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TECHNICAL REPORT

Satellite Radiances Monitoring System for NCUM Data Assimilation

Bushair M. T., Priti Sharma, S. Indira Rani, Sumit Kumar, Buddhi Prakash Jangid , Gibies George, Abhishek Lodh, John P. George and Munmun Das Gupta

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10	Abstract	An automated observation monitoring system was developed for operational monitoring of satellite radiance observations received and assimilated in NCMRWF Unified Model (NCUM). Three step monitoring is carried out in this new monitoring procedure: i) during reception, ii) after the quality control and iii) after assimilation. An automated mail delivery system sends the status of observations received and selected for assimilation after observation processing. Once in a day (12 UTC assimilation cycle), this automated mail includes the results of Forecast Sensitivity to Observations (FSO), indicating the types of observations which are not beneficial for forecast accuracy. A detailed report is generated and posted in the intra-net of NCMRWF after each data assimilation cycle. The final monitoring report contains spatial distribution plots of all useful channels reported from each satellite instrument, the scatter plots of its count, bias and standard deviation of the differences between observation and background (O-B). Plots of 15 day time series of above mentioned quantities and their mean values are also made. Similar statistics of observation minus analysis (O-A) are also calculated. This monitoring report helps to assess the health of all channels of all satellite instruments which are used in the NCUM data assimilation system. Accordingly the decision making about its use in data assimilation becomes simple once the instrument quality deteriorates.
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Abstract

An automated observation monitoring system was developed for operational monitoring of satellite radiance observations received and assimilated in NCMRWF Unified Model (NCUM). Three step monitoring is carried out in this new monitoring procedure: i) during reception, ii) after the quality control and iii) after assimilation. An automated mail delivery system sends the status of observations received and selected for assimilation after observation processing. Once in a day (12 UTC assimilation cycle), this automated mail includes the results of Forecast Sensitivity to Observations (FSO) indicates the types of observations which are not beneficial for forecast accuracy. A detailed report is generated and posted in the intranet of NCMRWF after each data assimilation cycle. The final monitoring report contains spatial distribution plots of all useful channels reported from each satellite instrument, the scatter plots of its count, bias and standard deviation of the differences between observation and background (O-B). Plots of 15 day time series of above mentioned quantities and their mean values are also made. Similar statistics of observation minus analysis (O-A) are also calculated. This monitoring report helps to assess the health of all channels of all satellite instruments which are used in the NCUM data assimilation system. Accordingly the decision making about its use in data assimilation becomes simple once the instrument quality deteriorates.

1. Introduction

With the advances of remote sensing technology, satellite observations have become the most important inputs to the Numerical Weather Prediction (NWP) systems. Satellite observations viz., radiances measured by various spectral channels, Atmospheric Motion Vectors (AMVs), Scatterometer Ocean Surface wind vectors, GPS Radio-Occultation etc., are being assimilated in the advanced global/regional data assimilation systems of leading global NWP centres of the world. Many of these observations viz., radiances, AMVs, and scatterometer winds have shown significant improvement in NWP forecasts globally. However satellite radiance observations containing information about atmospheric temperature and humidity have maximum impact on NWP analyses and forecasts compared to any other observations (Eyre et al.*, 1993;* Andersson et al., 1994, Kumar et al., 2018)

NCMRWF receives satellite data from different geostationary and polar satellites through Global Telecommunication System (GTS) and directly from satellite data providers. These satellite observations are regularly monitored before its use in the global and regional data assimilation systems. The purpose of the monitoring is to gather information on the quality and quantity of the various observations received for its effective use in the data assimilation system.

An observation monitoring system with improved features has been developed and operationalized at NCMRWF to monitor the quantity and quality of observations received from various sources and used in the NCUM data assimilation system. Automated reports are generated by the new monitoring system to provide information about the volume and quality of the observations to the concerned scientists. In this monitoring report gross statistics about all observations, both conventional and satellite are included. A detailed report is also generated and posted at the intranet of NCMRWF after the completion of each data assimilation cycle.

Satellite radiance observations received at NCMRWF are monitored in three different stages, first during reception/pre-processing, second after processing and quality control, and third after assimilation. In the first stage, spatial plots of observations received from each satellite instrument are prepared. In the second stage the statistical parameters like mean, bias and standard deviation of the difference between Observation and background (O-B) are calculated for each spectral channels of all satellite instruments used in the data assimilation system. In the third stage, the statistical parameters such as mean bias and root mean square error (RMSE) of the difference between Observation and Analysis (O-A) are calculated.

Reception of satellite radiance observations at NCMRWF is described in section 2, followed by the methodology adopted in computation of various statistics is described in section 3. Various observation monitoring products are described in section 4 and the details of the contents of the monitoring report and email are described in section 5, followed by the conclusions in section 6.

2. Reception of Satellite Radiance Observations at NCMRWF

NCMRWF receives the satellite radiance observations from different sources like GTS, Indian Space Research Organization (ISRO) and India Meteorological Department (IMD), National Environment Satellite Data and Information Service (NESDIS) and European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) data dissemination through EUMETcast.

Satellite radiance observations received at NCMRWF are from Low Earth Orbiting (LEO) satellites and Geostationary (GEO) satellites. NCMRWF receives both infrared (IR) and microwave (MW) radiances from LEO satellites. IR channel observations from LEO satellites comprise the radiance observations from multispectral and hyperspectral instruments whereas the MW channel observations are only multispectral. Instruments onboard geostationary orbits are making only IR multispectral (not hyperspectral) measurements. Radiance observations from LEO satellite's multispectral IR instrument like High Resolution Infra-Red Sounder (HIRS) onboard NOAA-18, 19 and MetOp-A and B, and hyperspectral instruments, namely, (i) Atmospheric Infra-Red Sounder (AIRS) onboard AQUA satellite, (ii) Infrared Atmospheric Sounding Interferometer (IASI) onboard MetOp-A, B and C (iii) Cross-track Infrared Sounder (CrIS) onboard Suomi NPP and NOAA-20 satellites are being regularly received at NCMRWF. The LEO MW radiances receiving at NCMRWF are mainly from Advanced Microwave Sounding Units –A (AMSU-A) and Microwave Humidity Sounder (MHS) onboard NOAA-18,19 MetOp-A, B and C, Special Sensor Microwave Imager and Sounder (SSMI/S) onboard DMSP satellites F17 and F18, Advanced Technology Microwave Sounder (ATMS) onboard Suomi NPP and NOAA-20, Advanced Microwave Scanning Radiometer (AMSR2) onboard GCOM-W1, Sondeur Atmospherique du Profil d'Humidite Intertropicale par Radiometrie (SAPHIR) onboard Megha-Tropiques, MicroWave Humidity Sounder (MWHS) onboard FY-3C, and Global Precipitation Mission (GPM) Microwave Imager (GMI). The instruments HIRS, AMSU-A and MHS together called Advanced TIROS (Television Infra-Red Observation Satellite) Operational Vertical Sounder (ATOVS).

The IR and Water Vapor (WV) radiances from geostationary satellites receiving at NCMRWF includes Sounder and Imager radiance observations from INSAT-3D, GOES-E and W, Advanced Himawari Imager (AHI) onboard Himawari-8, and Spinning Enhanced Visible and Infra-Red Imager (SEVIRI) onboard Meteosat-8 and11. The types of observations assimilated in the NCUM assimilation system and the data sources are provided in Table 1.

Table 1: Radiance observations received at NCMRWF for NCUM system and their source

Observation Type	***Observation Description (Instrument/Satellite)***	***Source***
AHI	Advanced Himawari Imager radiances from Himawari-8	GTS
AIRS	Atmospheric Infrared Sounder on-board AQUA Satellite	NESDIS
AMSR	Radiances from AMSR-2 on-board GCOM satellite	EUMETCAST/ NESDIS
ATOVS	AMSU-A, AMSU-B/MHS, HIRS from NOAA-18 &19, MetOp-A&B	EUMETCAST/ NESDIS
ATMS	Advanced Technology Microwave Sounder in NPP satellite	EUMETCAST
CrIS	Cross-track Infrared Sensor observations in NPP satellite	NESDIS
MWHS	Radiances from Micro Wave Humidity Sounder (MWHS) on-board FY3C Satellite	EUMETCAST
GMI	Global Precipitation Mission (GPM) Microwave Imager	EUMETCAST/ NESDIS
GOESClear	Cloud clear Imager radiances from GOES	NESDIS
IASI	Infrared Atmospheric Sounding Interferometer from MetOp A & B	EUMETCAST/ NESDIS
IN3DImgr	INSAT-3D Imager Radiances	IMD
IN3DSndr	INSAT-3D Sounder Radiances	IMD
MTSAPHIR	SAPHIR microwave radiances from Megha-Tropiques	ISRO
SEVIRIClear	Cloud clear observations from SEVIRI of METEOSAT 8 & METEOSAT 11	EUMETCAST/ GTS
SSMIS	SSMIS Radiances from DMSP satellites	NESDIS

3. Monitoring Methodology

Monitoring of radiance observations at NCMRWF for NCUM is done in three different stages of observation processing and assimilation, (i) during data reception and pre-processing, (ii) after data processing and quality control, and (iii) after the assimilation. We have developed a new Observation Pre-processing System (NOPpS) to pack the observations received at NCMRWF from different sources in the "OBSTORE" format ((Prasad (2012, 2014), Prasad and Rani (2014), Buddhi et al., (2019)) for further processing (quality control, thinning and assimilation). The NCUM data assimilation follows hybrid-4DVAR method incorporated in a six-hourly intermittent data assimilation cycle (Kumar et al., 2018). In the first stage of observation monitoring, spatial plots of the radiance observations from different satellite instruments received at NCMRWF are generated in each assimilation cycle. These plots present the locations of the satellite passes and information about observation from how many channels of a particular instrument are available at each location. These plots help to monitor the data coverage and density of the observations at different locations.

The second stage is done after observation processing and quality control. The observation processing and quality control procedures are done during its use in the Observation Processing System (OPS), which does the quality control and selection (Rajagopal et al., 2012, John et al., 2016, and Kumar et al., 2018). OPS uses one dimensional variational (1D-VAR) simulations to do quality control of the satellite radiances. The parameter assimilated is the brightness temperature (Tb), a measure of radiance. 1D-VAR simulates the model Tb of various channels of different satellite instruments to provide the background (first guess) for quality control of observation. In the second stage of the observation monitoring, statistical parameters like mean and standard deviation of satellite observed brightness temperature, observation minus background ("O-B" using 1-DVAR simulated background) of each channel of the satellite instrument are prepared. Scatter plots of these statistical parameters along with corresponding 15 day mean values are generated in each assimilation cycle. Along with the values of above parameters during the current assimilation cycle, the 15 day mean of these parameters corresponding to the same assimilation cycle are also plotted. These plots provide a handy and user friendly comparison of the observation against its 15 days mean value and background, which gives an indication of the quality of observations. Along with these scatter plots, time series plots of count; mean and standard deviation of (O-B) of different channels of each instrument for continuous 15 days are also prepared. These plots are very useful to check the health of the instrument. A check is implemented such that if the normalized standard deviation of "O-B" in the current assimilation cycle is greater than the threshold values (approximately 1.25 times 15 days mean value) for a long period, that channel would be removed from the assimilation system and monitored continuously for its health. Once the channel quality is improved to the acceptable limit, the same is re-introduced in the assimilation system.

The third stage of the monitoring is after the completion of data assimilation. This is similar to the monitoring done during the second stage but for the differences between observation and the analysis (O-A). Here also the scatter plots of global count mean and RMSE against analysis as well as the corresponding 15 day mean values are generated.

The three step satellite radiance monitoring for NCUM is carried out through automated procedures and generates a detailed report on the completion of data assimilation in each cycle. Along with the monitoring report, an automated email delivery system has also been developed to report instantly (to the concerned scientists) the information about the types of observations which are missing so that, if possible, remedial measures can be taken. If the normalized standard deviation of radiance observations from any instrument is greater than the threshold value, this information will be the part of automated mail. Besides, the automated mail being generated, in the 12 UTC assimilation cycle, Forecast Sensitivity to Observation (FSO) statistics of detrimental observation/channel information of the three previous assimilation cycles and current 12 UTC cycle are generated. These FSO statistics also help to determine the health of different satellite channels. The email contains plots depicting the number of observations received and the number of observations available for assimilation as an attachment. The email of monitoring report also contains the observation received and selected for assimilation with respect to Land Data Assimilation System (LDAS) as well. Three variables are currently assimilated in the LDAS namely, soil moisture (SM), Snow and Land Surface Temperature (LST). Satellite observations are used in the LDAS also part of the monitoring system.

4. Details of Satellite Radiance Observations

This section describes the details of various LEO and geostationary satellite radiance observations which are being monitored and assimilated. For brevity, monitoring of selected satellite instruments on-board LEO and geostationary are only discussed. The detailed monitoring report generated at a particular assimilation cycle is provided as annexure.

4.1 Infra-Red (IR) Radiances from LEO Satellites

Infrared sounders on-board LEO satellites are further classified as multispectral sounders and hyperspectral sounders. Multispectral sounders provide information about the vertical structure of temperature, humidity and composition of atmosphere in multiple bands of electromagnetic spectrum; while hyperspectral remote sensing involves data collection in thousands of very narrow (10-20 nm) bands. HIRS is a multispectral IR sounder whereas AIRS, IASI and CrIS are the hyperspectral infrared sounders, measure the top-of-atmosphere radiance emitted by the earth system with very high spectral resolution using thousands of channels.

Multispectral HIRS are from sun-synchronous LEO satellites NOAA-18/19 and METOP-A/B/C satellites. HIRS performs atmospheric sounding with 19 infrared channels (3.8-15 µm) and one visible channel. HIRS Level 1 data at 10 km resolution are used for pre-processing.

AIRS on-board AQUA is a high resolution spectrometer with 2378 channels in the thermal infrared spectral region (3.74 - 15.4 µm) and 4 bands in the visible spectral region (0.4 - 1.0 µm). CrIS on-board NPP satellite (and NOAA-20) is a Fourier transform spectrometer with 1305 spectral channels (3.92 - 15.38 µm). IASI on-board METOP-A, B and C measures the radiance emitted from the earth and atmosphere in 8641 channels, covering the spectral interval 645-2760 cm^{-1}. Level 1 data from AIRS at 13.5 km, CrIS at 16 km and IASI (not started using observations from MetOp-C in NCUM) at 25 km resolution are used in NCUM. Due to the limited computational resources and to reduce processing time for hyperspectral sensors, out of thousands of channels, only few channels are processed depending on the relevance of information required for atmospheric assimilation in NCUM system. For AIRS 324 channels, CrIS 399 channels and IASI 314 channels are processed for the utilization in the NCUM data assimilation systems (these channels are not the first 314 channels). Figure 1(a) and 1(b) show the satellite passes of IASI on-board MetOp -1(B) and MetOp - 2(A) orbital passes received at NCMRWF in a typical assimilation cycle.

Figure 2 shows the scatter plots of count, mean and the standard deviation of “O-B” of IASI from MetOp-A for a particular assimilation cycle. Though 314 channels of IASI are selected for processing, approximately 130 channels are only being assimilated; other channels are used only for quality control. Only those channels which are being assimilated in NCUM system are included in Figure 2.   In Figure 2, blue dots are the daily mean and the red dots are the corresponding 15 day mean valid for a particular assimilation cycle. Figure 3 represents the Hovemoller time series plot of “O-B” and count for continuous 15 days for one particular channel of IASI. This type of plot is generated for all the 130 assimilating channels, but for brevity only representative channel is showed in this report. Figure 4 is similar to Figure 2, but for observation minus analysis (O-A).

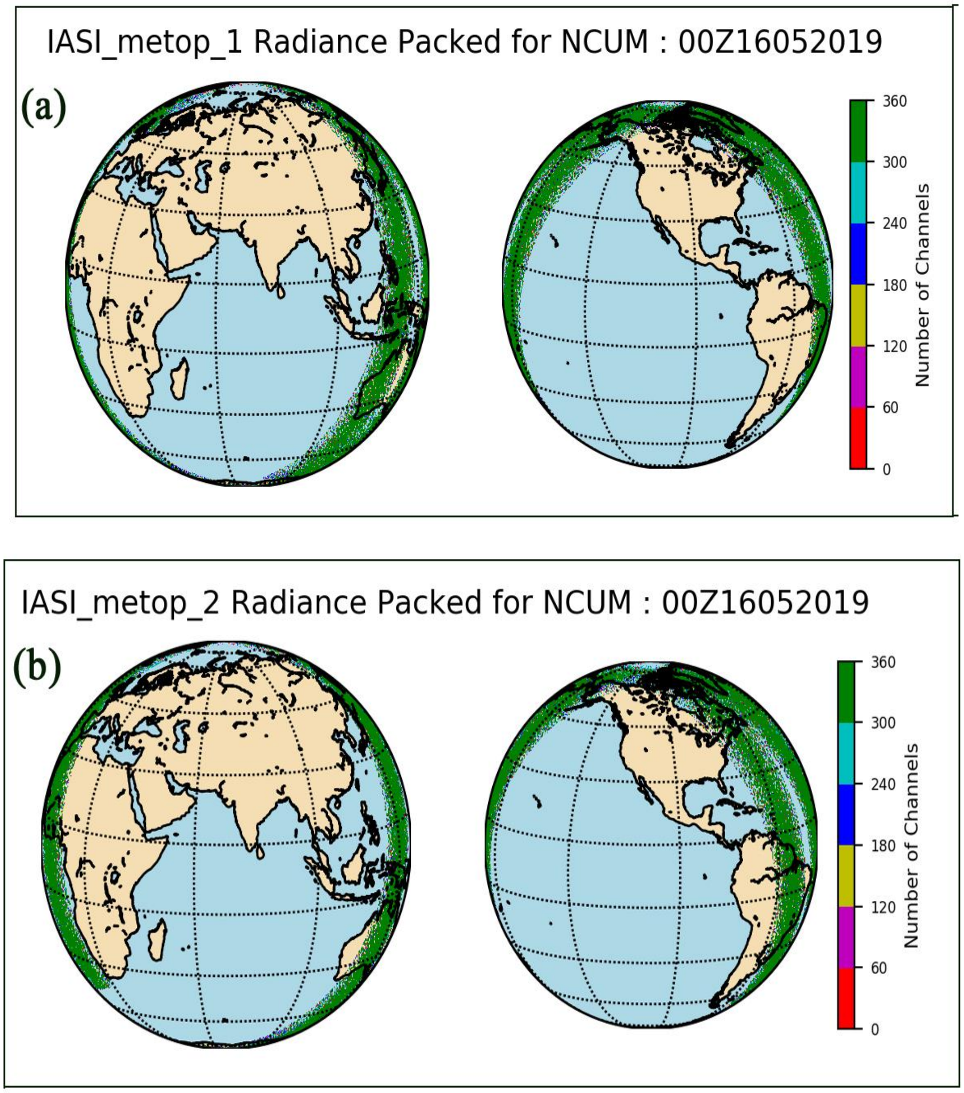

Figure 1: Satellite passes of IASI on-board (a) MetOp -1(B) and (b) MetOp - 2(A) for 00 UTC of a typical data assimilation cycle. Colour bar represents the number of channels available at each location.

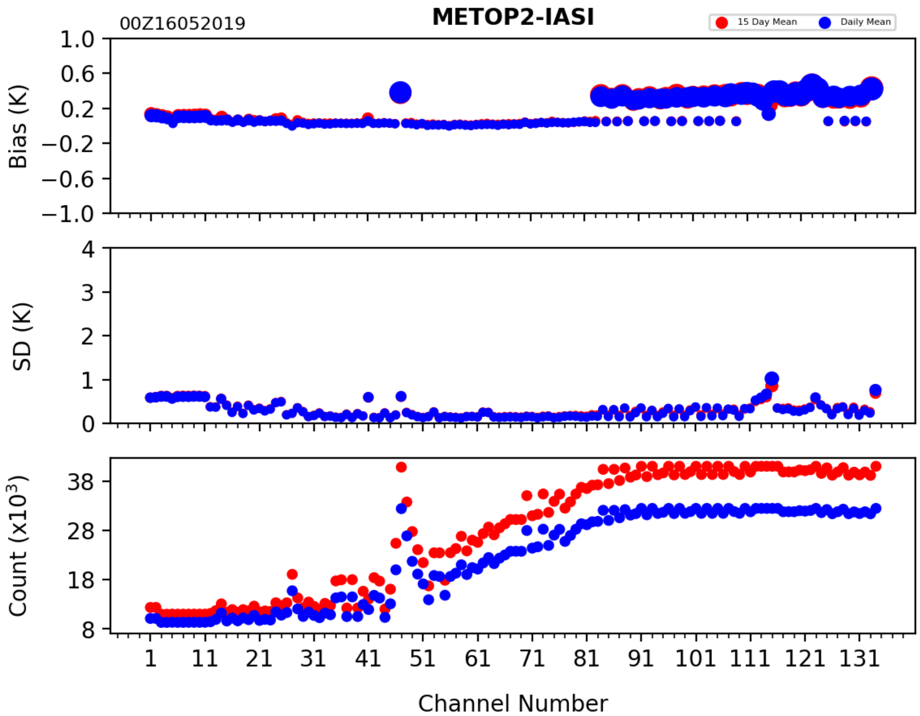

Figure 2: Scatter plots of count, mean and the standard deviation of "O-B" for 00 UTC of a typical data assimilation cycle and the 15 day mean for IASI-MetOp-A.

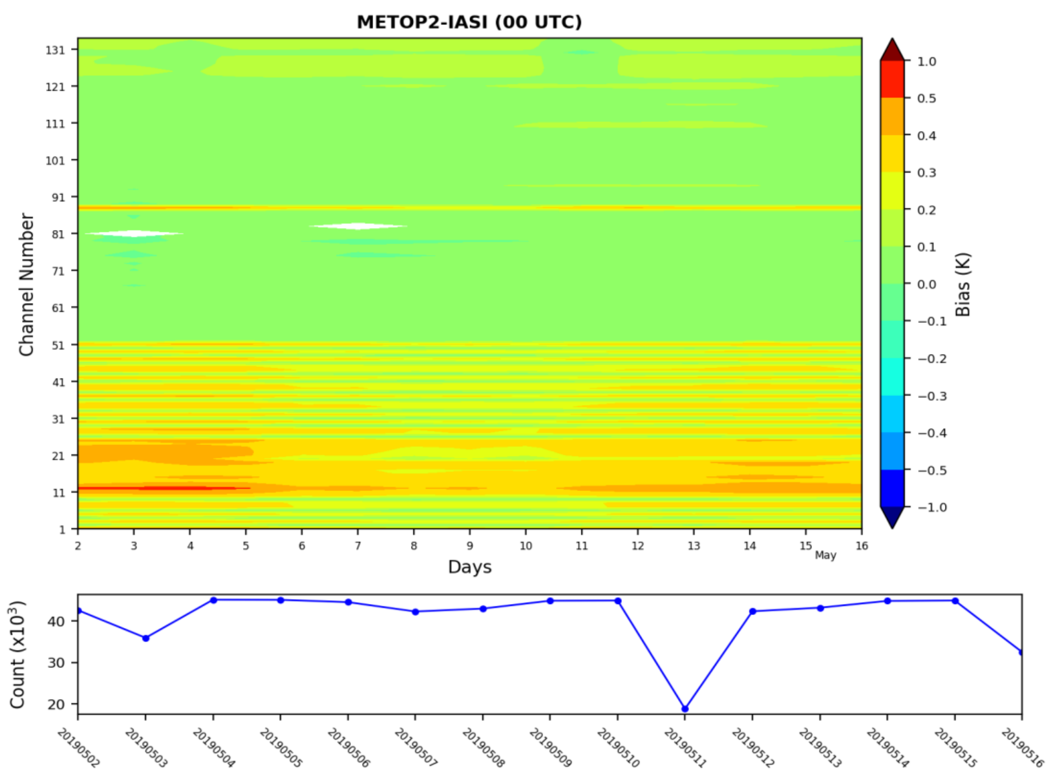

Figure 3: Hovemoller diagram for bias of "O-B" for continuous 15 days for IASI-MetOp

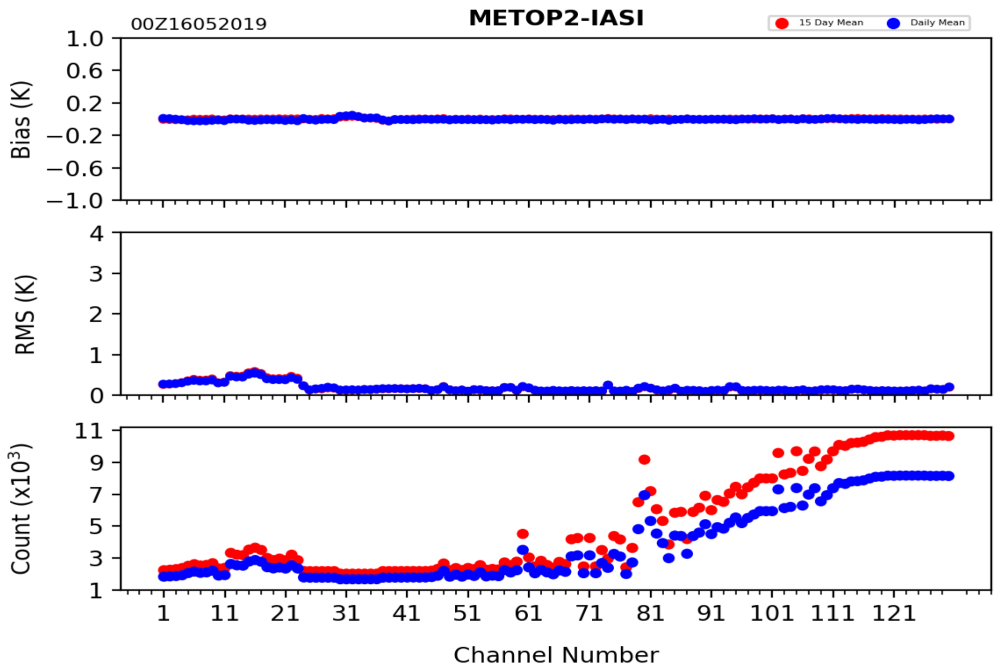

Figure 4: Scatter plots of count, mean and the standard deviation of "O-A" for a typical data assimilation cycle and the 15 day mean for IASI from MetOp-A.

4.2 Micro-Wave (MW) Radiances from LEO Satellites

Microwave (MW) radiance observations from LEO satellites are less affected by the presence of clouds compared to IR observations and therefore provide important information even over cloudy region. Unlike IR instruments, MW instruments on-board LEO satellites are only multispectral.

AMSU-A is a multi-channel microwave radiometer which measures radiances in 15 discrete frequency channels (23-90 GHz) and MHS is a microwave radiometer measures radiances in five microwave channels between 89 and 183.3 GHz. ATMS is a cross-track scanning microwave radiometer measures at 22 frequency bands in the range from 23 GHz to 183 GHz. SAPHIR onboard Megha-Tropiques satellite is a sounding instrument with 6 channels near the absorption band of water vapor at 183 GHz. The SSMI/S is a 24-channel microwave radiometer system covering the 54GHz and 183 GHz bands. AMSR-2 onboard GCOM-W1 satellite is a conically scanning passive microwave radiometer sensing microwave radiations of 7 frequencies, at both horizontal and vertical polarization, ranging from 6.9 GHz to 89 GHz.

AMSU-A Level 1 data at 48 km resolution, MHS at 16 km and SAPHIR at 10 km and AMSR 2 at 10 km are used in NCUM pre-processing system (NOPpS). ATMS Level 1 data at 16 km resolution for channels 165-183 GHz, 32 km for channels at 50-90 GHz and 75 km for channels at 23-32 GHz are used in NOPpS. Figure 5 shows the spatial plots of SAPHIR radiances for a typical assimilation cycle. The corresponding statistical parameters of "O-B", 15 day time series plot, and the statistical parameters of "O-A" are shown in figures 6, 7 and 8.

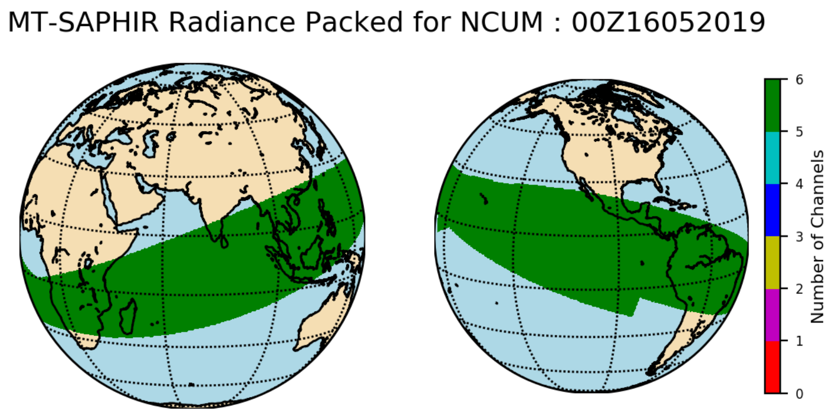

Figure 5: Spatial distribution of SAPHIR radiances available for 00 UTC data assimilation cycle of a typical day.

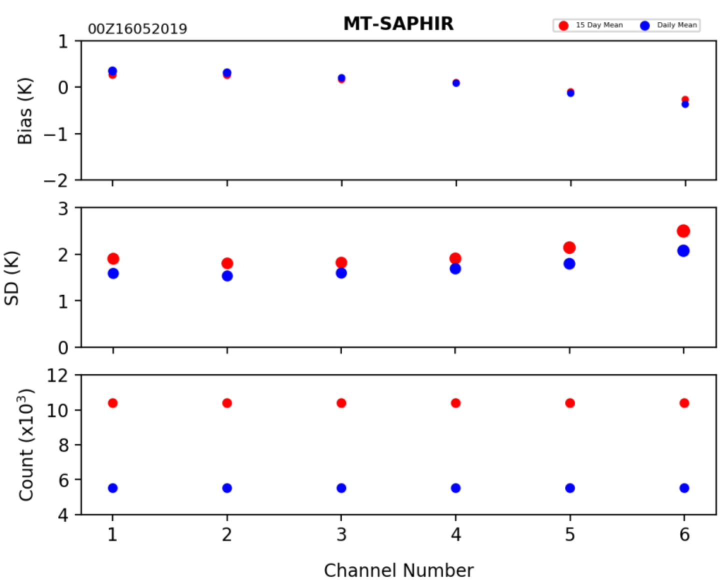

Figure 6: Scatter plots of count, mean and the standard deviation of "O-B" of SAPHIR for 00 UTC data assimilation cycle of a particular day.

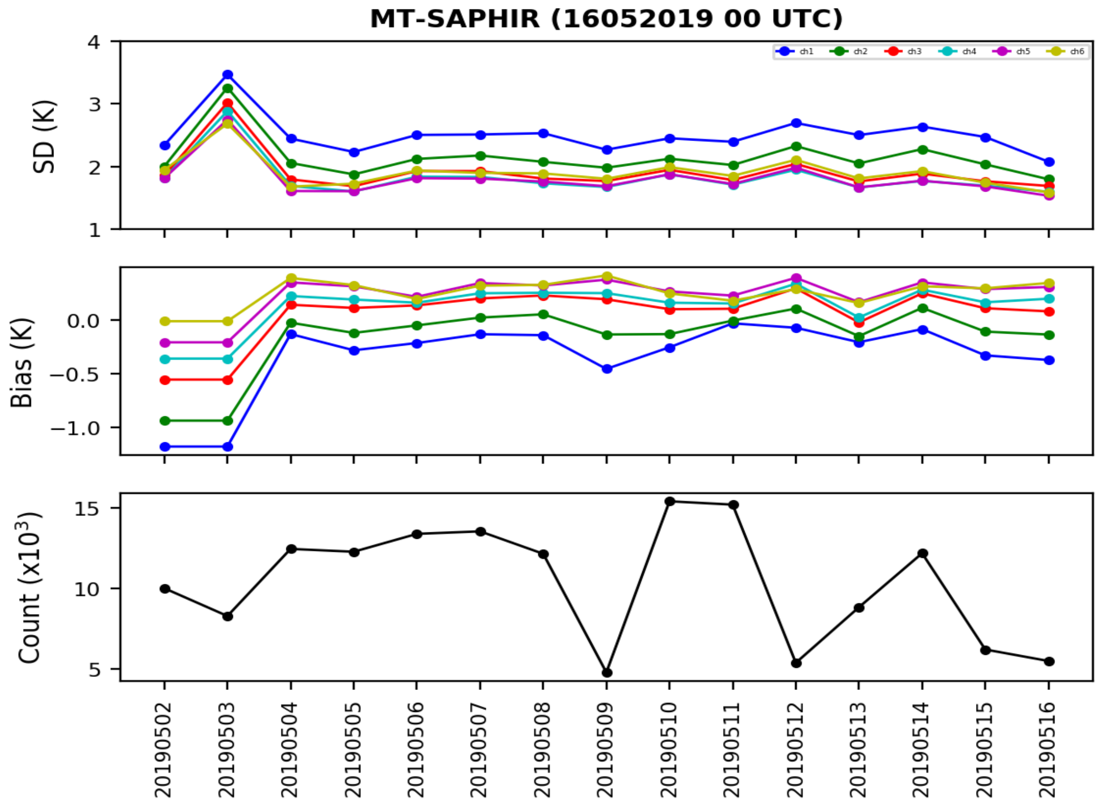

Figure 7: Time series of count, bias and standard deviation of "O-B" for a continuous 15 days for different channels of SAPHIR.

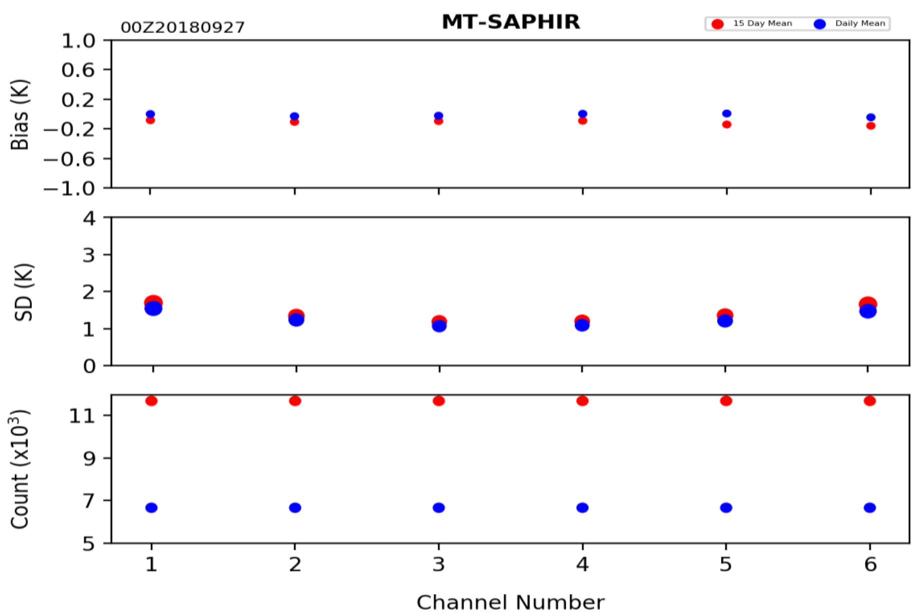

Figure 8: Scatter plots of count, mean and the standard deviation of "O-A" of SAPHIR for 00 UTC data assimilation cycle of a typical day and its 15 day mean.

4.4 Geostationary Satellite Radiances

Geostationary satellites provide high spatial and temporal resolution observations which are very crucial for the prediction of fast-evolving weather systems at the mesoscale to the convective scale (Stengel et al. 2009). NCMRWF assimilates Clear Sky Radiances (CSR) from geostationary satellites. Assimilation of water vapor (WV) channel radiances improves the relative humidity (RH) representation in the upper troposphere (Peubey and McNally, 2009). The geostationary CSR from GOES-15, SEVIRI onboard METEOSAT-8/11, HIMAWARI-8 and INSAT-3D are received and assimilated at NCMRWF. GOES-15 imager measures radiances in 6 channels, one visible and five IR with resolution of 1.0 km for visible channels and 4.0 km for IR channels. SEVIRI has the capacity to observe the earth in 12 spectral channels (4 visible/NIR channel and 8 IR channels) with resolution of 1 km for the high-resolution visible channel and 3 km for the infra-red and the 3 other visible channels. The Indian satellite INSAT-3D carries a 6 channel imager and a 19 channel sounder, 18 in IR region and one in visible region. The Sounder measures radiances in eighteen IR channels with the resolution of 10 km and for the imager, the visible and shortwave IR channel resolution is 1 km for middle IR, for thermal IR1 and thermal IR2 4 km, and WV channel 8 km. Figure 9 presents the spatial observation coverage plot of SEVIRI (METEOSAT-8) received for a typical assimilation cycle. Figures 10, 11, and 12 are the statistical parameters of corresponding "O-B", time series plot of 15 days, and the statistical parameters of "O-A".

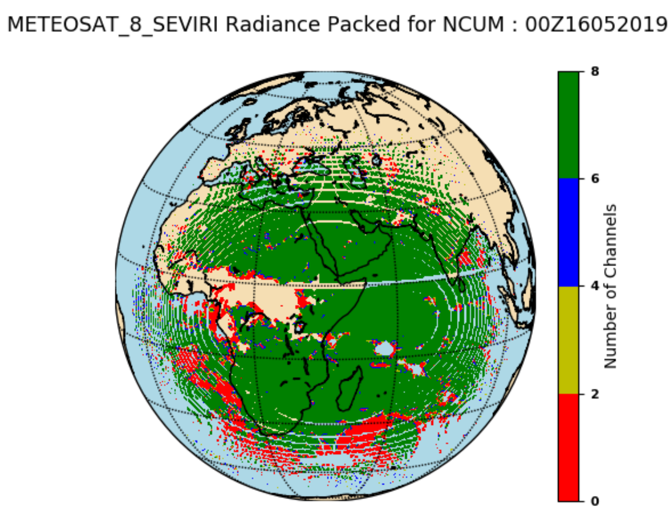

Figure 9: Spatial plot of METEOSAT-8 SEVIRI radiances received and used in NOPpS for 00 UTC data assimilation cycle of a typical day. Shading represents the number of channels reported at each location.

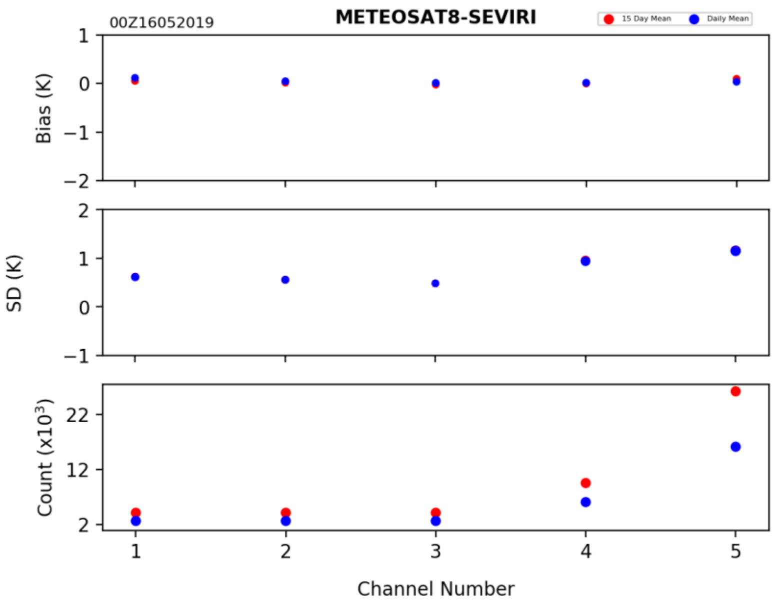

Figure 10: Scatter plots of count, mean and the standard deviation of "O-B" for 00 UTC of assimilation cycle of a typical day and its 15 day mean for METEOSAT-8 SEVIRI.

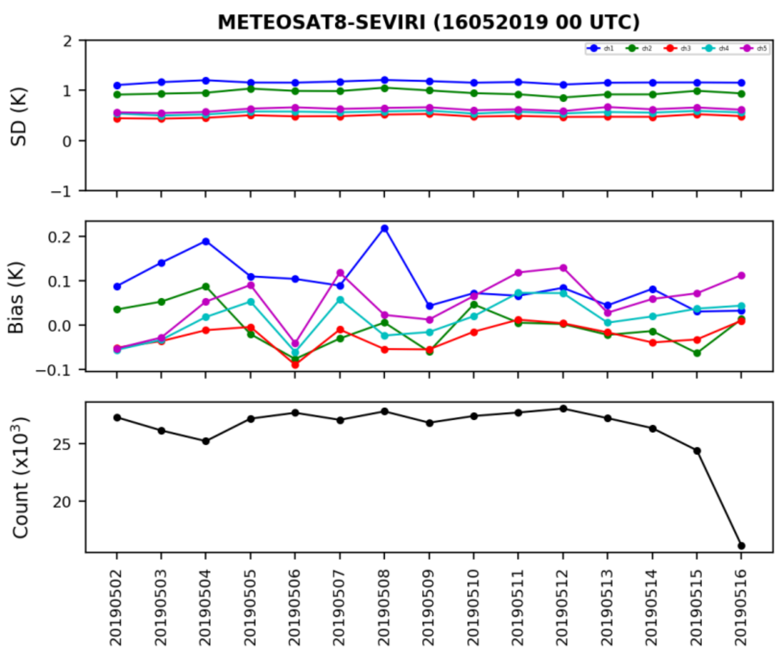

Figure 11: Time series of count, bias and standard deviation of "O-B" for continuous 15 days for different channels of METEOSAT-8 SEVIRI.

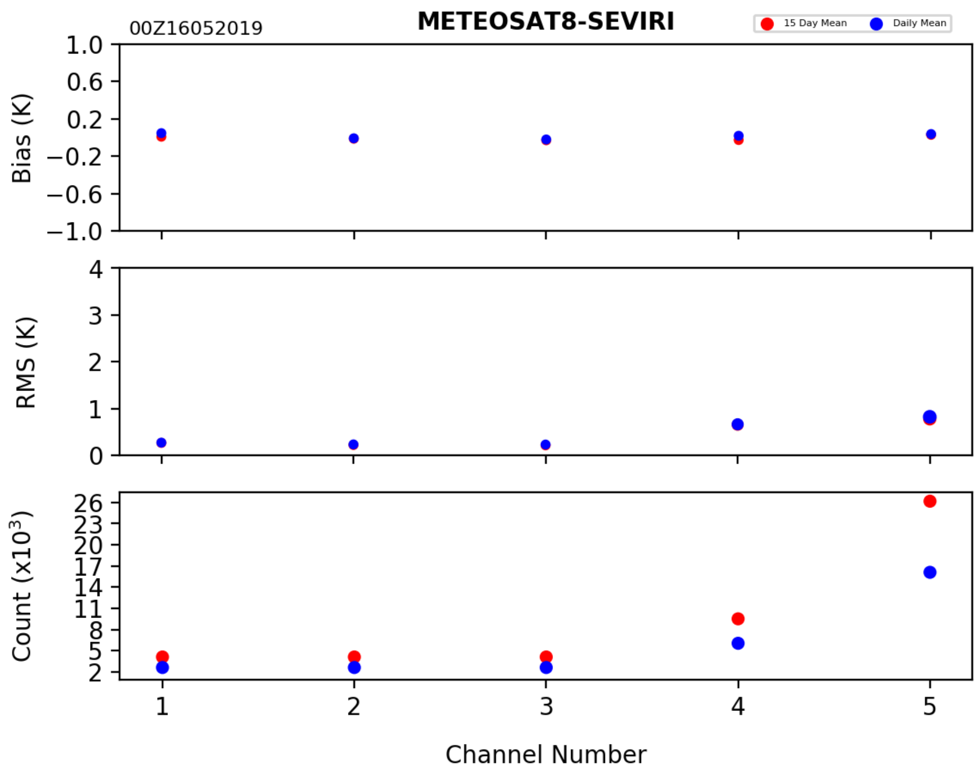

Figure 12: Scatter plots of count, mean and the standard deviation of "O-A" for 00 UTC assimilation cycle of a typical day and its 15 day mean for METEOSAT-8 SEVIRI

Figures 13, 14, 15 and 16 are similar to Figures 9, 10, 11 and 12 but for INSAT-3D imager radiance. INSAT-3D imager has the imaging capability of the earth disc in six different channels, one in visible and five in infrared. The visible imager (VIS) channel operates in the wavelength of 0.52 – 0.72 µm. The other five infrared channels are in shortwave infrared (SWIR) (1.55 – 1.70 µm), Mid wave infrared (MIR) (3.80 – 4.00 µm), water vapor (WV) (6.50 – 7.00 µm), and in two thermal infrared (TIR) channels. Measurements of split TIR are at 10.2 – 11.2 µm (TIR-1) and 11.5 – 12.5 µm (TIR-2). The ground resolution at the sub-satellite point is 1 km for both visible and SWIR channels. The ground resolution for MIR and TIRs is 4 km each, and for WV channel the ground resolution is 8 km. Only the WV channel radiances are currently assimilated in the NCUM system.

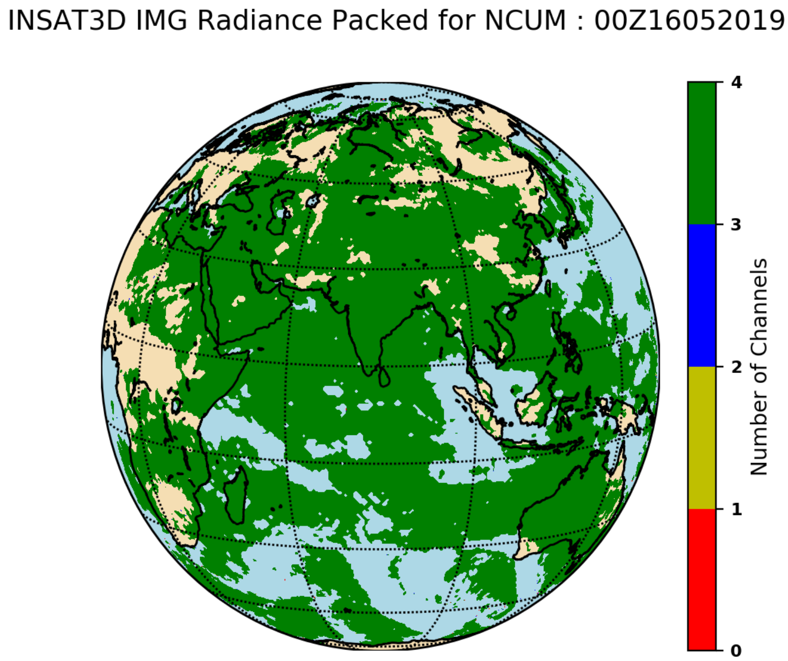

Figure 13: Spatial plot of INSAT-3D Imager radiances used in NOPpS for 00 UTC assimilation cycle of a typical day. Shading represents the number of channels available at each location.

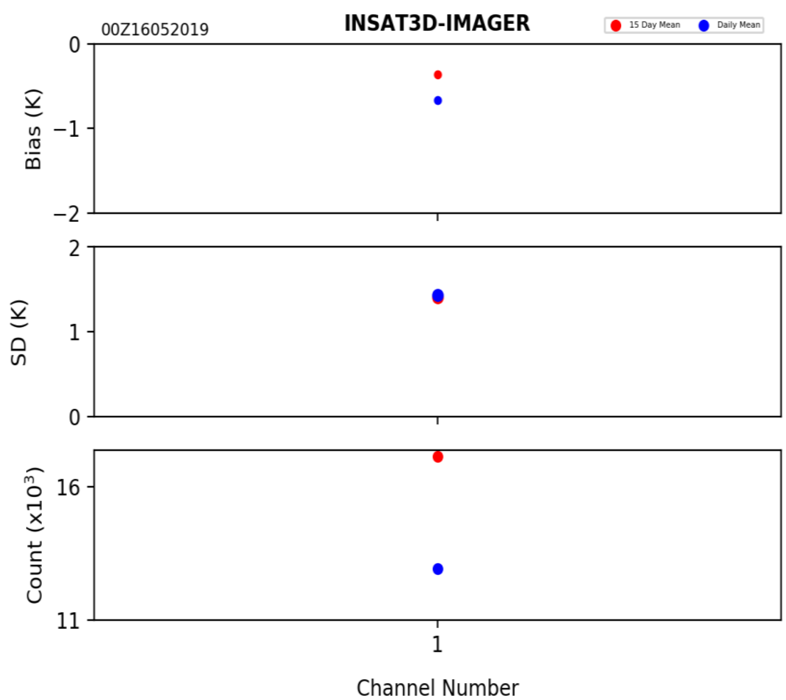

Figure 14: Scatter plots of count, mean and the standard deviation of "O-B" for 00 UTC assimilation cycle of a typical day and its 15 day mean for INSAT-3D imager WV channel.

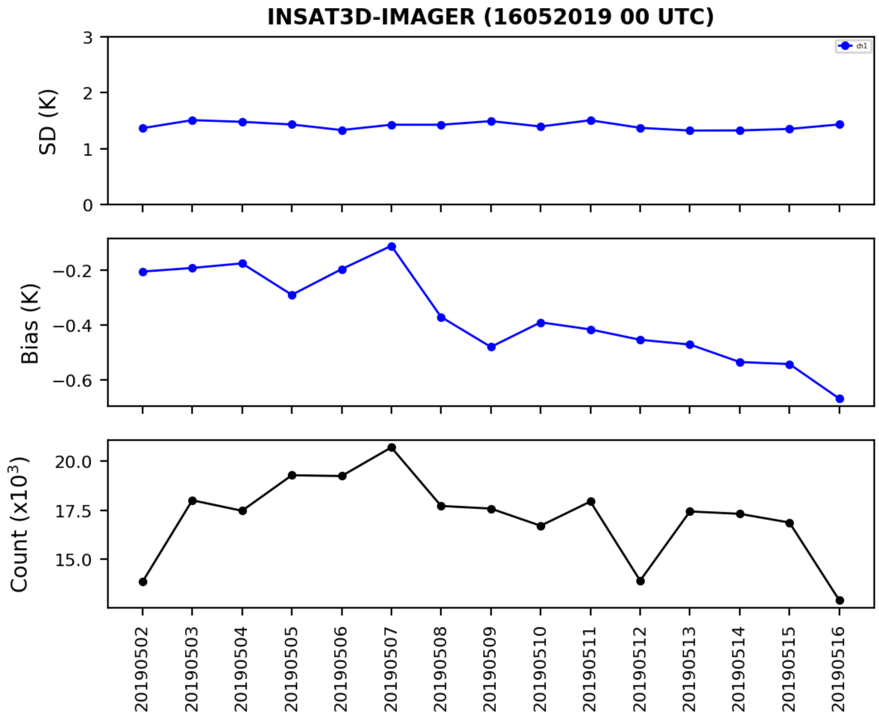

Figure 15: Time series of count, bias and standard deviation of "O-B" for continuous 15 days for INSAT-3D Imager WV channel.

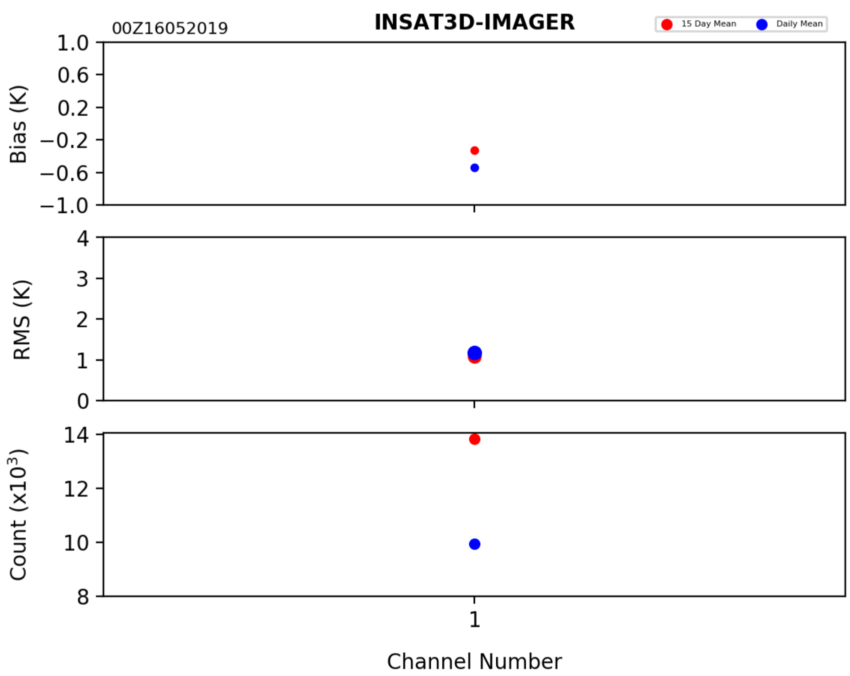

Figure 16: Scatter plots of count, mean and the standard deviation of "O-A" for 00 UTC assimilation cycle of a typical day and its 15 day mean for INSAT-3D Imager WV channel.

5. Monitoring Report and Automated email

At the end of the three steps monitoring procedure, a detailed report is generated and posted in the intranet of NCMRWF. A sample monitoring report generated during a particular assimilation cycle is provided in the annexure. An automated email generation system is developed to inform the status of observations used in the assimilation (in each data assimilation cycle) to the concerned scientists. This email contains the information regarding each observation and FSO system generated statistics, which indicate the types of observation which were not beneficial. Figure 16 shows the snapshot of the automatic email generated by the monitoring system. A bar diagram depicting the total number of observations received for each type of observation and the number of observations assimilated, both in logarithmic scale is also attached with this email. Figure 17 shows the bar diagram showing the total number of observations received and assimilated for a particular cycle. This figure contains the information about other observations (conventional) as well. The email attachment also includes the monitoring plot of land surface observations which are assimilated in LDAS. Figure 18 is the bar diagram of land surface observation monitoring.

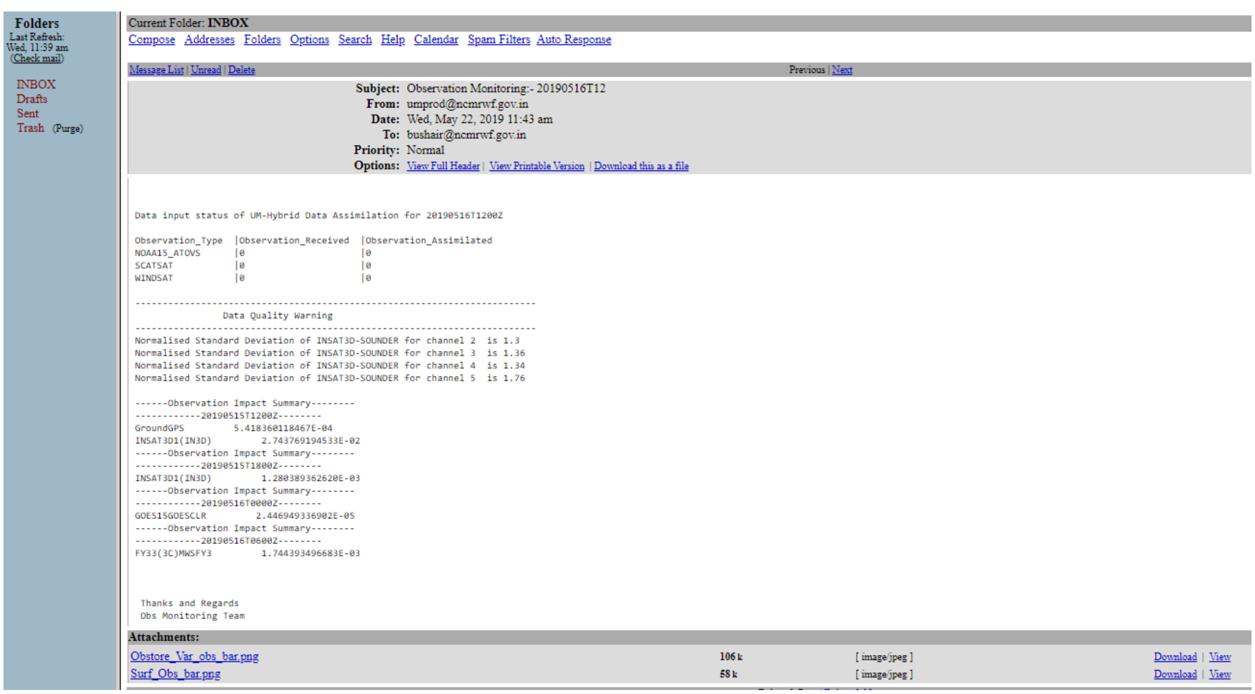

Figure 16: Email generated during typical data assimilation cycle

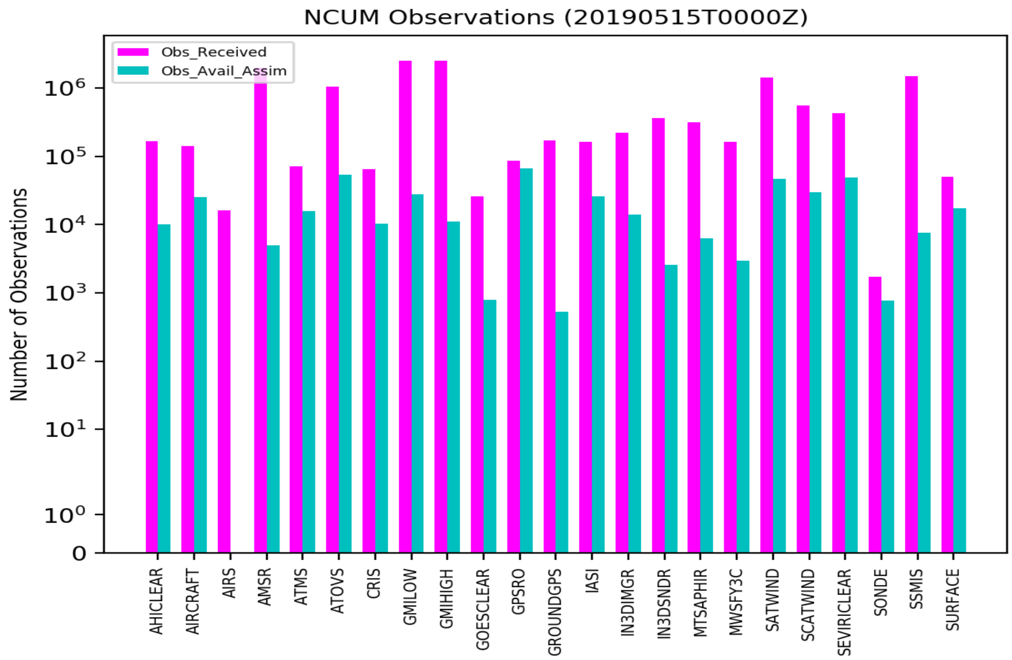

Figure 17: Bar diagram showing the total number of observations (both conventional and satellite observations) received and assimilated for a particular data assimilation cycle.

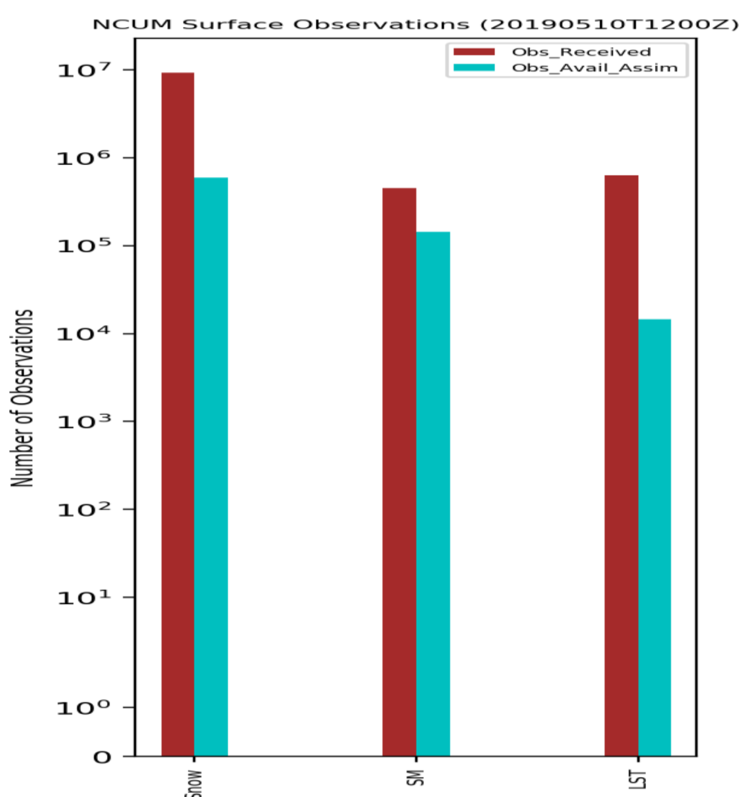

Figure 18: Bar diagram showing the total number of land surface observations (snow, soil moisture (SM) and land surface temperature (LST)) received and assimilated in the NCUM system in a typical assimilation cycle

6. Conclusions

A new satellite radiance monitoring system for NCUM has been developed for the improved monitoring of observations and for their effective use in the data assimilation system. Three stages monitoring of satellite radiances are being done; during reception, after quality control and after assimilation. The monitoring report indicates the health of different satellite instruments which are used in the NCUM assimilation system. This new data monitoring system continuously monitor both quality and quantity of satellite observation, in detail, which helps to improve the decision making with respect to its use in the assimilation.

Acknowledgements

Authors acknowledge the fruitful discussion with Drs. V. S. Prasad, C. J. Johny, and M. Satheesh during the development of the new monitoring system. Also acknowledge the support and encouragement rendered by Dr. E. N. Rajagopal, Head, NCMRWF. Authors extend their gratitude to Mihir HPCS Support team, particularly Ms. Shivali Gangvar, for technical assistance.

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Appendix

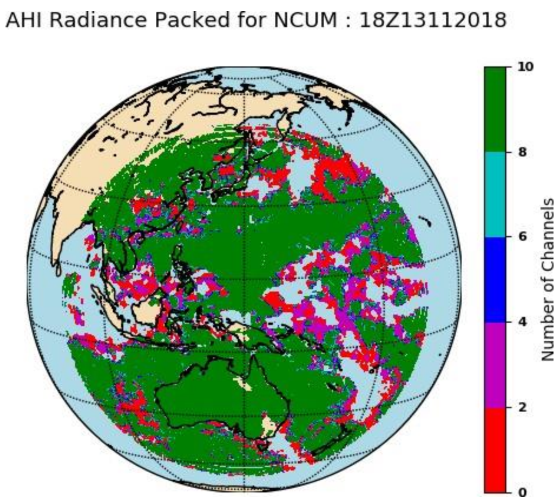
Data Assimilation Statistics
NCUM Data Assimilation System
(Global)

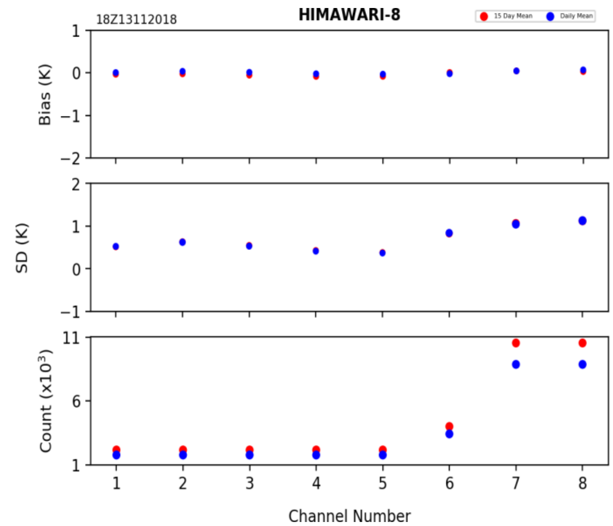
18 UTC 13-Nov-2018

National Centre for Medium Range Weather Forecasting (NCMRWF)
Ministry of Earth Sciences, Goverment of India
A-50, Sector-62, Noida (UP), India

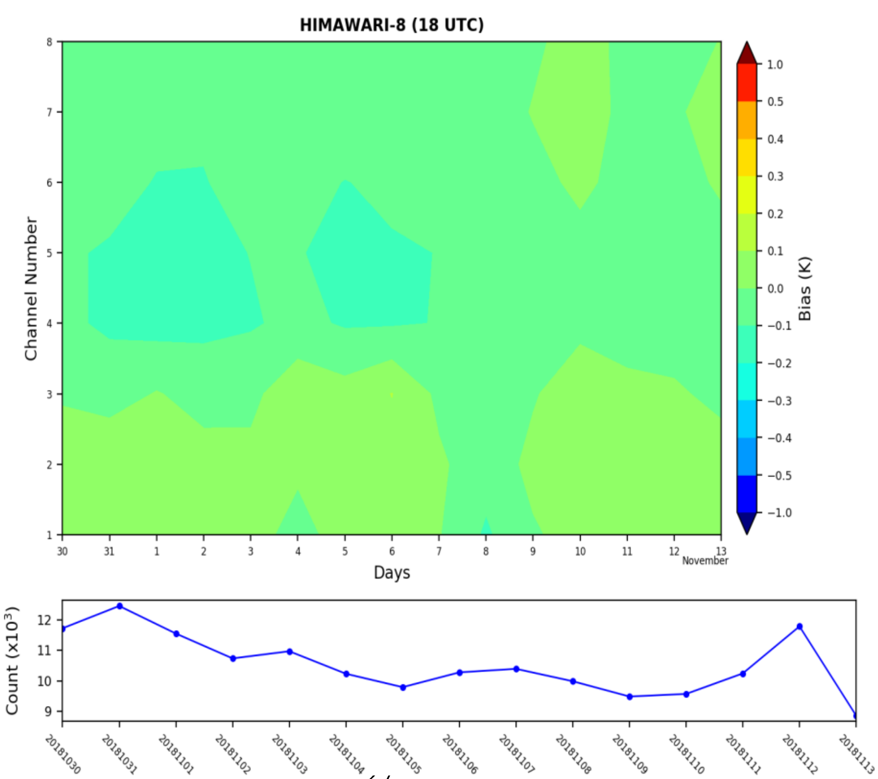
Satellite Radiances Used in NCUM Global DA Systems

Observation	Observation Description
AHIClear	Advanced Himawari Imager onborad HIMAWARI
AIRS	Atmospheric Infrared Sounder onboard AQUA
AMSR	Advanced Microwave Scanning Radiometer onboard GCOM-W1
ATMS	Advanced Technology Microwave Sounder onboard NPP
ATOVS	AMSU-A, AMSU-B/MHS, HIRS onboard NOAA and MetOp series
CrIS	Cross-track Infrared Sounder onboard NPP
GOESClear	Imager onboard GOES
GMIhigh & GMIlow	Microwave Imager onboard GPM
IASI	Infrared Atmospheric Sounding Interferometer onboard MetOp series
IN3DSndr	Sounder onborad INSAT-3D
IN3DImgr	IMAGER onborad INSAT-3D
MTSAPHIR	SAPHIR onboard Megha-Tropiques
MWSFY3C	Micro Wave Humidity Sounder onboard FY3C
SEVIRIClear	SEVIRI onboard METEOSAT
SSMIS	SSMIS onboard DMSP

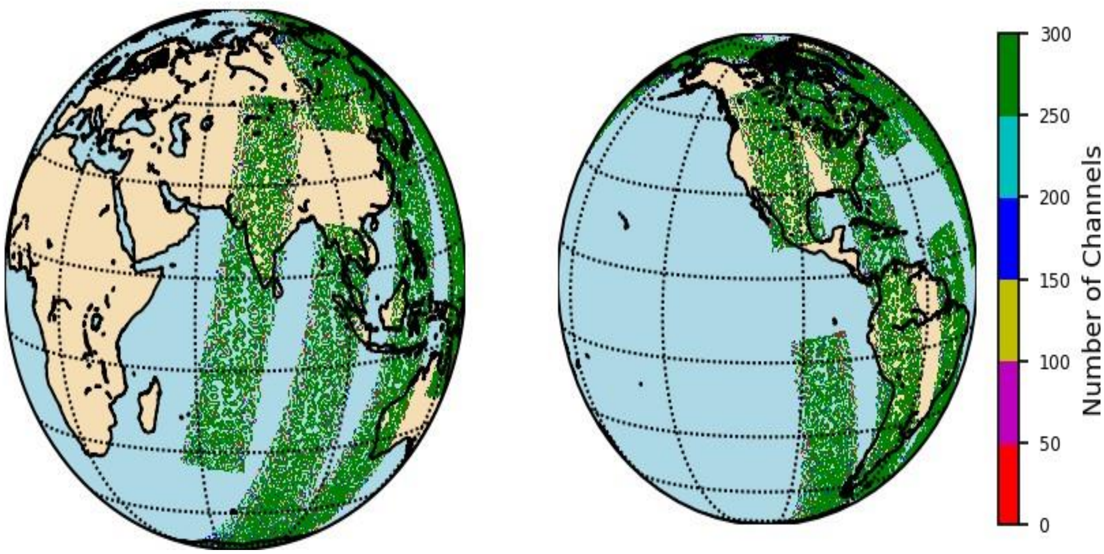


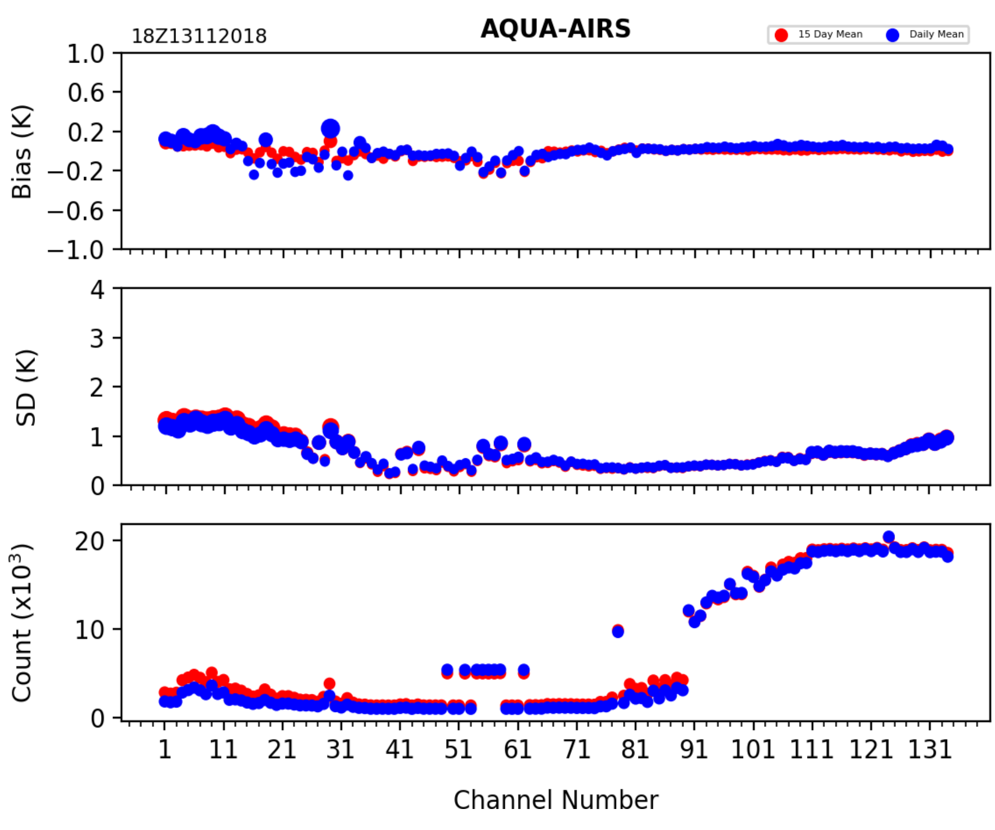


Channel No	1	2	3	4	5	6	7	8
Wavelength (μm)	13.30	12.35	11.20	10.45	8.60	7.35	6.95	6.25

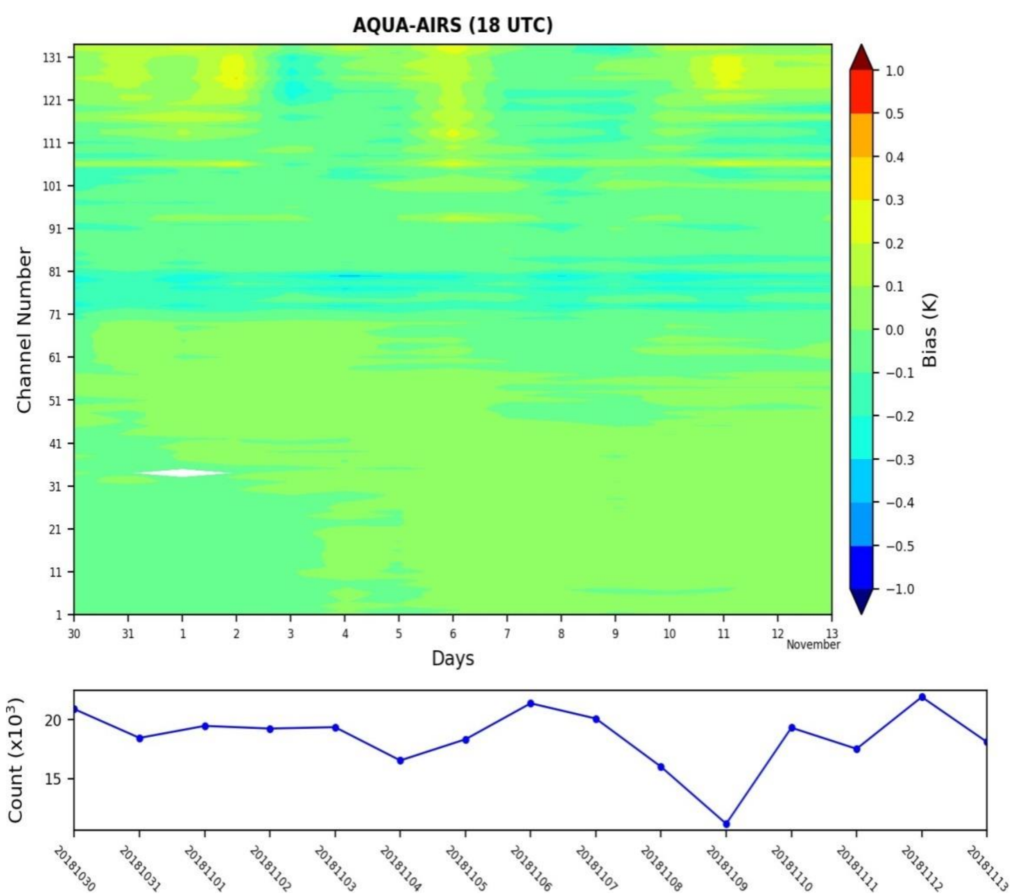


AQUA-AIRS Radiance Packed for NCUM : 18Z13112018

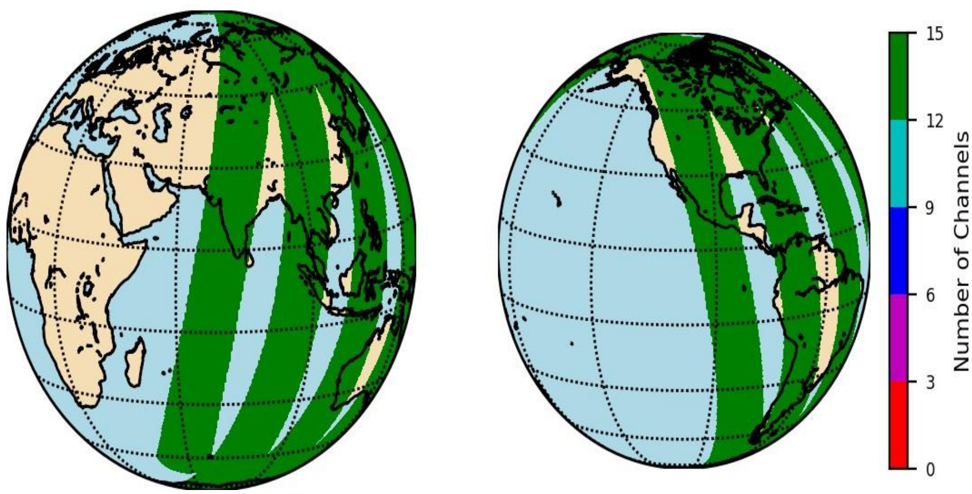


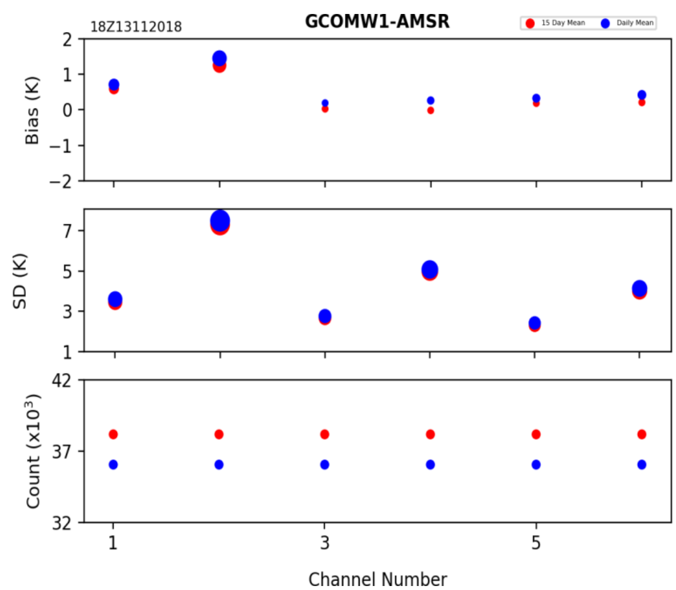


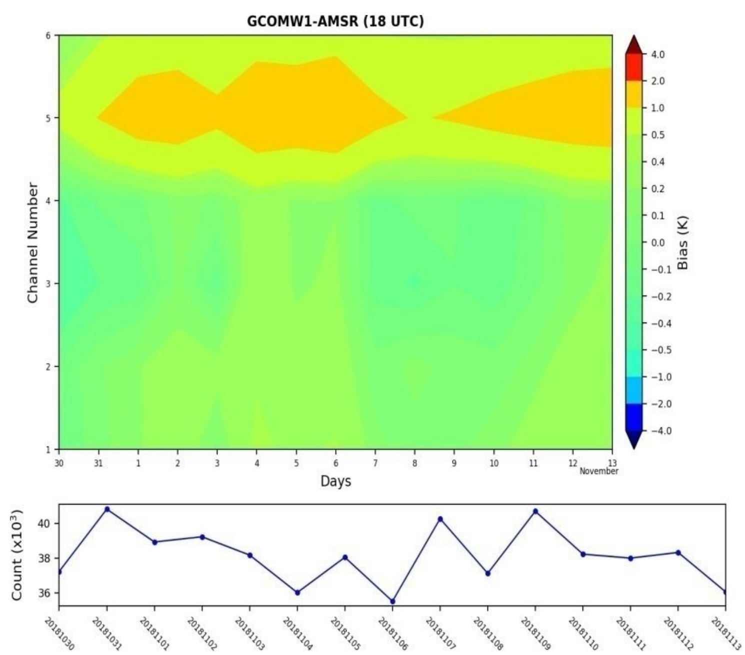
Channel No	1	2	3	4	5	6	7	8	9	10	11	12	13
Wavelength (µm)	6.230	6.256	6.304	6.361	6.378	6.395	6.443	6.460	6.583	6.606	6.654	6.737	6.808
Channel No	14	15	16	17	18	19	20	21	22	23	24	25	26
Wavelength (µm)	6.981	7.007	7.103	7.132	7.157	7.183	7.240	7.260	7.311	7.314	7.368	7.402	7.428
Channel No	27	28	29	30	31	32	33	34	35	36	37	38	39
Wavelength (µm)	7.433	7.450	7.464	7.493	7.513	7.598	7.629	7.742	7.779	7.991	8.077	8.087	8.125
Channel No	40	41	42	43	44	45	46	47	48	49	50	51	52
Wavelength (µm)	8.142	8.166	8.207	8.217	8.806	8.840	8.903	8.971	9.035	9.065	9.154	9.307	9.324
Channel No	53	54	55	56	57	58	59	60	61	62	63	64	65
Wavelength (µm)	10.213	10.358	10.546	10.884	10.901	11.477	11.850	12.183	12.358	12.483	13.239	13.376	13.405
Channel No	66	67	68	69	70	71	72	73	74	75	76	77	78
Wavelength (µm)	13.536	13.541	13.564	13.598	13.621	13.739	13.768	13.796	13.802	13.848	13.854	13.859	13.865
Channel No	79	80	81	82	83	84	85	86	87	88	89	90	91
Wavelength (µm)	13.928	14.013	14.047	14.059	14.065	14.076	14.093	14.110	14.127	14.144	14.162	14.190	14.196
Channel No	92	93	94	95	96	97	98	99	100	101	102	103	104
Wavelength (µm)	14.207	14.230	14.236	14.264	14.270	14.293	14.298	14.304	14.310	14.327	14.333	14.367	14.395
Channel No	105	106	107	108	109	110	111	112	113	114	115	116	117
Wavelength (µm)	14.401	14.429	14.464	14.469	14.498	14.503	14.669	14.674	14.703	14.737	14.743	14.771	14.777
Channel No	118	119	120	121	122	123	124	125	126	127	128	129	130
Wavelength (µm)	14.805	14.811	14.839	14.845	14.873	14.879	14.992	15.009	15.105	15.173	15.241	15.247	15.275
Channel No	131	132	133	134									
Wavelength (µm)	15.281	15.286	15.315	15.360									



AMSRE Radiance Packed for NCUM : 18Z13112018

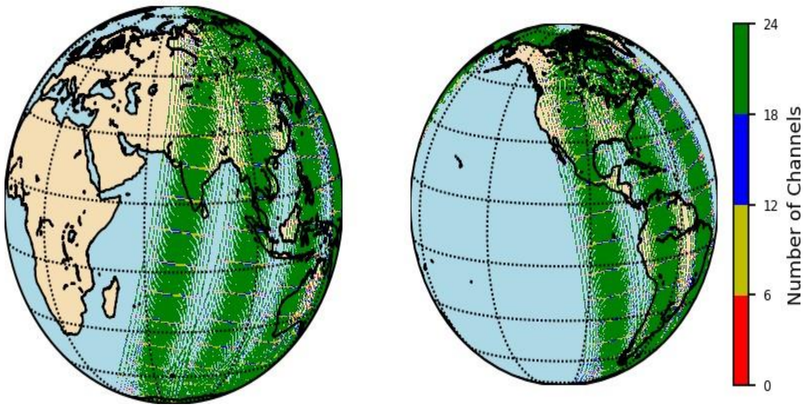


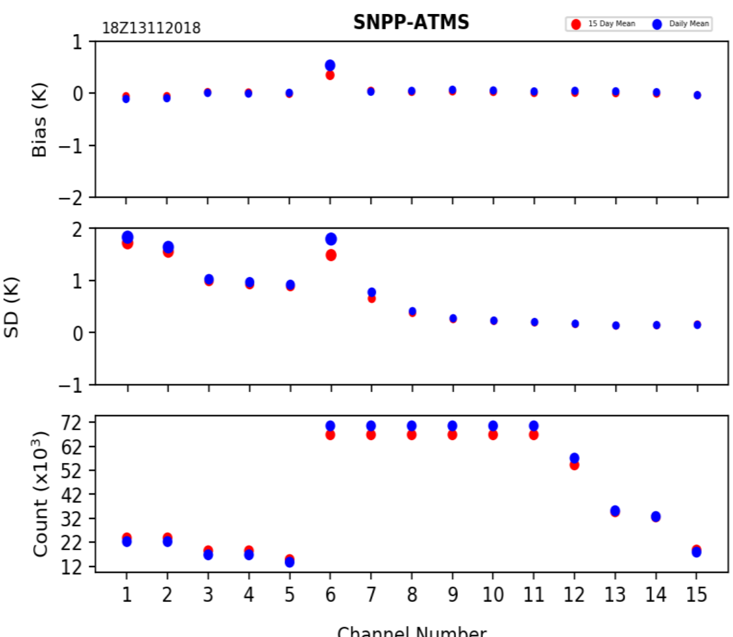


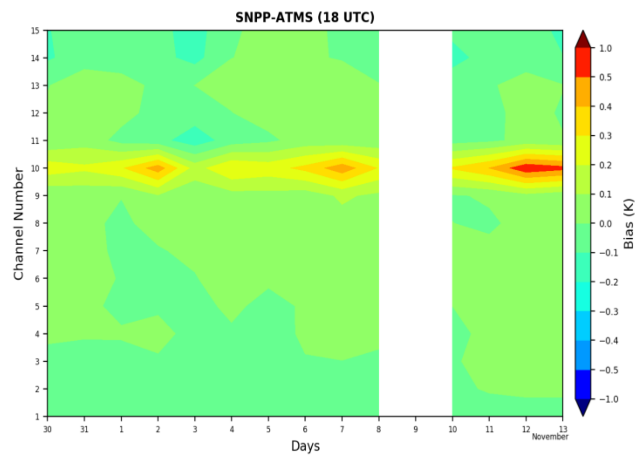


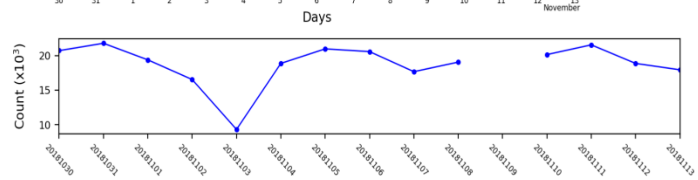
Channel No	1	2	3	4	5	6
Frequency (GHz)	36.5V	36.5H	23.8V	23.8H	18.7V	18.7H

ATMS Radiance Packed for NCUM : 18Z13112018



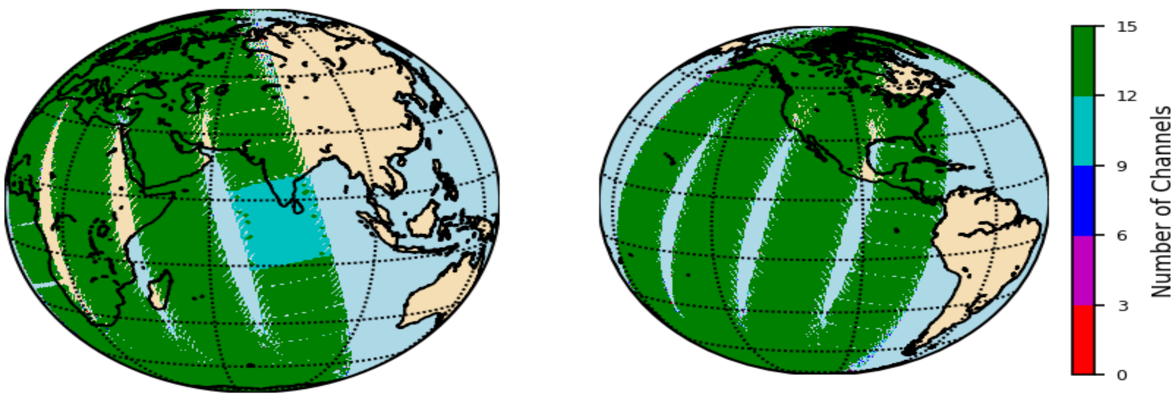




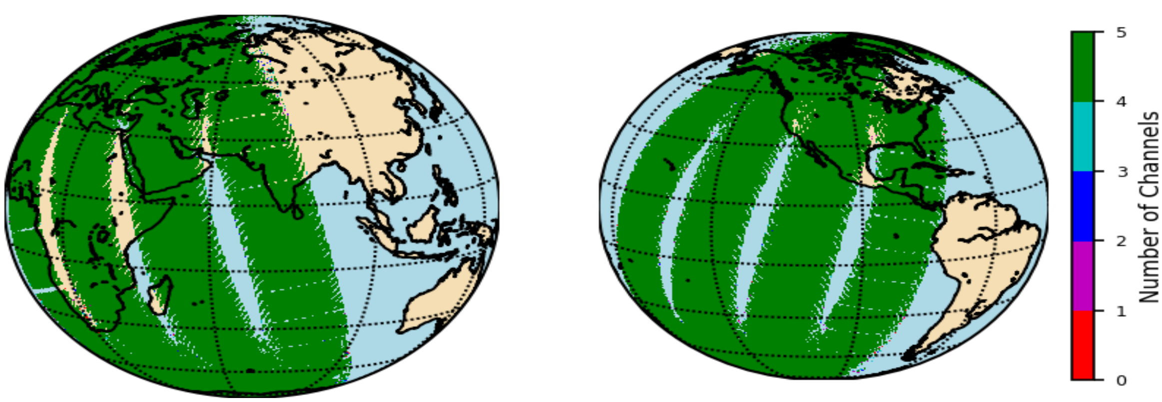


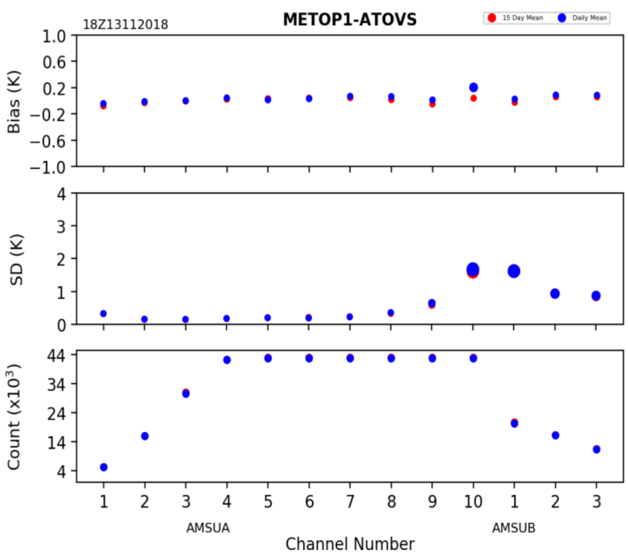
Channel No	1	2	3	4	5
Frequency (GHz)	183.31±1	183.31±1.8	183.31±3	183±4.5	183.31±7
Channel No	6	7	8	9	10
Frequency (GHz)	165.5	89.5	f0±0.322±0.0045	f0±0.322±0.01	f0±0.322±0.022
Channel No	11	12	13	14	15
Frequency (GHz)	f0±0.322±0.0048	f0±0.217	f0=57.29	55.5	54.94

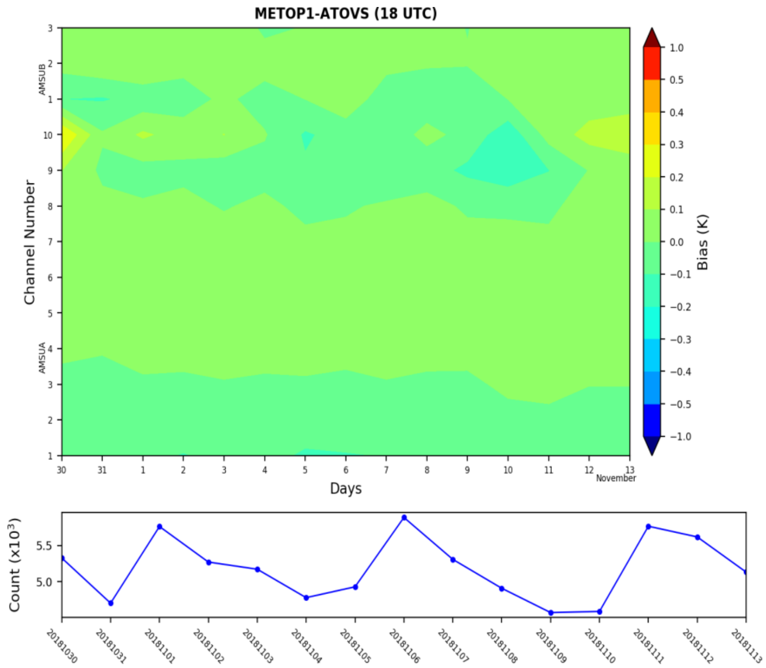
METOP_1-AMSU_A Radiance Packed for NCUM : 18Z13112018



METOP_1-MHS Radiance Packed for NCUM : 18Z13112018

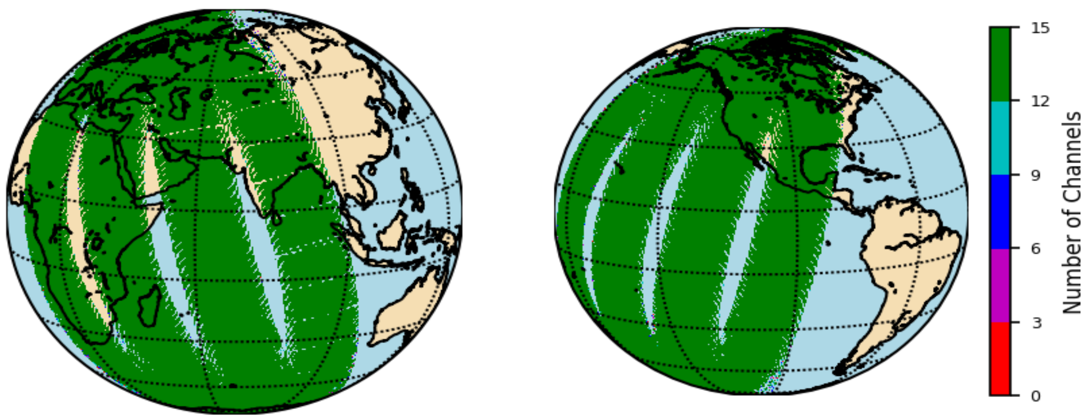




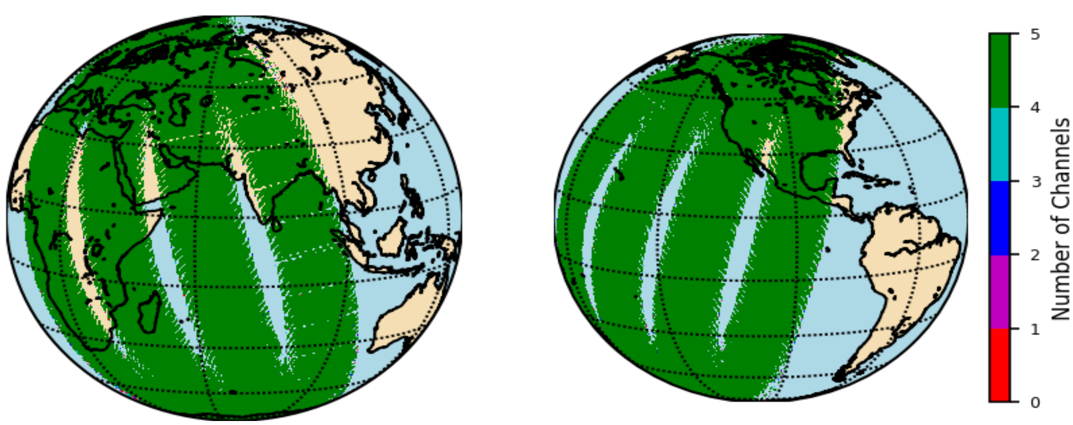


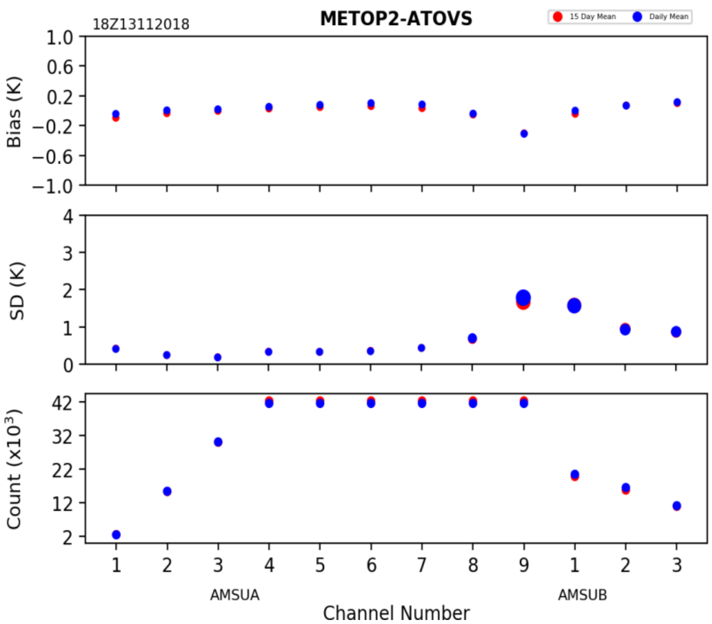
AMSU-A						
Channel No	1	2	3	4	5	6
Frequncy (GHz)	f0±0.322±0.0045	f0±0.322±0.010	f0±0.322±0.022	f0±0.322±0.048	f0±0.217	f0=57.2903
Channel No	7	8	9	10	11	
Frequncy (GHz)	55.500	54.94	54.400	53.596±0.115	52.800	
AMSU-B						
Channel No	1	2	3			
Frequncy (GHz)	183.21±1.0	183.31±3.0	183.31±7.0			

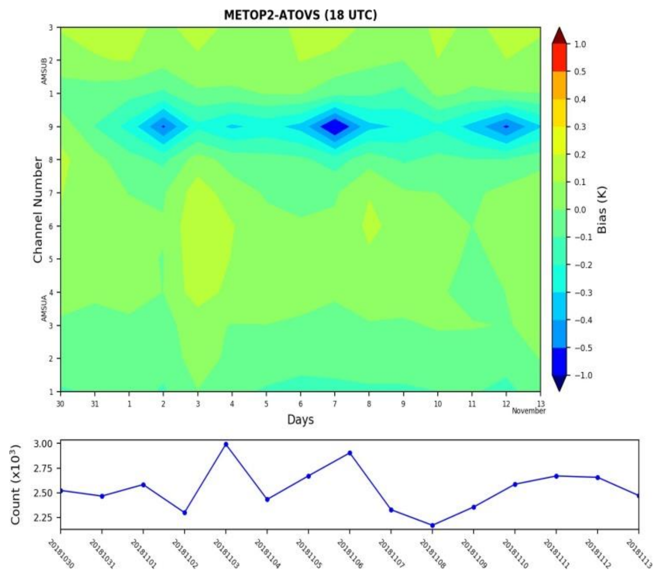
METOP_2-AMSU_A Radiance Packed for NCUM : 18Z13112018



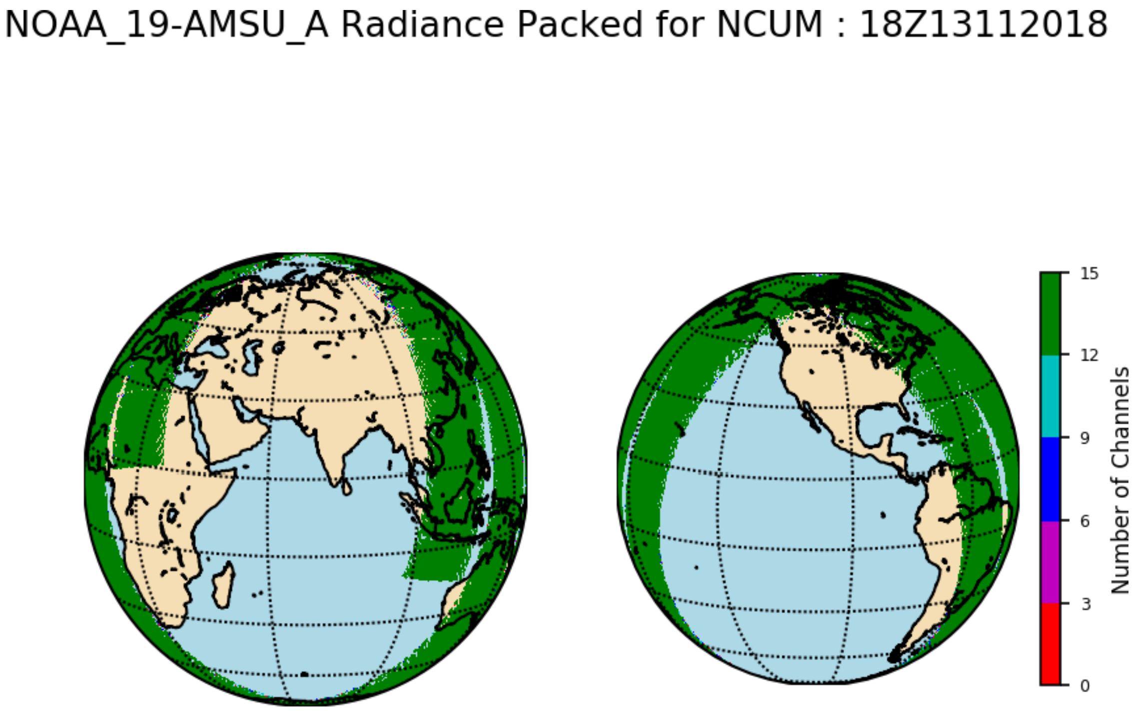
METOP_2-MHS Radiance Packed for NCUM : 18Z13112018

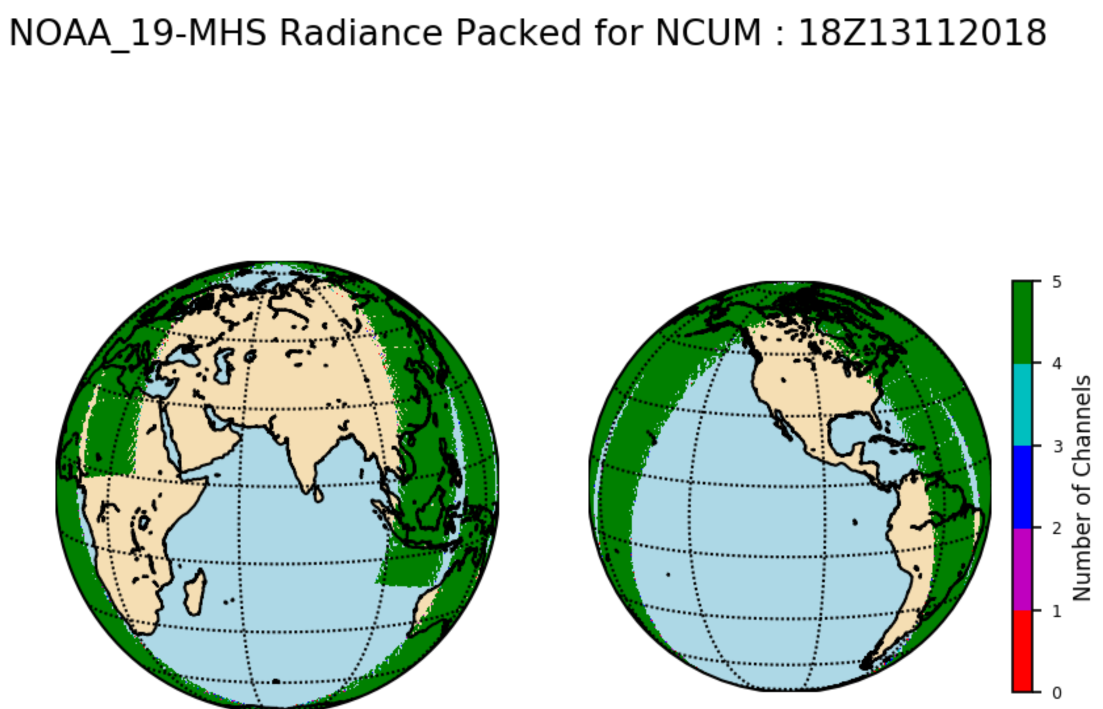


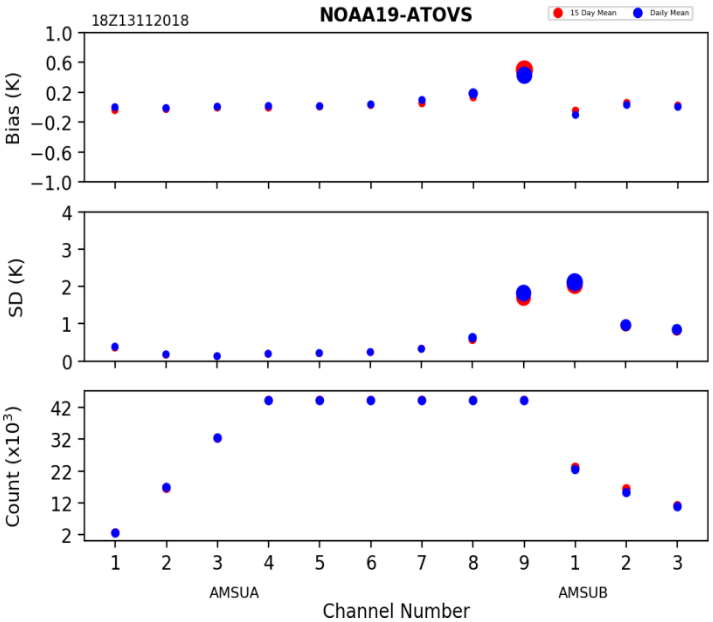


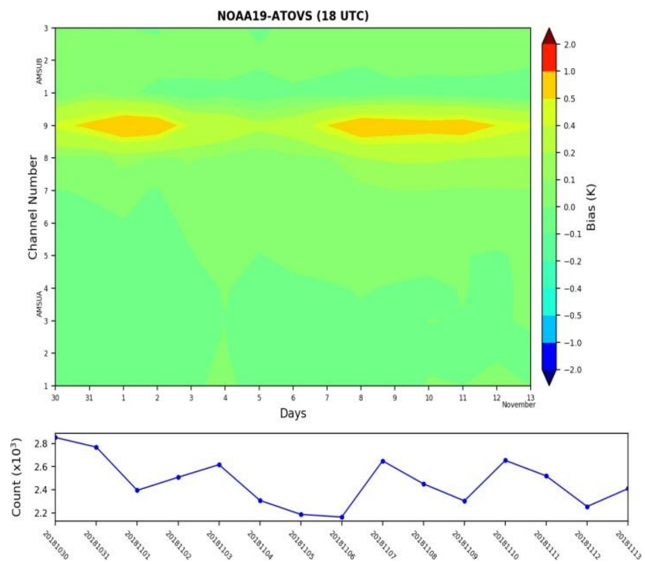


AMSU-A						
Channel No	1	2	3	4	5	6
Frequncy (GHz)	f0±0.322±0.0045	f0±0.322±0.010	f0±0.322±0.022	f0±0.322±0.048	f0±0.217	f0=57.2903
Channel No	7	8	9			
Frequncy (GHz)	54.400	53.596±0.115	52.800			
AMSU-B						
Channel No	1	2	3			
Frequncy (GHz)	183.31±1.0	183.31±3.0	183.31±7.0			


NOAA_19-AMSU_A Radiance Packed for NCUM : 18Z13112018
15
12
9
6
3
0
Number of Channels

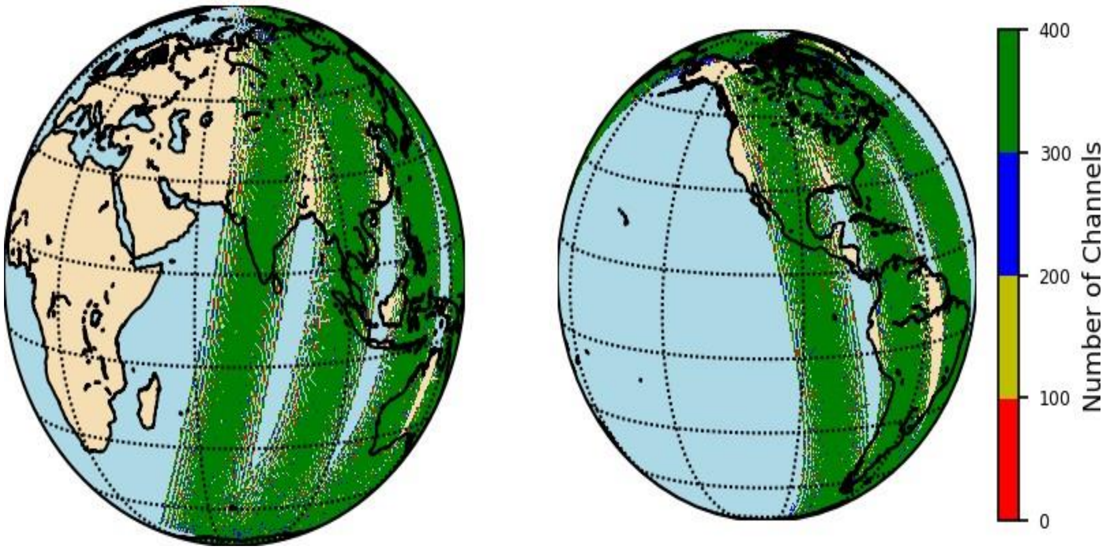

NOAA_19-MHS Radiance Packed for NCUM : 18Z13112018
5
4
3
2
1
0
Number of Channels

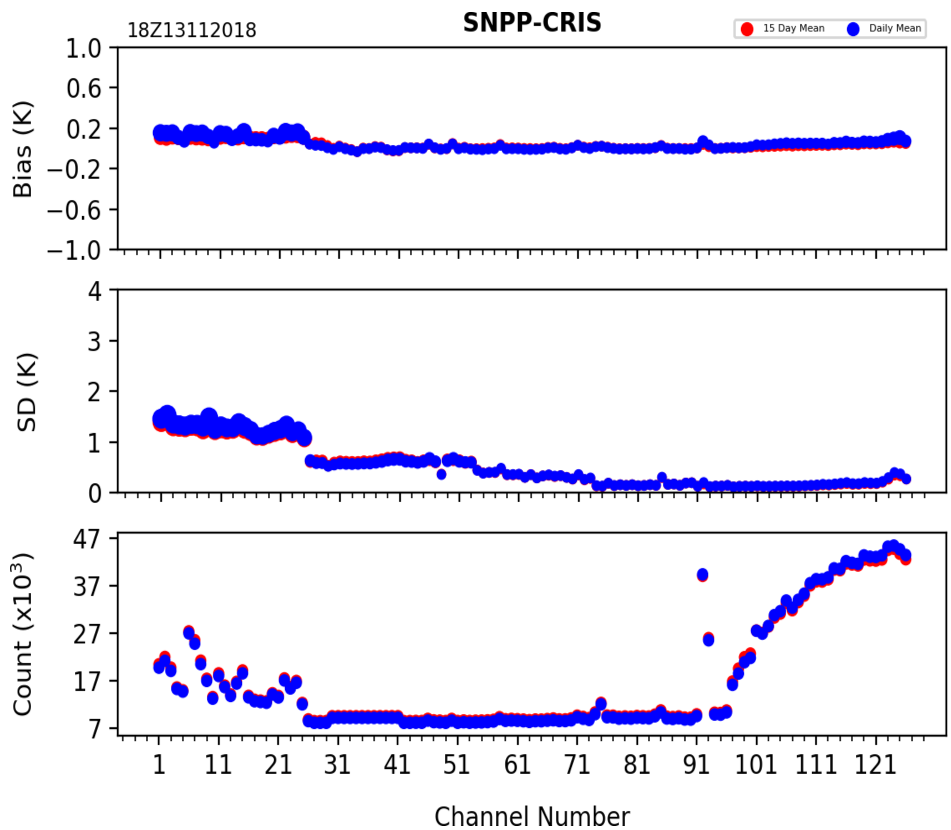




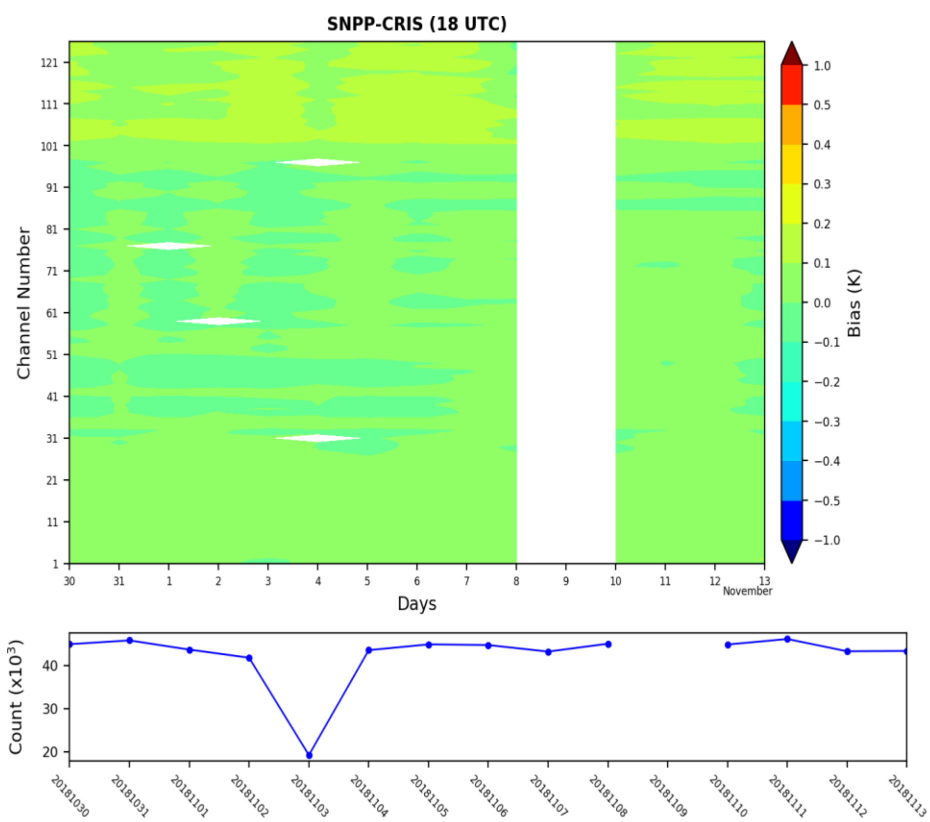
AMSU-A						
Channel No	1	2	3	4	5	6
Frequncy (GHz)	f0±0.322±0.0045	f0±0.322±0.010	f0±0.322±0.022	f0±0.322±0.048	f0±0.217	f0=57.2903
Channel No	7	8	9			
Frequncy (GHz)	54.400	53.596±0.115	52.800			
AMSU-B						
Channel No	1	2	3			
Frequncy (GHz)	190.311	183.31±1.0	183.31±3.0			

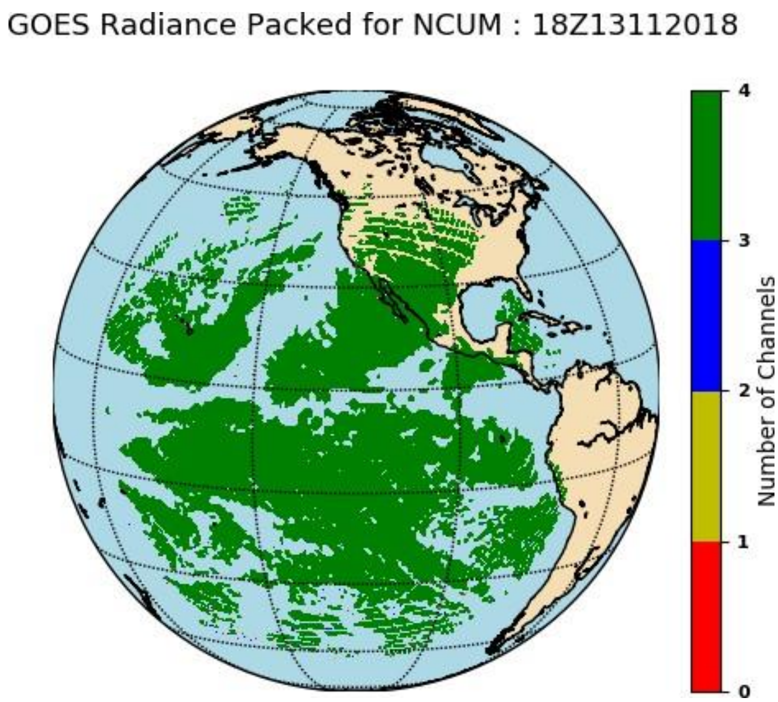
CrIS Radiance Packed for NCUM : 18Z13112018

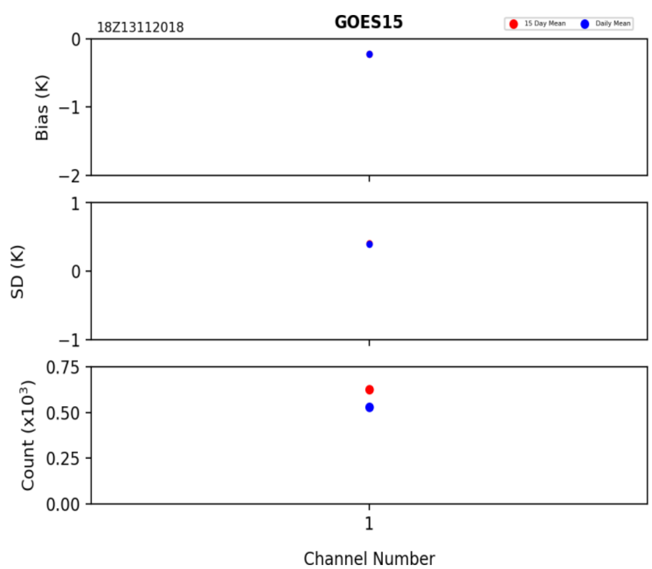


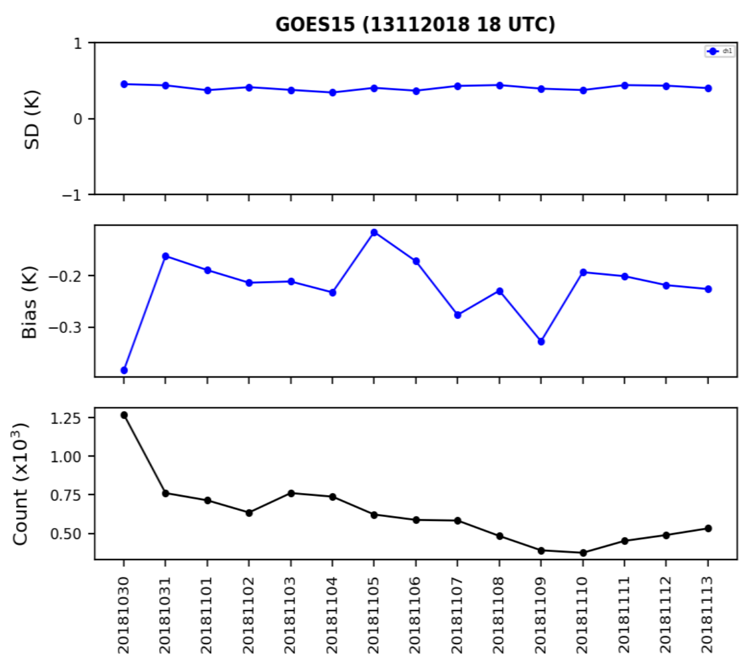


Channel No	1	2	3	4	5	6	7	8	9	10	11	12	13
Wavelength (µm)	5.731	5.760	5.780	6.231	6.304	6.426	6.672	6.774	6.809	6.932	6.993	6.999	7.011
Channel No	14	15	16	17	18	19	20	21	22	23	24	25	26
Wavelength (µm)	7.030	7.055	7.067	7.080	7.092	7.105	7.124	7.136	7.156	7.175	7.207	7.220	8.247
Channel No	27	28	29	30	31	32	33	34	35	36	37	38	39
Wavelength (µm)	9.132	9.148	9.164	10.204	10.390	10.506	10.519	10.582	10.645	10.767	10.914	11.088	11.852
Channel No	40	41	42	43	44	45	46	47	48	49	50	51	52
Wavelength (µm)	12.103	12.140	12.242	12.261	12.432	12.490	12.529	12.549	12.628	12.668	12.749	12.800	12.831
Channel No	53	54	55	56	57	58	59	60	61	62	63	64	65
Wavelength (µm)	12.935	13.180	13.201	13.223	13.234	13.256	13.278	13.289	13.300	13.311	13.322	13.333	13.344
Channel No	66	67	68	69	70	71	72	73	74	75	76	77	78
Wavelength (µm)	13.356	13.367	13.378	13.400	13.412	13.423	13.445	13.457	13.479	13.491	13.514	13.525	13.536
Channel No	79	80	81	82	83	84	85	86	87	88	89	90	91
Wavelength (µm)	13.548	13.594	13.605	13.617	13.652	13.664	13.687	13.734	13.746	13.758	13.769	13.805	13.853
Channel No	92	93	94	95	96	97	98	99	100	101	102	103	104
Wavelength (µm)	13.889	13.913	13.962	13.974	13.998	14.060	14.097	14.109	14.134	14.184	14.197	14.210	14.235
Channel No	105	106	107	108	109	110	111	112	113	114	115	116	117
Wavelength (µm)	14.260	14.286	14.298	14.311	14.363	14.388	14.414	14.440	14.467	14.493	14.506	14.519	14.545
Channel No	118	119	120	121	122	123	124	125	126				
Wavelength (µm)	14.572	14.652	14.679	14.706	14.870	14.925	14.939	14.995	15.009				



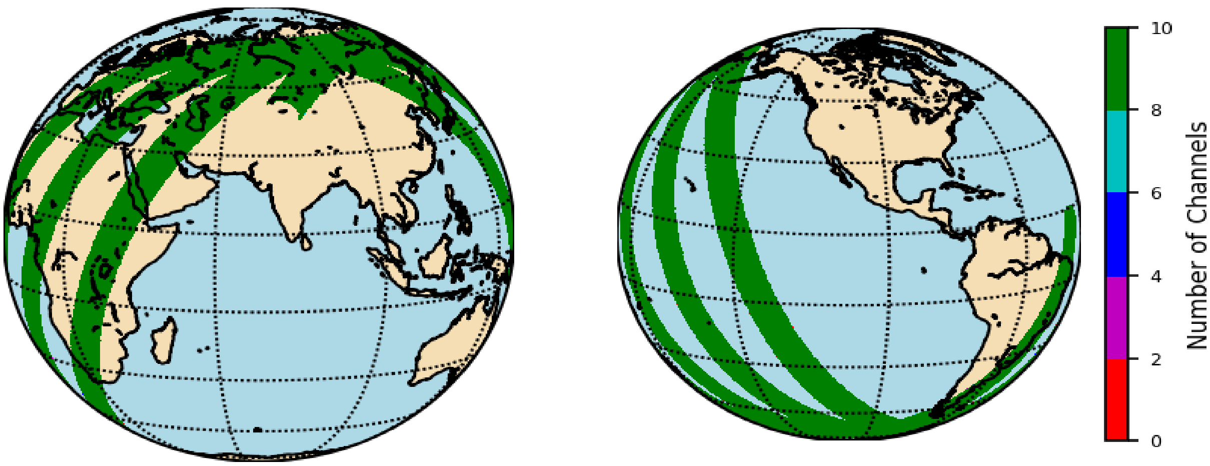




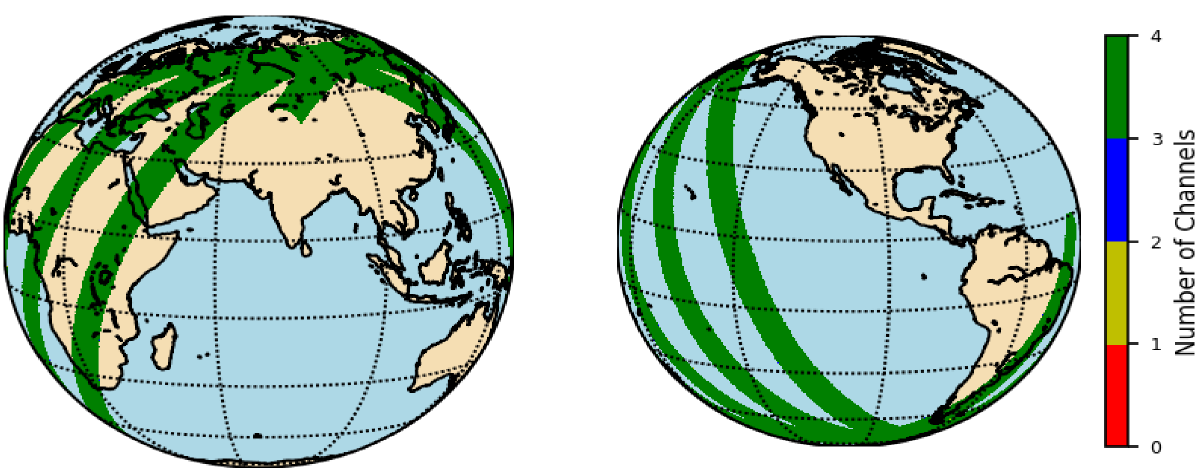


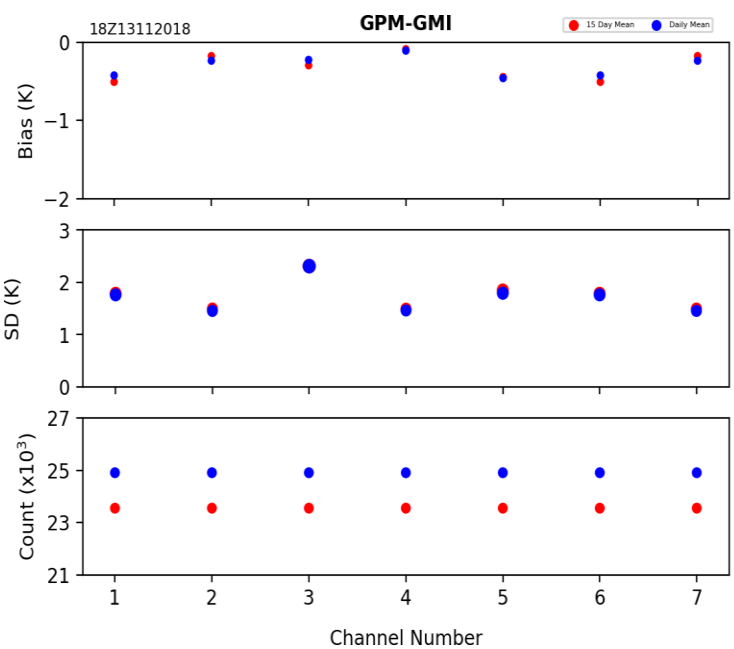
Channel No	1
Wavelength (μm)	6.55

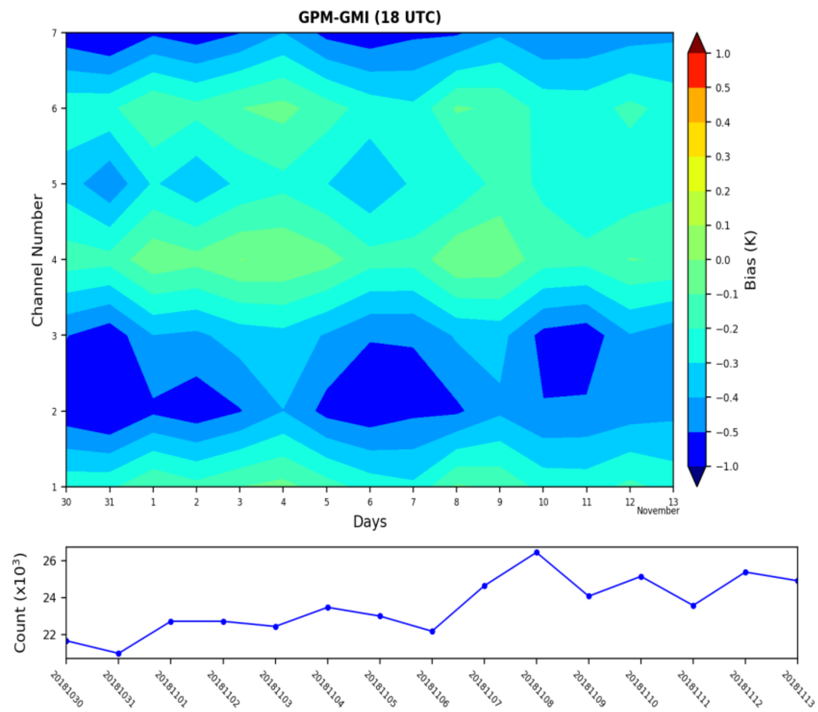
GMIlow Radiance Packed for NCUM : 18Z13112018



GMIhigh Radiance Packed for NCUM : 18Z13112018

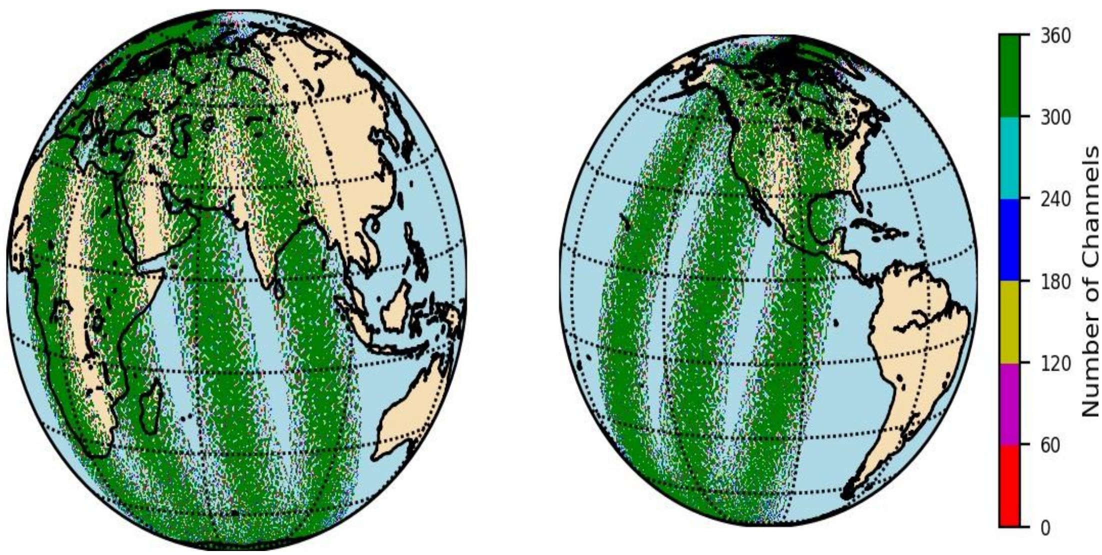


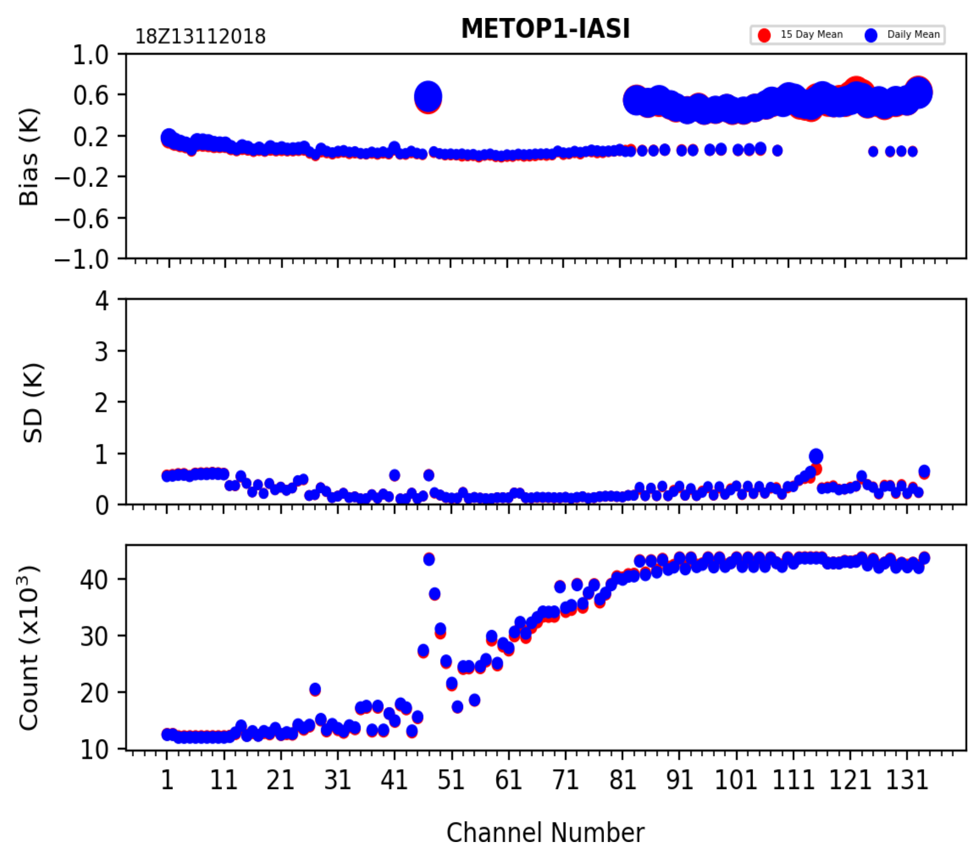




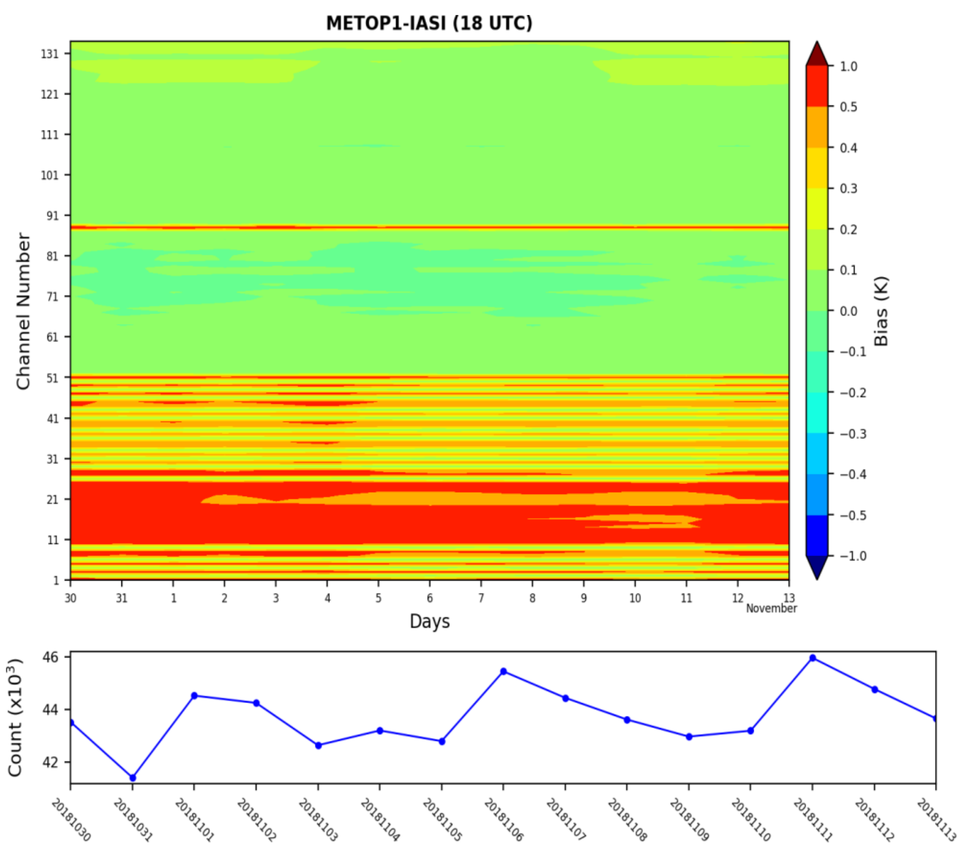
Channel No	1	2	3	4	5	6	7
Frequency (GHz)	18.7V	18.7H	23.8V	36.5V	36.5H	183.31±7	183.31±3

IASI_metop_1 Radiance Packed for NCUM : 18Z13112018

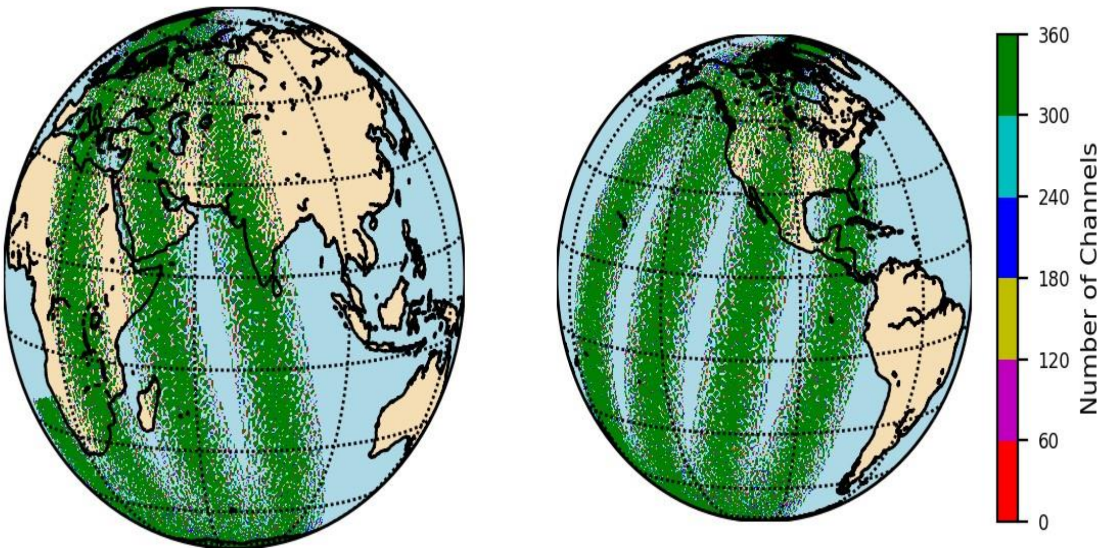


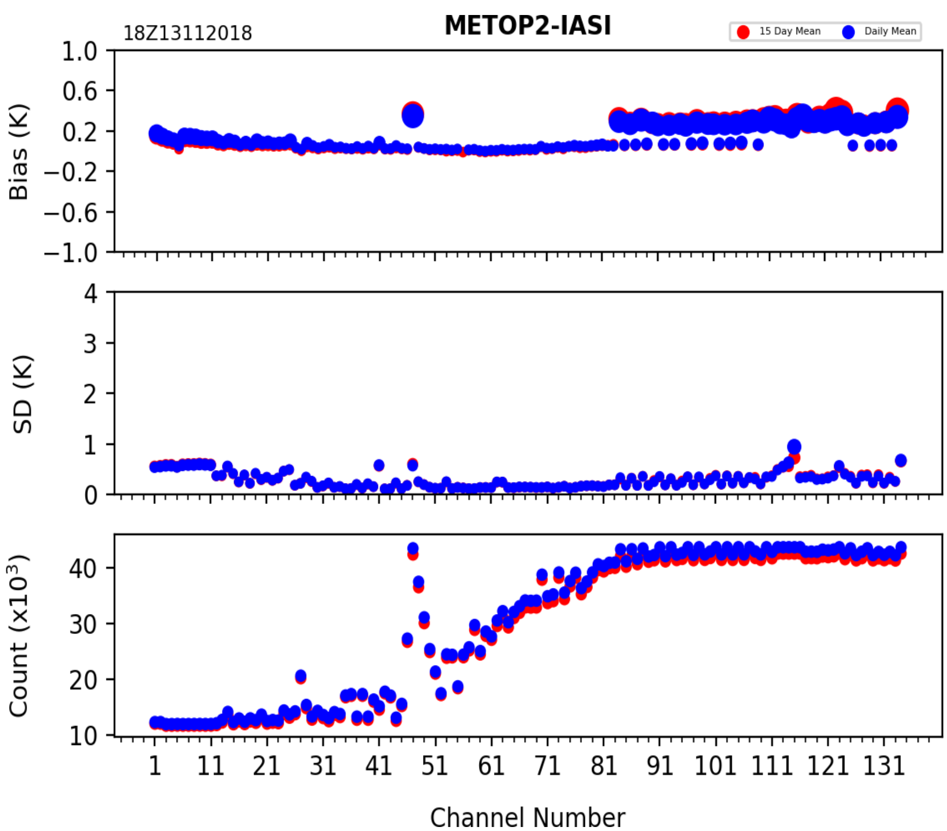


Channel No	1	2	3	4	5	6	7	8	9	10	11	12	13
Wavelength (μm)	5.010	5.011	5.013	5.014	5.015	5.024	5.025	5.026	5.031	5.033	5.189	7.088	7.096
Channel No	14	15	16	17	18	19	20	21	22	23	24	25	26
Wavelength (μm)	7.102	7.133	7.135	7.185	7.224	7.233	7.237	7.242	7.291	7.315	8.292	8.302	8.560
Channel No	27	28	29	30	31	32	33	34	35	36	37	38	39
Wavelength (μm)	8.752	8.963	9.124	10.390	10.602	10.776	11.093	11.429	11.608	11.994	12.319	12.342	12.690
Channel No	40	41	42	43	44	45	46	47	48	49	50	51	52
Wavelength (μm)	12.698	12.719	12.775	12.800	12.928	13.175	13.228	13.253	13.275	13.285	13.302	13.311	13.356
Channel No	53	54	55	56	57	58	59	60	61	62	63	64	65
Wavelength (μm)	13.365	13.382	13.396	13.409	13.423	13.436	13.477	13.491	13.504	13.513	13.523	13.532	13.541
Channel No	66	67	68	69	70	71	72	73	74	75	76	77	78
Wavelength (μm)	13.550	13.559	13.582	13.610	13.629	13.638	13.657	13.671	13.680	13.727	13.755	13.765	13.784
Channel No	79	80	81	82	83	84	85	86	87	88	89	90	91
Wavelength (μm)	13.865	13.899	13.913	13.923	13.981	13.990	14.015	14.055	14.065	14.080	14.090	14.119	14.129
Channel No	92	93	94	95	96	97	98	99	100	101	102	103	104
Wavelength (μm)	14.144	14.159	14.174	14.179	14.194	14.210	14.230	14.240	14.260	14.270	14.281	14.296	14.306
Channel No	105	106	107	108	109	110	111	112	113	114	115	116	117
Wavelength (μm)	14.322	14.332	14.342	14.358	14.368	14.399	14.430	14.461	14.471	14.498	14.503	14.535	14.567
Channel No	118	119	120	121	122	123	124	125	126	127	128	129	130
Wavelength (μm)	14.599	14.636	14.668	14.706	14.738	14.777	14.809	14.842	14.881	15.140	15.175	15.209	15.285

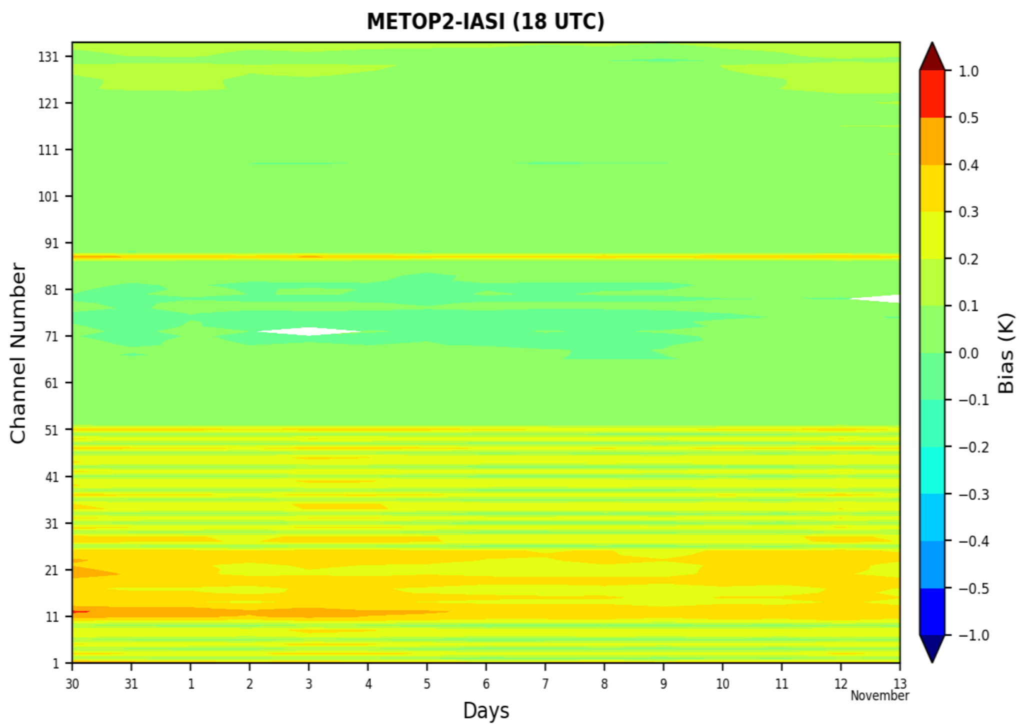


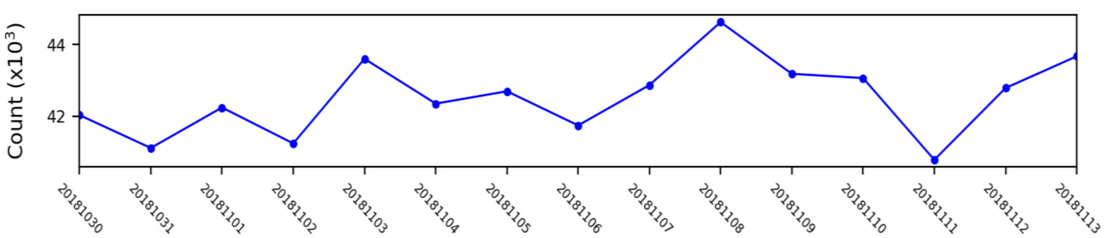
IASI_metop_2 Radiance Packed for NCUM : 18Z13112018

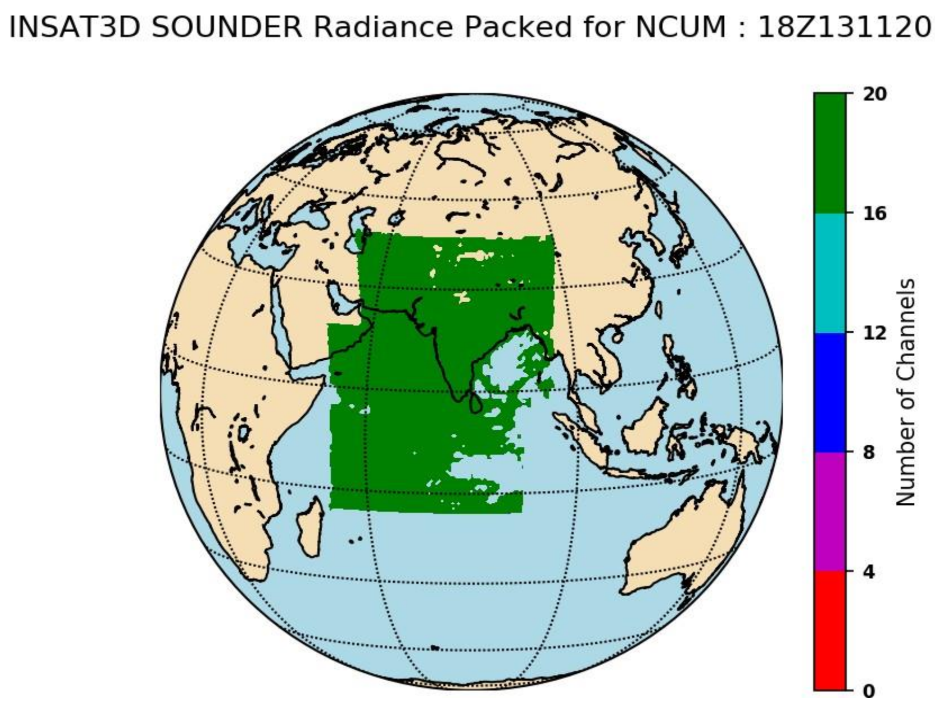


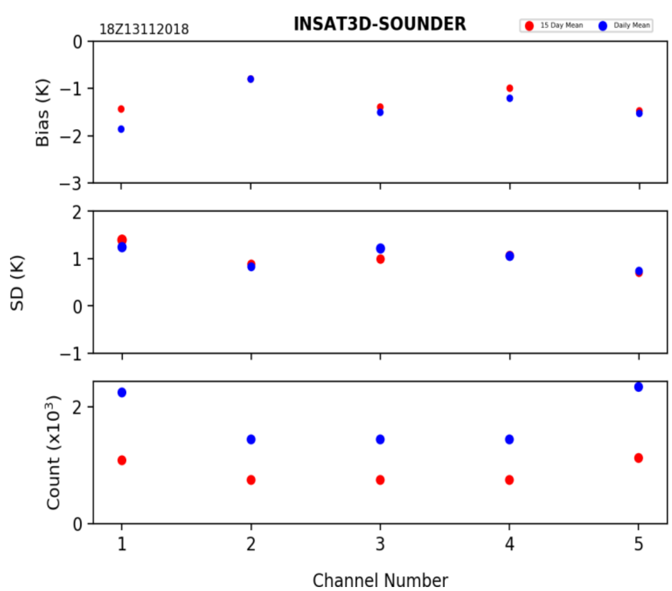


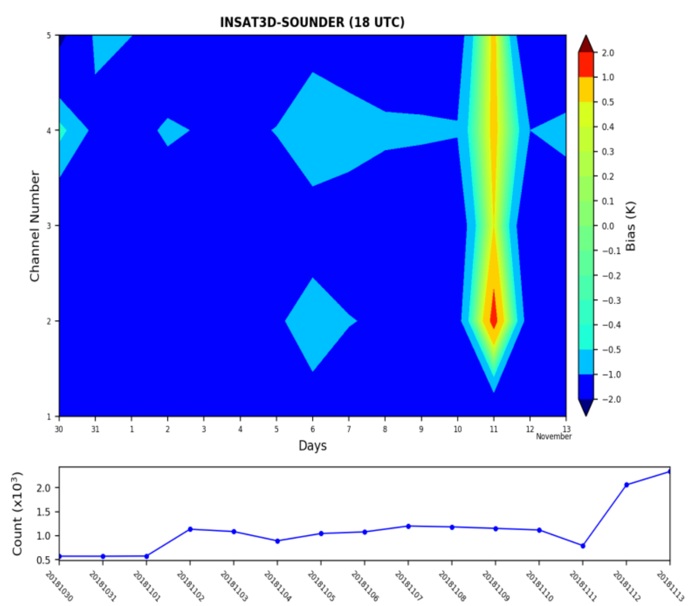
Channel No	1	2	3	4	5	6	7	8	9	10	11	12	13
Wavelength (µm)	5.010	5.011	5.013	5.014	5.015	5.024	5.025	5.026	5.031	5.033	5.189	7.088	7.096
Channel No	14	15	16	17	18	19	20	21	22	23	24	25	26
Wavelength (µm)	7.102	7.133	7.135	7.185	7.224	7.233	7.237	7.242	7.291	7.315	8.292	8.302	8.560
Channel No	27	28	29	30	31	32	33	34	35	36	37	38	39
Wavelength (µm)	8.752	8.963	9.124	10.390	10.602	10.776	11.093	11.429	11.608	11.994	12.319	12.342	12.690
Channel No	40	41	42	43	44	45	46	47	48	49	50	51	52
Wavelength (µm)	12.698	12.719	12.775	12.800	12.928	13.175	13.228	13.253	13.275	13.285	13.302	13.311	13.356
Channel No	53	54	55	56	57	58	59	60	61	62	63	64	65
Wavelength (µm)	13.365	13.382	13.396	13.409	13.423	13.436	13.477	13.491	13.504	13.513	13.523	13.532	13.541
Channel No	66	67	68	69	70	71	72	73	74	75	76	77	78
Wavelength (µm)	13.550	13.559	13.582	13.610	13.629	13.638	13.657	13.671	13.680	13.727	13.755	13.765	13.784
Channel No	79	80	81	82	83	84	85	86	87	88	89	90	91
Wavelength (µm)	13.865	13.899	13.913	13.923	13.981	13.990	14.015	14.055	14.065	14.080	14.090	14.119	14.129
Channel No	92	93	94	95	96	97	98	99	100	101	102	103	104
Wavelength (µm)	14.144	14.159	14.174	14.179	14.194	14.210	14.230	14.240	14.260	14.270	14.281	14.296	14.306
Channel No	105	106	107	108	109	110	111	112	113	114	115	116	117
Wavelength (µm)	14.322	14.332	14.342	14.358	14.368	14.399	14.430	14.461	14.471	14.498	14.503	14.535	14.567
Channel No	118	119	120	121	122	123	124	125	126	127	128	129	130
Wavelength (µm)	14.599	14.636	14.668	14.706	14.738	14.777	14.809	14.842	14.881	15.140	15.175	15.209	15.285



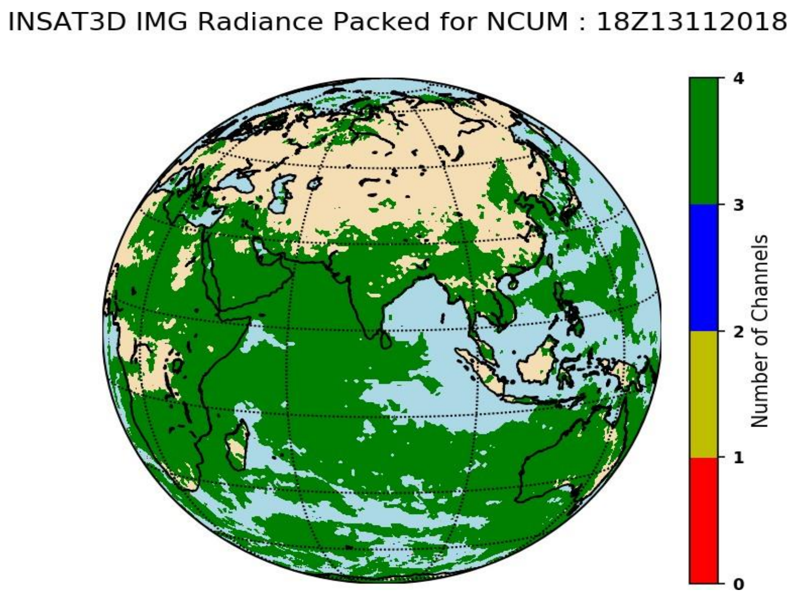


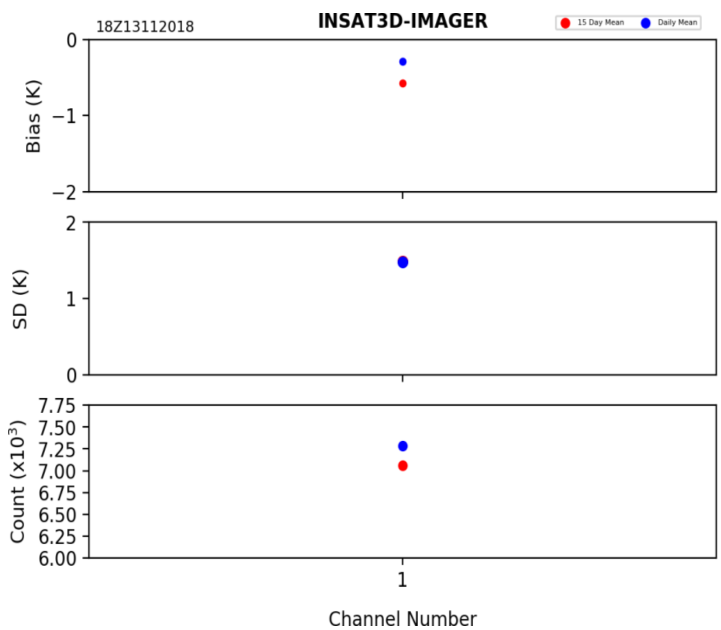


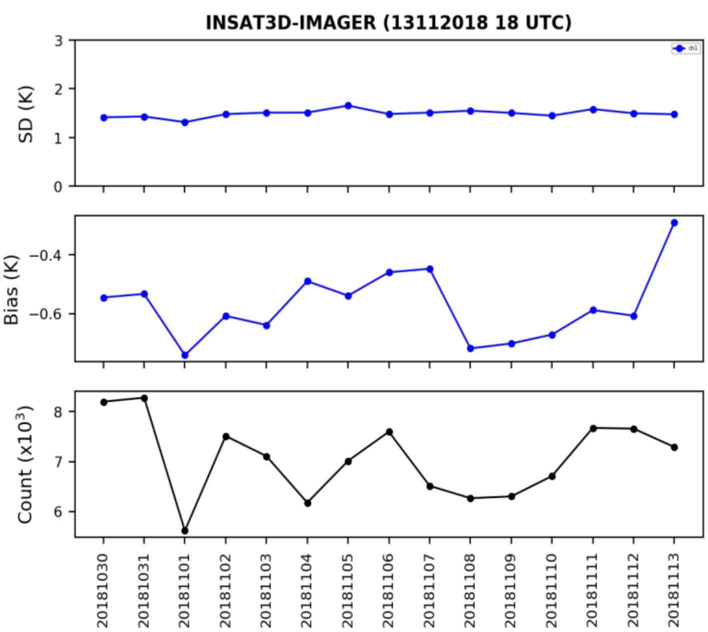




Channel No	1	2	3	4	5
Wavelength (μm)	7.43	11.03	12.02	12.66	14.08

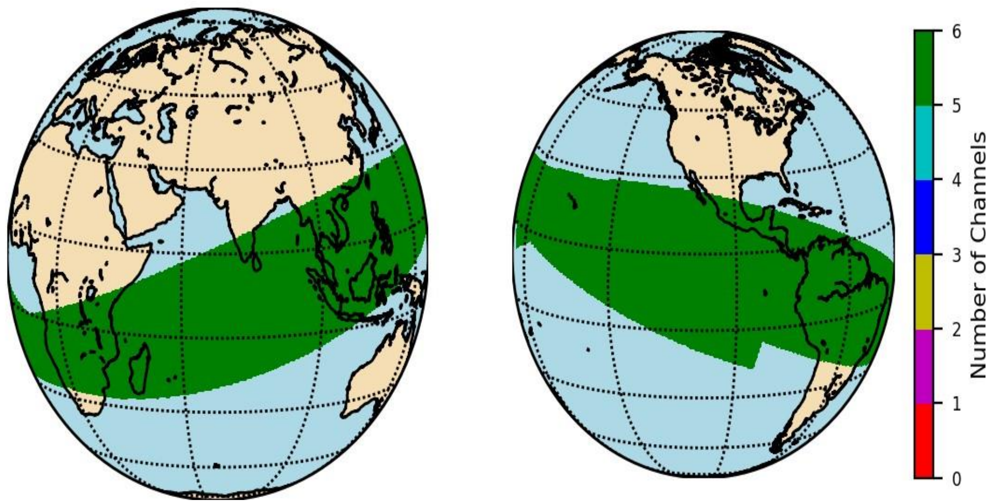


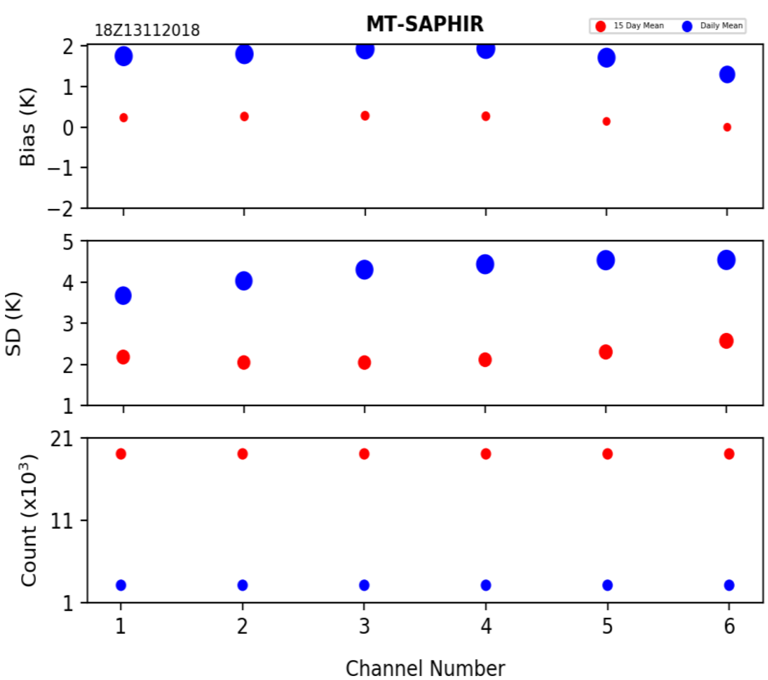


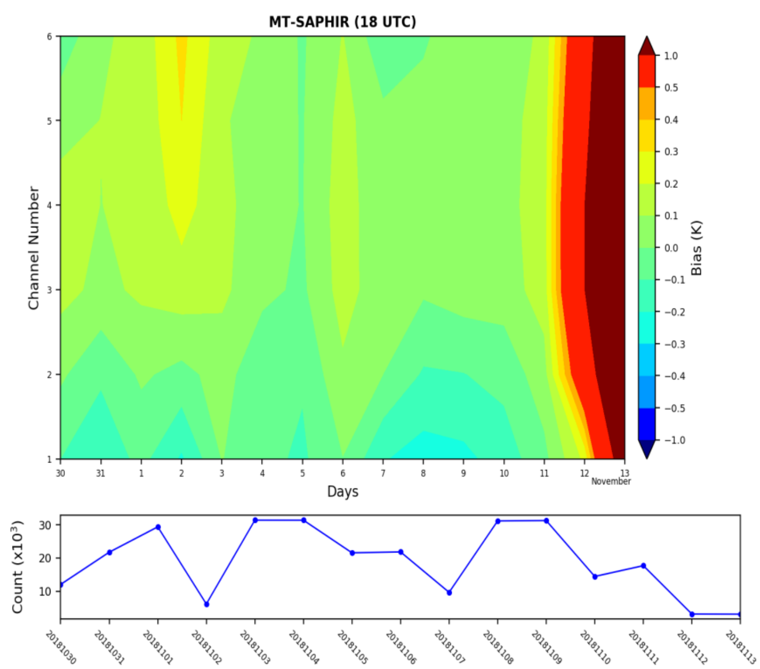


Channel No	1
Wavelength (μm)	6.55

MT-SAPHIR Radiance Packed for NCUM : 18Z13112018

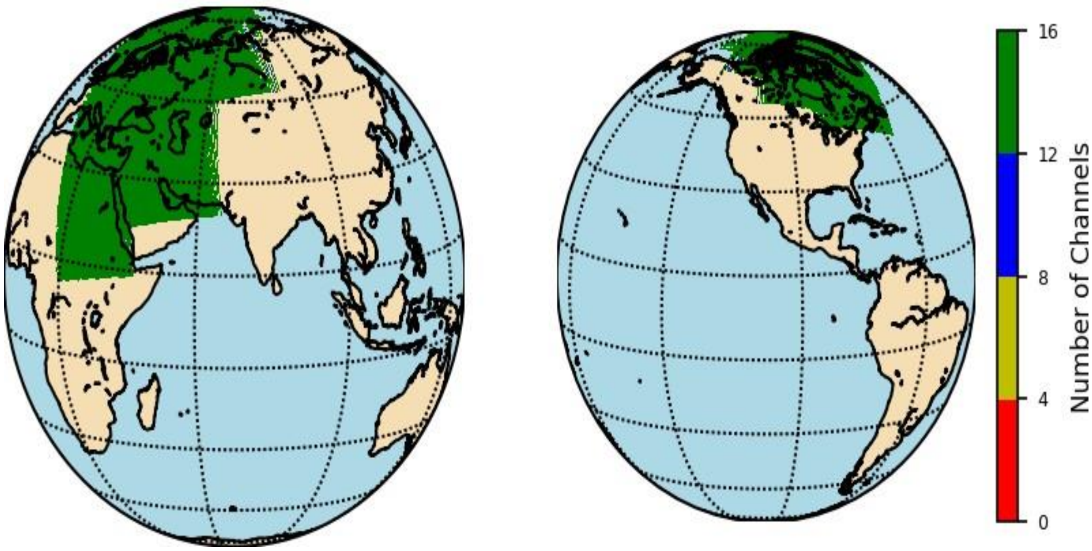


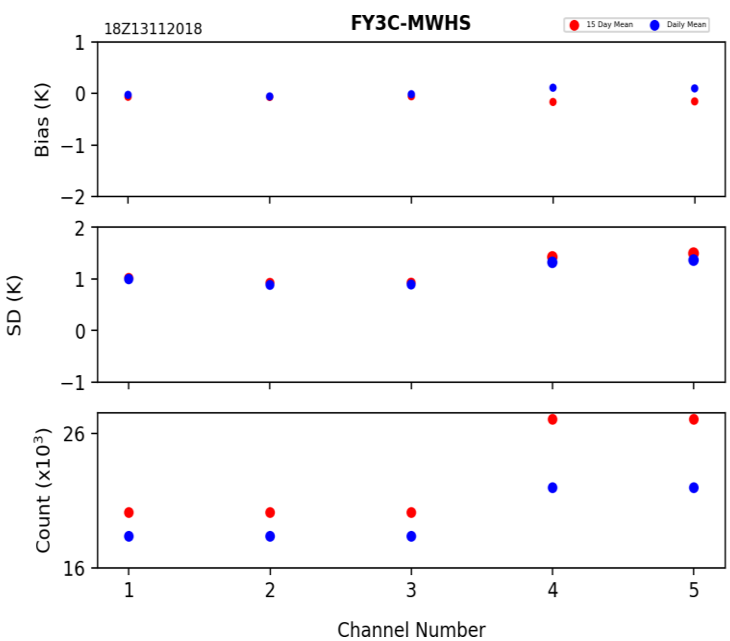


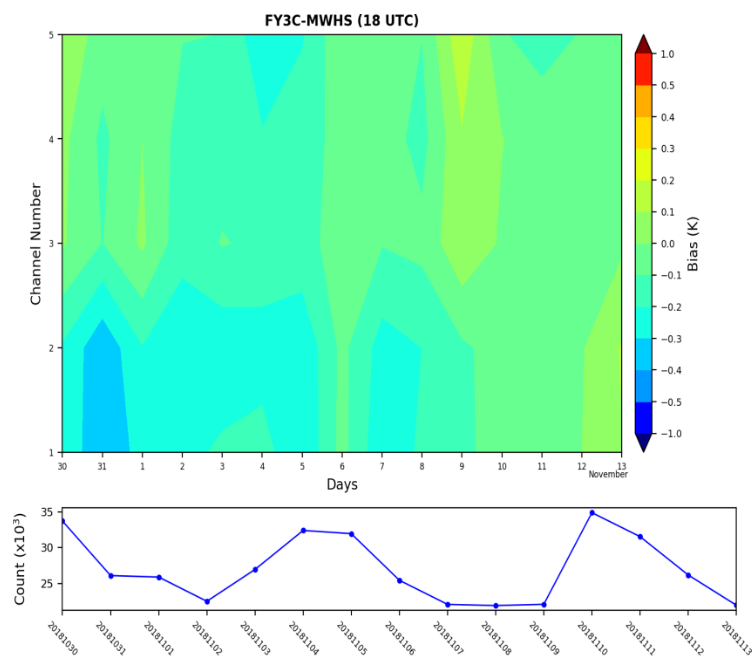


Channel No	1	2	3	4	5	6
Frequency (GHz)	183.31±11	183.31±6.8	183.31±4.2	183.31±2.8	183.31±1.1	183.31±0.2

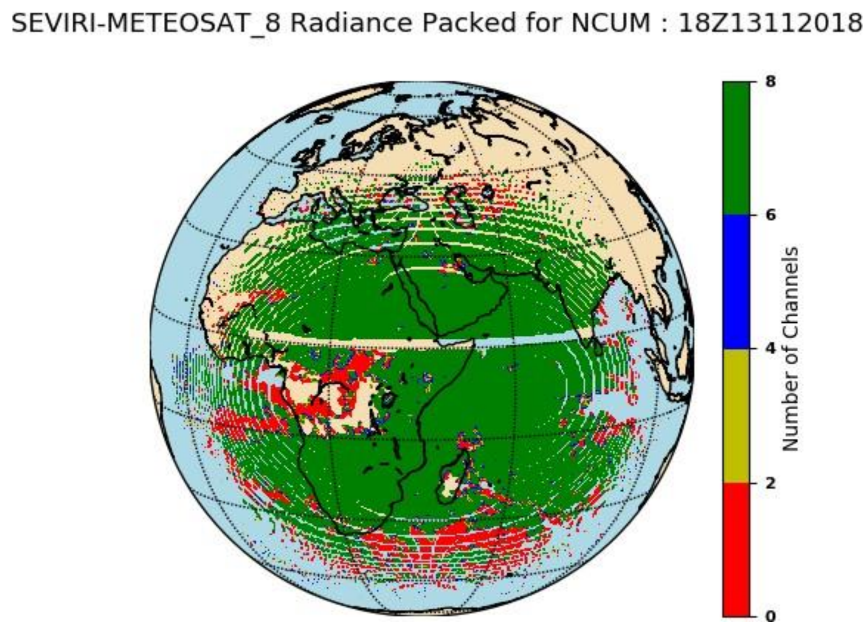
FY3C Radiance Packed for NCUM :18Z13112018

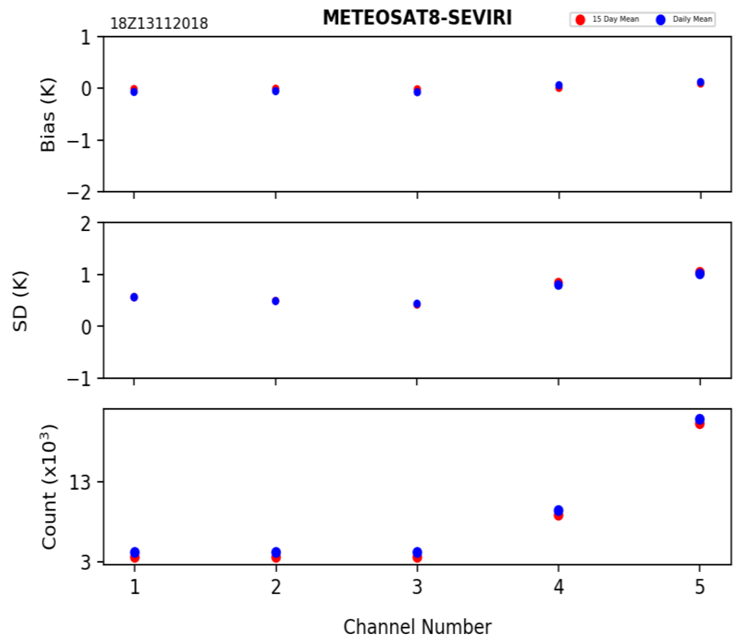


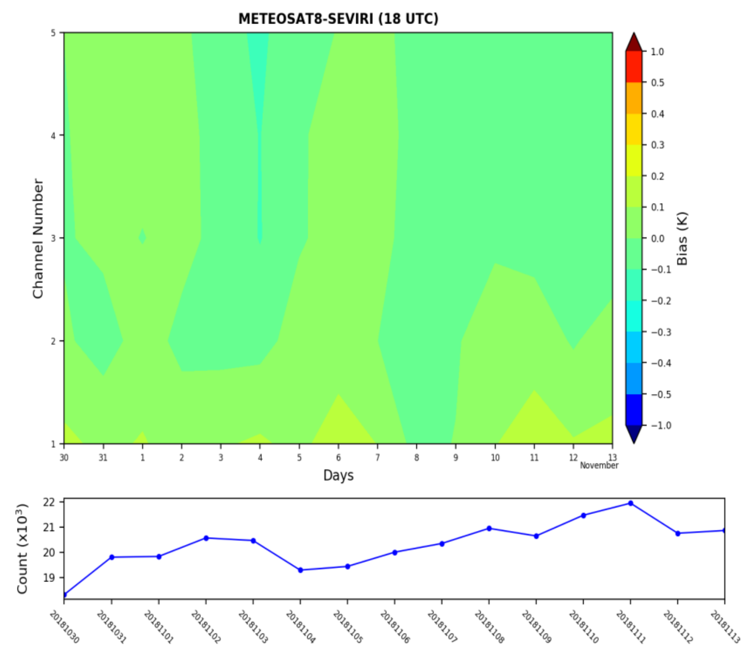




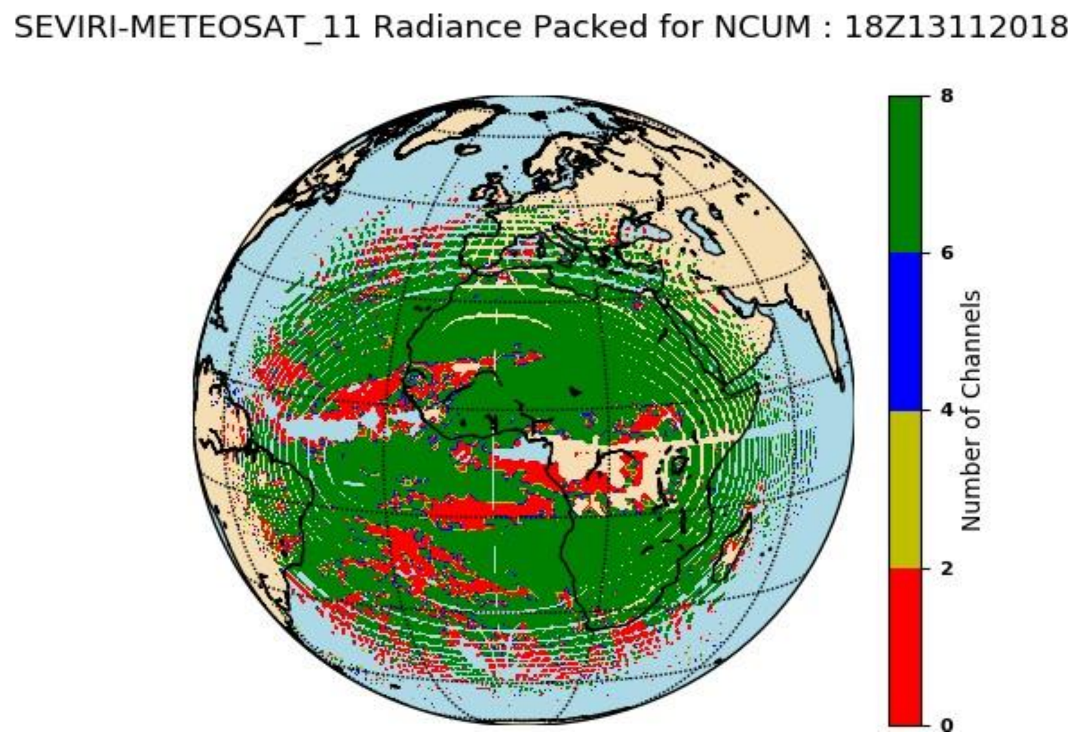
Channel No	1	2	3	4	5
Frequency (GHz)	183±1	183±1.8	183±3	183±4.5	183±7

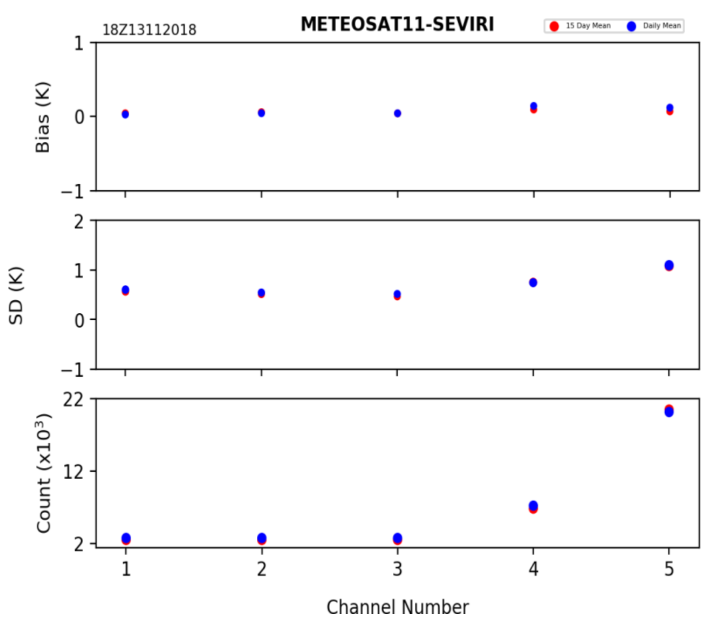


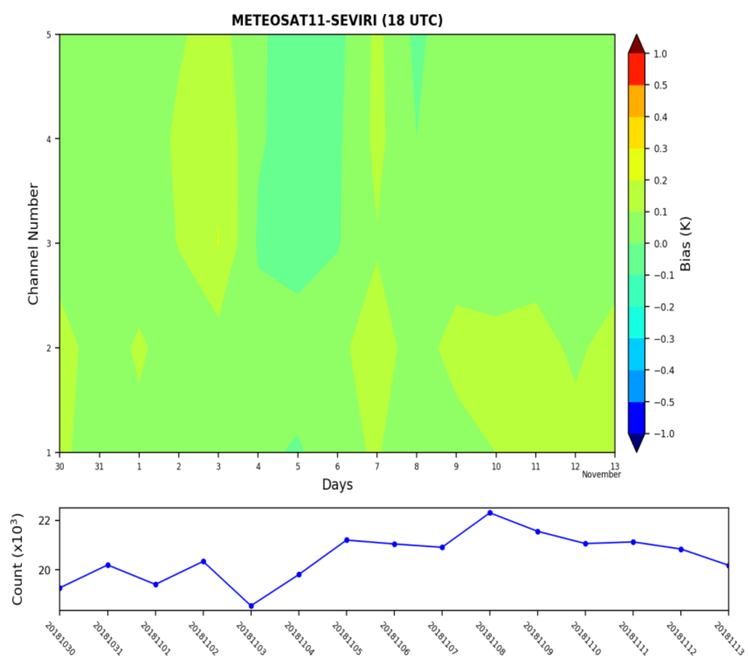




Channel No	1	2	3	4	5
Wavelength (μm)	12.0	10.8	8.7	7.35	6.25

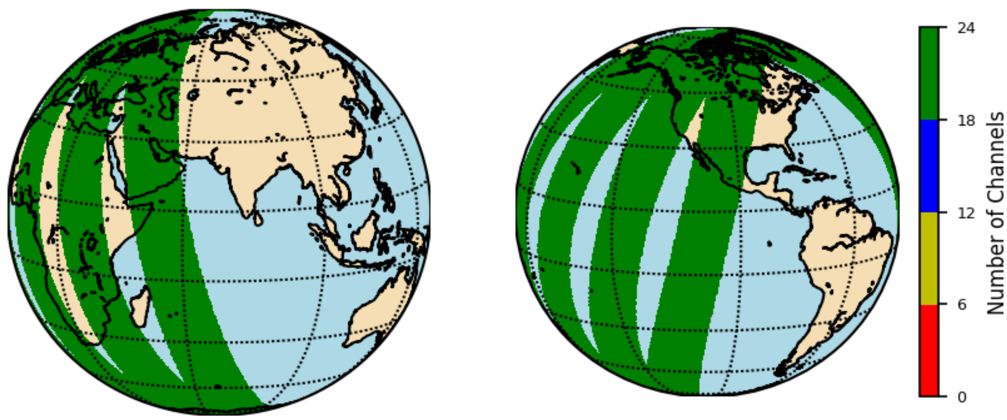




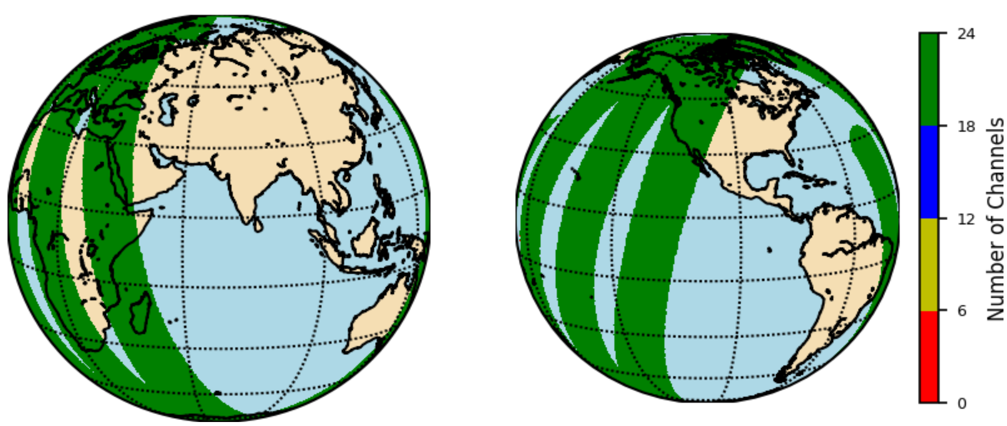


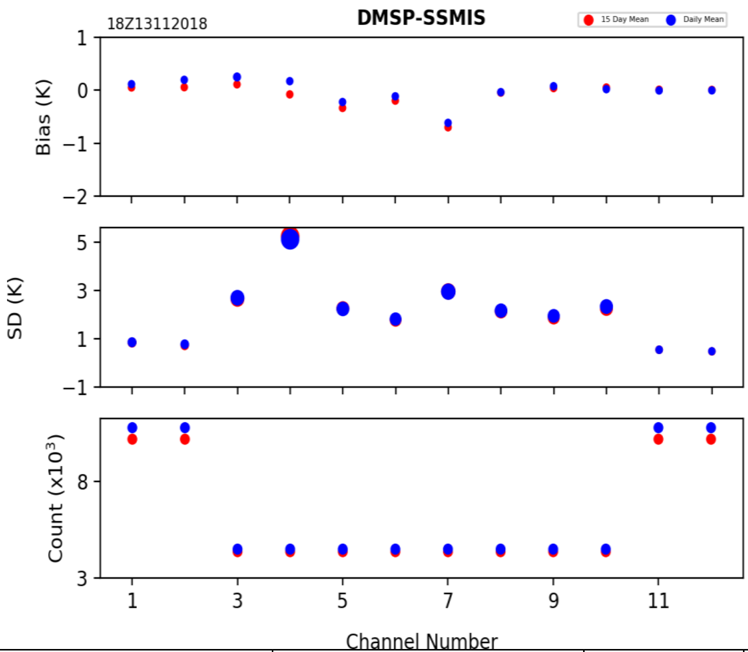
Channel No	1	2	3	4	5
Wavelength (μm)	12.0	10.8	8.7	7.35	6.25

DMSP_17-SSMIS Radiance Packed For NCUM : 18Z13112018

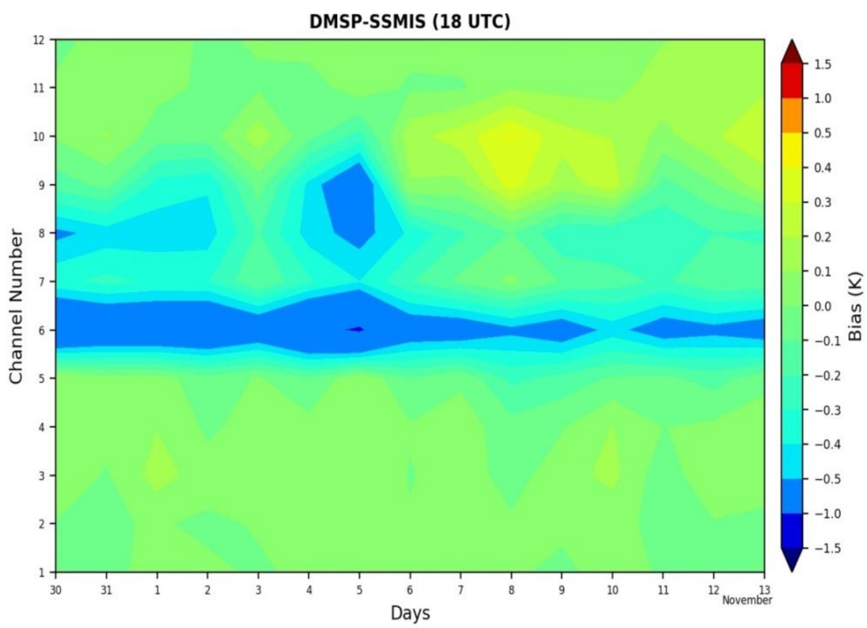


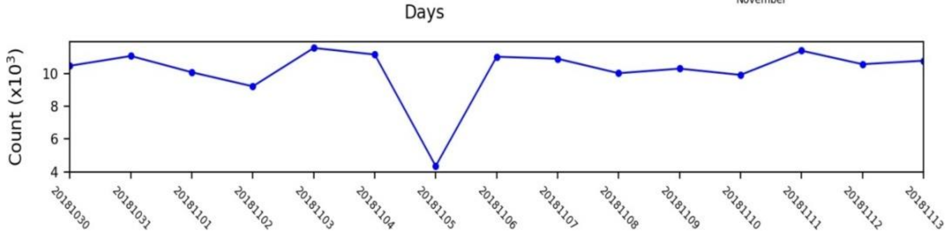
DMSP_18-SSMIS Radiance Packed For NCUM :18Z13112018

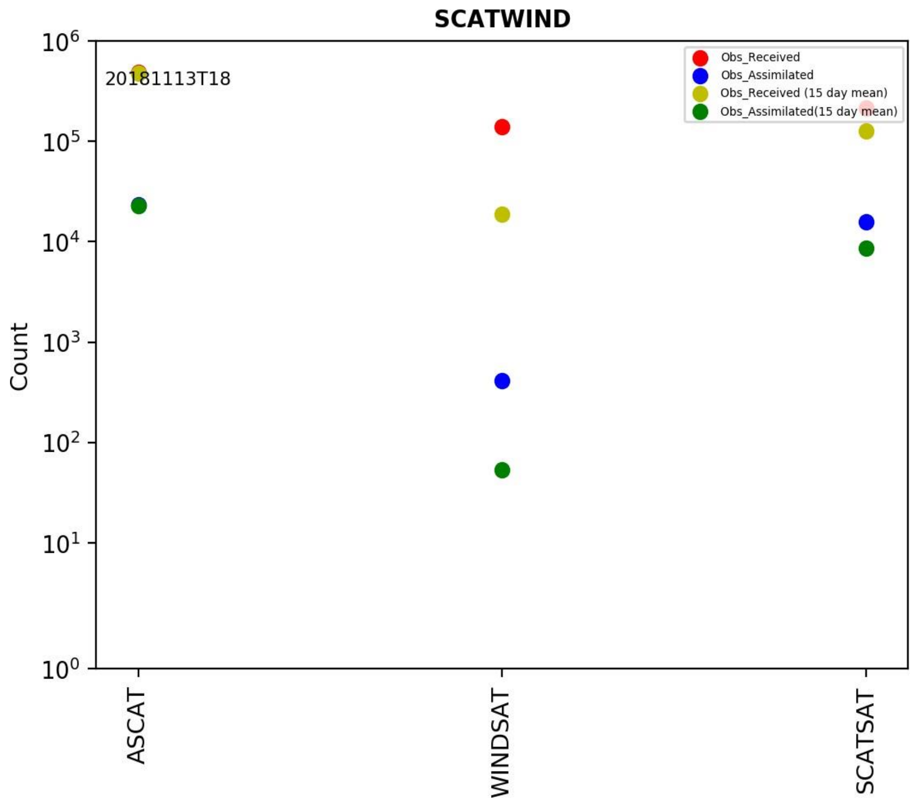




Channel No	1	2	3	4	5	6
Frequncy (GHz)	60.792±0.357±0.05	60.792±0.357±0.016	37V	37H	22.235	19.35V
Channel No	7	8	9	10	11	12
Frequncy (GHz)	19.35H	183.31±1	183.31±3	183.31±6.6	59.4	57.29



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20181113T18
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Obs_Assimilated
Obs_Received (15 day mean)
Obs_Assimilated(15 day mean)
Count
ASCAT
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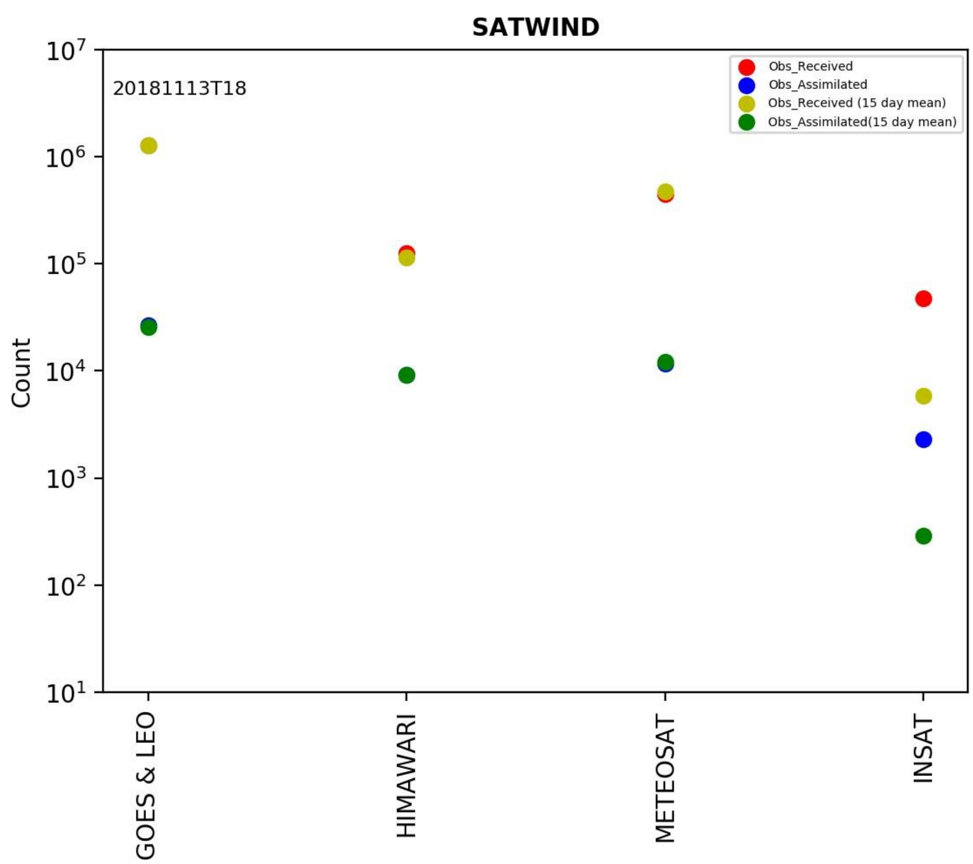
SCATSAT


SATWIND
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Obs_Received (15 day mean)
Obs_Assimilated(15 day mean)
Count
GOES & LEO
HIMAWARI
METEOSAT
INSAT