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16. The TOVS/ATOVS observing system in ERA-40

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Abstract

TOVS/ATOVS is a major component of the ERA-40 observing system. From October 1978, when TIROS-N was launched, the TOVS/ATOVS system has been providing global observations of the radiation emitted by the surface and atmosphere of the Earth, covering regions and atmospheric layers where the coverage by conventional observations is sparse.

Preparation of observations is an essential activity in any reanalysis, and in ERA-40 a special effort was devoted to preparing the TOVS and ATOVS radiance datasets. On one hand, the assimilation of the TOVS/ATOVS radiance data has a considerable impact on the quality of the analysis, and on the other, the relative uniformity of the datasets makes the task feasible despite of the massive volume of data involved.

This report describes the work carried out, as part of the ERA-40 project, to prepare the TOVS and ATOVS datasets for reanalysis. The whole ERA-40 TOVS level-1b archive from October 1978 to December 2002 has been processed to generate an archive of calibrated radiances. The TOVS and ATOVS datasets of calibrated radiances have been checked and monitored in order to obtain information that can help to make the best possible use of the observations in the reanalysis.

Quality monitoring of observations in general, and of satellite data in particular, is a key task of the day-to-day operations in NWP centres, as it is in reanalysis environments. However, there are some important differences: the scale of the tasks involved and the amount of available information. Consequently, methods and tasks are different as well; an important part of the preparation of the TOVS and ATOVS datasets for ERA-40 has been the development of methods appropriate for a reanalysis environment.

1. Introduction

From October 1978, when TIROS-N was launched, to the present, the spacecraft of the third and fourth generation of Polar Orbiting Environmental Satellites (POES) of the NOAA have been providing operationally global observations of the surface and the atmosphere of the Earth.

TOVS is part of the instrumental payload of the POES satellites TIROS-N, and NOAA-6 to NOAA-14, and ATOVS (Advanced TOVS) of NOAA-15 to NOAA-17. The instruments in the TOVS and ATOVS systems measure radiances emitted by the surface and the atmosphere of the Earth; these radiances are in particular sensitive to the vertical profiles of temperature and water vapour, and can be assimilated to extract information on atmospheric temperature and humidity.

TOVS/ATOVS is a major component of the ERA-40 observing system. It covers regions of the Earth and atmospheric layers where the coverage by conventional observations is sparse, e.g. the Southern Hemisphere or the stratosphere, and it has provided observations for a large part of the period covered by ERA-40 (from September 1957 to August 2002).

The introduction of TOVS and other new observing systems in late 1978 in connection with the First GARP Global Experiment (FGGE) had a large positive impact both on the performance of data assimilation and the forecast skill. The impact is particularly large in the extratropics of the Southern Hemisphere (Uppala et al, 2004). The TOVS system gives reanalyses the stability and continuity required by many applications.

Direct assimilation of satellite radiances is considered to be one of the main contributors to the improvement in forecast skill (especially in the Southern Hemisphere) shown in the last few years by the ECMWF and other global prediction systems (Simmons and Hollingsworth, 2002; Thepaut and Anderson, 2003).

Preparation of observations is an important activity in any reanalysis, and in ERA-40 a special effort was devoted to preparing the TOVS and ATOVS radiance datasets. On one hand, the assimilation of the TOVS/ATOVS radiance data has a considerable impact on the quality of the analysis, and on the other, the relative uniformity of the datasets makes the task feasible despite of the massive volume of data involved.

Section 2 gives a short description of the characteristics of the instruments in the TOVS and ATOVS systems. Section 3 gives an outline of the use of TOVS/ATOVS radiance data in the ERA-40 assimilation system. Section 4 describes the ERA-40 TOVS and ATOVS datasets and the calibration of TOVS data. Section 5 focuses on the quality monitoring, and section 6 presents some concluding remarks.

2. TOVS and ATOVS systems

TOVS is a system comprising three independent instruments:

- The High resolution Infra-Red Sounder/2 (HIRS/2), with 7 shortwave channels in the region 3.7 to 4.6 μm, 12 long wave channels in the region 6.7 to 15 μm and a visible channel at 0.7 μm.
- The Microwave Sounding Unit (MSU), with 4 channels in the region 50-58 GHz.
- The Stratospheric Sounding Unit (SSU), provided by the UK, with 3 pressure-modulated channels near 15 μm.

ATOVS (Advanced TOVS) comprises the following instruments:

- HIRS/3, with 1 visible channel at 0.69 μm, 7 shortwave channels in the region 3.7 to 4.6 μm and 12 long wave channels in the region 6.5 to 15 μm.
- Advanced Microwave Sounding Units AMSU-A with 15 channels and a frequency range of 23 to 89 GHz, and AMSU-B with 5 channels and a frequency range of 89 to 183 GHz.

Table 1 shows the levels of maximum energy contribution of the HIRS, MSU, SSU and AMSU-A channels used in ERA-40 (see section 3). For details of the weighting functions and channel characteristics, see Smith et al. (1979) for TOVS, and Goodrum et al. (2000) for ATOVS.

TOVS is part of the instrumental payload of the spacecraft TIROS-N and NOAA-6 to NOAA-14, and ATOVS of NOAA-15 to NOAA-17. Figure 1 shows the periods when observations from each TOVS/ATOVS instrument and spacecraft are available in the ERA-40 archive.

All HIRS/2, MSU, SSU, HIRS/3 and AMSU-A are cross-track step scanned instruments, but their scan geometries are quite different, with the exception of HIRS/2 and HIRS/3, which are almost identical. Figure 2 and Figure 3 illustrate the differences in scan geometry of HIRS, MSU, SSU and AMSU-A. Table 2 shows some scan parameters; for a detailed description of the scan geometry of the TOVS instruments, the reader is referred to Planet (1988), Schwalb (1978) or Kidwell (1998), and for the ATOVS instruments to Goodrum et al. (2000).

HIRS		MSU		AMSU-A	
2	60 hPa	1	Surface	1	Surface
3	100 hPa	2	700 hPa	2	Surface
4	400 hPa	3	300 hPa	3	Surface
5	600 hPa	4	90 hPa	5	600 hPa
6	800 hPa			6	400 hPa
7	900 hPa			7	250 hPa
8	Surface			8	150 hPa
11	700 hPa	**SSU**		9	90 hPa
12	500 hPa	1	15 hPa	10	50 hPa
14	950 hPa	2	4 hPa	11	25 hPa
15	700 hPa	3	1.5 hPa	12	10 hPa
				13	5 hPa
				14	2.5 hPa
				15	Surface

Table 1. Levels of maximum energy contribution for channels used in ERA-40. See main text.

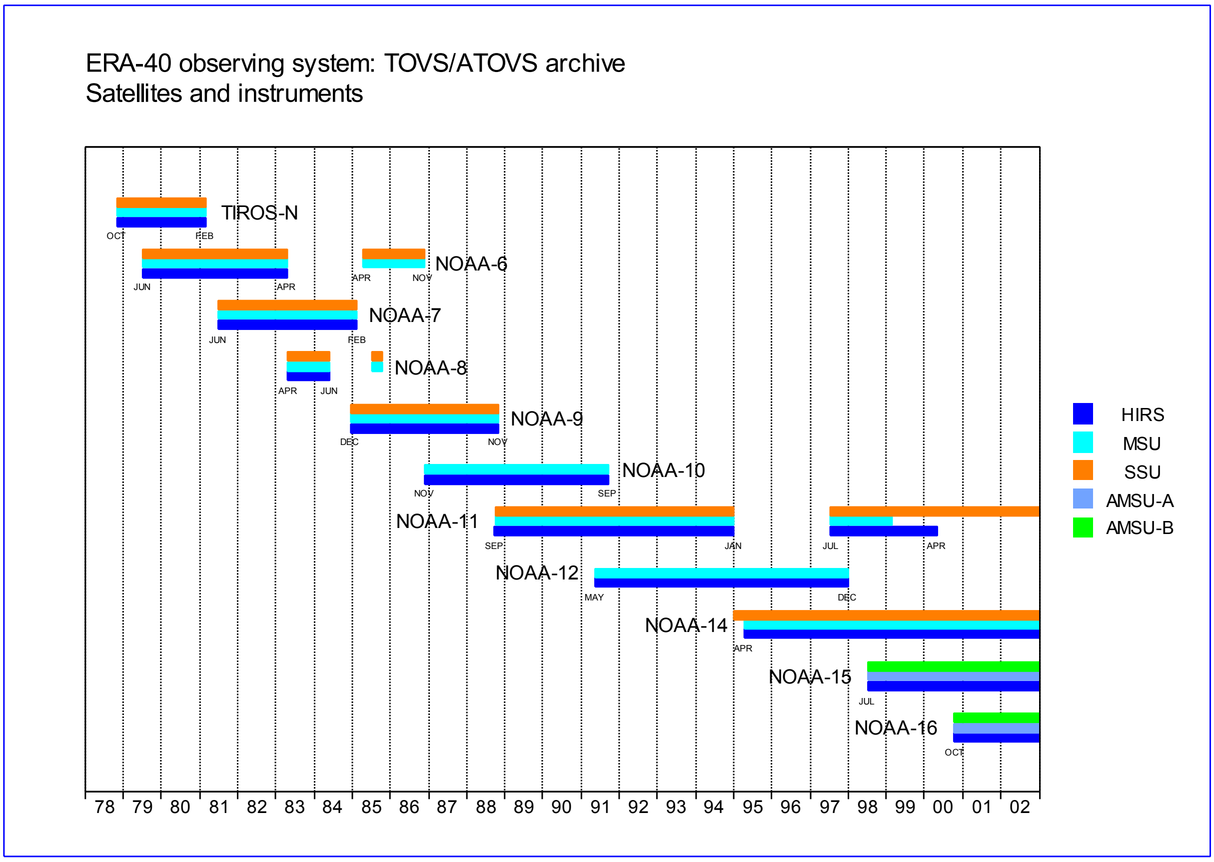

Figure 1 TOVS / ATOVS instruments and satellites in the ERA-40 archive.

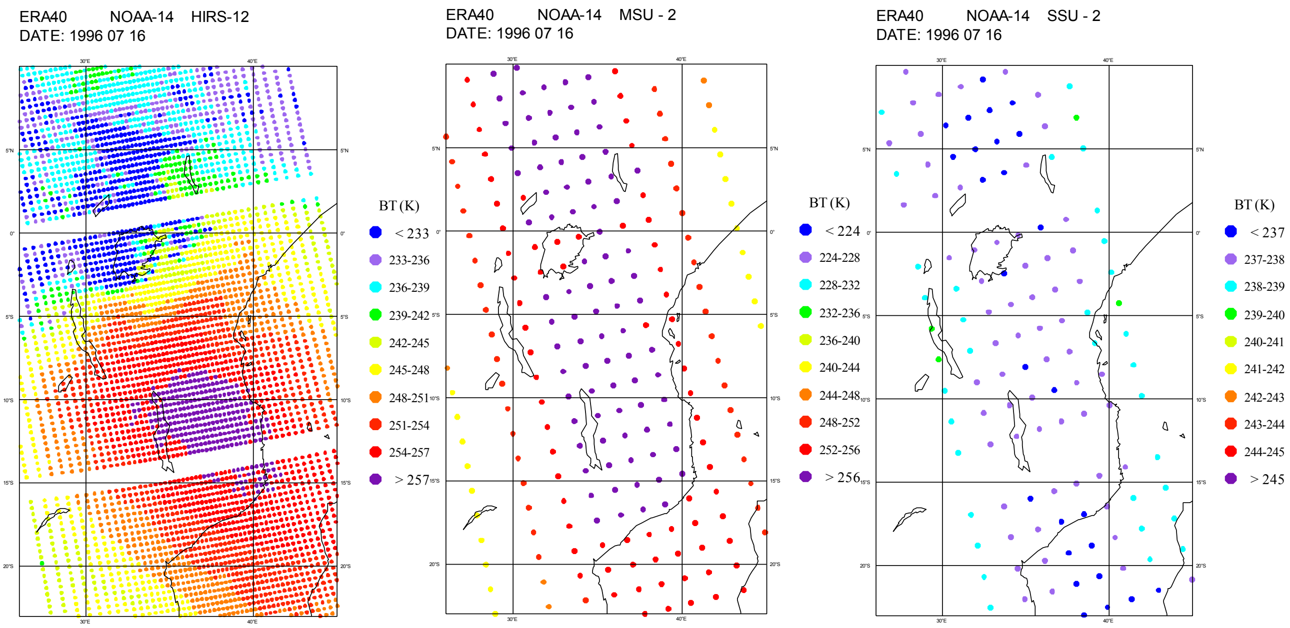

Figure 2: HIRS/2, MSU and SSU coverage - part of a NOAA-14 orbit on 16 July 1996 (eastern Africa and Mozambique channel).

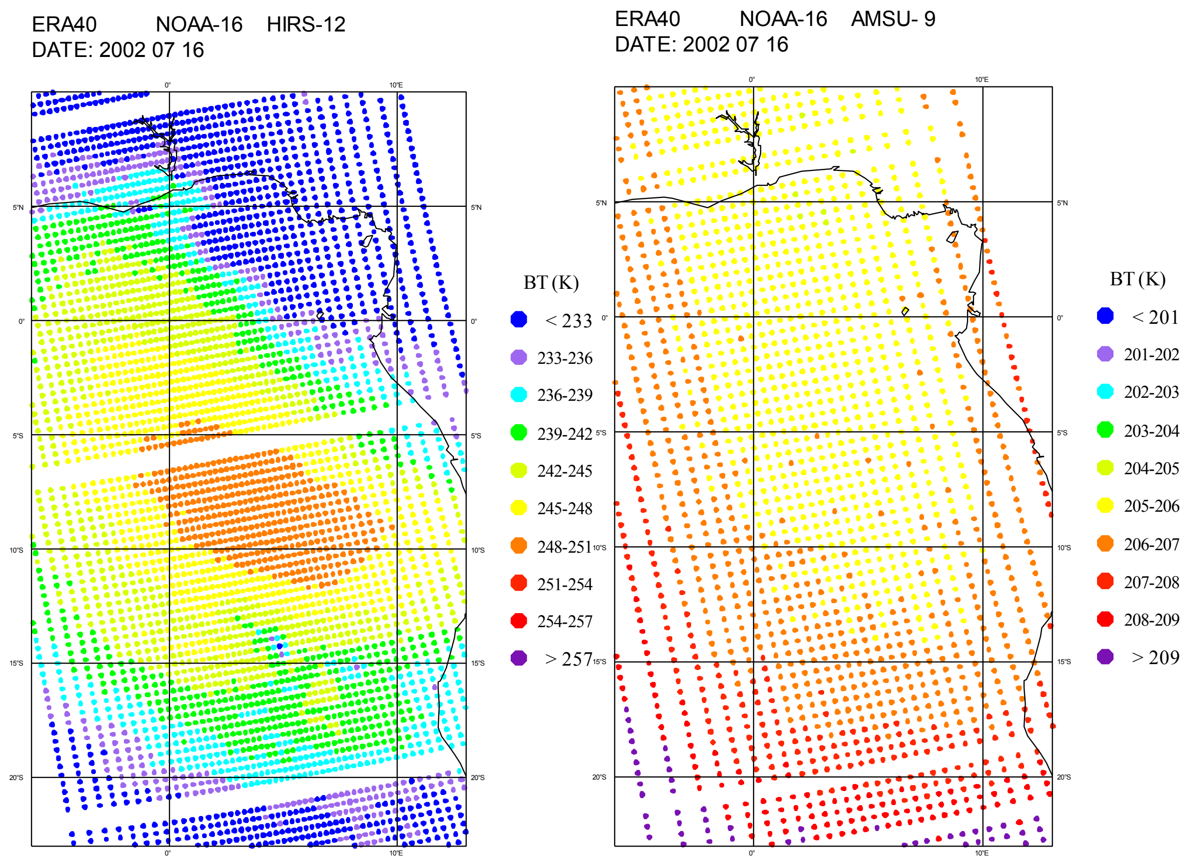

Figure 3. HIRS/3 and AMSU-A coverage - part of a NOAA-16 orbit on 16 July 2002 (Guinea gulf).

	HIRS/2	MSU	SSU	HIRS/3	AMSU-A	AMSU-B
FOVs in each scan line	56	11	8	56	30	90
Optical FOV (degree)	1.25	7.5	10	1.4 SW 1.3 LW	3.3	1.1
Diameter of ground IFOV at nadir (km) (*)	17.4	109.3	147.3	20.3 SW 18.9 LW	48.05	16.0
Scan time (second)	6.4	25.6	32.0	6.4	8	2.67
Cross-track scan angle from nadir (degree)	49.5	47.35	35.0	49.5	48.33	48.95

Table 2. Scan parameters of the TOVS and ATOVS instruments. (*) Based on a nominal altitude of 833 km.

In-orbit calibration is performed routinely by viewing space and onboard blackbodies. HIRS/2 and HIRS/3 start a calibration sequence every 256 seconds; in calibration mode the HIRS radiometers view space and internal blackbodies, and Earth view is interrupted. SSU also starts a calibration sequence every 256 seconds, synchronized with the HIRS/2 instrument. MSU and the AMSU instruments do not have a special calibration sequence but are automatically calibrated each scan. For details on the in-orbit calibration of the TOVS instruments, see Planet (1988), Paris (1994) or Kidwell (1998), and Goodrum et al. (2000) for the ATOVS instruments.

POES orbits are Sun-synchronous and circular at nominal altitudes of 833 or 870 km (see table 3). In normal conditions there are two operational satellites in orbit: the AM satellite, with a nominal southbound Equator crossing time at about 0730 LST (local solar time), and the PM satellite, with a nominal northbound Equator crossing time at about 1430 LST. However, orbits drift with time (Price, 1991), and most of the PM satellites have large orbital drifts.

Spacecraft	TOVS/ATOVS instruments	Nominal altitude	AM / PM	Pre-launch id
TIROS-N	HIRS/2, MSU, SSU	870	PM	TN
NOAA-6	HIRS/2, MSU, SSU	833	AM	NA
NOAA-7	HIRS/2, MSU, SSU	870	PM	NC
NOAA-8	HIRS/2, MSU, SSU	833	AM	NE
NOAA-9	HIRS/2, MSU, SSU	870	PM	NF
NOAA-10	HIRS/2, MSU	833	AM	NG
NOAA-11	HIRS/2, MSU, SSU	870	PM	NH
NOAA-12	HIRS/2, MSU	833	AM	ND
NOAA-14	HIRS/2, MSU, SSU	870	PM	NJ
NOAA-15	HIRS/3, AMSU-A, AMSU-B	833	AM	NK
NOAA-16	HIRS/3, AMSU-A, AMSU-B	870	PM	NL

Table 3. Set of TOVS/ATOVS instruments on board and other characteristics of the spacecraft.

3. Use of TOVS/ATOVS in ERA-40

The main reference for the data assimilation system and the observation system used in the ERA-40 reanalysis is http://www.ecmwf.int/research/era. The ERA-40 assimilation system is based on cycle 23r4 of the IFS, and it uses a 3D-Var analysis scheme with a FGAT (First Guess at the Appropriate Time) algorithm. The assimilation system (Simmons, 2002) allows the direct use of raw radiance data (McNally et al., 2000). Radiance data are assimilated at the scan position, time and geographical location of the observation. The fast radiative transfer model RTTOV-6 (Saunders et al., 1999) performs radiative transfer calculations along slant paths, allowing radiance data to be assimilated without previous limb corrections. The scientific and technical documentation on the IFS cycle used in ERA-40 is available online from the location http://www.ecmwf.int/research/index.html.

There are systematic differences between observed radiances and radiances simulated by the radiative transfer model from first guess fields. These biases can be significant, and may be due to biases in the instruments, the first guess fields or the radiative transfer model. Before radiance data are assimilated, a bias-correction scheme (Harris and Kelly, 2001) is applied to the raw radiance data to remove biases between observed and simulated radiances. Kelly and Li (2002) give details about the bias correction of satellite data assimilated in ERA-40, and in particular of TOVS and ATOVS data.

Table 4 shows the instruments and channels used in ERA-40. For some channels, radiance data are not assimilated, but they are used for some other purpose; for instance the window channel HIRS 8 is used in the cloud detection algorithm. Other channels are not used at all; for instance, channels HIRS 16 to 19 are not used because they are affected by sunlight contamination. Note that no channels from the AMSU-B instrument have been used in ERA-40.

	Rads used, but not assimilated	Rads assimilated over sea only	Rads assimilated over all surfaces
HIRS/2 HIRS/3	8 cloud detection	4, 5, 6, 7, 11, 14, 15	2, 3, 12*
MSU	1 surface microwave emissivity	2, 3	4
SSU			1, 2, 3
AMSU-A	1, 2, 3,15 surface microwave emissivity and cloud and rain detection		5*, 6*, 7, 8, 9, 10, 11, 12, 13, 14

Table 4. TOVS and ATOVS instruments and channels used in ERA-40. Channels marked with an asterisk not used over high orography.

Table 5 shows the FOVs (field of view) used. Data from the HIRS and AMSU-A instruments are thinned, partly to reduce computational costs, and partly for consistency with the horizontal resolution of the assimilation system (aprox. 125 km).

	Limb FOVs excluded	Thinning
HIRS/2 and HIRS/3	1 to 3 and 54 to 56	1 out of 4 FOVs used
MSU	1, 11	no
SSU	-	no
AMSU-A	1 to 3 and 28 to 30	1 out of 3 FOVs used

Table 5. FOVs used in the ERA-40 assimilation system.

4. TOVS archives in ERA-40 and calibration of TOVS radiance data

The starting point of the ERA-40 archive of TOVS is the level-1b dataset, which comprises radiometric counts to which Earth location and calibration information have been appended but not applied. These data are encoded in the usual NESDIS binary format, described e.g. in Kidwell (1998). Table 6 shows the sources from which the ERA-40 level-1b dataset has been built. The size of the TOVS level-1b ERA-40 archive is of approximately 1 Terabyte.

NCAR	October 1978 to March 1992
ECMWF ops archive	July 1998 to December 2002
LMD	January 1993 to December 1997
NASA	January to December 1992 and January to August 1998
NOAA-CIRES	To fill data gaps
NOAA-SAA	To fill data gaps
NCEP	To fill data gaps

Table 6: Sources of data for the ERA-40 level-1b dataset.

As a first task in the preparation of the data for the assimilation, the data must be converted to level-1c, i.e. Earth-located, calibrated radiance data. This task is completely independent of the assimilation system, and essentially the main steps involved are:

- Scan time, satellite height and Earth-location information contained in the level-1b dataset are used to provide time, location, and satellite zenith angle for each scan position in the scan line, according to the scan geometry of the instrument.
- Calibration coefficients contained in the level-1b dataset are extracted, scaled and applied to radiance counts, and the resulting values are corrected for non-linearity by using the normalization coefficients supplied with the 1b dataset to produce calibrated raw radiances.
- The resulting radiances are converted to brightness temperatures, following the method described in Kidwell (1998); for MSU and SSU the inverse of Planck's radiation equation is used to obtain brightness temperatures, and for HIRS data, a band correction algorithm is applied to the results of the inverse of Planck's equation.

- Quality control. Tests to check time consistency, satellite height and location, and brightness temperatures are applied. Part of the quality information included to the 1b dataset is also used. During this step some observations are rejected and some are flagged as suspect.

The software system that performs the decoding and the above processing was developed in ERA-40, and it has been used to produce the level-1c dataset for all the satellites carrying TOVS. The ERA-40 TOVS level-1c archive contains data from October 1978 to December 2002, the coding format is FM 94 BUFR, and its size is approximately 550 Gigabytes.

The ERA-40 ATOVS level-1c archive has been generated from the ATOVS level-1c archive in ECMWF operations; radiances for this dataset were calibrated by the UKMO. It contains data from July 1998 to December 2002, the coding format is FM 94 BUFR, and its size is approximately 200 Gigabytes.

Both TOVS and ATOVS level-1c archives have been added to the ECMWF MARS archive.

5. Quality monitoring

5.1 Pre-assimilation quality monitoring

The availability and the quality of observations need to be assessed well in advance of the assimilation. There are operational problems affecting specific channels or instruments, on specific satellites, for specific periods. The assimilation of data of poor quality may have a negative impact on the analysis, and in order to prevent that, it is necessary to detect those problems and to address them before the assimilation.

Understanding the long-term performance of the TOVS/ATOVS system is necessary in order to make a sensible use of the radiance observations. Devising suitable radiance bias correction strategies has been one of the main issues in ERA-40 (Kelly and Li, 2002), particularly in the case of the SSU instrument, as it is the dominant source of information on the middle and upper stratosphere, a region where the forecast model has large systematic biases.

Time series of BT (brightness temperature) statistics have been the main tool in the pre-assimilation quality monitoring of TOVS/ATOVS. Appendix B includes a selection of the time series plots produced for ERA-40. The whole set (six latitude bands, three scan position bands for each instrument and satellite) will be available from the ERA-40 website http://www.ecmwf.int/research/era. The selection in appendix B contains time series for the MSU and SSU instruments for two latitude bands (tropics and global) and the central scan position band. Table 7 shows the scan positions and types of underlying surfaces used in the calculations of the statistics shown in those figures.

	Scan positions used for the central scan band	Underlying surface	
		Only sea	All (sea, sea-ice, land)
MSU	4 to 8	1, 2	3, 4
SSU	3 to 6		1, 2, 3

Table 7. Scan positions and types of underlying surfaces selected for the MSU and SSU instruments in the calculation of statistics. See main text.

As an example, Figure 4 illustrates some of the problems found in the radiance data, and how time series of BT statistics can help to identify them. The failure of channel MSU 2 and the deterioration of MSU 3 from February 1987 are apparent. In fact, the deterioration of the MSU 3 channel started in late October / early November, where a sudden cooling of more than 0.5 K can be seen to occur. The spike in MSU 1 at the beginning of January 1986 is the signature of a bad Earth-location that affected NOAA-9 during 1 and 2 January 1986.

Channel SSU 2 on NOAA-7 provides another interesting example. This channel was affected by high leak rates in the pressure-modulated cell. Leaks in the cells of the SSU instrument cause the peaks of the weighting functions to rise. Figure 5 shows the apparent warming in brightness temperatures from SSU 2 that results. SSU 2 was not used from July 1983 onwards in ERA-40.

Figure 6 shows a change in behavior of the TIROS-N MSU channels at the end of June 1979. It also shows a large gap in the second half of January 1980, a considerable reduction in the number of observations from that gap onwards, and the signature of a bad Earth-location in September 1980.

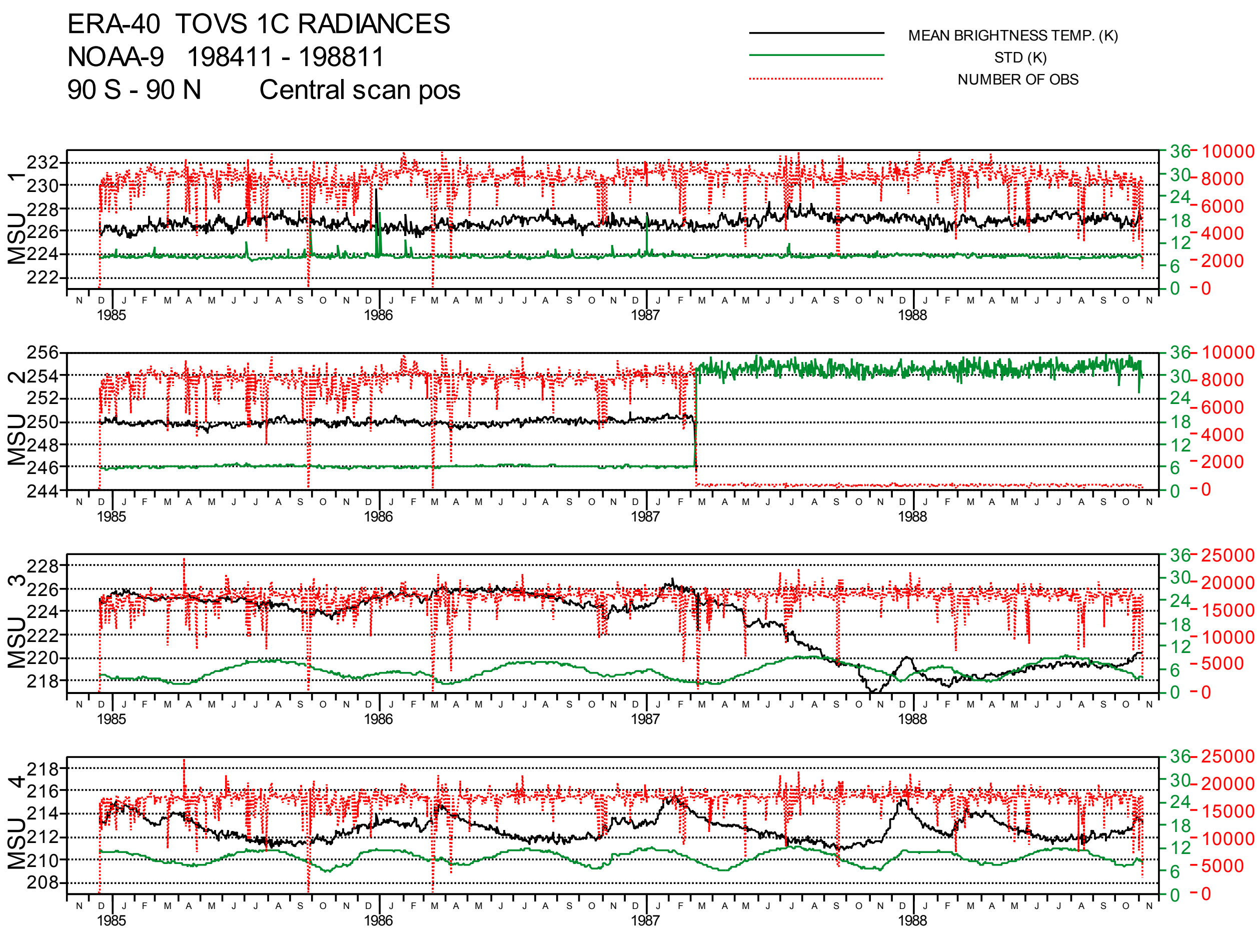

Figure 4. Time series of BT from MSU channels on NOAA-9 (scan positions 4 to 8). See main text.

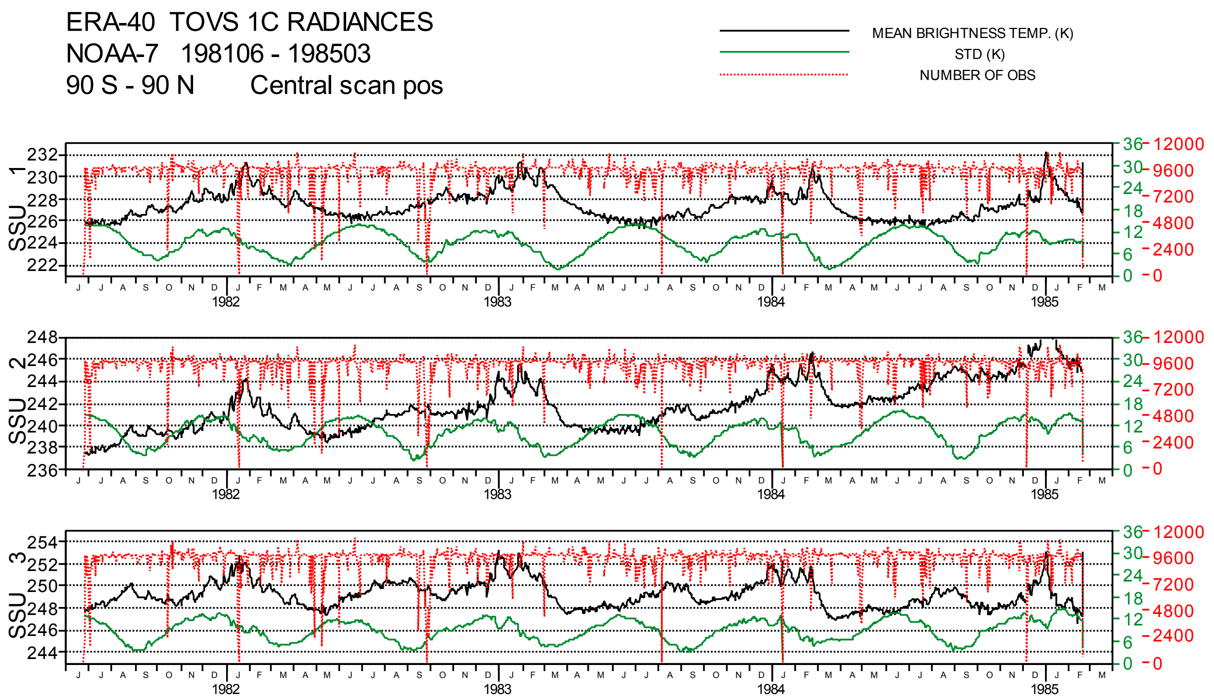

Figure 5. Time series of BT from SSU channels on NOAA-7 (scan positions 3 to 6).

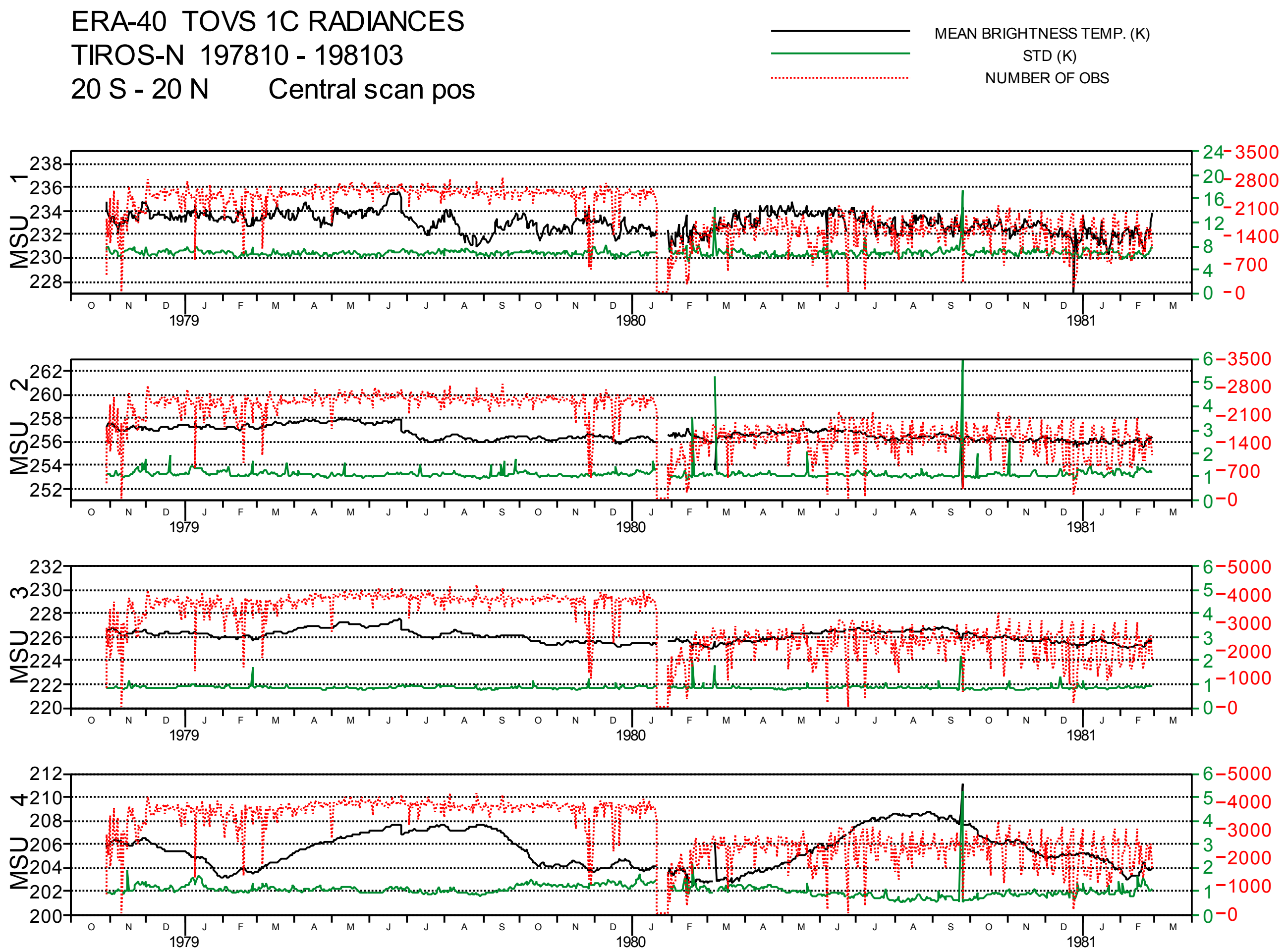

Figure 6. Time series of BT from MSU channels on TIROS-N (scan positions 4 to 8).

Apart from the time series of BT, other statistics were used in the pre-assimilation quality monitoring of TOVS observations. The level 1b dataset contains information concerning the quality of the measurements, both for scan lines and individual scan positions. As an example, Figure 7 shows the number of scan positions in which a mirror sequence error was detected, as a percentage of the total number of scan positions in the orbit file, for the MSU instrument on NOAA-11 during the period September 1988 to April 1991.

Some problems can often be handled successfully, in the sense that after some action or correction assimilation of the observations is possible (and hopefully beneficial). For instance, acquiring the data from other organizations can often help to fill data gaps. Changes in channel behavior can often be dealt with by the bias correction scheme; data from the channel(s) affected are used passively for a short period (typically two weeks), which allows the generation of new bias correction coefficients for that satellite and channel(s); then the same period is rerun with active assimilation of the data.

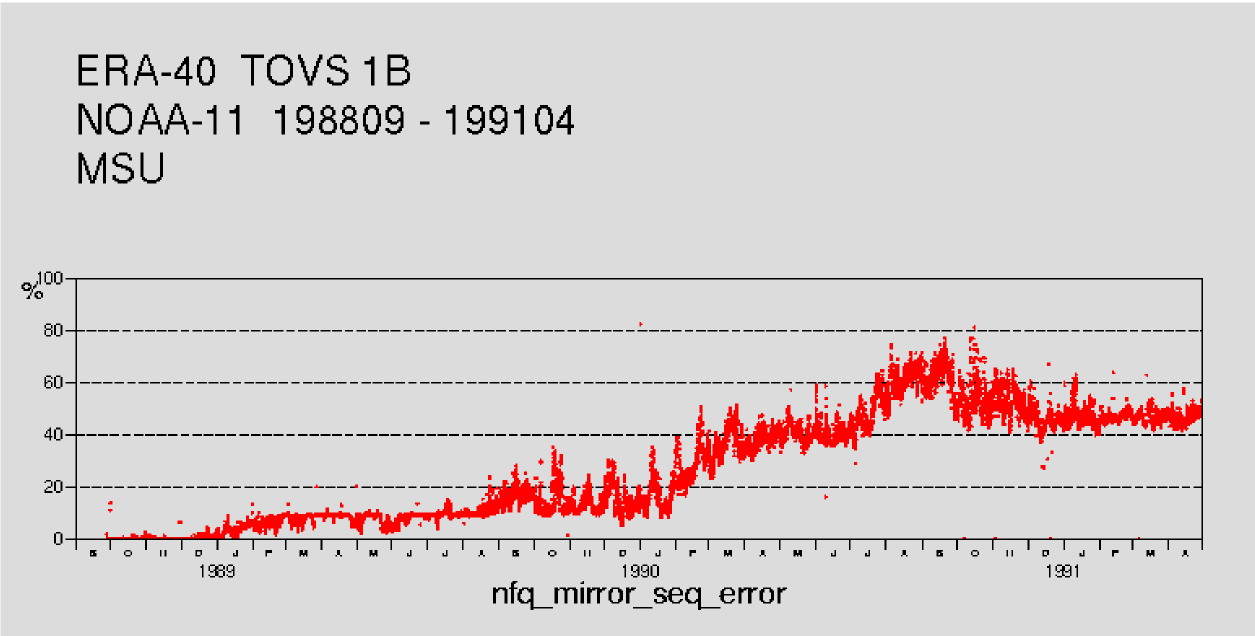

Figure 7. Number of scan positions in which a mirror sequence error was detected.

For other types of problems – e.g. channel malfunctions or failures, such as those shown in Figure 4 and Figure 5 - nothing can be done that allows a good use of the observations. In these cases the best option is to avoid the assimilation of the radiances. In practice this is done by including the channels and periods affected in the data selection blacklist (see next subsection).

Other types of problem fall in between. In principle they could be addressed in some way that allows the use of the observations, but the effort required is so costly that it may be impractical. Bad Earth-locations are a good example. It is a problem that affected the first satellites of the series on a number of occasions, typically for short periods of up to a couple of days. It is possible to routinely recalculate Earth-locations from a suitable series of orbital elements, and systematically check locations and replace those that are incorrect, but the effort required to do so outweighs the benefits.

Another example of corrections that are possible in principle but perhaps not practical are those gaps caused by defective files in the level-1b archive. Restoring the data - or at least a large part of them - is often possible, but it is a time-consuming task, and it may be sensible only in those cases when the restored data would cover regions not well covered by other instruments or satellites.

In some other cases the decision of whether to use suspect data or whether to have a data gap instead is not straightforward. This is often the case with suspect SSU data at times when only one satellite carries the SSU instrument. It might be better to assimilate suspect data than to withdraw from the assimilation the main source of data about the stratosphere. Monitoring observations after the assimilation is especially important in these cases.

5.2 The TOVS/ATOVS blacklist

The data selection blacklist is a tool that allows the specification of conditions related to e.g. periods, identifiers, channel or instruments. Observations matching the conditions in the blacklist are not actively used by the assimilation system. For details on the blacklist tool, the reader is referred to http://www.ecmwf.int/research/ifsdocs/index.html. There are two types of TOVS/ATOVS blacklist. One of them is common to all the satellites carrying the same instruments, and reflects the use of observations in the assimilation system, e.g. which channels are not used, which channels are used only over sea or which limb FOVs are excluded. There is another type of blacklisting whose purpose is to prevent the assimilation of data of poor quality. Here we concentrate on this second type of blacklist.

Monitoring the quality of the TOVS/ATOVS data in order to make the TOVS/ATOVS blacklist for the ERA-40 period might seem a daunting task. Fortunately, information about the quality of the observations can be obtained from a number of sources:

- Time series of radiance statistics produced in ERA-40 from the level-1c datasets (appendix B contains a sample)
- The Polar Orbiter Archived TOVS Sounding Data Change and Problem Record in the NOAA Polar Orbiter Data User's Guide (Kidwell, 1998)
- Data Changes and Problem Record in the NOAA KLM User's Guide (Goodrum et al., 2000)
- Quality information contained in the TOVS level-1b dataset
- Other TOVS/ATOVS users (literature, personal communications)
- Experience in the use of TOVS in the ERA-15 reanalysis project at ECMWF; for instance, in this project Earth-location of TOVS data was systematically checked for the whole ERA-15 period, and periods of bad Earth-location identified.

Appendix C contains the TOVS/ATOVS blacklist used in ERA-40.

5.3 Monitoring TOVS/ATOVS after the assimilation

During the production phase of ERA-40, the behavior of the TOVS/ATOVS observation system was routinely monitored. This monitoring can help to detect e.g. incorrect use of observations and also problems in the observations that passed unnoticed - or whose impact was underestimated - during the pre-assimilation quality monitoring. If a significant negative impact on the quality of the analysis is discovered quickly enough, the period can be rerun once the error has been rectified.

Time series of mean departures between observed radiances and those calculated from the first guess by using a radiative transfer model may alert attention to bad quality observations or errors in the use of observations. Also, when data from some channel or instrument are suspect, these plots can be used to obtain more accurate information than that provided by the time series of BT statistics. As an example, Figure 8 shows radiance departures for the MSU channels on NOAA-9. The radiance departures give a more detailed description than the time series in Figure 4, showing that the deterioration of the channel could have started as early as 27 October.

Time series of mean analysis increments (i.e. analysis minus first guess values) for variables and layers where TOVS/ATOVS are the main source of observational information – e.g. temperature in stratospheric levels – have also been a very valuable tool, as they can warn about errors or problems, either in the observations or in their use.

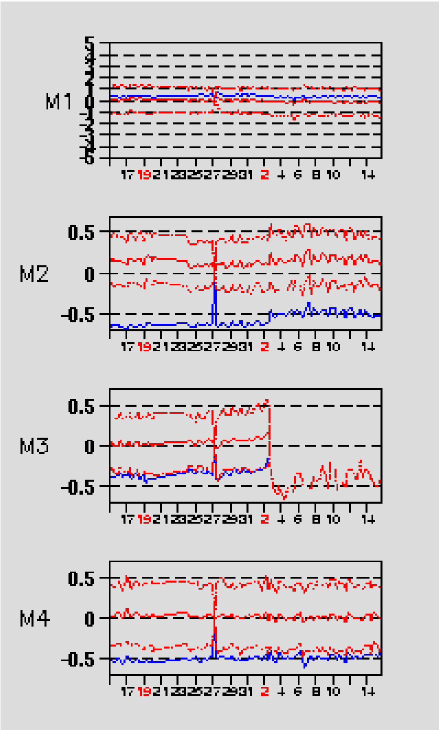

Figure 8. NOAA-9 MSU radiance departures (in K) from 14 October to 17 November 1986 (from a pre-production trial). Data selection for the plot is latitude=global, surface=sea. Blue line represents mean departures between observed radiances and first-guess estimates and red continuous line represents mean departures between bias-corrected observed radiances and first-guess estimates. Dotted red lines represent mean plus/minus one standard deviation

5.4 Observation monitoring in a reanalysis environment

Quality monitoring of observations in general, and of satellite data in particular, is a key task of the day-to-day operations in NWP centres, as it is in reanalysis environments. However there are several important differences:

- In a reanalysis environment there is wealth of information about the quality of the observations, available well in advance of the assimilation, which is not the case, for obvious reasons, in near real-time assimilation.
- The number of cycles to monitor in a reanalysis environment is of a different order of magnitude than in operational assimilation in NWP centres. For instance, in ERA-40 each production stream assimilated about ten days of observations per real day, on average, and up to four assimilation streams were running simultaneously. Methods used in near real-time monitoring are seldom feasible in reanalysis assimilations.
- In a reanalysis environment it is possible to rerun the assimilation for specific periods. However, before a rerun is undertaken its benefits and its costs need to be carefully considered.

In a reanalysis environment it is also possible to tackle tasks such as observation restoration. Often observational data can be recovered or improved, especially old data and data from observing systems that need a fair amount of preliminary processing, such as TOVS. Li (2000) gives an illustrative example of data restoration in his work on VTPR data.

There is a large amount of information available on observation systems and it can be used in ways that contribute to make the best possible use of observations. However, assessing the quality of observations and correcting errors needs time and resources. Before tackling each specific problem, the potential benefit of the task and its demands on time and resources need to be carefully considered, so that the overall benefits are maximized given the constraints on time and resources.

A long-term reanalysis involves the use of old observation datasets. Before the use of BUFR for encoding observations became widespread in NWP centres, many different coding formats were used. Some of them were WMO-standard and others were not. Documentation on those codes is not always easy to obtain, and it is almost impossible to recover all the documentation concerning small changes in those codes.

Using observations and monitoring them in a reanalysis environment is essentially different from day-to-day NWP assimilation. There is a need for the development and refinement of methods that are appropriate for a reanalysis environment. There is also the need to share experiences and results; the documentation and interchange of experiences in the use of observations can be an invaluable contribution to future reanalyses.

6. Concluding remarks

This report has focused on the work done, as part of the ERA-40 project, to build and prepare the TOVS and ATOVS radiance datasets for the assimilation. The datasets and the processing to build them have been described. The quality monitoring process carried out as preparation for the assimilation, has been presented with some detail, and has been illustrated with examples obtained during the production phase.

The kind of tasks involved in such work is typical of a reanalysis environment. In some ways they are similar to that of operational NWP, but in other ways they are very different. Methods used in NWP are seldom feasible in a reanalysis, and some methods that are not possible in NWP are indeed possible in a reanalysis. Reanalyses are a relatively young area, and there is a need to develop suitable new methods and to refine existing ones.

The quality of the products of a reanalysis depends both on the quality of the assimilation system and that of the observation systems. Each generation of reanalysis can improve the observation systems, and build on the datasets, results and experience of the previous one. Some activities that can bring this ongoing improvement of the observation systems are:

- Building datasets of observations, quality-monitored and as complete as reasonable. This involves gathering observations from different sources, filling gaps, etc, and organizing datasets in well structured archives – which is essential to allow an efficient subsequent processing. Data restoration (e.g. reconstruction of damaged records) is a time consuming task, but in some cases the end result is worth the effort. Although validation studies can help to detect errors in the observations when they have a significant negative impact on the reanalysis products, routine quality monitoring of the observation systems before the assimilation may be a more efficient way of detecting errors.

- Improving the pre-processing of those observation systems that need it (e.g. calculation of cloud motion winds or calibration of TOVS). Improvements in the pre-processing bring improvements in the quality of the 'observations' that are fed to the assimilation system.
- Using the feedback provided by earlier reanalyses. A wealth of data concerning quality of observations is produced by a reanalysis. However, extracting usable information from that data is not a trivial task, and there is a need for the development of methods that help making those data actually usable for future reanalyses.

Future reanalyses would benefit from sharing not only data and results, but also knowledge and experience with operational aspects such as the monitoring of observations in the context of reanalysis, or observation archaeology. Few organizations have experience in this area, which is very technical, a factor which makes it difficult to share experience. Refinement of archives of observations and related metadata is needed in preparation for an improved future reanalysis, and investment in this area should not be neglected.

Acknowledgements

Building the ERA-40 TOVS archive has only been possible thanks to the contribution of several organizations. NCAR, ECMWF operations, LMD and NASA have been the main sources of data for this archive; we also acknowledge and thank the help of Darren Jackson from NOAA-CIRES, Jack Woollen from NCEP and the Satellite Active Archive of NOAA.

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Appendix A: Acronyms

AMSU	Advanced Microwave Sounding Unit
ATOVS	Advanced TOVS
BT	Brightness temperature
CIRES	Cooperative Institute for Research in Environmental Sciences
FOV	Field of View
HIRS	High resolution Infra-Red Sounder
IFOV	Instantaneous FOV
IFS	Integrated Forecasting System
LMD	Laboratoire de Meteorologie Dinamique
LST	Local Solar Time
MSU	Microwave Sounding Unit
NASA	National Aeronautics and Space Administration
NCAR	National Centre for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
POES	Polar Orbiting Environmental Satellites
SAA	Satellite Active Archive
SSU	Stratospheric Sounding Unit
TIROS	Television InfraRed Observation Satellite
TOVS	TIROS Operational Vertical Sounder
UKMO	United Kingdom Meteorological Office

Appendix B: Time series of BT from the SSU and MSU instruments

See subsection 5.1 in the main text.

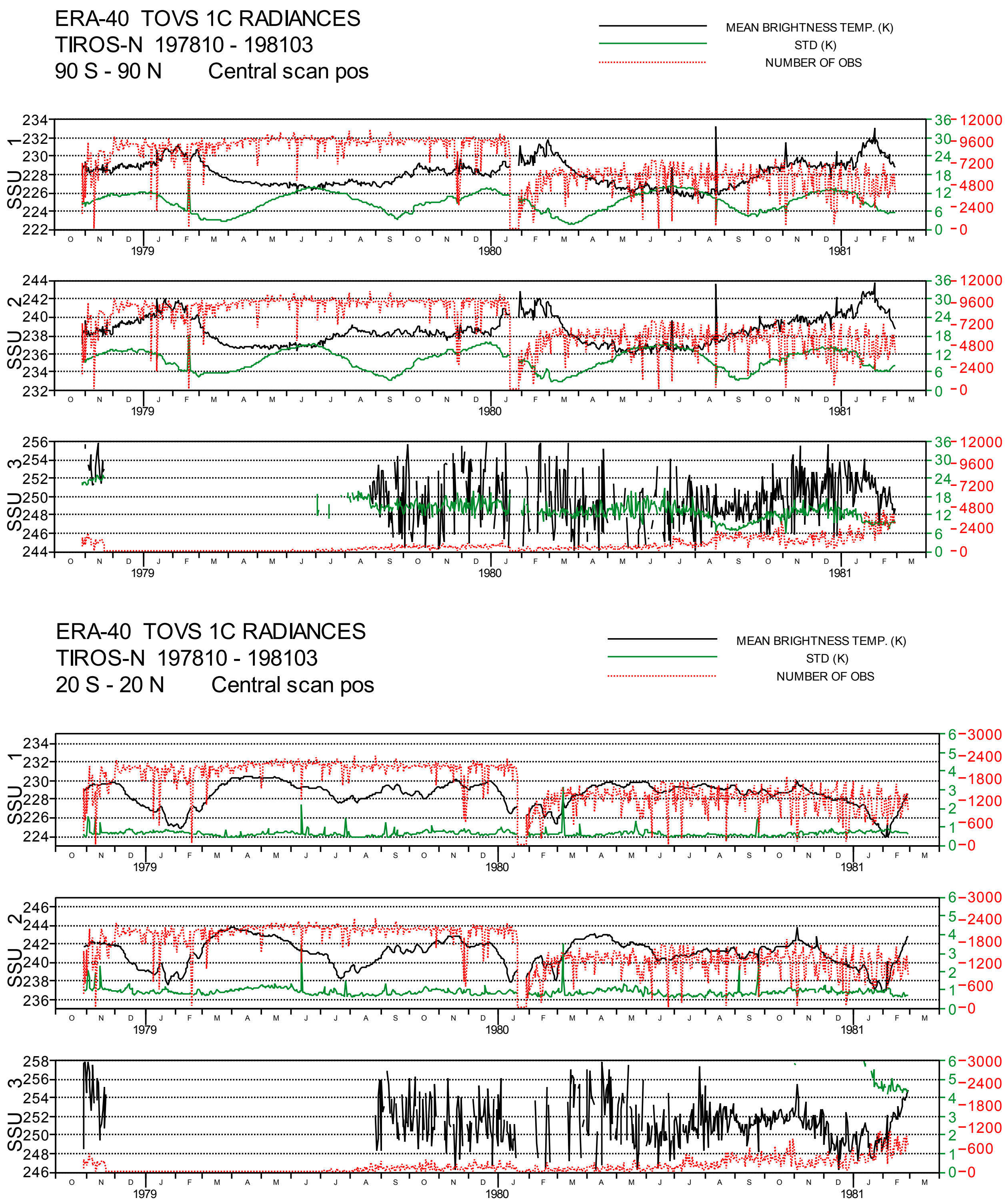


Figure B. 1. TIROS-N SSU, global (upper panel) and tropical belt (lower panel).

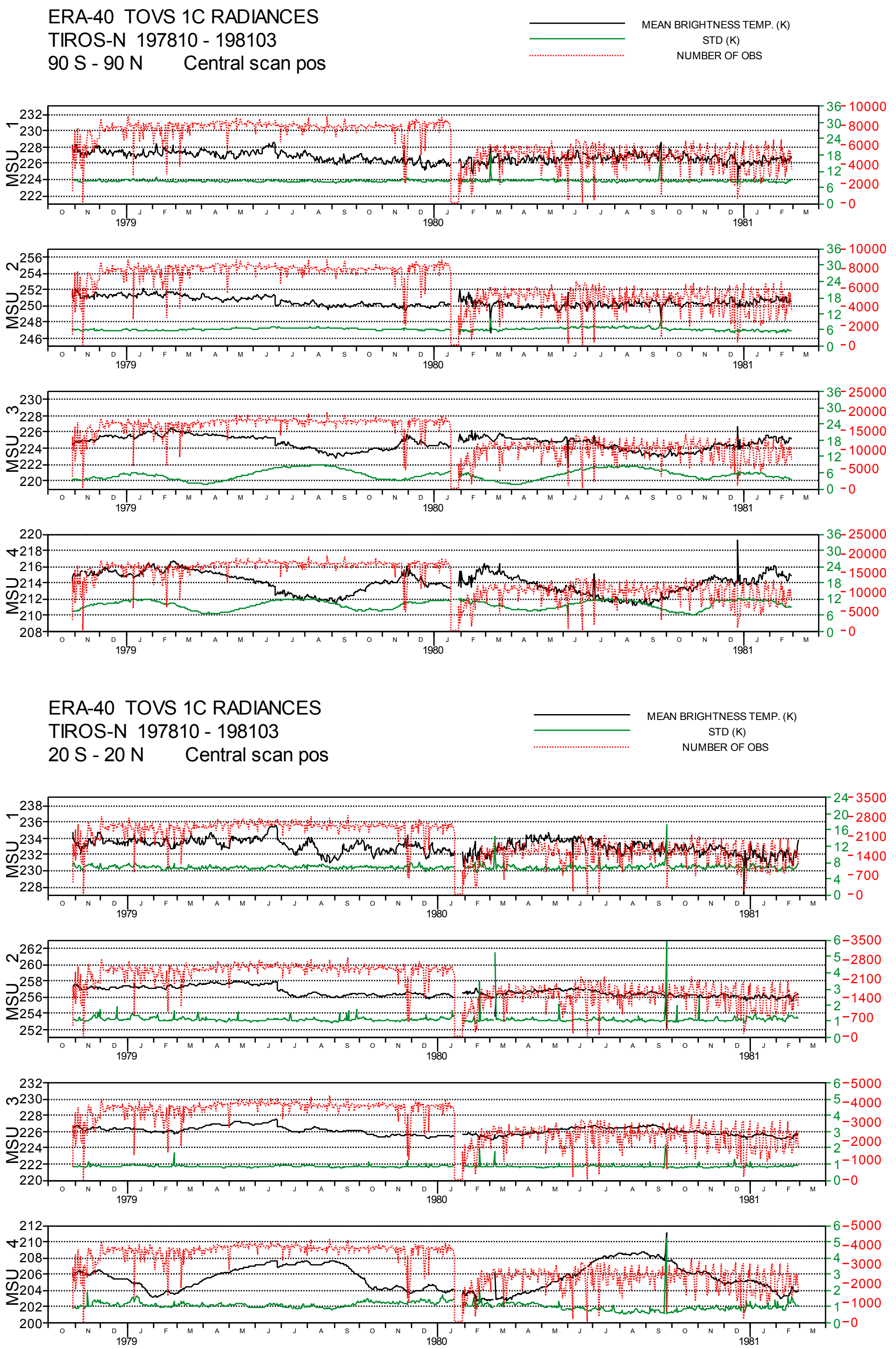


Figure B. 2. TIROS-N MSU, global (upper panel) and tropical belt (lower panel).

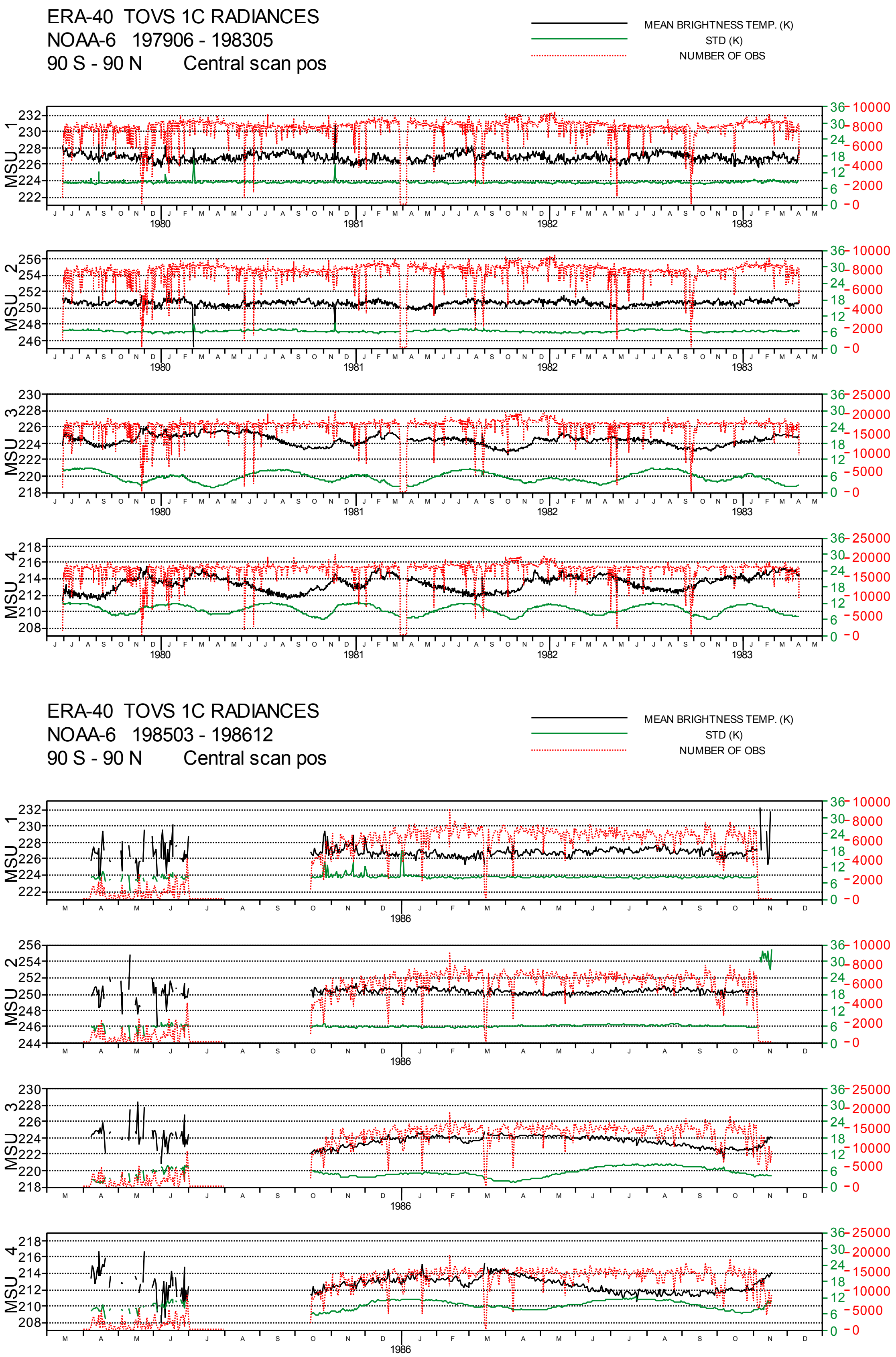


Figure B. 3. NOAA-6 MSU, global, Jun 79 to May 83 (upper panel) and Mar 85 to Dec 86 (lower panel).

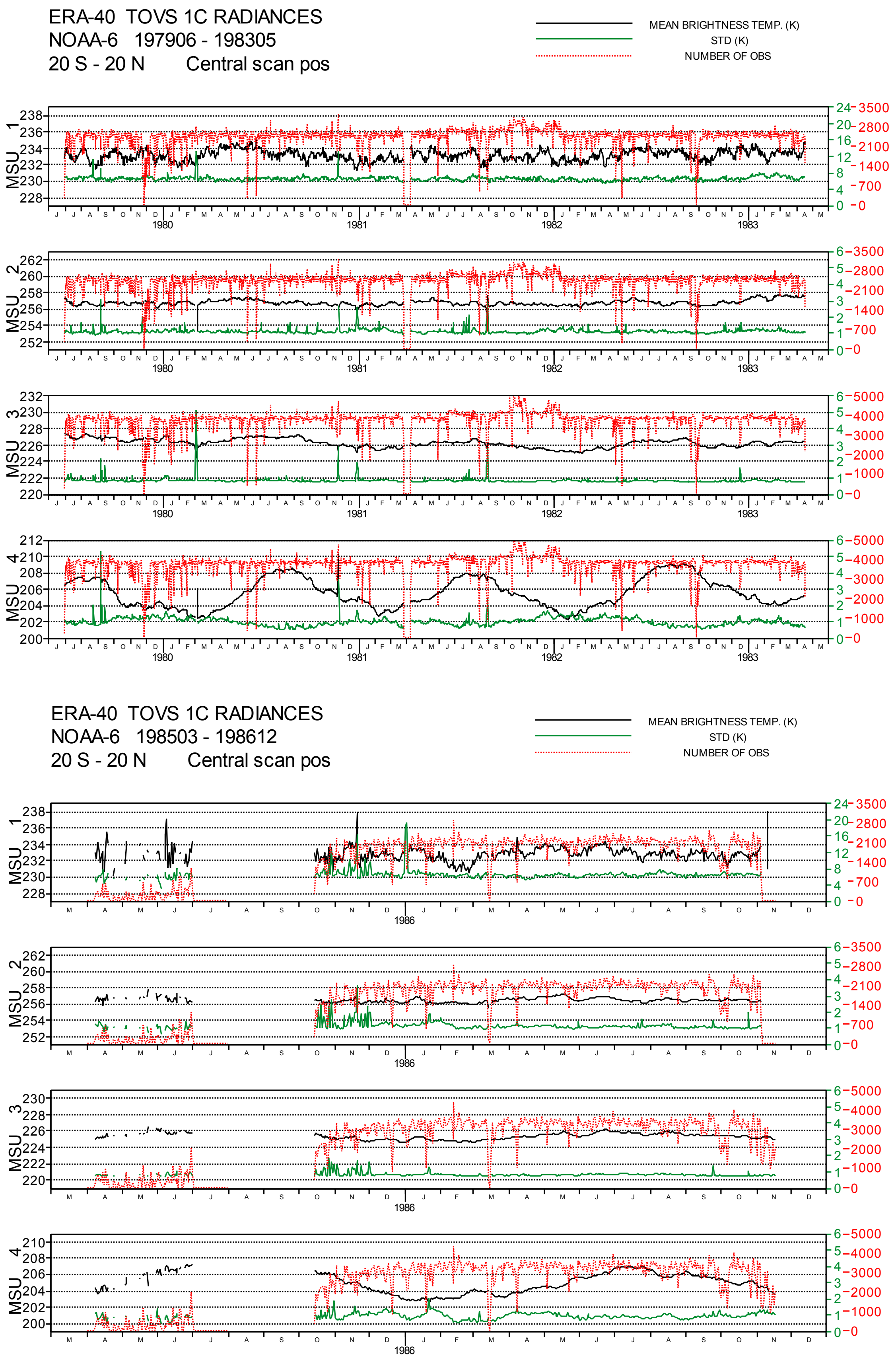


Figure B. 4. NOAA-6 MSU, tropics, Jun 79 to May 83 (upper panel) and Mar 85 to Dec 86 (lower panel).

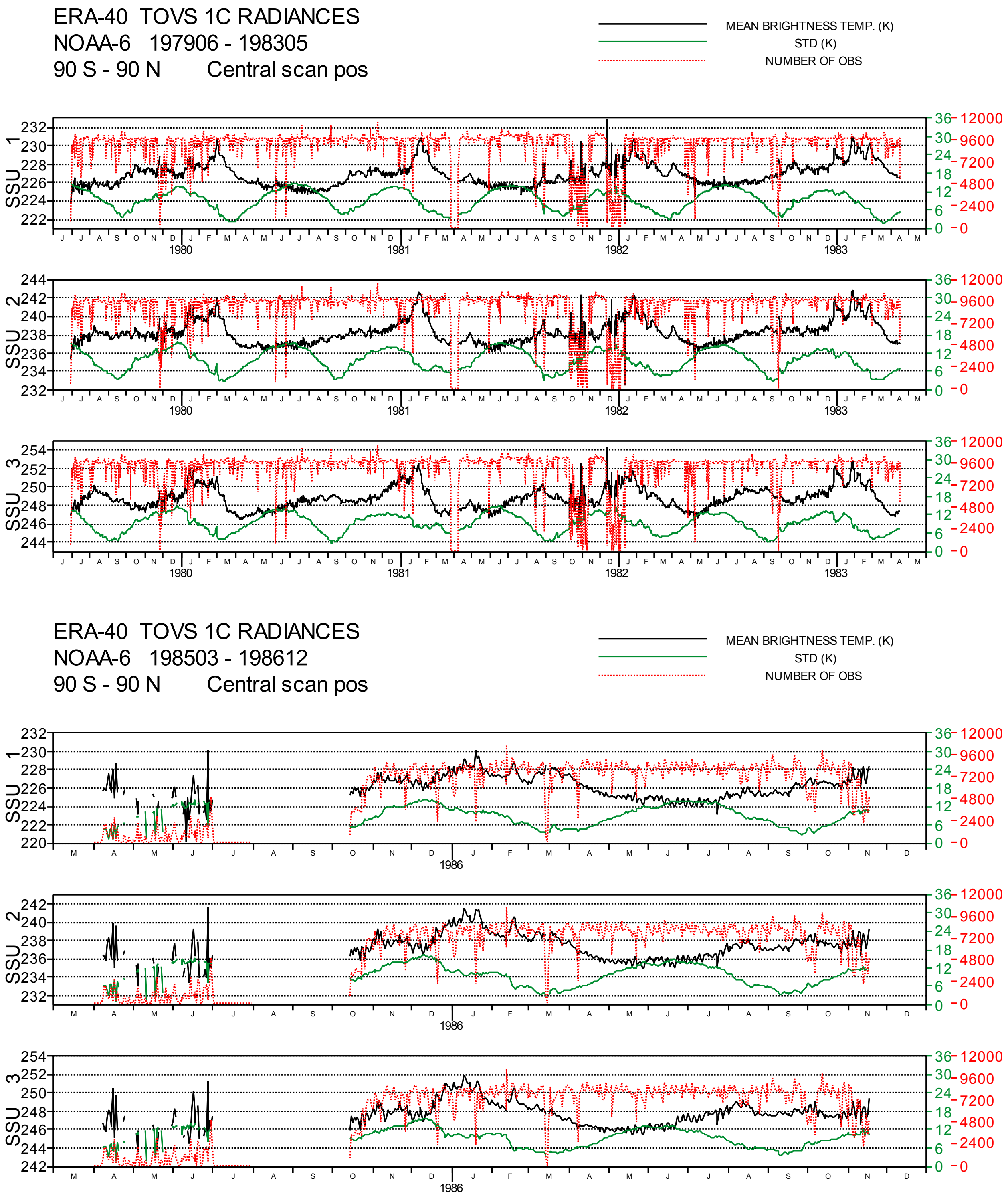


Figure B. 5. NOAA-6 SSU, global, Jun 79 to May 83 (upper panel) and Mar 85 to Dec 86 (lower panel).

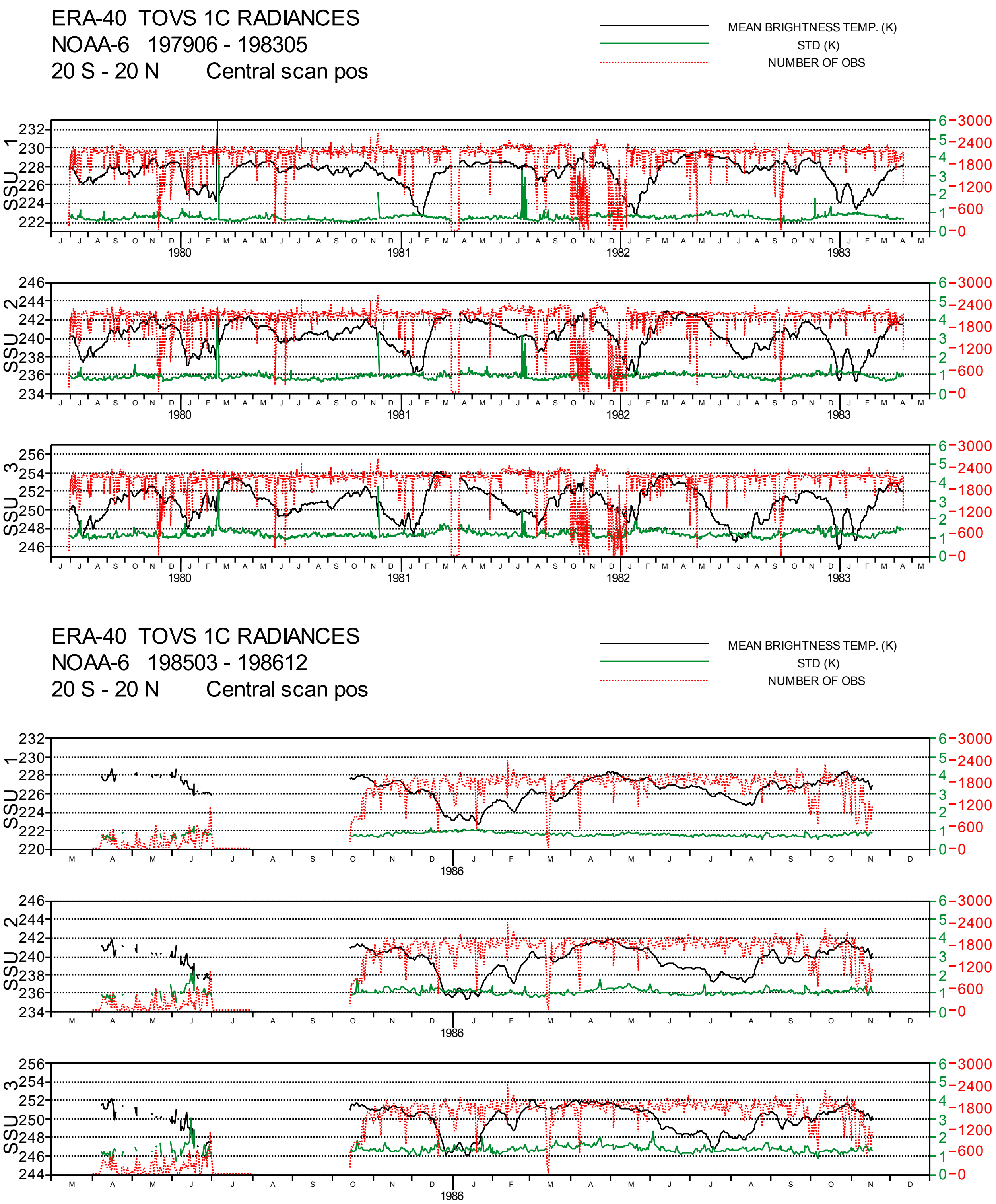


Figure B. 6. NOAA-6 SSU, tropics, Jun 79 to May 83 (upper panel) and Mar 85 to Dec 86 (lower panel).

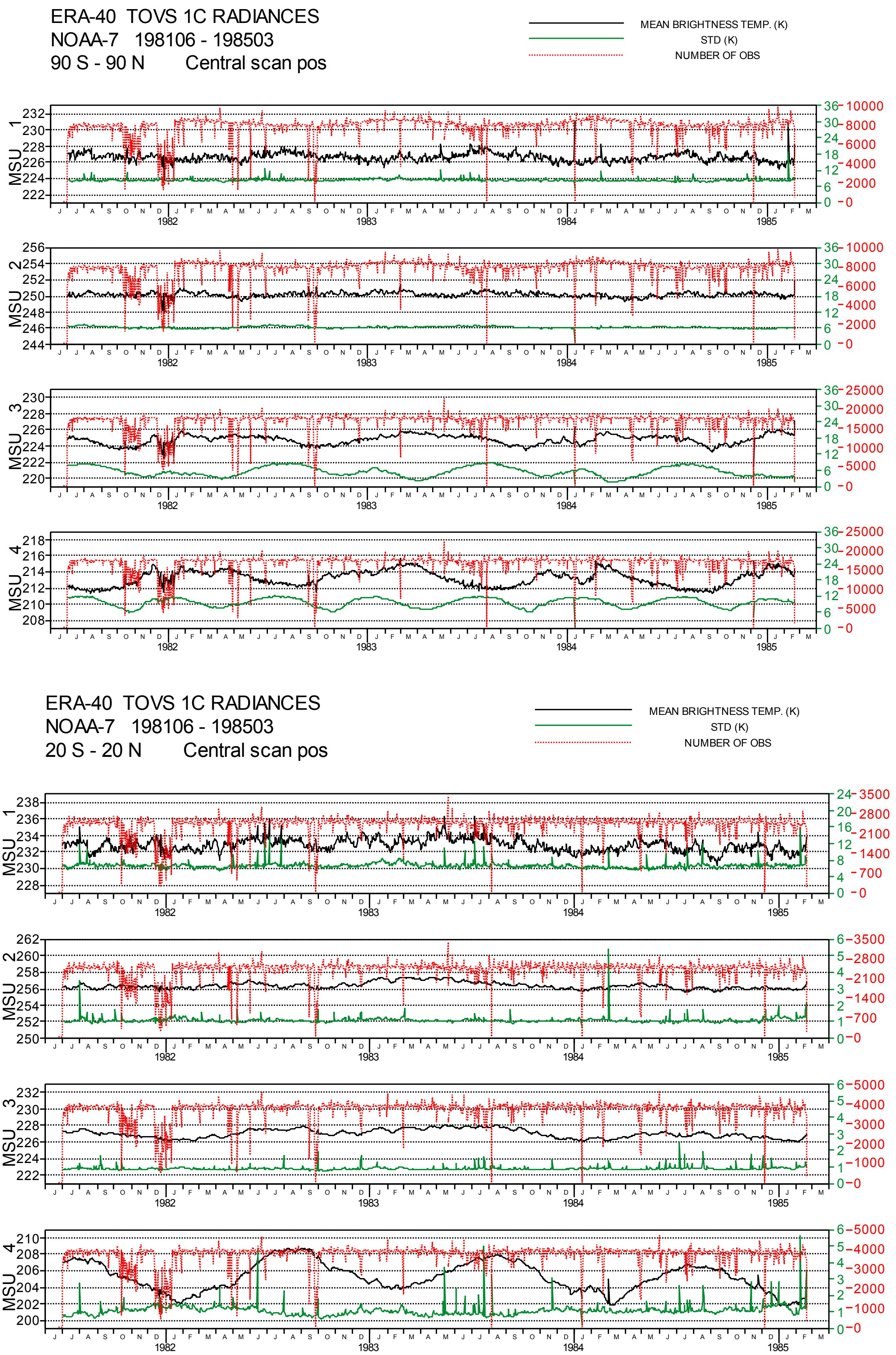


Figure B. 7. NOAA-7 MSU, global (upper panel) and tropical belt (lower panel).

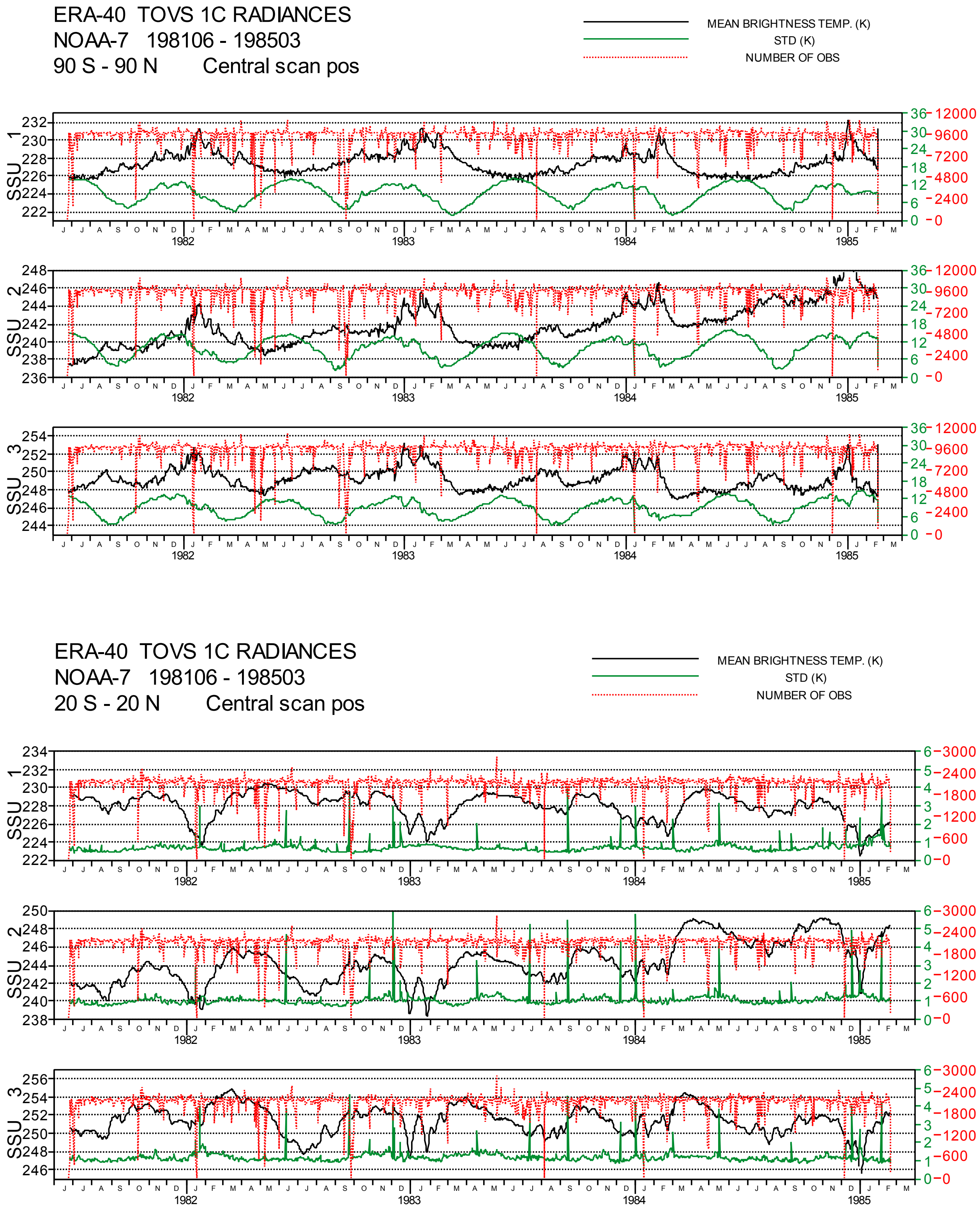


Figure B. 8. NOAA-7 SSU, global (upper panel) and tropical belt (lower panel).

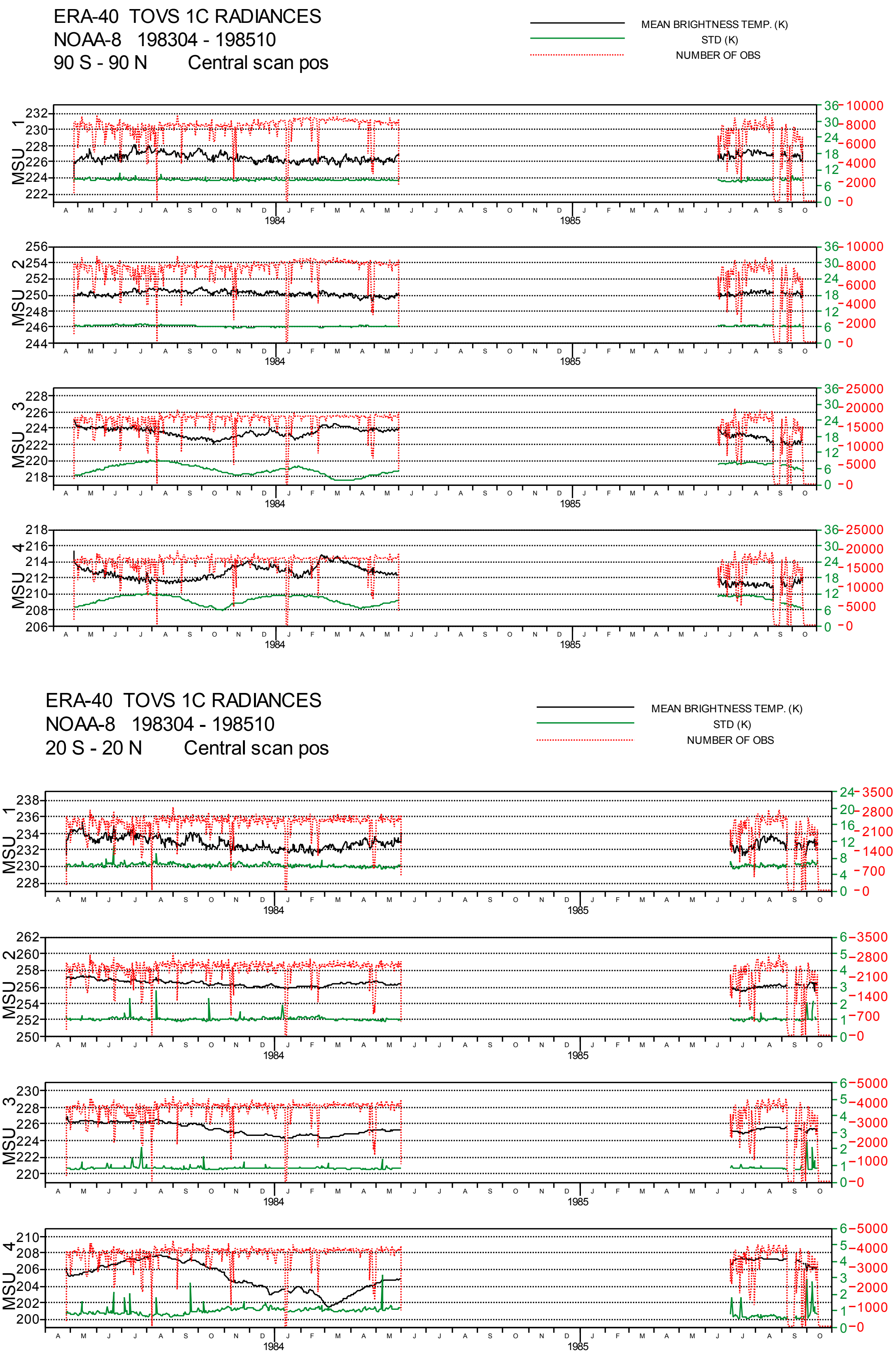


Figure B. 9. NOAA-8 MSU, global (upper panel) and tropical belt (lower panel).

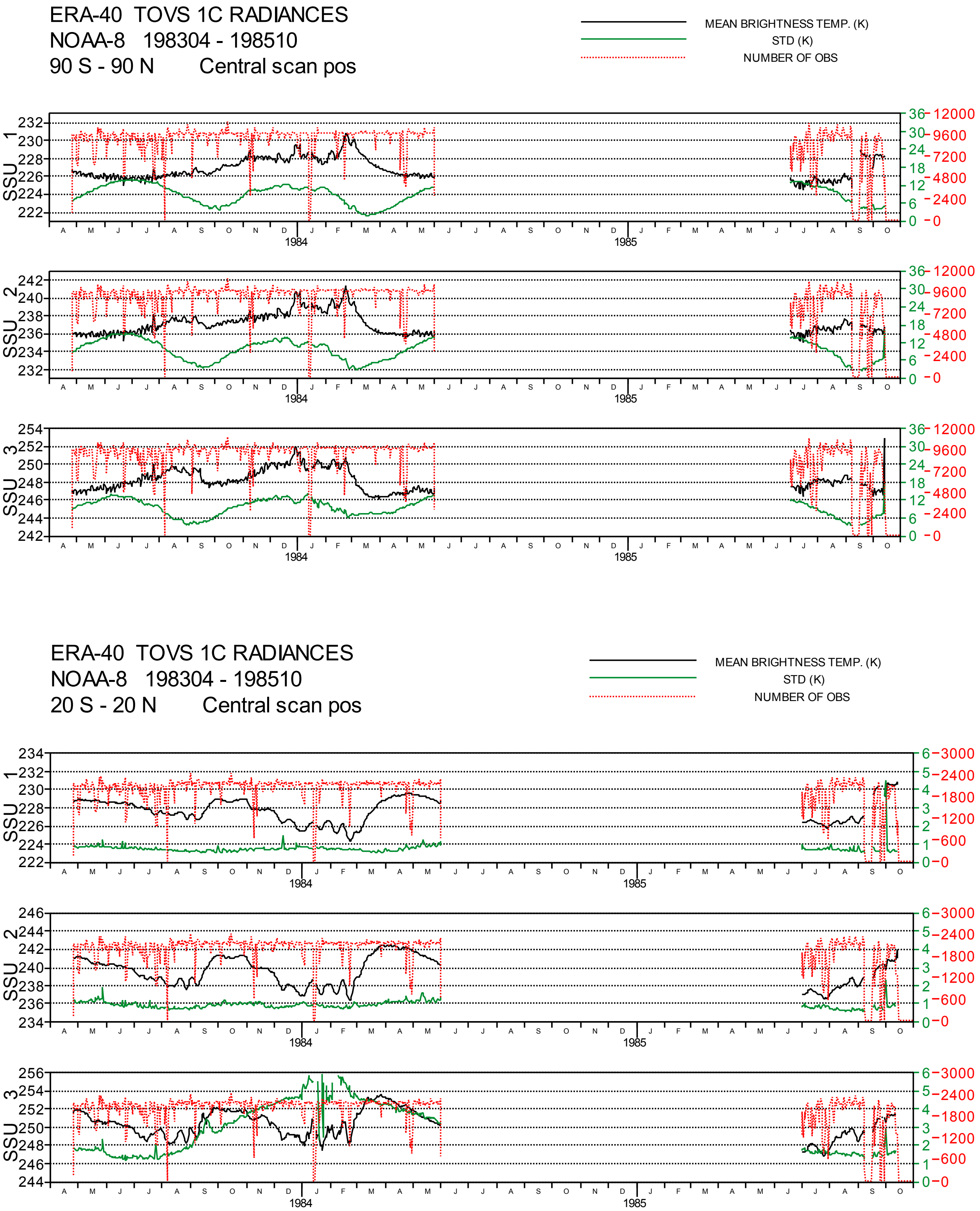


Figure B. 10. NOAA-8 SSU, global (upper panel) and tropical belt (lower panel).

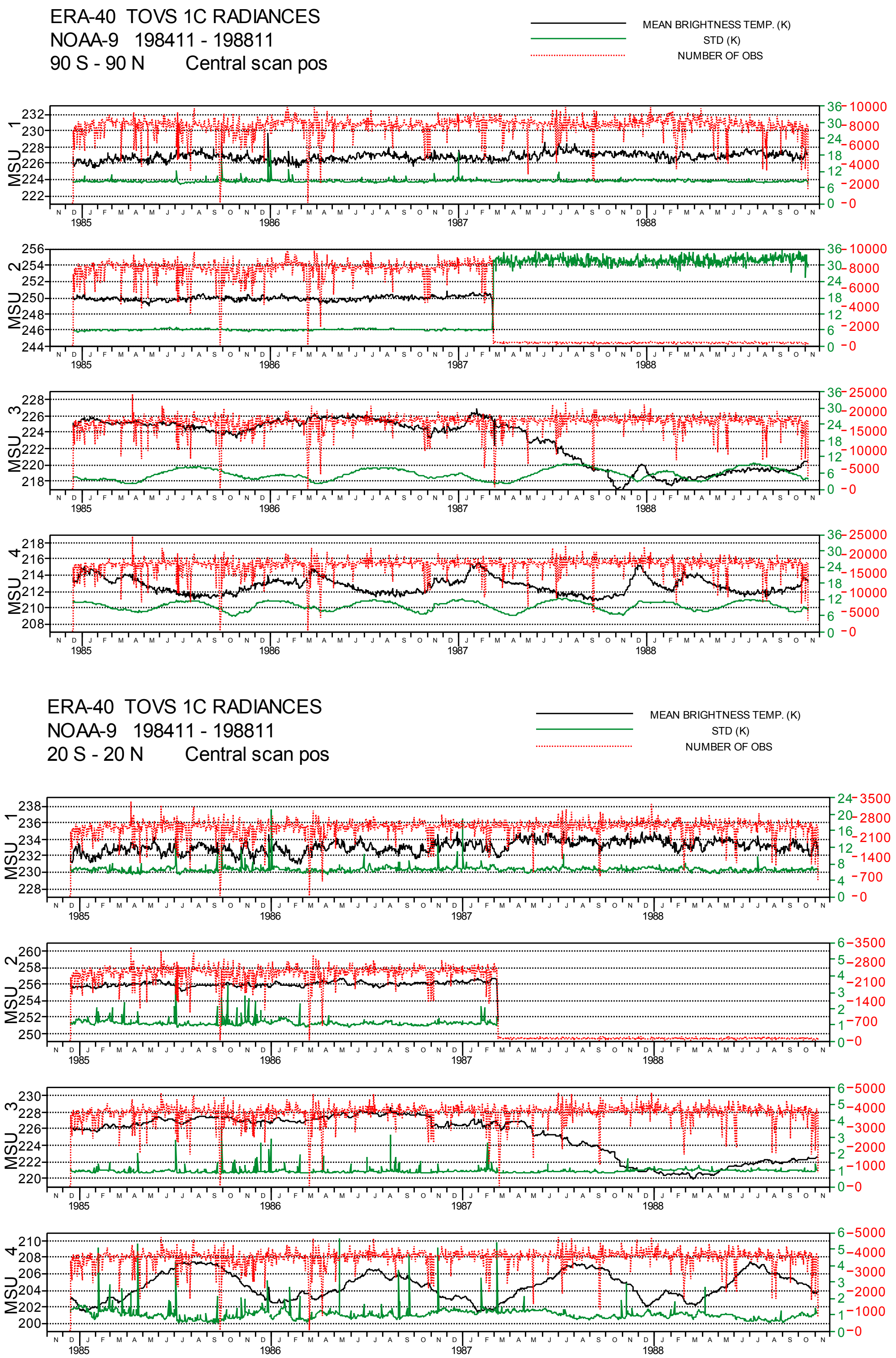


Figure B. 11. NOAA-9 MSU, global (upper panel) and tropical belt (lower panel).

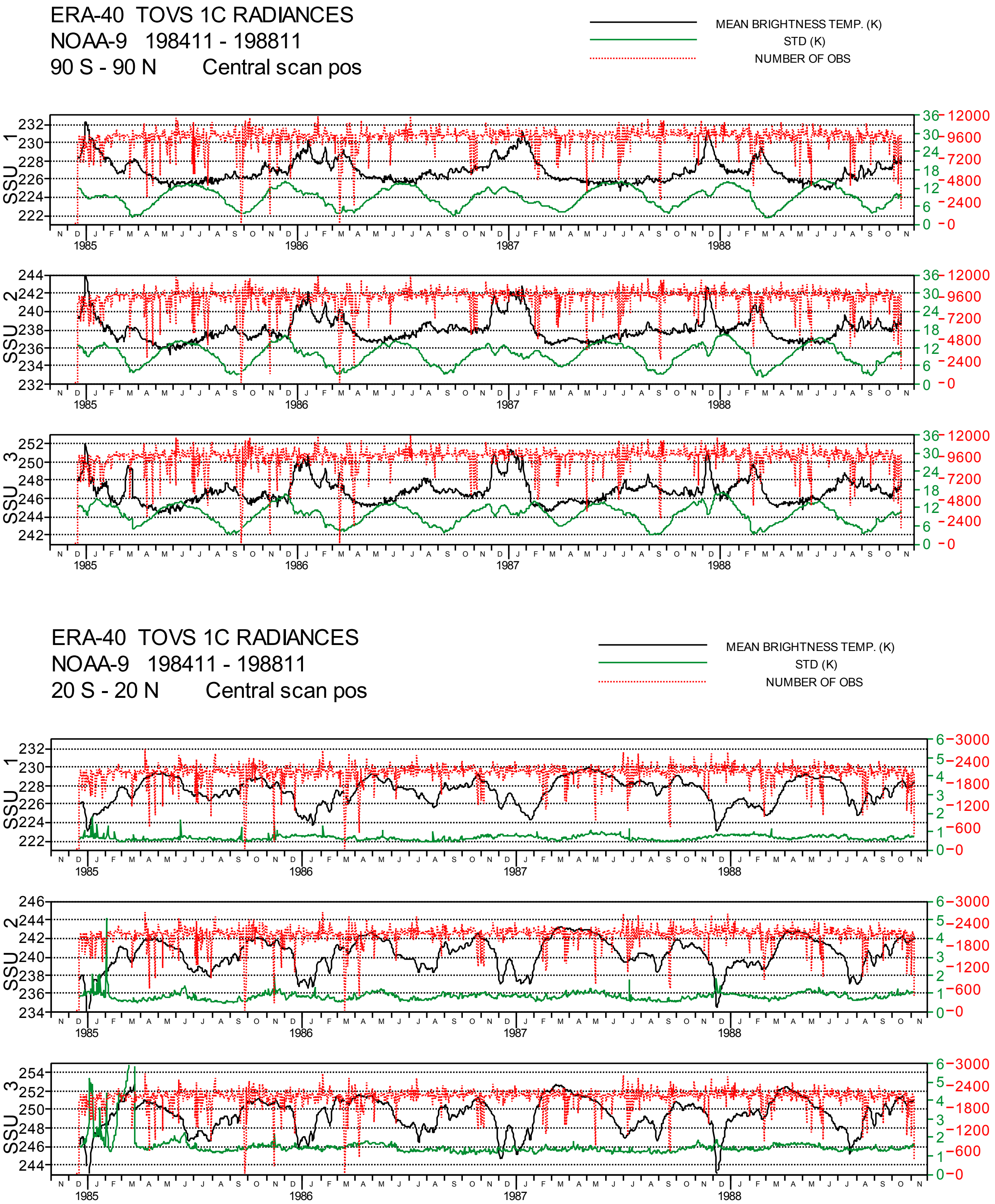


Figure B. 12. NOAA-9 SSU, global (upper panel) and tropical belt (lower panel).

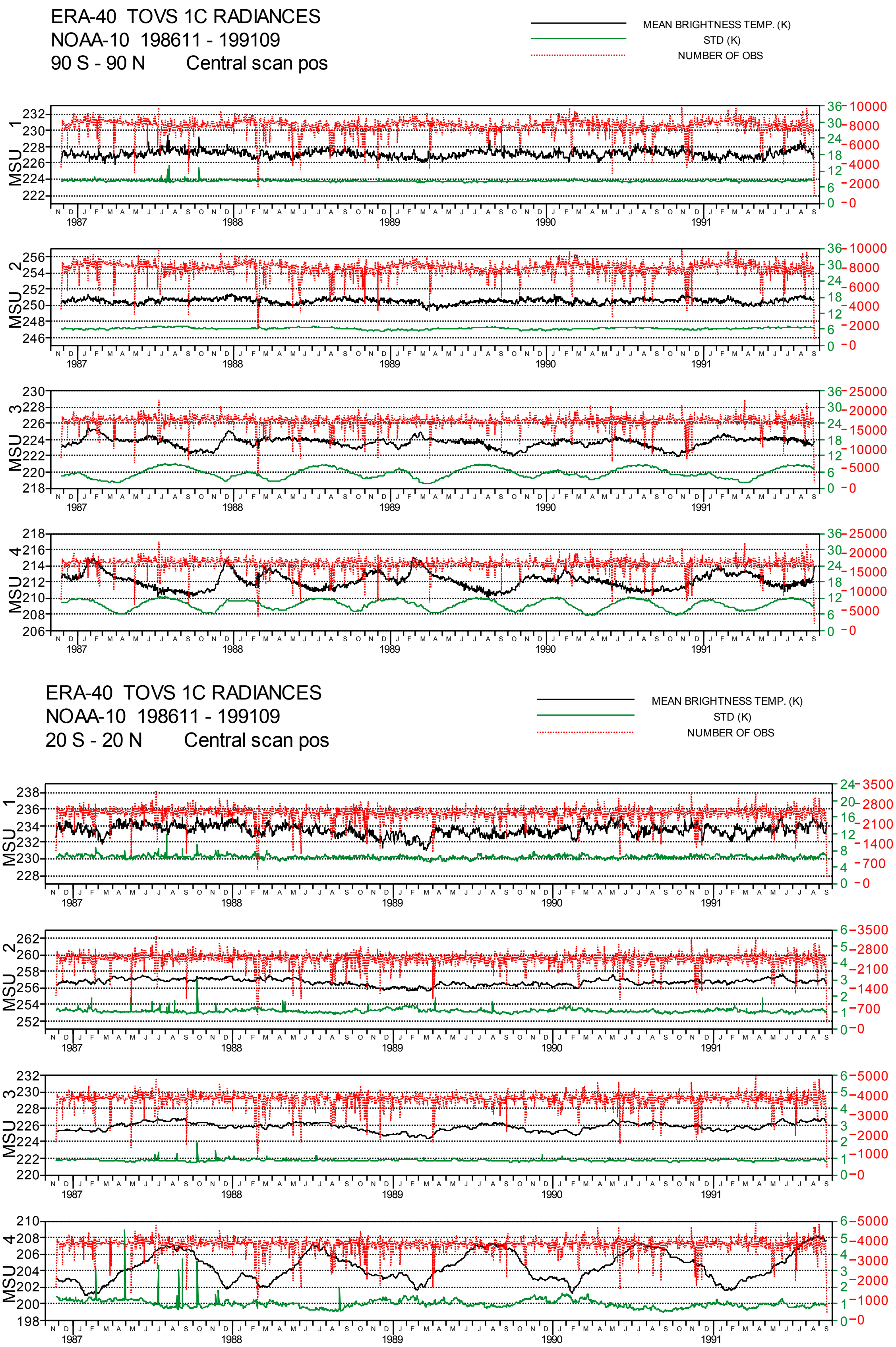


Figure B. 13. NOAA-10 MSU, global (upper panel) and tropical belt (lower panel).

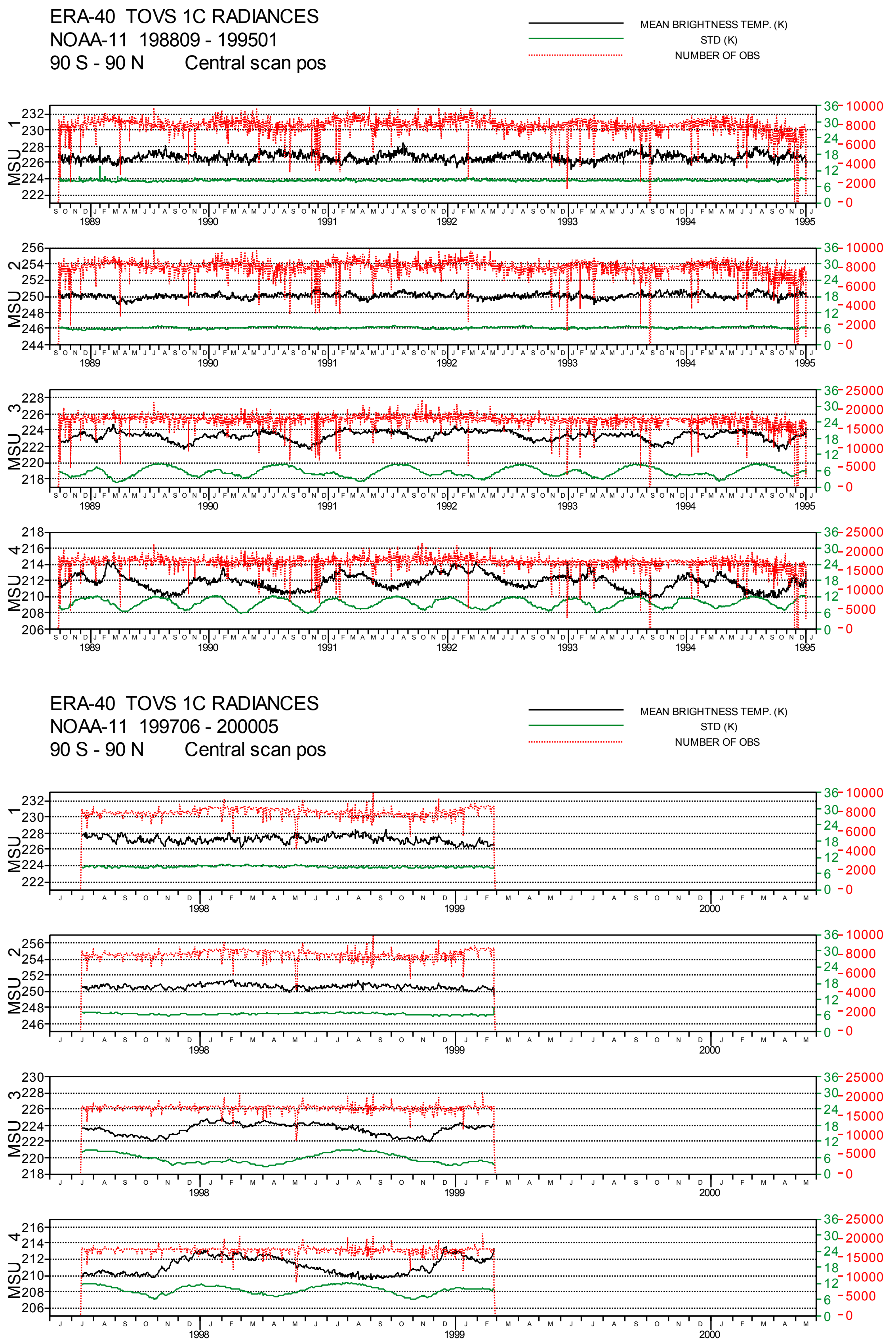


Figure B. 14. NOAA-11 MSU, global, Sep 88 to Jan 95 (upper panel) and Jun 97 to May 00 (lower panel).

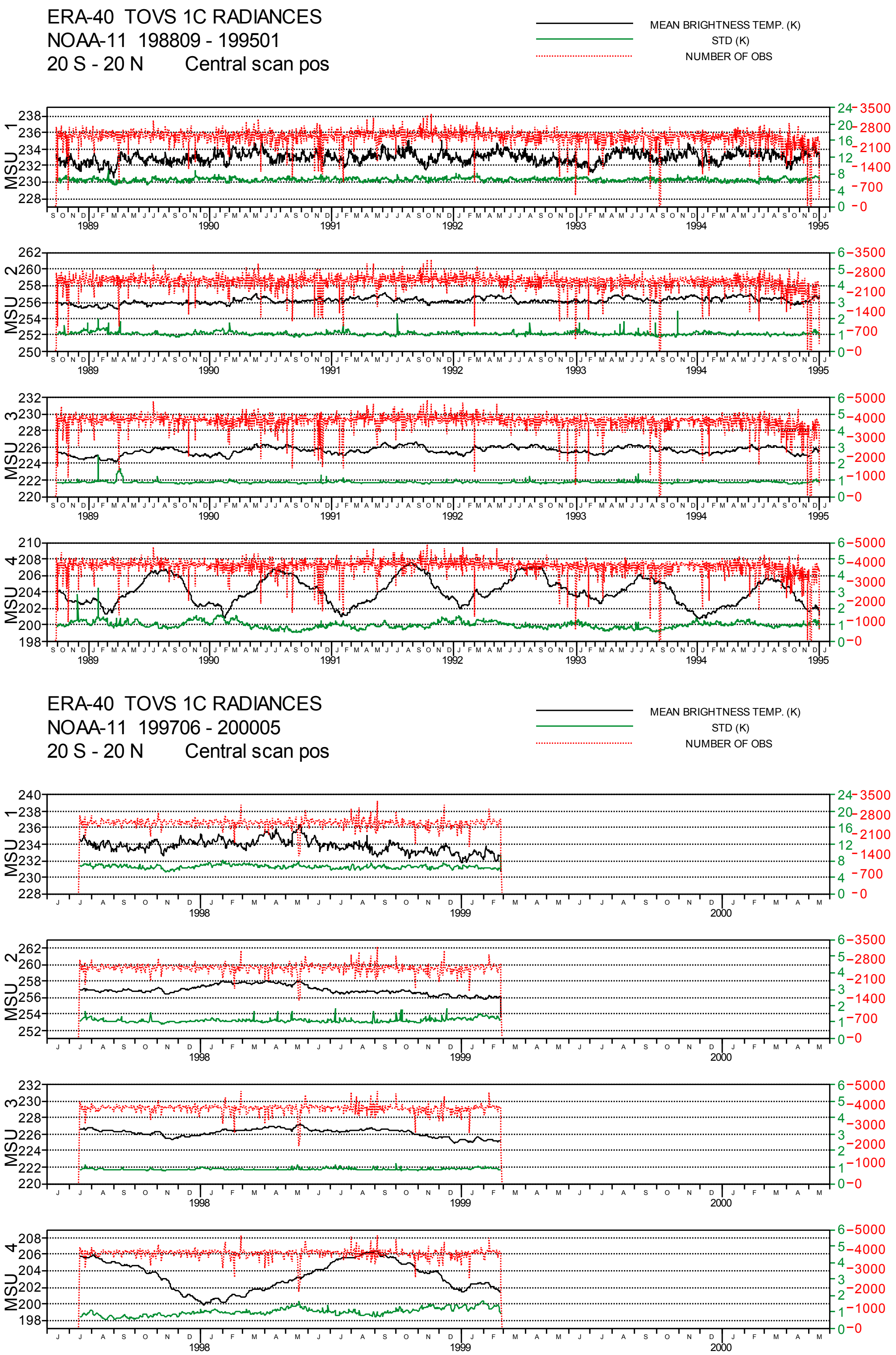


Figure B. 15. NOAA-11 MSU, tropics, Sep 88 to Jan 95 (upper panel) and Jun 97 to May 00 (lower panel).

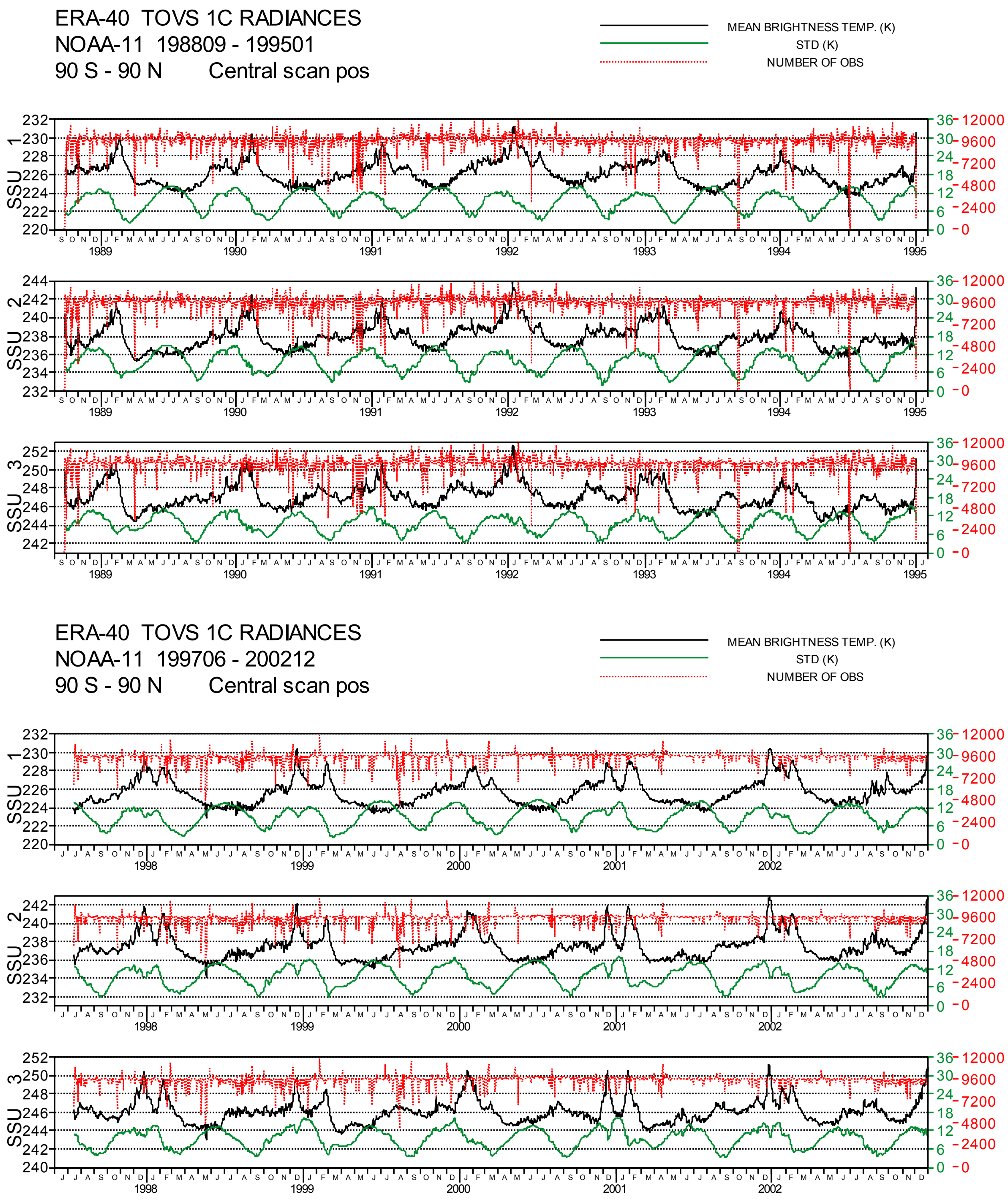


Figure B. 16. NOAA-11 SSU, global, Sep 88 to Jan 95 (upper panel) and Jun 97 to May 00 (lower panel).

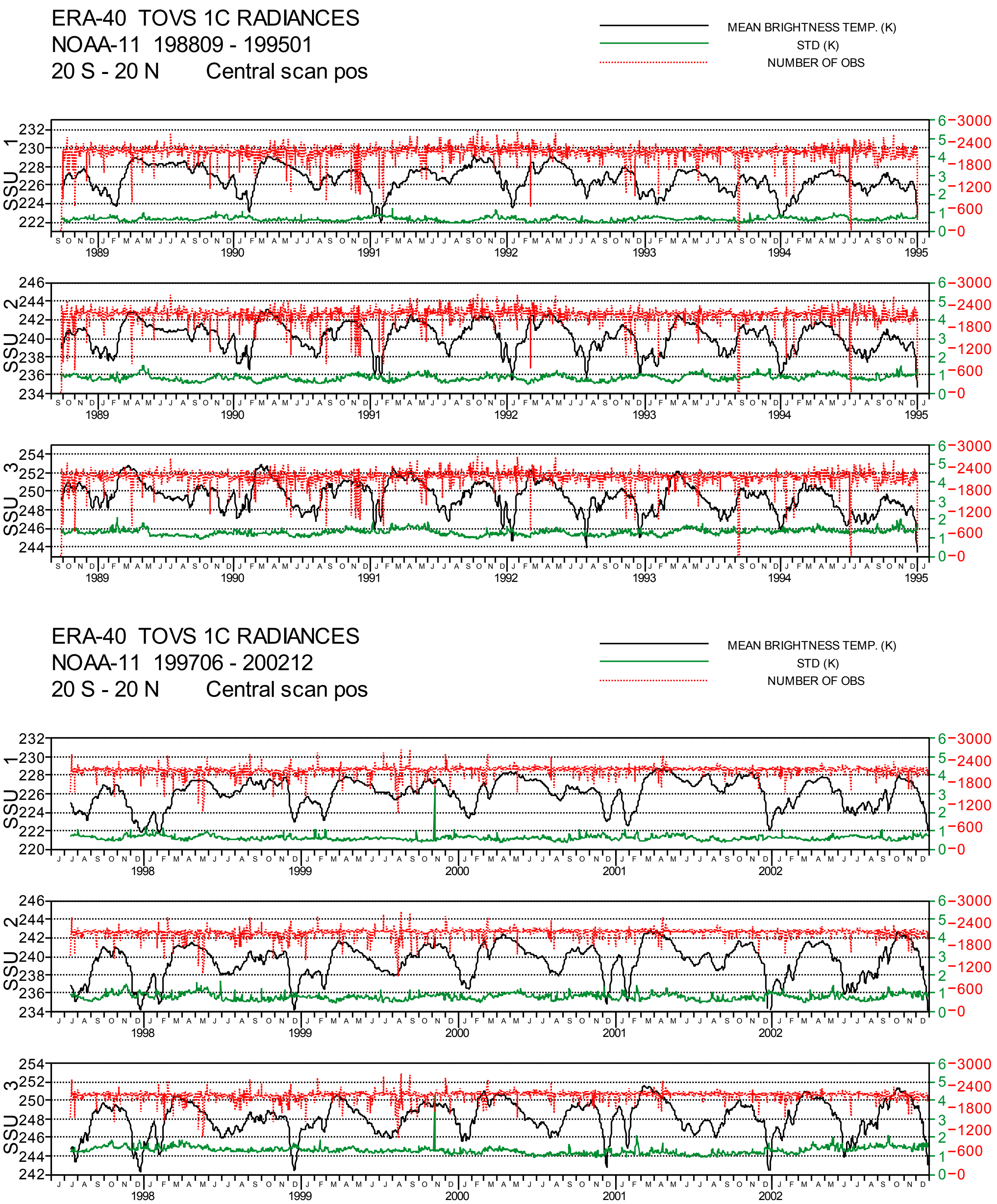


Figure B. 17. NOAA-11 SSU, tropics, Sep 88 to Jan 95 (upper panel) and Jun 97 to May 00 (lower panel).

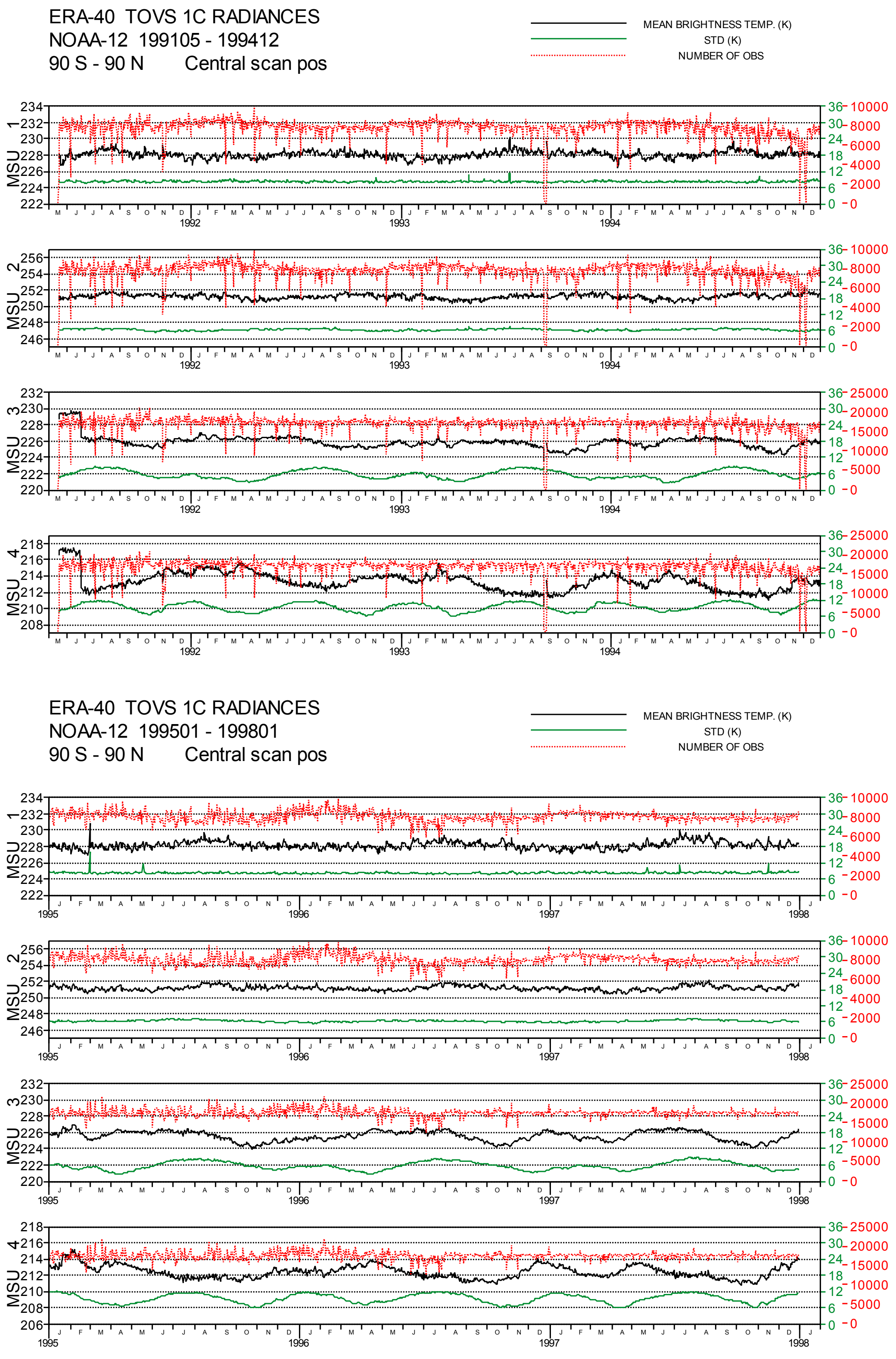
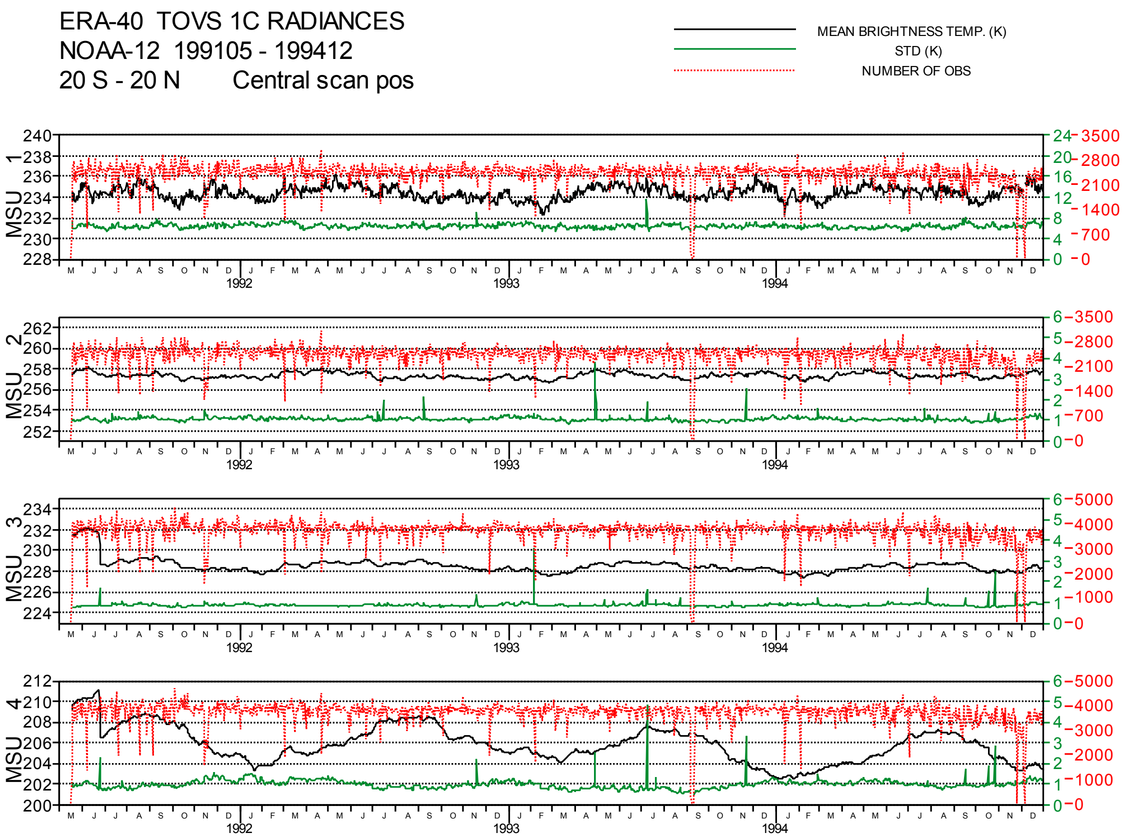


Figure B. 18. NOAA-12 MSU, global, May 91 to Dec 94 (upper panel) and Jan 95 to Jan 98 (lower panel).



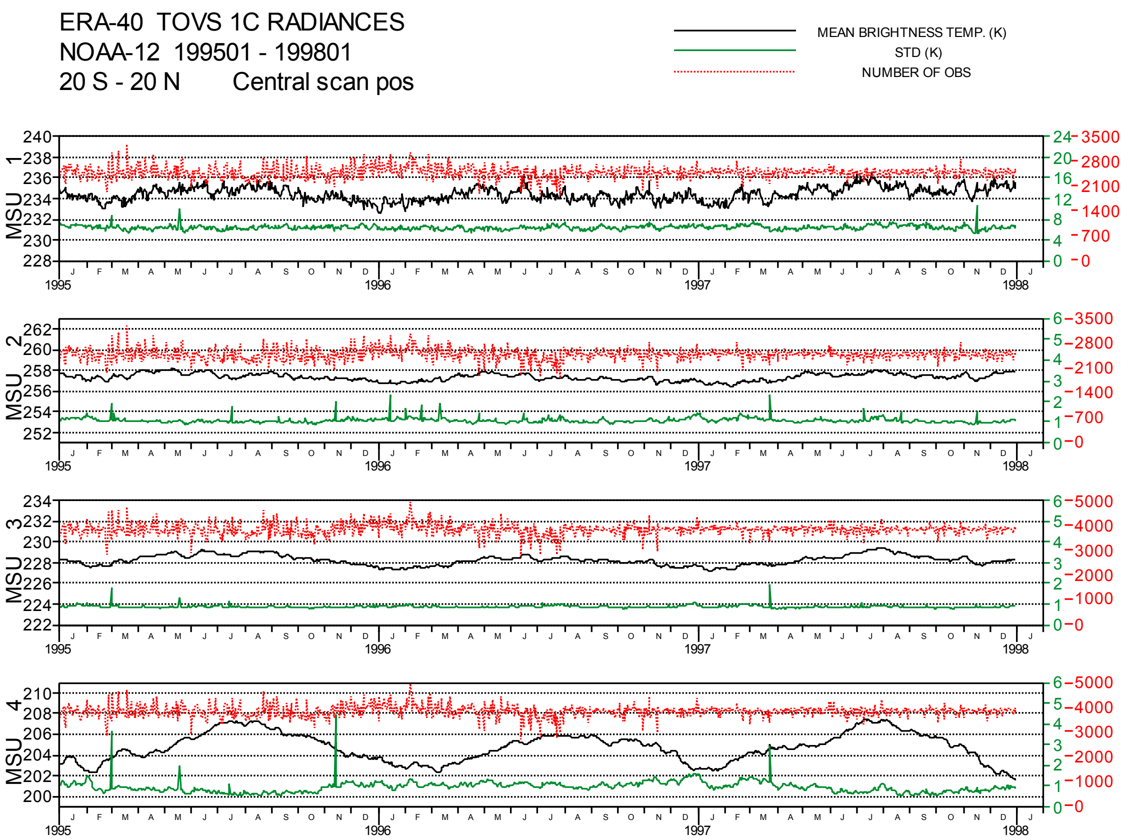


Figure B. 19. NOAA-12 MSU, tropics, , May 91 to Dec 94 (upper panel) and Jan 95 to Jan 98 (lower panel).

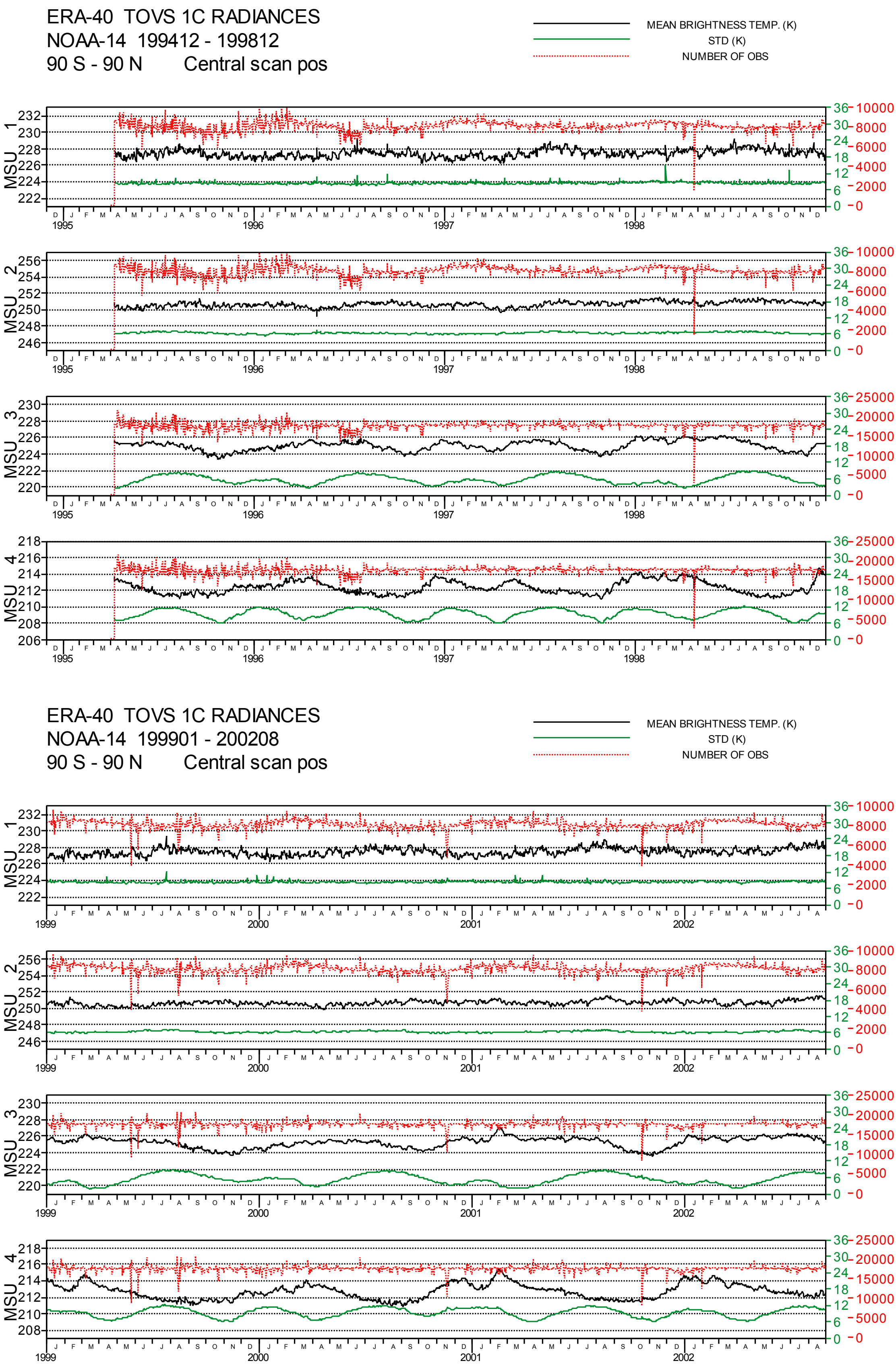


Figure B. 20. NOAA-14 MSU, global, Dec 94 to Dec 98 (upper panel) and Jan 99 to Aug 02 (lower panel).

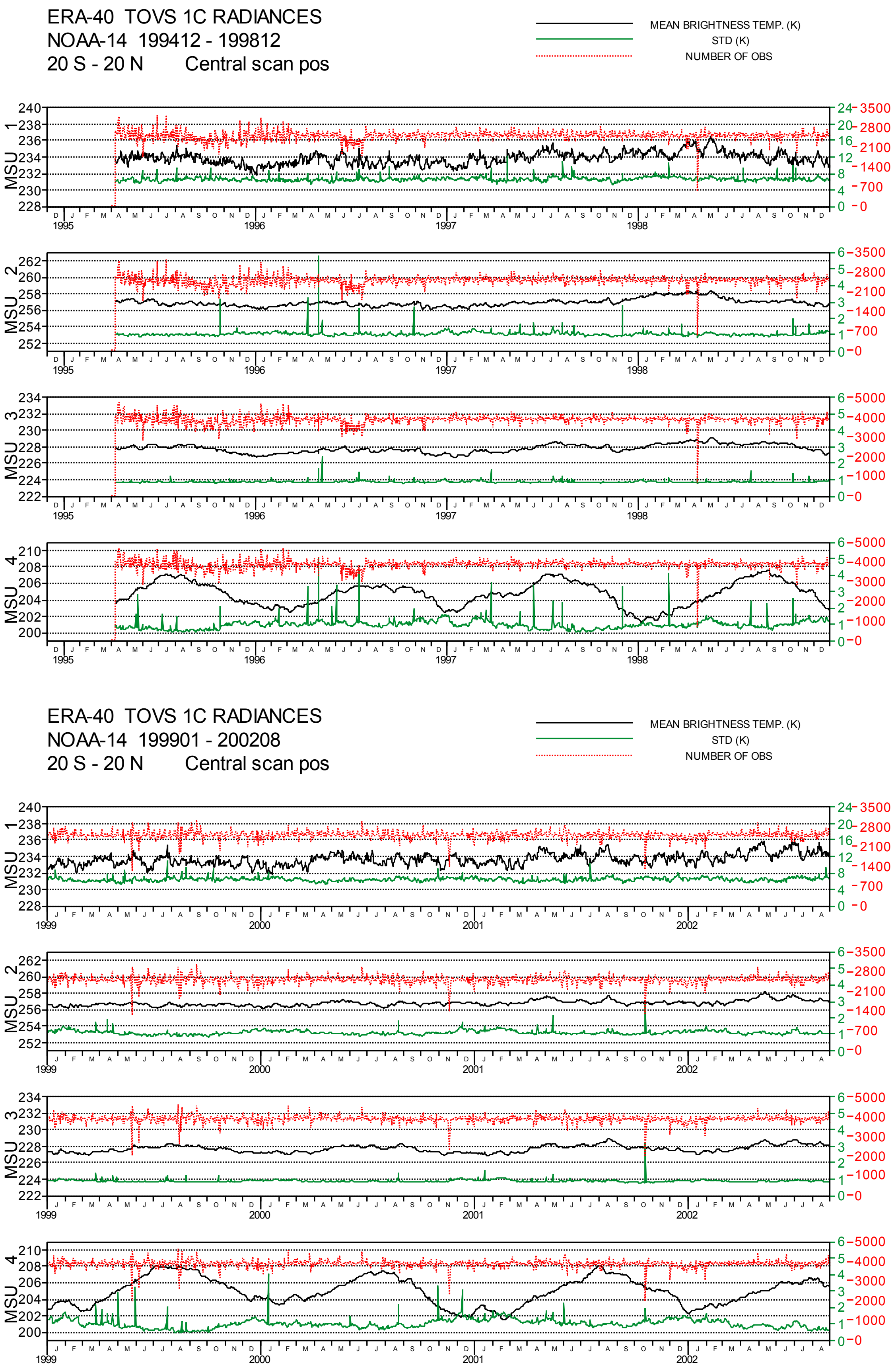


Figure B. 21. NOAA-14 MSU, tropics, Dec 94 to Dec 98 (upper panel) and Jan 99 to Aug 02 (lower panel).

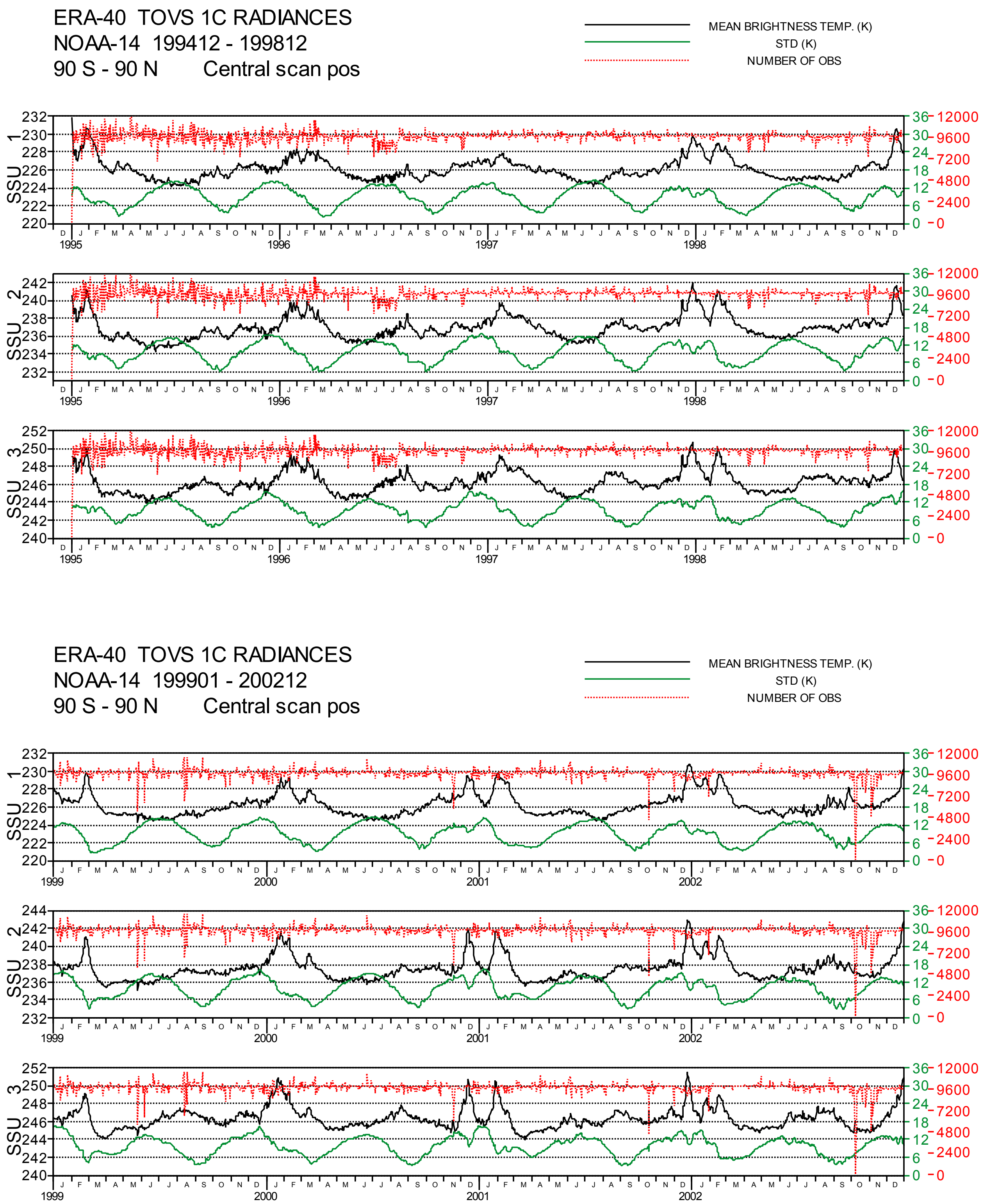


Figure B. 22. NOAA-14 SSU, global, Dec 94 to Dec 98 (upper panel) and Jan 99 to Aug 02 (lower panel).

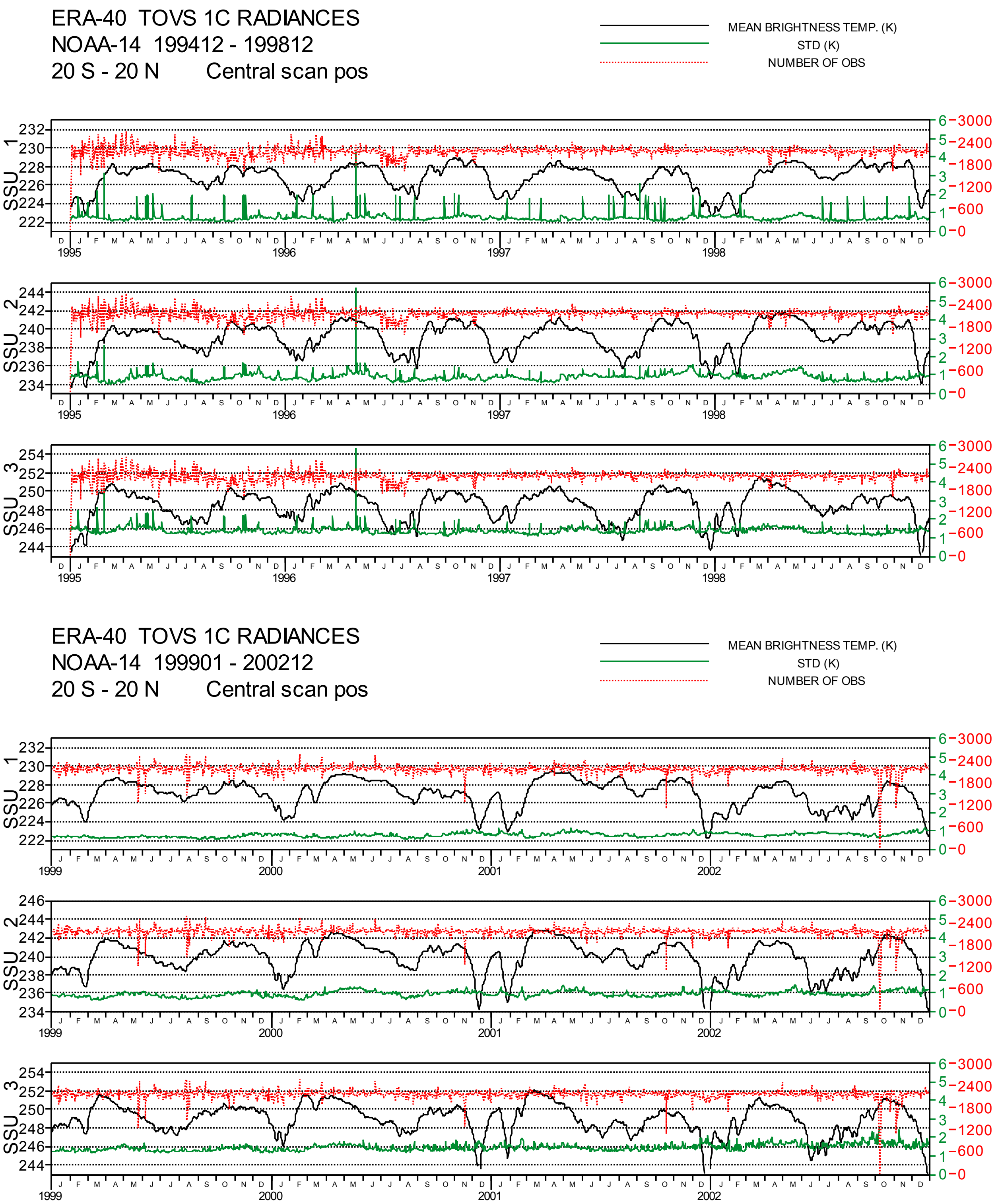


Figure B. 23. NOAA-14 SSU, tropics, Dec 94 to Dec 98 (upper panel) and Jan 99 to Aug 02 (lower panel).

Appendix C: TOVS/ATOVS data selection blacklist

TIROS-N

Initial active use

- Start: MSU and SSU from 19781201
- HIRS start from 19790101 - HIRS was unreliable for the first few months
- End: 19810226 - Severe attitude problems

Channels or instruments blacklisted

- SSU channel 3 - unusable
- All MSU channels from 19790626 - change of behaviour
- HIRS channels 4 and 5 - unstable
- All HIRS channels from 19800127 - change of behaviour after data gap

Isolated cycles or short periods blacklisted

- 1979071318 all instruments - bad Earth location
- 1979072412 and 1979072418 all instruments - bad Earth location
- 1979072912 all instruments - bad Earth location
- 1979080112 all instruments - bad Earth location
- 19800307 and 19800308 all instruments - bad Earth location
- 1980082300 and 1980082306 all instruments - bad Earth location
- 1980092412 to 1980092500 all instruments - bad Earth location
- 19810205 all SSU channels - very noisy, unknown reason

NOAA-6

Initial active use

- Start first period: MSU and SSU on 19790701, HIRS on 19790713
- End first period: 19830417
- Start second period: 19851101
- End second period: 19861031

Channels or instruments blacklisted

- MSU 3 from 19851101 – channel failure

Isolated cycles or short periods blacklisted

- 1979090612 all MSU channels - noise, unknown reason
- 1980030206 to 1940030400, all instruments – bad Earth location
- 1980110406 to 1980110500, all instruments – bad Earth location
- 1986010100 to 1986010218, all instruments – bad Earth location

Notes:

- No HIRS during the second period of NOAA-6

NOAA-7

Initial active use

- Start: 19810901
- End: 19850218

Channels or instruments blacklisted

- All HIRS channels from 19850205 - instrument failure
- SSU channel 2 from 19830701 - calibration of SSU-2 invalid

Isolated cycles or short periods blacklisted

- 1984030200 and 1984030206 all instruments
- 1984072112 all MSU channels
- 1985020406 all SSU channels
- 1985020800 and 1985020806 all MSU channels

Notes

- SSU channels 2 and 3 were affected by high leak rates in the cells. Channel 3 stabilized after some months. SSU channel 2 high leak rates continued, causing the weighting function peak to rise with time.
- Eastward drift

NOAA-8

Initial active use

- Start: 19830525
- End: 19840531

Channels or instruments blacklisted

- SSU channel 3 from 19830914 - Channel malfunction

Isolated cycles or short periods blacklisted - None

Notes

- During the second period of NOAA-8, due to a number of problems (no HIRS, malfunction of SSU 3, failure of SSU 1, attitude problems) data from TOVS were not used.

NOAA-9

Initial active use

- Start: 19841220
- End: 19881031

Channels or instruments blacklisted

- HIRS until 19850202 - calibration problems, channel 7 especially bad
- SSU 3 until 19850323 - unusable
- HIRS channels 1, 2 and 3 from 19861001 - stripping
- MSU channel 3 from 19861025 - channel failure
- MSU all channels from 19870308 - failure of MSU 2 and previous failure of MSU 3

Isolated cycles or short periods blacklisted

- 1986010100 to 1986010218 all instruments - bad Earth location
- 1987010100 to 1987010200 all instruments - bad Earth location

NOAA-10

Initial active use

- Start: 19861218
- End: 19910915

Channels or instruments blacklisted – None

Isolated cycles or short periods blacklisted

- Cycle 1987101212 all MSU channels - noise

NOAA-11

Initial active use

- Start first period: 19881101
- End first period: 19941231
- Start second period: 19970901
- End second period: 19980907 – from this date data not assimilated for operational reasons

Channels or instruments blacklisted

- MSU channel 3 from 19890316 to 19890416 – noise, unknown reason

Isolated cycles or short periods blacklisted

- 1993070706 all MSU channels – noise

Notes

- Very large orbital drift

NOAA-12

Initial active use

- Start: 19910916 – radiances could have been assimilated from July, but start was delayed for operational reasons
- End: 19970530 - HIRS deteriorates

Channels or instruments blacklisted

- All HIRS channels between 19911225 and 19920307 – instrumental problems and passive period for new bias correction
- All MSU channels from 19970524 – instrument considered unreliable

Isolated cycles or short periods blacklisted

- From 19930610 to 19930618 all HIRS channels - noise
- 19930708 and 19930709 all MSU channels – noise
- Cycle 1994072800 all instruments – bad Earth location
- 19950301 all MSU channels – noise
- Cycle 1997032406 all MSU channels – noise

NOAA-14

Initial active use

- Start of SSU: 19950101
- Start of HIRS: 19950501 - HIRS radiances became stable around mid April
- Start of MSU: 19950501 - Rotating mirror problem, rectified in April
- Used to end of ERA-40 period

Channels or instruments blacklisted

- SSU channel 3 from 19990703 - inconsistent with NOAA-15 AMSU-A

Isolated cycles or short periods blacklisted

- 19960430 all instruments - noise
- 20011019 all instruments - noise

Notes

- Large eastward drift

NOAA-15

Initial active use

- Start HIRS and AMSU-A from 19980907
- Used to end of ERA-40 period

Channels or instruments blacklisted

- AMSU-A channel 14 from 20001030 - Channel failure
- All HIRS channels from 20000607 - Filter wheel problems
- AMSU-A channel 11 from 20020401 - Channel failure

Isolated cycles or short periods blacklisted

- 1998100606 all HIRS channels - noise, unknown reason
- 1999010106 all AMSU-A channels - noise, unknown reason
- 1999030206 all HIRS channels - noise, unknown reason
- 20000219 and 20000220 all HIRS channels - noise, unknown reason

Notes

- AMSU-A channels 4 to 14 noise level decreases from February 2000

NOAA-16

Initial active use

- AMSU-A from 20001103
- HIRS from 20010116
- Used to end of ERA-40 period

Channels or instruments blacklisted

- All AMSU-A channels from 20021121 to 20021127

Isolated cycles or short periods blacklisted

- 2000120800 all HIRS channels
- 20010111 all AMSU-A channels
- 2002040512 all HIRS channels

Notes

- Data unusable before 26 October 2000 due to calibration errors