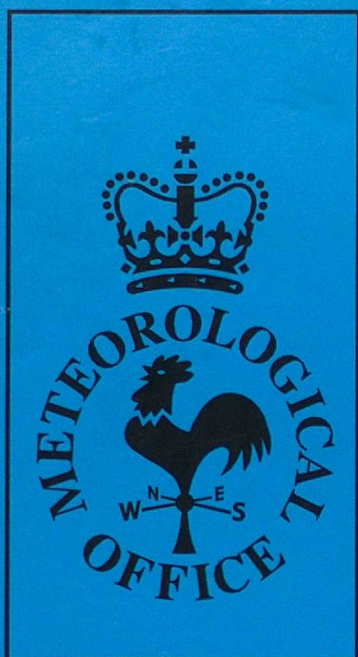


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Forecasting Research

Forecasting Research Division
Technical Report No. 167

Experiments with the assimilation of surface temperature and thermal profile observations into a dynamical model of the Atlantic Ocean

by

R M Forbes

July 1995

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Experiments with the assimilation of surface temperature and thermal profile observations into a dynamical model of the Atlantic Ocean

R. M. Forbes

July 1995

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Summary

Results are presented from a series of integrations in which sea surface temperature and thermal profile data are assimilated into a primitive equation model of the Atlantic Ocean. The number of sea surface temperature observations far exceeds the number of thermal profile observations in the Atlantic, so the surface data is potentially extremely useful. The assimilation of *in situ* and AVHRR satellite temperature data at the surface is shown to improve the thermal analyses at the surface. Projecting the surface temperature observation increments down to the base of the mixed layer improves the analyses in the upper layers further. A scheme to prevent the interpolation of observation increments across land is described, and an example is given for the case of an observation close to the Florida peninsula. Finally it is shown that there are significant differences in the potential temperature field at and below the surface between integrations using monthly mean climate and Unified Model surface fluxes.

| | |
|--|---------|
| 1. Introduction | Page 2 |
| 2. Model and Assimilation Details | Page 2 |
| 3. Description of Integrations | Page 5 |
| 4. Results from Integrations | Page 12 |
| 4.1 Characteristics of the Model Integration as a Control | Page 12 |
| 4.2 Results from Integrations Assimilating SST Observations | Page 18 |
| 4.3 Preventing the Interpolation of Observation Increments Across Land | Page 25 |
| 4.4 Comparison Between Integrations With Different Surface Forcing | Page 26 |
| 5. Concluding Summary | Page 29 |
| References | Page 30 |

1. Introduction

The aim of this report is to record results from developments to the FOAM (Forecasting Ocean Atmosphere Model) ocean data assimilation system (Bell 1994a,b). The main development to the system is the addition of a step to assimilate sea surface temperature (SST) observations. The report focuses on results from a series of 3 month integrations of the model from July to September 1993 using both SST and thermal profile observations. The results of the integrations are used to assess the performance of the SST analysis and to investigate the impact of using SST data in the mixed layer.

Brief details of the ocean model and observational data, and full details of new aspects of the assimilation scheme are presented in section 2. Section 3 describes the integrations performed, and section 4 discusses the results. A concluding summary is provided in section 5.

2. Model and Assimilation Details

(a) Ocean Model

The ocean model is identical to that used by Bell (1994b). It is based on the Princeton GFDL code (Cox 1984) with a rotated grid of uniform $1^\circ \times 1^\circ$ resolution and 20 levels in the vertical. The model domain covers the Arctic and Atlantic Oceans with the pole of the grid centred on 17°N 56°E with western and eastern boundaries corresponding to 45°S and 45°N in the rotated coordinates. There is a rigid wall (no-slip boundary condition) at the southern boundary. A thermodynamic ice model is included. Further details can be found in Bell (1994b).

(b) Observational Data

Good quality temperature observations were required for the 3-month assimilations. Quality controlled BATHY reports obtained from NMC¹ were passed through the FOAM quality control system described in Bell (1994a). *In situ* sea surface temperature observations from buoys and ships, and data from the AVHRR instrument aboard the NOAA satellite, were obtained via the GTS and quality controlled by the Numerical Weather Prediction (NWP) operational SST data preparation suite (Jones *et al.*, 1994). AVHRR SST observations had been

¹ National Meteorological Center, U.S.A.

converted from skin temperature to bulk temperature² prior to receiving the data over the GTS. ATSR sea surface temperature data from the ERS-1 satellite were not used because they had not been converted to bulk temperature, and no correction scheme was in place to deal with the possible bias from such uncorrected data.

(c) Assimilation details

The method used for assimilation is the analysis correction scheme of Lorenc et al. (1991), and is essentially the same as that used by Bell (1994b). Differences in the assimilation scheme from Bell (1994b) are described in this section.

The assimilation uses a grid point filter method to spread the observation increments horizontally, approximating a SOAR (second order auto-regressive) error correlation function (Lorenc, 1992). Weighted observation increments are interpolated to the nearest model grid points and spread with a recursive filter across the grid. Bell *et al.* (1993) describes this filtered increment scheme. The filter method is more efficient than spreading each observation increment separately within a few correlation scales, although the resulting error correlation using the filter is not perfectly circularly symmetric. The correlation scale was set to 300 km over the whole domain.

A further reason for using the filtered increment scheme is that it can be extended to prevent the spread of observations between uncorrelated basins. For a limited area grid, boundary corrections can be applied to the filtered increment field to reproduce the effect of extending the area to infinity (Purser 1987). This correction can also be applied to the boundary of ocean basins so that the coastline acts as a limited area boundary, preventing observation increments in one basin affecting the uncorrelated region of another.

An assimilation time window is defined for different observation types. This is the time over which an individual observation is nudged into the model as the model integration progresses. The time window extended from ten days before the current analysis time to ten days after for BATHY observations, and five days before to five days after for all SST observations. A longer time window was chosen for BATHY data because of the sparser data distribution.

The spatial coverage of sea surface temperature observations is denser and more uniform than the coverage of thermal profile observations, especially when satellite data is included. It is desirable to extract as much useful information as possible from this relatively abundant source of surface information. The surface temperature is well correlated with the temperature of the mixed layer, so it seems reasonable to project this surface information down through the

² Skin temperature is the temperature of the top few millimetres of the ocean measured by the satellite, and bulk temperature is the temperature representative of the top few metres of the ocean required by the model.

mixed layer in some way. The simplest option is to assume a perfect error correlation between the surface and the mixed layer, and apply the surface temperature increment down to the base of the mixed layer using a step weighting function, i.e. a constant weight of one above the mixed layer depth and zero below. This scheme is used in the relevant integrations described in the report.

The effect of assimilating increments in the mixed layer is to nudge the whole mixed layer water column closer to the observation. The resulting state of the upper ocean will eventually be different from that obtained by assimilating increments solely at the surface level. If a cold surface increment is assimilated at the surface level only, the upper layer will be unstable, and the model will mix the surface increment into the mixed layer through the processes of convection and wind mixing, **eventually** cooling the whole mixed layer water column. If a warm surface increment is assimilated at the surface level, the stability of the upper layer will increase and mixing of the increment within the mixed layer will depend on the wind mixing energy. The resulting state may be significantly different from that obtained by applying the increment to the whole of the mixed layer.

The mixed layer depth is a diagnostic calculated from the model thermal field, and the method described above does not take account of the possible error in the model mixed layer depth. A mixed layer depth analysis using thermal profiles could be performed to provide a better estimate, but there would still be associated errors. A different depth weighting function for the surface increment that decreases gradually near the base of the mixed layer might be an alternative to take account of the uncertainty. It is important, however, that there are no detrimental effects on the mixed layer depth due to surface increments in the mixed layer.

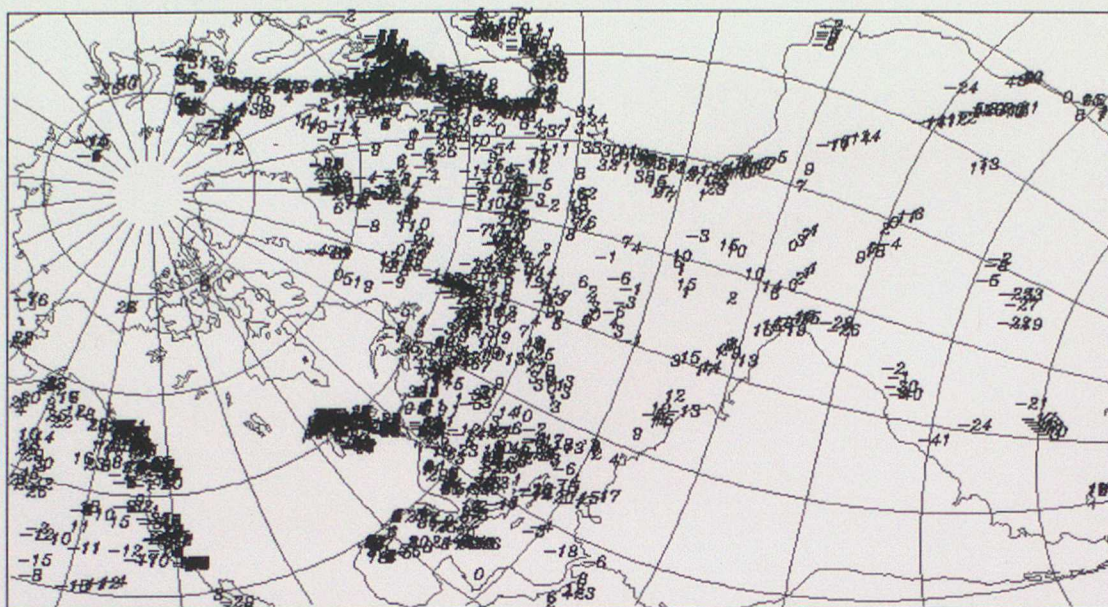
3. Description of Integrations

A series of model integrations was performed. Each started from an initial state valid on 1 July 1993 and ran for 3 months to the end of September. The integrations are listed in Table 1 with a brief description of the differences between the runs.

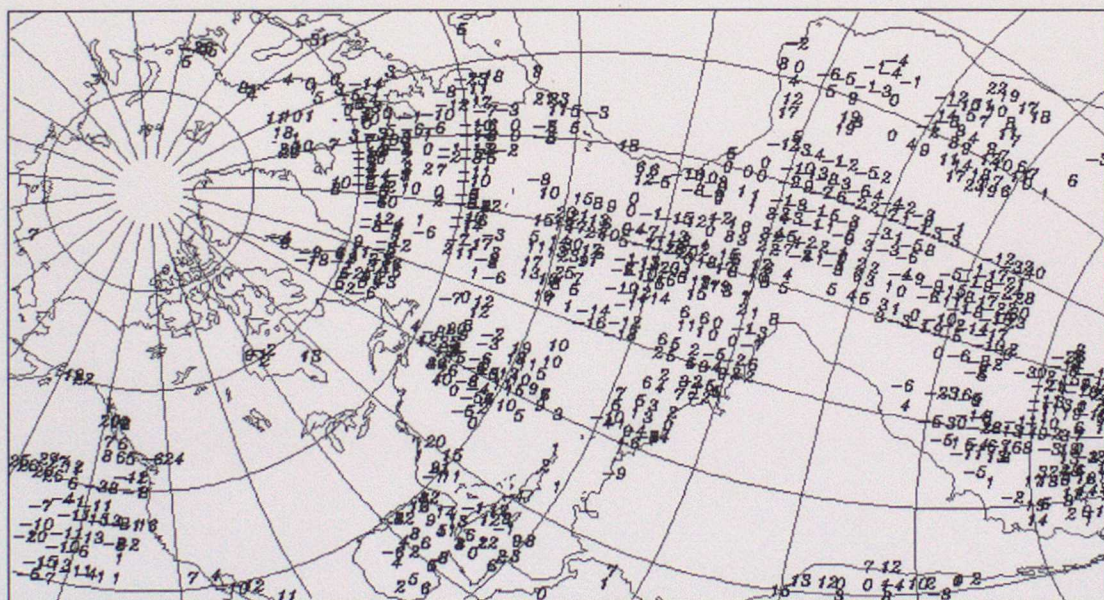
The initial state was a three month spin up of the model from a state of rest with the Levitus (1982) April monthly mean temperature and salinity fields. Climatological surface forcing fields were used in the spin up; surface momentum fluxes (Hellerman & Rosenstein, 1983), surface heat fluxes (Esbensen & Kushnir, 1981), and surface fresh water fluxes (Jaeger, 1983). The model was relaxed toward the Levitus surface temperature and salinity climatologies with a relaxation coefficient of $35 \text{ W m}^{-2} \text{ K}^{-1}$ during the spin up.

Table 1. Details of differences between integrations.

| Expt ID | Observation Data Assimilated (X=data sample X assimilated) (Y=data sample Y assimilated) | Forcing Fields | Sample used for statistics | Further comments |
|---------|--|-------------------|----------------------------------|----------------------------|
| MC | - None - | Climate | Y | Control |
| MU | - None - | UM | Y | |
| A1 | Bathy (X+Y) | Climate | Y | |
| A2 | Bathy (X+Y), <i>in situ</i> SST | Climate | Y | |
| A3 | Bathy (Y), <i>in situ</i> SST | Climate | X | |
| A4 | Bathy (X), <i>in situ</i> SST | Climate | Y | |
| A5 | Bathy (X), <i>in situ</i> SST | Climate | Y | FI mask |
| A6 | Bathy (X), <i>in situ</i> SST, AVHRR | Climate | Y | |
| A7 | Bathy (X), <i>in situ</i> SST, AVHRR | Climate | Y | SST used in mixed layer |
| A8 | Bathy (X), <i>in situ</i> SST, AVHRR | UM | Y | SST used in mixed layer |

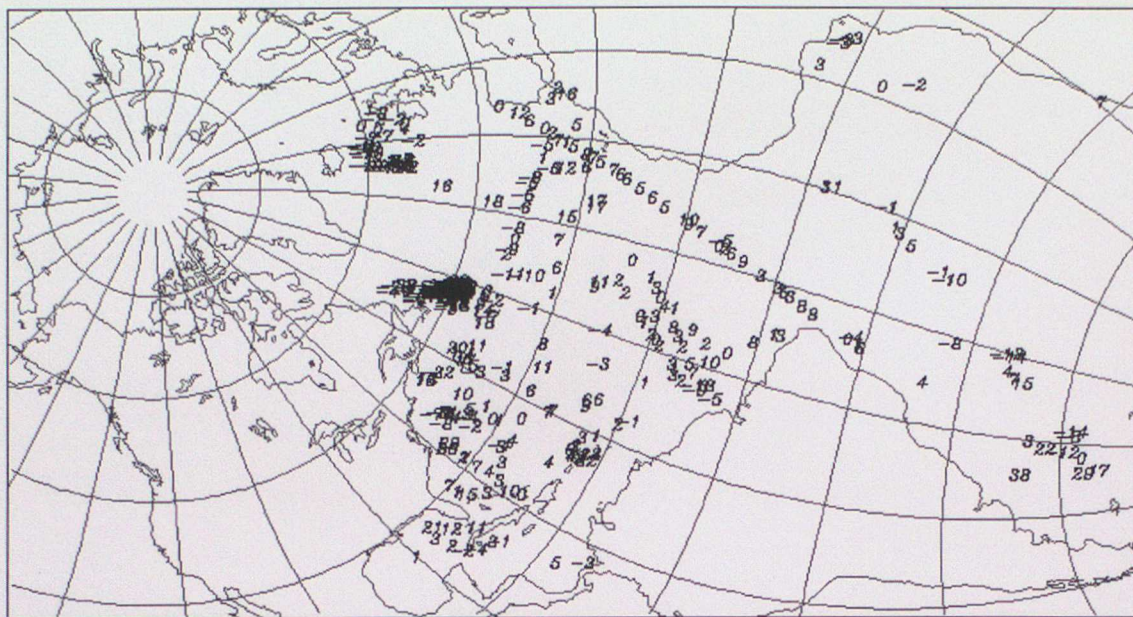


(a)

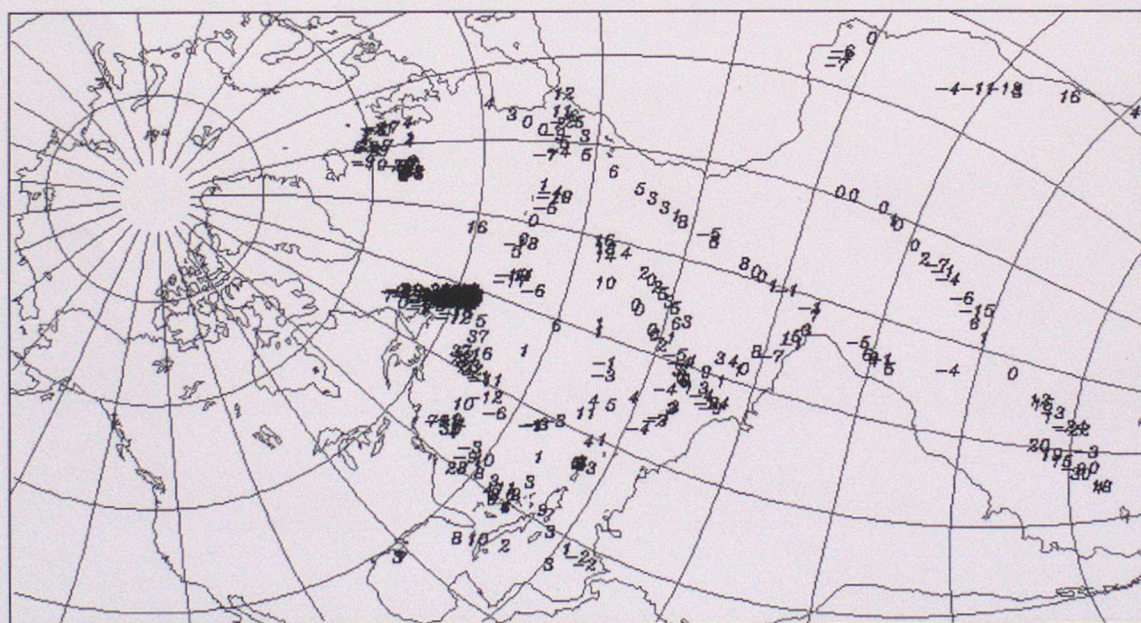


(b)

Figure 1. Observation distributions at the surface, (model level 1). At each observation point the observed value minus the climatology is shown in tenths of $^{\circ}\text{C}$.
 (a) *in situ* SST observations for *one day* on 15 September,
 (b) AVHRR SST observations for *one day* on 15 September,
 (c) BATHY sample X for the *month* of September 1993,
 (d) BATHY sample Y for the *month* of September 1993.



(c)



(d)

Figure 1. (continued)

Bell (1994b) highlights the temperature drift during a six year spin up of the ocean model and shows that the model bias increases over this period. A relatively short spin up time was chosen for the integrations in this report, but there is still a significant drift from climatology in many regions after three months. The model bias in the initial state does however provide a test of the ability of the assimilation scheme to bring the model temperature field closer to that observed. The model drift is analysed in more detail in Section 4.1.

Two model runs were performed with no assimilation, integrating the model for 3 months from the initial state. Integration MC (the control) is effectively a continuation of the spin up using monthly mean climatological surface forcing fields. The relaxation to Levitus surface temperature in this run and all other integrations is weaker than in the spin up, with a relaxation coefficient of $20 \text{ W m}^{-2} \text{ K}^{-1}$. Integration MU uses monthly mean momentum, heat and fresh water fluxes for 1993 from the U.K. Met. Office Unified Model. All other integrations assimilate temperature data which, for the purpose of this report, is grouped into three categories; BATHY thermal profile observations, *in situ* SST observations, and AVHRR satellite SST observations.

The *in situ* SST observations are fairly abundant in the North Atlantic, while AVHRR SST observations have a more uniform distribution over the whole of the Atlantic. Figures 1(a) and 1(b) show the SST observation distributions for one day in September. The distribution of BATHY reports is, however, much sparser. Figures 1(c) and 1(d) show the BATHY distribution for the month of September split into two roughly equally sized samples, denoted X and Y. For the majority of the assimilations one sample of BATHY observations, and 9 out of 10 of the SST observations were assimilated. The other sample of BATHY observations was used as independent data for verification statistics. All the BATHY observations were quality controlled and averaged to model levels, but not smoothed vertically. BATHY observations 5 days either side of a model field were used to form root mean square (r.m.s.) values of observation minus analysis potential temperature, and the statistics from three model fields ten days apart were combined for each month. The observations were also compared with the mean monthly climatology (denoted CL).

The September statistics shown in figure 9 are calculated for two depth ranges in separate regions in the Atlantic. Statistics for model level 1 (5m), and levels 4 to 6 (35m to 67m) are shown for six areas similar to those used by Sterl and Kattenburg (1994), which divide the North Atlantic into physically distinct homogeneous regions (Fig. 2). Unfortunately, there were only about ten BATHY observations grouped close to Newfoundland in area 1 (western subpolar gyre) in September 1993. Statistics are not calculated for area 1, because of this small and unrepresentative data sample.

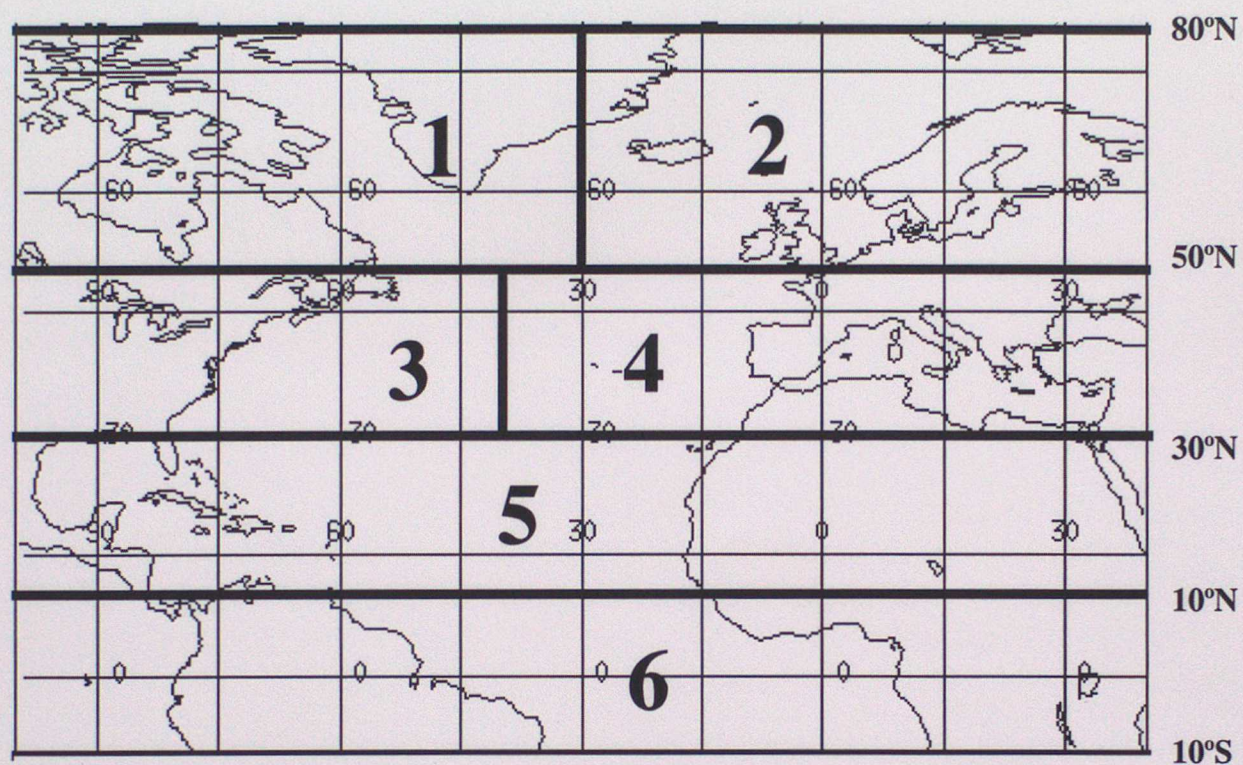
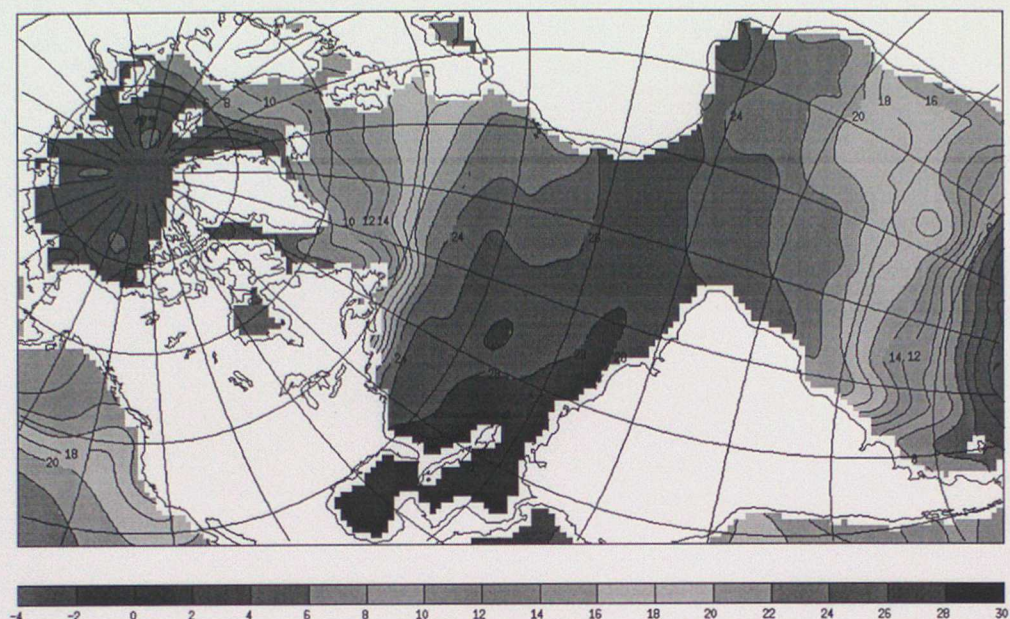
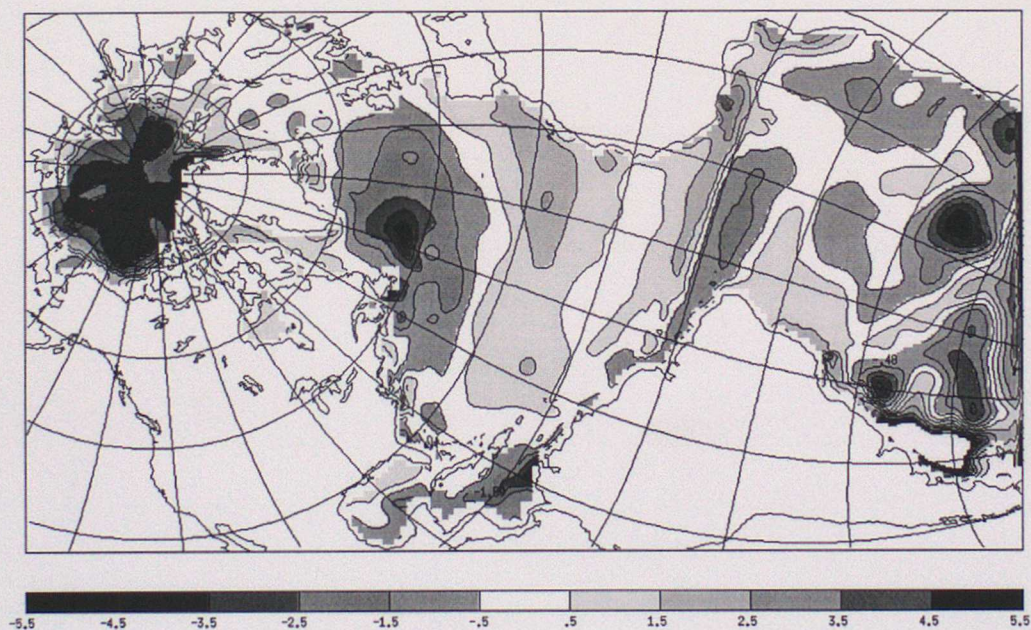


Figure 2. The areas used to calculate statistics for the integrations.



(a)



(b)

Figure 3. (a) Levitus (1982) September surface temperature climatology (level 1) and (b) the model departure from Levitus on 15 September after a six month integration. Units are $^{\circ}\text{C}$.

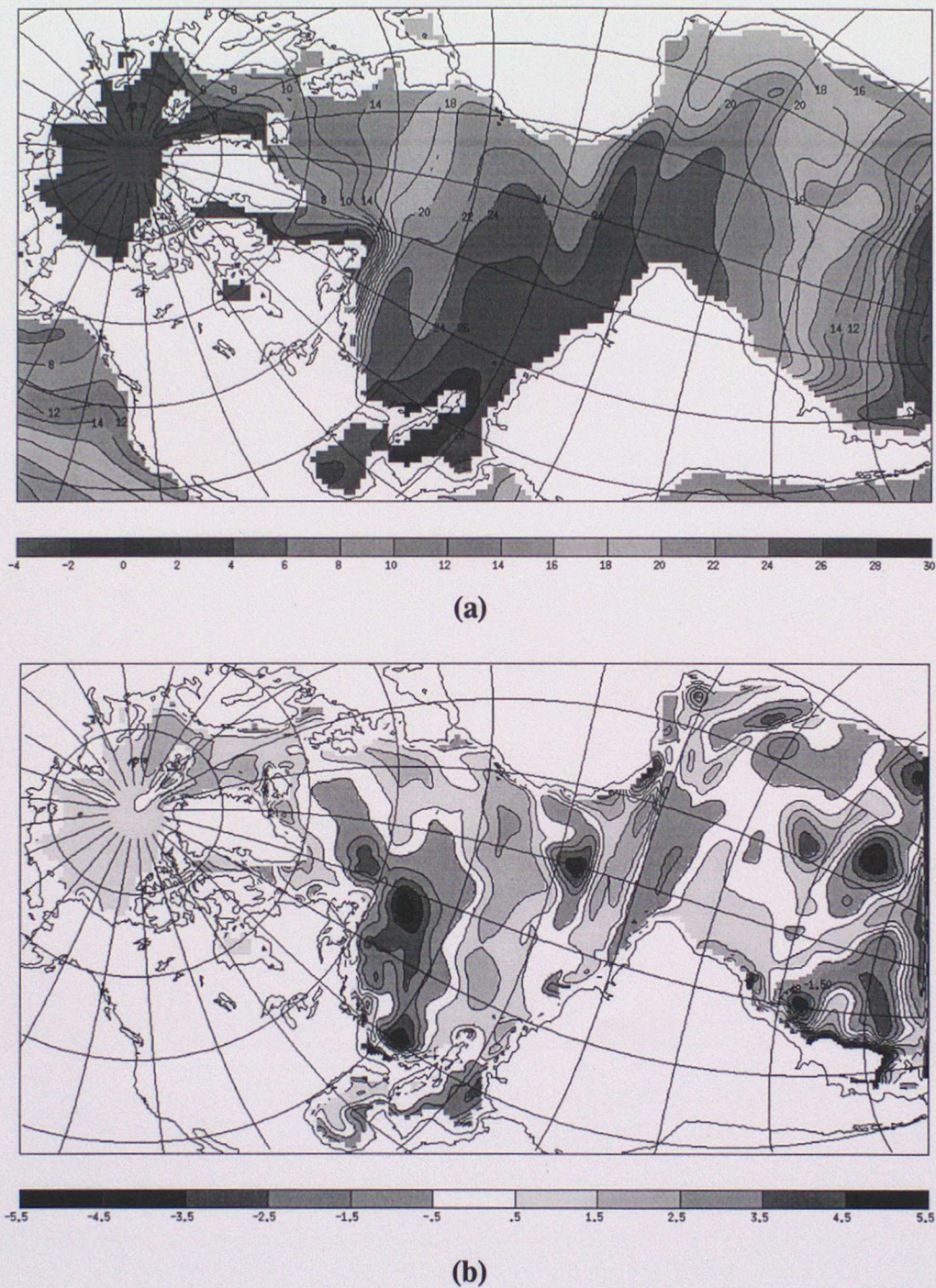


Figure 4. (a) Levitus (1982) September temperature climatology at 48 metres depth and (b) the model departure from Levitus at this depth (level 5) on 15 September after a six month integration. Units are °C.

4. Results from Integrations

4.1 Characteristics of the Model Integration as a Control

The model temperature drift from climatology in the upper layers becomes significant within the first few months of the integration. In some regions the magnitude of the drift is larger than the model's annual cycle. The model drift was shown to continue to increase and affect deeper layers over a six year period by Bell (1994b). This section describes the most significant characteristics of the model compared to climatology (Levitus 1982) in mid-September after a six month integration.

i) There is an extensive cold anomaly covering the northern part of the North Atlantic.

The cold anomaly is widespread at the surface with a maximum of about 5°C centred on 40°W 48°N. There is a second maximum below the surface at level 6 (67 metres). Figures 3 and 4 show the potential temperature anomaly fields at the surface and level 5 (48 metres) respectively. Figure 5 shows a cross section through the anomaly down to a depth of 1000m. It is still uncertain as to why this region is cooler than climatology, and in particular why there is a significant cold anomaly to the east of Newfoundland. The main anomaly is, however, located in a region of sharp temperature gradient and so may be the result of a relatively small displacement of the isotherm positions. The incorrect path of the Gulf Stream could possibly provide an explanation as to why the model is too cold in this area. The observed Gulf Stream separates from the North American coast at Cape Hatteras and flows towards the Grand Banks, a subsurface shelf to the east of Newfoundland. A branch of the current then follows the topography of the Grand Banks, and separates again at the Flemish Cap (45°W 47°N) to form the North Atlantic drift (Schmitz 1993). In the control integration, the Gulf Stream separates from the North American coast, but then turns north-eastward too far east, thus failing to bring warmer water to the region east of Newfoundland at around 40°W (Fig. 7).

It is possible that the inadequate resolution of the Gulf Stream and Labrador current and the interaction between the two in the region to the east of Newfoundland is contributing to the cold anomaly. The general upper level cold bias in the northern North Atlantic may also be due to inadequate heat transport by the Gulf Stream and North Atlantic Drift.

ii) There is a second significant cold anomaly at around 50 metres depth in the western North Atlantic that is less apparent at the surface.

A cold anomaly can be seen at 48°W 38°N with a maximum of 5°C at level 5 (48 metres) (Fig. 4). This is close to the level of the seasonal thermocline in the model, and is at least partly due to a difference between the tighter thermocline gradient in the model and smoothed

gradient in the climate field. A cross section through the anomaly is shown in figure 6. The North Atlantic current passes through this region and may be displaced slightly too far south contributing to the cold anomaly (Fig. 7).

iii) The southern half of the North Atlantic in the main sub-tropical gyre is warm compared to climatology.

A warm anomaly extends across the Atlantic and is a maximum in the eastern half of the region where the anomaly is 2°C warmer than climatology at the surface (Figs. 3 and 4). A comparison with the integration using Unified Model surface forcing presented in section 4.4 suggests that this warming is due, at least in part, to the climatological surface fluxes that were used in the integration.

iv) The Gulf Stream structure is represented better than climatology.

Figure 8 shows cross sections through the Gulf Stream at 28°N for the model and climatological potential temperature field. The model has tightened up the horizontal and vertical temperature gradients in the Gulf Stream, and is a significant improvement on the smoothed climatological temperature field.

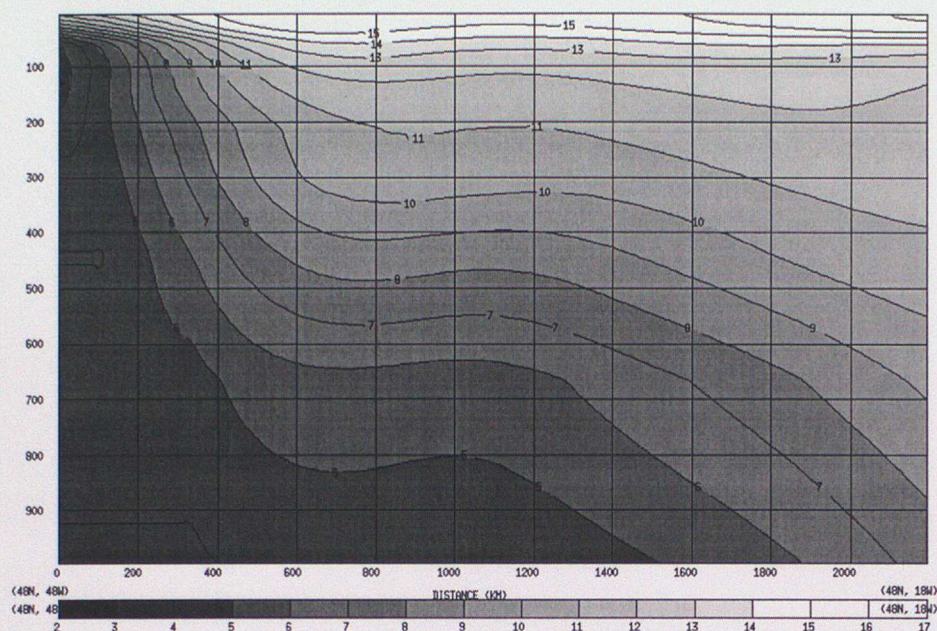
The cold anomaly to the east of the Gulf stream centred on 74°W 28°N (Fig.4) with a maximum at level 5 (48 metres), is mainly due to the tighter seasonal thermocline gradient in the model and is at least in part a consequence of comparing the model field against a smoothed climatology.

v) There is an anomaly dipole across the Equator.

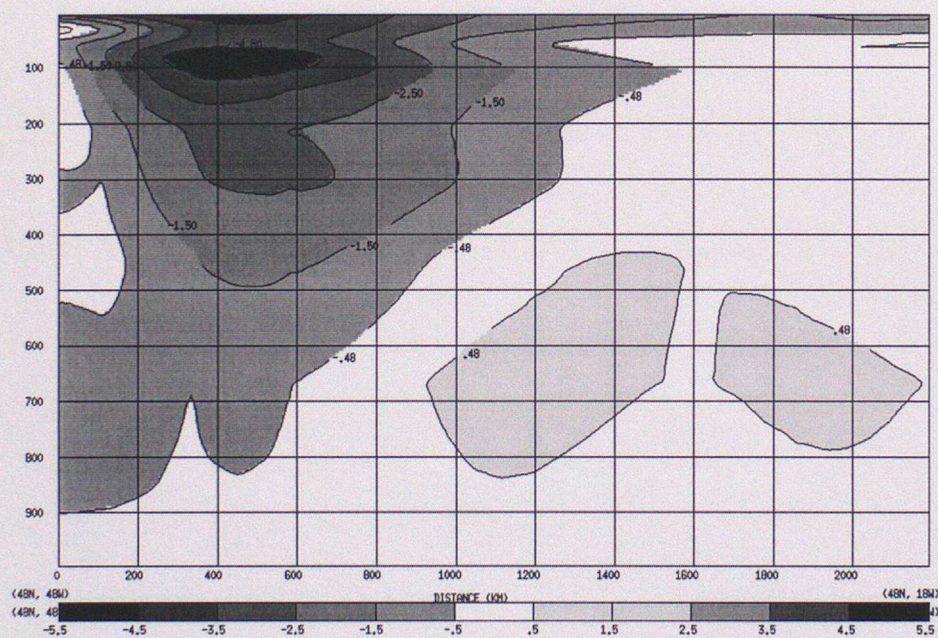
A dipole anomaly pattern is apparent across the Equator down to a depth of 140 metres; warm to the north, and cold to the south (Figs. 3 and 4). There is uncertainty at present as to why this feature occurs in the model, although a comparison between models with different surface forcing suggests that the anomaly is at least partly due to the fluxes (see section 4.4).

vi) The South Atlantic and Arctic anomalies are 'artificial'.

Many of the large anomalies in the Southern Atlantic can be attributed to deficiencies in the climatology due to lack of observations in the region (Alves *et al.* 1995), and problems caused by the closed (no slip) boundary condition at about 45°S (Fig. 3). The streamfunction in the Southern Atlantic (not shown) has clear errors that are caused by the boundary. The anomaly in the Arctic around the North Pole is due to a coding error in the thermodynamic ice model associated with the heat flux over ice. These regions are therefore not considered further in the discussion.



(a)



(b)

Figure 5. Cross sections along a great circle in the rotated grid from 48°N, 48°W to 48°N, 18°W from the surface to 1000m, for (a) Levitus potential temperature September climatology, (b) model potential temperature for 15 September 1993 minus Levitus. The vertical scale is depth in metres, the horizontal scale in kilometres. Temperature contours in °C.

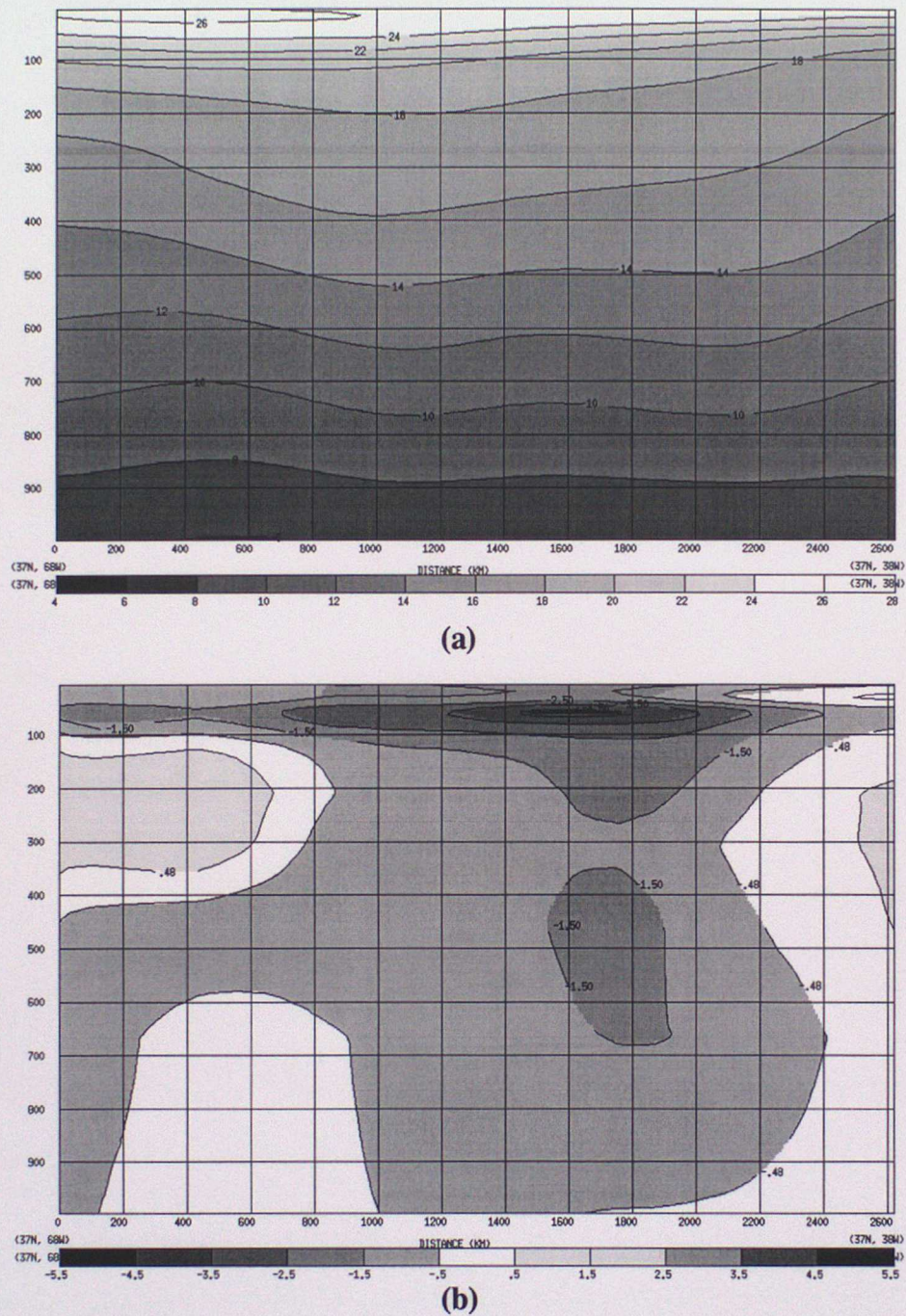


Figure 6. Cross sections along a great circle in the rotated grid from 37°N, 68°W to 37°N, 38°W from the surface to 1000m, for (a) Levitus potential temperature September climatology, (b) model potential temperature for 15 September 1993 minus Levitus. The vertical scale is depth in metres, the horizontal scale in kilometres. Temperature contours in °C.

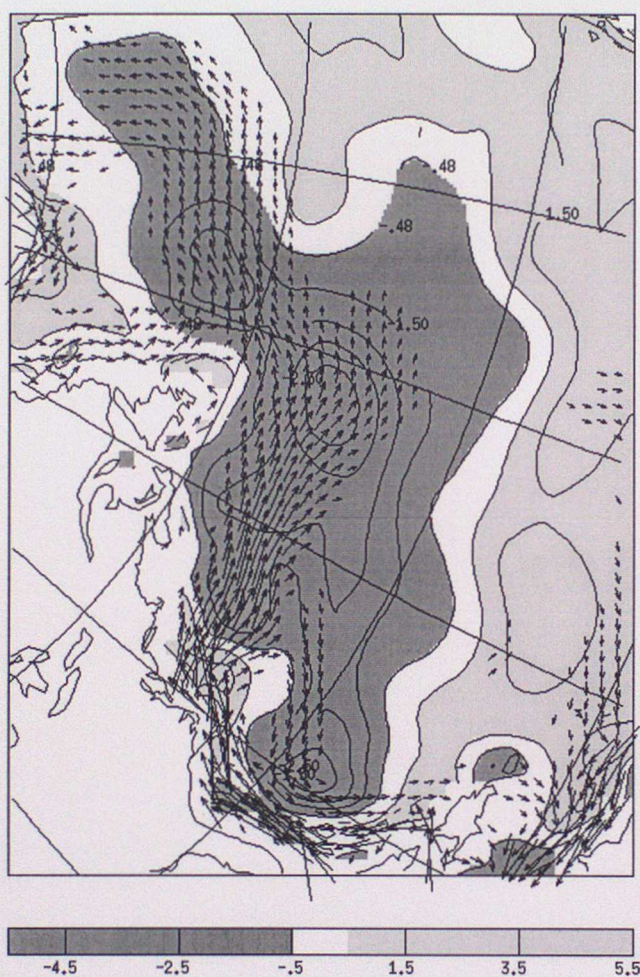


Figure 7. Model potential temperature minus Levitus overlaid with total current velocity at level 5 (48m) on 15 September. Arrows only shown for current velocities over 3 cm/s. Potential temperature contour units are °C from -5.5°C to +5.5°C.

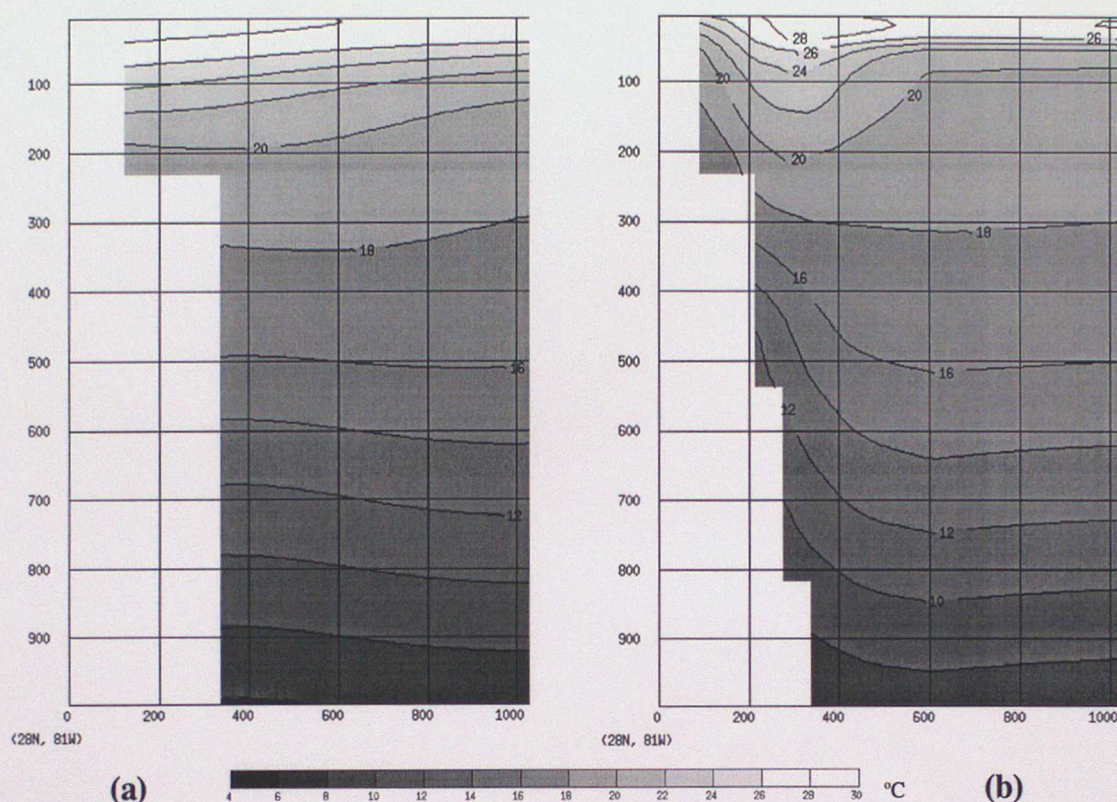


Figure 8. Potential temperature cross section across the Gulf Stream from the surface to 1000m depth, 1000km along a great circle in the rotated grid from 28°N 81°W to 28°N 71°W for (a) Levitus (1982) September climatology, and (b) the model control integration. The land on the left is the Florida Peninsula. The vertical scale is depth in metres, the horizontal scale is in kilometres. The contour interval is 2°C.

From the above discussion it is apparent that the model temperature anomaly from the Levitus climatology should be interpreted with care. Some of the differences are due to the model representing features better than climatology, (e.g. tighter frontal gradients), but some are due to the incorrect positioning of a temperature gradient, (e.g. North Atlantic current). Systematic model drift, which may have many different sources of error, nevertheless appears to be a serious problem. Assimilation will be fighting a constant battle in regions where there is a systematic model bias, and it is important to reduce these errors within the model to obtain the best results from the assimilation of observations.

4.2 Results from Integrations Assimilating SST Observations

The main results from a series of model integrations assimilating data are described in this section. The analysis fields from the assimilation runs are compared with the U.K. Met. Office Numerical Weather Prediction SST analysis which uses *in situ* and satellite SST data but contains no model. For a quantitative assessment of the impact of the data in the model integrations, root mean square (r.m.s.) statistics are calculated using independent BATHY observations. Sea surface temperature observations are not used for validation purposes in this report.

There were a limited number of BATHY observations available for the period of the experiment and the spatial distribution of the data is far from uniform (Figs. 1(c) & 1(d)). Half of the available BATHY data was assimilated and the other half used to form independent statistics (samples X and Y). The small number of observations is potentially a problem for both the quality of the analyses and the validity of the statistics.

Three integrations of the model assimilating different samples of BATHY data were performed to determine the dependence of the results on the observation sample. All integrations assimilated the same sample of *in situ* SST data. The BATHY data samples were formed by ordering the observations by validity time, and choosing every alternate profile, giving a fairly even temporal and spatial distribution between both samples (Figs. 1(c) & 1(d)).

Integration A2 assimilated all the BATHY observations (samples X and Y) and used sample Y to form non-independent verification statistics. Integration A3 assimilated sample Y and used sample X to form independent verification statistics. Integration A4 assimilated sample X and used sample Y to form independent statistics. All the other assimilations assimilated sample X and used sample Y to form independent statistics. Sample Y was also used to form statistics for the model integrations (MC, MU) and climatology (CL), (see Table 1).

The r.m.s. observation minus analysis potential temperature statistics for the three integrations are compared in figure 9. Integration A2 assimilating all BATHY data is generally *slightly* better than A4 assimilating half of the data (sample X), both using the same observations to calculate the statistics (sample Y). It is perhaps surprising that the r.m.s values for A2 are not *significantly* better than A4, but the distribution of observations is similar for both samples and a possible explanation is that halving the data sample thins out the observations in *data dense* regions, removing little information from the collective observation distribution. Of course there are still many data sparse regions not covered by either sample. A comparison of A3 and A4 indicates that the use of different observation samples for assimilation and independent statistics does affect the resulting statistics to a small degree. In fact, error distributions of sample X and sample Y contained outliers that were due to observations near coasts and in regions of strong temperature gradients where model errors can dominate, and these outliers were influencing the results.

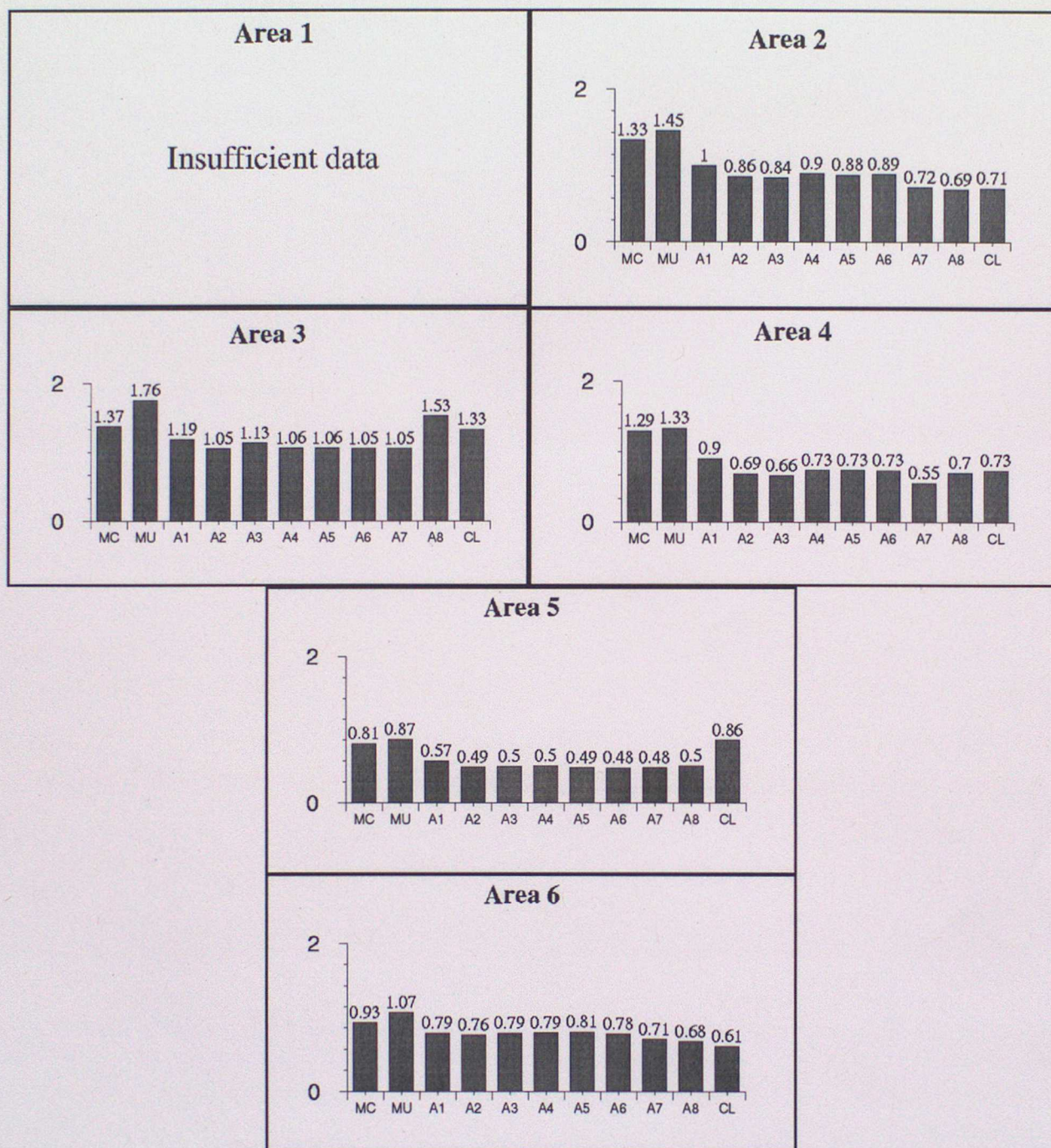


Figure 9 (a) Root mean square observation minus analysis surface temperature statistics for September 1993 for the six areas defined in Section 3.

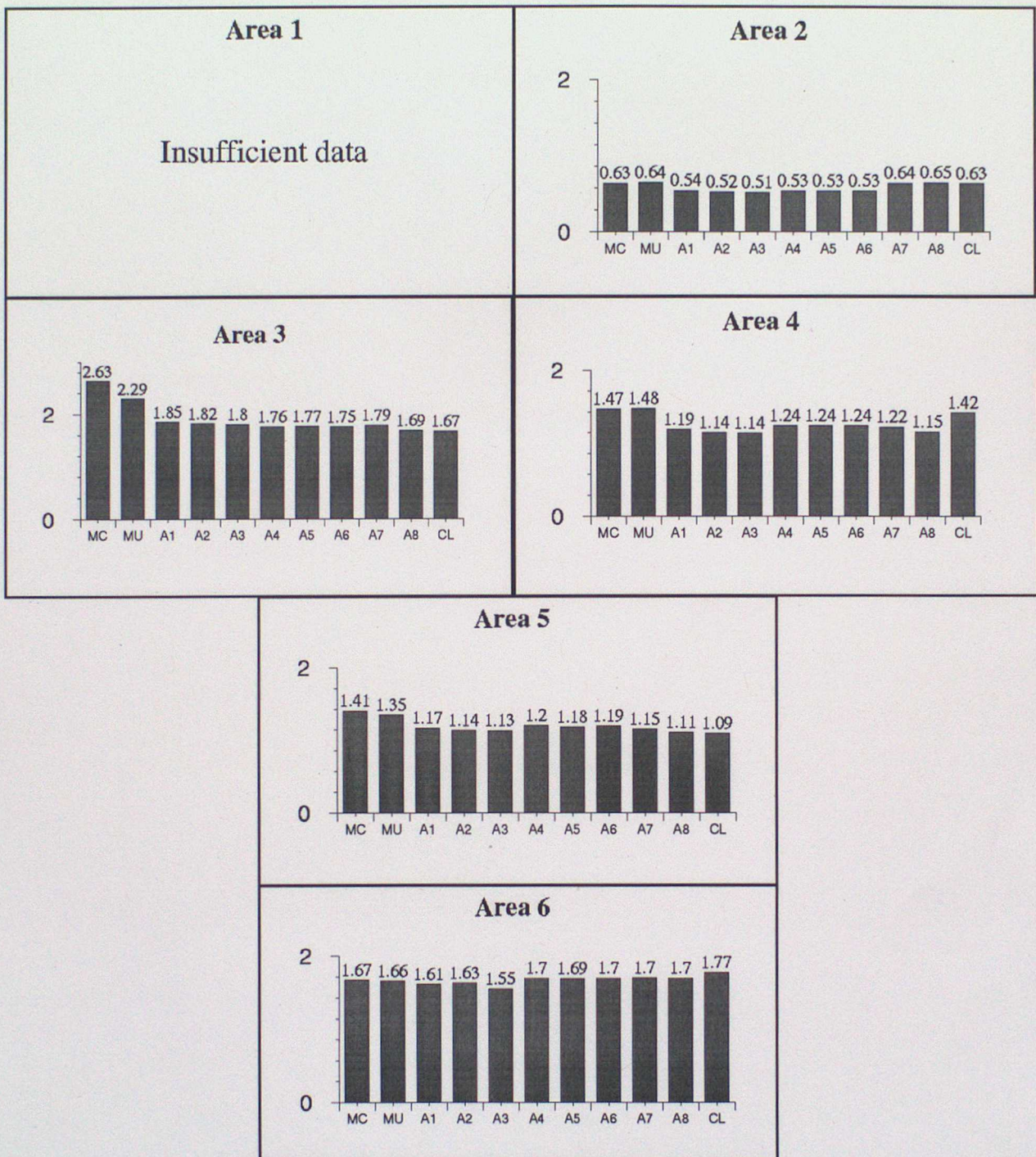


Figure 9 (b) Root mean square observation minus analysis temperature statistics for levels 4, 5, and 6 (35m to 67m) in September 1993 for the six areas defined in Section 3.

The conclusion from this investigation into observation samples is that the statistics must be calculated and treated with a certain amount of care. In order to minimise these problems, all the statistics, except those for A3, have been calculated using the same sample of observations (Y). Nevertheless, looking at statistics only, without referring to the observation distribution and model anomaly fields can be misleading.

Integrations A1, A4, A6, and A7 are all similar except observations from different sources are assimilated. Integration A1 assimilates BATHY data only and uses both data samples X and Y. The other three integrations (A4, A6, A7) assimilate BATHY sample X observations and use sample Y for independent statistics. A4 assimilates *in situ* SST data, and A6 assimilates *in situ* and AVHRR SST data as well as BATHY data. A7 is the same as A6 but applies SST increments in the mixed layer as described in section 2. The most significant points arising from the results are:

i) Assimilating data into the model improves the model temperature field compared to the control integration.

In almost all cases the assimilation r.m.s. statistics are smaller than those for the control integration (MC), showing that the assimilation of data has a positive impact on the accuracy of the model temperature field.

ii) The best assimilation is generally better at the surface than climatology.

The best assimilation has lower surface r.m.s. statistics than those calculated for Levitus climatology, except for area 6 (tropics).

iii) Assimilating sparsely distributed BATHY observations in regions of strong temperature gradients can be detrimental to the analysis.

The impact of assimilating BATHY observations is not the prime focus of this report and details from earlier experiments can be found in Bell (1994a,b). However, for the purpose of comparison, an integration assimilating only BATHY data was performed (integration A1). The statistics for this integration are not independent, and so can not be directly compared with the statistics for assimilations A4, A6, and A7. Figure 10(b) shows the difference field for analysis minus the reference NWP SST analysis in mid-September after ten weeks of assimilation of BATHY data. The surface anomaly in the eastern part of the North Atlantic has been reduced, but the cold anomaly at 43°W 48°N has actually increased in magnitude at the surface compared to the model only run (Fig. 10(a)). The BATHY observation distribution for August (not shown) and September (Figs. 1(c) & 1(d)) suggests a reason for this further drift. There are no BATHY observations close to the position of the maximum cold anomaly that might have warmed the model temperature field in this region. There is, however, a dense cluster of observations a few degrees to the west that gave predominantly negative increments in the

assimilation, i.e. cooling of the surface field. The increments are spread out to within a few correlation scales (300km) of the observation, and in this case, cooling increments were spread over the region of maximum anomaly, thus increasing the magnitude of the cold bias. This highlights one of the problems of assimilating such a non-uniform distribution of data in regions of significant temperature gradients at this resolution.

iv) Assimilating *in situ* SST observations improves the analysis in the surface layers.

Integration A4 assimilated BATHY data and *in situ* SST observations from ships and buoys (Fig. 10(c)). A comparison with the BATHY assimilation field (Fig. 10(b)) shows the cold bias in the North Atlantic reduced considerably. The r.m.s. statistics for the surface and at levels 4,5 and 6 are better than those for integration A1 assimilating BATHY data only, except in area 6 (tropics). There is good coverage of the North Atlantic with *in situ* SST observations (Fig. 1(a)), and it is apparent from the improved statistics below the surface that this information is propagating slowly down from the surface into the mixed layer due to mixing processes in the model.

v) Assimilating AVHRR SST observations has little impact in the North Atlantic, a region reasonably well observed with *in situ* data.

Figure 10(d) shows the surface anomaly field for September 15 for integration A6 assimilating BATHY, *in situ* SST, and AVHRR satellite SST observations. Comparing this with integration A4 which did not assimilate satellite data (Fig. 10(c)), the impact of the satellite data is seen to be small, with only a slight reduction in the magnitude of the anomalies. The statistics in figure 9 support this statement showing very little difference between the two integrations. Although the satellite tracks cover a large part of the Atlantic, the *in situ* SST observation distribution is good in the North Atlantic, and little information is gained from using the satellite data. The satellite data will, however, be extremely important in regions less well observed by *in situ* data, such as the South Atlantic.

vi) Applying SST increments in the mixed layer improves the surface analyses in the North Atlantic.

The surface temperature anomaly decreases considerably when SST observation increments are applied in the model mixed layer as described in section 2 (integration A7). The surface anomaly after ten weeks assimilation is shown in figure 10(e). The r.m.s. statistics for the integration are generally better for the North Atlantic, with some improvement also in the tropics, but no difference in area 3 (Gulf Stream), and area 5 (subtropics). Figure 10(f) shows the surface temperature difference between Levitus September climatology and the UKMO Numerical Weather Prediction SST analysis. Figures 10(e) and (f) have very similar characteristics, indicating that the assimilation has overcome much of the model drift at the surface within ten weeks of assimilating SST observations within the mixed layer.

The impact of the SST observations is generally small below the mixed layer. Level 5 (48m) is just below the mixed layer in the model at this time of year over most of the central North Atlantic, and so there is no direct influence from the SST increments. If the model mixed layer depth has significant errors then the assimilation of SST increments within the mixed layer will be detrimental to the analysis. This is a possible explanation for the poor r.m.s. statistics for integration A7 around 50m in area 2 (eastern subpolar gyre) where the variation in mixed layer depth tends to be larger (Fig. 9(b)).

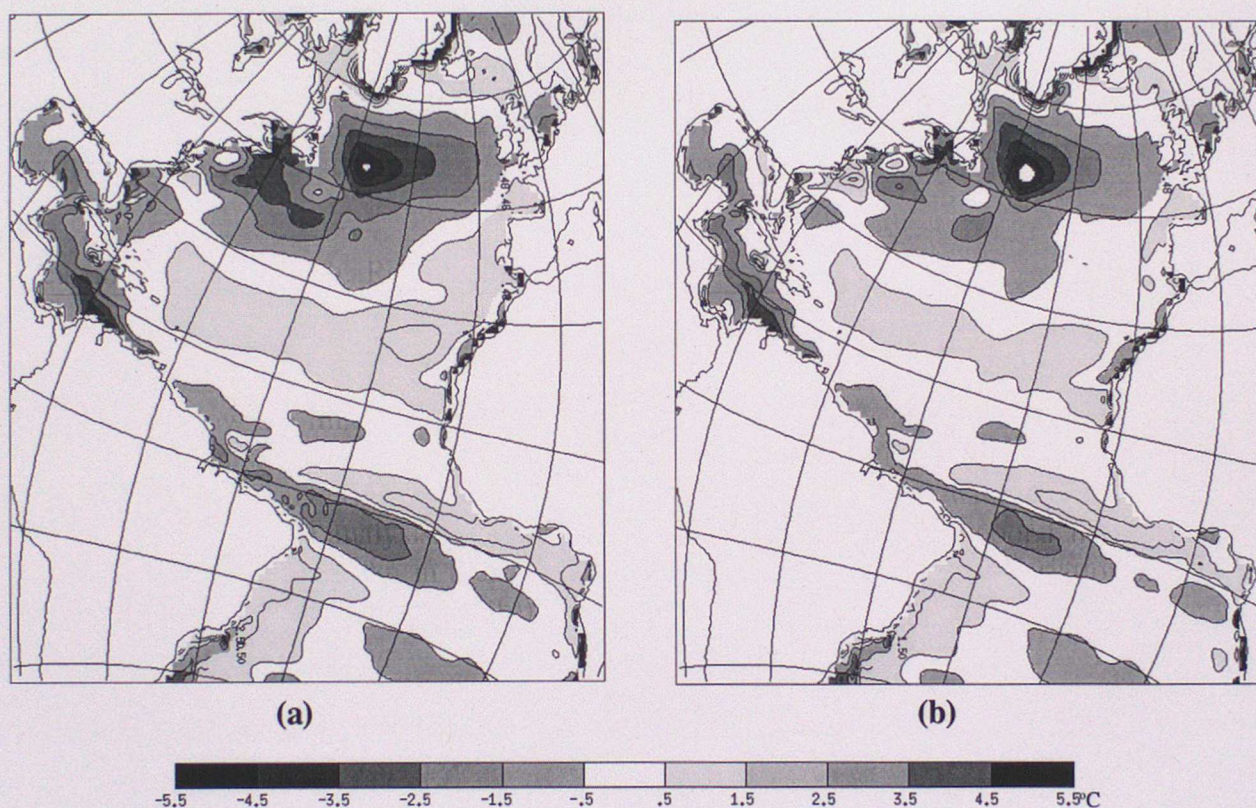


Figure 10. Sea surface temperature difference from the NWP analysis for 15 September, ten weeks into the integration for model, assimilation and climate fields,
(a) Model only
(b) BATHY profiles (integration A1),
(c) BATHY profiles, and *in situ* SST data at the surface (integration A4),
(d) BATHY profiles, *in situ* and AVHRR SST data at the surface (integration A6),
(e) BATHY profiles, *in situ* and AVHRR SST data in mixed layer (integration A7),
(f) Levitus September climatology.

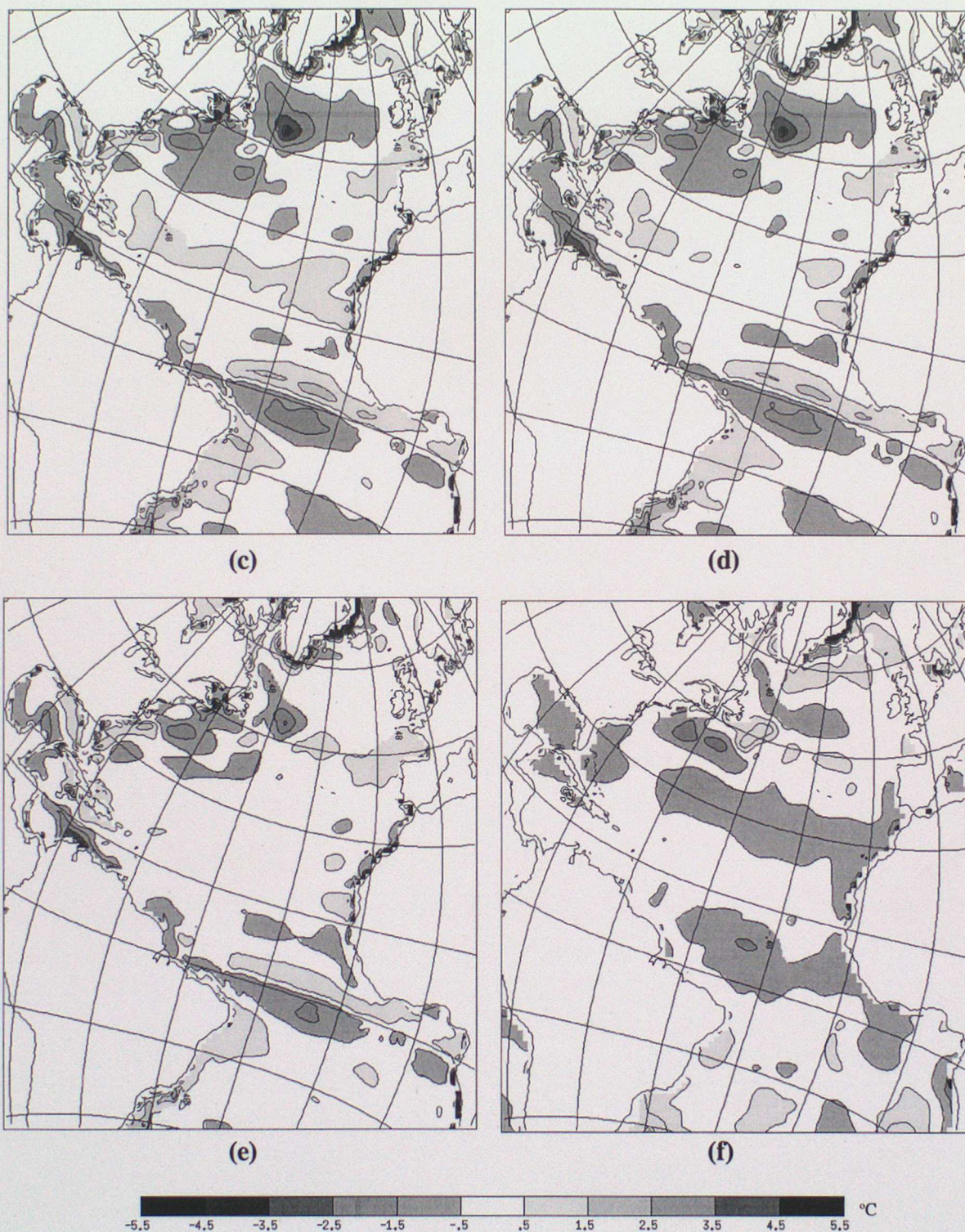


Figure 10. (continued)

4.3 Preventing the Interpolation of Observation Increments Across Land

Integration A5 used the scheme described in Section 3 to prevent the interpolation of observation increments across land. The impact of the scheme is expected to be small as differences only occur close to peninsulas, islands, and land dividing ocean basins. There are very few regions of this nature within the domain of the model grid, the Caribbean and Florida Peninsula being the main area of interest.

An example is shown in figure 11, where an observation close to the eastern coast of the Florida Peninsula is warming the model substantially. In most of the experiments the observation increment is spread over land into the Gulf of Mexico, where the temperature field is largely uncorrelated, (integration A4, fig. 11(a)). With the filtered increment masking scheme (using the model land-sea mask) turned on, the observation does not influence this uncorrelated region significantly (integration A5, fig. 11(b)). The r.m.s statistics for A4 and A5 are almost identical, as expected.

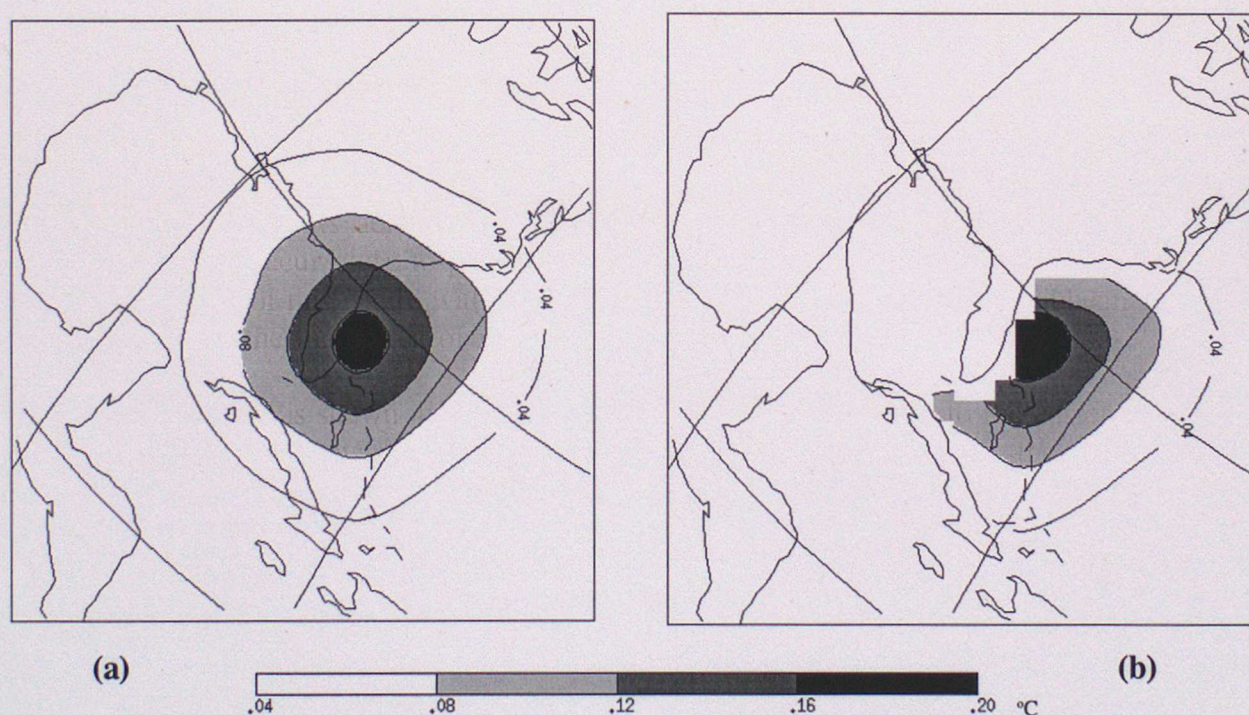


Figure 11. Surface temperature assimilation increment accumulated over 5 days for a BATHY observation at 28°N 79°W close to the east coast of Florida, (a) with no filtered increment masking, and (b) with filtered increment masking.

4.4 Comparison Between Integrations With Different Surface Forcing

Foreman *et al.* (1994) investigated the differences between climatological estimates of the surface forcing fluxes and those obtained from the UKMO Unified Model and ECMWF model, finding significant differences. To assess the effect of different surface forcing fields on the model evolution, two integrations were performed using monthly mean heat, fresh water, and momentum surface fluxes from the Unified Model. These could be compared directly with the integrations using monthly mean climatological fluxes. The three month integrations started on the 1 July from the spun up state (which used climatological fluxes), and so the model was only subjected to UM surface fluxes for three months.

The first integration using UM fluxes had no assimilation (integration MU) and is analogous to the control run (integration MC). A second integration assimilating BATHY, *in situ* SST, and AVHRR SST data using UM surface fluxes (integration A8) can be compared with the analogous integration using climate fluxes (integration A7). The main points arising from a comparison of the integrations are summarised:

i) Within three months, the effect of the surface forcing has penetrated to a depth of 50 metres in the North Atlantic and to around 140 metres in the tropics.

The largest differences between the potential temperature fields for integration MU using UM fluxes and the control integration MC using climate fluxes are at the surface, but there are significant differences down to level 5 (48 meters) over much of the Atlantic. Below level 5 differences are confined to the tropics, and these become small below level 8 (140 metres). Foreman *et al.* (1994) showed that the 1993 UM heat fluxes cooled the surface over much of the North Atlantic and warmed the Caribbean, when compared to climatological fluxes. These characteristic differences are clearly evident at the surface ten weeks into the integration (Fig. 12(a)), and extend down to 50m weakening with depth (Fig. 12(b)).

ii) Statistics show that the model integration using Unified Model fluxes is generally worse at the surface and a slight improvement below the surface compared to the control integration using climate fluxes.

Comparing the r.m.s. obs. minus analysis statistics for integrations MU and MC (Fig. 9), the most significant differences can be seen in area 3 in the western North Atlantic. The standard deviations are similar for both integrations, but the means are substantially different in some areas (these statistics are not shown). The anomalies from Levitus temperature climatology for the two model integrations are quite similar in some regions but of opposite

signs in others. Integration MU does not have the warm bias in the central North Atlantic that is in the control MC. However, the Caribbean is probably too warm in integration MU, and a cold bias has developed to the east, south of the Equator. The anomaly dipole across the equator in the control integration is reduced in magnitude when using UM fluxes. Both integrations clearly show drifts from climatology that are due to the different fluxes. It would be interesting to find out how integration MU would be different if it had been forced with UM fluxes during the spin up from climatology as well as during the three month period of the integration.

iii) The effect of different surface forcing fluxes on the model temperature field is smaller for an integration assimilating BATHY and SST observations in the mixed layer.

A comparison between assimilation A7 (using climate fluxes) and assimilation A8 (using UM fluxes) ten weeks into the integration shows little difference between the analysis fields at the surface (Fig. 13(a)). The state of the North Atlantic at the surface can be constrained reasonably well by the SST observations available, and the assimilation of this data will counteract any process that is forcing the ocean away from its observed state (such as incorrect

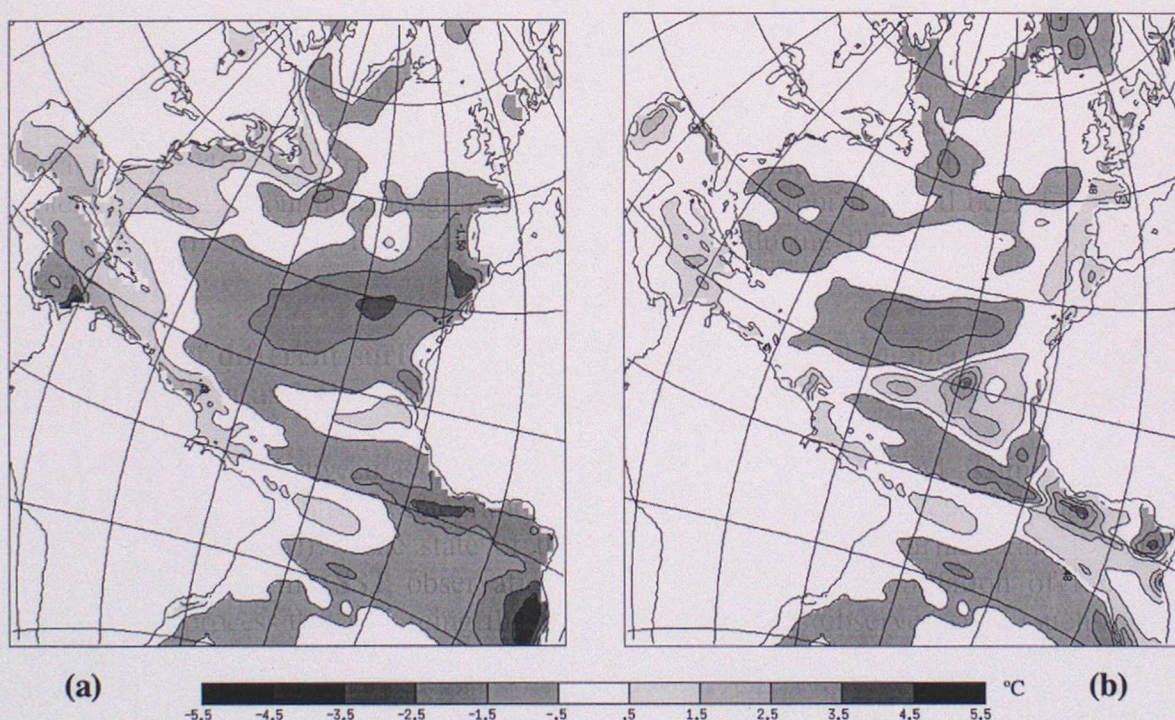


Figure 12. Difference between model integration using Unified Model fluxes and model integration using climate fluxes on 15 September for (a) the surface (level 1) and (b) 48m depth (level 5).

surface fluxes). Although there are differences between the two integrations, these are mainly confined to regions near the coast, and the differences are smaller than those between the model integrations MU and MC with no assimilation in figure 12(a). The differences between assimilations A7 and A8 increase below the surface due to the decrease in data (Fig. 13(b)), but are still generally less than the differences between integrations MU and MC, suggesting the surface fluxes have much less impact on the temperature field in the surface layers when data is assimilated. The r.m.s. statistics for A7 and A8 do show similar characteristics to those for MC and MU, with the assimilation using UM fluxes slightly worse at the surface but better below the surface.

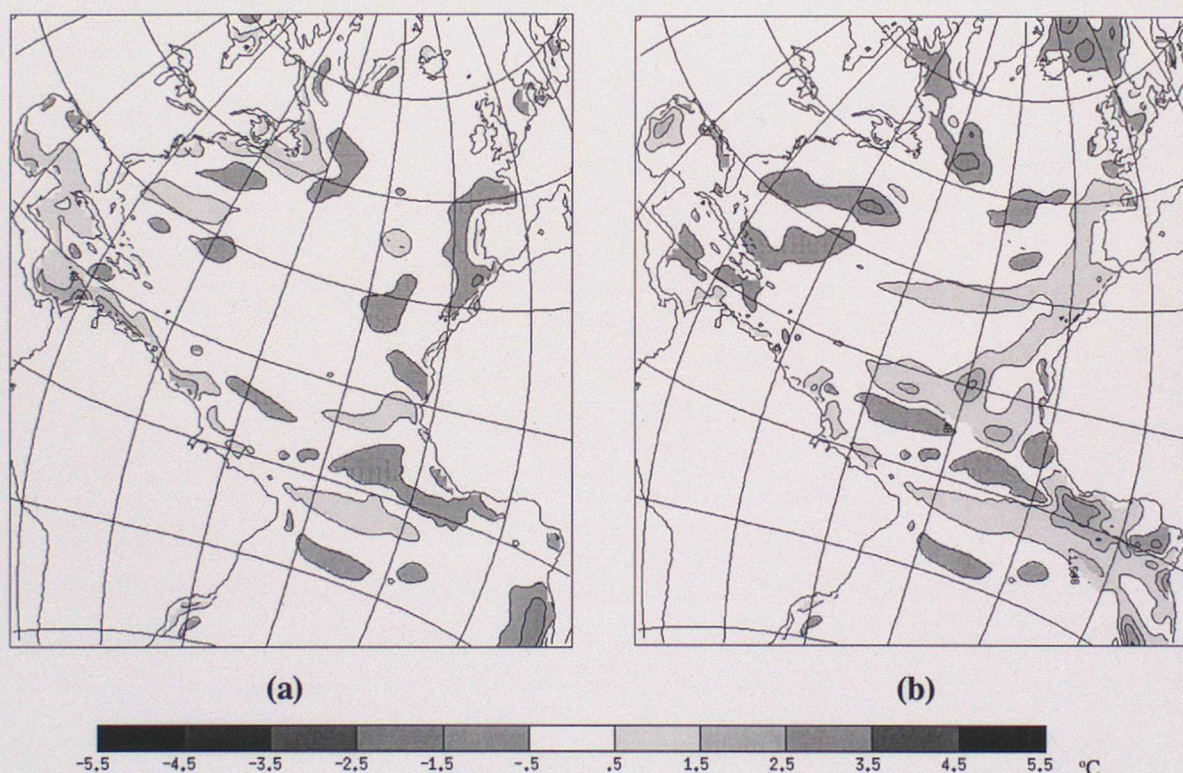


Figure 13. Difference between assimilation using Unified Model fluxes and assimilation using climate fluxes on 15 September for (a) the surface (level 1) and (b) 48m depth (level 5). BATHY, *in situ* SST and AVHRR SST data were assimilated.

5. Concluding Summary

A series of ocean model integrations has been performed assimilating sea surface temperature and thermal profile observations for a three month period starting in July 1993. The experiments were primarily designed to show the impact of assimilating the SST observations, and to highlight any problems associated with the assimilation of data.

The model bias was found to be significant in many areas after only a few months integration. Assimilating BATHY observations only is not sufficient to constrain the model upper level temperature field, although such data does significantly reduce the model bias (Bell 1994a,b). The assimilation of the more abundant sea surface temperature observations into the model at the surface improves the analyses at the surface and to a smaller extent in the mixed layer. Applying SST increments in the mixed layer shows an increased improvement of the surface field over a shorter time. The impact below the surface is beneficial in regions where the model mixed depth layer is reasonably accurate, but detrimental in isolated regions where the model mixed layer depth is significantly in error. Further work to the SST assimilation scheme will include an investigation of the longer term effect of applying SST increments in the mixed layer of the model.

A scheme to prevent the interpolation of observation increments across land has been shown to work successfully. The scheme is expected to be more important in a model with a global domain.

The model temperature structure evolution using climatological estimates and Unified Model surface forcing fields differs down to 50m in the North Atlantic and deeper in the tropics in a three month integration. The temperature differences are smaller when BATHY and SST data are assimilated, suggesting that differences in the surface forcing fields are less important when sufficient observations are assimilated.

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