NMRF/TR/03/2024

TECHNICAL REPORT

Assessing the quality of Indian Radiosondes against the global stations

Nishtha Agrawal and S. Indira Rani

June 2024

National Centre for Medium Range Weather Forecasting
Ministry of Earth Sciences, Government of India
A-50, Sector-62, NOIDA-201 309, INDIA

Assessing the quality of Indian Radiosonde observations against global stations

Nishtha Agrawal and S. Indira Rani

National Centre for Medium-Range Weather Forecasting

Ministry of Earth Sciences

A-50, Sector 62, NOIDA-201309, INDIA

Ministry of Earth Sciences

National Centre for Medium-Range Weather Forecasting

Document Control Data Sheet

1	Name of the Institute	National Centre for Medium Range weather Forecasting
2	Document Number	NMRF/TR/03/2024
3	Date of Publication	June 2024
4	Title of the Document	Assessing the quality of Indian Radiosonde observations against global stations
5	Type of Document	Technical Report
6	No. of Pages & Figures	27&11
7	Number of References	17
8	Author(s)	Nishtha Agrawal and S. Indira Rani
9	Organising Unit	NCMRWF
10	Abstract	Almost 54 radiosonde/rawinsonde (RS/RW) stations over India are operated and maintained by the Indian Meteorological Department (IMD). The number of RS/RW reports from India reduced drastically during the global pandemic. The Indian RS/RW reports start increasing gradually during 2022-2023. It is important to monitor the quality and consistency of the RS/RW reports in terms of statistical scores for different variables, particularly when they are re-initiated during the global pandemic. Regular monitoring of reception and assimilation of Indian RS/RW reports shows that NCMRWF receives more reports during 0000 UTC (30) than 1200 UTC (20) assimilation cycles, while the percentage rejections are less than 10 and ~ 3 during 0000 and 1200 UTC cycles during 2024. The objective of the present study is to assess the quality and consistency of Indian RS/RW data compared to the global co-latitudinal stations, particularly after the global pandemic. The quality of the Indian RS/RW stations is assessed by comparing the variables against the National Centre for Medium Range Weather Forecasting (NCMRWF) Numerical Weather Prediction (NWP) first guess and comparing those statistics with those of co-latitudinal global stations. The temporal variation of parameters like temperature, wind, and geopotential heights at different vertical pressure levels is evaluated over the Indian stations and the corresponding co-latitudinal global stations during the 2022 Indian summer monsoon period. The acceptance of RS/RW observation in the NCMRWF data assimilation system is also checked for the same period. The quality of the RS/RW variables is compared against the NCMRWF Global Forecast System (NGFS) short forecasts during 2022. Though there are many Indian RS/RW stations reported during 2022, global collocated stations at the near latitude belt has been obtained only for four stations, Delhi, Ahmedabad, Vishakhapatnam and Thiruvananthapuram considering the continuity of the data reception at NCMRWF. The corresponding collocated stations on the same latitudinal belts are Guimar (Spain), Mazatlan (Mexico), Luzon

		(Philippines) and Gudal (Philippines) respectively. The percentage acceptance of Indian RS/RW observations is larger than that of the global collocated stations. The statistical scores for different variables computed against the respective NGFS equivalents show that tin general the Indian RS/RW reports from the above four selected stations are consistent and within the specified errors for NWP assimilation.
11	Security Classification	Non-Secure
12	Distribution	Unrestricted Distribution
13	Key Words	Radiosonde, temperature, geopotential height, percentage acceptance

Assessing the quality of Indian Radiosonde observations against global stations

Nishtha Agrawal and S. Indira Rani

सारांश: भारत में लगभग 54 रेडियोसोंडे/रॉविनसोंडे (आरएस/आरडब्ल्यू) स्टेशन भारतीय मौसम विज्ञान विभाग (आईएमडी) द्वारा संचालित और रखरखाव किए जाते हैं। वैश्विक महामारी के दौरान भारत से आरएस/आरडब्ल्यू रिपोर्टों की संख्या में भारी कमी आई। भारतीय आरएस/आरडब्ल्यू रिपोर्ट 2022-2023 के दौरान धीरे-धीरे बढ़ने लगती हैं। विभिन्न चर के लिए सांख्यिकीय स्कोर के संदर्भ में आरएस/आरडब्ल्यू रिपोर्ट की गुणवत्ता और स्थिरता की निगरानी करना महत्वपूर्ण है, खासकर जब उन्हें वैश्विक महामारी के दौरान फिर से शुरू किया गया हो। भारतीय आरएस/आरडब्ल्यू रिपोर्टों के स्वागत और समावेशन की नियमित निगरानी से पता चलता है कि एनसीएमआरडब्ल्यूएफ को 1200 यूटीसी (20) आत्मसात चक्रों की तुलना में 0000 यूटीसी (30) के दौरान अधिक रिपोर्ट प्राप्त होती है, जबकि 0000 और 1200 यूटीसी चक्रों के दौरान अस्वीकृतियों का प्रतिशत 10 से कम और ~ 3 है। 2024 के दौरान वर्तमान अध्ययन का उद्देश्य वैश्विक सह-अक्षांशीय स्टेशनों की तुलना में भारतीय आरएस/आरडब्ल्यू डेटा की गुणवत्ता और स्थिरता का आकलन करना है, खासकर वैश्विक महामारी के बाद। भारतीय आरएस/आरडब्ल्यू स्टेशनों की गुणवत्ता का आकलन नेशनल सेंटर फॉर मीडियम रेंज वेदर फोरकास्टिंग (एनसीएमआरडब्ल्यूएफ) न्यूमेरिकल वेदर प्रेडिक्शन (एनडब्ल्यूपी) के पहले अनुमान के अनुसार चर की तुलना करके और सह-अक्षांशीय वैश्विक स्टेशनों के साथ उन आंकड़ों की तुलना करके किया जाता है। विभिन्न ऊर्ध्वाधर दबाव स्तरों पर तापमान, हवा और भू-संभावित ऊंचाइयों जैसे मापदंडों की अस्थायी भिन्नता का मूल्यांकन 2022 भारतीय ग्रीष्मकालीन मानसून अवधि के दौरान भारतीय स्टेशनों और संबंधित सह-अक्षांशीय वैश्विक स्टेशनों पर किया जाता है। एनसीएमआरडब्ल्यूएफ डेटा एसिमिलेशन सिस्टम में आरएस/आरडब्ल्यू अवलोकन की स्वीकृति की भी उसी अवधि के लिए जांच की जाती है। आरएस/आरडब्ल्यू चर की गुणवत्ता की तुलना 2022 के दौरान एनसीएमआरडब्ल्यूएफ ग्लोबल फोरकास्ट सिस्टम (एनजीएफएस) के लघु पूर्वानुमानों से की गई है। हालाँकि 2022 के दौरान कई भारतीय आरएस/आरडब्ल्यू स्टेशनों की सूचना दी गई है, एनसीएमआरडब्ल्यूएफ में डेटा रिसेप्शन की निरंतरता को देखते हुए, निकट अक्षांश बेल्ट पर वैश्विक कोलोकेटेड स्टेशन केवल चार स्टेशनों, दिल्ली, अहमदाबाद, विशाखापत्तनम और तिरुवनंतपुरम के लिए प्राप्त किए गए हैं। समान अक्षांशीय पट्टियों पर संबंधित स्थानान्तरित स्टेशन क्रमशः गुइमार (स्पेन), मजातलान (मेक्सिको), लूज़ॉन (फिलीपींस) और गुडाल (फिलीपींस) हैं। भारतीय आरएस/आरडब्ल्यू अवलोकनों की प्रतिशत स्वीकृति वैश्विक सह-आवंटित

स्टेशनों की तुलना में अधिक है। संबंधित एनजीएफएस समकक्षों के विरुद्ध गणना किए गए विभिन्न चर के लिए सांख्यिकीय स्कोर दर्शाते हैं कि सामान्य तौर पर उपरोक्त चार चयनित स्टेशनों से भारतीय आरएस/आरडब्ल्यू रिपोर्ट सुसंगत हैं और एनडब्ल्यूपी आत्मसात के लिए निर्दिष्ट त्रुटियों के भीतर हैं।

Abstract:

Almost 54 radiosonde/rawinsonde (RS/RW) stations over India are operated and maintained by the Indian Meteorological Department (IMD). The number of RS/RW reports from India reduced drastically during the global pandemic. The Indian RS/RW reports start increasing gradually during 2022-2023. It is important to monitor the quality and consistency of the RS/RW reports in terms of statistical scores for different variables, particularly when they are re-initiated during the global pandemic. Regular monitoring of reception and assimilation of Indian RS/RW reports shows that NCMRWF receives more reports during 0000 UTC (30) than 1200 UTC (20) assimilation cycles, while the percentage rejections are less than 10 and ~ 3 during 0000 and 1200 UTC cycles during 2024. The objective of the present study is to assess the quality and consistency of Indian RS/RW data compared to the global co-latitudinal stations, particularly after the global pandemic. The quality of the Indian RS/RW stations is assessed by comparing the variables against the National Centre for Medium Range Weather Forecasting (NCMRWF) Numerical Weather Prediction (NWP) first guess and comparing those statistics with those of co-latitudinal global stations. The temporal variation of parameters like temperature, wind, and geopotential heights at different vertical pressure levels is evaluated over the Indian stations and the corresponding co-latitudinal global stations during the 2022 Indian summer monsoon period. The acceptance of RS/RW observation in the NCMRWF data assimilation system is also checked for the same period. The quality of the RS/RW variables is compared against the NCMRWF Global Forecast System (NGFS) short forecasts during 2022. Though there are many Indian RS/RW stations reported during 2022, global collocated stations at the near latitude belt has been obtained only for four stations, Delhi, Ahmedabad, Vishakhapatnam and Thiruvananthapuram considering the continuity of the data reception at NCMRWF. The corresponding collocated stations on the same latitudinal belts are Guimar (Spain), Mazatlan (Mexico), Luzon (Philippines) and Gudal (Philippines) respectively. The percentage acceptance of Indian RS/RW observations is larger than that of the global collocated stations. The statistical

scores for different variables computed against the respective NGFS equivalents show that tin general the Indian RS/RW reports from the above four selected stations are consistent and within the specified errors for NWP assimilation.

1. Introduction

The upper air soundings play a key role in analyzing thermodynamic state of the atmosphere. The intense convective phenomenon such as thunderstorms, lightening and heavy rainfall give rise to atmospheric instability, which is elucidated using various in-situ observations including the Radiosonde/rawinsonde (RS/RW) instruments. RS/RW provides basic atmospheric parameters such as temperature, winds and humidity at multiple pressure levels from surface to 30-35 km above. They provide essential details about vertical stratification of the atmosphere, which is further fed into numerical models for calibration and assimilation. Due to this, the RS/RW soundings become extremely useful in enhancing the model forecast skills in the short and medium time ranges.

The active utilization of RS/RW became prominent between 1930s-1940s. The first RS/RW station over India was established in 1943 at New Delhi (Monthly normals of radiosonde and radiowind, 2010). Due to their utility and reliability, the demand of RS/RW data has grown and now the India Meteorological Department (IMD) has established more than 54 stations over major parts of the country. The locations of IMD stations from which NCMRWF received observations during 2022 are shown in figure 1.

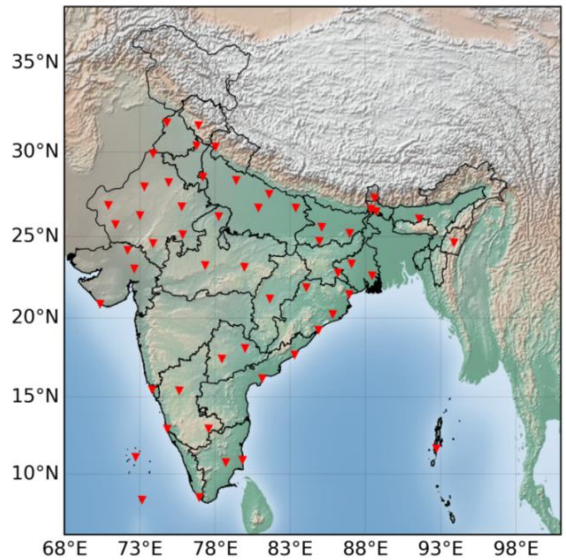

Figure1: Location of RS/RW stations (red marks) over India from which NCMRWF received observations during 2022.

Globally there are more than 1500 RS/RW stations. NCMRWF receives all the global RS/RW data including those from India through the Global Telecommunication System (GTS) via Regional Telecommunication Hub (RTH) New Delhi. Globally the RS/RW observations are recorded twice daily at 0000 UTC and 1200 UTC. There has been extensive research on the utilization of RS/RW data for operational and academic research purposes. In the absence of satellite data, RS/RW data were proven to be extremely helpful in improving the global observing system and Numerical Weather Prediction (NWP) forecasts (Dirksen et al., 2014; Ingleby et al., 2016). Apart from this, the upper air soundings obtained from the RS/RW data were found to be useful in detection and analysis of climate change by many studies (Luers and Eskridge, 1998; Free and Seidel, 2005; Haimberger et al., 2008). RS/RW data are sparse over the Oceans and unevenly spaced over land, yet are useful in production of reanalysis pressure level data having global and regional coverage (NCEP/NCAR Reanalysis 1; 1979 in NCEP/NCAR Reanalysis 2 and ECMWF's ERA-Interim; IMDAA and NGFS reanalysis). Similarly, the evaluation of Convective Available Potential Energy (CAPE) for multiple thunderstorm events and its relationship with upper troposphere temperature was studied by Manohar et al. (1999). Murugavel et al., (2012) performed trend analysis of monsoon CAPE using RS/RW data and postulated the dominance of low-level moisture and solar cycle in its growth. Similarly different studies have been performed to comprehend changes in tropospheric instability, boundary layer convection, solar effect and precipitation using radiosonde soundings (Murthy and Sivaramakrishnan, 2006; Allappattu and Kunnikrishnan, 2009; Xie et al., 2011; Basha and Ratnam, 2013; Saha et al. 2017).

Most of the RS/RW studies are often confined to lower and mid troposphere studies due to large inaccuracy over upper troposphere (Nash et al., 2011; Noh et al., 2016). The RS/RW observations are also known to suffer from radiation error in temperature data (Wang et al., 2003). Das Gupta (2006) compared the quality and consistency of Indian RS/RW reports by comparing them with global stations lying approximately on the same latitude belt. Statistical scores computed against the NCMRWF model equivalents showed that the Indian RS/RW reports were at par with the global stations (Das Gupta, 2006). The pandemic period witnessed a drastic reduction in the number of global RS/RW reports through GTS. Indian RS/RW reports were also less during this period either due to the lack of manpower or due to the non-availability of the payloads.

Figure 2a and b show the time series of the monthly mean reception count and percentage assimilation of Indian RS/RW observations in the NCMRWF Numerical Weather Prediction (NWP) systems during 0000 and 1200 UTC assimilation cycles for the period January 2018 to February 2024. Number of RS/RW reports being received during 1200 UTC assimilation cycles is lesser than the reports received during 0000 UTC assimilation cycles. The monthly average rejection of RS/RW observations in the NCMRWF assimilation system is less than 10% during both the assimilation cycles.

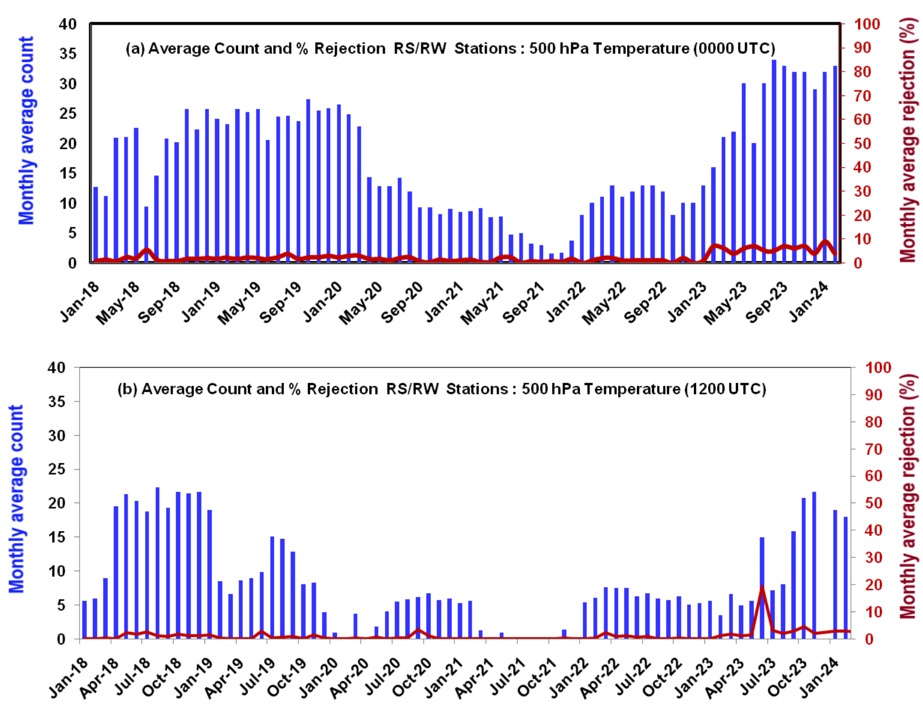

Figure 2: Monthly average number of RS/RW reports received at NCMRWF and their rejection percentage in the assimilation system from January 2018 to February 2024 during (a) 0000 UTC and (b) 1200 UTC assimilation cycles.

A drastic reduction in the reception of Indian RS/RW reports is noticed during the global pandemic period, particularly from January 2020 to December 2022. Afterwards, the Indian RS/RW reception count becomes nearly equal to the pre-pandemic period, particularly during 0000 UTC. The Indian RS/RW reception resumed approximately to the pre-pandemic period after September 2023 for the 1200 UTC assimilation cycle. It is important to ensure the quality and consistency of the RS/RW reports, especially after the re-introduction. The present study analyzes the quality of Indian RS/RW data as compared to their co-latitudinal global stations during the post pandemic period due to the reintroduction of new payloads at many Indian stations following Das Gupta, 2006. The manuscript is organized as follows, section 2 describes the details of data and methodology, section 3 discusses the results, and the main findings from this study and the future scope are briefed in section 4.

2. Data and Methodology

RS/RW data is received in World Meteorological Organization (WMO) Traditional ASCII Code (TAC) and Binary Universal Form for Representation (BUFR) formats through GTS via RTH New Delhi at NCMRWF. The GTS data received at NCMRWF is immediately decoded and appended into a tank file (bufrtank). Observations from the bufrtank files are extracted for various assimilation cycles depending on the assimilation window (generally ± 3 hours centred on the assimilation cycles at 0000, 0600 1200 1800 UTCs), called the dump files. These extracted observations are being monitored and stored in text format. These text files include the information of station metadata and variables like temperature, geopotential height, winds and dew point temperature at multiple pressure levels for each station. The observation processing part of NCMRWF Global Forecast System (NGFS) does the execution of a series of programs which assemble observations dumped from a number of decoders and encode information about the observation error and background values interpolated to the data location. This step also does rudimentary multi-platform quality control and more complex platform-specific quality control, and stores the output in a monolithic BUFR file, known as PREPBUFR.

The RS/RW observations extracted from the dump files in text format (without any quality information) and PREPBUFR (with quality information) are used in this study.

There are around 54 RS/RW stations installed all over India by IMD. All these stations are considered for the collocation with respect to the available global RS/RW stations. The criterion followed for the collocation is that the Indian station and the global station should lie approximately in the same latitudinal belt. We have fixed the latitude difference to be 0.5° (~50km). Out of 54 Indian stations, we have got collocated global stations for 22 Indian stations. Table 1 lists the 22 Indian stations and their collocated global stations along with their locations and elevation. We also checked whether these 22 Indian stations have any latitudinally collocated stations among the 54 Indian stations. Table 2 lists the mutually collocated Indian RS/RW stations latitudinally within 50 km. Out of globally collocated 22 Indian RS/RW stations, almost all stations have latitudinally collocated Indian stations within 50km latitudinally, except six stations (Gangtok, Sundernagar, Udaipur, Calcutta, Thiruvananthapuram and Mumbai), marked bold in Table 2. The 22 stations listed in Table 1 have not reported continuously during 2022. From the analysis, four Indian stations were selected such that those stations and their collocated global stations report for more than 300 days during 2022. The Indian stations extracted for this study include New Delhi, Ahmedabad, Vishakhapatnam and Thiruvananthapuram. From Table 1, their co-latitudinal stations were found to be Guimar (Spain), Mazatlan (Mexico), Luzon (Philippines) and Gudal (Philippines). The location of these four Indian stations and their nearest global station is shown in Figure 3.

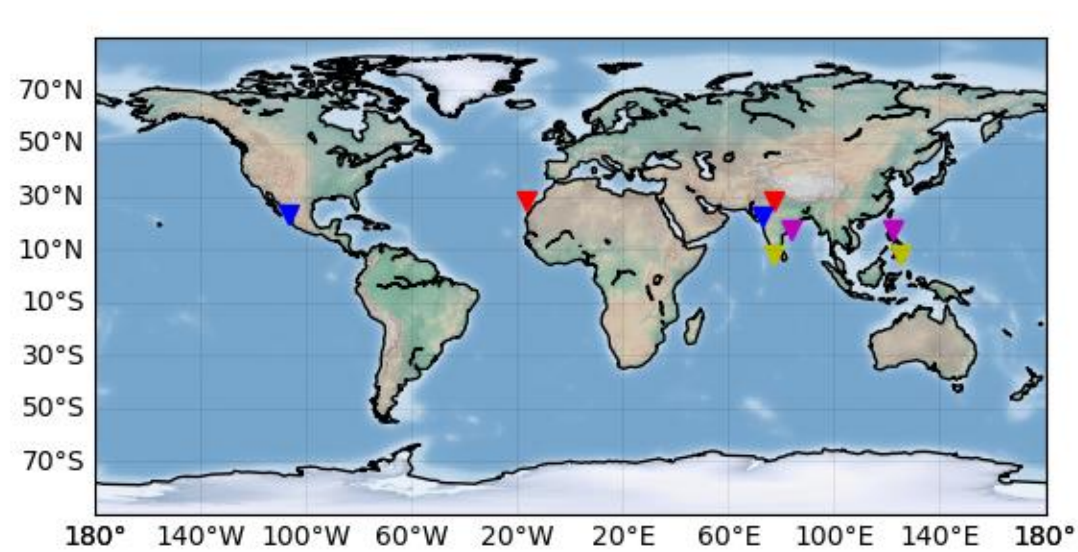

Figure 3: Locations of four Indian stations Delhi (red), Ahmedabad (blue), Vishakhapatnam (magenta) and Thiruvananthapuram (yellow) considered in the study and their corresponding co-latitudinal global stations, Guimar (Spain), Mazatlan (Mexico), Luzon (Philippines) and Gudal (Philippines) in respective colors.

Table 1: List of Indian stations with their corresponding co-latitudinal global stations.

Indian Stations					**Nearest Global Stations**				
Station Name	**WMO ID**	**LON**	**LAT**	**Elevation (m)**	**Station Name (country)**	**WMO ID**	**LON**	**LAT**	**Elevation (m)**
Ganganagar	42123	73.88	29.92	176	Lake Charles (US)	72240	-93.22	30.12	5
Bikaner	42165	73.3	28.00	224	Empalme (MX)	76256	-110.77	27.95	12
Churu	42170	74.92	28.25	291	Guimar (CR)	60018	-16.38	28.32	105
New Delhi	42182	77.2	28.58	267	Guimar (CR)	60018	-16.38	28.32	105
Gangtok	42299	88.62	27.33	1756	In Salah (AL)	60630	2.5	27.23	269
Jaisalmer	42328	70.92	26.90	231	Farafra (EG)	62423	27.98	27.05	78
Jodhpur	42339	73.02	26.30	224	Brownsville (US)	72250	25.92	-97.42	7
Jaipur	42348	75.8	26.82	390	Farafra (EG)	62423	27.98	27.05	78
Lucknow	42369	80.88	26.75	122	Farafra (EG)	62423	27.98	27.05	78
Gorakhpur	42379	83.37	26.75	77	Farafra (EG)	62423	27.98	27.05	78
Sundernagar	42079	76.9	31.53	874	Kagoshima (JP)	47827	130.6	31.63	31
Gauhati	42410	91.58	26.1	54	Brownsville (US)	72250	-97.42	25.92	7
Barmer	42435	71.38	25.75	194	Miami (US)	72202	-80.38	25.76	4
Kota	42452	75.85	25.15	274	King Khalid Airport (SD)	40437	46.72	24.93	612
Patna	42492	85.1	25.6	60	Miami (US)	72202	-80.38	25.76	4
Udaipur	42542	73.88	24.62	514	Key West (US) Medina (SD)	72201 40430	-81.79 39.72	24.55 24.55	13 636
Calcutta	42809	88.45	22.65	5	Guadalupe(MX)	76526	-102.51	22.75	2265
Thiruvananthapuram	43371	76.95	8.48	64	Gudal (PH)	98747	124.62	8.42	188
Mumbai	43003	72.85	19.12	14	Manzanillo (MX)	76654	-104.32	19.05	3
Ahmedabad	42647	72.63	23.07	55	Mazatlan	76458	-106.42	23.2	4

					(MX)				
Vishakhapatnam	43150	83.3	17.7	45	Luzon (PH)	98233	121.75	17.3	62
Madras	43279	80.18	13	16	Legaspi (PH)	98444	123.73	13.13	17

Table 2: List of Indian stations and their co-latitudinal Indian station(s)

Indian Station					**Nearest Indian Station**				
Station Name	**WMO ID**	**LON**	**LAT**	**ELEV**	**Station Name**	**WMO ID**	**LON**	**LAT**	**ELEV**
Ganganagar	42123	73.88	29.92	176	Dehradun	42111	78.03	30.32	682
Bikaner	42165	73.3	28.00	224	Churu	42170	74.92	28.25	291
Churu	42170	74.92	28.25	291	Bikaner	42165	73.3	28.00	224
New Delhi	42182	77.2	28.58	267	Churu	42170	74.92	28.25	291
Gangtok	42299	88.62	27.33	1756					
Jaisalmer	42328	70.92	26.90	231	Lucknow Gorakhpur	42369 42379	80.88 83.37	26.75 26.75	122 77
Jodhpur	42339	73.02	26.30	224	Gauhati	42410	91.58	26.1	54
Jaipur	42348	75.8	26.82	390	Lucknow Gorakhpur	42369 42379	80.88 83.37	26.75 26.77	122 77
Lucknow	42369	80.88	26.75	122	Gorakhpur	42379	83.37	26.75	77
Gorakhpur	42379	83.37	26.75	77	Lucknow	42369	80.88	26.75	122
Sundernagar	42079	76.9	31.53	874					
Gauhati	42410	91.58	26.1	54	Jodhpur	42339	73.02	26.3	224
Barmer	42435	71.38	25.75	194	Patna	42492	85.1	25.6	60
Kota	42452	75.85	25.15	274	Patna	42492	85.1	25.6	60
Patna	42492	85.1	25.6	60	Kota	42452	75.85	25.15	274
Udaipur	42542	73.88	24.62	514					
Calcutta	42809	88.45	22.65	5					
Thiruvananthapuram	43371	76.95	8.48	64					
Mumbai	43003	72.85	19.12	14					
Ahmedabad	42647	72.63	23.07	55	Calcutta	42809	72.63	23.07	5
Vishakhapatnam	43150	83.3	17.7	45	Hyderabad	43128	78.46	17.45	530
Madras	43279	80.18	13	16	Bangalore	43295	77.58	12.97	921

The present analysis is being performed for these eight stations at 0000 UTC on the annual and seasonal scales during 2022. The summer monsoon season of India (June-July-August-September) is chosen for the seasonal analysis as this period is crucial for agriculture production and economy of India. Variables like temperature, winds and geopotential at lower (850 hPa), middle (500 hPa) and upper (200 hPa) atmospheric levels are considered for the assessment.

Usually, the quality and consistency of different variables are estimated through various statistical scores. The average value of observation variables is estimated with the help of mean, which is described in equation (1).

$$\mu = \frac{\sum X}{n} \qquad \text{______ } \mathbf{(1)}$$

The spread of observations is estimated via analyzing the pattern of Standard deviation, which is described in equation (2).

$$\sigma = \sqrt{\frac{\sum (X-\mu)^2}{n}} \qquad \text{______} \mathbf{(2)}$$

where, ‘X’ is the time series of length ‘n’.

Comparison of RS/RW observations and NGFS short forecasts is estimated with the help of correlation coefficient which is obtained as per the equation (3).

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \qquad \text{_______} \mathbf{(3)}$$

where x_i and y_i are time series of RS/RW and NGFS datasets, $\bar{x}$ and $\bar{y}$ are mean values of these datasets.

3. Results and Discussions

We discuss the results for four Indian RS/RW stations and their corresponding global co-latitudinal stations considering the data continuity during 2022. PREPBUFR files (described in section 2) during 2022 are considered for the estimation of the acceptance of observations from these stations in the NCMRWF NWP model. The text files from the dump files are used for analyzing the RS/RW observation quality during the southwest monsoon season of 2022.

3.1 Analysis of RS/RW data during the Indian south-west monsoon season

The temporal variability of observations (temperature, wind speed and geopotential height) from the four Indian RS/RW stations and their corresponding collocated global stations were analyzed during the southwest monsoon season in terms of statistical scores. The instrument error can vary depending on the type of sensors used for the measurement of different variables like temperature, relative humidity, pressure, geopotential height, wind vector etc. If the station is using same RS/RW payload throughout the period (for example annually) then the instrument error is supposed to remain same, this in turn can ensure a constant magnitude of the standard deviation when comparing the observation against the NWP short forecasts, unless there is a major change in the data assimilation and forecast system of the NWP model. The following sections discuss the temporal variation of temperature, wind speed and geopotential height at different pressure levels over the Indian stations and the corresponding co-latitudinal global stations. This provides a clearer picture on the synoptic weather conditions over the respective locations during the period of study.

3.1.1. Temperature:

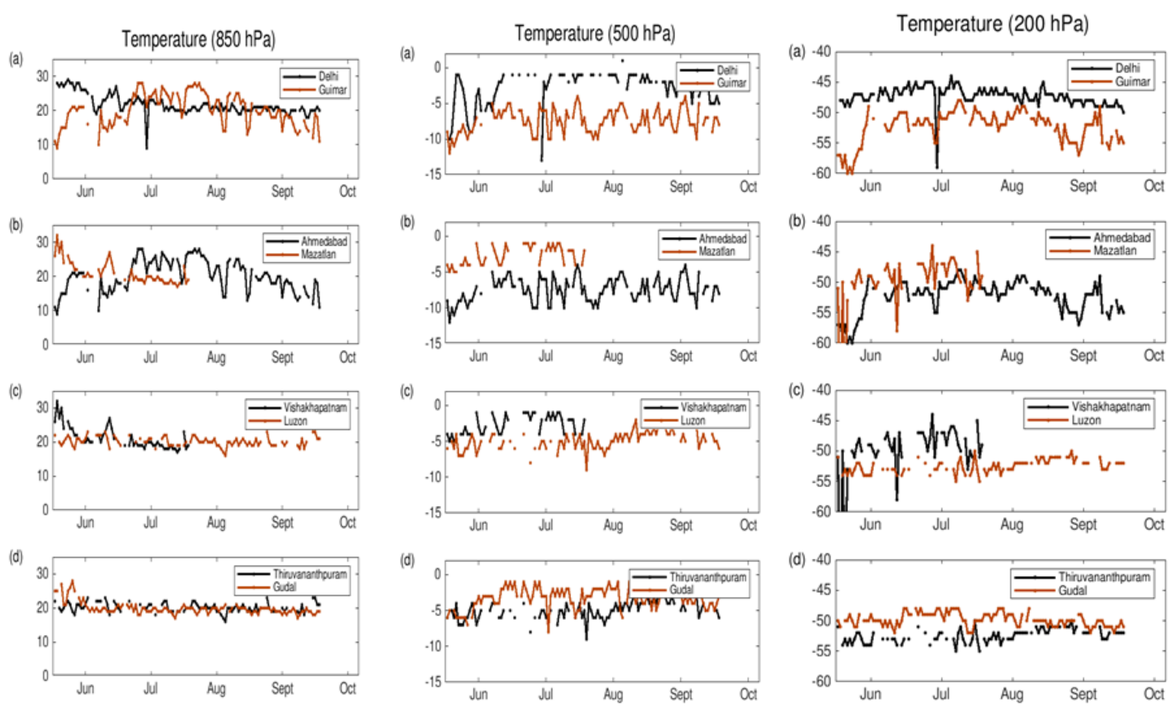

Figure 4: Daily time series of temperature (in ^{0}C) at lower (850 hPa), middle (500 hPa) and upper (200 hPa) troposphere at the four Indian stations and their co-latitudinal global stations.

Indian monsoon is known to bring large variability in temperature, winds and humidity due to strong convection in major parts of India. Figure 4 shows the daily (00 UTC) time series of temperature at the four Indian stations and their co-latitudinal global stations at 850 hPa, 500 hPa and 200 hPa during June-July-August-September (JJAS) period. The Indian stations show high variability in temperature in the middle and upper tropospheric levels. While their co-latitudinal stations remained cooler during this period. The mean temperature and the corresponding standard deviation (SD) at three different levels are shown in Tables 3, 4 and 5.

Table 3 shows the statistics of 850hPa temperature during JJAS for the Indian stations and their corresponding global stations. The SD of temperature at 850 hPa in Delhi is comparatively lower than the corresponding global station Guimar. Rest of the other stations is having higher SD as compared to their corresponding global stations. Similarly, Table 4 shows the statistics for 500 hPa temperature. The SD at all the Indian stations is higher than the corresponding global stations. The mean temperature over the Indian stations was slightly higher than that of the corresponding global collocated stations. In general, the Indian stations show a slightly higher SD both at 850 and 500 hPa levels primarily due to the dominance of monsoon.

Table 3: Statistics of 850 hPa Temperature during JJAS 2022.

Station Name	Mean (°C)	Standard Deviation (°C)	Station Name	Mean (°C)	Standard Deviation (°C)
Delhi	21.74	2.82	Guimar	20.13	4.63
Ahmedabad	21.10	3.27	Mazatlan	20.17	1.39
Vishakhapatnam	19.89	1.82	Luzon	18.58	0.87
Thiruvanathapuram	17.26	1.33	Gudal	18.08	0.73

Table 4: Statistics of 500 hPa Temperature during JJAS 2022.

Station Name	Mean (°C)	Standard Deviation (°C)	Station Name	Mean (°C)	Standard Deviation (°C)
Delhi	-2.94	2.46	Guimar	-7.44	1.67
Ahmedabad	-2.65	1.34	Mazatlan	-4.98	1.21
Vishakhapatnam	-3.34	1.41	Luzon	-3.91	0.85
Thiruvanathapuram	-4.35	1.13	Gudal	-4.40	0.67

3.1.2. Wind Speed:

Figure 5 shows the time series of wind speed at the four Indian stations and their corresponding global stations at low, middle and upper tropospheric levels during the JJAS season. The low level wind over the Indian stations is faster than that over the collocated global stations. In the middle level, the wind speeds are of nearly the same magnitudes over the station pairs. In the upper level, the winds over the Indian stations are faster than the collocated global stations, except over Thiruvananthapuram.

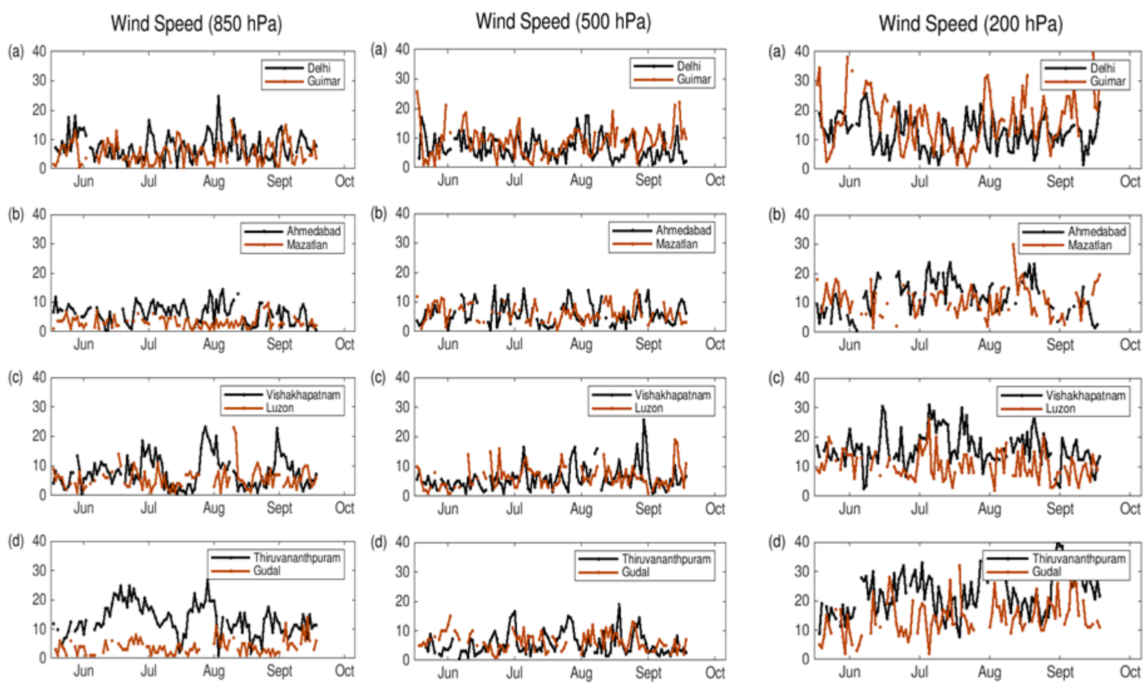

Figure 5: Daily time series of Wind Speed m/s) at lower (850 hPa), middle (500 hPa) and upper (200 hPa) tropospheric levels at the Indian stations and their co-latitudinal global stations.

Tables 5, 6 and 7show the mean wind speeds and the corresponding SDs at 850 hPa, 500 hPa and 200 hPa over all the stations. The mean wind speed in the lower level ranges between 6-13 m/s over Indian stations and 3-5.5 m/s over the corresponding global stations. Strong low level winds are observed over Thiruvananthapuram, which is part of monsoon Low Level Jet. Since there is a high variability in wind speed over the Indian stations during the south-west monsoon period, the SD values also high compared to the collocated global stations as seen from Table 5. The wind magnitudes are comparable over the Indian stations and the corresponding collocated global stations in the middle level and the corresponding SDs are also of comparable magnitude as seen from Table 6. At 200 hPa, the mean wind speeds are higher over all the stations and hence the SD as well as shown in Table 7.

Table 5: Statistics of 850 hPa Wind speed during JJAS 2022

Station Name	Mean (m/s)	Standard Deviation (m/s)	Station Name	Mean (m/s)	Standard Deviation (m/s)
Delhi	7.48	4.24	Guimar	5.33	3.66
Ahmedabad	6.19	3.34	Mazatlan	3.21	1.85
Vishakhapatnam	7.77	5.24	Luzon	5.72	3.54
Thiruvananthapuram	13.11	5.19	Gudal	3.90	2.49

Table 6: Statistics of 500 hPaWind speed during JJAS 2022

Station Name	Mean (m/s)	Standard Deviation (m/s)	Station Name	Mean (m/s)	Standard Deviation (m/s)
Delhi	6.74	3.85	Guimar	8.78	4.87
Ahmedabad	5.92	3.66	Mazatlan	6.16	2.97
Vishakhapatnam	6.17	4.09	Luzon	6.37	3.67
Thiruvananthapuram	5.62	3.85	Gudal	6.36	2.97

Table 7: Statistics for 200 hPa Wind speed during JJAS 2022

Station Name	Mean (m/s)	Standard Deviation (m/s)	Station Name	Mean (m/s)	Standard Deviation (m/s)
Delhi	12.06	5.48	Guimar	16.81	9.00
Ahmedabad	11.88	5.75	Mazatlan	10.95	4.96
Vishakhapatnam	16.21	5.75	Luzon	10.39	4.52
Thiruvananthapuram	22.64	7.19	Gudal	14.10	6.13

3.1.3. Geopotential Height:

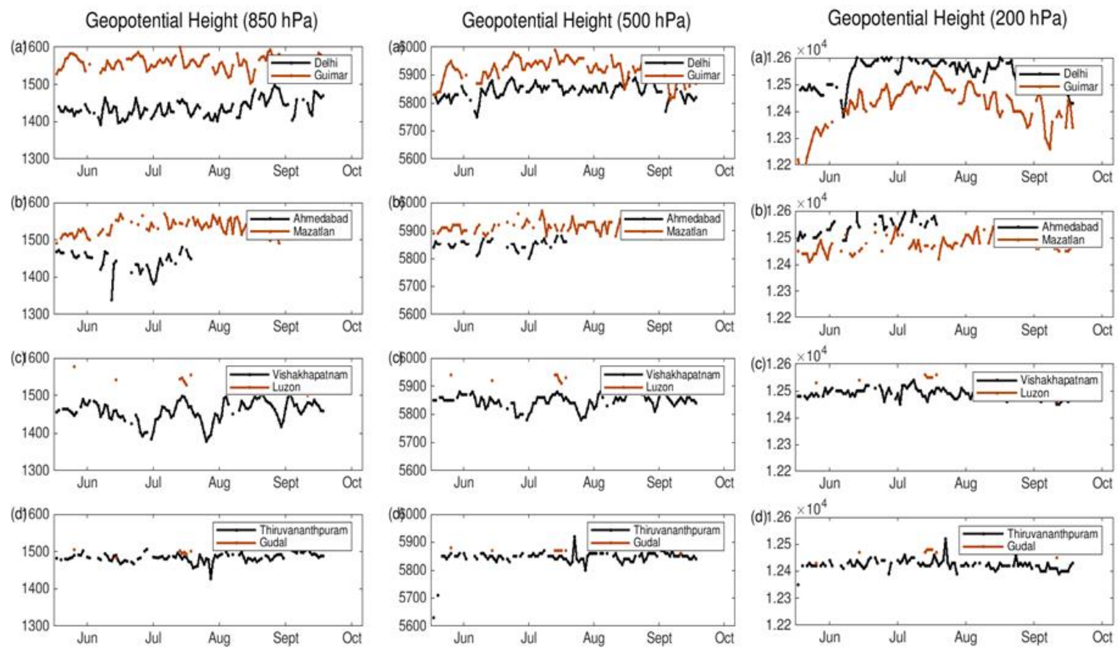

Figure 6: Daily time series of Geopotential Height (m) at lower (850 hPa), middle (500 hPa) and upper (200 hPa) troposphere at the four Indian stations and their co-latitudinal global stations.

Figure 6 shows the time series of geopotential height at the three different tropospheric levels from the eight stations considered in this study. The geopotential height of Indian stations at 850 and 500 hPa are shorter (cooler) than the same over the collocated global stations, while the geopotential heights at 200 hPa over the Indian stations are taller (warmer) than that of the global collocated stations. We can also relate the time series plot of temperature at different levels (Figure 4) with Figure 6. The mean and SD of geopotential height at multiple pressure levels are shown in Tables 8,9 and 10. At 850 hPa, the mean geopotential height in the Indian stations are slightly lower than the corresponding collocated global stations even if the station elevation of the collocated pairs are approximately in the same range (differences < 100 m from Table 1). In general, the differences in the 850 hPa geopotential height between the Indian and the global stations are less than 100 m, except over Delhi. The SD of geopotential height at 850 hPa over the Indian stations appears to be slightly higher than the global stations due to the large variability during the monsoon season. The geopotential heights and the SD at the middle (500 hPa) and upper (200 hPa) levels are approximately same at the collocated pairs as seen from Tables 9 and 10 except for Ahmedabad at 200 hPa.

Table 8: Statistics of 850 hPa Geopotential Height during JJAS 2022

Station Name	Mean (m)	Standard Deviation (m)	Station Name	Mean (m)	Standard Deviation (m)
Delhi	1437	23.00	Guimar	1556	18.87
Ahmedabad	1439	28.53	Mazatlan	1532	18.54
Vishakhapatnam	1458	27.85	Luzon	1539	19.94
Thiruvananthapuram	1485	12.51	Gudal	1500	8.83

Table 9: Statistics of 500 hPa Geopotential Height during JJAS 2022

Station Name	Mean (m)	Standard Deviation (m)	Station Name	Mean (m)	Standard Deviation (m)
Delhi	5844	27.02	Guimar	5920	36.14
Ahmedabad	5849	17.73	Mazatlan	5910	18.78
Vishakhapatnam	5847	24.51	Luzon	5916	23.66
Thiruvananthapuram	5848	19.41	Gudal	5872	6.32

Table 10: Statistics of 200 hPa Geopotential Height during JJAS 2022

Station Name	Mean	Standard Deviation	Station Name	Mean	Standard Deviation
Delhi	12542	52.21	Guimar	12421	73.96
Ahmedabad	12330	324.53	Mazatlan	12379	102.01
Vishakhapatnam	12490	17.93	Luzon	12520	46.90
Thiruvananthapuram	12425	17.40	Gudal	12465	15.81

3.2 Percentage acceptance of RS/RW stations in NGFS during 2022:

The PREPBUFR files provide the details of quality flags that are assigned to each variable at all the levels. NGFS assigns 2 and 9 as the main quality flags indicating acceptance and rejection respectively. Figure 7-4 shows the percentage acceptance of RS/RW temperature for the eight stations at different pressure levels. The percentage acceptance of wind is similar to that of temperature. The highest acceptance is for Vishakhapatnam for the three pressure levels.

Its co-latitudinal global station, Luzon, has shown lesser percentage acceptance (<10%) at these levels. Similarly, Thiruvananthapuram has shown percentage acceptance between 60%-70%, and its corresponding global station shows less than 10% of acceptance. Ahmedabad and Mazatlan have shown ~80% and ~65% acceptance respectively. Delhi has shown slightly less acceptance percent as compared to its nearest global station Guimar. This shows that all the four Indian stations selected in this study have shown higher reliability of temperature information (percentage acceptance > 80%) throughout the period of study compared to their nearby global stations.

Figure 8 is similar to Figure 7, but for the percentage acceptance of RS/RW geopotential height from the Indian as well as their collocated stations in the NGFS model. The Indian stations, Delhi and Vishakhapatnam have the highest percentage acceptance followed by Thiruvananthapuram and then Ahmedabad. Comparison with their collocated stations shows relatively higher percentage acceptance for Guimar and Mazatlan compared to the collocated Indian stations, Delhi and Ahmedabad. Luzon and Gudal have comparatively less percentage acceptance (< 10%) as compared to Vishakhapatnam and Thiruvananthapuram. In general data from Indian stations have higher acceptance (> 60%) except for Ahmedabad (<30%) for geopotential height.

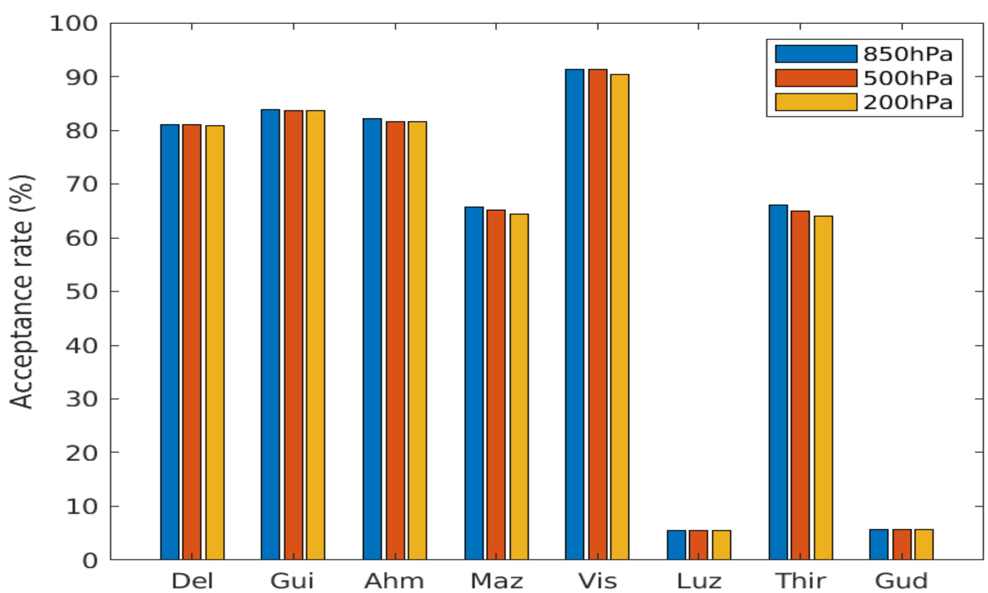

Figure 7: Percentage acceptance of RS/RW temperature from eight stations at 850 hPa, 500 hPa and 200 hPa levels.

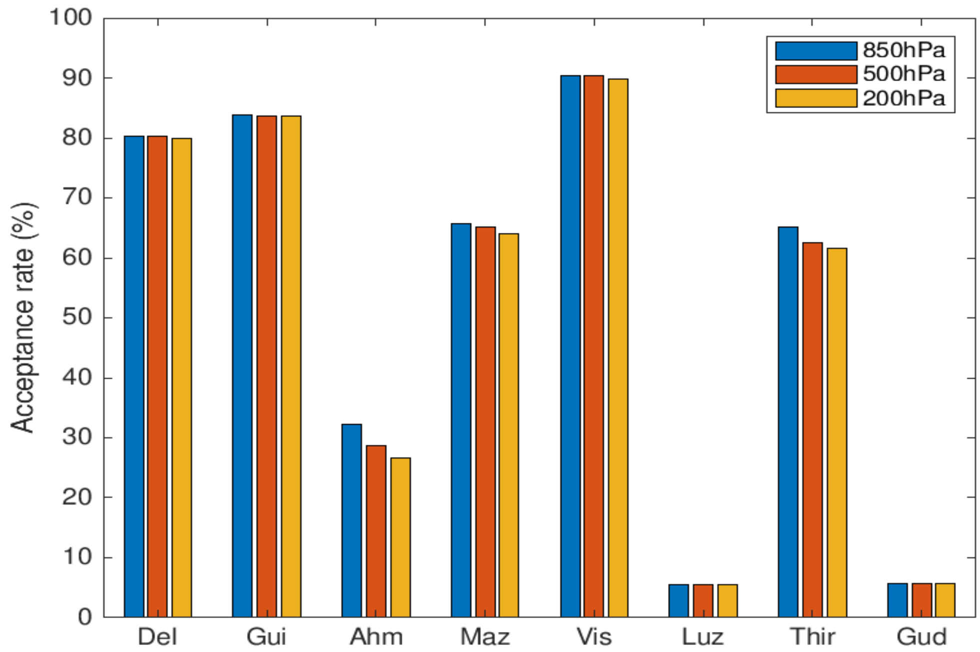

Figure 8: Similar to Figure 7, but for the geopotential height.

3.3. Comparison of RS/RW observations with the NGFS short forecasts:

Correlations between the observed RS/RW variables and the corresponding NWP equivalents from the NGFS short forecasts with $p < 0.05$ are computed for eleven pressure levels, between 1000 hPa and 100 hPa. Figure 9 shows the correlation between the RS/RW temperature and the corresponding NWP equivalents for the four Indian stations and the corresponding collocated global stations. In general, the RS/RW temperature observations at various pressure levels show better correlation with the first guess over the Indian stations than the global collocated ones, except over Ahmedabad. Low level temperatures are better collated at all the four Indian stations, while the correlation above 200 hPa is slightly less over the Indian stations. Maximum correlation between the observation and NWP equivalent is seen over Delhi and Guimar, the corresponding collocated global station, while the minimum correlation is noticed over Thiruvananthapuram and Gudal, the corresponding collocated global station.

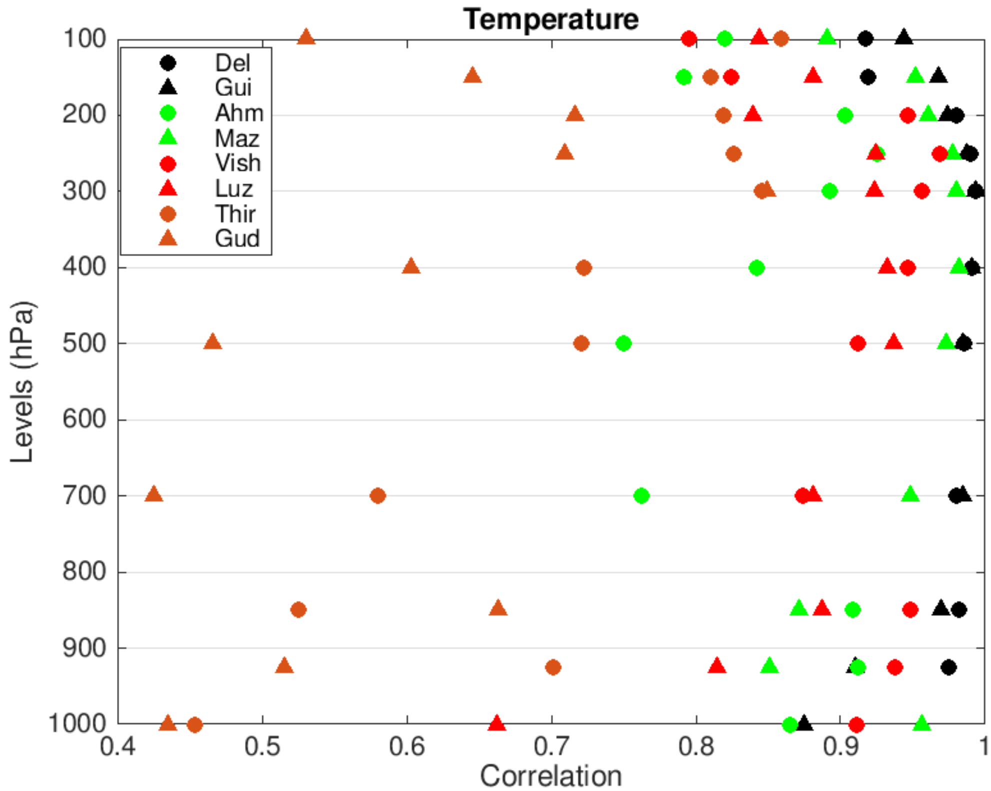

Figure 9: Correlations between RS/RW and NGFS temperature values at eleven pressure levels from the Indian stations and their co-latitudinal global stations. The correlations are obtained at $p < 0.05$.

Figure 10 is similar to Figure 9, but for wind speed. In contrary to temperature, the correlation between observed wind speed and model background is slightly poor over all the locations. The correlation is better over the Indian stations compared to the global collocated stations, except over Ahmedabad. Highest correlation is noticed at the lower levels over Thiruvananthapuram. Weakening of correlation is noticed in the vertical over all the stations. The global stations, Luzon and Gudal show negative correlation with the NWP background almost at all levels, except in a few lower levels. The acceptance of observations from these stations also lesser compared to other stations as seen from Figures 7 and 8.

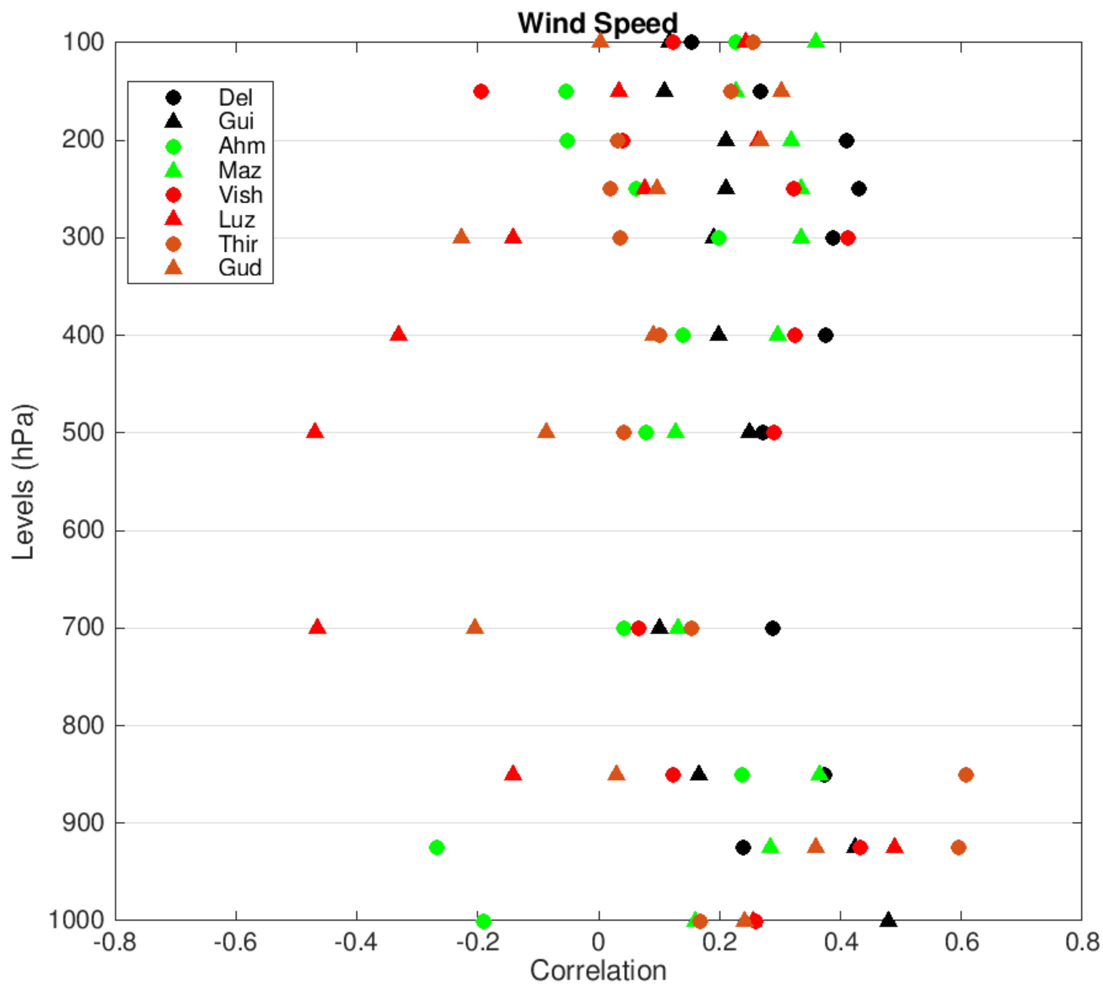

Figure 10: Correlations between RS/RW and NGFS wind speed at eleven pressure levels from the Indian stations and their co-latitudinal global stations. The correlations are obtained at $p < 0.05$.

Figure 11 is similar to Figure 9, but for the geopotential height at the eleven pressure levels. The correlation between the observed and the first guess geopotential heights are positive over all the stations in all the eleven pressure levels. Stronger correlation is noticed over the global collocated stations than over the Indian stations, except over Thiruvananthapuram.

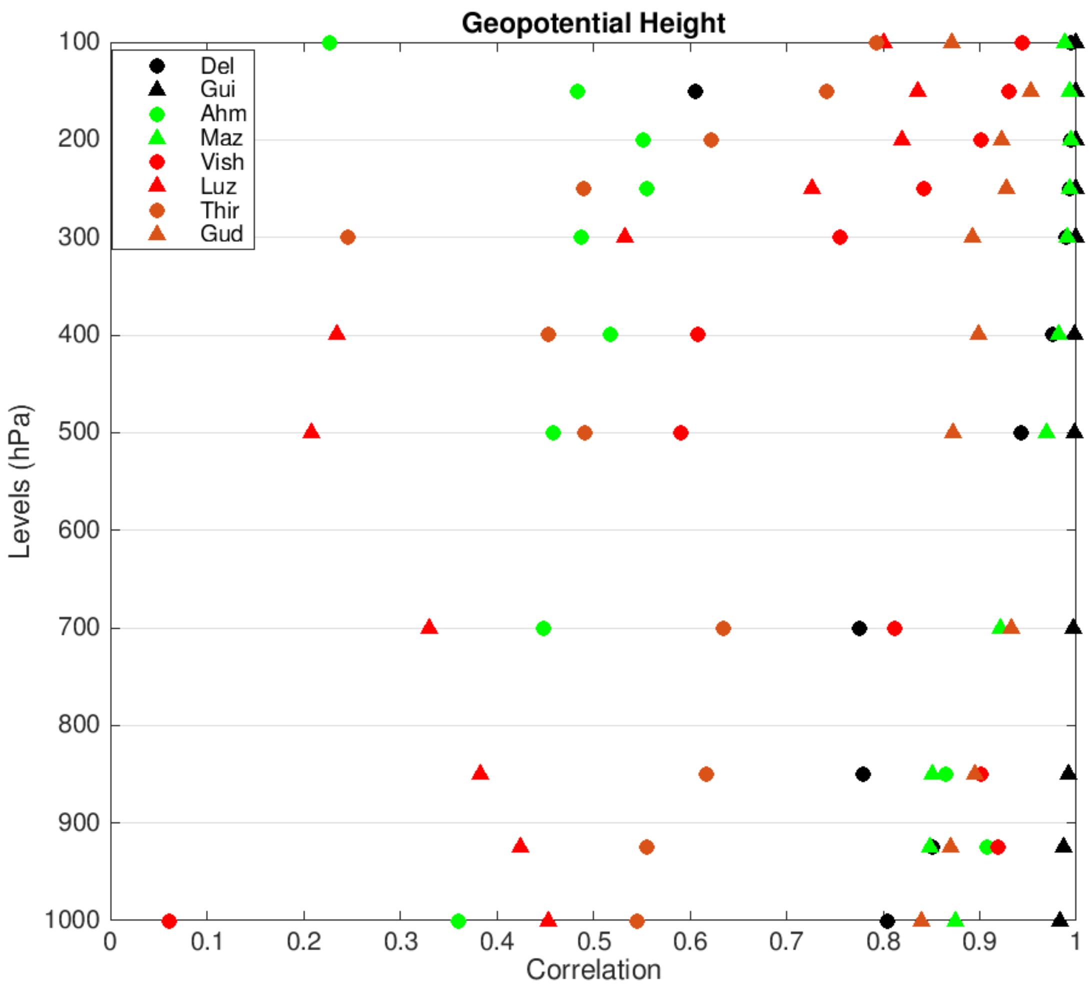

Figure 11: Correlations between RS/RW and NGFS geopotential height at eleven pressure levels from the Indian stations and their co-latitudinal global stations. The correlations are obtained at $p < 0.05$.

4. Conclusions

Radiosonde observations are extremely crucial for enhancing forecasting skills of NWP models. Regular monitoring of reception and assimilation of Indian RS/RW reports shows that NCMRWF receives more reports during 0000 UTC than the 1200 UTC assimilation cycle, with percentage acceptance of more than 90. This study is aimed to analyse the quality and acceptance of Indian RS/RW observations in the NCMRWF NWP system after the global pandemic period.

Indian RS/RW stations are collocated against the global RS/RW stations which are lying approximately within the same latitudinal (difference ±0.5°) belt. Considering the regularity, four Indian RS/RW stations (Delhi, Ahmedabad, Vishakhapatnam and Thiruvananthapuram) were collocated respectively against the global Guimar (Spain), Mazatlan (Mexico), Luzon (Philippines) and Gudal (Philippines). The temporal variation of different parameters over the eight stations was analysed during the Indian summer monsoon period of 2022. The Indian stations showed more variability in different parameters than the corresponding collocated stations. The NCMRWF NGFS assimilation system accepts more observations from the Indian stations than the corresponding global stations. When compared against the first guess, the Indian RS/RW temperature observations showed better correlation than the global stations except for Ahmedabad. The correlation between the observed wind speed and first guess was poor over all the stations, however the Indian stations show a slightly high correlation. The correlation between observed and the first guess wind speed over the two global stations was negative, and their acceptance in the NGFS assimilation system was also less. The geopotential height shows better correlation over the global stations, but the correlations were more than 0.5 for all the Indian stations. The present study reveals that the quality of Indian RS/RW observations with respect to the NGFS first guess is better than that of the global collocated stations, and hence more observations from the Indian stations were used in the assimilation system.

5. Acknowledgments:

The authors greatly acknowledge IMD for sharing the near-real-time Indian RS/RW data through GTS. Authors also acknowledge the support rendered by Head NCMRWF and other senior scientists.

6. **Author contribution:**

Nishtha Agrawal has done data curation, analysis, visualization of results and preparation of first draft. Indira Rani has contributed in conceptualization, guidance, revision, discussion and finalization of report.

References:

Allappattu, D. P. and Kunhikrishnan, P. K.: Premonsoon estimates of convective available potential energy over oceanic region surrounding Indian subcontinent, J. Geophys. Res.-Atmos., 114, D08108, https://doi.org/10.1029/2008JD01152, 2009.

Basha, G., Ratnam, M. V., and Krishna Murthy, B. V.: Upper tropospheric water vapor variations, J. Earth Syst. Sci., 122, 1583–1591, 2013.

Das Gupta, M: Ph.D Thesis (2006)

Dirksen**,** R.J.**,** M. Sommer**,** F.J. Immler**,** D.F. Hurst**,** R. Kivi **&** H. Vömel, 2014: Reference quality upper-air measurements: GRUAN data processing for the Vaisala RS92 radiosonde. *Atmos. Meas. Tech.*, **7**, 4463–4490, doi:10.5194/amt-7-4463-2014.

Free, M. and Seidel, D. J.: Causes of differing temperature trends in radiosonde upper air data sets, J. Geophys. Res., 110, D07101, https://doi.org/10.1029/2004JD005481, 2005.

Haimberger, L., Tavolato, C, and Sperka, S: Toward elimination of the warm bias in historic radiosonde temperature records – Some new results from a comprehensive intercomparison of upper-air data, J. Climate, 21, 4587–4606, https://doi.org/10.1175/2008JCLI1929.1, 2008.

Ingleby**,** B.**,** P. Pauley**,** A. Kats**,** J. Ator**,** D. Keyser**,** A. Doerenbecher**,** E. Fucile**,** J. Hasegawa**,** E. Toyoda**,** T. Kleinert**,** W. Qu**,** J. St James, W. Tennant **&** R. Weedon**, 2016:**

Luers, J. K. and Eskridge, R. E.: Use of radiosonde temperature data in climate studies, J. Climate, 11, 1002–1019, https://doi.org/10.1175/1520- 0442(1998)0112.0.CO;2, 1998.

Manohar, G. K., Kandalgaonkar, S. S., and Tinmaker, M. I. R: Thunderstorm activity India and Indian southwest monsoon. J. Geophys. Res.-Atmos., 104, 4169–4188, 1999.

Monthly normals of radiosonde and radiowind for Indian stations,.Issued by upper air climatological section, IMD, Pune.2010

Murugavel, P., Pawar, S. D., and Gopalakrishnan, V.: Trends of convective available potential energy over the Indian region and its effect on rainfall, Int. J. Climatol., 32, 1362–1372, 2012.

Murthy, B. S. and Sivaramakrishnan, S.: Moist convective instability over the Arabian Sea during the Asian summer monsoon, 2002, Meteorol. Appl., 13, 63–72, https://doi.org/10.1017/S135048270500201X, 2006.

Nash, J., Oakley, T., Vömel, H., and Wei, L. I.: WMO intercomparison of high quality radiosonde systems (Yangjiang, China 12 June–3 August 2010), WMO Instruments and Observing Methods Rep. 107, 238 pp., available at: http://www.wmo.int/ (last access: 28 December 2018), 2011.

Noh, Y.-C., Sohn, B.-J., Kim, Y., Joo, S., and Bell, W: Evaluation of temperature and humidity profiles of Unified Model and ECMWF analyses using GRUAN radiosonde observations, Atmosphere, 7, 94, https://doi.org/10.3390/atmos7070094, 2016

Saha, U., Chakraborty, R., Maitra, A., and Singh, A. K.: East-west coastal asymmetry in the summertime near-surface wind speed and its projected change in future climate over the Indian region, Glob. Planet.Change, 152, 76–87, https://doi.org/10.1016/j.gloplacha.2017.03.001, 2017.

Wang, J., D. J. Carlson, D. B. Parsons, T. F. Hock, D. Lauritsen, H. L. Cole, K. Beierle, and E. Chamberlain, Performance of operational radiosonde humidity sensors in direct comparison with a chilled mirror dew-point hygrometer and its climate implication, Geophys. Res. Lett., 30(16), 1860, doi:10.1029/2003GL016985. 2003

Xie, B., Zhang, Q., and Ying, Y.: Trends in precipitable water and relative humidity in China: 1979–2005, J. Appl. Meteorol. Clim., 50, 1985–1994, 2011.