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सत्यमेव जयते

TECHNICAL REPORT

NCMRWF Observation Reception, Processing and Monitoring (NCObsProM) System

S. Indira Rani, D. Srinivas, Upal Saha,

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December 2024

National Centre for Medium Range Weather Forecasting
Ministry of Earth Sciences, Government of India
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10	Abstract	NCMRWF Observation Reception, Processing, and Monitoring (NCObsProM) System is a legacy system existing in place since the inception of NCMRWF. Many NCMRWF scientists have contributed immensely to the development of the NCObsProM System. The heritage of this system has been followed with timely improvements and updates. This report describes the current status of NCObsProM. Similar to other global operational Numerical Weather Prediction (NWP) centres, NCMRWF also has the facility to receive near-real-time global observations (conventional and remote sensing) from various sources/agencies (GTS, NOAA, EumetCast, ISRO, IMD, CMA, KMA, etc.) for using them in the NCMRWF NWP models. NCMRWF has bilateral agreements (mainly through the India Meteorological Department, IMD) with many data providers, ensuring the timeliness of observation reception. Over time, there has been a tremendous increase in the quantity and quality of observations received at NCMRWF. This is mainly due to the increase in the observation network, the availability of more meteorological satellites, and better connectivity for data transfer. NCMRWF has a state-of-the-art observation processing system that uses open-source software, including NCEP BUFR decoder, ECcode, AAPP, etc. The observations being received at NCMRWF have been decoded instantaneously. These decoded observations are stored separately in a file known as "bufr-tank". The data assimilation system extracts the observations from the "bufr-tank" as per the specified cutoff time. To ensure the quality of the observations used in the assimilation system, it is one of the mandates of NCMRWF to monitor the observations being received. NCMRWF has been adding new and novel observations in the processing, monitoring, and assimilation as and when they are available.
11	Security classification	Non-Secure
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Table of Contents

संक्षेप

NCMRWF अवलोकन रिसेप्शन, प्रसंस्करण और निगरानी (NCObsProM) एक विरासत प्रणाली है जो NCMRWF की स्थापना से मौजूद है। NCMRWF के कई वैज्ञानिकों ने NCObsProM के विकास में बहुत योगदान दिया है। समय पर सुधार और अद्यतन के साथ इस प्रणाली की विरासत का पालन किया गया है। यह रिपोर्ट NCObsProM की वर्तमान स्थिति का वर्णन करती है। अन्य वैश्विक परिचालन संख्यात्मक मौसम पूर्वानुमान केंद्रों के समान, NCMRWF में भी विभिन्न स्रोतों/एजेंसियों (GTS, NOAA, EumetCast, ISRO, IMD, CMA, KMA, etc.) से लगभग वास्तविक समय के वैश्विक अवलोकन प्राप्त करने की सुविधा है। NCMRWF ने कई डेटा प्रदाताओं के साथ द्विपक्षीय समझौते (मुख्य रूप से भारत मौसम विज्ञान विभाग के माध्यम से) किए हैं, जो अवलोकन रिसेप्शन की समयबद्धता सुनिश्चित करते हैं। समय के साथ, NCMRWF में प्राप्त टिप्पणियों की मात्रा और गुणवत्ता में जबरदस्त वृद्धि हुई है। इसका मुख्य कारण अवलोकन नेटवर्क में वृद्धि, अधिक मौसम संबंधी उपग्रहों की उपलब्धता और डेटा स्थानांतरण के लिए बेहतर कनेक्टिविटी है। NCMRWF के पास एक अत्याधुनिक अवलोकन प्रसंस्करण प्रणाली है जो NCEP BUFR डिकोडर, ecCode, AAPP आदि Open Source software का उपयोग करती है। NCMRWF में प्राप्त होने वाली टिप्पणियों को तुरंत डिकोड किया गया है। इन डिकोड किए गए अवलोकनों को "bufr-tank" नामक फ़ाइल में अलग से संग्रहीत किया जाता है। डेटा एसिमिलेशन सिस्टम निर्दिष्ट कटऑफ समय के अनुसार " bufr-tank" से अवलोकन निकालता है। आत्मसात प्रणाली में उपयोग किए गए अवलोकनों की गुणवत्ता सुनिश्चित करने के लिए, प्राप्त किए जा रहे अवलोकनों की निगरानी करना NCMRWF के आदेशों में से एक है। उपलब्धता के अनुसार प्रसंस्करण, निगरानी और आत्मसात में नए अवलोकन जोड़े गए हैं।

Abstract

NCMRWF Observation Reception, Processing, and Monitoring (NCObsProM) System is a legacy system existing in place since the inception of NCMRWF. Many of the NCMRWF scientists have contributed immensely to the development of NCObsProM. The heritage of this system has been followed with timely improvements and updates. This report describes the current status of NCObsProM. Similar to other global operational Numerical Weather Prediction (NWP) centres, NCMRWF also has the facility to receive near-real-time global observations (conventional and remote sensing) from various sources/agencies (GTS, NOAA, EumetCast, ISRO, IMD, CMA, KMA, etc.) for using them in the NCMRWF NWP models. NCMRWF has bilateral agreements (mainly through the India Meteorological Department, IMD) with many data providers, ensuring the timeliness of observation reception. Over time, there has been a tremendous increase in the quantity and quality of observations received at NCMRWF. This is mainly due to the increase in the observation network, the availability of more meteorological satellites, and better connectivity for data transfer. NCMRWF has a state-of-the-art observation processing system that uses open-source software, including NCEP BUFR decoder, ECcode, AAPP, etc. The observations being received at NCMRWF have been decoded instantaneously. These decoded observations are stored separately in a file known as "bufr-tank". The data assimilation system extracts the observations from the "bufr-tank" as per the specified cutoff time. To ensure the quality of the observations used in the assimilation system, it is one of the mandates of NCMRWF to monitor the observations being received. NCMRWF has been adding new and novel observations in the processing, monitoring, and assimilation as and when they are available.

1. Introduction

The real-time Numerical Weather Prediction (NWP) has different components. They are (i) acquisition, processing, and monitoring of observations, (ii) quality control of observations, (iii) data assimilation, (iv) dynamic prediction model, (v) post processing and visualizations, and (vi) application models and customization of products. Out of the above components, the first and foremost component is the observations, their reception, processing, and monitoring. Figure 1 shows the framework of the World Meteorological Organization (WMO) Global Observing System (GOS). The GOS comprises many surface and space-based observing systems operated by national and international agencies. The Global Satellite Observing System (GSOS) is a part of the GOS. Figure 2 shows the constellation of meteorological satellites achieved through unparalleled international cooperation. The meteorological observations can be classified into in-situ (conventional) and remote sensing. Figure 3 shows the broad classification of meteorological observations with various components.

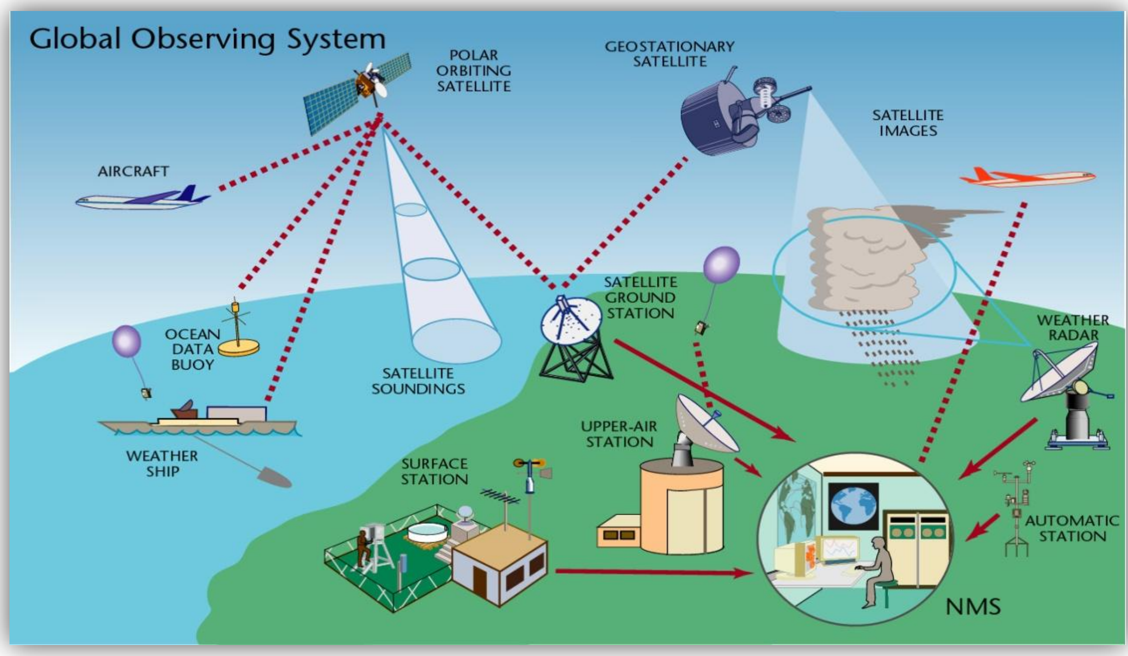

Figure 1: Global Observing System (GOS) framework (Courtesy: WMO)

NCMRWF receives global meteorological and oceanic observations from different sources and agencies. These observations are used for NWP assimilation, verification, and validation purposes. Observations are the backbone of the NWP assimilation, which generates the analysis or initial condition after combining them with the model background, respecting the uncertainty in both. One of the mandates of NCMRWF is to provide the initial condition/analysis to sister organizations of the Ministry of Earth Sciences (MoES) and other government organizations to run their operational NWP, Ocean, and coupled models.

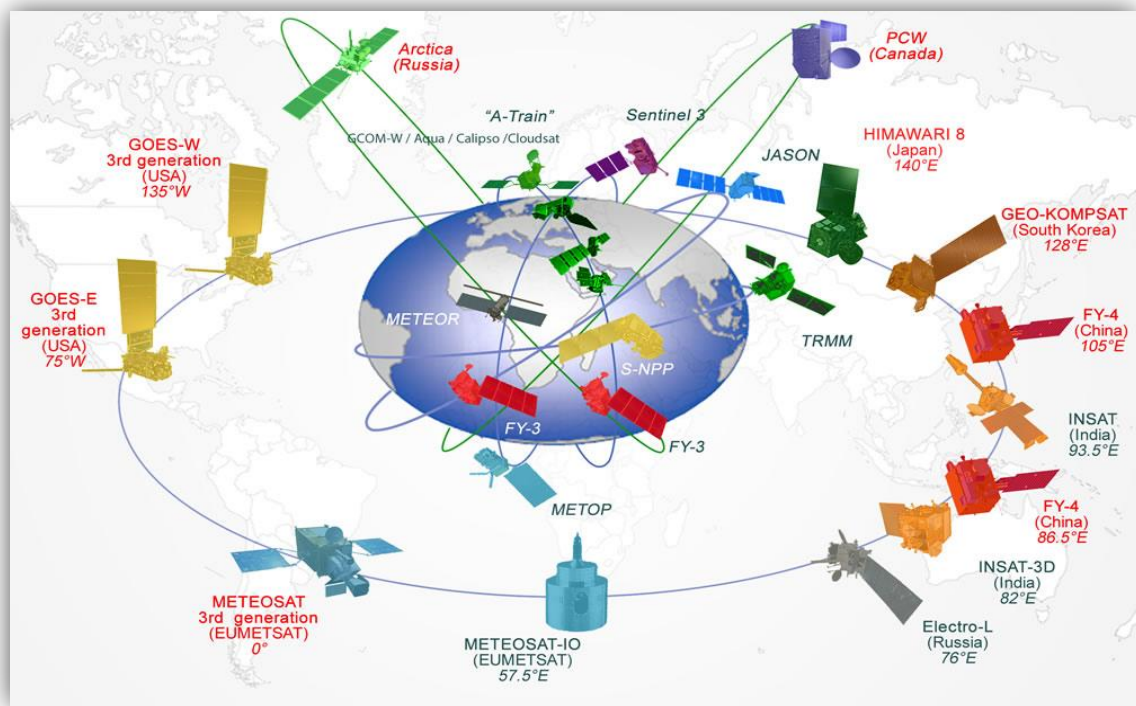

Figure 2: Constellation of Meteorological satellites (Courtesy: WMO)

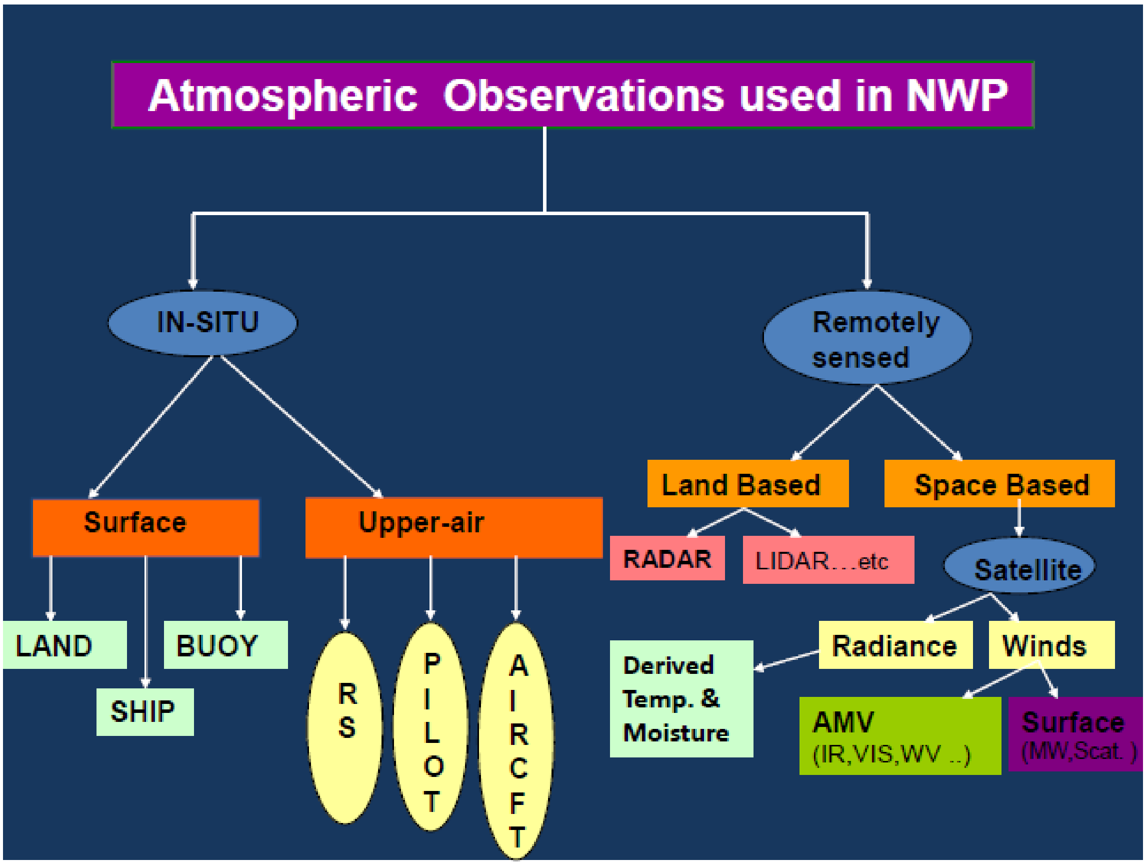

Figure 3: Classification of meteorological observations.

This report discusses the details of various meteorological observations being received at NCMRWF and their processing and monitoring. Section 2 discusses the observation reception at NCMRWF. A brief overview of the observation processing at NCMRWF is discussed in section 3. General observation monitoring at NCMRWF is discussed in section 4. Details of the various conventional and satellite observations being received at NCMRWF are discussed in sections 5 and 6, followed by a summary of this report in section 7.

2. Observation Reception

NCMRWF receives global meteorological, oceanic, and land observations from different sources/agencies in near-real-time. Most of the conventional observations like Surface and Upper air (Radio-sonde, pilot balloons, wind profilers, Aircraft, etc.) are received through the Global Telecommunication System (GTS), via the Regional Telecommunication Hub (RTH), India Meteorological Department (IMD), New Delhi. Apart from conventional observations, some of the satellite derived Atmospheric Motion Vectors (AMVs) and satellite radiances are also being received at NCMRWF through the GTS. Figure 4 shows the six different Regional Associations (RA) of WMO. As seen in Figure 4, India falls in WMO RA-II. Figure 5 shows the GTS network with the three WMO centres, Washington, Moscow, and Melbourne, and the associated RTHs and National Meteorological Centres (NMC). Figure 6 shows the GTS network over India with the interconnections among the international centres.

Figure 4: WMO Regional Associations (Courtesy: WMO)

In the recent past, NCMRWF has made special efforts to increase the volume of its satellite data reception by making arrangements to receive these data directly from the data providers. These arrangements complement the reception of conventional data through the GTS from RTH New Delhi. Data from NOAA, CMA, and KMA are being received from their respective data access servers, PDA, FY4, and GK5, using internet file transfer protocols. Data from EumetSat is being received from its terrestrial broadcast using the connectivity between NKN of India and NERN of Europe. The establishment of the EumetCast reception system, the primary data dissemination mechanism of EumetSat at

NCMRWF, became possible due to the signing of an MoU between IMD and EumetSat. Further, to enhance the availability of various LEO satellite radiance data, India has joined the WMO's DBNet coordination group, which uses GTS connectivity for data transfer. Apart from these main sources, NCMRWF receives Indian data from CUSAT (ST Radar), NAVY (wind profilers), and state-owned AWS/ARGs (Maharashtra, Karnataka and Telangana). Figure 7 depicts various types of observation received at NCMRWF from different sources. Table 1 lists various types of observations being received at NCMRWF in near-real-time. Table 1 also includes the variables from different observation platforms being assimilated in the NCMRWF NWP systems. There has been a tremendous increase in the volume of meteorological and oceanographic data we have received at NCMRWF since 2008. This is partly due to more reliable data transfer through the GTS by various NMCs, including IMD, and the collaboration without boundaries, particularly for satellite observations. Figure 8 shows the annual time series of the volume of meteorological data received at NCMRWF since 2008. There is a more than tenfold increase in the data reception through GTS (1 GB to 12 GB) and an approximately fivefold increase in the data reception through FTP (< 100 GB to >500 GB) since 2014-2015, as seen in Figure 8. NCMRWF keeps an update on various types of observations being received at NCMRWF from different agencies/sources with their file name conventions and descriptions. These details can be found at https://docs.google.com/document/d/1JHVfEnGasKT2jpcL0nqAo9k8cmwzpOdy/edit.

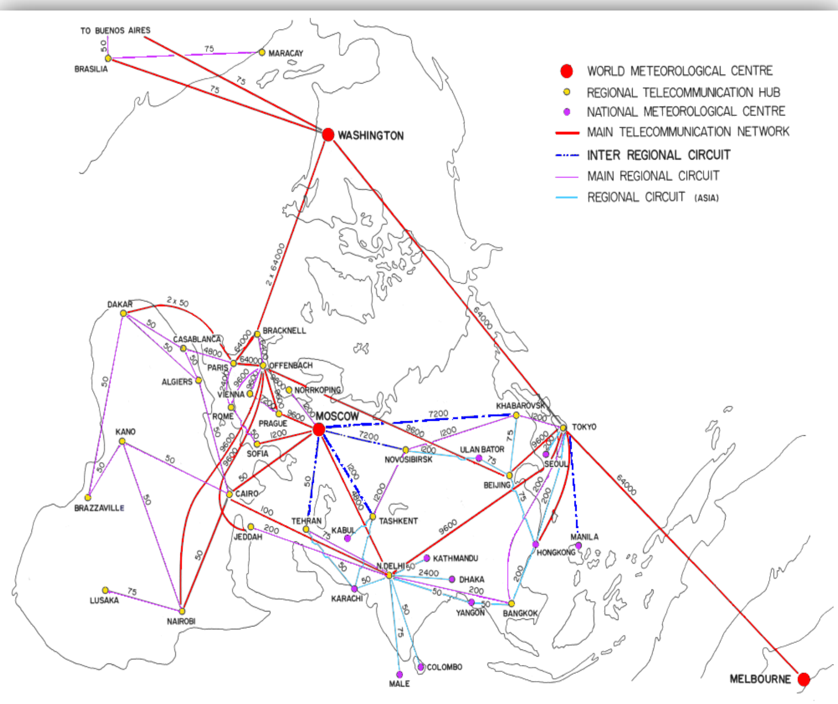

Figure 5: Global GTS Network (Courtesy: WMO)

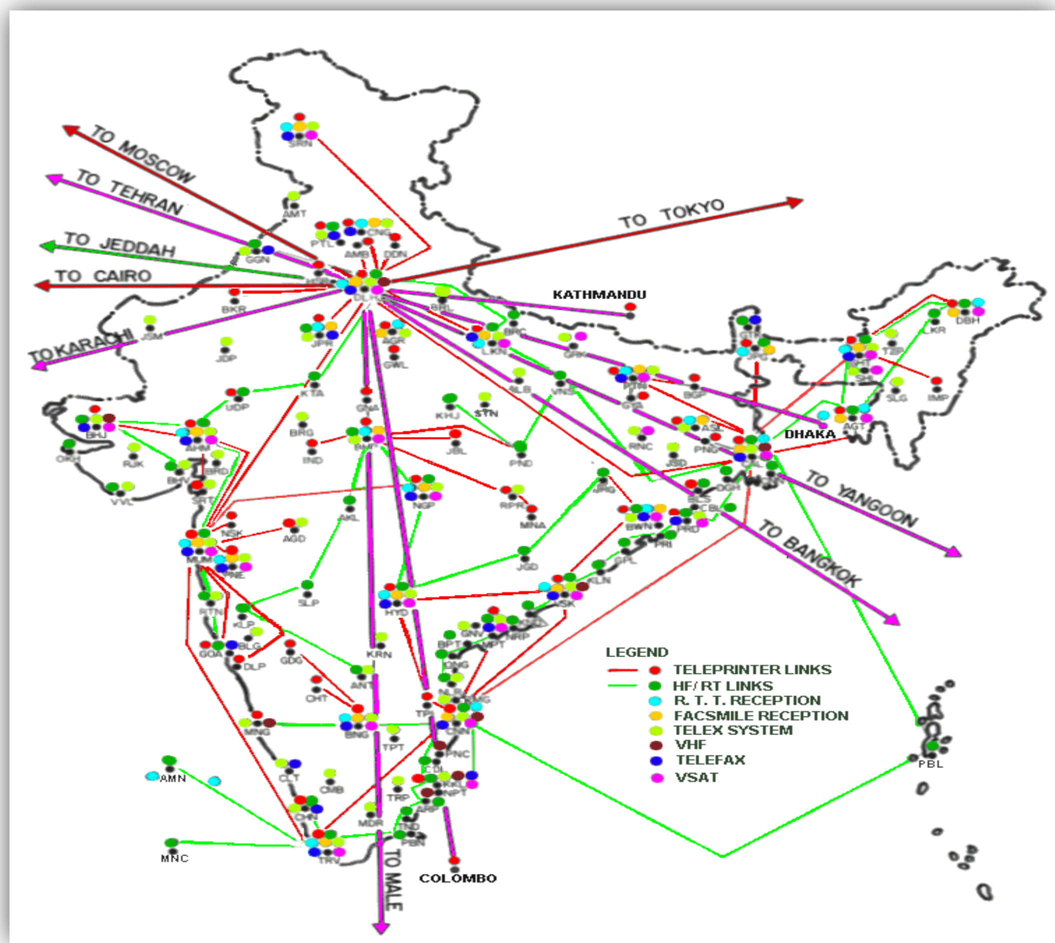

Figure 6: GTS network over India (Courtesy: WMO)

Table 1: Details of the near-time observations being received at NCMRWF

Observation	Description	Source
(a) Surface (in-situ)		
SYNOP	Surface Synoptic Reports	GTS
SHIP	Ship Synoptic Reports	GTS
METAR	Aviation reports from airports	GTS
BUOY	Buoy Observations	GTS, INCOIS via FTP
MOBIL/AWS	AWS observations	GTS, FTP
Agro AWS	AWS observations, including soil parameters	FTP
(b) Upper Air (in-situ)		
TEMP	Upper level observations	GTS, FTP (IITM)
TEMP SHIP	Upper level observations	GTS
TEMP DROP	Aircraft Dropsonde observations	GTS
TEMP MOBIL	Upper level observations	GTS
PILOT	Upper level wind	GTS
PILOT SHIP	Upper level wind	
PILOT MOBIL	Upper level wind	
PROFILER	Upper level wind	GTS, FTP (CUSAT, NAVY, IITM)

(c) Aircraft		
AIREP/PIREP	Pilot reports of standard variables	GTS
AMDAR	Aircraft Observations	GTS
(d) Global Navigation System Satellite (GNSS) data		
GNSS-Radio Occultation (GNSS-RO)	TerraSAR-X	GTS
	TenDEM-X	
	FY-3D/3E	
	COSMIC-2E (1-6)	
	MetOp-B	
	MetOp-C	
	PAZ	
	KOMPSAT	
	Sentinel-6	EumetCast
	SPIRE	FTP (NOAA PDA)
	GeoOptics	FTP (NOAA PDA)
GNSS- Zenith Total Delay (ZTD)/Integrated Precipitable Water Vapor (IPW)		GTS, IMD, EuMet, SuomiNet, CORS (SoI)
(e) Satellite winds		
Sea Surface winds	Advanced Scatterometer (ASCAT) onboard MetOp-B and MetOp-C	NOAA, EumetCast
	OSCAT-3 onboard Oceansat-3	NRSC-ISRO
	HY-Scat (B, C, D)	EumetCast
Atmospheric Motion Vectors (AMVs)	INSAT-3DR	GTS
	Meteosat	GTS, EumetCast
	Himawari	GTS
	GeoKompsat	KMA (FTP)
	GOES-16,18	NOAA
	Polar winds	NOAA, EumetCast
	Dual MetOp winds	EumetCast
Wind Profilers	Aeolus (Mission period over)	EumetCast
(f) Satellite Radiances		
(f-1) Geostationary (Multispectral-Infrared)		
INSAT-3DR Imager	Imager radiances from INSAT-3DR	FTP (IMD)
INSAT-3DR Sounder	Sounder radiances from INSAT-3DR	FTP (IMD)
SEVIRI	Spinning Enhanced Visible and Infra-Red Imager (SEVIRI) radiances from Meteosat-9 and 10	GTS, NOAA, EumetCast
AHI	Advanced Himawari Imager (AHI) radiances from Himawari-9	GTS
ABI	Advanced Baseline Imager (ABI) radiances from GOES-16 and 18	NOAA

(f-2) Polar (Multispectral: Infrared and MicroWave)			
ATOVS	AMSU-A	Advanced Microwave Sounding Unit-A (AMSU-A) onboard NOAA-18, NOAA-19, MetOp-B and MetOp-C	NOAA, EumetCast
	MHS	Microwave Humidity Sounder (MHS) onboard NOAA-18, NOAA-19, MetOp-B and MetOp-C	
	HIRS	High resolution Infra-Red Sounder (HIRS) onboard NOAA-18, NOAA-19, MetOp-B, and MetOp-C	
ATMS		Advanced Technology Microwave Sounder (ATMS) onboard SNPP, NOAA-20 and NOAA-21	NOAA, EumetCast
AMSR-2		Advanced Microwave Scanning Radiometer-2 (AMSR-2) onboard GCOM-W	NOAA, EumetCast
GMI		Global Precipitation Mission (GPM) Microwave Imager (GMI)	NOAA, EumetCast
SSMI/S		Special Sensor Microwave Imager/Sounder (SSMI/S) onboard DMSP satellites	NOAA
(f-3)Polar (Hyperspectral)			
AIRS		Atmospheric Infra-Red Sounder (AIRS) onboard AQUA satellite	NASA
IASI		Infrared Atmospheric Sounding Interferometer (IASI) onboard MetOp-B and MetOp-C	NOAA, EumetCast
CrIS		Cross-track Infrared Sounder (CrIS) onboard NPP, NOAA-20 and NOAA-21	NOAA, EumetCast
(f-4) RARS/EARS/DBNet			
ATOVS	AMSU-A		GTS, NRSC, INCOIS, EumetCast
	MHS		
ATMS			NRSC, INCOIS, EumetCast
MWTS		MicroWave Temperature Sounder (MWTS) onboard FY-3C and FY-3D	EumetCast
MWHS		MicroWave Humidity Sounder (MWTS) onboard FY-3C and FY-3D	EumetCast
MWRI		Micro Wave Radiation Imager (MWRI) onboard FY-3D	EumetCast
IASI			EumetCast, NRSC, INCOIS

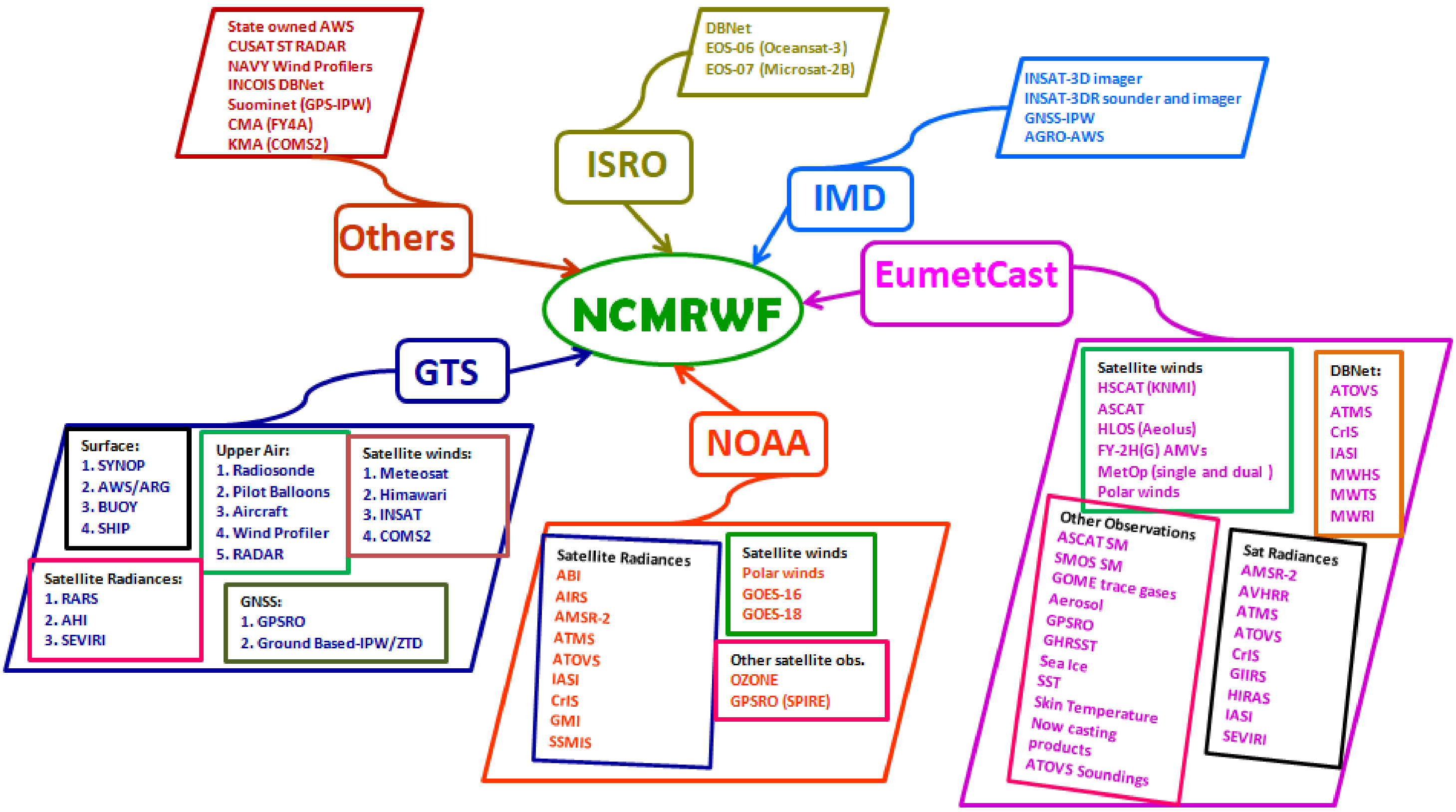

Figure 7: Meteorological data reception at NCMRWF from various sources.

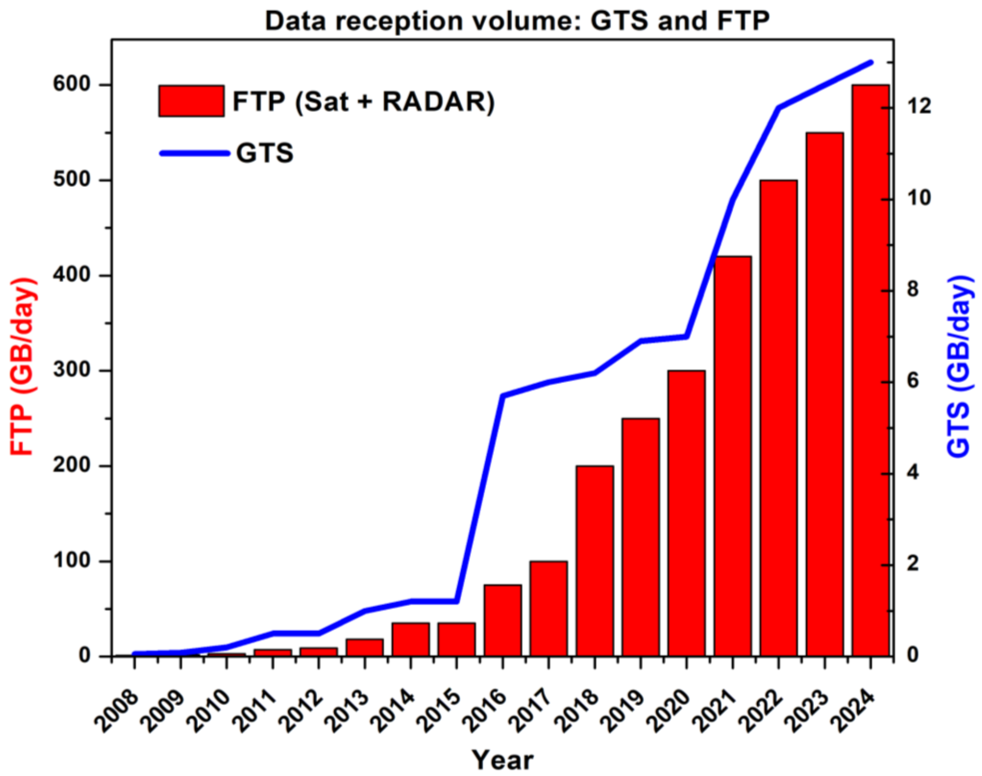

Figure 8: Annual time series of volume of data reception at NCMRWF since 2008.

3. Observation Processing

When the recording of meteorological observations has been completed, this information has to be transmitted to a meteorological centre. The message must be prepared in a form suitable for transmission over a communication system (GTS, FTP, etc), generally known as a weather report. Reducing the message length helps in the rapid and efficient transmission of weather reports. WMO has developed a system of meteorological codes for transmitting weather reports. Large amounts of weather and satellite data are exchanged each day routinely in real time around the world. These weather reports are decoded at the reception centres to get the weather information. A sound understanding of the coding practices is necessary for decoding and encoding. Common procedures for data representation and transmission are based on the concept of using codes designed by WMO. These codes help to reduce the message length, avoid language problems, and facilitate automatic processing.

Table 2: List of some of the conventional decoders available at NCMRWF

	Type of Observations	Decoder Name	WMO Code Name
1	Upper air sounding	dcusnd	TEMP & PILOT
2	Land surface	dclsfc	SYNOP & SYNOP MOBIL
3	Marine surface	dcmsfc	SHIP
4	Drifting Buoy	dcdrbu	BUOY
5	Sub-surface buoy Obsn.	dcbthy	BATHY & TESAC
6	Aircraft observations	dcacft	AIREP & AMDAR
7	Automated Aircraft Observation	dcacft	BUFR (ACARS)
8	Airport Weather Obsn	dcmetr	METAR
9	Satellite winds	dcsaob	SATOB
10	High density satellite winds	dceums	BUFR (winds from EUMETSAT & Japan)
11	Wind profiler observation	dcprof	BUFR (wind profiler from US/Europe/Hongkong)

WMO codes are mainly of two types: ASCII and Binary. ASCII code examples are SYNOP (surface), TEMP (Radiosonde), etc. (Refer to Table 1 for more details). Binary codes are BUFR (Binary Universal Form for the Representation of Meteorological Data) and GRIB (GRIdded Binary Data). BUFR is the primary format used operationally on the GTS for real-time global exchange of weather and satellite observations. BUFR is self-describing and is table-driven. GRIB is the primary WMO format for storing and transmitting weather and climate forecasts in grids, including all-important numerical weather forecasts.

The observations received at the NMCs have to be decoded and encoded for further usage in the NWP. Decoders/Encoders are a set of software for decoding/encoding different WMO codes. There are many decoders available. Some of them are the NCEP decoder (https://www.nco.ncep.noaa.gov/sib/decoders/), Python toolkit for WMO BUFR decoder (https://pybufrkit.readthedocs.io/en/latest/), ECMWF eCcodes (https://confluence.ecmwf.int/display/ECC/Releases), etc. NCMRWF mainly uses the eCcodes and the NCEP decoder/encoders for operational purposes. NCMRWF routinely develops indigenous decoders/encoders to include new datasets, particularly the Indian satellites, and observation of opportunity. Table 2 lists some of the decoders installed at NCMRWF High Performance Computing System (HPCs) to decode observations. More details of observation processing at NCMRWF can be seen in *Prasad (2012, 2014, 2020), Prasad and Rani (2014), and Jangid et al. (2019).*

4. Observation Monitoring

NCMRWF routinely does four six hourly intermittent assimilation cycles daily with a data cutoff time of ±3 hours. It is important to process the observations and keep them ready for the assimilation cycles centered at 00, 06, 12, and 18 UTCs. NCMRWF makes two runs for each assimilation cycle: an "Early run" with a cutoff time of -3 to +2 hours and an "Update run" by including the observations received later within +3 hours of the assimilation window. This Early-Update pair helps to ensure the impact of observations in the next cycle through the model first guess update. The purpose of monitoring is to provide detailed information on the availability of different types of observations at NCMRWF during each assimilation cycle. This routine monitoring of observations helps to improve the usage of observations in the NCMRWF data assimilation systems. Automated observation monitoring packages are implemented separately for Early and Update cycles. NCMRWF monitors the observations during four six hourly intermittent (00Z, 06Z, 12Z, and 18Z) assimilation cycles (https://www.ncmrwf.gov.in/Daily_MR_00.php, https://www.ncmrwf.gov.in/Daily_MR_06.php, https://www.ncmrwf.gov.in/Daily_MR_12.php, https://www.ncmrwf.gov.in/Daily_MR_18.php) and also in the monthly scale. (https://www.ncmrwf.gov.in/NCMRWF_MMR.php). The daily assimilation cycle wise monitoring reports include data coverage charts of various types of observations. Each plot shows the available data for a group of similar observations (e.g., Surface, Upper Air, Aircraft, AMVs, Radiances, etc.). In addition to the coverage plots, time series of the count of various observations (both global and Indian region) and their departure from the last 45 days are also included in the daily monitoring reports. These time series help us to make critical decisions when there is a considerable departure. Figure 9 shows the time series of the global count of various observations (SYNOP, SHIP, BUOY, Aircraft, RS/RW, and AMVs) for the last 45 days, valid for 21 November 2023. The figure also includes the average count of various types of observations for the 45 days, the current day (valid day) count, and the percentage departure of the count.

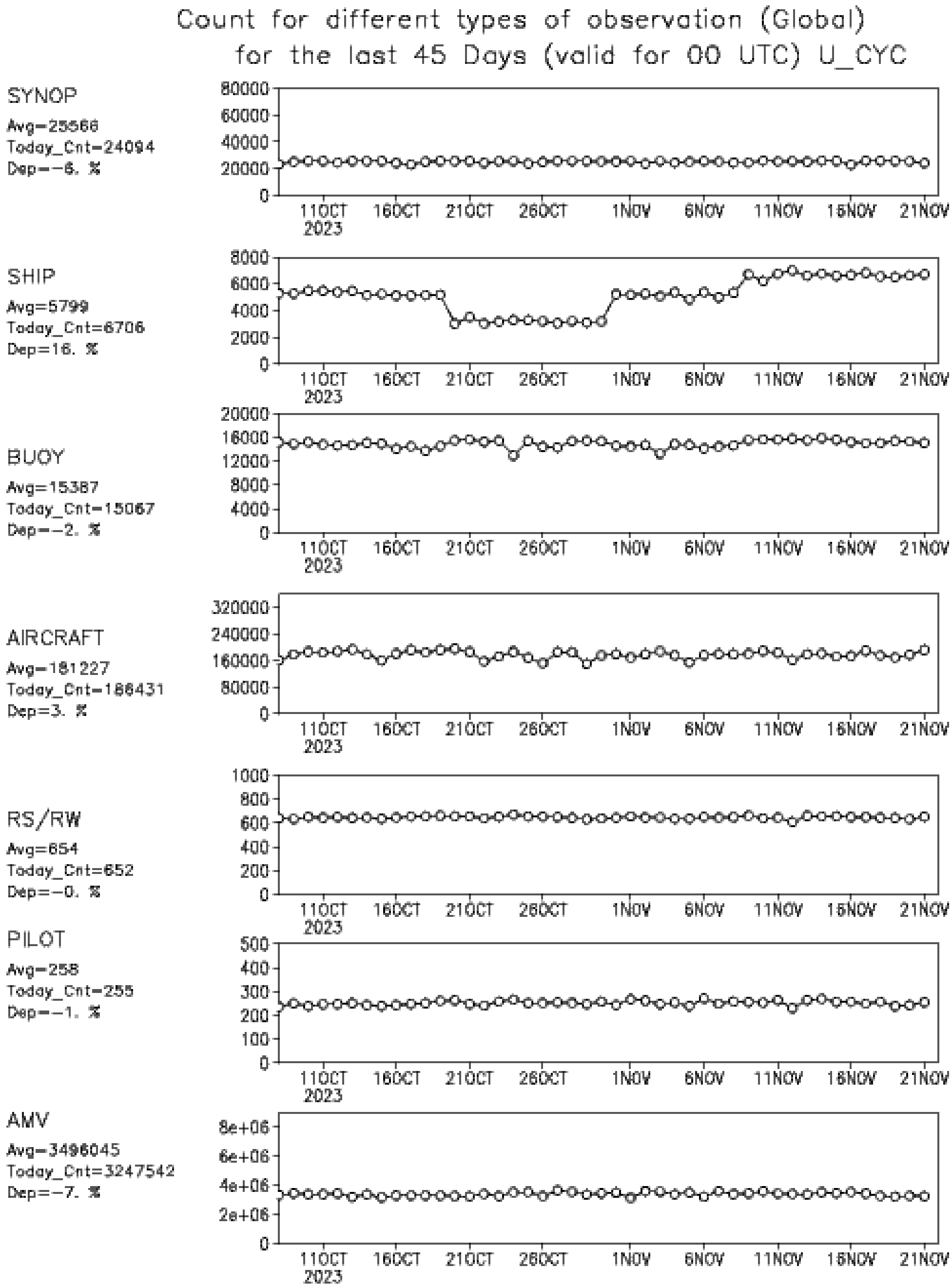

Figure 9: Time series of the global count of various types of observations (SYNOP, SHIP, BUOY, AIRCRAFT, RS/RW, and AMV) for the previous 45 days, valid for the current day (here it is 21 November 2023).

NCMRWF regularly monitors the volume of data received through GTS and FTP (various sources). It is a good practice to compare the data reception volume with that of other leading global operational centres. NCMRWF compares the monthly count of meteorological data reception with that of the European Centre for Medium-Range Weather Forecast (ECMWF). Figure 10 shows the time series of comparison of various data reception at NCMRWF and ECMWF from January 2012 to May 2024.

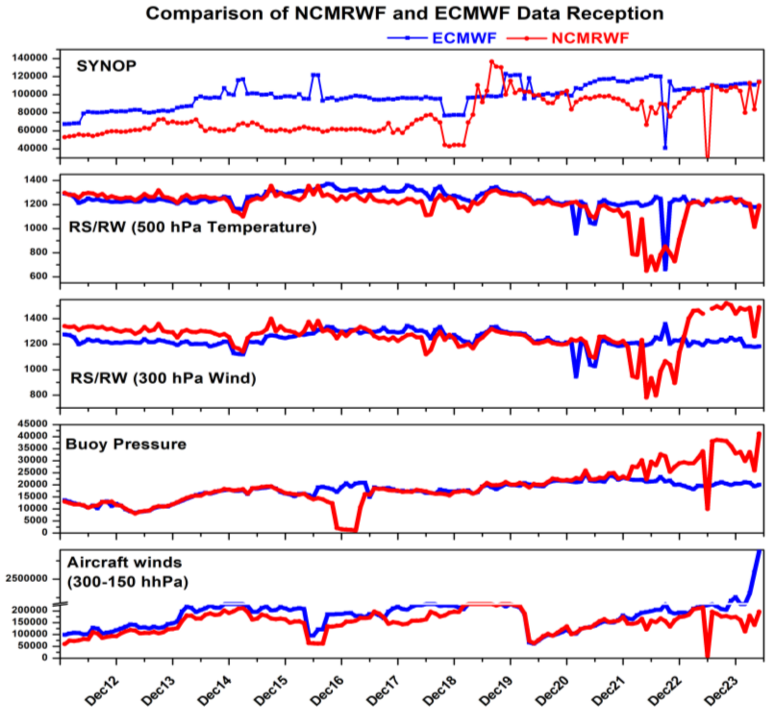

Figure 10: Comparison of NCMRWF and ECMWF data reception from January 2012 to May 2024.

5. Conventional Observations

NCMRWF receives global in-situ observations (land and ocean) mainly through the GTS (Details in Table 1.), in Traditional Alphanumeric Codes (TAC), and BUFR. The majority of the NMCs are slowly migrating from TAC to BUFR, but many of the stations still report observations both in TAC and BUFR. The processing and monitoring of the TAC and BUFR coded observations (surface and upper sir) are carried out separately. It is the norm that if a station reports data both in TAC and BUFR, the station has not been fully migrated to the BUFR, and the NCMRWF assimilation systems prefer data in TAC.

5.1 Surface

Figure 11 shows the coverage of various global surface in-situ observations received at NCMRWF during a typical assimilation cycle of "Update run". There is good coverage of surface observations over the Northern Hemisphere, particularly the land regions. It can be seen from Figure 11 that the Southern Hemisphere Oceanic region is sparsely observed, mainly south of 30°S. Though there is good coverage of in-situ surface observations, these observations are limited to the surface, with no information above. The frequency of these observations is not identical; there are half-hourly, hourly, three-hour, and six-hour observations. Regular monitoring of the Indian surface observations, like SYNOP, AWS-ARG, and BUOY, are also carried out separately. If the total number of Indian surface observations received at NCMRWF during each assimilation cycle (both early and update) is less than 20% of the mean of the previous 45 days count, then action will be taken by informing the concerned agencies, IMD, INCOIS, etc. NCMRWF monitors the Indian Buoy observations, emphasizing the quality of the variables including surface pressure, temperature, relative humidity, and wind. Figure 12 shows the Indian Buoy data monitoring implemented at NCMRWF for a particular update assimilation cycle of 0000 UTC. More details of different types of surface observations, quality control processes, and statistics are available at *Srinivas et al. (2023).* Details of the monitoring of AWS-ARG data are available at *Saha et al. (2021, 2023).*

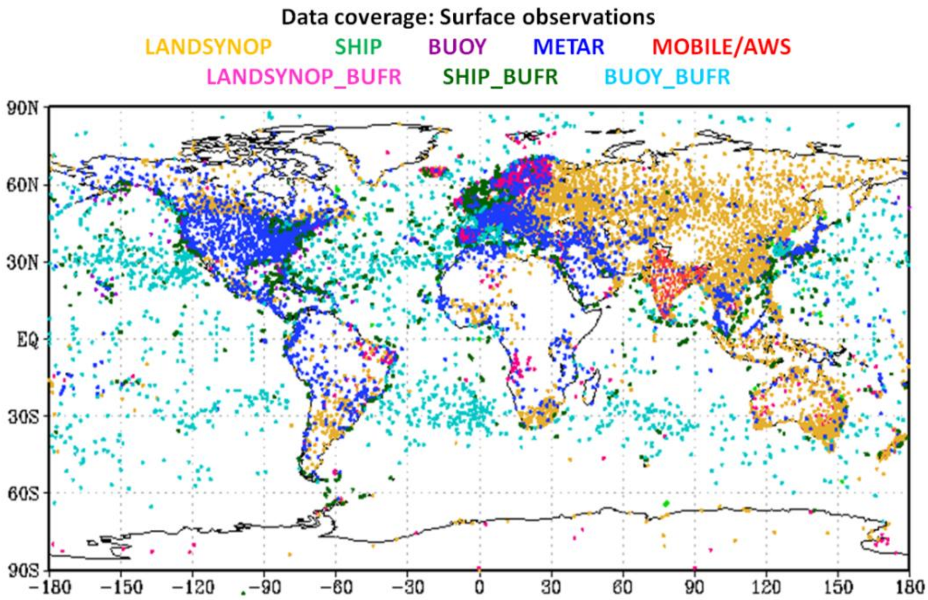

Figure 11: Coverage of global in-situ surface observations (land and ocean) received at NCMRWF during a typical assimilation cycle.

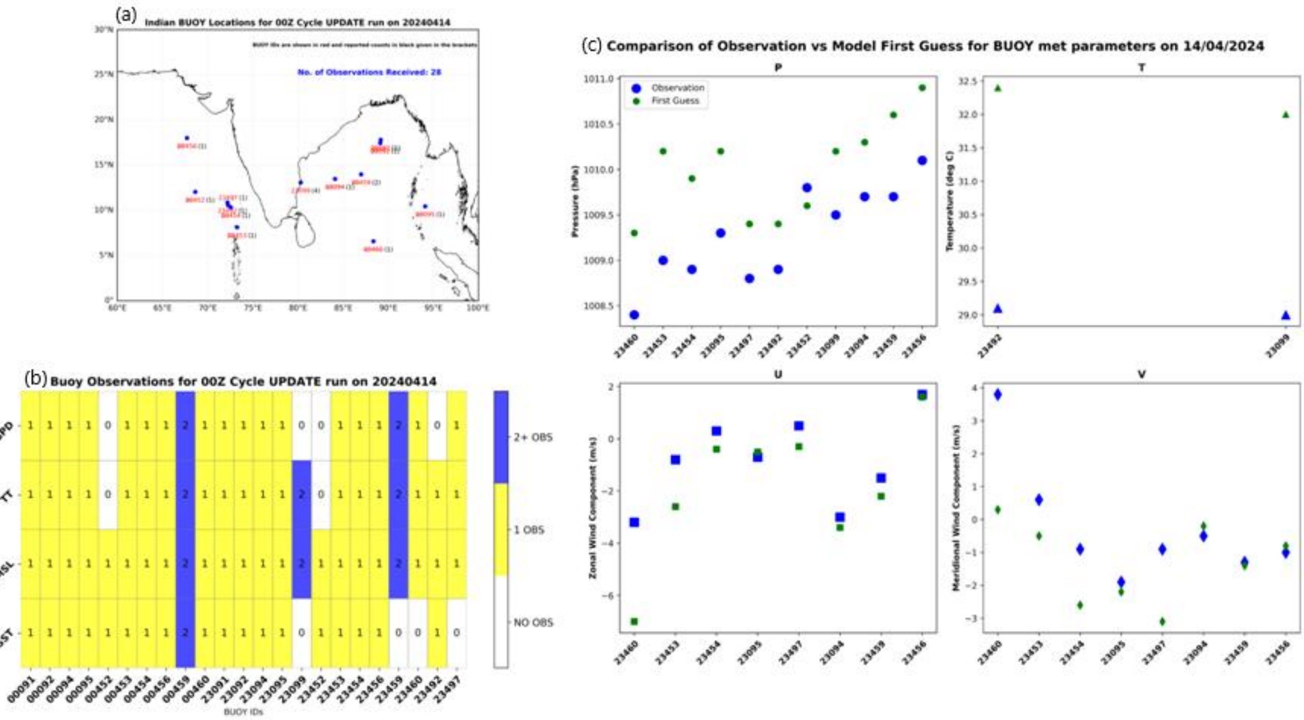

Figure 12: (a) Locations of INCOIS/NIOT Buoys, (b) Heat map of the reception frequency of various parameters from different Indian Buoys at NCMRWF during a particular update cycle, and (c) comparison of Buoy observed parameters against the model equivalents for a typical update assimilation cycle.

5.2 In-situ upper air observations

In-situ upper air observations consist of vertical profiles from radiosondes over land and ocean (temperature, humidity, wind components, and geopotential/pressure), pilot balloons (wind components and geopotential), dropsondes (similar to radiosonde variables), and wind profiler (wind components and geopotential height). For more details, refer to Table 1. The global radiosonde stations make ascents twice daily, at 00 and 12 UTCs, while the pilot balloon ascents are generally scheduled at 06 and 18 UTCs. Radiosonde ascents onboard ships and dropsondes are not regular and can be considered observations of opportunity. Generally, the wind profiler data are of high frequency with 5-10 minutes temporal resolution if operated continuously. Figure 13 shows the coverage of global upper air (in-situ) observations being received at NCMRWF during a typical assimilation cycle (update). The majority of the upper air observations are located over the Northern Hemisphere. Upper air in-situ observations over land are very sparse, as seen from Figure 13. Similar to the Indian surface observations, special monitoring of Indian upper air observations (radiosonde and pilot balloons) is also carried out regularly. Observed radiosonde profiles (temperature, humidity, and wind components) are also compared against the model equivalents at the observation location. For more details, kindly refer to the NCMRWF observation monitoring reports (https://www.ncmrwf.gov.in/Daily_MR_00.php, https://www.ncmrwf.gov.in/Daily_MR_06.php, https://www.ncmrwf.gov.in/Daily_MR_12.php, https://www.ncmrwf.gov.in/Daily_MR_18.php).

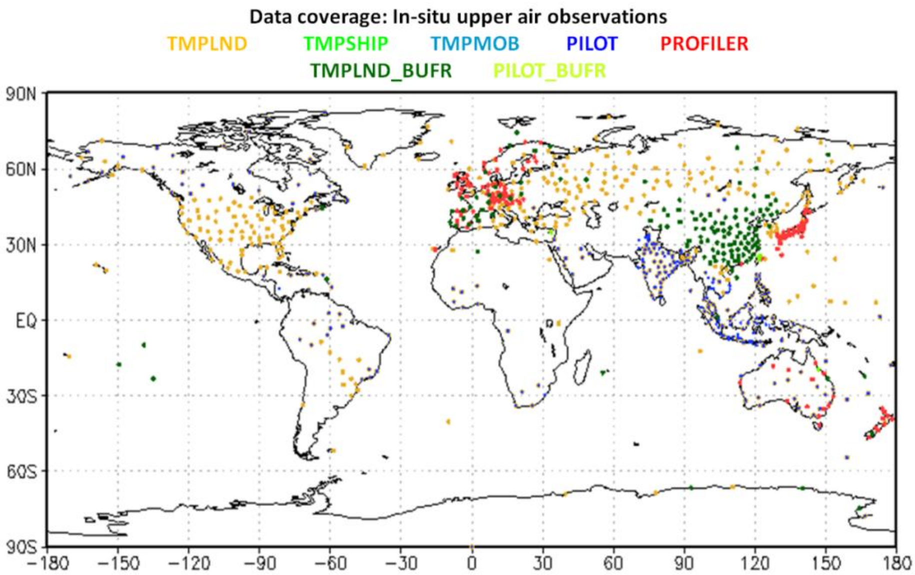

Figure 13: Coverage of global in-situ upper-air observations (land and ocean) received at NCMRWF during a typical assimilation cycle.

Currently, almost 56 radiosonde stations in India are operated and managed by the IMD. Many of these stations have been upgraded to GPS sondes under the IMD modernization program. Figure 14a shows the coverage of Indian radiosondes and pilot balloon observations received at NCMRWF during a typical assimilation cycle of 00 UTC. The red and blue dots in Figure 14a indicate the locations from which radiosondes and pilot balloon reports were received at NCMRWF. The grey open circles are the stations where no ascent was taken during that particular day. It is also noted from Figure 14a that most of the Pilot reports are the subset of radiosonde reports. The upper air reports may often contain one or two levels due to some problem in the radiosonde system. It is essential to monitor how many levels of data have been reported from the radiosonde ascent and the maximum height the payload reaches. Figure 14b shows the Indian radiosonde stations with their WMO station identification number and the maximum level reached in hPa.

NCMRWF monitors the monthly reception and acceptance of Indian Radiosonde/GPSsonde station data in the NCMRWF NWP models and provides feedback to IMD. Figure 15a and b show the reception count and percentage rejection of Indian radiosonde observations (500 hPa temperature) from January 2018 to February 2024 for 0000 UTC and 1200 UTC assimilation cycles. The blue bars show the monthly count of radiosonde reports, which reported 500 hPa temperature, and the red line shows the percentage of rejection of 500 hPa radiosonde temperature in the assimilation system. The number of radiosonde observations drastically reduced during the global pandemic, and the numbers started increasing since March-April 2023. NCMRWF regularly updates the sonde list to process all the in-situ upper air data received through the GTS.

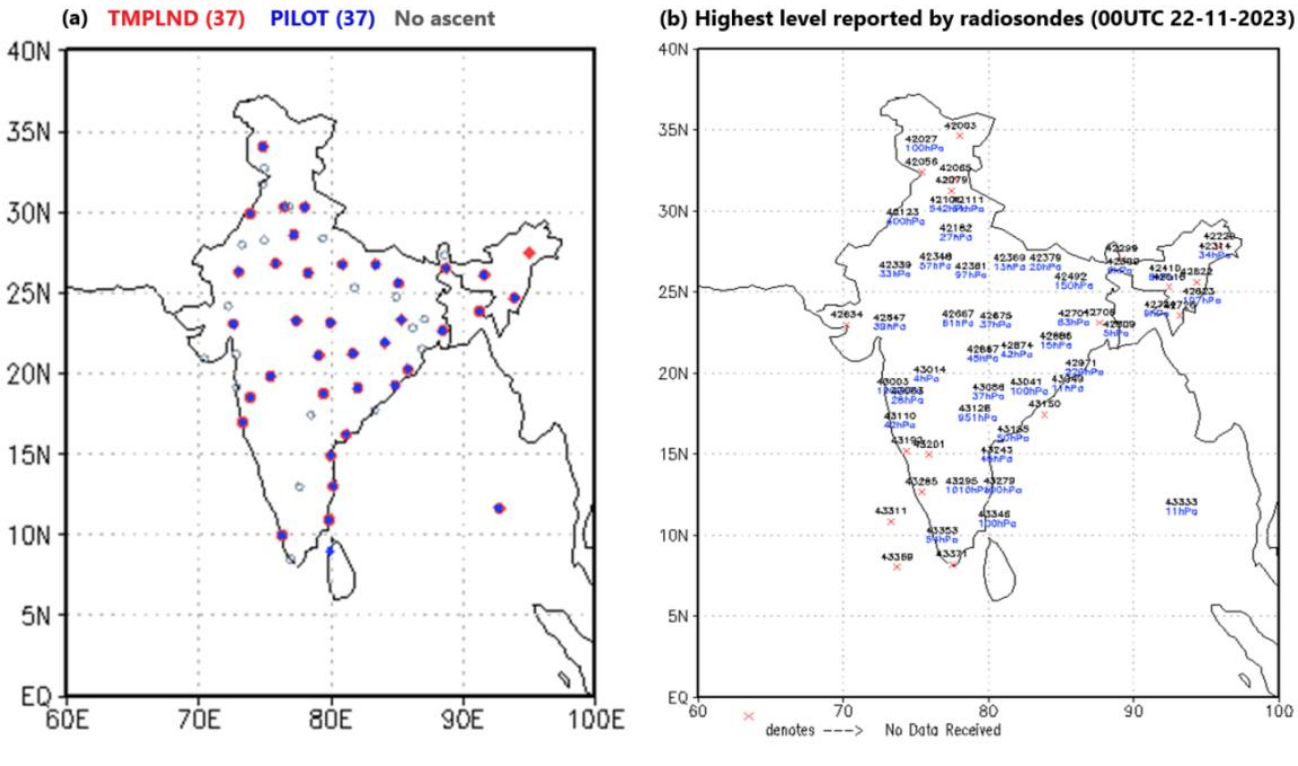

Figure 14: Indian radiosonde data monitoring (a) coverage of Indian radiosonde and pilot balloon reports and (b) the maximum height at which the profiles are reported from each station on a typical assimilation cycle of 00 UTC.

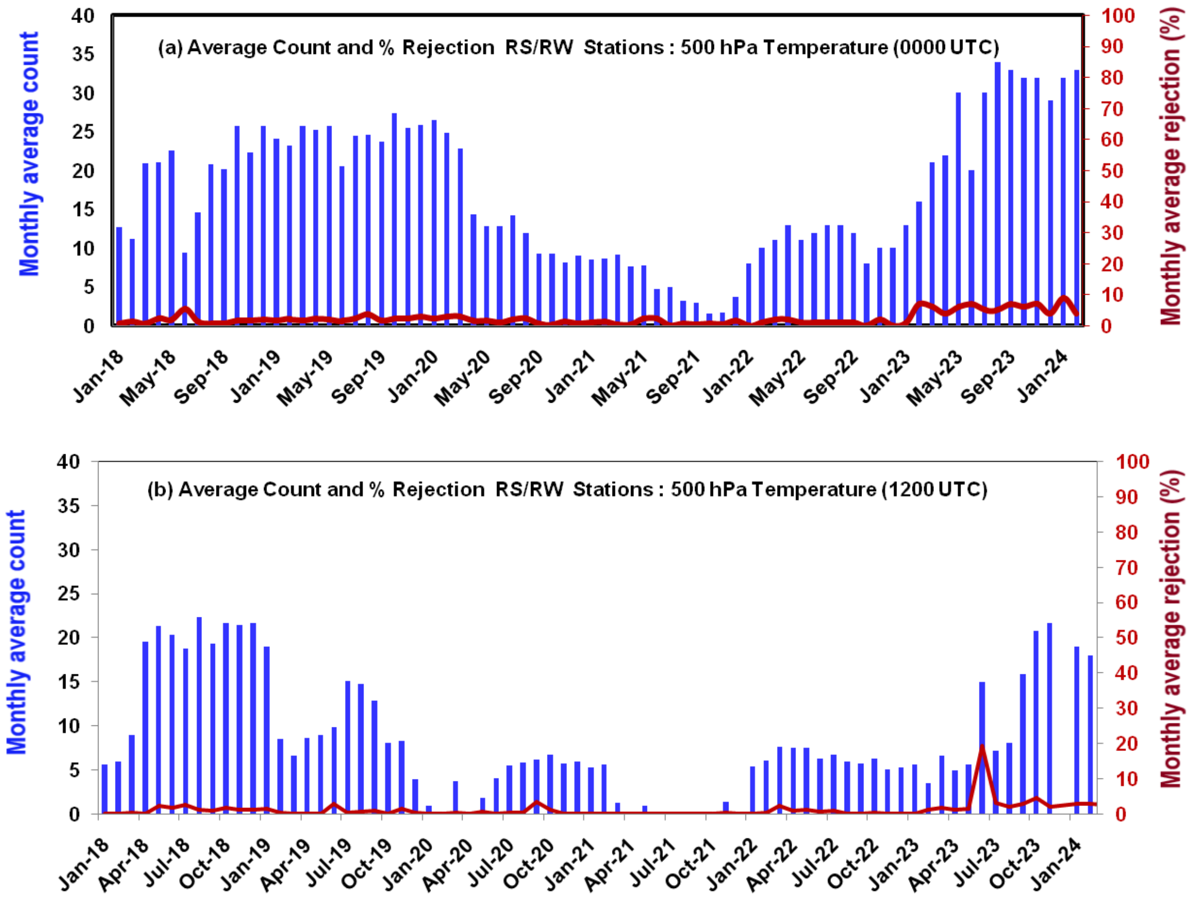

Figure 15: Monthly average number of RS/RW reports received at NCMRWF and their rejection percentage in the assimilation system from January 2018 to February 2024 during (a) 0000 UTC and (b) 1200 UTC assimilation cycles.

5.3 Aircraft

Aircarft-based observations are another conventional upper air dataset available for NWP assimilation. Unlike sondes, the aircraft observations generally provide information at the flight level and profiles during take-off and landing. Most aircraft data received through GTS contains only flight level observations, particularly above 500 hPa. There are two types of aircraft meteorological observations: AIREP (pilot reports) and AMDAR (Aircraft Meteorological Data Relay).

Figure 16 shows the coverage of Aircraft observations received at NCMRWF during a typical assimilation cycle. The WMO Integrated Global Observing System (WIGOS) framework allows the establishment of AMDAR regional centres operated by the National Meteorological and Hydrological Services (NMHS). WIGOS-AMDAR, shown in Figure 16, represents various regional AMDAR programs. The AIREP observations over the Indian Ocean region have doubled since December 2022, mainly due to the collaborative efforts between MoES (IMD and NCMRWF) and the Ministry of Civil Aviation. Figure 17 shows the time series of AIREP observations received at NCMRWF through GTS from November to December 2022. The AIREP coverage over the Indian Ocean region is marked in a green rectangle in Figure 16. The impact of aircraft observations over the Indian domain is described in *Rani et al. (2023a).*

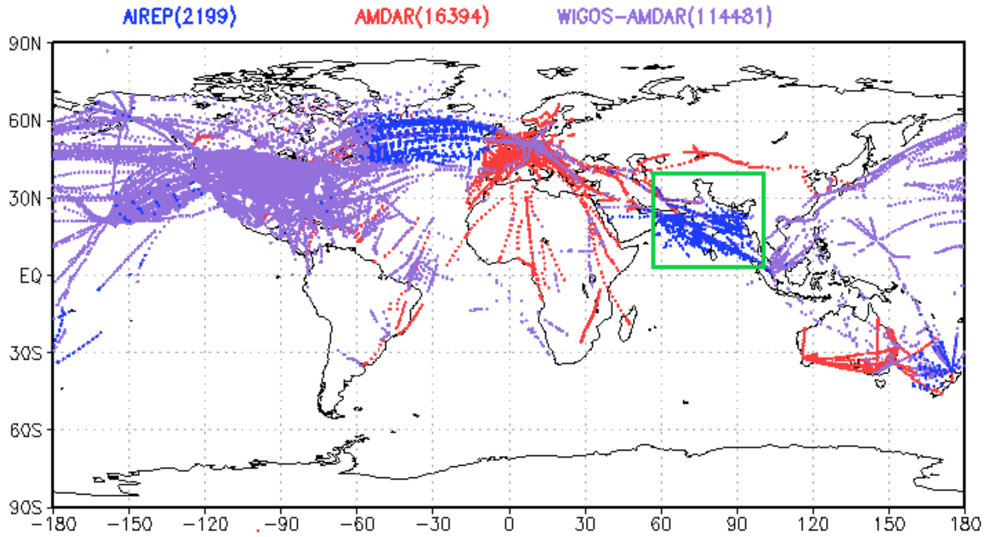

Figure 16: Global coverage of aircraft observations received at NCMRWF during a typical assimilation cycle. A green rectangle marks the AIREP observation coverage over the Indian Ocean region.

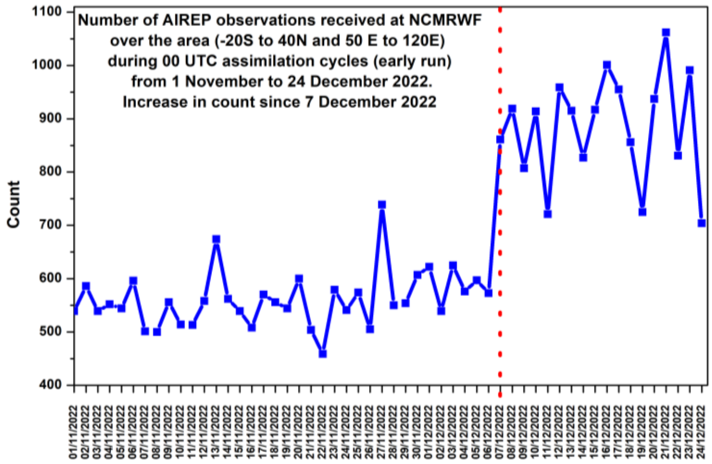

Figure 17: Time series of AIREP observations received at NCMRWF (20°S to 40°N and 50°E to 120°E) during 00 UTC assimilation cycles for November-December 2022.

6 Satellite observations

As discussed in Section 4.1, the in-situ observations are very sparse. Though surface observations have good coverage over the Tropics, they are limited to a single level. The upper air profiles are confined over the northern hemisphere land region. The aircraft observations are mainly flight-level data concentrated in heavy air traffic areas. Remote sensing techniques collect observations over the Oceans and data sparse regions. Satellite observations supplement their in-situ counterparts. NCMRWF receives observations from Geosynchronous Equatorial Orbit (GEO), Medium Earth Orbit (MEO), and Low Earth Orbit (LEO) satellites from national and international agencies (Figure 7). Satellite radiances (Table-1 section f), winds (Table-1 section e), and radio occultation (Table-1 section d) data are used in the NCMRWF assimilation systems.

6.1 Satellite Radiances

Satellite instruments do not measure the geophysical variables. Satellites can measure outgoing thermal radiation (radiance) from the Earth's surface and atmosphere. The radiative transfer equation can convert this thermal energy to the geophysical parameters. The brightness temperature corresponding to the radiance is assimilated in the NWP assimilation systems. Depending on the selection of frequency in different regions of the electromagnetic spectrum, information on different parts of the atmosphere can be collected. All weather satellites have onboard radiance sensors called radiometers, which make measurements of the emitted radiation in a series of discrete spectral intervals of the electromagnetic spectrum. The sensors are designated according to the wavelength band utilized.

Currently, meteorological satellite instruments operate in the visible, infrared, and microwave regions of the electromagnetic spectrum. The visible sensors detect the visible portion of the sunlight reflected back to space from the clouds, the Earth's surface, and the atmosphere. The spectral range of these sensors typically lies within the atmospheric window. The amount of the short wave radiation detected by the sensor is a function of the reflectivity of the earth-atmosphere system. The onboard infrared sensors respond to the upwelling infrared radiation emitted by clouds, the Earth's surface, and the atmosphere. Most infrared sensors detect radiation within the wavelength band, a reasonably transparent window region of the atmosphere. These satellite sensors can detect the long wave radiation upwelling from the radiating Earth's surface in cloud free regions. Technically, the water vapor image is often considered a different channel. The water vapor channel measures infrared near the water vapor absorption band. A set of water vapor channel radiometers senses the infrared radiation emitted by water vapor located in the mid to upper troposphere. Some satellites have a scanning microwave radiometer that senses the microwave radiation emitted by the Earth. Microwave radiation can penetrate clouds and distinguish between ground, ice, or snow surfaces.

Present meteorological satellites in the geostationary orbits operate in visible and infrared regions. In contrast, the satellite instruments in the LEOs, including polar and inclined, also operate in the microwave region. There are multispectral and hyperspectral instruments onboard meteorological satellites (kindly refer to Table 1 for more details). Currently used geostationary satellite instruments are multispectral, while hyperspectral instrument observations from LEO satellites are also used in the NCMRWF models. Details of the satellite data monitoring at NCMRWF are available at *Bushair et al. (2019), Sharma et al. (2019), and Pattanayak and Prasad (2020).*

6.1.1 Geostationary satellites

NCMRWF receives geostationary satellite imager/sounder radiances many satellites. This includes data from international space agencies and the Indian Space Research Organization (ISRO). INSAT-3DR imager and sounder are the geostationary multispectral radiances being received at NCMRWF from the IMD/ISRO. Advanced Baseline Imager (ABI) onboard GOES-16 and GOES-18 of NASA/NOAA, Spinning Enhanced Visible and InfraRed Imager (SEVIRI) onboard Meteosat-10 and Metosat-9 of ESA, Advanced Himawari Imager (AHI) onboard Himawari-9 of JMA are the other geostationary satellite radiances being received and used in the NCMRWF NWP models. Figure 18a shows the geostationary multispectral satellite radiance coverage received at NCMRWF during a typical assimilation cycle. Meteosat-9 and INSAT-3DR have nearly the same geographical coverage area. The coverage plot of INSAT-3DR on a typical day is shown separately in Figure 18b. Selected infrared channel radiances from the geostationary multispectral instruments in the clear sky conditions are assimilated in the NCMRWF NWP models. Clear sky radiance data validation and monitoring over the Indian region are available at *Rani et al. (2019) and Bushair et al. (2021a)*

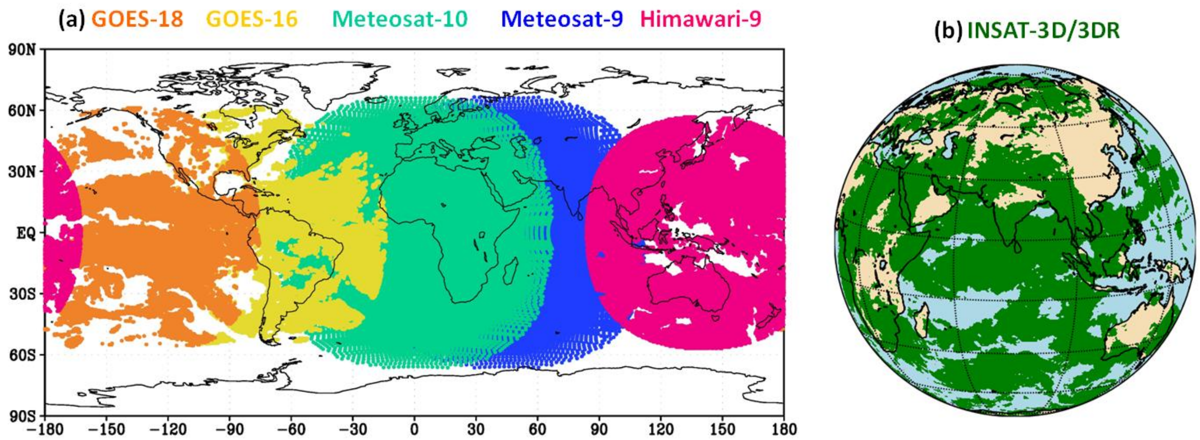

Figure 18: (a) Global coverage plot of Geostationary multispectral radiances being received at NCMRWF during a typical assimilation cycle and (b) coverage plot of INSAT-3D/3DR.

6.1.2 Polar orbiting satellites

NCMRWF receives near-real-time imager and sounder radiances from LEO satellite instruments from various data providers. Unlike geostationary satellites, LEO satellites have both multispectral and hyperspectral instruments onboard. Most multispectral instruments onboard LEO satellites operate in the microwave region of the electromagnetic spectrum, while the currently available hyperspectral instruments use the infrared wavelengths. Advanced TIROS Operational Vertical Sounding (ATOVS) comprising of three instruments, Advanced Microwave Sounding Unit-A (AMSU-A), AMSU-B, and High Resolution Infrared Sounder (HIRS), is a legacy instrument onboard NOAA and MetOp series of satellites. Advanced Technology Microwave Sounder (ATMS) is a successor to ATOVS, combining atmospheric temperature and humidity channels. ATMS onboard S-NPP, NOAA-20, and NOAA-21 are being received and operationally used at NCMRWF. Special Sensor Microwave Imager/Sounder (SSMI/S) instrument onboard Defence Meteorological Satellite Program (DMSP) satellites is a combination of microwave imaging and sounding channels. Other microwave imaging instruments used in the NCMRWF NWP models include Advanced Microwave Scanning Radiometer (AMSR) onboard GCOM-W and Global Precipitation Mission (GPM) Microwave Imager (GMI). Apart from these multispectral instruments, radiances from hyperspectral instruments such as Infrared Atmospheric Sounding Interferometer (IASI) onboard MetOp satellites, Cross-track Infrared Sounder (CrIS) onboard S-NPP, NOAA-20 and NOAA-21 satellites, and Atmospheric Infrared Sounder (AIRS) onboard AQUA satellite are also used in the NCMRWF NWP models. Figure 19 shows the coverage plots of radiances from various LEO satellite instruments received at NCMRWF on a typical assimilation cycle. Monitoring and assimilation of hyperspectral radiances in the NCMRWF NWP system is discussed in *Jangid et al. (2021).*

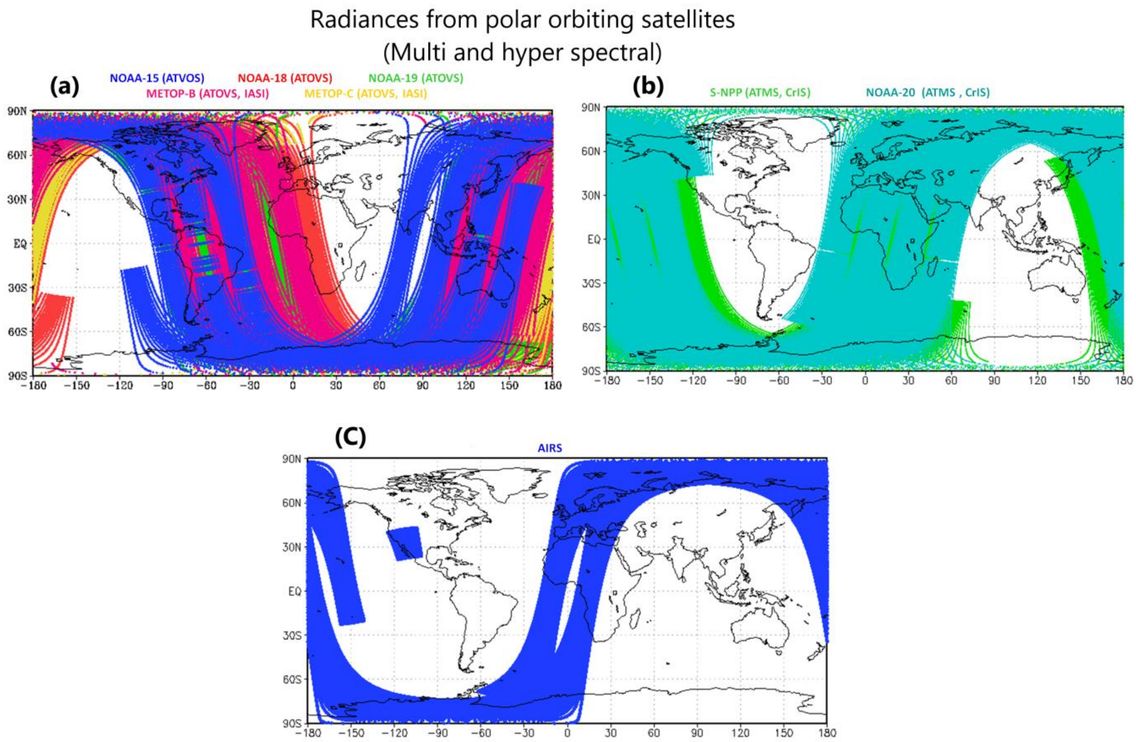

Figure 19:Coverage plots of LEO satellites' multispectral and hyperspectral radiances on a typical assimilation cycle.

Apart from the global data from LEO satellite multispectral and hyperspectral instruments, NCMRWF also receives regional DBNet (Direct Broadcast Network) data from the LEO satellites through the GTS, EumetCast ATOVS Retransmission Service (EARS) and Regional ATOVs Retransmission Service (RARS). The data latency is generally less than 1 hour for the DBNet compared to the full orbit data. This early access to the data helps operational NWP centres to manage the data assimilation and, hence, the accurate initial condition.

6.1.3 Indian DBNet Data

Since the IMD DBNet stations (Delhi, Chennai, and Guwahati) are non-functional, NCMRWF has put effort to access the DBNet data from INCOIS and NRSC. In-house packages are developed to process the level-0 DBNet data from these stations. As per the requirement of the global DBNet community, NCMRWF is packing the Indian DBNet data (ATOVS, IASI, ATMS, and CrIS) in the WMO BUFR format and disseminating it through the GTS via IMD. Figure 20 shows the coverage of Indian DBNet data received at NCMRWF on a typical day. Initial assimilation experiments show that these observations play an important role in simulating cyclone track and intensity over the North Indian Ocean (*Rani et al., 2023b; Srinivas et al., 2024*).

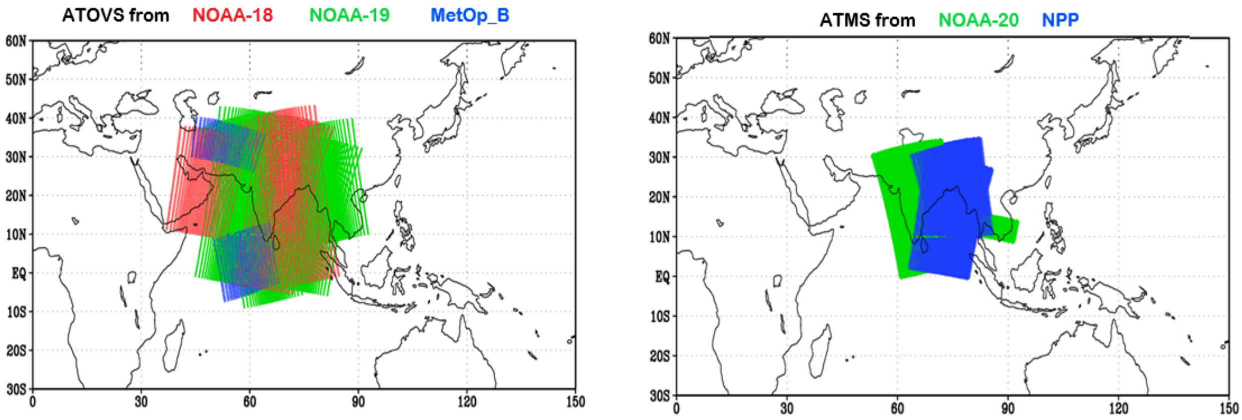

Figure 20: DBNet data coverage received from NRSC/INCOIS and processed at NCMRWF on a typical day (a) ATOVS and (b) ATMS.

6.2 Global Navigation Satellite System-Radio Occultation (GNSS-RO)

Radio Occultation (RO) is a remote sensing technique used for measuring the physical properties of a planet's atmosphere. The GNSS-RO technique involves a LEO satellite receiving a signal from a GNSS satellite in the MEO at an altitude of ~20000 km above the Earth's surface. The signal has to pass through the atmosphere and gets refracted along the way due to the density gradient. The changes in the relative position of the GNSS satellite and the LEO with time allow the vertical scanning of successive layers of the atmosphere. The information on the temperature, pressure, and water vapor content in the neutral atmosphere can be derived using GNSS-RO data applications.

NCMRWF receives the global GNSS-RO data through GTS, NOAA, and EumetCast. The COSMIC-2 series of GNSS-RO data received at NCMRWF during the pandemic helped balance the lack of aircraft observations (*Rani et al., 2023a*). The MoU between IMD and NOAA has provided access to the SPIRE GNSS-RO observations through private partnerships. Unlike other satellite and conventional observations, the GNSS-RO observations (bending angle) are nearly bias-less. The rejection by the assimilation system is less, and these observations act as anchoring observations to adjust the biases in the other assimilated satellite observations. Figure 21a shows the coverage of GNSS-RO observations received at NCMRWF on a typical day assimilation cycle. Figure 21b shows the time series of GNS-RO observations received and assimilated at NCMRWF. NCMRWF has carried out many studies to understand the impact of GNSS-RO data in the assimilation systems (*Johny and Prasad, 2014; Johny and Prasad, 2018; Dutta et al., 2024; Dutta and Prasad, 2024a*)

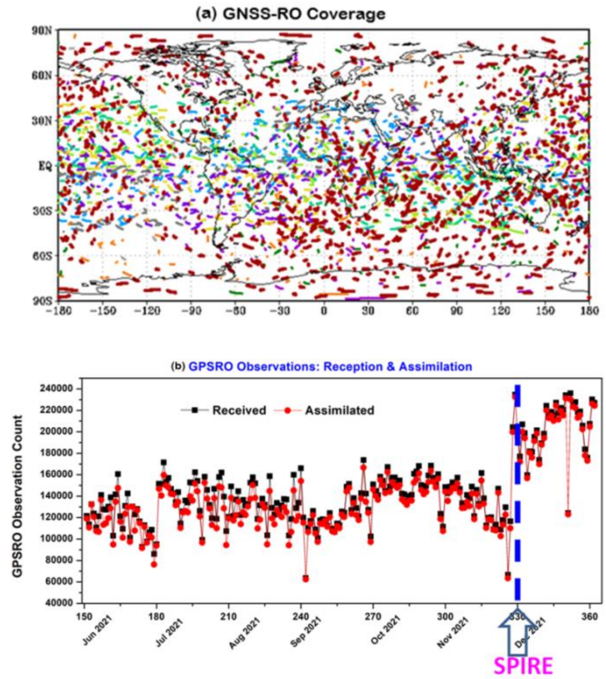

Figure 21: GNSS-RO Reception and Assimilation (a) coverage on a typical assimilation cycle, (b) time series of GNSS-RO observations received and assimilated. An increase in the observations is noted while adding SPIRE in late November 2021.

6.3 Satellite wind products

The wind field is essential to incorporate synoptic and mesoscale features in the NWP initial conditions. Atmospheric Motion Vectors (AMVs) are the winds derived by tracking the features in successive satellite images using different techniques. Though the AMVs provide winds over remote and oceanic regions, their height assignment and vertical sampling are often limiting issues. Scatterometers and radiometers provide reliable sea surface wind information at 10m. Doppler Wind Lidar (DWL) onboard the Aeolus satellite provided high quality wind observations at different troposphere and stratosphere levels. This section discusses various satellite wind products operationally assimilated in the NCMRWF NWP models.

6.3.1 Atmospheric Motion Vectors (AMVs)

NCMRWF receives global satellite winds from various sources. AMVs from geostationary satellites cover between 70°N and 70°S. Winds from polar satellites cover the gap north of 70°N and south of 70°S. Figure 22 shows the coverage of AMVs received at NCMRWF during a particular assimilation cycle. The geostationary AMVs consist of GOES-W (GOES-18), GOES-E (GOES-16), Meteosat-10, Meteosat-9 (IODC), Himawari-9 with additional data from INSAT-3D, INSAT-3DR and COMS-2. In addition to the geostationary AMVs, NCMRWF receives AMVs from polar satellites over both poles. The polar winds include AMVs from AQUA, TERRA, NOAA, and MetOp satellites. In addition, NCMRWF also receives the Dual MetOp winds generated by tracking the images from MetOp-B and MetOp-C. Validation and assimilation of AMVs at NCMRWF are well documented *(Das Gupta and Rani (2013), Rani and Das Gupta (2014), Das Gupta et al. (2015), Sharma et al. (2021)).*

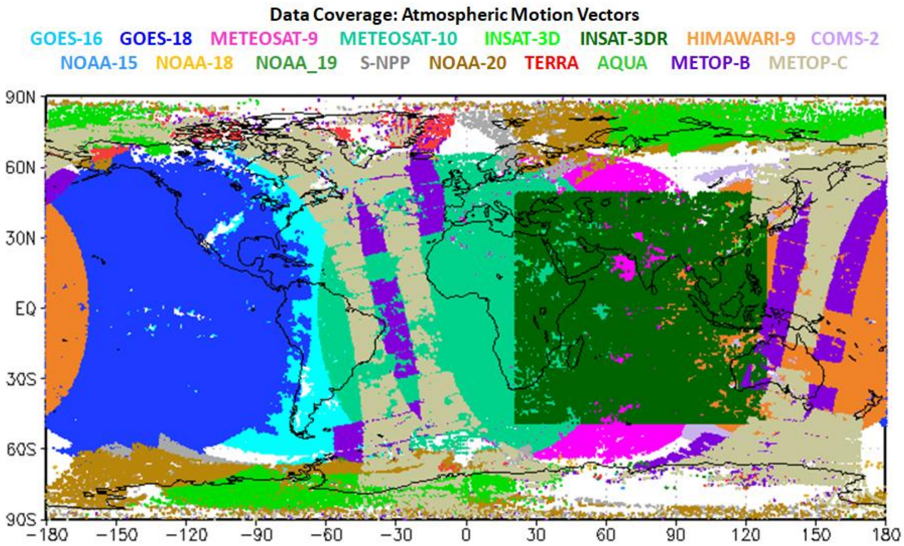

Figure 22: Global coverage of AMVs from geostationary, polar, and dual satellites received at NCMRWF during a typical assimilation cycle.

6.3.2 Sea Surface Scatterometer Winds

Sea surface wind products from space-based scatterometers play an important role in creating accurate NWP analysis over the data sparse oceanic region. NCMRWF receives sea surface winds from Advanced Scatterometers (ASCAT) onboard the MetOp series of satellites and the latest Indian satellite, Oceansat-3. Figure 23 shows the scatterometer data coverage received at NCMRWF during a typical assimilation cycle of 00 UTC. Validation and assimilation of sea surface scatterometer winds at NCMRWF can be found in *Rani and Das Gupta (2013), Rani et al. (2014), Prasad et al. (2014), Johny et al. (2019), Bushair et al. (2021b), Sankhala et al., (2024).*

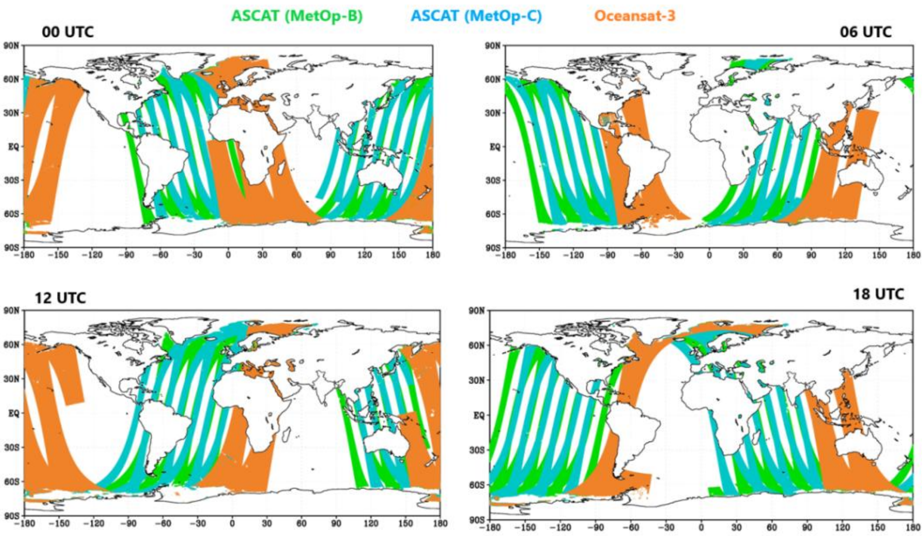

Figure 23: Global coverage of sea surface scatterometer winds from ASCAT-B, ASCAT-C, and Oceansat-3 received at NCMRWF during four different six hourly intermittent assimilation cycles.

6.3.3 Aeolus Doppler Wind Lidar

NCMRWF has been continuously making efforts to access many new satellite observations on par at global operational NWP centres. Aeolus is the first satellite launched by the European Space Agency (ESA) with a Wind LIDAR onboard to probe the atmosphere in two different channels, Mie and Rayleigh, depending on the scattering particles present in the atmosphere. NCMRWF received these observations through the EumetCast. Validation of Aeolus HLOS (Horizontal Line of Sight) winds against in-situ observations (Radiosonde and Aircraft), satellite winds, and NWP model equivalents shows that the error characteristics of the HLOS winds are independent of the validation datasets. The Indian monsoon circulation features like the Low Level Jet (LLJ), Tropical Easterly Jet (TEJ), and sub-tropical jets are well represented in the ascending and descending passes of Aeolus *(Rani et al., 2022)*. Figure 24 shows the global coverage of HLOS winds for a particular day. Figure 25 represents circulation features like LLJ, TEJ, and Subtropical Jets in the Aeolus HLOS winds during the Indian monsoon season. After successfully validating Aeolus HLOS winds, the same were assimilated in the NCMRWF assimilation systems *(George et al., 2021; Dutta and Prasad, 2024b)*. ESA announced the end of Aeolus operations on 30 April 2023.

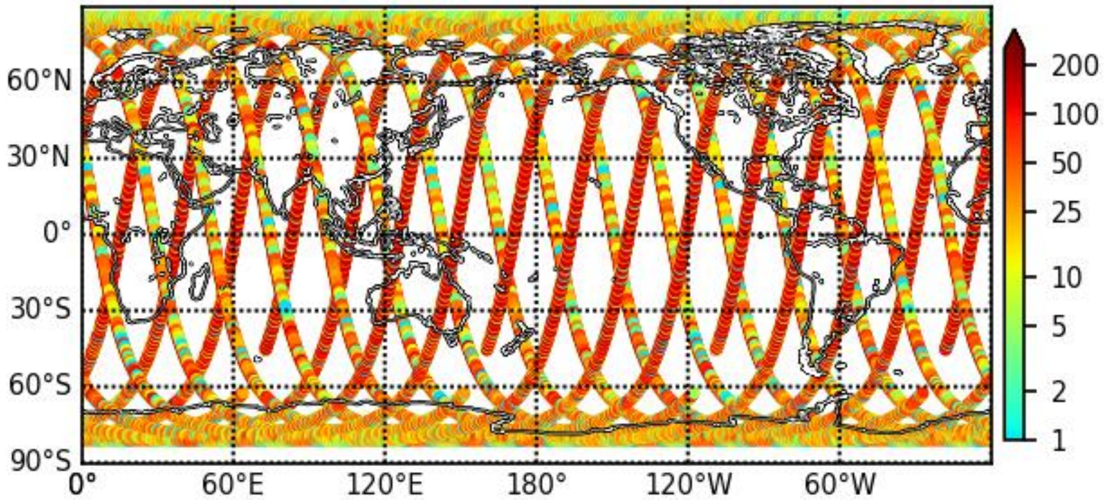

Figure 24: Global coverage of Aeolus HLOS winds during a typical day.

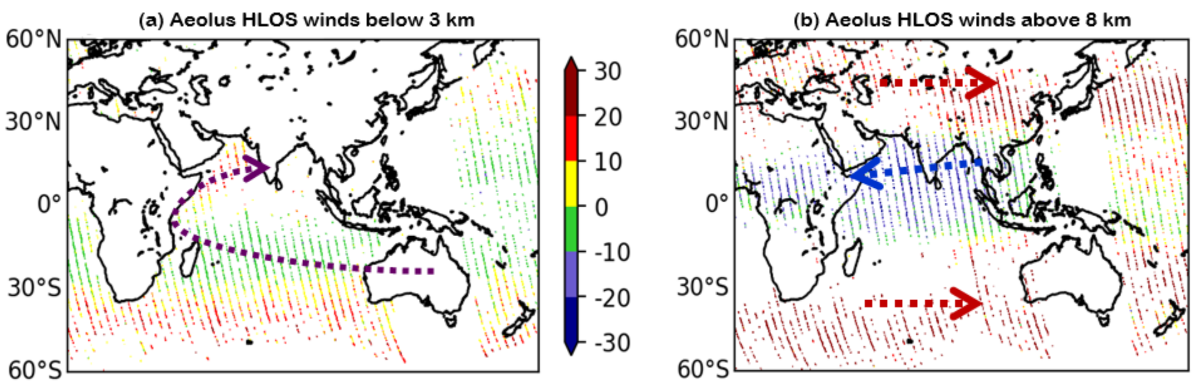

Figure 25: Aeolus HLOS winds during the Indian summer monsoon period (JJAS) (a) below 3 km, the LLJ is marked with the arrow, and (b) above 8 km, the TEJ is marked in blue arrow, and the sub-tropical jets in both the hemispheres are marked in red arrows.

7. Summary

This report summarises the observation reception, processing, and monitoring at NCMRWF for NWP assimilation. The NCMRWF Observation Reception, Processing, and Monitoring (NCObsProM) System is a unique and advanced legacy system developed indigenously at NCMRWF by adapting many open-source software. The NCObsProM alarms the issues, if any, so that the NCMRWF scientists can take further necessary actions. The plethora of observations received at NCMRWF include those from both conventional and remote sensing platforms. Each observation type has a unique role in the assimilation system while complementing and acting as anchor observations. The NCObsProM is a flexible system that can be modified to include the processing and monitoring of new and novel observations. NCMRWF's tireless effort to access global observations and their processing made NCMRWF a centre of excellence in data assimilation and NWP.

Acknowledgments

Many NCMRWF scientists (retired and existing) were/are involved in the continuous development of the NCObsProM, a legacy system. The authors express their heartfelt gratitude to all those directly and indirectly involved in developing NCObsProM at different periods.

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