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A bias correction scheme for simulated TOVS brightness temperatures

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1. INTRODUCTION

All modern systems for retrieving or assimilating information from satellite sounding radiances include schemes for simulating the radiances (or brightness temperatures) corresponding to collocated forecast or radiosonde profiles. These calculations are required either as part of the real-time retrieval/assimilation processes or in off-line monitoring and tuning activities or in both. The radiative transfer models involved are subject to errors. The random components of these errors are usually important, in that they are comparable to or greater than the instrument noise and so are a significant part of the "total system noise". They should therefore be taken into account when determining the appropriate weight to give to the radiance data (see *Eyre*, 1989). Equally if not more important are the systematic errors in the radiative transfer models which arise mainly from errors in the spectroscopic data on which the radiative transfer model are based. Although active research continues in atmospheric spectroscopy in order to reduce these errors, it is clear that, for the foreseeable future, they will continue to be significant, i.e. comparable to or greater than the total system noise. More importantly, they are often comparable to the radiance changes corresponding to typical errors in the atmospheric temperature field in short-range forecasts from a numerical weather prediction (NWP) model. Unless radiative transfer errors are controlled and corrected to below this level, it is difficult to use the measured radiances to positive effect in NWP.

The importance of the radiance bias problem has been recognized for many years and empirical correction schemes have been developed (e.g see *Smith et al.*, 1984; *Chedin and Scott*, 1984; *Susskind et al.*, 1983). Methods have also been proposed for addressing the problem indirectly at the inversion stage (*Fleming et al.*, 1986). Most work to date has used comparisons with radiances computed from collocated radiosonde profiles to study the bias problem, but radiosonde data also contain biases which present significant problems (e.g. see *Uddstrom*, 1988). In addition, it has been demonstrated that a successful bias correction scheme must take into account the spatially varying and air-mass dependent nature of the radiance biases (*Kelly and Flobert*, 1988; *McMillin et al.*, 1989; *Uddstrom*, 1991).

This paper describes a scheme for monitoring the biases between measured TOVS brightness temperatures and those calculated from forecast temperature/humidity profiles, and for generating corrections for the biases for application in the TOVS one-dimensional variational analysis (1DVAR) scheme (see *Eyre et al.*, 1992). This scheme is now used at ECMWF as part of the operational assimilation of TOVS radiance information. The same bias correction method is also applicable to TOVS data used in three-dimensional variational analysis (3DVAR) (see *Pailleux*, 1990; *Pailleux et al.*, 1991).

Section 2 discusses the characteristics of the TOVS bias correction problem. Section 3 describes the data for which the bias correction scheme has been developed. Section 4 describes the theory of the method, and section 5 its implementation. Section 6 presents results from the application of the scheme and discusses some of their implications.

2. THE BIAS CORRECTION PROBLEM

It is not possible to monitor the bias in a radiative transfer scheme in isolation. We can accumulate statistics of the differences between measured radiances and those calculated from collocated atmospheric profiles (from forecasts, analyses or radiosondes) and study their bias characteristics. These data may contain contributions to the bias from several sources. It is important to recognise these and to consider which we may wish to correct and which we may not (see *Watts*, 1989).

The available "measurements" have undergone calibration and pre-processing. Measured-minus-calculated brightness temperature differences may contain contributions from biases in the measurements, resulting from calibration errors or from biases introduced in the pre-processing of the data (e.g. systematic errors in limb correction or cloud clearing). Ideally these should be identified and corrected at source, but whilst they are present they have the same effect as errors in the radiative transfer calculations; it is the bias in the difference which affects the retrieval/assimilation. The correction should therefore include the effects of measurement bias.

Apart from biases in the radiative transfer model itself, which we intend to correct, there are possible biases in its input data. These include the temperature/humidity profiles — forecast, analysed or sonde. The treatment of the biases in the context of NWP data assimilation is problematic and is discussed below. There are other inputs not derived from the NWP model, such as ozone amount. These may contain biases which should be corrected as though they were radiative transfer model errors, with the additional problem that these biases may vary with time.

Returning to the temperature/humidity profile biases, we have to consider carefully the requirements of our application. Are we seeking to correct the radiances absolutely? Or are we just trying to remove relative biases between two systems? For NWP applications, the primary requirement is that the radiance data do not appear biased relative to the forecast model and relative to other data (e.g. radiosondes). Absolute biases should also be removed if possible, but they are of secondary importance.

One potential problem when correcting biases relative to a NWP model is any tendency of the system to drift: bias in the NWP model would then be interpreted as bias in the radiative transfer model, and correcting for it could lead to positive feedback, reinforcing the drift. Tuning against radiosondes avoids this problem but is affected by others: the biases between different radiosondes, higher levels of noise in the difference statistics, and problems in constructing sufficiently large and representative samples of collocated data.

We are adopting the following strategy to address these problems:

(a) Biases between measured brightness temperatures and those calculated from forecast profiles are corrected as described in this paper.

(b) Only forecast profiles close to active radiosonde stations are used. Since the forecast/assimilation system will have used radiosonde data from these stations recently, this should prevent significant problems caused by model drift.

(c) Statistics of radiosonde-forecast differences are to be used to remove relative biases between different radiosondes (in a separate system, not described here). Data from radiosonde comparison campaigns will be used to confirm results on relative and absolute radiosonde errors.

In this way it is planned to use the NWP model as a transfer medium to tune radiosondes against each other and against satellite radiance data in a consistent manner. In any operational context, the observing systems and the NWP model are subject to frequent changes, and so the whole bias correction system will require continual monitoring. Moreover, the biases themselves will be specific to the particular NWP system within which they are derived; they will not necessarily be applicable to other NWP systems.

The biases in the radiative transfer model for some channels are found to vary systematically between the equator and the poles, and a successful correction scheme for global data must take account of this. Various schemes have been proposed to apply a correction which is a function of "air-mass", in some sense. In this work, we demonstrate acceptable performance from a simple scheme which uses a sub-set of the measured brightness temperatures as detectors of "air-mass" and hence as predictors in a regression relation which generates a spatially-varying bias. In this context, "air-mass" is rather a loose term but can refer to any aspect of the atmospheric profile which is correlated with the predictors.

Some contributions to the bias may vary with time. It is therefore desirable that the bias be monitored continuously and updated as necessary. Experience so far suggests that updating about once per month is both desirable and practicable.

3. THE DATA

The TOVS brightness temperatures on which the scheme has been developed are global, cloud-cleared data generated by NOAA/NESDIS and available in Europe in near real-time as part of the "120 km BUFR TOVS" data set. These data have already undergone substantial pre-processing at NESDIS (see *Smith et al.*, 1979) followed by cloud-detection and cloud-clearing (*McMillin and Dean*, 1982; *Reale et al.*, 1986). The cloud-clearing route is identified with the data and can be either "clear", "partly cloudy" or "cloudy".

The calculated brightness temperatures are generated within the framework of the PRESAT scheme which has been used operationally at ECMWF for pre-processing 120 km BUFR TOVS data since May 1991. The initial operational use of PRESAT has been to improve the quality control and data selection of TOVS temperature/humidity profiles received from NESDIS. However another important role for PRESAT has been to calculate and store the differences between the clear-column brightness temperatures (which accompany the NESDIS retrievals) and corresponding brightness temperatures computed from short-range (nominally 6-hour) forecast profiles.

NWP model fields at 3-hour intervals are interpolated quadratically in time and bilinearly in space to the location of each TOVS sounding. The temperature and humidity profiles are then interpolated linearly from the NWP model levels to the 40 pressure levels of the TOVS radiative transfer scheme (*Eyre*, 1991). Above the top of the NWP model (i.e. currently for pressures less than 10 hPa), the profile is extrapolated as described by *Eyre* (1989). The radiative transfer scheme then operates on the input atmospheric profile to generate corresponding brightness temperatures for all the TOVS channels required. An important aspect of the radiative transfer model which affects the subsequent bias correction is the use of the so-called γ-correction method (*Smith et al.*, 1984). The computed transmittance from each pressure level to space is raised to the power γ, where γ is a constant for each channel. At present, the values of γ are obtained from NOAA/NESDIS once for each satellite. Since their effect is to raise or lower the whole weighting function, they affect the brightness temperature bias, and so the bias corrections will be specific to the particular value of γ used.

PRESAT computes the measured-minus-forecast brightness temperature differences and stores them along with the measurements themselves. An archive of these data is currently available from mid-April 1991. Up to the time of writing, the information on the instrument scan angle (the so-called NESDIS "mini-box" number) is missing from these data, and so the first part of the bias correction scheme described below cannot be applied. However, PRESAT has also been run on an experimental data set (in February 1989) in which scan angle information is available, and the full bias correction scheme has been developed and tested.

4. THE BIAS CORRECTION METHOD

The correction scheme is in two parts: firstly a correction for the bias in the measurement at each scan angle relative to nadir (if scan angle information is available), followed by a bias correction which varies as a function of "air-mass". The cloud-cleared brightness temperature in channel j measured at scan angle θ (but adjusted to nadir) is $T_j(\theta)$. The datum to be corrected is the departure of this measurement from the corresponding forecast brightness temperate T_j^F calculated at nadir:

$$d_j(\theta) = T_j(\theta) - T_j^F \tag{4.1}$$

4.1 Scan bias correction

The first step is to use the information on the scan angle (if available) to make a correction for the relative mean biases between measurements at different scan angles. The scan bias correction is given by:

$$s_j(\theta) = \overline{d_j(\theta)} - \overline{d_j(\theta=0)} \tag{4.2}$$

where the overbar represents a global mean for data at scan angle θ calculated from a large quantity of data. $s_j(\theta)$ is thus a mean bias relative to scan centre $(\theta = 0)$. The scan bias correction is applied as follows to form corrected departures:

$$d_j' = d_j(\theta) - s_j(\theta) \tag{4.3}$$

Since the cause of this relative bias lies in the measurements or their pre-processing, the same correction can also be applied to the measurements themselves:

$$T_j' = T_j(\theta) - s_j(\theta) \tag{4.4}.$$

4.2 Bias correction varying with air-mass

The second step is to correct for biases which are correlated with "air-mass" as sensed by the measurements themselves. A sub-set of channels is selected to represent the air-mass predictors, and any bias in the departures which is correlated with these predictors is removed. The bias correction is given by:

$$b_j = a_{oj} + \sum_{i=1}^{M} a_{ij}\, T_i^P \tag{4.5}$$

where T_i^P, $i = 1 \rightarrow M$, is a sub-set of the corrected measurements T_j', $j = 1 \rightarrow N$. Using the notation T^P and A_j to represent vectors with elements T_i^P and a_{ij} $(i = 1 \rightarrow M)$ respectively, the coefficients A_j are calculated by linear regression as follows:

$$A_j = S\{d_j', T^P\} \cdot [S\{T^P, T^P\}]^{-1} \tag{4.6}$$

where $^{-1}$ represents matrix inverse and $S\{...\}$ represents a covariance matrix calculated from a large quantity of global data. The offset constant, a_{oj}, is given by:

$$a_{oj} = -\overline{d_j'} - A_j^T \cdot \overline{T^p} \tag{4.7}$$

where ^{T} represents matrix transpose. The bias correction is then applied as follows to form further corrected departures:

$$d_j'' = d_j' - b_j \tag{4.8}$$

5. APPLICATION

This method describes the separate stages through which the bias correction method is applied in practice at ECMWF. The corresponding software is described in Annex A.

5.1 Data selection

Data are extracted from archived files containing all the data output by PRESAT (including measured brightness temperatures and their departures) for each 6-hour NWP assimilation cycle for both NOAA operational satellites (currently NOAA-11 and -12). The first stage is to assemble data from each satellite individually covering an adequate period. 14 days of data has been found more than adequate for calculation of stable coefficients and also sufficient for studying spatial variations in the residual bias fields (see section 6). To produce bias corrections for operational use, our current practice is to take data covering a whole month selecting all assimilation cycles from every other day (i.e. about 60 6-hour cycles).

The next stage is to select the most suitable and reliable data for computing correction coefficients. Data can be selected according to land and/or sea and according to cloud-clearing route. At present only clear soundings over sea are used. Clear soundings are likely to be the highest quality measurements and contain data for all channels. Data over the sea are likely to have the least problems from residual cloud-contamination, because the sea surface temperature is used in one of the cloud detection tests, and also to have the most accurate surface temperature for the forecast brightness temperature calculation. A potential problem with this approach is that the corrections generated are biased towards clear areas. Examination of the corrections applied to data from partly cloudy areas has shown that this does not appear to be a significant problem in practice.

At this stage the data set tends to be dominated by the tropics and southern hemisphere mid-latitudes. In order to create a more balanced distribution between different latitude bands, soundings are selected every nth sample, where n is given (at present) by:

band index	latitude band	n
1	90 - 60 S	1
2	60 - 30 S	3
3	30 S - 30 N	4
4	30 - 60 N	1
5	60 - 90 N	1

5.2 Quality control

Before data are used to calculate coefficients, they are subjected to the following stages of quality control:

a) Gross check. If any brightness temperature for a predictor channel is outside limits (currently 150 K to 350 K) or any brightness temperature departure is outside limits (currently -20 K to +20 K), then the data in all channels are rejected.

b) Window channel check. If the departure in a selected window channel is too great then data in all channels are rejected. Ideally, HIRS channel 8 should be used here. However, at present NESDIS apply a water vapour absorption correction to this channel, and the correction itself has peculiar error characteristics which differ between satellites. HIRS channel 10 is used; it is not such a clean window but is free from these problems. Data are rejected at present if the departure is outside the limits, -4 K to +8 K. The negative side is the most effective quality control and mainly traps residual cloud effects. [This test should be consistent with the corresponding quality control used for processing real-time data, otherwise the data used may be biased with respect to the NWP model.]

A further check, rejecting areas of sea-ice, has also been tried but is not currently used. It was found to lead to coefficients which produced large errors when applied back to data over sea-ice, because the atmospheric profiles there tend to be well outside the range of the profiles used in the generation of coefficients.

The mean and standard deviation of departures are then calculated in all channels for data which pass the above tests. All data are then processed a second time with an additional check.

c) Rogue check. If the departure in any channel differs from the mean departure by more than R times the standard deviation (currently R = 3), then data in all channels are rejected.

At present, bias corrections are only calculated for the following channels: HIRS channels 1-8 and 10-15, and MSU channels 2-4. See Fig. 1 for their weighting functions. Only the departures in these channels determine quality control decisions.

As an option in the quality control, data can be selected inside a "radiosonde mask" which identifies only those areas within a given radius of an active radiosonde station. This is to address the potential problem of model drift discussed in section 2. A radius of 5 degrees (latitude equivalent) is currently used, which causes about 35% of data over sea to be accepted.

5.3 Scan bias correction

The scan bias corrections can only be calculated if scan angle information (the NESDIS mini-box number) is available. If not, $s_j(\theta)$ is set to zero for all θ. When the mini-box number is available, $d_j(\theta=0)$ is set to the mean value for the two central mini-boxes (numbers 9 and 10). The values of $s_j(\theta)$ are calculated from eq. 4.2 and stored.

5.4 Bias correction varying with air-mass

If the scan bias corrections have been calculated, they are applied to give corrected measurements and departures using eqs. 4.4 and 4.3 respectively. In this case, although the quality control procedure is again as described in section 5.2, it may have slightly different effects, as it is now applied to corrected data.

After the quality control, the bias correction coefficients are calculated using eqs. 4.6 and 4.7. For most of the work performed so far, the predictors have been MSU channels 2, 3 and 4. They were selected because they are always present (whereas most HIRS channels are unavailable for cloudy soundings). They appear to give satisfactory results for use in the 1DVAR scheme (see section 6). However recent experiments have suggested that the inclusion of HIRS channel 1 would lead to significant improvement in stratospheric channels.

6. RESULTS AND DISCUSSION

Table 1 gives results from the calculation of bias coefficients for May 1992 for NOAA-11. The radiosonde mask has been used, giving about 14 000 soundings for use in the coefficient generation. MSU channels 2, 3 and 4 have been used as predictors, and no scan bias correction has been applied. Note that the global standard deviations of the departures are significantly reduced by the bias correction procedure in several channels. The procedure ensures that the residual global bias will be zero for the dependent data set, but this may disguise significant regional biases. For this reason, the residual biases (and standard deviations) have been calculated separately for the 5 latitude bands listed in section 5.1 by applying the coefficients back to all the data (i.e. without the radiosonde mask). The results are shown in Table 2; "band index 6" represents the total data set. Note that the effect of the radiosonde mask is negligible in most channels. Table 3 shows the results for the same data but using the coefficients calculated from data of April 1992. This simulates an operational scenario in which the coefficients are changed once per month. The results appear satisfactory: the biases in the departure after correction for each band are generally much smaller than the standard deviations, and there is little change when using coefficients from the preceding month. This has been confirmed by examining other pairs of months over the period May 1991 to May 1992 for NOAA-10, -11 and -12.

The effect of the bias correction is illustrated in Fig. 2 which shows the field of the local monthly mean bias before and after correction in MSU channel 3. This channel has one of the largest problems of air-mass-dependent bias. It is removed almost completely by the bias correction procedure. [The major cause of the air-mass-dependence in this channel (and to a lesser extent other MSU channels) has been identified with a problem in the coefficients which describe the temperature-dependence of transmittance. Clearly this type of error can be corrected very effectively using the MSU channels themselves as predictors, since they are sensitive to the temperature profile.]

Figure 3 gives maps of the local mean and standard deviation of the departure (after correction) for selected tropospheric temperature-sounding channels, again for May 1992. Figures 4 and 5 illustrate the results of monitoring such plots monthly for one year for NOAA-11. Figure 4 is a sequence of plots of residual standard deviation in MSU channel 2 and Fig. 5 shows the monthly mean residual biases in HIRS channel 11.

From studies of these and similar figures, the following points of interest emerge:

(a) For the critical tropospheric temperature sounding channels (HIRS 4-7 and 13-15 and MSU 2-3), the zonal biases are generally lower than the standard deviations — a good sign, suggesting that we have some chance of seeing the "signal" of forecast error above the additional local "noise" created by measurement or radiative transfer model bias.

(b) Nevertheless, the standard deviations in all these channels are surprisingly low. On the one hand this is a good sign, as it can only occur if all the contributions to the departures — from measurement, forward model and first-guess error — are low. On the other hand, it demonstrates how carefully these data must be handled if they are to lead to improvement on the forecast first-guess. These data have been used to re-tune the error statistics of the forecast first-guess and the measurements in the 1DVAR system (see *Eyre et al.*, 1992).

(c) First-guess biases which are correlated with the regression predictors will be compensated by the correction procedure. Such biases cannot therefore be corrected subsequently in the data assimilation by the radiance information, and this is a weakness which can only be addressed by using another data source such as sondes (see section 2).

(d) However, local/regional forecast biases which are not correlated with the MSU predictors will appear as biases in the mean departure fields and can potentially be corrected in the data assimilation. In the figures, there are areas of bias which are probably caused by biases in the analysis/forecast system (or the data it uses, eg NESDIS retrievals). They could possibly be caused by regional biases in the measurements or radiative transfer model, but it is difficult to think of plausible mechanisms here. Also, when channels with similar weighting functions, but from different bands (e.g. HIRS channel 15 and MSU channel 2) show similar bias patterns, it suggests that the problem lies with the forecast field.

(e) The spatial variations of the residual standard deviation are broadly consistent with expectations, taking into account the season, conventional data density, distance from data dense areas, etc. It is also encouraging that they are found not to change greatly from one month to the next. Although the highest values are in the southern hemisphere mid-latitudes, it should be noted that the values here are less than a factor of 2 greater than over the northern hemisphere oceans. These data should be useful for studying the spatial variation of forecast error.

(f) The mid/upper tropospheric humidity channels — HIRS channels 11 and 12 — show interesting bias patterns (Fig. 5). They suggest that the NWP model is systematically too moist in the latitudes of the sub-tropical anticyclones and too dry along the inter-tropical convergence zone. This is consistent with results from comparisons between NWP model analysis and total precipitable water vapour derived from SSM/I data (*Phalippou*, 1992). The interpretation of these plots is not straightforward, as the relationship between brightness temperature difference and humidity profile difference depends on the lapse rates of both temperature and humidity. However a bias of 1 K in HIRS channel 11 represents a bias of about 10-20% in mid-tropospheric specific humidity (with positive biases on the figures corresponding to measurements dry with respect to NWP model). Note that there are monthly mean biases of magnitude 3 K in some areas, which correspond to very large biases in specific humidity. The measurements used are only cloud-free data, whereas the model values attempt to represent the local mean of clear and cloudy conditions. There is therefore a concern that the measured values will tend to show a dry bias. However, in the moist areas of the deep tropics, where we might expect this effect to be a problem, we find that the model is currently drier than the measurements indicate. The model shows a moist bias in the subsidence regions of the sub-tropics, where problems of clouds at mid and upper levels are not expected to be significant.

(g) The residual biases in HIRS channel 1 show a marked latitudinal banding. This is reflected to a lesser extent in channels 2 and 3. The problem here lies mainly in the systematic errors in extrapolating the temperature profile above the top of the model. Clearly this error is not strongly correlated with the measurements in MSU channels 2, 3 and 4. When HIRS channel 1 is added to the predictors, the global residual standard deviation and the regional biases are strongly reduced in HIRS channel 1 itself and to a lesser extent in HIRS channels 2 and 3 (see Fig. 6). Other channels are not significantly affected. HIRS channel 1 has not been included in the predictors in the first operational implementation 1DVAR, but these results indicate that it should be added in future. When (as planned) SSU channels are added to the 1DVAR system, their use as bias correction predictions will also need to be considered.

7. CONCLUSIONS

A scheme has been developed for correcting the spatial-varying biases between measured TOVS brightness temperatures and those calculated from a forecast model. The scheme is relatively simple — an advantage for an operational system — using linear regression with measured brightness temperatures in a small number of TOVS channels as predictors. Despite this, it appears to be successful in its main task of controlling the bias in the critical channels which sound tropospheric temperature.

Other useful diagnostics have emerged as by-products of the bias correction work. The fields of residual standard deviation have already proved useful in re-tuning the error statistics of the 1DVAR, and they also show potential for studying the spatial variation of error in the assimilation system. The residual biases in the water vapour channels appear to be a valuable diagnostic of problems with the NWP model's hydrological cycle.

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Table 1. Bias correction coefficients.
Data from May 92, NOAA-11, using radiosonde mask.

channel	data uncorrected mean	data uncorrected SD	data corrected SD	coefficients a_{22}	coefficients a_{23}	coefficients a_{24}	coefficients a_c
1	1.48	1.78	1.66	-0.01285	0.08991	0.04820	-25.974
2	-0.97	0.77	0.70	-0.03950	0.05051	0.00579	-3.761
3	-1.69	0.85	0.55	-0.07093	0.04957	0.01782	1.005
4	-0.12	0.48	0.37	-0.04378	0.10917	-0.07075	1.343
5	-0.22	0.58	0.47	-0.00815	0.04727	-0.04841	1.528
6	-0.48	0.72	0.63	0.00285	-0.01230	-0.03558	9.231
7	-0.52	1.12	1.03	0.04102	-0.06235	-0.01772	7.128
8	0.91	2.88	1.94	0.04581	0.32041	-0.22166	-35.329
10	-0.75	1.56	1.53	0.09209	-0.21749	0.06903	10.559
11	-1.48	2.38	2.20	0.03096	0.02412	-0.08445	3.465
12	-1.33	3.62	3.15	0.03816	0.22500	-0.18867	-21.182
13	-1.21	0.93	0.90	-0.01916	-0.03644	-0.01318	14.637
14	-0.88	0.63	0.59	-0.00117	-0.05930	0.01487	9.621
15	-0.32	0.58	0.47	-0.04484	0.03192	0.00220	3.197
22	-0.08	0.42	0.42	-0.00760	-0.00594	-0.00641	4.534
23	-0.25	0.85	0.28	0.01718	0.07770	-0.08529	-3.782
24	-1.16	0.46	0.44	-0.01240	0.05000	-0.02654	-3.657

channel 1-15 = HIRS channels 1-15
channel 22-24 = MSU channels 2-4

Table 2. Mean and standard deviation of corrected data in each latitude band. data from May 1992, NOAA-11, corrected using coefficients in Table 1. "Band 6" includes data in all latitude bands.

band	1		2		3		4		5		6	
no. of data	4259		3843		15983		6734		5161		35980	
channel	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
1	-1.46	2.98	-3.35	1.43	0.11	1.31	0.23	1.09	0.58	0.94	-0.36	1.94
2	-0.44	0.99	-0.87	0.62	0.07	0.68	-0.07	0.59	0.27	0.52	-0.09	0.76
3	-0.21	0.70	-0.60	0.50	0.05	0.60	0.02	0.48	0.17	0.45	-0.04	0.60
4	0.00	0.35	-0.06	0.36	0.06	0.42	-0.07	0.35	0.10	0.28	0.02	0.38
5	-0.02	0.48	0.04	0.46	0.11	0.55	-0.13	0.42	0.09	0.37	0.04	0.50
6	0.03	0.66	0.07	0.55	0.16	0.72	-0.18	0.53	0.11	0.58	0.06	0.65
7	-0.04	1.18	-0.13	0.78	0.16	1.06	-0.20	0.83	0.19	1.14	0.04	1.04
8	-0.74	2.30	-1.09	1.33	-0.17	1.70	-0.23	1.59	0.43	2.29	-0.26	1.87
10	-0.08	1.88	-0.40	1.07	0.07	1.34	-0.14	1.21	0.20	1.92	-0.02	1.48
11	0.30	1.95	1.21	2.41	0.58	2.72	-0.34	2.18	0.26	1.58	0.40	2.41
12	0.44	3.08	1.41	3.56	0.71	3.71	-0.32	3.15	0.34	2.24	0.51	3.38
13	-0.08	1.23	-0.36	0.64	0.00	0.56	-0.20	0.76	0.20	1.19	-0.06	0.84
14	0.00	0.81	-0.29	0.52	0.00	0.45	-0.07	0.53	0.08	0.74	-0.04	0.58
15	-0.04	0.65	-0.28	0.50	0.06	0.39	-0.07	0.46	0.08	0.46	-0.01	0.48
22	0.03	0.61	-0.24	0.46	0.06	0.39	-0.04	0.38	0.11	0.44	0.01	0.45
23	0.07	0.47	0.06	0.34	-0.03	0.23	0.06	0.25	0.00	0.35	0.02	0.30
24	0.04	0.50	-0.26	0.43	0.08	0.45	-0.15	0.41	0.20	0.40	0.01	0.46

Table 3. Mean and standard deviation of corrected data in each latitude band.
Data from May 1992, NOAA-11, corrected using coefficients from April 1992 data.
"Band 6" includes data in all latitude bands.

band	1		2		3		4		5		6	
no. of data	4259		3843		15983		6734		5161		35980	
channel	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
1	-2.44	2.20	-3.60	1.32	-0.20	1.35	0.25	1.05	2.55	1.19	-0.35	2.22
2	-0.70	0.86	-1.03	0.60	0.11	0.73	-0.18	0.54	0.63	0.57	-0.09	0.83
3	-0.14	0.68	-0.64	0.51	0.03	0.62	-0.02	0.45	0.45	0.47	-0.01	0.63
4	0.12	0.36	-0.10	0.35	-0.05	0.42	-0.13	0.35	0.19	0.29	-0.02	0.39
5	-0.07	0.47	0.00	0.45	-0.01	0.55	-0.17	0.41	0.20	0.38	-0.02	0.50
6	-0.06	0.67	0.03	0.55	0.05	0.72	-0.21	0.53	0.05	0.58	-0.02	0.65
7	-0.16	1.19	-0.19	0.81	0.11	1.07	-0.26	0.85	-0.13	1.15	-0.06	1.05
8	-2.30	2.22	-1.51	1.43	0.56	1.77	-0.43	1.65	-0.46	2.26	-0.33	2.10
10	0.22	1.94	-0.41	1.10	-0.03	1.35	-0.25	1.26	-0.53	1.95	-0.15	1.51
11	-0.47	1.94	0.72	2.40	0.34	2.71	-0.77	2.18	-0.08	1.58	0.02	2.41
12	-1.08	3.06	0.77	3.55	0.61	3.71	-0.76	3.16	0.25	2.26	0.12	3.41
13	-0.33	1.24	-0.33	0.69	0.09	0.56	-0.13	0.80	-0.01	1.21	-0.06	0.85
14	-0.05	0.82	-0.26	0.55	0.00	0.45	-0.04	0.55	-0.05	0.74	-0.05	0.59
15	0.00	0.64	-0.32	0.46	-0.05	0.39	-0.12	0.45	0.28	0.48	-0.04	0.48
22	-0.03	0.60	-0.20	0.48	0.04	0.40	0.02	0.39	0.11	0.44	0.01	0.45
23	0.22	0.43	0.09	0.32	-0.03	0.22	0.06	0.25	-0.12	0.35	0.02	0.30
24	-0.17	0.52	-0.36	0.43	0.28	0.47	-0.22	0.40	0.13	0.38	0.04	0.51

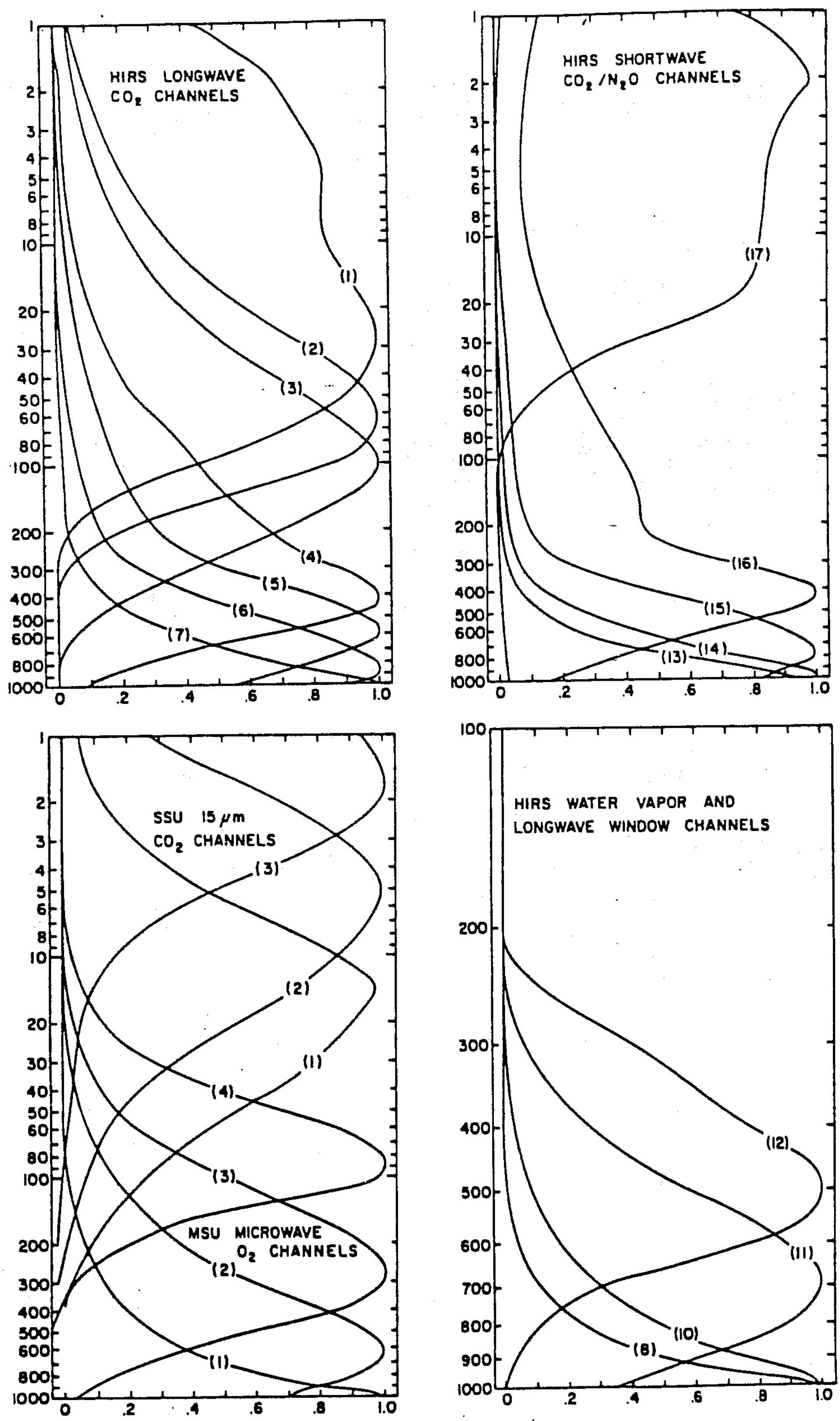


Fig. 1 TOVS weighting functions (taken from *Smith et al.*, 1979).

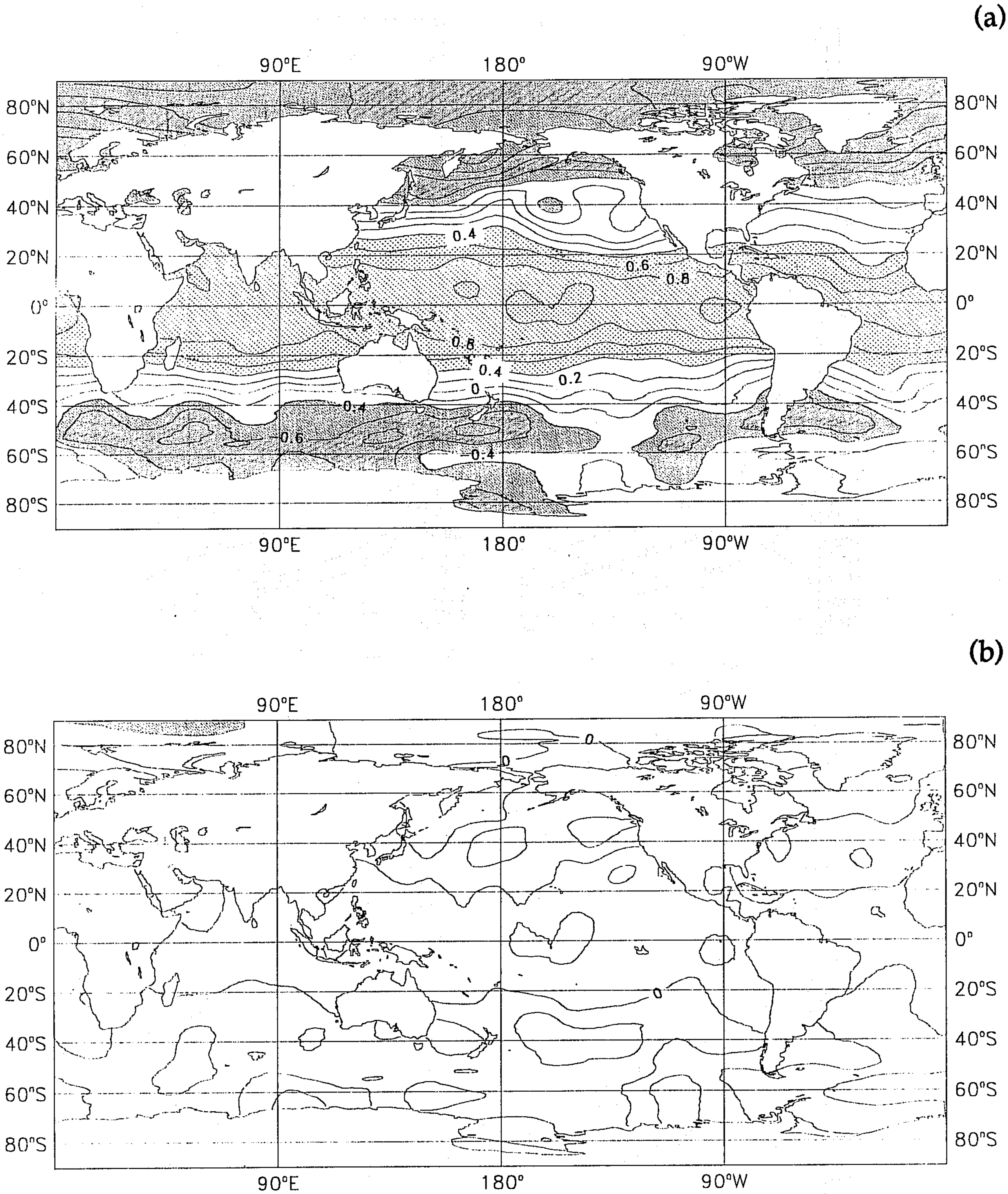
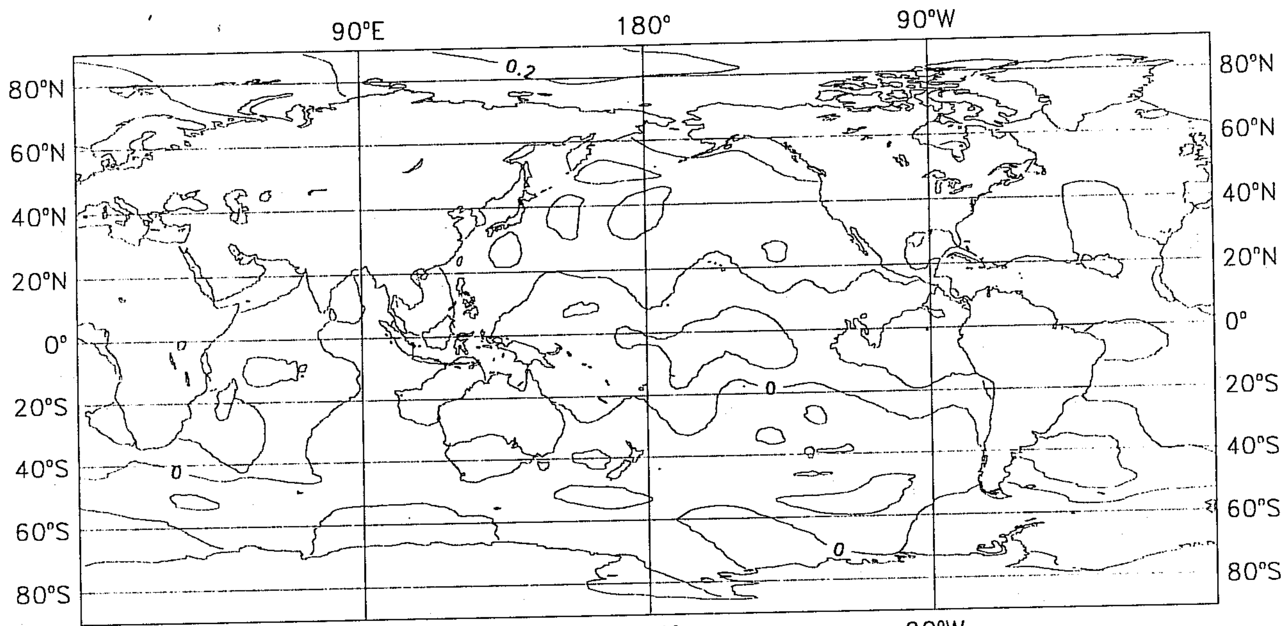


Fig.2 Local mean difference between measured and forecast brightness temperatures in MSU channel 3, NOAA-11, in May 1992 (a) before bias correction and (b) after bias correction.
Contour interval = 0.2K; light shading > 0.4K; dark shading < -0.4K.

HIRS channel 4

(a)



(b)

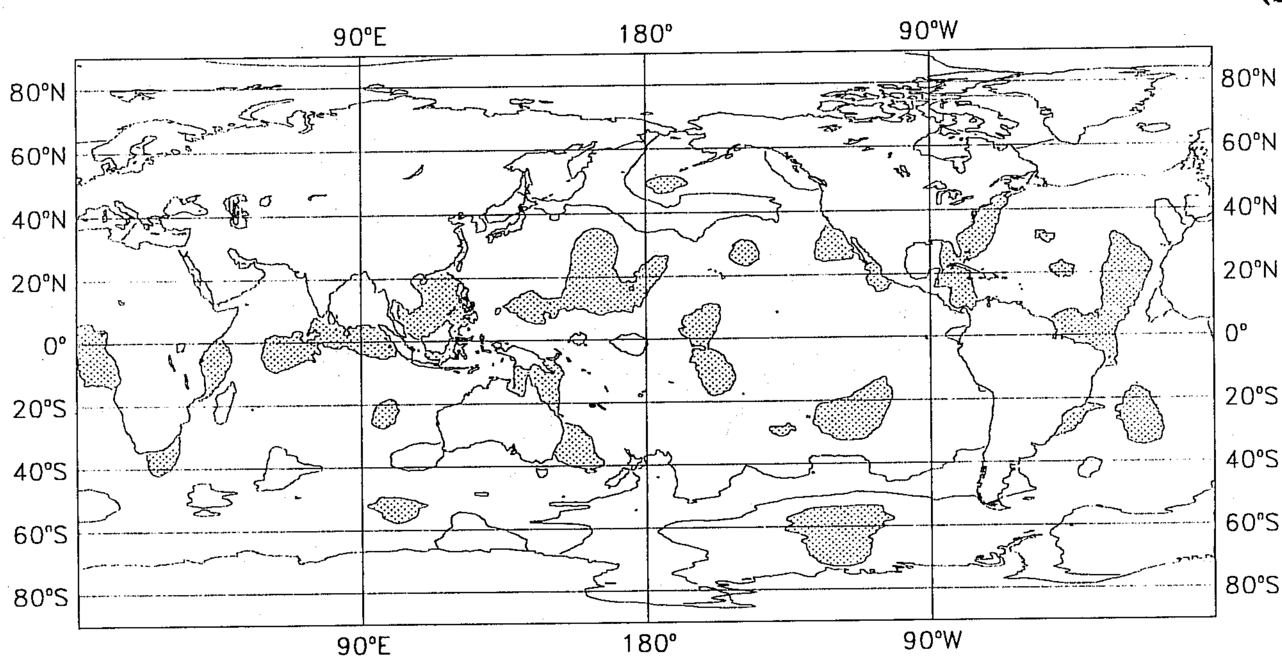
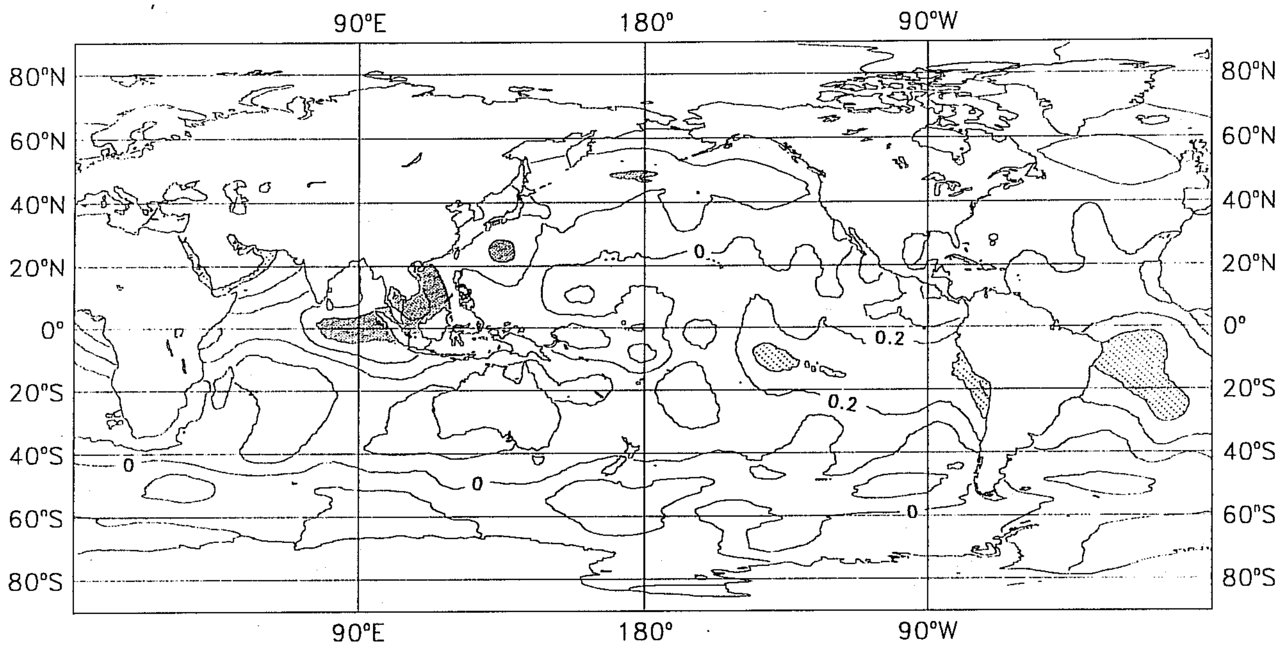


Fig.3 **Local mean and standard deviation (SD) of the difference between measured and forecast brightness temperatures (after bias correction) in TOVS channels for NOAA-11, in May 1992: HIRS channel 4 (a) mean and (b) SD, HIRS channel 5 (c) mean and (d) SD, HIRS channel 15 (e) mean and (f) SD, and MSU channel 2 (g) mean and (h) SD.**
For mean plots: contour interval = 0.2K; light shading > 0.4K; dark shading < -0.4K.
For SD plots: contour interval = 0.1K; shading > 0.4K.

HIRS channel 5

(c)



(d)

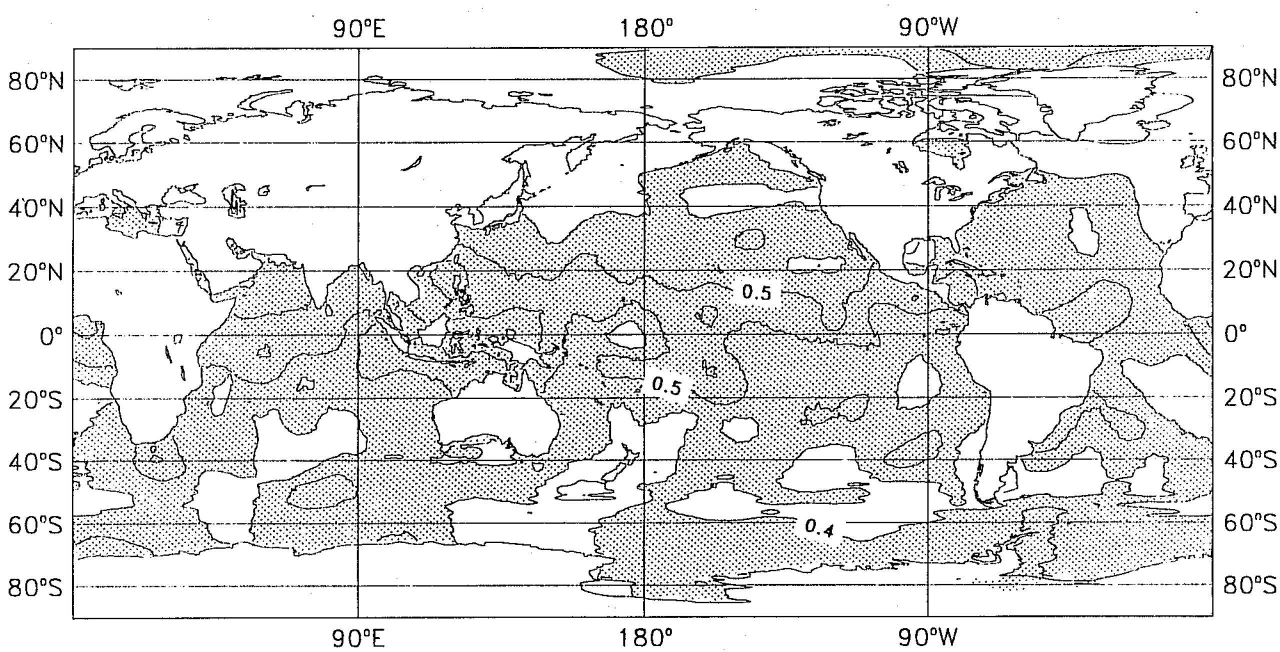
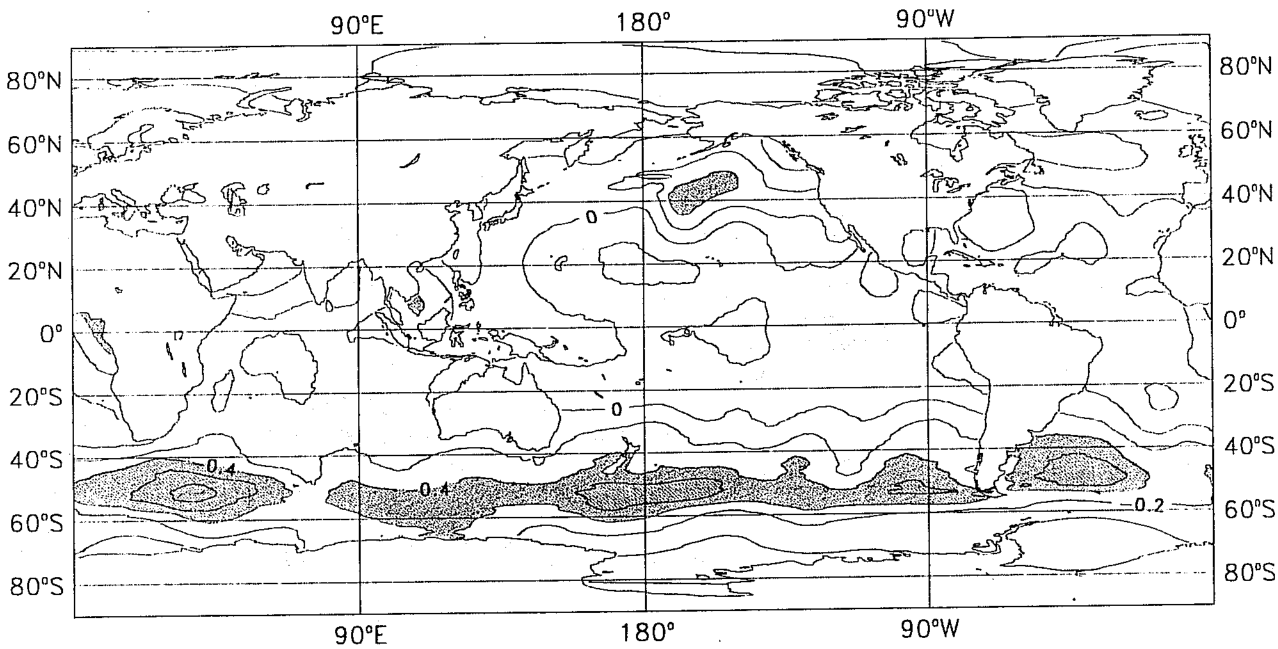


Fig. 3 (continued)

HIRS channel 15

(e)



(f)

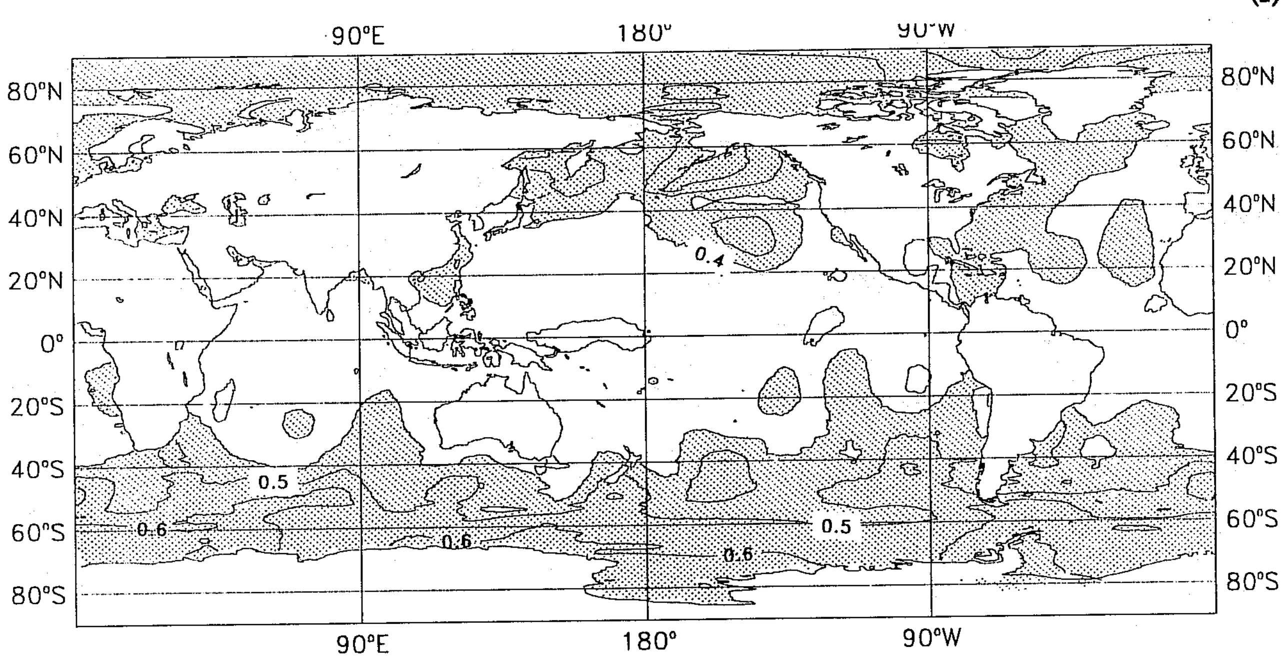
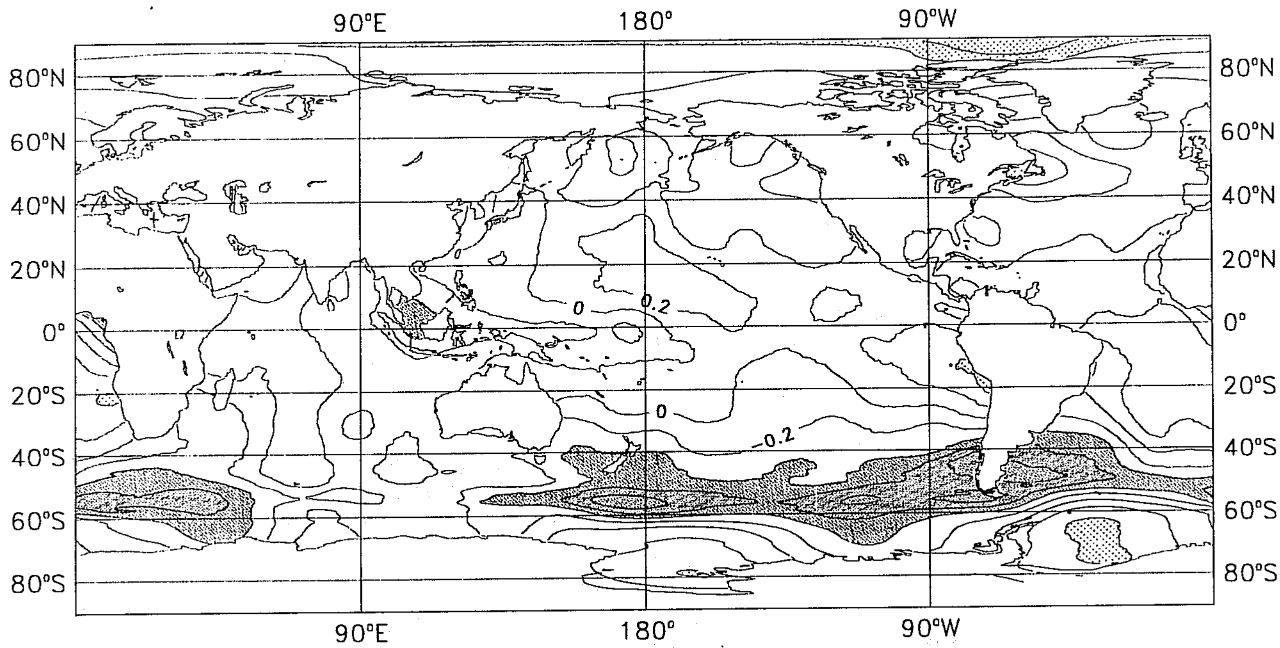


Fig. 3 (continued)

MSU channel 2

(g)



(h)

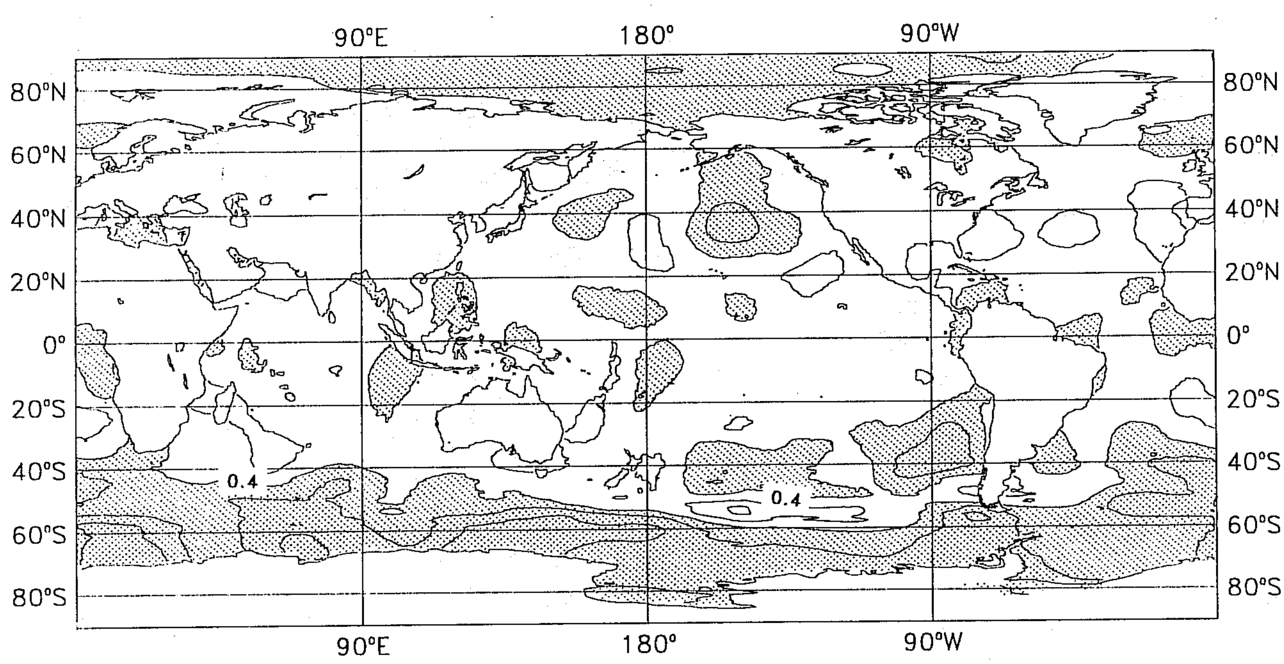
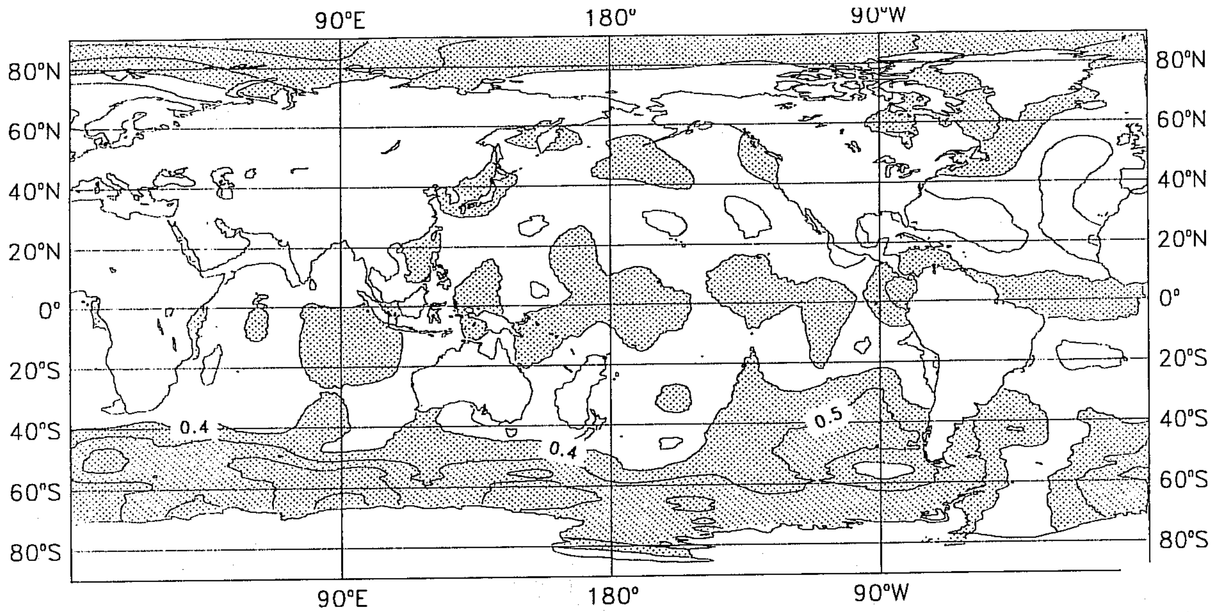
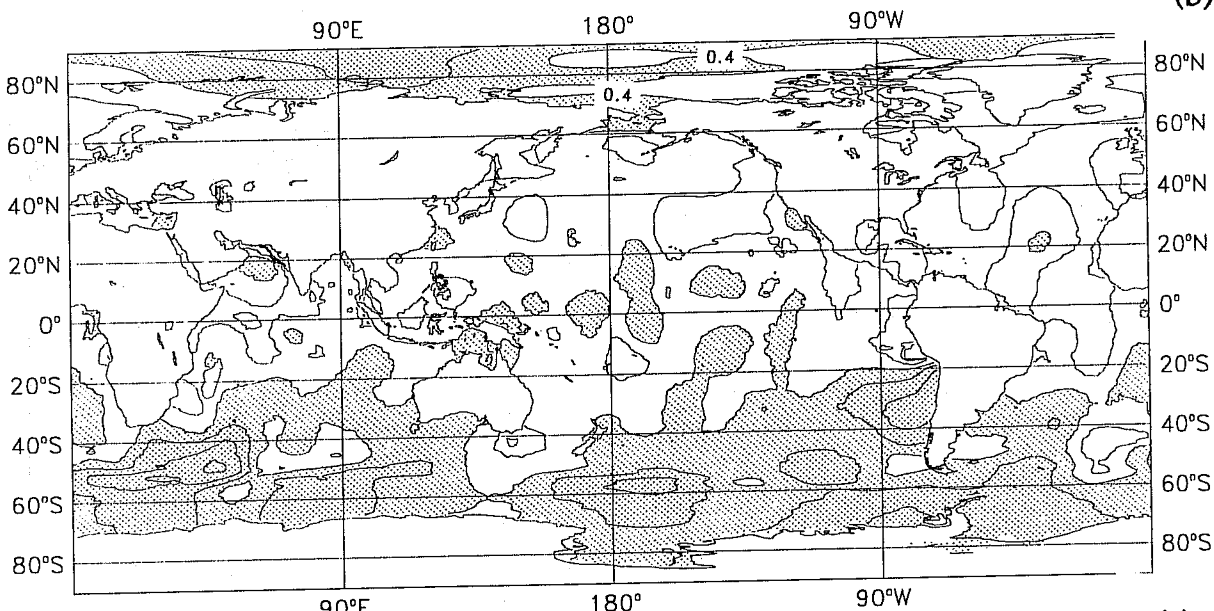


Fig. 3 (continued)



(b)



(c)

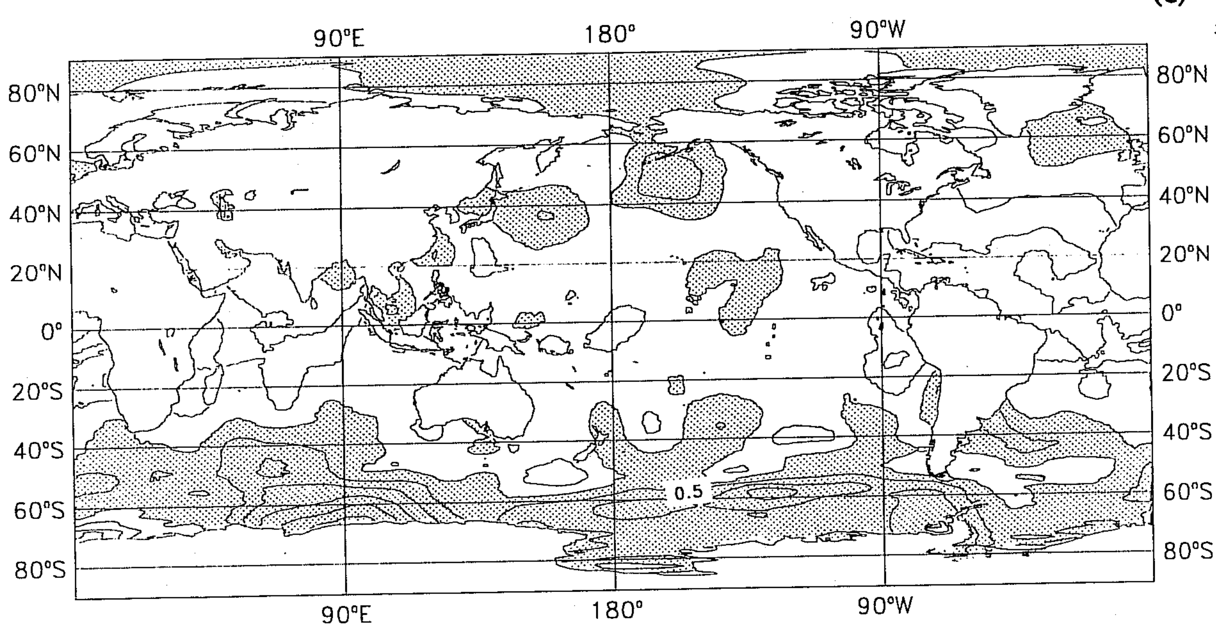


Fig.4 Local standard deviation of the difference between measured and forecast brightness temperatures (after bias correction) in MSU channel 2, NOAA-11: (a) May 1991, (b) July 1991, (c) September 1991, (d) November 1991, (e) January 1992 and (f) March 1992.
Contour interval = 0.1K; shading > 0.4K.

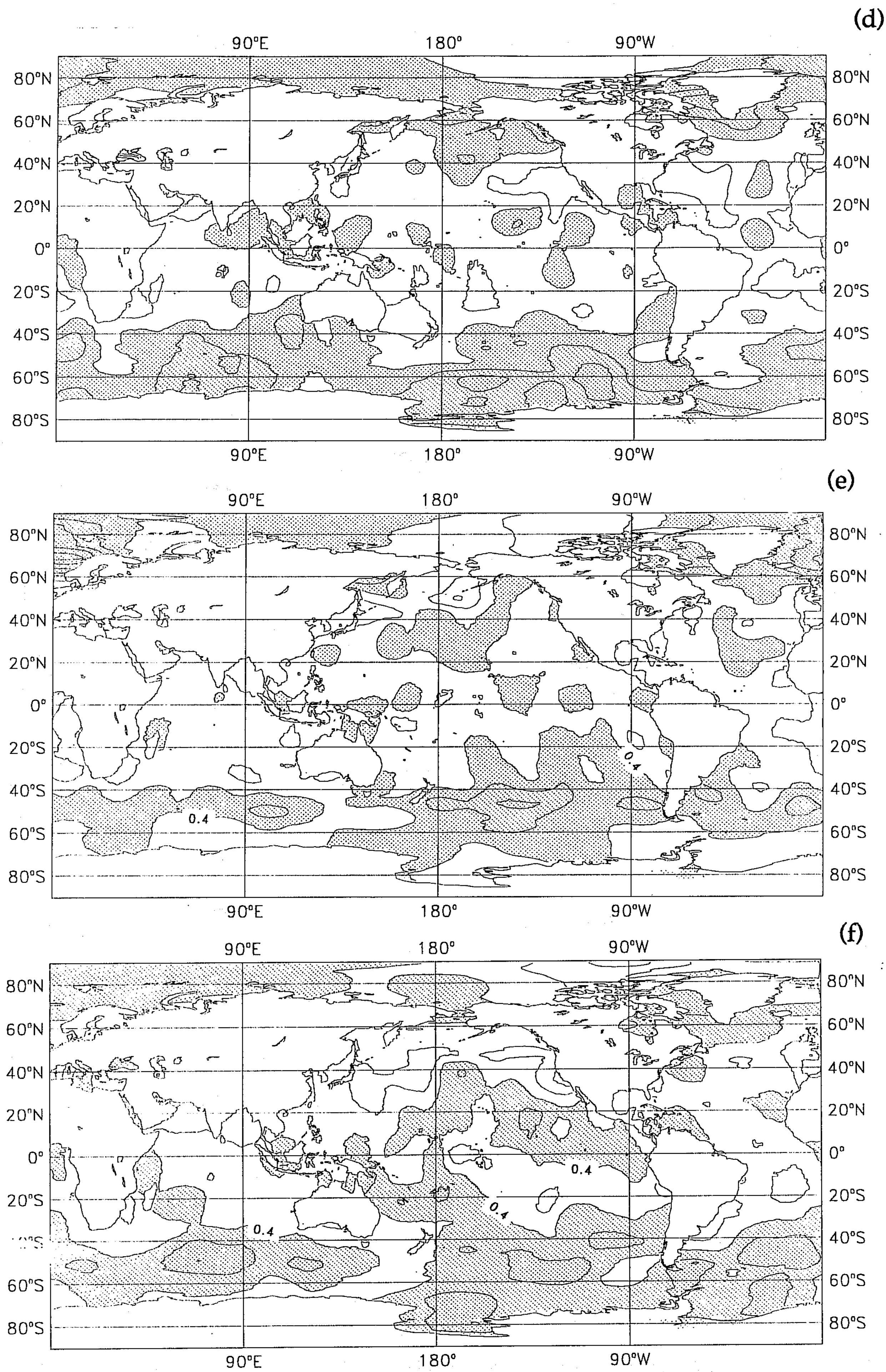


Fig. 4 (continued)

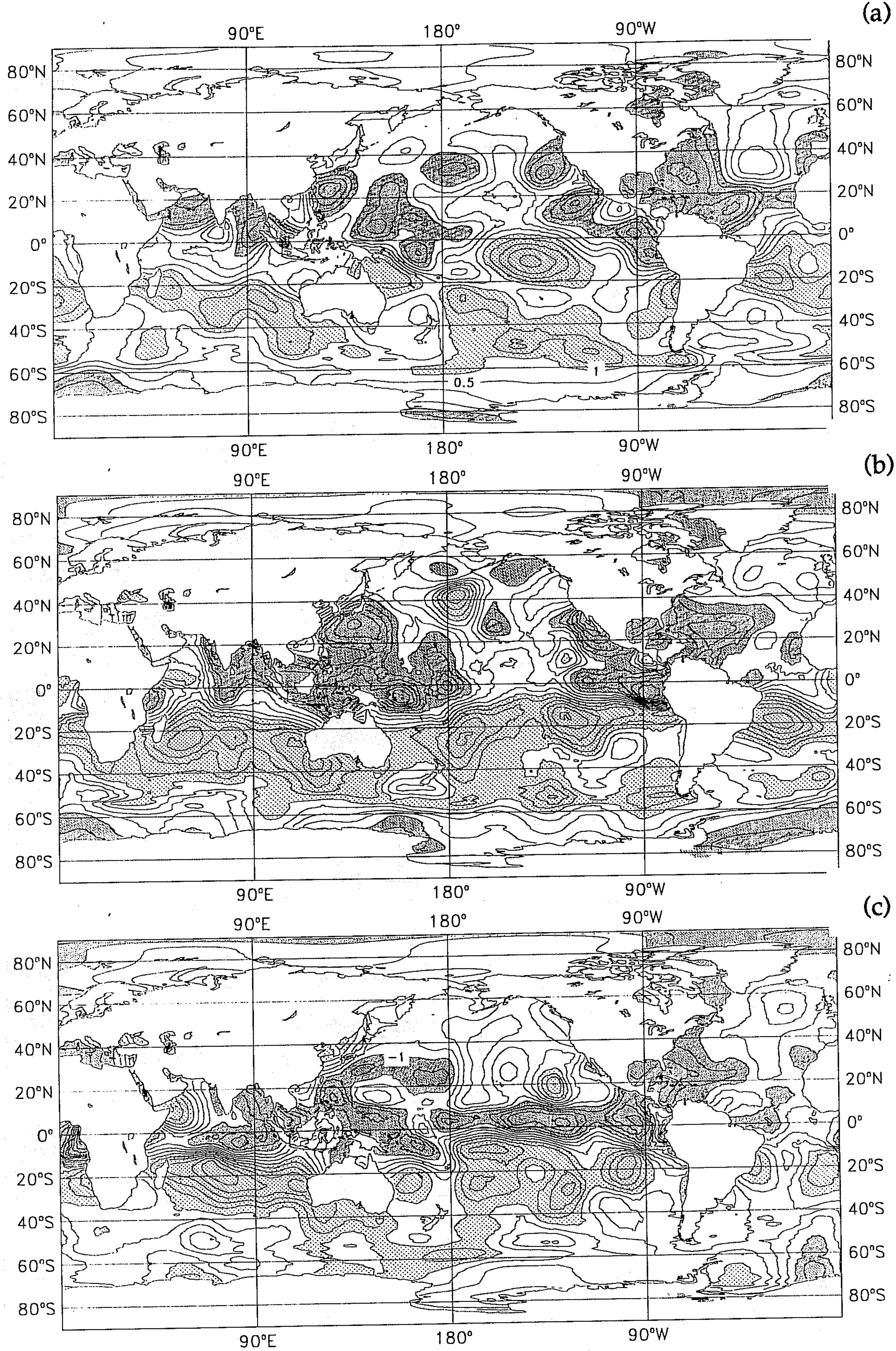


Fig.5 Local mean difference between measured and forecast brightness temperatures (after bias correction) in HIRS channel 11, NOAA-11: (a) May 1991, (b) July 1991, (c) September 1991, (d) November 1991, (e) January 1992 and (f) March 1992.
Contour interval = 0.5K; light shading > 1.0K; dark shading < -1.0K.

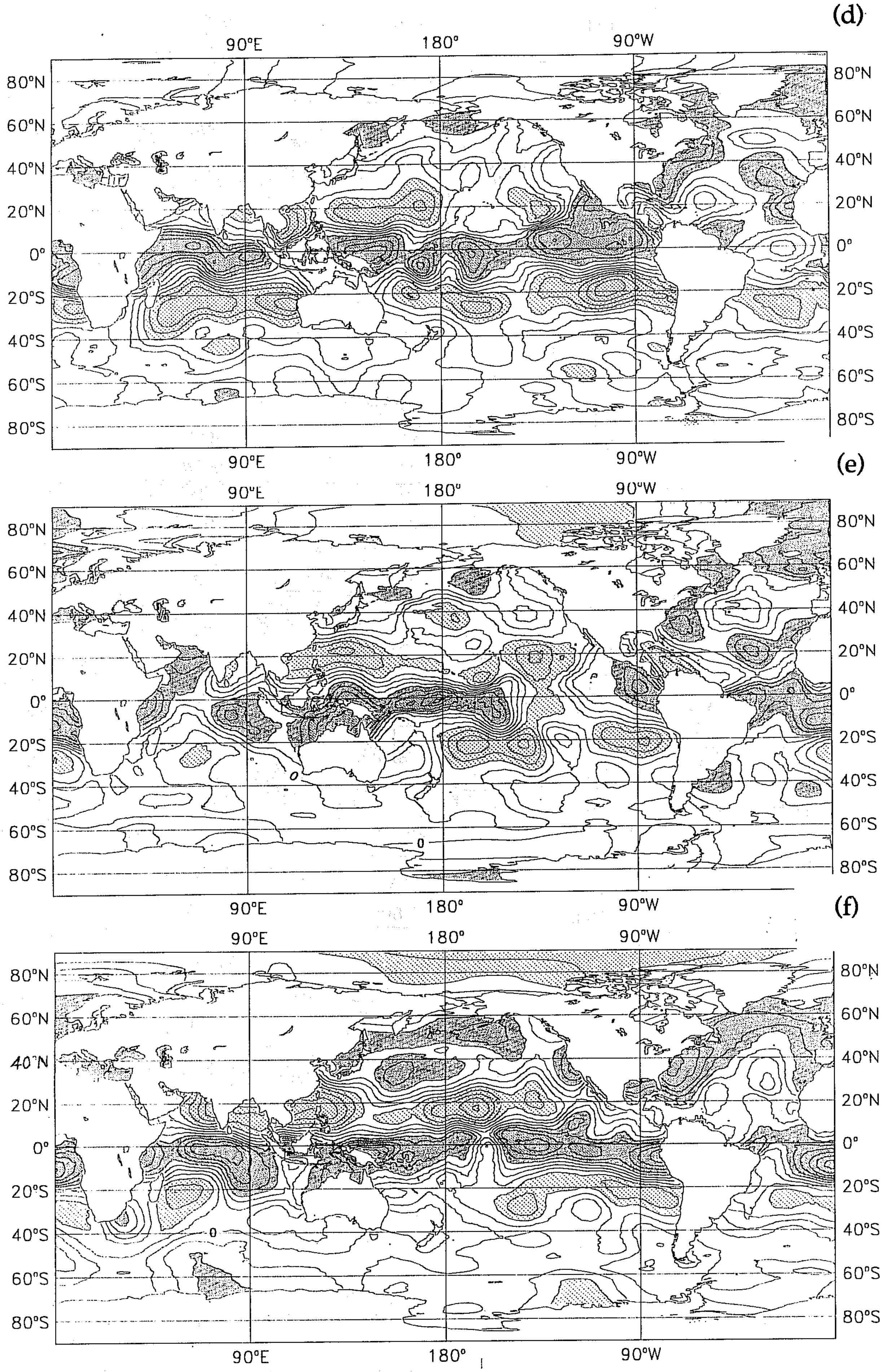


Fig. 5 (continued)

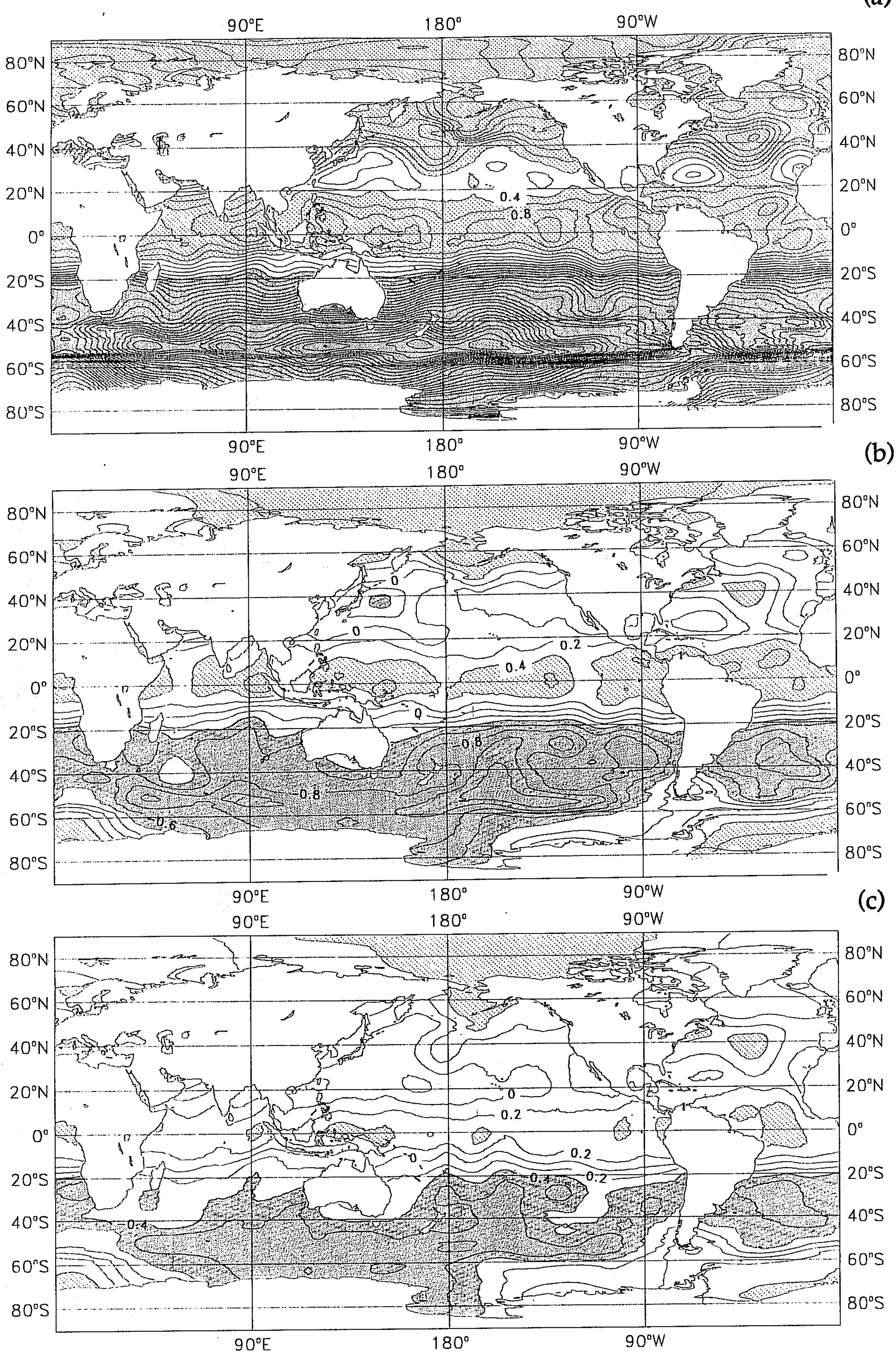
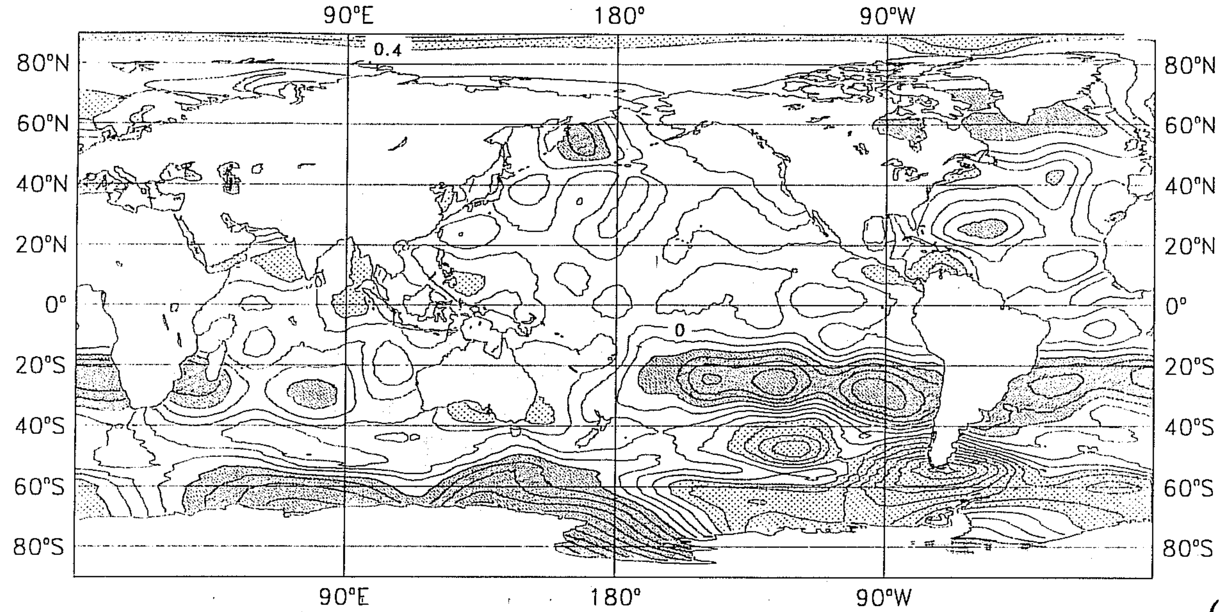
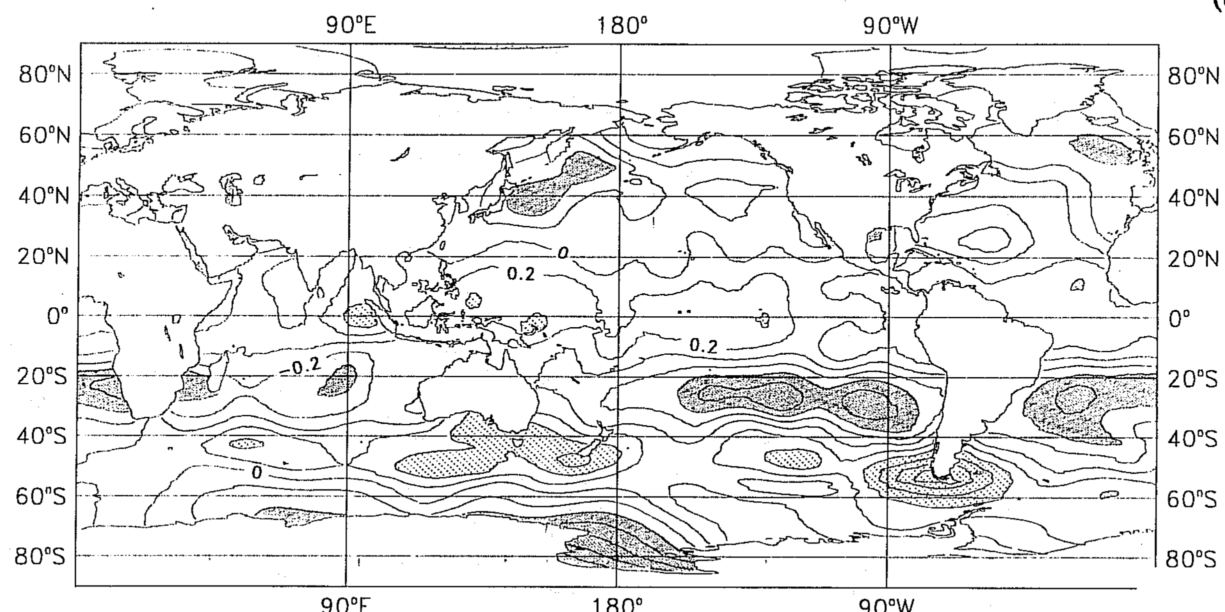


Fig.6 Local mean difference between measured and forecast brightness temperatures (after bias correction) in HIRS channels 1, 2 and 3, NOAA-11, for May 1992: (a)-(c) with and (d)-(f) without HIRS channel 1 as a bias predictor.
Contour interval = 0.2K; light shading > 0.4K; dark shading < -0.4K.

(d)



(e)



(f)

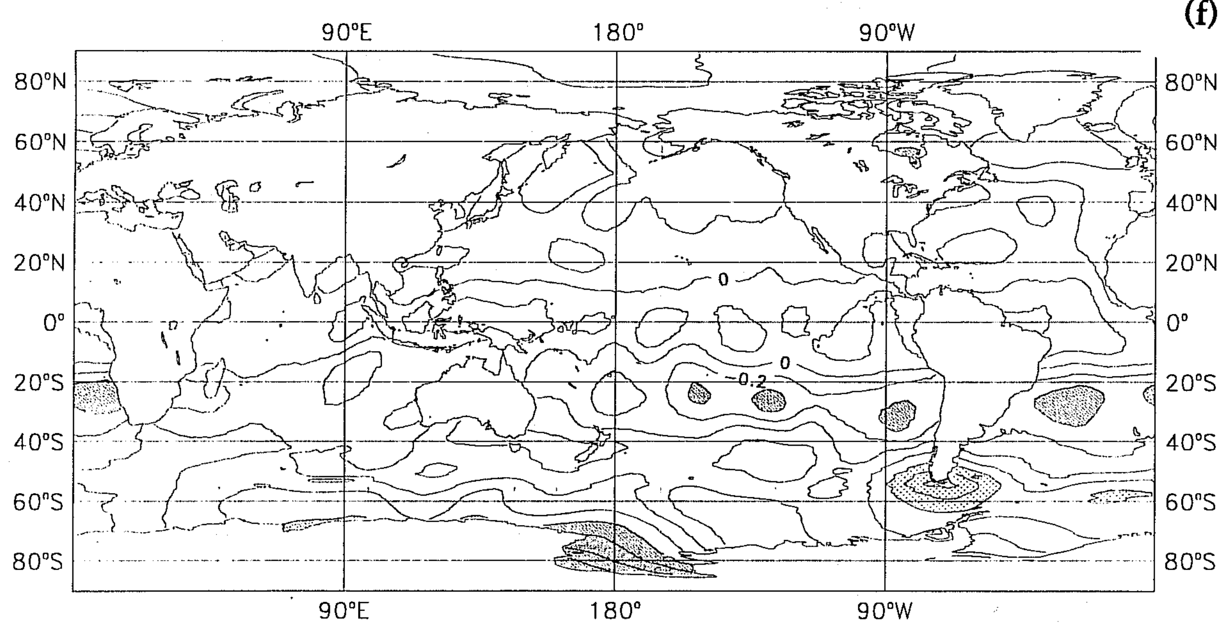


Fig. 6 (continued)

ANNEX A.

USER GUIDE TO BIAS CORRECTION PROGRAMS.

1. PROGRAMS

1.1 Data selection

This is described in section 5.1.

Jobs are in: .STE.CRAY_JOBS.BIASPREP92_##,
where ## = 11 for NOAA-11, = 12 for NOAA-12.

Each job contains 2 FORTRAN programs: the first (BIASPREP) selects data for the required satellite and cloud-clearing route (currently set to "clear" soundings only) and concatenates data for required days. The second (BIASSELE) selects data for sea or land (set to sea at present) and equalises data quantities for different latitude bands.

Input from ECFILE: /ANALF/O/PRESAT1D/STAT/yymmddhh.
Output to ECFILE: /STE/UNICOS/PRESAT92/BIASPREP_mm_##.

To modify for new month, make changes shown in Figure A.1.

1.2 Scan bias correction

This is described in sections 5.2 and 5.3. The job is not currently active.

Source code is in .STE.BIAS.SOURCE_LIBRARY, with main program BIASSCAN. (Currently requires some modification to make consistent with other programs.)

Input:
- TOVS data from ECFILE: /STE/UNICOS/PRESAT92/BIASPREP_mm_##,
- radiosonde mask: /ec/ste/rsmask.

Output:
- scan bias corrections.

1.3 Spatially-varying bias correction

This is described in sections 5.2 and 5.4.

Jobs are in: .STE.CRAY_JOBS.BIAS92_##rs,
where ## = 11 for NOAA-11, = 12 for NOAA-12.

Source code is in .STE.BIAS.SOURCE_LIBRARY, with main program BIASCOR.

Input:
- TOVS data from ECFILE: /STE/UNICOS/PRESAT92/BIASPREP_mm_##,
- radiosonde mask: /ec/ste/rsmask,
- scan bias corrections (not currently active).

Output:
- bias correction coefficients: /STE/UNICOS/PRESAT92/COEF_mm_##R,
- corrected TOVS data: /STE/UNICOS/PRESAT92/BIASCOR_mm_##R,
- uncorrected TOVS data: /STE/UNICOS/PRESAT92/BIASUNC_mm_##R.

To modify for new month, make changes shown in Figure A.2.

BIASCOR can also be run in a mode in which it reads in "external coefficients" calculated beforehand (e.g. from the previous month) and uses these to generate corrected data.

1.4 Creation of radiosonde mask

Job is in: .STE.CRAY_JOBS.RSMASK. Source code is in:
.STE.PPEMISC.SOURCE_LIBRARY, with main program RSMASK_CRAY.

Input:
- list of active radiosonde stations (obtained from Met.Ops): /ec/ste/templist.

Output:
- mask, with resolution of 1 deg x 1 deg, denoting points within a radius of X degrees (latitude equivalent) of an active radiosonde station (currently X = 5 deg): /ec/ste/rsmask.

1.5 Plotting fields of local bias and standard deviation

Job is in: .STE.CRAY_JOBS.PLOTBIAS.

Input:
- output of BIASCOR, either corrected or uncorrected data:
/STE/UNICOS/PRESAT92/BIASCOR_mm_##R,
/STE/UNICOS/PRESAT92/BIASUNC_mm_##R.

Output:
- contoured plots of local mean and standard deviation of data.

To modify for new month or channels, make changes shown in Figure A.3. Appropriate contour intervals are 0.5K for HIRS channels 10, 11 and 12, and 0.2K for other channels.

2. PROCEDURE TO GENERATE AND CHECK NEW BIAS CORRECTIONS

The current practice is to generate bias corrections once per month as soon as the PRESAT output is available for all days in the preceding month, and to use data from all cycles on alternate days.

2.1 Edit BIASPREP92_## and BIAS92_##rs to new month for both satellites.

2.2 Run BIASPREP92_##, then BIAS92_##rs, for each satellite. Check that the coefficient files have been successfully stored.

2.3 Check the application of bias correction using PLOTBIAS: edit it to the appropriate month. Run one job for each batch of channels (e.g. 1-4, 5-8, 10-12, 13-15, 22-24).

Fig. A.1 Job for data selection.

```
                    .ste.cray_jobs.biasprep92_11 (selected parts)

|
#QSUB -r biasprep              # Job name
|
cat > test.f <</EOF
      PROGRAM BIASPREP
C
C         ACCUMULATE PRESAT OUTPUT STATS FOR BIAS CORRECTION PROGS
|
      CHARACTER*80        YPARMS, YPFTABB
      CHARACTER*6         YTABB
      CHARACTER*2         YTIM(4)
      DATA YTIM/'00','06','12','18'/
|
      ILFN=JYEAR*10000+JMON*100+JDAY
      WRITE (YTABB,'(16)') ILFN
      YPFTABB='/tmp/ste/prss'//YTABB//YTIM(ITIM)
      YPARMS='-p /analf/o/presat1d/stat'//YTABB//YTIM(ITIM)//'get'
     1//YPFTABB
      CALL ECFILE(NFAIL,IRSN,YPARMS)
|
      END
EOF
|
assign -a biasprep_07[1]_11.d fort.20
./a.out <<\EOF
201 32
92 07 01 92 07 31 02[2]
EOF
#
cat >biassele.f <<\EOF         # put code from stdin into file bias.f
      PROGRAM BIASSELE
C
C**** *BIASCOR* - TO SELECT DATA FOR BIAS CORRECTION PROGRAMS.
C
|
      END
EOF
|
assign -a biasprep_07[1]_11.d fort.10
assign -a /tmp/ste/biasprep_07[1]_11 fort.11
./biassele.out
#
ecfile -h O -v U/PUB/R/-/S -p /STE/UNICOS/PRESAT92/BIASPREP_07[1]_11 save \
/tmp/ste/biasprep_07[1]_11
#
fi
```

[1] month

[2] start year, month, day; end year, month, day; day-increment

Fig. A.2 Job for spatially-varying bias correction.

```
                 .ste.cray_jobs.bias92_11rs (selected parts)

PROC RUN_BIAS( )
|
#QSUB -r stebias                # Job name
|
#       SCAN BIASES
#ecfile -p /STE/UNICOS/SCANBIAS_89R11 get /tmp/ste/scanbias_89r11
#assign -a /tmp/ste/scanbias_89r11 fort.15
#       INPUT DATA FROM SELECT
ecfile -p /STE/UNICOS/PRESAT92/BIASPREP_07[1]_11 get /tmp/ste/biasprep_07[1]_11
assign -a /tmp/ste/biasprep_07[1]_11 fort .10
#       INTERNAL COEFFICIENTS
assign -a /tmp/ste/coef_07[1]_11r fort.11
#       EXTERNAL COEFFICIENTS
#ecfile -p /STE/UNICOS/PRESAT92/COEF_01_11 get /tmp/ste/coef_01_11
#assign -a /tmp/ste/coef_01_11 fort.21
#       CORRECTED OUTPUT
assign -a /tmp/ste/biascor_07[1]_11r fort.12
#       UNCORRECTED OUTPUT
assign -a /tmp/ste/biasunc_07[1]_11r fort.13
#       mask
assign -a /ec/ste/rsmask fort.39
#
cat > biasdata << EOFB
201 0 0 1
sat id, int/ext coeffs (0/1), scan corr: no/yes (0/1), raob mask: no/yes (0/1)
EOFB
bias.out < biasdata
#
fi
#
ecfile -h O -v U/PUB/R/-/S -p /STE/UNICOS/PRESAT92/COEF_07[1]_11R save \
/tmp/ste/coef_07[1]_11r
ecfile -h O -v U/PUB/R/-/S -p /STE/UNICOS/PRESAT92/BIASCOR_07[1]_11R save \
/tmp/ste/biascor_07[1]_11r
ecfile -h O -v U/PUB/R/-/S -p /STE/UNICOS/PRESAT92/BIASUNC_07[1]_11R save \
/tmp/ste/biasunc_07[1]_11r
```

[1] month

Fig. A.3 Job for plotting local bias and standard deviation.

.ste.cray_jobs.plotbias (selected parts)

```
PROC UNL_RADS_ANAL_MAIN( )
|
#QSUB -r steplot                # Job name
|
cat > pltrad.f <<\EOF
        PROGRAM ANALRAD
C
|
        END
EOF
|
ecfile -p /ste/unicos/presat92/biascor_06[1]_12[2]r get fort.50          # input
#ecfile -p /ste/unicos/presat92/biasunc_03_11r    get fort.50       # input
a.out << \eof
 $namin
        anwlon= 0., aselon=360., anwlat=90., aselat=-90., xlen=10.,
        NLNDSEA=1, NRET=0, NDEV=0, cint=.2[3],
        NCHS= $VALUE(NCHS) ,
        NCHE= $VALUE(NCHE) ,
        NSAT= $VALUE(NSAT) ,
 $end
 $namtx
        CTEXT='presat92 06/cor rsmask'[4]
 $end
eof
if [ $? -ne 0 ]; then
        debug; exit 1
fi
# rename plotfile
#
#mv qms pltrad.qms
# gksplot -f qms pltrad.qms
mv ps pltrad.ps
gksplot -d ps -f ps -n pltrad.ps
exit
??end
disv' Submitting rads_anal job to CRAY ...'
subcj $fname(cray_job_file)
procend UNL_RADS_ANAL
??
$local.rads_anal          'ste' '920601'[5] '12'[2] '22'[6] '24'[6]
disv ' End of MAIN VE-procedure, OK!
"delf $user.rads_anal
procend UNL_RADS_ANAL_MAIN
```

1 month
2 satellite
3 contour interval
4 plot title
5 start date
6 channel limits