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COMPARISONS BETWEEN MEASURED AND SIMULATED TOVS BRIGHTNESS TEMPERATURES

by

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1. Introduction

The TOVS (TIROS-N Operational Vertical Sounder) instruments on the TIROS-N series of polar-orbiting satellites measure radiances in the infra-red and microwave regions (see Schwalb, 1978, and Smith et al., 1979). These measurements can be used to retrieve the temperature and humidity profiles of the atmosphere. This paper gives the results of the study in which TOVS data were colocated with radiosonde profiles. The radiosonde data were then used in conjunction with a radiative transfer model to simulate the TOVS brightness temperatures expected from these profiles. The differences between the measured and simulated brightness temperatures were analysed statistically.

TOVS consists of 3 instruments: HIRS-2 (High-resolution Infra-Red Sounder), MSU (Microwave Sounding Unit) and SSU (Stratospheric Sounding Unit). In this study only HIRS-2 and MSU were considered using data from satellites NOAA-6 and NOAA-7.

An accurate radiative transfer model is a pre-requisite for most types of retrieval scheme, particularly those which use inversion methods of a physical or mixed physical-statistical nature. The purpose of this study was to make a preliminary assessment of the accuracy of the radiative transfer model used and to explore the problems involved in using radiance-radiosonde colocations to make empirical corrections to simulated radiances.

2. The data base

The HERMES (High-resolution Evaluation of Radiances from MEteorological Satellites) system, under development in Met O 19, will have as its principal function the real-time processing of local-area TOVS data for operational use. This study made use of 3 sets of TOVS data which were recorded and processed during data experiments in the development phase of the HERMES project (see Eyre and Jerrett, 1982; Jerrett, Eyre and McCallum, 1982). The experiments were undertaken to investigate the potential of high-resolution satellite soundings in operational forecasting.

Raw data can be received at Lasham (51.1°N, 1.0°W) for all overpasses during which the satellite is trackable above the local horizon. This gives data coverage over a roughly circular region of about 3000 km radius centred at Lasham, i.e. Europe and much of the N. Atlantic. Two of the data sets were received in this way: 18-21 June 1981 (NOAA-6 only) and 30 November - 20 December 1981 (NOAA-6 + NOAA-7). The third data set for 4-5 March 1982 (NOAA-7 only) was obtained from NOAA-NESS, Madison, in calibrated, earth-located form, for use in connection with the 1st International TOVS Study Conference (to be held in Igls, August 1983). These data cover a more limited area of western Europe.

The data were processed using the retieval scheme which was obtained from NOAA/NESS, Madison, and which is intended for initial operational implementation on HERMES. The processing scheme is described in more detail elsewhere, but the following aspects are relevant to the study described here:

a. HIRS and MSU data are calibrated and earth-located.

b. HIRS radiances are converted to brightness temperatures (equivalent black body temperatures).

c. HIRS brightness temperatures are corrected for scan angle (to yield the brightness temperatures which would be expected when viewing the same atmospheric profile at nadir). HIRS window channels (numbers 8, 18 and 19) are also corrected for water vapour absorption. In both steps each channel is corrected using a regression on other channels. The regression coefficients used are pre-computed once for each satellite by NOAA/NESS, Washington D.C.

d. MSU antenna temperatures are corrected in a similar way for scan angle, surface emissivity and field of view effects (to give the brightness temperatures which would be expected viewing at nadir with a "black" lower boundary, i.e. surface emissivity = 1).

e. Tropospheric HIRS channels (4 to 16) are then "cloud-cleared" using the adjacent field of view or N* method (McMillin, 1978). MSU channel 2 is used to determine which HIRS soundings are cloud-free (in which case they are used directly) and which are partly cloudy (in which case they are corrected to give cloud-free values). Soundings which are too cloudy to be successfully "cloud-cleared" are not considered further here, but they are used in the retrieval to give MSU-only results.

It must be remembered that the "measured" brightness temperatures used in this study have been pre-processed and cloud-cleared in the ways listed above. Retrievals were performed from these brightness temperatures using a statistical regression method with coefficients obtained from NOAA/NESS, Washington D.C. The outcome of the retrieval is not relevant to this study, except in so far as quality control procedures applied to the retrievals will have rejected certain soundings which, therefore, were not used here.

The Met Office synoptic data bank archive was used to obtain all available radiosondes close in time and space to the measured brightness temperatures. Colocations were saved if:

- the satellite sounding location and radiosonde site were less than 150 km apart,
- the two soundings were made within 3 hours of each other,
- the radiosonde was the closest (of all available radiosondes) to the satellite sounding,
- the radiosonde data passed certain gross quality checks.

It should be noted that NOAA-7 provides many more of such colocations over Europe than does NOAA-6, because the overpasses of NOAA-6 are not close in time to 00Z and 12Z when most radiosonde measurements are made.

3. The radiative transfer model

Each radiosonde profile was processed using a model known as TOVSRAD to generate simulated brightness temperatures for HIRS and MSU channels. TOVSRAD is essentially a combination of two models obtained from NOAA/NESS, Madison - RAOBHIRS and RAOBMSU - which compute respectively the HIRS and MSU brightness temperatures equivalent to a radiosonde profile. These have been amalgamated and changed in minor detail only. The transmittance algorithms used in TOVSRAD are fast, parameterised models specific to the HIRS and MSU channels of each satellite. They are based on the methods described by McMillin and Fleming (1976), Fleming and McMillin (1977) and McMillin, Fleming and Hill (1979).

It has been recognised by NOAA/NESS that the results of these routines are not in exact agreement with measurements. An attempt to allow for this has been made by introducing an empirical factor, γ, for each channel: all simulated transmittances, τ, are converted to τ^{γ}. The γ-values used in this study were obtained from NOAA/NESS, Madison in May 1982 and are shown in Table 1. γ for each channel has been calculated by minimising the r.m.s. difference between measured and simulated radiances using studies similar to this (Smith, 1980). One would therefore naively expect the present study to show very small biases between measured and simulated radiances. Any other result indicates imperfections either in this study or in those on which the γ-calculations were based. These problems are discussed below.

A major problem arises with the specification of the stratosphere. Radiosondes do not define the temperature profile to the highest level required for the transmittance model (0.1 mb). Also stratospheric levels above those measured by radiosondes contribute to the radiances of some of the channels, particularly HIRS channels 1, 2, 3 and 17 and MSU channel 4. TOVSRAD rejects any profile which does not specify temperatures up to 50 mb, but for missing levels above this it extrapolates a profile using a regression relation based on the temperatures at lower levels. This obviously introduces scope for error, particularly when the shape of the atmospheric profile is unusual.

In this study TOVSRAD was used to simulate the TOVS brightness temperatures in their pre-processed form: nadir viewing with a black lower boundary (earth's surface) and no cloud. Specification of the lower boundary temperature, T_s, presents a problem since it is not available in the radiosonde data. For this reason, the measured brightness temperature in HIRS channel 8 (corrected for viewing angle and water vapour absorption) was taken as the best estimate of T_s. For the purpose of this study, profiles were rejected if the absolute difference between T_s and the air temperature at the surface was greater than 5K.

4. Calculation of difference statistics

All colocations were processed as described above and the differences between measured and simulated brightness temperatures computed. For the reasons discussed above NOAA-7 colocations were more numerous. The data were analysed in the following groups:

				Number of good colocations
NOAA-7	DEC 81	WEEK 1	(30 Nov-6 Dec)	329
		WEEK 2	(7 Dec-13 Dec)	288
		WEEK 3	(14 Dec-20 Dec)	595
NOAA-6	DEC 81	WEEK 1		82
		WEEK 2		40
		WEEK 3		71
NOAA-6	JUNE 81	ALL	(18 June-21 June)	32
NOAA-7	MAR 82	ALL	(4 Mar-5 Mar)	83

Preliminary calculations of the mean and standard deviation, σ, of the brightness temperature difference for each channel were used to detect "rogues": differences from the mean greater than 3σ were rejected and the statistics recalculated. The mean and standard deviation for each channel for each group are presented in table 2. The results are also plotted in figures 1 and 2.

The NOAA-7 data for December 81 were also examined on a daily basis. This confirmed that the means and standard deviations were stable from day to day.

5 Discussion

Different factors must be considered when attempting to explain the results for each channel or group of channels. Typical weighting functions for all channels are shown in figure 3.

HIRS 1, 2, 3 (15 μm, stratospheric temperature). The December 81 data show large biases and standard deviations for both NOAA-7 and NOAA-6. They are smaller for March 82, and the biases are very small for the limited sample of June 81. It is therefore probable that the December results were affected by poor extrapolations of the stratospheric profiles (and March also to a lesser extent). December 81 was anomalously cold over Europe. This would have resulted in atypical tropospheric profiles and probably caused large errors in the stratospheric extrapolation. This illustrates a major problem in verification studies for stratospheric channels.

HIRS 4, 5, 6, 7 (15 μm, tropospheric temperature). The standard deviations are low - generally about 1K, which is as low as can be expected when colocation separations up to 150 km and 3 hours are allowed. Biases are small (mainly less than 1K) and mainly positive (i.e. simulated brightness temperature greater than measured value).

HIRS 8 (11 μm, window channel). Since this channel was used to specify the lower boundary temperature, its statistics cannot be interpreted in the same way as for other channels.

HIRS 9 (10 μm, ozone). There are neither ozone profile measurements nor a transmittance algorithm in TOVSRAD to allow comparisons for this channel.

HIRS 10 (8.3 μm, lower tropospheric water vapour + surface). The standard deviations are low and the biases consistently small and negative (about -1K).

HIRS 11, 12 (7 µm, mid and upper tropospheric water vapour). These channels show large standard deviations and biases of 2-5K. The large standard deviations are expected because of the large errors and unrepresentative nature of radiosonde humidity profiles. Noting that NOAA/NESS γ-factors have been applied, the biases may be caused by:

- systematic differences between European and N. American radiosondes,
- the degree to which the γ-factors for these channels were calculated using comparisons with only cloud-free radiosonde ascents,
- differences between TOVSRAD and the routines used in the γ-factor calculation with respect to the treatment of moisture variables,
- the fact that the "measured" brightness temperatures have been cloud-cleared which biases them towards clear air values, whereas the radiosonde samples will contain a large number of sondes which passed through clouds.

HIRS 13, 14, 15 (4.5 µm, tropospheric temperature). The standard deviations are low and the biases fairly small (less than 1.5K). For channel 13 there appears to be a significant difference between the biases of NOAA-6 and NOAA-7.

HIRS 16 (4.4 µm, upper tropospheric temperature). Biases and standard deviations are generally larger than for channels 13-15, suggesting a significant contribution from stratospheric profile error (see channels 1-3).

HIRS 17 (4.2 µm, stratospheric temperature). The same problems as for channels 1-3 apply here. Also this channel is sensitive to fluorescence effects in the day time. It is not currently used in the inversion algorithm.

HIRS 18, 19 (4.0 µm and 3.7 µm, window channels). The use of channel 8 to specify surface temperature and the effects of solar reflection make interpretation of statistics for these channels difficult. They are not currently used in the inversion process.

MSU 1 (50.3 GHz, window channel). The large standard deviation is caused by errors in the corrections for surface emissivity effects. Also differences between HIRS channel 8 and the true surface brightness temperature will cause an apparent error in MSU channel 1. This channel is not currently used in the inversion; it is only used in the correction of other MSU channels for surface effects.

MSU 2, 3 (53.7 GHz and 55.0 GHz, tropospheric temperature). Both channels have low standard deviations and MSU channel 2 has a very low bias for both satellites. MSU channel 3 has a significant bias for NOAA-6 but not for NOAA-7.

MSU 4 (58.0 GHz, lower stratospheric temperature). The biases for this channel are around 1-2K. The December values do not show as large biases as HIRS channel 3, perhaps because of a smaller contribution from the upper stratosphere.

6. Conclusions

The principle conclusion of this study is that the interpretation of differences between measured and simulated radiances is not straightforward, with different factors applying to each channel. The biases found cannot usually be attributed to errors in the radiative transfer model. The characteristics of radiosonde measurements must be allowed for and the way in which the raw radiosonde data are converted for use by the model taken into account. Also the treatment of surface effects, by the model and by the pre-processing of the measured radiances, complicates the interpretation. However, more specific conclusions are as follows:

a. It is apparent that no useful conclusions about the modelling of the stratospheric channels (HIRS 1, 2, 3, 17; MSU 4) will be possible without a more careful treatment of the extrapolation of radiosonde profiles in the stratosphere.

b. The model appears reasonably good for HIRS 4-7, 10, 13-15 and MSU 2-3 with current γ-factors, although these brightness temperatures could be further corrected in most cases by removal of the small, consistent, residual biases. For HIRS 13 and MSU 3, there appears to be a significant difference between the biases of NOAA-6 and NOAA-7.

c. HIRS 11 and 12 are difficult to study from gross statistics over Europe where the characteristics of radiosonde humidity elements are so varied. However both channels for both satellites in all the periods studied show large positive biases. These may be caused by inappropriate γ-factors, by errors in the conversions between humidity parameters, or by the biasing of "measured" brightness temperatures towards clear air values.

d. For HIRS 16, the difference in bias between December 81 and other periods suggests that the effects of errors in the stratospheric extrapolation are significant for this channel.

e. Differences between the statistics of the 3 periods studied suggest that further statistics from other periods would be helpful in determining the reasons for some of the biases.

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Table 1

γ - values used in TOVSRAD
for NOAA-6 and NOAA-7

HIRS -	1	0.924
	2	1.017
	3	1.147
	4	1.032
	5	0.964
	6	0.957
	7	0.887
	8	1.
	9	1.
	10	1.073
	11	1.023
	12	1.077
	13	1.073
	14	1.009
	15	1.055
	16	0.997
	17	1.
	18	1.
	19	1.
MSU -	1	1.
	2	1.01
	3	1.009
	4	1.105

Table 2. RADIANCE COLOCATION STATISTICS

Mean (upper value) and standard deviation (lower value) of simulated minus measured brightness temperature (in K).

	NOAA-7				NOAA-6			
	DEC 81 WEEK 1	DEC 81 WEEK 2	DEC 81 WEEK 3	MAR 82 ALL	DEC 81 WEEK 1	DEC 81 WEEK 2	DEC 81 WEEK 3	JUN 81 ALL
NUMBER OF COLOCATIONS	329	288	595	83	82	40	71	32
HIRS 1	6.7	4.0	6.5	2.3	9.1	8.4	5.8	0.0
	3.1	4.6	2.6	1.9	3.1	3.1	2.9	1.2
HIRS 2	5.1	3.7	4.4	2.5	5.7	4.7	3.8	0.2
	2.2	2.1	1.5	1.3	1.5	1.5	1.2	0.8
HIRS 3	3.7	2.7	3.3	2.1	4.5	3.8	3.1	0.5
	1.6	1.7	1.2	1.3	1.2	1.3	1.0	0.6
HIRS 4	1.1	0.8	1.0	1.0	1.3	1.0	0.8	0.4
	0.9	0.9	0.7	1.2	0.7	0.9	0.8	0.7
HIRS 5	1.3	1.1	1.3	1.5	0.9	0.8	0.9	0.3
	0.8	0.8	0.8	0.9	0.8	0.7	0.7	0.8
HIRS 6	0.6	0.6	0.8	0.7	0.5	0.3	0.5	0.0
	1.0	0.9	0.8	0.9	0.9	0.9	0.9	1.1
HIRS 7	0.4	0.5	0.6	0.3	0.3	0.2	0.5	-0.5
	1.0	0.8	0.7	0.9	1.0	1.1	1.0	1.2
HIRS 10	-1.1	-1.3	-1.2	-0.9	-0.6	-0.9	-1.2	-0.5
	1.0	1.0	1.1	1.1	1.0	1.0	0.9	1.3
HIRS 11	3.1	2.6	2.1	2.5	3.7	3.7	2.8	4.3
	2.5	2.5	2.2	3.0	2.3	3.2	2.4	3.1
HIRS 12	3.3	2.5	1.4	2.1	4.5	4.7	2.2	5.3
	3.6	3.7	3.1	4.9	3.7	4.8	2.2	3.6
HIRS 13	0.8	1.4	1.4	1.2	-0.3	-0.7	-0.4	-0.3
	1.0	1.0	0.9	1.0	1.2	1.0	1.1	1.1
HIRS 14	0.8	1.1	1.2	1.3	0.6	0.5	0.7	1.2
	0.8	0.8	0.9	0.8	0.9	0.7	0.9	1.2
HIRS 15	0.6	0.5	0.7	0.5	-0.3	-0.4	-0.2	0.1
	1.0	1.1	1.1	1.1	0.8	0.6	0.8	1.2
HIRS 16	1.7	0.6	1.8	-0.4	2.0	2.3	1.2	-0.6
	1.8	2.2	1.7	1.7	1.5	1.2	1.4	1.2
HIRS 17	5.3	2.5	7.3	2.1	10.9	10.7	6.8	-2.0
	4.2	7.7	4.5	2.5	5.2	6.0	5.5	1.7
MSU 1	-0.7	0.4	-2.4	2.6	-2.4	1.3	2.5	-4.5
	4.7	3.1	3.7	2.4	5.4	3.1	2.9	1.0
MSU 2	0.2	0.1	0.0	0.8	0.0	0.5	0.8	0.6
	1.1	0.9	0.9	1.3	0.9	1.0	0.8	0.8
MSU 3	-0.1	-0.1	-0.1	0.3	1.7	1.4	1.4	2.4
	1.0	0.8	0.8	1.3	0.9	1.3	0.8	0.9
MSU 4	1.4	0.9	0.8	0.9	2.6	1.4	1.7	0.9
	1.6	1.4	1.2	0.9	1.2	1.1	1.1	0.7

Figure 1. BRIGHTNESS TEMPERATURE DIFFERENCE STATISTICS : NOAA-7

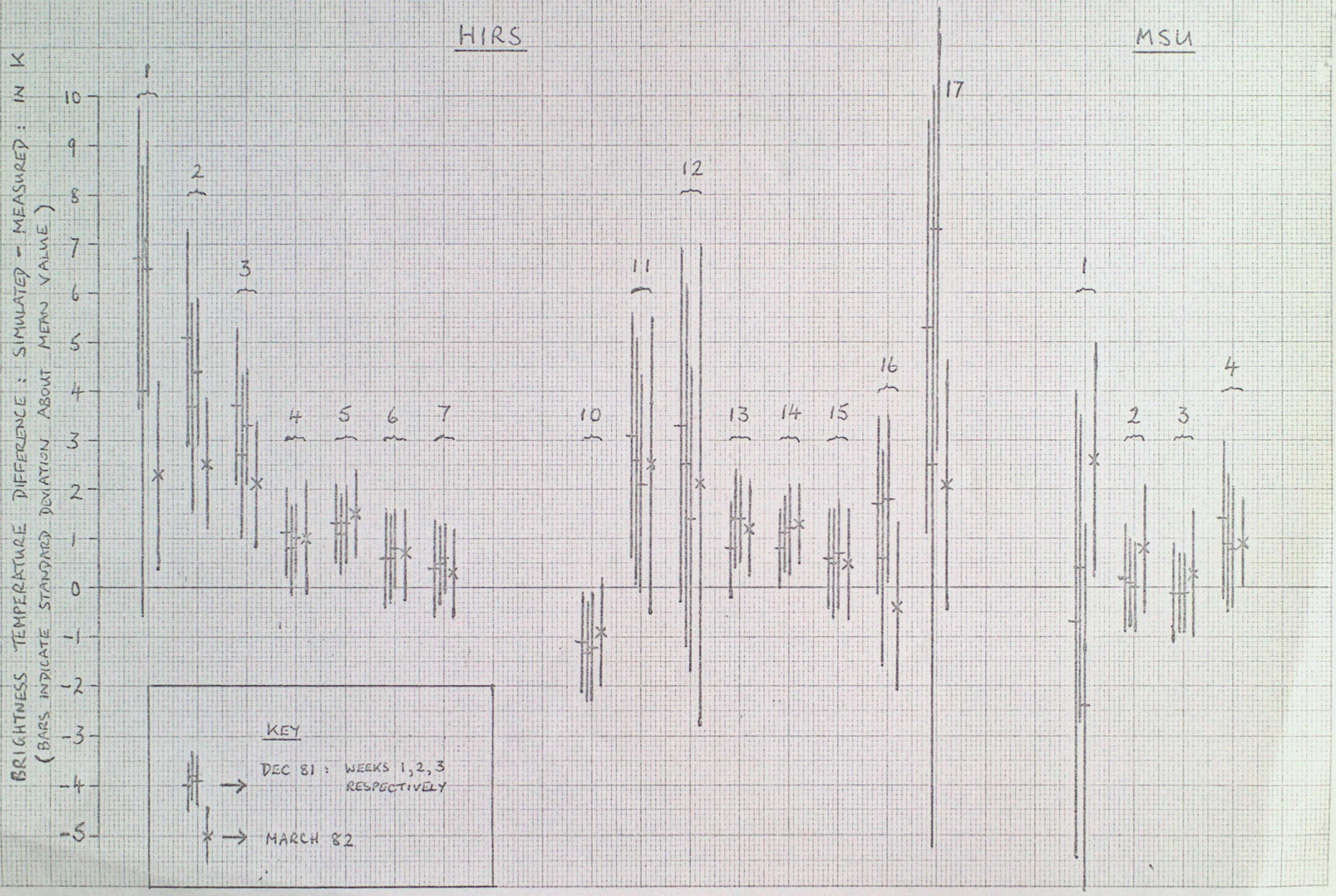

Figure 2. BRIGHTNESS TEMPERATURE DIFFERENCE STATISTICS : NOAA-6