

PyGAC AVHRR FDR Release 1 Validation Report

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1 INTRODUCTION

Measurements from the three generations of AVHRR instruments represent one of the longest time series of Earth imaging available. For that reason, AVHRR data offer great potential to detect, map, and quantify long-term environmental changes.

There are more than four decades (1978 to present) of Advanced Very High Resolution Radiometer (AVHRR) measurements from instruments on board a series of National Oceanic and Atmospheric Administration (NOAA) and Meteorological operational (Metop) satellites. These data offer the opportunity to produce Fundamental Data Records (FDRs), which can serve as an input to the retrieval of the various Essential Climate Variables (ECVs) listed by the Global Climate Observing System (GCOS), and thus support the United Nations Framework Convention on Climate Change (UNFCCC).

This AVHRR FDR consists of reflectance and brightness temperatures using Level 1b (L1b) GAC raw data as provided by NOAA CLASS (Comprehensive Large Array-data Stewardship System)¹ for 17 different instruments flying on board Metop and NOAA satellites. The FDR was homogeneously produced for the period November 1978 until the end of 2021 using PyGAC, a Python software package to read, calibrate and navigate AVHRR data in GAC and LAC format [RD 1, the version of the code used for this processing is also available [here](#)²].

Note that measurement conditions were unstable during each of the currently available 17 satellite missions having carried the AVHRR sensor. Orbital drift causes changes in the equator crossing time and introduces artefacts into derived time series, and continuous instrument degradation needs to be accounted for by careful recalibration of the entire dataset. The Near Real Time (NRT) AVHRR measurements thus need to be reprocessed in order to produce an FDR, and – after further efforts such as complete and thorough cross-calibration and uncertainty quantification – finally a Fundamental Climate Data Record (FCDR). Orbital drift however probably cannot be completely eliminated and remains a challenge for climate studies based on an AVHRR FCDR.

Note that this FDR is a first step towards the derivation of an FCDR (Fundamental Climate Data Record). This FDR is not yet an FCDR, as the calibration for thermal channels is satellite specific (i.e. the instrument record is not cross-calibrated), and uncertainty quantification is missing. Nevertheless, the production framework used to produce this FDR is the foundation for a future FCDR.

1.1 Purpose and scope

This validation report is a quality analysis of the entire FDR, providing insight into the dataset's temporal consistency and highlighting remaining limitations. This way, future users shall be able to make an informed decision about the applicability of this FDR for their own use case.

The document provides validation results for the first release of AVHRR FDR reflectance and brightness temperatures. It is targeted to users looking for detailed information on the quality of the FDR data record, which was quantified by verification against various other data sets and through statistical analysis of time series data.

¹ [NOAA's Comprehensive Large Array-data Stewardship System](#)

² [GitHub - py troll/pygac-fdr at 397c5e92125e79978849d42bc9c9cbc2233cb4d5](#)

1.2 Document structure

This document is structured as follows:

- Section 1 – This introduction
- Section 2 – FDR overview
- Section 3 – Verification
- Section 4 – Quality evaluation
- Section 5 – Summary and conclusions

1.3 Reference documents

- RD 1 **PyGAC**, <https://pygac.readthedocs.io/en/latest/>
- RD 2 ESA Cloud_cci Technical Report on AVHRR GAC FCDR generation, May 2017, http://www.esa-cloud-cci.org/sites/default/files/upload/Cloud_cci_RAFCDR_v1.0.pdf
- RD 3 Hersbach, H., B. Bell, P. Berrisford, and Co-authors, 2020: The ERA5 global reanalysis. Quart. J. Roy. Meteorol. Soc. 2020, 1-51. <https://doi.org/10.1002/qj.3803>
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- RD 5 Donlon, C.J., M. Martin, J. Stark, and Co-authors, 2012: The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) system, Remote Sens. Environ., 116, 140-158, <https://doi.org/10.1016/j.rse.2010.10.017>
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- RD 12 Schulz, J., Albert, P., Behr, H.D., et al., 2009: Operational climate monitoring from space: the EUMETSAT Satellite Application Facility on Climate Monitoring (CM-SAF), Atmos. Chem. Phys., 9, 1687-1709, doi:10.5194/acp-9-1687-2009
- RD 13 Hollmann, R., Merchant, C.J., Saunders, R., et al., 2013: The ESA Climate Change Initiative: Satellite Data Records for Essential Climate Variables, Bull. Amer. Meteor. Soc., 94, 1541–1552. doi:10.1175/BAMS-D-11-00254.1
- RD 14 Mittaz, J., C.J. Merchant and E.R. Woolliams, 2019: Applying principles of metrology to historical Earth observations from satellites. Metrologia, 56, 032002, <https://doi.org/10.1088/1681-7575/ab1705>.
- RD 15 Algorithm Theoretical Baseline Document for the PyGAC FDR processing framework, EUMETSAT, 2022

- RD 16 Bhatt R., D. R. Doelling, B. R. Scarino, A. Gopalan, C. O. Haney, P. Minnis, and K. M. Bedka, 2016: A Consistent AVHRR Visible Calibration Record Based on Multiple Methods Applicable for the NOAA Degrading Orbits. Part I: Methodology, <https://doi.org/10.1175/JTECH-D-16-0044.1>, JAOT, Vol. 33, No 11, pp 2499–2515.
- RD 17 Doelling, David R., Bhatt, Rajendra, Scarino, Benjamin R., Gopalan, Arun, Haney, Conor O., Minnis, Patrick, and Bedka, Kristopher M., A, 2016: Consistent AVHRR Visible Calibration Record Based on Multiple Methods Applicable for the NOAA Degrading Orbits. Part II: Validation Journal of Atmospheric and Oceanic Technology Vol. 33, No. 11, pp 2517, 1520-0426.
- RD 18 Borbas, E. and M. Feltz, 2019: Updating the CAMEL surface emissivity atlas for RTTOV. Report of Visiting Scientist mission NWP_AS18_01 Document NWPSAF-MO-VS-058, Version 1.0, 18-01-19. https://nwp-saf.eumetsat.int/publications/vs_reports/nwpsaf-mo-vs-058.pdf
- RD 19 Loew, A., Bennartz, R., Fell, F., Lattanzio, A., Doutriaux-Boucher, M., and Schulz, J., 2016: A database of global reference sites to support validation of satellite surface albedo datasets (SAVS 1.0), Earth Syst. Sci. Data, 8, 425-438, doi:10.5194/essd-8-425-2016
- RD 20 Kidwell, K. B., 1995: NOAA Polar Orbiter Data Users Guide / edited by Kidwell, K.B. and National Climatic Data Center (U.S.). National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Climatic Data Center, Satellite Data Services Division
- RD 21 Woolliams, E.R., J.P.D. Mittaz, C.J. Merchant, S.E. Hunt and P.M. Harris, 2018: Applying metrological techniques to satellite fundamental climate data records. J. Phys. Conf. Ser. 2018, 972, 012003.

1.4 Acronyms

<i>Acronym</i>	<i>Meaning</i>
AVHRR	Advanced Very High Resolution Radiometer
BRDF	Bidirectional Reflectance Distribution Function
BT	Brightness Temperature
Cal/Val	Calibration/Validation activities
CCI	Climate Change Initiative
CLARA	CLOUD, Albedo and RADIATION dataset from AVHRR
CLASS	Comprehensive Large Array-data Stewardship System
CM-SAF	SAF on Climate Monitoring
CLAVR-x	CLOUDs from AVhRr eXTended
ECT	Equator Crossing Time
ECV	Essential Climate Variables
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
ERA	European ReAnalysis
ESA	European Space Agency
FCDR	Fundamental Climate Data Record
FDR	Fundamental Data Record
FIDUCEO	FIDelity and Uncertainty in Climate data records from Earth Observations
GAC	Global Area Coverage
GCOS	Global Climate Observing System
HIRS	High-resolution Infrared Radiation Sounder
ICT	Internal Calibration Target
ITCZ	Inter Tropical Convergence Zone

K	Kelvin
KLM	NOAA K,L,M,N,N' satellites (NOAA-15 to -19 and MetOpA-C)
L1b	Level 1b
LAC	Local Area Coverage
Metop	Meteorological operational satellite
NH	North Hemisphere
NIR	Near InfraRed
NOAA	National Oceanic and Atmospheric Administration
NRT	Near Real Time
NWP	Numerical Weather Prediction
Op	Operational
OSTIA	Operational Sea Surface Temperature and Ice Analysis
PATMOS-x	avhrr PATHfinder atMOSpheres – eXtended
POD	Polar Orbit Data NOAA TIROS-N and A,C,D,E,F,G,H,I,J satellites (NOAA-6 to -14)
PRT	Platinum Resistance Thermometer
RD	Referenced Document
RTTOV	Radiative Transfer for Television infrared observation satellite Operational Vertical Sounder
SAF	Satellite Application Facility
SCOPE-CM	Sustained, Coordinated Processing of Environmental Satellite Data for Climate Monitoring
SST	Sea-Surface Temperature
SAF	Satellite Application Facility
TCDR	Thematic Climate Data Records
TIR	Thermal Infrared
TIROS-N	Television and Infra-Red Observation Satellite - N
UNFCCC	United Nations Framework Convention on Climate Change
VIS	Visible

2 FDR OVERVIEW

2.1 The AVHRR instrument

NOAA and EUMETSAT operate a series of polar orbiting satellites that carry the AVHRR instrument for more than four decades (Figure 1).

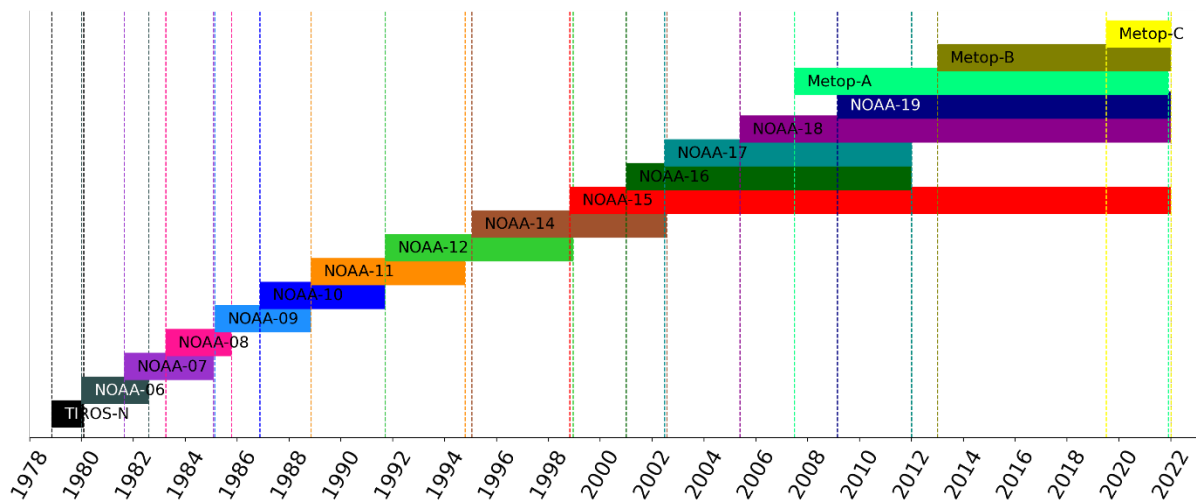


Figure 1: List of polar satellites embarking an AVHRR instrument used for the FDR.

Table 1 gives the start time and end time each platform used in this FDR.

Table 1: Period of operation of each AVHRR instrument in the FDR

Platform	Instrument	Start date	End date
TIROS-N	AVHRR/1	05 November 1978	30 January 1980
NOAA-06	AVHRR/1	01 January 1980	03 August 1982
NOAA-07	AVHRR/2	24 November 1981	01 February 1985
NOAA-08	AVHRR/1	01 April 1983	14 October 1985
NOAA-09	AVHRR/2	25 February 1985	07 November 1988
NOAA-10	AVHRR/1	17 November 1986	16 September 1991
NOAA-11	AVHRR/2	08 November 1988	16 October 1994
NOAA-12	AVHRR/2	16 September 1991	14 December 1998
NOAA-14	AVHRR/2	20 January 1995	26 July 2002
NOAA-15	AVHRR/3	26 October 1998	31 December 2021
NOAA-16	AVHRR/3	01 January 2001	31 December 2011
NOAA-17	AVHRR/3	25 June 2002	31 December 2011
NOAA-18	AVHRR/3	21 May 2005	31 December 2021
NOAA-19	AVHRR/3	22 February 2009	31 December 2021
Metop-A	AVHRR/3	28 June 2007	27 November 2021
Metop-B	AVHRR/3	01 January 2013	31 December 2021
Metop-C	AVHRR/3	03 July 2019	31 December 2021

AVHRR instruments are embarked aboard both afternoon and morning sun-synchronous polar satellites. The NOAA and EUMETSAT satellites circle the Earth 14 times per day at an altitude of about 833 km.

The NOAA satellites did not include a system to maintain their sun-synchronous orbit. This results in a drifting of the satellites from their nominal orbit, and thus causes variability in local equator crossing time throughout the satellites' lifetimes (Figure 2). Metop satellites on the

other hand are orbit controlled as long as the required power supply is provided. Once this was unavailable, Metop-A also started drifting by the end of its lifetime.

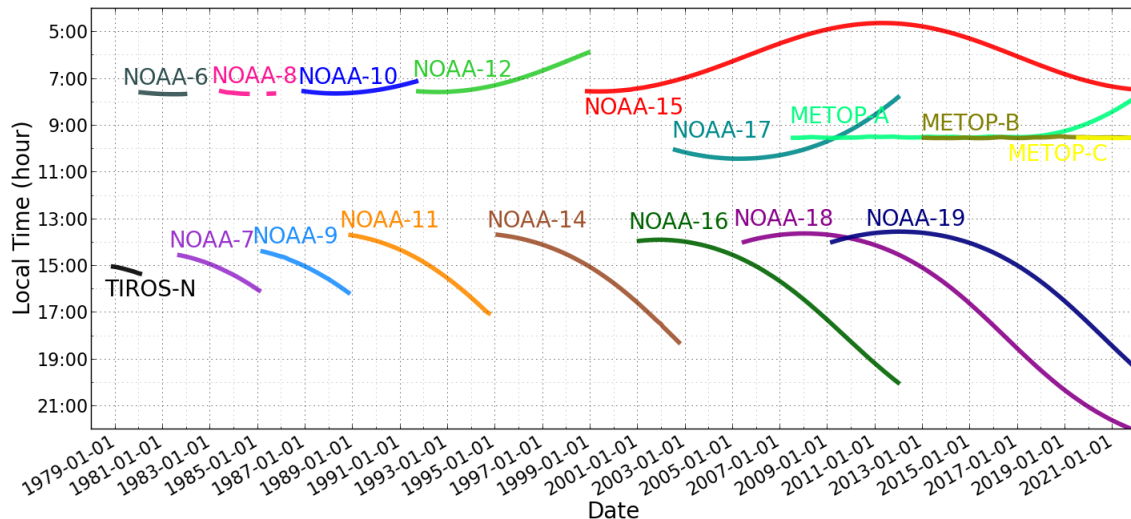


Figure 2: Local equator crossing time (ascending node) for the entire lifetime of each of the NOAA and Metop satellites carrying an AVHRR instrument.

The AVHRR instrument includes visible (VIS), near infrared (NIR), and thermal infrared (TIR) channels. Three generations of AVHRR sensors existed throughout time. The AVHRR passive imager was first a 4-channel radiometer and subsequently improved to 5 and 6 channels at wavelengths between 0.55 and 12.5 μm (Table 2). Note however that only data for 5 channels will be available simultaneously in all cases. For AVHRR/3, 6 channels are technically available, but operation switches between channel 3A and 3B. Regarding channel naming, we will refer to the 3.74 μm channel as 3B for all satellites and AVHRR versions throughout this document, regardless whether an additional channel 3A existed or not.

Table 2: Details about the three versions of the AVHRR instrument. Information was derived from the OSCAR WMO website.

	AVHRR/1	AVHRR/2	AVHRR/3
Period	1978 – 2001	1981 – 2007	1998 – 2025
Satellites	TIROS-N NOAA: 6, 8, 10	NOAA: 7, 9, 11, 12, 13, 14	NOAA: 15, 16, 17, 18, 19 Metop: A, B, C
Num of channels	4	5	6
Channels central wavelength (μm) and spectral interval (μm)	1: 0.615 (0.55-0.68*) 2: 0.912 (0.725-1.1) 3: 3.74 (3.55-3.93) 4: 11.0 (10.5-11.5) *0.55-0.9 for TIROS-N	1: 0.615 (0.55-0.68) 2: 0.912 (0.725-1.1) 3: 3.74 (3.55-3.93) 4: 10.80 (10.3-11.3) 5: 12.00 (11.5-12.5)	1: 0.630 (0.58-0.68) 2: 0.862 (0.725-1.00) 3A: 1.61 (1.58-1.64) 3B: 3.74 (3.55-3.93) 4: 10.80 (10.3-11.3) 5: 12.00 (11.5-12.5)
Swath (in pixels)	across track: 2048 (LAC), 409 (GAC) along track: 6		
Resolution at nadir (km) ³	1.1 (LAC)		

³ The swath and resolution indicated in the table refer of the full AVHRR LAC resolution. The FDR is derived using AVHRR GAC resolution (see figure 3).

The AVHRR instrument takes 2048 Earth views per scan and per channel, having a swath width of 2893 km and a pixel resolution of about 1.1 km at nadir. The AVHRR data are available in two spatial resolutions. Firstly, as provided by the Local Area Coverage (LAC) format, which stores measurements at original pixel resolution with $1.1 \times 1.1 \text{ km}^2$ at the sub-satellite point. Secondly, as provided by the Global Area Coverage (GAC) format, for which four out of every five samples along the scan line are used to compute one average value. The data from only every third scan line are processed, resulting in a spatial resolution of GAC data near sub-satellite point of $1.1 \times 4.4 \text{ km}^2$ with a 2.2 km gap between two scan lines. For the instruments on the NOAA satellites, this format was created because the data volume of the original format was too high to be stored aboard the satellite until the data were downlinked to the major ground station. Metop data are available in LAC format and have been reformatted to the GAC format for this CDR generation. The LAC to GAC resampling principles are illustrated in the Figure 3.

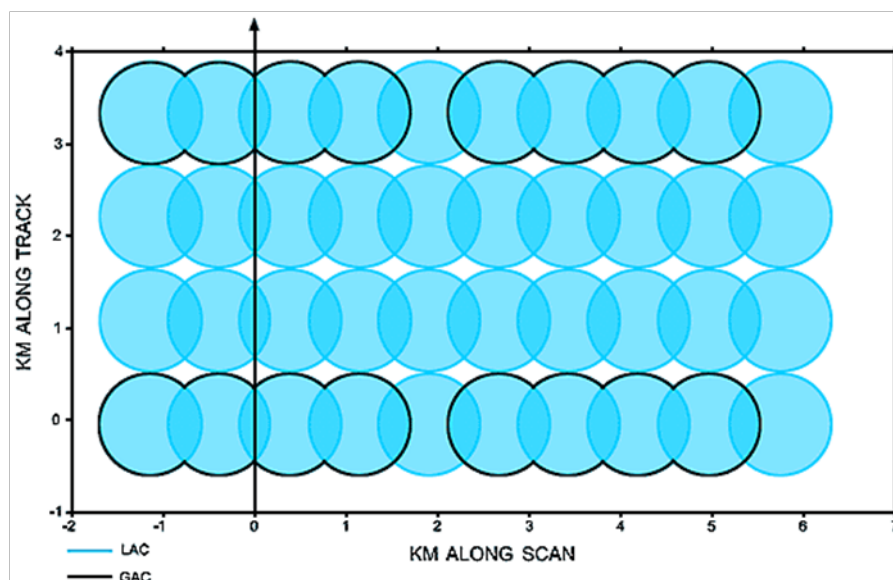


Figure 3: Idealised view of LAC and GAC spatial sampling.

2.2 Instrument calibration

There is no on-board calibration system for the AVHRR sensor's visible channels. Consequently, calibration coefficients needed to be calculated based on independent MODIS and ground-truth data. As the MODIS record extends back in time only until the year 2000, calibration information using MODIS/AVHRR SNOs was transferred via AVHRR/AVHRR SNOs also into the pre-MODIS era in order to minimise satellite-to-satellite inconsistencies. PyGAC visible calibration coefficients and their updates were provided by NOAA [M. Foster and A. Heidinger, personal communication, 2021 + 2022], and are based on version PATMOS-x SOLCAL, v2017r1 [M. Foster, personal communication, 2021 + 2022]. This visible calibration minimises spectral differences among the various AVHRR sensors.

The infrared calibration is only based on on-board calibration data, starting from obtaining Platinum Resistance Thermometer (PRT), space and Internal Calibration Target (ICT, blackbody) counts. ICT temperatures are obtained from PRT counts based on coefficients provided in the POD and KLM Data User Guides [RD 20].

A detailed description of the calibration method can be found in the ATBD [RD 15]. Note that the IR calibration procedure is satellite specific, thus there is no cross-calibration between satellites for IR channels.

2.3 AVHRR FDR reprocessing

This FDR was processed with the PyGAC software package. It is a python based open source, community driven interface to preprocess AVHRR data [RD 11]. PyGAC was initially developed under the framework of ESA's Cloud Climate Change Initiative Phase II [RD 13] with user feedback from EUMETSAT's Satellite Application Facility on Climate Monitoring [RD 12], and is now maintained by the Pytroll community (<http://pytroll.github.io/>). PyGAC takes advantage of the modular and object oriented philosophy of Python and its vast cache of public utilities. Further details on PyGAC's fundamental design can be found in the Algorithm Theoretical Baseline Document (ATBD) [RD 15].

The FDR dataset is produced using input from AVHRR Level 1b data in NOAA-GAC format. Figure 4 presents a high-level overview of the two steps processing. In the first step, the PyGAC-FDR software [RD 1] is used to read, navigate and calibrate the GAC data and to produce one NetCDF output file for each Level 1b input file. In the second step, a number of metadata are collected (e.g. longitude and time of ascending equator crossing time, global quality flags, etc), stored in a database and finally added to the global NetCDF attributes in the files. Note that some metadata require analysis of more than one file, which is why the processing is done in two steps. The metadata database itself will be published together with the FDR NetCDF archive.

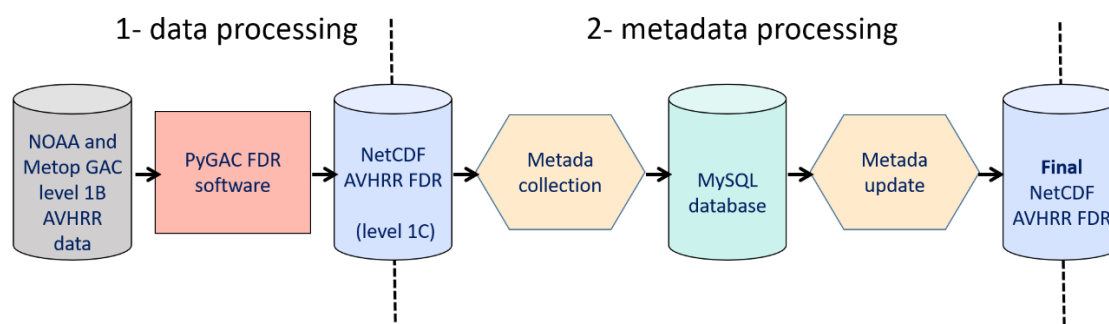


Figure 4: Idealised view of the FDR processing for the production of one final NetCDF FDR file (= most of the time one AVHRR orbit)

3 VERIFICATION: STATISTICAL DATA QUALITY EVALUATION

3.1 Data completeness

Data completeness is highly variable from satellite to satellite (Figure 6 to Figure 10). The PyGAC FDR data of early satellites (TIROS-N, NOAA-6 to -8) show more periods with missing data. The maximum mean daily count is around 172,000 nadir pixels or scanlines (NOAA-19), but only around 120,000 for NOAA-8 and 145,000 for NOAA-6. For later satellites (from NOAA-9 until Metop-C), there are few periods of data outages covering several days (exceptions are NOAA-14: 08-1988, 06-1989, 04-1990, 01/02-1991; NOAA-12: 10-1993; NOAA-14: 12-2001; NOAA-15: 07-2000 to 02-2001; Metop-B: 04/05-2013).

For the following periods, we find extended anomalies in data availability in one or several channels:

- TIROS-N: variable throughout, but in particular late 1979
- NOAA-6: variable throughout, and becoming very sparse from 1981-08
- NOAA-7: lower data count 1984-02 to 1984-09 in channel 1, but only due to nighttime values being set as missing rather than 0 as in channel 2 (same phenomenon also visible for other satellites at irregular intervals, such as NOAA-11-12-18 and MetopB/C)
- NOAA-8: very variable throughout, with few data < 1983-10 and no data 1984-07 to 1985-07
- NOAA-10: low data count for all channels around 1989-07 to 1989-09
- NOAA-17: intermittent data gaps in all channels from 2010-02, and very low availability from 2010-10

The measurement counts of reflectance channels are influenced by PyGAC's treatment of nighttime observations. For some satellites, these are stored as fill values throughout (e.g. NOAA-6, -10, -15), so that counts are only half of those satellites for which nighttime reflectance are recorded as (close to) 0. This treatment of nighttime reflectance however is not always consistent within individual satellite datasets or amongst channels. For example, there are less NOAA-9 nighttime data for channel 2 than channel 1 due to a higher number of fill values in channel 2. For NOAA-16, channel 1 nighttime data are set to fill values throughout, but not for channel 2. The number of nighttime fill values for Metop-B in channel 1 is variable throughout the dataset, which is also the case for various other satellite and channel combinations. In future, PyGAC should be updated to apply a consistent approach amongst all satellite datasets when recording nighttime data.

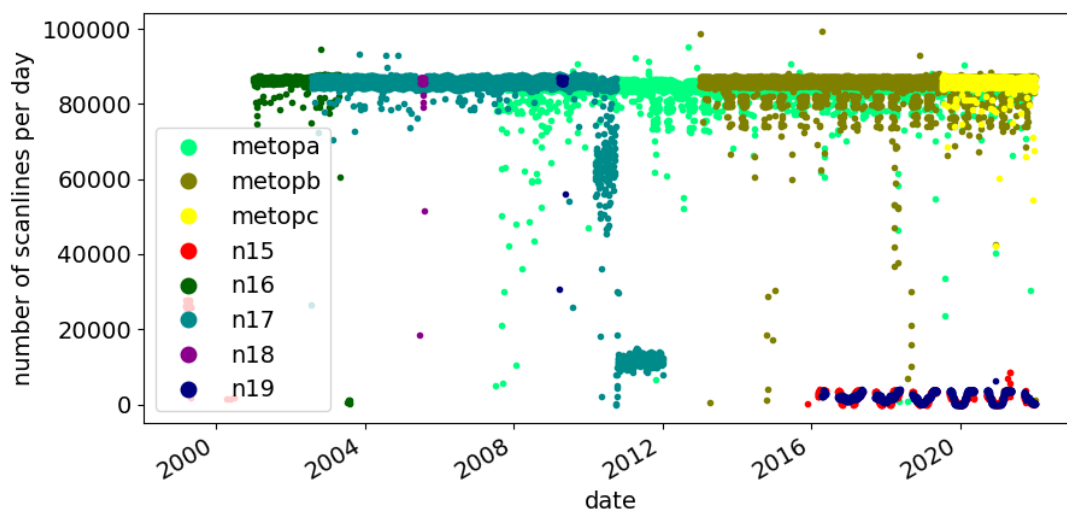


Figure 5: Daily count of scanlines containing ch3a measurements. For satellites not shown, all counts are 0.

Furthermore, this analysis (but in particular Figure 5) shows the duration of periods when channel 3a was turned on at daytime (3b off) and channel 3b at nighttime (3a off). This switching was/is performed for the following satellites:

- NOAA-15: 1999-03-09 to 1999-04-20, and during NH summer over Alaska from 2016 onwards (see low counts in red starting 2016 in Figure 5)
- NOAA-16: until 2003-05-01, and channel 3b always on afterwards
- NOAA-17: throughout
- NOAA-18: 2005-06-23 to 2005-08-05, and channel 3b always on otherwise
- NOAA-19: 2009-03-19 to 2009-05-14, and during NH summer over Alaska from 2016 onwards (see low counts in blue starting 2016 in Figure 5)
- Metop-A/B/C: throughout

The reason for this switching is to better exploit the relative merits of each channel for cloud detection over snow/ice surfaces during daytime (channel 3a) and (sub-)tropical fire monitoring (channel 3b). NOAA decided to activate channel 3b also during daytime for afternoon satellites (i.e. no switching for NOAA-16/-18/-19), and otherwise do channel switching for morning satellites (NOAA-17 and all Metop satellites). In 2016, NOAA activated switching during NH non-summer periods for NOAA-15 and NOAA-19 over the Alaska region only.

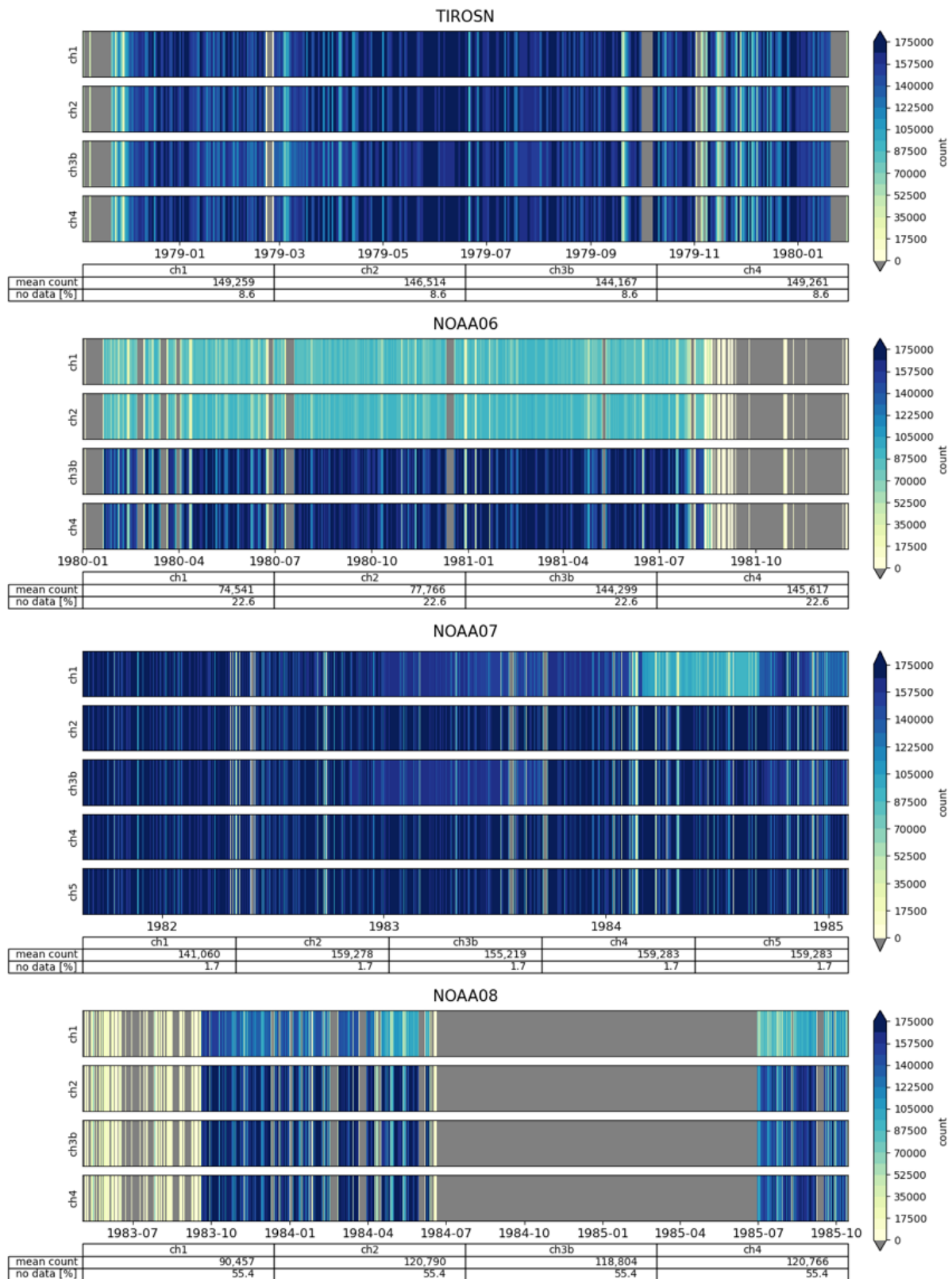


Figure 6: Gap analysis of AVHRR PyGAC data for all channels available per satellite. Data were resampled into daily time chunks, with “count” being the number of observations per day at nadir. The table below the plot shows the mean daily count of nadir observations throughout a satellite’s dataset, and the percentage of days with no data. In GAC resolution, the maximum daily count is around 175,000 nadir observations (or scanlines).

PyGAC AVHRR FDR Release 1 Validation Report

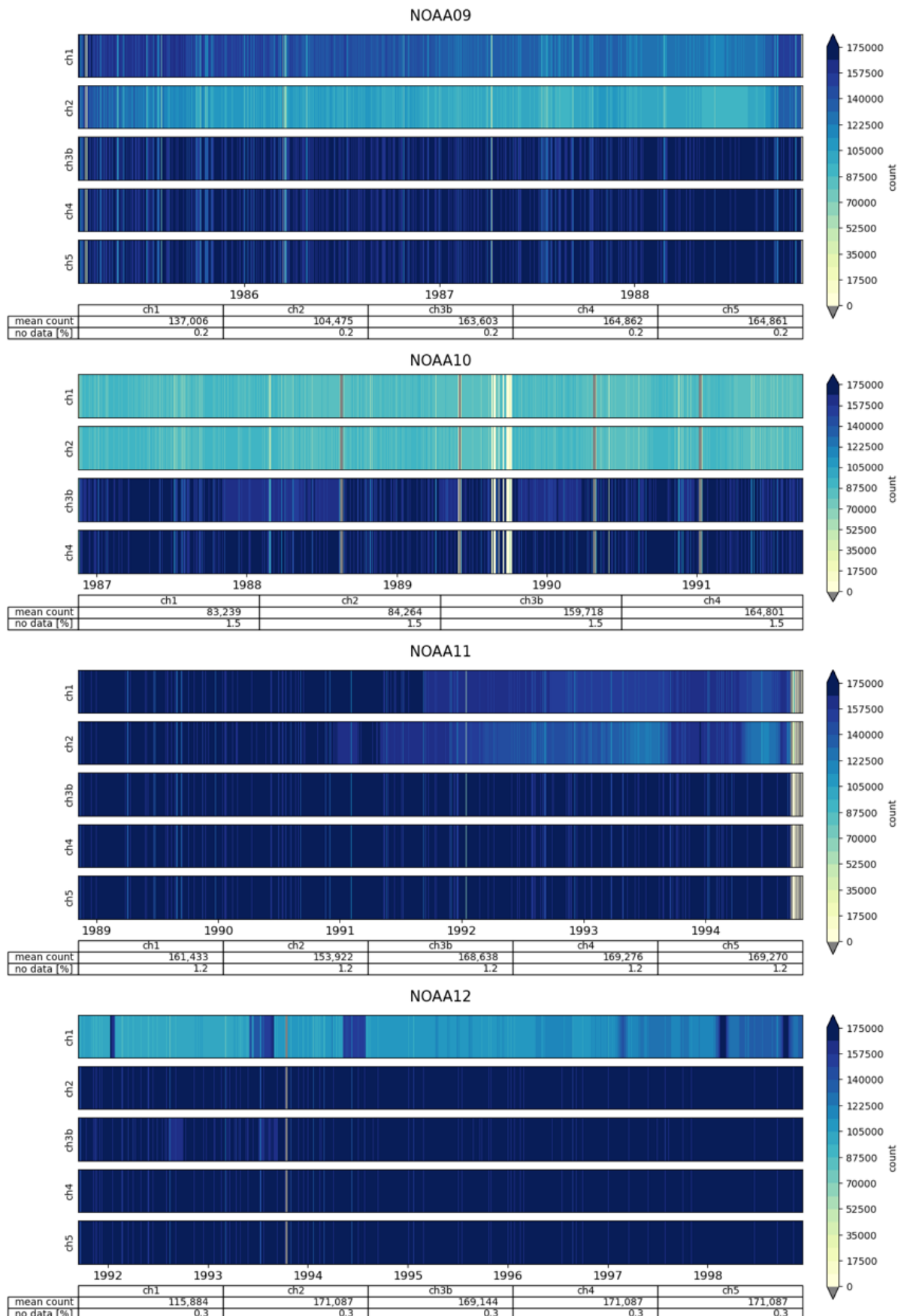


Figure 7: As Figure 6, but for AVHRR aboard NOAA-09-10-11 and -12.

PyGAC AVHRR FDR Release 1 Validation Report

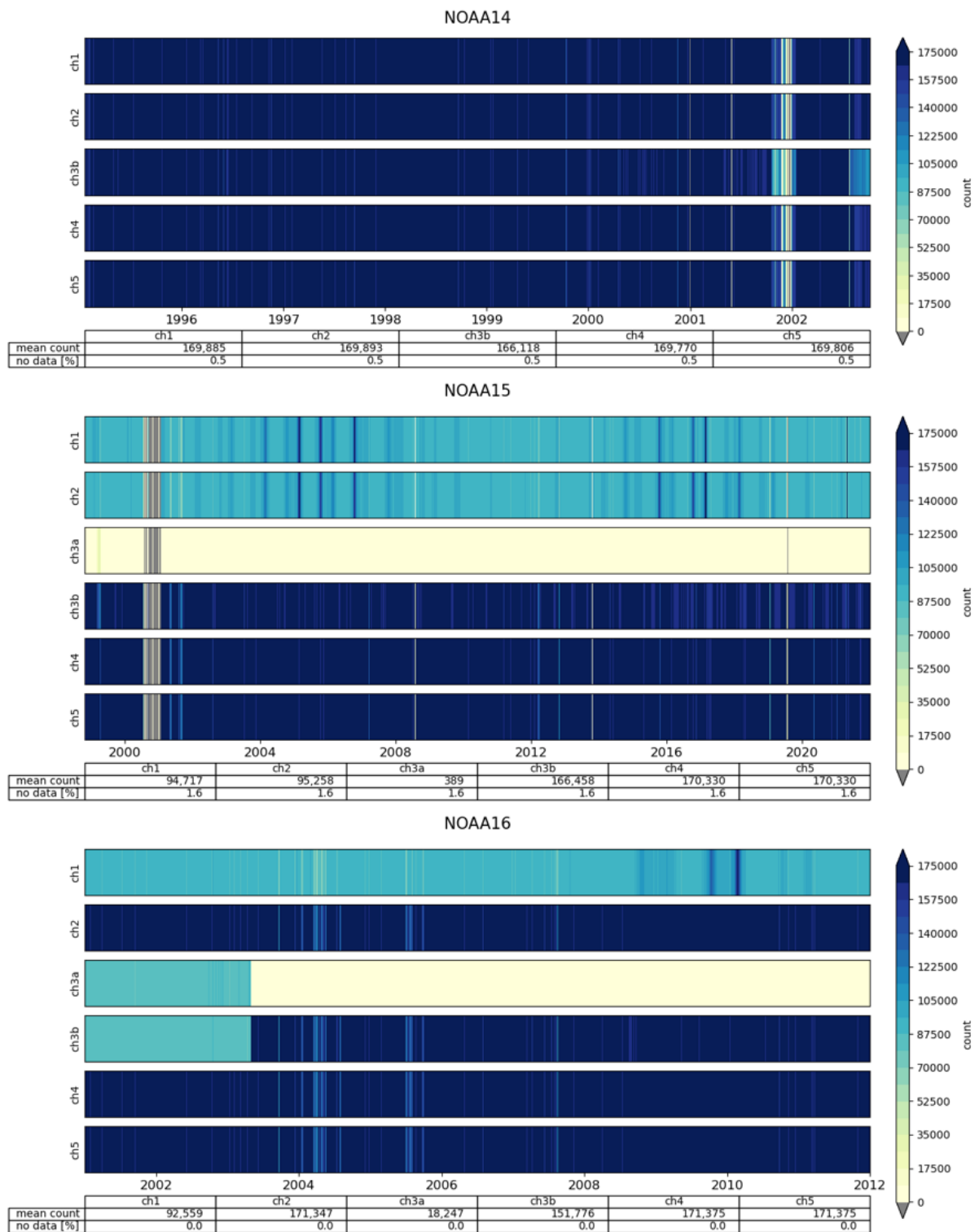


Figure 8: As Figure 6, but for AVHRR aboard NOAA-14-15 and -16.

PyGAC AVHRR FDR Release 1 Validation Report

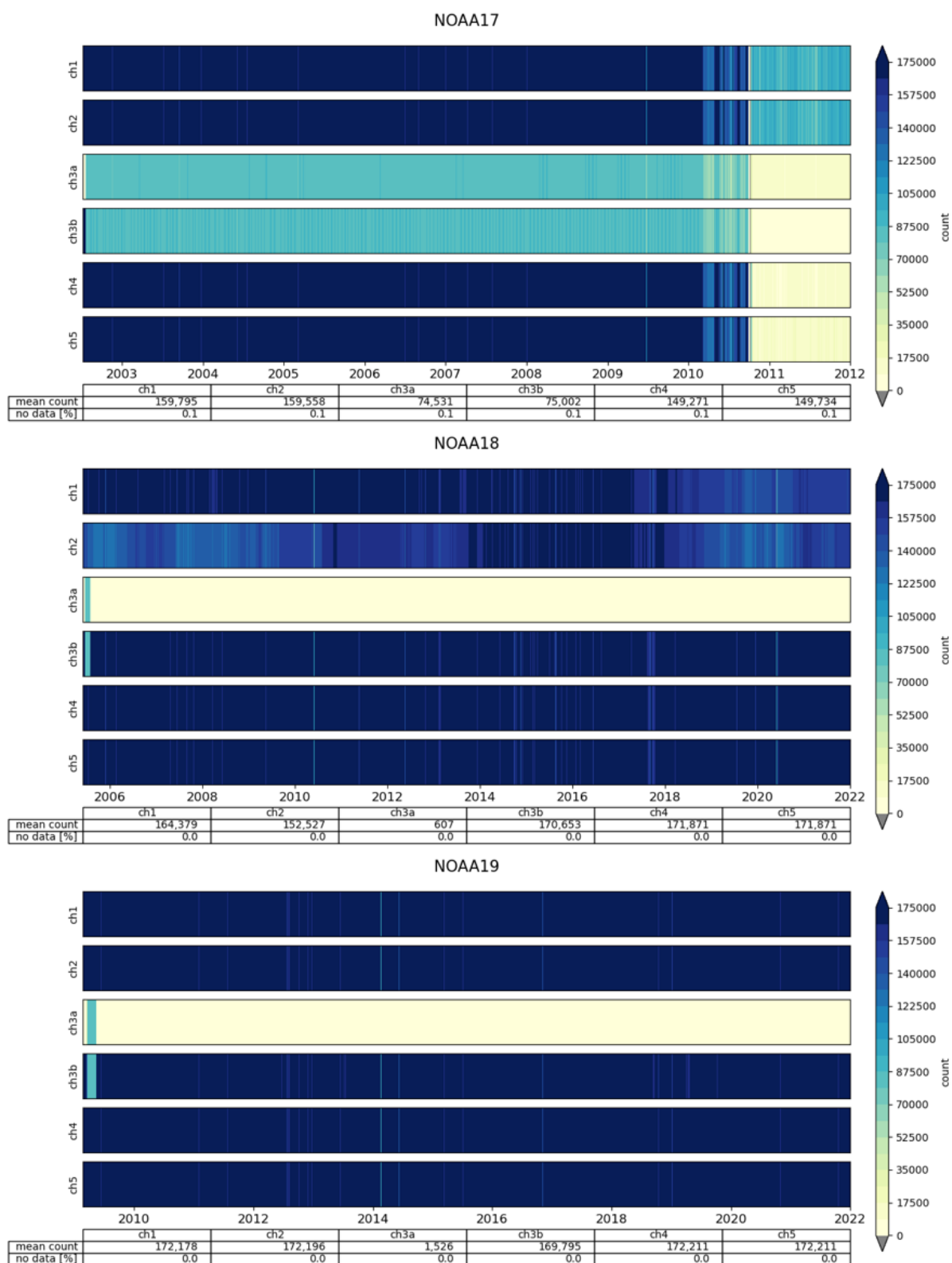


Figure 9: As for Figure 6, but for AVHRR aboard NOAA-17, -18, and -19.

PyGAC AVHRR FDR Release 1 Validation Report

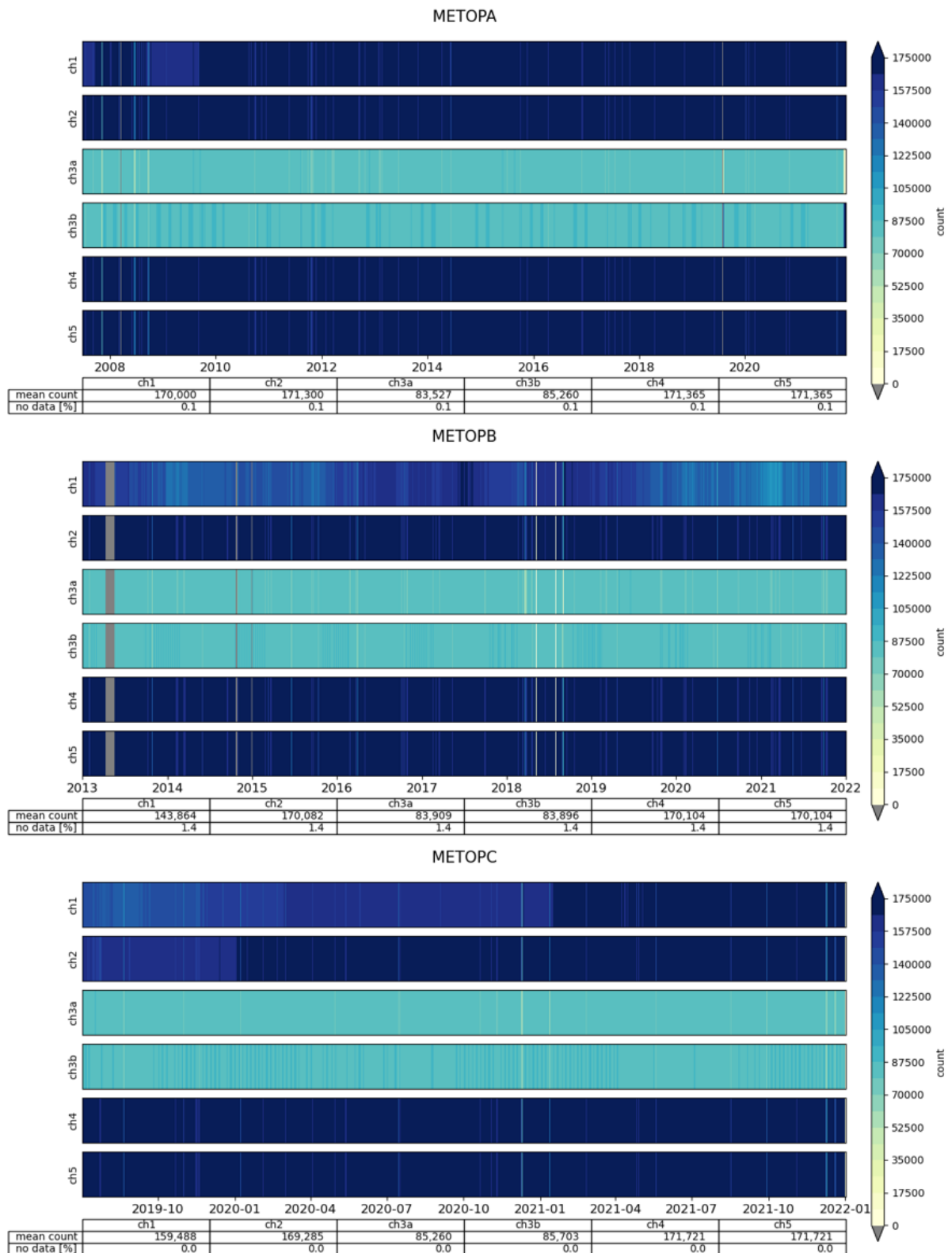


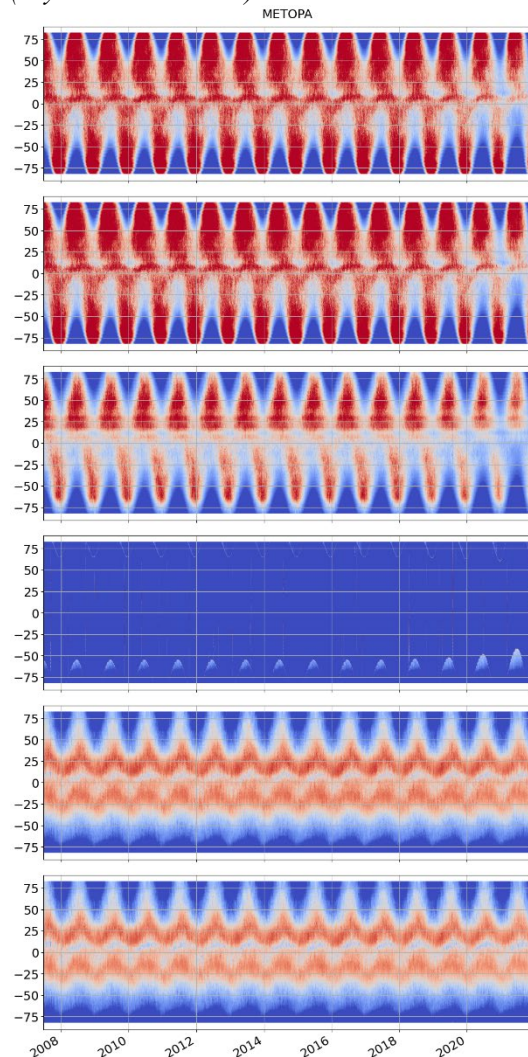
Figure 10: As for Figure 6, but for AVHRR aboard Metop-A, -B, and -C.

3.2 Overall radiance analysis

The data show expected patterns in reflectance and brightness temperatures, both in terms of spatial distribution and temporal variability. Figure 11 shows the zonal mean of the daily averaged reflectance and brightness temperature per 1° latitude band for Metop-A measurements separately for descending and ascending nodes. Figures for all satellites can be found in Appendix A.

In the case of Metop-A, it covers a range of around 13.5 years. Metop-A was orbit controlled, thus its Equator Crossing Time (ECT) in ascending node (Figure 2) remained almost constant until early 2018, when orbit control was shut off and orbital drift to earlier ECTs began. The impact of orbital drift on spatiotemporal measurement patterns is small for Metop satellites (and when orbit control is activated), but is evident for all other non-orbit controlled platforms. In particular, NOAA-15 (the longest AVHRR PyGAC time series covering 22 years and 2 months, Figure 53 and Figure 54) clearly shows how the drift from 7:30 AM ECT to 4:30 AM ECT (and almost back to 7:30 AM ECT by 2021) impacted measurements. While descending node reflectance measurements started in daytime conditions in 1999, they are almost completely dominated by nighttime conditions around 2012. Accordingly, BTs show a drift from warmer to colder conditions during that period.

a) Data are shown for the descending node (daytime observations)



b) Data for the ascending nodes (night time observations)

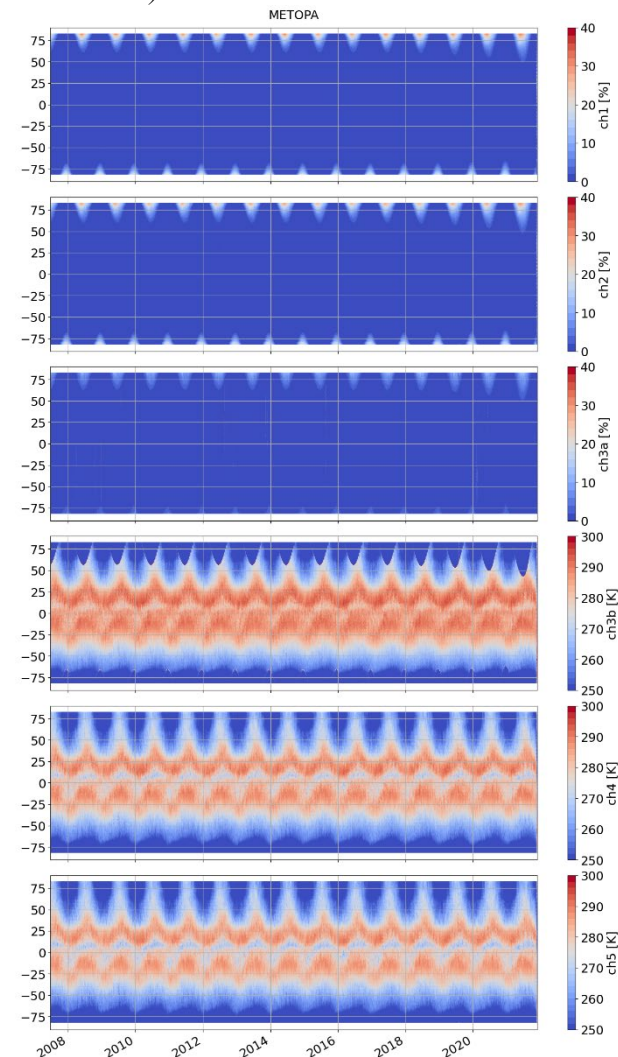


Figure 11: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for Metop-A. Data are shown for the a) descending node only, i.e. daytime observations and b) ascending node only i.e. night-time observations.

As shown for Metop-A, reflectance measurements display expected seasonal patterns, such as polar night and day at extreme latitudes and transition from summer to winter illumination conditions (and vice versa) across all latitude bands. Channels 3a and 3b are switched from day (3a) to night time (3b). Brightness temperatures are very homogeneous and stable in terms of seasonality: hemispheric warming consistently follows sun illumination conditions. Tropical BTs appear somewhat colder during summer, probably caused by the cold surfaces of deep convective clouds in the Inter Tropical Convergence Zone (ITCZ).

Finally, these hovmöller plots reveal periods when data appear anomalous and their quality information should be consulted for filtering. Such periods are:

- NOAA-08: before October 1983
- NOAA-11: 1994-09-21 until 1994-10-20 (the end of the dataset)
- NOAA-14: end of 2001

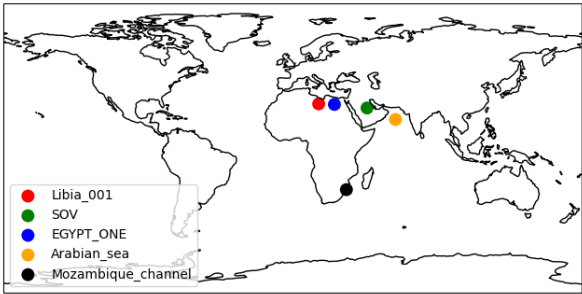
- NOAA-15: end of 2000
- NOAA-17: from 2010-09-30 until 2011-12-31 (the end of the dataset)
- Metop-C: starting around early 2021, a gradual increase in reflectance of channel 3a (see also Figure 32)

3.3 Radiance analysis at surface albedo validation sites

We extracted time series of PyGAC reflectance and brightness temperatures from an average of pixels surrounding five (sub-)tropical sites. These sites, which we selected from a network of surface albedo validation sites [RD 19] (SAVS 1.0)⁴, are considered to be temporally stable, spatially homogeneous, and relatively cloud free over time. Given these characteristics, we can analyse the small-scale, long-term behaviour and stability of PyGAC data, its seasonal variability, the effect of orbital drift, and how data of overlapping satellite missions compare to each other.

Table 3: List of specific locations used

Site name	Longitude	Latitude
Libia_0001	16.276	27.474
SOV	46.41	24.91
EGYPT_ONE	26.1	27.12
Arabian_sea	64.1,	17.75
Mozambique_channel	33.55	-25.9



For this analysis, we collected PyGAC observations around validation sites based on the following two criteria: 1) satellite zenith angle is lower than 45° and 2) distance between pixel geolocation and validation site is not larger than 10 km. The separation between day and night in the plots (Figure 12 and Figure 13) is based on channel 1 reflectance. If that is larger than 2%, we classify a pixel as daytime.

Monthly time series are shown in Figure 12, Figure 13, Figure 14, and in Appendix C. These show the following main features:

- For morning satellites, more recent satellite missions (NOAA-17 and Metops) show warmer daytime BTs and higher reflectance than all other morning missions. Those recent missions have about 2 hours later equator crossing times, resulting in increased daytime illumination and a warmer land surface. As expected, this effect is smaller to absent for the ocean sites (Mozambique channel and Arabian Sea) due to their larger thermal inertia and lower albedo.
- The above effect decreases for NOAA-15 when drifting into equator crossing times at even earlier morning hours.
- By the end of NOAA-17's lifetime (starting mid-2010), data appear corrupt and as outliers in the plots. This is also shown by Figure 9, Figure 57, and Figure 58.
- For afternoon satellites, the effects of orbital drift are much more pronounced for visible channels and land surface sites.

⁴ <http://savs.eumetsat.int>, doi:10.15770/EUM_SEC_CLM_1001

- Reflectance and brightness temperatures are in good agreement for overlapping satellite data as long as equator crossing times are similar. As an example, this is shown by the early overlap period between NOAA-18 and NOAA-19 (Figure 15). Once NOAA-18 starts drifting away from NOAA-19 into later equator crossing times (i.e. from 2011), these data, and in particular reflectance, begin to diverge. Short term deviations are likely to be caused by cloud contamination, leading in such cases to higher reflectance and colder brightness temperatures.

Overall, this analysis shows that the time series of the selected validation sites show plausible patterns. The effects of orbital drift, land surface, and seasonality are represented as expected. When differences between equator crossing times of overlapping satellite missions are comparably small, measurements are in good agreement. This indicates that the visible cross-calibration was successful.

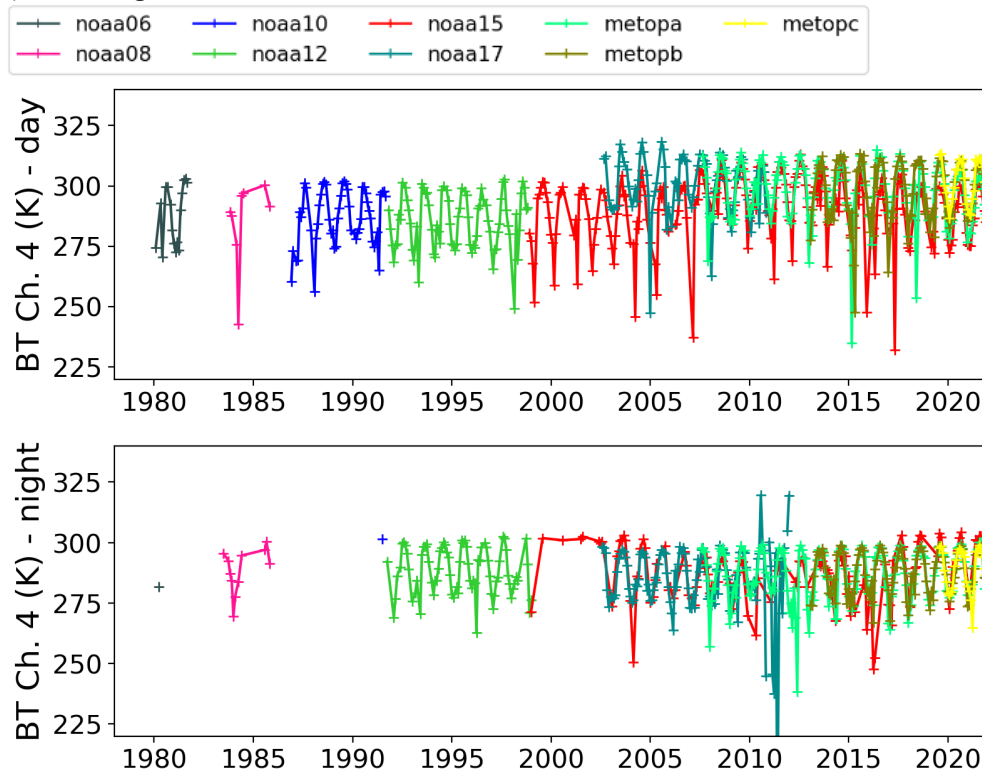
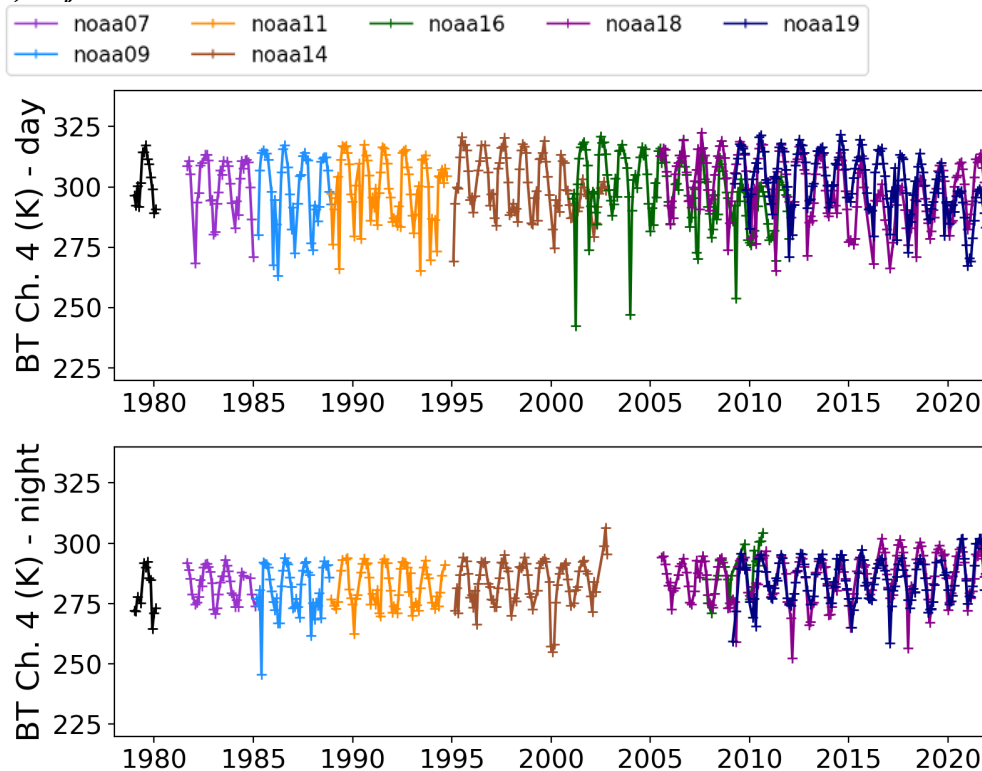
a) Morning satellites

b) Afternoon satellites


Figure 12: Monthly timeseries of AVHRR BT in IR channel 4 for day and night at site Egypt for all AVHRR instrument aboard the morning and afternoon satellites for daytime and night-time observations.

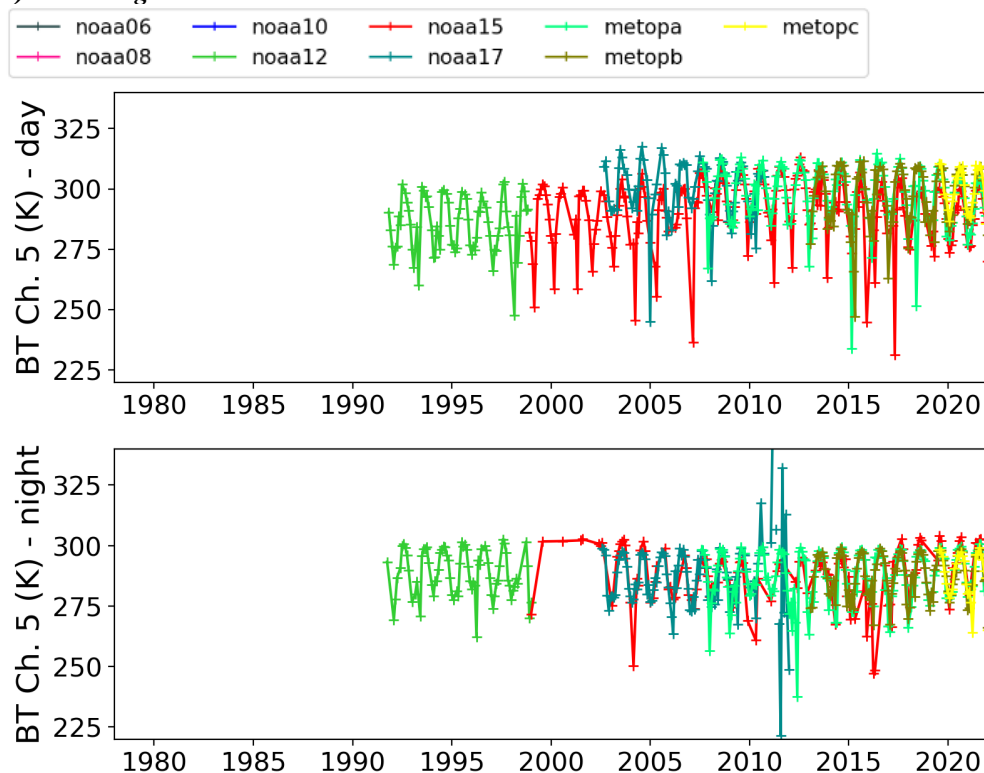
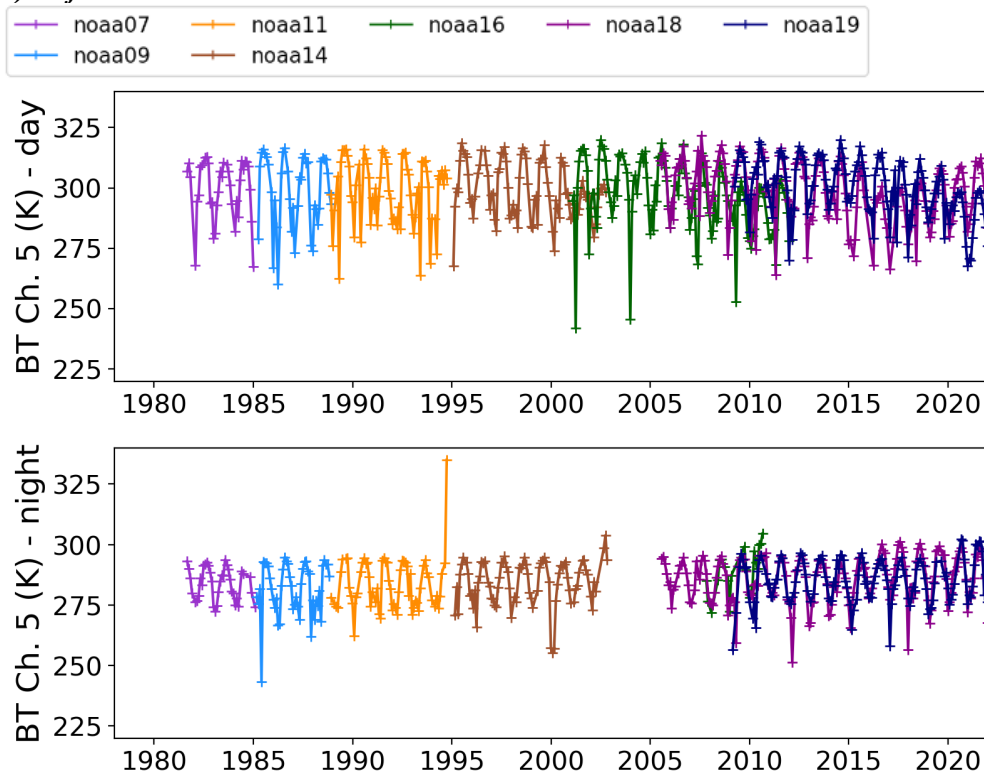
a) Morning satellites

b) Afternoon satellites


Figure 13: Monthly timeseries of AVHRR BT in IR channel 5 for day and night at site Egypt for all AVHRR instrument aboard the morning and afternoon satellites for daytime and night-time observations.

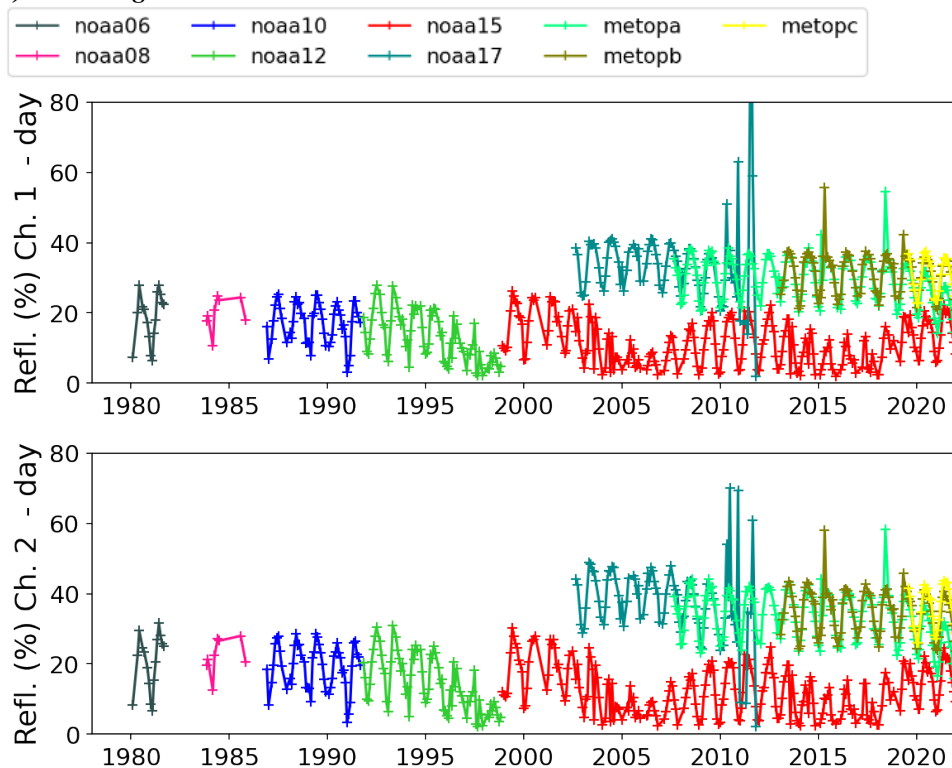
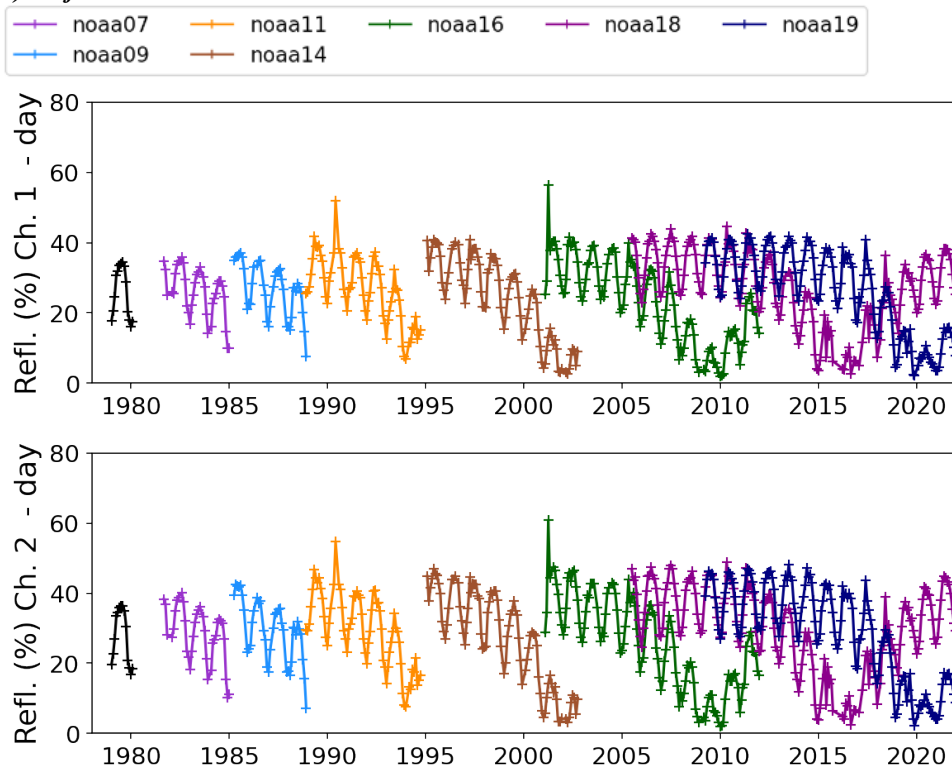
a) Morning satellites

b) Afternoon satellites


Figure 14: Monthly timeseries of AVHRR radiances for channel 1 and channel 2 for day time at site Egypt for all AVHRR instrument aboard the morning and afternoon satellites for daytime observations.

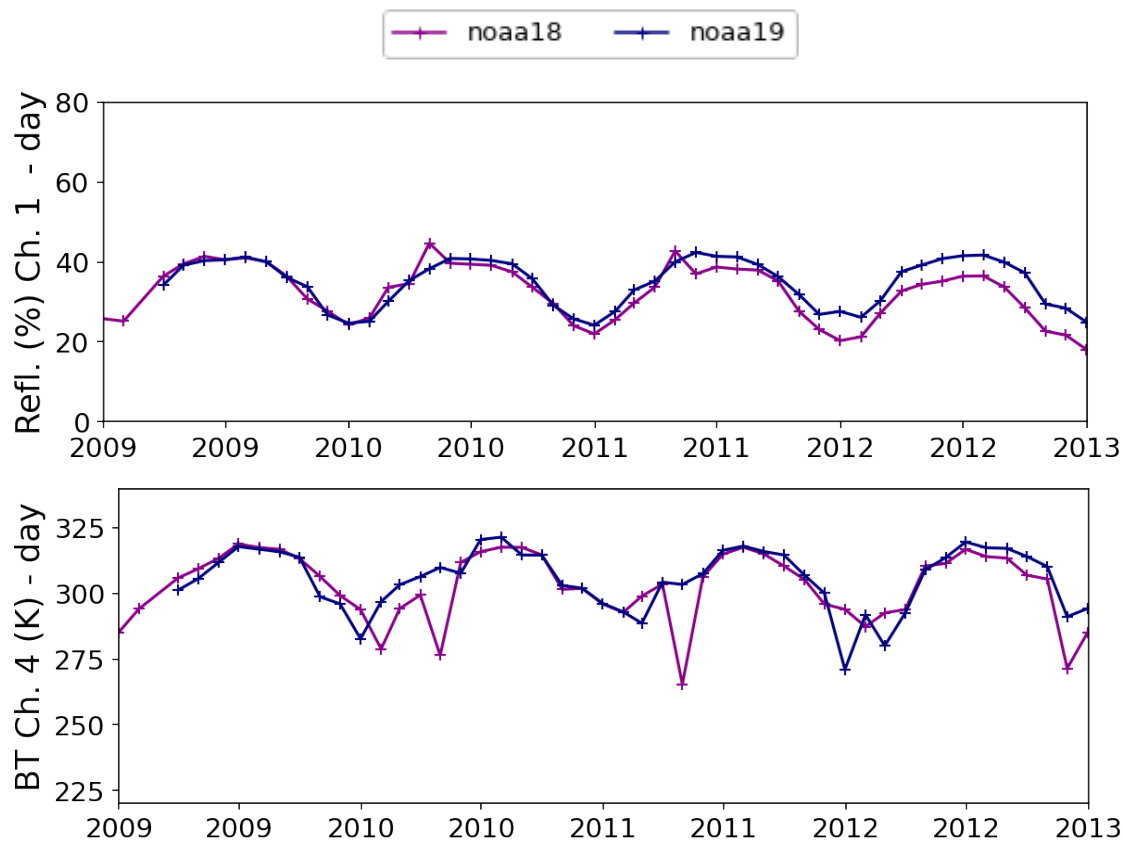


Figure 15: Monthly average daytime observations for channel 1 and 4 at the site EGYPT_ONE for the period 2009 until 2012 for NOAA-18 and NOAA-19 for daytime observations.

4 QUALITY EVALUATION

In this section, the PyGAC FDR is evaluated against other existing FDRs.

4.1 Comparison with PATMOS-x

The Pathfinder Atmospheres Extended (PATMOS-x) product is a unique, long-term, satellite-based dataset covering almost 40 years. It contains over 120 parameters including radiance, cloud, and surface products in HDF format. PATMOS-x evolved from CLAVR-x (Clouds from AVHRR Extended System), which was developed at NOAA/NESDIS and UW/CIMSS to generate quantitative cloud products in real-time from AVHRR. PATMOS-x consists of twice-daily fields of satellite measurements obtained by AVHRR/2 and AVHRR/3 sensors from 1981 onwards. The data can be accessed via this link: <http://cimss.ssec.wisc.edu/patmosx/>.

Both PATMOS-x and the PyGAC FDR share the same set of visible channel calibration coefficients. Accordingly, this analysis is based on the assumptions that data of both processing systems are similar, albeit not exactly identical. We expect small differences to arise due to differences in processing designs, algorithms, and software libraries and versions.

A direct comparison of PATMOS-x data with PyGAC however is complicated by the fact that the PATMOS-x FDR is a gridded level 2 product. Level 1 data in orbit resolution have been integrated in level 2 product files and are not readily available for download. Gridding our PyGAC FDR would probably introduce further differences due to deviations in methodology, and is generally beyond the scope of this validation report. Instead, we decided to evaluate differences between 27 randomly selected orbits (PATMOS-x orbits were provided by Mike Foster from University of Wisconsin - Madison) at full resolution. To do so, PyGAC reflectance need to be normalised by the cosine of the solar zenith angle to match PATMOS-X reflectance.

The comparison for those 27 orbits shows that:

- Brightness temperature channels 4 and 5 show a high degree of similarity. Both difference plots and histograms show little deviations throughout.
- Ch3b BTs are generally close, i.e. within ± 0.25 K difference. This channel contains both solar and thermal irradiance contributions. Data are only available for a small area on Antarctica, where channel 1 and 2 reflectance disagree most between PyGAC and PATMOS-x.
- Reflectance in channel 1 and 2 largely agree outside of polar regions, and in particular for channel 2. In channel 1, PyGAC reflectance are almost exclusively lower (but never by more than 1% reflectance), except for Antarctica. There, reflectance of both channels are considerably larger for PyGAC than PATMOS-X, but illumination conditions are approaching night-time. At such extreme solar zenith angles, differences between datasets due to numerical errors and solar angle normalisation are emphasised. The histogram differences in Figure 17 are all found for conditions when solar zenith angles are close to 90° .

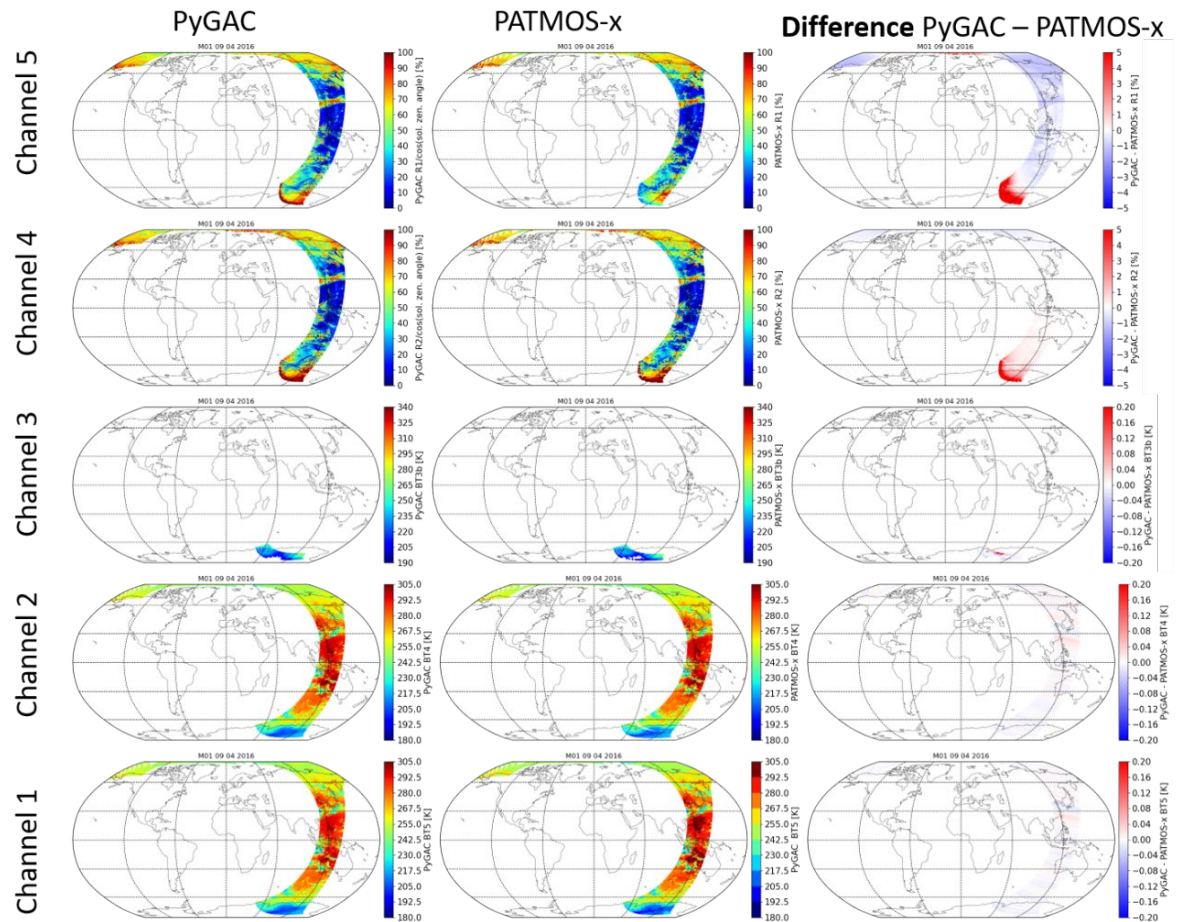


Figure 16: Example of the comparison for one orbit Metop-B, 9th April 2016, orbit starting at 00:56:40Z and finishing at 01:45:37Z

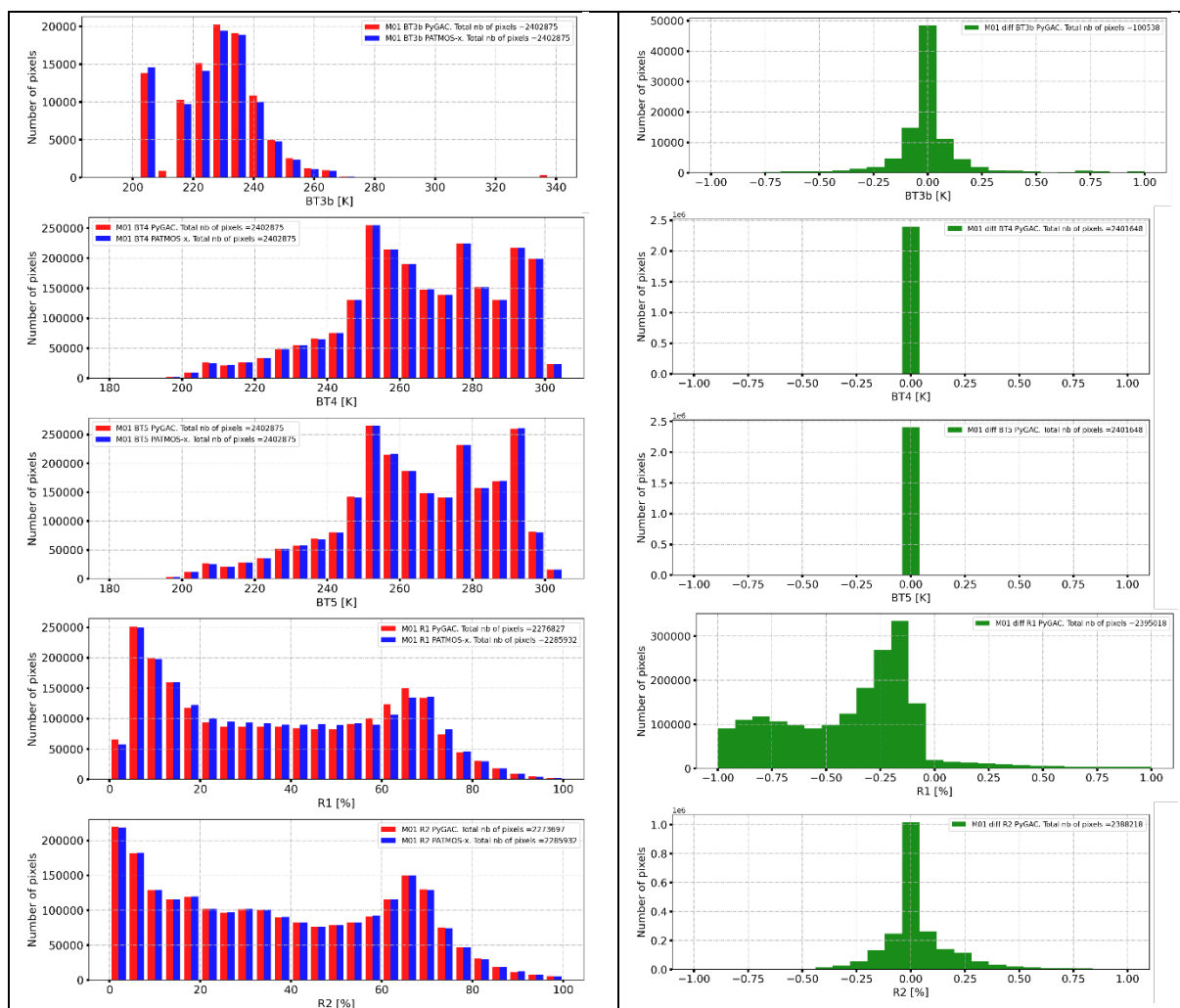


Figure 17: Histogram of the distribution of the number of pixels for PyGAC and PATMOS-x Metop-B orbit of the 9th April 2016, orbit starting at 00:56:40Z and finishing at 01:45:37Z. The right column is the distribution of the difference PyGAC – PATMOS-x.

4.2 Comparison with FIDUCEO

Even though the AVHRR sensor family flew aboard NOAA and Metop satellites since 1978, these sensors were not originally designed to provide climate-quality observations (i.e. satisfying requirements such as harmonization and uncertainty quantification at the pixel level). Therefore, deriving a harmonised FCDR and quantifying the uncertainties therein pose enormous challenges. The EU project FIDUCEO⁵ (FIDelity and Uncertainty in Climate data records from Earth Observations) brought and applied the principles of metrology to Earth observation data. The intention was to establish traceable, uncertainty-quantified, and harmonised FCDRs based on, among others, the AVHRR/GAC thermal channels brightness temperature data. To produce a harmonised FCDR from a series of AVHRR sensors, the sensor measurement models were recalibrated simultaneously while respecting mutual spectral response differences. Although FIDUCEO harmonisation at a first glance resembles standard

⁵ <https://research.reading.ac.uk/fiduceo/> valid on the 21 November 2022

sensor bias correction and cross-calibration methodologies, it implements a higher level of metrological rigour and traceability (RD 6; RD 14; RD 21).

Since the FIDUCEO AVHRR FCDR was one of the candidates considered for the development of the CM-SAF CLOUD, Albedo and Radiation dataset from AVHRR (CLARA-A3), the CM-SAF project offered to carefully evaluate the FIDUCEO AVHRR GAC FCDR and compare it with the EUMETSAT PyGAC FDR, even though it was later decided not to use the FIDUCEO FCDR. The evaluation of brightness temperatures as well as their impact on cloud detection were studied. Some of the main conclusions that came out of this evaluation exercise were:

- The FIDUCEO project showed tremendous promise and laid a robust foundation to derive a harmonised FCDR with associated uncertainty information. While the newer, KLM series of satellites could be constrained and harmonised properly, the older, POD family of satellites (especially NOAA-9 and NOAA-11) proved to be difficult to harmonise within the FIDUCEO framework, mainly due to the lack of representative match-ups with a suitable reference instrument.
- The most concerning feature in the FIDUCEO FCDR are the inter-satellite jumps in the BT difference between channel 4 and channel 5 as show below in Figure 18. This feature is of utmost importance for the detection of thin high clouds by the CM-SAF/PPS retrieval framework. The PyGAC/EUMETSAT FDR shows much better stability regarding this feature.
- Achieving harmonisation while maintaining both natural trends and trends caused by the orbital drift of NOAA satellites is proving very difficult. This was clearly visible in the time series of channel 3b BTs. While the PyGAC/EUMETSAT FDR shows the orbital drift signal in the channel 3b BTs (as it should), the harmonisation process in FIDUCEO seems to be artificially suppressing such a trend.

Based on these evaluations together with other important limitations of FIDUCEO FCDR (e.g. shorter time period, delayed release, etc.), it was deemed that the PyGAC/EUMETSAT FDR described in this report is the better data record despite not being an FCDR.

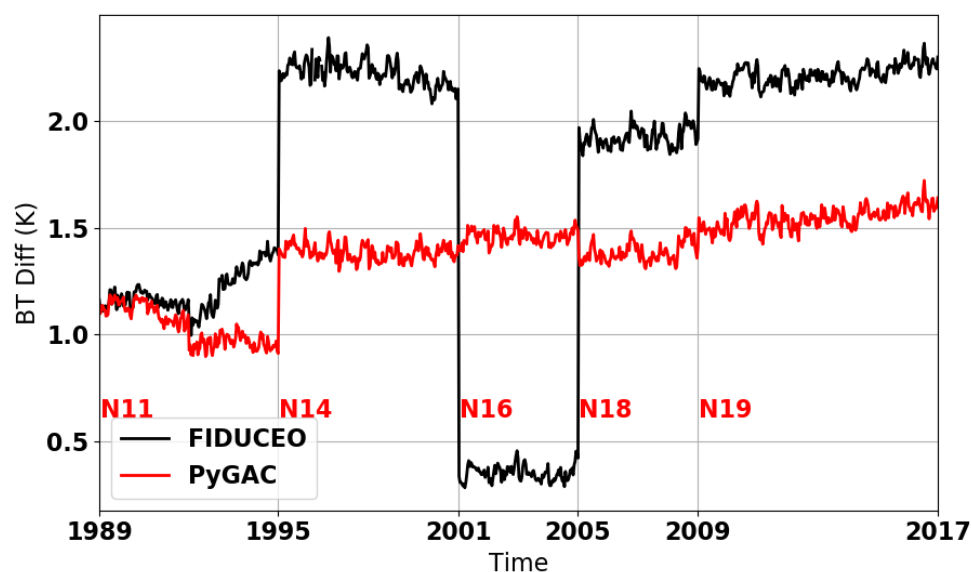


Figure 18: Daily global mean BT difference between channel 4 and channel 5 for the month of July in the case of afternoon satellites.

4.3 Comparison with HIRS

AVHRR brightness temperatures in channel 4 at 11 μm (AVHRR/1) and 10.8 μm (AVHRR/2-3) are compared to High-resolution Infrared Radiation Sounder (HIRS) brightness temperatures in channel 8 at 11.11 μm . For this comparison, the new HIRS data record as reprocessed at EUMETSAT is used ([10.15770/EUM_SEC_CLM_0026](https://doi.org/10.15770/EUM_SEC_CLM_0026)). The sensors have different spatial resolutions, with 5 km at nadir for AVHRR and 20 km at nadir for HIRS (10 km for HIRS/4), and different spectral response functions, which are slightly broader for the AVHRR channel.

4.3.1 Methodology

This comparison is based on collocations, for which differences between pixel pairs in space and time are minimised. As both sensors operate on the same platform with the exception of Metop-C, which only carried AVHRR, collocations are not limited to high latitudes but are distributed globally. Hence, they represent the complete observable temperature range. However, the duration of measurement campaigns is not guaranteed to be identical for AVHRR and HIRS instruments mounted on the very same satellite platform. One of these two sensors might stop operation, but collocations might still be possible with data from a separate, simultaneously operating satellite platform. That way, the length of periods without collocations is minimised by building collocations for all possible combinations between AVHRR and HIRS. All of the following results contain data both from same-platform and between-platform collocations.

Collocations are defined as two pixel measurements which are within 10 km and 5 minutes. Further, satellite zenith angles must meet the constraints defined by equation 1:

$$\text{abs}\left(\frac{\cos SZ_{Ax}}{\cos SZ_{Ay}} - 1\right) < 0.05 \text{ where } x \text{ and } y \text{ stands for the 2 sensors} \quad (1)$$

A further quality screening is performed by excluding all collocations whose 3x3 pixel average surrounding the collocated geolocation exceeds a threshold close to sensor accuracy. This threshold is set to 0.5 K for HIRS and to 0.75 K for AVHRR. The latter test avoids the comparison of inhomogeneous scenes, which can cause large differences due to the different spatial resolutions of AVHRR and HIRS. For the following analysis, collocations are averaged to monthly means per AVHRR sensor.

4.3.2 Results

Figure 19 shows the time series of the bias (AVHRR - HIRS) in the upper panel, the standard deviation over a month in the middle panel, and the number of collocations used for a monthly mean in the lower panel. With the exception of TIROS-N, all sensors show absolute biases of less than 0.5 K with a standard deviation of mostly less than 0.7 K. For most sensors the standard deviation is even below or about 0.5 K. TIROS-N shows a bias of -0.7 to -1 K and a standard deviation of 0.8 K to 1 K.

The bias increase for NOAA-15 in 2001 is most likely caused by quality issues in the HIRS data. Also, the increasing standard deviation of Metop-A after 2016 could be related to increasing noise in the HIRS data.

NOAA-7 and NOAA-9 show a negative trend in the bias with increasing standard deviation, while NOAA-8 shows a positive trend in the bias. Except TIROS-N, NOAA-6, and NOAA-12, all sensors show biases around 0 K or slightly above (NOAA-17 onwards). Besides NOAA-18, showing a reduced bias from 2012 to 2018, all sensors from NOAA-17 onwards show a similar bias. The number of data points is stable throughout the entire time series at around 1 million collocations per month.

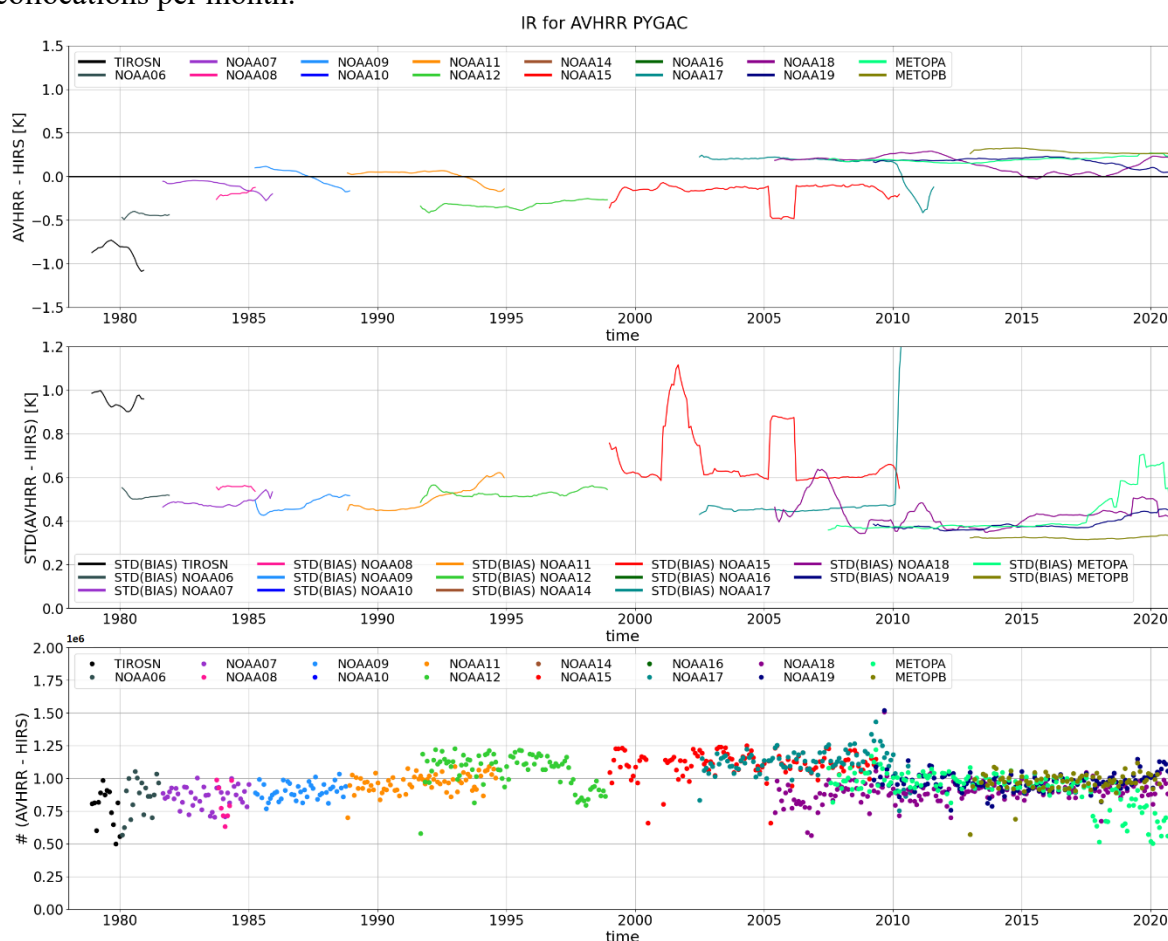


Figure 19: Time series of the monthly mean brightness temperature difference HIRS's channel 8 minus AVHRR's channel 4, the standard deviation and the number of data points per month. The platform refers to the AVHRR platform.

Figure 20 shows the collocations of each AVHRR sensor to all available HIRS sensors as a histogram divided by the number of collocations. All histograms, except TIROS-N, show a Gaussian like distribution. TIROS-N shows a local maximum at about -1.5 K.

For most sensors, the maximum is around 0 K and the half maximum full width is mostly around 1.5 K. This shows that the comparison is not biased by cloud contamination, when clouds are observed by only one instrument. Furthermore, it supports the results from Figure 19, showing low bias and low standard deviations.

In summary, the comparison shows a good quality of the AVHRR data record in terms of stability. Considering that neither spatial resolution nor the spectral response functions of HIRS and AVHRR are identical, both sensors agree quite well. Especially NOAA-15 and newer sensors show over their long time series almost no trend. Weak trends are found mainly for earlier sensors, which cannot be attributed to AVHRR directly based on this comparison.

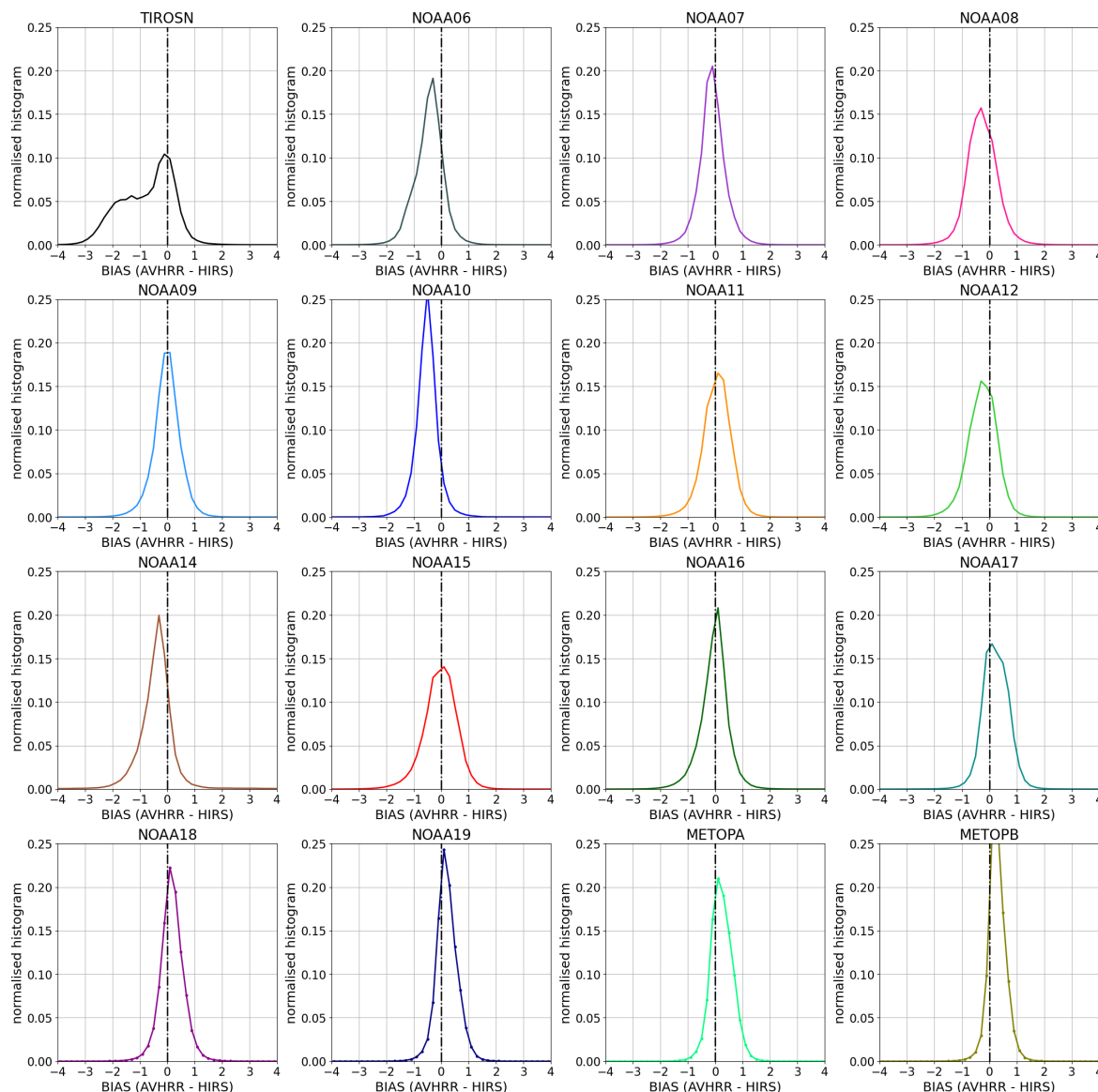


Figure 20: Histogram of the bias of the monthly mean difference HIRS' channel 8 minus AVHRR's channel 4 (K). The platform refers to the AVHRR platform.

4.4 Evaluation against radiative transfer calculation

This comparison generates time-series of differences with other state-of-the-art multivariate climate products, such as global climate reanalyses. While the distance between AVHRR reprocessed radiances and a reanalysis does not inform, by itself, about each product's intrinsic quality and limitations, any sudden change in this distance informs about a potential issue in either product. These results complement other comparison approaches, and their combination

can help disentangle between the sources of discrepancies. This approach introduces a restriction to the range of validity of the radiative transfer operator, i.e. only clear-sky atmosphere.

4.4.1 Methodology

The ERA5 reanalysis [RD 3] provides spatio-temporally complete and multivariate data that cover the spatial and temporal extent of AVHRR operations. AVHRR radiances were not assimilated in ERA5. However, one must note that:

1. ERA5 is forced by Sea-Surface Temperature (SST) products, some of which have used AVHRR radiances. The ERA5 input for SST in the satellite era are [RD 3]:
 - a. HadISST2.1.1.0 until August 2007, which uses ARC-ATSR Reprocessing for Climate (until 2010) and SST-CCI AVHRR (only for years 1991-2010);
 - b. OSTIA⁶ operational SST from September 2007.

Both inputs above use AVHRR radiances from 1991 until 2007 for the SST-CCI product [RD 4] and from 2007 onwards for the OSTIA SST operational product [RD 5], with the caveat that AVHRR radiances were homogenised or bias-corrected a priori, to match a reference sensor (ATSR-2 and AATRS when available, and VIIRS in recent times) as well as in situ reference observations (including buoys). This process has hence removed some of the low-frequency variability uncertainty in AVHRR data, by imposing the low-frequency variability of reference observations.

2. ERA5 assimilated atmospheric motion vector retrievals that were generated from cloud tracking of consecutive AVHRR images over the polar regions. These observations will have affected to some extent the temperature and humidity in ERA5, via the general circulation.

Consequently, one may consider AVHRR radiances as reprocessed here largely independent from ERA5, more particularly for the low-frequency SST. If one were to focus on small regions and higher-resolution, one should however expect to find an imprint of the AVHRR information content in the ERA5 SST (and possibly upper-air circulation).

Using the NWP-SAF radiance simulator [RD 7], the atmospheric and surface representation provided by ERA5 at the time and location of the AVHRR data is projected into the space of AVHRR observations for the VIS, NIR, and TIR channels. This then allows comparing reprocessed AVHRR channel data with these simulations. However, the two datasets are not entirely independent, because of the partial assimilation of information from AVHRR data, noted in the previous paragraph.

Radiative transfer simulations are only carried out for observations that fall within a ‘reasonable’ time difference with respect to the reanalysis fields’ validity times. The choice of this time difference takes into account the reanalysis time resolution. In the present case, this maximum time difference is 15 minutes, noting the ERA5 products’ temporal resolution is 1 hour.

The horizontal resolution of AVHRR far exceeds the ERA5 reanalysis horizontal resolution, which is approximately 30 km for the atmospheric numerical model, and 80 km for the analysed

⁶ <https://ghrsst-pp.metoffice.gov.uk/ostia-website/> valid as of April 2022

products. This means AVHRR data contain more horizontal variability than the reanalysis one compares it with. This offers in principle the ability to compare low-resolution reanalysis radiative transfer estimates with many nearby AVHRR pixels, at the cost of running (computationally expensive) radiative transfer simulations that generate very similar results for all neighbouring pixels. For this reason, and in order to select the better comparison combination in each case, the AVHRR data are thinned in the horizontal domain, by selecting the pixel that is closest in distance to the centre of an equal-area grid with separation angle of 0.5 degrees (this amounts to a resolution of 65 km along a great circle).

Given the dependence of atmospheric absorption with the satellite zenith angle (e.g., the absorption is greater for slanted atmospheric paths at the edge of scans than at nadir), this thinning operation bins together 2 observations only if the difference between the two corresponding satellite zenith angles θ_1 and θ_2 obeys the following inequality [RD 8]:

$$\left| \frac{\cos \theta_1}{\cos \theta_2} - 1 \right| < 0.01(2)$$

This separation yields a rather narrow beam of comparable values, and avoids comparing observations with simulations that would inherently differ because of the viewing geometry.

For the NIR and TIR channels (channels 3, 3B, 4, and 5 in Table 2), the AVHRR brightness temperatures are simulated assuming clear-sky. For the NIR channel (numbered 3 or 3B in Table 2), an additional filtering is applied to remove scenes possibly contaminated by solar radiation. For this channel, only scenes with a solar elevation angle inferior to -10 degrees are retained, effectively removing sunlit and dawn/dusk areas.

For the VIS channels (channels 1, 2, and 3A in Table 2), the AVHRR reflectance are simulated assuming clear-sky, using the RTTOV v13 atlas for the Bidirectional Reflectance Distribution Function (BRDF) and solar radiation. For these channels, only scenes with a solar zenith angle inferior to 80 degrees are retained, effectively removing night-time and dawn/dusk areas.

The radiative transfer coefficients are 54-level, RTTOV v13 predictors [RD 9], with variable ozone and carbon dioxide. Vertical profiles of temperature, humidity, and ozone are interpolated to the AVHRR location by the radiance simulator. For the carbon dioxide concentration, the information that is provided in input to the simulator is not location-dependent (in the horizontal and the vertical). Instead, the reference vertical profile of carbon dioxide used in the RTTOV coefficients calculations is rescaled before calling RTTOV, so that the maximum value in the carbon dioxide profile concentration matches the concentration observed in a given month by the NOAA Mauna Loa observatory [RD 10]. Other trace gases such as methane are assumed constant throughout the time period. The surface emissivity is simulated using an emissivity atlas [RD 18].

Regarding quality controls, scenes returned with non-nominal flags by the radiative transfer simulator are also rejected. On the AVHRR side, pixels are excluded from the comparison if they fail any of the following criteria:

- “*global_quality_flag*” differs from 0 (at the file level),
- “*qual_flags*”: bit number 2 or above is set (at the scanline level),
- “*scanline*” is before “*overlap_free_start*” or after “*overlap_free_end*”.

4.4.2 Results for the Infra-Red Channels

For the NIR and TIR channels, the differences are calculated in the form of observation minus radiative transfer calculations, in brightness temperature space (K). Differences are aggregated every month, in bins of 0.1 K. This allows to plot histograms of distribution on a monthly basis, shown in Figure 21, Figure 22, and Figure 23.

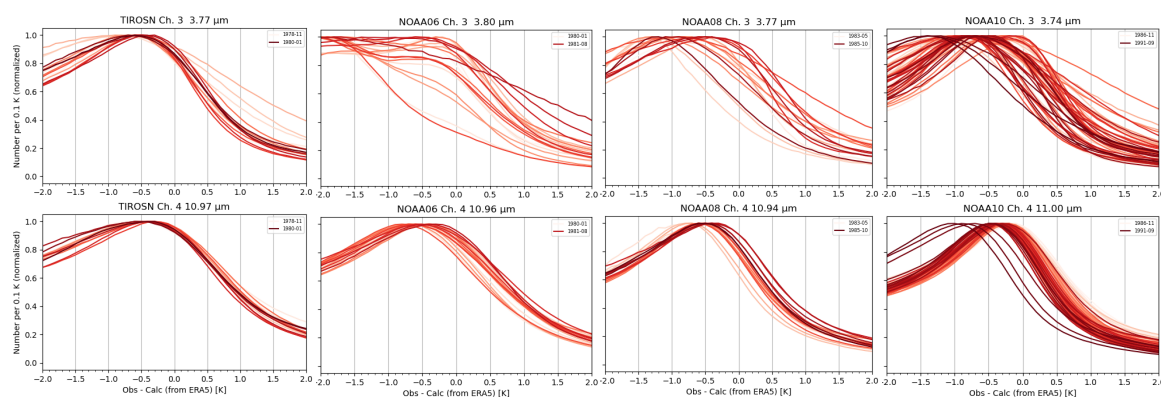


Figure 21: Monthly histograms of departures (in K), between AVHRR FDR brightness temperatures and ERA5 clear-sky radiative transfer simulations, for AVHRR/1 instruments on satellites TIROS-N, NOAA-6, NOAA-8, and NOAA-10 (from left to right). Top row shows results for the short-wave IR channel (channel 3), bottom row shows results for the IR window channel near 10.8 microns (channel 4). In each panel, colours range from light red for the first available month of data to dark red for the last available month of data (see legend).

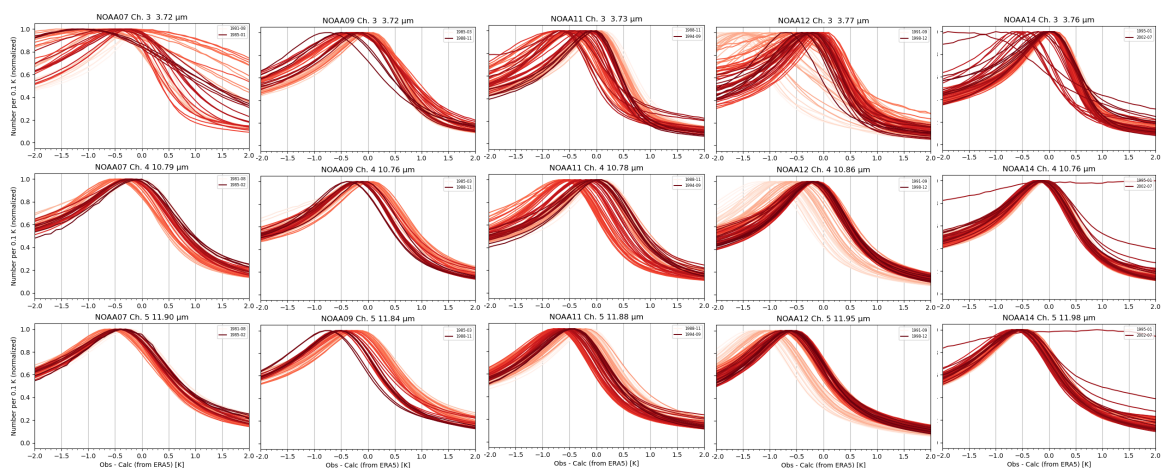


Figure 22: Similar to the previous figure, but with the addition in the third row of results for the long-wave IR channel near 12 microns (channel 5), for AVHRR/2 instruments on satellites NOAA-7, -9, -11, -12, and -14.

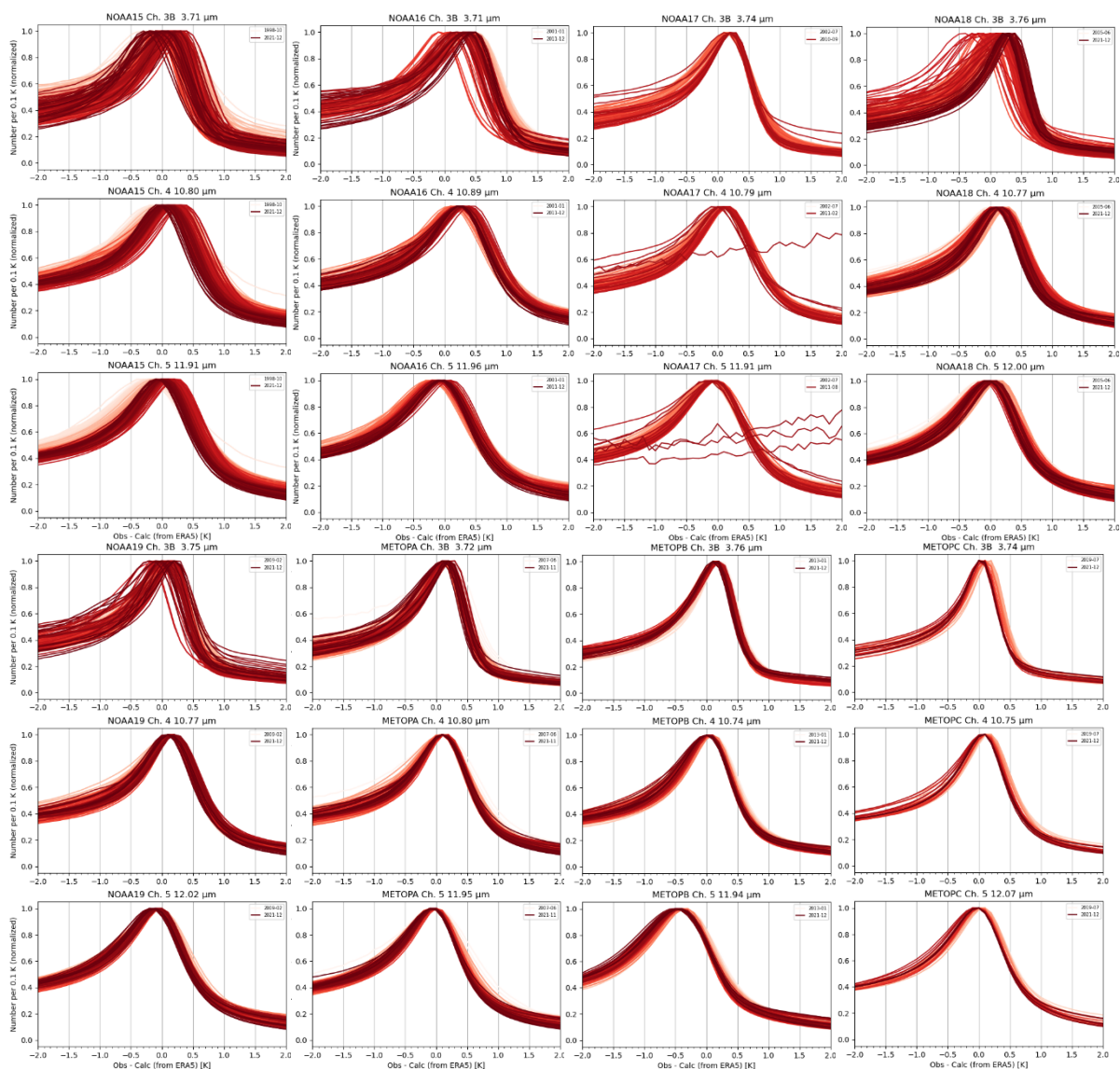


Figure 23: Similar to the previous figure, but for AVHRR/3 instruments aboard NOAA satellites-15 to -19, and satellites Metop-A to -C.

These histograms are all single-peaked except for a few problematic months when a flat or very wide distribution casts doubt on the information contained in the data, such as:

- NOAA-14, November 2001
- NOAA-17, February 2011

Please note that NOAA-17 data appear to be corrupt throughout all channels from ~October 2010 onwards. This is also clearly visible in the Hovmöller plot for that satellite (Figure 58). Data from this period have not been removed for this analysis, and will show up as anomalies in all plots.

The distributions appear to be asymmetric, with negative bins being more populated than positive ones. This is most likely caused by thin clouds (opaque clouds yield large negative departures), which are not simulated here (clear-sky simulations).

These distributions appear to become more Gaussian as the earlier satellites are considered, as compared to the more recent satellites. This is reminiscent of the central limit theorem, whereby

a superposition of distributions, regardless of their shape, will tend to make a resulting error distribution approach a Gaussian distribution. One possible explanation would be that the errors captured by these differences would be of more multiple sources for earlier satellites than for more recent satellites. One obvious source of error in all computations is the reanalysis used as input to the radiative transfer computations, known to have improved over time. For the errors to become gradually less Gaussian over time, the disappearing source of error must not have been solely in temperature space, but probably in another (possibly less linear) space such as emissivity. This points to possible errors in the surface (e.g. sea-ice) in the early years, corrected in later years. Improvements in the quality of the radiometers is another factor to consider.

Another information from these graphs is the gradual narrowing of the peak widths, from earlier satellites to more recent satellites. The improvement in the quality of the reanalysis and/or the radiometers are possible explanations, in particular the quality of the ERA5 surface temperatures and the noise performance of the radiometer (with generally-better controlled thermal environments on more recent satellites).

The following information is extracted from each monthly histogram (per satellite and channel):

- location of peak of the distribution (or mode),
- right- and left-hand-side locations of the 88% peak: the difference between these two quantities is the Full Width at 88% Maximum (noted FW88M), and
- right- and left-hand-side locations of the 60% peak: half of the difference between these two quantities is the Half Width at 60% Maximum (noted HW60M).

For a normal distribution, FW88M and HW60M are approximately equal to the standard deviation. The ratio between FW88M and HW60M is indicative of the departure of the distributions from the Gaussian distribution. If the distributions were Gaussian, this ratio would equal approximately unity (1). Instead, one observes the values lower than 1.0 in Table 4.

Table 4: Mean ratio of (FW88M/HW60M), per satellite and channel.

Satellite	Channel 3 (or 3B)	Channel 4
TIROS-N	0.79	0.76
NOAA-6	0.85	0.76
NOAA-7	0.76	0.72
NOAA-8	0.80	0.75
NOAA-9	0.75	0.71
NOAA-10	0.81	0.74
NOAA-11	0.68	0.73
NOAA-12	0.62	0.73
NOAA-14	0.70	0.72
NOAA-15	0.67	0.73
NOAA-16	0.69	0.71
NOAA-17	0.64	0.69
NOAA-18	0.62	0.69
NOAA-19	0.61	0.69
METOP-A	0.65	0.70
METOP-B	0.65	0.72
METOP-C	0.60	0.64

As this ratio (generally) decreases, the underlying distribution becomes (generally) sharper than a Gaussian distribution, confirming the analysis of Figure 21 to Figure 23.

The time series of mode and FW88M, HW60M are shown in Figure 24, Figure 25, and Figure 26. The effects of the El Chichon and Pinatubo volcanic eruptions are visible in 1982 and 1991 (respectively), with deviations edging towards negative values for a few months for channels 3 (or 3B), 4, and also 5 (albeit to a lesser extent). The recovery seems to be faster after El Chichon than after Pinatubo for channels 3 (or 3B) and 4. The results also confirm the bad performance of comparisons for a few odd months as noted earlier (from flat distributions).

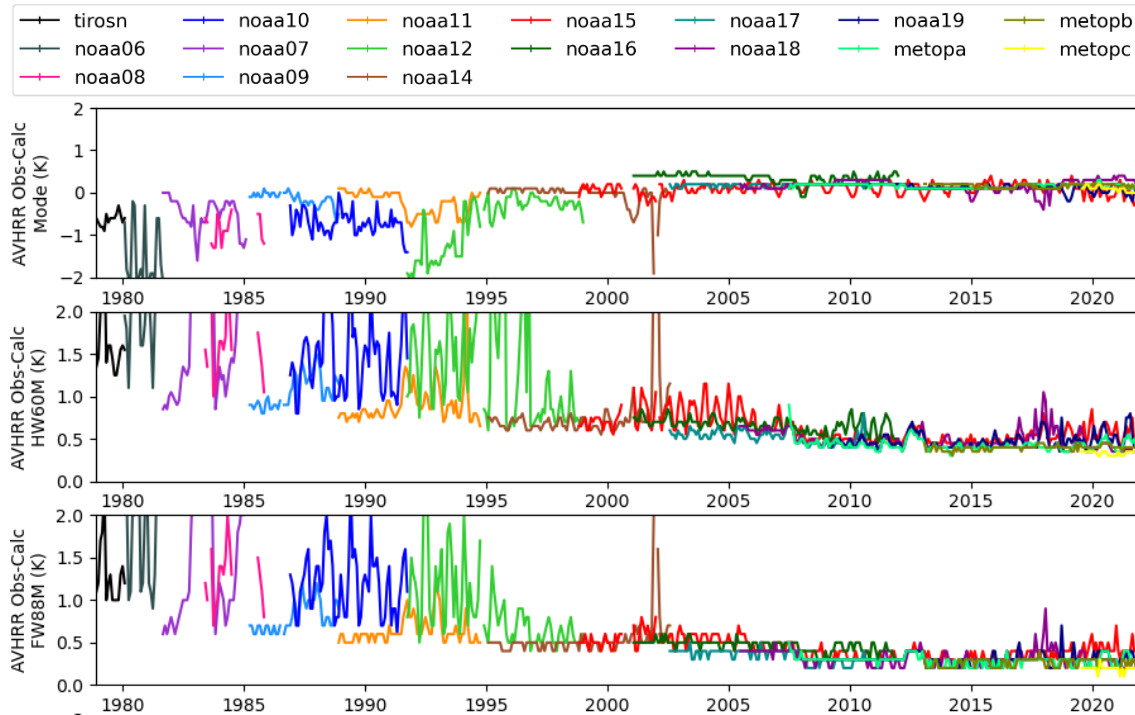


Figure 24: Time series of the monthly mode of departures between AVHRR channel 3 (or 3B) brightness temperatures minus clear-sky radiative transfer calculations using ERA5 (top row). Middle (bottom) row shows the monthly HW60M (FW88M, respectively) of the departures. The colours show the various satellites (see legend at the top).

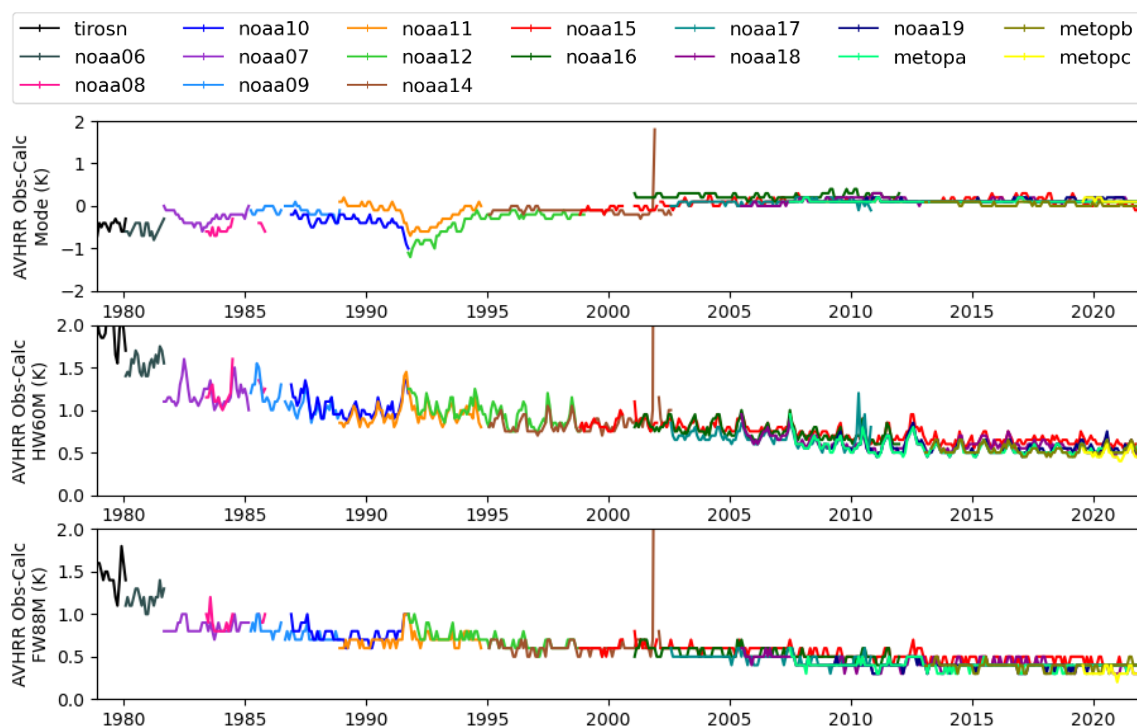


Figure 25: Similar to the previous figure, but for channel 4.

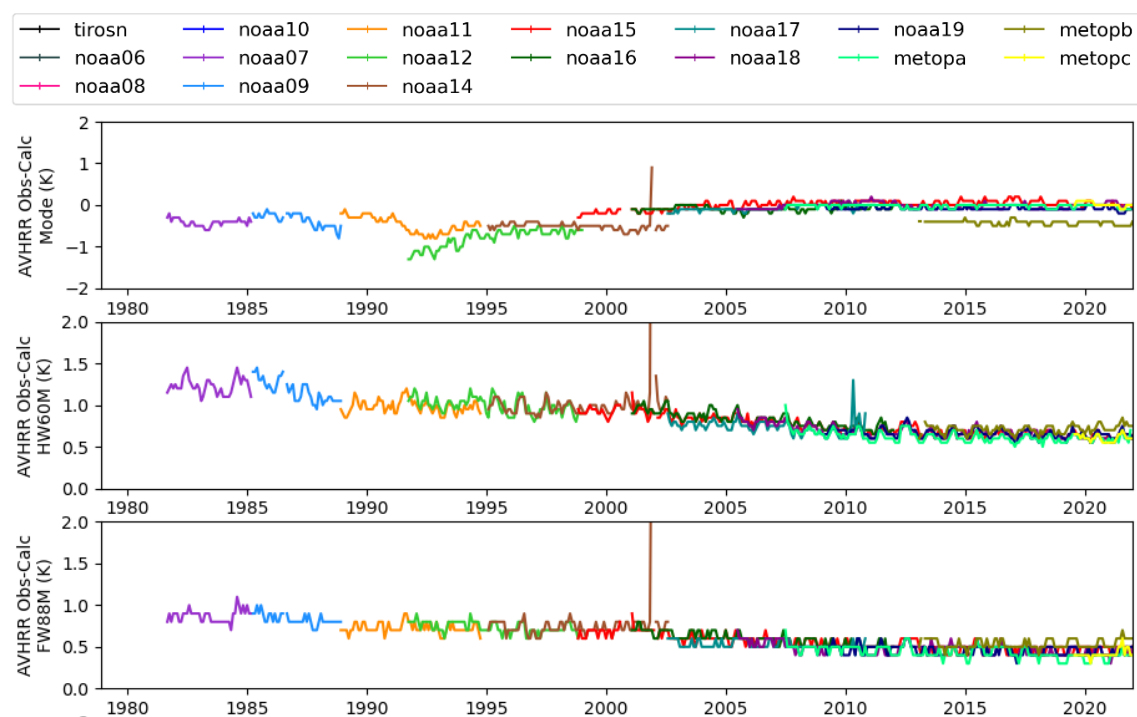


Figure 26: Similar to the previous figure, but for channel 5.

The modes of departures generally increase over time and get closer to zero. For the NIR channel (3 or 3B), the mode of departures is generally between -2 K and 0.5 K. For the first TIR channel (10.8 microns, channel 4), the mode of departures is generally between -1 K and 0.4 K. For the second TIR channel (12 microns, only on AVHRR/2 and /3, channel 5), the mode of departures is generally between -1.2 K and 0.2 K. However, one notes that Metop-B

channel 5 differences stand out relative to other post-2000 satellites but is comparable to differences in the earlier satellites. This is confirmed by the mean mode of monthly departures in Table 5.

Table 5: Mean mode of departures (observation minus simulations), in K, per satellite and channel.

Satellite	Channel 3 (or 3B) (in K)	Channel 4 (in K)	Channel 5 (in K)
TIROS-N	-0.6	-0.5	N/A
NOAA-6	-1.5	-0.6	N/A
NOAA-7	-0.5	-0.3	-0.4
NOAA-8	-0.9	-0.6	N/A
NOAA-9	-0.2	-0.1	-0.4
NOAA-10	-0.7	-0.4	N/A
NOAA-11	-0.2	-0.2	-0.5
NOAA-12	-0.7	-0.4	-0.8
NOAA-14	0.0	-0.1	-0.5
NOAA-15	0.1	0.1	0.0
NOAA-16	0.3	0.2	-0.1
NOAA-17	0.2	0.2	0.1
NOAA-18	0.2	0.1	0.0
NOAA-19	0.1	0.1	-0.1
METOP-A	0.2	0.1	0.0
METOP-B	0.2	0.0	-0.4
METOP-C	0.1	0.2	0.1

4.4.3 Results for the Visible Channels

For the VIS channels, the differences are calculated in the form of observation minus radiative transfer calculations, in reflectance space (%). Differences are aggregated every month, in bins of 0.1 %. This allows to plot histograms of distribution on a monthly basis, shown in Figure 27, Figure 28, and Figure 29.

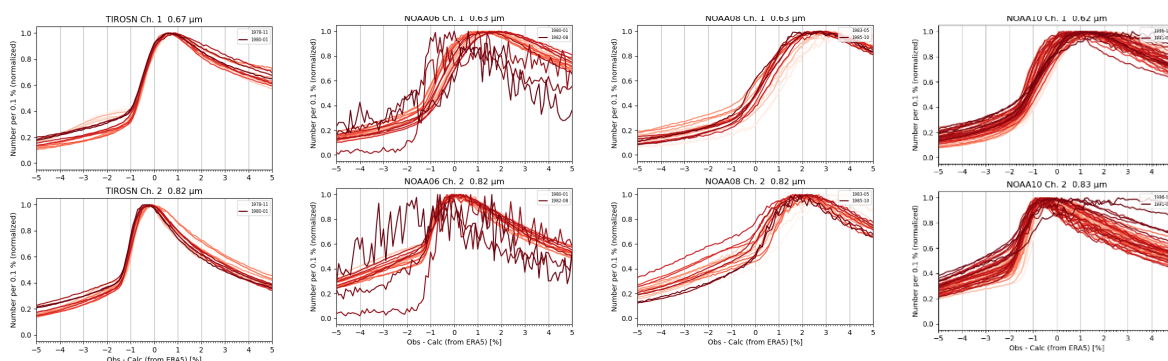


Figure 27: Monthly histograms of departures between AVHRR FDR reflectance percentage and ERA5 clear-sky radiative transfer simulations, for AVHRR/1 instruments on satellites TIROS-N, NOAA-6, NOAA-8, and NOAA-10 (from left to right). Top row shows results for the channel 1, bottom row shows results for channel 2. In each panel, colors range from light red for the first available month of data to dark red for the last available month of data (see legend).

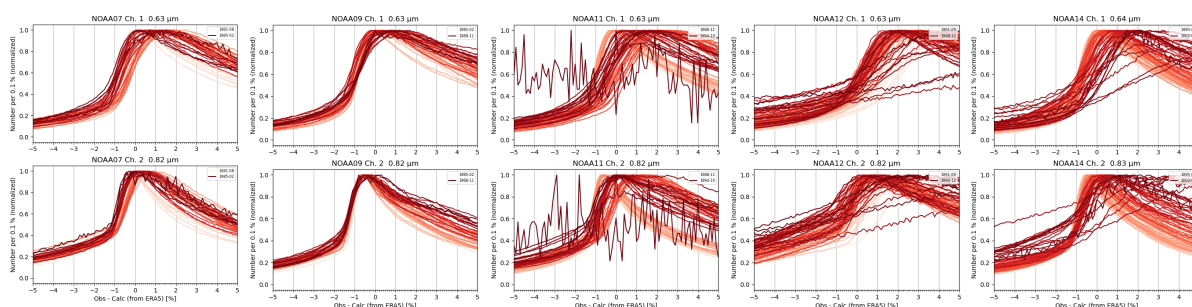


Figure 28: Similar to the previous figure, but for AVHRR/2 instruments on satellites NOAA-7, -9, -11, -12, and -14.

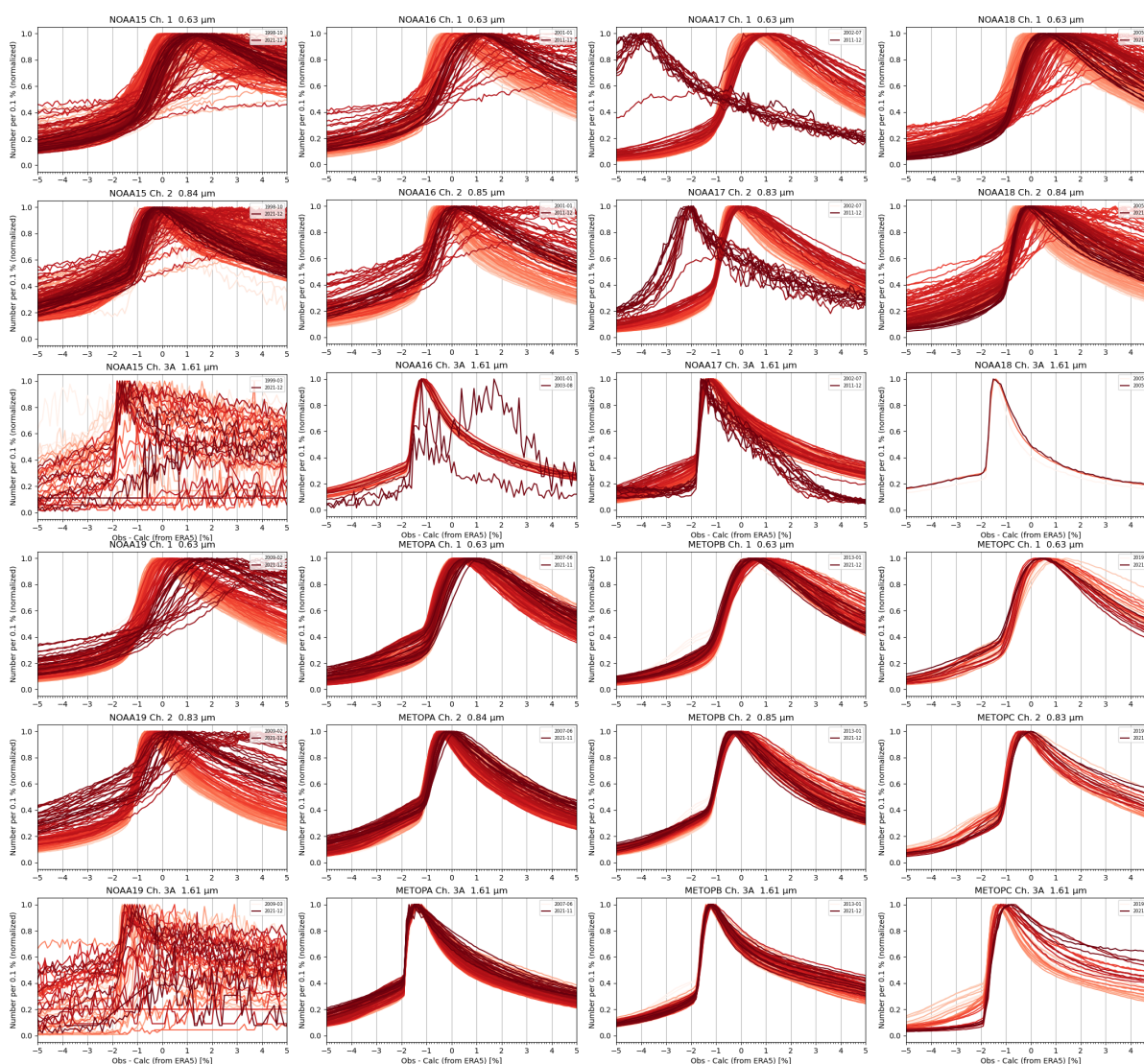


Figure 29: Similar to the previous figure, but with the addition of channel 3A (bottom row), for AVHRR/3 instruments aboard NOAA satellites-15 to -19, and satellites Metop-A to -C.

These histograms are all single-peaked except for problematic months when flat or very wide distributions cast doubt on the information contained in the data. This affects all satellites except Metop-A, -B, and -C, especially as the instruments age. The channel 3a time series for

NOAA-15 and -19 are too short (possibly only covering Alaska in North Hemisphere (NH) summer) to be statistically representative, inducing very noisy plots in Figure 29.

The distributions are sharply asymmetric, with positive bins being more populated than negative ones. This is most likely caused by clouds, which are not simulated here (clear-sky simulations).

Similar to brightness temperatures, another information from these graphs is the gradual narrowing of the peak widths, from earlier satellites to more recent satellites. The timeseries of mode and FW88M, HW60M are shown in Figure 30, Figure 31, and Figure 32.

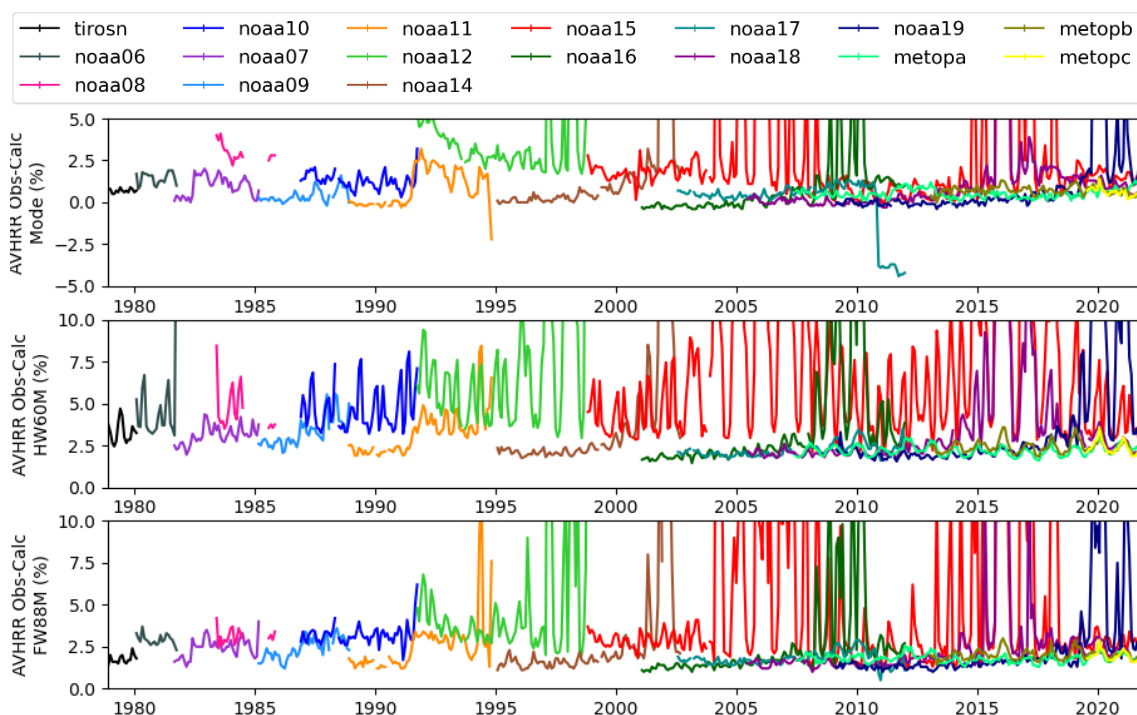


Figure 30: Time series of the monthly mode of departures between AVHRR channel 1 reflectance percentage minus clear-sky radiative transfer calculations using ERA5 (top row). Middle (bottom) row shows the monthly HW60M (FW88M, respectively) of the departures. The colours show the various satellites (see legend at the top)

The effects of the El Chichon and Pinatubo volcanic eruptions are visible again in 1982 and 1991 (respectively), with deviations increasing for a few months especially for channel 2. The modes of departures generally increase slightly over time for channels 1 and 2, with fewer inter-satellite differences for the most recent ones.

On Figure 30, we also notice a large seasonal departure from some of the newer NOAA satellites, especially NOAA-15 being the obvious standout.

The results for HW60M and FW88M also confirm the effect of instrument ageing identified earlier in the monthly histograms. This affects several (or many) months of data from NOAA-7, -9, -11, -12, -14, -15, -16, -17, -18, and -19. Only TIROS-N, NOAA-6 and -8 (all short-lived), NOAA-10, and all Metop satellites appear to be free of such issues. Note however that for Metop-C, channel 3a shows a clear increase from 2021 onwards. This is particularly true for the HW60M time series (Figure 32). This observation confirms the analysis of Hovmöller

plots, in which we see increased channel 3a reflectance for the same satellite and time period (Figure 36).

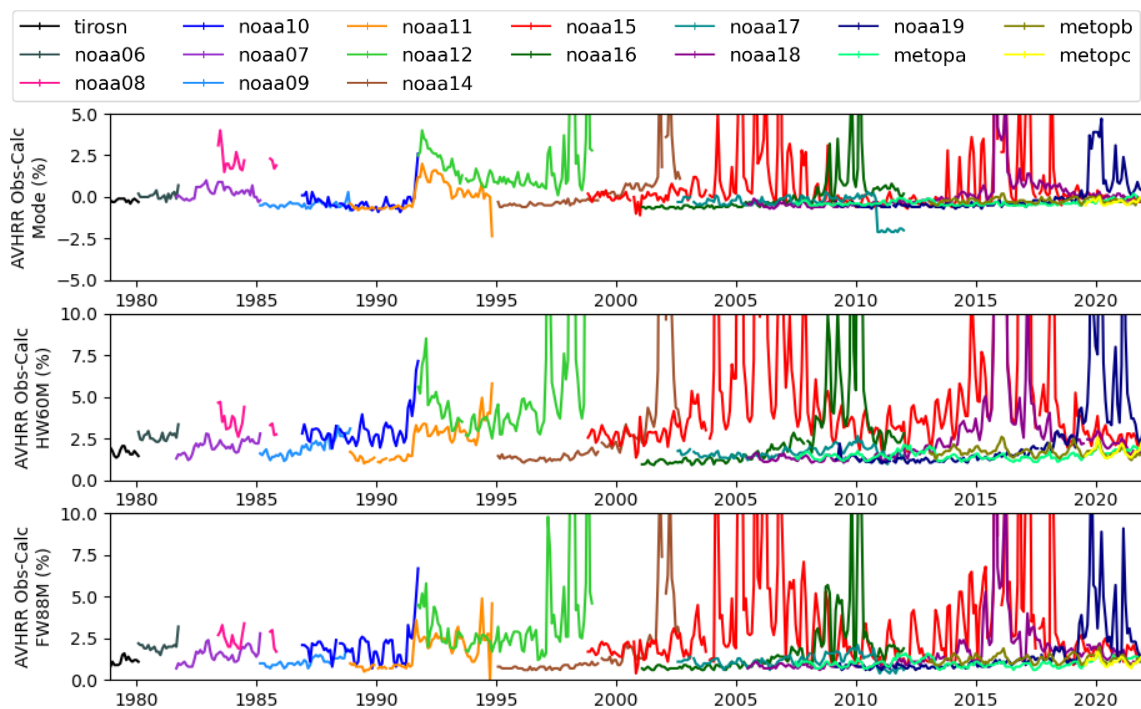


Figure 31: Similar to the previous figure, but for channel 2.

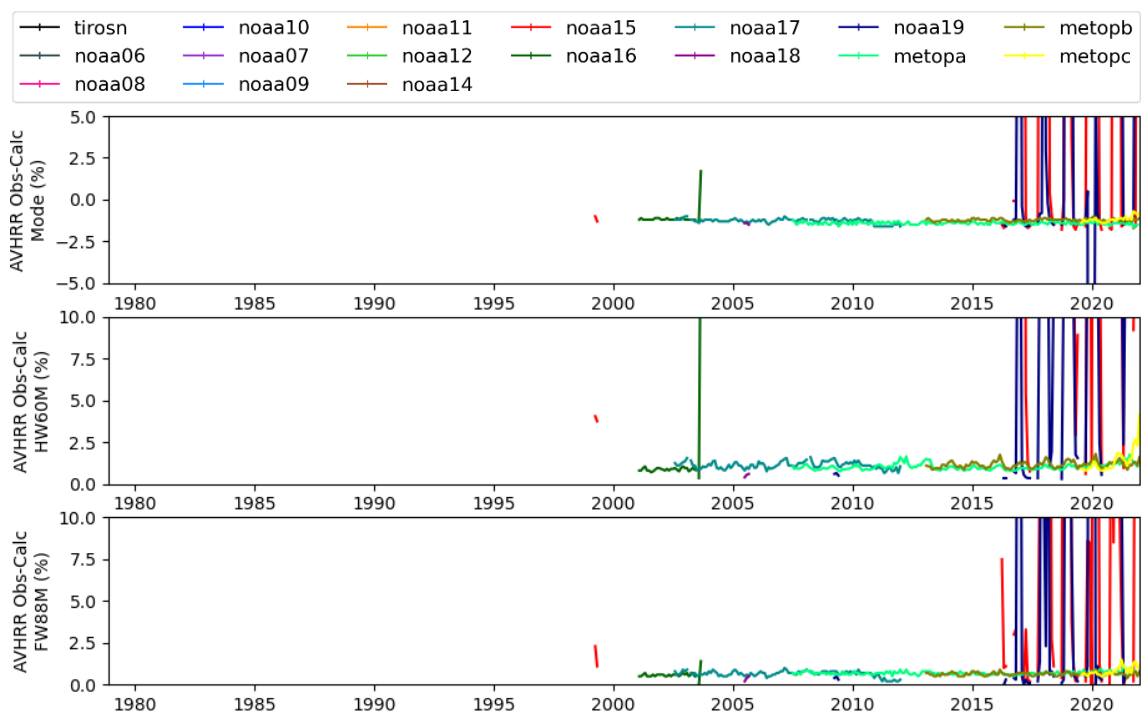


Figure 32: Similar to the previous figure, but for channel 3A (this channel is only available from AVHRR/3 instruments).

5 SUMMARY AND CONCLUSIONS

This validation report presents a detailed analysis of EUMETSAT's new AVHRR FDR. The FDR was derived using 17 AVHRR instruments covering three generations of instruments for the period 1978 until 2021. The report provides insight into their temporal consistency and possible issues with the data record.

5.1 Validation summary

A statistical verification was applied to the FDR. It shows that:

- The FDR processing is overall complete, but the treatment of night-time reflectance is inconsistent between satellites (sometimes these are reported as fill values, sometimes as close to 0). More periods of missing data are found for earlier satellites (prior to NOAA-9).
- The FDR radiances are in line with expected behaviour:
 - Reflectance data display the expected seasonal patterns, such as polar night and day at extreme latitudes and transition from summer to winter illumination conditions (and vice versa) across all latitude bands.
 - Time series of reflectance and brightness temperature at spatially homogeneous desert sites show how changes in equatorial crossing times due to orbital drift impact the measurements. When equatorial crossing times are similar between satellites, simultaneous observations are also similar.
 - Brightness temperatures appear homogeneous and stable in terms of seasonality: hemispheric warming consistently follows sun illumination conditions. Tropical brightness temperatures appear somewhat colder during summer, probably caused by colder tops of deep convective clouds in the ITCZ.

For the IR channels, a quality evaluation was done against some PATMOS-x orbits, FIDUCEO and HIRS data records. Major results are:

- As expected, there is a good agreement for the few PATMOS-x orbits analysed, although minor differences do exist between visible channels.
- Despite the fact that the FDR isn't explicitly harmonised, the comparison with FIDUCEO shows that the PyGAC brightness temperatures exhibit better temporal consistency. This is shown by less and smaller jumps between the split-window channels.
- The comparison with HIRS shows a good quality of the AVHRR FDR in terms of temporal consistency. Considering the differences between both sensors in terms of spectral response functions and spatial sampling, both agree quite well for the majority of AVHRR instruments. Particularly NOAA-15 and newer sensors show over their long time series almost no bias trend. Small trends are found, mainly for the earlier sensors, which cannot be attributed to AVHRR directly based on this comparison.

In addition, the PyGAC FDR was compared with RTTOV radiative transfer calculations using ERA5 reanalyses as input data. Data were compared when they are within 15 minutes and 30 km of an AVHRR observation. The results show that the departures of infrared channels are generally close to 0 (between -1.2 K and 0.4 K for channels 4 and 5) and improve through time. This is likely to result from improvements in reanalysis quality and associated input data (in particular surface emissivity and sea-ice), and improvements in the quality of radiometers. As simulations are clear-sky, contamination by thin clouds increases the bias between AVHRR

GAC IR data and simulations. The short-lived effects of volcanic eruptions (El Chichon 1982 and Pinatubo 1991) also do show in the data. For visible channels 1 and 2, effects of instrument ageing are visible throughout all analyses and for all satellites with sufficiently long time series except Metop. Problematic months show as flat or very wide distributions of monthly departures. As simulations are clear-sky, cloud contamination explains the higher occurrence of positive departures. For most recent sensor generations, departures are smaller, with the mode being $\leq 1\%$ overall.

This report provides a detailed analysis of the overall quality of this first release of the PyGAC FDR. With this information, any future user will be able to make an informed decision about the data's suitability for a specific usage. The absence of thermal channel cross-calibration and in particular the effects of orbital drift are two major points to be addressed while using this FDR to derive a Climate Data Records (CDR) for a geophysical variable. Whilst this FDR does not satisfy all requirements for climate applications, considerable progress has been made in various aspects to approach this goal.

5.2 Limitations and recommendations

This is a list of known limitations, and it is very likely that further unknown limitations exist. We strongly advise that the user consults the validation report, and in particular data availability and hovmoeller plots in that report. If in doubt please also use the EUMETSAT User Service Helpdesk for questions by email: ops@eumetsat.int.

- Periods of data outages covering at least several days:
 - NOAA-14: 08-1988, 06-1989, 04-1990, 01/02-1991, 12-2001
 - NOAA-12: 10-1993
 - NOAA-15: 07-2000 to 02-2001
 - Metop-B: 04/05-2013
- Periods when channel 3a was turned on at daytime (3b off) and channel 3b at nighttime (3a off):
 - NOAA-15: 1999-03-09 to 1999-04-20, and during NH summer over Alaska from 2016 onwards
 - NOAA-16: until 2003-05-01, and channel 3b always on afterwards
 - NOAA-17: throughout
 - NOAA-18: 2005-06-23 to 2005-08-05, and channel 3b always on otherwise
 - NOAA-19: 2009-03-19 to 2009-05-14, and during NH summer over Alaska from 2016 onwards
 - Metop-A/B/C: throughout
- In the absence of Two Line Element data, angles are computed based on a fixed satellite height of 850 km. The following number of orbits are affected:
 - NOAA-6: 307 orbits
 - NOAA-8: 592
 - NOAA-9: 1385
 - NOAA-10: 3
 - TIROS-N: 94

Without TLE data, satellite angles will probably be less accurate. We did not assess whether a switch from TLE usage to the non-TLE fallback approach introduces discontinuities into satellite angle time series. If interested, the user can identify such

orbits (metadata variable “orbital_parameters_tle” does not exist in NetCDF file) and compare satellite angles to adjacent orbits.

- The orbits of most satellites are not stabilised and thus drift regarding their equator crossing time. This drift introduces artefacts into derived products such as time series and trend analyses. We thus recommend that this PyGAC FDR should be used with extreme caution for climatological applications. The PyGAC FDR itself is not a climate data record.
- There is no on-board calibration of solar channels. Instead, SNOs with MODIS data are used as an independent calibration source. For years before MODIS started operation (i.e. in and before 2000), AVHRR data are intercalibrated through AVHRR-to-AVHRR SNOs, starting with the earliest AVHRR record that was cross-calibrated to MODIS as the initial reference.
- There is no cross-calibration of thermal channels, which are calibrated only based on on-board instrumentation.
- There is no homogeneous treatment of night time observations in VIS channels. For some satellites, these are always set to 0, while for others these are close to 0. We recommend that users flag night-time VIS data as a function of solar azimuth angle.
- There is no blacklisting/filtering of irregular or potentially corrupt orbits. We recommend that the user applies own quality control/monitoring metrics based on the metadata variable “global_quality_flag”. For a previous internal release of PyGAC, we found that ~6 % of orbits were affected by at least one of the issues in the following list. Some issues are probably fixed with this release, in particular those related to timestamp corruption:
 - file overly long due to corrupt 11b timestamps
 - file contains data of 2 or more orbits
 - file containing only redundant orbit fragments
 - negative orbit length, i.e. end date and time before start
 - wrong 11c timestamp
- For this release, the following periods are associated with bad 11c quality:
 - NOAA-17 between 2010-03-01 and 2011-12-31
 - NOAA-6 between 1981-08-14 and 1982-08-02
 - NOAA-8 between 1983-05-04 and 1983-09-19
 - Metop-C channel 3a from 2021 (gradually increasing reflectance); all of these time periods also appear as anomalous in the data availability plots.We recommend that users should treat data from such orbits with care. The channel 3a trend for Metop-C is a gradual phenomenon, and affected data might still be useful for qualitative applications. However, the data listed for NOAA-6/8/17 above should be blacklisted completely.
- For this release, the FDR geocoding quality has not been assessed and the geolocation should be taken with care when using the data to derive certain level 2 land products such as snow, vegetation dynamics, lake surface water temperature etc. It is planned to include a geolocation assessment in the next release.

APPENDIX A HOVMOELLER PLOTS

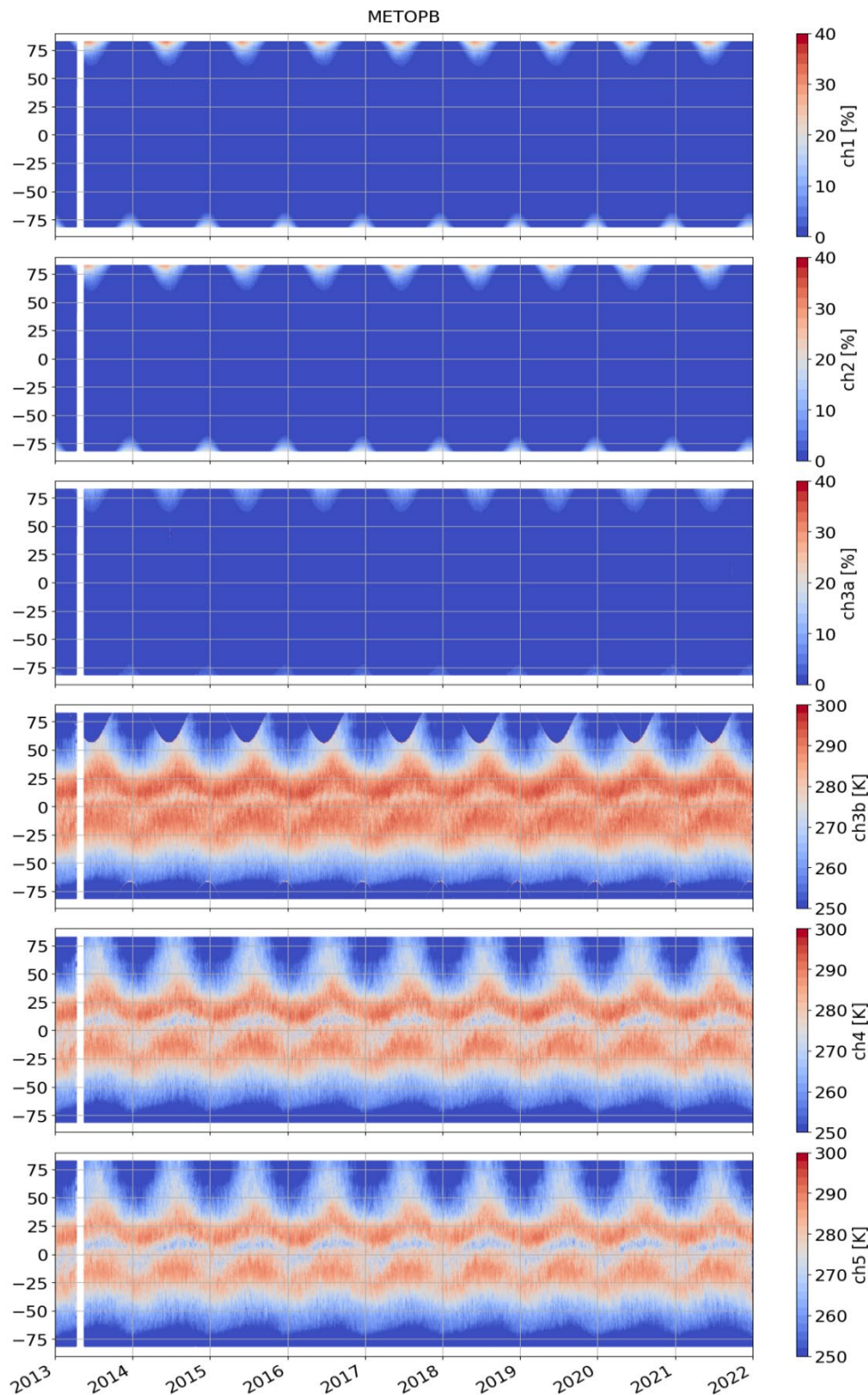


Figure 33: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for Metop-B. Data are shown for the ascending node only.

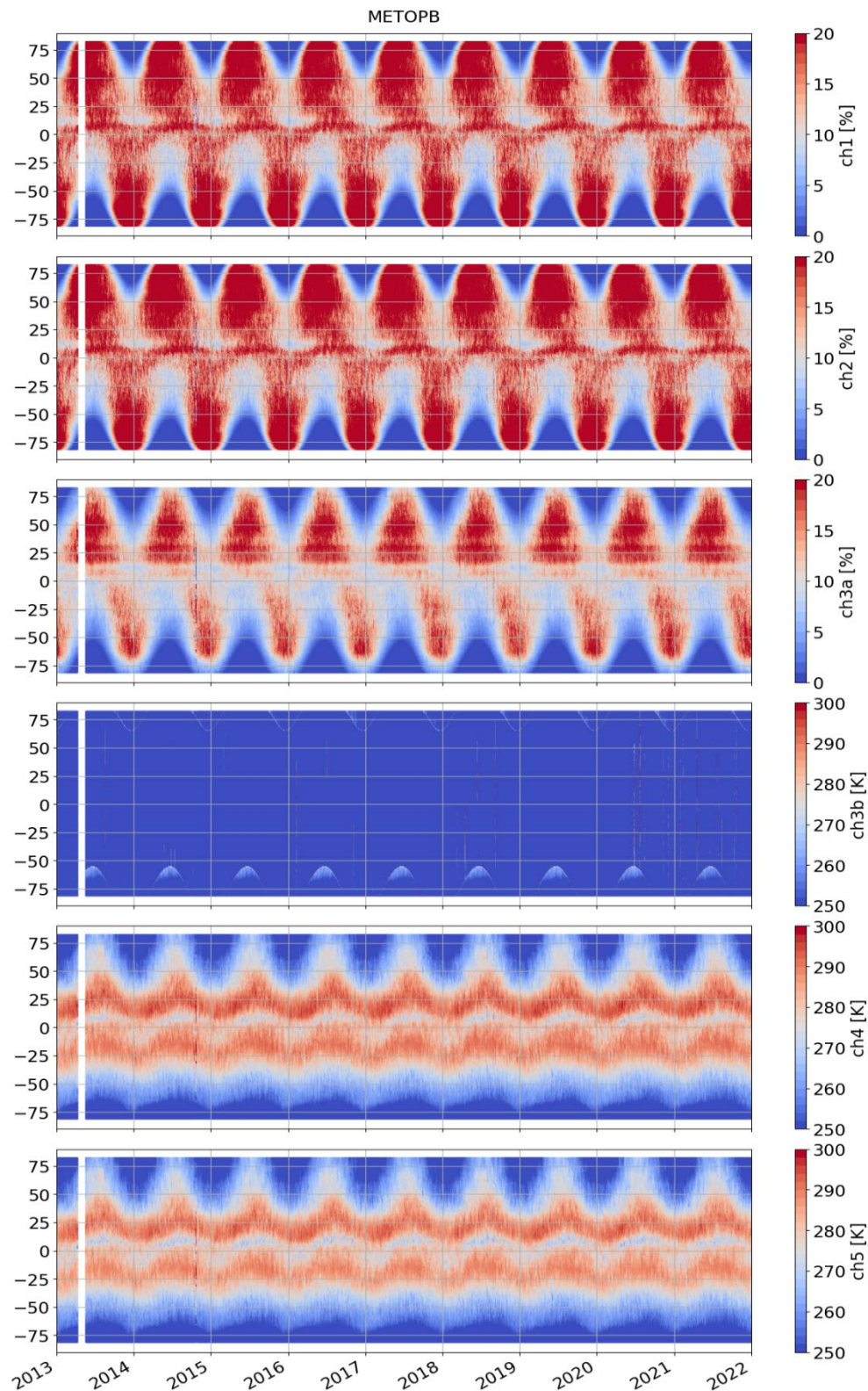


Figure 34: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for Metop-B. Data are shown for the descending node only.

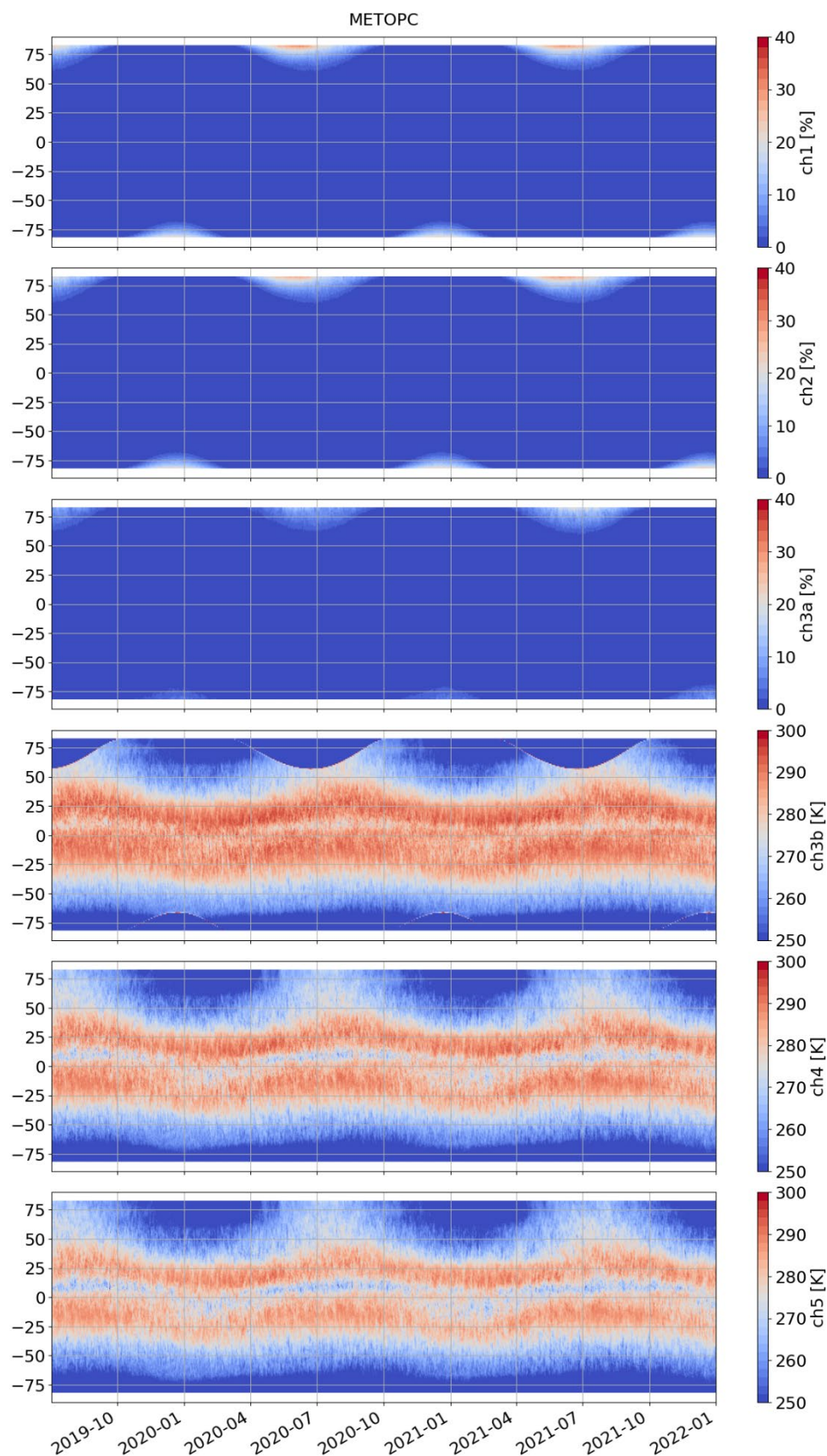


Figure 35: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for Metop-C. Data are shown for the ascending node only.

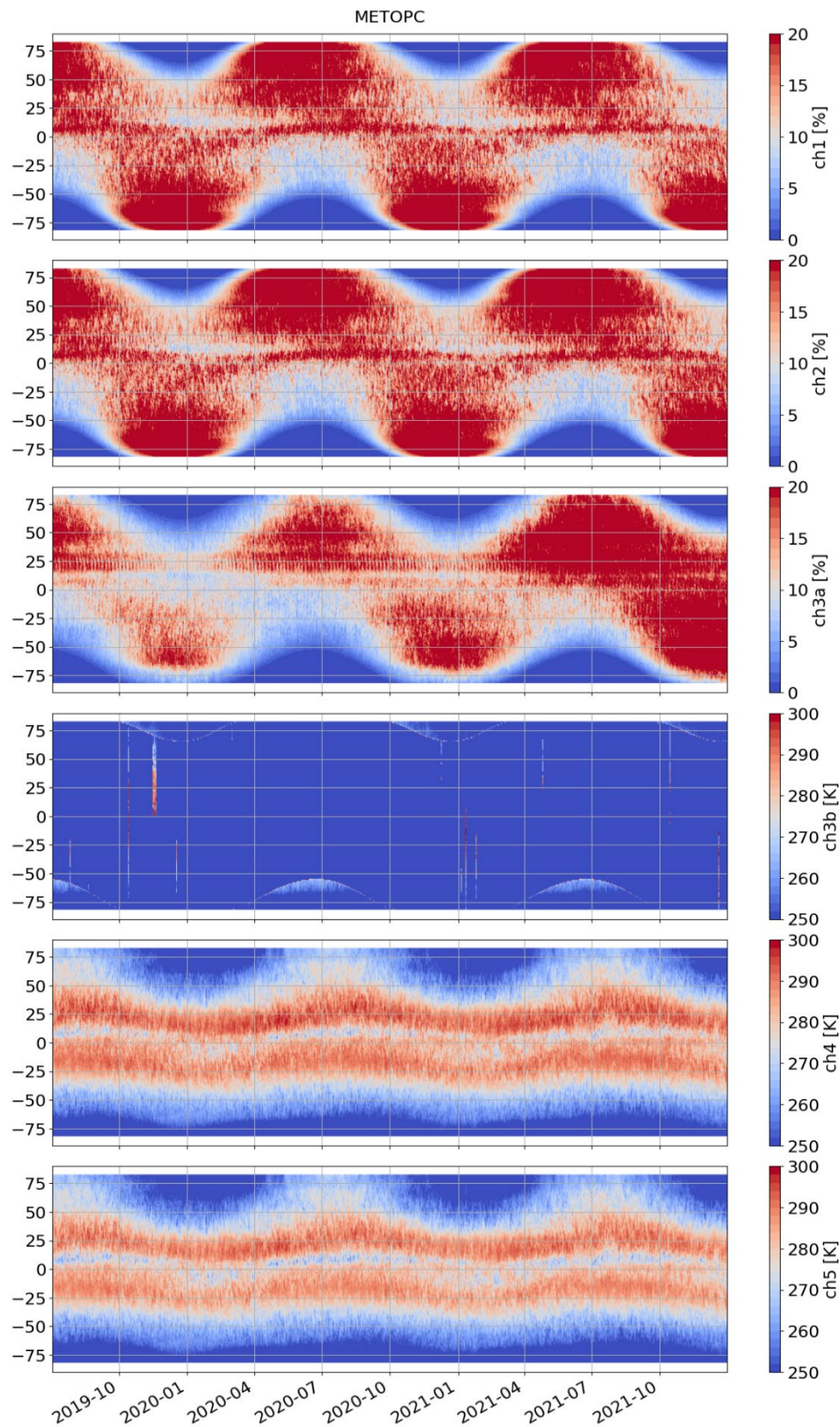


Figure 36: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for Metop-C. Data are shown for the descending node only.

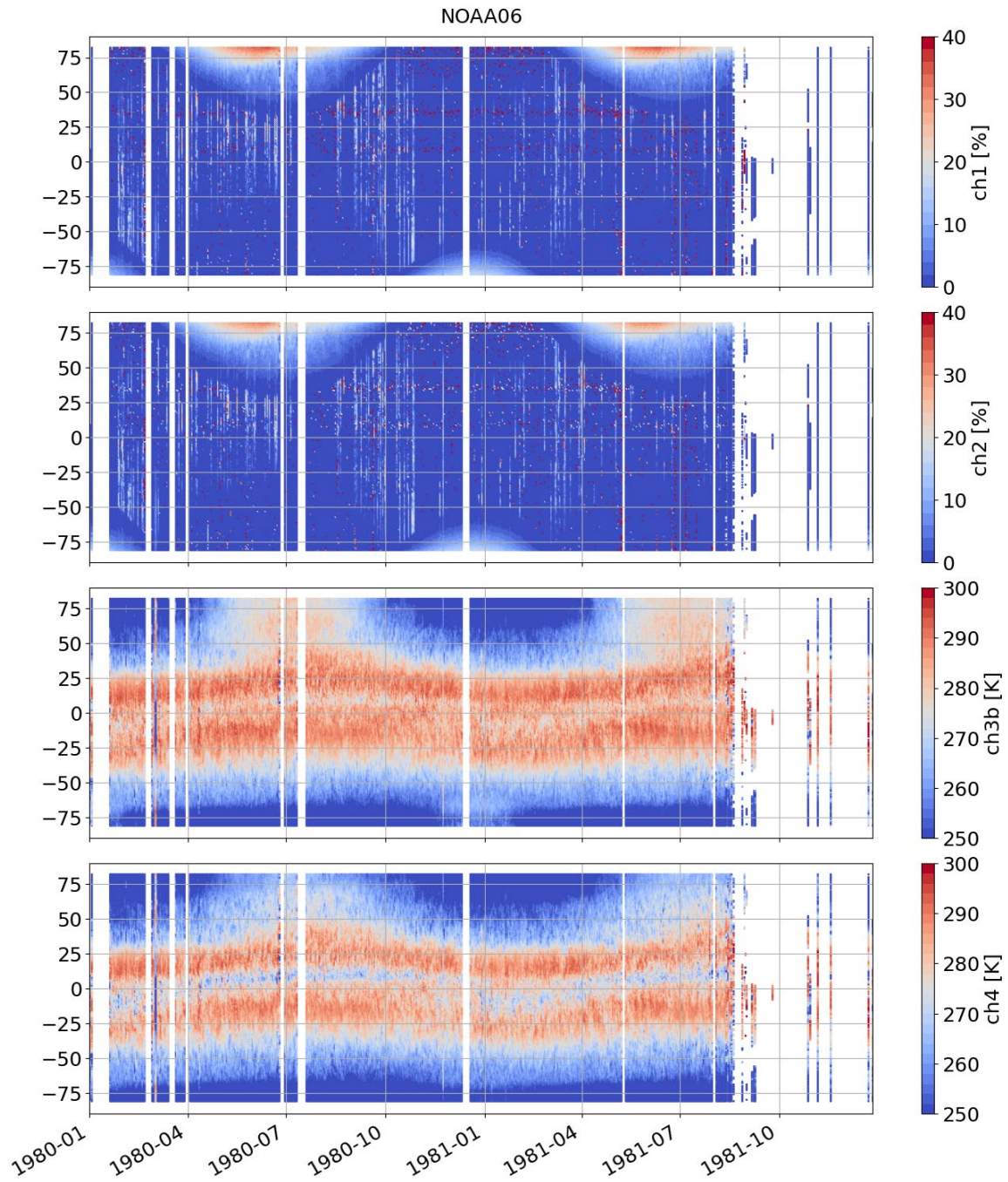


Figure 37: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-06. Data are shown for the ascending node only.

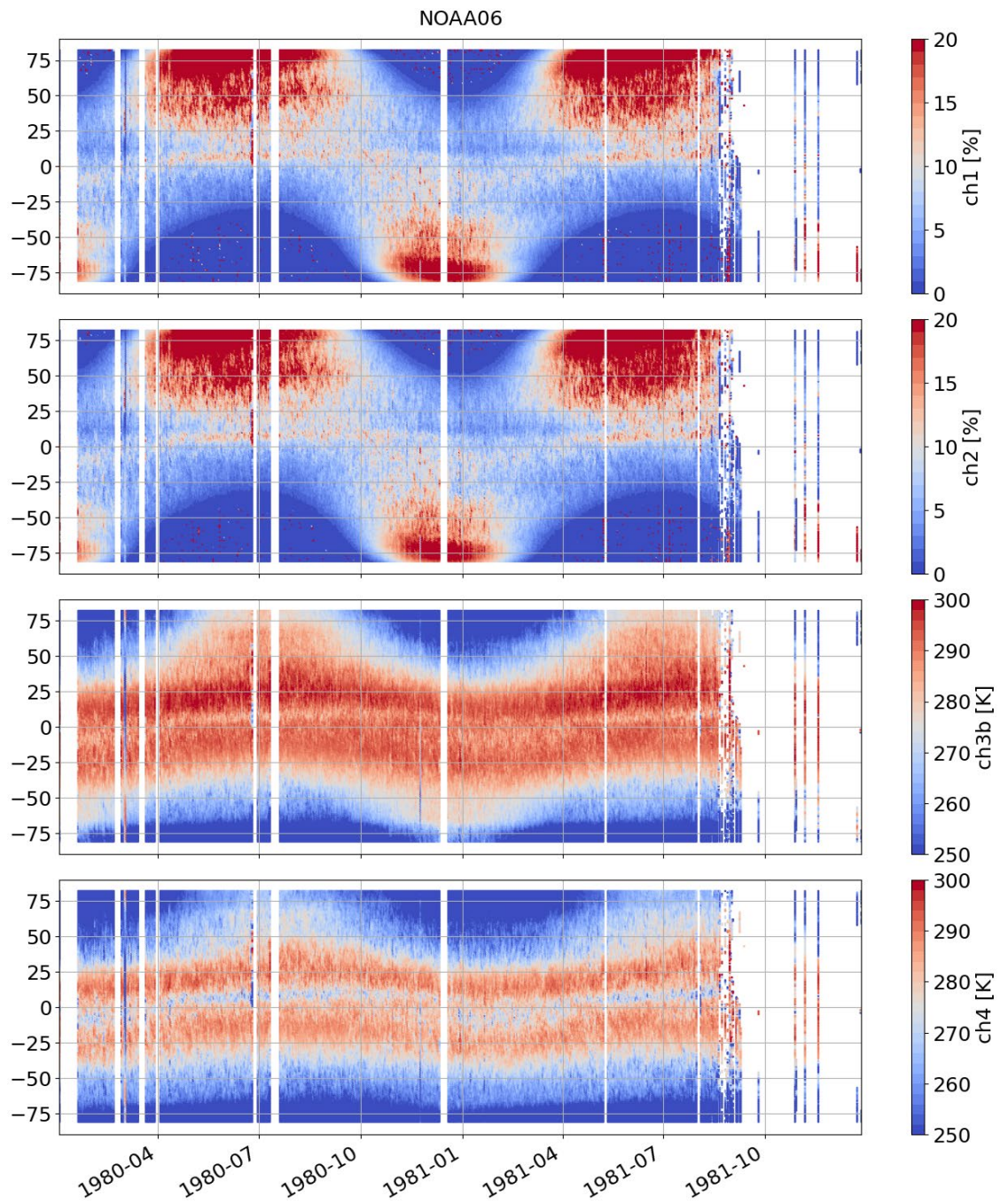


Figure 38: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-06. Data are shown for the descending node only.

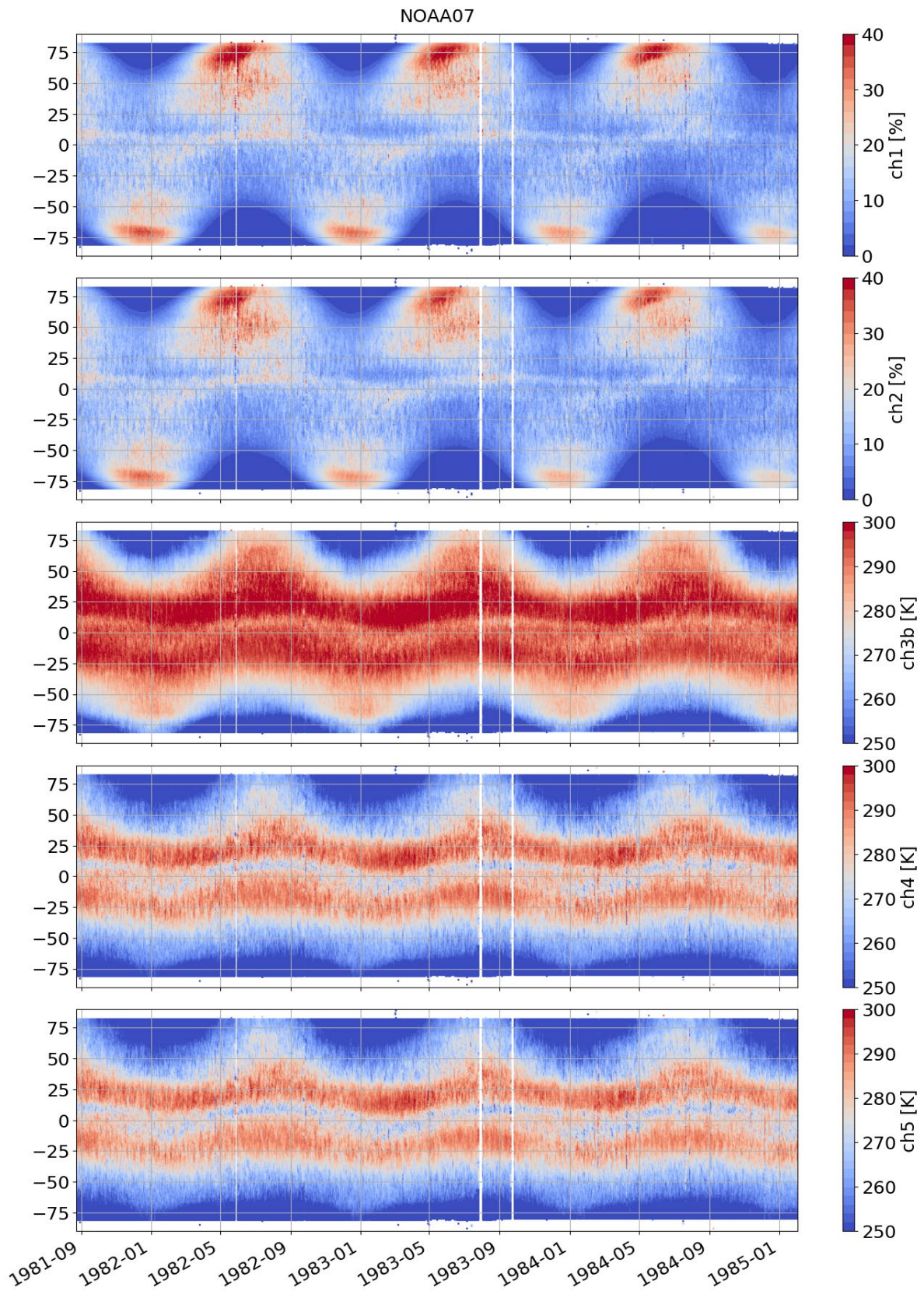


Figure 39: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-07. Data are shown for the ascending node only.

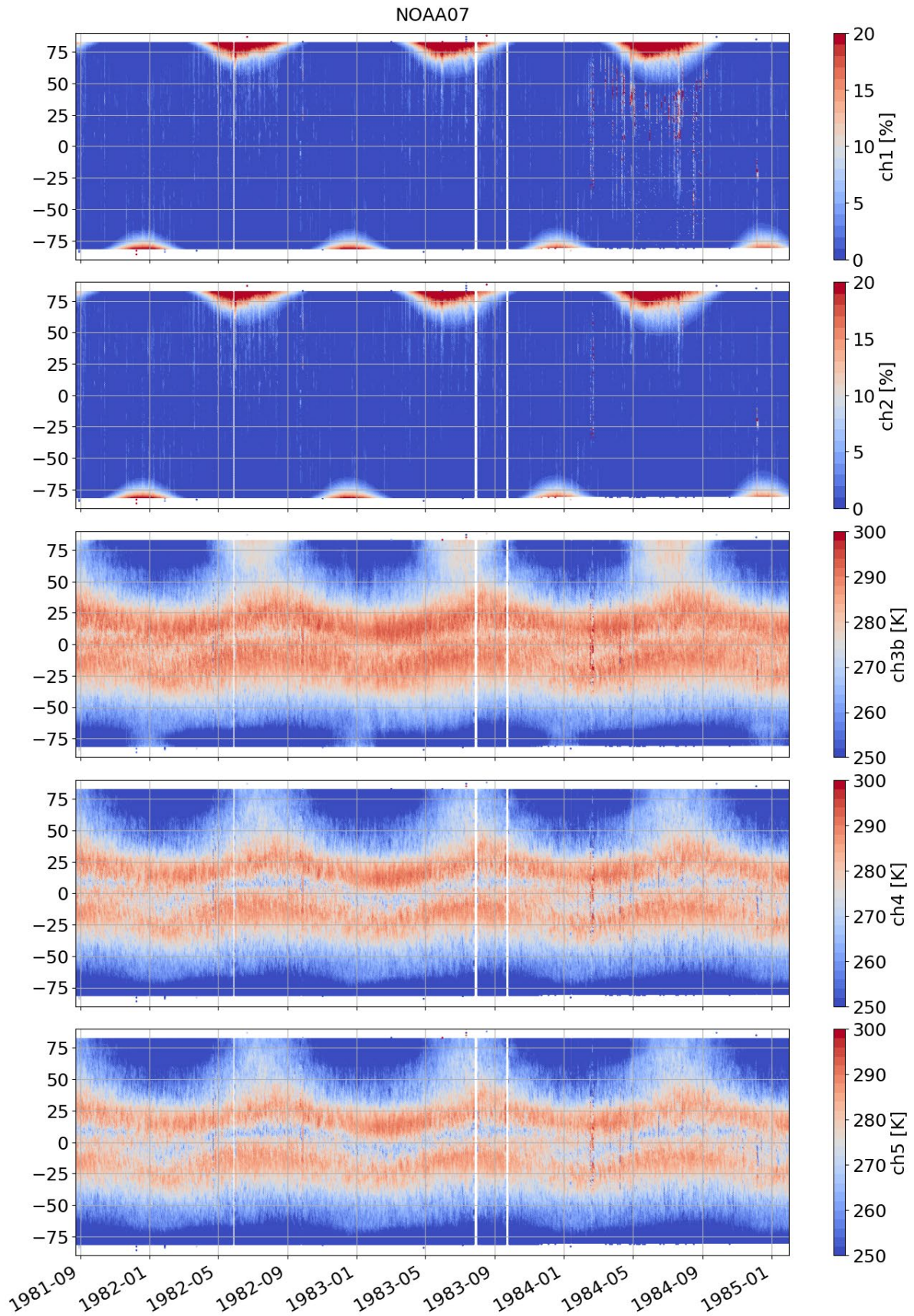


Figure 40: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-07. Data are shown for the descending node only.

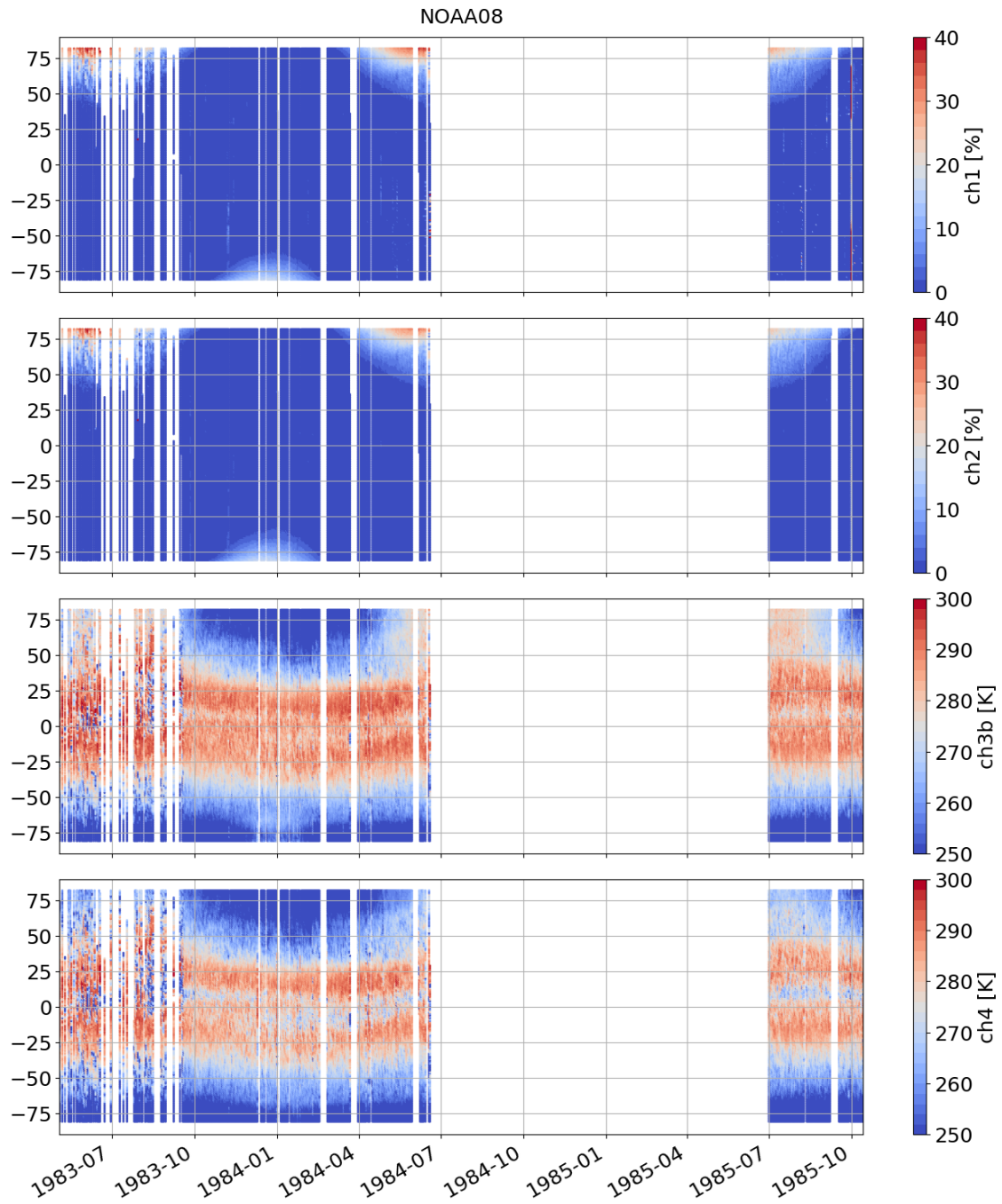


Figure 41: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-08. Data are shown for the ascending node only.

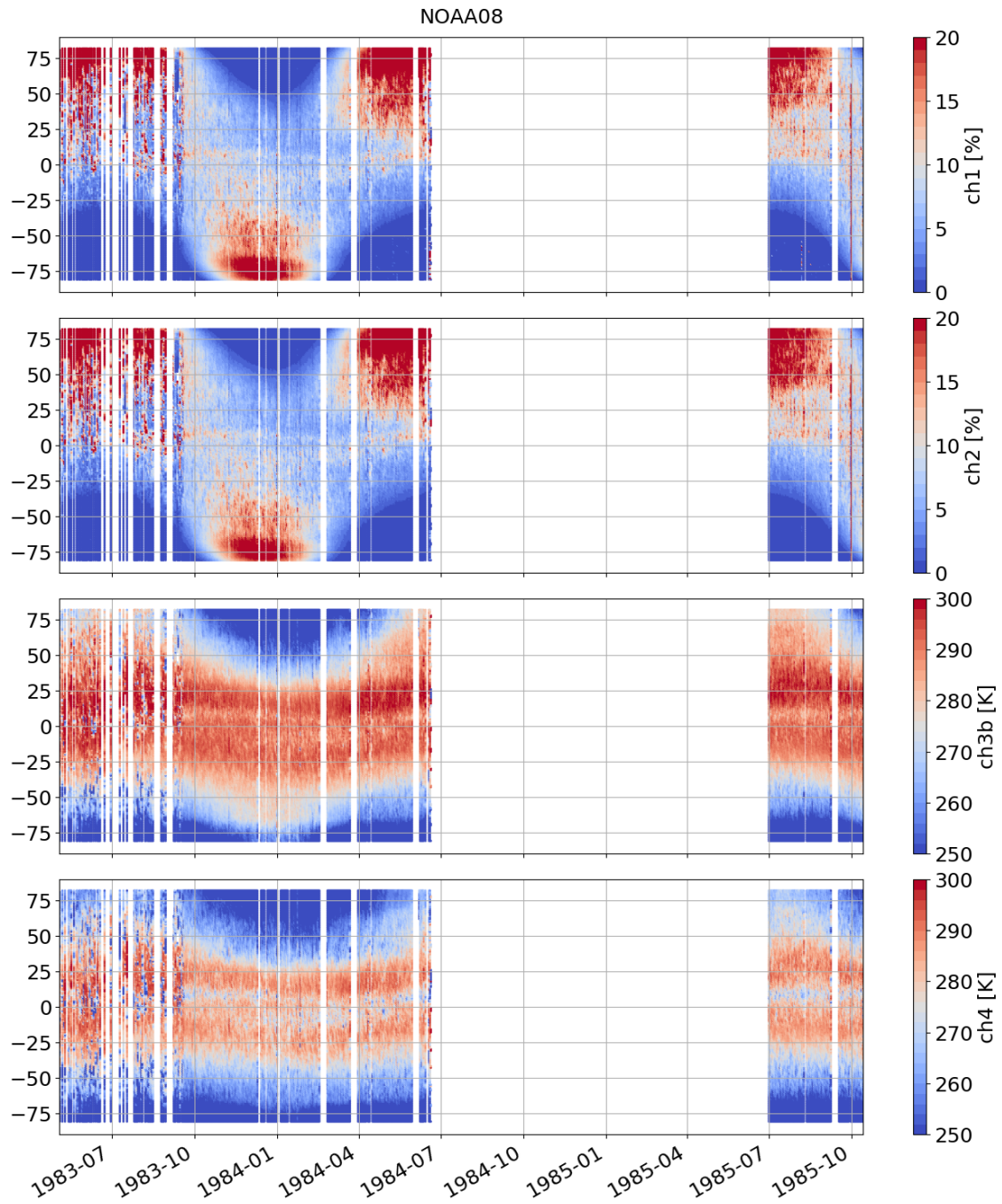


Figure 42: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-08. Data are shown for the descending node only.

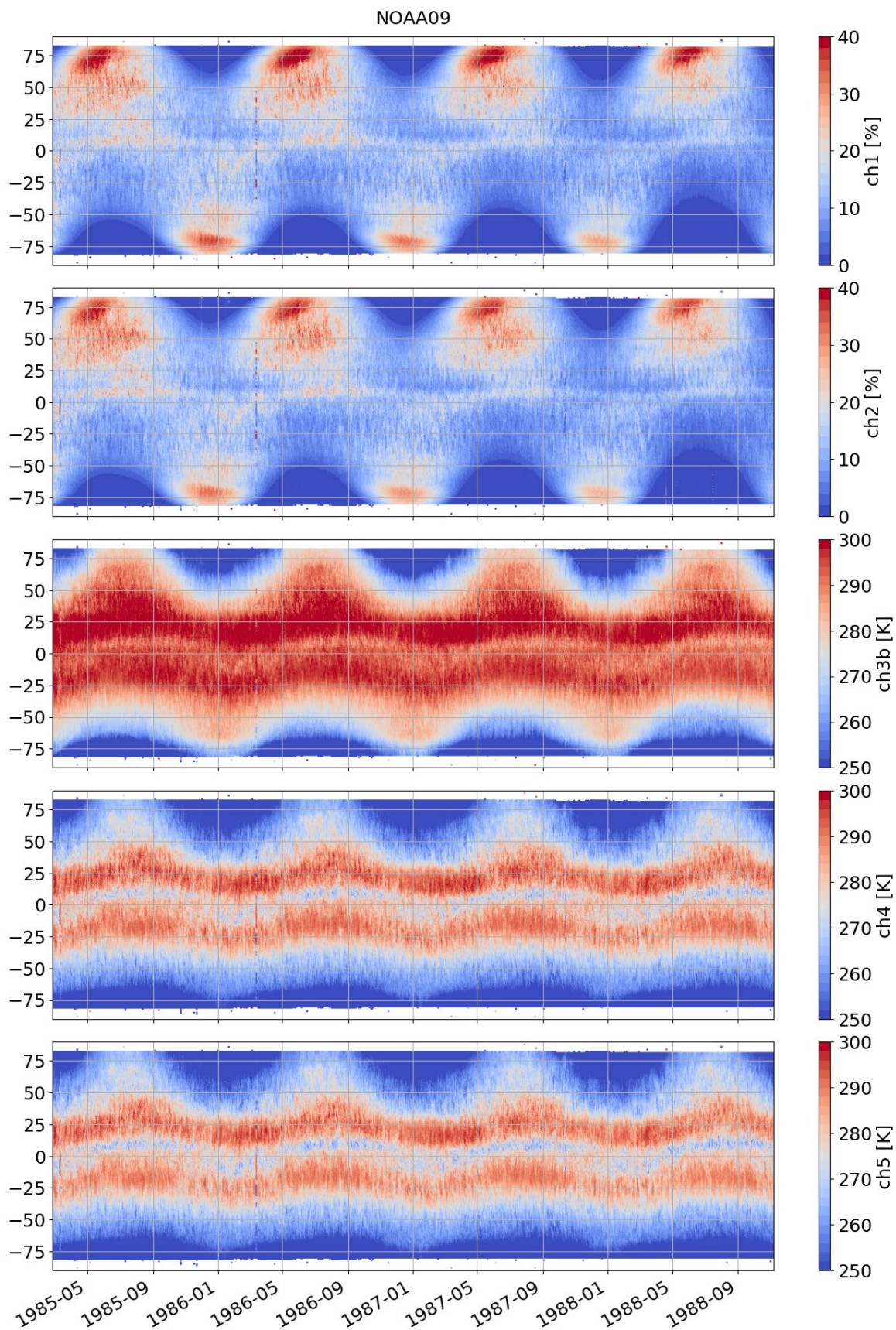


Figure 43: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-09. Data are shown for the ascending node only.

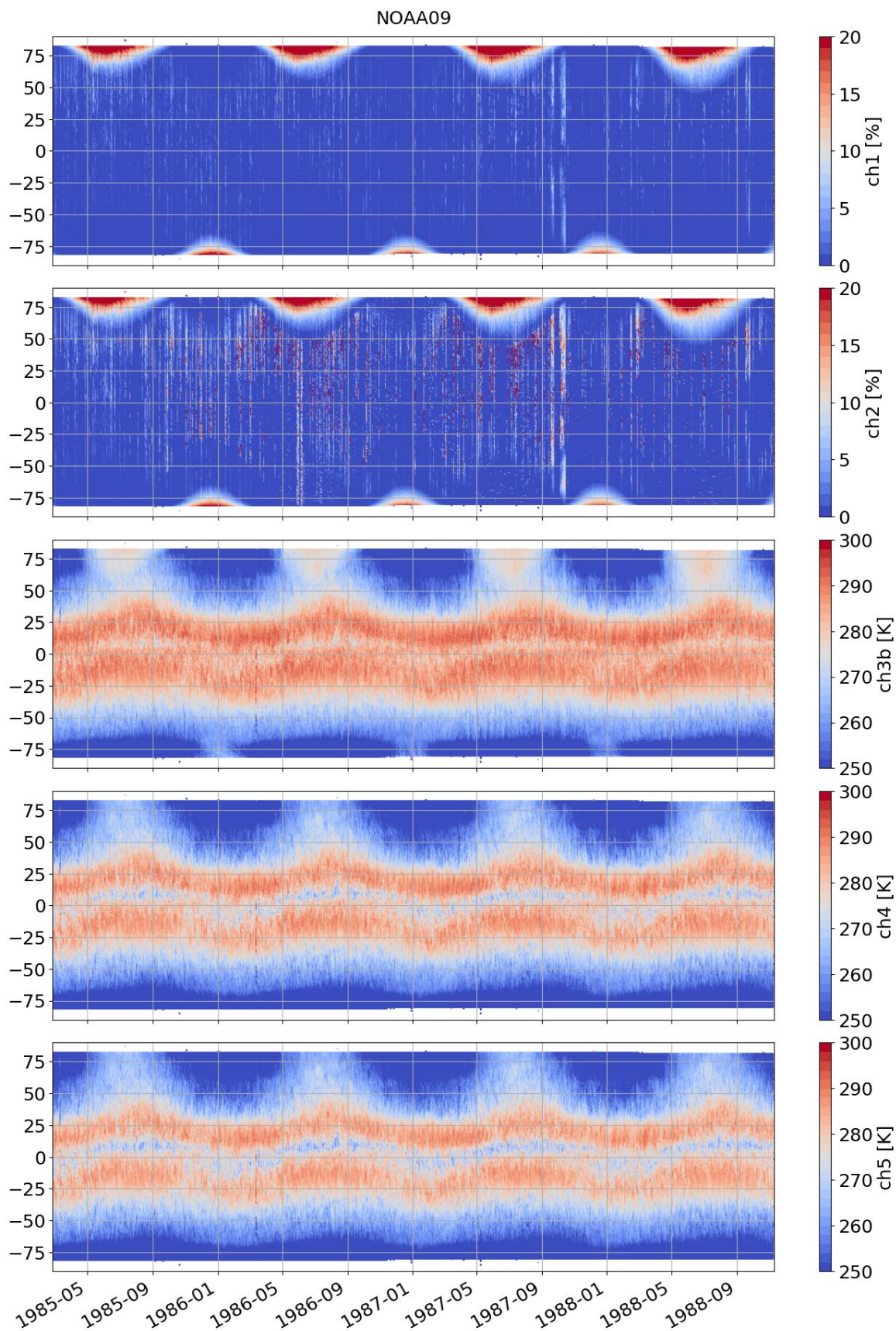


Figure 44: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-09. Data are shown for the descending node only.

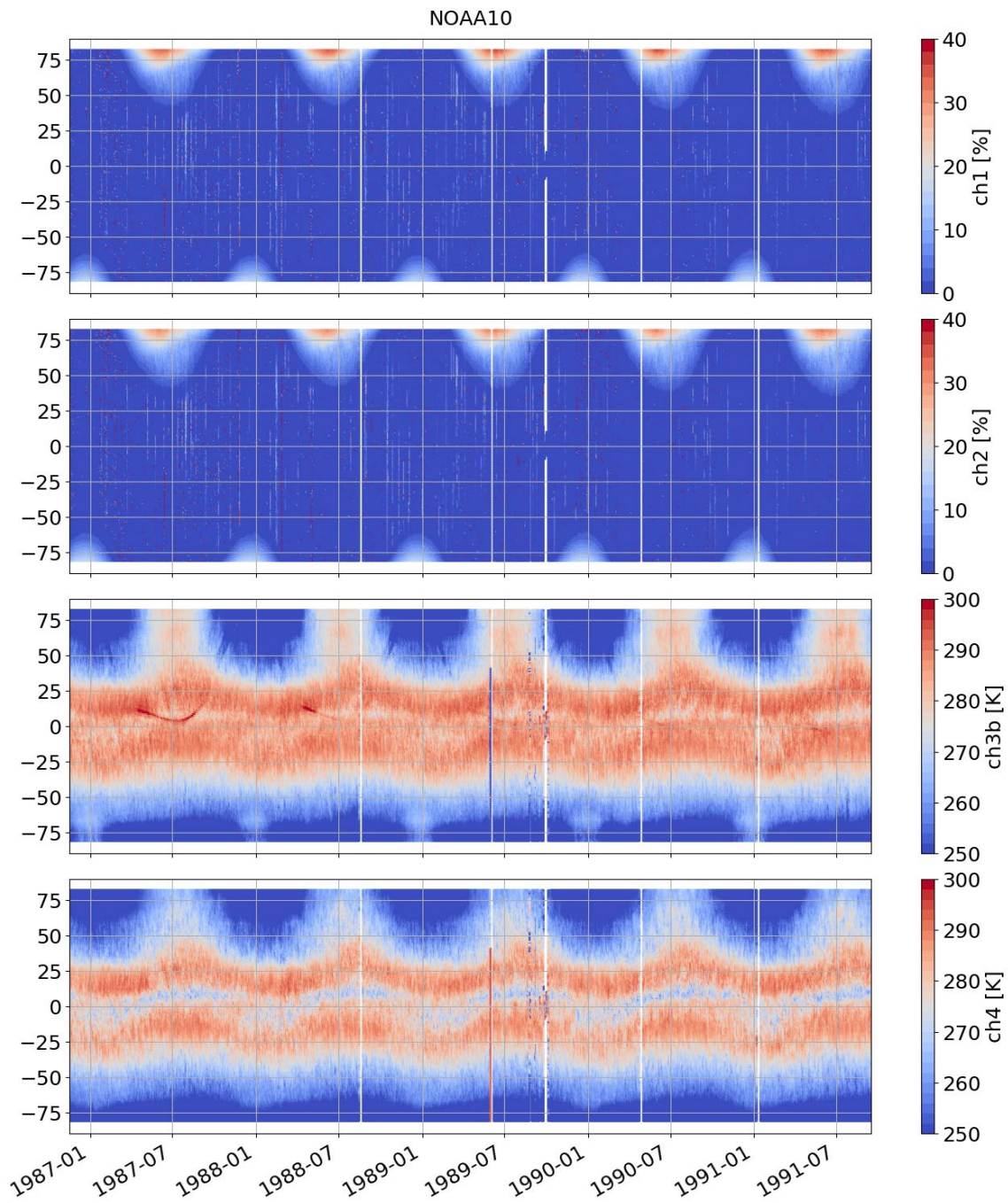


Figure 45: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-10. Data are shown for the ascending node only.

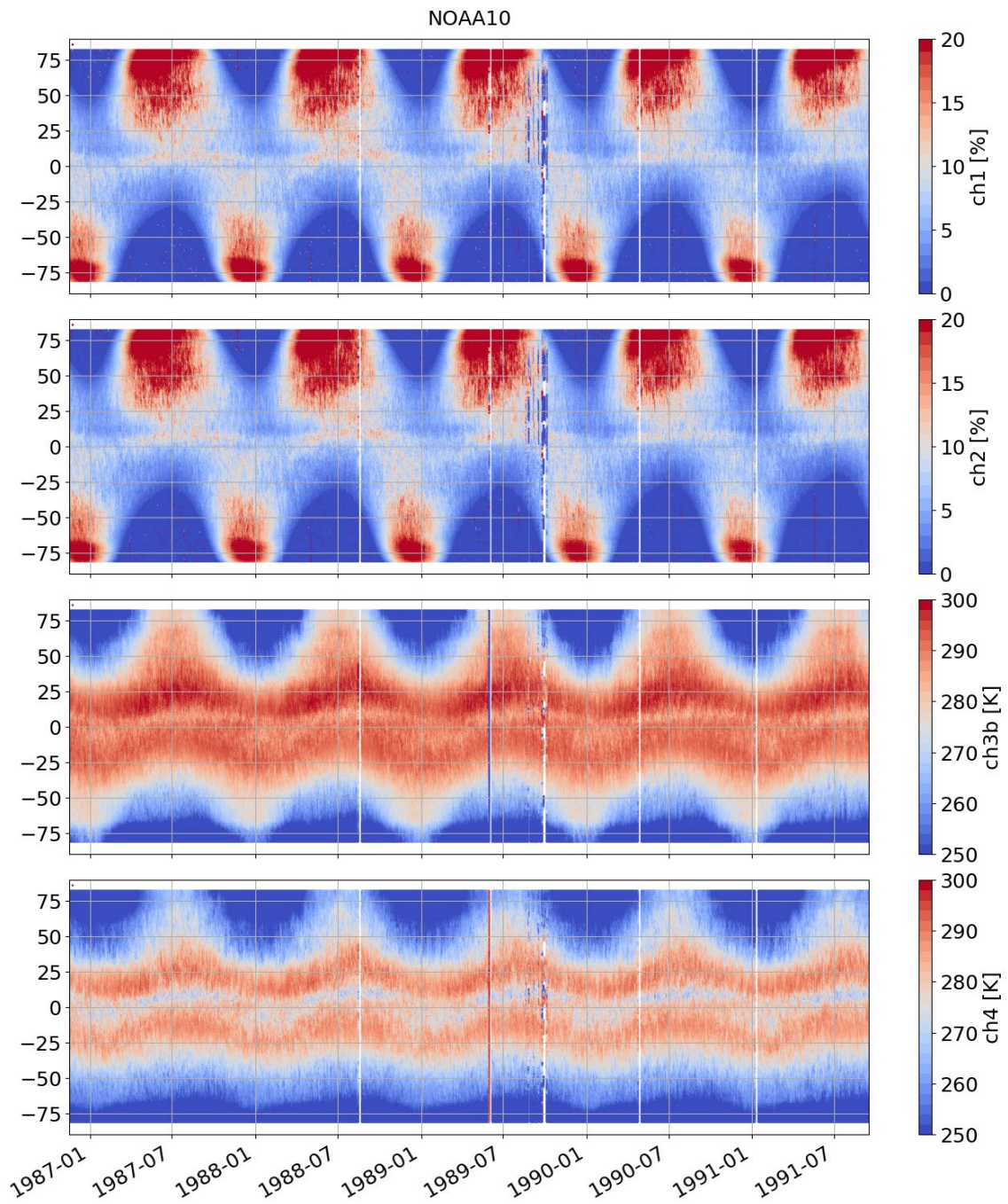


Figure 46: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-10. Data are shown for the descending node only.

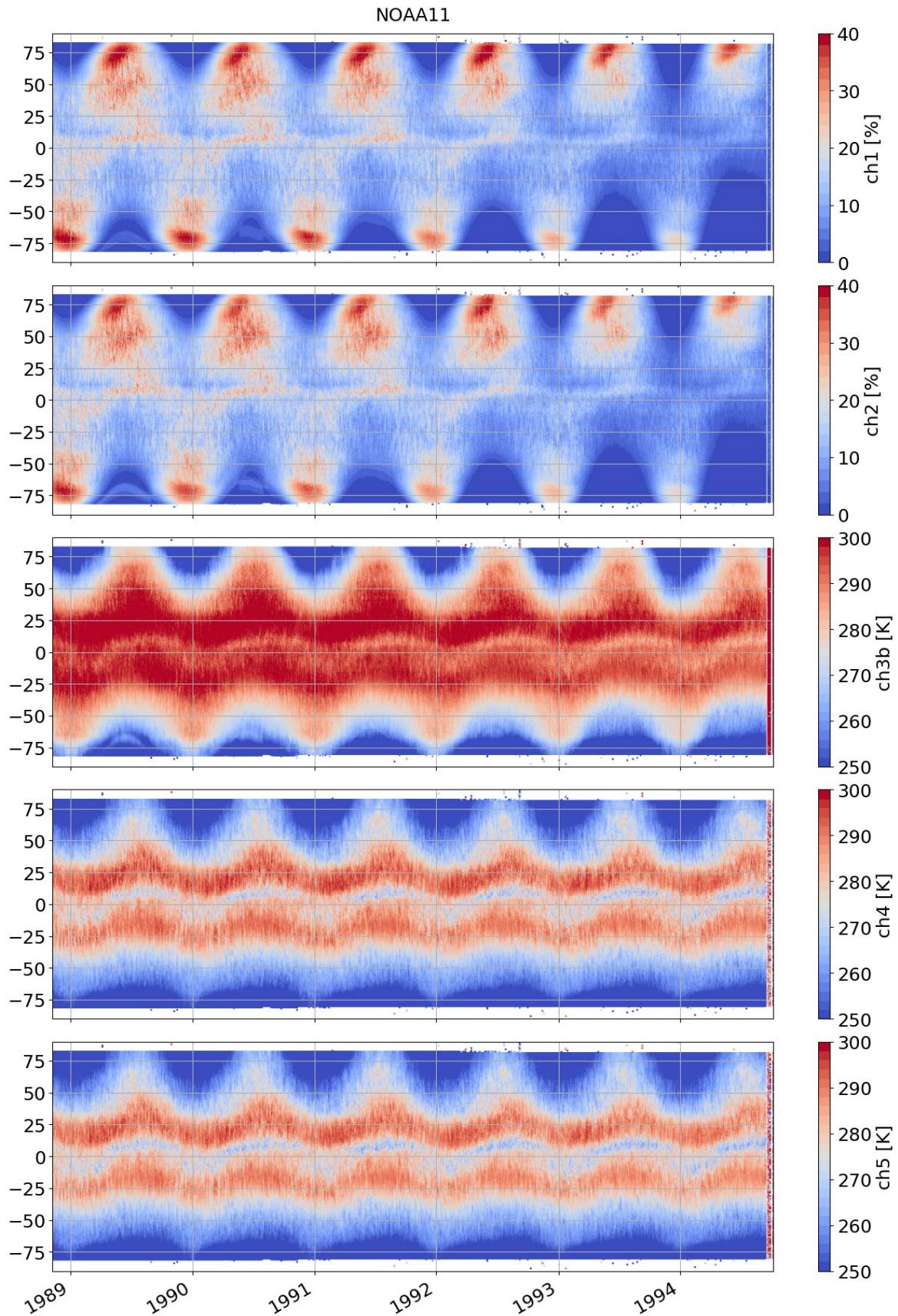


Figure 47: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-11. Data are shown for the ascending node only.

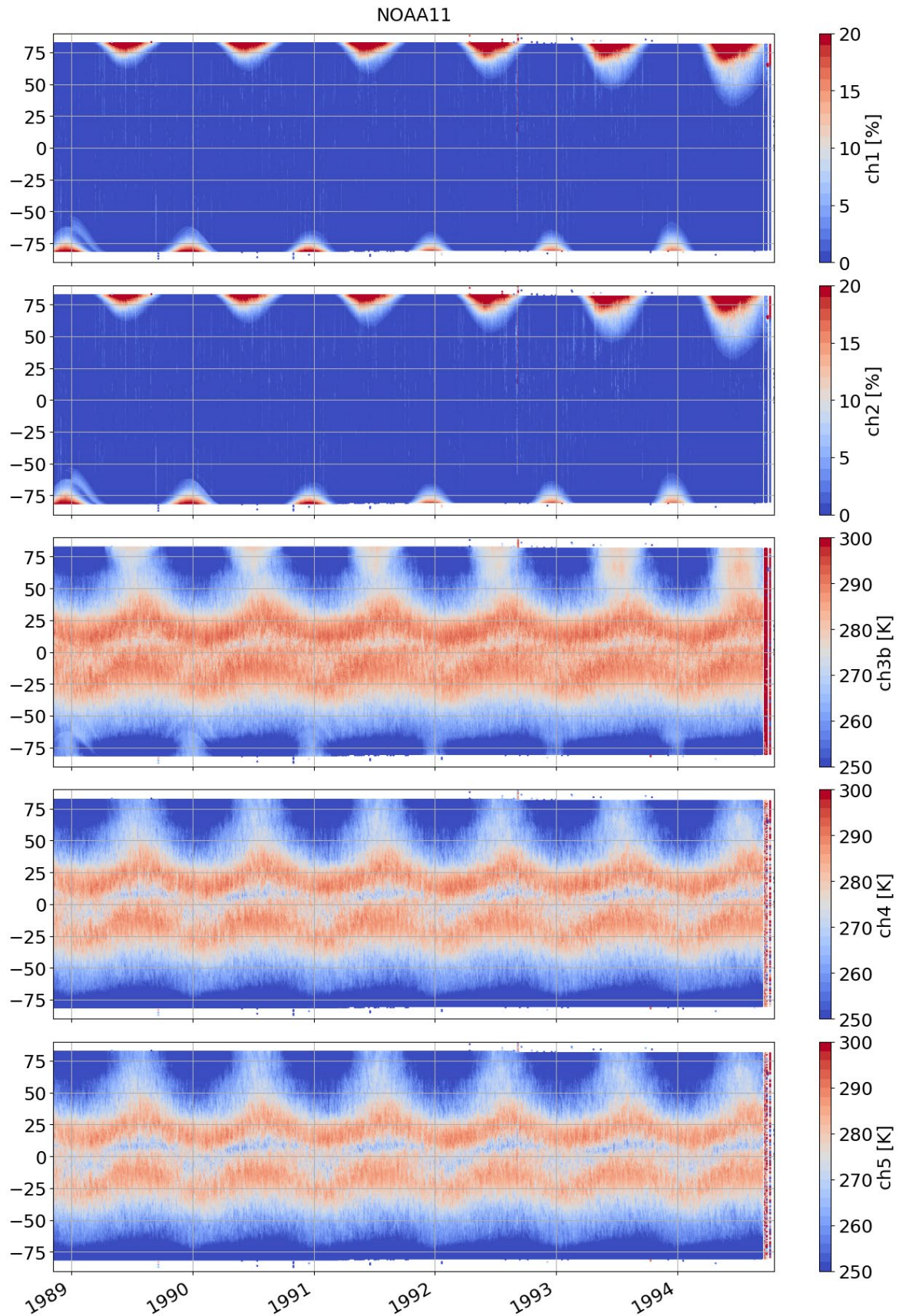


Figure 48: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-11. Data are shown for the descending node only.

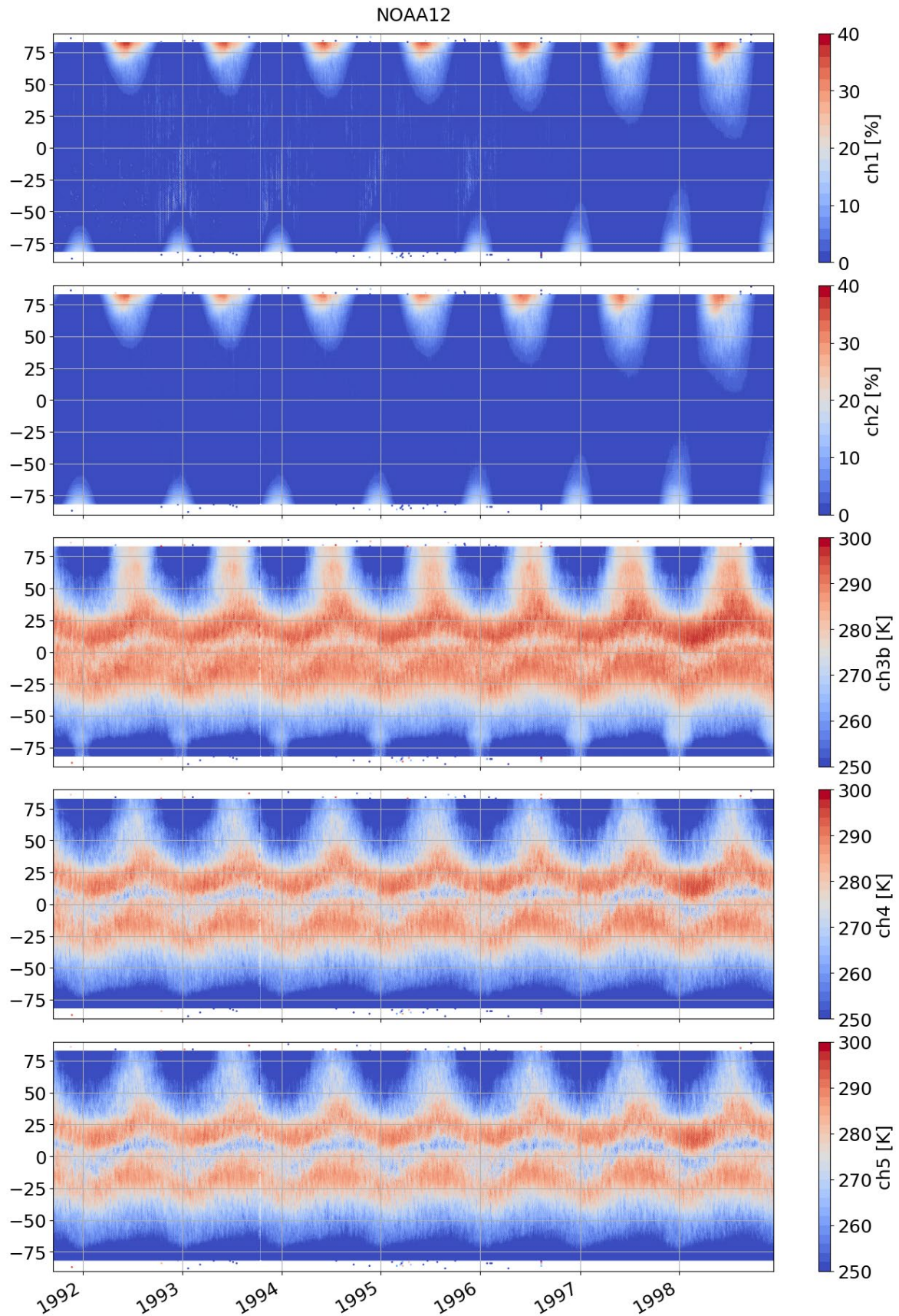


Figure 49: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-12. Data are shown for the ascending node only.

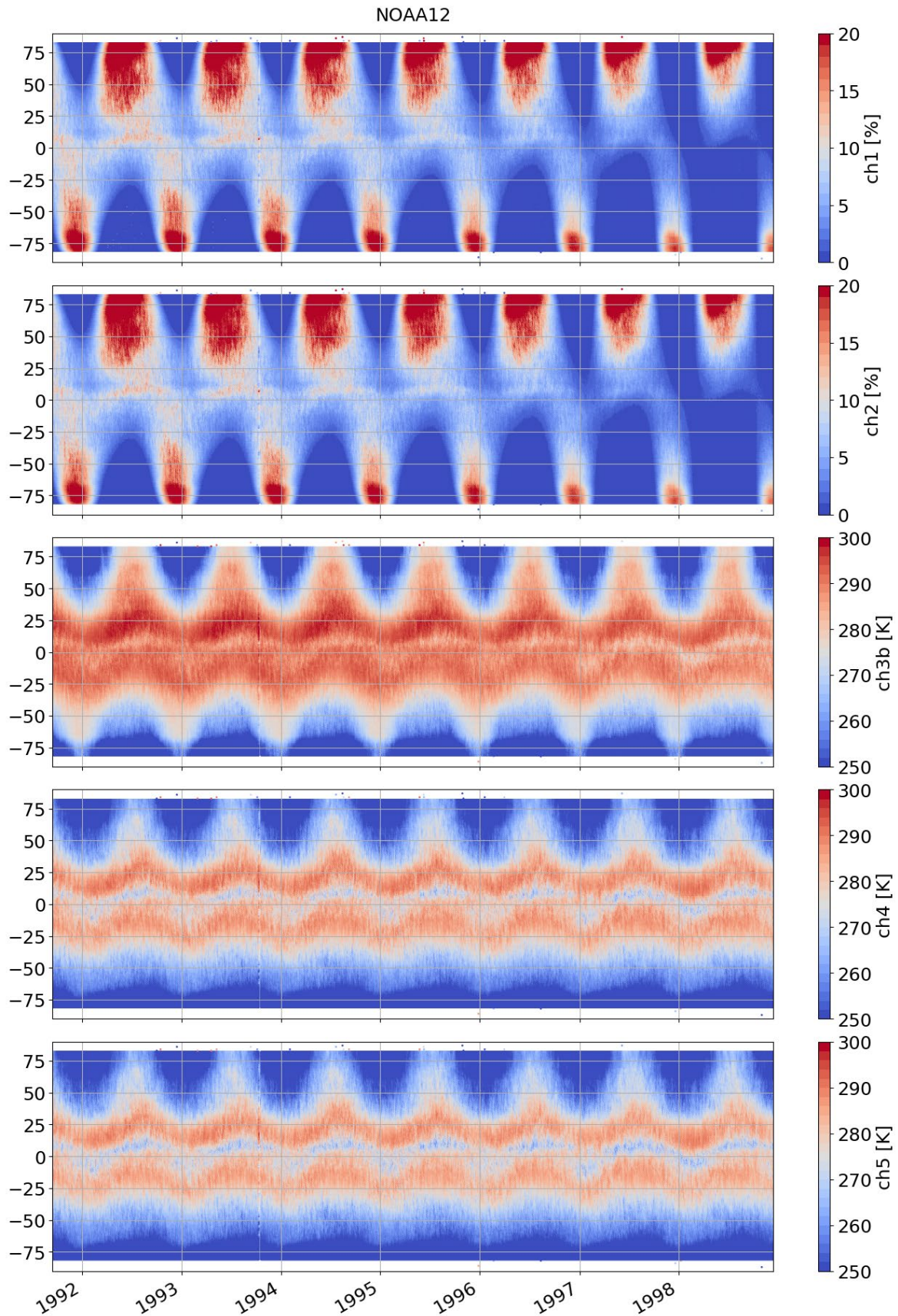


Figure 50: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-12. Data are shown for the descending node only.

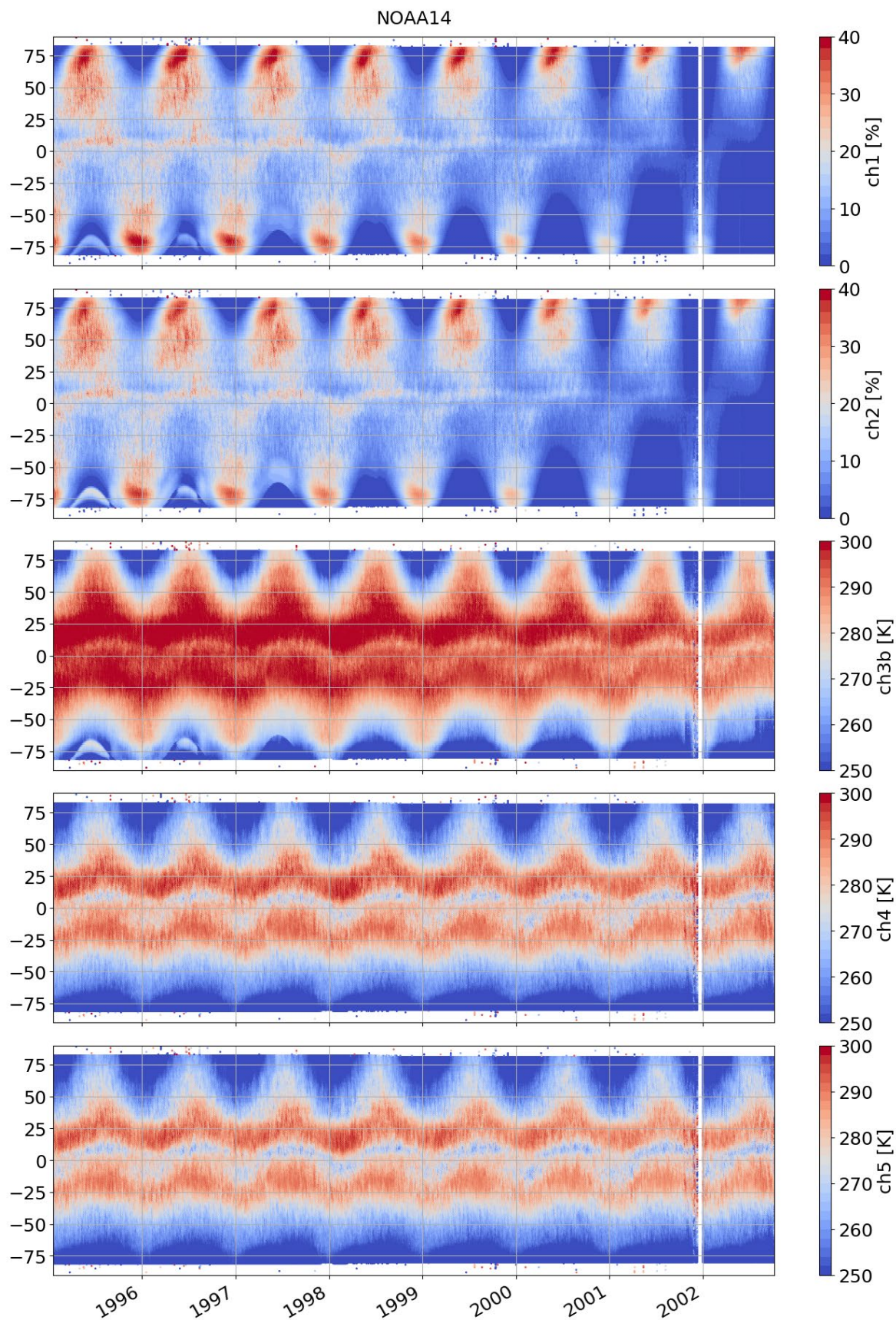


Figure 51: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-14. Data are shown for the ascending node only.

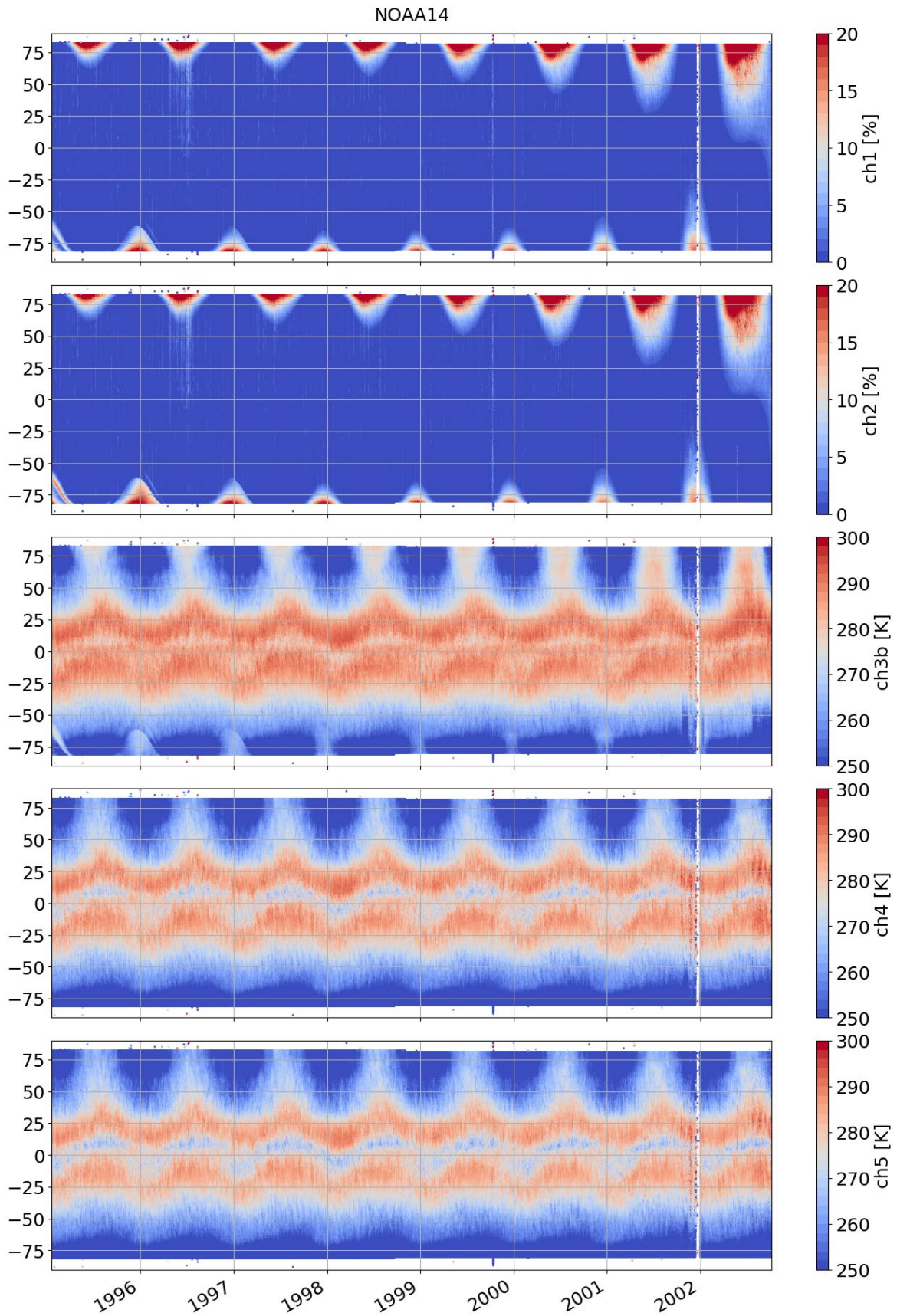


Figure 52: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-14. Data are shown for the descending node only.

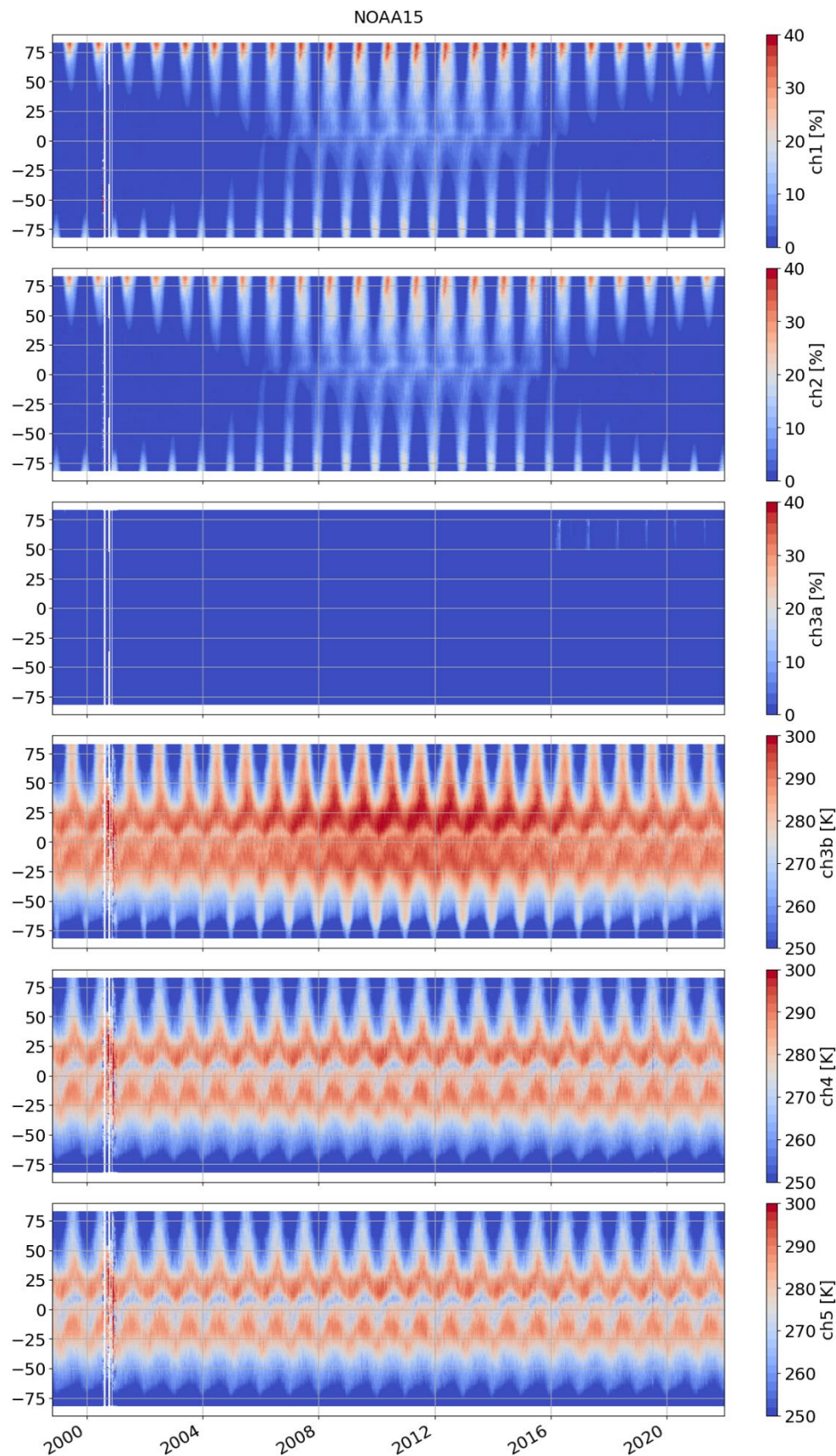


Figure 53: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-15. Data are shown for the ascending node only.

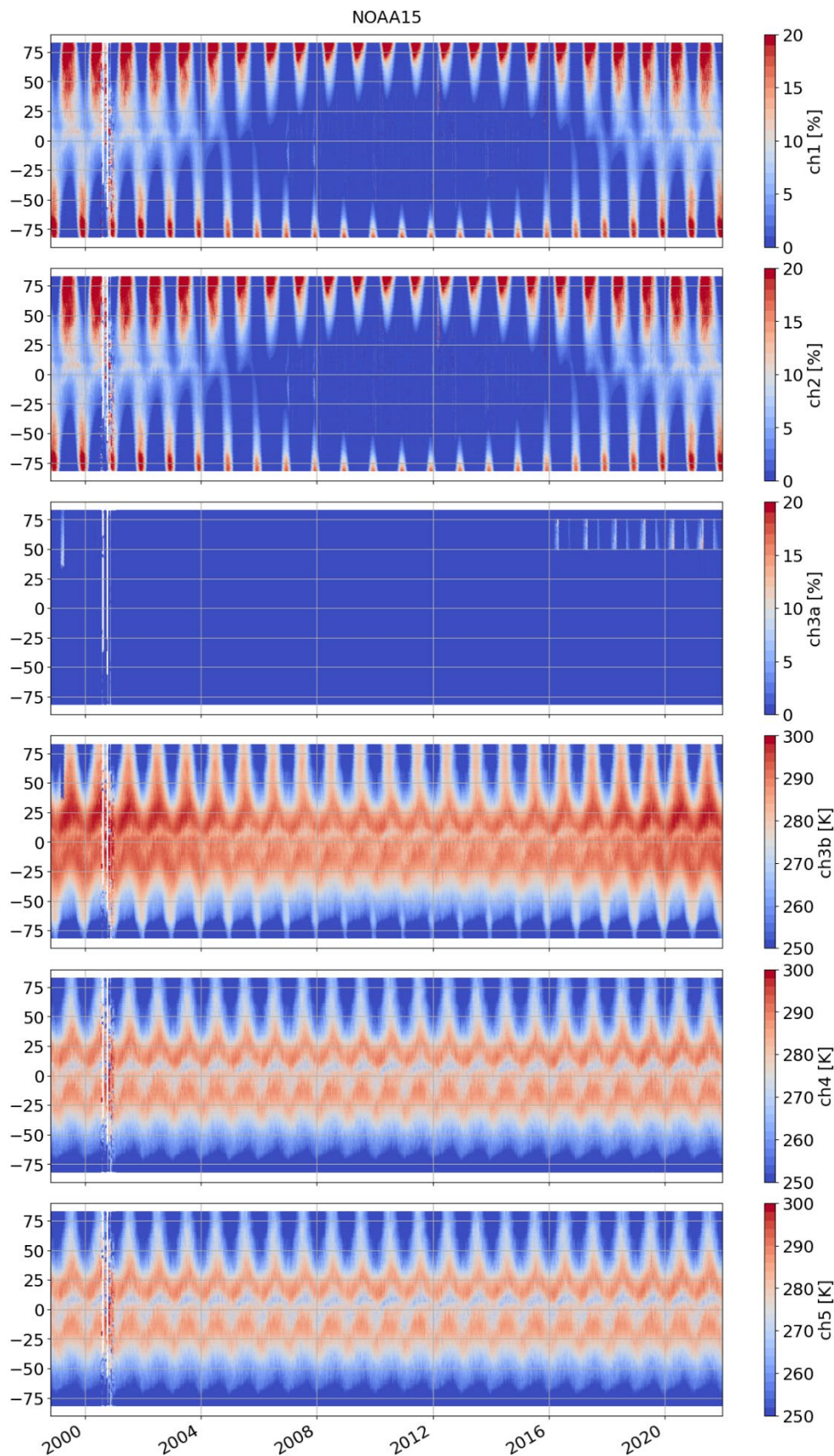


Figure 54: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-15. Data are shown for the descending node only.

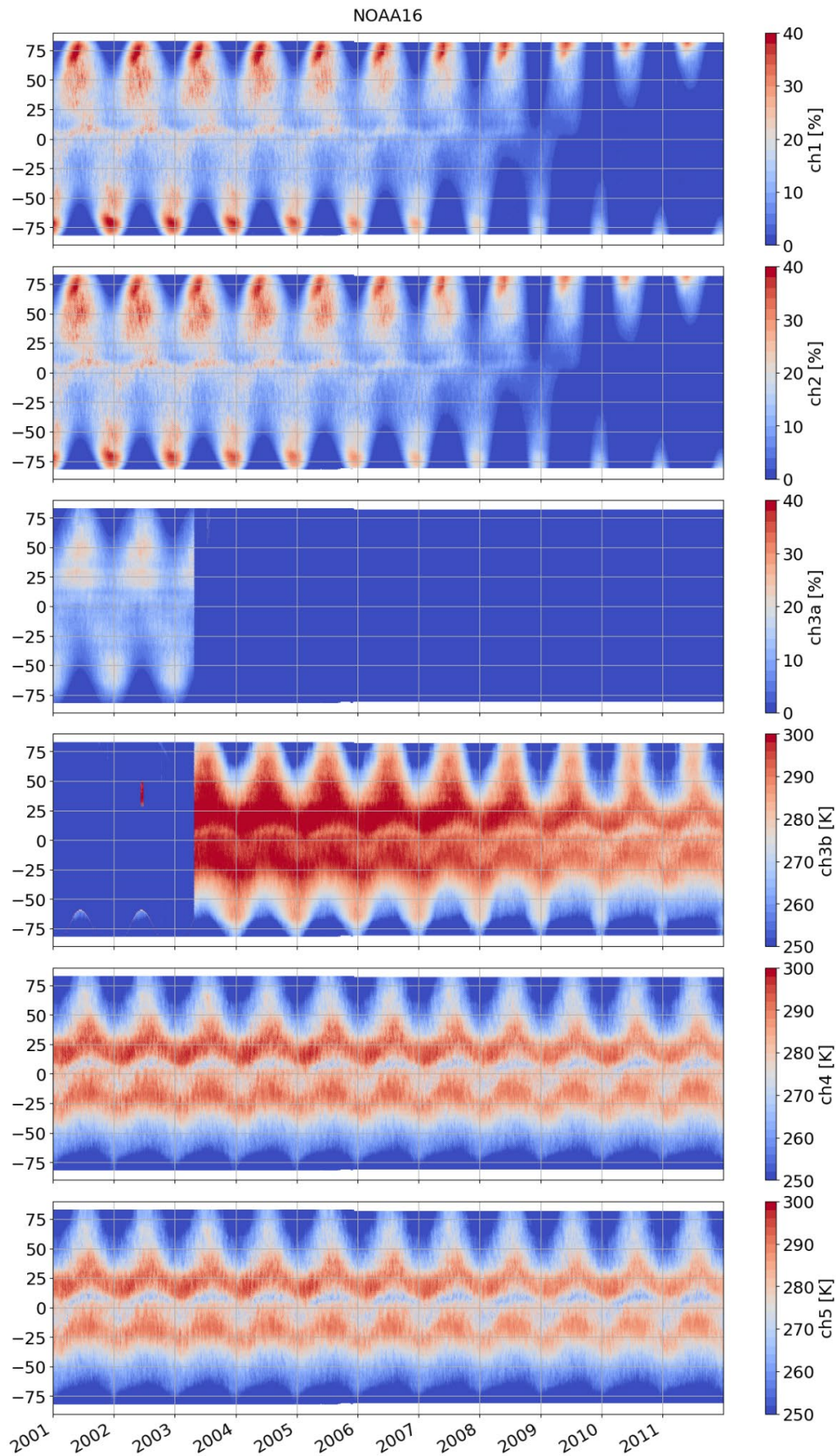


Figure 55: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-16. Data are shown for the ascending node only.

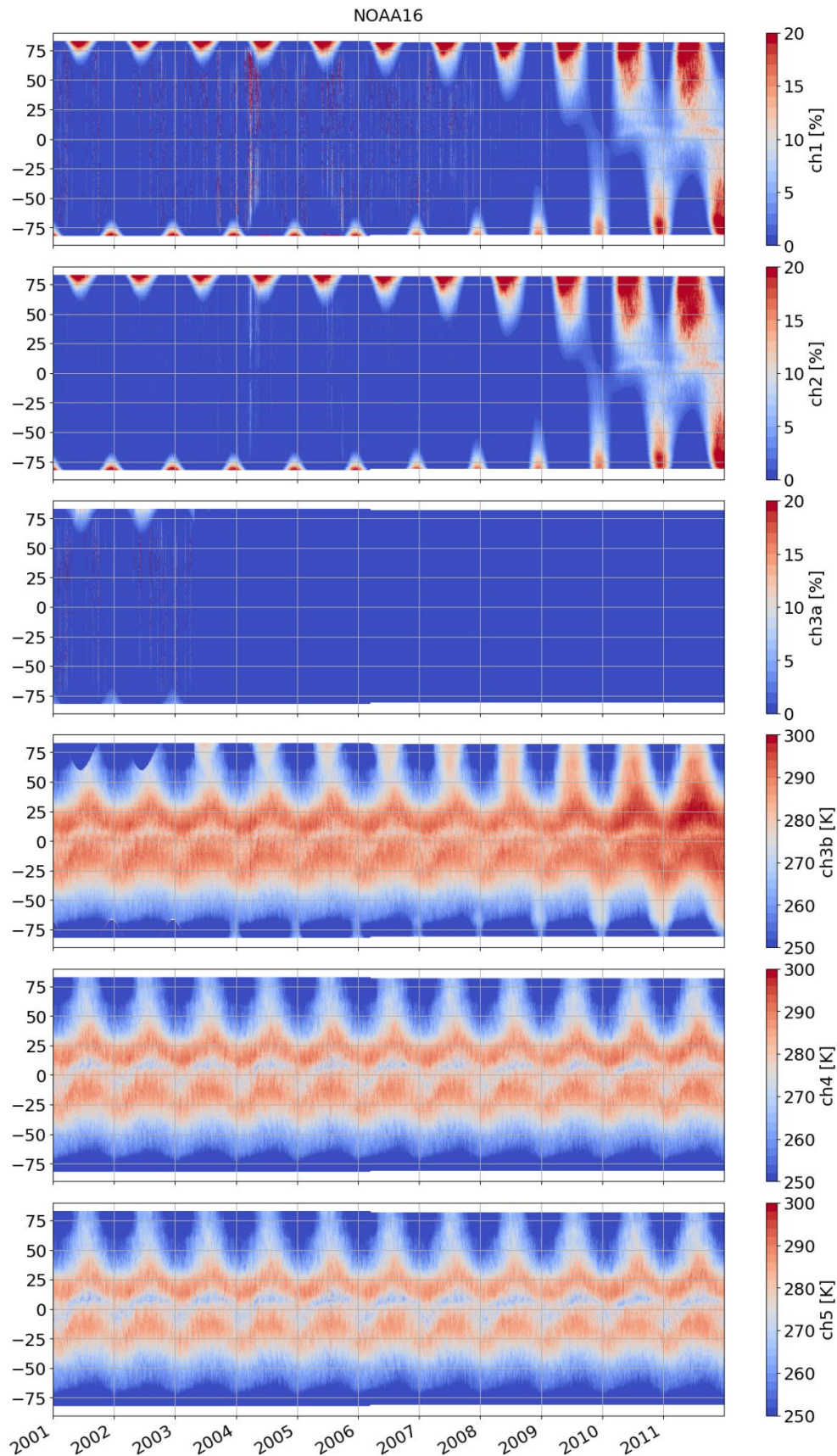


Figure 56: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-16. Data are shown for the descending node only.

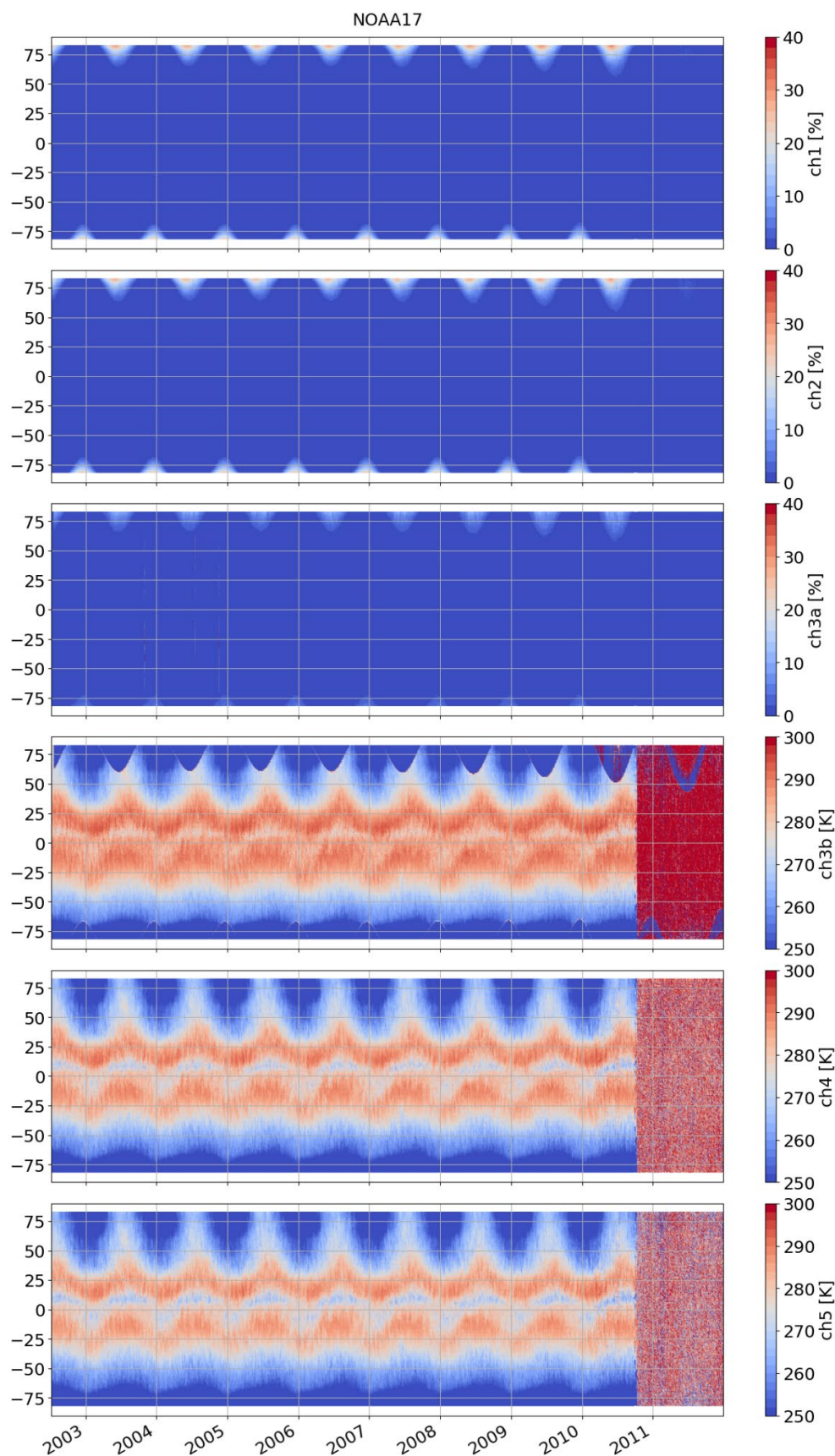


Figure 57: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-17. Data are shown for the ascending node only.

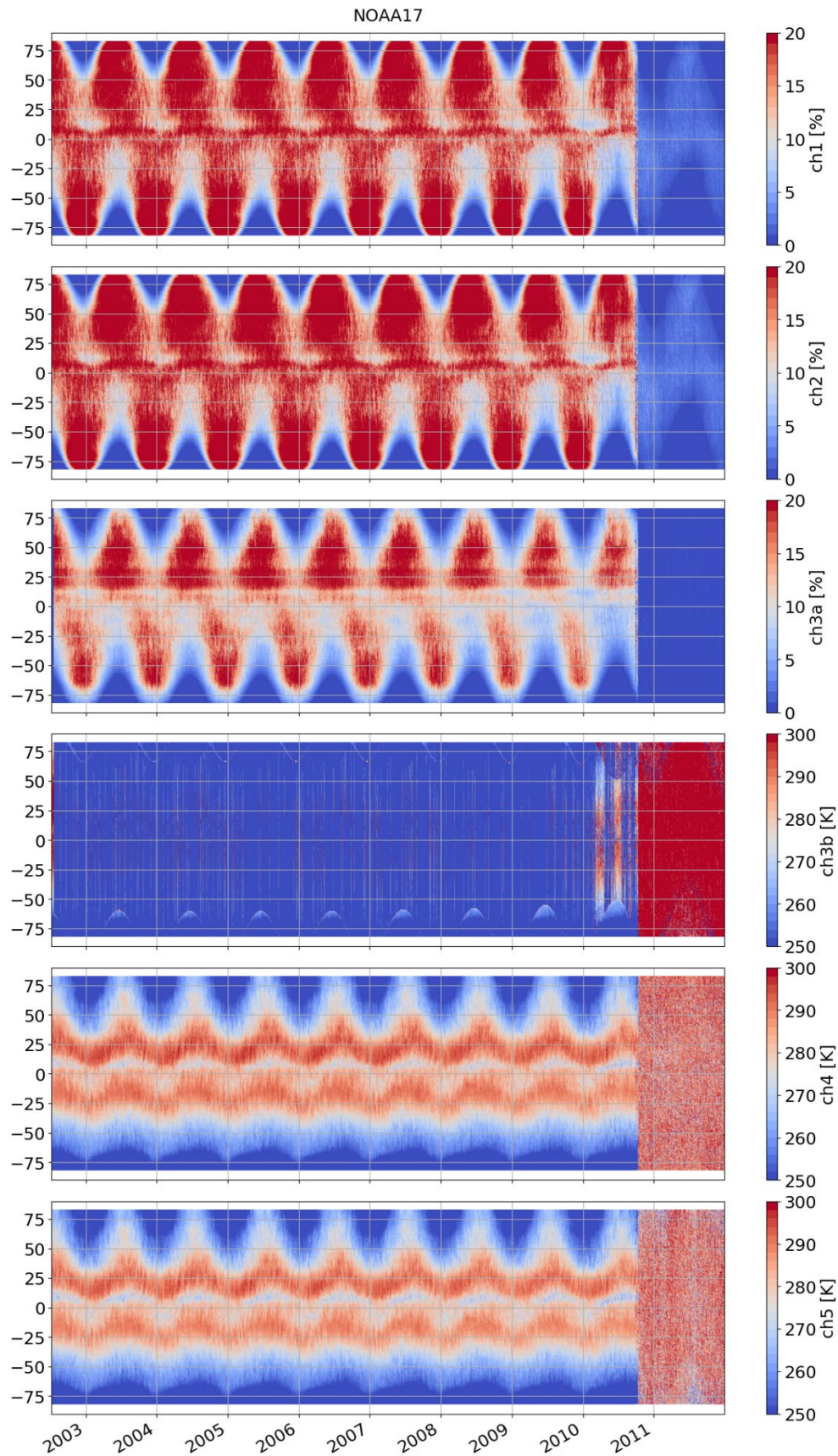


Figure 58: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-17. Data are shown for the descending node only.

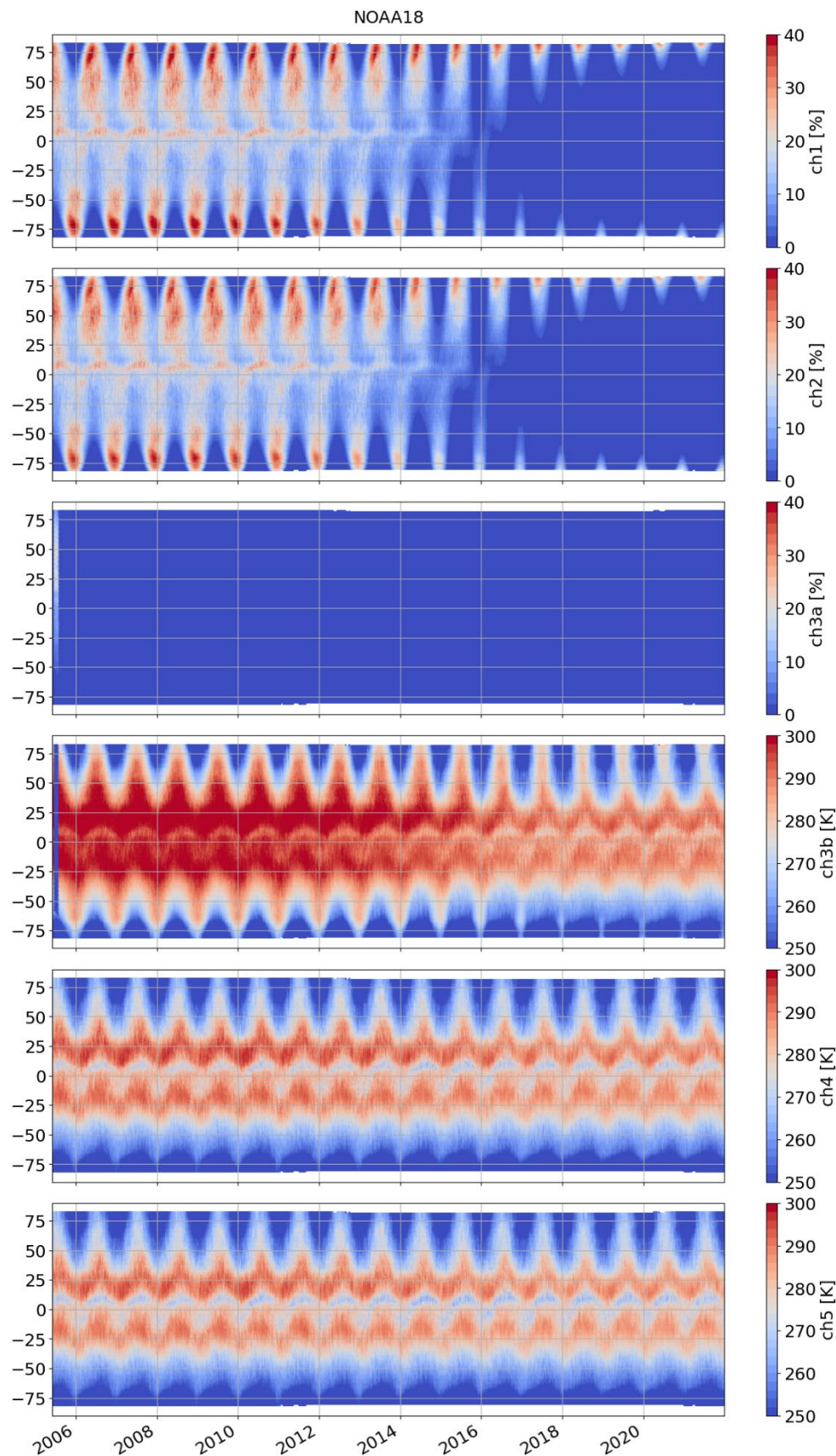


Figure 59: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-18. Data are shown for the ascending node only.

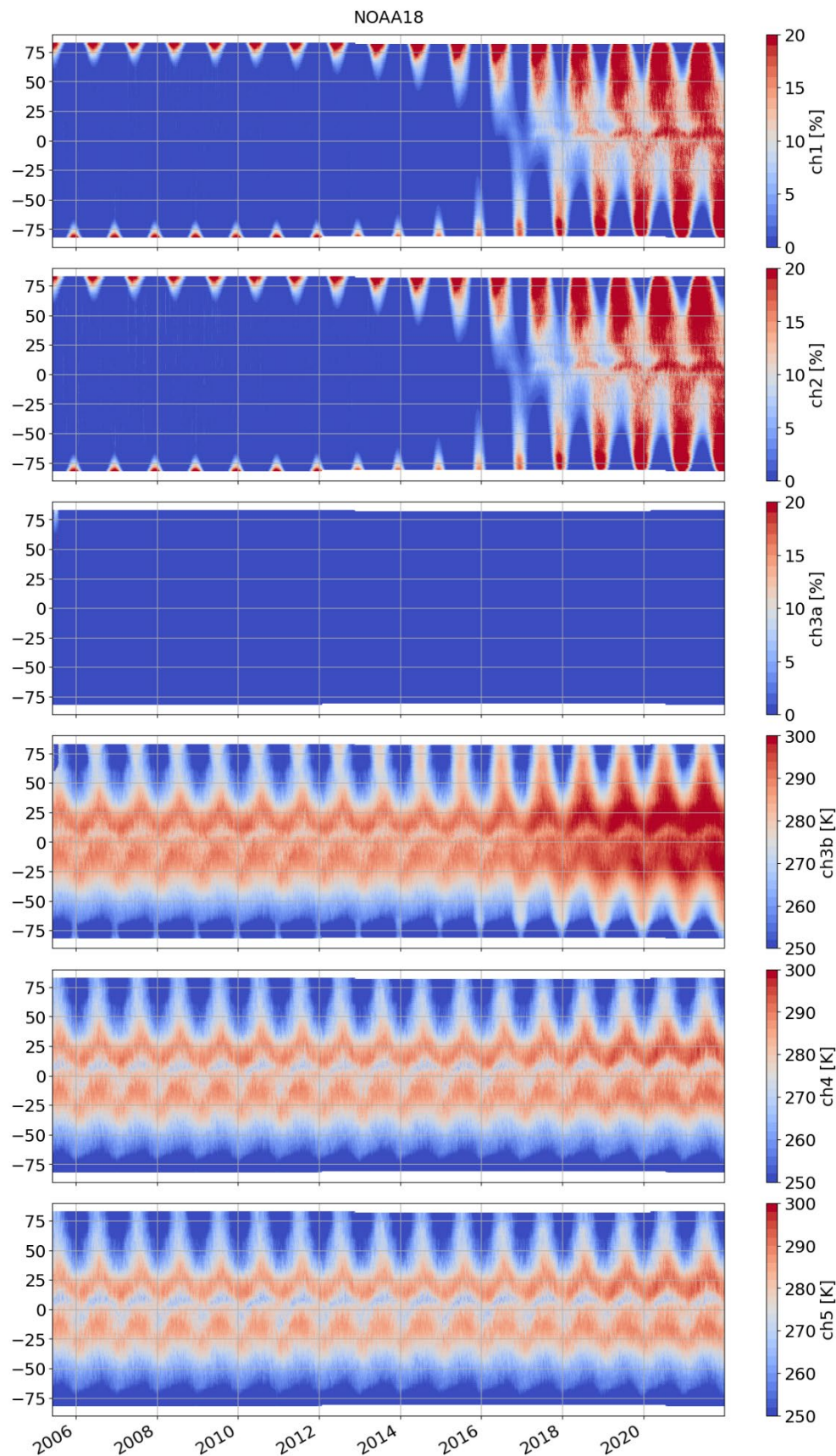


Figure 60: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-18. Data are shown for the descending node only.

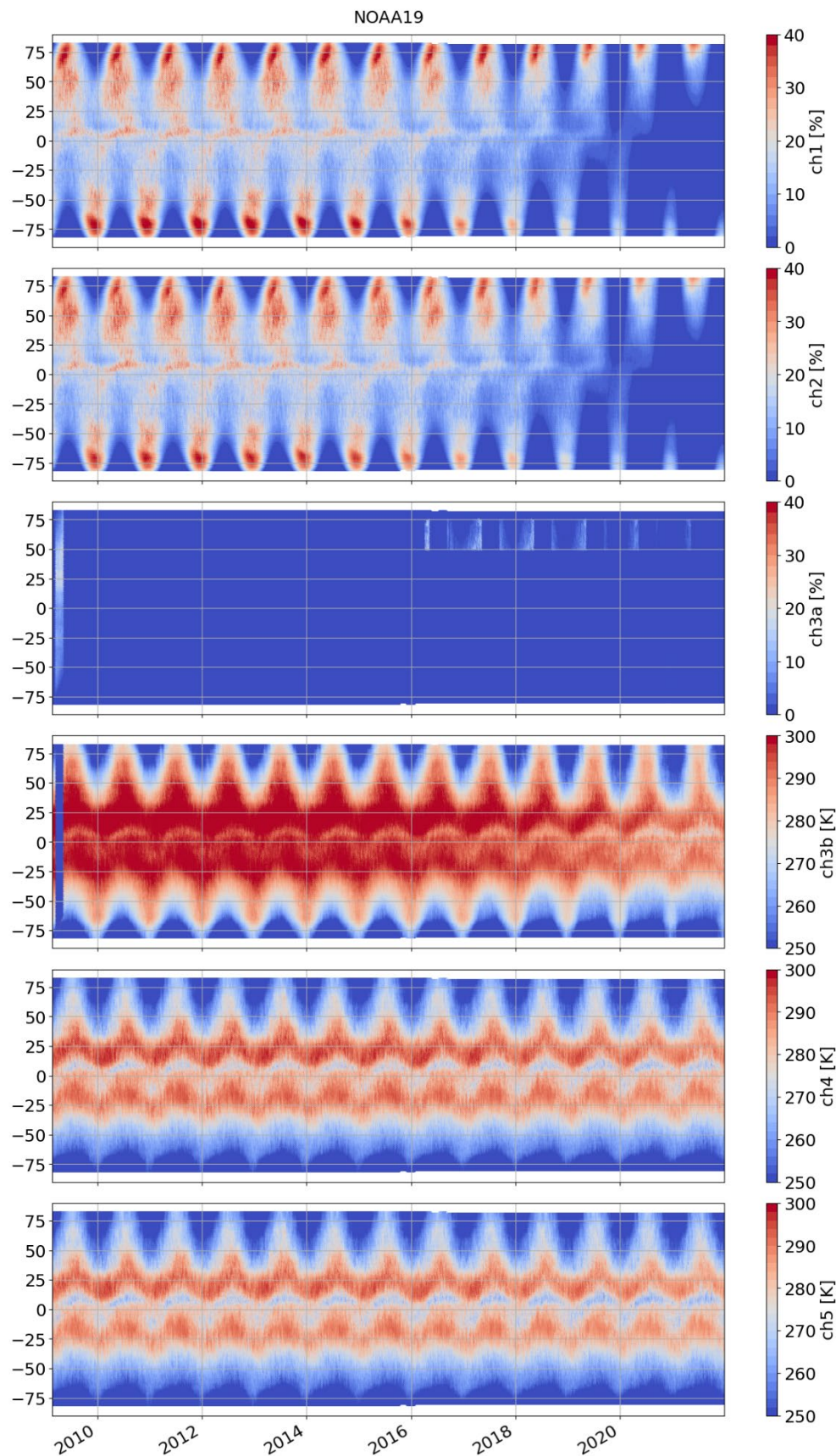


Figure 61: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-19. Data are shown for the ascending node only.

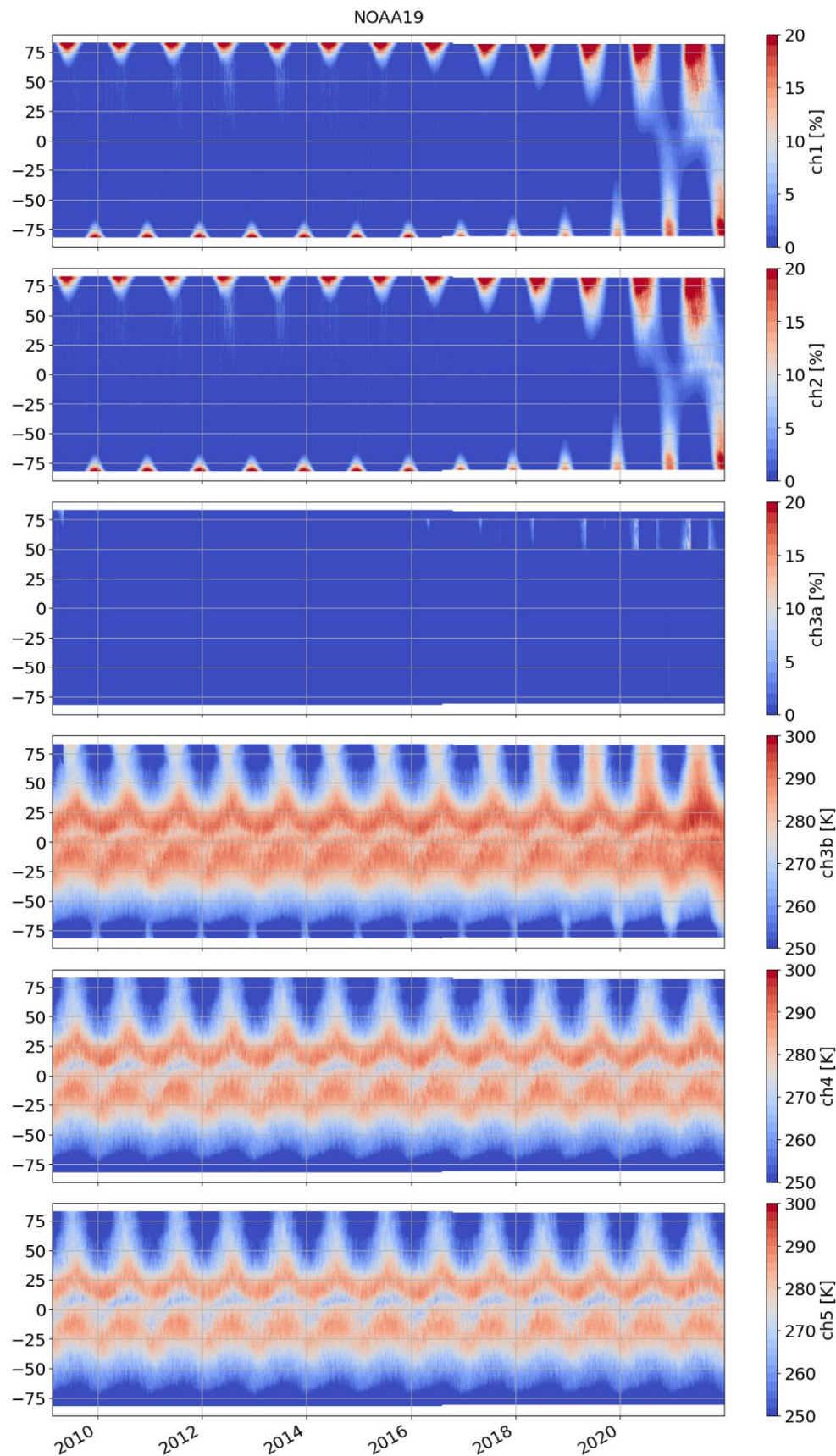


Figure 62: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for NOAA-19. Data are shown for the descending node only.

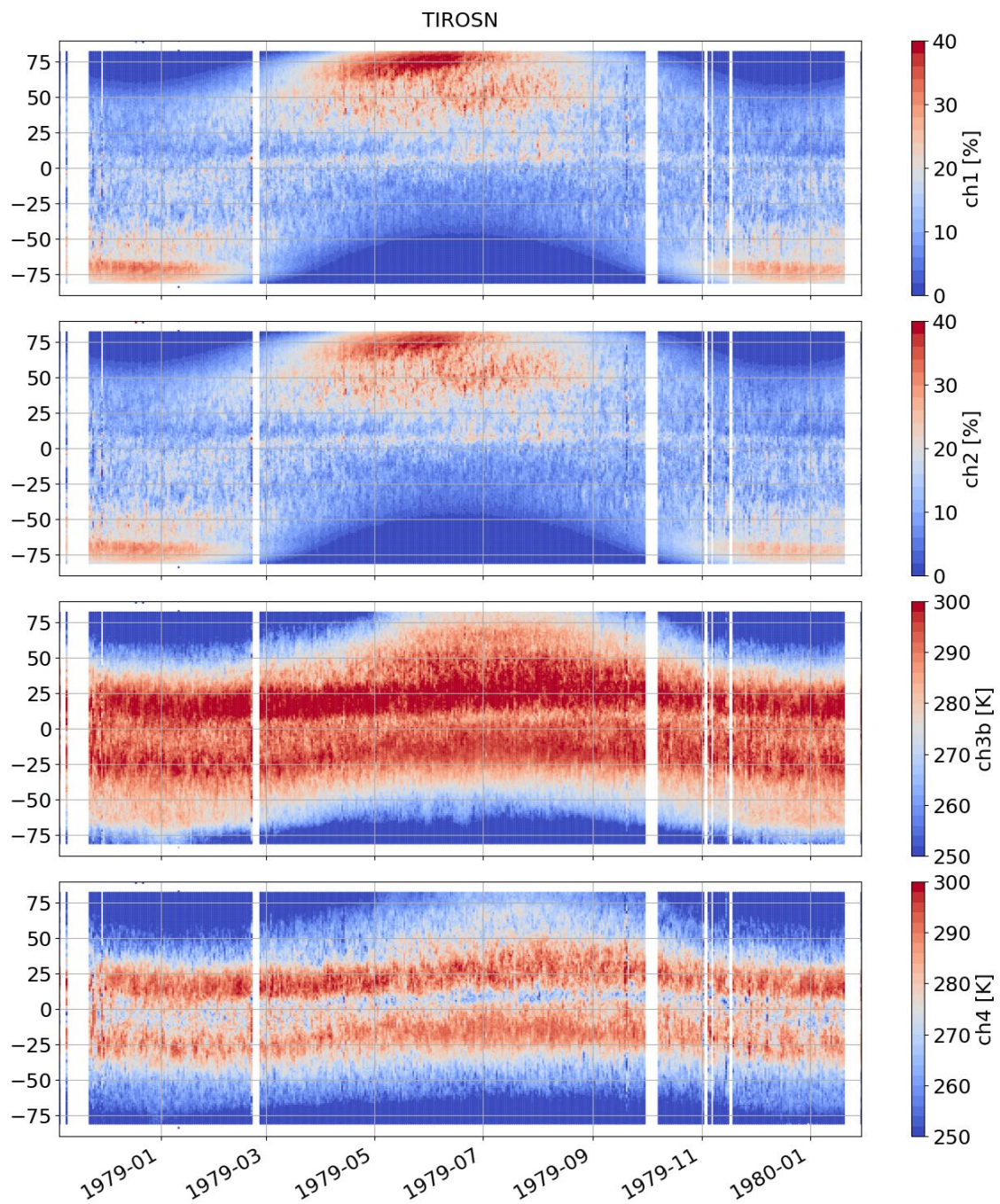


Figure 63: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for TIROS-N. Data are shown for the ascending node only.

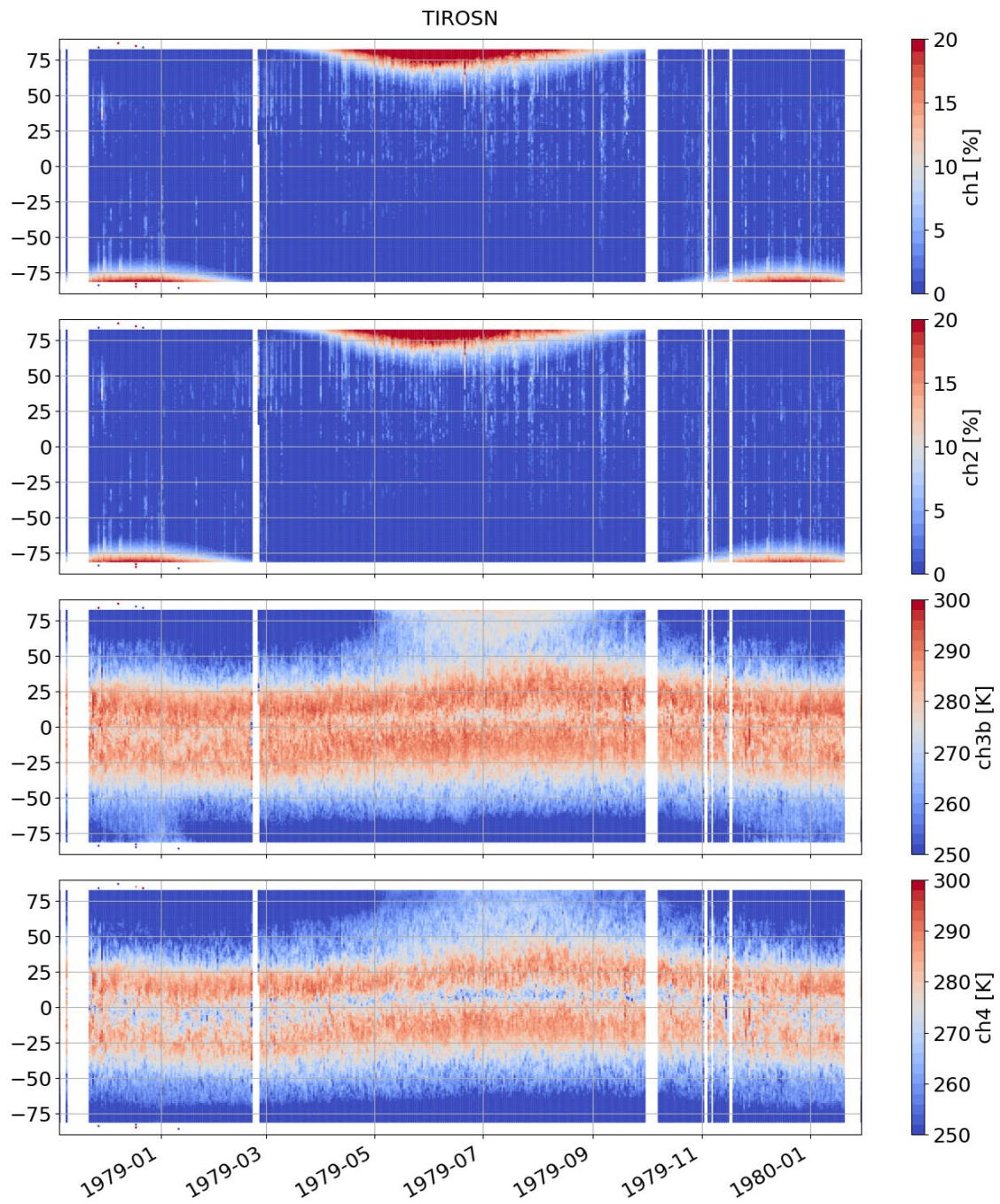
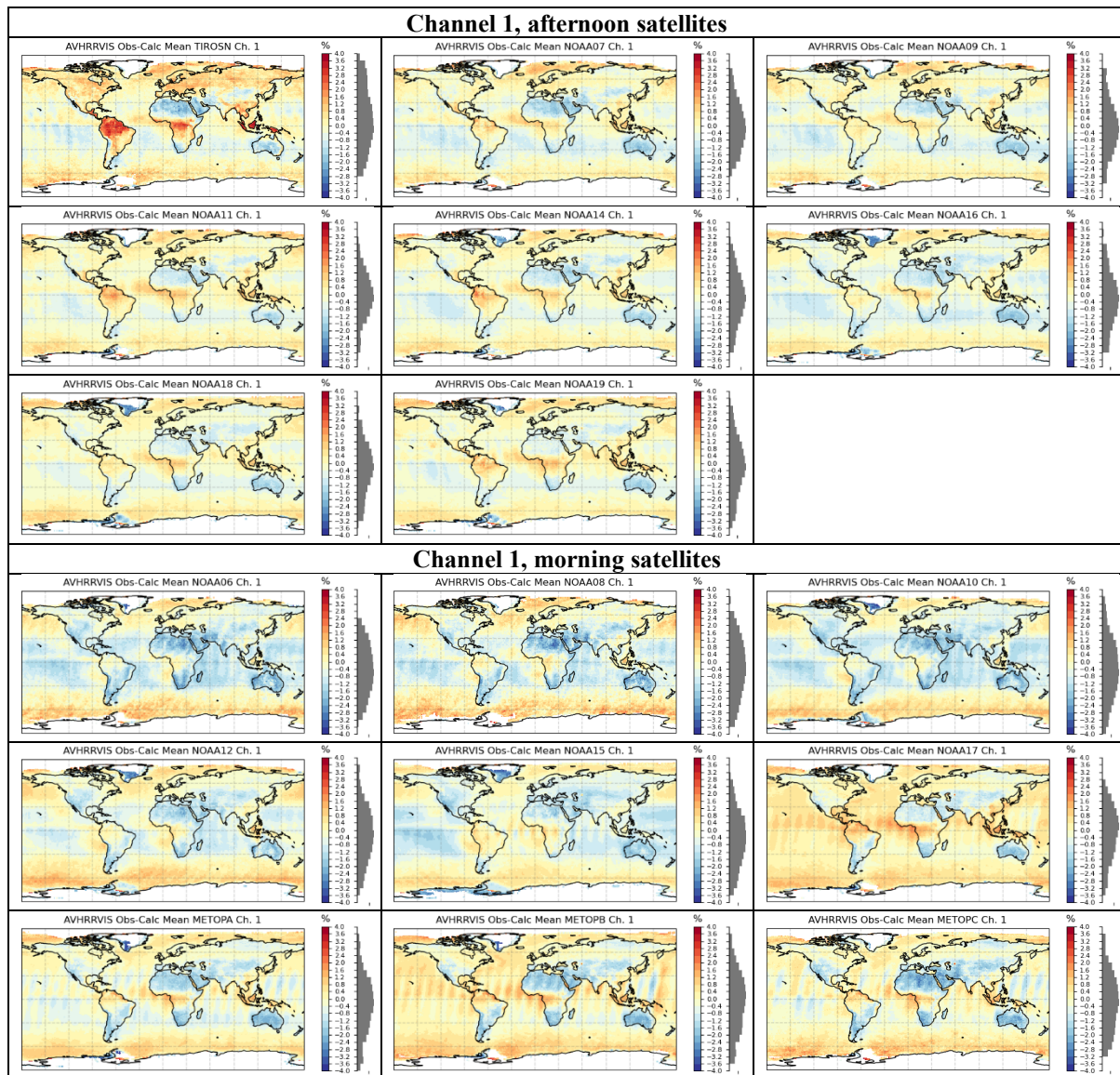


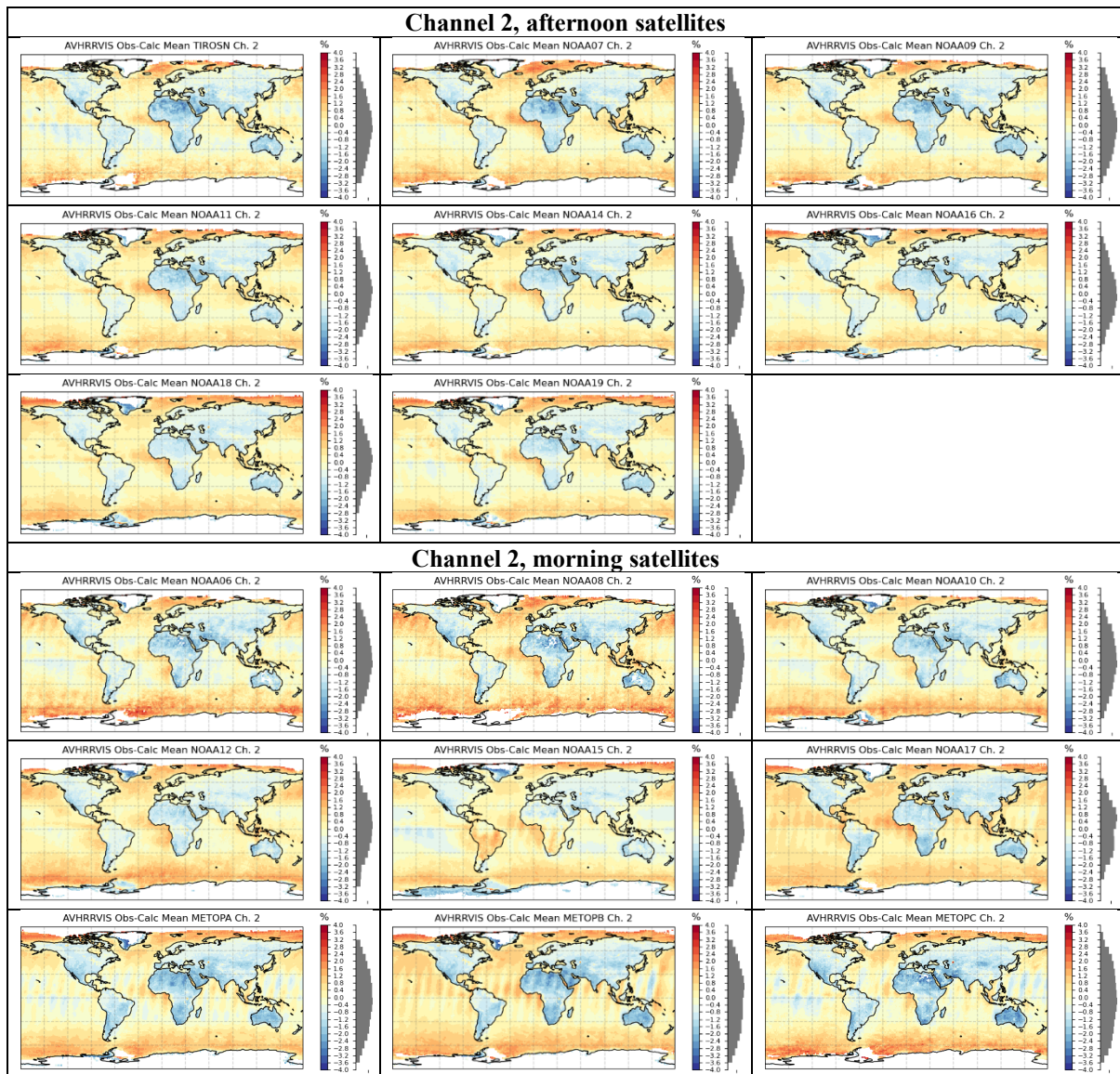
Figure 64: Hovmöller plot of daily averaged reflectance [%] and brightness temperatures [K] per 1° latitude band for TIROSN. Data are shown for the descending node only.

APPENDIX B MAPS

B.1 Visible channels (reflectance)

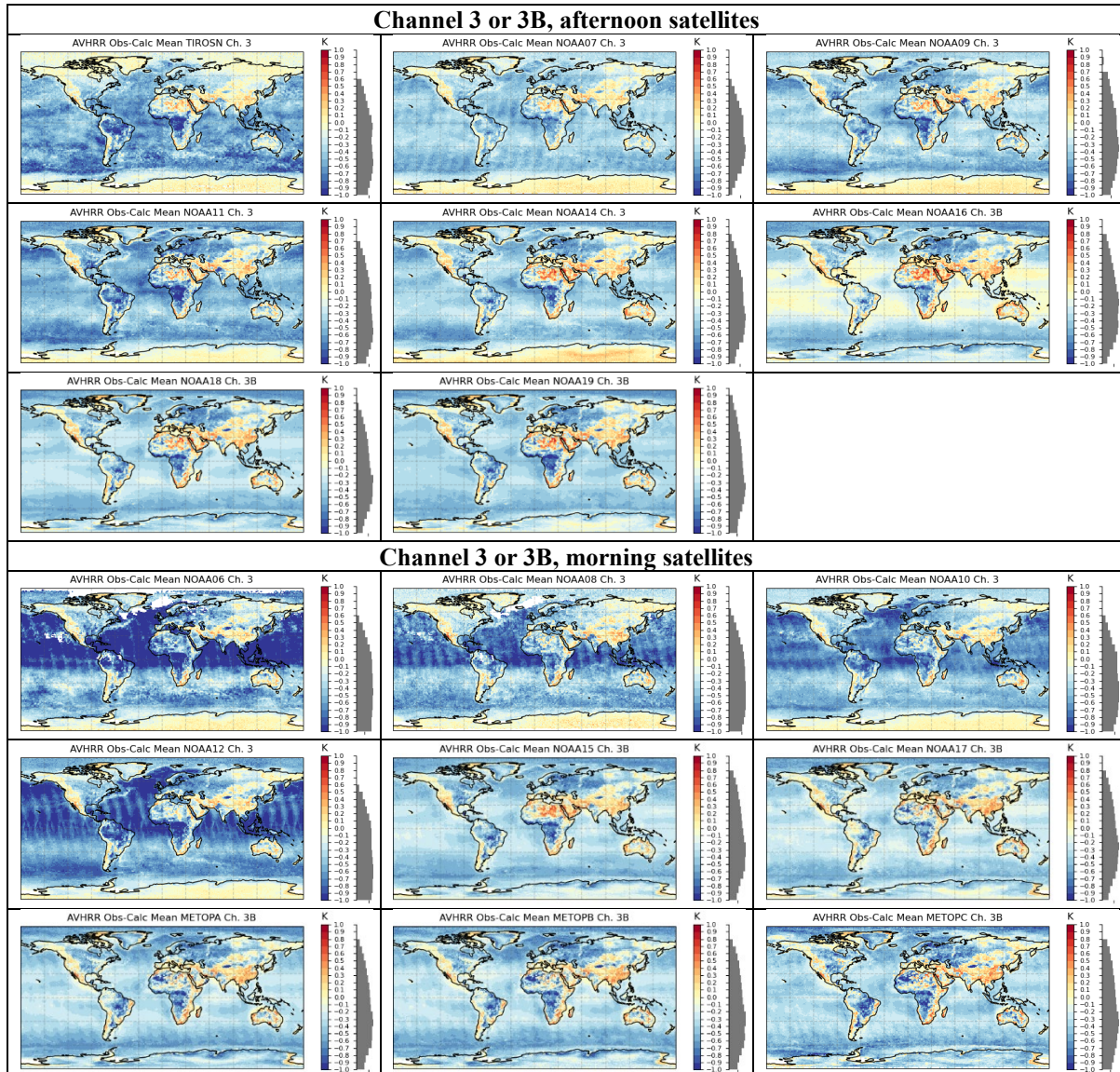
The following maps show means of differences observation reflectance (in %) minus simulated reflectance (in %), for data that are within the range [-5 %, 5 %].

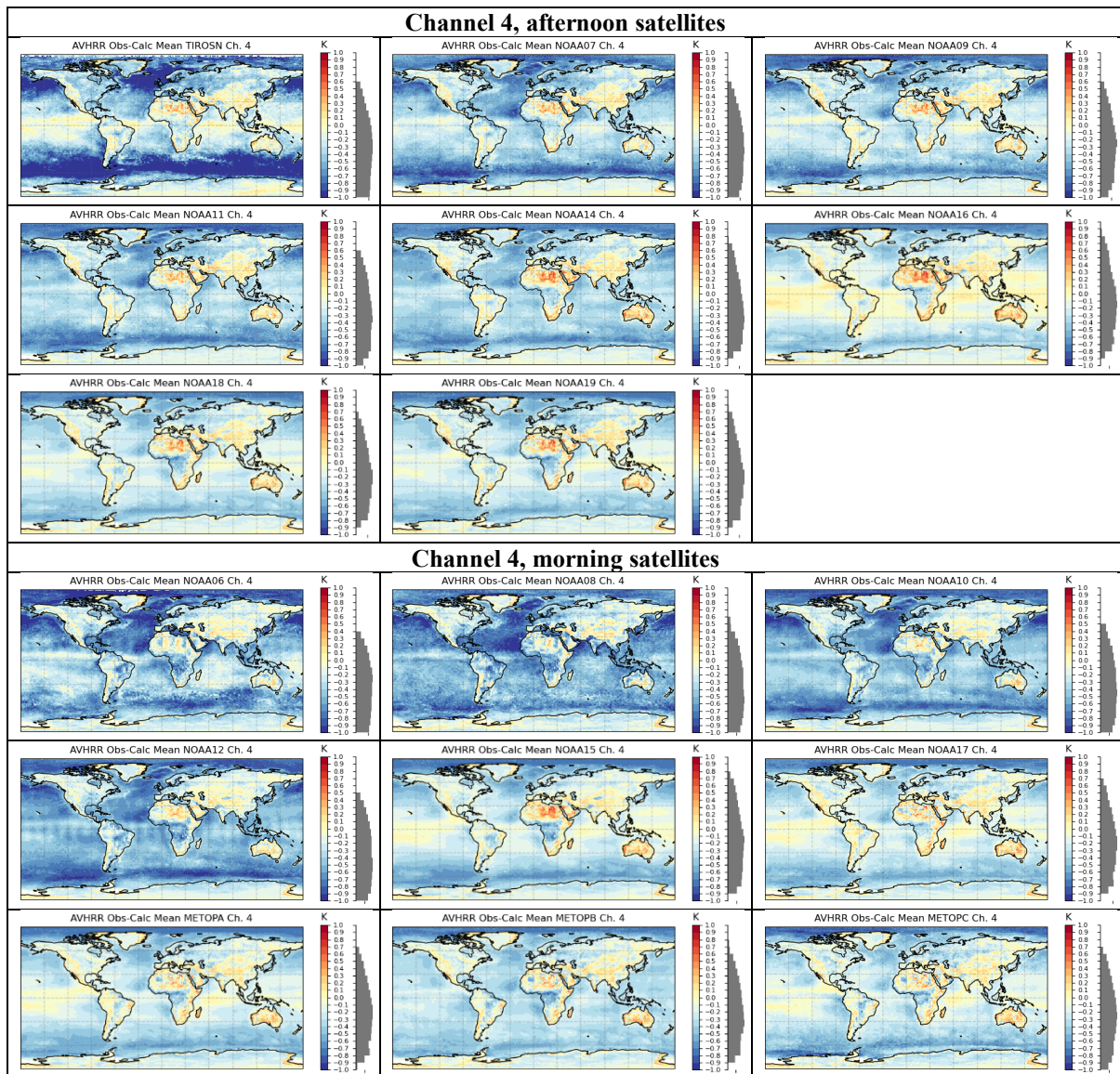


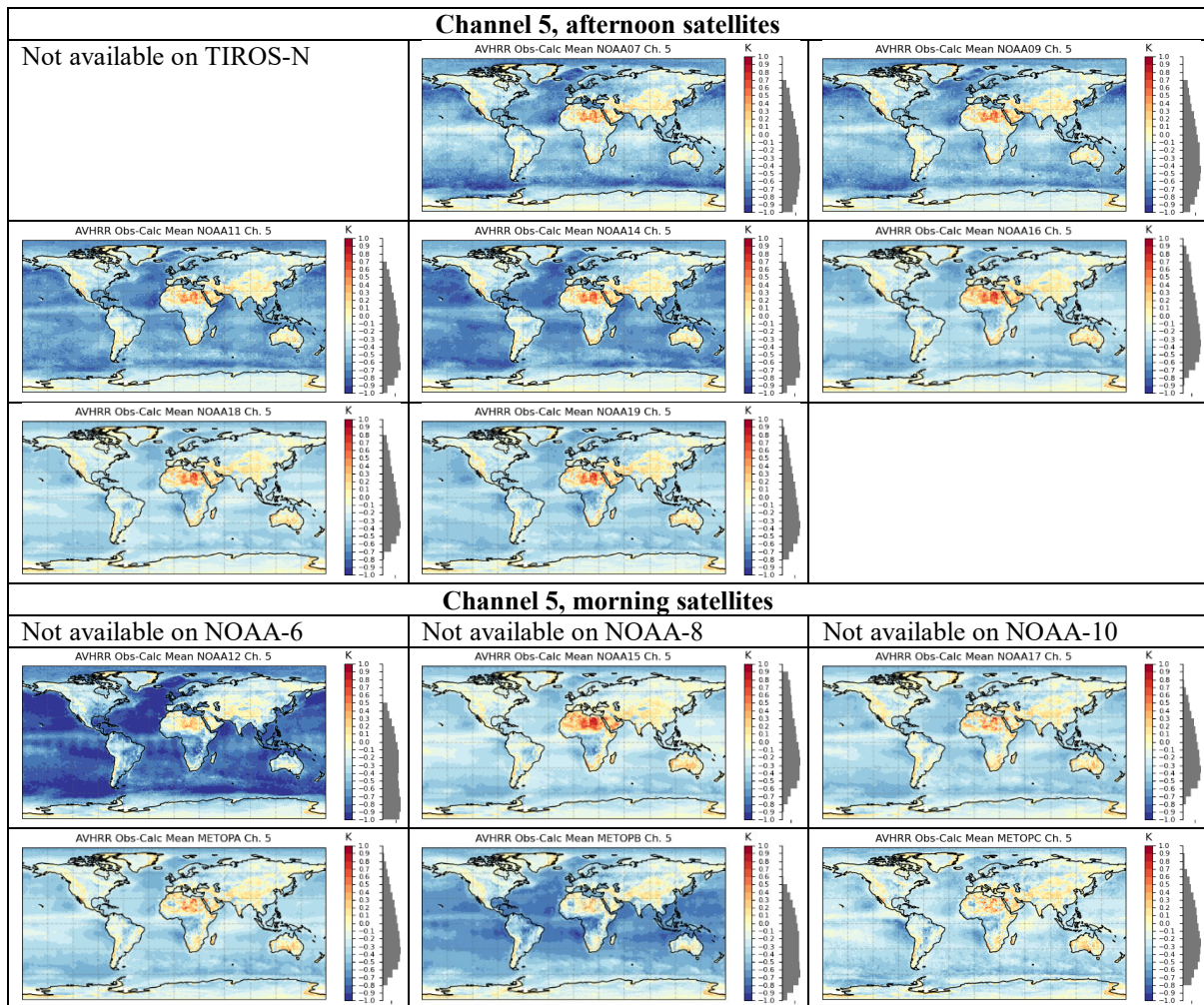


B.2 Infrared channels (brightness temperatures)

The following maps show means of differences observation minus simulated brightness temperature (in K), for data that are within the range [-2 K, 2 K].







APPENDIX C RADIANCE AT SOME SPECIFIC LOCATION

In this section, we show the plots as in section 3.3 for 4 sites: Lybia 1, Mosambic and Arabian sea and SOV.

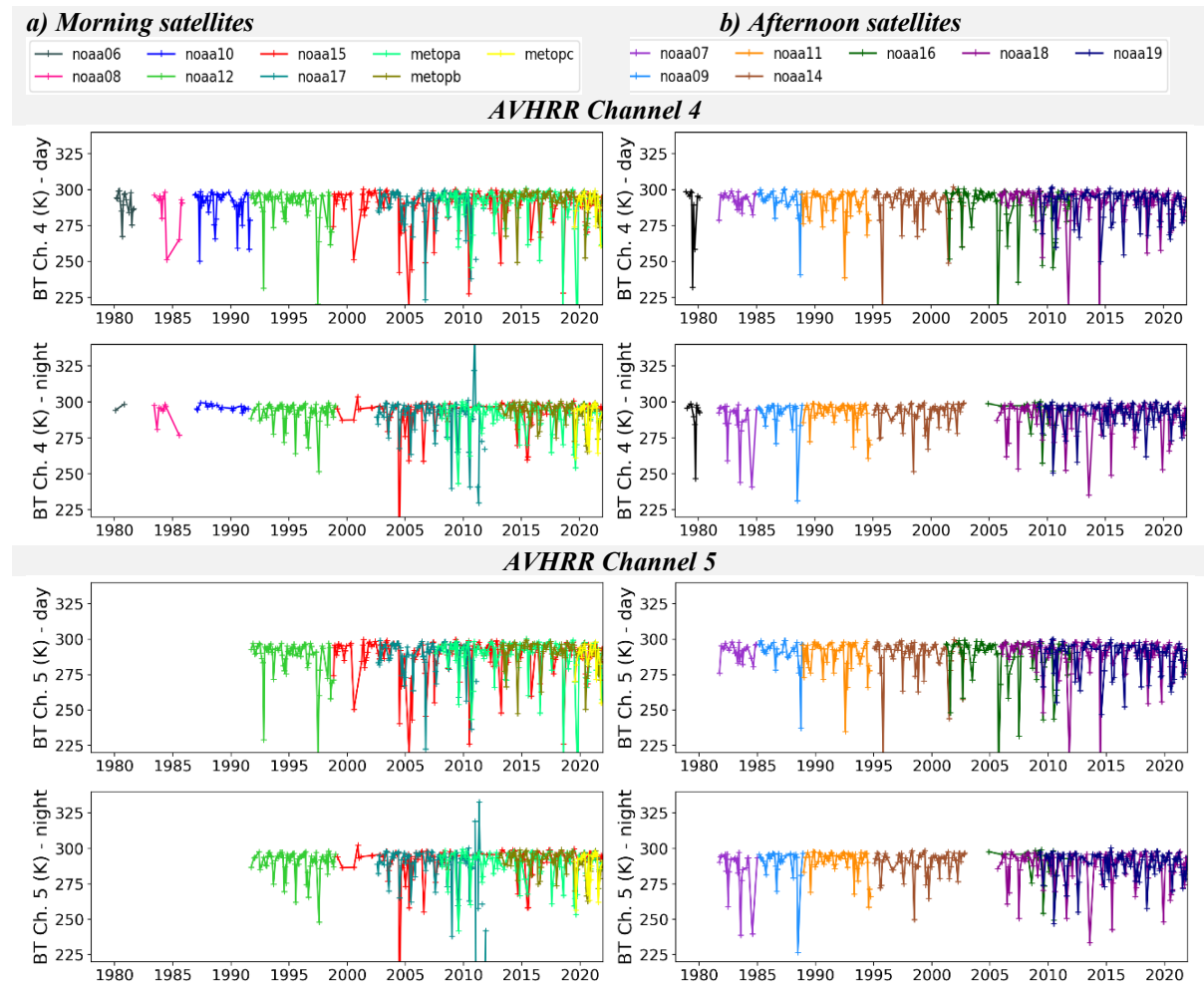


Figure 65: Monthly timeseries of AVHRR BT in IR channels 4 and 5 for day and night at site Arabian_sea for all AVHRR instrument aboard the morning (left) and afternoon (right) satellites.

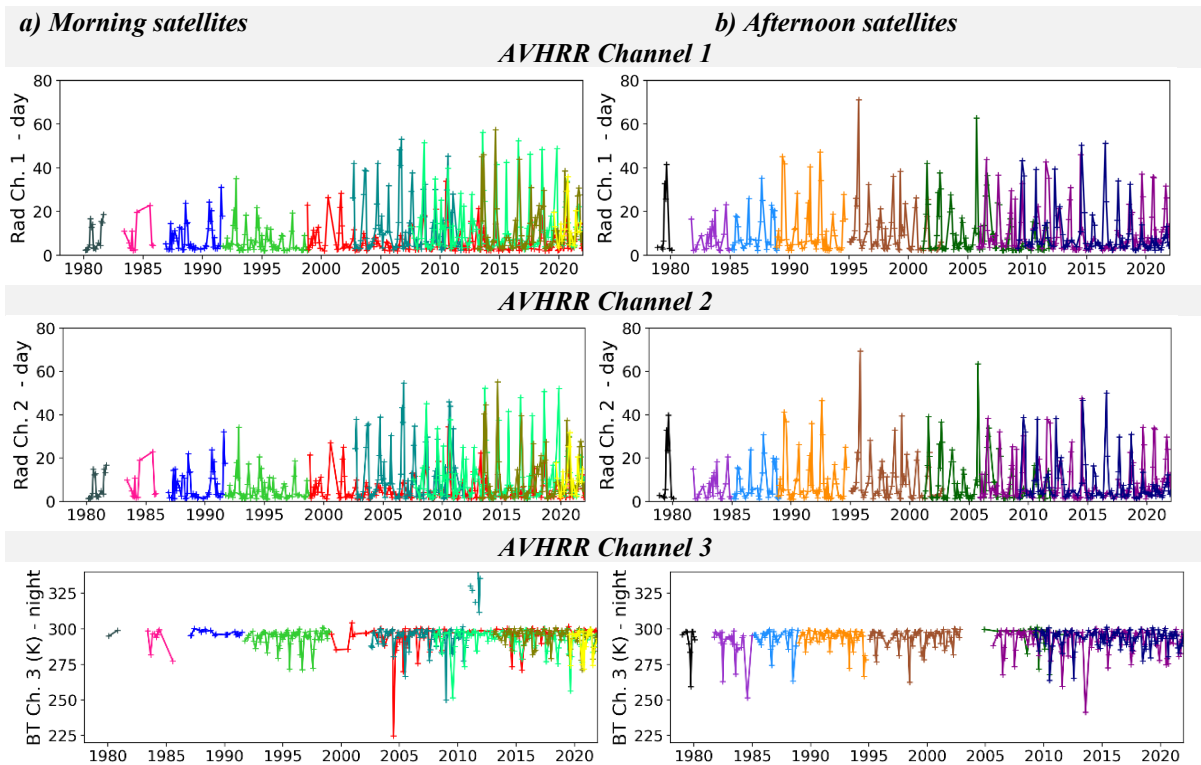


Figure 66: Monthly time series of AVHRR BT in the VIS channels 1,2 and 3a for day at site Arabian_sea site for all AVHRR instrument aboard the morning (left) and afternoon (right) satellites.

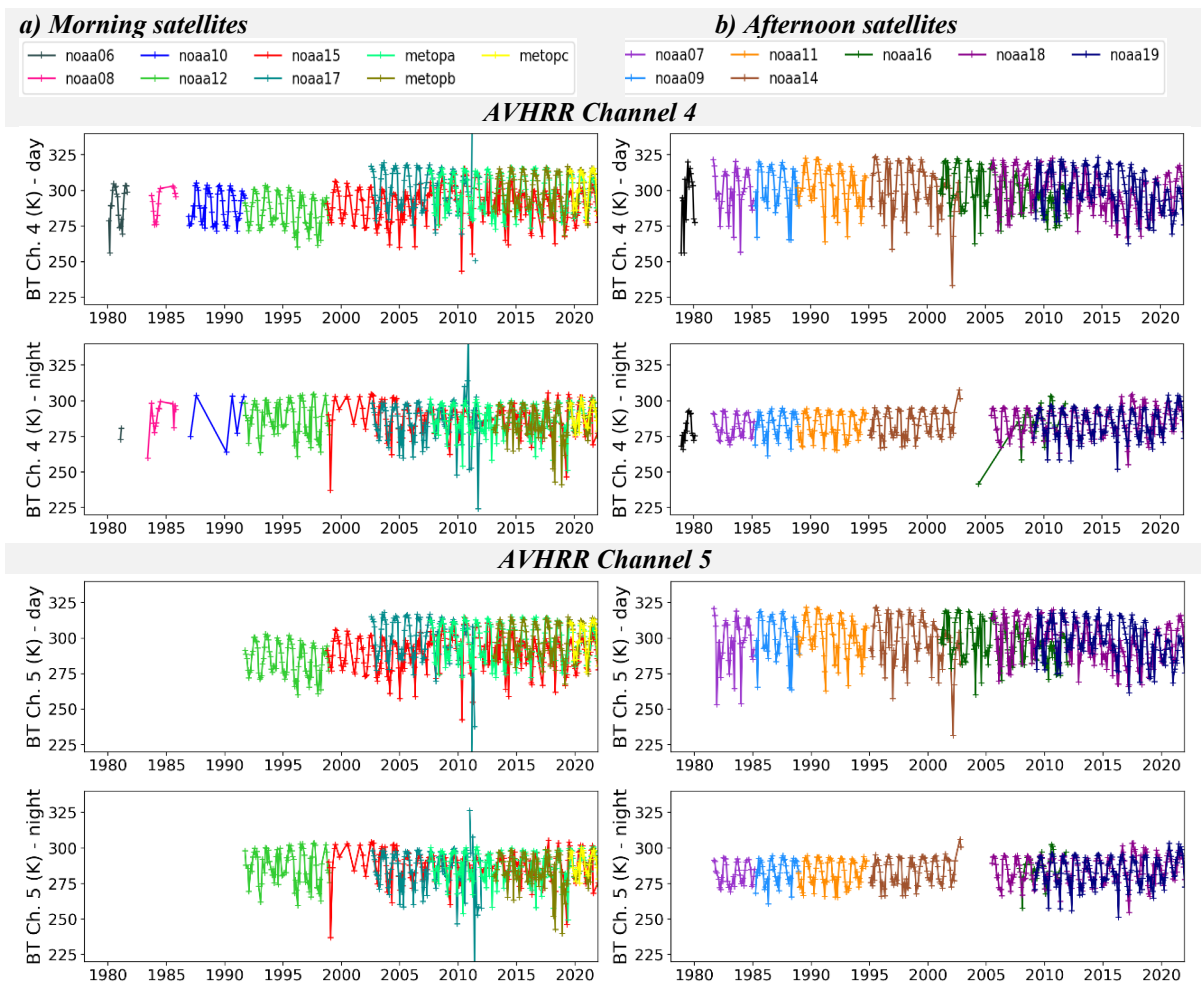


Figure 67: Monthly time series of AVHRR BT in IR channels 4 and 5 for day and night at site SOV for all AVHRR instrument aboard the morning (left) and afternoon (right) satellites.

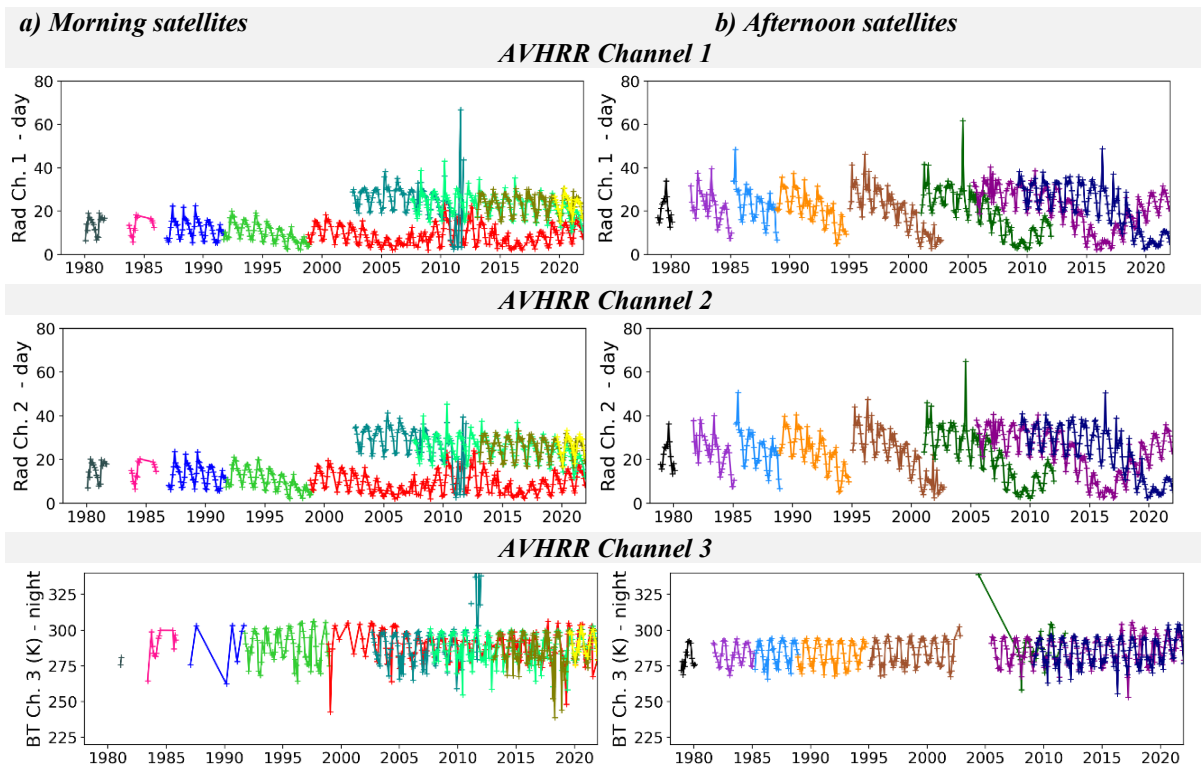


Figure 68: Monthly time series of AVHRR BT in the VIS channels 1,2 and 3a for day at site SOV for all AVHRR instrument aboard the morning (left) and afternoon (right) satellites.

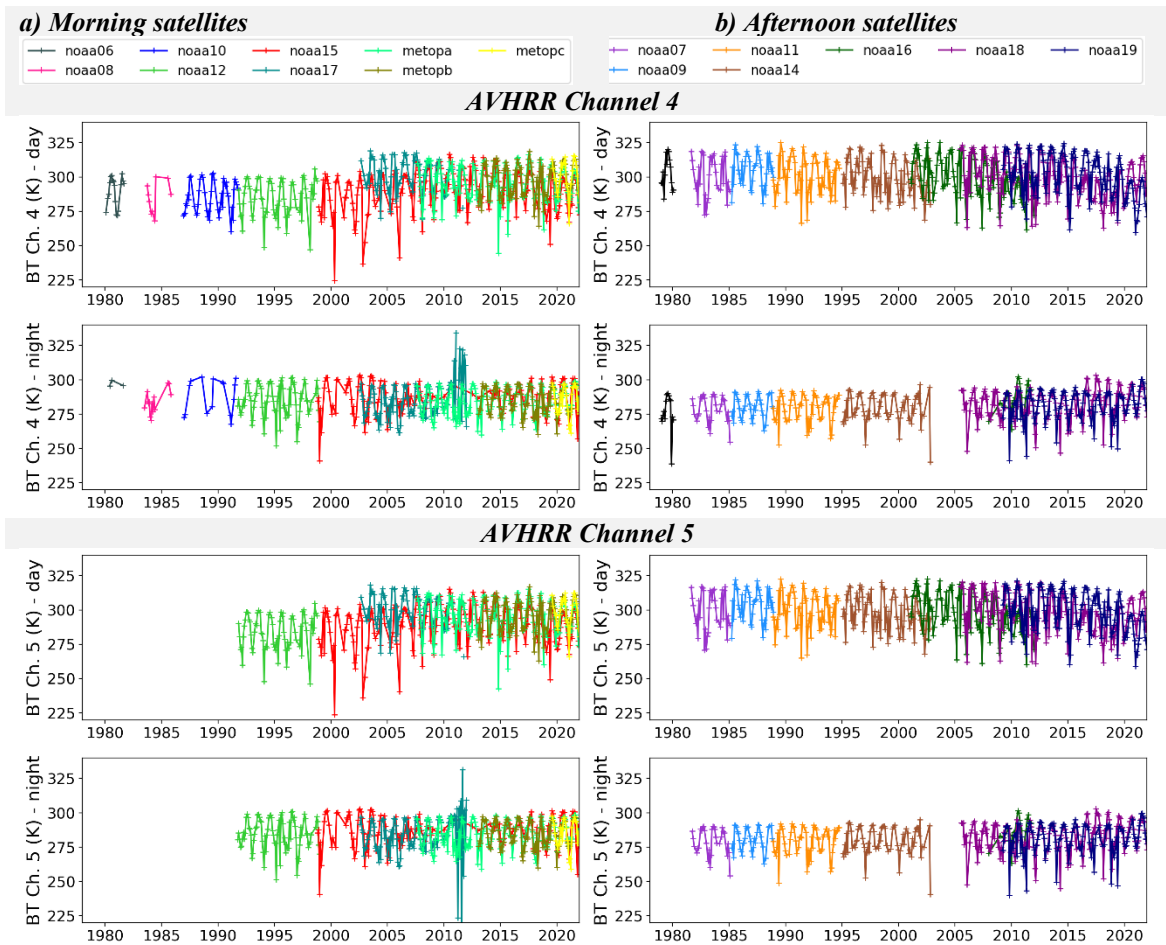


Figure 69: Monthly timeseries of AVHRR BT in IR channels 4 and 5 for day and night at site Libia_0001 for all AVHRR instrument aboard the morning (left) and afternoon (right) satellites.

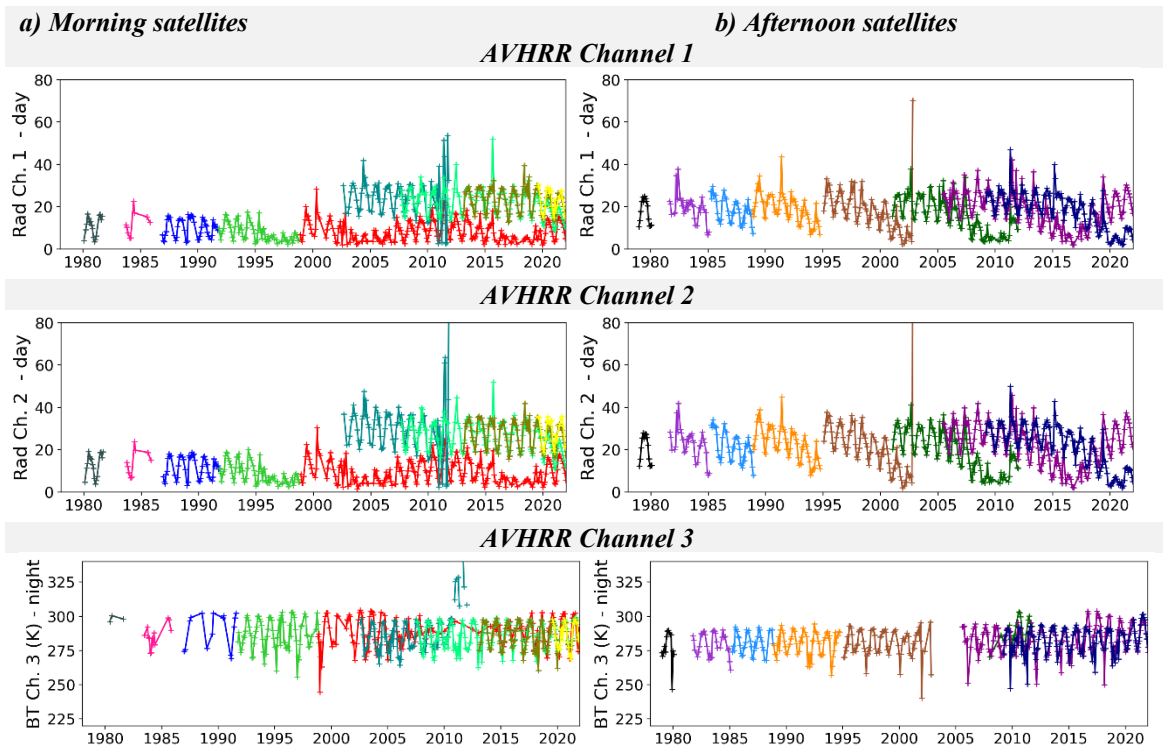


Figure 70: Monthly timeseries of AVHRR BT in the VIS channels 1,2 and 3a for day at site Libia_0001 for all AVHRR instrument aboard the morning (left) and afternoon (right) satellites.

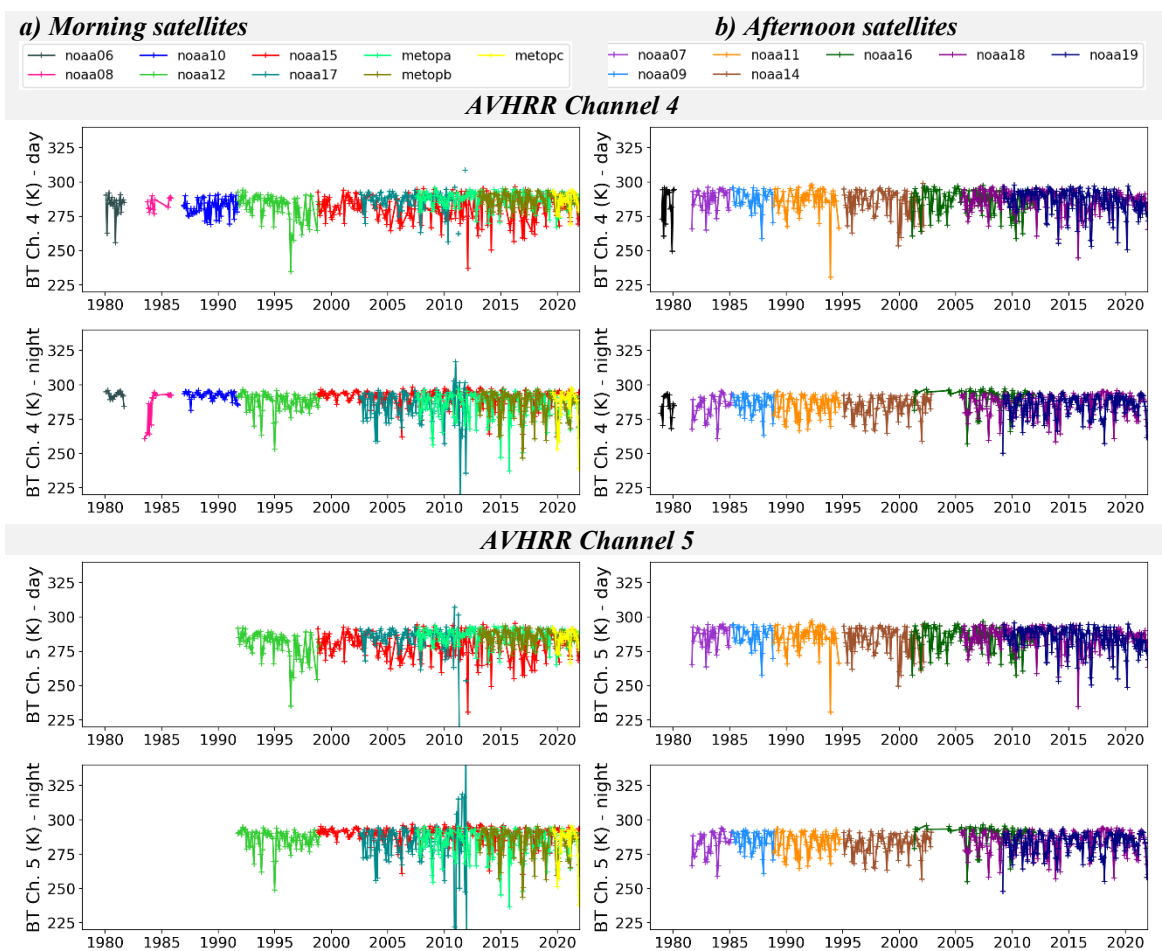


Figure 71: Monthly timeseries of AVHRR BT in IR channels 4 and 5 for day and night at site Mozambique for all AVHRR instrument aboard the morning (left) and afternoon (right) satellites.

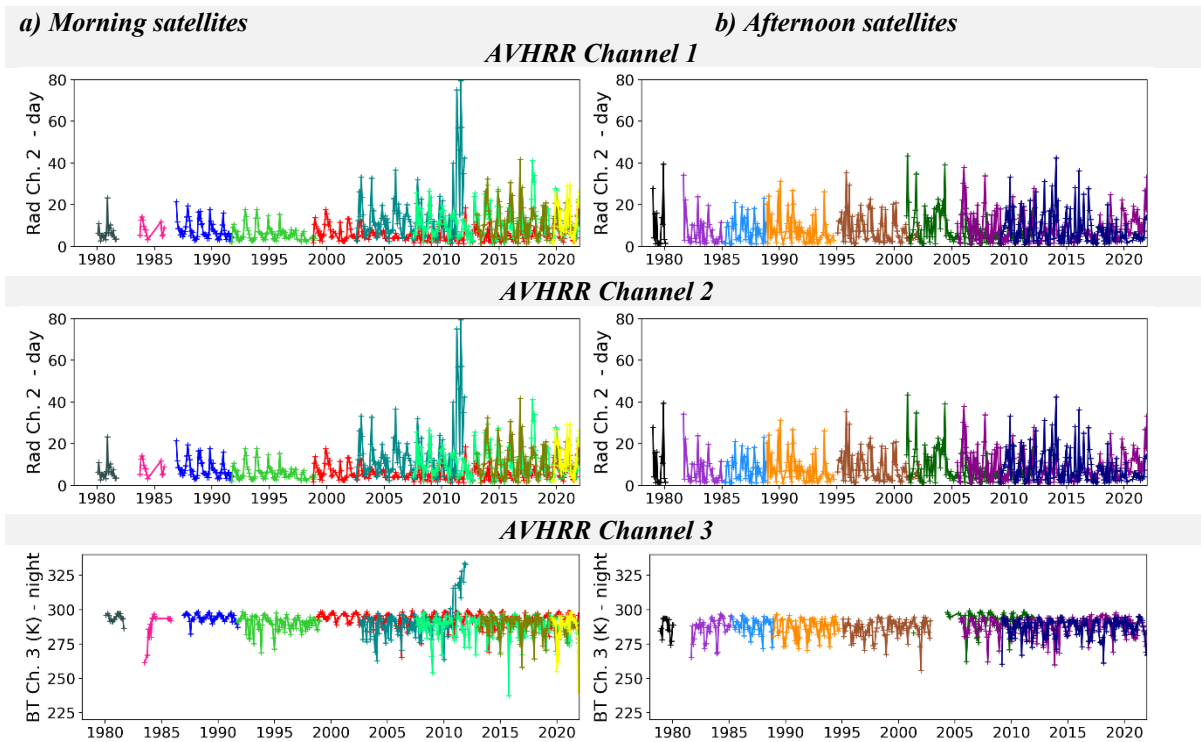


Figure 72: Monthly timeseries of AVHRR BT in the VIS channels 1,2 and 3a for day at site Mozambique for all AVHRR instrument aboard the morning (left) and afternoon (right) satellites.