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L E T T E R S

CELEBRATING 150 YEARS OF IMD: A CHRONICLE OF WEATHER GUARDIANS AND TECHNOLOGICAL MARVELS

1. As the India Meteorological Department (IMD) prepares to celebrate 150 years of meteorological excellence, it's a moment to honor the legacy of India's Weather Eye. Since its establishment in 1875, the IMD has steadfastly guided the nation through the challenges of nature. The journey from early weather tracking to today's cutting-edge technology is a captivating odyssey. Founded in 1875 during British rule, the IMD's origin aligns with the British East India Company's interest in establishing observatories for astronomy, meteorology, and geomagnetism. The first astronomical observatory was inaugurated in Madras (now Chennai) in 1792. Subsequently, observatories were set up in Colaba, Bombay (now Mumbai) in 1823, Calcutta (now Kolkata) in 1829, and Shimla in 1841. This historical timeline reflects the British East India Company's commitment to advancing scientific observation and research in various parts of colonial India. Fig. 1 shows Ms. Anna Mani, the first woman meteorologist of India, during a field experiment in 1948, releasing an upper-air sounding instrument.

Over a period of time many experts from the field of Meteorological Instrumentation kept the Research & Development momentum as per the operational requirements. Among them, Ms. Anna Mani, holds the distinction of being the first female meteorologist at IMD (Taba, *1991*). she joined IMD's instruments laboratories in Poona and played a key role in making IMD self-sufficient in designing and producing meteorological instruments. Anna Mani, known for her perfectionism, also conducted her own research on atmospheric radiation and ozone, earning global recognition. She took a proactive role in establishing instrument standardization at the IMD and supported the internal design and development of instruments within the country in IMD.

Casting our minds back to the bustling era of the 1970s, we recall a nation rapidly transforming. India was witnessing a surge in agricultural activities through Green Revolution, a burgeoning air traffic network, and an upsurge in urban development. It was during this transformative epoch that the meteorological landscape underwent a ground-breaking revolution, propelled by the remarkable advent of satellites and radars for meteorological applications. Concurrently, the installation of crucial technological infrastructure, including Automatic Weather Stations (AWS) and Automatic Rain Gauge Stations (ARG), along with the implementation of Radiosonde and Radio Wind observations (RS/RW), and High Wind Speed Recording (HWSR) Systems, elevated the precision and scope of our weather monitoring capabilities.

Fig. 1. Ms. Anna Mani, the first woman meteorologist in India releasing upper air sounding in 1948

From empowering farmers to make informed decisions about the opportune moment for sowing crops to ensuring the safety of airborne travellers, these cutting-edge technologies and sophisticated instruments not only reshaped the art of meteorological predictions but also laid the cornerstone for strategic decision-making processes. As these advanced systems became integral to the fabric of the nation's progress, they heralded a new era of comprehensive foresight and readiness, positioning India at the forefront of meteorological innovation and preparedness.

2. *From traditional tools to technological wonders: the evolution of weather monitoring*- The genesis of weather observations in India traces back to the early endeavours of the British East India Company, who laid the foundation for meteorological study by establishing a series of weather stations. It was in 1785 that the inaugural weather station took root in the bustling city of Calcutta (present-day Kolkata), followed by the establishment of the Madras observatory (now Chennai) in 1792. As the first half of the 19th century unfurled its pages, the India Meteorological Department (IMD) was commissioned with the pivotal task of comprehensively studying the intricate tapestry of India's weather and climate.

During its nascent phase, the IMD found its initial headquarters nestled in the historical environs of Kolkata. Subsequently, the IMD's operational hub traversed through the serene landscapes of Shimla, the vibrant city of Poona (now Pune), before finding its enduring abode in the heart of the nation, New Delhi.

A testament to the meticulous approach of the British East India Company, the period between 1785 and 1875 witnessed the establishment of 77 meteorological observatories, scattered across the vast expanse of the Indian subcontinent. These observatories served as the vanguards of surface weather observation, laying the cornerstone for the rich legacy of meteorological exploration that continues to unfold in India's contemporary meteorological landscape.

Presently, IMD upholds an extensive network of surface observatories (523), complemented by a substantial constellation of agriculture observatories (127), hydro-meteorological and rain gauge stations (5279). Within this expansive network, a notable subset of surface observatories, constituting a significant proportion, has surpassed the centennial (100 years) mark, earning prestigious recognition through certification bestowed by the World Meteorological Organization (WMO). The intricate architecture of the IMD observatory network is vividly illustrated in following sections, underscoring the department's steadfast commitment to comprehensive and meticulous meteorological monitoring across the expanse of the Indian subcontinent.

Traveling through time, we witness the captivating saga of the IMD's meteorological expertise, as it weaves a tale of remarkable evolution in weather monitoring techniques. Over the course of history, the art of meteorological observation has evolved from the meticulous work of human observers taking synoptic readings every three hours to a landscape enriched by an array of sophisticated and automated technologies. The human observers are the backbone of meteorological data collection, diligently recording synoptic observations at designated intervals. These dedicated observers measure key parameters such as surface temperature, humidity, wind direction, and atmospheric pressure, forming the bedrock of weather forecasting.

As technology advanced, the meteorological landscape underwent a seismic shift with the integration of modern observational tools. The advent of Automatic Weather Stations (AWS) revolutionized data collection, enabling real-time monitoring of a comprehensive range of meteorological parameters. These stations, equipped with a multitude of sensors, provided continuous and accurate weather data at a higher temporal (15 minutes) and spatial resolution (District/Tehsil) without the need for constant human intervention. Additionally, the deployment of Automatic Rain Gauge Stations (ARGs) facilitated precise and timely measurement of rainfall, crucial for agricultural planning, water resource management, and flood prediction.

Over the years, the IMD has orchestrated a transformative journey from the simplicity of traditional weather tools to the intricacies of cutting-edge technology. This narrative is adorned with milestones, including the augmentation of 523 Manned Surface Observatories to form an expansive network, now comprising over 1000 state-of-the-art Automatic Weather Stations and approximately 1400 Automatic Rain Gauge Stations across the country.

With regard to aviation meteorological services, from conventional analog systems to the introduction of Automated Weather Observing Systems (AWOS) has been transformative. These sophisticated systems deliver real-time, accurate, and comprehensive weather information such as instantaneous and averaged meteorological parameters including runway visual range at airports in accordance with ICAO regulations, enabling pilots to make informed decisions about take offs, landings, and flight routes, ensuring the safety and efficiency of air travel in accordance with DGCA guidelines

This metamorphosis in the IMD's approach to weather monitoring represents a testament to India's meteorological progress, showcasing a relentless commitment to embracing modern marvels. The transition from relying solely on basic weather instruments to integrating sophisticated and smart weather gadgets into the fabric of meteorological operations reflects the IMD's

Figs. 2(a-e). (a) Ultra-cryogenic bath for calibration of all type of thermometers, **(**b) Temperature and Humidity chamber **(**c) and **(**d) Wind Tunnel for wind speed measurement calibration and testing, environmental chamber for calibration of AT/RH sensors, Thermographs and Hygrographs **(**e) Druck and Mensor pressure standards for calibration of all types of pressure sensors **(**f) Burret, pulse counter and dispenser for calibration of all types of rain measuring instruments and Tipping Bucket Rain Gauges

unwavering dedication to precision and excellence in weather forecasting. This evolution proclaims a new chapter in India's meteorological legacy, where technology intertwines seamlessly with the art of weather prediction, ensuring that the nation remains at the forefront of meteorological innovation and preparedness.

3. *Calibrated for accuracy: The IMD's precision assurance measures*- In the pursuit of precision, the IMD has left no stone unturned in its relentless quest for accurate weather predictions. With an unwavering commitment to reliability, the department has meticulously established stringent protocols and quality control measures. These measures are akin to the watchful eye of a master craftsman, ensuring that each weather observation is as precise as the second hand of a clock. A meticulous approach underpins the rigorous testing and calibration of all manufactured and procured surface instruments within the IMD. At the helm of this precision-driven process lies the dedicated calibration laboratory at the Surface Instruments Division (SID) in Pune. This sophisticated facility caters to an array of vital meteorological instruments, encompassing temperature sensors, pressure sensors, rain gauges, and wind sensors.

The calibration laboratories operate in strict accordance with the prescribed standards established by the Bureau of Indian Standards (BIS), ensuring the deployment of state-of-the-art reference instruments for meticulous calibrations. Each calibration endeavour culminates in the issuance of a comprehensive Calibration Certificate or a detailed Laboratory Test Report, meticulously outlining the performance tolerance limits of the tested instruments, in accordance with the exacting criteria set forth by the BIS

In respect of liquid-in-glass thermometers, the calibration process involves meticulous scrutiny utilizing specialized reference standards such as temperature baths and digital temperature indicators. This rigorous evaluation culminates in the preparation of a Laboratory Test Report, meticulously delineating the permissible limits of tolerance for each thermometer, adhering closely to the stringent guidelines laid down by the World Meteorological Organization (WMO). Fig. 2. shows the calibration facilities used in meteorological instrumentation, including an ultra-cryogenic bath for thermometers, a temperature and humidity chamber, wind tunnel for wind speed calibration and testing, an environmental chamber for calibration of AT/RH sensors, thermographs and hygrographs, Druck and Mensor pressure standards for pressure sensor calibration, and a burette, pulse counter, and dispenser for calibration of rain-measuring instruments and tipping bucket rain gauges.

Furthermore, the Barometer Calibration laboratory operates as a sanctuary of precision, equipped to calibrate a diverse array of barometer types, including Mercury, Aneroid, and Digital Standard Barometers. Notably, the esteemed Standard Fortin's barometer, Newmann No. 112 is designated as the Regional Association - II, Asia (RA-II) standard barometer, finds meticulous upkeep at the Kolkata facility. In line with *Minamata Convention* adopted by WMO, for phasing out mercury-based barometers, department has migrated from mercury barometers to Digital Station Barometers (DSB) at all 200 surface meteorological observatories. The calibration laboratory at Surface Instruments Division (SID), Pune achieved NABL certification for temperature and pressure parameters in May 2024.

Emphasizing the dedication to meticulous standards, a specialized wind tunnel facilitates the calibration of all wind sensors, adding another layer of assurance to the IMD's commitment to the highest standards of meteorological precision and excellence. Within the hallowed halls of the IMD, lies a chamber dedicated to ensuring the accuracy of every weather tool at its disposal. These calibration facilities, akin to the sanctuaries of precision, meticulously scrutinize and fine-tune every instrument, guaranteeing that each reading is as exact as a maestro's musical note.

In alignment with its precision-driven ethos, the IMD adheres to the stringent guidelines prescribed by the World Meteorological Organization (WMO) for site inspection, station selection, installation standards, and calibration procedures. All calibration laboratories function in strict compliance with the norms of the Bureau of Indian Standards (BIS) and are accredited under the National Accreditation Board for Testing and Calibration Laboratories (NABL), ensuring global credibility. The wide spectrum of meteorological instruments including those installed at full-fledged surface observatories, part-time observatories, remote automatic weather stations, and aviation meteorological stations are subject to routine inspection and calibration. Specialized portable reference standards are employed for on-site calibrations, ensuring that even the most remote stations maintain the highest levels of accuracy in weather observations. This meticulous methodology reinforces IMD’s unwavering commitment to producing reliable, standardized, and internationally benchmarked meteorological data.

4. *An ode to the sentinels of time: IMD's centennial observatories*- The legacy of meteorological observations in India is epitomized by a remarkable cohort of 20 time-honoured observatories that have withstood the test of time, each boasting a century-long legacy of invaluable data. These venerable institutions, nestled across the length and breadth of the nation from Mumbai's Colaba, Nungambakkam, Panjim, Pune, Thiruvanthapuram, Srinagar, Port Blair, Alipore, Ahmedabad, Gopalpur, Puri, Cuddallore, Kodaikanal, Minicoy, Bahraich, Shillong and Patna, Dwarka, Veraval and Cuttack serve as custodians of a precious time series of meteorological data that stretches across generations.

TABLE 1

WMO recognized 20 centennial stations from India

Sl. No.	Station	Start of observation
1	Ahmedabad	1893
2	Alipore	1877
3	Gopalpur	1881
4	Mumbai (Colaba)	1841
5	Nungambakkam	1792
6	Panjim	1860
7	Patna	1867
8	Port Blair	1866
9	Pune	1856
10	Puri	1888
11	Cuddallore	1889
12	Kodaikanal	1899
13	Minicoy	1891
14	Bahraich	1892
15	Shillong	1902
16	Srinagar	1891
17	Thiruvananthapuram	1853
18	Dwarka	1901
19	Veraval	1890
20	Cuttack	1867

Recognized as meteorological heritage, these longstanding observatories play a pivotal role in shaping the trajectory of weather research and analysis, anchoring the nation's historical meteorological narrative within a robust temporal framework. The treasure trove of data encapsulated within their meticulous archives serves as a timeless testament to the ever-evolving dynamics of the Indian climate, providing a panoramic view of its cyclical patterns and long-term fluctuations.

Under the aegis of the World Meteorological Organization's (WMO) visionary initiatives, these venerable observatories assume a critical significance. Serving as vital components of the WMO's esteemed programme, they contribute invaluable insights into the global understanding of climate trends and variations.

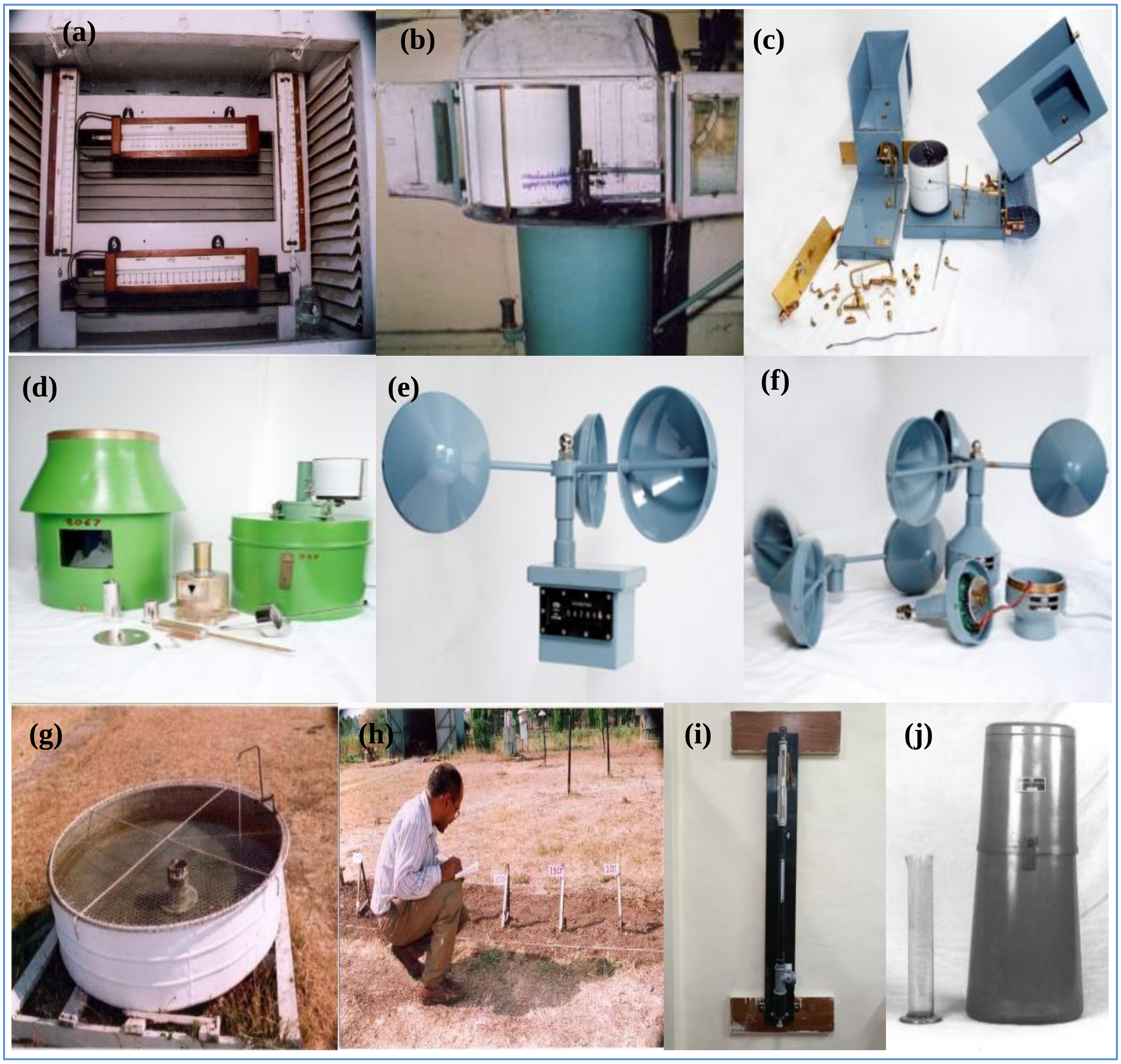
Recently the World Meteorological Organization started recognizing the centennial stations over the world that have the continuous data of 100 years or more. Table 1 (year of establishment) and Fig. 3 show the centennial

Figs. 3(a-l). (a) Madras Observatory, **(**b) Colaba Observatory, **(**c) Madras Astronomical Observatory, (d) Gopalpur Observatory, **(**e) Cuddallore Observatory, **(**f) Kodaikanal Observatory, **(**g) Nungambakam Observatory, **(**h) Patna Observatory, **(**i) Puri Observatory, **(**j) Srinagar Observatory, (k) Thiruvananthapuram Observatory, (l) Kolkata Alipore Observatory

observatories of India recognized by WMO, including the Madras Observatory, Colaba Observatory, Madras Astronomical Observatory, Gopalpur Observatory, Cuddalore Observatory, Kodaikanal Observatory, Nungambakkam Observatory, Patna Observatory, Puri Observatory, Srinagar Observatory, Thiruvananthapuram Observatory, and Kolkata Alipore Observatory.

Their rich and extensive time series of data serve as invaluable benchmarks, facilitating a deeper comprehension of climate dynamics, aiding in the calibration and validation of contemporary meteorological models, and informing the formulation of evidence-based climate policies on an international scale.

As bastions of historical meteorological information, these observatories serve as beacons of resilience, their enduring data offering an indispensable bridge connecting the past, present, and future of meteorological research. Within the realm of the WMO's concerted efforts, they stand as living testaments to the profound importance of preserving and harnessing the wealth of meteorological data, underscoring the indelible impact of historical observatories in the perpetual quest for a comprehensive



Figs. 4(a-j). Surface Meteorological Instruments in standards Meteorological Observatory *viz*. (a) Thermometers in Stevenson's Screen, (b) Dines Pressure Tube Anemograph, (c) Hair Hygrograph with parts, (d) Self-Recording Rain Gauge, (e) Cup Counter Anemometer, (f) Optical Anemometer, (g) Open Pan Evaporimeter, (h) Soil Temperature thermometers, (i) Casella Fortin Barometer and (j) Non-Recording ordinary Rain Gauge

understanding of the Earth's climate dynamics. Fig. 4 shows the conventional surface meteorological instruments in a standard meteorological observatory, including thermometers in Stevenson's screen, the Dines pressure tube anemograph, hair hygrograph, self-recording rain gauge, cup counter anemometer, optical anemometer, open pan evaporimeter, soil temperature thermometers at various depths, Casella Fortin barometer, and non-recording ordinary rain gauge.

A standard meteorological observatory is equipped with instruments installed in accordance with WMO norms, including Stevenson screens housing various thermometers for temperature and humidity measurements rain gauges, and devices for measuring wind speed and direction at standard heights. Digital barometers are also available in the observatory. Observations are recorded every three hours as part of WMO synoptic procedures, and a central (sentinel) observatory is maintained for reference. Surface observations, along with oceanic and upper-air observations, form the foundation for day-to-day weather forecasting, early warning systems, long-term climate databases, climate projections, and impact assessments. Ensuring data quality and consistency is critical to all these functions.

5. *Global collaborations: IMD's participation in the World Meteorological Organization* - Beyond national borders, the IMD's influence extends to the global stage through its active participation in the World Meteorological Organization. Symbolizing India's meteorological camaraderie with the world, this partnership fosters a symbiotic exchange of knowledge expertise, and insights, enriching the collective understanding of weather phenomena across continents.

IMD has been a founding member of WMO since 1950**,** and has had continuous representation on its Executive Board for over 60 years-the longest among Asia-Pacific nations. This continuity reflects enduring leadership and influence. Currently, Dr. Mrutyunjay Mohapatra**,** Director General of Meteorology at IMD, serves as Third Vice-President of WMO**,** offering strategic leadership at the highest level.

As a founding WMO member, IMD follows WMO-No. 8 (Guide to Instruments and Methods of Observation**)** for all its observing systems. This ensures that IMD’s surface and upper-air instruments (barometers, AWS sensors, radiosondes, ceilometers, etc.) are interoperable with global networks. Through WMO’s Instrument Inter-comparisons**,** IMD participates in pyranometer /pyrgeometer, precipitation gauge, and radiosonde evaluations, aligning Indian networks with global benchmarks.

WMO’s GBON requires every NMHS to maintain mandatory surface pressure, temperature, wind, and humidity observations with minimum spatial and temporal coverage. IMD contributes via its network of ~1000 AWS+ conventional stations**,** and upper-air observatories using GPS radiosondes (*Ansari et al.*, *2015*)**,** ensuring India’s data feeds global NWP models. Instrument-wise, this involves digital barometers, aspirated T/RH sensors, ultrasonic wind sensors, weighing precipitation gauges, and GPS sondes being reported in near-real time.

6. *Embracing the digital horizon: IMD's journey from analog to digital precision* - Leaping into the digital era, the IMD has embraced a revolutionary transformation, transcending the confines of analogue instrumentation. Through the assimilation of cutting-edge digital and smart instruments, the department has harnessed the power of technology, offering real-time and precise weather predictions that resonate with the pulse of the contemporary world.

In commemorating the 150th anniversary of the IMD, we celebrate not merely a legacy of meteorological excellence but a saga of resilience, innovation, and unwavering commitment. Amidst the ever-changing skies, the IMD remains an enduring beacon, guiding the nation through the winds of change and the storms of progress.

TABLE 2

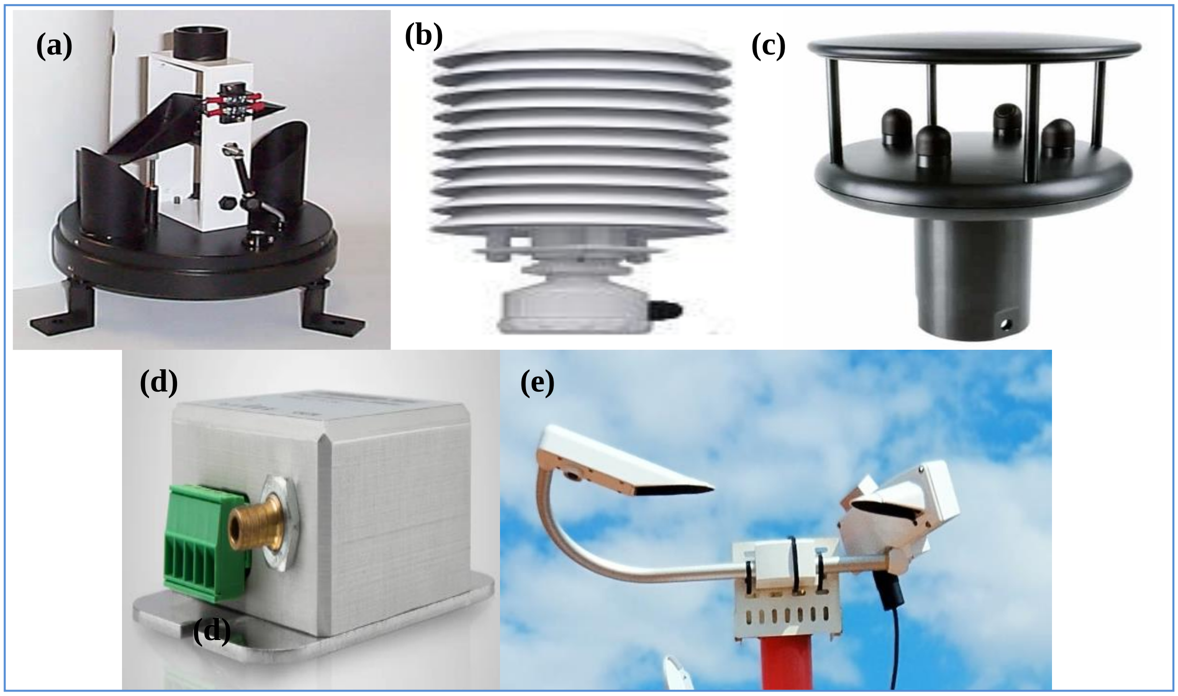
The solar radiation parameters measured at IMD network.

Sr. No	Parameters	No. of Stations
1	Global	47
2	Diffuse	47
3	Direct	21
4	Terrestrial	47
5	UV-A	47
6	UV-B	47

Smart meteorological observatory - Revolutionizing weather monitoring with advanced technology, Cutting-edge IOT sensors and AI enhance precision in data collection. Real-time insights for accurate forecasting and climate analysis. A new era in meteorological observation. As depicted in Fig. 5, the advanced meteorological sensors for weather monitoring include the tipping bucket rain gauge, naturally aspirated thermoplastic radiation shield, ultrasonic wind sensor, digital atmospheric pressure sensor, and forward scatter meter.

Artificial Intelligence (AI) is becoming increasingly powerful, and in the coming years, its role in meteorology is expected grow significantly. Long-term and historical data are essential for training AI models, with quality-controlled datasets forming the strongest foundation for accurate forecasting. From both a forecasting perspective and a database generation perspective, past data plays a crucial role in enhancing AI based model performance. High-quality, consistent data will further strengthen AI applications in weather forecasting and climate analysis. Archival of observations is therefore invaluable. IMD has also made data sharing easier for students, stakeholders, and academic institutions, fostering wider access and research opportunities.

Solar radiation monitor network -Validation of satellite-derived radiation data remains most effectively achieved through solar radiation measurements at specific points above ground level. Table 2 presents the solar radiation parameters measured at the India Meteorological Department (IMD) network, while Fig. 6 illustrates the Solar Radiation Network of IMD. At present, IMD is maintaining a network of 47 solar radiation stations distributed across the country, which provide valuable data for studying solar energy potential, climatological research, and weather forecasting applications.



Figs. 5(a-e). Advanced Met. Sensors for Weather Monitoring viz. (a) Tipping Bucket Rain Gauge, (b) naturally aspirated thermoplastic Radiation Shield, (c) Ultrasonic Wind Sensor, (d) Digital Atmospheric Pressure Sensor & (e) Forward Scatter Meter

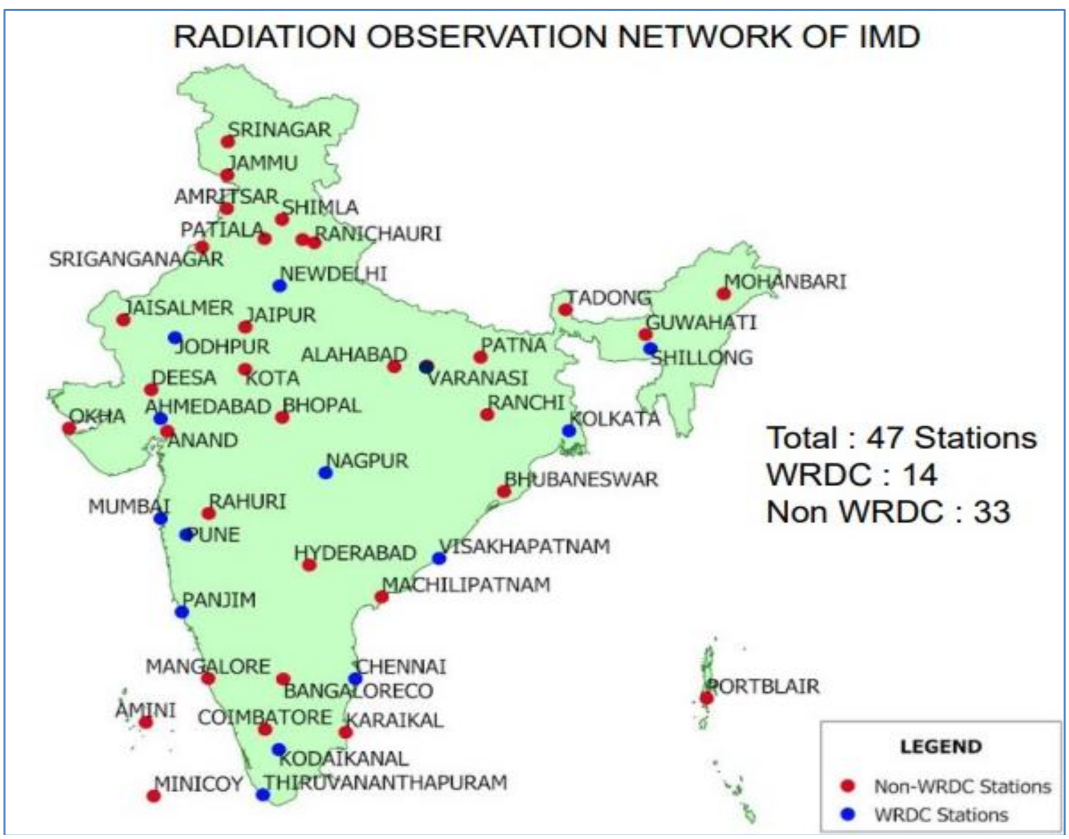


Fig. 6 Solar Radiation Network of IMD

Figs. 7(a-i). Campbell Stoke duration of bright sunshine recorder, (b) Thermoelectric pyranometer, pyrgeometer, UV A radiometer, UV B radiometer, (c) Diffuse Shading ring with Pyranometer (d) Electronic sunshine duration sensor (e) Pyranometer sensors for outdoor calibration (f) Cavity Radiometer (g) Four Cavity Radiometers (h) IPC 2015 at Davos, Switzerland (i) IMD Cavity Radiometer at IPC 2015

Calibration of solar radiation sensors is vital for accuracy, reliability, and traceability to the World Radiometric Reference (WRR). IMD, with a dedicated solar–terrestrial radiation network of 47 stations, measures global, diffuse, direct, terrestrial, and UV irradiance for forecasting, research, and climate monitoring. This legacy, begun in 1932 under Prof. K.R. Ramanathan with Ångström instruments, has evolved into a robust national programme, the early work *The Handbook for Solar* Radiation data for India (1980) paved the way for milestones like solar radiation over India (*Mani and Rangarajan*, *1982*) and Solar Radiant Energy over India (*Tyagi*, *2009*). IMD ensures international traceability through participation in the International Pyrheliometer Comparisons (IPC) at the World Radiation Centre, Davos, where its primary cavity radiometer (AHF 18742) was benchmarked in 2005, 2010, and 2015. Calibration follows ISO 9847 and ISO/IEC 17025 standards, involving rigorous field and laboratory procedures, from sensor co-location and side-by-side testing to analysis, coefficient adjustment, and documentation. Primary standards absorb solar radiation in precision cavities, converting it to traceable electrical signals that anchor all secondary instruments. This meticulous process guarantees reproducibility, compliance with global standards, and high-quality data-enabling accurate solar energy assessments, robust climate studies, better model performance, and seamless comparability across WMO member states. With reference to Fig. 7, the solar radiation instruments and related facilities include the Campbell-Stokes sunshine duration recorder, thermoelectric pyranometer, pyrgeometer, UV-A

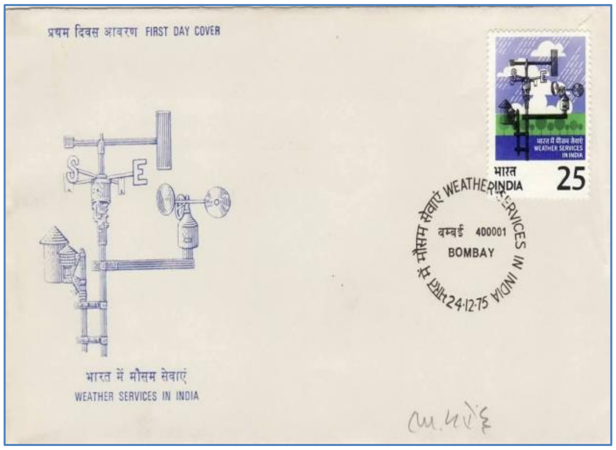


Fig. 8. First Day Cover – Weather Services in India

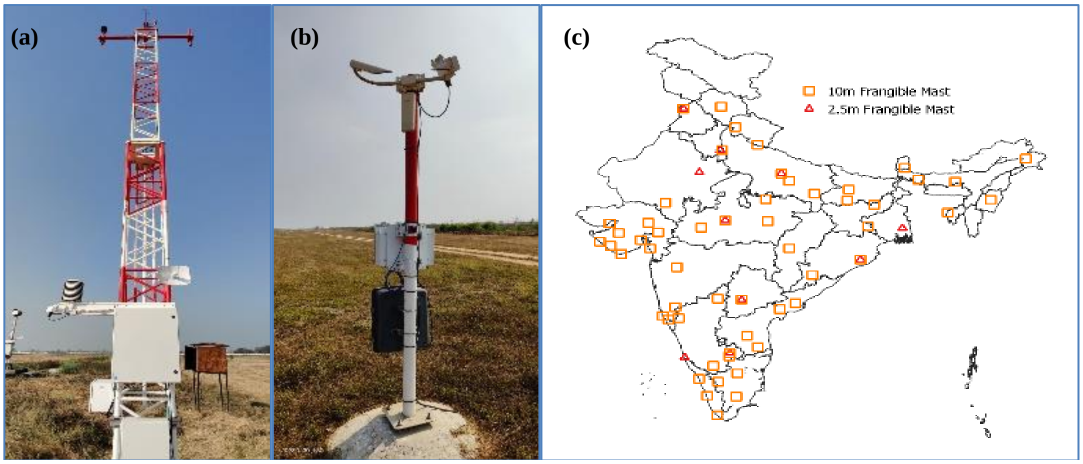
and UV-B radiometers, diffuse shading ring with pyranometer, electronic sunshine duration sensor, IMD calibration facilities for outdoor calibration of pyranometer sensors, cavity radiometer, four-cavity radiometers, and IMD's participation in the international five-year comparison with primary standards (IPC, 2015) at Davos, Switzerland, where the IMD cavity radiometer was also tested.

IMD ensures high-quality solar radiation observations through its nationwide and polar networks. Instruments are regularly calibrated under WMO programs, with secondary standards maintained by IMD. These accurate measurements support renewable energy assessment, climate studies, and related analyses.

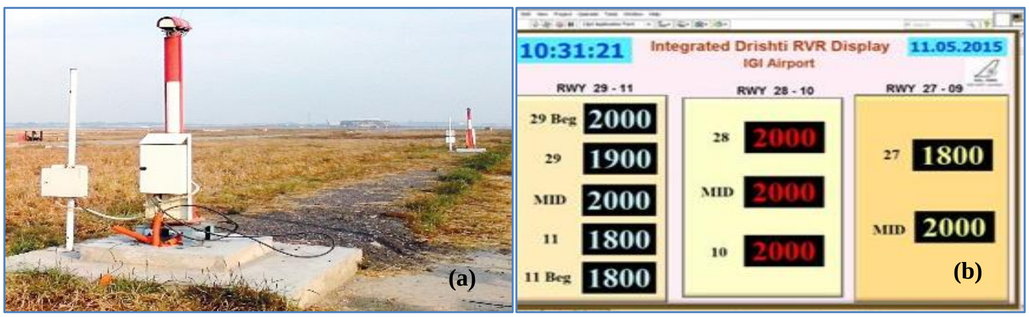
Meteorological aviation instrumentation - India Post issued a stamp in 1975 to commemorate 100 years of formation of the India Meteorological Department in1875. The Fig. 8 stamp shows stylized illustration of the weather and the line drawing of weather cock. IMD is the nodal agency which is responsible in all matters related to provision of MET support to aviation in India. The principal requirements in the aviation point of view are; IMD issues current weather observations, forecast and warnings on meteorological hazards to all aeronautical users (*Hosalikar et al., 2012*). The design, installation and maintenance of Airport Meteorological Instruments are done by Surface Instruments Division, Pune. IMD follow the guideline of International Civil Aviation Organization (ICAO) and endorsed by the World Meteorological Organization (WMO) (WMO, 1992(a), WMO, 1992(b)). Surface wind, air temperature and dewpoint, atmospheric pressure, cloud, visibility and runway visual range (RVR) are the essential observations required at aerodrome. The operational and desirable accuracy of the sensors are prescribed by the ICAO (ICAO, 2007). The meteorological instruments are installed near the runway on a 10 m or 2.5 m frangible masts in a designated area, meteorological park. Sensors in the meteorological park are connected to data logger. The data logger is interfaced with a server in Air Traffic Control (ATC) room through radio frequency or optical through. A trained meteorologist at the aerodrome scrutinizes data observed by the automated systems and issues to the aeronautical users periodically to support the safety services at the aerodrome. In recent years, the India Meteorological Department (IMD) has significantly upgraded the meteorological infrastructure at all airports across the country, irrespective of their category, to ensure full compliance with ICAO regulations and international standards. A key advancement has been the replacement of non-frangible and non-standard masts with ICAO-compliant frangible masts, thereby enhancing both safety & conformity. Additionally, Forward Scatter Meters have been commissioned at every airport in India to provide reliable instrumental visibility or Runway Visual Range (RVR) assessments. Accurate and timely estimation of RVR is of critical importance, particularly during fog and heavy rainfall events, which remain the principal causes of reduced visibility in the Indian aviation environment. These transformative initiatives by IMD have not only standardized aviation meteorological instrumentation nationwide but have also contributed substantially to reducing flight diversions arising from the unavailability of RVR data or adverse visibility conditions. As shown in Fig. 9, 10 m and 2.5 m frangible masts are installed at airports in India along with meteorological sensors. Fig. 10 illustrates the Drishti transmissometer and the Runway Visual Range (RVR) display dashboard.

Under the *Make in India* initiative, the indigenously developed *Drishti* RVR (Runway Visual Range) instrument, designed for accurate runway visibility and visual range measurements, has been successfully developed by a national agency. The system is now installed and operational at approximately 49 major airports across the country, serving as a flagship example of India's self-reliance in visibility measurement technology. The Ministry of Earth Sciences (MoES) has now embarked on ambitious "Mission Mausam" scheme which aims to further enhance and upscale meteorological observational systems with state-of-the-art equipment. In order to accomplish this objective for aviation weather services, 18 major airports in India are being equipped with state-of-the-art Automated Weather Observing Systems (AWOS) along with ICAO compliant software features.

Automatic weather station network **-** IMD operates and maintains an extensive network of high-standard



Figs. 9(a-c). a) 10 m & b) 2.5 m Frangible masts installed at airports in India along with Meteorological Sensors

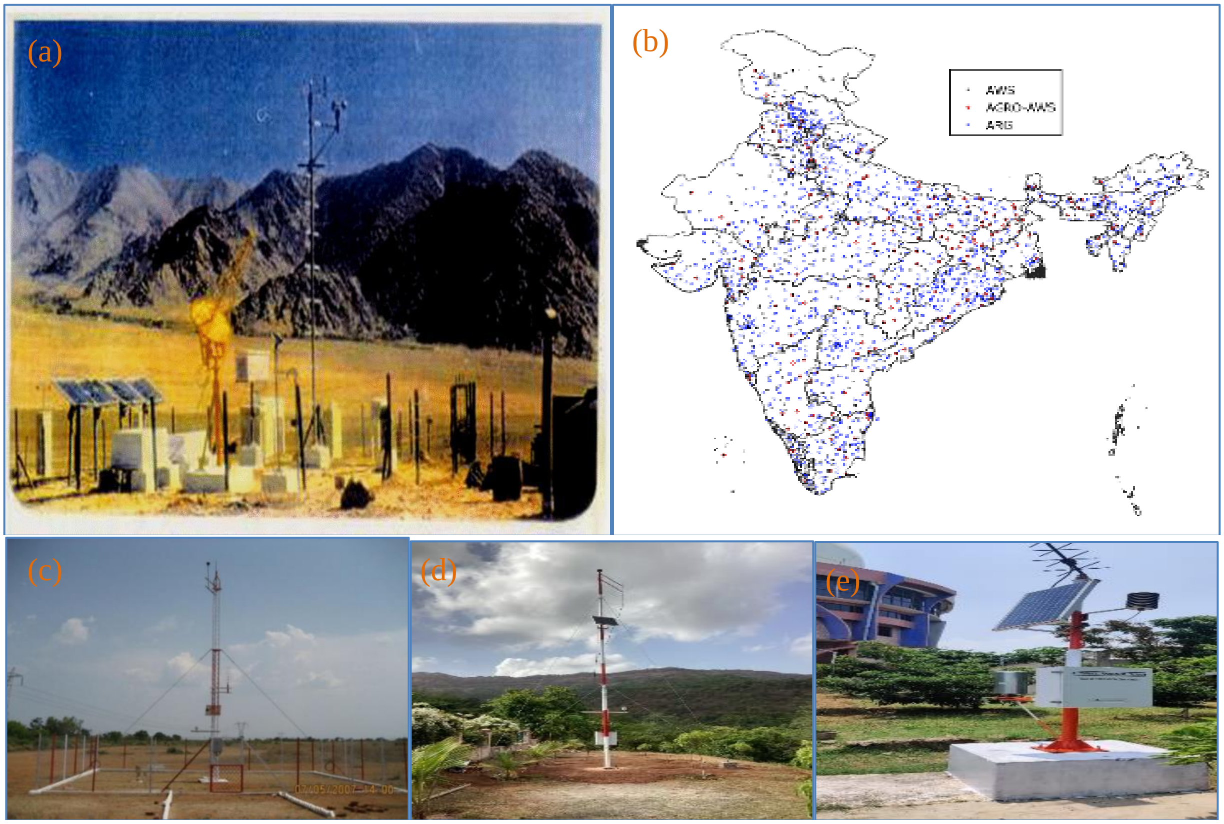


Figs. 10(a-b). (a) Dristi Transmissometer **(**b) RVR Display Dashboard

AWS (Automatic Weather Station), AGRO-AWS (Agricultural Automatic Weather Station), and ARG (Automatic Rain Guage) dense networks throughout the country (Ranalkar *et al.*, *2012*, Ranalkar *et al.*, *2014*). Fig. 11 represents the typical installations of Automatic Weather Stations & Automatic Rain Gauge (ARG) stations maintained by IMD, including TDMA-based AWS, the AWS network across India, Agro-AWS, AWS with tiltable mast, & standalone Automatic Rain Gauge stations.

In addition, IMD developed High Wind Speed Recording (HWSR) System (*Vasishtha et al.*, *2010*) and now maintains 37 coastal stations equipped with HWSR. Recently, significant initiatives, such as the Mumbai mesoscale network (*Sunilkukar et al.*, *2022*) and Pune mesoscale observational network, have expanded networking capabilities through the installation of AWS and ARG systems for better district-level forecasts and urban climate monitoring. Additionally, automatic weather observational networks in Leh Ladakh have been expanded.

IMD operates a nationwide network of Automatic Weather Stations (AWS) strategically located across diverse climatic regions. These include AWS units measuring temperature, humidity, pressure, wind speed/direction, and rainfall; Automatic Rain Gauge (ARG) stations monitoring rainfall, temperature, and humidity; Agro-AWS systems capturing temperature, humidity, pressure, wind speed/ direction, rainfall, solar radiation, and soil temperature and moisture at depths of 10, 30, 70, and 100 cm below ground; and Automatic Snow Gauge (ASG) stations for snowfall measurements. Data from all these stations are transmitted to central servers in Pune and Delhi at 15-minute intervals, with the flexibility to increase transmission frequency to 1-minute intervals during severe weather events. Primary quality checks are performed at the data logger level, while advanced quality control procedures at the server level such as spatial and temporal consistency checks further ensure data integrity and accuracy. This high-quality, near real-time data is disseminated through public data portals, supporting rainfall rate estimation, cloudburst detection, heatwave monitoring, disaster preparedness, and timely alerts, thereby enhancing the precision and reliability of forecasts (*Amudha and Raj, 2013*).



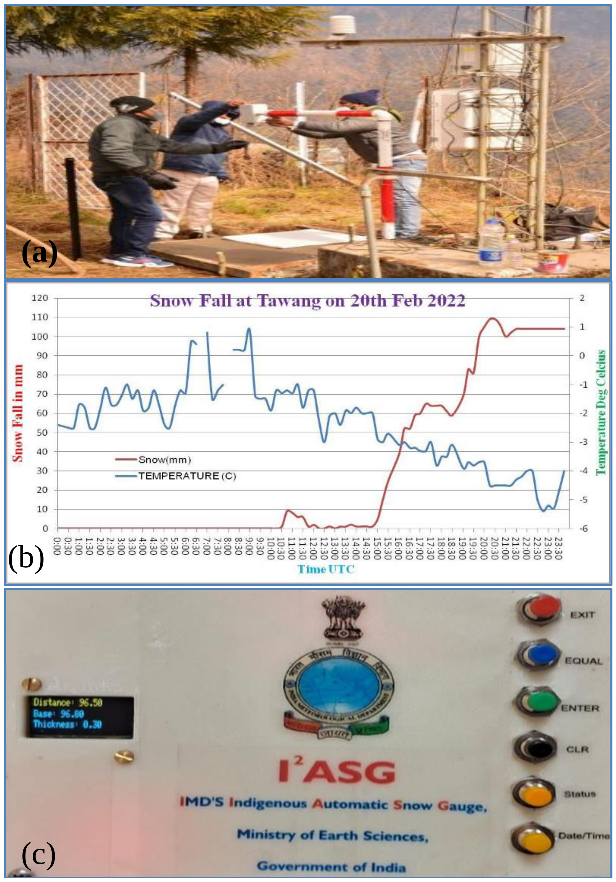
Figs. 11(a-e). Typical installation of Automatic Weather Stations and Automatic Rain Gauge Stations. (a) TDMA-based AWS, (b) AWS network across India, (c) Agro-AWS, (d) AWS with tiltable mast, (e) Automatic Rain Gauge Station

In house research & development **-** In-house-developed digital snow gauge revolutionizes snowfall measurement with innovation. This cutting-edge instrument is defined by precision and efficiency, significantly enhancing accuracy in monitoring snow levels. IMD indigenously developed system seamlessly blends robust hardware with advanced software algorithms, creating a reliable instrument for real-time monitoring of snow depth. Fig. 12 shows the integration of the indigenously designed and developed Digital Snow Gauge (DSG) with an AWS at Tawang, Arunachal Pradesh, along with recorded snowfall and the DSG logger equipped with an LED display.

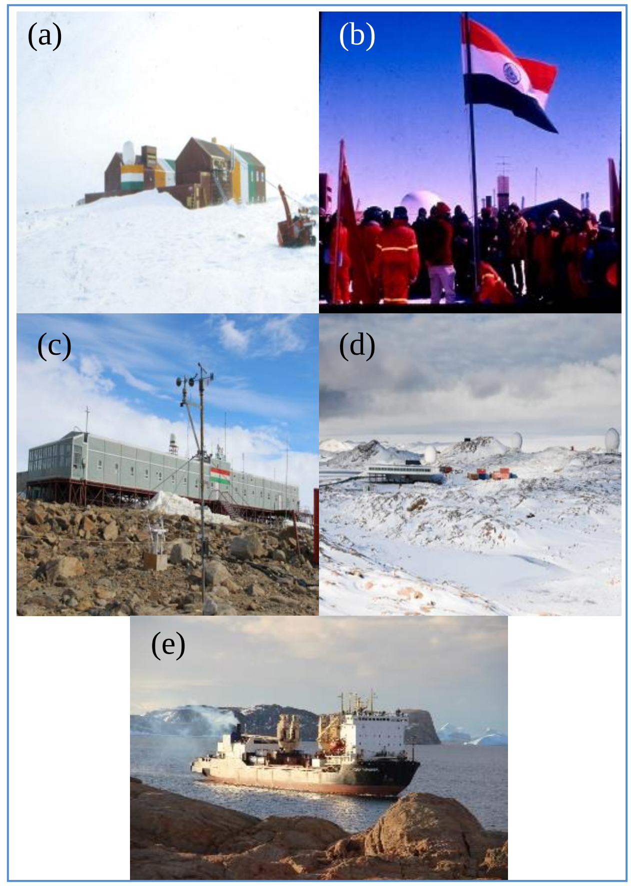
This innovative technology eliminates the need of clearing the deposited snow either by manually or by means of heating. the issues with existing measurement methods, the analysis of snowfall trends in North India, and the strategic deployment of ASG systems based on climatological studies. The ASG system was meticulously tested in both laboratory and field settings, proving its operational capabilities in harsh environments. The strategic deployment based on climatological studies ensures comprehensive coverage and accuracy in snowfall data collection. Overall, the sensors and installation worked well with only a few problems noted. The system is compared well with both manual observations taken adjacent to each sensor as well as traditional total snow depth (TSD) on ground measurements. This advancement marks a significant improvement in the automation and precision of snowfall measurement, providing invaluable data for future research and operational planning.

7. *Meteorological services for the Char Dham yatra* - MD has been instrumental in supporting the Char Dham Yatra since 1997, providing crucial real-time weather updates. IMD officials maintain continuous communication with Yatra Managers, delivering timely meteorological information to prioritize safety. The collaboration between IMD offices, Defence organizations, and local government officials enhances overall preparedness and safety for the pilgrimage, contributing significantly to its success.

8. *Meteorological observation in Antarctica*- IMD has been actively engaged since the start of the



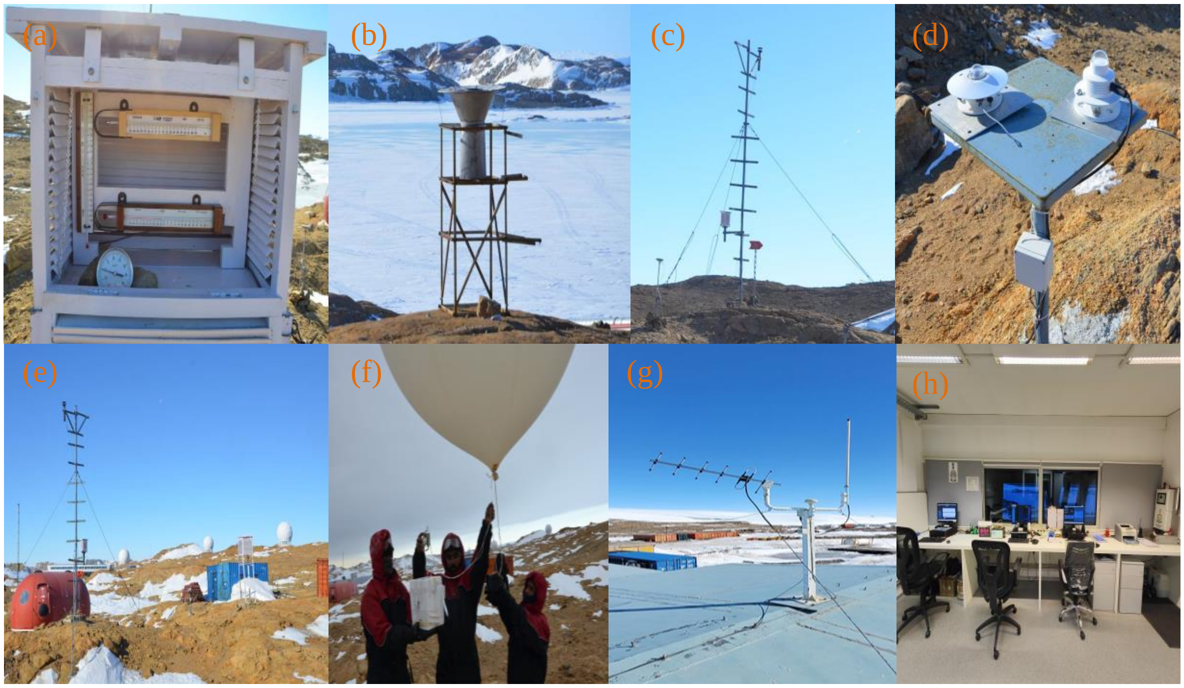
Figs. 12(a-c). (a) Integration of indigenously designed and developed Digital Snow Gauge (DSG) with AWS at Tawang, Arunachal Pradesh **(**b) Snow fall recorded **(**c) DSG logger with LED display



Figs. 13(a-e). IMD Weather services at Antarctica: **(**a) Dakshin Gangotri Antarctic Station, **(**b) National celebration in Antarctica, **(**c) Maitri Indian Antarctic Station, **(**d) Bharati Indian Antarctic Station, **(**e) Arrival of ship near Bharati Antarctic coast

Antarctica expedition in 1981, delivering meteorological services to the Indian Antarctic expedition. Moreover, the organization conducts meteorological experiments at Meteorological Observatories set up at both the Maitri and Bharati Indian Antarctic stations. Fig. 13 illustrates the India Meteorological Department's (IMD) weather services in Antarctica, including the Dakshin Gangotri Antarctic Station, national celebrations in Antarctica, Maitri Indian Antarctic Station, Bharati Indian Antarctic Station, and the arrival of a ship near the Bharati Antarctic coast.

IMD records meteorological observations at its observatories located at Maitri and Bharati stations in Antarctica, providing continuous weather services to the National Centre for Polar and Ocean Research (NCPOR) since the inception of India's Antarctic expeditions. These services support summer time ship-based routine and convoy operations, daily activities of scientific explorers, and specialized weather forecasts essential for field missions. The observations form a critical dataset for cross-domain research, analysis, and correlation studies of Antarctic weather parameters (*Hosalikar et al.*, 2011; *Vishwakarma et al.*, 2013). The scope of observations includes surface meteorological measurements, convection monitoring, Snow gauges and data from automatic weather stations (AWS). Specialized systems deployed include high-wind speed recorders (HWSR) for blizzard monitoring, digital current weather instrument system, and solar radiation measurement setups comprising data logger with global and diffuse pyranometers installed, solar tracker. (RSRW) system has been installed, equipped with GPS, omnidirectional, and Yagi antennas mounted on the station rooftop for upper-air observations. Ozone monitoring is carried out using the Serinus 10 Ozone Analyzer, which employs non-dispersive ultraviolet (UV) photometric technology to measure ozone concentrations with a sensitivity of 0.5 ppb over a 0-20 ppm range, supported by an Ozone-Log system for measurement and data logging. These observations provide critical real-time data for safe Antarctic operations and accurate weather forecasting, while also supporting global climate research, climate



Figs. 14(a-h). IMD Meteorological Observatories at Matri and Bharati stations, Antarctica: **(**a) Stevenson screen with thermometers and conventional instruments, **(**b) IMD make snow gauge, **(**c) Solar radiation measurement with global radiation sensor and UV-A sensor,**(**d) Automatic Weather Station (AWS),e) IMD Meteorological Observatory, (f) GPS ozone sonde ascent experiment with launching balloon, (g) GPS with omnidirectional and Yagi antenna

change studies, and cross-disciplinary scientific work. They help improve understanding of polar–tropical atmospheric linkages, enabling better prediction of weather and climate patterns over the tropics and the Indian region. Fig. 14 depicts the IMD meteorological observatories at Maitri and Bharati stations in Antarctica, showcasing the Stevenson screen with thermometers and conventional instruments, the IMD-designed snow gauge, solar radiation measurements using a global radiation sensor and UV-A sensor, an Automatic Weather Station (AWS), the IMD meteorological observatory setup, a GPS ozone sonde ascent experiment with launching balloon, and GPS systems with omnidirectional and Yagi antennas.

9. *International Meteorological Organization (IMO), World Meteorological Organization (WMO)* - The establishment of the International Meteorological Organization (IMO) in 1873 aimed to facilitate the global collection and exchange of weather information. India joined as a member in 1878, with several IMD meteorologists participating in IMO commissions and committees. In 1950, the IMO was succeeded by the World Meteorological Organization (WMO), a United Nations agency headquartered in Geneva. India, a founding member of WMO, has actively engaged in its activities and programs, consistently holding a seat on the WMO Executive Council. Indian meteorologists have played integral roles in WMO commissions, with notable figures such as Dr. P. Koteswaram and Dr. N. Sen Roy serving as Vice-Presidents. Currently, Dr. M. Mohapatra, DGM, holds the position of Vice-President for the 2023-27 term.

Efforts are continuously being made to enhance indigenous development of meteorological instruments and sensors in every field, with strong support from IMD and the Ministry of Earth Sciences (MoES). The MoES actively encourages extensive R&D in this area. As a result, IMD is emerging as a leader in the indigenous development of meteorological instrumentation, alongside other aspects of meteorology. In the coming years, ongoing R&D aims to produce indigenous low-cost, rugged surface instruments, with a strong focus on maintaining data quality and consistency. These efforts are vital for addressing climate change, improving early warning systems, supporting climate projections, and assessing their impacts. In the coming time advanced AI, IOT, Quantum techniques integration, crowdsources weather data platforms such as citizen weather stations, mobile devices, development of low-flying drones-based observations, capable of capturing specific observations during thunderstorms, adverse weather, and in the upper atmosphere. These projects are currently in progress and are expected to become part of regular observation systems, incorporating various advanced methods of source observations. Supported by the Ministry of Earth Sciences (MoES).

10. *Conclusions* - With the vision that No Severe Weather shall go undetected, unobserved and unpredicted or unwarned, India Meteorological Department (IMD) commemorates 150 years of meteorological excellence, and reflects on a robust legacy of guiding the nation through the intricacies of weather. Established in 1875, IMD has evolved from humble weather tracking to embracing cutting-edge technologies. The 1970s witnessed a meteorological revolution with the introduction of satellites, radars, and advanced infrastructure such as Automatic Weather Stations, Aviation Meteorological sensors, and High Wind Speed Recorders (HWSR). These innovations have not only revolutionized meteorological predictions but have also played a crucial role in strategic decision-making processes, empowering farmers, and ensuring the safety of air travel. Significantly, advancements in cyclone forecasting accuracy stand out as a hallmark achievement, underscoring IMD's commitment to providing timely and precise information during critical weather events. From the early weather stations in the late 18th century to the present comprehensive study of weather, climate, and enhanced cyclone forecasting, IMD remains at the forefront of meteorological innovation, embodying India's enduring commitment to preparedness and foresight.

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Author Contributions

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Anjit Anjan: Technical inputs related to the AWS and Radiation Network.
Uday Shende: Technical inputs on surface observations and calibration.
Shijo Zacharia: Technical inputs related to Aviation meteorology, RSRW and the High Wind Speed Recorder network.
P. C. Trivedi: Technical inputs related to the Radiation Network.
Ashwin Raju D K: Technical inputs related to Aviation meteorology and the High Wind Speed Recorder network.
K. S. Hosalikar: Conceptualization, methodology design, supervision, original idea of manuscript flow, critical review of the manuscript. proofreading.

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Abbreviations

Agro-AWS – Agricultural Automatic Weather Station
ARG – Automatic Rain Gauge
ASG – Automatic Snow Gauge
AWS – Automatic Weather Station
AWOS – Automated Weather Observing System
BIS – Bureau of Indian Standards
DGCA – Directorate General of Civil Aviation
DSB – Digital Station Barometer
DSG – Digital Snow Gauge
EW4All – Early Warnings for All (UN initiative)
GTS – Global Telecommunication System
HWSR – High Wind Speed Recorder
ICAO – International Civil Aviation Organization
IMD – India Meteorological Department
IMO – International Meteorological Organization
IPCC – Intergovernmental Panel on Climate Change
MoES – Ministry of Earth Sciences
NABL – National Accreditation Board for Testing and Calibration Laboratories
NDC – National Data Centre
NIO – National Institute of Oceanography
NCMRWF – National Centre for Medium Range Weather Forecasting
NWP – Numerical Weather Prediction
QA/QC – Quality Assurance / Quality Control
RA-II – Regional Association II (Asia)
RS/RW – Radiosonde/Radio Wind
RVR – Runway Visual Range
SID – Surface Instruments Division
TDMA- Time Division Multiple Access
UNEP – United Nations Environment Programme
UV-A / UV-B – Ultraviolet Radiation A / B
WMO – World Meteorological Organization

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