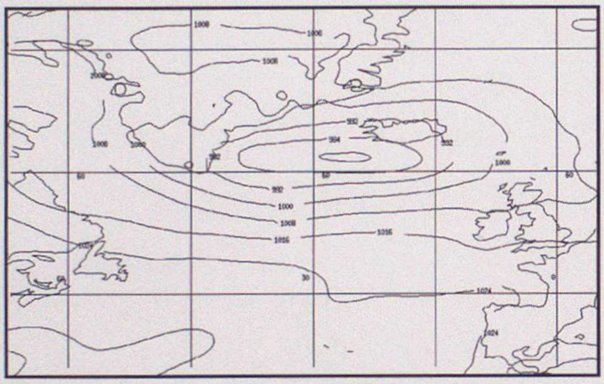

Figure 25 4 September 1994. MSLP

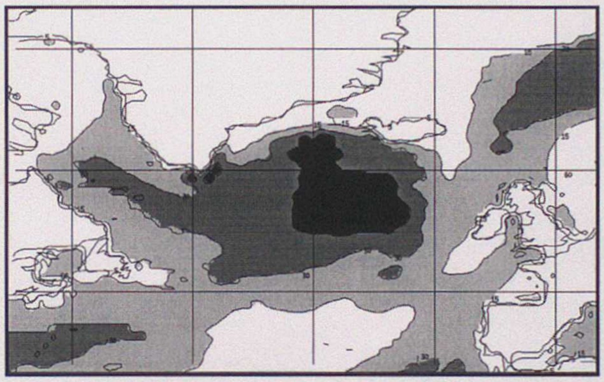

Figure 26 4 September 1994. MLD

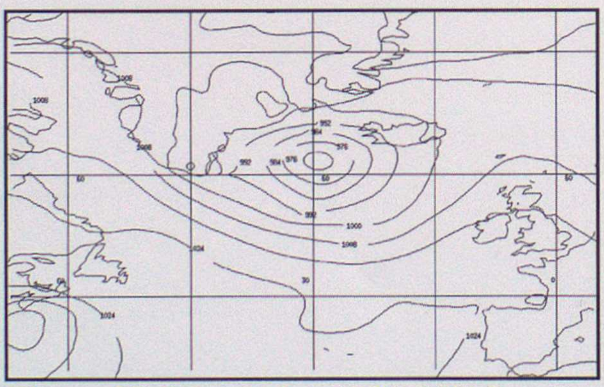

Figure 27 5 September 1994. MSLP

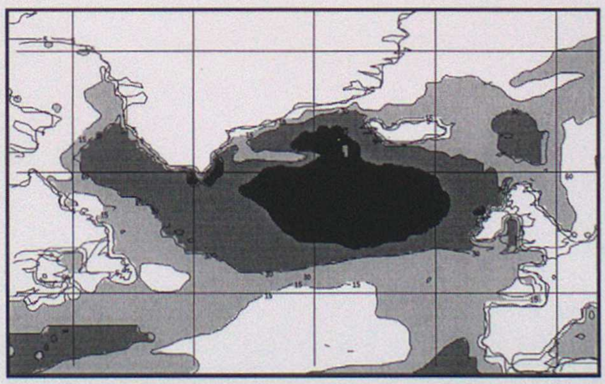

Figure 28 5 September 1994. MLD

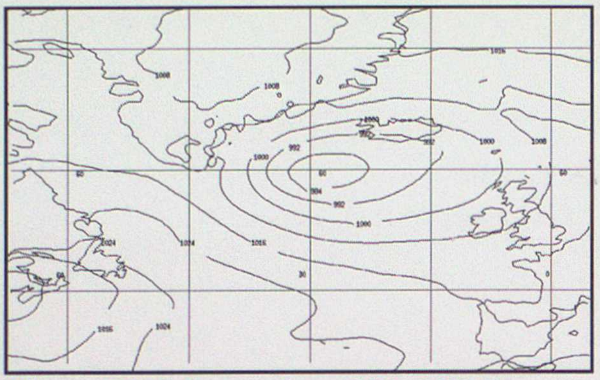

Figure 29 6 September 1994. MSLP

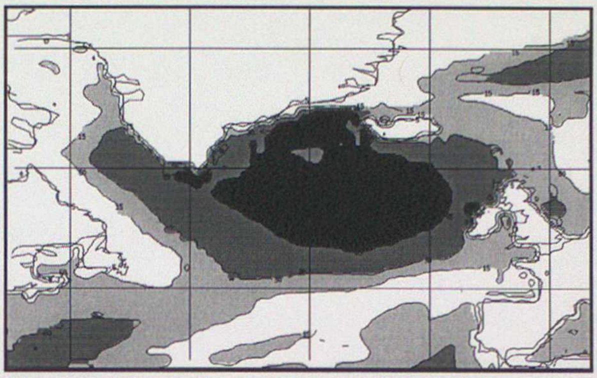

Figure 30 6 September 1994. MLD

One of the main features of the FOAM model is that it uses NWP six hourly surface fluxes. This means that the fluxes are able to resolve both the diurnal cycle and synoptic variability. Figures 19 to 30 illustrate the impact of the synoptic variability of the surface fluxes on the ocean. These figures show a sequence of daily plots for mean sea level pressure (MSLP) and daily maximum mixed layer depth (MLD) from the model, for the period 1 to 6 September 1994. Over this period an intense storm crossed the North Atlantic; its central pressure was less than 968 mb on 5 September. As the storm intensified and traversed the North Atlantic it led to deepening of the daily maximum mixed layer depth. On 1 September the daily maximum mixed layer depths were around 15 to 30m, with a few small areas just exceeding 30m. By 6 September a large proportion of the North Atlantic had a daily maximum mixed layer depth of over 30m; over a large area of the central North Atlantic it exceeded 45m.

5.2 Specific case studies

5.2.1 Use of SST through mixed layer depth

A set of experiments has been performed to assess the impact of surface temperature data on the model fields.

The experiments used the Atlantic model and assimilation system described in section 3.5 of Bell (1994b). The model was run from 1 March 1993 with climatological forcing to 1 July 1993 and then observations were assimilated over a 3 month period. As surface temperature data were to be assimilated the relaxation to the Levitus surface temperature climatology was reduced from the value of 35 W m^{-2} K^{-1} used in previous experiments to 20 W m^{-2} K^{-1}. The difference from the operational NWP analysis surface temperature for 15 September 1993 is shown for the following fields: fig. 31 control run (no assimilation), fig. 32, climatology, fig. 33 assimilation of SSTs in surface layer only, and fig. 34 assimilation of SSTs through the mixed layer.

It is clear that the large scale biases which have accumulated during the control run (see fig. 31) are much larger than the probable departures of the SST field from climatology (fig. 32). Use of surface temperature observations over a period of 75 days at the surface reduces these biases, fig. 33, but does not eliminate them. Temperature increments made just at the surface will tend to be reduced by mixing within the model's mixed layer. Applying the surface increments throughout the mixed layer, as in fig. 34, effectively gives them much greater weight and counters the model bias more satisfactorily.

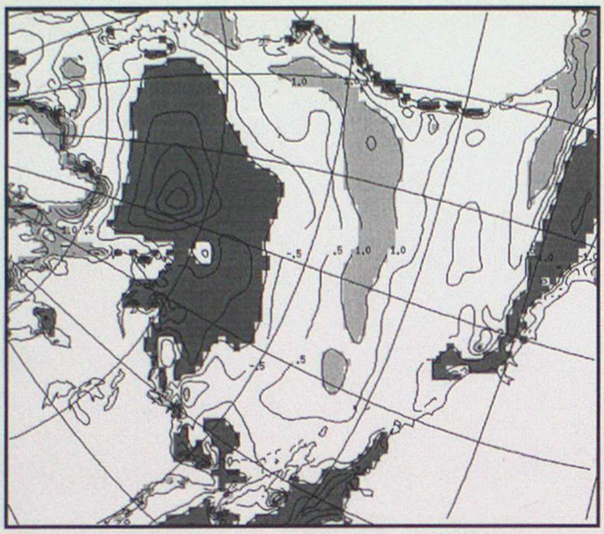

Figure 31 Difference between SST in the control integration for 15 September 1993 and the operational NWP SST analysis. Contours are at ±0.5°C and thereafter at intervals of 1°C. Values exceeding ±1°C are shaded.

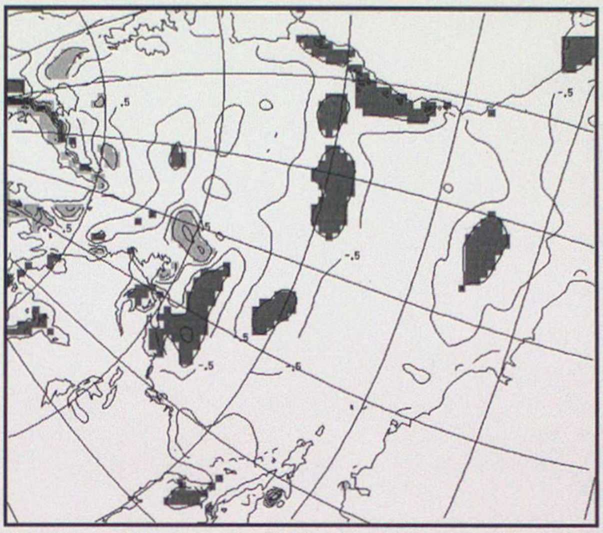

Figure 32 As fig. 31 but comparing the Levitus climatology with the NWP analysis.

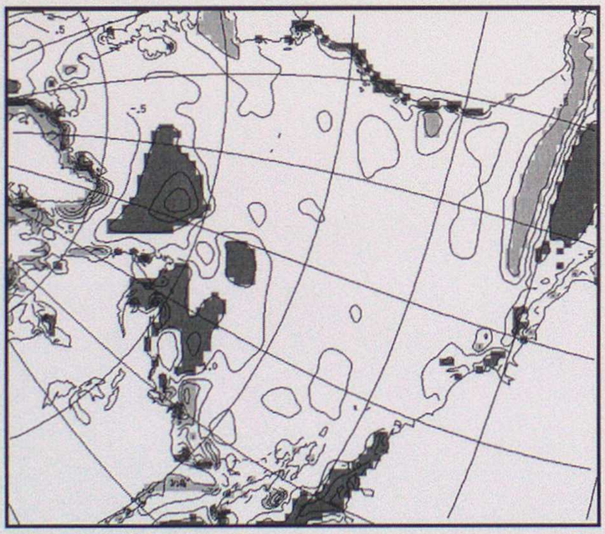

Figure 33 As fig. 31 but comparing the standard assimilation with the NWP analysis.

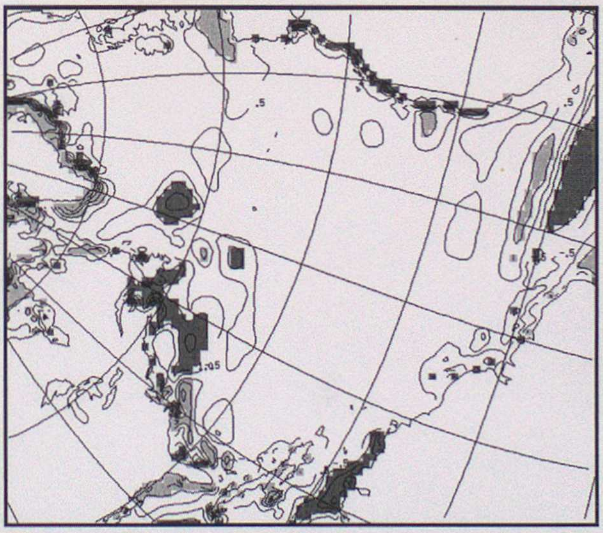

Figure 34 As fig. 31 but comparing the analysis that extrapolated SST information through the mixed layer with the NWP analysis.

Although extrapolating the surface increments was beneficial in the above experiments, the method used to implement it was not entirely satisfactory; from a conceptual point of view other methods may merit consideration.

5.3 Model biases and problems near the coast

Figures 11 and 14 in section 4.2 showed that the differences between the climate run, which will be referred to as the control in this section, and the climatology in January 1995 were large at the surface and at 300 metres in the area affected by the Gulf Stream. Figures 35 to 38 present the differences between the control run and the climatology at 100, 300, 666 and 1000 metres depth in this region.

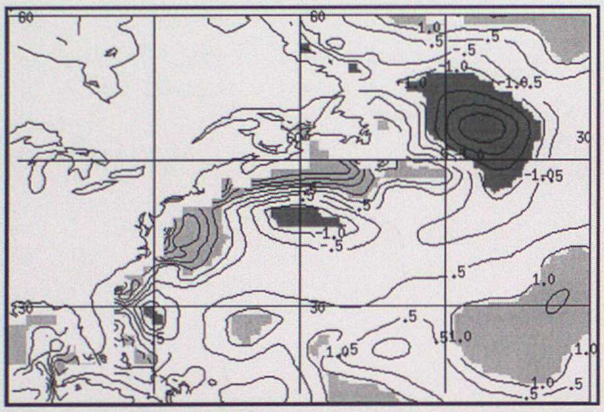

Figure 35 Difference between control integration and Levitus climatology for January at 100m. Contours are every 0.5°C and values exceeding ±1°C are shaded.

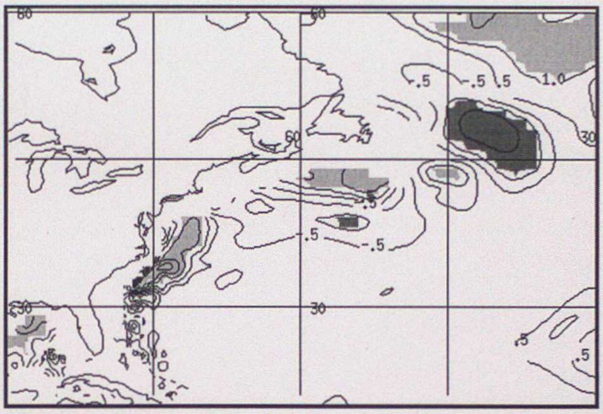

Figure 36 As fig. 35 but at 300m.

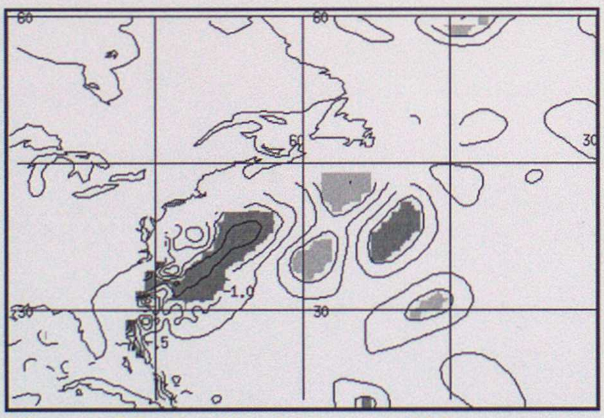

Figure 37 As fig. 35 but at 666m.

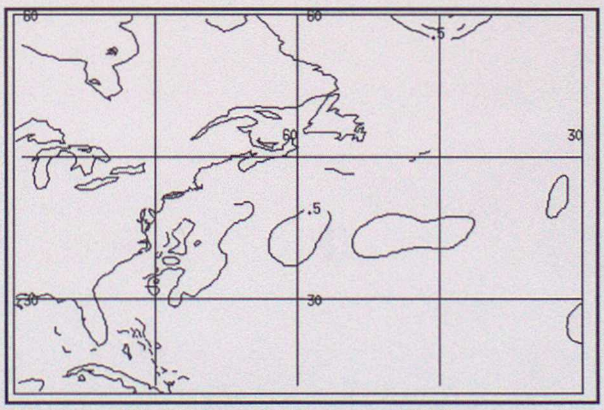

Figure 38 As fig. 35 but at 1000m.

The large cold anomaly in the model field at about 43°W, 47°N is present after 2 to 4 months in both global and Atlantic versions of the FOAM model and appears to be insensitive to the start month of the run and the fluxes used. It penetrates to about 300 m depth and may be associated with a poor representation of the cold (Labrador) current in the model.

Anomalies in the model field in the Gulf Stream region (between 30°N and 45°N) are not stationary and hence more difficult to compare between two integrations. They penetrate to more than 666 m. Generally, as shown in figs. 35 to 38, the control run tends to warm near the east coast of the US at the surface and cool at depth (666 m) just off the coast. This point is confirmed by figs. 39 to 41. These show cross-sections to 1000 m through the Gulf Stream at 35°N (at which point the real Gulf Stream between 80°W and 50°W at 35°N (where the real Gulf Stream separates from the coast). This is shown for (fig. 39) the control run, (fig. 40) the climatology and (fig. 41) the difference between them. These show that the model tightens the horizontal temperature gradient across the Gulf Stream and moves it much closer to the coast. The vertical temperature difference across the Gulf Stream is increased and from fig. 41 it appears that the horizontal temperature difference across the Gulf Stream is reduced. Note, however, that the cold water side of the model's Gulf Stream is so close to the coast (eg 8°C contour in figs. 39 and 40) that it is not captured in the difference charts (figs. 35 to 38 and 41) because of the land sea mask of the climatological dataset.

More work is needed to distinguish between shortcomings in the initial state and climatological fields (which are broad scale) and model biases. It will also be necessary to diagnose the adjustment processes involved.

Plots are presented in figs. 43 to 46 for the FOAM analyses that correspond to figs. 35 to 38 for the control run. The cold anomaly at 43°W, 47°N has been warmed only slightly at 100 m and 300 m, and warm anomalies near the coast at 100 m have not been greatly reduced. The analysis field is, however, much cooler than the control just off the coast at 100 m and much warmer there at 666 m.

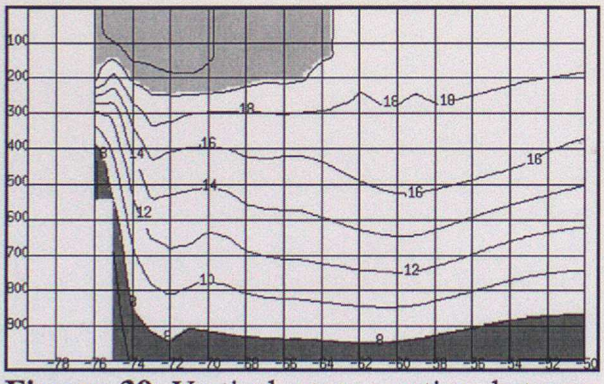

Figure 39 Vertical cross section between 80°W and 50°W at 35°N through the control integration of the FOAM model for January. Contours are at intervals of 2°C. Temperatures below 8°C and above 20°C are shaded.

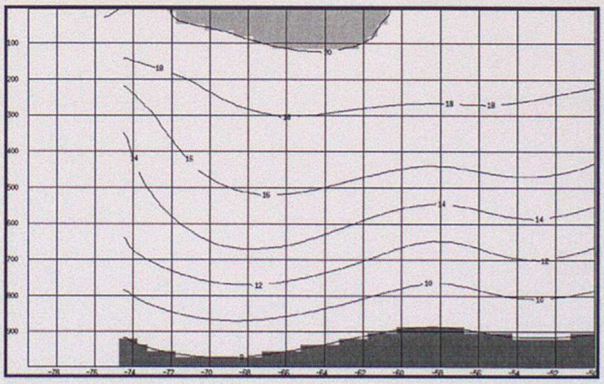

Figure 40 As fig. 39 but for the Levitus climatology.

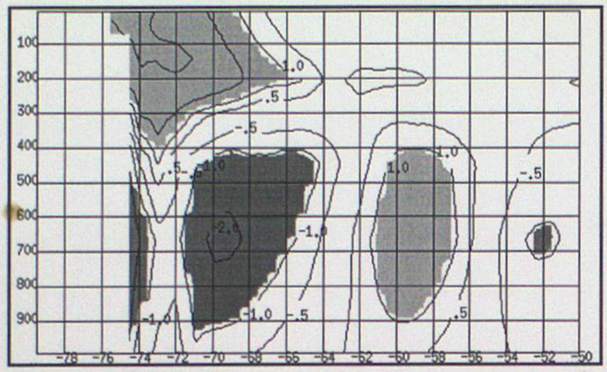

Figure 41 Difference between control and climate for January. Contours are at ±0.5°C, and every 1°C after that. Dark shading represents values less than -1°C and light shading those over +1°C.

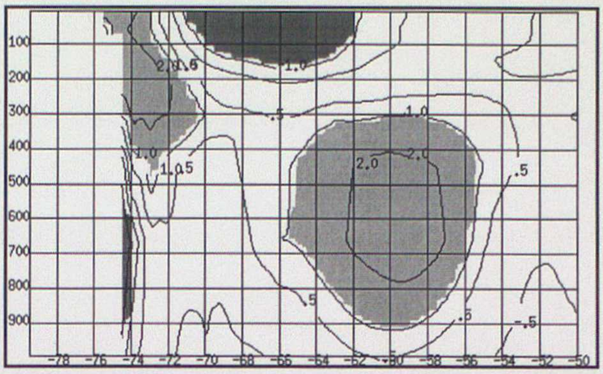

Figure 42 Difference between FOAM analysis for January 1995 and the Levitus climatology. Contours as fig. 41.

Differences between observations close to the Florida coast and the model are particularly noisy and often have values greater than 5°C. A small number of such observations can have a major impact on statistical results and make comparisons between results for different sets of observations unreliable. The assimilation statistics for area 2 in January, for example, suffered from a set of observations near the west coast of Africa where the model error was particularly large. More thought needs to be invested in how to use observations near the coast. The model itself still has grid point noise near the Florida coast and the observations sample mesoscale features not represented by the model. It is clear that the horizontal scale of the model errors is much smaller in these than in other areas and that the model is likely to have large errors in this region because its resolution and that of its orography is not adequate to model the flow accurately.

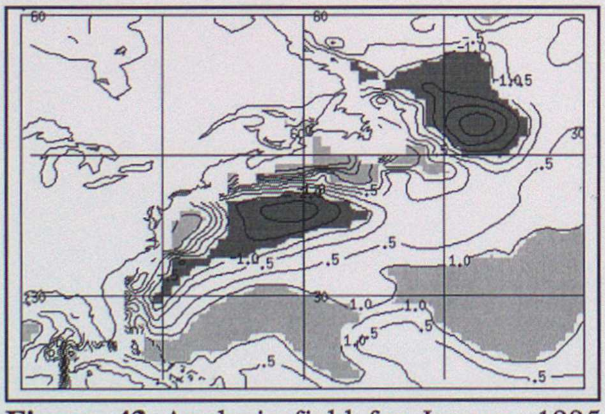

Figure 43 Analysis field for January 1995 less Levitus climatology for January at 100m. Contours are at ±0.5°C and every 1°C thereafter. Dark shading corresponds to temperatures less than -1°C and light shading to those above +1°C.

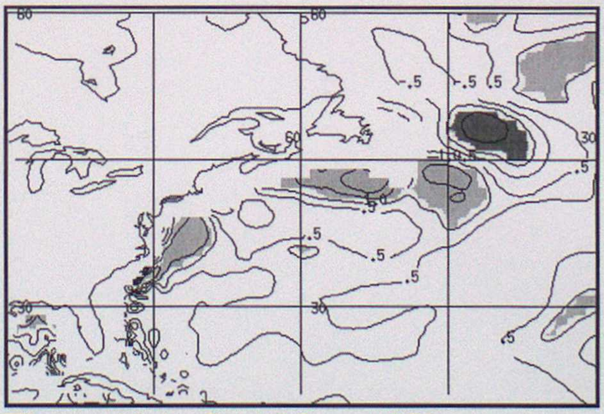

Figure 44 As fig. 43 but at 300m.

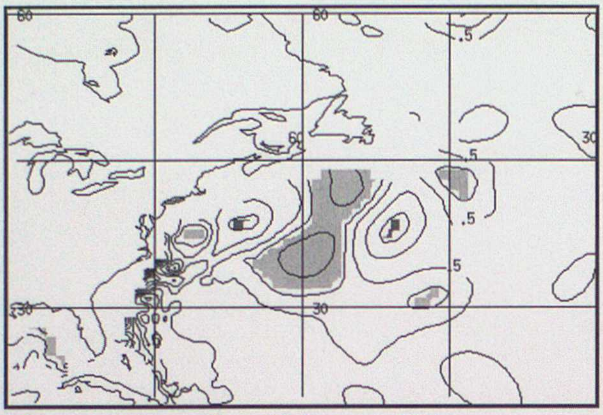

Figure 45 As fig. 43 but at 666m.

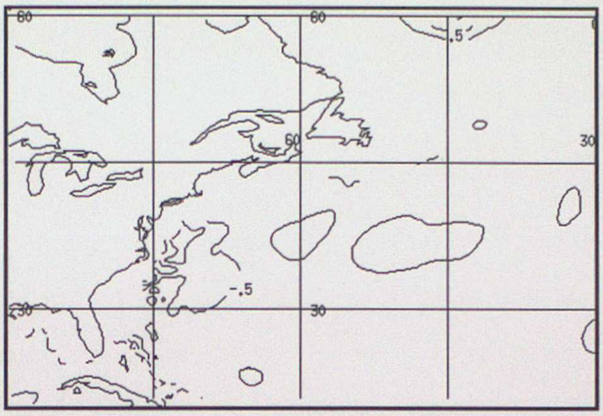

Figure 46 As fig. 43 but at 1000m.

5.4 Polynia

Polynias are large openings in pack ice caused by divergent ice velocities or local melting. They can have a large impact on the regional heat budget, allowing large sensible and latent heat fluxes, and increasing the short wave solar radiation absorbed into the ocean.

By 30 November 1994, FOAM had produced a low concentration polynia (fig. 47), centred at about 65°S 15°E, and with a radius of 300km to 1000km (depending on the concentration used to define the polynia). The National Ice Center analysis for the end of November shows a similar polynia, centred several hundred kilometres to the west of that in the model.

The FOAM polynia evolved from a region of low ice concentration by a reduction in the ice cover in the polynia area, and an increase in the ice concentration just to its north. The polynia dissipated during early December when the concentration of the whole region decreased, as would be expected with the onset of the Antarctic summer.

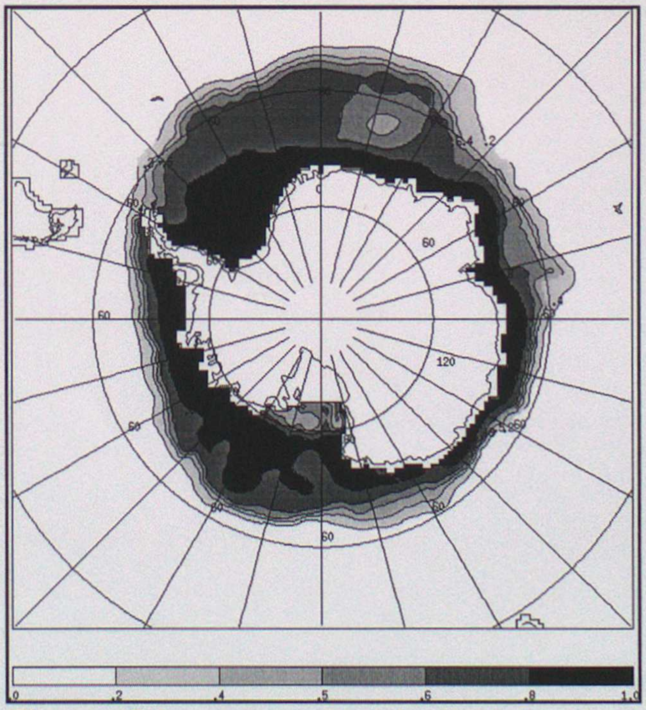

Figure 47 Ice concentration in the Antarctic at 00Z on 30 November 1994 in the FOAM analysis.

A brief analysis of the model fields has shown that the polynia was not an artifact of the model ice depth relaxation; indeed this acted to reduce both the size and magnitude of the feature. The near surface waters in the polynia area were anomalously warm, and those in the area of increased concentration were anomalously cold. During the period of formation, however, there was no sizeable or consistent upwelling in the ocean, nor divergence in the ice velocity. It is likely therefore that at least part of the impetus for the production of the polynia came from the NWP atmospheric fluxes of net heat and solar radiation. These do indeed show a positive anomaly in the area of he polynia during its period of growth. The heat would have entered the mixed layer through leads and hence indirectly melted the ice. This is consistent with diagnoses of the NMC ice model (R. Grumbine, personal communication) which produced a similar polynia at that time.

5.5 Relaxation scheme for cavitation

FOAM allows for the strength of ice under compression by calculating the velocity the ice would attain were it allowed to drift freely in equilibrium with the winds, the ocean currents and the Coriolis force, and applying a correction to it. This 'cavitation' correction is applied iteratively across the entire model grid, until the velocity change between iterations is small.

When used with the climate model, the computing cost of the cavitation routine was small but noticeable - approximately 5% of the total model CPU time. Within the FOAM system the cost is always at least 7% of the total (model and assimilation), is usually about 20%, and has on occasion risen to over 60%. Such increases were both unexpected and costly, and therefore are a cause for concern.

The CPU time required by the routine is directly proportional to the number of iterations it performs, the variability of which is obvious from fig. 48. It is noticeable that there were

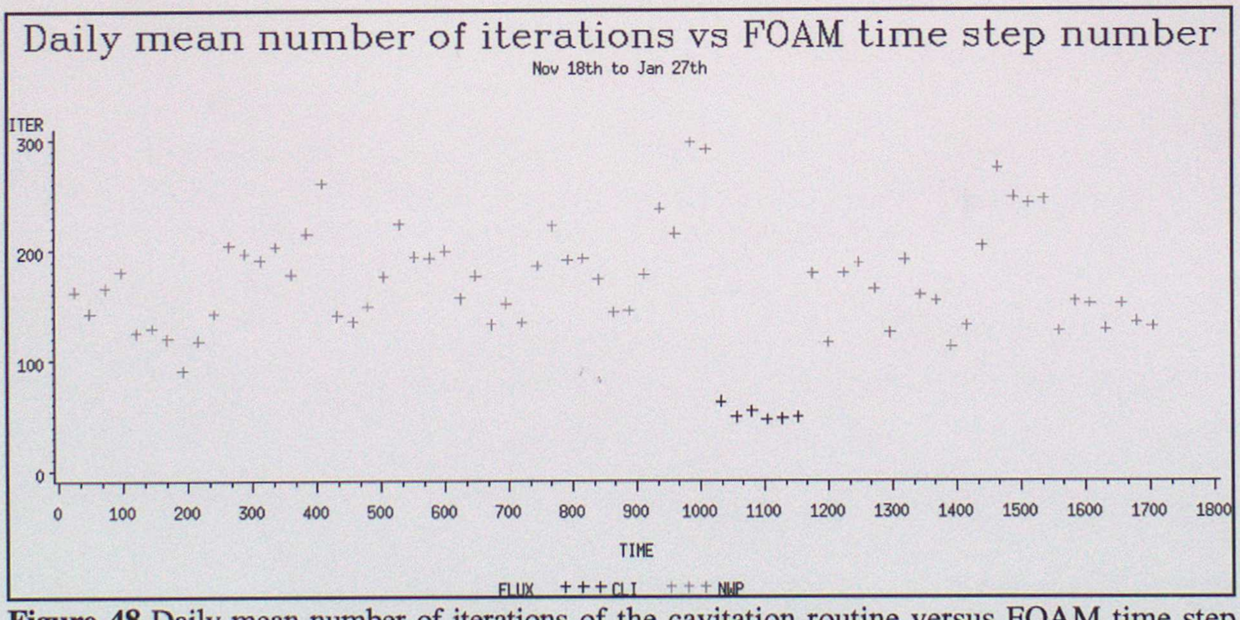

Figure 48 Daily mean number of iterations of the cavitation routine versus FOAM time step number.

six consecutive days (bolder) with significantly low and consistent mean numbers of iterations. For these six days FOAM was using climatological forcing, as the NWP fluxes were not available; on all other days in the period shown FOAM used NWP fluxes. The same trends are observed when the number of iterations is examined from time step to time step; use of NWP fluxes considerably increases both the variability and the mean of the number of iterations required for convergence.

The number of iterations performed by the routine is roughly inversely proportional to the grid spacing (personal communication, G. Flato), thus it is to be expected that the cost of the cavitation relative to the rest of the model should increase with the resolution of the grid. An explanation of the variability both with NWP forcing and between NWP and climatological forcing is not so straightforward. Several experiments have been conducted, but no firm conclusion has been drawn. Certainly the cavitation corrections applied to the free drift ice velocity appear to be much larger, and spatially more frequent and more variable, when FOAM is subject to NWP forcing. However, workstation experiments with a reduced ice model show no significant correlation between the number of iterations, and the temporal or spatial variability of the forcing, or its magnitude.

5.6 Fluxes over ice

Climatological and NWP heat fluxes which drive both ice and leads in FOAM are unsatisfactory at present. Both climatological (penetrating and non-penetrating) and NWP (non-penetrating) leads heat fluxes are derived by extrapolating fields into regions where there is sea ice. This introduces a considerable bias, which increases with penetration into the pack ice, because values at the ice edge are not representative of those nearer the poles.

Heat fluxes into the sea ice are not yet produced by the NWP suite, and climatological values are unlikely to become available in the foreseeable future. It has been necessary to create approximate climatologies by meaning the fluxes from a long run of the coupled climate model. The model contained an error that had not been identified when the climatologies were created. An improved estimate of the climatological fluxes has been prepared by using a more recent integration of the coupled climate model and improved algorithms for producing values over ice.

A measure of both the sensitivity of the ice to the thermodynamic forcing, and of the bias in the forcing, was given by running FOAM with climatological fluxes and no relaxation of ice depth for two years; most of the central arctic pack ice had vanished after 14 months.

6 Possible developments

This report has identified several weaknesses of the FOAM system. Actions that might overcome them are discussed in this section.

6.1 Standard deviations of errors used for observation quality control

The climatological standard deviation of temperature used in the quality control of observations is taken from Levitus (1982). The value for a 1° square is used regardless of the number of observations on which the standard deviation is based; where one observation was present the standard deviation was misleadingly set to zero. Using Levitus *et al* (1994) for the climatology and being more critical of the values within it should allow more effective quality control. It is also necessary to examine the sensitivity of analyses to the proportion of the climatological standard deviation by which an observation may differ from the background value before the observation is rejected.

6.2 Improved initial state

Although the model assimilates observations, there are too few observations to overcome major errors that may be in the initial state. A better initialisation method for the model fields is still desirable. The climatology used in this study was based on Levitus (1982) and had large variations from one month to the next, especially in the Indian and Southern Oceans. One possible way of generating a new initial state would be a one or more year spin up run that assimilated 10 years of profile data (such a dataset has been collected and quality controlled by NMC).

Another requirement is to assess the reasons for the drifts in the model simulations. This will need model integrations of at least a year.

6.3 Change the values archived from observations

Archiving of observations and their associated values should be done on original observation levels so that statistics can be calculated on the number of observation values which do not pass quality control. Quality control steps for stability and spike tests should be introduced.

6.4 The sea ice model dynamics must be reassessed

The cavitating fluid sea ice model was chosen to be compatible with the version used for climate studies. It is not giving the benefits that were expected from it for either application.

For the climate model it has been decided to use a simpler representation of sea ice dynamics. Once a data assimilation scheme for sea ice has been developed it will be necessary to reassess the type of ice model to be used in FOAM.

6.5 Fluxes over sea ice must be improved

Heat fluxes over sea ice were a major source of error in polar regions. Extrapolation from ice-free to ice-covered regions is not appropriate. Archiving the fluxes over ice from the NWP model goes part way towards a solution. Fluxes over leads are important but they cannot be calculated by the NWP model because it is driven by files that assume that any grid point with ice is totally covered. It will be necessary to modify the NWP suite to obtain the fields needed for FOAM.

7 Summary

7.1 Running the system

FOAM ran unattended for most of the time. Those interruptions that did occur were most often the result of bottlenecks on one or other of the computers that prevented the FOAM jobs completing before a deadline for the next stage had passed. Other problems resulted in changes to the suite which should prevent them happening again.

7.2 Statistics

Globally the statistics show the model analyses to improve on climatology, but this conclusion must be qualified by the uncertainty resulting from the low number of observations. Near coasts FOAM has significant problems that must be addressed.

7.3 Synoptic response

Sea surface temperature analyses from FOAM are close to those of the NWP suite. It is noticeable that many of the anomalies detected by FOAM reflect uncertainties in the climatology that was used to initialise FOAM. The synoptic response to atmospheric forcing appears realistic, but there are too few observations to verify this objectively.

7.4 Actions

Several areas of work have been identified that would lead to improvements in the FOAM system. The most significant of these is to address the climate drift of the FOAM model. This will need longer (say one year) integrations of the model to identify the causes of the drift. In addition it will be necessary to improve the surface fluxes over sea ice and to understand the computational behaviour of the sea ice model.

Quality control of observations is an area of weakness. This should be improved by using a better estimate of the expected differences from climatology and by introducing further tests.

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