Forecasting Research Division
Technical Report no. 48

Use of Satellite data in the Operational Sea Surface Temperature Scheme.

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CONTENTS

1. INTRODUCTION

A daily SST analysis has been running as part of the UM operational suite since February 1991 and is described fully in Jones (1991). Observations from ships, fixed buoys, drifting buoys, bathythermographs, TRACKOBS and various satellite derived products were used in the original scheme. Lately, products derived from the along track scanning radiometer (ATSR) carried aboard the ERS-1 satellite have also become available.

This paper describes problems that have been encountered with the current satellite products, concentrating on the Advanced Very High Resolution Radiometer (AVHRR), and a scheme to overcome these problems is described. A series of experiments was performed in order to test the effectiveness of the scheme and the results are described.

Finally, a number of experiments were performed to test the impact of ATSR data. The aims of these experiments were to compare the quality of the ATSR data, compared to AVHRR data, and to test the impact of using ATSR data in the analysis using the same correction scheme developed for AVHRR data.

2. DATA DISTRIBUTIONS

Data is received daily from ships, fixed buoys, drifting buoys, bathythermographs and TRACKOBS. These platforms are collectively known as *in situ* platforms. Satellite products derived from both the polar orbiting NOAA series of satellites using the AVHRR instrument and from the geostationary Meteosat satellite, using a single channel radiometer, are also received. Although Meteosat data was used originally it has now been withdrawn and is not considered further in this paper.

The various observation types are not distributed evenly over the globe. The data distributions for each observation type between the dates 25 May 1992 to 24 June 1992 are shown in figure 1(a-f). In the plots, a '*' indicates that an observation which has passed the quality control has been received at that location.

The plot of ships clearly shows the busy shipping lanes of the North Atlantic and North Pacific. There is also a reasonable supply of data from the Central Atlantic, North Indian Ocean and the shipping lanes around Indonesia. There is however, a lack of data for most of the southern oceans, including a large section of the South East Pacific Ocean.

Data from drifting buoys supplements the data in the South East Pacific and the Northern sections of the Atlantic and Pacific Oceans. Again though, data for the Southern Oceans is lacking, with no data at all for the South Atlantic. The remaining *in situ* platforms merely provide additional data for areas which already have a good supply of data.

Global coverage is achieved by the use of AVHRR data, although there are areas of the ocean where even AVHRR data is diminished, notably the North West Pacific and South Atlantic Oceans.

3. AVHRR DATA AND MOUNT PINATUBO

The AVHRR product received is one observation in a 2.5 degrees latitude/longitude box. The SST value is derived using the multichannel algorithm developed by McClain et al (1985). The algorithm used has also been tuned against drifting buoy data so that the value is a 'pseudo bulk' SST value. As explained in Jones, *in situ* platforms measure the bulk SST whereas satellites measure the skin SST and the difference between the two can be several tenths of a degree. Even though the AVHRR is a pseudo bulk SST value a slight bias still exists, Reynolds (1989) et al, Pichel (1991). However, under normal circumstances this bias is only of the order of one or two tenths of a degree which is within an acceptable accuracy.

Of bigger concern is the effect of atmospheric aerosols on the data. The AVHRR instrument measures the radiation emitted from the sea surface. Some of this radiation is absorbed by the atmosphere but the algorithms have been adjusted to allow for this. Mount Pinatubo in the Philippines erupted in late June 1991 injecting huge amounts of aerosols into the atmosphere. The resulting sudden, massive increase in atmospheric aerosols quickly deteriorated the accuracy of the AVHRR product before the algorithms could be changed. Meteosat data was also affected so all satellite data was withdrawn from the analysis on 13 August 1991 and the analysis allowed to rely solely on *in situ* data.

Figure 2a shows the mean AVHRR observation minus analysis for the period 1 May 1991 to 1 May 1992 for latitude bands 90N to 30N, 30N to 30S and 30S to 90S. Figure 2b shows the mean AVHRR observation minus climatology for the same period and latitude bands.

Fig 2a shows several interesting points. Before the eruption, AVHRR data was slightly warmer than the analysis in the northern hemisphere but very close to the analysis in the tropics and southern hemisphere. This is probably because AVHRR data was by far the most abundant data source in these two regions and the analysis had become biased towards the data. After the eruption, AVHRR data quickly developed a negative bias, especially in the tropics but in the northern and southern hemispheres also. The true extent of bias is not seen until after AVHRR, and indeed all satellite data, was removed from the analysis on the 13 August 1991. The bias in the tropics quickly increased into a negative bias of almost 1.5K. As time passes, the bias slowly decreases, partly due to the aerosols being dispersed but also due to changes to the product algorithm.

Fig 2b shows a similar picture, although some differences and similarities are interesting. The bias in the northern hemisphere remains positive for a much longer period, probably because of a climatological anomaly during this period. Also, the similarity between the curves for the southern hemisphere and tropics again indicate that the largest source of data for these regions is satellite data.

The impact of Mount Pinatubo on the accuracy of AVHRR data shown here is consistent with the findings of Reynolds (1991).

4. A SATELLITE CORRECTION SCHEME

The effect that Mount Pinatubo had on AVHRR data was the motivation to develop a correction scheme that could be applied to satellite data. Under normal circumstances, any bias would be immediately corrected and such a scheme would enable data to be used in the event of another infusion of aerosols into the atmosphere. Since biases in satellite data are not homogeneous across the globe, it is important that any correction applied is localised.

Such a scheme was developed by Bell (1991). Bell performed a basic *in situ* only analysis using the analysis scheme, degraded the resulting increment field and observation fields by a factor of 10, searched for areas of low *in situ* data volume and changed the increment to be the mean of the surrounding points or a global value if the surrounding points also had a low data volume. A second analysis is then performed of satellite data and again the increment field is degraded by a factor of 10. The difference between the increment fields is found and this difference interpolated to the satellite observation locations and added to the satellite observations. The ideas of Bell's scheme have been further developed in the scheme described here.

The correction scheme involves the following steps.

1) A basic *in situ* data only analysis is performed using the analysis correction method of the full SST analysis using only one iteration and the relaxation factor set to 1.0. The scale factor used in this analysis is 500km and the influence radius 1000km.

2) A second analysis using satellite data only is performed in a similar fashion, again only a single iteration and the relaxation factor set to 1.0.

3) The satellite only analysis is subtracted from the *in situ* only analysis to create a difference field.

4) The difference field is interpolated to the location of every satellite observation using bi-linear interpolation or the nearest sea point if one of the surrounding grid points is land.

5) The interpolated difference value is added to the original satellite observation.

6) Steps 2) to 5) are repeated for each satellite type.

7) The SST analysis is then performed in the normal manner.

The differences between this scheme and the scheme described by Bell are:

i) The initial *in situ* analysis and satellite analysis are used on the full model resolution, not degraded by a factor of 10. This means that the corrections calculated in our scheme will be more localised. Bell pointed out the problem of repeatedly reporting buoys, especially if they themselves are biased, as there is no superobbing or thinning mechanism in the analysis scheme. It is for this reason that Bell checked for anomalous points in the initial *in situ* only analysis as his correction are spread over a much larger area and therefore any induced bias in the *in situ* observation will also be spread over a larger area. Repeatedly reporting buoys are still a problem in the scheme described here but as the corrections applied are more localised any induced bias will also be localised and therefore no check is made for anomalous points. This scheme is designed to correct for the large scale bias that exists in satellite data, not small scale biases in isolated *in situ* data sources.

ii) No account is taken of low *in situ* data volumes. In this scheme any isolated *in situ* data source will automatically correct surrounding satellite data towards its value. The final analysis will therefore be greatly influenced by this *in situ* report. Should the following period be void of *in situ* data, corrections applied to satellite data will be calculated from the background field (the previous analysis) which will still have memory of the *in situ* data report and therefore the trend of the analysis to become biased towards the satellite data will be limited. If there are no further *in situ* observations are received for a substantial period, several months, the analysis may become biased towards the satellite data but even in the southern hemisphere, this is unlikely to occur. This will be kept under review.

iii) We calculate the difference between the separate analysis fields rather than the separate increment fields, this is for coding reasons and has no affect on the calculation of the difference field from which the corrections are calculated.

5. EXPERIMENT RESULTS

The success of the technique was assessed by running a series of SST analysis for the period 26 May 1992 to the 25 June 1992. All the analyses started from the same climatological field for the 25 May 1992 and the 30 day assimilation period ensured that there were no 'spin-up' errors in the final analyses. Four experiments were performed;

A) *In situ* data only.

B) AVHRR data only.

C) *In situ* data and AVHRR data with no correction to the satellite data applied.

D) *In situ* data and AVHRR data with the correction scheme implemented.

The four analyses are shown in figure 3. They all appear to be a reasonable SST analysis with the Gulf Stream and Kuroshio Currents clearly identifiable. The differences begin to become evident when the differences from climatology are studied.

Figures 4a and 4b show the anomalies from climatology produced by experiments A and B respectively. It can be seen that generally B tends to increase the anomalies also produced by A irrespective of sign. For instance, A produces an anomaly of approximately -2.0K at 0N, 15W but B produces an anomaly of -2.0K over a much larger area. In the South East Pacific A shows a +2.0K anomaly at 50S 105W and B increases that anomaly to over 2.0K over a large area. Both experiments produce similar positive anomaly fields in the North Atlantic near Newfoundland, although here *in situ* data produces a slightly warmer anomaly. The Central Pacific Ocean is interesting as in this region A produces a significantly warmer anomaly than B. Notice the warm anomaly to the east of Africa which only features in A. The 'bulleyes' anomalies in the Southern Oceans produced by A which have no corresponding feature in B are of the result of isolated data points and show the value of using satellite data. The feature centred on 0 degrees latitude/longitude in A is not real but as a result of incorrect coding of location by some buoys, and will appear in any analysis which uses buoy data This is a quality control issue and these buoys have since been removed from the analysis.

Figures 4c and 4d show the anomalies from climatology produced by experiments C and D respectively. C produces an anomaly field very similar to B, showing that AVHRR data will swamp areas with low *in situ* data volumes. The anomaly field produced by D shows patterns from both experiments A and B. For instance, the Central Pacific and Atlantic Oceans show an anomaly pattern akin to A but the positive anomaly centred at 50S 105W is featured as in B. Also, the warm anomaly to the east of Africa, present only previously in A, is again clearly seen.

EXPERIMENT	ANALYSIS		ANOMALY	
	MEAN	SD	MEAN	SD
A	17.9739	10.2569	0.0406	0.6121
B	17.8188	10.2042	-0.1262	0.6852
C	17.8073	10.1859	-0.1386	0.6940
D	17.9455	10.2673	0.0100	0.6625

Table 1: Mean and standard deviation in degrees C of analysis and anomaly fields created by experiments A,B,C and D.

Table 1 shows that using AVHRR data does produce an analysis which is globally cooler, by over 0.1 degree C if the data is used uncorrected. This value is consistent with the known bias in the AVHRR product. The bias correction scheme does however, almost eliminates any bias. Experiment A has the lowest value for standard deviation in the anomaly field as there are areas with only isolated observations in which case the analysis will be dominated by the current climatological field. The standard deviation is increased when AVHRR data is used as these data void areas are eliminated and climatological anomalies are better resolved.

Figures 5a and 5b show the difference fields of experiment A minus experiment B and experiment A minus experiment C respectively. In figure 5a most of the difference between the fields is in the southern hemisphere although there are significant differences in the northern hemisphere. The most important of these is in the North Atlantic in the area near Newfoundland. Generally most of the differences are positive, indicating again that *in situ* data is warmer than AVHRR data. There are two significant areas where *in situ* data is cooler than AVHRR data, in the far south east Pacific, where *in situ* data is sparse and interesting along the east coast of North America. This is confirmed by looking at the anomaly fields in figures 4a and 4b. This area contains many automatic buoys and every observation reported by these buoys is being used in the analysis. A possible explanation is that several of these buoys are reporting temperatures that are too low, hence cooling the analysis. This illustrates the problem of repeatedly reporting buoys mentioned earlier. Figure 5b shows that the areas most affected by combining AVHRR data with *in situ* data are areas where *in situ* data is sparse

Figures 5c and 5d show the difference fields of experiment A minus experiment D and experiment D minus experiment C respectively. Both figures show that using AVHRR data, despite the correction scheme, is having an effect on the subsequent analysis, again mostly in the southern hemisphere. The cool anomaly in the far south Pacific Ocean is evident and this clearly shows that where there is a genuine anomaly which only AVHRR data 'can see', the analysis will still be able to resolve it. The correction scheme is able to utilize information from AVHRR data but control it at the same time.

	MEAN	SD	MAX	MIN
A-B (5a)	0.1552	0.4003	1.8411	-2.4680
A-C (5b)	0.1667	0.5237	2.8405	-3.3877
A-D (5c)	0.0287	0.2328	1.3071	-1.7200
D-C (5d)	0.1382	0.4011	2.7021	-3.1794

Table 2: Mean, standard deviation, maximum value and minimum value (degrees C) of difference fields plotted in figs 5a to d.

The mean differences between A and B and A and C again shows the bias that exists in AVHRR data. The mean difference between A and D shows that the bias has been practically eliminated.

Figure 6a shows the mean observation density over the 30 day assimilation cycle of *in situ* data. (This is the observation density term calculated within the AC scheme). This clearly shows how *in situ* data is largely confined to the northern hemisphere. The location of buoys in the southern hemisphere is also clearly shown. Figure 6b shows the mean observation density over the 30 day assimilation cycle for AVHRR data. The data coverage is now global and the north-south orientation of the data, under the satellite pass, is clearly seen, as is the lack of data in the South Atlantic and North West Pacific as stated in section 1. The relative low values in the North Atlantic are somewhat surprising. Figure 7 shows the mean difference between the *in situ* only analysis and the AVHRR only analysis performed within the correction scheme, ie. it is the mean of the corrections applied to AVHRR data. The areas where there has been a significant correction to the AVHRR data are relatively few. This suggests that corrections are only applied where they are really necessary and confirms once again that the correction scheme does not loose information provided by the AVHRR data.

As was seen from the data distribution maps shown in figure 1, *in situ* data sources are not distributed evenly over the globe. To see the effect of this, two further experiments were performed;

E) An analysis using only data from ships

F) An analysis using only data from drifting buoys.

The analysis fields produced from these experiments are shown in figures 8a and 8b, again both show a reasonable analysis. The anomaly from climatology maps are shown in figures 9a and 9b. The anomalies produced by E show that the analysis will respond even if there are only isolated reports. For instance, the warm anomaly in the South East Pacific is clearly seen even though figure

1a shows that the area is covered by a single ship tracking from New Zealand to Cape Horn. This could be the result of a warm bias in the ship but since the feature is also observed in the AVHRR analysis, the feature must be real. The warm anomaly to the east of Africa is only identified in the ship analysis. Since this feature is not seen in analyses which have not used ship data it is more difficult to determine whether this feature is real. It may be the result of an individual ship having a warm bias but there are several ships in the area and since it is unlikely that all ships would have the same warm bias the feature is probably real. Only further investigation of the actual ship reports in the area would resolve the issue.

DRIFTERS are distributed more sparsely and this seen in the anomaly map created by F. In areas where there are no observations, the analysis field is the same as the climatological field. Hence, there are no anomalies identified in the North Indian and South Atlantic Oceans. Sites of isolated buoys in the southern hemisphere are identified by the bullseyes in the anomaly field and the bullseye centred on 0 latitude/longitude is again clearly seen.

EXPERIMENT	ANALYSIS		ANOMALY	
	Mean	SD	Mean	SD
E	18.0243	10.2475	0.09478	0.6100
F	17.9318	10.2131	0.00464	0.4360

Table 3: Mean and standard deviation (degrees C) of fields analysis and anomaly fields created by experiments E and F.

	MEAN	SD	MAX	MIN
A-E	-0.0501	0.2851	3.4109	-3.4156
A-F	0.0424	0.3947	2.8350	-2.0408
E-F	0.0925	0.5219	4.2705	-4.6807

Table 4: Mean, standard deviation, maximum value and minimum value of the difference fields between experiment A with experiments E and F and between experiments E and F. (Difference maps are not shown)

The above tables shows that data from ships tends to have a slight positive bias with respect to DRIFTERS. The very low mean in the anomaly field for F and the low standard deviation value is an indication of how limited the global coverage of DRIFTER data really is, in areas void of DRIFTER data the analysis has stayed as the climatological field.

6. OBJECTIVE VERIFICATION

To investigate objectively each of the experiments, each experiment was verified against observations collected for the 26 June 1992, which have not been used in any of the experiments. However, if the verifying observation type was used in the experiment being verified there will not be total independence between the observations and the experiment. This has to be considered when analysing the results.

Each experiment was verified against ship observations, DRIFTER observations and AVHRR observations. The observations were also compared against the climatological sea surface temperature (item G in the figures). The mean and root mean square of observation minus analysis are shown in figures 10a to c.

Against ships (figure 10a)

The ship observations are warmer than any of the experiments, suggesting that the verifying observations have a warm bias. The ship only experiment has the lowest bias which would be expected. The largest bias is against the DRIFTER only experiment again suggesting that ship observations have a warm bias with respect to other *in situ* observing platforms, although part of this bias may be due to the different global distributions of ships and DRIFTERS. It is interesting to note that the AVHRR only experiment has almost the same bias as the *in situ* only experiment but when AVHRR data is used with *in situ* data, either with or without the bias correction scheme, the bias is greater. However, the rms in the AVHRR only experiment is greater, suggesting that there are a greater number of extreme values, both positive and negative. The rms values in the other experiments involving *in situ* data are all about the same value. A possible explanation for these figures is that AVHRR data has resolved both anomalous warm and cool areas better, as was suggested earlier, hence the rms of the AVHRR experiment is greater but the warm and cool areas have cancelled themselves out in the calculation of the mean. We have already suggested that ship data has a warm bias with respect to other *in situ* hence a higher bias in experiments A, C and D. It should be noted that the rms values for all experiments is fairly large, even against the ship only experiment, suggesting that care should be taken when using ship data to verify a SST analysis.

Against DRIFTERS (figure 10b)

We consider DRIFTERS to be the most reliable data source, even if they are not globally distributed, and it is these verification statistics that we attach greatest importance. It can be seen that experiment A has almost no bias and experiment D even less of a bias, therefore the correction scheme is clearly working. Experiment C has a slight positive bias indicating once more that using uncorrected AVHRR data will cool the analysis and using AVHRR only produces an even cooler analysis, as shown by the mean of experiment B. The rms of experiment B is also noticebly larger than experiments A,C or D. So, using AVHRR data ony will produce an analysis with a cold bias and large rms. Combining AVHRR data with *in situ* data without a bias correction scheme produces an analysis still with a cold bias, but less than AVHRR only, and a rms value similar to an *in situ* only analysis. Introducing the bias correction scheme practically eliminates the bias and the rms value remains about the same. Experiment E produces a large negative bias, suggesting once more that ships do have a positive bias with respect to DRIFTERS. The largest negative bias is against climatology, indicating again that the climatology may have a warm bias. It also shows that performing an analysis is more beneficial for NWP than simply relying on a climatological sea surface temperature value.

Against AVHRR (figure 10c)

Experiment A has a bias of almost -0.2K clearly showing that AVHRR data has a negative bias. Experiment E, the ship only analysis, has an even larger negative bias suggesting once more that ship data have a warm bias. Notice that the bias in experiment F, DRIFTER only, is less than half the bias in experiment A again suggesting that ship data has a warm bias. The rms values of experiments B and C suggest that AVHRR will swamp the analysis if the data is used uncorrected. the rms value of experiment D is slightly larger than experiment A but about the same as experiments E and F and against climatology.

The conclusions to be drawn from figures 10b and 10c are that the correction scheme is having the desired effect of eliminating the bias in AVHRR data. Using AVHRR data is beneficial in that it reinforces the detail in areas of high *in situ* data volume and fills in the gaps in areas of low *in situ* data volume. However, using AVHRR data without any correction tends to swamp the *in situ* data. This will be discussed further in the conclusions at the end of the paper.

7. DISCUSSION OF OBSERVATION BIASES

It has been suggested that AVHRR data has a negative bias with respect *in situ* observing platforms but different *in situ* platforms also have differing biases. It is impossible to estimate accurately the relative biases using an analysis such as the one used here because of the different global distributions of the differing types, an observation error has to be assumed in the analysis and to be completely independent the observation type being used as the verification type will need to be left out of the actual assimilation, this means an analysis not using all the available data leading back to problems with observation distributions. A further problem is that not all ships measure the SST in the same way and not all DRIFTERS have the same design and these differences lead to different biases.

Most ships measure the SST using either a bucket lowered into the sea and winched back on board the ship where the temperature is taken using a thermometer, the temperature of the water being drawn in by the engine, this is continually monitored as it is used as a coolant to the engine or a sensor fitted to the outside of the hull. Engine intake thermometers will vary from ship to ship and they are unlikely to be calibrated to the accuracy required for meteorological measurements. Water sampled using the bucket method is unlikely to originate from much below the surface but the water sampled by the other two methods may have originated from a depth of several meters. Kent et al (1991) performed a study of the SST values reported by ships compared to the SST value in the old CYBER model. They found that engine intakes are more scattered and have a warm bias of about 0.3K when compared to either the bucket or hull sensor methods. They also found that this bias increases with the size of the ship as the SST became warmer. A study performed by James and Fox (1972) also found that the engine intake values were warmer on larger ships with respect to buckets compared to smaller ships. Folland et al (1992) also found that bucket SST's were generally cooler than other methods, although only by 0.08K. Furthermore, since measurements from ships are made manually, human error will also have an effect. Although gross errors, eg errors in coding, will be identified by the quality control in the analysis scheme other errors such as parallax errors will not be. At the current time, ships do not report which method they have used to measure the SST hence no differentiation can be made between different ships in the analysis scheme.

We consider DRIFTERS to be the most reliable data source although even these are not without problems. Coding errors may still arise even though the process is automatic, the sensor on the buoy may be damaged leading to incorrect readings or the buoy may beach. Furthermore there are different designs of buoys in operational and these have different characteristics. Three such designs are the Low Cost Tropical Drifter (LCTD), the Low Cost Drifter (LCD) and the Ministar Drifter (MD). Bitterman and Hansen (1993) have studied the biases that these three buoy designs have with regard to high quality conductivity, temperature and depth (CTD) measurements from research ships and expendable bathythermographs which are more numerous but of lower quality than the CTD measurements. They found that all three buoy designs have a positive bias with respect to the CTD measurements of 0.08K (LCTD), 0.27K (LCD) and 0.15K (MD). The LCTD and MD designs show a negative bias with respect to the bathythermograph data. They also found that bathythermographs have a warm bias of 0.29K with respect to the CTD measurements. As with ships, we do not know which type of buoy is reporting hence no differentiation can be made in the analysis scheme.

It has already been stated that AVHRR data have a cold bias with respect to DRIFTER data. This bias is generally under 0.3K except under exceptional circumstances such as high concentrations of Volcanic aerosols, Pichel (1991). Considering the results of Bitterman and Hansen, AVHRR data is probably more accurate than has been generally assumed here and elsewhere.

The analysis scheme attempts to combine all these observations types together to produce a reasonable SST analysis although only an observation error can be assumed, not a systematic bias. Even with AVHRR data, the bias will not be systematic across the globe due to factors such as possible cloud and isolated pockets of aerosols contaminating the product. Allowing for all these factors, the SST analysis is a good representation of reality and is of more benefit to the NWP model than simply relying upon a climatological prescribed SST field.

8. ATSR DATA

The ERS-1 satellite was launched on 17th July 1991. One of the instruments carried is the along track scanning radiometer (ATSR) specifically designed to measure the skin sea surface temperature. The ATSR is a four channel radiometer, like AVHRR, but it differs from AVHRR in that the surface of the sea is measured at the same location through both a forward and nadir view. This dual view technique means that ATSR data is affected far less by atmospheric attenuation, especially in times of high concentrations of volcanic aerosols. If one of the views is cloudy then a SST value using just the single view is produced. It is important to note that the ATSR product is the skin SST measured, ie. it has not been converted to a pseudo-bulk SST as is done with AVHRR data. A full description of the ATSR can be found in Edwards et al (1990).

Since November 1991, near real time (NRT) ATSR products have been received and archived in the meteorological data base. The quality of the data has been assessed with a view of using this new data source in the operational SST analysis. Results of this study will be found in Saunders et al (1993).

Some experiments using ATSR data in the SST analysis have been performed and are described here. All experiments started from the climatological field for the 31 January and data was assimilated for the period 1 February 1993 to 28 February 1993, as with the previous experiments this avoids any 'spin-up' errors. The aims of these experiments were; to compare the extra information given by ATSR data to *in situ* data with the extra information given by AVHRR data, to see the impact of using ATSR data in the operational system and to assess how well the bias correction scheme deals with data that has a large bias. The experiments performed were;

ATSR A) *In situ* data only.

ATSR B) ATSR data only.

ATSR C) *In situ* data and AVHRR data with bias correction.

ATSR D) *In situ* data and ATSR data with bias correction.

ATSR E) *In situ* data and AVHRR data and ATSR data with bias correction.

Saunders et al show that dual view ATSR soundings are superior to single view soundings and therefore only dual view ATSR soundings are used in the test analyses. Furthermore, the channel used for cloud screening at night is no longer working and Saunders et al also show that this has resulted in a deterioration in the quality of the nighttime data. Therefore, although nighttime data is used in the assimilation, separate corrections are calculated for day and nighttime data.

Note that ATSR experiments A and C are repeats of the earlier experiments A and D but for a different period of time.

Figure 11a shows the global distribution of day ATSR data for the month of February and figure 11b shows the global distribution of night ATSR data for the same period The satellite is in a 35-day repeat orbit, which means that it passes over the same path on the earth's surface every 35 days. Thus, the 28 days shown here is not quite the full data coverage that is possible.

it is clear that the eastern Indian Ocean/Australia area is only covered at night whereas the area either side of the Americas is only covered at day. This is because the NRT system can only process 10 out of the 14 available orbits each day. Also clearly seen is the lack of data for high latitudes, especially the North Atlantic, this is due to imperfections in the cloud screening routines used in the NRT system.

Figures 12a and b show the anomalies from climatology of experiments ATSR A and ATSR B. The bias in the ATSR data is clearly seen, with most areas having a negative anomaly. However, if the bias is ignored and the patterns studied, then many similarities emerge. For instance, the warm area in the SE Pacific is evident, as is the cold region stretching from Cape Horn to the central Pacific. The warm eddy at the tip of the Cape of Good Hope is seen in both patterns as is the cooler waters around Australia. Thus, the data is biased but it is identifying the features that are present in the SST field.

Figures 13a to c show the anomalies of experiments ATSR C,D and E respectively. The anomaly patterns in all three charts are very similar and when compared to figure 12a, similar results as those in the earlier experiments are found. That is, very little difference in areas when *in situ* data is sufficient but anomalies better resolved in areas where *in situ* data is sparse. It appears that ATSR data is given us broadly the same additional information as AVHRR data,

Figures 14a to c show maps of experiments ATSR C minus ATSR A, ATSR D minus ATSR A and ATSR E minus ATSR A. Figures 14a and 14b confirm once again that ATSR data is providing similar information as that provided by AVHRR, although AVHRR data does appear to be providing more additional information. Figure 14c is very similar to figure 14a with only minor differences.

Figure 15a shows experiment ATSR E minus ATSR C and figure 15b shows experiment ATSR E minus ATSR D. Figure 15a is effectively showing what information would be lost if ATSR data was not used in the analysis and figure 15b is showing what information would be lost if AVHRR data was not used in the analysis. As would be expected from the previous maps, more information would be lost if AVHRR data was not used in the analysis, although again this is due more to the relative weighting in the analysis rather than the data itself. Figure 16 shows the SST analysis produced by experiment ATSR E.

EXPERIMENT	ANALYSIS		ANOMALY	
	Mean	SD	Mean	SD
ATSR A	18.2498	10.0773	0.0515	0.6139
ATSR B	17.5370	9.95787	-0.7041	0.5930
ATSR C	18.2330	10.0900	0.0338	0.6645
ATSR D	18.1830	10.0815	-0.0193	0.6108
ATSR E	18.1953	10.0850	-0.0062	0.6507

Table 5: Mean and standard deviation (degrees C) of the analysis and anomaly fields created by ATSR experiments A to E.

This table shows that ATSR has a mean bias of about 0.7K when compared to *in situ* data. The analysis field also has a lower standard deviation which is probably explained by the fact that ATSR data does not extend into high latitudes. In these areas the analysis field have been maintained at the climatological field which would be warmer than any ATSR measurement, hence less temperature range. The table also confirms that the bias correction scheme eliminates most of the bias in the data.

These experiments show that allowing for the skin-bulk bias, ATSR data is providing broadly the same information as that provided by AVHRR data. Therefore, should AVHRR data cease completely ATSR data could be used instead. This fact is an encouraging signal for ATSR data as it shows that the instrument is working correctly. The experiments also show that the satellite bias correction scheme developed can successfully correct data that has a relatively large bias.

ATSR data does have advantages over AVHRR data. Firstly, because the dual view technique is largely unaffected by volcanic aerosols it will be more consistence over time. Secondly, the ATSR products are provided at a far higher spatial resolution, 0.5 degree averages opposed to one observation per 2.5 degree box, thus there is a potential for far more detail to be analyzed on limited area grids. For the UK area this would require data for the North Atlantic which is not provided at the current time.

9. CONCLUSIONS

This report has described a satellite bias correction scheme and has described several experiments which demonstrate that the scheme is having the desired affect. The scheme is rather *ad hoc* , being more pragmatic than based on theory, but it does work. It was introduced into the operational system in December 1992.

Also highlighted are some of the problems associated with *in situ* data, the inadequate data coverage and difficulty in determining the accuracy of various observation types as the method of observing is unknown. Satellite data has the advantage of providing global data and the accuracy of the observations, or at least the bias in the data, is understood more precisely. Unfortunately, a systematic bias cannot be assumed for satellite data due to local effects such as isolated aerosol pockets.

If satellite data was not used the analysis would be dominated by the climatological field in areas of low data volume. The objective verification of the experiments (see section 7) shows that an AVHRR analysis is better than climatology when compared to both ship and drifter data. It therefore follows that using AVHRR data to fill in the detail missed by the *in situ* data coverage is better than simply allowing the field to revert to climatology. However, if AVHRR data is used with no corrections it dominates areas with sufficent *in situ* data sources damaging the analysis, this is what the bias correction scheme prevents. We refer to areas of low *in situ* data volme but even in these areas it is unlikely that a very long period would pass without any ship data at all. The analysis scheme allows data sources to have a large influence radius (1000km) so isolated ships will influence a large area, although with decreasing effect as we move away from the data source. As was explained in section 4, the bias correction scheme has a long memory of any isolated *in situ* data source and therefore it is unlikely that the analysis will become totally dominated by biased AVHRR data in any one area.

The most accurate satellite instrument to date has been the AVHRR but as we have seen this instrument does suffer from atmospheric contamination. The ATSR is designed to be free of such atmospheric contamination and the results to date, eg Saunders et al (1993), indicate that this is largely the case. Both instruments can contribute an important part in operational SST analyses as it is far better to have too much good data than not enough data.

The experiments involving ATSR data show that introducing the data into the operational analysis would not have a detrimental affect on the analyses. They also show that the bias correction scheme can successfully correct data with a large bias, even in areas with low *in situ* data volumes, confirming that the analysis does have memory of isolated *in situ* data reports. However, for the time being ATSR data will not be used. The reason for this is that the NRT system is still being developed. Work is underway to solve the cloud screening problem for high latitudes, to enable the NRT system to process all 14 orbits each day and the algorithms that produce SST products still need some additional tuning. When some or all of this work is done then the situation will be reassessed and there may be a future requirement of additional SST analyses such as an operational ATSR only analysis.

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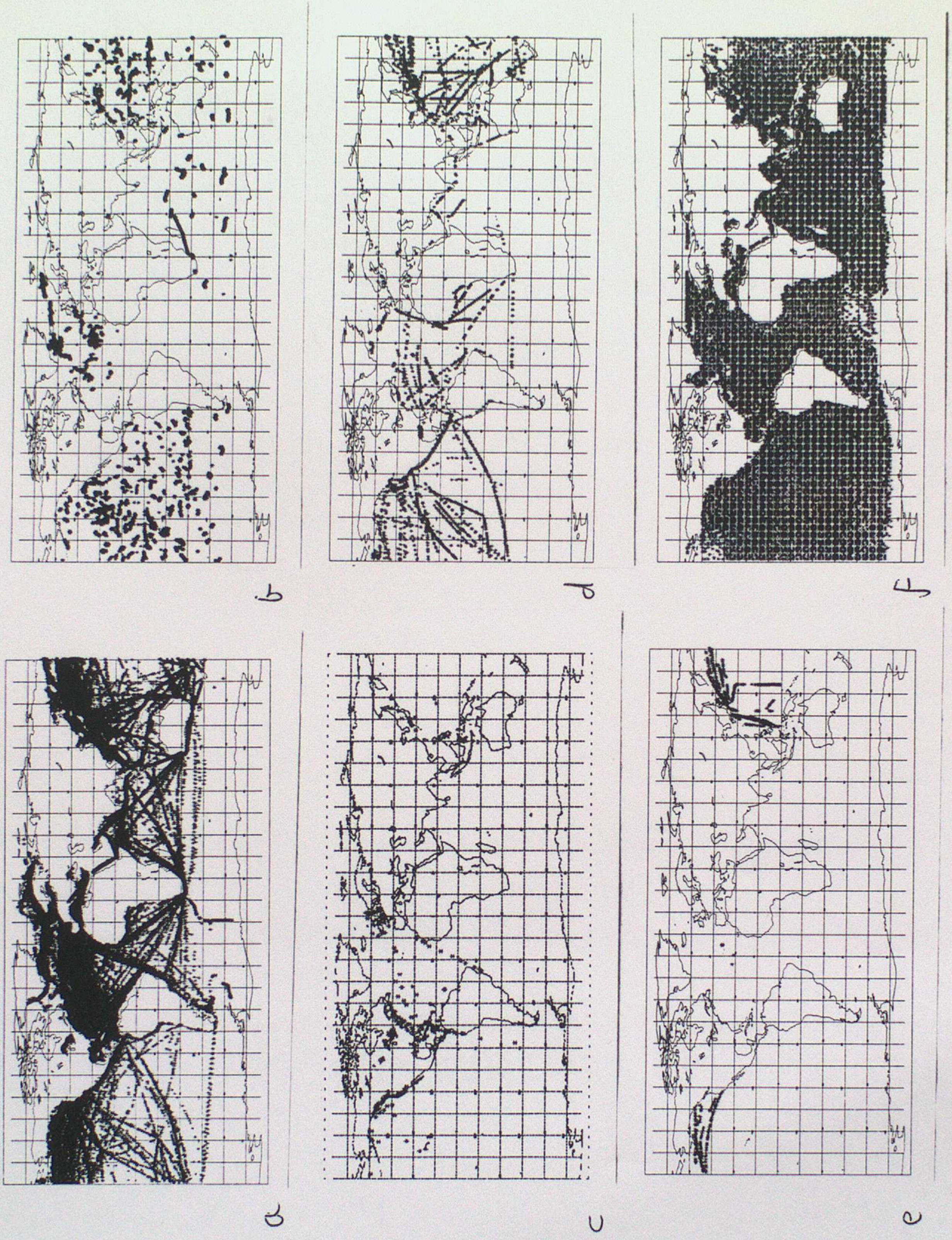
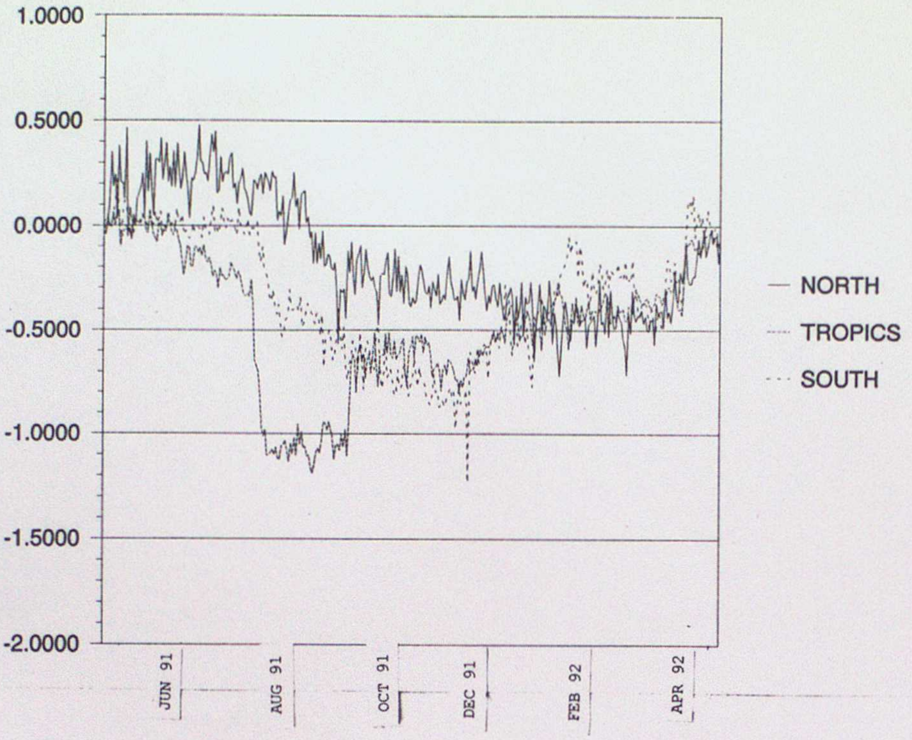


Figure 1 a-f: Distributions of observations received for the period 25 May 1992 to 24 June 1992. Each '*' indicates that an observation has been received at that location. a-ships, b-drifters, c-fixed buoys, d-bathythermospheres, e-trackobs, f-AVHRR products (one observation per 2.5 degrees box).



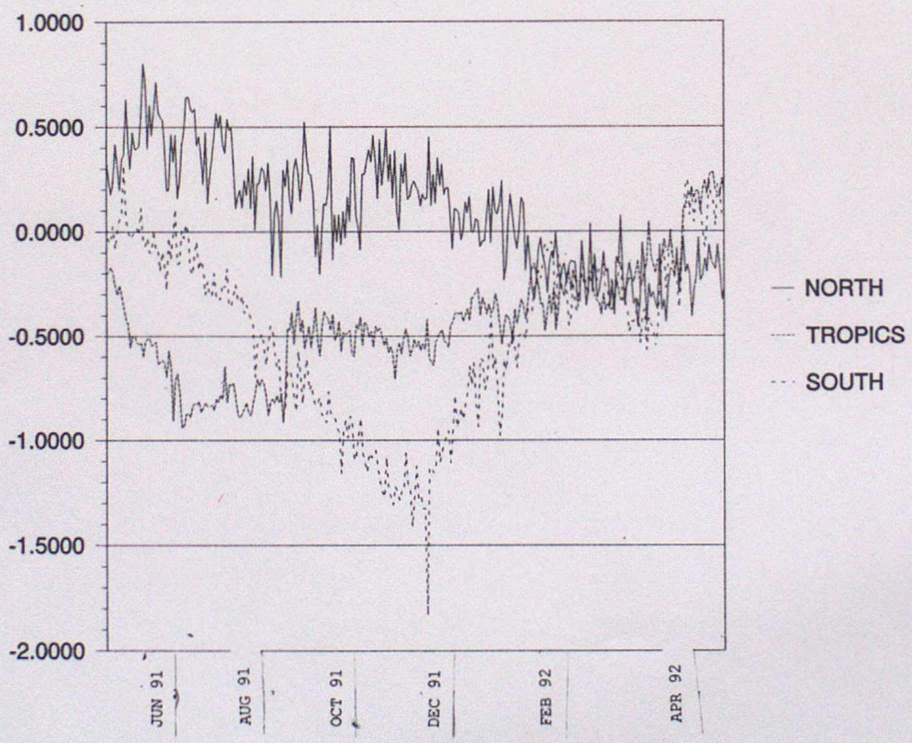


Figure 2 a -b: Zonally averaged time series of AVHRR observation minus analysis (2a - top) and AVHRR observation minus climatology (2b) from May 1991 to May 1992. Solid line northern hemisphere (90N to 30N), dashed line tropics (30N to 30S) and dash dot dot line is the southern hemisphere (30S to 90S).

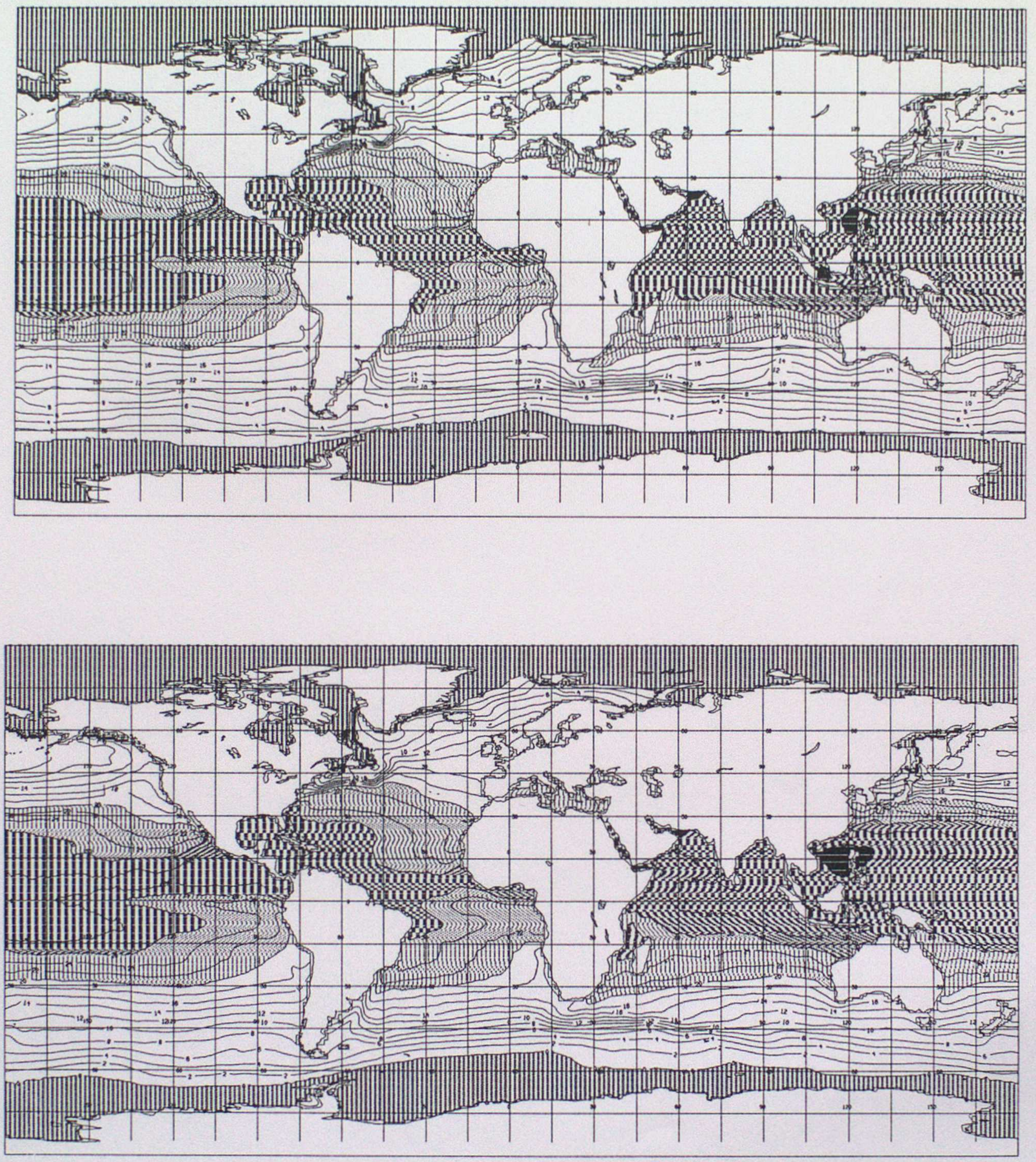


Figure 3 a-b: Analysis using *in situ* data only , experiment A (top) and analysis using AVHRR data only, experiment B. Contours drawn at every 2K. 'x' indicates sub-zero areas (mainly seaice covered areas), light shading is for 20°C to 26°C, medium shading is for 26°C to 30°C and dark shading is for above 30°C.

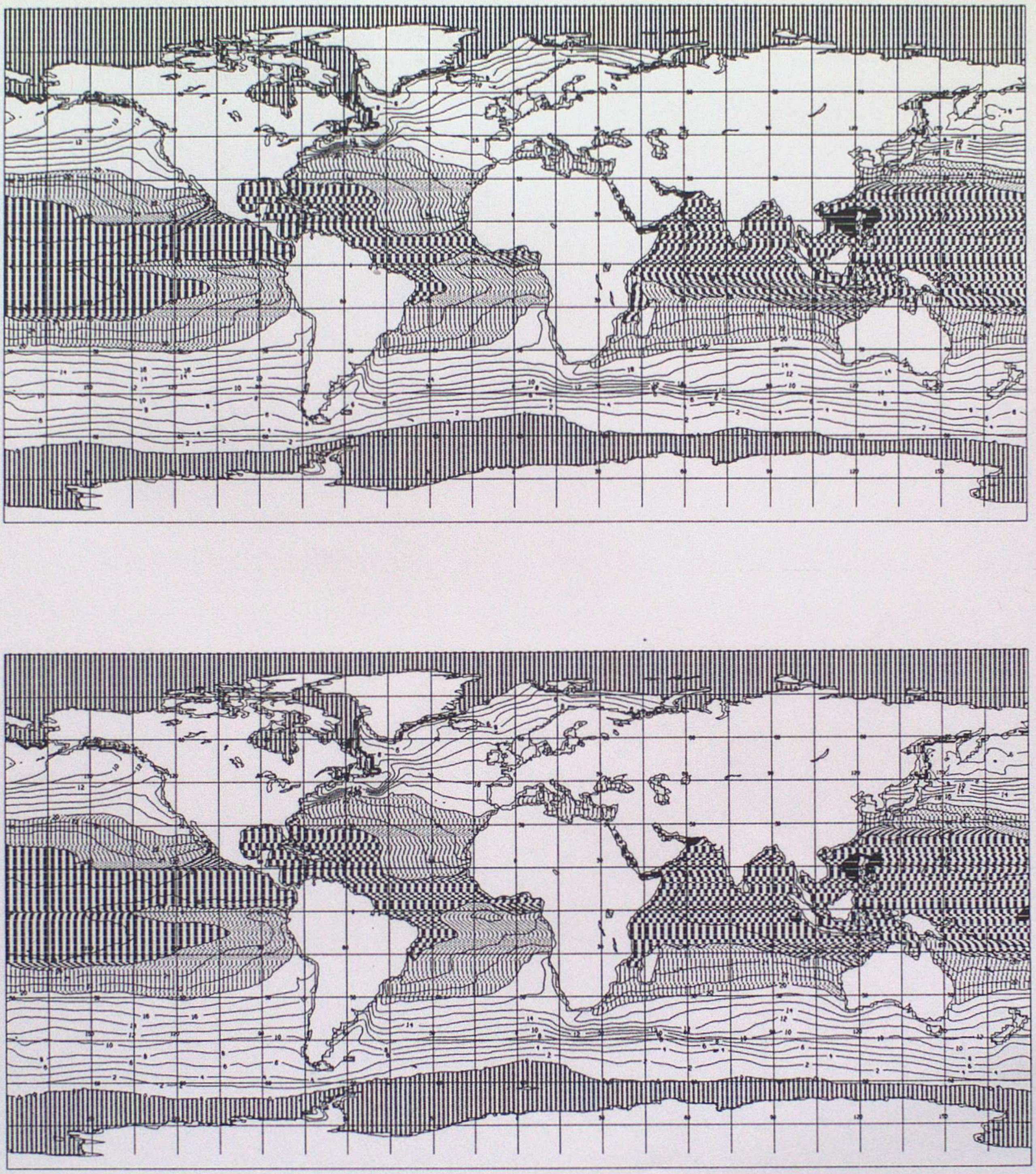


Figure 3 c-d: Analysis using *in situ* and AVHRR data without bias correction scheme, experiment C (top) and analysis using *in situ* and AVHRR data with bias correction scheme, experiment D. Contours drawn at every 2K. 'x' indicates sub-zero areas (mainly seaice covered areas), light shading is for 20°C to 26°C, medium shading is for 26°C to 30°C and dark shading is for above 30°C.

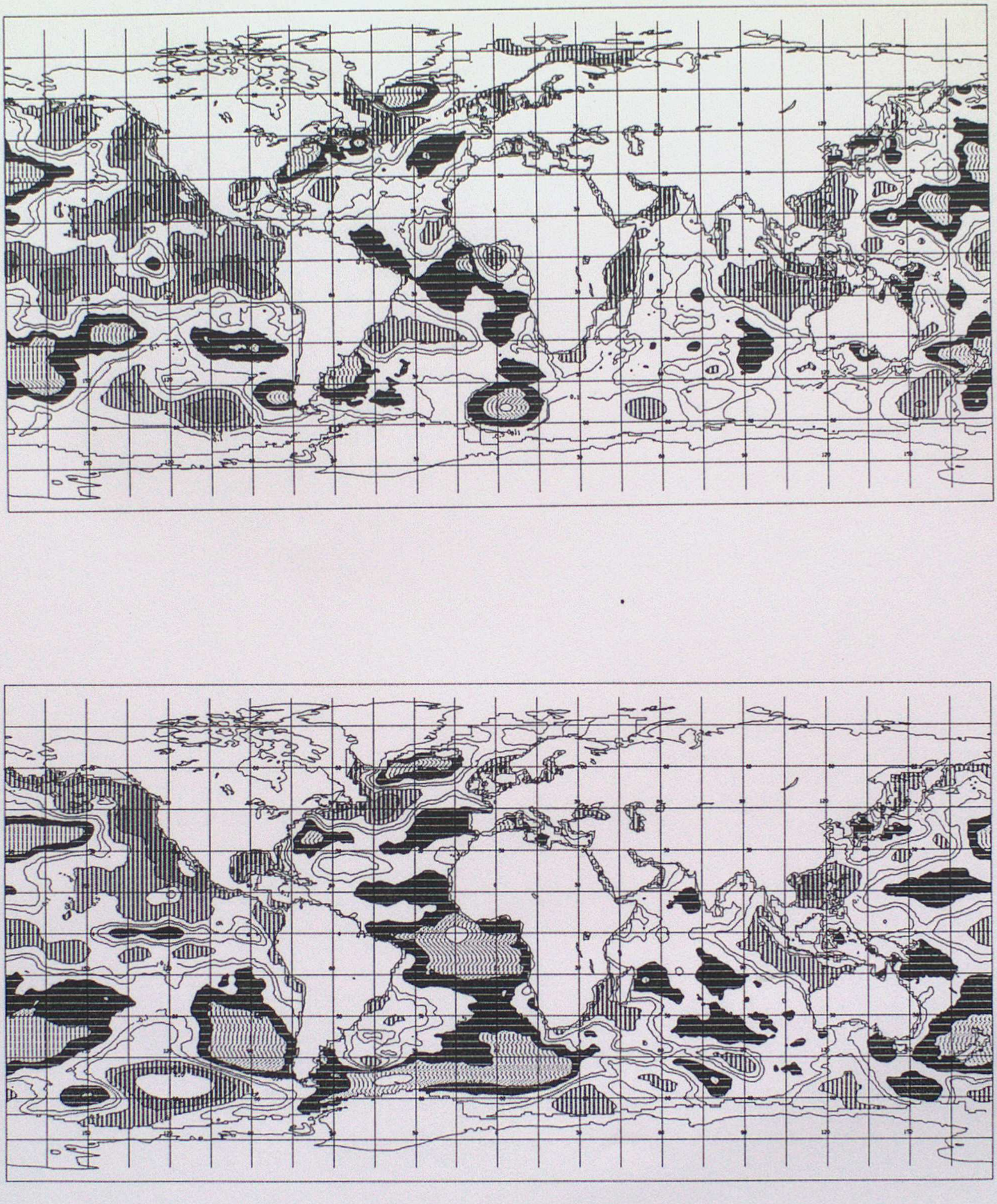


Figure 4 a-b: Anomalies from climatology using *in situ* data only , experiment A (top) and anomalies from climatology using AVHRR data only, experiment B. Contours drawn at -2.0°C, -1.0°C, -0.5 °C, -0.1°C, 0.1°C, 0.5°C, 1.0°C, 2.0°C. Dots indicate -2.0°C to -1.0°C, line shading indicate -1.0°C to -0.5°C, 'x' indicate 0.5°C to 1.0°C and '*' indicate 1.0°C to 2.0°C.

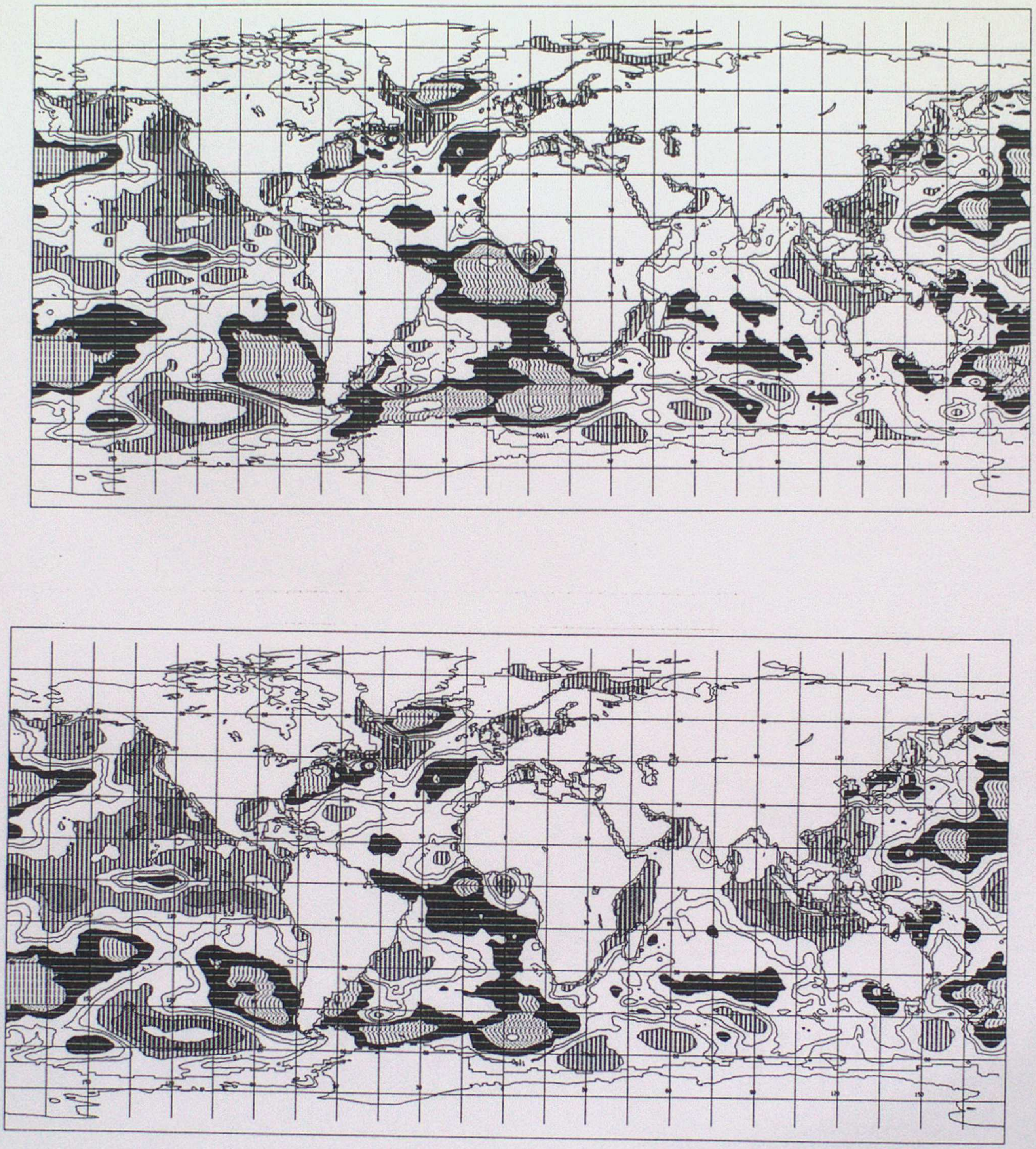
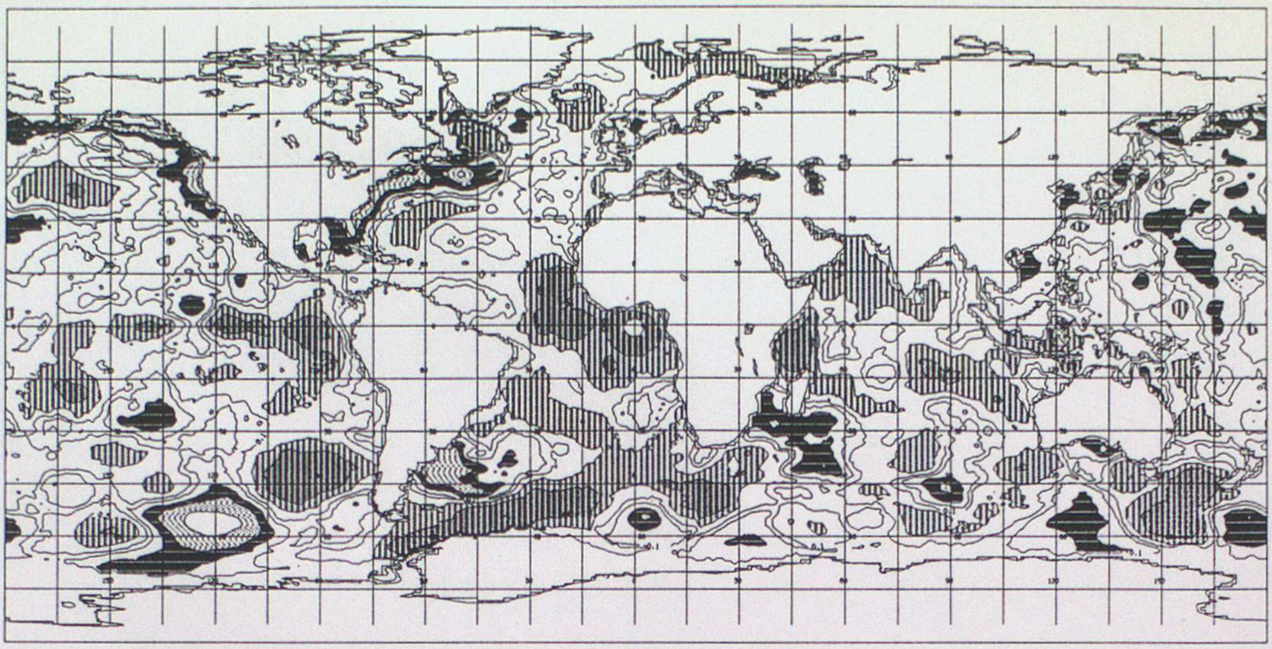


Figure 4 c-d: Anomalies from climatology using *in situ* and AVHRR data without bias correction scheme, experiment C (top) and anomalies from climatology using *in situ* and AVHRR data with bias correction scheme, experiment D. Contours drawn at -2.0°C, -1.0°C, -0.5 °C, -0.1°C, 0.1°C, 0.5°C, 1.0°C, 2.0°C. Dots indicate -2.0°C to -1.0°C, line shading indicate -1.0°C to -0.5°C, 'x' indicate 0.5°C to 1.0°C and '*' indicate 1.0°C to 2.0°C.



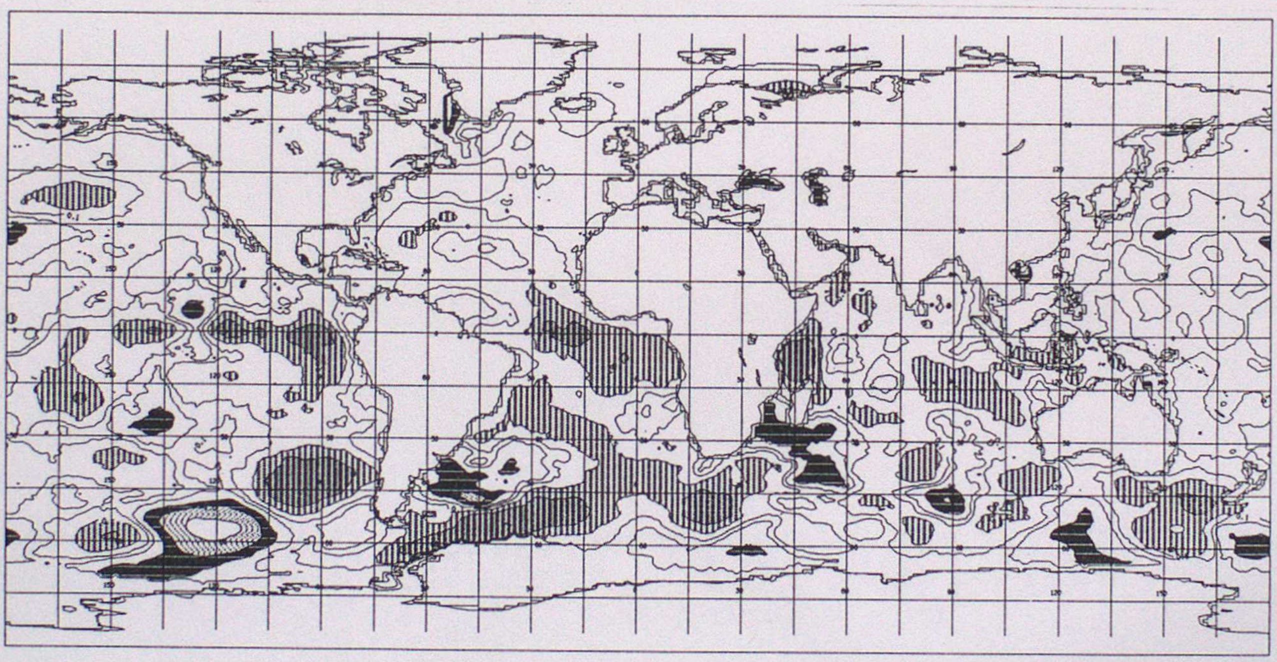
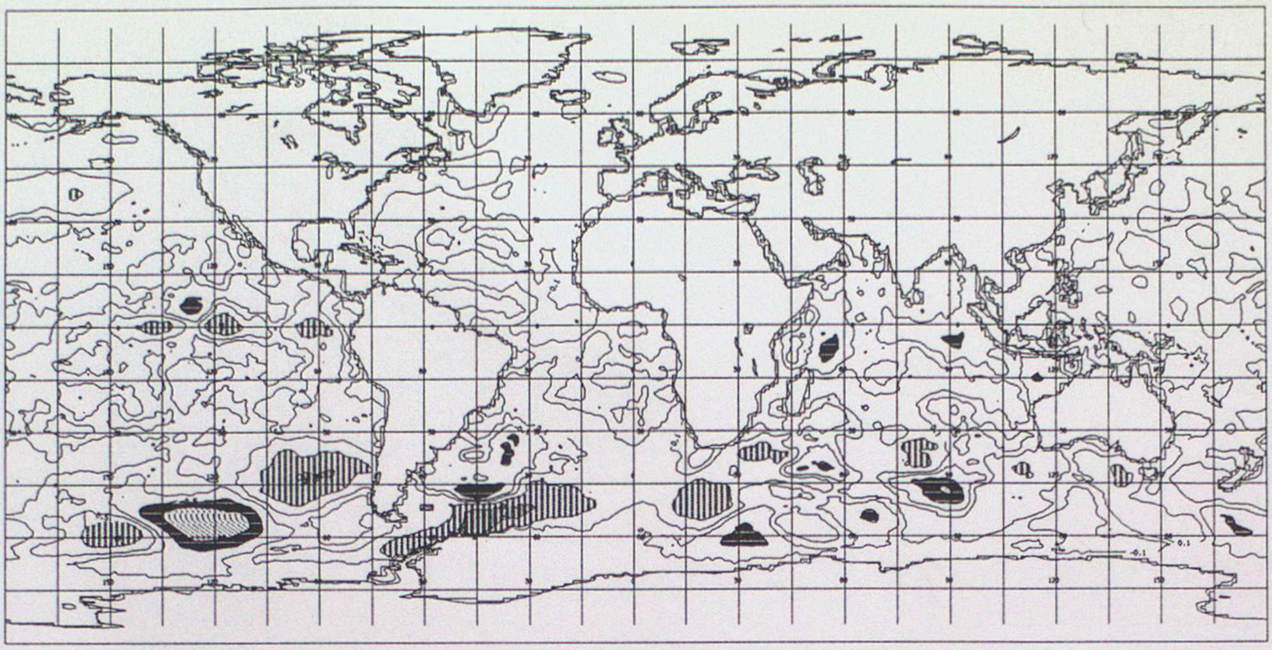


Figure 5 a-b: Difference fields of *in situ* data only minus AVHRR data only, experiment A minus experiment B (top) and difference field of *in situ* data only minus *in situ* and AVHRR data without bias correction, experiment A minus experiment C. Contours drawn at -2.0°C, -1.0°C, -0.5 °C, -0.1°C, 0.1°C, 0.5°C, 1.0°C, 2.0°C. Dots indicate -2.0°C to -1.0°C, line shading indicate -1.0°C to -0.5°C, 'x' indicate 0.5°C to 1.0°C and '*' indicate 1.0°C to 2.0°C.



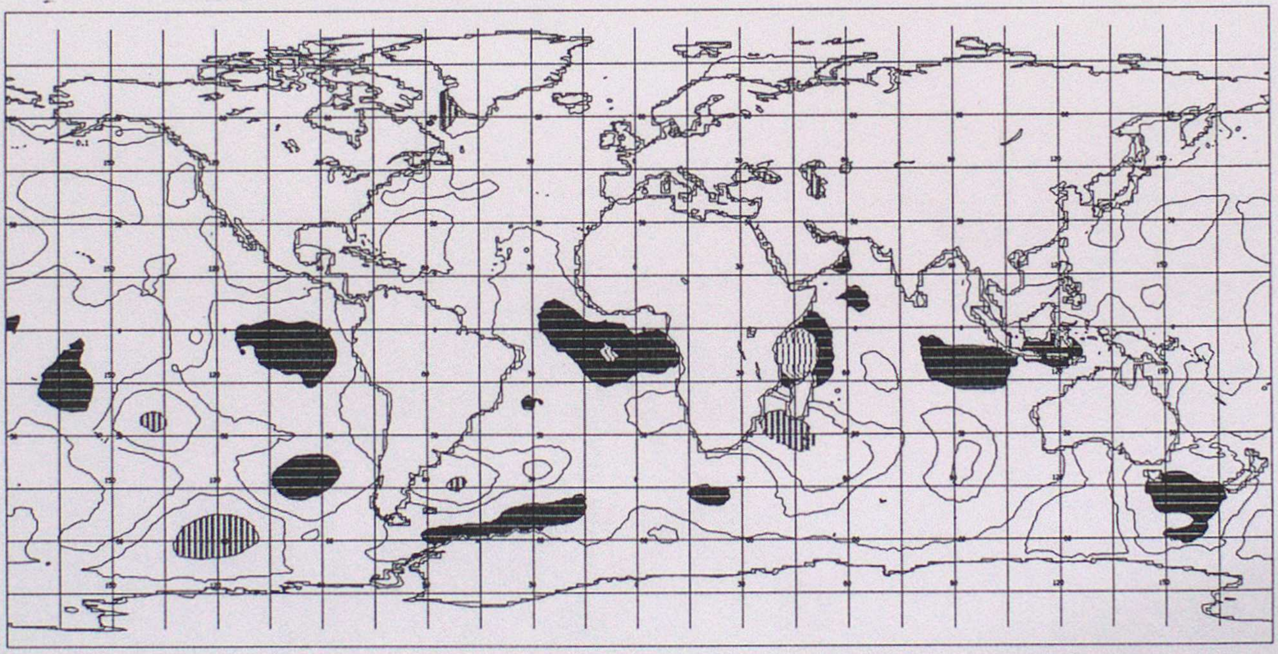


Figure 5 c-d: Difference fields of *in situ* data only minus *in situ* and AVHRR with bias correction, experiment A minus experiment D (top) and difference field of *in situ* data and AVHRR with bias correction and *in situ* data and AVHRR data without bias correction, experiment D minus experiment C. Contours drawn at -2.0°C, -1.0°C, -0.5 °C, -0.1°C, 0.1°C, 0.5°C, 1.0°C, 2.0°C. Dots indicate -2.0°C to -1.0°C, line shading indicate -1.0°C to -0.5°C, 'x' indicate 0.5°C to 1.0°C and '*' indicate 1.0°C to 2.0°C.

Figure 6 a-b: Mean observation density (in AC scheme) of *in situ* data (top) and AVHRR data over the assimilation period. Contours drawn at 0, 5, 10, 20, 30, 40, 50, 60, 70, 80, 100, 150, 200, 250, 300, 350, 400, 500, 800, 1000. Dot shading indicates 50 to 100, dashed shading indicates 100 to 250, '*' indicates 250 to 500 and line shading indicates 500 to 1000.

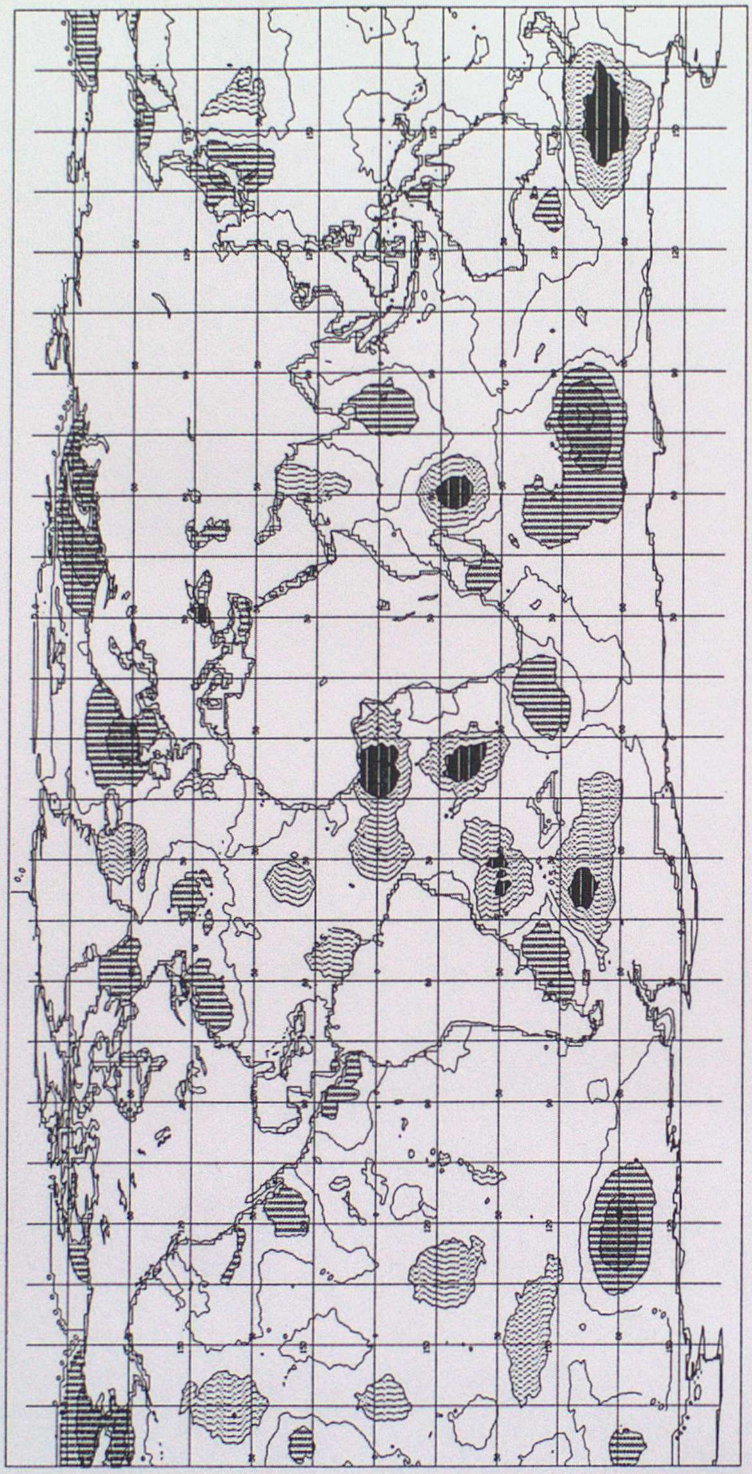


Figure 7: Mean difference of *in situ* only analysis and AVHRR only analysis performed within the satellite bias correction scheme, ie the mean corrections applied to the AVHRR data. Contours drawn at -2.0°C, -1.0°C, -0.5 °C, -0.0°C, 0.5°C, 1.0°C, 2.0°C. '*' indicate -2.0°C to -1.0°C, 'x' indicate -1.0°C to -0.5°C, dots indicate 0.5°C to 1.0°C and line shading indicates 1.0°C to 2.0°C.

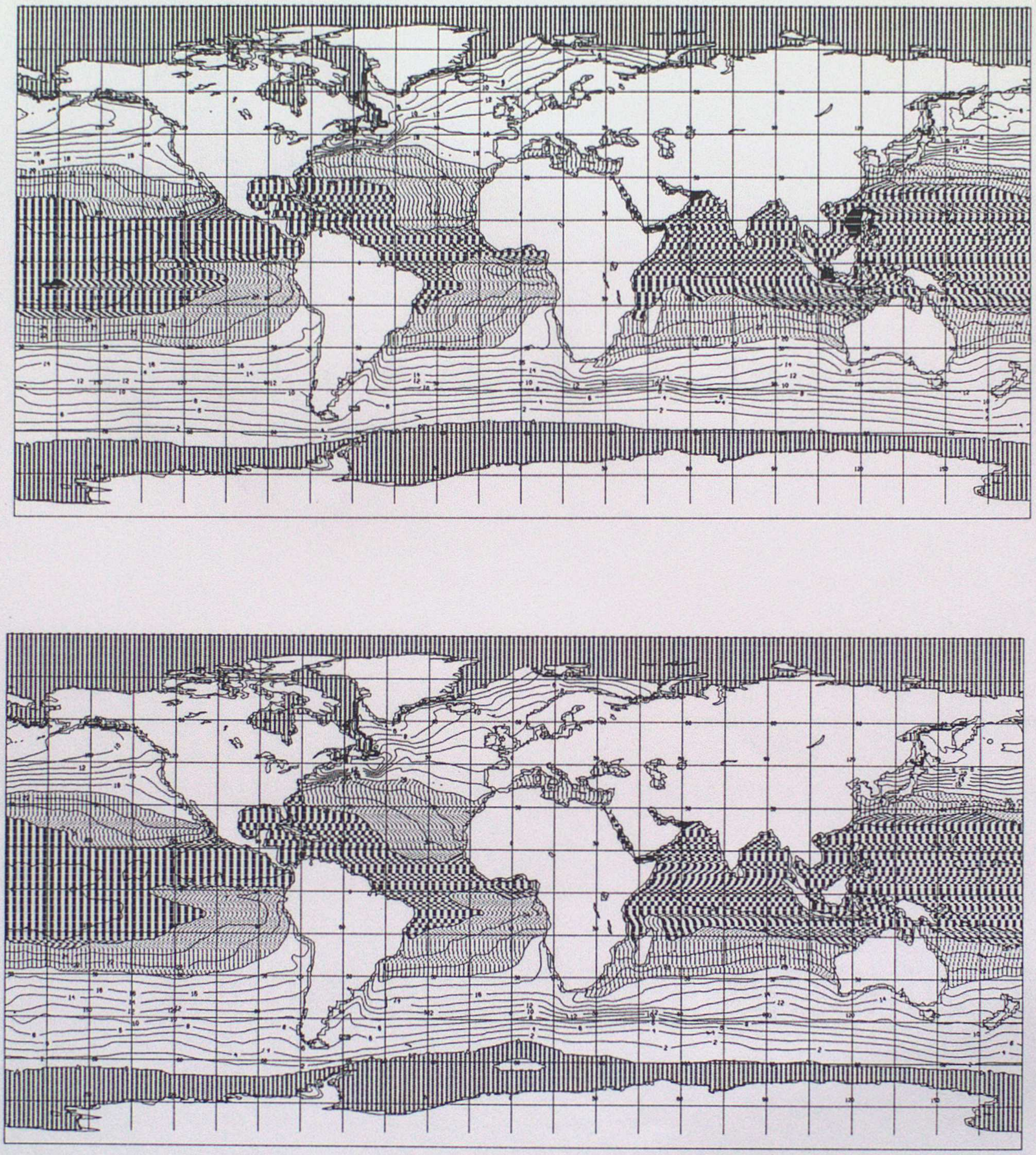
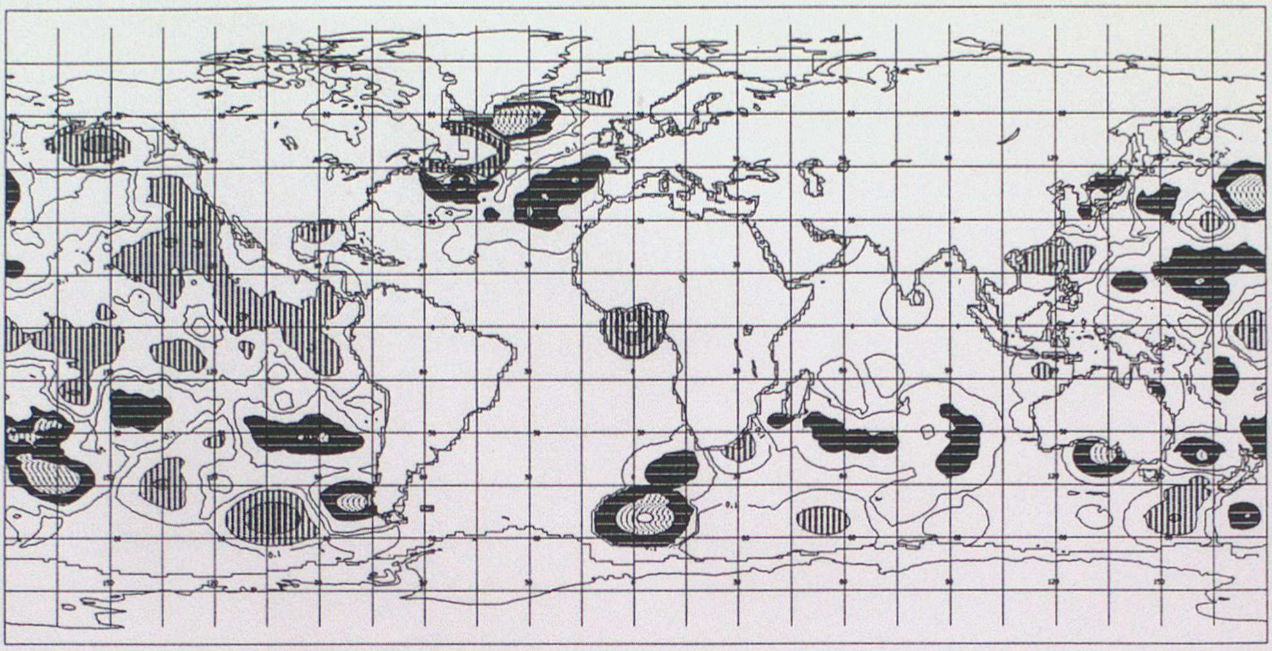


Figure 8 a-b: Ship only analysis, experiment E (top) and drifter only analysis, experiment F. Contours drawn at every 2K. 'x' indicates sub-zero areas (mainly seaice covered areas), light shading is for 20°C to 26°C, medium shading is for 26°C to 30°C and dark shading is for above 30°C.



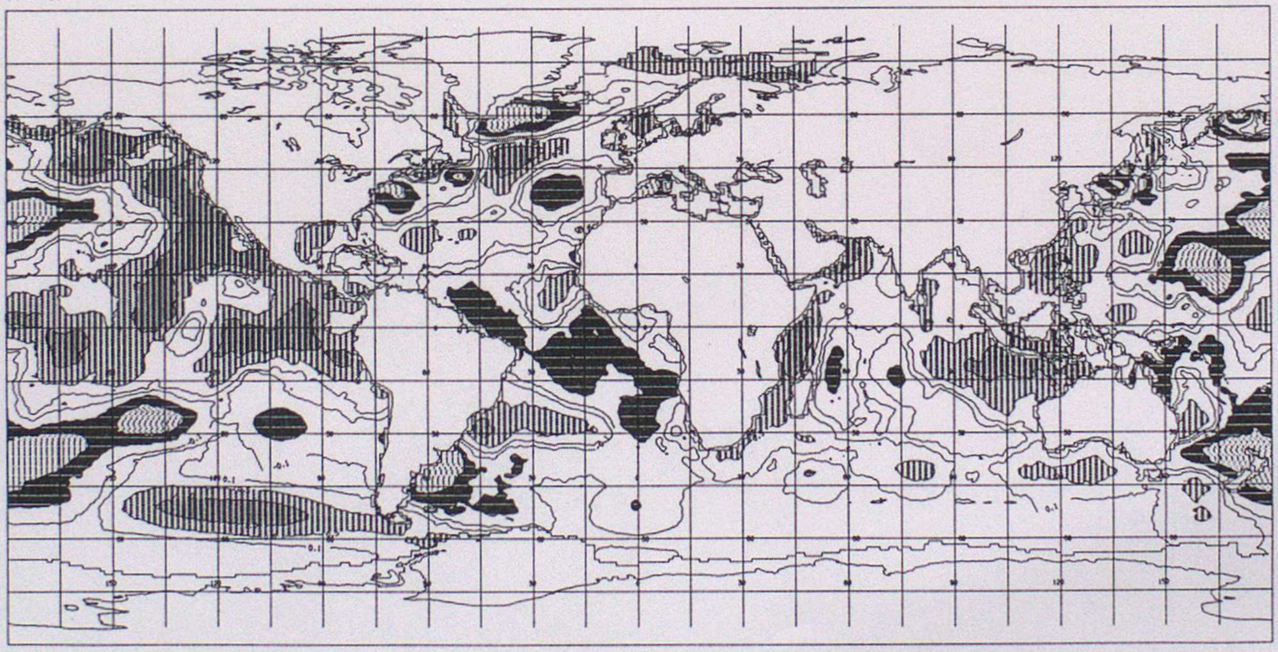


Figure 9 a-b: Anomalies from climatology using ship only data, experiment E (top) and anomalies from climatology using only drifter data, experiment F. Contours drawn at -2.0°C, -1.0°C, -0.5 °C, -0.1°C, 0.1°C, 0.5°C, 1.0°C, 2.0°C. Dots indicate -2.0°C to -1.0°C, line shading indicate -1.0°C to -0.5°C, 'x' indicate 0.5°C to 1.0°C and '*' indicate 1.0°C to 2.0°C.

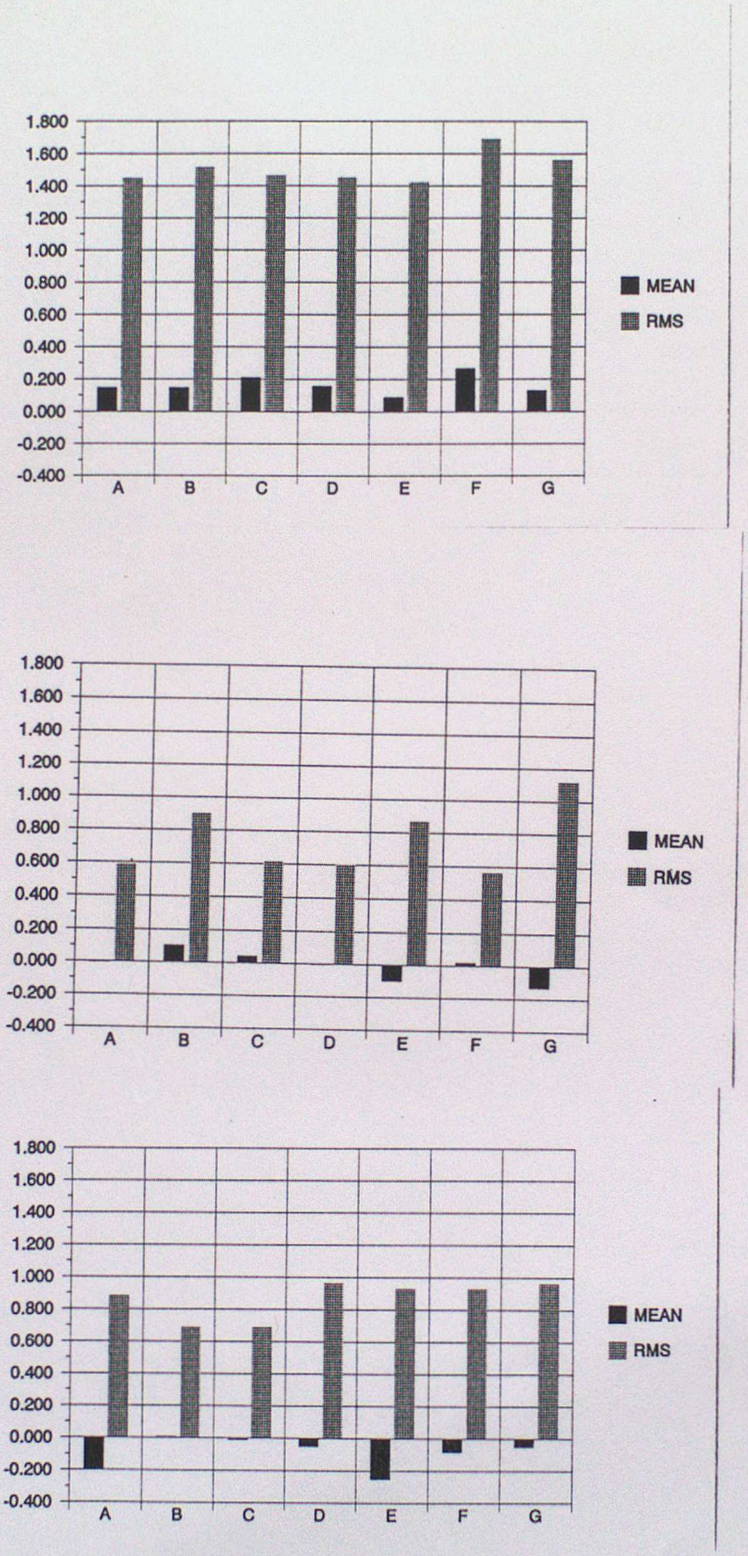
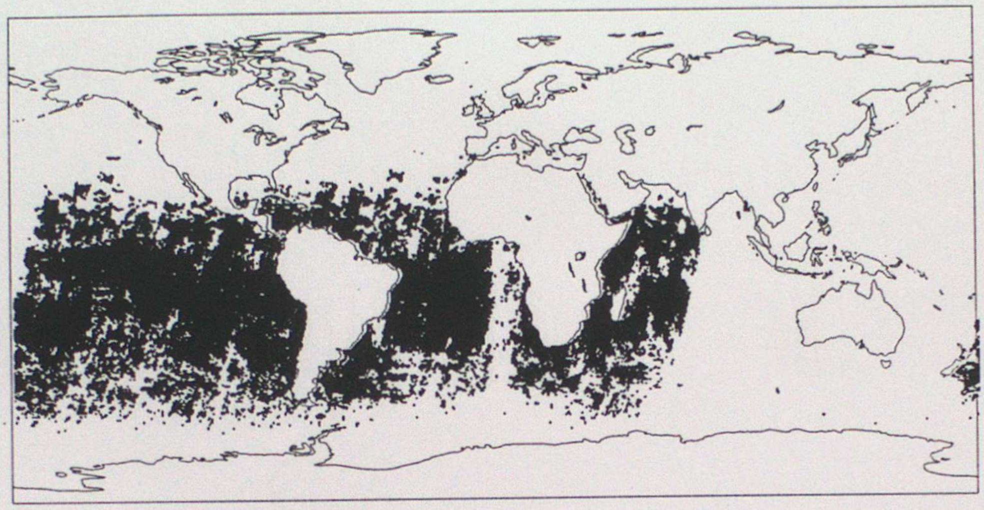


Figure 10 a-c: Mean and root mean square of observations for the 26 June 1992 against experiments A to F and climatology (G). Verifying observations are ships (top), drifters (middle) and AVHRR.



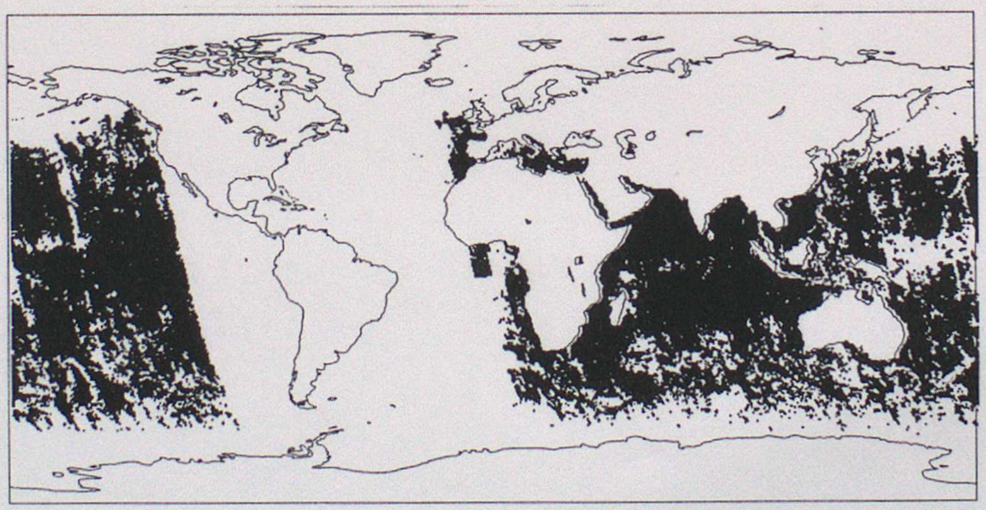


Figure 11 a-b: Distribution of ATSR daytime data (top) and nighttime data received for February 1993.

Figure 12 a-b: Anomalies from climatology of ATSR experiment A, *in situ* data only (top) and experiment B, ATSR data only. ATSR data used is dual views only but both day and nighttime. Contours drawn at -2.0°C, -1.0°C, -0.5 °C, -0.1°C, 0.1°C, 0.5°C, 1.0°C, 2.0°C. Dots indicate -2.0°C to -1.0°C, line shading indicate -1.0°C to -0.5°C, 'x' indicate 0.5°C to 1.0°C and '*' indicate 1.0°C to 2.0°C.

Figure 13 a-c: Anomalies from climatology of ATSR experiment C, *in situ* and AVHRR data with bias correction (top), ATSR experiment D, *in situ* and ATSR data with bias correction (middle) and ATSR experiment E, *in situ* and AVHRR and ATSR data with bias corrections. Contours drawn at -2.0°C, -1.0°C, -0.5 °C, -0.1°C, 0.1°C, 0.5°C, 1.0°C, 2.0°C. Dots indicate -2.0°C to -1.0°C, line shading indicate -1.0°C to -0.5°C, 'x' indicate 0.5°C to 1.0°C and '*' indicate 1.0°C to 2.0°C.

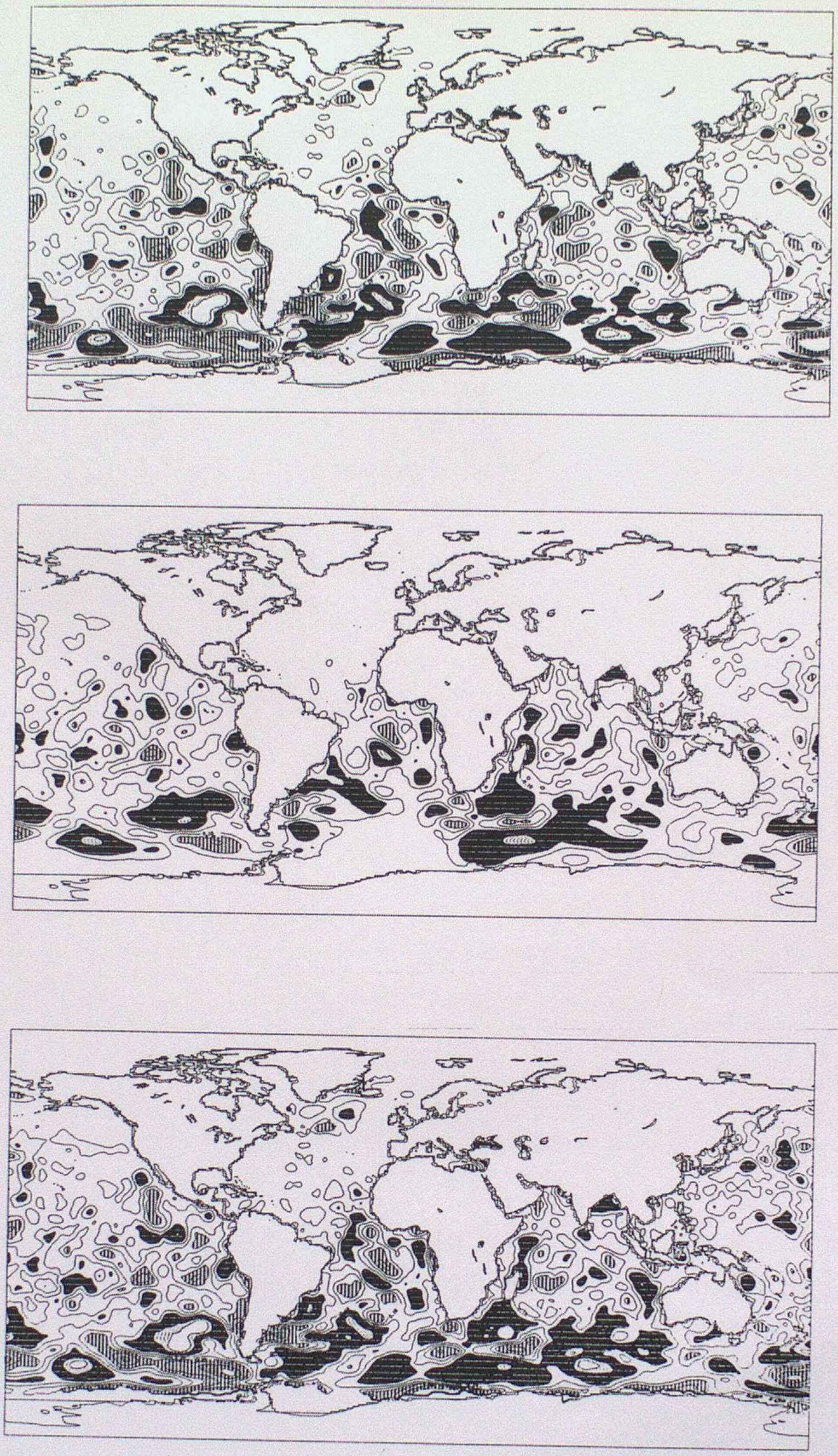


Figure 14 a-c: Differences of ATSR experiment C minus ATSR experiment A (top), ATSR experiment D minus ATSR experiment A (middle) and ATSR experiment E minus ATSR experiment A. Contours drawn at -1.0°C, -0.75°C, -0.5 °C, -0.25°C, 0.0°C, 0.25°C, 0.5°C, 0.75, 1.0°C. Dots indicate -1.0°C to -0.75°C, line shading indicate -0.75°C to -0.25°C, 'x' indicate 0.25°C to 0.75°C and '*' indicate 0.75°C to 1.0°C.

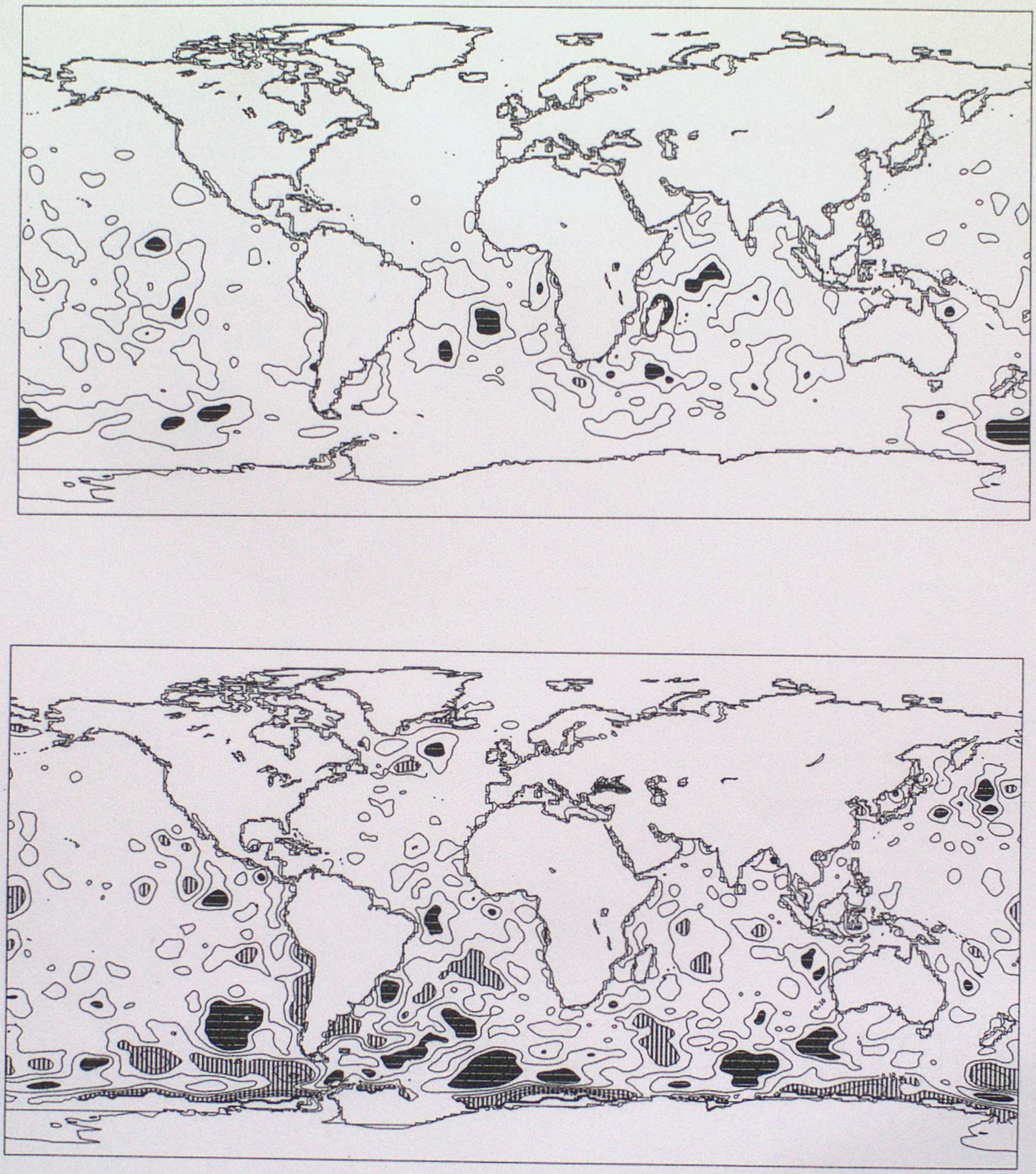


Figure 15 a-b: Differences of ATSR experiment E minus ATSR experiment C (top) and ATSR experiment E minus ATSR experiment D. Contours drawn at -1.0°C, -0.75°C, -0.5 °C, -0.25°C, 0.0°C, 0.25°C, 0.5°C, 0.75, 1.0°C. Dots indicate -1.0°C to -0.75°C, line shading indicate -0.75°C to -0.25°C, 'x' indicate 0.25°C to 0.75°C and '*' indicate 0.75°C to 1.0°C.

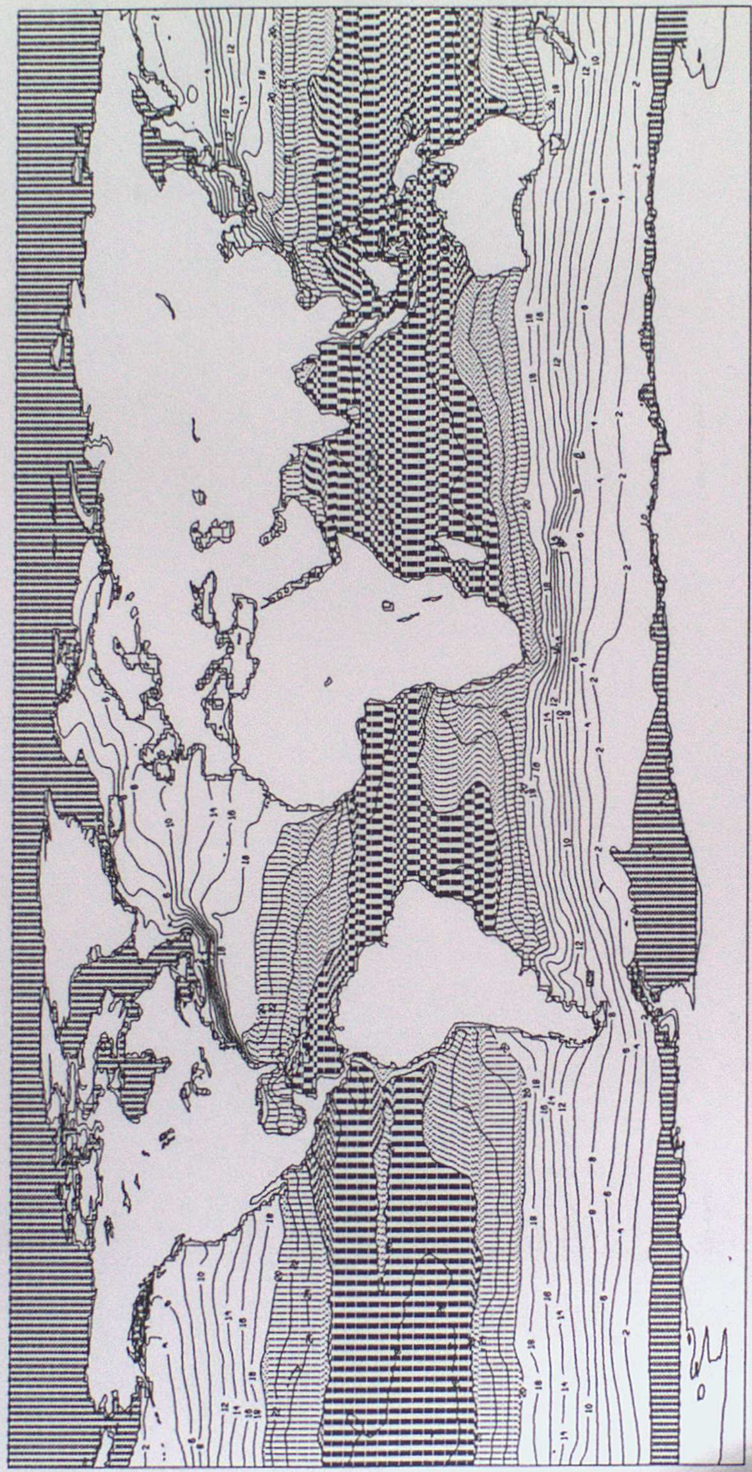


Figure 16: SST analysis using *in situ* data, AVHRR data and ATSR data. The satellite data is used with the bias correction scheme and separate corrections are calculated for AVHRR data, ATSR daytime data and ATSR nighttime data.