OCEAN APPLICATIONS TECHNICAL NOTE 3.

FOAM - AN OPERATIONAL FORECAST SYSTEM FOR GLOBAL OCEAN TEMPERATURES

by

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1. Introduction

FOAM, the Forecasting Ocean Atmosphere Model, is being developed by the Met. Office to produce near real time analyses and forecasts of upper ocean temperature and salinity. The main customer for the output will be the Royal Navy, who will use the information to calculate the acoustic properties of the ocean. Another use of the system is to analyse historical observations to produce an ocean climatology for climate research.

Our knowledge of the ocean is limited by our ability to observe it. Most of the information we are able to collect is based on measurements of the surface properties. By far the most common observation of the ocean is that of sea surface temperature. Although measurements of sea surface temperature made by ships have been available for over a century, in the last two decades they have been supplemented by those made from satellites. These observations have allowed reliable climatologies of the sea surface temperature to be produced that are proving invaluable for climate research (e.g. Bottomley *et al*, 1990). Below the surface there are far fewer observations and satellites are unable to help fill the gaps.

Numerical models have formed the basis of weather forecast systems for many years. These models assimilate observations to correct their evolving atmospheric assimilation and can be thought of as complex interpolation systems that are able to project the information from the observations in both space and time in a dynamically consistent way. FOAM aims to do the same for oceanographic observations.

This paper outlines the FOAM system and illustrates some results from the prototype system.

2. Components of FOAM

FOAM is based on a numerical model of the ocean derived from that of Bryan (1969) and Cox (1984). Just as the Met. Office uses essentially the same model to produce weather forecasts as it uses to investigate atmospheric climate, FOAM applies a modified version of the ocean model used for climate studies to produce analyses and forecasts of the ocean in near real time. Experience with the atmosphere model has demonstrated that improvements to the model developed for one application often directly benefit the other application as well. This dual benefit is even more likely to be felt in the ocean because of the sparsity of ocean observations. Figure 1 shows the locations of sub-surface observations of the ocean received at the Met. Office in December 1995. Even on this global scale plot it is clear that most of the globe is under sampled. Many areas remain unobserved for many years. Only 91% of 1° squares have temperature observations at 100m in the historical archive (Levitus and Boyer, 1994), and the distribution of observations worsens rapidly with depth. Thus, in many areas of the ocean a major requirement of an ocean forecast model is that it should simulate climate well.

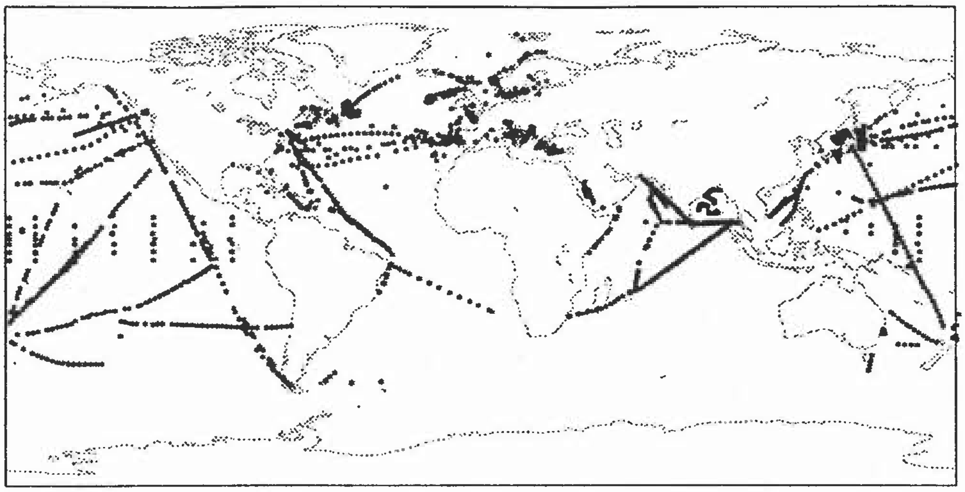

Figure 1 Positions of observations of temperatures below the ocean surface in December 1995. Observations reaching the Met. Office real time archives are shown.

The version of the ocean model used in FOAM has a horizontal resolution of 1° in both latitude and longitude with 20 unequally spaced levels in the vertical. Vertical spacing of layers is 10 m near the surface, increasing to 600 m at the bottom of the model. This resolution is not adequate to resolve the small scale features in the ocean. Mixing along isopycnal surfaces by unresolved features is included by using the modified diffusion scheme of Redi (1982). It uses a bulk mixing scheme based on that of Kraus and Turner (1967) to simulate the mixed layer. Vertical mixing of momentum and of heat outside the mixed layer uses the stability dependent technique of Pacanowski and Philander (1981). A "cavitating fluid" model of sea ice, after Flato and Hibler (1992) has been added to the ocean model. This includes a representation of thermodynamic features of the sea ice that follows Semtner (1976) with a leads component that follows Hibler (1979).

A good climate model is not enough to create a forecast system. Ocean circulation is driven by the surface fluxes of heat, fresh water and momentum across the ocean surface, and a source of these is needed. Ocean climate models can apply climatological fluxes, such as those compiled by da Silva *et al.* (1995), but much of the evolution of the upper ocean is determined by the synoptic features of the atmosphere. FOAM therefore uses estimates of the surface flux that are calculated by the Met. Office weather forecast system (Cullen, 1993).

FOAM needs observations of the ocean to constrain the model and to set the initial fields for its forecast phase. A major part of the development of the FOAM system has concentrated on creating a data assimilation scheme for the ocean model and a data processing system to quality control the observations and present them to the model in an appropriate format.

FOAM uses the analysis-correction method of Lorenc (1992) in which a simple analysis is carried out at each time step of the model and the evolving forecast is modified towards this. This meets the theoretical requirement of the analysis technique for repeated iterations while allowing the model to adjust smoothly to the information in the observations. As a result of the interleaving of analysis and model time steps, observations of one physical quality (e.g. temperature) can influence values of another variable (e.g. current). This removes the need for a separate initialisation step.

Quality control within the present FOAM system is relatively simple, consisting of checks against the model and climatological estimates of what the observed quantity should be.

3. Description of the FOAM system

Section 2 outlined the main modelling and data assimilation components of FOAM. FOAM is designed for operational use, and one of the challenges is to build a robust system that can run in operational mode unattended. A prototype of the FOAM system has been running since August 1994. This runs two days behind real time (so that on Tuesday an analysis is performed for the preceding Sunday). At this stage the system only produces an analysis. These restrictions were chosen to reduce the cost of the prototype system. When FOAM becomes operational it is expected to produce analyses within a day of the observation time and to generate forecasts up to five days ahead.

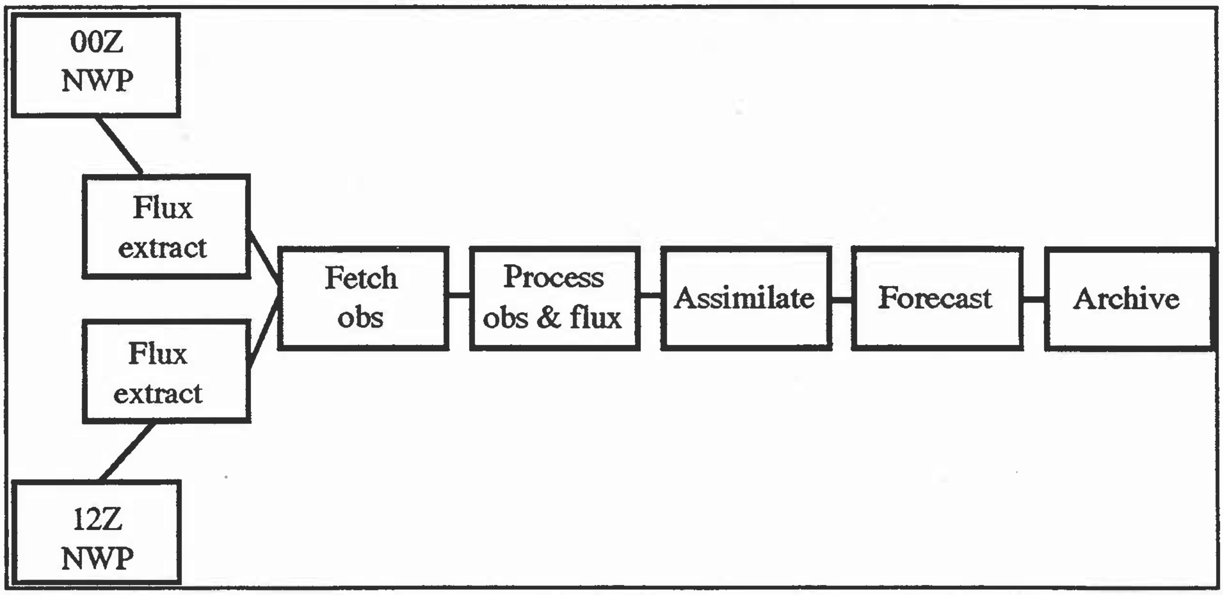

Figure 2 Flow diagram for prototype FOAM system. Runs of FOAM are triggered by the weather forecast model. Although it has been tested, the forecast step is not usually run in the prototype system.

An outline of the prototype system is shown in fig. 2. The trigger for FOAM is the weather forecast suite that creates the surface fluxes. Once the weather forecast has completed, a job is run to access the surface fluxes. This releases a job to extract the observations. The prototype FOAM system is not operational and on occasions it is unable to retrieve the data it would normally use. If this happens, the system can run without observations and using climatological fluxes.

Once the surface fluxes and observations have been prepared, the assimilation is run. Although the suite has been tested with a forecast step, this is turned off in the prototype system.

As it runs, the system archives the analysed fields from the model and also the differences between the model values and observations. This archive is used to derive statistics on the accuracy of the analysis system and, because values of the model fields are extracted before the observations are used in the analysis, the observations provide an independent assessment of the accuracy of the system.

4. Results from a year long series of analyses

FOAM has run routinely since August 1994. This allows time series of the model products to be assessed.

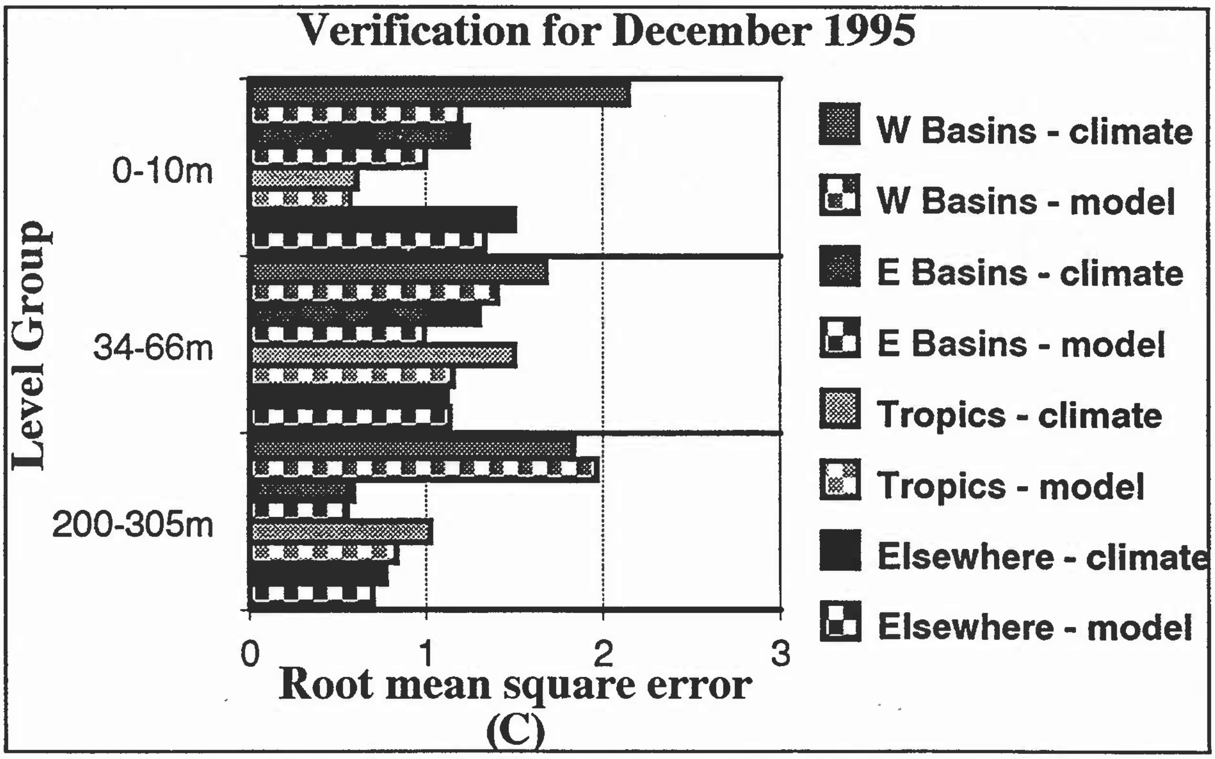

Figure 3 Root mean square temperature errors of the FOAM system for December 1995. Statistics are shown for four areas: Western basins of the northern hemisphere; eastern basins of the northern hemisphere; tropics and the remainder of the world. The statistics are also broken down into depth bands. Statistics for the accuracy of both climatology and the model are shown. Units are degrees Celsius.

One of the easiest quantities to assess is the accuracy of the model fields compared with observations. This is readily derived from the archives, and fig. 3 shows the root mean square temperature errors in the model for December 1995. The statistics were calculated for four areas and three depth bands. The areas were grouped by the dominant ocean dynamics.

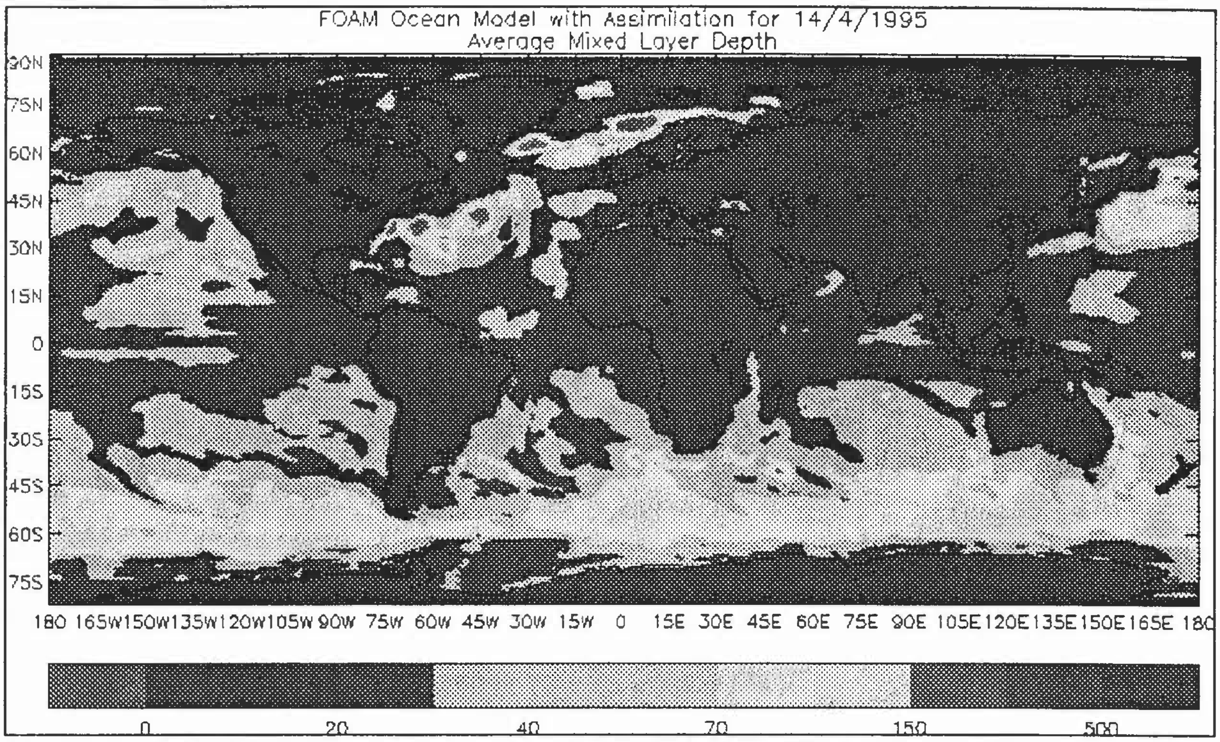

Figure 4 Mixed layer depth in the FOAM analysis scheme for 14 April 1995 when the model was using NWP fluxes. Units of mixed layer depth are metres.

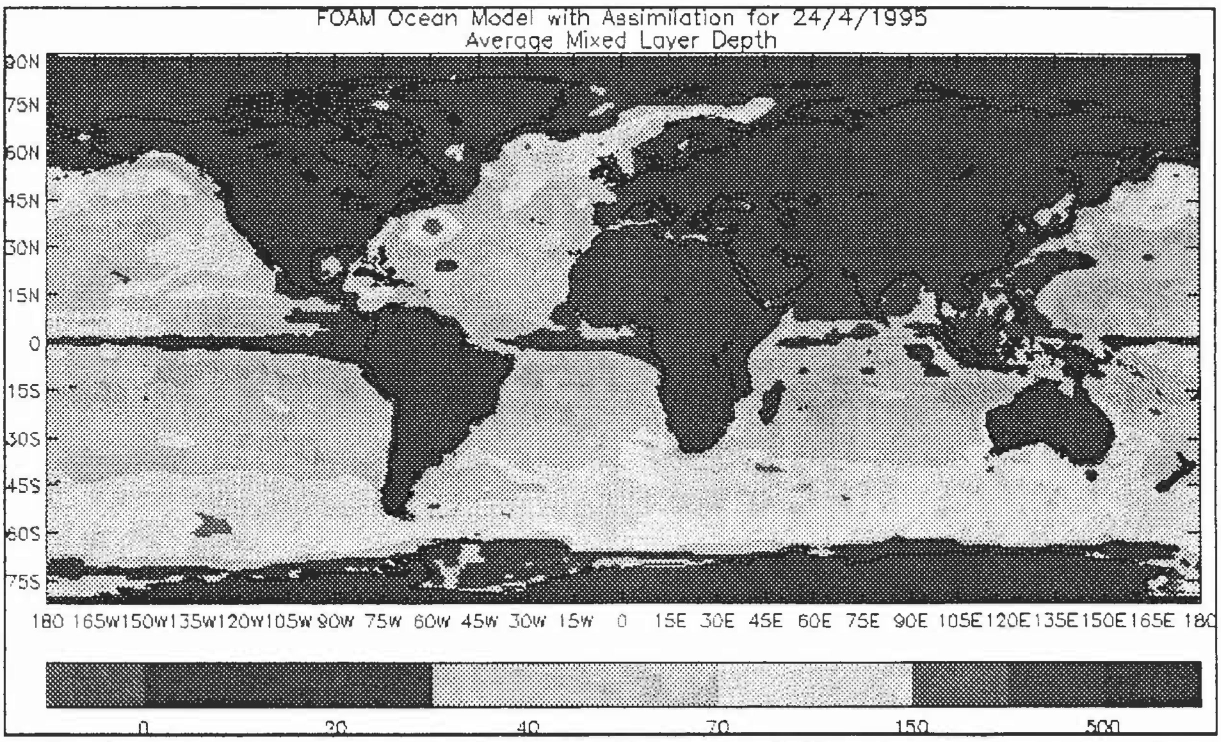

Figure 5 Mixed layer depth in the FOAM analysis scheme for 24 April 1995 after climatological fluxes had been used. Units of mixed layer depth are metres.

Thus, one area included the western parts of both the North Pacific and North Atlantic, another contained the eastern parts of those basins, a third contained the tropics and the final group collected statistics for the remainder of the world. Within each area statistics were grouped by bands of depths. In December, the model was more accurate than climatology in each of the areas for which statistics were calculated, except at middle depths in the "rest of the world". Errors were greatest in the western basins, where the model is unable to resolve the active dynamics of the Gulf Stream and Kuroshio and where small errors in the position of a feature translate into large temperature errors. The model was most accurate in the tropics, helped by the regular and dense observations of the TAO array in the Pacific. Comparing the statistics for different months (not shown) gives broadly the same message, but there are notable changes in the accuracy of both the model and climatology with season, and the relative performance of the climatology and model also changes during the year.

Sensitivity of the model to the surface forcing is seen in figs 4 and 5 which shows the mixed layer depth before and after the model reverted to climatological fluxes following a problem in retrieving the weather forecast fluxes. The top panel shows the mixed layer when the model was being driven by surface fluxes from the weather forecast model. Several features can be seen that are driven by the forcing from the atmosphere systems as they pass over the ocean. It is clear that the mixed layer in the model responded within days to the different character of the forcing when the fluxes changed to climatological ones. The response of the mixed layer cannot be meaningfully verified given the distribution of observations and is thus not a suitable means of validating the surface fluxes.

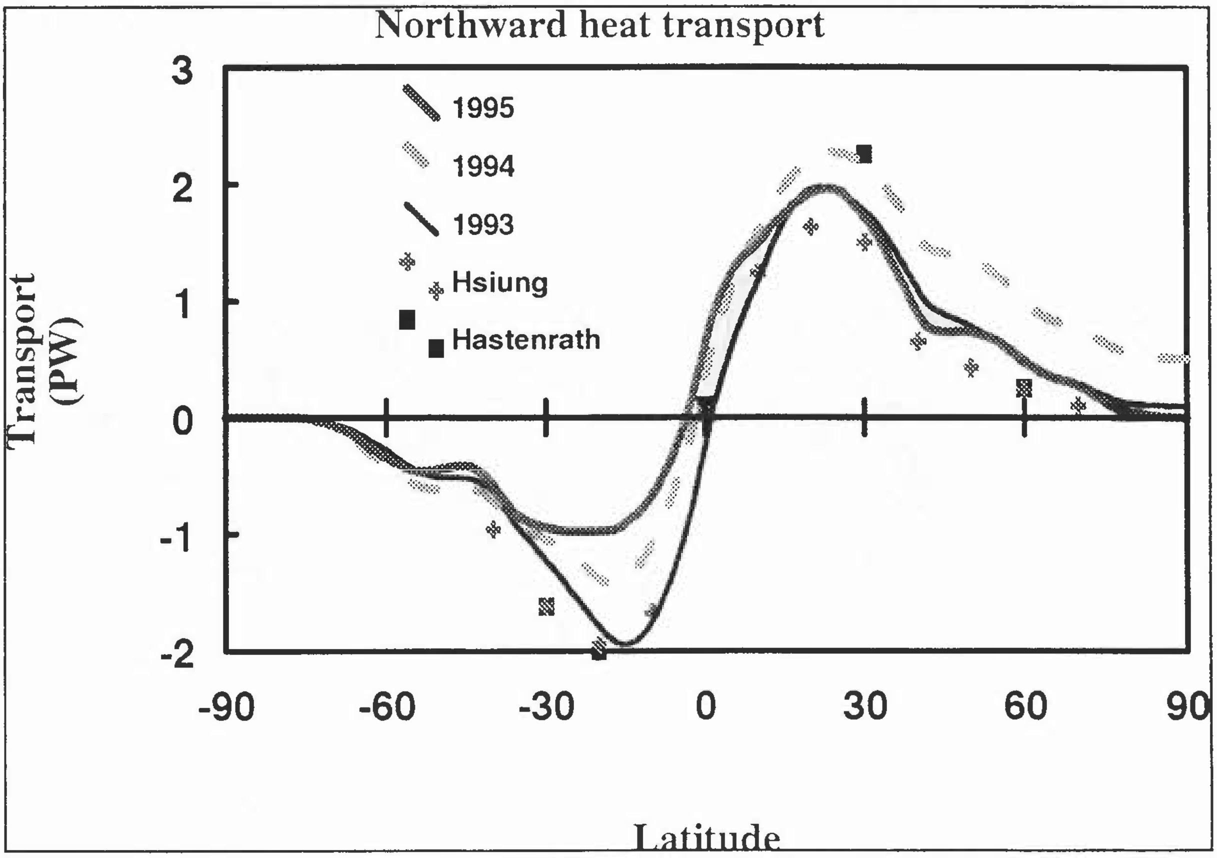

Figure 6 Northward heat transport implied by annual mean heat fluxes from the Met. Office weather forecast model. Values are shown for 1993, 1994 and 1995. Also shown are values from climatological estimates of Hsiung (1985) and Hastenrath (1982). Values are in PW (10^{15} W).

Integrating the surface heat fluxes over the ocean northwards from the south pole allows the accuracy of the fluxes to be assessed by comparing this integrated quantity with other, climatological, estimates of the poleward heat flow. This is shown in fig. 6. This demonstrates that the heat budget in the Met. Office NWP analyses is close to balancing (an imbalance would show itself as a flow across the North Pole), but that the NWP estimates of the heat flux in the Southern Ocean has decreased over the past three years. Several changes were made to the NWP system over this time, in particular changes that affected cloudiness over the southern oceans and in the tropics. These changes may be reflected in the heat transport.

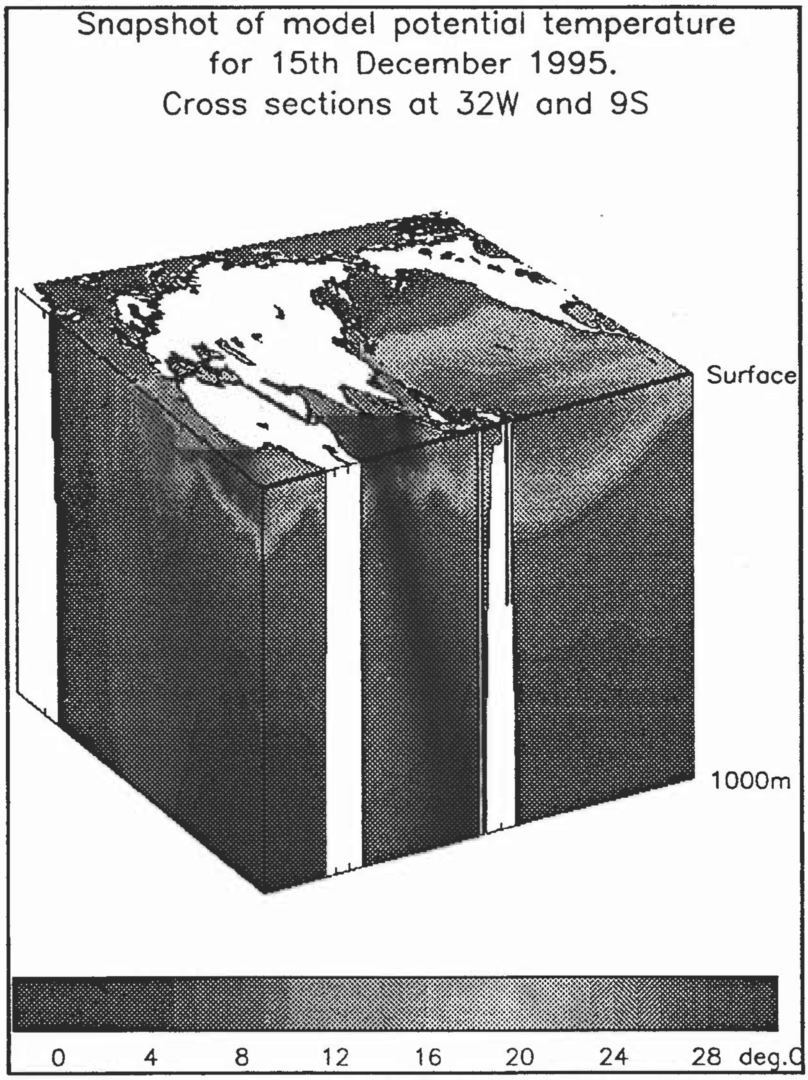

Figure 7 Temperature analysis for the top 100m of the ocean on 15 December 1995.

Figure 7 shows the temperature structure in top 1000m of the FOAM model analysis for 15 December 1995. It shows the eastern part of the Atlantic and the Pacific Ocean. The large scale patterns of shallow layers of warm water in the tropics and deep cold waters at high latitudes are readily seen. Doming of the water under the InterTropical Convergence Zone can be seen in the Atlantic and the west to east slope of isotherms in the tropical Pacific is represented. FOAM and similar systems allow the variations in the ocean to be assessed in a way that is not possible with conventional techniques for analysing the ocean.

5. Summary and plans

FOAM is a system for analysing and forecasting the ocean temperature and salinity. A prototype has been run routinely since August 1994 to generate analyses, allowing the accuracy and robustness of the system to be assessed. Work has started on a project to make FOAM operational in 1997, including a forecast in the cycle and delivery of products to the Royal Navy.

FOAM has shown itself to be robust and to have an accuracy that improves on climatology. Qualitatively it is able to describe the synoptic evolution of the upper layers of the ocean in response to atmosphere forcing.

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