Copernicus Climate Change Service

Quality Evaluation Report

Fundamental Climate Data Record of Microwave Humidity Sounder SSM/T-2

Issued by: EUMETSAT
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Fundamental Climate Data Record of Microwave Humidity Sounder Release 2

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1 Introduction

This Quality Evaluation Report describes the validation of the SSM/T-2 Fundamental Climate Data Record (FCDR) Release 2 produced for the Copernicus Climate Change Service (C3S) [AD1]. The SSM/T-2 instruments were flown aboard Defense Meteorological Satellite Program (DMSP) satellites F11, F12, F14, and F15. This FCDR is built upon the Release 1 of SSM/T-2 FCDR produced by the EU FIDUCEO (FIDelity and Uncertainty in Climate data records from Earth Observations) Horizon 2020 project. A key objective of the FIDUCEO project was the derivation and provision of fully characterised measurement uncertainties, following the fundamental principles of metrology. Thus, the FCDR is provided with detailed quality and uncertainty information that offer users additional value compared with the conventional datasets that only contain antenna temperature (Ta) or brightness temperature (BT). On top of this, Release 2 incorporates additional quality and meteorological information such as cloud and surface flags based on retrievals using Special Sensor Imager (SSMI) instruments, which were flown together with the SSM/T-2 instruments.

This report is concerned only with the validation of the overall data record considering the additional parameters added in the Release 2. The Ta and their uncertainties have already been validated in the FIDUCEO project and the information is provided in [RD1, RD2, RD3]. The validation of the method to derive the cloud flags is described in [RD4].

1.1 Purpose of the document

Within OTask 7.5 in C3S_311b [AD1] EUMETSAT provides an FCDR from SSM/T-2 measurements. The FCDR is defined by a set of three documents. These documents are essential for users to use and understand the products. The documents are:

- Algorithm Theoretical Baseline Document (ATBD) (methods and algorithm description) [RD5];
- Quality Evaluation Report (informs on the accuracy, precision, and stability of the product) [this document];
- User Guide (provides essential information for the user on the product definition, how to access and work with the data, and contains information on major limitations on the usage) [RD6].

This Quality Evaluation Report aims to provide information on the product quality for the SSM/T-2 FCDR.

1.2 Structure

This document is structured as follows:

Section 1	Introduction describing the purpose and scope of this quality evaluation report
Section 2	Background provides an overview on the data used in the study
Section 3	Validation strategy summarises the approaches for validating the data records and the reference data
Section 4	Technical validation results on the file meta data and the data completeness
Section 5	Scientific validation results
Section 6	Conclusions

1.3 List of Abbreviations

Abbreviation	Description
AMSU-B	Advanced Microwave Sounding Unit - B
BT	Brightness Temperature
CEDA	U.K. Centre for Environmental Data Analysis
CF	Climate and Forecast
CM SAF	Climate Monitoring Satellite Application Facility
DMSP	Defense Meteorological Satellite Program
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA	ECMWF Re-Analysis
EU	European Union
FCDR	Fundamental Climate Data Record
FIDUCEO	Fidelity and uncertainty in climate data records from Earth Observations
FCDR	Fundamental Climate Data Record
FOV	Field of View
HOAPS	Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data
MHS	Microwave Humidity Sounder
MW	Microwave
QC	Quality control
NetCDF	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration
NRT	Near-Real-Time
NWP-SAF	Numerical Weather Prediction Satellite Applications Facility
RTTOV	Radiative Transfer for TIROS Operational Vertical Sounder
SSM/I	Special Sensor Microwave Imager
SSM/T-2	Special Sensor Microwave Humidity
Ta	Antenna Temperature

1.4 Applicable Documents

AD1.	C3S_311b Implementation Plan 2020 EUMETSAT-D9.3_v2, EUM/OPS/PLN/19/1065006

1.5 Reference Documents

RD1. Hans, I.; Burgdorf, M.; Buehler, S.A.; Prange, M.; Lang, T.; John, V.O., 2019, An Uncertainty Quantified Fundamental Climate Data Record for Microwave Humidity Sounders. *Remote Sens.*, *11*, 548.

RD2. Mittaz, J., G. Holl, I. Hans, M. Burgdorf, F. Ruethrich, Y. Govaerts, C. Merchant, R. Phipps, R. Roebeling, V. O. John, M. Taylor, J. Mollard (2019) D4_6 Metrological assessment of consistency, stability and uncertainty of FIDUCEO FCDRs, Technical Report. FIDUCEO project. http://cedadocs.ceda.ac.uk/1412/

RD3. Hans, I. M. Burgdorf, and E. Woolliams, 2019: Product user guide – Microwave FCDR release 4.1. Technical Report. FIDUCEO project. http://cedadocs.ceda.ac.uk/1415/

RD4. Poli, P., T. Hanschmann, V. O. John, M. Grant, and Jörg Schulz, 2020: Report on method for deriving cloud and rain flags from SSM/I for SSM/T2 pixel characterisation. Copernicus Climate Change Service Deliverable 7.7, D311b-T7.5_OD7.7_Cloud_and_rain_flags_for SSM_T2

RD5. T. Hanschmann, V. O. John, P. Poli, M. Grant, and Jörg Schulz, 2020: Algorithm Theoretical Basis Document (ATBD) - Fundamental Climate Data Record of Microwave Humidity Sounder SSM/T-2 Release 2, Copernicus Climate Change Service, Task 7.5, Deliverable 7.8.

RD6. T. Hanschmann, V. O. John, P. Poli, M. Grant, and Jörg Schulz, 2020: Product user Guide (PUG) - Fundamental Climate Data Record of Microwave Humidity Sounder SSM/T-2 Release 2, Copernicus Climate Change Service, Task 7.5, Deliverable 7.8.

RD7. Falcone, J., R. Kakar, K. Griffin, J. Wang, R. G. Isaacs, P. Racette, J. D. Pickle, D. J. Boucher, J. F. Morrissey, and B. H. Thomas, 1992: SSM/T-2 Calibration and Validation Data Analysis. *Environm. Res. Papers*, **1111**, Phillips Laboratory Direct. of Geophys., PL-TR-92-2293, 29 October 1992.

RD8. Galin, I., D.H. Brest, and G.R. Martner, 1993: The DMSP SSM/T-2 microwave water-vapour profiler. *SPIE Proc.* **1935**, 189-198, doi:10.1117/12.152603.

RD9. John, V. O., Holl, G., Buehler, S. A., Candy, B., Saunders, R. W., and Parker, D. E. (2012), Understanding intersatellite biases of microwave humidity sounders using global simultaneous nadir overpasses, J. Geophys. Res., 117, D02305, doi:10.1029/2011JD016349.

RD10. Pickle, J.D., R.G. Isaacs, V. Jakabhazy, M.K. Griffin, and V.J. Falcone, 1995: Effects of precipitation on SSM/T-2 brightness temperature. *Proc. SPIE,* **2584**, Synthetic Aperture Radar and Passive Microwave Sensing, 21 November 1995, doi:10.1117/12.227153.

RD11. Buehler, S. A., M. Kuvatov, T. R. Sreerekha, V. O. John, B. Rydberg, P. Eriksson, and J. Notholt, 2007, A cloud filtering method for microwave upper tropospheric humidity measurements, Atmos. Chem. Phys., 7, 5531-5542, doi: https://doi.org/10.5194/acp-7-5531-2007

RD12. Kobayashi, S., P. Poli, and V.O. John, 2017: Characterisation of Special Sensor Microwave Water Vapour Profiler (SSM/T-2) radiances using radiative transfer simulations from global atmospheric reanalyses. *Adv. Space. Res.*, **59** (4), 917-935, doi:10.1016/j.asr.2016.11.017.

RD13. Andersson, A., K. Graw, M. Schröder, K. Fennig, J. Liman, S. Bakan, R. Hollmann, and C. Klepp, 2017: Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data - HOAPS 4.0, Satellite Application Facility on Climate Monitoring, doi:10.5676/EUM_SAF_CM/HOAPS/V002.

RD14. Dee, D., S.M. Uppala, A.J. Simmons, and Co-authors, 2011: The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc.***137**, 553 – 597, April 2011 A, doi:10.1002/qj.828.

RD15. Hersbach, H., B. Bell, P. Berrisford, and Co-authors, 2020: The ERA5 global reanalysis. *Quart. J. Roy. Meteorol. Soc.* **2020***, 1-51.* doi:10.1002/qj.3803

RD16. Smith, A., and J. Hocking, 2019: Radiance Simulator v2.2. User Guide. NWPSAF-MO-UD-040, v0.5, 17/09/2019. https://www.nwpsaf.eu/site/download/documentation/rad_sim/user_documentation/RadSim_UserGuide.pdf

RD17. Hocking, J., P. Rayer, D. Rundle, R. Saunders, M. Matricardi, A. Geer, P. Brunel, and J. Vidot, 2019: RTTOV v12 Users Guide. NWPSAF-MO-UD-037, v1.3, 05/03/2019.

https://www.nwpsaf.eu/site/download/documentation/rtm/docs_rttov12/users_guide_rttov12_v1.3.pdf

RD18. Hans, I. M. Burgdorf, and E. Woolliams, 2019b: Product user guide – Microwave FCDR release 4.1. Technical Report. FIDUCEO project. http://cedadocs.ceda.ac.uk/1415/

RD19. Uppala, S.M., P.W. Kallberg, A.J. Simmons, and Co-authors, 2005: The ERA-40 re-analysis. *Quart. J. Roy. Meteorol. Soc.,* **131**, 2961-3012. doi:10.1256/qj.04.176.

RD20. Calbet, X., N. Peinado-Galan, S. DeSouza-Machado, E.R. Kursinski, P. Oria, D. Ward, A. Otarola, P. Rípodas, and R. Kivi, 2018: Can turbulence within the field of view cause significant biases in radiative transfer modeling at the 183 GHz band? *Atmos. Meas. Tech.*, **11**, 6409–6417, doi:10.5194/amt-11-6409-2018, 2018.

2 SSM/T-2 instrument

The SSM/T-2 instrument is a 5-channel microwave sounder mounted on several DMSP satellites [RD7, RD8]. The instrument scans the surface across-track (28 pixels), and features a resolution of 48 to 88 km at nadir, depending on the channel frequency. The instrument operates 5 channels. The two channels at 91.665 GHz and 150 GHz are sensitive to the surface, but can also be affected by clouds of liquid water or ice, and rainfall. The essential value of this instrument for climate monitoring lies in the three other channels. These channels are positioned in the 183 GHz water band, at 183.31±1.0 GHz, 183.31±3.0 GHz, and 183.31±7.0 GHz (Table 1). These channels are double-sideband symmetric about the water vapour line. Their data provide information about the distribution of water vapour in the atmosphere. The channel closest to the centre of the line is most sensitive to upper-tropospheric humidity, and the other two channels are gradually more sensitive to humidity located lower in the troposphere. Available records for this instrument start in 1994, and end in 2005.

The SSM/T-2 data have so far been considered for retrieval of tropospheric humidity [RD9]. Such retrievals require screening out cloud- and precipitation-affected pixels [RD10]. A first approach for this relied on inter-channel difference with some thresholds [RD11], but was shown to have limitations [RD12]. As described in the ATBD for this FCDR, the methodology employed for cloud/rain detection has been refined, using the SSM/I instrument mounted on the same or nearby DMSP platforms and the retrievals in the HOAPS product [RD12]. These cloud flag also open the way towards a potential use of the SSM/T-2 data in clear-sky data assimilation, by screening only clear scenes.

Table 1: SSM/T-2 channel characteristics.

FCDR channel number	RTTOV channel number	Channel frequency [GHz]	Instantaneous Field-Of-View (IFOV) size at nadir [km]	NEDT (K)	Nominal polarization orientation at nadir
4	1	91.655 ± 1.25	88	0.6	Horizontal
5	2	150.00 ± 1.25	54	0.6	Horizontal
2	3	183.31 ± 1.00	48	0.8	Horizontal
1	4	183.31 ± 3.00	48	0.6	Horizontal
3	5	183.31 ± 7.00	48	0.6	Horizontal

3 Validation strategy

Product validation amounts to verifying the conformity of the product with respect to user requirements. Two aspects are covered hereafter, a technical validation, and a scientific validation.

A first element of the technical validation is verifying the compliance of the metadata with respect to the CF metadata convention. A second element consists in verifying data completeness, in terms of information provided (i.e., data are present and non-missing).

For the scientific evaluation, since the Ta and uncertainty estimates are unchanged from a previous release, a focus of this report is to validate the correctness of the added cloud flags, in line with how they were designed [RD5]. This is achieved by comparing clear scenes with radiative transfer simulations from a global reanalysis.

The ERA-Interim global reanalysis [RD14] is used for simulations. Comparisons between AMSU-B and that reanalysis are also used in the discussion, as well as comparisons between AMSU-B and ERA5 [RD15].

The clear sky simulations considered here ignore the scattering process. The NWP-SAF software employed for simulations is RADSIM v2.2 [RD16] based on RTTOV v12.3 [RD17].

4 Technical Validation results

4.1 File metadata compliance

The file format of the FCDR data is NetCDF-4. All the files in the FCDR have been tested to be readable by NetCDF4 libraries as indicated in the Product User Guide [RD6]. For example, the 'panoply' software enables direct viewing of the data, as illustrated below on a sample file.

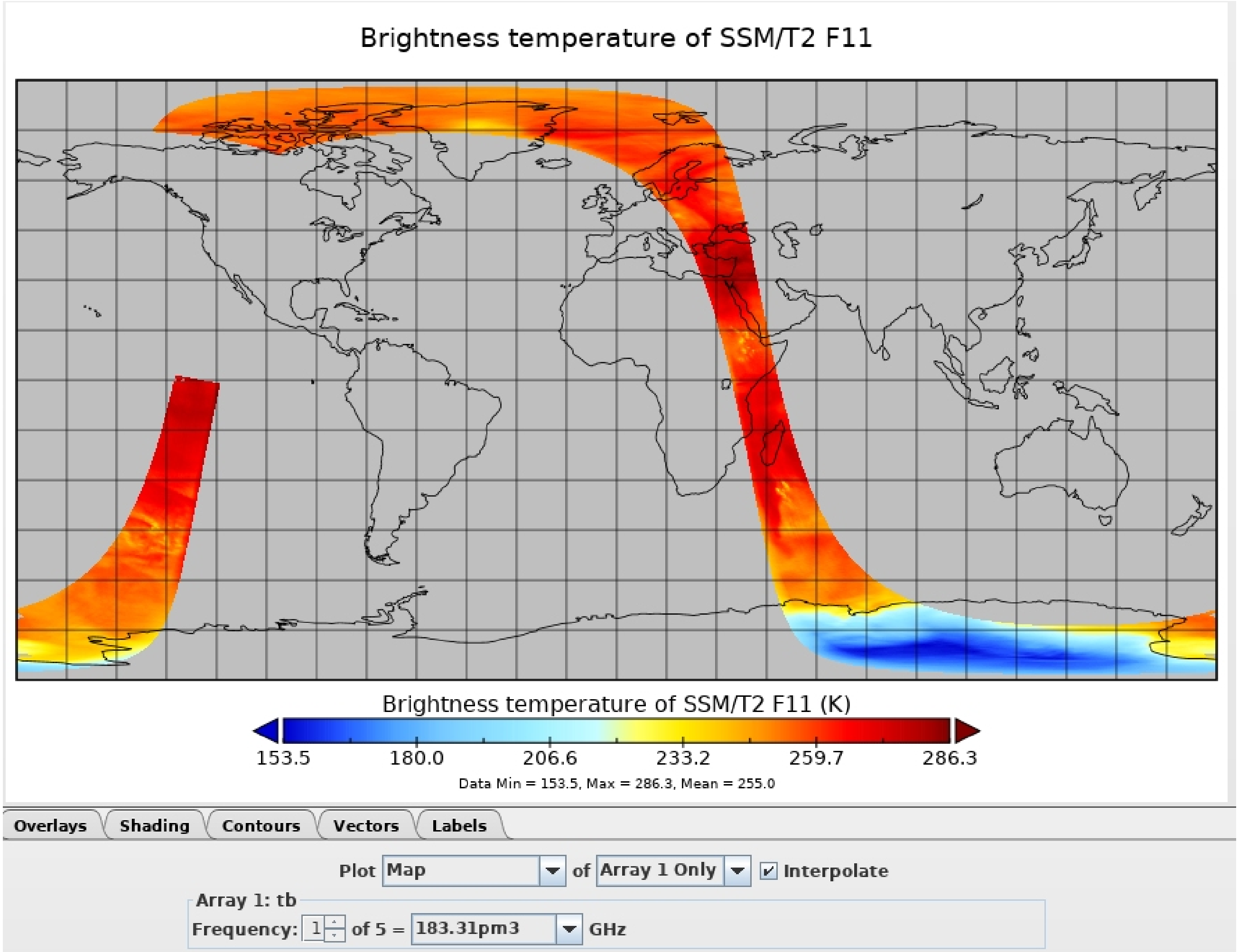

Figure 1: Sample data from the SSM/T-2 FCDR plotted with software `panoply' after 3 operations: 1) opening the file, 2) selecting the variable to plot from the list displayed, and 3) requesting a plot, using all default settings. Note the variable contents is properly self-described with channel, time, and spatial references, as well as units.

The compliance of the data, following the Climate and Forecast (CF) convention (Version 1.9), has been assessed, using publicly-available software from the U.K. Centre for Environmental Data Analysis (CEDA: https://github.com/cedadev/cf-checker/wiki). The convention version 1.9 being recent, the CF checker is not yet available for this version; for that reason, the validation is made with respect to the CF standard version 1.8. For completeness, the compliance report is reproduced in Appendix A, using a sample SSM/T-2 file from the F12 satellite.

Departures from the CF convention are explained, and generally due to the specific nature of the data (level-1, *i.e.*, sensor- and mission-specific, including correlation matrices and several flags). Generally, attributes are included to reflect what each variable means in the FCDR (and to describe the units, as illustrated in Figure 1), following the approach followed by the FIDUCEO project [RD18].

4.2 Data completeness

Validating the data completeness amounts to counting occurrences of missing values in the data record.

Given the nature of the data record (changes in quality over time, and between satellites), this information is evaluated by variable, by satellite, and per month.

The results are indicated in Table 2. The variables are listed sequentially, followed by the satellite.

Table 2: FCDR completeness table, showing data counts per variable and per month. Min. (avg., max.) refers to minimum (respectively: average, maximum). In the last 3 columns, data are counted as valid if non-missing.

FCDR Variable name	Sat-ellite	Number of data, per month			Percentage of valid data, per month		
		Min.	Avg.	Max.	Min.	Avg.	Max.
channel	F11	75	1 155	1 615	100	100	100
	F12	5	911	2 035	100	100	100
	F14	25	1 541	2 190	100	100	100
	F15	10	1 228	2 195	100	100	100
channel_correlation_matrix_common	F11	375	5 775	8 075	60	63	64
	F12	25	4 555	10 175	12	84	100
	F14	125	7 709	10 950	20	68	100
	F15	50	6 141	10 975	34	66	99
channel_correlation_matrix_independent	F11	375	5 775	8 075	60	63	64
	F12	25	4 555	10 175	12	84	100
	F14	125	7 709	10 950	20	68	100
	F15	50	6 141	10 975	34	66	99
channel_correlation_matrix_structured	F11	375	5 775	8 075	60	63	64
	F12	25	4 555	10 175	12	84	100
	F14	125	7 709	10 950	20	68	100
	F15	50	6 141	10 975	34	66	99
cloud_flag	F11	1 250 900	20 949 208	29 812 860	43	46	52
	F12	107 100	16 918 395	40 373 760	3	17	42
	F14	509 180	29 154 757	42 190 960	42	46	54
	F15	152 320	23 416 656	43 209 880	31	46	49
cross_element_correlation_coefficients	F11	6 750	103 950	145 350	100	100	100
	F12	450	81 991	183 150	100	100	100
	F14	2 250	138 764	197 100	100	100	100
	F15	900	110 539	197 550	100	100	100
cross_line_correlation_coefficients	F11	525	8 085	11 305	100	100	100
	F12	35	6 377	14 245	100	100	100
	F14	175	10 792	15 330	100	100	100
	F15	70	8 597	15 365	100	100	100
data_quality_bitmask	F11	250 180	4 189 841	5 962 572	100	100	100
	F12	21 420	3 383 679	8 074 752	100	100	100
	F14	101 836	5 830 951	8 438 192	100	100	100
	F15	30 464	4 683 331	8 641 976	100	100	100
latitude	F11	250 180	4 189 841	5 962 572	95	97	99
	F12	21 420	3 383 679	8 074 752	82	94	99
	F14	101 836	5 830 951	8 438 192	90	95	99
	F15	30 464	4 683 331	8 641 976	98	99	99

FCDR Variable name	Satellite	Number of data, per month			Percentage of valid data, per month		
		Min.	Avg.	Max.	Min.	Avg.	Max.
longitude	F11	250 180	4 189 841	5 962 572	95	97	99
	F12	21 420	3 383 679	8 074 752	82	94	100
	F14	101 836	5 830 951	8 438 192	90	95	99
	F15	30 464	4 683 331	8 641 976	98	99	100
quality_issue_pixel_bitmask	F11	1 250 900	20 949 208	29 812 860	100	100	100
	F12	107 100	16 918 395	40 373 760	100	100	100
	F14	509 180	29 154 757	42 190 960	100	100	100
	F15	152 320	23 416 656	43 209 880	100	100	100
quality_pixel_bitmask	F11	250 180	4 189 841	5 962 572	100	100	100
	F12	21 420	3 383 679	8 074 752	100	100	100
	F14	101 836	5 830 951	8 438 192	100	100	100
	F15	30 464	4 683 331	8 641 976	100	100	100
quality_scanline_bitmask	F11	8 935	149 637	212 949	0	0	0
	F12	765	120 845	288 384	0	0	0
	F14	3 637	208 248	301 364	0	0	0
	F15	1 088	167 261	308 642	0	0	0
satellite_azimuth_angle	F11	250 180	4 189 841	5 962 572	100	100	100
	F12	21 420	3 383 679	8 074 752	100	100	100
	F14	101 836	5 830 951	8 438 192	100	100	100
	F15	30 464	4 683 331	8 641 976	100	100	100
satellite_zenith_angle	F11	250 180	4 189 841	5 962 572	100	100	100
	F12	21 420	3 383 679	8 074 752	100	100	100
	F14	101 836	5 830 951	8 438 192	100	100	100
	F15	30 464	4 683 331	8 641 976	100	100	100
scanline_map_to_origl1bfile	F11	8 935	149 637	212 949	100	100	100
	F12	765	120 845	288 384	100	100	100
	F14	3 637	208 248	301 364	100	100	100
	F15	1 088	167 261	308 642	100	100	100
scanline_origl1b	F11	8 935	149 637	212 949	96	97	100
	F12	765	120 845	288 384	82	94	100
	F14	3 637	208 248	301 364	90	95	100
	F15	1 088	167 261	308 642	98	99	100
tb	F11	1 250 900	20 949 208	29 812 860	73	76	79
	F12	107 100	16 918 395	40 373 760	9	75	99
	F14	509 180	29 154 757	42 190 960	20	73	96
	F15	152 320	23 416 656	43 209 880	51	76	96
time	F11	8 935	149 637	212 949	96	97	100
	F12	765	120 845	288 384	82	94	100
	F14	3 637	208 248	301 364	90	95	100
	F15	1 088	167 261	308 642	98	99	100

FCDR Variable name	Sat-ellite	Number of data, per month			Percentage of valid data, per month		
		Min.	Avg.	Max.	Min.	Avg.	Max.
u_common_tb	F11	1 250 900	20 949 208	29 812 860	73	76	79
	F12	107 100	16 918 395	40 373 760	9	75	99
	F14	509 180	29 154 757	42 190 960	20	73	96
	F15	152 320	23 416 656	43 209 880	51	76	96
u_independent_tb	F11	1 250 900	20 949 208	29 812 860	73	76	79
	F12	107 100	16 918 395	40 373 760	9	75	99
	F14	509 180	29 154 757	42 190 960	20	73	96
	F15	152 320	23 416 656	43 209 880	51	76	96
u_structured_tb	F11	1 250 900	20 949 208	29 812 860	73	76	79
	F12	107 100	16 918 395	40 373 760	9	75	99
	F14	509 180	29 154 757	42 190 960	20	73	96
	F15	152 320	23 416 656	43 209 880	51	76	96
RAIN	F11	250 180	4 189 841	5 962 572	43	46	52
	F12	21 420	3 383 679	8 074 752	3	17	42
	F14	101 836	5 830 951	8 438 192	42	46	54
	F15	30 464	4 683 331	8 641 976	31	46	49
SURFACE	F11	250 180	4 189 841	5 962 572	85	88	93
	F12	21 420	3 383 679	8 074 752	13	40	82
	F14	101 836	5 830 951	8 438 192	81	88	93
	F15	30 464	4 683 331	8 641 976	78	92	93
TWP	F11	250 180	4 189 841	5 962 572	43	46	52
	F12	21 420	3 383 679	8 074 752	3	17	42
	F14	101 836	5 830 951	8 438 192	42	46	54
	F15	30 464	4 683 331	8 641 976	31	46	49
WVP	F11	250 180	4 189 841	5 962 572	41	43	49
	F12	21 420	3 383 679	8 074 752	2	16	40
	F14	101 836	5 830 951	8 438 192	40	44	51
	F15	30 464	4 683 331	8 641 976	29	43	47

The highlights in grey correspond to variables/satellites with unusually lower availability percentages (last columns):

- Satellite F11, channel 5 (150 GHz) data were not valid and are hence missing in the FCDR. This limits the maximal Ta data availability to only under 80% for this satellite. This affects the Ta as well as the three corresponding uncertainty estimates (*u_common_tb*, *u_independent_tb, u_structured_tb*) and correlation matrices (*channel_correlation_matrix_common*, *channel_correlation_matrix_independent*, *channel_correlation_matrix_structured*);
- The quality scanline bitmask (*quality_scanline_bitmask*) is set to missing for all satellites because there was no particular reason to discard single scanlines in the processing beyond the reasons for flagging bad data using the other quality information elements;

- The cloud flag (*cloud_flag*) is less often available for F12 than for the other satellites, because F12 carried no functional SSM/I unit, so the corresponding information is limited by the availability of other DMSP satellites. This affects also the variables that depend on SSM/I and were collocated from HOAPS (*RAIN*, *TWP*, *WVP*).

5 Scientific evaluation results

5.3.1 Quality flags

This section investigates the impact of applying the additional quality flags contained in the FCDR, on the full SSM/T-2 time-series of observation minus simulation differences, from 1994 to 2004. It is an end-to-end testing, considering all the quality flags in the FCDR.

In addition to the data quality information already present in the previous version of the SSM/T-2 FCDR, the following effects are now flagged in the SSM/T-2 FCDR Release 2 evaluated here:

- rain, liquid, and ice water can cause scattering of the microwave radiation, depending on their particle size and the measured frequency;
- the obstruction bracket (GLOB) can be seen by the instrument, when scanning towards the outer edges.

To address these two issues, the following flags are to be interpreted as follows (respectively):

- 'cloud_flag': if non-zero (and non-missing), indicates that cloud and/or rain may affect the quality of the Ta;
- 'quality_issue_pixel_bitmask', bit number 5 ('bad_data_earthview'): if non-zero, indicates that the GLOB may affect the quality of the Ta.

Both of these variables are time-dependent, scan position-dependent, and channel-dependent.

5.3.2 Total number of data in the FCDR

The total number of SSM/T-2 data in the FCDR, before the application of any quality flags is shown in Figure 2, for channel 1. This number is in fact identical for the other channels. This figure is a time-series of the data counts for all channels summarized in Table 2, for the Ta, albeit showing here the numbers of soundings, peaking at 8 Million per month.

The number of soundings per satellite fluctuates largely throughout the time period. The drops in the data count reflect data availability at the source, as archived by NOAA/CLASS and based on availability and quality of required parameters for recalibration (soundings with too much missing data could not be processed into a FCDR). Data gaps are attributed to instrument-related, data transmission-related and operational issues. Some of these issues are non-recoverable.

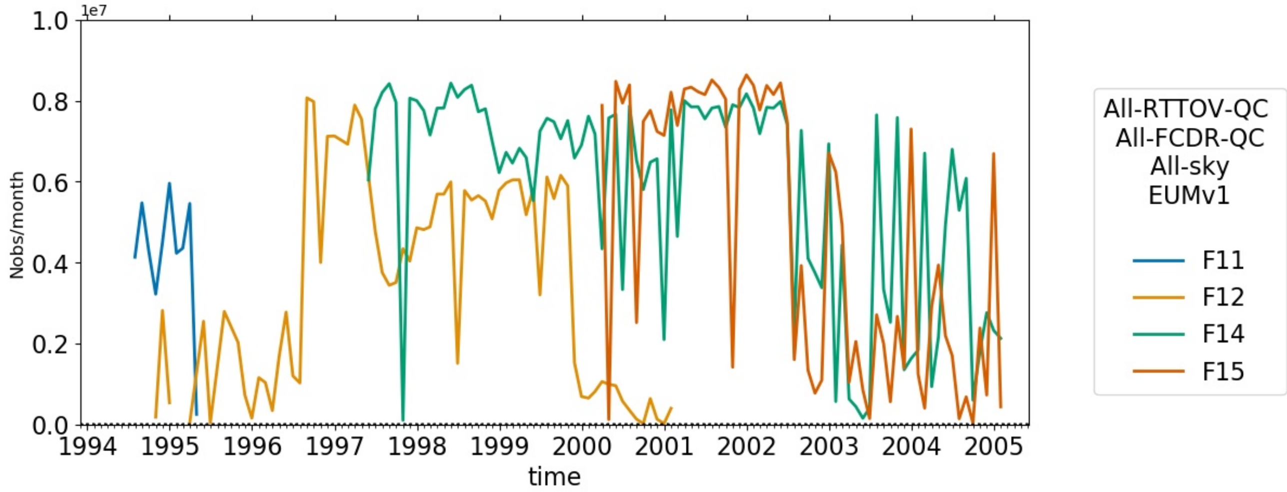

Figure 2: Monthly number of soundings in the SSM/T-2 FCDR.

5.3.3 Number of data after application of the quality flags

Before proceeding with the scientific analysis of the data, the following exclusions are applied, using the quality flags contained in the FCDR Release 2:

a. Scenes with suspected or dubious data quality are excluded as follows (each of the following conditions is sufficient to trigger rejection):
- if 'quality_pixel_bitmask' is missing; or
- if 'quality_pixel_bitmask' is non-missing and the first bit is set (flag 'invalid'); or
- if 'quality_issue_pixel_bitmask' is missing; or
- if 'quality_issue_pixel_bitmask' is non-missing and is greater than or equal to 4 (this removes the cases where any of the following flag is set: 'no_calib_bad_DSV', 'no_calib_bad_IWCT', 'bad_data_earthview').

b. In addition, for a comparison with radiative transfer simulations only valid in clear-sky, a scene is excluded if any of the following condition is met:
- if 'cloud_flag' is missing (these are scenes for which no HOAPS-collocated information is available, such as over land for example);
- if 'cloud_flag' is non-missing and non-zero (these are scenes over ocean, where HOAPS-collocated information is available, and where cloud/rain are believed to adversely affect the quality of the Ta data).

c. Finally, only successful RTTOV simulations are retained, by excluding any scene/channel:
- not within +/- 1 hour of 00, 06, 12, and 18 UTC (for these scenes, the time difference with respect to ERA-Interim profiles is considered to be too large to yield reasonable estimates); or
- with missing Ta for a given channel (however, other channels, if present, may be simulated); or
- where RTTOV returned non-zero 'qcflags'.

Users of the data interested in humidity retrievals or clear-sky data assimilation may apply the first and second types of exclusions. However all-sky data assimilation users may only need to apply the first type of exclusions. The number of scenes retained by these filters is shown in Figure 3, per channel and per satellite.

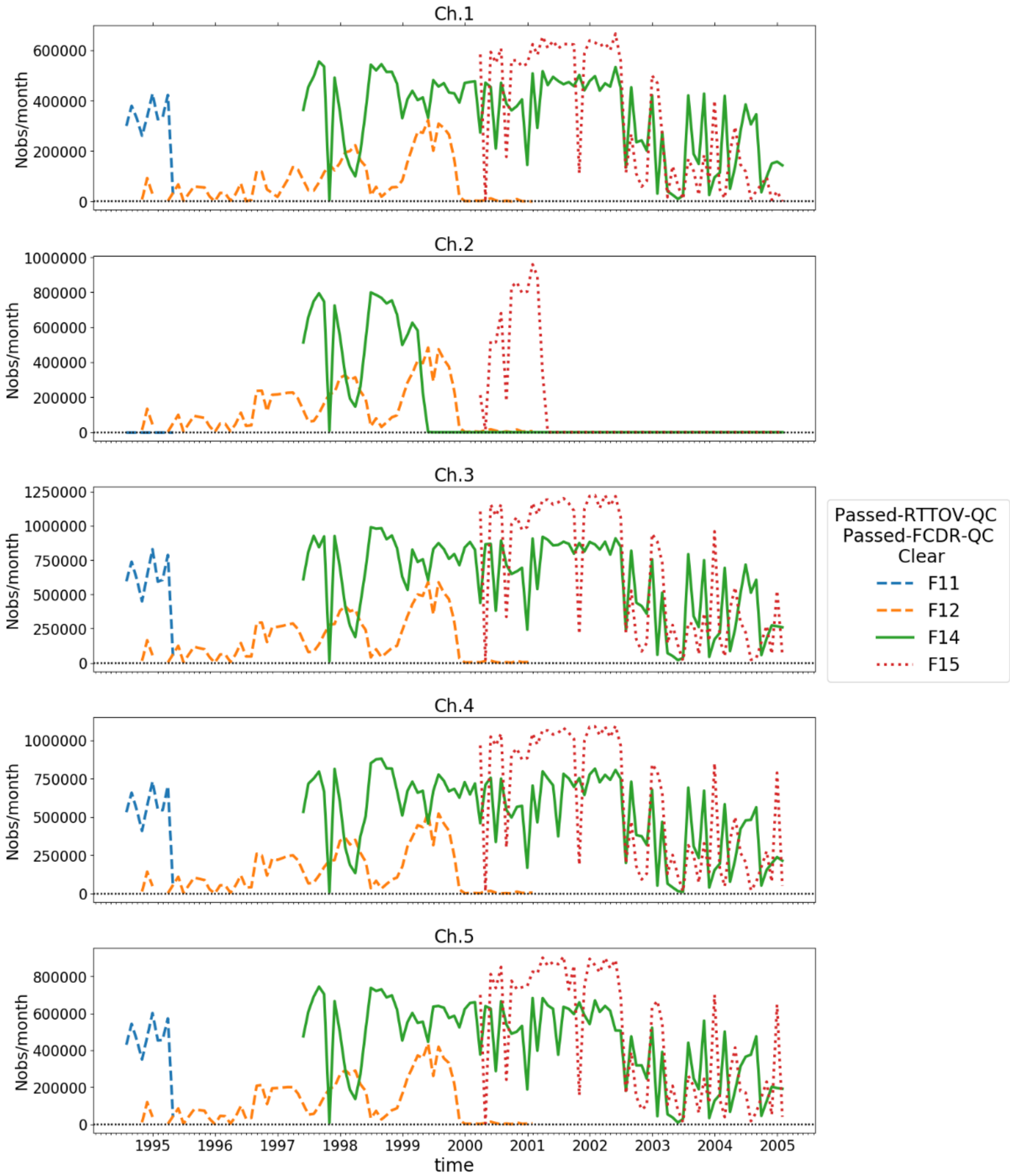

Figure 3: Time-series of SSM/T-2 monthly data counts in the FCDR, per satellite (see legend), and per channel (from top to bottom, following the RTTOV channel number convention, i.e., from top to bottom: 91.665 GHz, 150 GHz, 183.31±1.00 GHz, 183.31±3.00 GHz, and 183.31±7.00 GHz), after application of quality flags and to retain only clear scenes that could be successfully simulated by RTTOV based on ERA-Interim.

The large decrease as compared from Figure 2 is explained as follows. The restriction in time to 8 hours per day (+/- 1 hour around 00, 06, 12, and 18 UTC instead of the entire 24-hours in a day covered the missions), combined with omitting missing scenes/channels where the Ta are missing (see Table 2, generally 10-20%), leads to a reduction in terms of data count by a factor of 3.3. This would have brought the number of comparisons from peaks of 8 M per month to approximately 2.4 M per month. In fact, a further reduction in data counts for the scientific analysis is due to the availability of HOAPS collocations. These collocations are available only approximately half the time as shown in Table 2 (except for F12, one-fifth of the time). Cumulated with the previous factor, this would indicate an expected number of comparisons peaking at 1.2 M per month, for the highest-peaking channel. Furthermore, only clear scenes are retained. This percentage of clear (non-precipitating cloudy) scenes is never 100%, and explains that the expected number of data counts would peak lower than 1.2 M, around 1 M for the lower-peaking channels. Finally, the inclusion of FCDR quality flags (at channel level and at scene level, for example to omit some scan positions), leads to a further reduction in the total number of data retained for scientific data analysis thereafter.

5.4 Mean differences between SSM/T-2 FCDR and simulations based on ERA-Interim

Considering the same scenes as above, after application of quality flags described in the previous section, the mean differences in Ta between observations and radiative transfer simulations are shown in Figure 4.

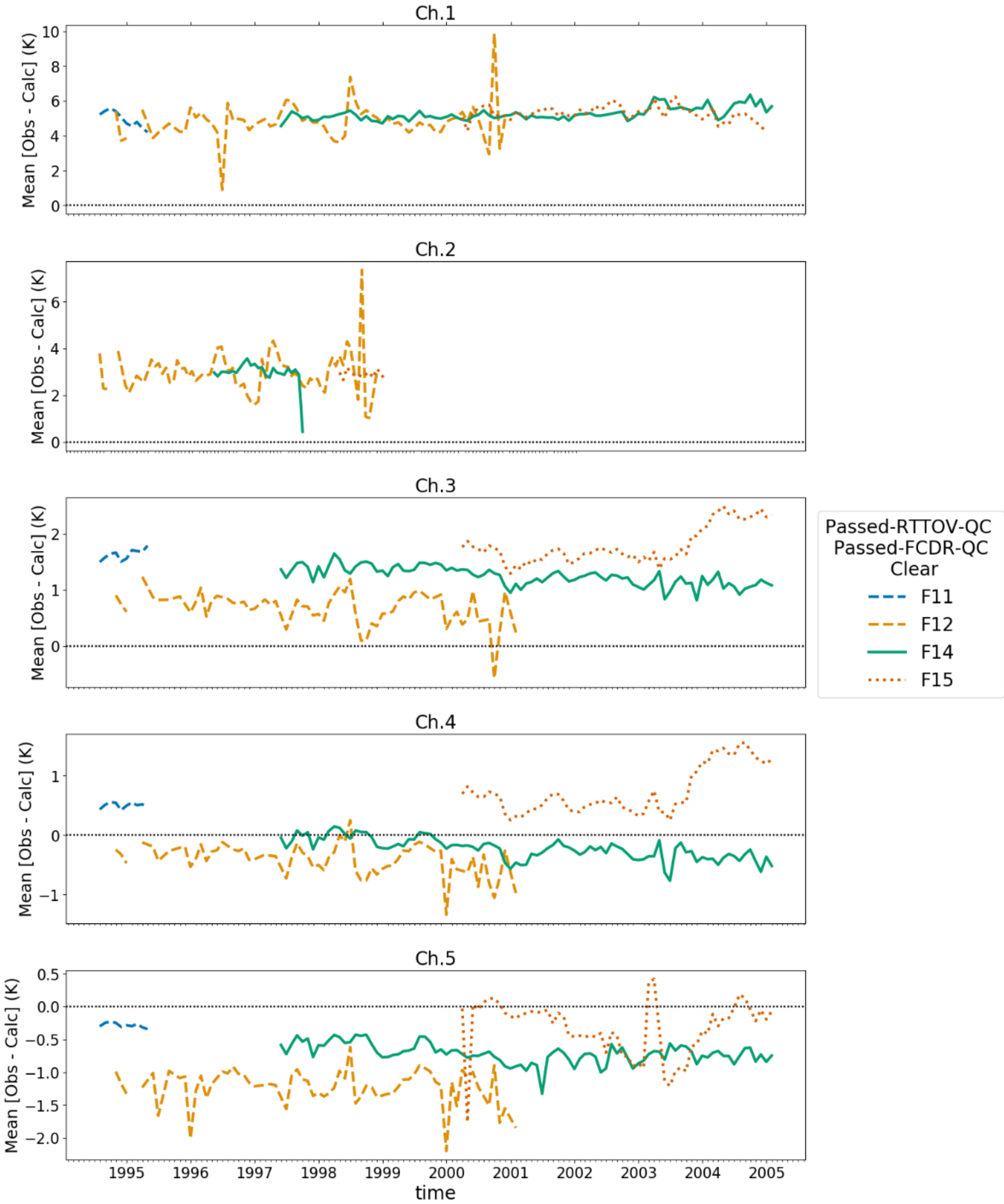

Figure 4: Monthly bias between SSM/T-2 observed and simulated temperatures, for clear scenes having passed the FCDR quality flags and for which RTTOV simulations based on ERA-Interim were successful, for the five SSM/T-2 channels as in Figure 3.

For the two surface-sensitive channels (first two rows in Figure 4), the inter-satellite differences are much smaller than the general offset from zero. This offset represents the combined effect of instrumental biases and errors in the skin temperature and the surface emissivity (dependent on sea-surface roughness) used in the radiative transfer simulations.

For the humidity sounding channels (last three rows in Figure 4), the mean differences go from generally positive, for the highest-peaking channel (183.31±1.00 GHz, RTTOV channel number 3), to generally negative, for the lowest-peaking channel (183.31±7.00 GHz, RTTOV channel number 5). Accordingly, the mid-tropospheric-peaking channel (183.31±3.00 GHz, RTTOV channel number 4) features mean differences that are closest to zero.

For the upper-tropospheric channel, the positive biases are mostly between 0.5 and 2.0 K, except for the last year of F15, which stands out as different from the others. This suggests that ERA-Interim has a possible wet bias of +5% to +20%, if the observations and the simulations are to be trusted, assuming an approximate equivalence of 10% humidity to -1 K in Ta near the center of the 183 GHz line.

For the mid-tropospheric channel, the mean differences are clustered between -0.5 and 1.0 K, with the same exception as before (last year of F15).

For the low-tropospheric channel, the differences are generally coherent between satellites, around 0.0 to -1.5 K. This suggests a dry bias in ERA-Interim, if all assumptions are correct. This is consistent with the known issue of drying of the troposphere in ERA-Interim as the assimilation of SSM/I retrieval data over oceans proceeded to gradually include more satellites.

While these results may be perceived as only indicative of the quality of the simulations, they are interesting to consider in comparison with results of AMSU-B brightness temperature differences with ERA-Interim (and ERA5 as well). Indeed, the AMSU-B instrument features characteristics that are very close to SSM/T-2 (see Table 3), hence considering it here.

Table 3: AMSU-B channel characteristics

RTTOV channel number	Channel frequency [GHz]	Instantaneous Field-Of-View (IFOV) size at nadir [km]	NEDT (K)	Nominal polarization orientation at nadir
1	89.0	16	0.4	Vertical
2	150.0	16	0.8	Vertical
3	183.31 ± 1.00	16	1.1	Vertical
4	183.31 ± 3.00	16	0.7	Vertical
5	183.31 ± 7.00	16	0.6	Vertical

For this analysis, the ERA-Interim (and ERA5) observation feedback from ECMWF is used. The counts of data available for this analysis are shown in Figure 5, considering the same time period as shown before for SSM/T-2, to ease comparison. In ERA-Interim and ERA5, only the AMSU-B channels 3 to 5 are assimilated. Also, the following AMSU-B data are excluded from the clear-sky assimilation: over sea-ice, in case of identified rain, over high terrain for channels 3 and 4, and over land for channel 5.

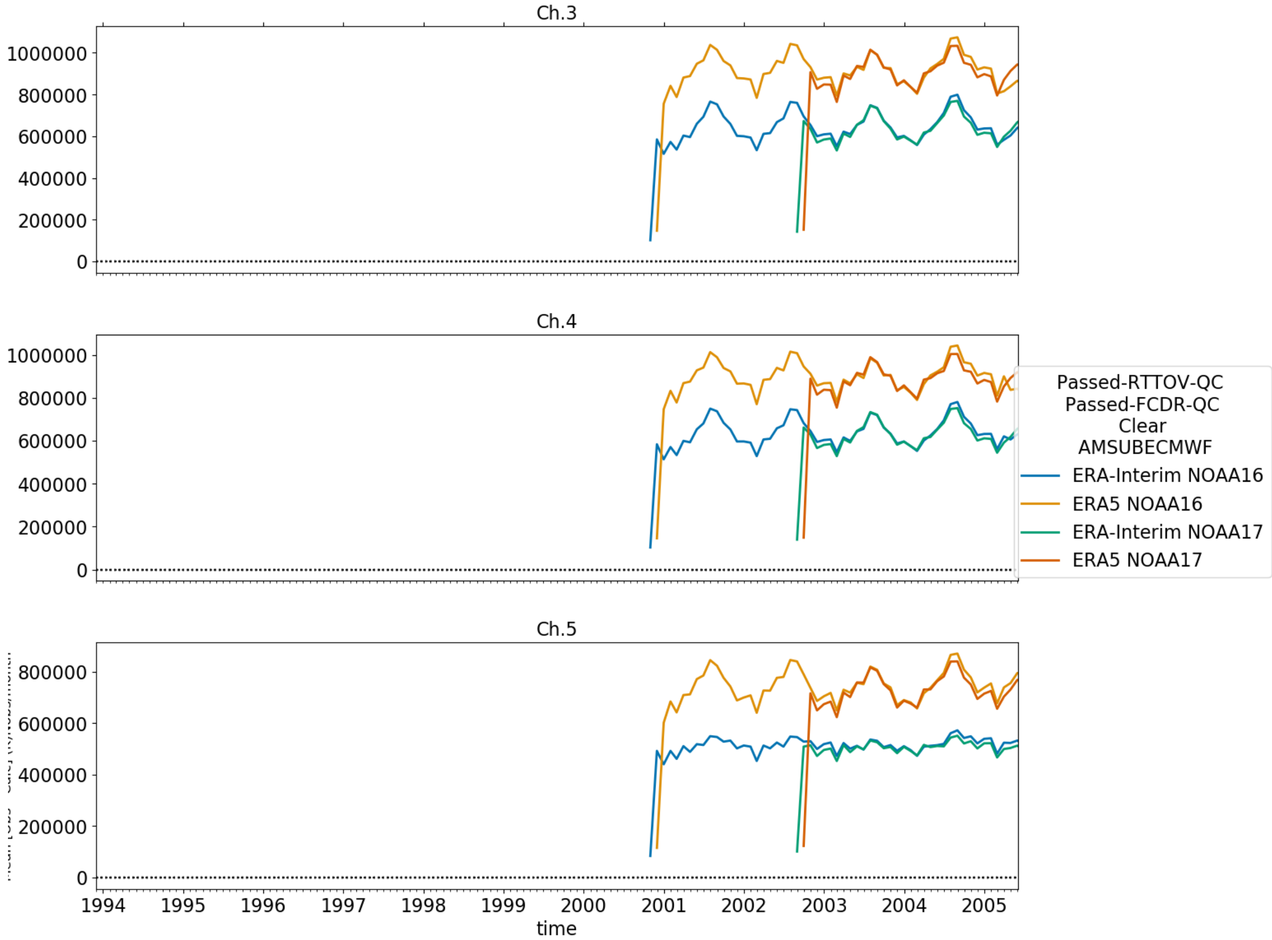

Figure 5: Monthly data count for AMSU-B brightness temperatures assimilated by ERA-Interim and ERA5. The quality controls featured in legend indicate that the data shown here passed all the data assimilation checks and were retained for clear-sky assimilation.

The mean differences between AMSU-B brightness temperatures and ERA-Interim (and ERA5) background are shown in Figure 6 (plotting using different line styles). Generally, the findings are similar to the conclusions of the SSM/T-2 FCDR comparison to ERA-Interim. The departures are positive for the higher-peaking channel, around 1.2 K, closer to zero for the mid-tropospheric channel, and negative for the lower-peaking channel. Note, these AMSU-B data are not *per se* a FCDR but the result of operational data acquisition, except for NOAA-16 data before 2002, which results from a reprocessing carried out at ECMWF for ERA-40 [RD19].

Interestingly, the differences remain rather similar for ERA5, except for the mid-tropospheric channel. Given the rather different bias characteristics of ERA-Interim as compared to ERA5, this suggests that the systematic differences may find their root causes in other aspects than 'simply' a wet or dry bias in the reanalysis, but probably more a spatial representativeness issue [RD20].

Overall, the good agreement in terms of mean differences between SSM/T-2 and AMSU-B, as compared to ERA-Interim, is an indication that the data contained in the FCDR are mature enough for consideration in reanalysis. Furthermore, the inter-satellite biases are smaller between SSM/T-2 platforms than found for AMSU-B data as used in ERA-Interim and ERA5 (NOAA-16 vs. NOAA-17).

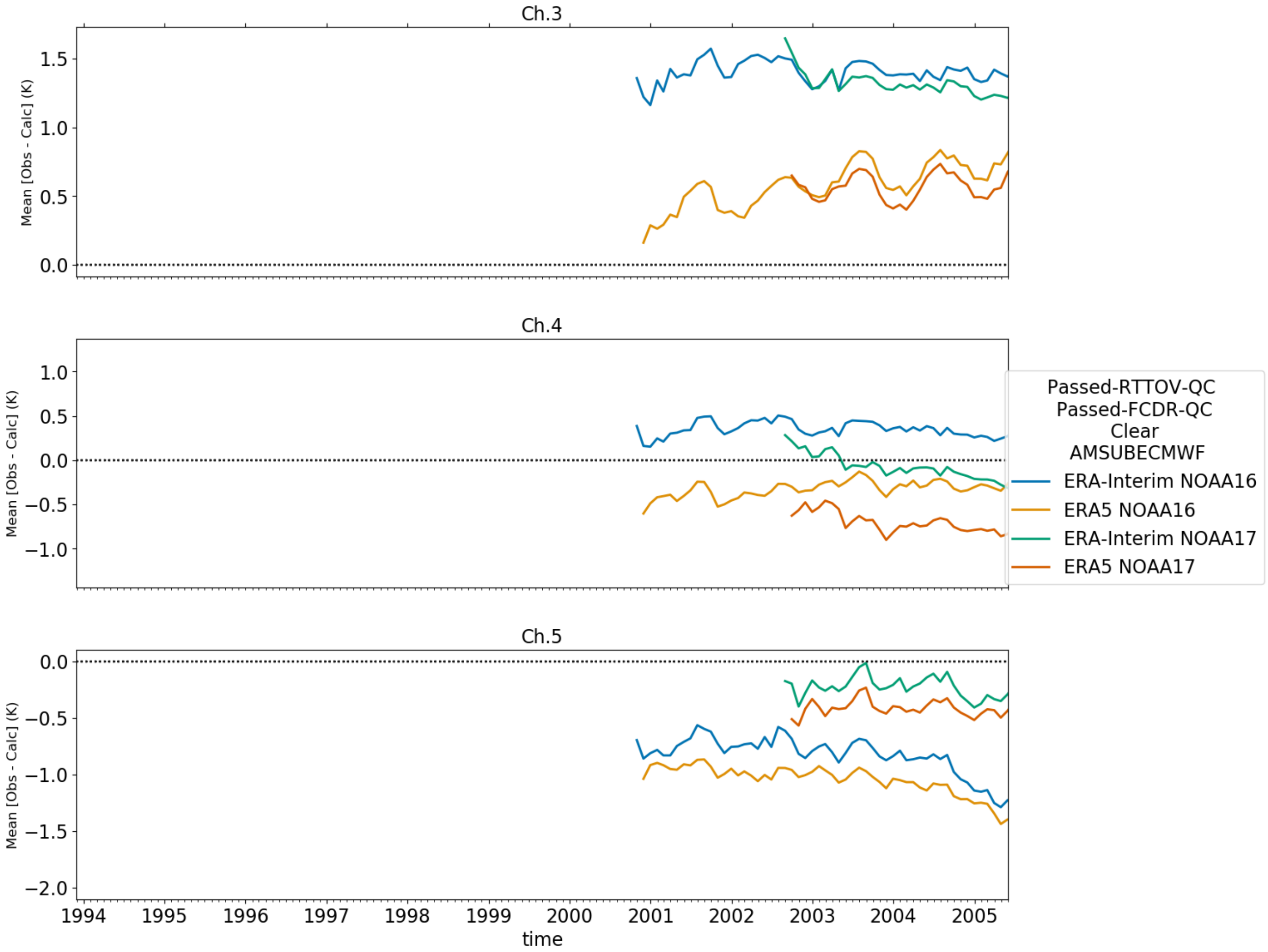

Figure 6: Monthly mean differences between AMSU-B brightness temperatures and ERA-Interim (ERA5) background forecasts, before assimilation and before bias correction, as provided by the ERA-Interim (ERA5, respectively) observation feedback, for AMSU-B observations that were assimilated and passed all quality controls.

5.5 Standard deviation of differences between SSM/T-2 FCDR and simulations based on ERA-Interim

Consideration is now given to the intra-month and global variability of the departures. Figure 7 shows the standard deviation of the differences FCDR minus radiative transfer simulations. The standard deviations are largest for the first channel (approximately 5 K), and comparable in magnitude with the mean bias. This suggests that the simulations fail to represent a large part of the variability in the observations near 90 GHz. For the second channel (150 GHz), the standard deviations are approximately 5 K, quite larger than the mean bias (3 K), which may then be interpreted as being not necessarily robust.

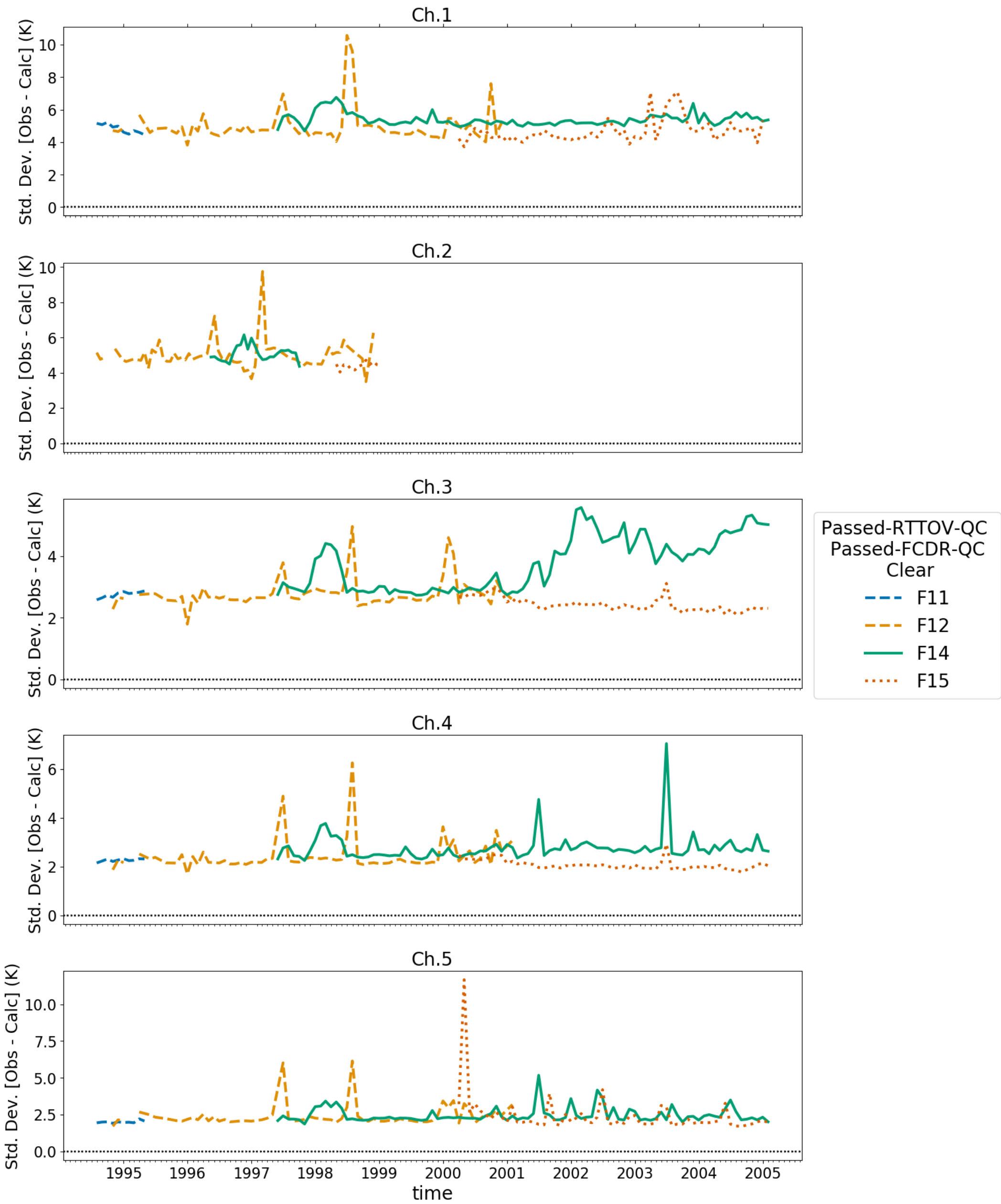

Figure 7: Standard deviations (monthly resolution) of the SSM/T-2 FCDR minus radiative transfer simulations.

For the sounding channels, the differences feature lower standard deviations (near 2-3 K). Some peaks and changes over time are also visible. They are investigated thereafter.

The SSM/T-2 FCDR contains three estimates of uncertainty: structured, independent, and common. These were estimated by the FIDUCEO project. The uncertainty estimates are shown in Figure 8.

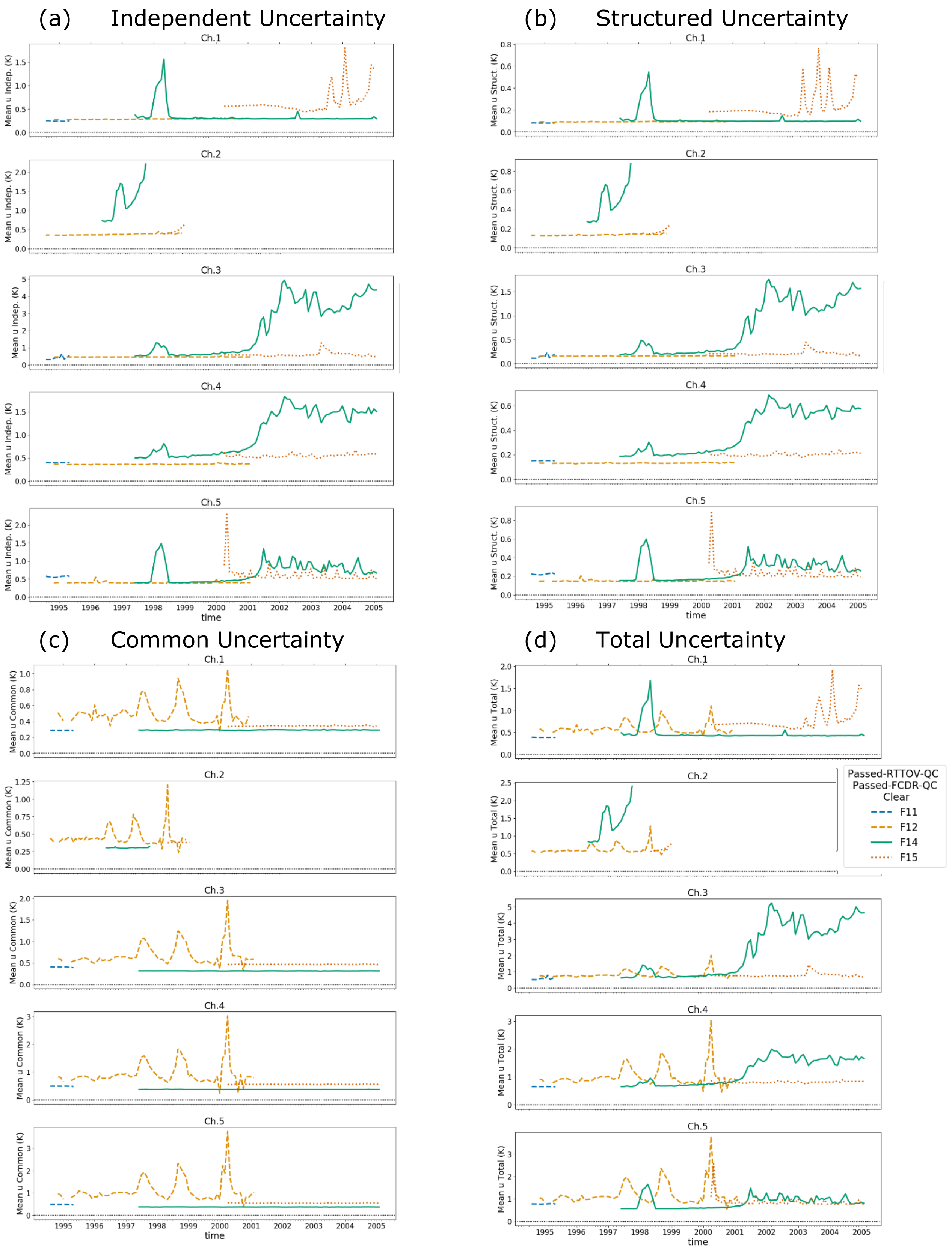

Figure 8: Estimates of uncertainty in the SSM/T-2 FCDR, from FIDUCEO, for the selection of scenes that passed all quality controls and were estimated to be free of rain contamination, in the SSM/T-2 FCDR. Several estimates of uncertainty are shown: (a) Independent, (b) Structured, (c) Common, and (d) Total (square root of the sum of squares of the 3 previous quantities).

For an in-depth analysis of these estimates, background information is given by prior references [RD1, RD2]. However, some features are worth pointing out. First, the independent uncertainty (Figure 8a) generally dominates, with the common uncertainty (Figure 8c). Second, the structured uncertainty (Figure 8b), albeit smaller than the others, is generally approximately half the independent uncertainty.

A total uncertainty is also estimated (Figure 8d), by computing the square root of the sum of squares of all uncertainties. Notable features in the SSM/T-2 FCDR are as follows:

- For F11, all uncertainties in Figure 8 appear to be in line with the mean observed for other satellites. This is consistent with Figure 7, where standard deviations of differences for this satellite do not particular stand out.

- For F12, spikes are visible in Figure 8 in the common uncertainties, in years 1997, 1998, and 2000, for all channels. Also, these spikes dominate the variability of the total uncertainty of that satellite (and all channels). The timings of these spikes is consistent with timings of larger departure standard deviations in Figure 7 (all channels).

- For F14, a spike is observed in Figure 8 in the independent (and structured) uncertainties end 1997-mid 1998 (for all channels and particularly the first two). Also, a large increase gradually takes place in 2000 and leaves the instrument in a state of higher noise until 2005 (although only for the water vapour sounding channels). The first feature is found in the departure standard deviations in Figure 7 (channels 1 and 2), but the second feature is not reflected there, except for channel 3. For the other channels, the standard deviations do not appear to be affected adversely after 2000, although the time-series appear to be more noisy for channels 4-5.

- For F15, a spike in the independent and structured uncertainties is visible in Figure 8 at the beginning of the mission, in 2000, for channel 5. This spike is visible in Figure 7. Generally, the independent uncertainty in Figure 8a for that satellite is larger than for other satellites, for channels 4-5, and in line with what is observed for F14. Again, these findings match with larger standard deviations in Figure 7. Increases in noise for channel 1 in 2003-2005 are also reflected in Figure 7, however they appear much smaller as there are probably other dominating factors that justify the overall larger background departures for this channel.

6 Conclusions

The results presented here indicate an increase in maturity of the FCDR, with the inclusion of quality flags. The technical and scientific assessments indicate the product is adequate for usage. After applying the FCDR quality flags and the cloud flag, the mean differences in antenna temperatures by comparison to ERA-Interim are contained with values that are similar to those found in the ERA-Interim observation feedback for the AMSU-B instrument (which observed similar frequencies). In addition, the SSM/T-2 FCDR features smaller inter-satellite biases.

The mean departures with respect to ERA-Interim are generally between 0.5 and 2.0 K for the highest-peaking water vapour channel, between -0.5 and 1.0 K for the mid-tropospheric channel, and between 0.0 and -1.5 K for the lowest-peaking water vapour channel. In ERA5, similar differences are found in the observation feedback, for the AMSU-B instrument, which observed similar frequencies as SSM/T-2.

Another finding of this quality evaluation is that larger standard deviations with respect to ERA-Interim are often explained, in qualitative terms, by variations in the uncertainties as contained in the FCDR. Although this does not constitute a quantitative validation of the absolute level of these uncertainties (many other factors contribute to the differences, including ERA-Interim and radiative transfer errors), this finding gives further confidence that the FIDUCEO uncertainty estimates contain valuable information.

The following points were noted as possible venues for improvements:

- acquisition of additional level-1 DMSP data, possibly from the original source if not available at NOAA;
- investigation of whether (inter-satellite) biases between SSM/T-2 and AMSU-B and reanalysis are reduced in AMSU-B FCDR, as compared to results obtained with the AMSU-B operational data.

In addition, it is reminded that the SSM/T-2 data in the FCDR are antenna temperatures, and not antenna temperatures that would have been obtained after correction for the antenna pattern, because the latter is unknown. Gaining an understanding of such information should remain an objective. This would help improve eventually the data record, and correct for the influence of the spacecraft and outer space on the measurements, whose temperatures were possibly seen by the SSM/T-2 antenna, depending on the field-of-view and exact spacecraft configuration.

Appendix A CF-Compliance results

The output from the CF compliance checker is shown hereunder, for a sample file. When errors have been detected, comments have been inserted, highlighted in yellow.

File name: C3S_FCDR_L1C_SSMT2_F12_20000602210823_20000602225108_R02.0.nc

```
CHECKING NetCDF FILE: C3S_FCDR_L1C_SSMT2_F12_20000602210823_20000602225108_R02.0.nc
=====================
Using CF Checker Version 4.0.0
Checking against CF Version CF-1.8
Using Standard Name Table Version 74 (2020-08-04T14:43:55Z)
Using Area Type Table Version 10 (23 June 2020)
Using Standardized Region Name Table Version 4 (18 December 2018)

ERROR: (2.6.1): This netCDF file does not appear to contain CF Convention data.

          Comment: A global attribute 'Conventions = "CF-1.9"' is present in the files.

------------------
Checking variable: latitude
------------------

------------------
Checking variable: longitude
------------------

------------------
Checking variable: quality_pixel_bitmask
------------------

------------------
Checking variable: data_quality_bitmask
------------------
ERROR: (3.5): Invalid syntax for 'flag_meanings' attribute

          Comment: This is due to a flag meaning containing 'N/A', for 'non-applicable'.

------------------
Checking variable: quality_scanline_bitmask
------------------

------------------
Checking variable: scanline_origl1b
------------------
INFO: (3.1): No units attribute set.  Please consider adding a units attribute for completeness.

------------------
Checking variable: scanline_map_to_origl1bfile
------------------
INFO: (3.1): No units attribute set.  Please consider adding a units attribute for completeness.

------------------
Checking variable: channel_correlation_matrix_independent
------------------
ERROR: (2.4): variable has repeated dimensions

          Comment: This is unavoidable in order to properly describe a correlation matrix.

------------------
Checking variable: channel_correlation_matrix_structured
------------------
ERROR: (2.4): variable has repeated dimensions
```

```
          Comment: This is unavoidable in order to properly describe a correlation matrix.

------------------
Checking variable: channel_correlation_matrix_common
------------------
ERROR: (2.4): variable has repeated dimensions

          Comment: This is unavoidable in order to properly describe a correlation matrix.

------------------
Checking variable: cross_line_correlation_coefficients
------------------

------------------
Checking variable: cross_element_correlation_coefficients
------------------

------------------
Checking variable: RAIN
------------------

------------------
Checking variable: TWP
------------------

------------------
Checking variable: WVP
------------------

------------------
Checking variable: SURFACE
------------------
ERROR: (3.5): flag_masks values must be non-zero

          Comment: One of the flags has value zero for traceability with HOAPS.

------------------
Checking variable: satellite_zenith_angle
------------------

------------------
Checking variable: satellite_azimuth_angle
------------------

------------------
Checking variable: time
------------------
INFO: attribute calendar is being used in a non-standard way

------------------
Checking variable: tb
------------------

------------------
Checking variable: cloud_flag
------------------
ERROR: (3.5): flag_masks values must be non-zero

          Comment: One of the flags has value zero to indicate no-cloud.

------------------
Checking variable: quality_issue_pixel_bitmask
------------------

------------------
Checking variable: u_independent_tb
------------------

------------------
Checking variable: u_structured_tb
------------------

------------------
Checking variable: u_common_tb
```

```
------------------

------------------
Checking variable: channel
------------------
WARN: (5): Possible incorrect declaration of a coordinate variable.

ERRORS detected: 7
WARNINGS given: 1
INFORMATION messages: 3
```

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