Extending the satellite sounding archive back in time: the Vertical Temperature Profile Radiometer data

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Abstract. The Vertical Temperature Profile Radiometer (VTPR) was an operational 8-channel infrared sounding system mounted on the NOAA-2 through NOAA-5 spacecraft. The instrument was a predecessor of the High-Resolution Infrared Radiation Sounder (HIRS) on the continuing NOAA polar orbiting satellite series. The VTPR measurements covered more than six years of data from late 1972 to early 1979. Major work has been done to clear erroneous data records. Theoretical biases between similar channels of VTPR and HIRS are derived using a radiative transfer model to show the potential bias features between the observations of the two instruments. The model simulation shows that for about half of the channels the biases can be in the order of 1 K for certain temperature ranges. Because each spacecraft carried two sets of VTPR instrument, but only one set was turned on at a given time, differences between two sets of channel measurement are expected to exist. It is shown that the differences between two sets of VTPR instrument can range from nearly zero for some channels to about 2 K for other channels. To make the VTPR dataset accessible to the general scientific research community, we have processed the whole VTPR data to common formats and placed the data online along with data quality statistics.

Keywords: Vertical Temperature Profile Radiometer, infrared sounder, satellite remote sensing.

1 INTRODUCTION

The Vertical Temperature Profile Radiometer (VTPR), with measurements starting from November 1972, was the first atmospheric sounding instrument onboard the operational National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellite series. VTPR radiance data had not become public by any national or international data services until recently, although data from its successor High-resolution Infrared Radiation Sounder (HIRS) since November 1978 are available on-line and widely used in various studies. The VTPR data had been poorly known and little used by the general research community.

There were only a few VTPR studies in the past. At the beginning of the VTPR operation, the satellite sounding group at the NOAA National Environmental Satellite Service presented a pioneer study of obtaining clear radiances to retrieve temperature and moisture from VTPR data [1]. VTPR temperature and moisture profile retrieval was also carried out at the Australian Numerical Meteorology Research Centre which used retrieved profiles as input to the Australian Hemispheric assimilation system [2]. There were other efforts to use VTPR derived temperature profiles to examine the impact of VTPR data on numerical forecasts [3] and to apply the derived profiles in global model reanalysis [4].

The late-1970s marked a transition of the Pacific decadal oscillation from the cool phase to warm phase [5]. Many studies used HIRS data to examine inter-annual variabilities and

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trends of upper tropospheric water vapor in relationships with dynamical and thermo-dynamical processes [6-8]. The HIRS data in these studies covered one phase of the Pacific decadal oscillation. A longer time series would be required to see if the same relationships hold during the opposite phase. The VTPR data can be particularly useful in examining the atmospheric thermo-dynamical interactions in the cool phase before the HIRS records.

One copy of the VTPR data was kept at the National Center for Atmospheric Research (NCAR) at full resolution in level-1c format, which are time-referenced and annotated with ancillary information including radiometric and geometric calibration coefficients and geo-referencing parameters. Work was done at the European Centre for Medium-range Weather Forecasts (ECMWF) [9-10] to remove bad values and convert the data to BUFR format. In order to make the data available and usable to the general science community and particularly the climate research community, we further converted the data to NetCDF format and produced data quality statistics.

2 DESCRIPTION OF VTPR DATA

2.1 VTPR instrument

The VTPR was an operational 8-channel sounding system mounted on the NOAA-2 through NOAA-5 spacecraft. The instrument made routine observations of the atmosphere from surface to lower stratosphere. The measurements covered more than six years from November 1972 to February 1979. The infrared sounder was later replaced by HIRS on subsequent satellites including the Television Infrared Observation (TIROS-N) satellite, NOAA-6 to NOAA-18, the recently launched Meteorological Operational Satellite Program (METOP-A), and two more satellites to be launched in the near future (NOAA-N' and METOP-B). Figure 1 shows the operation periods of satellites carrying the VTPR instruments and the first two satellites carrying the HIRS instruments.

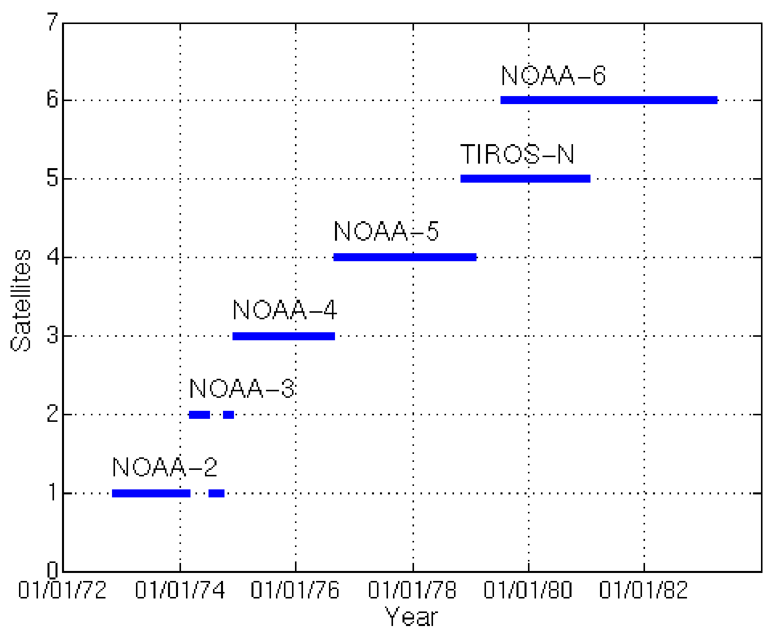

Fig. 1. The observation periods of the early NOAA satellites. NOAA-2 to NOAA-5 carried the VTPR instruments. TIROS-N, NOAA-6 and the subsequent NOAA satellites carried the HIRS instruments.

A detailed description of the VTPR instrument has been provided by Ref. 1. The early NOAA satellites with VTPR instruments orbited the earth in 78.3° retrograde orbits each 115 minutes at an altitude of 1464 km. The VTPR instrument scans perpendicular to the satellite motion, from left to right facing the direction of travel, in 23 discrete steps. Fields of view, scanning times, and apparent motion on the earth provide spot pixels which are contiguous both across and along the orbital track. The VTPR sounder has a horizontal resolution of 55km x 57km at the nadir and 67km x 91km at the end of scan. Six of the eight channels are used to derive radiances in the 15 μm carbon dioxide band and are very similar to the HIRS channels in the later NOAA satellite series. Channel 6 is a near-surface channel. The weighting function of channel 5 peaks at mid-troposphere. Channel 4 peaks in the upper troposphere. Channel 3 is around tropopause. Channels 2 and 1 are stratospheric channels. . Based on the data provided by Ref. 1, the weighting functions of these six channels for a VTPR instrument at 0 degree zenith angle are plotted in Fig. 2. In addition to the sounding channels, there is one channel in the 12 μm atmospheric window region and another channel in the 19 μm water vapor absorption band.

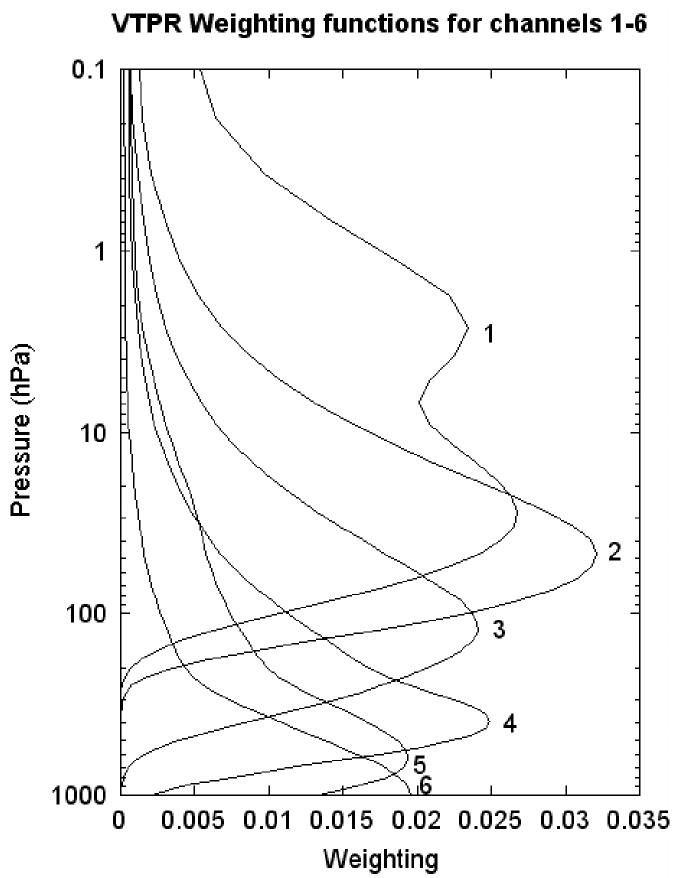

Fig. 2. VTPR weighting functions for channels 1-6 at 0 degree zenith angle.

For the HIRS instrument, the sounder measures the incident radiation in both the infrared longwave (15 μm) and shortwave (4.3 μm) spectrum regions with twenty channels. Comparison of the spectral characteristics between VTPR channels and the TIROS-N HIRS longwave channels (channels 1-12) are shown in Table 1. The HIRS system on TIROS-N and NOAA-6 to NOAA-14 is known as the HIRS/2 design. The instantaneous field of view of the HIRS/2 channels is stepped across the satellite track by use of a rotating mirror. The width of the crosstrack scan is 99 degrees or 2240 km and consists of 56 steps. The optical field of view is 1.25 degrees which gives a ground instantaneous field of view of 17.4 km diameter at the nadir. At the end of the scan, the ground instantaneous field of view is 58.5 km cross-track by 29.9 km along-track.

Table 1. Spectral characteristics of the VTPR channels and the HIRS longwave channels on TIROS-N. Similar channels of the two instruments are listed next to each other.

VTPR				HIRS			
Channel	Central Wave Length (μm)	Central Wave Number (cm^{-1})	Half-Power Width (cm^{-1})	Channel	Central Wave Length (μm)	Central Wave Number (cm^{-1})	Half-Power Width (cm^{-1})
1	14.96	668.5	3.5	1	14.97	668	3
2	14.77	677.5	10	2	14.72	679.23	10
3	14.38	695	10	3	14.47	691.12	12
4	14.12	708	10	4	14.21	703.56	16
				5	13.97	716.05	16
5	13.79	725	10	6	13.65	732.38	16
6	13.38	747	10	7	13.36	748.27	16
8	11.97	833	10	8	11.14	897.71	35
				9	9.73	1027.87	25
				10	8.22	1217.1	60
				11	7.33	1363.69	40
				12	6.74	1484.35	80
7	18.69	535	18				

Two sets of VTPR instrument were carried on each operational satellite to assure continued operation in the event of a failed set. During the VTPR operation, only one of the sets was switched on. Even though both sets had the same channels, their channel filter functions were not completely identical. Correct selection of filter function is essential to accurately simulate VTPR radiances with a radiative transfer model. In the VTPR data files, the satellite name and the VTPR set associated with each pixel measurement are provided in terms of satellite identification and instrument identification. Other related data provided include scan line, field of view, time, latitude, longitude, satellite height, and satellite zenith angle.

2.2 Relative biases between VTPR and HIRS

As many of the VTPR channels are similar to the HIRS channels, potentially the time series of measurements from these similar channels can be extended six years back in time. However, as there are spectral differences between VTPR and HIRS channels, relative biases exist between VTPR and HIRS channels. An important step for connecting the time series is to find out and correct the relative biases.

When there is a sufficient overlapping of multiple satellites in the time series, the intersatellite biases can be estimated using simultaneous nadir overpass observations [11]. Unfortunately there was no overlapping of observations archived among the VTPR series. At a given time, only one set of VTPR on one satellite was operational. There were several months of overlapping between the VTPR on NOAA-5 and the HIRS on TIROS-N, but the overlapping was not long enough to generate statistically significant samples for intersatellite calibration.

With known spectral response functions, both VTPR and HIRS channel brightness temperatures can be simulated by a radiative transfer model. A broad band radiative transfer model, the Radiative Transfer for TOVS (RTTOV-8) [12], is used in this study to simulate the VTPR on NOAA-5 and the HIRS on TIROS-N. In the model computation, 13,495 atmospheric profiles from ECMWF reanalysis were used as input. These profiles were selected to have global representation of the atmosphere [13], and include both cloudy and clear cases. The differences between each pair of the similar VTPR and HIRS channels at 0 degree zenith angle are calculated. Since there are variations of biases across the brightness temperature ranges, the differences are further derived for every 10 K of the brightness temperatures.

Relative biases between the similar channels of first set of VTPR on NOAA-5 and HIRS on TIROS-N are shown in Fig. 3. The relative biases for each pair of the channels are different in not only the bias values but also the variation patterns across the channel brightness temperature ranges. Details are described below.

VTPR channel 1 – HIRS channel 1: The bias values between VTPR and HIRS are consistently between -1.3 and -1.7 K for all temperature measurements.

VTPR channel 2 – HIRS channel 2: The bias values between VTPR and HIRS vary significantly across the temperature range from near 0 to 0.9 K, and the variation is nonlinear.

VTPR channels 3-6 – HIRS channels 3-7: These are the tropospheric sounding channels with spectrums located in the sharp slope of the transmission line. The biases are generally more sensitive to changes in spectral response functions. Bias values larger than 1 K can occur for any of these channels. There are large decreases or increases of bias values with respect to the variations of temperature. The temperature dependent features need to be carefully taking into account in bias adjustments.

VTPR channel 8 – HIRS channel 8: The biases are small for temperatures from 200 to 280 K (within 0.1 K), but for temperatures greater than 280 K, the VTPR data are significantly smaller than HIRS data. The nonlinear variation pattern of bias with respect to temperature is mostly caused by both the shift of central wave length and the width of the spectrums (see the half-power width values in Table 1) between these window channels of the two instruments.

There are three water vapor channels in the HIRS instrument (channels 10-12), but there is only one water vapor channel in VTPR (channel 7). Both VTRP channel 7 and HIRS channel 11 are mid-tropospheric channels, however they observe the atmosphere at different spectrums. The VTPR channel 7 is located at 18.7 μm, while the HIRS channel 11 is at 7.3 μm. Due to the large difference in the spectrum, the bias values between the two channels are significant. The biases range from -1 K at scene temperature of 190 K to 16 K at scene temperature of 300 K (not included in Fig. 3).

These comparisons provide estimates of the relative biases between VTPR and HIRS based on theoretical examinations with a radiative transfer model. In general, the values from a radiative transfer model are not the same as those from real observations due to differences in the pre-launch and post-launch filter response functions. However, based on a reasonably accurate measurement of pre-launch channel spectral response functions, the results from a radiative transfer model are expected to show the sign (positive or negative, when the bias values are large), the magnitude, and the temperature dependent feature of the biases that would be measured in real observations.

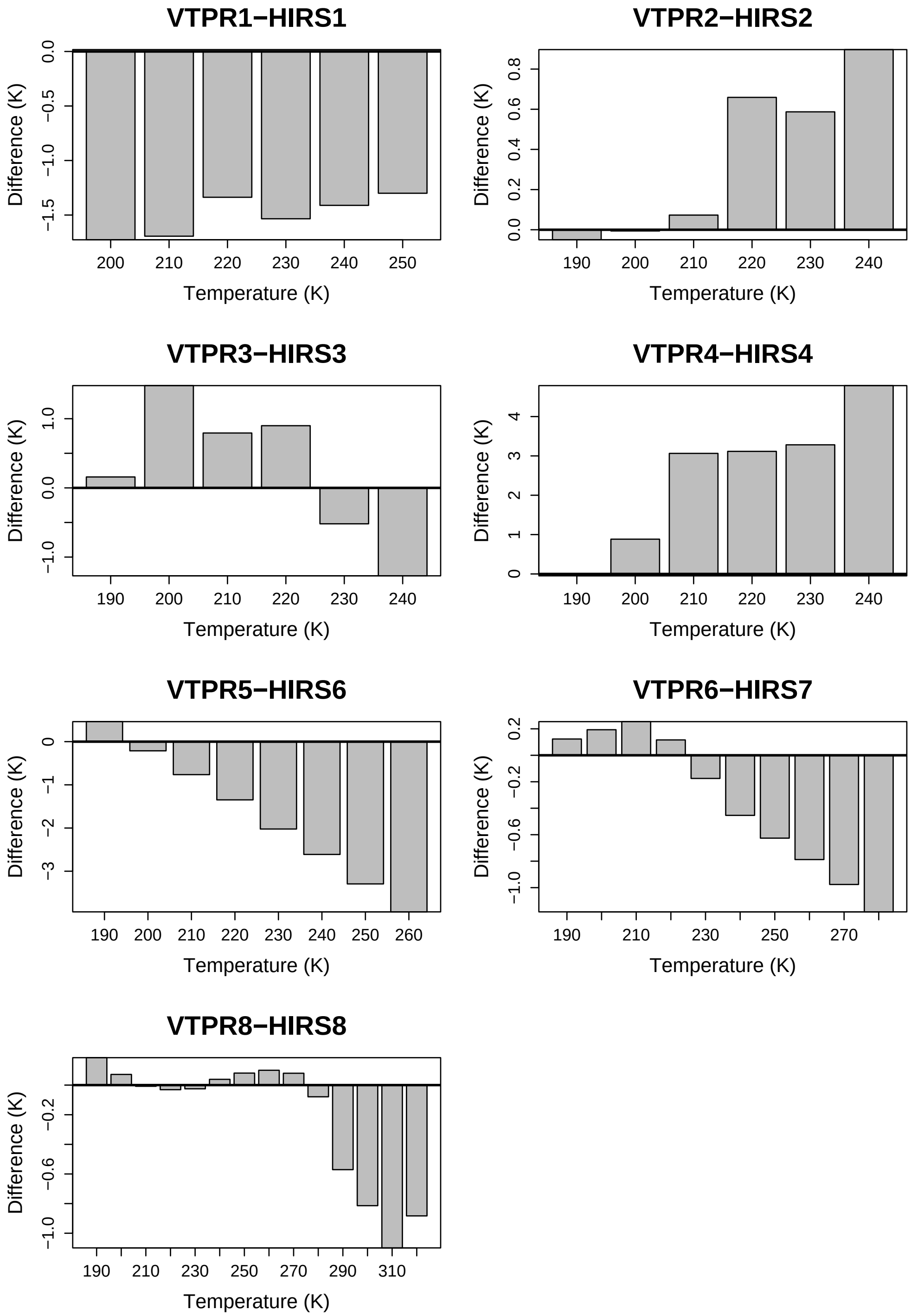

Fig. 3. The relative biases (differences) of similar temperature sounding channels between VTPR and HIRS on TIROS-N. In the title of each panel, the numbers denote the channel numbers of VTPR and HIRS.

The relative bias is meaningful only when the standard deviation (STD) of the relative biases in each temperature bin considered is small. For each pair of the VTPR and HIRS channels discussed above, the STD values of the relative biases in each temperature bin are computed and shown in Fig. 4. For almost all the pairs, the STD values are less than the bias values. For the pairs associated with VTPR channels 1, 2, 3, and 6, the STD values are less than 0.7 K. For the channel 8 pair, the STD values are very small (less than 0.1 K) for temperatures below 270 K. The feature of these small STD values coupled with extremely small biases (less than 0.1 K) indicate a general agreement of the window channel measurements between VTPR and HIRS for this temperature range. Larger STD values are found for the pairs associated with VTPR channels 4 and 5, consistent with their larger bias values as shown in Fig. 3.

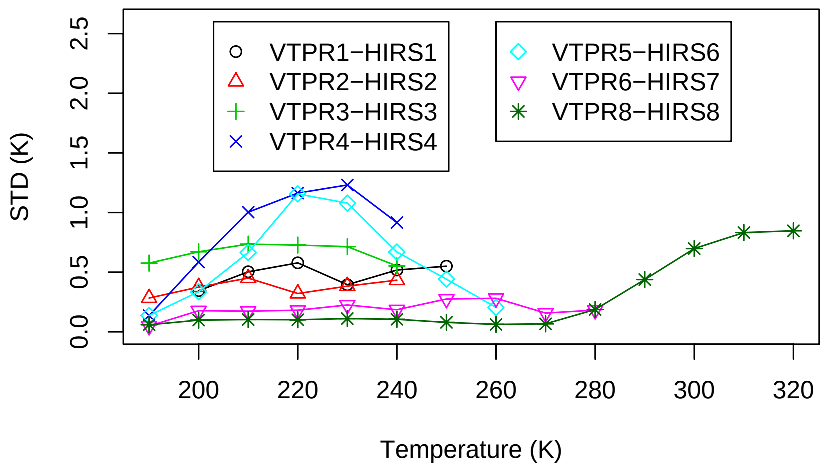

Fig. 4. The STD values of the relative biases for the channel pairs shown in Fig. 3.

2.3 Relative biases between two operational VTPR sets

During satellite operations, only one of the two sets of VTPR instrument on board the satellite was turned on. The channels on each set had slightly different spectral response functions which can lead to different radiance readings. To estimate the differences, RTTOV-8 is used to simulate the channel brightness temperatures of two sets of VTPR based on the 13,495 global atmospheric profiles used in the previous section. The averaged difference for every 10 K bin for each channel is plotted in Fig. 5.

The relative biases for some of the channels are negligible. Such as for channels 2 and 3, the biases are within ±0.05 K. The biases for channels 6 and 8 are small, within ±0.24 K and ±0.15 K, respectively. However, the biases can reach to -1 K for channel 4 and even -2 K for channels 1 and 5 at some temperature ranges. The biases also vary significantly with temperature. These features need to be properly considered in data analysis.

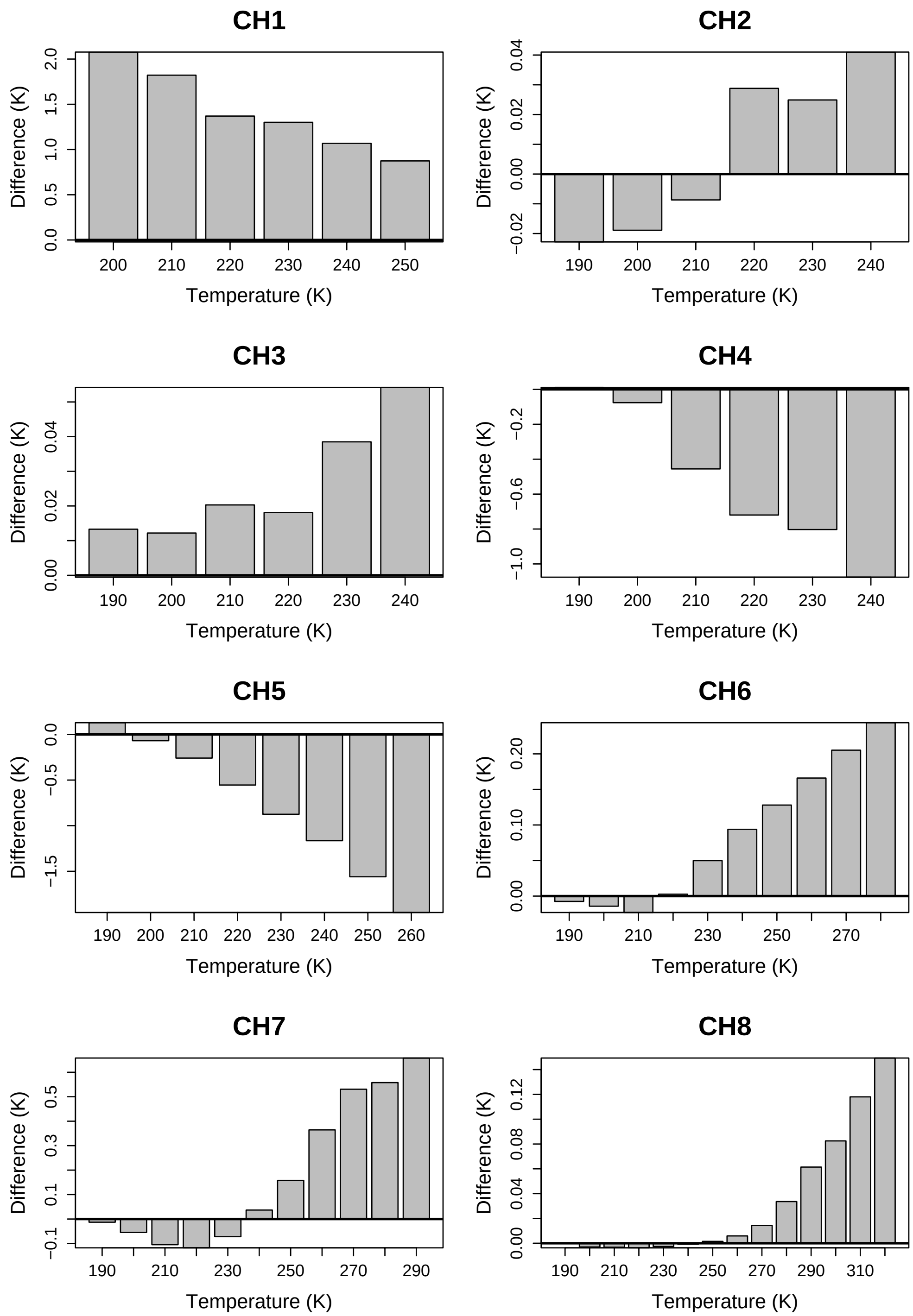

Fig. 5. The relative biases (differences) of the eight channels between two sets of VTPR.

3 PROCESSING OF VTPR DATA

Significant work was done at ECMWF to identify and recover the erroneous data in the original VTPR dataset [9-10]. Quality control criteria were set up based on several factors including sum of the lengths of blocks and correctness of data record time and orbit starting time. Particular attentions were placed on the header record, end-of-file record, and block type. The average error (rejected data) rate is determined being less than 1%.

Most errors occurred mainly in three periods. The first was from November 1972 to April 1974, which was the initial operation of NOAA-2. The second was from January to August 1976, at the end of NOAA-4 operation. The third period was June through October 1978 of NOAA-5 data. During these three periods, the error rates often reached 8%.

The VTPR data from NCAR were coded as Cray datasets (64 bit) in data blocks. The header and associated data record resided in either a single block or multiple blocks. Detailed description of NCAR's data format was provided by Ref. 9 and Ref. 10. Based on the description in these two references, the NCAR VTPR's data headers and records are listed in Table 2. The earth location information in the NCAR data was availbale to only the so-called "principal points". There are only three principal points in an area of 8 x 23 pixels. As shown in Table 2, these are the pixels in spots 5, 12, and 19 of the forth scan line in every 8 lines.

Table 2. List of headers and data records in NCAR VTPR data.

Headers	Satellite ID
	Start date (year, month, day)
	Day number in a year
	Start time (hour, minute, second)
	End time (hour, minute, second)
	Calibration ID
	Standard deviations
	Orbit parameters
	Epoch data (year, month, day)
	Epoch time (hour, minute, second)
	Maximum roll in the orbit
	Right ascension of maximum yaw
Data Records	Radiances (8 x 23 x 8)
	Latitude of spot (4, 5)
	Longitude of spot (4, 5)
	Latitude of spot (4, 12)
	Longitude of spot (4, 12)
	Latitude of spot (4, 19)
	Longitude of spot (4, 19)
	Hour, minute, second of spot (4, 11)
	Zenith angle of 7 spots
	Line count
	Sea surface temperatures
	Instrument number
	Clock for spot (1, 1)

In an effort to make the data readable and usable to the general scientific community, the data are converted to common data formats, in the BUFR format at ECMWF and the NetCDF format at NCDC. With these self-describing data formats, users no longer need to know the lengths of bits and words in a data file. The VTPR channel brightness temperatures and associated geometric and earth-location variables are linked together in a data file. In addition, the latitude and longitude of every pixel are calculated and provided in the re-formatted data. As an example, Fig. 6 shows the data structure of a NetCDF file with six-hours of data that starts at 6 UTC, February 28, 1979, by using the NetCDF header-showing command.

The text in Fig. 6 tells that there are 38499 observations (pixels) in the file, for eight channels of VTPR data. The variables include the satellite from which the observation was made, the set of the VTPR instrument that was switched on, the channel brightness temperatures, earth location (latitude and longitude), viewing geometry (satellite altitude, viewing zenith angle, and line and position of the sample), and the observation time.

Each of the VTPR files contains about six hours of data. The total number, standard deviation, mean, minimum, and maximum values for each of these six-hour files are computed for the entire dataset. As an example, Fig. 7 shows some of these descriptive statistics for July 1977. The measurements are taken from the VTPR channels on NOAA-5. In general, the total number of pixels in 6-hour intervals is close to 40,000. Occasionally large amounts of erroneous data are identified and removed. The removal of the data can be seen in Fig. 7A as significantly reduced number of pixels, on July 10, 17, 22, and 30.

The mean values per 6-hour of the VTPR channels 2, 4, 6, and 8 are shown in Fig. 7B. It depicts that the mean brightness temperature values are largest at the surface (channel 8). The mean temperature decreases with height, as measured by channels 6, 4, and 2, from the troposphere to the lower stratosphere. Several larger departures of the mean values occur on the days when there are fewer valid pixels. Figs. 7C and 7D respectively show the minimum and maximum values of channels 7 and 8. Diurnal variations of the 6-hour files are clearly exhibited by the plots. However, these diurnal variations are not the temperature variations of local regions. They are the results of different observations over different longitudes as the satellite orbits the earth through the day. Often these diurnal differences of 6-hour files are resulted from the different heat capacities between land and ocean areas. The maximum value of channel 8 saturates at 311.7 K. All together, these plots facilitate the assessment of data quality.

4 SUMMARY AND DISCUSSION

The VTPR data are available online at NOAA's National Climatic Data Center in NetCDF format and available at ECMWF in BUFR format. The dataset covers VTPR records observed by the NOAA-2 through NOAA-5 from November 1972 to February 1979. The online data are located at web site http://www.ncdc.noaa.gov/oa/rsad/vtpr.html. The site contains both an ftp server and a server that allows users to view individual files, including header and data, in text format. To facilitate the understanding of each file's general data characteristics, descriptive quality control statistics associated with each file are computed.

The dataset offers an opportunity to examine if VTPR can provide improvement in climatic and oceanic researches for the 1970s. Using the processed VTPR radiances, ECMWF incorporated VTPR data together with more recent satellite sounder measurements in the reanalysis of ERA-40 [14]. It was shown that the ERA-40 forecast quality began to improve in 1973 due to the assimilation of VTPR radiance data backed up by surface pressure observations. It was also shown that due to the VTPR water vapor channel the total column water vapor variations over the tropical oceans correlate significantly better with the sea surface variations after the introduction of VTPR data than during the pre-1973 period.

```
netcdf vtpr1979022806 {
dimensions:
        ch = 8 ;
        number = UNLIMITED ; // (38499 currently)
variables:
        int satid(number) ;
                satid:long_name = "satellite_id" ;
        int instid(number) ;
                instid:long_name = "instrument_id" ;
        float bt(number, ch) ;
                bt:long_name = "brightness temperature" ;
                bt:units = "Kelvin" ;
                bt:coordinates = "lon lat" ;
        float lat(number) ;
                lat:units = "degrees_north" ;
                lat:valid_range = -90., 90. ;
                lat:long_name = "latitude" ;
        float lon(number) ;
                lon:units = "degrees_east" ;
                lon:valid_range = -180., 180. ;
                lon:long_name = "longtitude" ;
        int number(number) ;
                number:long_name = "number" ;
                number:units = "index" ;
        float zen(number) ;
                zen:long_name = "zenith" ;
        float alt(number) ;
                alt:long_name = "altitude" ;
                alt:units = "km" ;
        int line(number) ;
                line:long_name = "line" ;
        int posi(number) ;
                posi:long_name = "position" ;
        int year(number) ;
                year:long_name = "year" ;
        int month(number) ;
                month:long_name = "month" ;
        int date(number) ;
                date:long_name = "date" ;
        int hour(number) ;
                hour:long_name = "hour" ;
        int minute(number) ;
                minute:long_name = "minute" ;
        int second(number) ;
                second:long_name = "second" ;
// global attributes:
                :Conventions = "COARDS" ;
                :title = "vtprbt" ;
                :history = "Created in Jul 2007" ;
                :description = "VTPR brightness temperature" ;
                :platform = "NOAA polar " ;
}
```

Fig. 6. Example of headers describing the data structure of a NetCDF VTPR file.

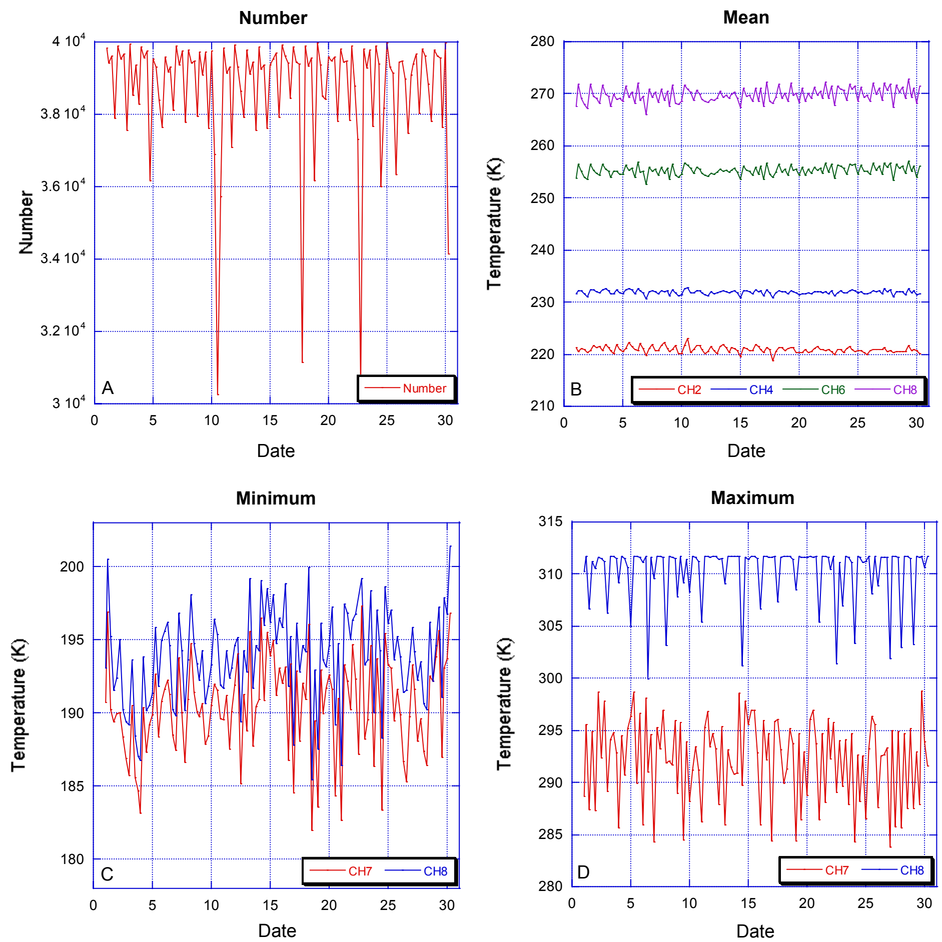

Fig. 7. Sample statistics for total number (A) of pixels and the mean (B), minimum (C), and maximum (D) values of selected VTPR channels for July 1977 from NOAA-5.

Due to differences in spectral response functions, relative biases exist between VTPR and HIRS channels. By use of a radiative transfer model, the relative biases between similar channels of the two instruments are derived. The variations of the biases with respect to temperature are obtained to provide a potential tool to adjust and compare the observations from the two instruments. The model simulation shows that for about half of the channels the biases can be in the order of 1 K for certain temperature ranges. The biases for the mid-troposphere channels can reach 4 K. Large differences of more than 10 K are found between the mid-troposphere water vapor channels in certain temperature ranges. For almost all channels, the variations of bias values across the temperature ranges are significant, and the variations are often non-linear. Within the VTPR series, each satellite carried two sets of the VTPR instrument, and only one set was turned on at a given time. Relative biases between two sets of the VTPR instrument are also obtained from radiative transfer model simulation. The result shows that the biases range from negligible amount for some of the channels to about 2 K for some of other channels.

Several important factors contribute to the relative biases between VTPR and HIRS channels. Besides the non-identical spectral response functions which can be simulated by a radiative transfer model, there are different foot print sizes between the two instruments that are not in the results of model simulation. The resolution of VTPR is about 56 km at nadir, compared to about 20 km for HIRS. Thus the VTPR measurement is basically an average of a much larger area than what is observed by HIRS. The satellites with VTPR instruments also observed at a much higher altitude. In addition to these specific differences between VTPR and HIRS, a climatic study also faces the challenges common to all polar orbiting satellite instrument measurements. The effects of different orbit times and thus observations at different times in a diurnal cycle can lead to discontinuity in a mean time series. The VTPR dataset presented in this study retains as much metadata as possible, which contains earth location, time of observation, and satellite viewing geometry to facilitate researches in development of intersatellite calibration methods for specific studies.

The VTPR dataset represents a unique global atmospheric sounding time series before the widely used HIRS measurement. It offers opportunities to apply the satellite sounding observation to climate targets during the time when few of other global sounding measurement were available.

Acknowledgments

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