



Copernicus Climate Change Service



Quality Evaluation Report for Atmospheric Motion Vectors generated with Metop-AVHRR data for the period 2007-2017

D5.1 and D5.2

Issued by: EUMETSAT

Date: 19/07/2019

REF.: C3S_311b T5.1 M07 D5.1 and D5.2



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Quality Evaluation Report for Atmospheric Motion Vectors generated from Metop-AVHRR data for the period 2007-2017

D5.1 and D5.2

EUMETSAT

Roger Huckle

Marie Doutriaux-Boucher

Alessio Lattanzio

Oliver Sus

Mike Grant

Jörg Schulz

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Acronyms

AMV	Atmospheric Motion Vector
AVHRR	Advanced Very High Resolution Radiometer
C3S	Copernicus Climate Change Service
CCC	Cross Correlation Contribution
CDR	Climate Data Record
CGMS	Coordination Group for Meteorological Satellites
CIMSS	Cooperative Institute for Meteorological Satellite Studies
EBBT	Equivalent Black Body Temperature
ECMWF	European Center for Medium-Range Weather Forecasts
EUMETSAT	EUropean organisation for the exploitation of METeorological SATellites
ERA	European ReAnalysis
ERA-CLIM	European Reanalysis of Global Climate Observations
ERA-Interim	ECMWF interim reanalysis
EPS	EUMETSAT Polar System
IASI	Infrared Atmospheric Sounding Interferometer
IR	InfraRed
ITCZ	Inter Tropical Convergence Zone
IWWG	International Winds Working Group
L1b	Level 1b data
L2	Level 2 data
Metop	Meteorological Operational Satellite
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NRT	Near Real Time
NWP	Numerical Weather Prediction
OPE	Operational NRT product
PDU	Product Data Unit
QI	Quality Indicator
RAOBCORE	RAdiosonde OBservation COrrrection using REanalyses
RD	Referenced Document
RMSE	Root Mean Square Error
UTC	Universal Time Coordinated



1. Introduction

At EUMETSAT, the polar and global Atmospheric Motion Vectors (AMVs) are derived from the Advanced Very High Resolution Radiometer (AVHRR/3) on-board the Metop-A and B satellites in the period 2007 – 2017. The AMVs were derived using the operational algorithm developed by EUMETSAT [RD1].

The C3S AMVs for this release include AMVs derived from Metop-AVHRR imagery over the poles (single mode) and globally (dual mode). The data record temporal length is reported in Table 1.

Table 1: Satellite, instrument, spatial and temporal coverage of the CDR.

Satellite	Instrument	Coverage	Reprocessed Years
Metop-A (single)	AVHRR/3	Polar	01/03/2007 - 31/12/2017
Metop-B (single)	AVHRR/3	Polar	24/04/2013 - 31/12/2017
Metop-A/B (dual)	AVHRR/3	Global	24/04/2013 - 31/12/2017
Metop-B/A (dual)	AVHRR/3	Global	24/04/2013 - 31/12/2017

1.1 Purpose and scope

This document contains the results inherent to Work Package 5 → Task 5.1 → Milestone 7 in [AD1]. The document provides the results of the quality evaluation of the AMVs derived from Metop-A and -B AVHRR images for the period 2007 - 2017. The results cover the two AVHRR AMV data records:

- D5.1: the single Metop polar AMV product derived using AVHRR images on board one single Metop satellite (Metop-A and Metop-B);
- D5.2: the dual Metop global coverage AMV product derived using images pair taken successively by the two satellites Metop-A and Metop-B.

The quality evaluation is presented in three parts:

- Temporal analysis to identify if the reprocessed AMVs contain significant gaps, are stable in time and exhibit geographical and seasonal features in line with well-known atmospheric circulation patterns;
- Comparison with corresponding operational real time products to infer the main differences. This difference should be kept in mind by users who may want to assimilate differently those reprocessed AMVs with respect to real time data used for weather prediction;
- Statistical comparison with reanalysis outputs, radiosonde data and Moderate Resolution Imaging Spectro radiometer (MODIS) AMVs to evaluate the quality of the data records against independent AMVs.

1.2 Structure

This document has the following Sections:

Section 1	General Information (this section)
Section 2	AMV data record generation summary
Section 3	Data used for the validation
Section 4	Temporal and statistical evaluation of the reprocessed AMV
Section 5	Comparison with EUMETSAT operational AMVs
Section 6	Validation against independent dataset



Section 7	Summary of the validation
Section 8	Known Limitations
Section 9	Conclusions

1.3 Applicable Documents

AD1.	Multi-Annual Implementation Plan 2016 - 2021. C3S_311b D9.2
AD2.	Product User Guide Metop-AVHRR AMV. EUM/USC/DOC/19/1060577

1.4 Reference Documents

RD1.	Holmlund, K., 1998: The utilization of statistical properties of satellite-derived atmospheric motion vectors to derive quality indicators. Wea. Forecasting, 13, 1093–1104. doi: 10.1175/1520-0434(1998)013,1093:TUOSPO.2.0.CO;2.
RD2.	EUMETSAT AVHRR L2 wind product ATBD. EUM/RSP/SPE/14/781004
RD3.	AVHRR Level 1b Product Guide. EUM/OPS-EPS/MAN/04/0029.
RD4.	Dee et al., 2011: The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quat. J. Res. Met. Soc., 137, 553–597.
RD5.	Report on quality analysis of comparison data for AMV evaluation, C3S report 2018 C3S_311b T5.1 M05.
RD6.	Velden, C. S., and K. Holmlund, 1998: Report from the working group on verification and quality indices (WG III). Proc. Fourth Int. Winds Workshop, Saanenmoser, Switzerland, EUMETSAT, 19–20.
RD7.	GCOS 154, Systematic observation requirements for satellite-based data products for climate, 2011 update: Supplemental details to the satellite-based component of the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC.
RD8.	Haimberger, L., 2007: Homogenization of radiosonde temperature time-series using innovation statistics. J. Climate 20, 1377–1403.
RD9.	Buizza, R. et al., 2018: The EU-FP7 ERA-CLIM2 Project Contribution to Advancing Science and Production of Earth System Climate Reanalyses, https://doi.org/10.1175/BAMS-D-17-0199.1
RD10.	Sand et al., 2013: The Arctic Response To Remote And Local Forcing Of Black Carbon. Atmospheric Chemistry and Physics. 13. 10.5194/acp-13-211-2013.
RD11.	Report on analysis of impact of background field on AMV retrieval, C3S_311b T5.1 M04, 2018.
RD12.	Borde R., M. Doutriaux-Boucher, G. Dew, and M. Carranza, 2014: A direct link between feature tracking and height assignment of operational EUMETSAT atmospheric motion vectors. Journal of Atmospheric and Oceanic Technology, 31, 33–46. doi: http://dx.doi.org/10.1175/JTECH-D-13-00126.1 .
RD13.	Warrick F, and J. Cotton, 2018: NWP SAF AMV monitoring: the 8 th analysis report (AR8). https://nwpsaf.eu/monitoring/amv/analysis.html
RD14.	Key, J., D. Santek, C. S. Velden, N. Bormann, J.-N. Thepaut, L. P. Riishojgaard, Y. Zhu, and W. P. Menzel, 2003: Cloud-drift and water vapor winds in the polar regions from MODIS. IEEE Trans. Geosci. Remote Sens., 41, 482–492, doi:10.1109/TGRS.2002.808238.



RD15.	Akos, H., O. Hauteccoeur, R. Borde, H. Deneke, and S. A. Buehler, Evaluation of the EUMETSAT global AVHRR wind products, 2017: J. of Apl. Met. and Clim., doi: 10.1175/JAMC-D-17-0059.1
RD16.	Borde R., O. Hauteccoeur, and M. Carranza, 2016: EUMETSAT global AVHRR wind product. J. Atmos. Oceanic Technol., 33, 429–438, doi:10.1175/JTECH-D-15-0155.1.
RD17.	Hauteccoeur, O., and R. Borde, 2017: Derivation of wind vectors from AVHRR/MetOp at EUMETSAT. J. Atmos. Oceanic Technol., 34, 1645–1659, doi:10.1175/JTECH-D-16-0087.1.
RD18.	August T. et al., 2012: IASI on Metop-A: Operational level 2 retrievals after five years in orbit. J. Quant. Spectrosc. Radiat. Transfer, 113, 1340–1371, doi:10.1016/j.jqrst.2012.02.028
RD19.	Report on the quality of AVHRR L1B LAC data. C3S_311b T5.1 M04, 2018

2. AMV Data Record generation summary

The Atmospheric Motion Vector (AMV) product provides information on speed (ms^{-1}), direction ($^{\circ}$), and height (hPa) of vectors (as shown in Figure 1) which are derived by tracking clouds between two adjacent images in time.

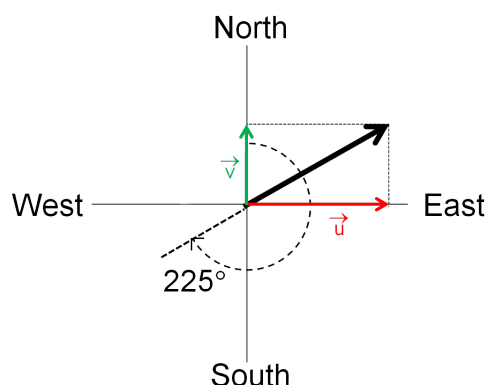


Figure 1: Wind direction measured in degrees in clockwise direction starting from the north. For example a direction of 225° represents a wind blowing from the southwest. The altitude of the wind is expressed in hPa.

Every AMV product needs data from two consecutive orbits. In the single mode, is the previous orbit from the same satellite, in the dual mode this is the previous orbit from the paired satellite. The geographical coverage of Metop-A/B and-B/A is complementary to the single satellite derived product.

Each AMV contains a wind speed (in m/s), a wind direction (in degree), and a wind altitude information together with geolocation data (latitude and longitude). The height is given as a pressure in Pascal (Pa); the corresponding brightness temperature (in K) is also recorded in the product. It is accompanied by a quality index and other metadata. The quality indicator amongst others takes into account the temporal consistency, the spatial consistency with the surrounding vectors and consistency with the model (ERA-interim) forecast field at the same time and location [RD1, and RD4].

In the wind field, the meteorological convention is used:

- 0° : Winds blowing from North
- 90° : Winds blowing from West
- 180° : Winds blowing from South
- 270° : Winds blowing from East

2.1 Basic retrieval description

AMVs are retrieved by tracking the motion of clouds or patterns of other atmospheric constituents such as water vapour. Very generally, as a first step a feature is identified in the first image, the second step is to identify this feature again in the second image. If this is successful then wind speed and direction are calculated based on the geographical displacement and time between images. A height is assigned to each vector based in the case of AVHRR on the brightness temperature. Finally, a quality index is calculated for each AMV.

In this report, two complementary AVHRR datasets are evaluated:

- AMV retrieved using only one single Metop satellite (Figure 2a). This will allow retrieving AMVs over both poles poleward of 40° north and south. This dataset is called single AMV [RD16] and it refers to C3S delivery 5.1.
- AMV retrieved using two Metop satellites (Figure 2b). This is possible because Metop-A and -B fly in the same polar orbit with a 180° phase difference. This will allow retrieving AMV over the entire globe. This dataset is called dual AMVs [RD16, and RD17] and it refers to C3S delivery 5.2.

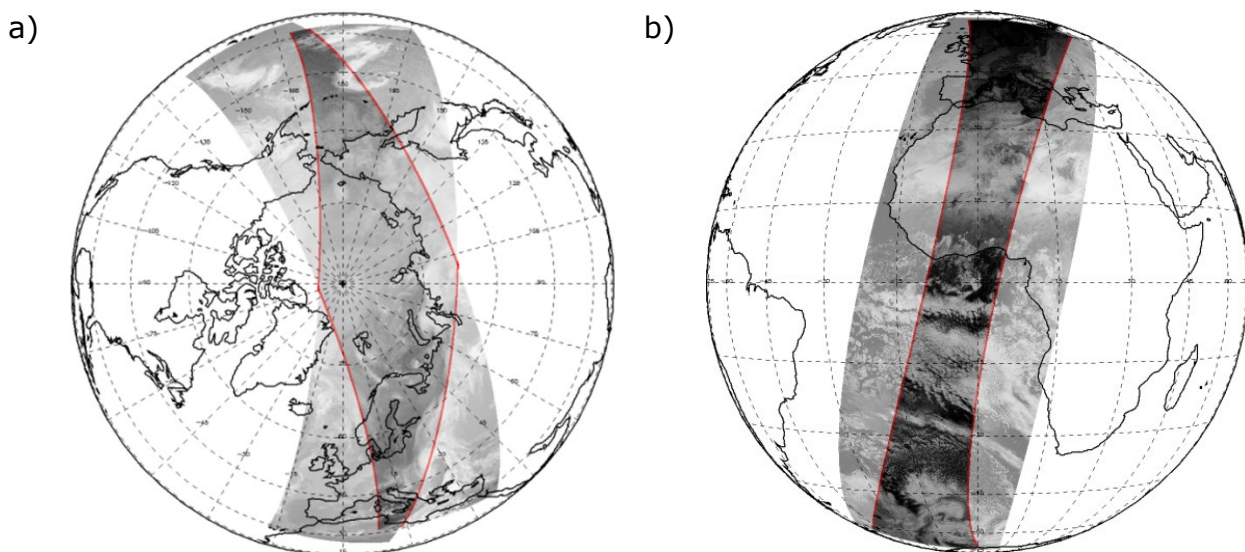


Figure 2: Example of geographical coverage. a) “single mode”: Using two successive orbit paths of one Metop satellite allowing coverage of north and south poles polewards of 45° . The time difference between two images is ~ 101 minutes. b) “dual mode”: Using two successive orbit paths of two different Metop satellites. The time difference between two images is ~ 50 minutes allowing a full globe coverage.

2.2 Main steps

The operational EUMETSAT AVHRR AMV algorithm is described in detail in [RD2]. In real time at EUMETSAT, AVHRR data are received every three minutes. Each small 3-minutes file received is called a Product Data Unit (PDU). The EUMETSAT algorithm has been developed with this concept of PDUs as a base line. Therefore, the algorithm uses 3-minute PDUs from AVHRR as input. For each PDU, three PDUs with an overlap from the previous orbit are used to do the matching and to allow the full coverage of the reference PDU. Only data from two orbits are used. The AMV can be retrieved to a maximum poleward of $\pm 40^\circ$. Because the time difference between two images is long (50 or 100 minutes) NWP forecast data from ERA-interim reanalysis is used as a “first guess” for speed and direction in order to save computation power and increase the quality of the retrieved winds. NWP temperature profiles are also used for the height assignment.

The EUMETSAT algorithm is summarised by Figure 2. It uses only two orbits, allowing winds to be retrieved up to 40° north and south.

Cloud tracking and height assignment are done in separate steps. The pixels that influenced most the tracking could slightly differ from the one affecting the height

assignment. A cross correlation contribution (CCC) method is used to establish a strong link between the two processes [RD12] and calculate averaged height weighted by their contribution to the tracking.

The cloudiness of each pixel could be retrieved using AVHRR information available in level 1b data. This information is reliable only since 2015.

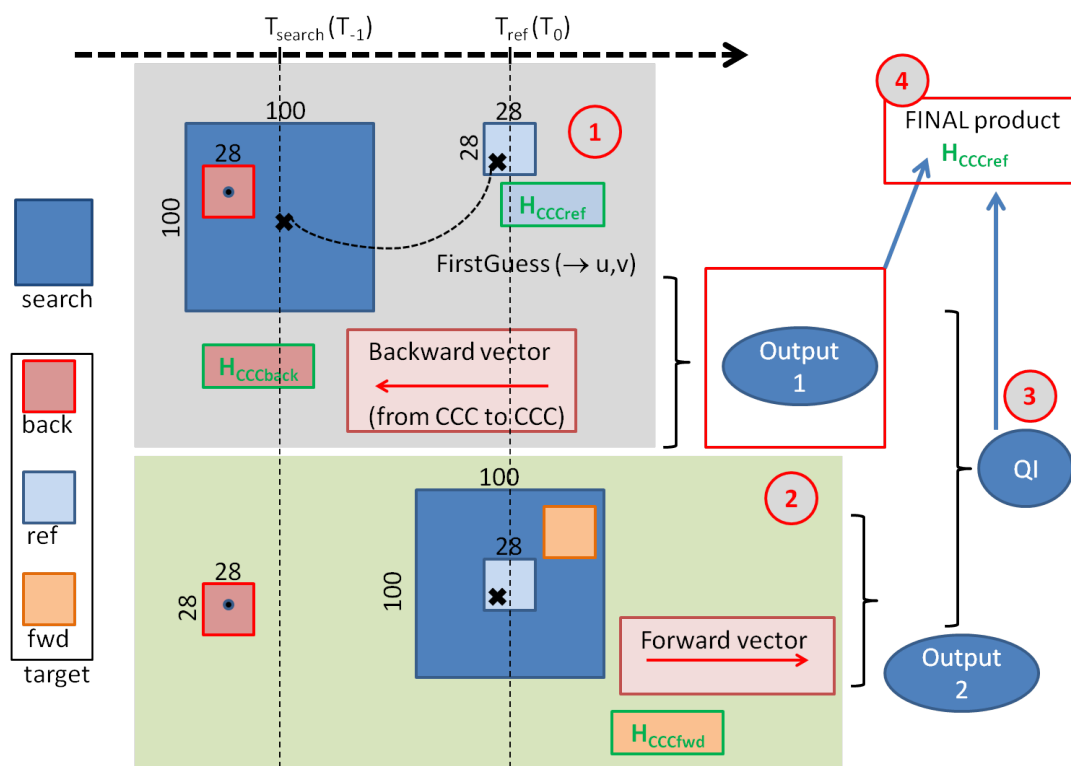


Figure 3: Schematic view of the EUMETSAT polar winds retrieval. The reference image is observed at time T_{ref} (or T_0), the second image (100 minutes before) is observed at time T_{search} (or T_{-1}). First a reference's target (*ref*) is selected in the image at T_0 , the height is computed using the CCC method [RD12]. Using this location, the height and the first guess, a location is found to be the centre of the search box in the previous image at T_{-1} . In this search box (50 pixels on each side of the centre), the *ref* target is tracked and when found it's named backward target (*back*). The speed is derived using the distance between the *ref* and the *back* targets. The height is assumed unchanged and is provided by the height of the *ref* target. As a second step -2- The forward vector is computed by doing a forward tracking starting from the *back* target and looking for the forward (*fwd*) target in a new search box in image at T_0 . QI are computed comparing backward and forward tracking results. Note that for dual AMVs, Metop-A/B means *ref* is a Metop-A image.

2.3 Input data

AMV products are derived using Metop-AVHRR infrared images [RD3] together with ERA-interim forecast data [RD4].

2.4 Spatial and Temporal Coverage

Using instruments on board of polar orbiting satellites allows the geographical coverage of the Polar Regions with single satellite operations and global geographical coverage using the dual mode. The Figure 4 shows the coverage of the poles and the Figure 5 shows the global coverage.

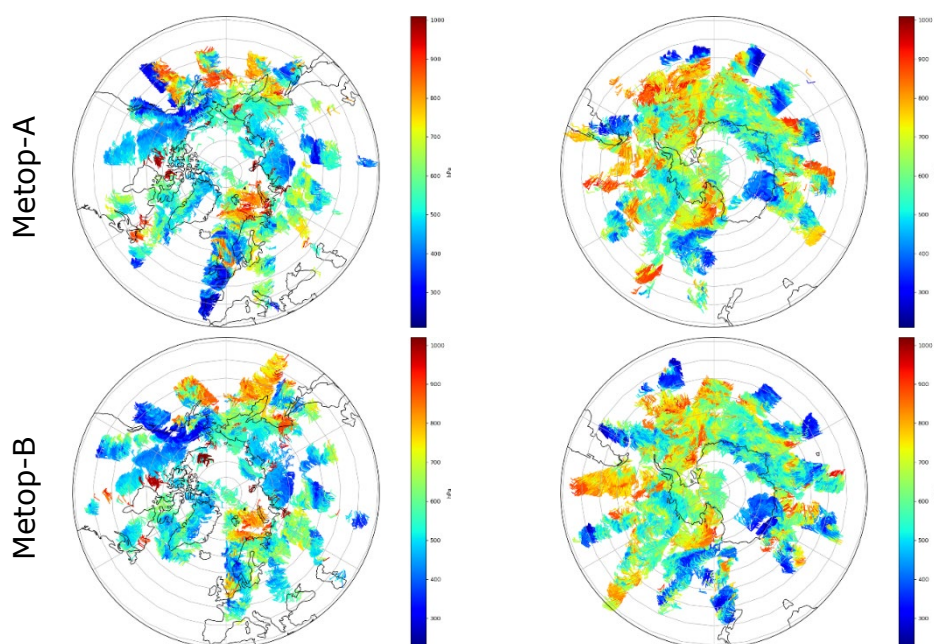


Figure 4: Example of retrieved AMVs for the 1st of January 2014 at 00UTC to 12UTC using one single Metop satellite. *Top row:* Metop-A North Pole (right) and South Pole (left). *Bottom row:* Metop-B North Pole (right) and South Pole (left).

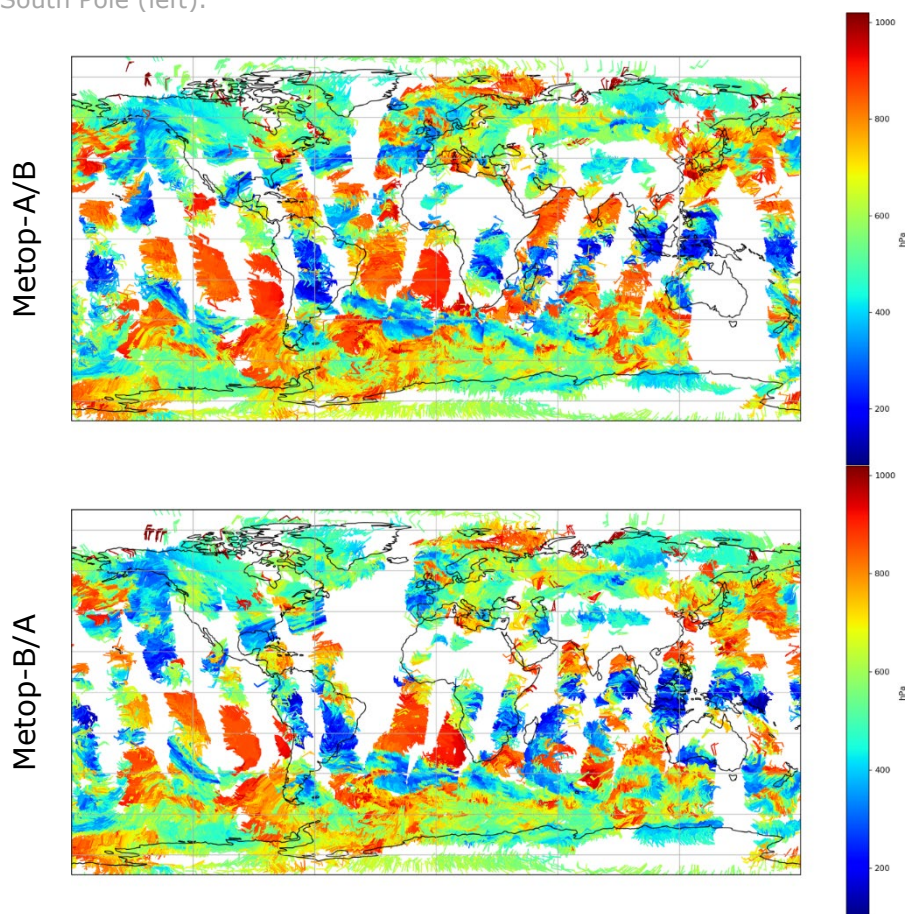


Figure 5: Example of retrieved AMVs for the 1st of January 2014 at 00UTC to 12UTC using two Metop satellites. *Top row:* Metop-A/B dual. *Bottom row:* Metop-B/A dual.

3. Data used for the validation

AMVs are validated at EUMETSAT against independent wind datasets such as radiosondes, ERA-interim reanalyses and other satellite AMVs from MODIS instrument. As reanalyses data are available globally in a high spatial resolution, the validation against NWP is done globally, while the comparison against radiosondes depends on the number of observations for the locations where a radiosonde is available (see 3.1). These two analysis (using radiosonde and NWP data) have then a different objective and are complementary. The first one focuses mainly on an average but global geographical analysis, while the second aims to a more local but absolute comparison. Table 2 presents the data used for this validation. The following sub-sections describe the data in more detail.

Table 2: List of data used for the AVHRR AMV validation. The last column indicates the number of images used to derive a wind vector.

Instrument/Data source	Description	Spatial coverage	Temporal coverage	Frequency between two images	Number of images
Operational Metop-AVHRR AMVs 2S (single)	EUMETSAT operational product single satellite	Pole ward of 40° north and south	2011 -2017	101 minute orbit	2
Operational Metop-AVHRR AMVs 2D (dual)	EUMETSAT operational product dual satellite	Global coverage	2013 - 2017	50 minutes	2
RAOBCORE	Radiosonde data	Specific location over land only and mainly in the northern hemisphere	2283 stations available: co-location with AMVs for the period 2007-2016	Every 12 hours	--
ERA-Interim	Model data	Global	2007 - 2017	Every 3 hours	--
MODIS	AMVs from Terra and Aqua	Pole ward of 65° north and south	2007 - 2017	101 minute orbit	3

3.1 Radiosonde data

A radiosonde is an instrument that is carried into the atmosphere by a balloon to send back information on vertical profiles of meteorological variable such as atmospheric temperature, pressure, humidity and winds by means of a small radio transmitter.

Radiosonde data are one of the rare means of validation for satellite AMVs. They are a key independent reference data. To validate an AMV climate data record there is a need for temporally stable and high quality datasets. In that respect, the Radiosonde OBServation COrection using Reanalyses dataset is ideal (RAOBCORE, <https://www.univie.ac.at/theoret-met/research/raobcore/>). RAOBCORE [RD8] has also been used as an independent source of validation within the ERA-CLIM and ERA-CLIM2 projects. The data are homogenised and are thus suitable for climate analyses. From 1979 onwards, the homogenisation involved the detection and removal of time series discontinuities through comparison with ERA-Interim data [RD4]. There are 2283 radiosonde stations over the globe (Figure 6). The RAOBCORE data coverage is concentrated on the Northern Hemisphere. Radiosondes are launched at most twice a day, which limits the available times this comparison is possible. Due to the sun-synchronous orbit of the Metop satellites, this temporal restriction is equal to a spatial restriction, as the area covered during the nominal radiosondes launches (0 and 12 UTC), will be more or less the same every day. Figure 7 shows the used stations for one month.

Locations of RAOBCORE radiosonde stations (n = 2283)

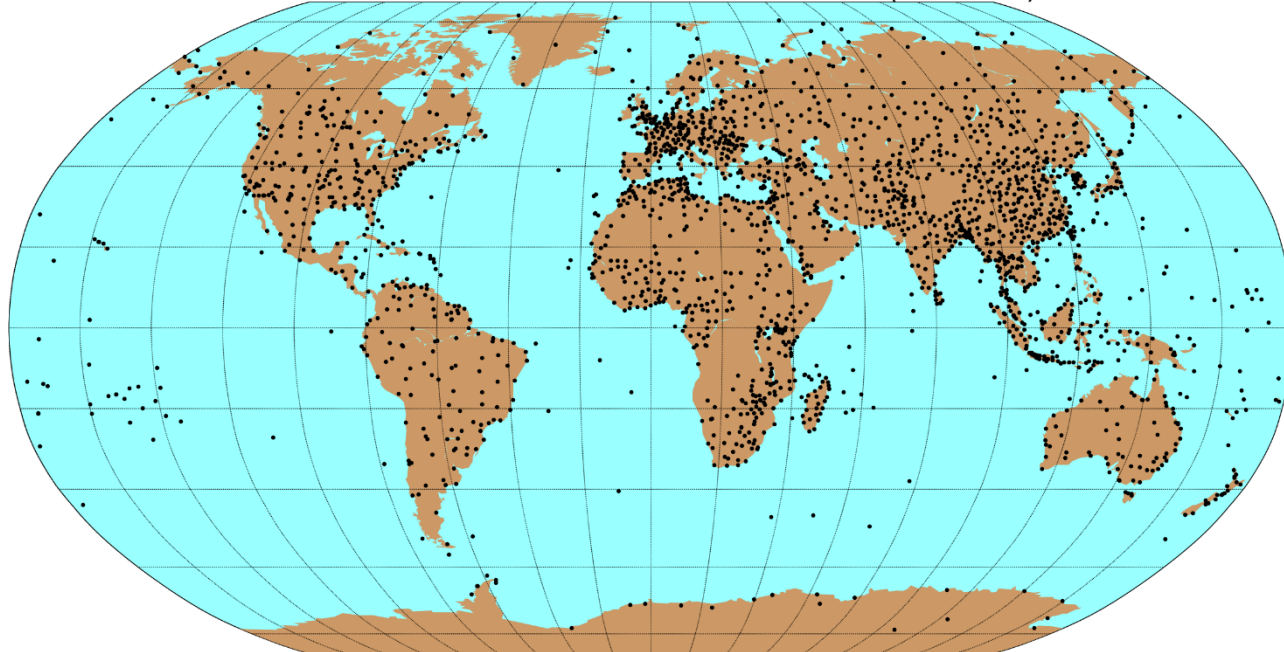


Figure 6: Locations of RAOBCORE radiosonde stations. All stations with corrupt or missing data are excluded.

A wind measurement from a radiosonde does not necessarily represent the same wind as the one derived from satellite, as the radiosonde-wind could be sensitive to smaller scale and more local winds. A complete quality analysis of radiosonde data currently used at EUMETSAT to validate AMVs can be found in [RD5].

Co-locations have been done over the period from January 2007 and April 2013 respectively until August 2016, as RAOBCORE data are not yet available after August 2016.

From the total 2283 available radiosonde stations during the validated period, only a small fraction is actually usable and used for the validation. Figure 7 shows the number of co-locations for the month of January 2014 for the two Metop single and dual products. Due to the satellite orbit, the radiosonde daily launch times of 0 and 12 UTC and the co-location criteria (see section 3.1.1), the co-locations for single Metop data are over an area covering Siberia, Greenland and Western Europe, only very few co-locations over Alaska and northern Canada can be recorded. For the southern hemisphere, most co-locations are at the edge of the Antarctic continent. The co-locations for the dual Metop AMV products cover the same area as the single Metop AMVs and additionally northwest Africa, the western part of South America, New Zealand, Australia and parts of Eastern Asia. Any validation against radiosondes will therefore be biased towards the winds over these regions.

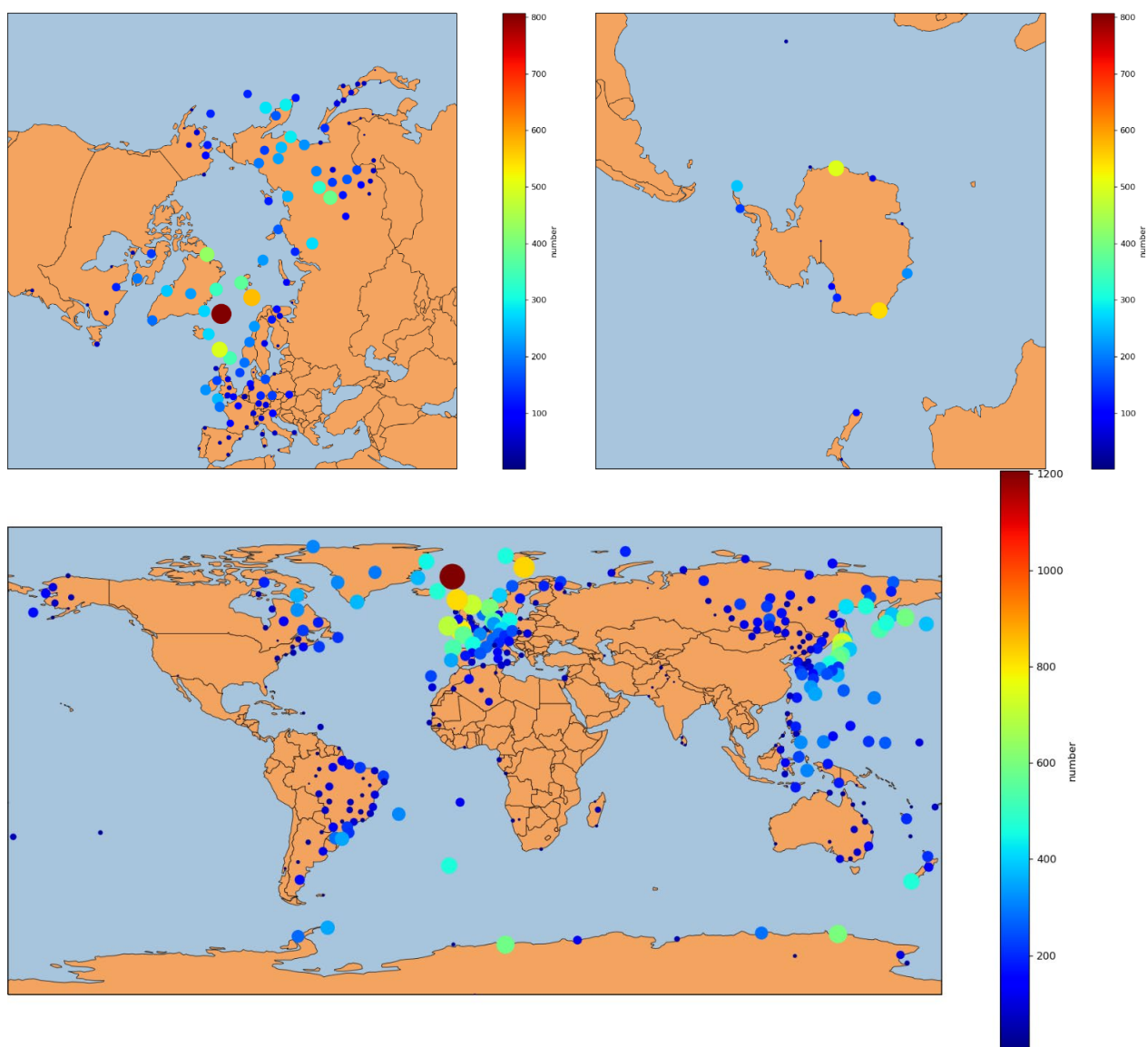


Figure 7: RAOBCORE stations with co-locations against AVHRR AMVs. Top row Metop-A (left Arctic, right Antarctic), bottom row METOP-A/B dual. All plots for collocations of one month (January 2014).

3.1.1 Co-location criteria

Figure 8 shows the co-location criteria used in this validation report, which are based on the recommendations of the Third International Wind Workshop (Ascona, Switzerland, 1996) and the Coordination Group for Meteorological Satellites (CGMS) International Winds Working Group (IWWG) for the international comparison of satellite winds (Velden and Holmlund 1998, [RD6]). Table 3 lists these criteria in detail.

Table 3: Collocation criteria for radiosondes and AMVs

Horizontal distance	Vertical Distance	Temporal Difference	Direction difference
150 km	25 hPa	90 minutes	60 deg

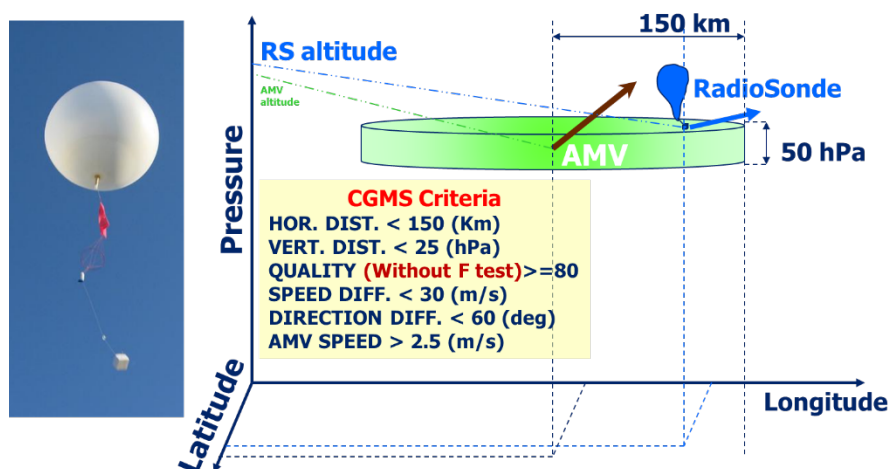


Figure 8: Criteria of co-location recommended for AMV co-location.

3.2 Reanalysis data

Comparison against model data is a common measure used among AMV producers and users to evaluate AMV quality. We are using the ERA-Interim forecast data to evaluate our reprocessed AMVs. ERA-Interim [RD4] is a global atmospheric reanalysis starting in 1979, continuously updated in real time until the 31 of August 2019. It provides time series of a comprehensive set of atmospheric variables. ERA-Interim uses a fixed version of the ECMWF Numerical Weather Prediction (NWP) model (IFS - Cy31r2) to produce reanalysed data. The system includes a 4-dimensional variational analysis (4D-Var) with a 12-hour analysis window. The spatial resolution of the data is 0.5° on 60 vertical levels spread from the surface to 0.1 hPa.

Each valid AMV is compared with its corresponding model wind. The closest model data in time and space is provided in the AVHRR AMV product and is used for this analysis.

3.3 Operational Metop AVHRR AMVs

EUMETSAT produces in real time Metop AVHRR AMVs [RD17] that are routinely assimilated and monitored by NWP forecasting centres [RD13]. Throughout the time, the operational EUMETSAT algorithm versions evolved as shown in Table 4.

Table 4: History of the major changes in the operational EUMETSAT processing software

Version	Time	Change
1.4	26 January 2011	First operational version
2.0.2	13 December 2011	- Introduction of IASI for height assignment - Low level an parallax correction
2.1.3	20 Mars 2013	- Change in forecast interpolation - Change of QI - Introduction of triplets
2.2.4	10 July 2013	- Determination of the tropopause height - Bug in T inversion corrected
2.3.1	5 February 2014	- Introduction of dual time difference (real time between 2 images) - Parallax removed for IASI h - Vector calculation uses center of target to center target rather than CCC center to CCC center



2.3.3	3 June 2014	• QI calculation update to make dual and single quality consistent • Update of the calibration parameters • Bug fixes
2.4.0	11 November 2014	• Some minor changes
3.0.1	20 May 2015	• Introduction of the triplet
3.1.0	2 December 2015	• Input handling updated to manage large orbit drift
3.1.1	21 June 2018	• Bug fixed in 3.1.0

For this report, time-series and monthly averages are compared. The operational and reprocessed AVHRR AMV data share the same operational EUMETSAT algorithm (v3.1.1) at the time of reprocessing [RD2]. At this time, the differences are only caused by differences in the setup of the algorithm. They mainly arise from the input forecast data that differs (3-hourly forecast data from real time NWP versus 6-hourly ERA-interim reanalysis). When possible, the operational algorithm also uses the IASI cloud top pressure [RD18] to set up the winds altitude, which is not the case in the reprocessed data that does not use IASI data.

3.4 MODIS AMVs

The National Oceanic and Atmospheric Administration (NOAA) was the first to produce operational AMVs from polar-orbiter imagers. Their wind retrieval algorithm was pioneered for MODIS. It relies on image triplets for cloud tracking, using in total data from three consecutive orbits, tracking features from the middle orbit back to the first and forward to the last, spanning in total 200 minutes between the first and the last orbit [RD14]. The usage of a triplet of images facilitates the consistency between two intermediate wind vectors. However, the number of images used, along with orbit inclination and sensor swath width, constrains the size of the overlap region available for cloud tracking. As a result, the coverage of NOAA polar winds is generally limited to latitudes poleward of 65° – 70° for single-satellite and 60° – 65° for mixed-satellite AMVs. Like for the Metop retrieval, the AMV derivation is guided by an a priori temperature and wind profiles interpolated from the 6th and 9th hour forecast from the NOAA global forecast system.

Satellite AMVs are derived in real-time from MODIS instrument on board Terra and Aqua satellites. The MODIS instruments on Terra and Aqua image the same area on Earth approximately three hours apart. Terra (*Aqua*)'s sun-synchronous, near-polar circular orbit is timed to cross the equator from north (*south*) to south (*north*) (descending (*ascending*) node) at approximately 10:30 A.M. (1:30 P.M.) local time. As for Metop, MODIS winds a mixed-satellite product was developed, in order to improve the timeliness of the winds and to extend the coverage equatorward. The difference in time between Terra and Aqua satellite overpasses does not allow the global coverage as it is obtained from Metop data. The primary MODIS wind products are based on 1 km MODIS Level 1B (MOD021KM) HDF files are obtained through the NOAA Real-Time System, or bent pipe, located at NASA Goddard Space Flight Center. MODIS data used in this report are available from CIMSS at:

http://stratus.ssec.wisc.edu/products/rtpolarwinds/pwinds_RTdatadescription.html.



4. Temporal and statistical evaluation

For most analysis, the data record is divided into four classes of retrieved wind vectors depending on their assigned height as described in Table 5. In addition, three geographical regions are considered as shown in Table 6.

Table 5: AMV height (pressure in hPa) classes used for the validation

CLASS	Description
ALL	All vectors are considered for calculating the statistics
HIGH	Only vectors with a height < 400 hPa are considered for calculating the statistics
MID	Only vectors with $400 \leq \text{height} \leq 700$ hPa are considered for calculating the statistics
LOW	Only vectors with a height > 700 hPa are considered for calculating the statistics

Table 6: Geographical regions used for the validation

REGION	Description
Global	Global
North Pole (NP)	Latitude > 40°N
South Pole (SP)	Latitude > 40°S

4.1 Temporal analysis

The single Metop-AVHRR AMVs are available over the poles pole wards of 40° North and South, therefore analysis on the single Metop product will be performed per pole. The dual Metop product is available globally the analysis will hence be done globally in most cases. Overall, global averages for the produced AMVs can be found in the Table 7.

Table 7: Averaged number, speed and height of AMs (with a $QI > 60$) derived per day in the three height classes and total for the complete possible coverage of each dataset.

		Low level	Mid level	High level	All level
Metop-A (single)	Number	18422	53096	12104	83623
	Speed (ms^{-1})	13.0	16.0	24.3	16.5
	Height (hPa)	804	541	346	571
Metop-B (single)	Number	19845	56495	12853	89195
	Speed (ms^{-1})	13.0	16.1	24.4	16.5
	Height (hPa)	803	542	346	572
Metop-A/B (dual)	Number	78327	111563	48322	238213
	Speed (ms^{-1})	12.2	17.5	24.4	17.1
	Height (hPa)	822	541	311	587
Metop-B/A (dual)	Number	70234	103474	44541	218250
	Speed (ms^{-1})	12.3	17.5	24.4	17.2
	Height (hPa)	822	541	313	585

In Figure 9 the daily number of winds and average wind speed for Metop-A single product is shown for the North (*a* and *b*) and South Pole (*c* and *d*). As described in Table 5 the time series is shown for the three height classes representing the wind in 'high', 'mid' and 'low' level of the atmosphere. In contrary to AMVs from geostationary satellites,



polar AMVs are generally lower, so the highest number shows up for the medium height class. Roughly, 30000 mid-level AMVs are recorded per day over the North Pole and 25000 over the South Pole. In the high and low class, we only find 10000 AMVs per day or even less. The little number of high level AMVs can be explained by the fact that over polar areas, the tropopause is relatively low (~250-300 hPa). Optically thin low level clouds, particularly in summer as well as omnipresent temperature inversion lead to quite challenging height assignment at those levels.

The number of winds shows a clear seasonal cycle with the maximum in summer time, over the North Pole the high and mid winds peak then, whereas the low level AMVs have a low in summer and winter and peak in spring and autumn. This is most likely because high low level winds fall into the mid level bin for some months of the year. For the South Pole the picture changes a bit, again mid level winds peak in summer, so do the low levels, however the high level AMVs peak in wintertime and are nearly zero in summer. This seasonal cycle can be linked to the total cloud cover in the arctic regions that also peaks in summer time (see [RD10]).

The daily average wind speed derived from the AMVs also follows a clear annual cycle. Over the Arctic, we see a high in winter and a minimum in the summer months for all heights. This can be linked to the polar vortex which is stronger in winter times resulting in higher wind speeds. Mid and low level winds in over Antarctica show the same summer low and winter high pattern. The high level winds have the opposite cycle with average wind speeds reaching 30-35 ms⁻¹ in southern hemispheric summer, dropping to 20-25 ms⁻¹ during winter times. During the summer months only very few high level AMVs are retrieved, how this affects the high wind speeds is unclear.

Figure 41 in Appendix A shows the same as Figure 9 for Metop-B. The annual cycle for the number of winds and average speed is the very similar to Metop-A. This shows that there is a high consistency between data records from both satellites (see section 4.3).

In Figure 10 and Figure 42 the same statistics are displayed, this time for the dual product of Metop-A/B and B/A respectively. There is a higher number of retrieved winds in the dual products compared to the single; this is due to the greater spatial coverage (all globe) of the dual product. Otherwise, the same vertical distribution and annual cycle occurs as for the single products. For the South Pole the number of retrieved low-level winds is constantly at 20000 AMVs per day more than the high-level winds and without any annual cycle. For the dual AMVs, when compared to the low and mid level, high level AMVs shows an anticyclical behaviour. Again, a very low number of AMVs can be the reason.

For all four data records, we see that we have a stable time series and that seasonal annual cycles are present in all data records.

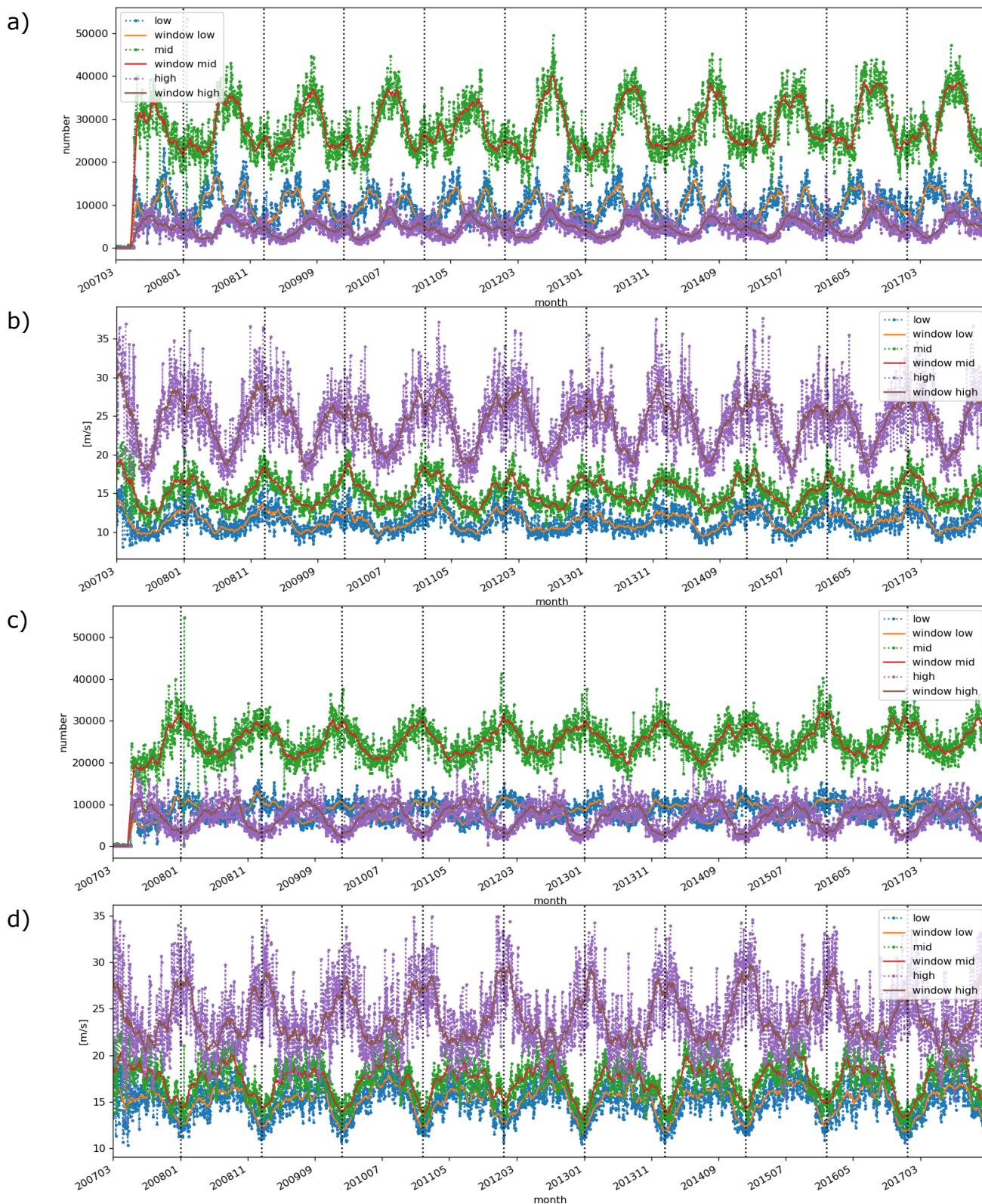
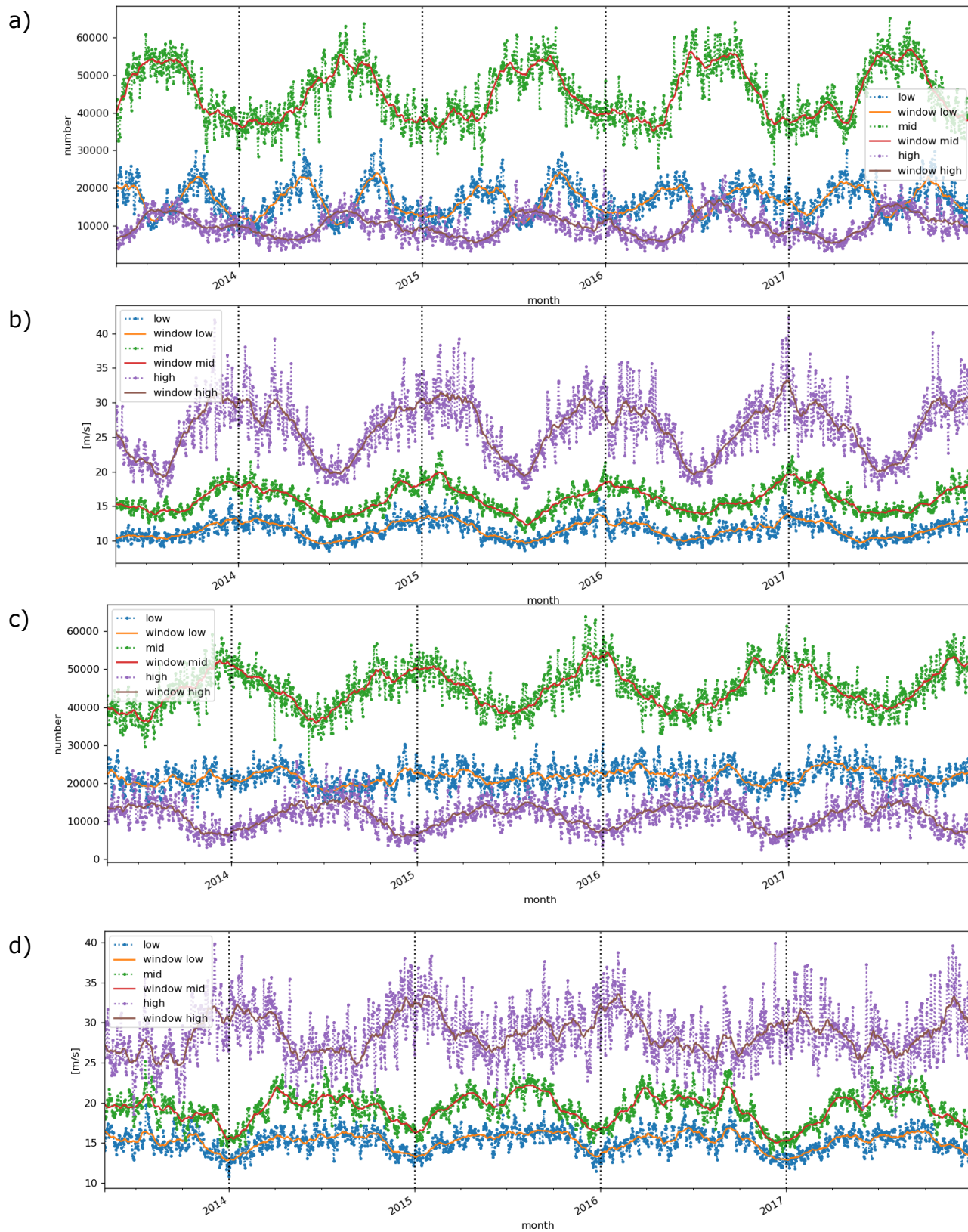


Figure 9: Metop-A time series of the number of winds and their speed for the three height classes. Each dot represents a daily average for the North (a and b) and South Pole (c and d), only wind vectors with a $QI > 60$ and a speed $> 5 \text{ ms}^{-1}$ are considered. The lines represent the running mean over 30 days.



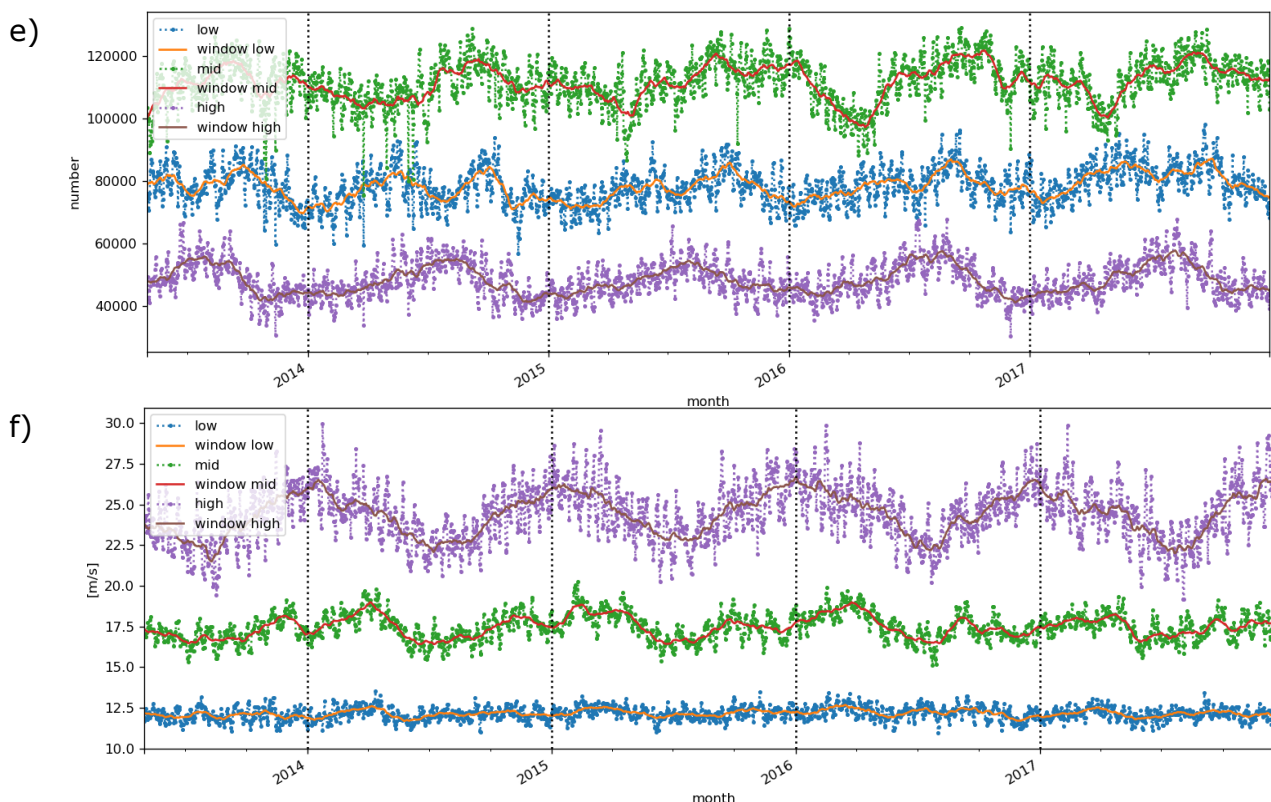


Figure 10: Metop-A/B (dual) time series of the number of winds and their speed for the three height classes. Each dot represents a daily average for the North (a and b), South Pole (c and d), and global (e and f), only wind vectors with a $QI > 60$ and a speed $> 5 \text{ ms}^{-1}$ are considered. The lines represent the running mean over 30 days.

4.2 Temporal and regional stability

In this section, we present the temporal and spatial stability of the products. For this analysis, Hovmoeller plots for daily averaged zonal (u) and meridional (v) vector components, speed and pressure are analysed. The height of the wind vector is inferred from the temperature of the IR AVHRR image (channel 4) using the Equivalent Black Body Temperature (EBBT) method that uses NWP temperature profiles. For the first few months until the 23rd of May 2007, the number of retrieved AMVs is very low (see also section 8 on limitations). The first few months in Figure 11 and Figure 12 should be ignored. Figure 11 and Figure 12 show data for Metop-A single product, while Figure 13 displays Metop-B/A dual data. Metop-B single and Metop-A/B dual data are not shown, but are very similar and show no discrepancy between the products.

The zonal averaged u and v components for the North Pole for Metop-A single mode show a slight annual variation (Figure 11 (a and b)), with higher wind speeds of around 20 ms^{-1} in winter and 15 ms^{-1} in summer for the u -component between 45 and 55°N . The v -component is quite stable at around 5 ms^{-1} only towards the pole we get some higher wind speeds up to 20 ms^{-1} in winter.

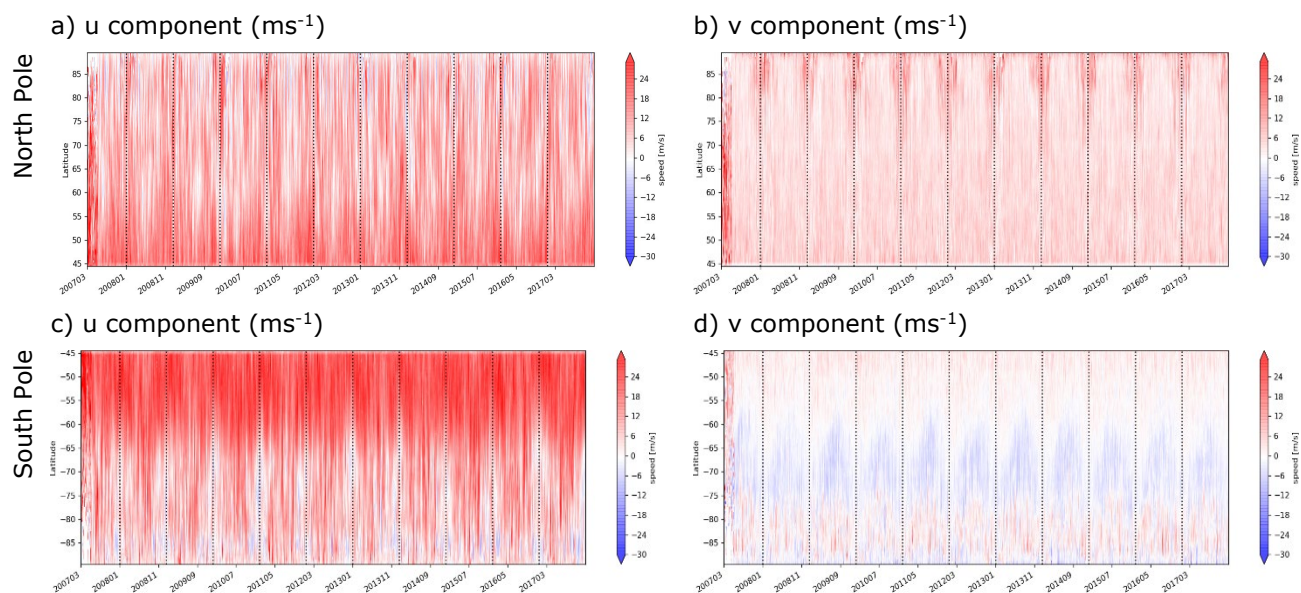


Figure 11: Zonal (a/c) and meridional (b/d) component of zonal averaged wind components in ms^{-1} for the period 2007–2017 for Metop-A. Only $\text{QI} > 60$ are retained.

The 'roaring forties' in the southern hemisphere can be clearly seen in sub-plot c) of Figure 11, with a high u -component above 25 ms^{-1} . Towards the Antarctic continent, the speed drops below 10 ms^{-1} and we get easterly winds. The v -component is near zero for most of the time. An expected behaviour showing the very pronounced polar vortex in the southern hemisphere, which has only slight variations over the year.

In Figure 12, the average speed and height for Metop-A single mode AMVs are displayed. North and South both show the higher wind speeds between 45° and 55° , with a stronger annual cycle for the north.

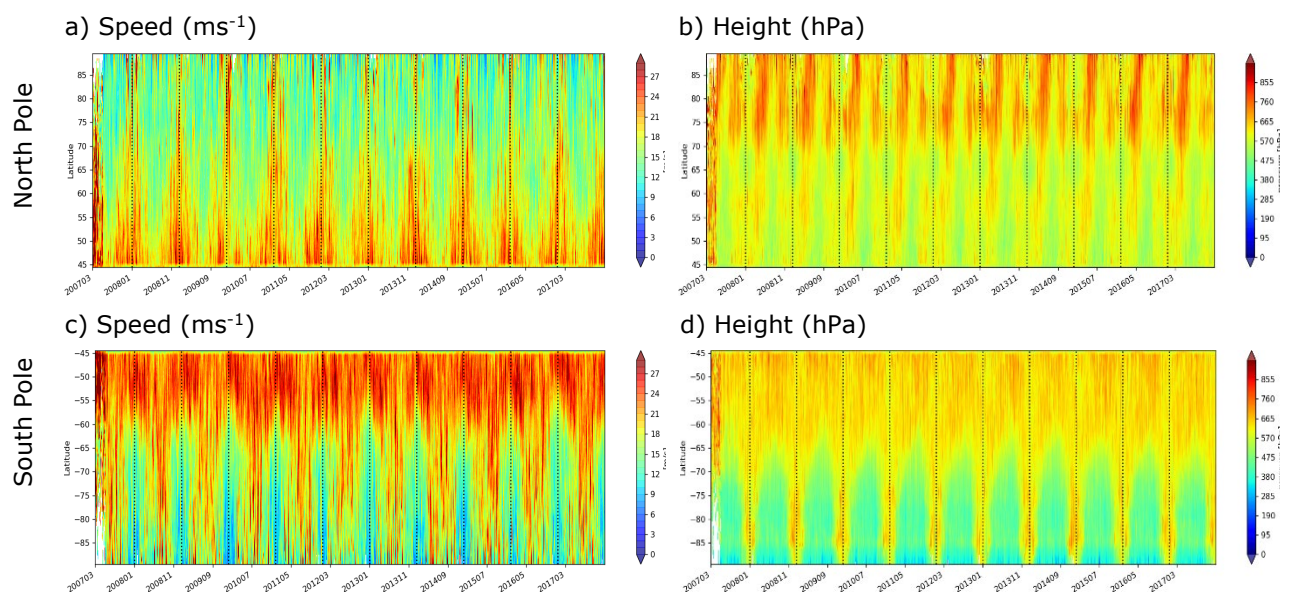


Figure 12: Wind speed in ms^{-1} (a and c) and height in hPa (b and d) of the zonal averages for the period 2007–2017 for Metop-A. Only $\text{QI} > 60$ are used.

The average height distribution differs between North and South Pole. Low values are found near the North Pole and over the southern oceans, showing the absence of low-level winds over the Antarctic continent. The slight decrease in average height during the winter is most likely due to the absence of high level AMVs.

In Figure 13, the data for Metop-B/A dual is shown. As the product is available on a global scale the, global Hovmoeller plots are used. The sub-plot a) shows the zonal u -component. Very clearly, the jet streams in the northern and southern hemisphere can be detected with positive (i.e. westerly winds) wind speeds of 30 ms^{-1} and more. The position and strength of the southern jet is stable year round and has hardly any variation. Zonal wind speeds of more than 25 ms^{-1} are found between 30 and 60 degrees south. The northern hemispheric jet has more variation. In winter times it can extend between 20 and 60 degrees north, while in summer it is limited to a smaller region around 40 degrees. In the tropics, we see easterly flows and wind speeds up to 15 ms^{-1} . The meridional v -component (sub-plot b)) has much lower values, peaking at 15 ms^{-1} in winter times. In the tropics and sub-tropics, the v -component is low year round.

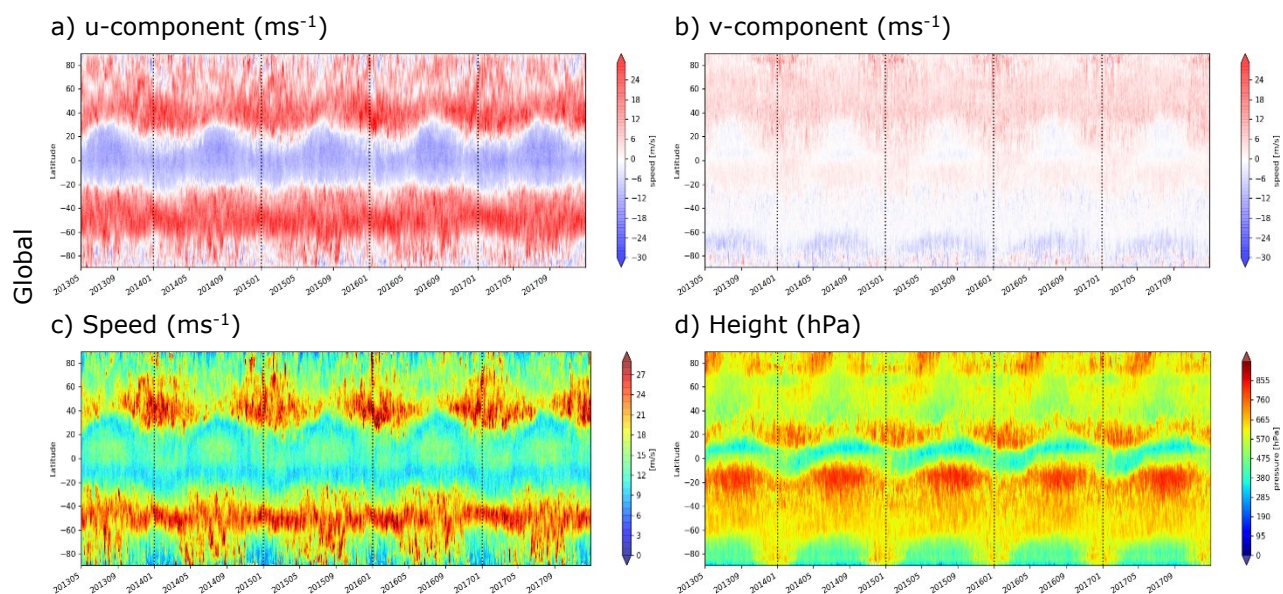


Figure 13: u and v components in ms^{-1} (a and b), wind speed (c) in ms^{-1} and height in hPa (d) of the zonal averages for the period 2013-2017 for dual Metop-B/A. Only $\text{QI} > 60$ are used.

Sub-plot c) of Figure 13 shows the wind speed, again the jets, dominated by the u -component, stand out, with the clear annual cycle in the north and the more constant flow in the south. In sub-plot d) the average pressure is displayed. A very distinct annual cycle can be made out. Low-level winds dominate the southern subtropics, following the movement of the ITCZ. Towards the South Pole, we have medium to low-level clouds between 600 and 700 hPa. Further south high level winds prevail, except for the summer months when we also get lower level AMVs. This corresponds well with the findings in section 4.1, where we see an increase in mid-level winds. The northern sub tropics show also predominantly low-level AMVs following the ITCZ, however not so clear as for the south. In the mid latitudes medium level AMVs dominate, with lower winds over the pole. In the tropics, the height of the AMVs is clearly following the ITCZ, resulting in a narrow band of high level AMVs.



In conclusion, the reprocessed AMVs are stable and exhibit geographical and seasonal features in line with well-known atmospheric circulation patterns.

4.3 Product Inter-comparison

In this section, we compare the different data records with each other. For this comparison, the various datasets were independently gridded on a regular $1 \times 1^\circ$ grid. Comparisons can only take place after 2013 once Metop-B was launched.

We compare wind roses from single Metop-A, and -B and dual Metop-A/B and -B/A for each height sector (Figure 14 and Figure 15). We see an excellent agreement in height, speed and direction distribution between the different products. For a comparison on daily averaged numbers, please refer to Table 7.

As expected, the highest wind speeds appear in the regions above 400 hPa in the north and south. For the month of January we have southwesterly wind directions and close to no winds from northeasterly directions for these high winds over the North Pole. In the middle atmosphere, the main direction is westerly; however, winds from all directions are now present. In the lowest part of the atmosphere, we have predominantly easterly and westerly winds and only few winds blowing in a north south direction or vice versa.

The situation for the South Pole is similar for the high winds with high wind speeds (ranging above 50 ms^{-1}) from a northwesterly direction. In the middle atmosphere, the main direction is still from west with some winds also coming from the east. The low-level winds come clearly from a west to southwesterly direction.

For the month of July, the speed and direction change significantly for the North Pole but not for the South. High winds in the north have a predominant southerly flow. In the middle atmosphere, there is now preferred direction and in the lower atmosphere, we see mainly northerly flows. However, these findings are not typical for summer or winter months over the North Pole. Data from other years show that especially the directions can vary significantly. The situation over the South Pole seems to be more stable.

We have compared the AMVs generated using a single satellite with the dual ones generated using two satellites. The dual AMVs have a slightly higher percentage of fast winds above 50 ms^{-1} , and the direction variation is smaller and concentrates around west-southwest. Similarly, for the mid-level AMVs, we see some higher speeds and narrow to westerly winds. The same pattern is shown for the low level, although some winds from northern and easterly directions are present. For the South Pole there is hardly any difference between single and dual AMVs. The higher speeds in the dual AMVs can possibly be explained by the smaller time step between the images, that allows to track faster cloud movements, which otherwise would have moved outside the covered area. For the month of July, we see similar differences in speed and direction over the North Pole between single and dual AMVs. The Dual AMVs from Metop-A/B and Metop-B/A however agree very well.

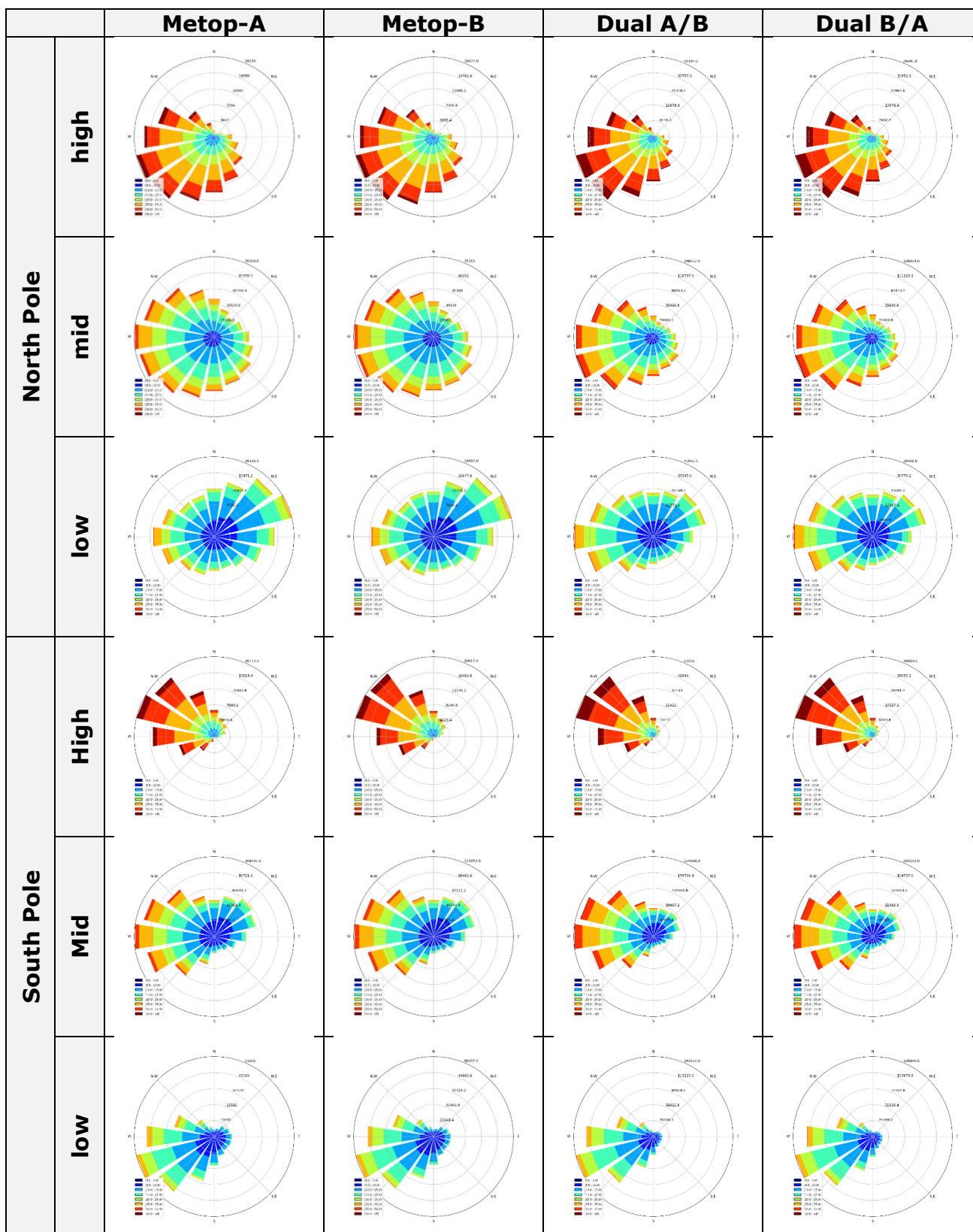


Figure 14: Wind roses for Metop-A single (first column), Metop-B single (second), dual Metop-A/B (third) and Dual Metop-B/A (fourth) for January 2015. The three different height classes are displayed (high, mid, low) for the North Pole (upper three rows) and South Pole (lower three rows).

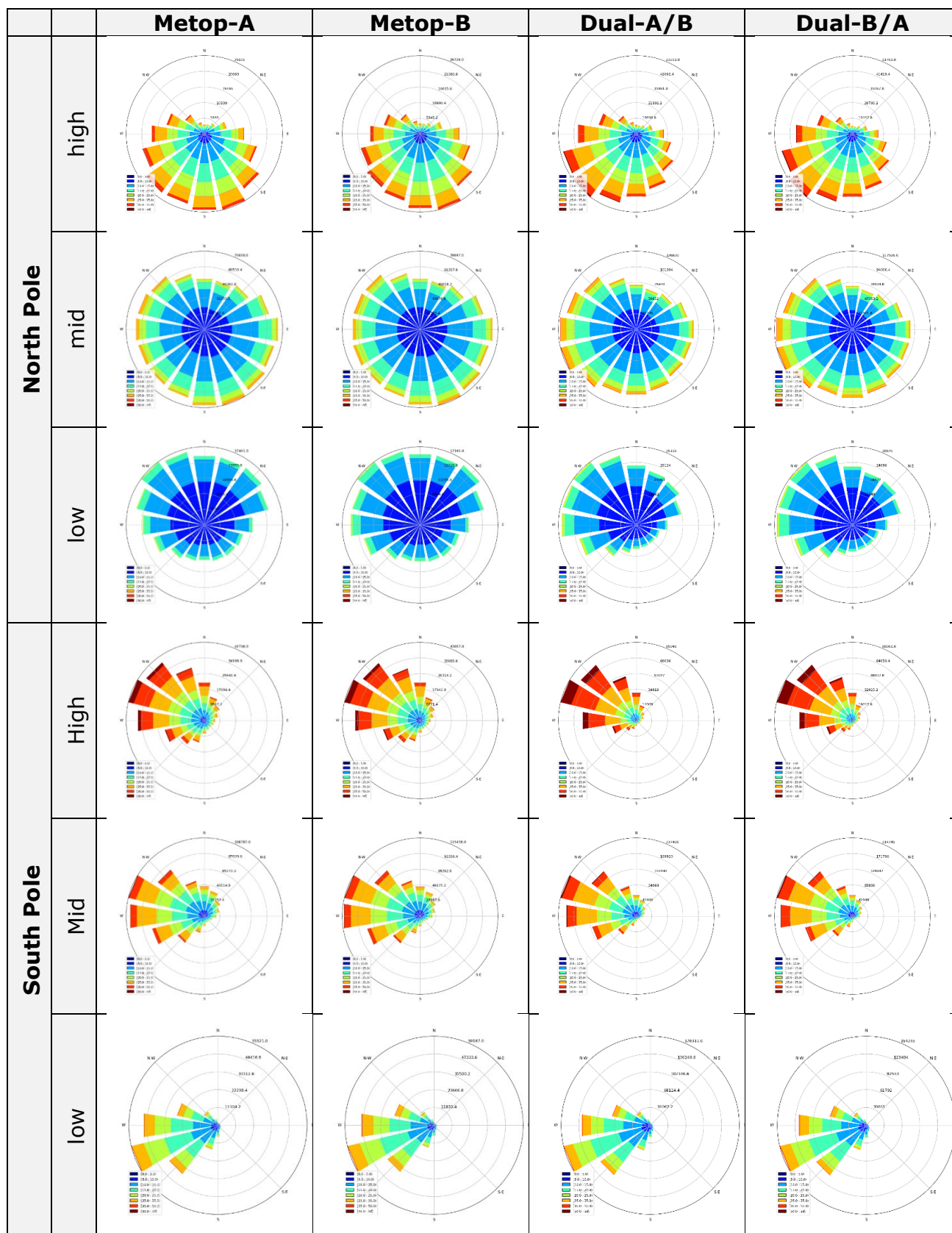


Figure 15: Wind roses for Metop-A single (first column), Metop-B single (second), dual Metop-A/B (third) and Dual Metop-B/A (fourth) for July 2015. The three different height classes are displayed (high, mid, low) for the North Pole (upper three rows) and South Pole (lower three rows).

This section focuses on the geographical comparison between Metop-A and -B for the single and dual products. In general, the agreement between the Metop-A and -B winds is very good. Nevertheless, there are some small differences, as shown in Figure 16 and Figure 17 for the single AMV. The speed difference between Metop-A/B and -B/A is small as shown in Figure 18. The two dataset have not been co-located (but gridded then compared), that can partly explain the difference in this comparison. For clarity, only one month is shown but results are similar over the period. The pattern and sign of the difference varies for every month, there is no clear bias or trend, just a random noise in the difference.

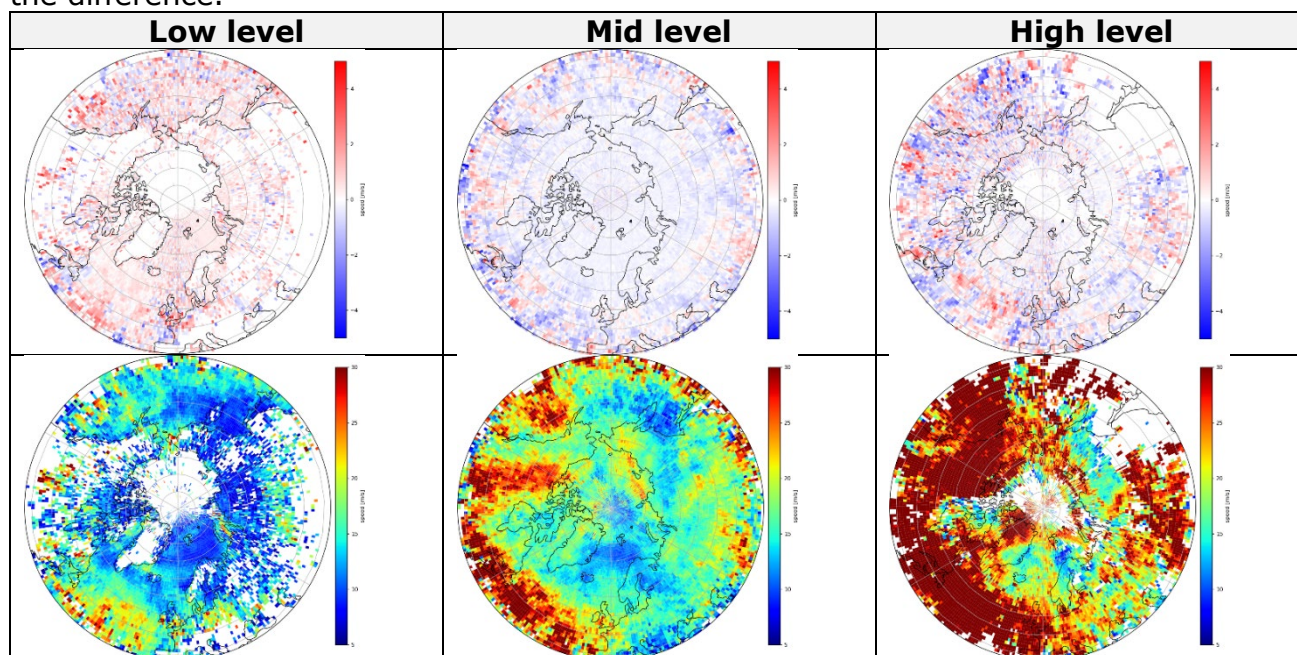


Figure 16: North Pole speed comparison between Metop-A and Metop-B for January 2014. The top row is the speed difference (ms^{-1}) and the bottom row is the corresponding average speed for Metop-A displayed in the three height classes for North Pole.

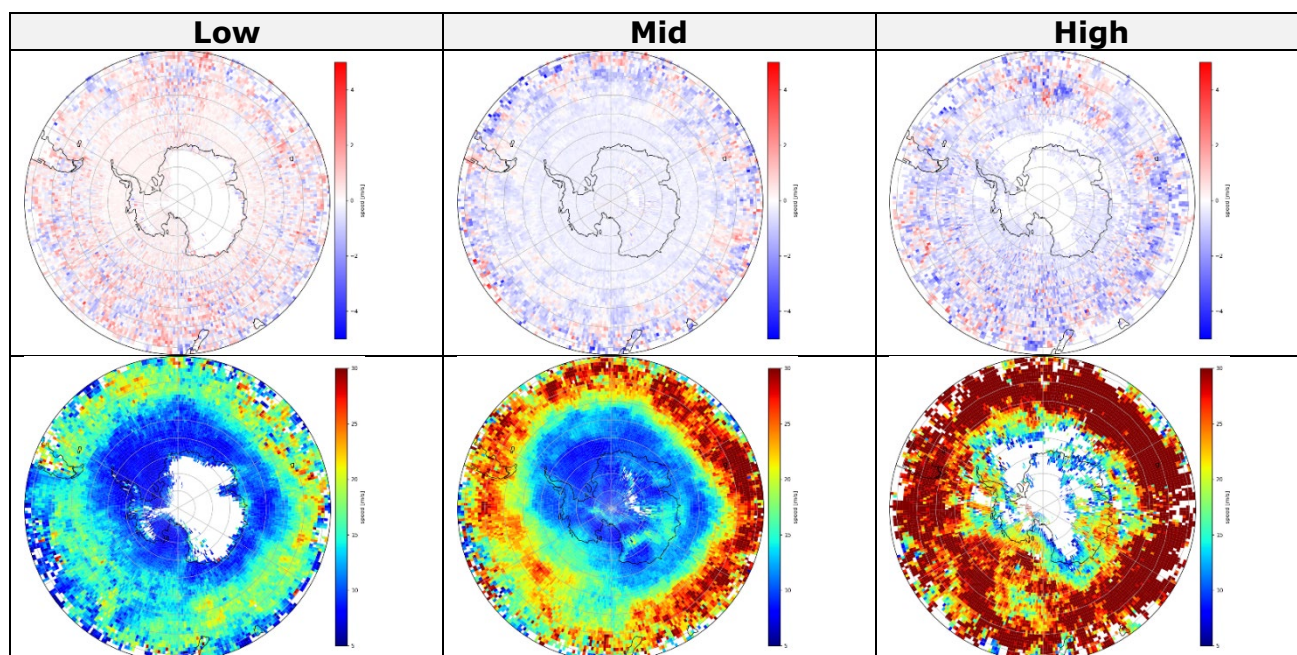


Figure 17: Same as Figure 16 for the South Pole.

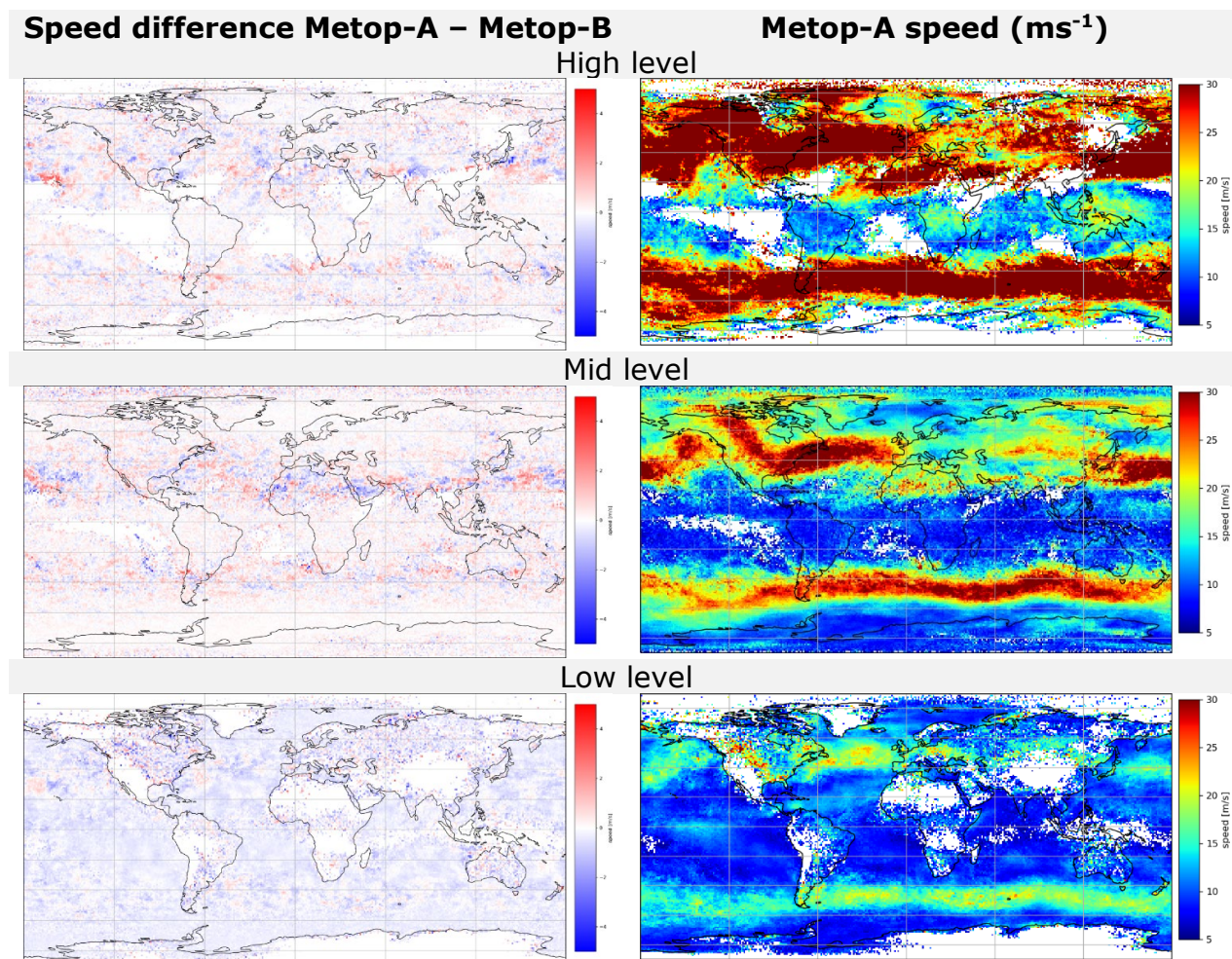


Figure 18: Metop-A vs. Metop-B dual, January 2014. Speed difference (ms^{-1}) and Metop-A speed (ms^{-1}) displayed in the three height classes.

Figure 19 also highlight how single and dual Metop-A and -B speed differs in the three height classes. Data were not co-located; instead, all results are based on the comparison from the 1° grid boxes. In general, the wind speed agrees very well and most data points are on the 1:1 line. For the low- and high-level classes there is a higher degree of scatter between AMVs from Metop-A and -B. A combination of a smaller numbers of AMV and issues with cloud detection might be the reason here. At mid-level, there is a very good agreement for north and south and for the global product.

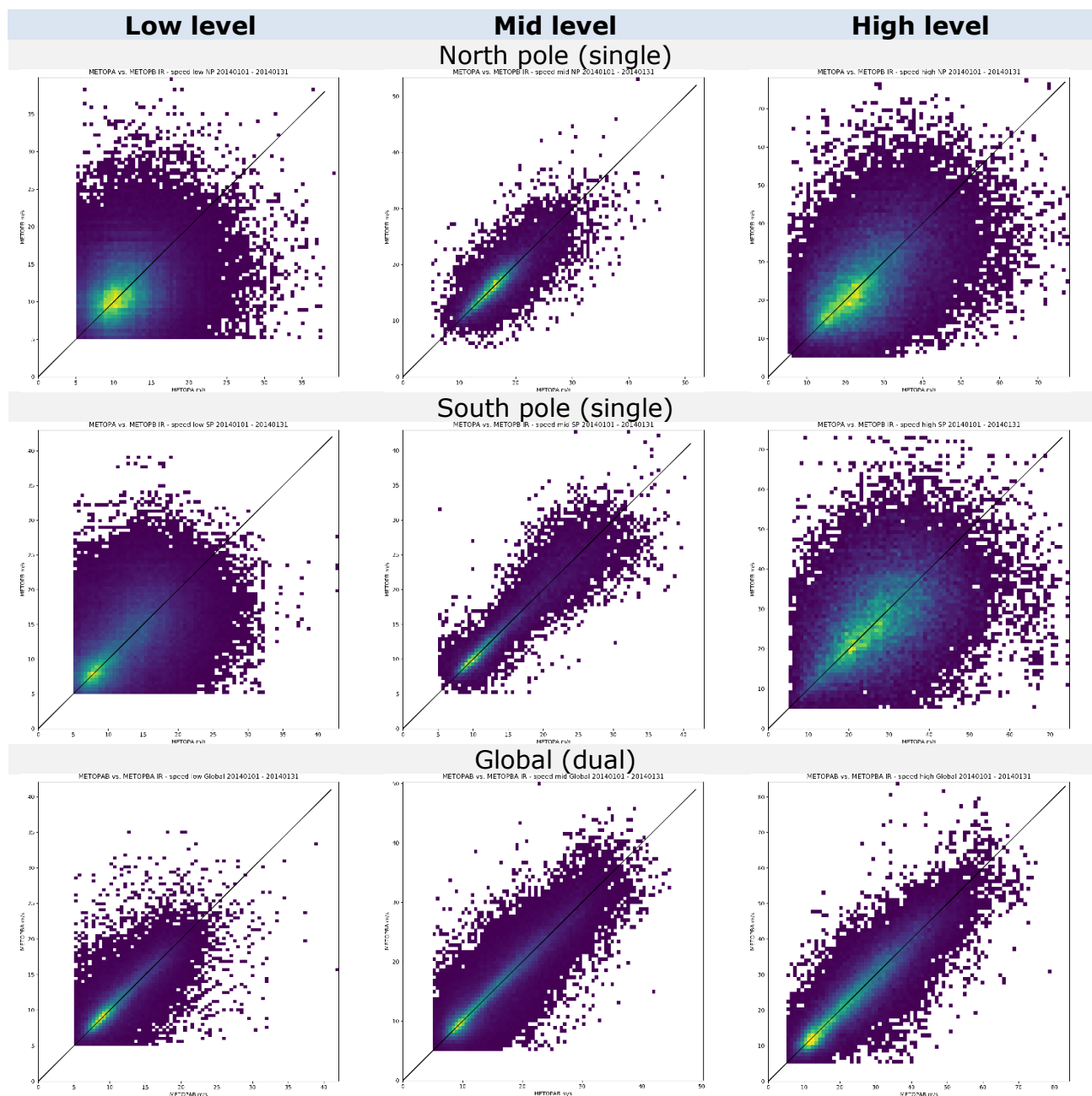
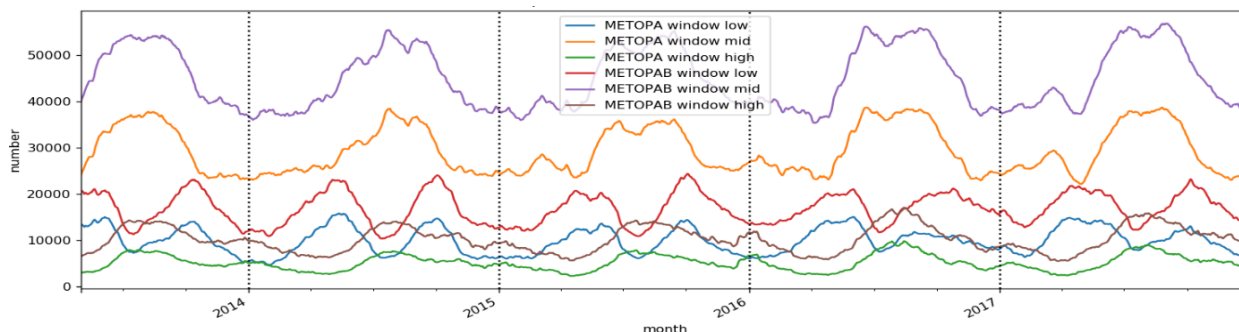


Figure 19: Scatter plot of Metop-A vs Metop-B speed (ms^{-1}) for January 2014. Metop-A on x-axis, Metop-B on y-axis, for low, mid and high (left to right) and north (top) and south (middle) and global dual (bottom). Note that all wind speeds below 5 ms^{-1} and with a $\text{QI} < 60$ have been disregarded.

As a conclusion to the inter comparison between Metop-A and Metop-B derived AVHRR AMVs, we can conclude that in general the retrieved winds agree very well. However, some statistical noise remains that can be linked to sampling issues and some known retrieval deficits.

a) Daily number of AMV – north pole



b) Daily number of AMV – north pole

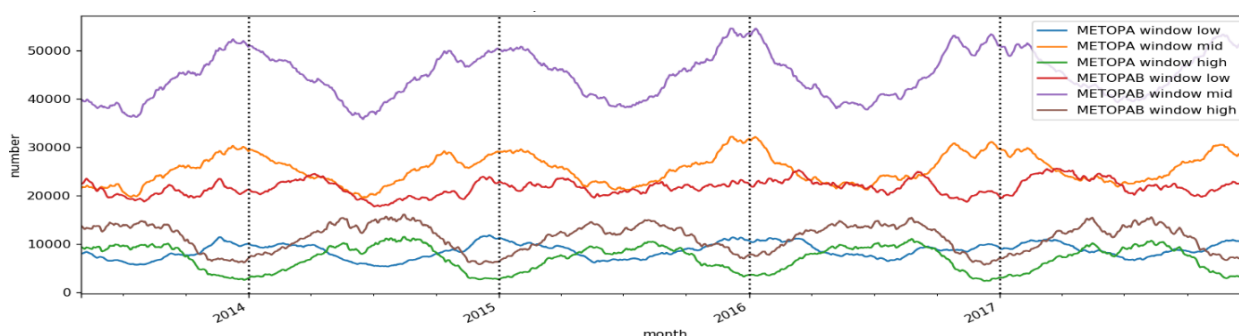
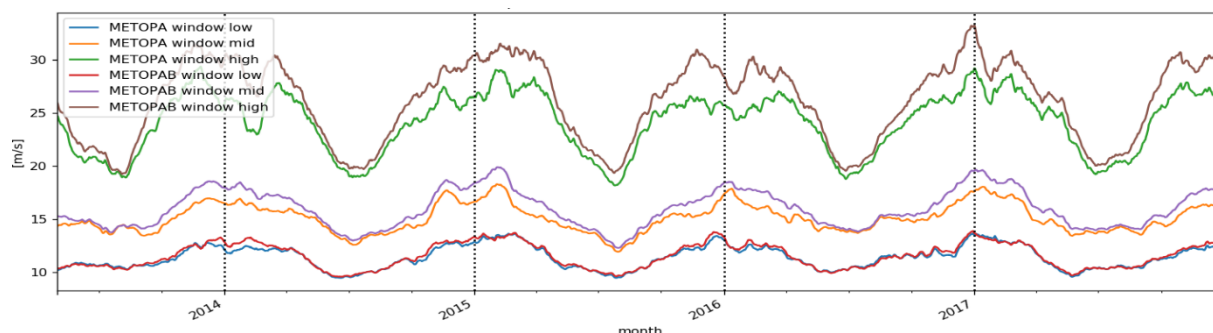
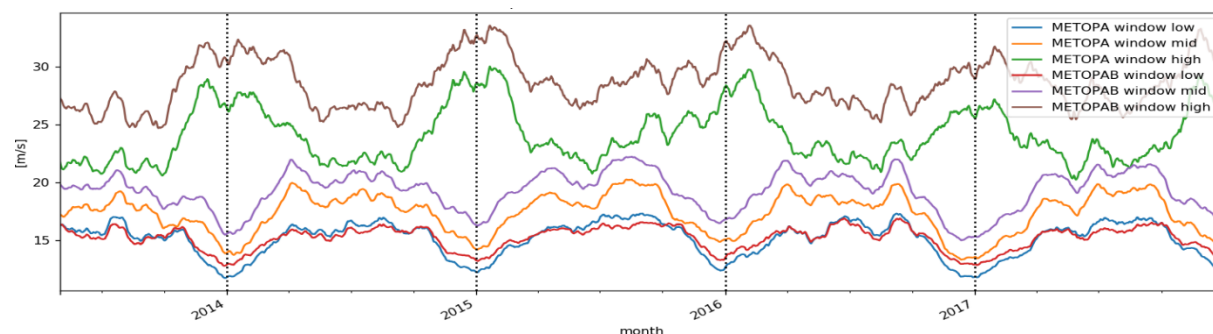
c) Daily speed (ms^{-1}) – north poled) Daily speed (ms^{-1}) – south pole

Figure 20: Metop-A (single) vs Metop-A/B (dual). Comparing number of AMVs (top two rows) and average speed (bottom two rows) for Arctic and Antarctic. Only AMV with a QI >60 are retrained.

Using two distinct Metop to retrieve AMV allows deriving more and faster AMVs as shown in Figure 20. The daily number of AMVs and average speed for Metop-A (single) and Metop-A/B (dual) for each height classes are presented. The annual seasonal behaviour are the same for both data records, however with more than 20000 AMVs more in the dual record. The average speed for the dual series is also higher especially for the high-



and mid-levels (Figure 20). This can be related to the time difference between the overpasses (100 minutes for the single and only 50 for the dual) hence very fast moving clouds will not be captured by the single mode, as they are likely to have moved outside of the area covered.

As in [RD16], we can also conclude that Metop-A/B and -B/A can be considered as statistically equivalent.

5. Comparison with EUMETSAT operational product

In this section, we compare the reprocessed AMVs (abbreviated to CDR) with the operational NRT product from the EUMETSAT operational ground segment (abbreviated to OPE).

The CDR has been produced using the latest version of the operational software available (v3.1.1) at the time of the reprocessing. There are some differences in the way the algorithm is used operationally and in reprocessing mode. The difference comes from the input data:

- **Image level 1:** OPE and CDR both use the L1b of AVHRR, currently no reprocessed L1b data of the LAC AVHRR record exists. This does not affect the quality of the AMVs very much as target identification does not depend much on differences in the quality of the instrument calibration in the time series. For the CDR 3 minutes PDU are reconstructed from the archived dump (orbit) data.
- **Model data:** OPE uses operational ECMWF NWP real time forecasts (3-hourly), CDR used ERA-Interim forecast data (6-hourly). In [RD11] the impact of background NWP data was analysed, we expect differences between the two records due to this.
- **IASI-L2:** The OPE record uses IASI L2 information to assign, when possible, the wind height. IASI information is not used in the generation of the CDR.
- **Coverage:** The geographical coverage of the OPE AMV retrieval has changed over time while for the CDR it remains constant over the period. The latitude considered for the polar AMV retrieval allows AMV retrievals to a minimal latitude of at most 35° from the poles. The initial setup of the OPE allowed to retrieve polar AMVs to a maximal latitude of 55° from the pole. It was successively changed to allow a retrieval up to 50° and finally 35° on 25 June 2013 and 20 May 2015, respectively.

The OPE data used for the comparison in the following section was retrieved from the EUMETSAT data centre. For a couple of months in 2016, OPE AMVs from Metop-A are corrupted in the EUMETSAT archive, hence some 'flat lines' appear in the time series comparisons.

5.1 Time series analysis

In this section, time series comparison of OPE versus CDR number of AMVs per day and average daily speed are presented. For better visibility only the 30-day running windows are shown for the three different height classes.

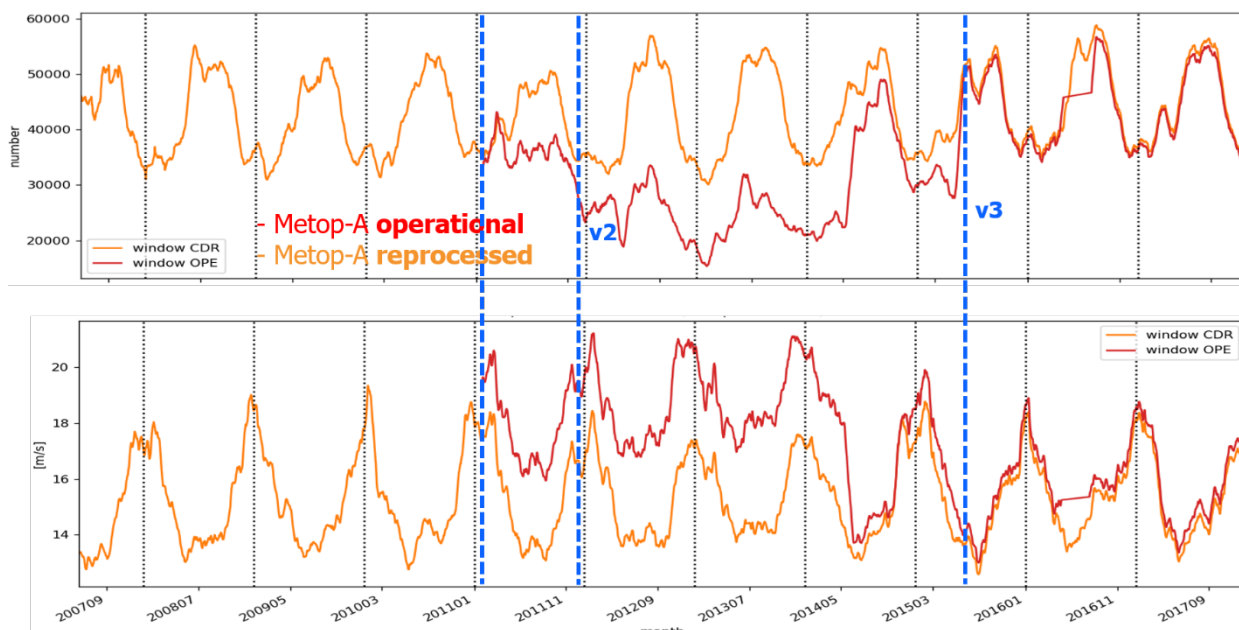


Figure 21: North pole number of winds and speed (ms-1) daily reprocessed (CDR) vs operational (OPE) Metop-A AVHRR AMVs at all heights for AMVs with QI > 30 and all wind speeds. The blue vertical bars indicate the start of the production of the OPE AMV, the start of operational software v2 and v3, respectively.

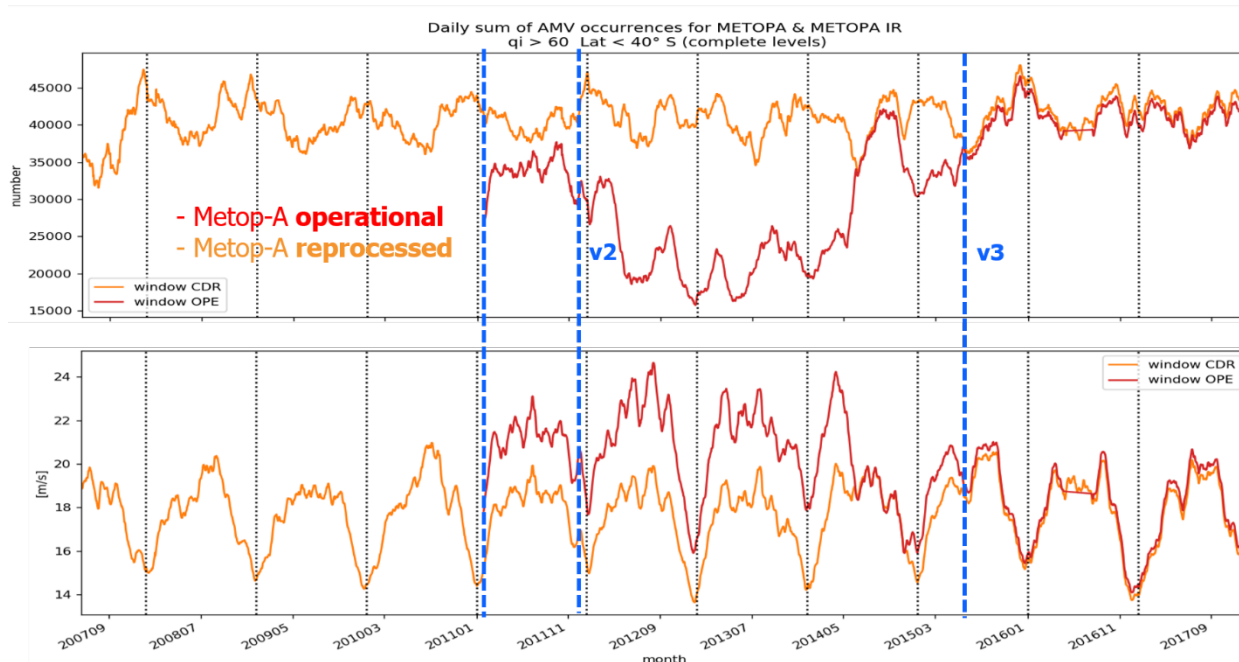


Figure 22: same as Figure 21 for the South Pole.

Figure 21 and Figure 22 present a comparison of CDR and OPE AMVs for Metop-A, including all AMVs over the whole globe, counting per day, with no speed selection and all AMVs QI higher than 30. The operational Metop-A AMV production starts only in 2011. The big differences between OPE and CDR appear at the beginning of the OPE series until December 2015 where the version 3.1 is used for both retrievals.

The following figures show the differences in number and speed in more detail. For clarity reasons only Metop-A single and dual are presented in this section. The behaviour of Metop-B data is very similar. Metop-B plots can be found in Appendix A.

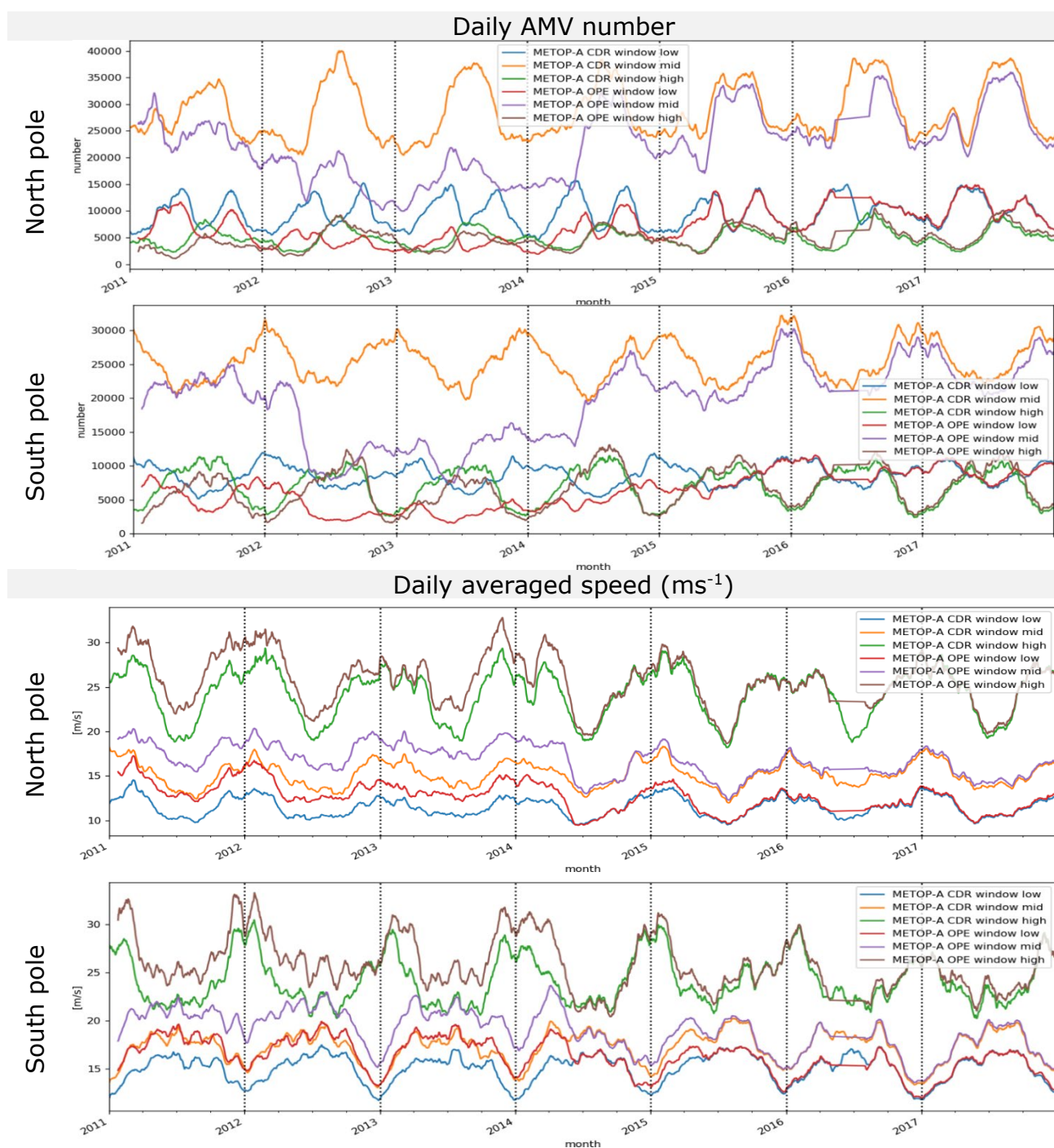


Figure 23: Comparison of the daily number and speed (ms⁻¹) between reprocessed (CDR) and operational (OPE) Metop-A AMVs over the north and the South Pole.

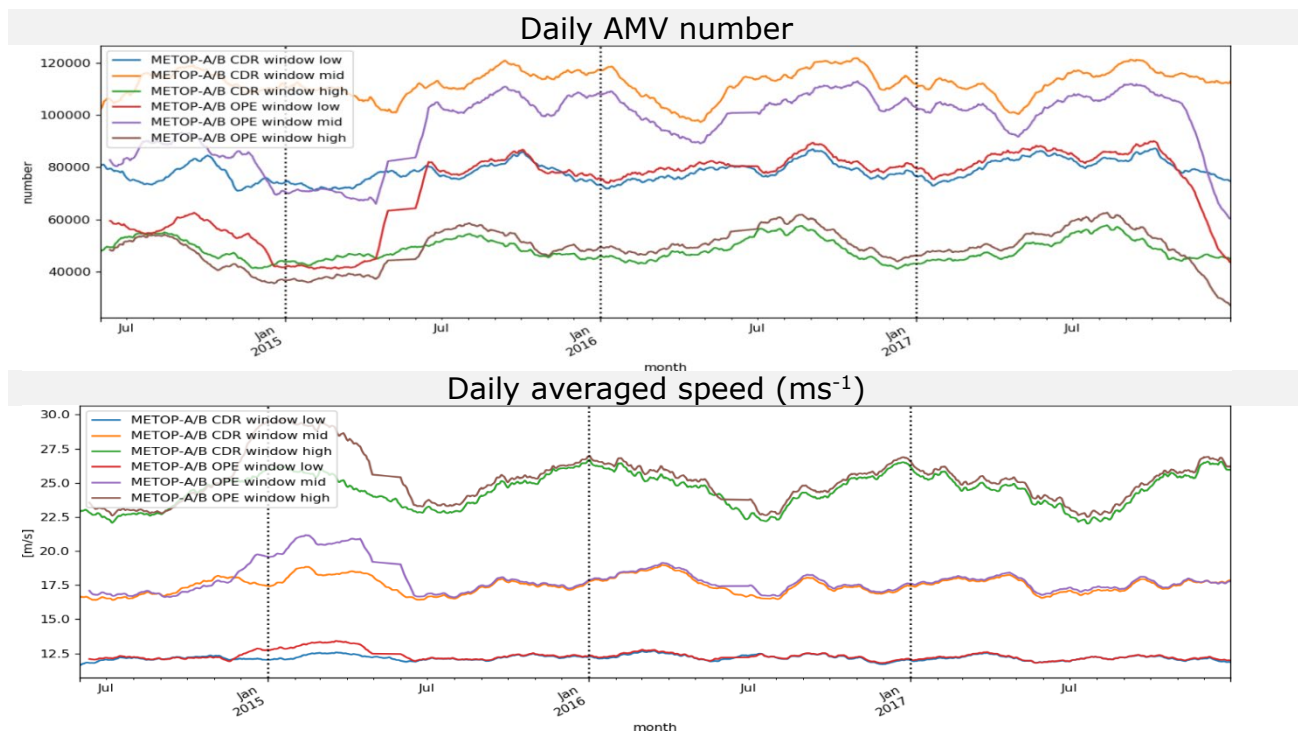


Figure 24: Comparison of the daily number and speed (ms^{-1}) between reprocessed (CDR) and operational (OPE) Metop-A/B dual AMVs. The values are for the entire globe.

In Figure 23 and Figure 24, the daily number of AMVs and average speed are compared between the reprocessed (CDR) and operational products (OPE) in all plots for the three different height classes. In Figure 23, Metop-A AMVs are split into Arctic and Antarctic, we clearly see the about 50% lower number of winds in the OPE record until mid-2014, especially for the mid and high levels, the lower levels agree better. From the end of 2014 to the first half of 2015, we again see less AMVs in OPE, this time mainly in the Antarctic. After that the numbers are very similar, only mid-level CDR are slightly higher. For the average speed the picture is similar, after the introduction of the version 3 of the operational algorithm mid-2015 that is used for this reprocessing, the speed is nearly identical for OPE and CDR. Before the average OPE wind speeds are up to 3 ms^{-1} higher.

The comparison for the dual products follows a similar pattern with differences at the beginning of the time series (until mid-2015) and a good agreement later. Two big differences compared to the single mode can be noticed. The Metop-A/B product (Figure 24) has a significant drop in the OPE record towards the end of 2017, this was due to the orbital drift of Metop-A, this has been corrected for since and the correction was applied for the CDR. Note that when Metop-B becomes the referenced image (Metop-B/A) this is not present (Figure 44). The average speed is higher for the OPE record in the beginning of 2015.

In conclusion, from this time series analysis we can say that the reprocessing has extended the available AMV product back in time until the beginning of the Metop-A mission. Difficulties in the development and changes in the operational processor have been successfully removed in the CDR. The entire time series is more stable with the CDR data. The major changes in the algorithm and the impact in the OPE time series is listed in Table 4.

5.2 Spatial and direct comparison

In this section, we compare the reprocessed and the operational products on a spatial level for different months and perform a component comparison, i.e. scatter plots, for the different height regions. As already explained in the previous section, the difference between OPE and CDR Metop is decreasing with time. In 2012, the operational geographical coverage was reduced with respect to the current one (see the difference map in Figure 25).

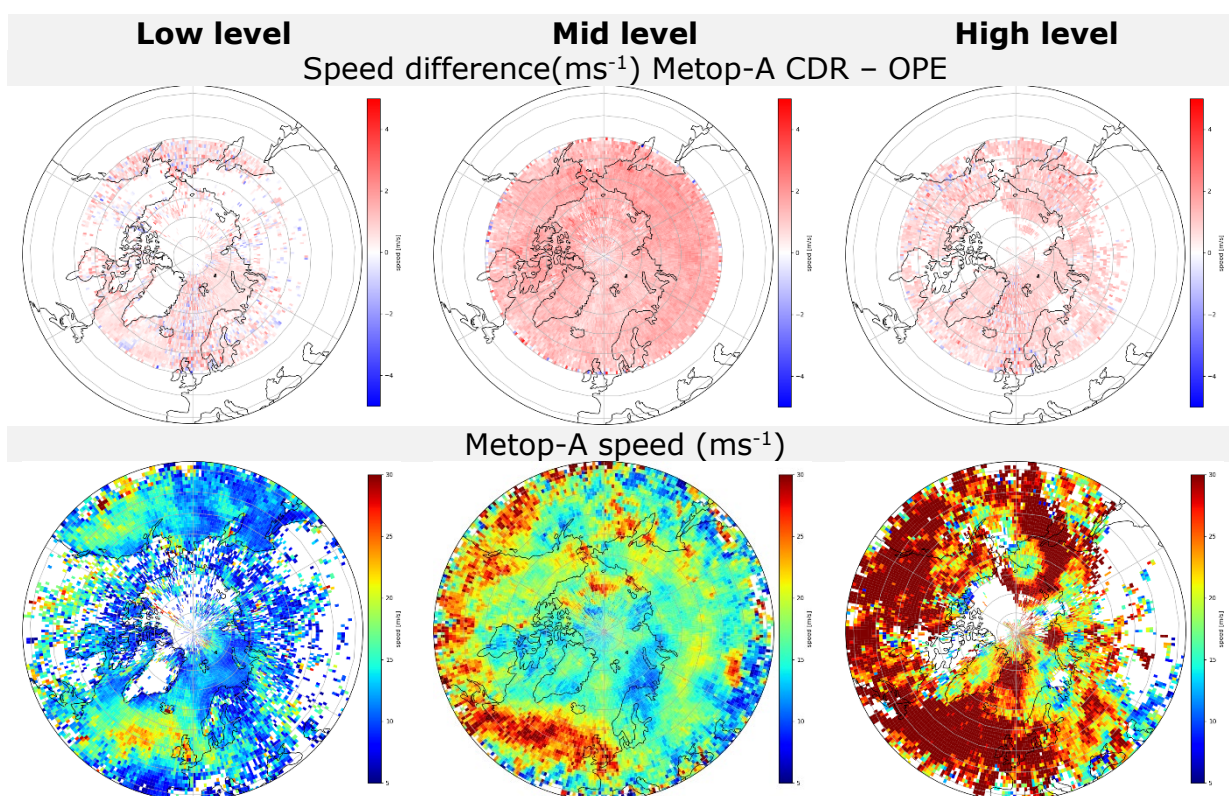
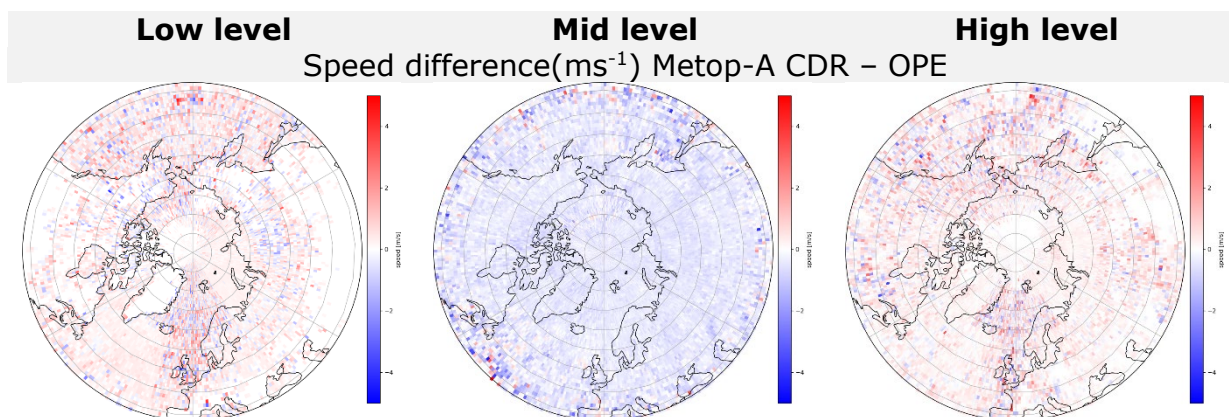


Figure 25: Metop-A CDR - OPE. Speed difference (ms⁻¹) and Metop-A speed or the three heights classes low, mid, and high for January 2012.



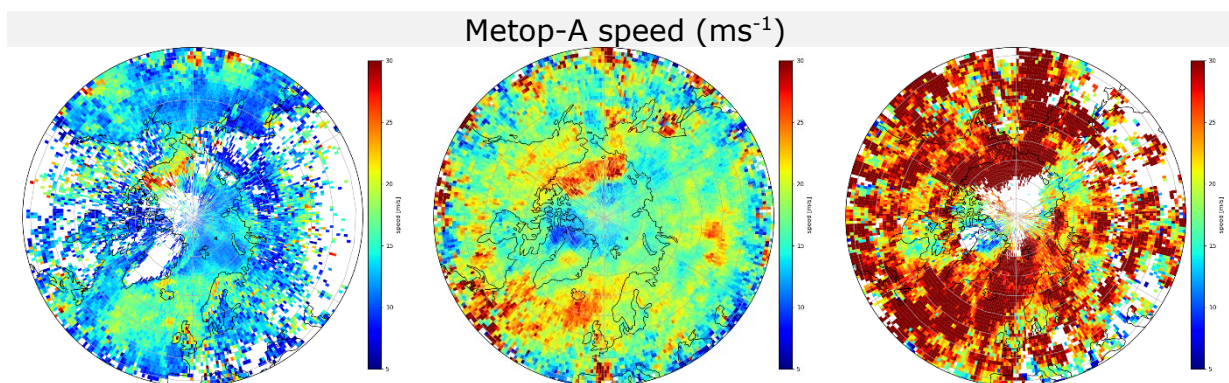


Figure 26: As Figure 25 for January 2017.

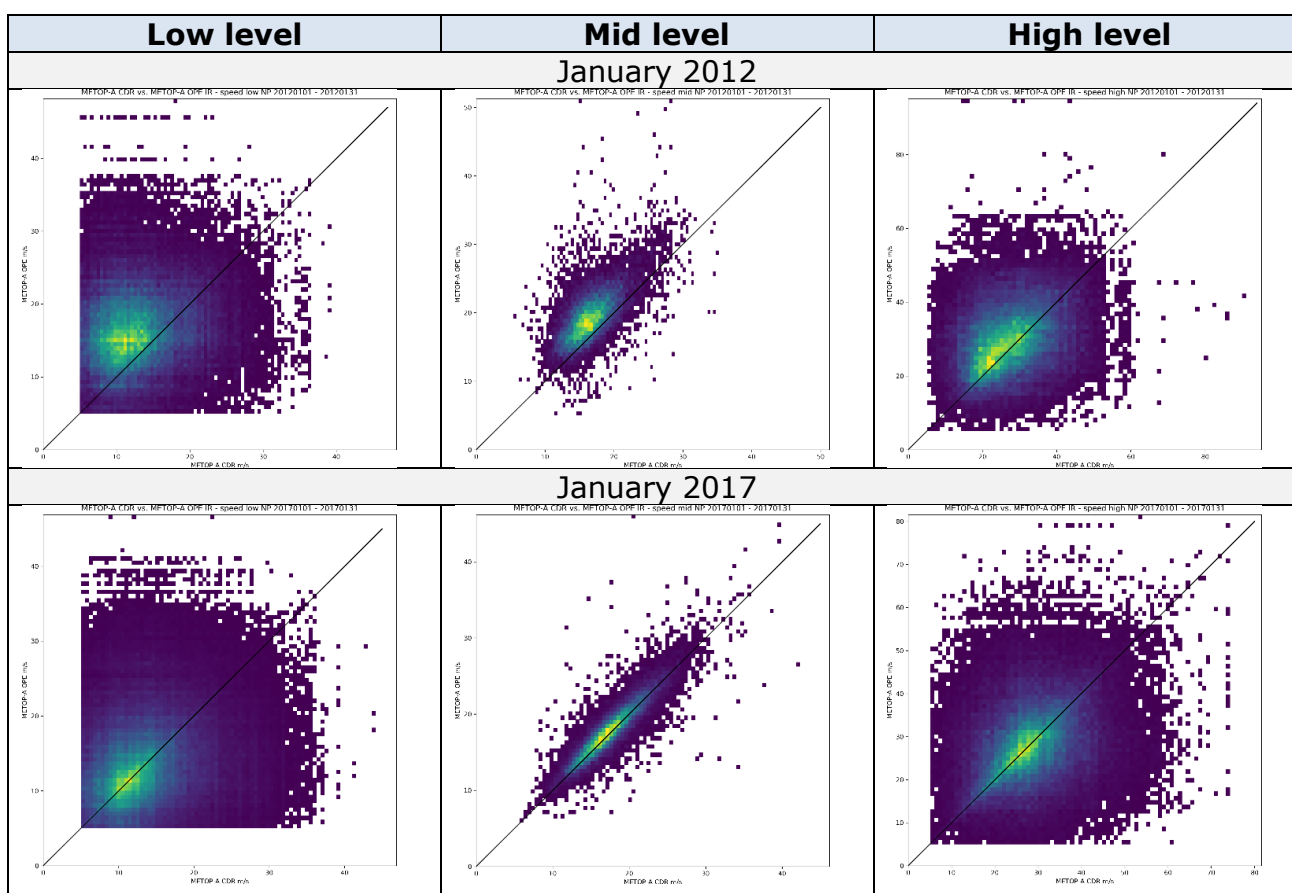


Figure 27: 2D-Scatter plot comparing the AMV speed (ms^{-1}) for CDR (x-axis) and OPE (y-axis) data, one month of. Top row January 2012, bottom row January 2017 Metop-A Arctic.

Figure 27 shows a comparison of Metop-A CDR and OPE products. When the same version of the algorithm is applied to the AVHRR data (e.g. in 2017), the agreement between the two dataset is much better. The variability comes from the different NWP data used and from the comparison set up that is not a proper co-location. This highlights the importance of using the same algorithm throughout the period at least for climate analyses such as trend analysis or change in jet stream patterns.

6. Validation against independent data records

In this section, the CDR data will be compared to independent data records. Radiosondes, reanalysis data and AMVs from MODIS (as described in section 3).

Comparison of the retrieved AMVs to reference data is performed following standards outlined in the CGMS guidelines for quality evaluation of Atmospheric Motion Vectors [RD7]. Bias (see **Error! Reference source not found.**) and Root Mean Square Error (RMSE) are computed for the retrieved wind vectors vs. model and radiosonde data. The analysis along the full time series is divided into three geographical and four altitude regions as defined in Table 5 and Table 6.

A correct height assignment for this comparison is most important as theoretically, a negative speed bias is most likely due to a wind vector that was assigned too high in the atmosphere whereas a positive bias might be explained by a wind being assigned too low (Figure 28). While the analysis against forecast can be done globally, the comparison against radiosondes depends on the number of observations for the locations where a radiosonde is available (see 3.1). The two analyses have then a different objective. The first one focuses mainly on an average but global geographical analysis, while the second aims to a more local but absolute comparison.

We only use information provided by the AVHRR channel 4 to assign the cloud height. The only possible way is then to use the Equivalent Black Body Temperature method (EBBT-method). The quality of the height assignment depends significantly on the cloud type observed. For example, semi-transparent clouds (e.g. the anvil of convective clouds) appearing warmer than they actually are, the AMV could be placed too low in the atmosphere. For low level and optically thick clouds, this is not the case. As only EBBT is used for the height assignment, the height will most likely be retrieved too low in the atmosphere, except for very low-level clouds for which, if a temperature inversion exists in the forecast data, an inversion correction is used placing the retrieved cloud at the bottom of it.

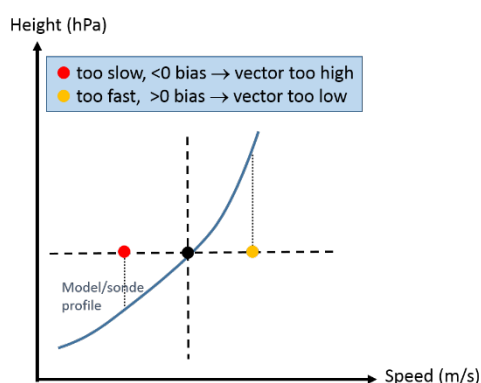


Figure 28: Graphical definition for the bias between observed and reference speeds.

This comparison was performed using both model data (Section 6.1), radiosondes (Section 6.2), and satellite (MODIS in Section 6.3) as reference. Model data, derived also assimilating satellites and ground-based observations, are a good reference because they are available globally in a (relative) high spatial and temporal resolution. Radiosondes are in situ measurements, done generally only twice a day at 0 and 12 UTC. MODIS data are completely independent estimation of the wind as they are retrieved

over the same geographical area but using other satellite measurements and other model data.

6.1 Comparison with reanalysis model data

6.1.1 Time series

In this section, only the time series for the speed bias between AMVs and the forecast data used in the retrieval is analysed. In the Figure 29 to Figure 31, the different products are compared.

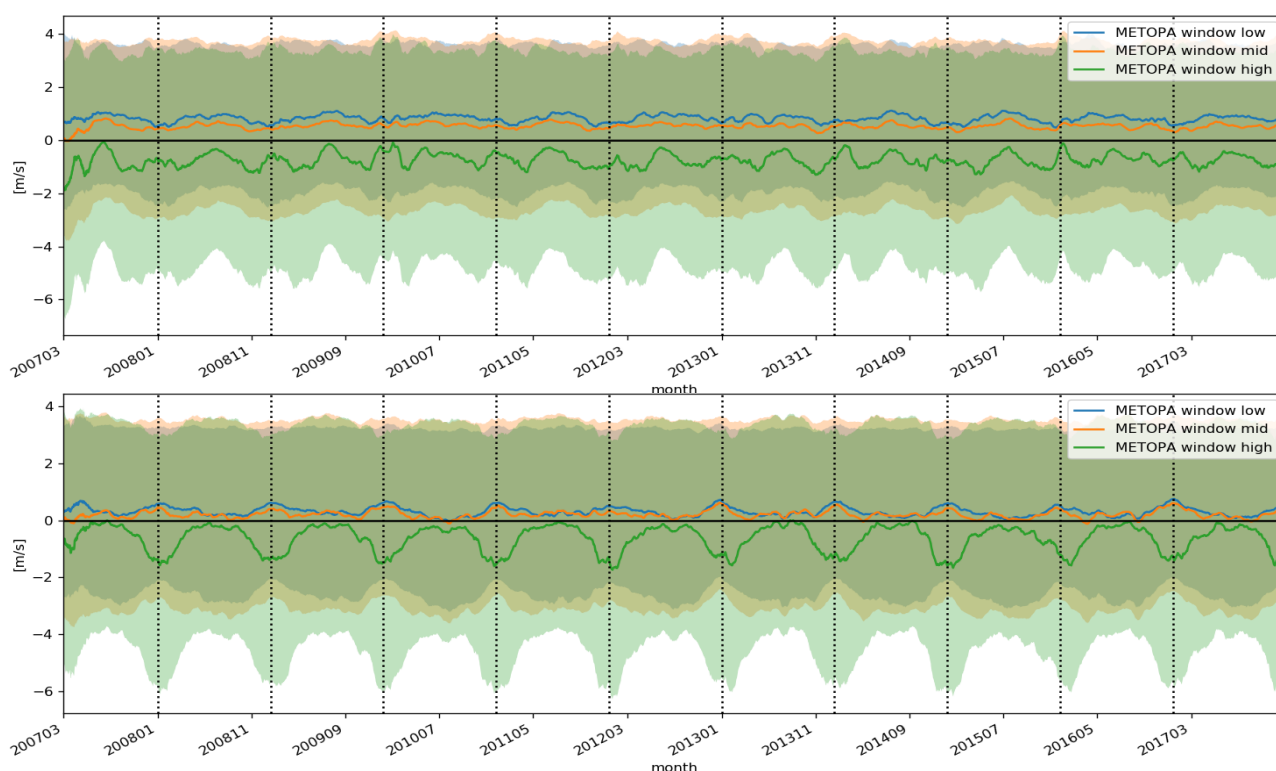
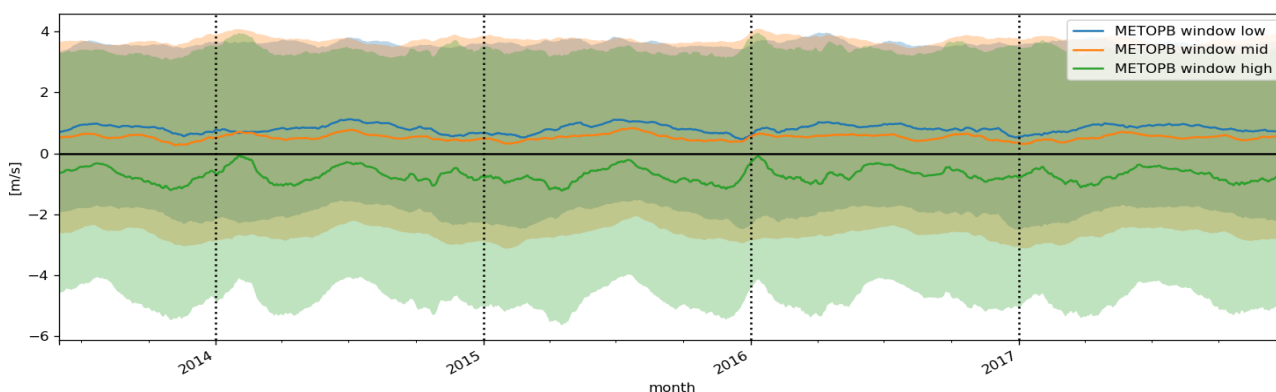


Figure 29: Time series showing the average daily speed difference (ms^{-1}) between Metop-A AMVs and the forecast used in the retrieval as first guess. Top image Arctic, lower image Antarctic. Solid lines display for each height classes the running 30-day mean of the daily bias. Shaded areas depict the mean $\pm$ RMSE.



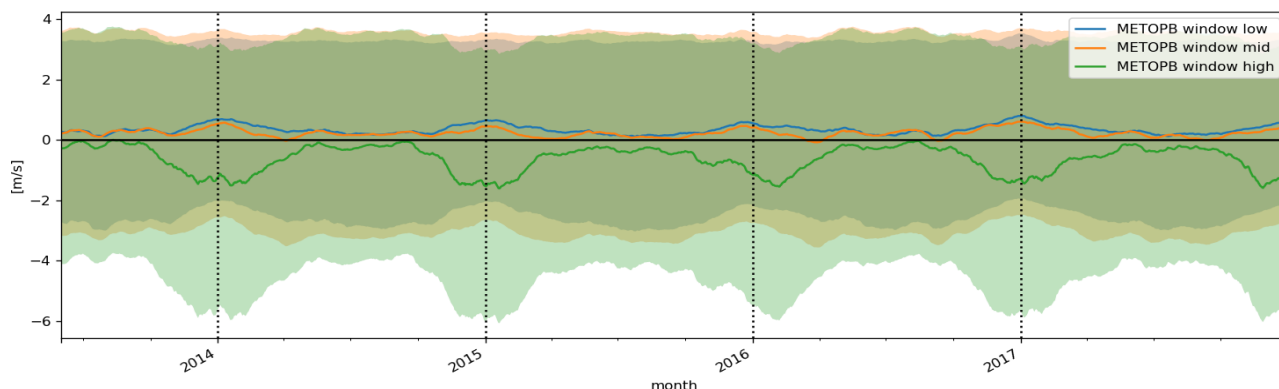


Figure 30: same as Figure 29 but for Metop-B.

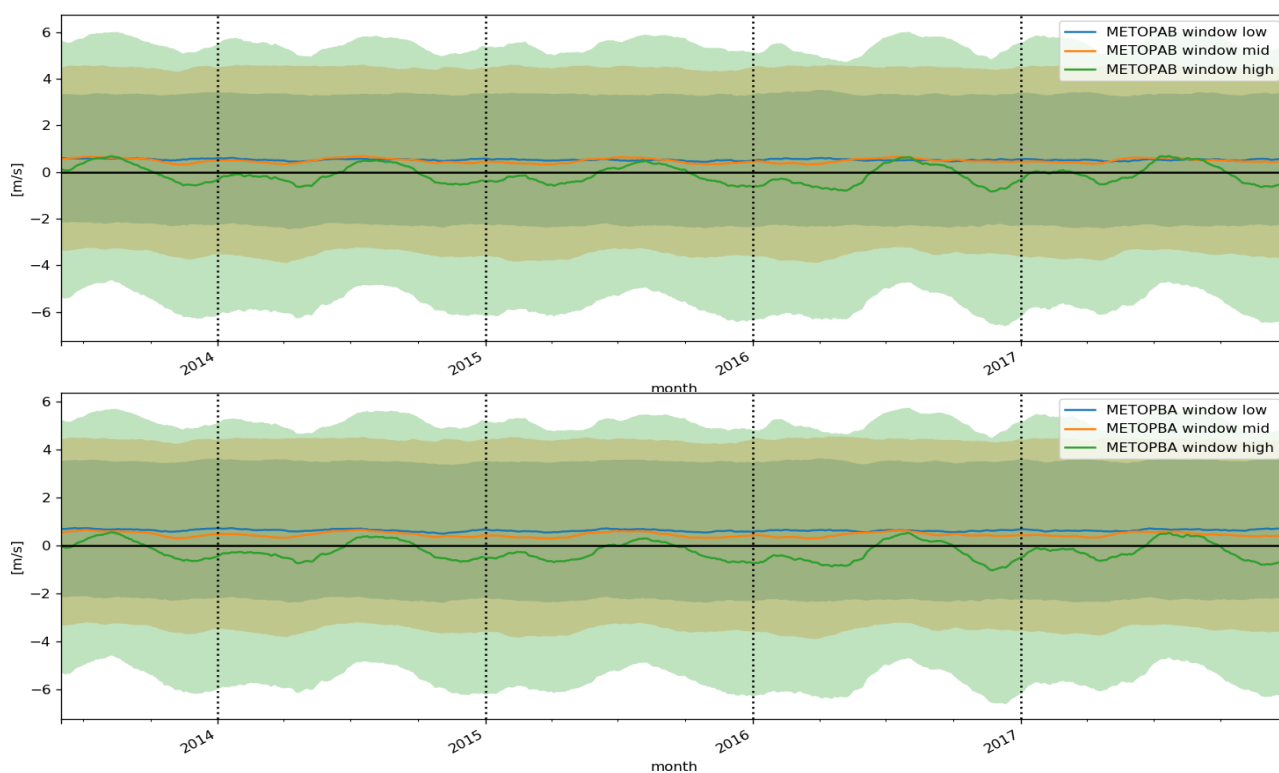


Figure 31: Time series showing the average daily speed difference (ms^{-1}) between dual Metop AMVs and the forecast used in the retrieval as first guess on a global scale. Top image Metop-A/B, lower image Metop-B/A. Solid lines display the running 30-day mean of the daily bias for each height class. Shaded areas depict the mean $\pm$ RMSE.

For Metop-A (Figure 29) the averaged bias for the Arctic for low and mid level winds is slightly positive for the AMVs ($< 1 \text{ ms}^{-1}$) and very stable with hardly any annual cycle. The high level AMs are slower than the NWP data between 0 and -1 ms^{-1} , although no clear annual cycle is visible the bias is not as stable as for mid and low levels. In the Antarctic, the AMV bias is generally lower in all heights resulting in even smaller differences for the low and mid-levels, but increasing the slow bias for the high levels to -1.5 ms^{-1} during the summer months. A pronounced annual cycle is visible especially for the high levels with nearly no bias in winter and the mentioned -1.5 ms^{-1} in summer.

For Metop-B similar results are obtained with stable small positive bias in the low and mid atmosphere and higher negative biases in the high regions. The dual products on a

global level show a positive and stable bias of less than 1 ms^{-1} for the low and mid-levels. The high-level bias has an annual cycle around the zero line with a positive bias in the middle of the year and a small negative bias at the beginning and end of the year.

In conclusion, the reprocessed AVHRR AMVs are very good. The retrieved winds are in good agreement with the reanalysis data, and there are no trends and only slight annual variability.

6.1.2 Monthly Maps

In order to further analyse the geographical distribution of the bias and root mean square error (RMSE) presented in the previous section, monthly average maps were produced for 2015 (January and July). These two months were selected to highlight the small annual variability found in the time series analysis in section 6.1.1. The maps for bias, RMSE and number of vectors have been generated with the following configuration:

- Temporal average: January and July 2015
- Spatial Gridding: $1 \times 1^\circ$
- $QI > 60$
- All levels

In Figure 32 and Figure 33, the monthly bias and RMSE against the forecast and number of vectors are displayed for Metop-A data covering the Arctic and Antarctic. There is a slightly positive bias over the North Pole, Siberia and Alaska with negative biases towards the mid latitudes. This is true for January and July and fits well with the time series analysis that also shows no significant variation over time.

Metop-B is very similar to Metop-A. A positive bias towards the poles and a slight negative bias towards the mid latitudes. The RMSE is low in both cases with a slight increase towards the mid latitudes, which can be explained by the lower number of retrieved AMVs.

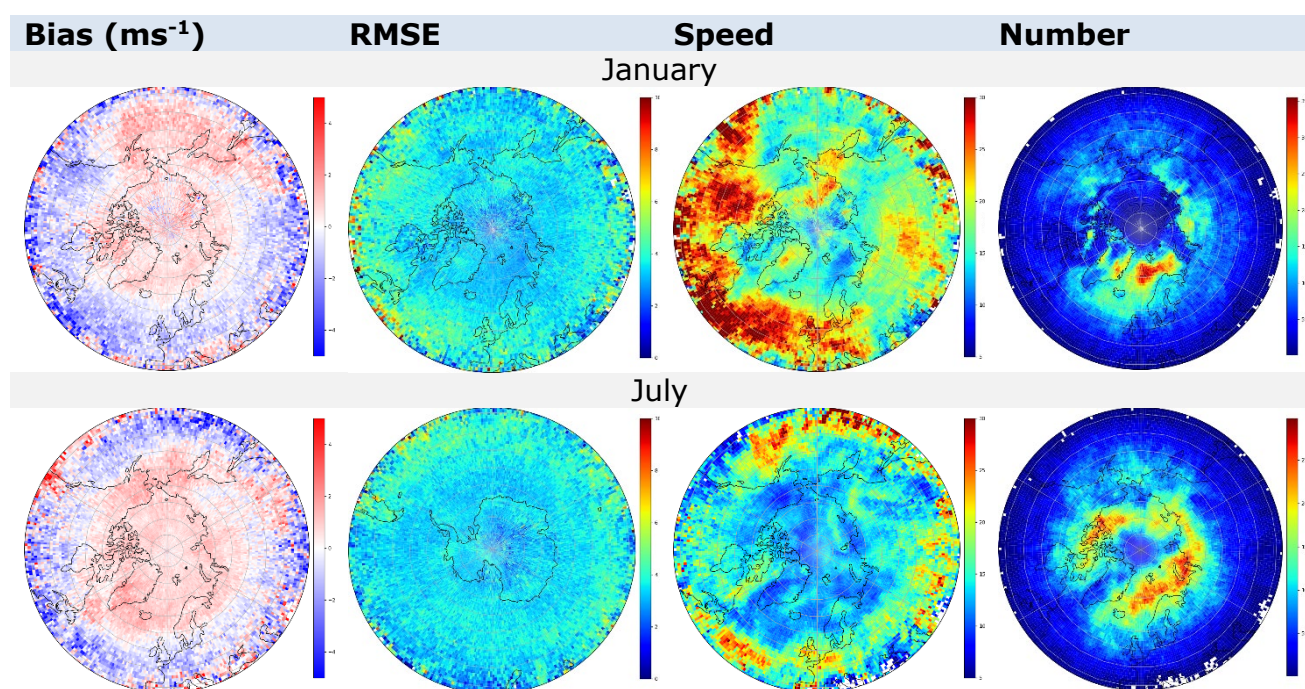


Figure 32: Monthly mean bias and RMSE against forecast speed, number of AMVs and mean speed (ms^{-1}) for Metop-A, January 2015 and July 2015, Arctic.

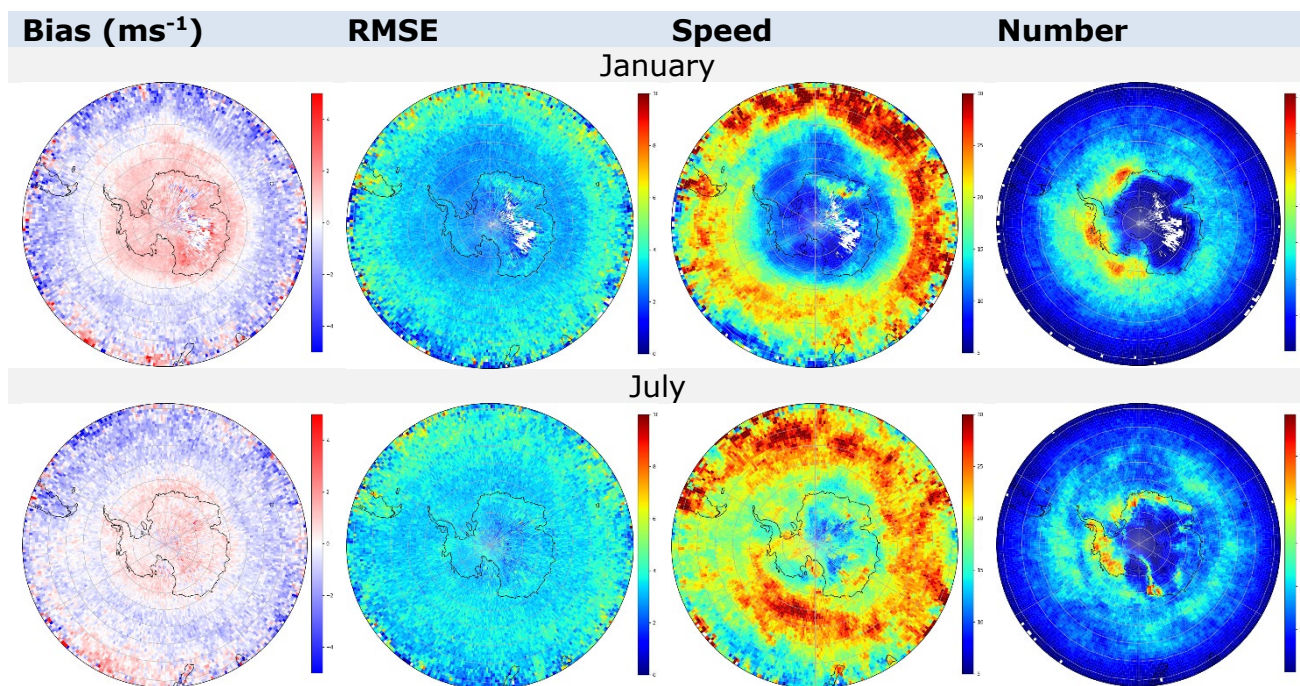


Figure 33: Same as Figure 32 but for the Antarctic.

The regional distribution of bias and RMSE for the global products is more diverse than those over the Polar Regions. For the Metop-A dual product there is a significant positive speed bias over the tropics with up to 5 ms^{-1} , shifting with the annual movement of the ITCZ. In the subtropics, a negative bias exists but not as large, only up to 3 ms^{-1} . Towards the poles, the same slight positive speed bias is present as for the single products. The RMSE is highest within the ITCZ, where the speed bias is the largest and over high altitudes such as the Himalaya and the Andes, most likely caused by less AMVs retrieved.

For Metop-B dual product the picture is very similar, however the magnitude of bias is smaller than that of Metop-A dual. The reason for the higher bias in the ITCZ region is probably linked to a height assignment issue [RD13], placing the retrieved winds lower in the atmosphere than they actually are.

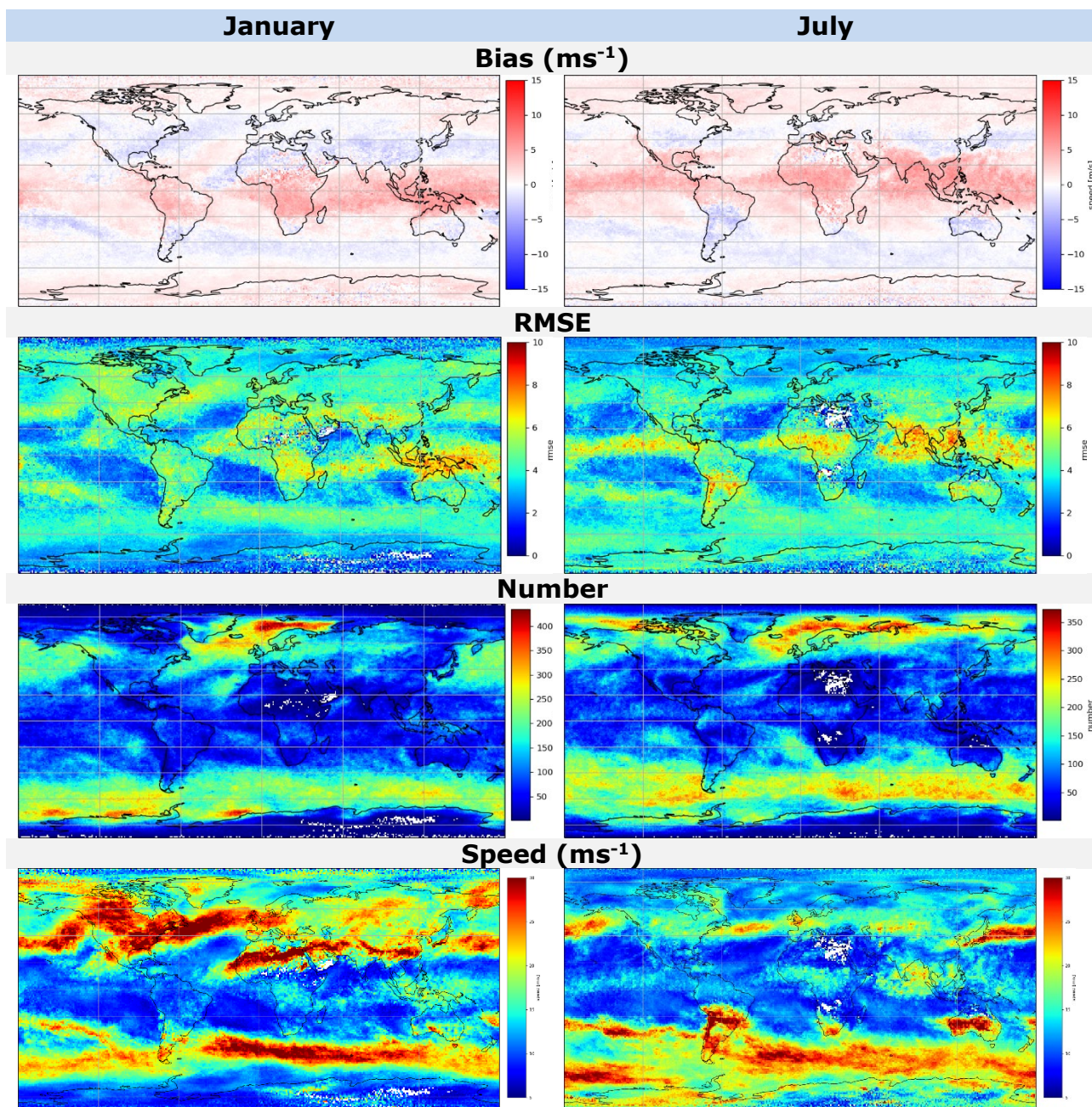


Figure 34: Monthly mean speed bias (top row), RMSE (second row) against forecast speed, number of AMVs (third row) and average speed (bottom row) for Metop-A dual. January 2015 (left) and July 2015 (right).

6.2 Comparison with radiosondes observation

In this section, we show the comparison between collocated AMVs and radiosonde wind information. Co-location is described in section 3.1.1. At the beginning of 2014, there is a gap of several days with no co-locations. This is due to missing data in the RAOBCORE data record.

Figure 35 to Figure 37 present the average time series of the global wind speed bias for Metop-A (single) and Metop-A/B (dual) AMVs versus radiosondes, separate for high-, mid- and low-level AMVs. The corresponding plots for Metop-B (single and dual) can be found in the Appendix. When looking at the following plots one should remember that, the possible co-locations are geographically limited as described in section 3.1.1 and shown in Figure 7.

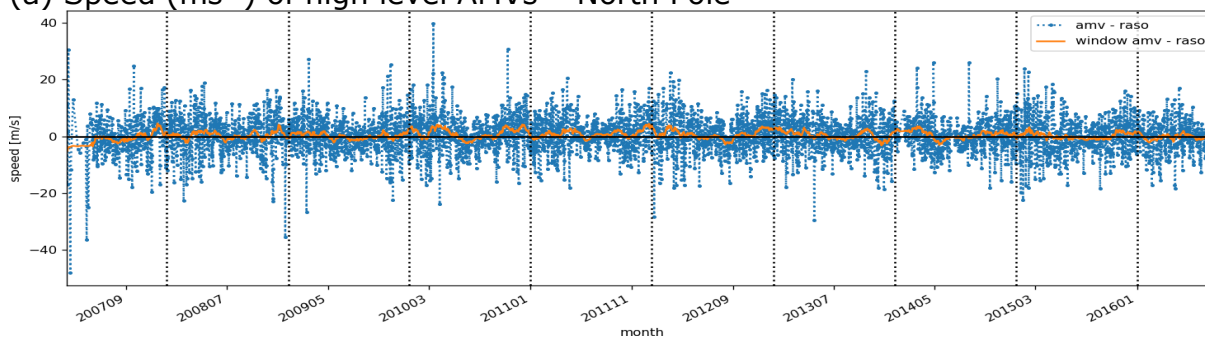
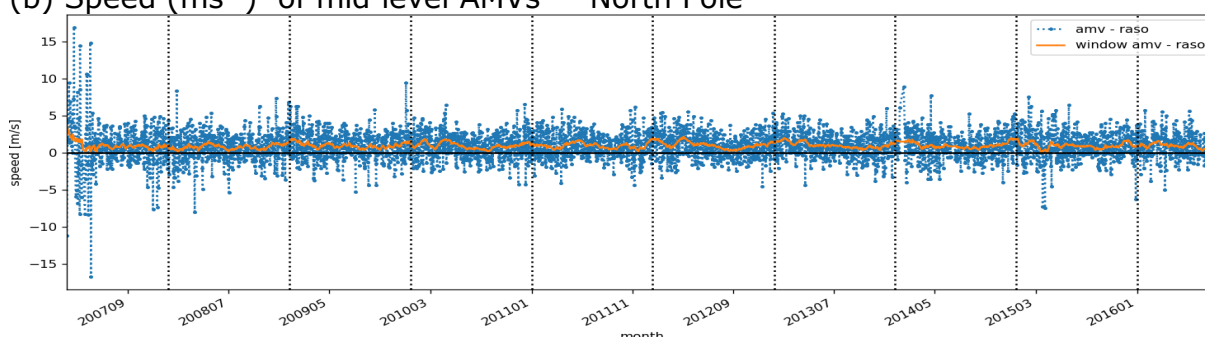
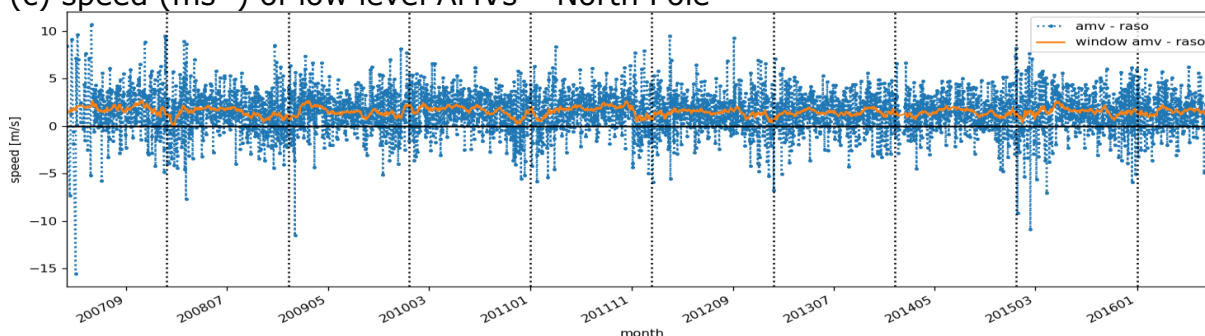
(a) Speed (ms^{-1}) of high level AMVs – North Pole(b) Speed (ms^{-1}) of mid level AMVs – North Pole(c) speed (ms^{-1}) of low level AMVs – North Pole

Figure 35: Average of wind speed bias for good IR AMVs ($\text{QI} > 60$) in ms^{-1} (reprocessed AMV - radiosonde) for Metop-A for all possible collocations in the Arctic. The orange line is a 30-days running mean.

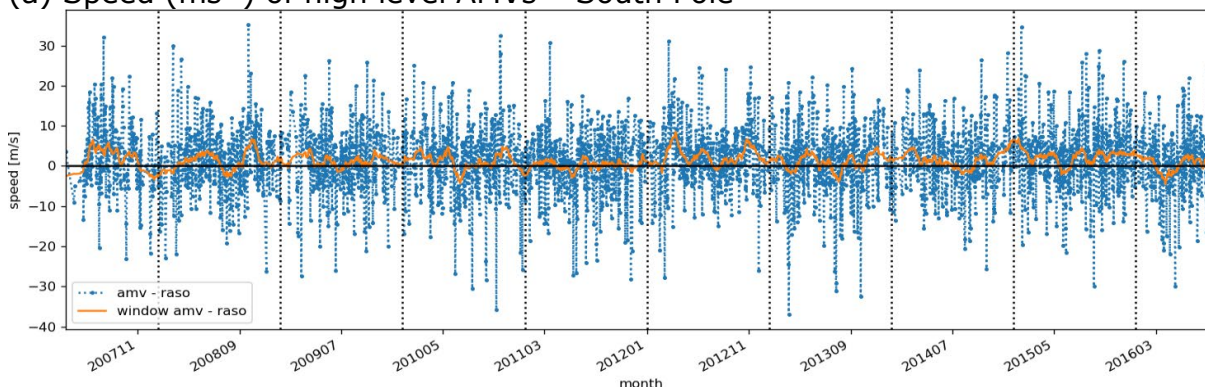
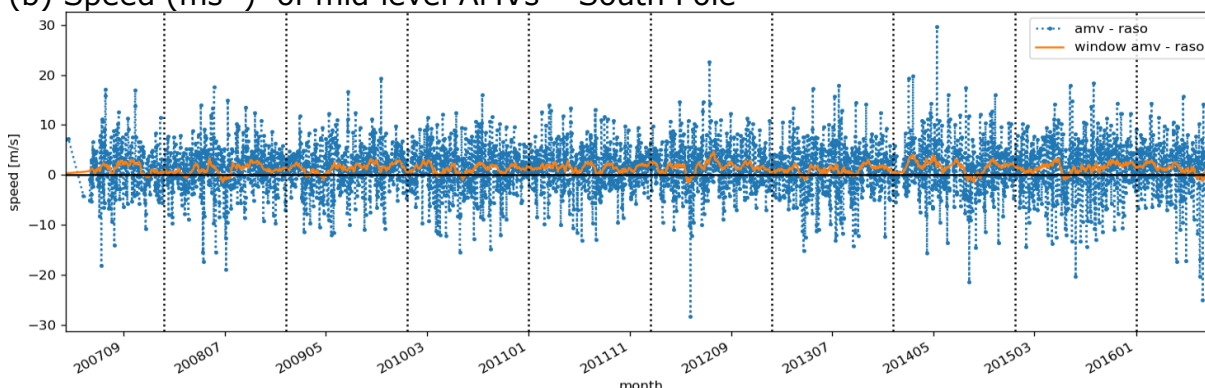
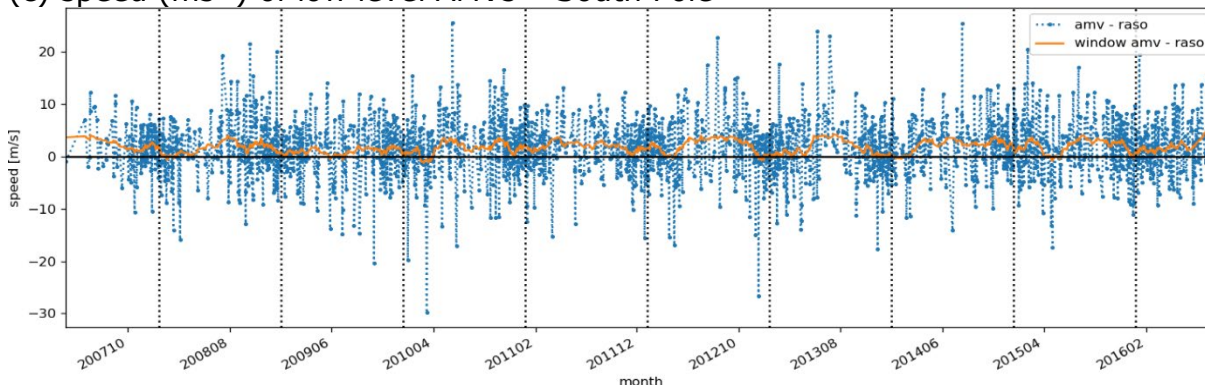
(a) Speed (ms^{-1}) of high level AMVs – South Pole(b) Speed (ms^{-1}) of mid level AMVs – South Pole(c) speed (ms^{-1}) of low level AMVs – South Pole

Figure 36: Average of wind speed bias for good IR AMVs ($QI > 60$) in ms^{-1} (reprocessed AMV - radiosonde) for Metop-A for all possible collocations in the Antarctic. The orange line is a 30-days running mean.

For Metop-A the best average agreement with radiosondes is for the high level AMVs (Figure 35 and Figure 36), however the spread of the daily difference is also quite large with at times more than 20 ms^{-1} . For the mid and especially the low level AMVs there is a positive speed bias of the AMVs versus the radiosonde data. For the Arctic, during the winter months there is a larger daily variability than in the summer half year. However, a clear, repeated annual cycle cannot be detected. Results are very similar for Metop-B (see the corresponding figures in Appendix).

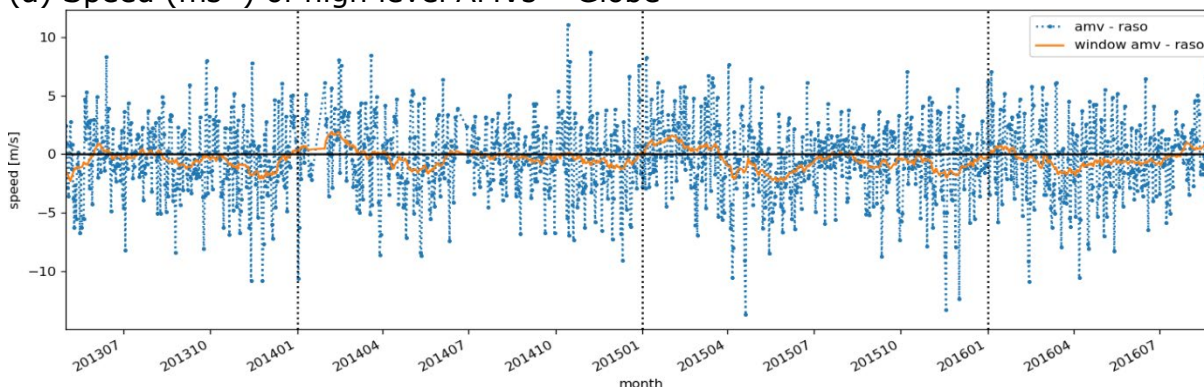
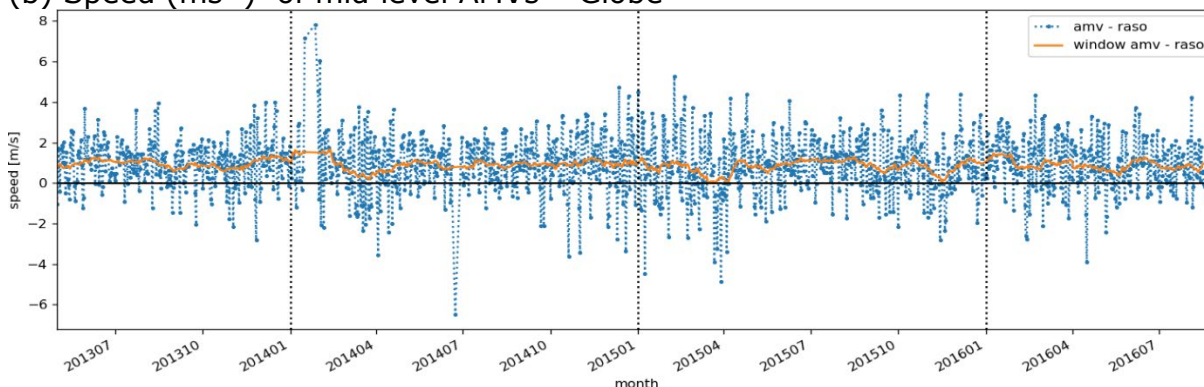
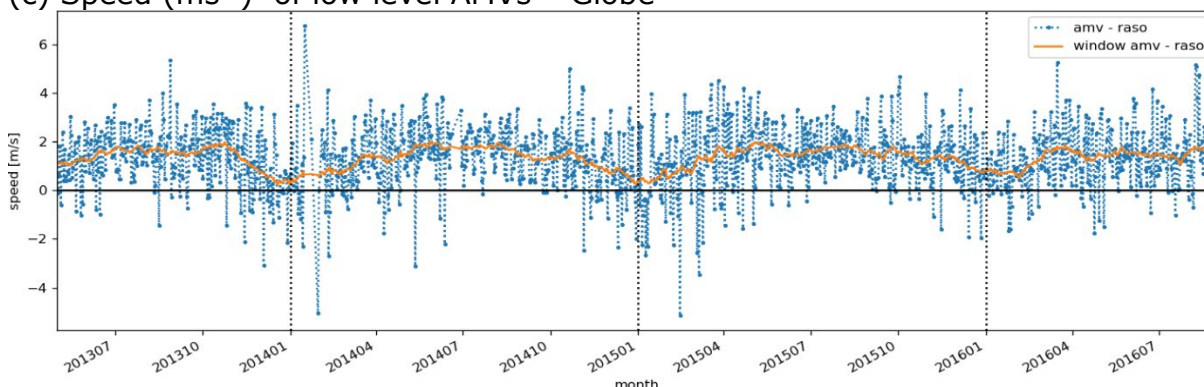
(a) Speed (ms^{-1}) of high level AMVs – Globe(b) Speed (ms^{-1}) of mid level AMVs – Globe(c) Speed (ms^{-1}) of low level AMVs – Globe

Figure 37: Average of wind speed bias for good IR AMVs ($QI > 60$) in ms^{-1} (reprocessed AMV - radiosonde) for dual Metop-A/B for all possible collocation over the entire globe AMVs. The orange line is a 30-days running mean.

For the dual data from Metop-A/B, again there is the best agreement for the high level AMVs, and a fast bias for the AMVs of $1\text{--}2\text{ms}^{-1}$ for the mid- and low-levels. In the dual AMVs, a small annual cycle for the high and low levels can be seen. The high-level AMVs being a little faster at the beginning of the year, the low-level AMVs in the middle of the year.

In conclusion, there is a very good agreement between the co-located AMVs and radiosondes. This good agreement is positive for the usage of AMVs in NWP and reanalysis as radiosondes are the major input for wind profile information. AMVs can therefore complement this information where no radiosonde data is available.

6.3 Comparison with MODIS AMVs

In this section, comparisons of the CDR AMVs with the AMVs generated from MODIS data on-board the TERRA and AQUA satellites are discussed. The comparison can only be done for Metop single AMVs due to the MODIS AMV data coverage. The comparisons are presented only with MODIS on TERRA as TERRA has a morning orbit, similar to Metop. For the following plots, the geographical region was restricted to latitudes higher than 65° at both poles. The reason being that MODIS is operated in the triplet mode, using three overpasses for retrieving AMVs, effectively limiting the area to be covered to these 65° [RD14]. This can lead to some different results if the time series of the single Metop record is compared with these here. The speed over the common area is quite similar as shown in Figure 39 for January 2013.

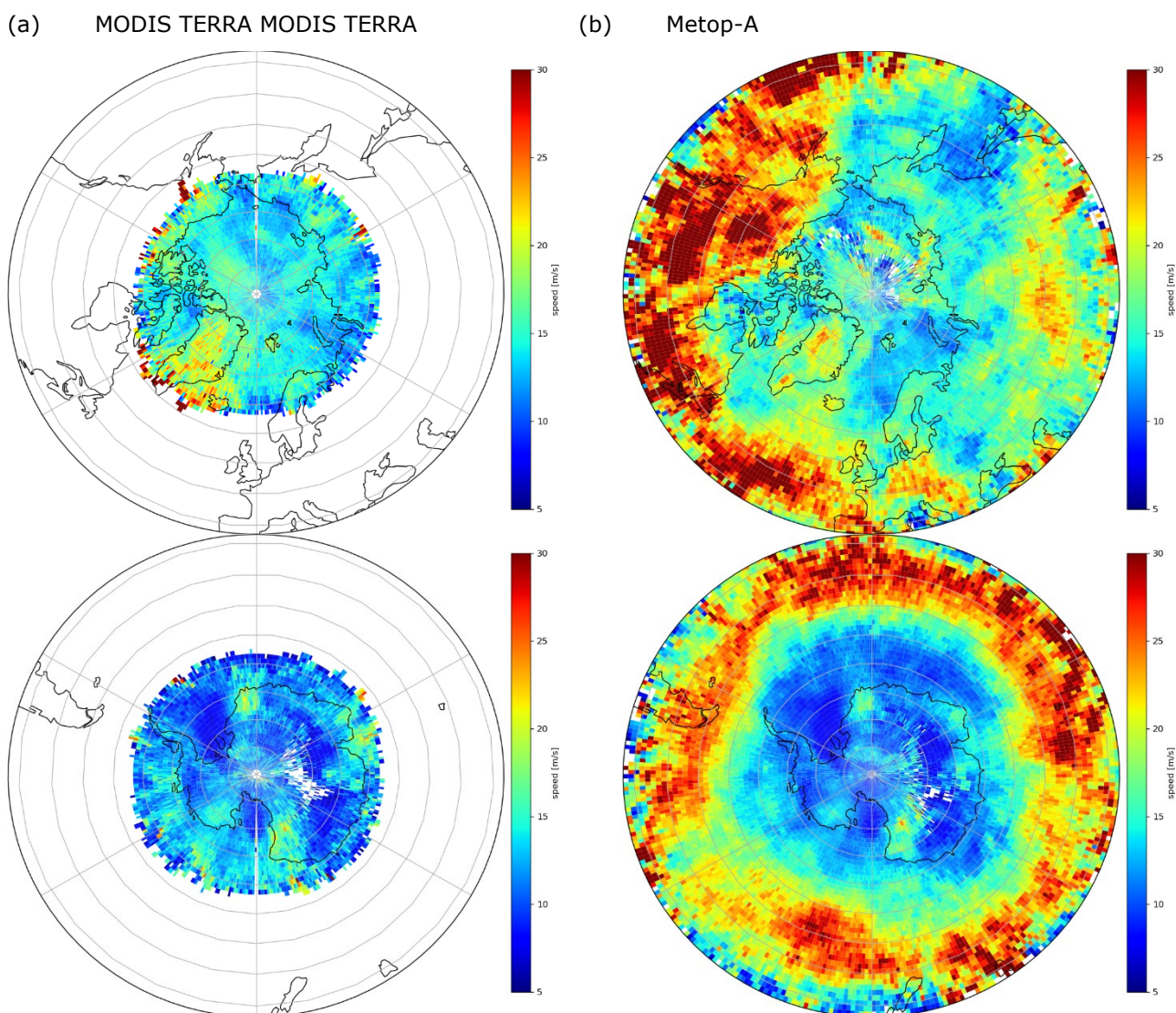


Figure 38: MODIS and Metop-A average speed (ms^{-1}) for January 2013 (top: Arctic, bottom: Antarctic). The different geographical coverage is due to the usage of three orbits (triplet) by MODIS and only two by Metop-A.

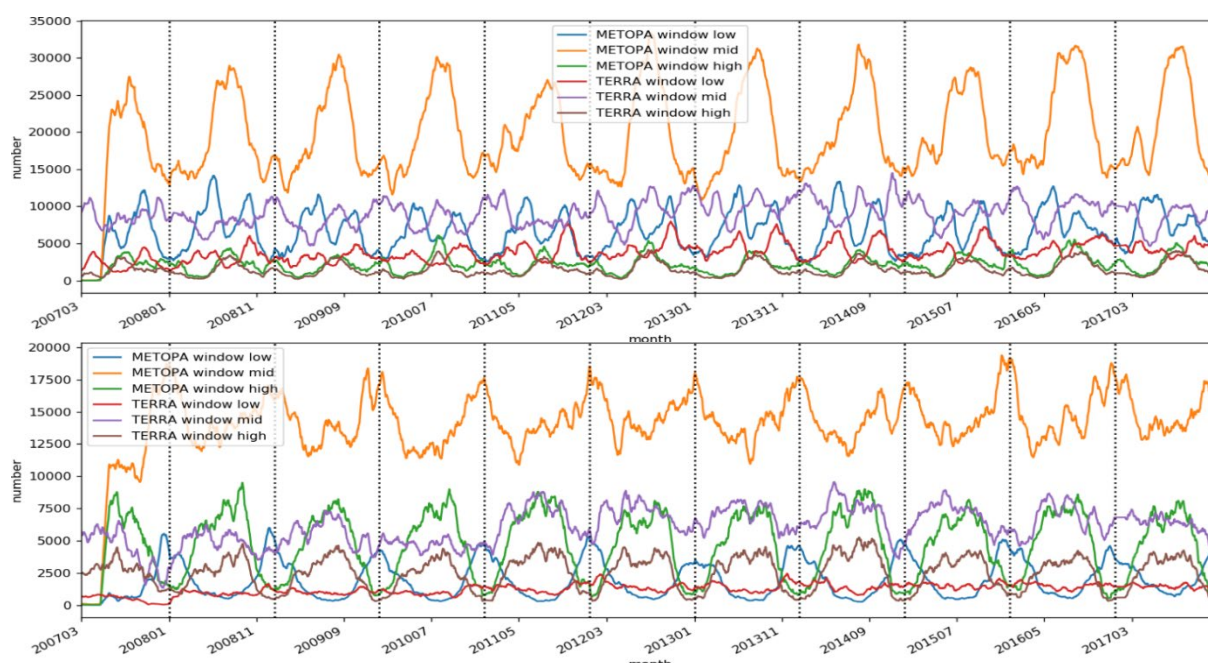


Figure 39: Comparison between Metop-A and MODIS on TERRA. Number of AMVs for Arctic (top, latitude > 65°) and Antarctic (bottom, latitude < -65°). Daily count smoothed using 30-day sliding window.

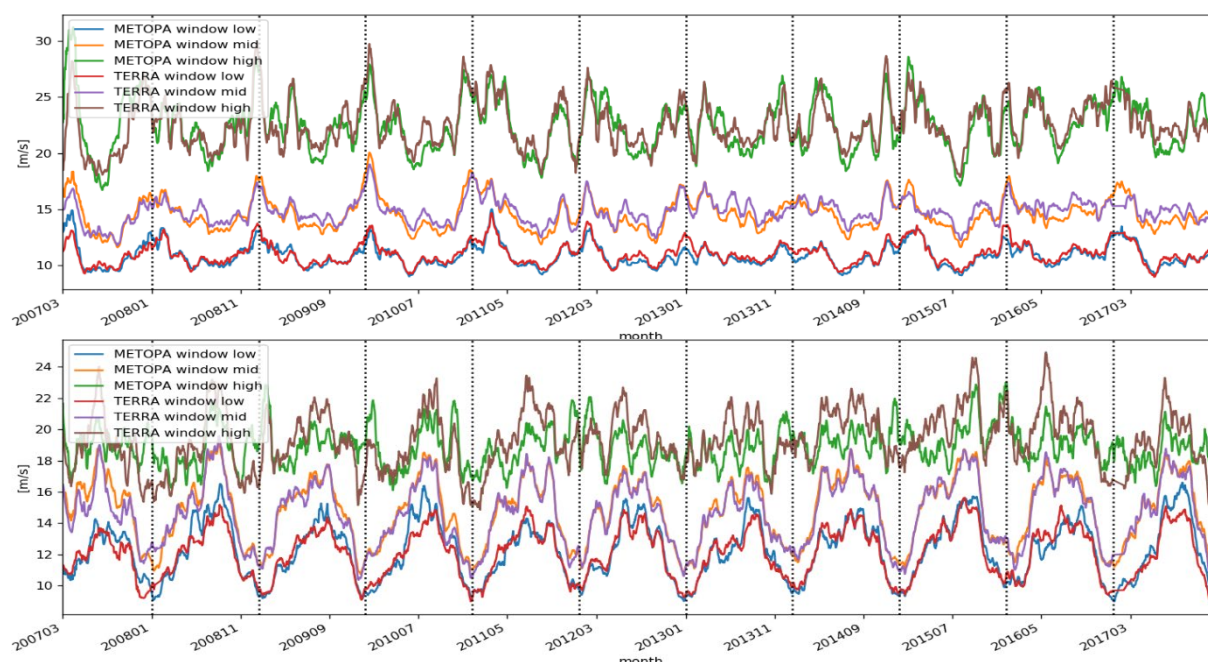


Figure 40: Comparison between Metop-A and MODIS on TERRA. Average speed of AMVs for Arctic (top, latitude > 65°) and Antarctic (bottom, latitude < -65°). Daily value smoothed using 30-day sliding window.

Comparing the number of retrieved AMVs from Metop and MODIS (Figure 39 and Figure 38) there is a large number of mid-level AMVs for Metop (between 15000 and 30000 per day for the north and 12000 to 17000 in the south) compared to only 5000 to 10000 for



MODIS. The same pattern is observed for the low level AMVs, but with much smaller numbers in total. In the Arctic, there is a very good agreement for the low-level AMVs during winter times and a good agreement in numbers per day for the high level AMVs all year round. Over the Antarctic, MODIS shows only very few low-level AMVs uniformly spread over the year whereas there are more Metop AMVs peaking at summer time. MODIS and Metop high level AMVs present a similar pattern with more AMVs during the wintertime even if there are fewer MODIS AMVs.

The daily averaged speed is in very good agreement between Metop and MODIS in all height levels (Figure 40) for Arctic and Antarctic. The maximum speed is observed in wintertime. Over Antarctic, the high level AMVs peak at 22 ms^{-1} in summer time for Metop, but is slightly lower (about 20 ms^{-1}) for MODIS. The mid-level AMVs in the Antarctic have an identically phased cycle. For the low level, there is a very good agreement, slightly slowest winds for the northern hemisphere (12 against 16 ms^{-1}) and having their maximum speed during the winter month as for the mid level AMVs. The seasonal cycle is less pronounced in the northern hemisphere for both dataset.

In conclusion, there is a very good agreement between MODIS and single Metop AMVs speed for all height classes over the common covered area.

7. Summary of the validation

Metop-AVHRR AMVs have been produced for the period 2007-2017 over the polar regions (single mode) and for 2013 – 2017 globally (dual mode). Metop-A single mode starting in 2007, Metop-B single in 2013. AMVs are retrieved using the same processing chain and algorithm for both satellites. The validation strategy followed the CGMS guidelines for quality evaluation of Atmospheric Motion Vectors [RD7]. The AMVs have been compared with independent AMV dataset: reanalysis data (ERA-interim), ground based reference radiosonde data (RAOBCORE) and AMVs from MODIS on TERRA. Metop-A AMVs were also compared with the current operational EUMETSAT real time products from Metop.

Over the considered period, the data record is stable and appears consistent between the two satellites and the in total four different CDRs generated (single Metop-A and -B and dual Metop-A/B and -B/A). Using one single Metop Satellite allowed retrieving AMV over the north and south poleward of 40° latitude whereas using a combination of two Metop satellites allows to retrieve AMVs globally. Because of the smaller time difference between two images, dual Metop AMVs are faster than single AMVs.

Single and dual reprocessed AMVs exhibit geographical and seasonal features, in line with well-known atmospheric circulation patterns. AMVs present a clear seasonal cycle linked with the cloudiness being more pronounced for mid and high level clouds. The increase of clouds during the summer months over the Polar Regions can be clearly seen in the number of retrieved AMVs, the movement of the ITCZ for example is visible in wind speed, direction and heights of retrieved AMVs in the tropics. The wind speed increases with the altitude in all regions.

Comparing CDR AVHRR AMV to OPE clearly highlights the benefit of the reprocessing that allowed producing a homogeneous, complete and stable time series over the entire



period. Compared with the operational EUMETSAT near real time AVHRR AMVs, there are more reprocessed AVHRR AMVs, especially during the initial development phase of the algorithm. When the same algorithm is applied, the number and speed of AMVs are very close. The differences can be mostly linked to a different NWP data source used in the reprocessing.

Overall, the produced AVHRR AMV are in line with the existing reanalyses. The comparison shows a positive (fast) speed bias for low- and mid-level winds, and a negative (slow) speed bias for high-level winds in the arctic regions. For the global product from the dual processing the high-level wind speed bias is oscillating around zero depending on the season.

When and where possible a comparison with RAOBCORE radiosonde data was made. There is a very good agreement between the co-located AMVs and radiosondes. The average wind speed bias at high levels is fluctuating around zero lower in the atmosphere with a positive bias against radiosonde data but smaller than 2 ms^{-1} . This good agreement is positive for the usage of AMVs in NWP and reanalysis as radiosondes are the major input for wind profile information. AMVs can therefore complement this information where no radiosonde data is available.

EUMETSAT single Metop AMVs were compared with a completely independent satellite dataset, the CIMSS MODIS AMVs. There is very good agreement between the speeds retrieved for both datasets for all heights.

In conclusion, the time series produced will be suitable for data assimilation and climate studies. For the future, the entire AVHRR time series on board all NOAA and EUMETSAT polar satellites will be reprocessed using AVHRR GAC data and the EUMETSAT algorithm leading to almost 40 years of AMVs from several different platforms.

8. Limitations

In the current release, there is no limitation for the usage. The Metop AMV CDR is very similar to the operational data for the recent period. However, it should be noted that there are some differences compared to the operational v3.1.1 Metop single and dual AMVs:

- No IASI information is used to assign the AMV height;
- 6-hourly ERA-Interim NWP forecast data are used instead of ECMWF operational stream.

AVHRR AMVs for Metop-A should be used only from the 23rd May 2007, due to some unknown issues with AVHRR L1B data on board Metop-A prior to this date.

9. Conclusions

Metop-A and -B (single and dual) AMVs have been produced for the period 2007 – 2017 for the Polar Regions (D5.1) and globally (D5.2). AMVs are retrieved using the same processing chain and algorithm for both satellites. The data delivered are suitable for data assimilation. The comparison of CDR AMVs with the near real time operational EUMETSAT AMVs shows some expected differences at the beginning of the series. It shows the importance of reprocessing the AMVs to improve the stability and remove operational gaps over the entire period. Comparisons against independent data sources such as ground based and satellite demonstrated the very good quality and usability of the single and dual AVHRR AMV CDR.

Appendix A Additional Plots

To help readability of the document, this section contains additional plots complementary of those found in the main sections of the document.

Additional plots to chapter 4.1

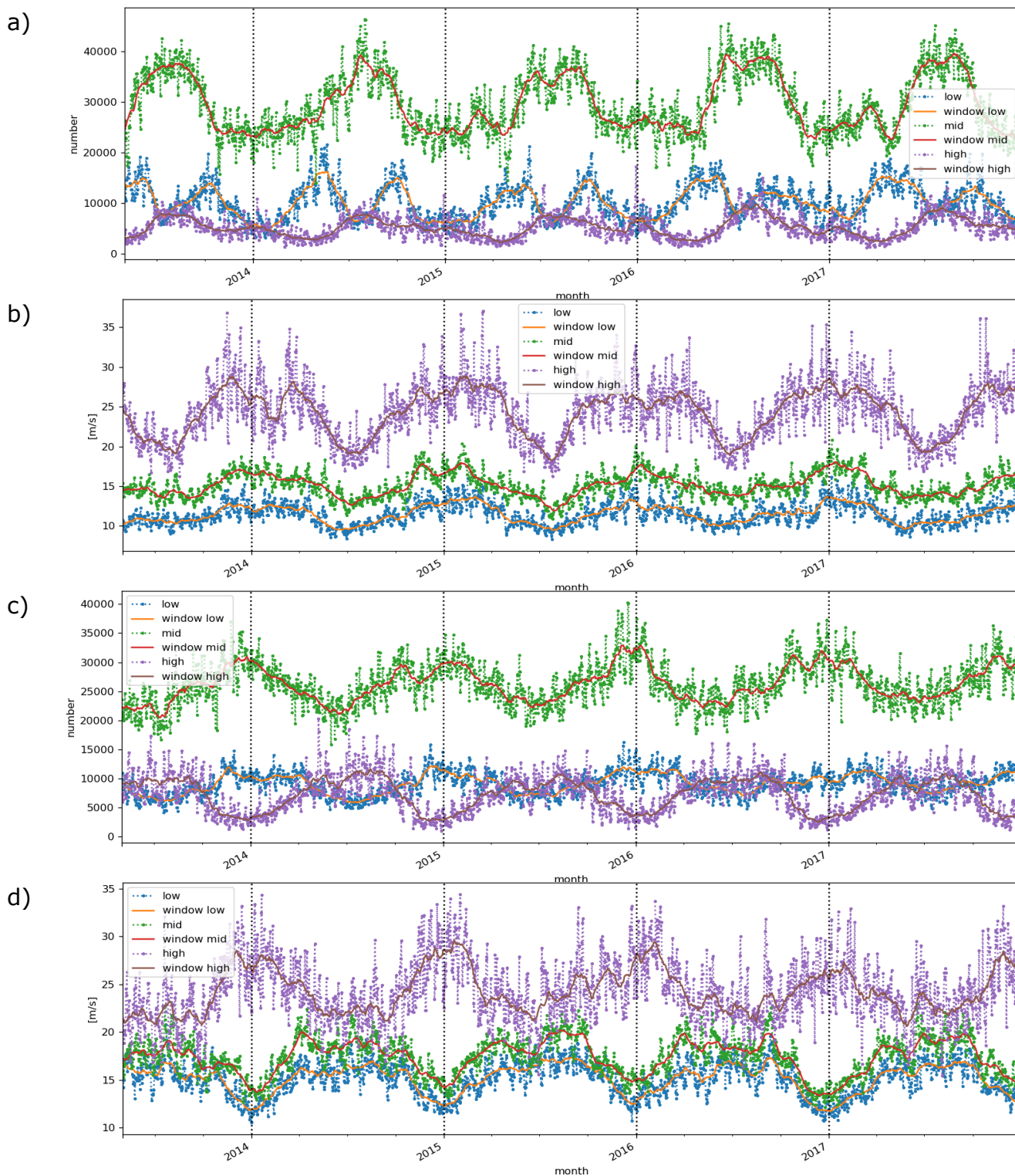
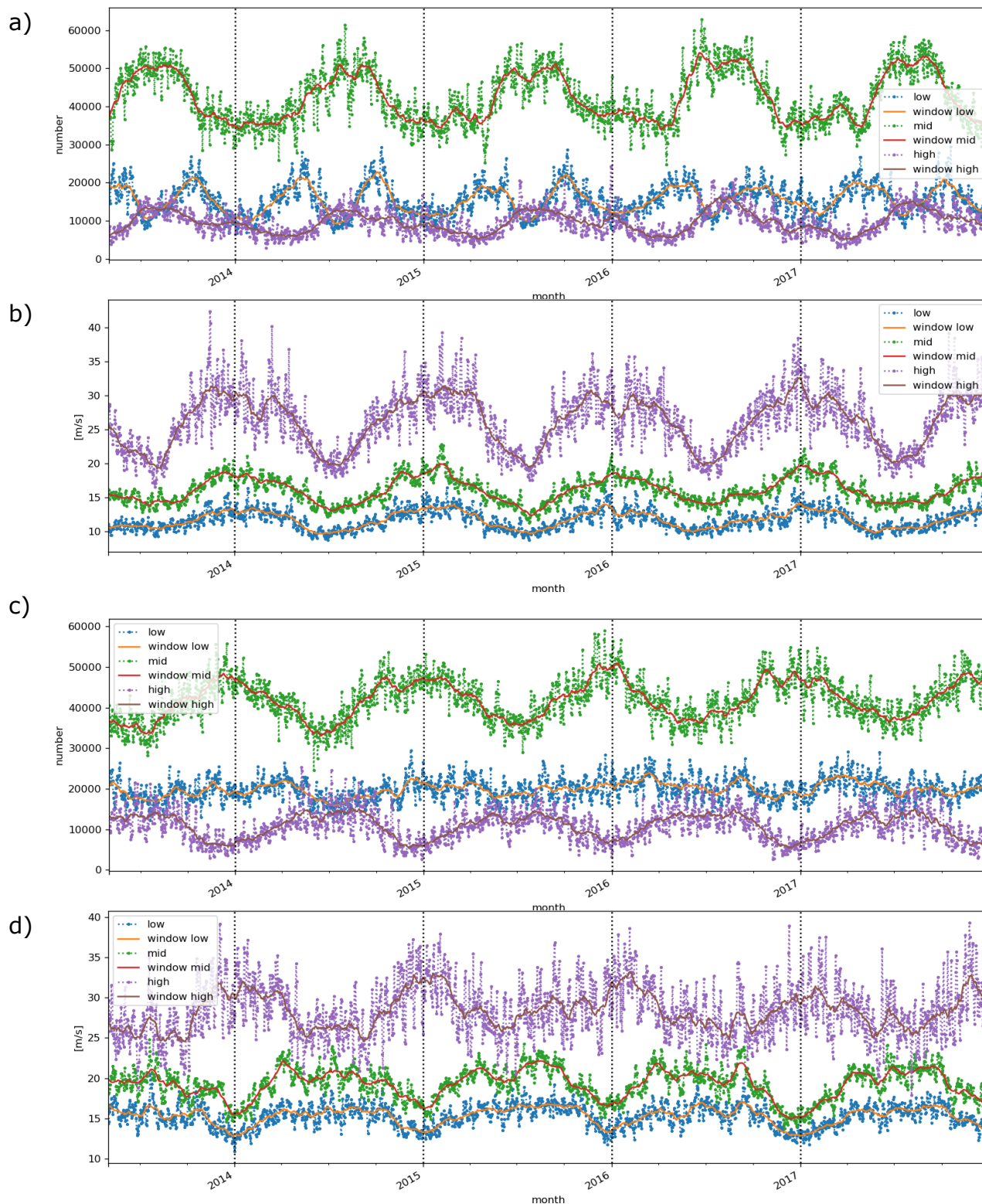


Figure 41: Metop-B time series of the number of winds and their speed for the three height classes. Each dot represents a daily average for the North (a and b) and South Pole (c and d), only wind vectors with a $QI > 60$ and a speed $> 5 \text{ ms}^{-1}$ are considered. The lines represent the running mean over a month.



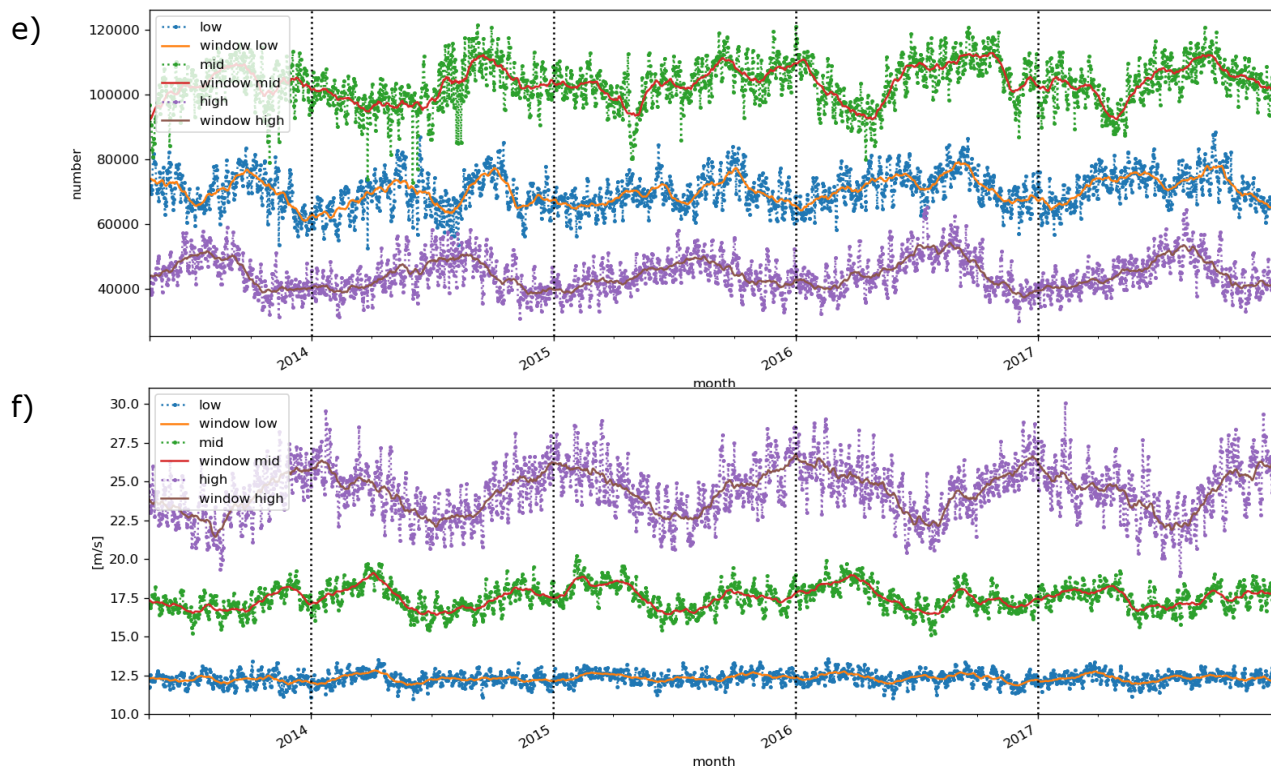
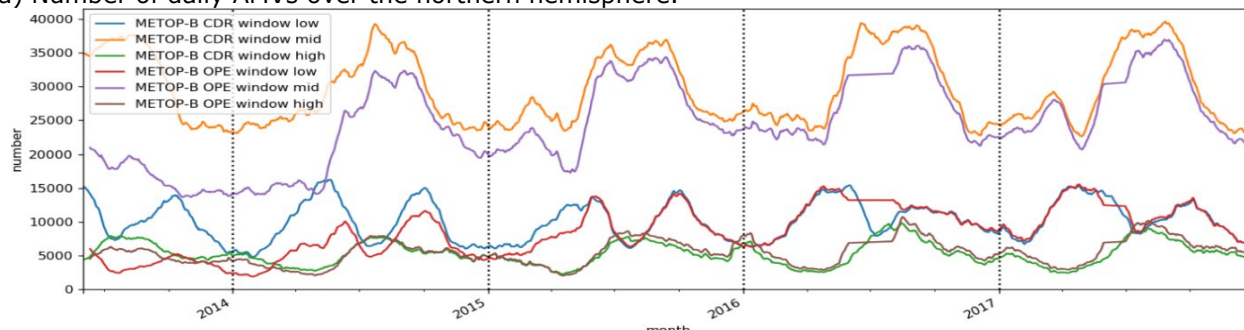


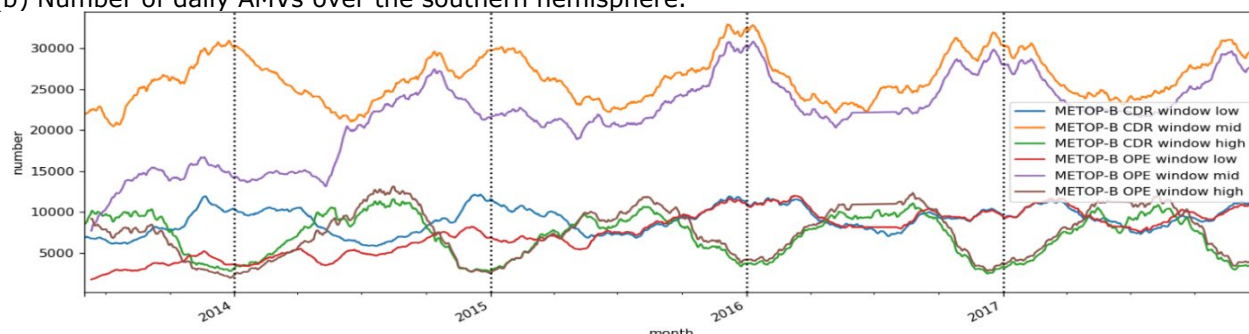
Figure 42: Metop-B/A (dual) time series of the number of winds and their speed for the three height classes. Each dot represents a daily average for the Arctic (a and b), Antarctic (c and d) and globally (e and f), only wind vectors with a $QI > 60$ and a speed $> 5 \text{ ms}^{-1}$ are considered. The lines represent the running mean over a month.

Additional plots for chapter 5

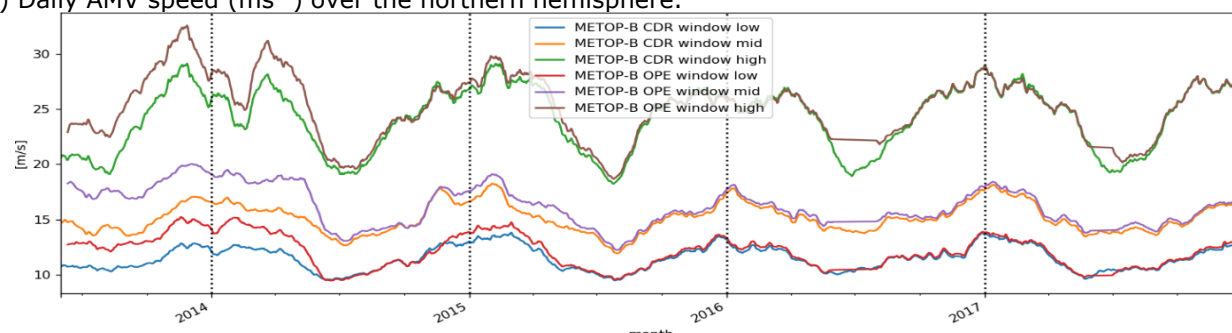
(a) Number of daily AMVs over the northern hemisphere.



(b) Number of daily AMVs over the southern hemisphere.



(c) Daily AMV speed (ms^{-1}) over the northern hemisphere.



(c) Daily AMV speed (ms^{-1}) over the southern hemisphere.

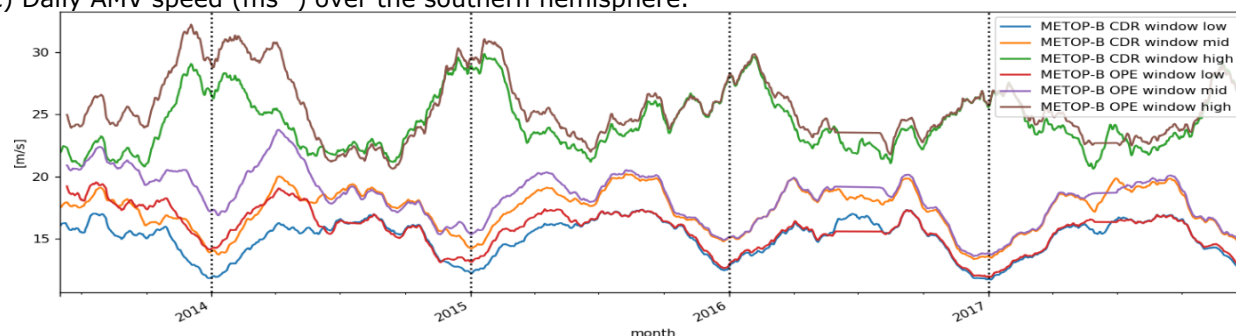
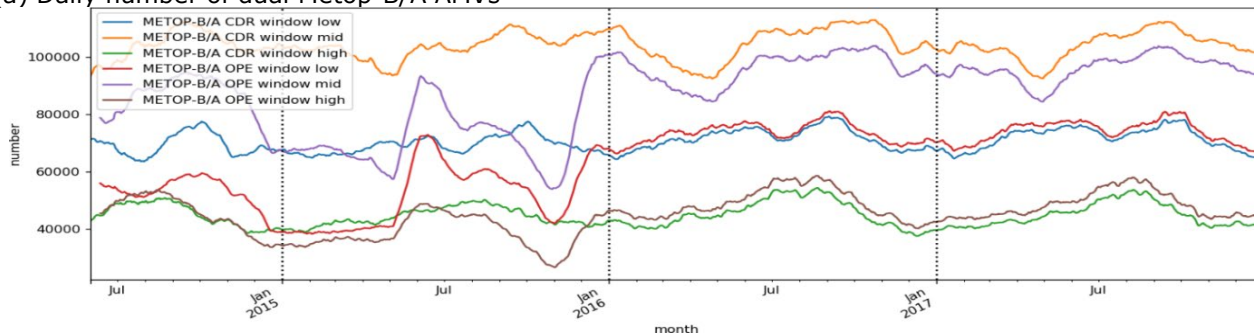


Figure 43: Comparison between reprocessed (CDR) and operational (OPE) Metop-B AMVs. First two rows number of AMVs per day for North (first row) and South Pole (second). Bottom two rows daily speed average, North (third row) and South Pole (fourth).

(a) Daily number of dual Metop-B/A AMVs



(a) Daily dual Metop-B/A AMV speed (ms^{-1})

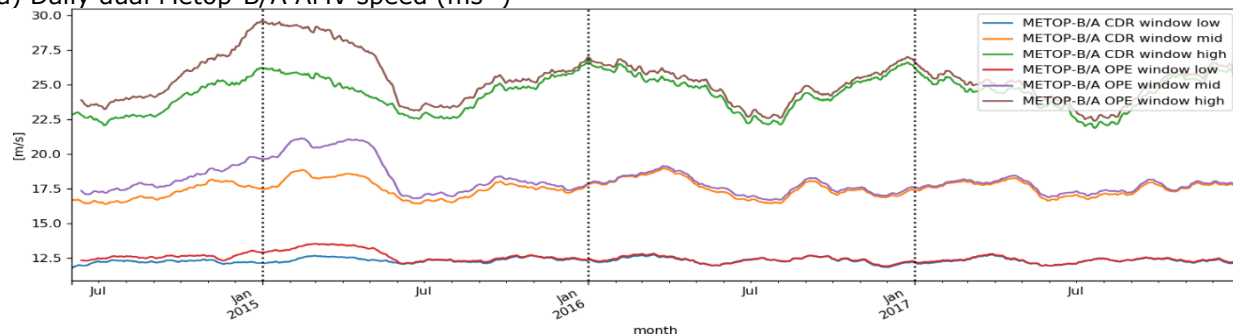


Figure 44: Comparison between reprocessed (CDR) and operational (OPE) dual Metop-B/A AMVs. All values on a global scale.

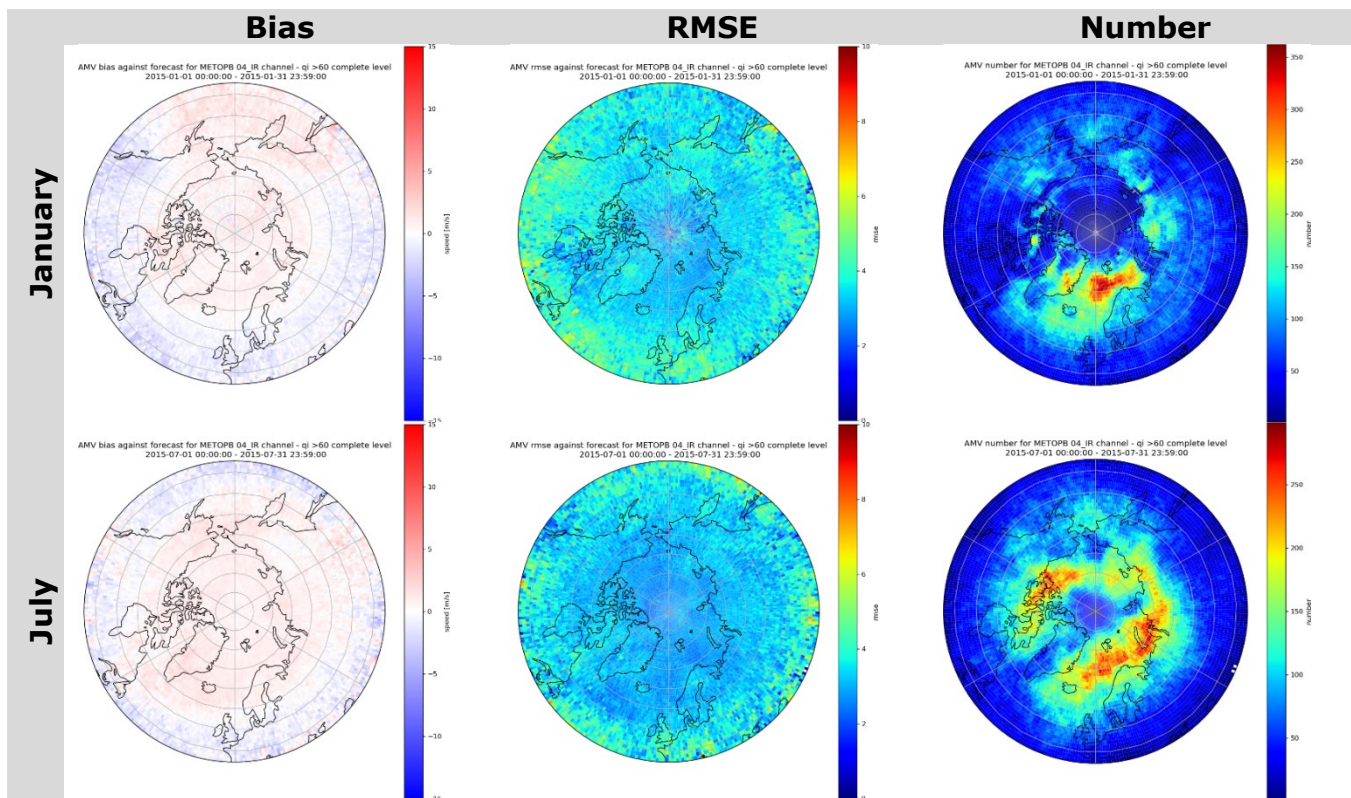


Figure 45: Monthly mean speed bias (ms^{-1}), RMSE against ERA-interim forecast and Metop-B number of AMVs for the months of January and July 2015 over the North Pole.

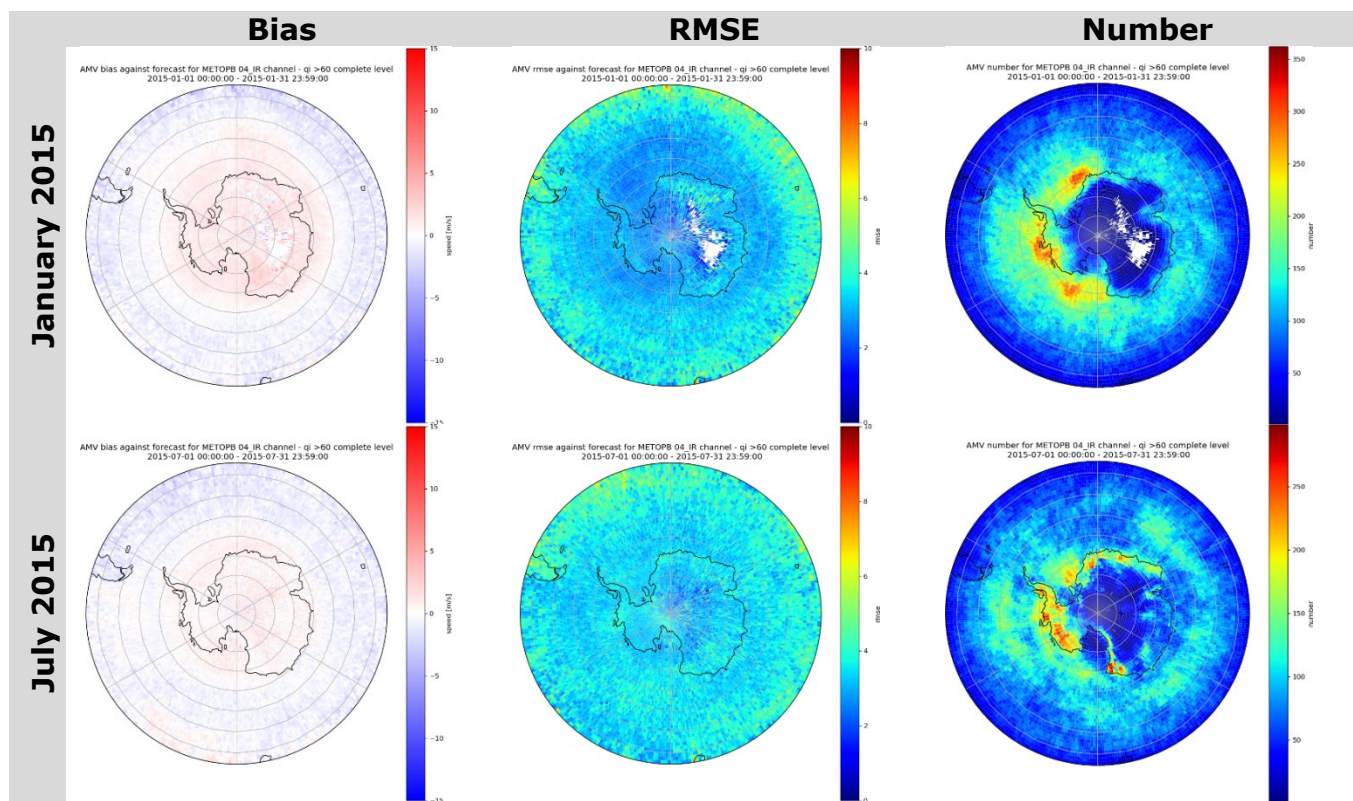


Figure 46: Monthly mean speed bias (ms^{-1}), RMSE against ERA-interim forecast and Metop-B number of AMVs for the months of January and July 2015 over the South Pole.

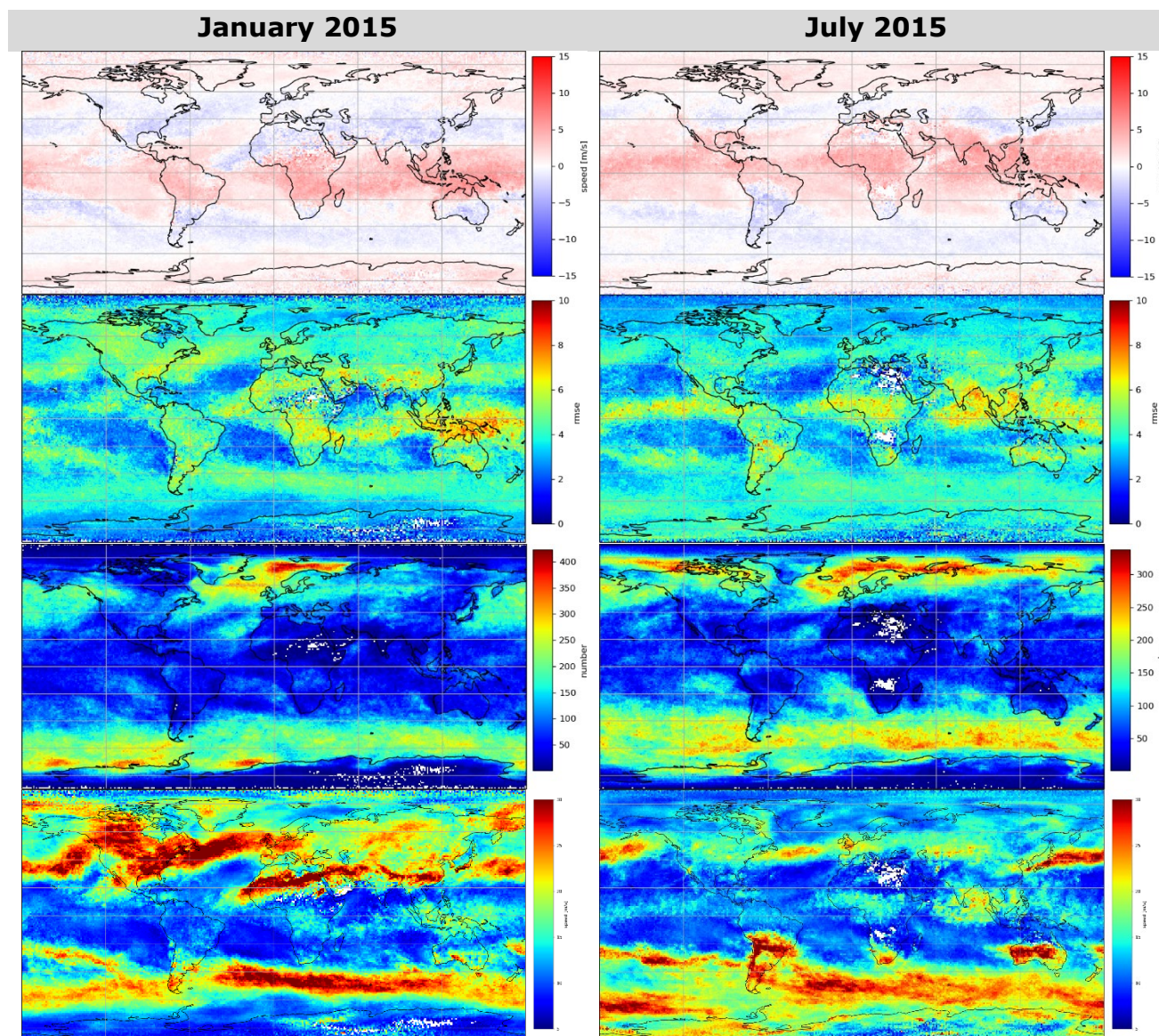
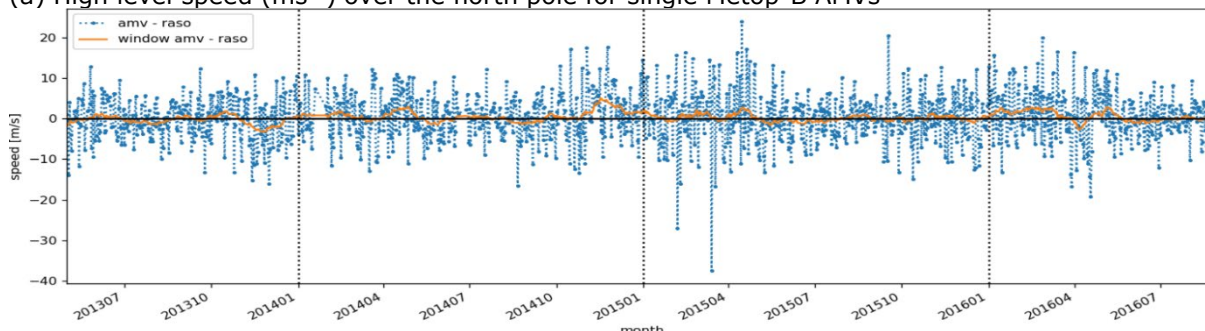


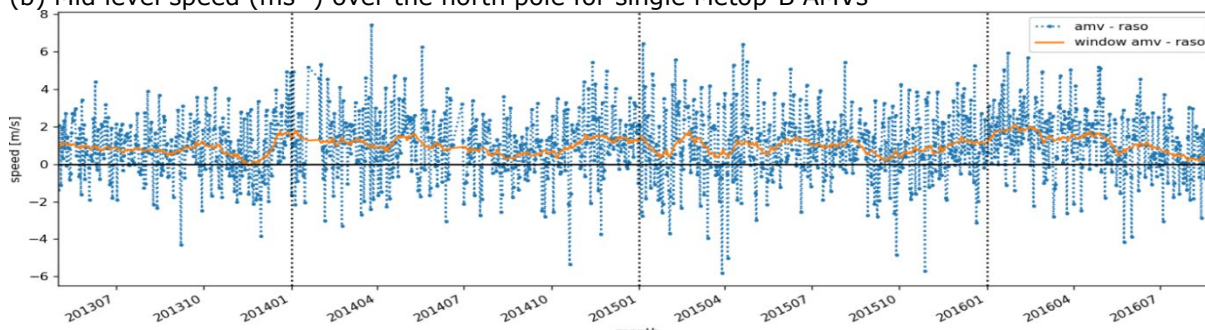
Figure 47: Monthly mean speed bias (top row), RMSE (second row) against forecast speed, number of AMVs (third row) and average speed (bottom row) for Metop-B/A dual for January (left) and July 2015 (right).

Additional plots for chapter 6.2

(a) High level speed (ms^{-1}) over the north pole for single Metop-B AMVs



(b) Mid level speed (ms^{-1}) over the north pole for single Metop-B AMVs



(c) Low level speed (ms^{-1}) over the north pole for single Metop-B AMVs

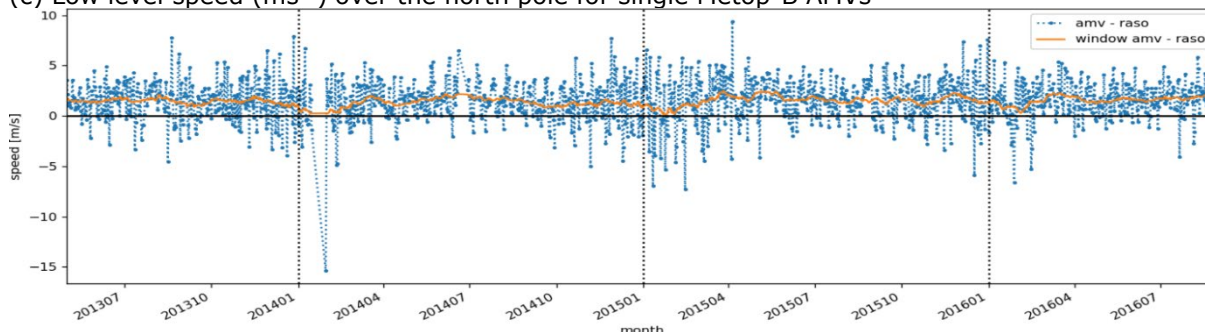


Figure 48: Average of wind speed bias for good AMVs ($\text{QI} > 60$) in ms^{-1} (reprocessed AMV - radiosonde) for Metop-B for the North Pole. The orange line is a 30-days running mean. From top to bottom is high, middle and low levels AMVs.

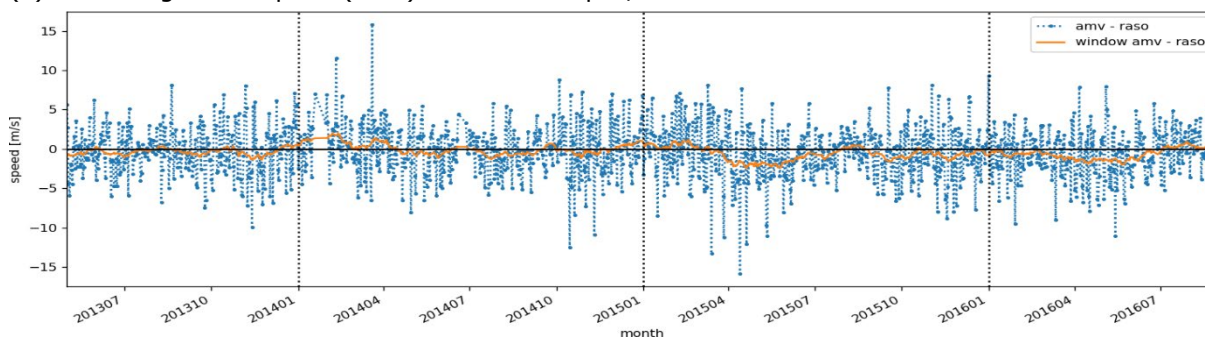
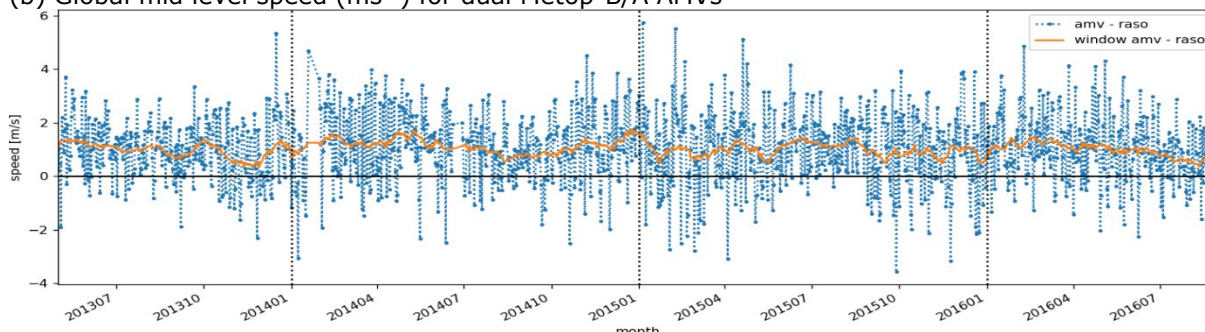
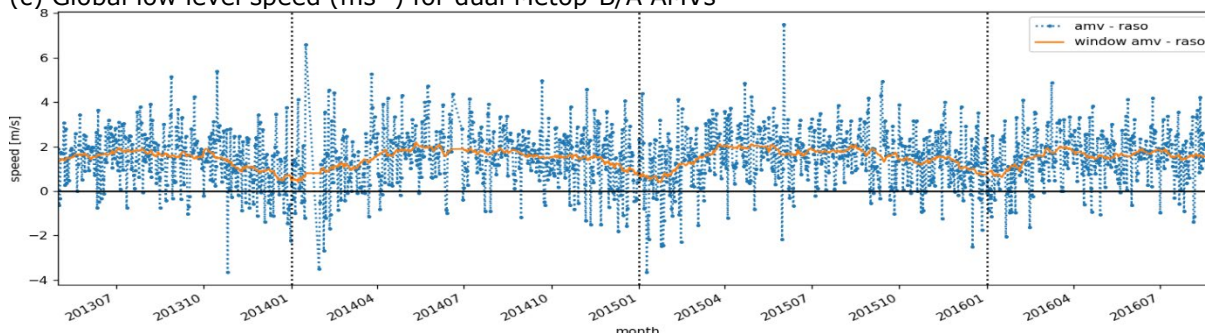
(a) Global high level speed (ms^{-1}) for dual Metop-B/A AMVs(b) Global mid level speed (ms^{-1}) for dual Metop-B/A AMVs(c) Global low level speed (ms^{-1}) for dual Metop-B/A AMVs

Figure 49: Average of wind speed bias for good AMVs ($\text{QI} > 60$) in ms^{-1} (reprocessed AMV - radiosonde) for dual Metop-B/A for global AMVs. The orange line is a 30-days running mean. From top to bottom is high, middle and low levels AMVs.

Additional plots for chapter 6.3

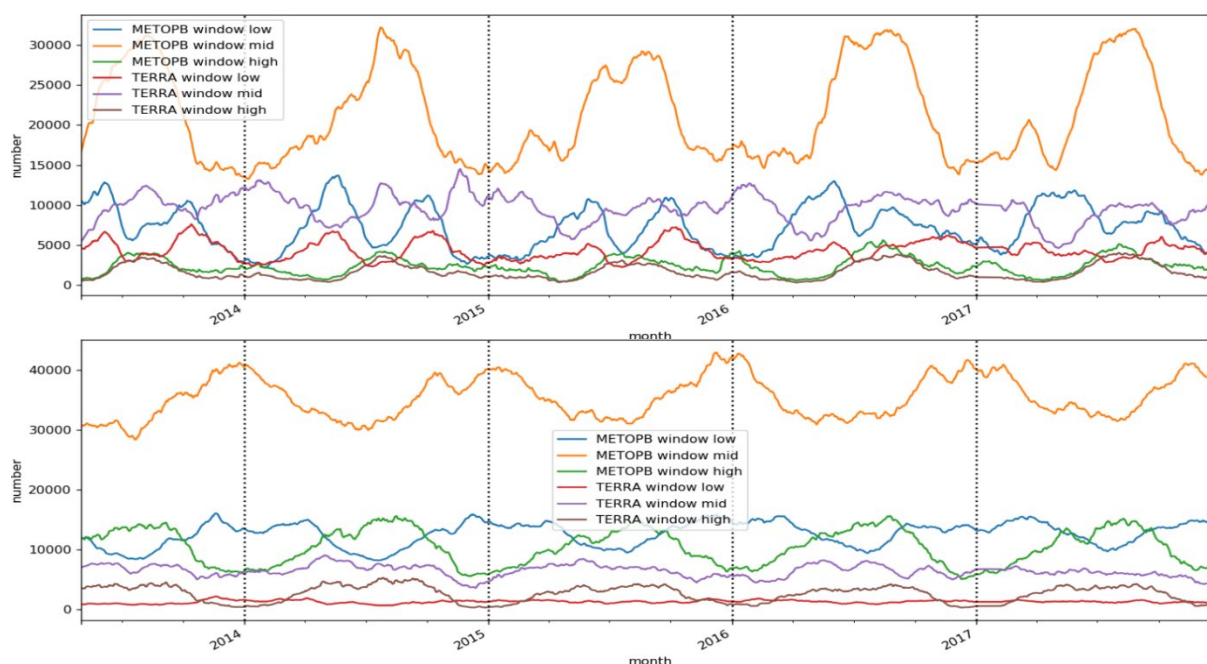


Figure 50: Comparison between Metop-B and MODIS on TERRA. Number of AMVs for Arctic (top, latitude $> 65^\circ$) and Antarctic (bottom, latitude $< -65^\circ$). Daily count smoothed using 30-day sliding window.

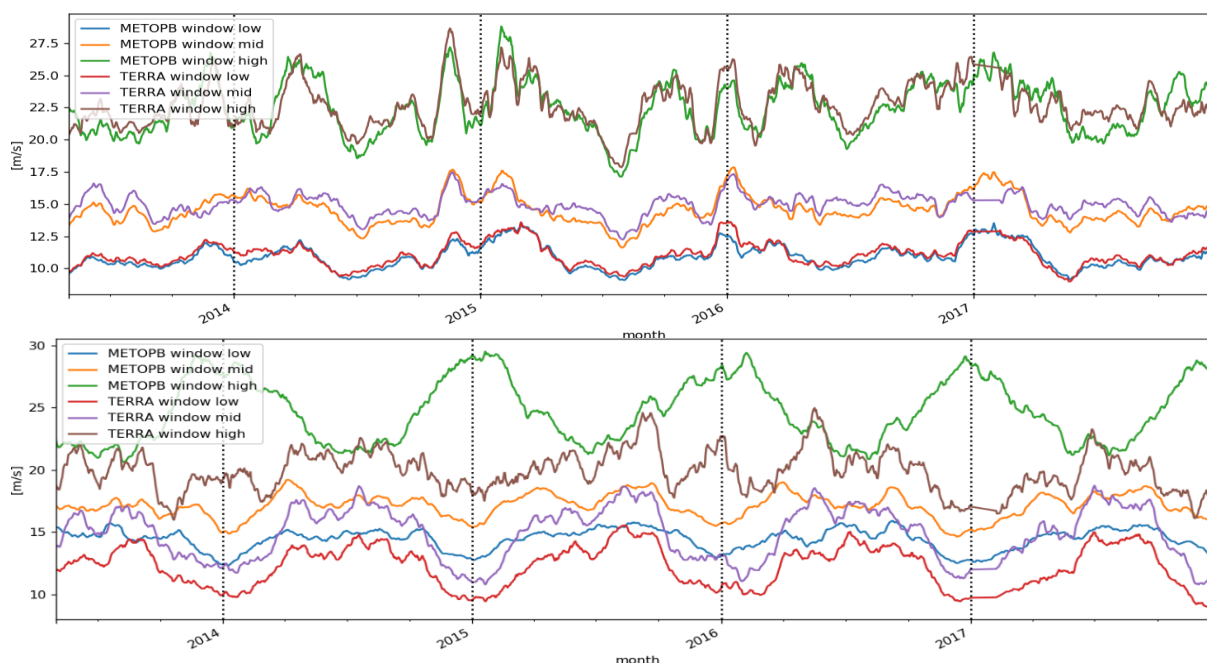


Figure 51: Comparison between Metop-B and MODIS on TERRA. Average speed of AMVs for Arctic (1. & 3. Row, latitude $> 65^\circ$) and Antarctic (2. & 4. Row, latitude $< -65^\circ$). Daily value smoothed using 30-day sliding window.



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