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India Meteorological Department: A journey of 40-Year of polar meteorology

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सार– राष्ट्रीय और वैश्विक प्रासंगिकता वाले अंटार्कटिका के लिए बहु-विषयक और बहु-संस्थागत वैज्ञानिक अभियान भारत द्वारा पहली बार 1981 में शुरू किया गया था। भारत मौसम विज्ञान विभाग (आईएमडी) ने पहले अभियान से ही मौसम संबंधी अवलोकन शुरू कर दिया था। दक्षिण गंगोत्री (70.75^{o} S 11.58^{o} E), मैत्री (70.76^{o} S 11.73^{o} E) और भारती (69.4^{o} S 75.18^{o} E) स्टेशनों से एकत्र किए गए व्यापक मौसम संबंधी अवलोकन पिछले चार दशकों में अंटार्कटिक जलवायु का एक व्यापक अवलोकन प्रदान करते हैं।

यह पेपर जलवायु विज्ञान के व्यापक संदर्भ में ध्रुवीय मौसम विज्ञान के महत्व पर प्रकाश डालता है। यह इन चरम वातावरणों में निरंतर डेटा संग्रह से जुड़ी चुनौतियों और उपलब्धियों पर जोर देते हुए, उपरोक्त ध्रुवीय स्टेशनों पर मौसम संबंधी बुनियादी ढांचे की स्थापना और रखरखाव में आईएमडी की भागीदारी का एक सिंहावलोकन प्रदान करता है। विश्लेषण में तापमान, वर्षा, हवा के पैटर्न, सौर विकिरण और वायुमंडलीय ओजोन सहित मौसम संबंधी चर की एक श्रृंखला शामिल है।

ABSTRACT. The multi-disciplinary and multi-institutional scientific expedition to Antarctica of national and global relevance was initiated by India for the first time in 1981. India Meteorological Department (IMD) started meteorological observations since the very first expedition. The extensive meteorological observations collected from Dakshin Gangotri (70.75^{o} S 11.58^{o} E), Maitri (70.76^{o} S 11.73^{o} E) and Bharati (69.4^{o} S 75.18^{o} E) stations provide a comprehensive overview of the Antarctic climate over the past four decades.

The paper highlights the significance of polar meteorology within the broader context of climate science. It provides an overview of IMD's involvement in setting up and maintaining meteorological infrastructure at the aforementioned polar stations, emphasizing the challenges and achievements associated with continuous data collection in these extreme environments. The analysis includes a range of meteorological variables, including temperature, precipitation, wind patterns, solar radiation and atmospheric ozone.

Key words – Polar meteorology, Antarctica, IMD, Climate research, Extreme weather events, Climate change and Ozone.

1. Introduction

It is well understood that the Polar Regions play vital role in regulating the weather and climate of different continents and the world as a whole. Effort has been made to find and establish co-relation between its weather and its influence on Indian weather systems, particularly the monsoon, occurrence of devastating tropical cyclones, ozone *etc*. The Antarctic continent and its surrounding southern ocean, south of the Antarctic convergence, is probably the least known region of the world. The meteorological data bank, formed over the years of observation at Maitri, is fundamental to our understanding of its climatology and its cotemporary process of global relevance like, ozone depletion, atmosphere pollution, climate change, melting of ice shelves, Blizzards, Glacier and sea level rise *etc*.

The linkages between climatic variations of the Polar Regions and various Earth system processes in general make the study of the Polar Regions an attractive pursuit. Subjects of immediate interest are forecasting of weather and climate and understanding the effects and likely impacts of climate change. The general circulation of the whole atmosphere is mainly driven from the temperature difference between the equatorial and the Polar Regions, resulting from the differential absorption of solar energy. Without the knowledge of the Antarctic and Arctic climatology, the general circulation of the whole atmosphere cannot be understood. Thus, meteorological observatories in Antarctica and Arctic have a fundamental importance, not only for Polar Regions but for the whole world as the region experiences change that has global implications. Despite the fact that Antarctica is an important part of our climate system and its sensitivity to climate changes, only very few meteorological measurements are available. To reduce this problem, the World Meteorological Organization (WMO) strongly recommends that any research station established in Antarctica should run a meteorological observatory.

Antarctica is endowed with unique features such as cold temperatures, strong winds, blizzards and the vast glaciers on the earth. The synoptic systems around Antarctica are typically inhospitable and dreadful, unlike elsewhere. Meteorology is considered paramount because it can foresay the weather conditions in any particular region. The Antarctic region is a "natural laboratory" for scientific research of importance. The climate, physical and biological properties of the continent and the surrounding ocean is closely coupled to other parts of the global environment by the ocean and the atmosphere. For example, the Antarctic ozone hole was one of the most significant scientific discoveries of the last century. Antarctic and global climate will remain areas of interest for the foreseeable future. Understanding of the dynamics of polar climate systems is rudimentary at best and a lack of fundamental knowledge limits predictions of future change with confidence. A lot remains to be done to produce a truly integrated view of the planet's climate system and the role of Antarctica and Arctic in it.

India first participated in the 17th Soviet Antarctic Expedition during 1971-1973 under a joint Indo-Soviet agreement. A young researcher from **Physical Research Laboratory** Dr. Paramjit Singh Sehra became the first Indian ever to winter over the Antarctica and worked for more than a year at the Russian Antarctic station Molodezhnaya in East Antarctica. to carry out research related to upper atmospheric meteorological rocket soundings. The investigation of the atmospheric wind and thermal structure over Antarctica from surface up to about 80km were studied using data from about 52 successful meteorological rocket soundings at Molodezhnaya, Antarctica (Sehra, 1976a, 1976b, 1975).

The Indian scientific expeditions to Antarctica started in 1981 when the first summer expedition code-named "Operation Gangotri" was flagged-off from Goa on December 6, 1981, onboard MV Polar Circle, a chartered ship from Norway. The expedition landed in Antarctica on January 9, 1982 and a base camp was set up on ice shelf named Dakshin Gangotri (69º 59' 23.12" S, 11º 56' 2 6. 82" E). Two meteorologists Mr A. K. Sharma and Mr K. N. Katyal of IMD participated in the first Indian Scientific Expedition to Antarctica. MV Polar Circle left Antarctica on 18 January, 1982 and returned to Goa on February 21, 1982, thus marking the end of their 77-day expedition. The Second Indian Expedition contingent left Goa on 1 December, 1982 and reached Antarctica on 28 December, 1982. The first expedition stayed in Antarctica for 10 days while second expedition stayed on the 57 days. The second expedition was led by Mr. V. K. Raina of Geological Survey of India and Dr. C. R. Sreedharan (Deputy Leader) of IMD. The automatic Weather Station (AWS) powered by solar energy was installed during the first expedition. The data tape of the AWS set up by the first expedition was recovered by the second expedition. The tape contained data from 16 January 1982 to 13 June 1982.The first two scientific expeditions of 1981-82 and 1982-83 were carried out during Antarctic summer months. These two summer expeditions laid down the significant groundwork for scientific research in Antarctica. India officially acceded to the Antarctic Treaty System on 1 August, 1983. On 12 September, 1983, the country became the fifteenth Consultative Member of the Antarctic Treaty. The Third Indian Scientific Expedition (1983-84) to Antarctica established a permanent station at Dakshin Gangotri (70º 05' 37" S, 12º 00' 00" E) on ice-shelf on Princess Astrid coast. This expedition was also the first wintering Indian expedition (Headland, 1993). During the Third Indian Scientific Expedition extensive meteorological measurements were made at base camp and also at the permanent meteorological station which was established at Dakshin Gangotri on February 24, 1984. The WMO station index number 89510 was assigned to Dakshin Gangotri. The first Indian wintering team consisted of 3 scientists, 1 each from Defence Research and Development Organisation (DRDO), IMD and National Institute of Oceanography (NIO) and 9 maintenance personnel drawn from various branches of Defence Services. Dr S. R. H. Rizvi became the first meteorologist from IMD to participate in the first winter expedition to Antarctica. The meteorological observatory at Dakshin Gangotri was installed on an ice-shelf about 20 km from the coast. Data Collection Platform (DCP) for accessing satellite INSAT-IB data was installed during fourth expedition (1984-85) and it was made fully functional during fifth expedition (1985-86). Measurement of global solar radiation was started during 1984-85. The Dakshin Gangotri station remained functional till 1990 after which it was abandoned due to burial under the ice (Ramesh and Soni, 2018; Soni *et al*., 2017).

In the year 1988-89, India built its second indigenous station "Maitri" over a rocky, mountainous area known as

'Schirmacher Oasis'. Maitri is located in the valley of central part of Schirmacher Range, Dronning Maud Land, East Antarctica. This oasis is about 16 km long stretching in an east-west direction between 70º 44′ 30″ S to 70º 46′ 30″ S and 11º 22′ 40″ E to 11º 54′ 00″ E with a maximum width of about 2.7 km in the central part. The Schirmacher Range lies between the Wolthat Mountains about 80 km to the south and the tip of the shelf ice that is about 100 km to the north. The northern boundary of the Schirmacher oasis has an abrupt and steep fall towards the shelf ice. The altitude of Maitri is 117 m above sea level. There is a large glacial lake (Priyadarshini Lake) in front of the station. Towards its south, high glaciers occupy vast areas extending upto South Pole and towards the north, the ice shelf extends upto about 100 Km. The Schirmacher oasis forms a group of low lying hills about 50 to 200 m high. One such small hill is located in the vicinity of Maitri by the side of Priyadarshini Lake. There is a small hillock of conical shape surrounded by continental ice is located west of Maitri at a distance of about 2.5 km. A wall of glacier ice (snout) about 6 to 7.5 m high is located towards the south at a distance of about 500 m approximately in the east-west direction. During the summer months the melt from the northern periphery of the continental ice sheet cascades gently down over the exposed bedrock. The meteorological observatory at Maitri has been assigned WMO index number 89514.

India's third permanent research base, Bharati, is located on the northern tip of the Grovesnes Peninsula in the Larsemann Hills region of East Antarctica. The Larsemann Hills are a group of ice-free islands on the coast of Prydz Bay. Bharati is situated on a rocky outcrop that rises above the ice sheet, providing a stable foundation for the station's facilities. The station is located approximately 2500 kilometers south of the Indian subcontinent and is one of three enduring research facilities established by India in Antarctica. It was initiated in 2012 for testing purposes and became fully operational in 2014. The meteorological observatory at Bharati has been assigned the WMO index number 89776.

India Meteorological Department has been continuously participating in all the Antarctic Expeditions, since the first Expedition. This is an ongoing programme of recording and analyzing the meteorological data from Antarctica. Standard equipment and procedures approved by World Meteorological Organization (WMO) are being followed for meteorological data collection. A permanently manned meteorological observatory equipped with the instruments to monitor weather system exists at the Indian Antarctic stations Maitri and Bharati continuous meteorological parameters are being recorded since 1990 and 2014 respectively.

Maitri and Dakshin Gangotri stations are influenced by the west to east moving low-pressure systems that are synoptic scale frontal systems. These systems move in the circumpolar trough zone that lies between 60º S and 65º S meandering north and south between seasons. The large amplitude cloud bands in association with these systems move across the station, producing dramatic variation in cloud cover. The cyclonic circulation associated with these low-pressure systems is frequently seen on the 500 hPa chart. These systems bring warm and moist air to the coastal areas of the Antarctic continent from northern latitudes. Therefore, when a depression approaches the station, pressure starts falling continuously and temperature starts rising. The rise in temperature, which can be of the order of 10 ºC during a blizzard, is also due to the fact that the low level inversion is broken due to turbulence caused by increase in wind speed.

The pressure gradient in the field of the system is very steep and consequently produces very strong winds. It is very difficult to assess whether there is snowfall or not due to drifting snow. After the system moves away, often pressure increases steeply, temperature falls, wind becomes light or calm and the sky clears. On some occasions when small lows move at relatively higher latitudes, the skies are overcast with stratus clouds and calm or light wind prevails. Such situations result in heavy snowfall at the station. It has been observed that the intensity of blizzards as well as their duration was higher at Dakshin Gangotri than at Maitri, for the simple reason that the former location is closer to the coast.

Large scale patterns of atmospheric circulation influence Antarctica to varying levels. On an inter-annual to decadal timescale, the Southern Annular Mode or Antarctic Oscillation (SAM/AAO) and to a lesser extent the El Niño Southern Oscillation (ENSO), primarily drive the tropospheric Antarctic circulation. SAM is the principal mode of variability in the atmospheric circulation of the mid and high latitudes of the Southern Hemisphere, with synchronous anomalies of opposite sign in the mid and high latitudes. It represents the periodical strengthening and weakening of the circumpolar vortex, which is the belt of tropospheric westerlies surrounding the Antarctic continent, and provides a means of coupling the Antarctic climate with that of lower latitudes. During times of high SAM index, most of East Antarctica experiences cooling while the Antarctic peninsula experiences warming and strengthening of westerlies. ENSO, on the other hand, is characterized by a pattern of warm and cold sea surface temperature anomalies in the central and eastern equatorial Pacific with coupled atmospheric changes, which extend to Antarctica.

2. Data and Methodology

2.1. *Meteorological Instruments installed at Dakshin Gangotri*

The meteorological observatory at Dakshin Gangotri was equipped with

(*i*) 401-MHz audio modulated radiosonde/ozonesonde ground equipment,

(*ii*) Dobson Ozone Spectrophotometer (1987-88),

(*iii*) Complete wind mast assembly with temperature and humidity sensors anemometer and wind vane attached with continuous recording and dial display facility,

(*iv*) Barograph and aneroid barometers for measurement of atmospheric pressure,

(*v*) Potential gradient unit for measuring atmospheric electricity,

(*vi*) ECC based Surface Ozone Analyzer

(*vii*) Automatic Picture Transmission (APT) receiver unit to receive cloud pictures from NOAA and METEOR weather satellites at periodic intervals,

(*viii*) Weather facsimile recorder to receive weather charts from various meteorological centres namely Molodyozhnaya (USSR station in Antarctica) and Pretoria (South Africa), and

(*ix*) Different portable instruments for taking manual observations in the event of power failure.

(*x*) Data Collection Platform (DCP) for accessing satellite INSAT-IB data.

(*xi*) Pyranometer for measurement of global solar radiation installed during 1984-85.

2.2. *Meteorological Instruments installed in the field observatory at Maitri*

(*i*) Stevenson Screen and two wind masts were installed during January 1990.

(*ii*) The installation of self-recording instruments, Radiosonde/ozone Ground Equipment.

(*iii*) AWS (Automatic Weather System).

(*iv*) Stevenson Screen with dry bulb thermometer, the maximum and the minimum thermometer.

(*v*) Electrical thermometer (YSI Thermister) was installed in a mini screen on DCP wind mast at the same height of Stevenson Screen for continuous recording of surface air temperature.

(*vi*) Cup generator anemometer and wind vane were installed on the top of the building structure.

(*vii*) Surface Ozone UV-Analyzer.

(*viii*) The omni-directional antenna and helical antenna were installed at the top structure of the building to receive cloud imagery and signals from upper air soundings, respectively.

(*ix*) Pyranometer for measurement of Global Solar Radiation.

(*x*) High Wind Speed Recorder.

(*xi*) Brewer Spectrophotometer (1997-2007).

(*xii*) Sunphotometer to measure atmospheric turbidity (till 2012).

2.3. *Instruments installed in the Maitri lab*

(*i*) Radiosonde/Ozonesonde Ground Equipment for receiving signals from upper-air soundings (Ozone Sonde, Radio Sonde and Radio Meter Sonde).

(*ii*) Automatic Picture Transmission (APT) receiver-cum-recorder for receiving the visible and infra-red cloud pictures from Polar Orbitting (NOAA-10 and NOAA-11) Satellites (not functional now).

(*iii*) Temperature recorder for continuous recording of surface air temperature.

(*iv*) Wind direction and speed recorders for continuous recording of wind data.

(*v*) Recorder for continuous monitoring of surface ozone.

(*vi*) Recorder for continuous recording of Global Solar Radiation.

(*vii*) Microbarograph for self-recording of atmospheric pressure.

(*viii*) Sunphotometer to measure atmospheric turbidity (till 2012).

(*ix*) Weather Facsimile Recorder: Weather fax recorder was installed in March 1990 to receive analyzed weather charts from Molodezhnaya and Pretoria. On an average about two charts per day were received from Molodezhnaya. (not functional now)

2.4. *Data Collection Platform (DCP)*

The DCP Unit was installed at Maitri in February, 1990. The helical antenna was installed on top of the eastern end of the building. Since Maitri is surrounded by hills, the direct line of sight with the satellite was available from this corner only. The main unit consisting of Signal Conditioner and DCSTS (Data Conversion Storage and Transmission Sub-System) were installed in the loft. The system was commissioned in mid February 1990 after calibration and comparison with ground truth values of various parameters. Since then the data was being transmitted and received at MDUC (Meteorological Data Utilization Centre), New Delhi through INSAT-1B. The DCP unit is not operational now after the installation of AWS.

The seasons for Antarctica are categorized as summer (DJF; December-February), autumn (MAM; March-May), winter (JJA; June-August) and spring (SON; September-November).The data utilized in this study spans multiple decades and encompasses observations from different Antarctic research stations of IMD. The meteorological observations from Dakshin Gangotri for the period 1982 to 1990, Maitri station for the period 1990 to 2022, and Bharati station for the period 2014 to 2022 are used in this study. The locations of the Indian Antarctic stations are shown in Fig. 1. The meteorological instruments installed at Antarctic stations follow the standards specified by the World Meteorological Organization, thereby ensuring a high degree of accuracy. Temperature measurements have accuracy of ±0.05 °C, atmospheric pressure of ±0.1 hPa, wind speed of ±0.5 m/s and wind direction of ±1°.

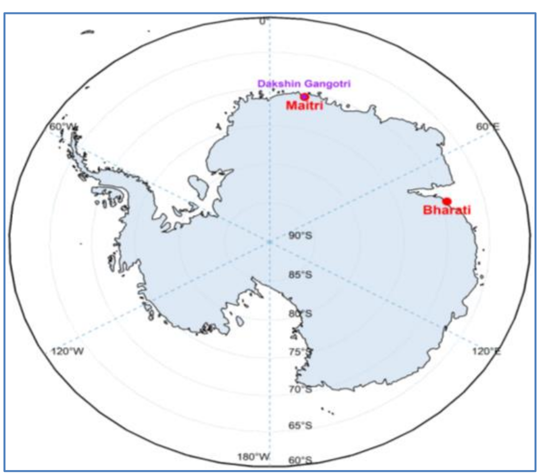


Fig. 1. Indian Antarctic stations and their location

2.5. *Meteorological Instruments installed at Bharati*

(*i*) Radiosonde/Ozonesonde Ground Equipment for receiving signals from upper-air soundings (Ozone Sonde, Radio Sonde and Radio Meter Sonde).

(*ii*) Temperature recorder for continuous recording of surface air temperature.

(*iii*) Wind direction and speed recorders for continuous recording of wind data.

(*iv*) Recorder for continuous monitoring of surface ozone.

(*v*) Recorder for continuous recording of Global Solar Radiation.

(*vi*) Microbarograph for self-recording of atmospheric pressure.

(*vii*) Digital Current Weather Instrument System (DCWIS).

3. Results and Discussion

The transantarctic mountain ranges divide the Antarctica in two contrasting regions East and West-Antarctica. The mountain ranges extend across the Antarctic continent from Cape Adare in northern Victoria Land to Coats Land. East Antarctica is also called Greater Antarctica and constitutes majority of the Antarctic continent. The East Antarctic ice sheets rest on bedrock that is mostly well above sea level, but the ice in West Antarctica is grounded on a bed that is up to 2 km below sea level (Otosaka *et al*., 2023). Contrasting temperature trends have been observed in East and West Antarctica.

The southern hemisphere annular mode (SAM) index is defined as zonal mean sea level pressure difference between latitudes of 40° S and 65° S (Marshall, 2003). It is linked to variability in surface air temperature, sea surface temperature and other aspects of climate of higher latitudes in southern hemisphere. The SAM index is also known as Antarctic Oscillation (Gong and Wang, 1999) and High-Latitude Mode (Rogers and Van Loon, 1982). The SAM index plays a major role in variability of southern hemispheric extra-tropical atmospheric circulation on weekly, monthly and inter-annual time scale (Thompson and Wallace, 2000). The positive (negative) SAM index corresponds to anomalous low (high) pressure over Antarctica and anomalous high (low) pressure in the mid-latitudes. The positive SAM index is characterized by strengthening circumpolar vortex and intensification of westerly zonal winds that encircle Antarctica. Change in the SAM index contributed considerably to the observed warming in the Antarctic Peninsula and cooling over most of the East Antarctica (Thompson and Solomon, 2002). Depressions are more frequent in the surrounding Ocean compared to the interior region of Antarctica. Most Southern Hemisphere cyclones in fact occur at latitudes around 60° S in the circumpolar trough (King and Turner, 1997). Maitri is affected by the eastward moving depressions which move in the circumpolar trough that encircles Antarctica between the latitudes 60° and 65° S. These depressions bring warm and moist air to the coastal areas of the Antarctic continent resulting in cloudiness. The surface air pressure falls and temperature rises when depression approaches the station. Synoptic systems move from the Antarctic circumpolar trough southward and when approaching the coast, these systems generally turn to the east moving parallel to the continental ice sheet. The circumpolar trough and region south of it are regions of actively decaying depressions (Simmonds and Keay, 2000). Some of the dissipating depressions around the Antarctica coast often exist in that state for several days as they are slow moving systems. These systems have major influence on climatology of Antarctica. The temperature can increase up to 10 °C during a blizzard, as the low level inversion breaks because of turbulence caused by high winds. After synoptic system moves away, the atmospheric pressure rises sharply and air temperature decreases. Also, the wind slows down or becomes calm and the sky clears. When small low pressure system progresses at relatively higher latitudes, the stratus clouds appear with calm or light winds resulting in heavy snowfall at the station.

3.1. *Ambient Air Temperature*

The large slant angle of incoming solar radiation, high albedo of snow/ice surface, low atmospheric turbidity, absence of vegetation and snow covered land are responsible for low temperature of Antarctic. The ambient air temperature in Antarctic region is mainly influenced by the heat transport mechanisms, wind and weather phenomena which perturb solar radiation. Continuous clear sky with light wind only can cause gradual fall in air temperatures. At sub-zero temperature the water content in soil freezes with particles of soil, sand and rock embedded. This is called permafrost layer which is hard and poor in thermal conductivity. Hence, when temperature changes are noticed even on land it is almost limited to top one meter layer.

The Figs. 2 (a, b & c) depict the monthly mean temperature variation at Dakshin Gangotri, Maitri and Bharati. The temperature gradually decreases from January onwards due to onset of winter, up to August. From August to September temperature rises slightly and thereafter increases sharply from October. The surface air temperature rises slightly from May to June. This may be

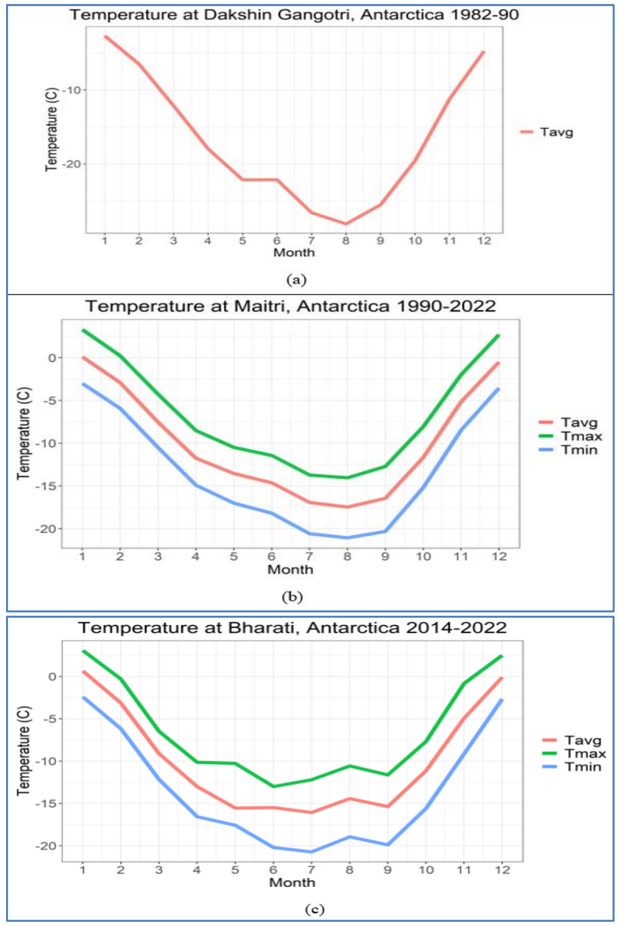


Fig. 2: Variation of monthly mean, maximum and minimum temperature at (a) Dakshin Gangotri (1982-1990) (b) Maitri (1990-2022) (c) Bharati (2014-2022)

due to the frequent movement of extra-tropical low pressure systems which caused the warm and moist air drawn from lower latitudes and mixed with dry and cold continental air thus causes increase in temperature. Generally, during the blizzard period, a rise in the temperature was observed due to the same reason. The highest average monthly temperature observed at Maitri was 2.0 °C in December 1991, while the lowest was -23.6 °C in July 2006.The average annual temperature is equal to -9.8 °C. The winter air temperatures are observed and stay around -14 ºC to -17 ºC during the succeeding months at Maitri. By the temperature regime, the winter season continues for six months from April to September. August is the coldest month with mean temperature of -17.4 ºC. Summer is warm and continues for two months from December to January when average monthly temperature is close to zero. The highest temperatures are recorded during the summer solstice. During this period, rapid snow and ice melting occurs and numerous relief depressions are filled with water. Based on the temperature, two other seasons can be categorized as spring (October-November) and autumn (February-March). During the day, maximum temperature is observed around midday and the minimum at night. The non-periodic air temperature oscillations are related to changes in the synoptic conditions. On cloudy days, diurnal variation of temperature was found to be very low as compared to that on clear sky days as expected.

The low pressure systems move from west to east round the Antarctic coast along the polar low pressure belt which fluctuates north-south on both diurnal and seasonal basis. These low pressure systems which are associated with cyclonic (clockwise in southern hemisphere) circulation carry warm and moist air to the south of it. As a result, continuous rise in temperature is observed with the approach of these systems. Continuous fall of atmospheric pressure with the approach of low pressure system carrying of heat is by the continuous rise of surface air temperature. The rise in surface air temperature may also have been due to the breaking up of low level surface inversions, which is one of the prominent features of the Antarctic atmosphere. These moving low pressure systems are found to be the main agencies of transporting heat from southern latitudes towards the higher Antarctic latitudes. On the other hand, the extension of high pressure cells in the southern latitudes in the form of ridges, moving slowly to the east was found to be an ideal situation for drawing in the cold and dry Antarctic continental air.

Highest maximum at Maitri is recorded as 12.5 °C on February 4, 1996 and at the Bharati research station was 9.9 °C on January 5, 2018. The lowest temperature ever recorded on Earth was -89.2 °C at the Vostok Station on July 21, 1983 (Marshall, 2003; Turner *et al*., 2009), while the lowest temperature recorded at Maitri as -44.6 °C on October 2, 2006 and at the Bharati station to date is -40.3 °C on September 6, 2016.A very unusual warming was observed during February 1996 when surface air temperature reached +12.5 ºC on February 4, 1996 at Maitri. This type of unusual warming has not been observed since 1990 when meteorological observations started at Maitri. The surface air temperature started increasing gradually from January 25, 1996 and peaked on February 4 and subsided abruptly by February 5, 1996. Similar warming was also observed at nearby Russian station Novolazarevskaya (Kaur *et al*., 2013).

The mean temperature of Maitri was more than that of Dakshin Gangotri by about 8-10 °C during all the months. This is due to the fact that Maitri is situated over rocky area whilst Dakshin Gangotri was on ice shelf. The solar radiations are mostly absorbed by the land during day time. During night, the land emits heat energy as terrestrial radiations and warms the lower atmosphere at Maitri. Solar radiations are mostly reflected back to the space due to high albedo of snow at Dakshin Gangotri and virtually no terrestrial emission take place from ice during night. The lowest minimum temperature -52 °C & highest temperature of 6 °C were recorded on August 16, 1985 and December 21, 1985 respectively at Dakshin Gangotri (Lal, 2008).

3.3. *Mean Sea Level Pressure*

Annual variations of atmospheric pressure, similar to the other Antarctic stations have two maximums (in June and January) and two minimums (in April and October). One peak in the month of June has mean value of 989 hPa and the other in January with value of 988 hPa. The MSL pressure fell to a low value of 985 hPa in February and then steadily increases till June. It fell again gradually till October with a very low value of 983 hPa and then again increases gradually. Fig. 3 (a, b and c) shows monthly mean sea level pressure variation at Dakshin Gangotri, Maitri and Bharati. From January to March, the pressure decreases, which can be attributed to the warming of the Antarctic continent during the summer months. Conversely, from September to December, the atmospheric pressure increases due to the cooling of the continent during the winter months.

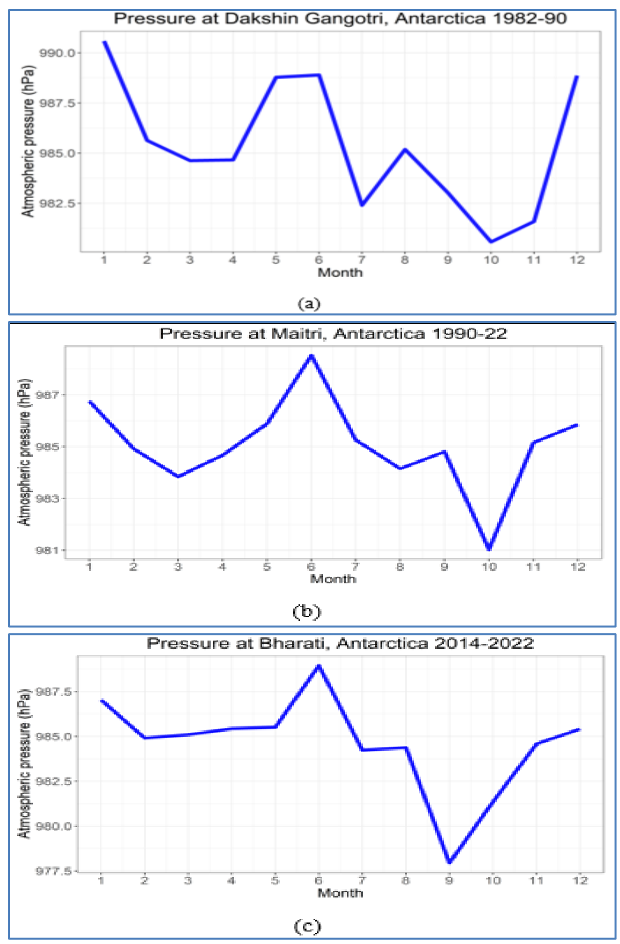


Fig. 3. Variation of monthly mean sea level pressure at (a) Dakshin Gangotri (1982-1990) (b)Maitri (1990-2022) (c) Bharati (2014-2022)

3.4. *Surface Winds*

Maitri Station lie between the high pressure regions centred about the South Pole and the circumpolar trough of low pressure roughly along 63º S. Therefore atmospheric pressure at the stations is influenced by the relative position and strength of these features. In the coastal areas high wind occurs and it decreases inland towards the polar plateau. The surface wind regime at Maitri is characterized by alternating spells of strong wind and light or calm wind. The duration of these spells varies considerably from a few hours to several days. Generally, Maitri experiences daily mean wind speed between 5 and 10 ms^{-1} (~10 and 20 kt) from East-South-East and South-easterly directions. During the passage of extra-tropical systems, strong gusty winds from south-easterly direction prevail. The near-surface wind field in Antarctica is dominated bylarge-scale downslope wind systems known as katabatic winds. Katabatic winds are particularly strong in austral winter, as cold and dense air on the snow-covered interior plateau blows down to the coastal Antarctic region (Mather and Miller, 1966). Kulandaivelu and Dang (2003) also observed that pure katabatic winds prevail in all the months with higher frequency in winter than summer at Maitri. For few days in a month, katabatic winds caused by radiative cooling of the near-surface air, winds from the south are experienced and this phenomenon prevails almost throughout the year. The cooling of air causes a thermal inversion to develop along the continental slopes, resulting in a favorable pressure gradient for the down slope or katabatic wind component. In summer, the daytime heating destroys thermal inversion and, therefore, katabatic wind flow ceases during daytime. Thus thermal inversion is only a nighttime phenomenon in summer. The strongest katabatic winds in summer occur near local sunrise and the weakest wind speeds are seen approximately an hour after local noon. Fig. 4(a, b and c) shows monthly mean wind speed variation at Dakshin Gangotri, Maitri and Bharati.

Winds in the Schirmacher Oasis are weaker than at the coast. The average annual wind speed at the Maitri station comprised 17 knots. The maximum wind speed is observed in winter and the minimum in summer. May and June months are distinguished by the largest average wind speed (20 knots). December and January are characterized by the lowest average wind speed of 13 knots. One maximum (in the morning and at night during the intermediate seasons) and one minimum (in the evening) are observed in daily wind speed variations. In winter, number of extra tropical systems around the continent are more, which cause strong gusty winds most of the days.

The low pressure systems generally move from west to east at Maitri station. The pressure fall is a general indication of low pressure system approaching the station.

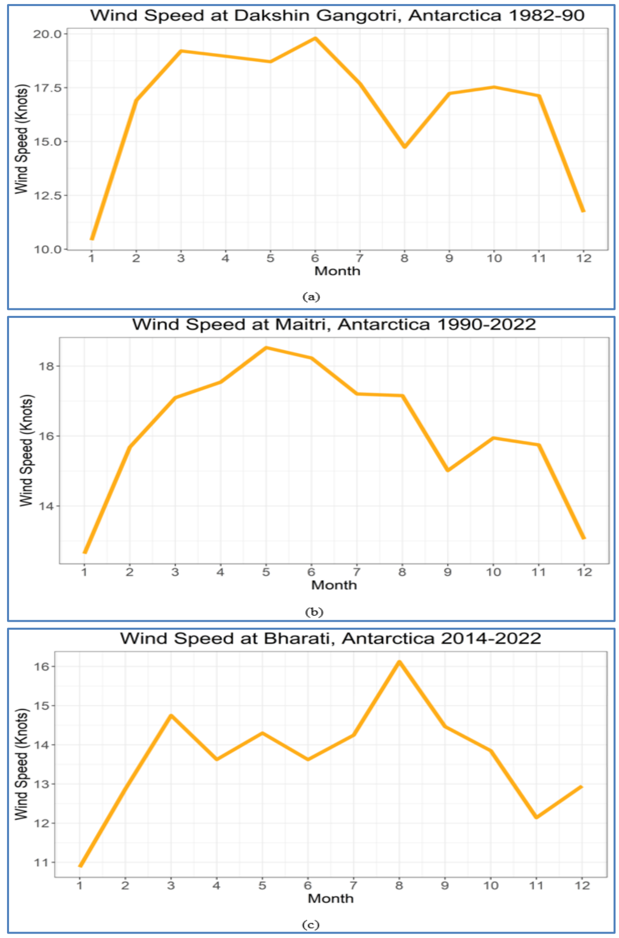
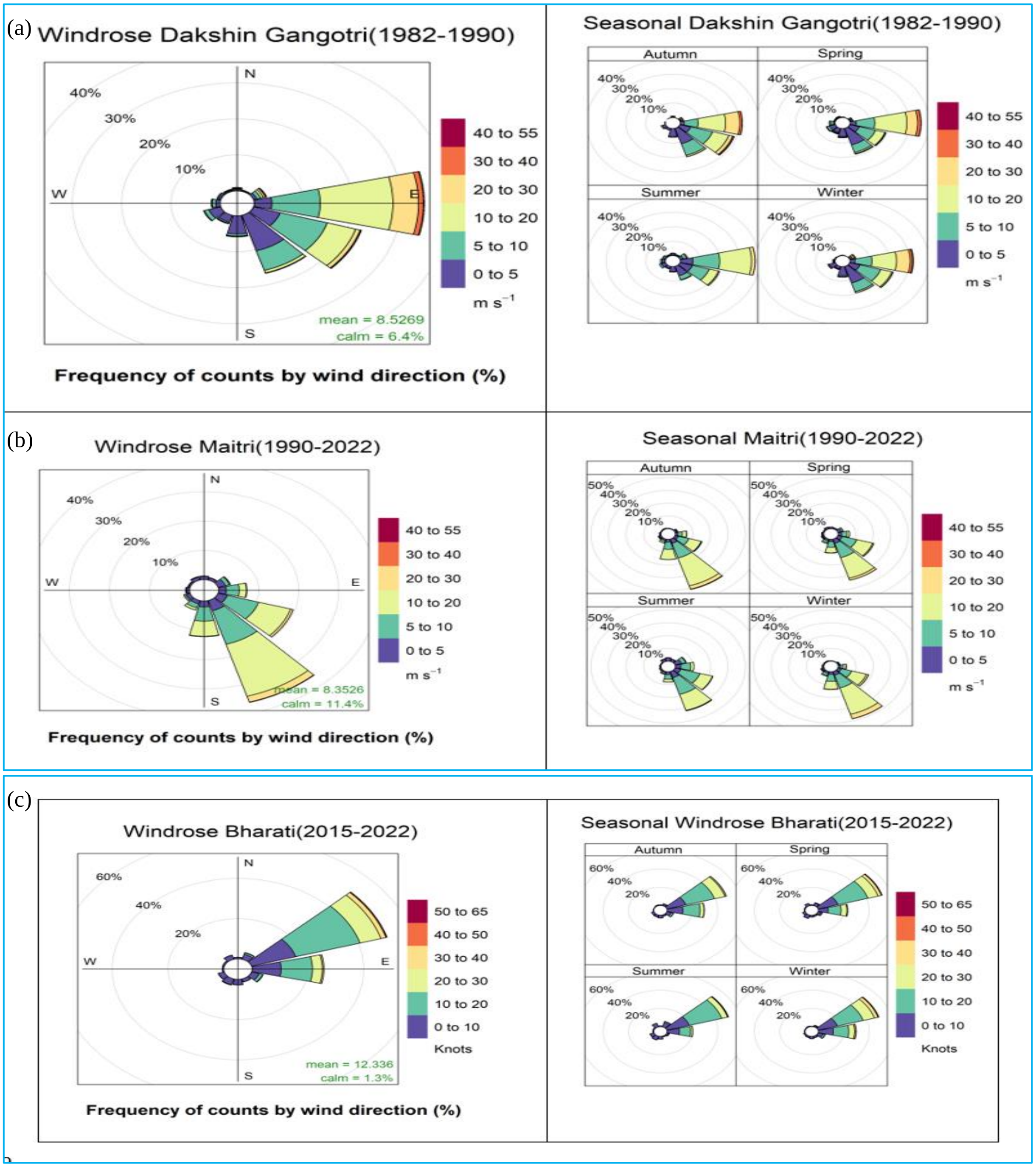


Fig. 4. Variation of monthly surface winds at (a) Dakshin Gangotri (1982-1990) (b)Maitri (1990-2022) (c) Bharati (2014-2022)

Some times when a 'low' moves across the station longitude form west to east without a significant southward component, there may not be significant dip in the atmospheric pressure. The passing of low pressure systems can be seen from wind speed and direction records under such circumstances.

Coastal regions near the Antarctic continent display unique katabatic wind patterns (Connolley and Cattle, 1994). In the Bharati region, a coastal site, the monthly variation in average wind speed ranges from 11 to 17 knots. This fluctuation indicates that the highest wind speeds coincide with months characterized by frequent blizzards at the research base. Dakshin Gangotri, being located on ice, experienced comparatively windier conditions with variations in mean monthly wind speeds ranging from 10 to 20 knots.

Figs. 5(a, b and c) provides a comprehensive representation of wind patterns at Dakshin Gangotri, Maitri, and Bharati. At Dakshin Gangotri, as shown in Figure 5(a), prevailing easterly and south easterly winds



Figs. 5: Overall and seasonal wind roses at (a) Dakshin Gangotri (1982-1990) (b)Maitri (1990-2022) (c) Bharati (2014-2022)

dominate the region. Autumn experiences the lowest wind speeds, while spring and winter are comparatively windier. At Maitri, Figure 5(b), depicts a seasonal wind pattern breakdown, with south easterly winds prevailing consistently throughout the year. The seasonal wind roses reveal predominant north easterly winds at Bharati, with summer experiencing the lowest wind speeds and winter being relatively windier (Fig. 5c).

3.5. *Blizzards*

Weather in Antarctica is subject to frequent and sudden changes due to migratory low pressure systems. These low pressure systems cause drifting and blowing of snow reaching several hundred metres above the surface and reducing the horizontal visibility drastically. Such weather systems are called blizzard and these are the most hazardous weather phenomenon in Antarctica. The cold surface air tends to flow down-slope, as a density current, towards the coast increasing in mean speed with the surface slope and the channelling of the flow by the surface orography. The katabatic flow is also strongly influenced by the synoptic scale pressure systems. At the coast the combination of strong katabatic flow with favourable synoptic gradients gives rise to the blizzards.

The classification of the blizzard is made on the following criteria:-

(*i*) Blowing snow with or without snowfall.

(*ii*) Visibility less than 1 km

(*iii*) Wind speed greater than or equal to 23 kts.

Depending on the situation to call a meteorological condition 'blizzard', sometimes any one of the above criteria is waived off (Ramesh and Soni, 2018). For example, copious snowfall is recorded for two days at a stretch followed by winds, as low as 10 to 15 knots can cause a severe blizzard with visibility less than 10 metres as the area covered by snowfall sometimes exceed several hundred square kilometres in Antarctic regions. At times even in very high winds (around 60 to 70 knots) the visibility may not decrease to 1 km level due to little snowfall or very low temp. Such cases are also considered as blizzard.

Even light to moderate winds upto 15 knots can cause moderate to intense blizzards if fresh snow is present on the ground. Such blizzards sometimes last for periods beyond 12 hours as the ground level snow is swept across the station from far off places, as far as 200 km continuously. Visibility of less than 10m is quite common during such blizzards. Reasonably good vertical visibility is an indicator of such blizzards. Lal and Ram (2009) studied the blizzards at Maitri and fond that blizzard is mostly associated with extra-tropical storms and is normally preceded by precipitation. While analyzing blizzards in 1996, Rasal (2003) observed that interactions between the two air masses, one warm and moist air from the overseas area and the other the cold and dense katabatic flow, gave rise to strong blizzards, reducing the visibility to nearly zero. Kulandaivelu *et al*. (2005) discussed synoptic features of some blizzards experienced during 1996 and 2000 at Maitri. They found that blocking high formed between 40° E and 60 °E in the south Indian Ocean in the Southern Hemisphere generates number of blizzards with strong surface wind over the East Antarctica coast. Tyagi *et al*. (2011) found that surface pressure rises before the onset of blizzards and then falls rapidly under the influence of a trough of low-pressure system and strong wind events. Furthermore, surface temperature increases as the system

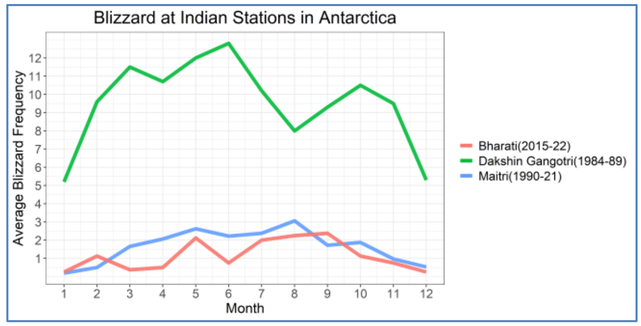


Fig. 6. Monthly Blizzard frequency at Dakshin Gangotri (1984-1989, Maitri (1990-2021) and Bharati (2015-2022) sations

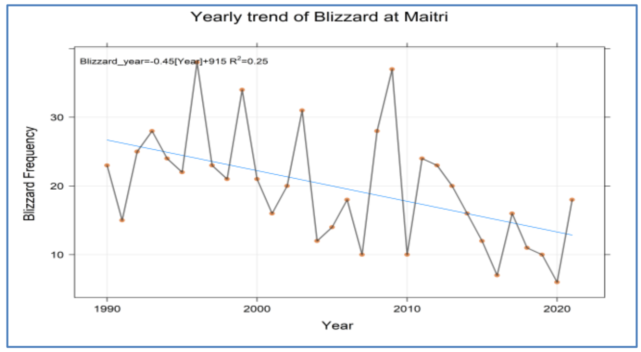


Fig. 7: Yearly mean blizzard frequency and trend at Maitri between 1990-2021

approaches due to the advection of warm air. Fig. 6 depicts the mean monthly blizzard frequency at Dakshin Gangotri, Maitri and Bharati.

The data spanning from 1990 to 2021 presents a notable long-term trend indicating a decline in the annual occurrence of blizzards at Maitri, as shown in Fig. 7. This trend underscores a reduction in the frequency of blizzard events over the examined period.

3.6. *Indian efforts to ozone monitoring in Antarctica*

The atmospheric ozone monitoring programme in Antarctica is an important activity to understand the physical, chemical and dynamical processes which cause the ozone-depletion over Polar Regions. A number of countries including India are actively involved in ozone observation programme in Antarctica. The IMD started ozone monitoring at Indian stations in Antarctica, during the second scientific expedition in the year 1982-83 during which Ozonesonde ascents were taken to obtain the vertical profile of ozone at the temporary Indian station, Dakshin Gangotri (Sreedharan *et al*., 1986) using IMD make electro-chemical ozonesonde. Regular systematic observations of atmospheric ozone started at Dakshin Gangotri in 1987 (Koppar and Nagrath, 1991; Sreedharan *et al*., 1989). Regular ozone profile measurement continued at Dakshin Gangotri till it was abandoned in 1989. The results of vertical distribution of ozone measured during January - February, 1983 of second expedition from 70° S, 12° E reveal that the highest ozone concentration over Antarctica occur around 20 to 22 km above ground as against the 27 to 28 km over tropics while lowest ozone concentrations in the Antarctic atmosphere occur at about 7.5 km above ground as against the 15 to 17 km over the tropics. The highest ozone concentration over Antarctica is of the order of 10 g/g as against the15 g/g over tropics. The surface ozone measurement and ozonesonde observations started at second station Maitri in 1990. Fortnight ozone soundings were taken at Maitri in general but more frequent observations were taken during the ozone hole period (September-November). The detailed study of year to year observations has been carried out by several scientists on ozonesonde data of Maitri (Peshin *et al.*, 1997, 1996; Peshin, 2008; Sreedharan *et al.*, 1993). These observations indicated presence of ozone hole. Fig. 9 clearly shows ozone hole during October month using ozone sonde and Brewer data.

Dobson Spectrophotometer for the measurement of total columnar ozone was installed during 7th expedition in 1987-88. Recognizing the importance of Ozone measurements over Antarctica, an International Ozone Campaign had been organized during 1987 for which IMD had set up observational facilities at Dakshin Gangotri during the summer and winter expeditions of 1987. Meteorological observations continued till January 1990 at Dakshin Gangotri until this station was decommissioned. Brewer Spectrophotometer (Mark IV, No. 153) was installed and commissioned at Maitri in July 1999 by Shri R. P. Lal, IMD team leader and operated till 2011 for the measurement of total column ozone. Simultaneously, this instrument also provides measurement of the total column density of sulphur dioxide (SO_2) and Nitrogen dioxide (NO_2) and the maximum value of UV-B flux. The daily TCO measured at Maitri during the year 2000 using Brewer Spectrophotometer is depicted in Fig. 8. Peshin (2011) studied vertical column density of SO_2 and NO_2 measured at Maitri from September, 1999 to December, 2006 and found an increase in total column SO_2 during the ozone-hole event which is due to the downward penetration of UV-B flux in the troposphere under stratospheric ozone depleted condition. The column density of NO_2 also showed an increase after the onset of spring but not identical with that of SO_2 column. This increase in total column NO_2 is due to the decrease of the duration of night as the austral summer approaches.

The surface ozone is measured at Maitri using Electrochemical Conductivity Cell method. The surface ozone data showed insignificant diurnal variation of approximately 5 ppbv since sun appears for all the 24 hours during October to February and solar radiation does not

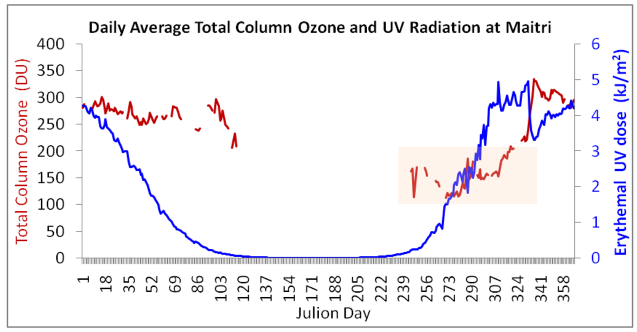
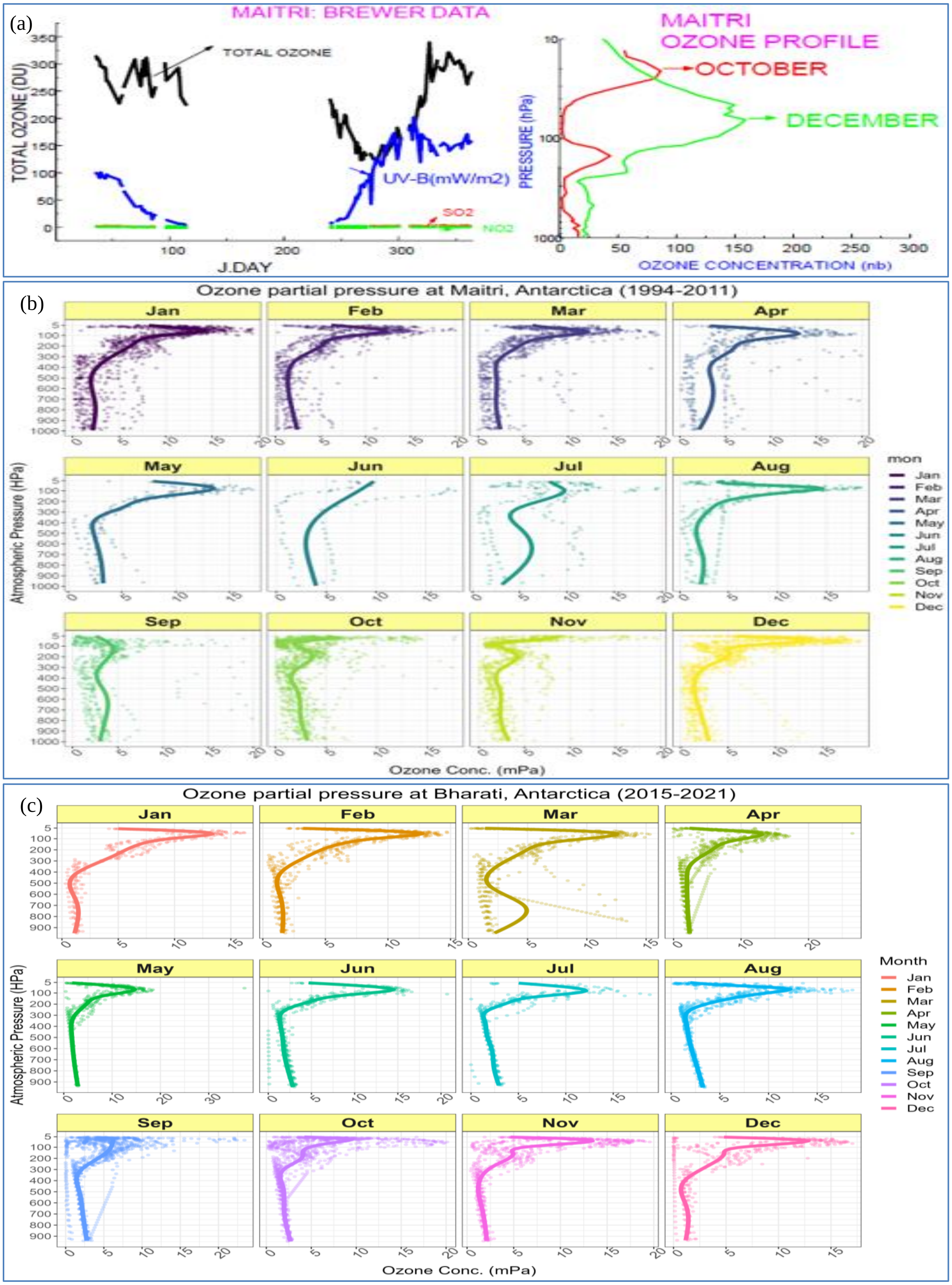


Fig. 8: Total Column Ozone (in Dobson Unit) variation at Maitri measured using Brewer Spectrophotometer (shown in red). The data gaps in the figure are because of non-availability of solar radiation due to polar nights. The satellite retrieved daily erythemal UV dose (kJ/m2) is shown in blue.

vary much from morning to night hours, resulting in very small variation in ozone concentration. The daily variations of surface ozone have been observed to be of lesser magnitude during polar nights compared to polar days. Ali *et al*. (2017) reported daily average surface ozone concentration at Larsemann Hills to vary between ~ 13 and ~ 20 ppb with overall average value of ~ 16 ppb (Kumar *et al*., 2023) and at Maitri, it varied between ~ 16 and ~ 21 ppb with overall average value of ~ 18 ppb. Surface ozone is a secondary pollutant and produced through the oxidation of precursors gases such as CO or hydrocarbons in the presence of sufficient concentrations of NOx. As anthropogenic pollution is almost negligible at Maitri, the insitu photochemical production of ozone may not be very significant. Depletion in the stratospheric ozone during ozone hole period gives way to highly energetic UV radiation to reach to the surface layer and initiate photolysis of oxygen and NOx molecules in the surface boundary layer leading to production of surface ozone. The NOx is produced from surface snow pack. The NOx production is directly driven by incident radiation and photolysis of nitrate deposited in the snow. Moreover, the surface ozone concentrations can also be increased by the downward transport of stratospheric ozone rich air during deep convection and stratosphere-to-troposphere exchange event. Episodes of high surface ozone in the Antarctica region associated with stratospheric intrusion have been reported at Maitri (Ganguly, 2013).

More recently, the ozone observations have been started by IMD at another Indian station Bharati since 2015 (Das *et al.*, 2020; Kumar *et al.*, 2023). Fig. 9 illustrates the monthly variation of vertical ozone profile using ozonesonde over both Maitri and Bharati. Bharati is close to the coast and falls in and out of the ozone hole over Antarctica due to the atmospheric dynamics of the polar vortex, resulting in drastic variability. Ozonesonde data from this station were used for validation of total ozone columns (TCOs) and vertical profiles from satellite retrieved data. Hulswar *et al*. (2021, 2020) validated OMI



Figs. 9: (a) Brewer spectrophotometer and Ozone sonde comparison at Maitri and Monthly Ozone partial pressure at (b) Maitri (1994-2011) (c) Bharati (2015-2021)

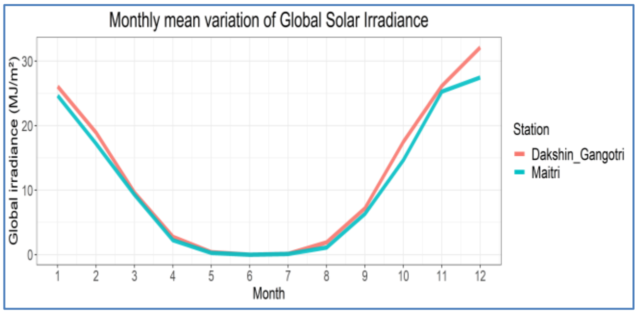


Fig. 10. Monthly variation of Global Solar Irradiance at Dakshin Gangotri and Maitri

and MLS retrieved TCO and vertical profile of ozone by comparing with the in-situ ozonesonde observations at Bharati. They found that MLS reproduced the vertical profile variation and peak heights of the ozone layer but overestimated the concentrations compared to the ozonesondes.

3.7. *Global Solar Radiation*

The polar region receives almost the equal hours of sunshine as do the equatorial regions. However, most of the solar radiation is reflected from the polar region to space due to the low elevation of sun and high albedo of the snow. The surface absorbs only a little percentage of solar radiations falling over it. Global solar radiation was monitored using the pyranometer at Dakshin Gangotri and Maitri. Sunshine duration of 24 hours in a day is experienced at Maitri for two months, from 21 November to 21 January. The sun moves around the horizon. Gradually the daylight hours decrease till the station comes under total darkness for 2 months, 22 May to 22 July. Thereafter the daylight hours start increasing and again reaches to 24 hours by 21 November.

The monthly mean values of global solar radiation at Maitri is presented in Fig. 10 and hourly mean values of radiations for each month are shown in Fig. 11. During June and July the radiation is nil due to the absence of the sunshine and very low solar elevation angle. The second half of the year receives more heat energy than the first half. The mean daily global solar radiation was maximum around 34 MJ/m^2 in December when the sun never sets over the station. This intensity of solar radiation is sufficient to defreeze the Antarctic ice but due to high albedo of snow/ice most of the solar radiations are reflected back to the space without affecting the icy continent. The snow surface that covers the Antarctic continent has very high albedo, averaging about 0.85, means that most of the solar radiation in summer is reflected with relatively little absorbed. On the other hand the high emissivity (~0.97) relative to that of the atmosphere means that the strong radiation loss, along with the low snow thermal conductivity, tends to keep the surface temperature low allowing strong surface inversions to develop in the boundary layer over the interior, particularly during winter and when it is calm. Maximum global solar irradiance of 35.0 MJm^{-2} and 30.1MJm^{-2}was observed in summer and a minimum of 0 MJm^{-2} in winter season at Dakshin Gangotri and Maitri Station respectively. Mean global radiation of 26.8MJm^{-2} is received during December month while no solar radiation is received in June month at Maitri.

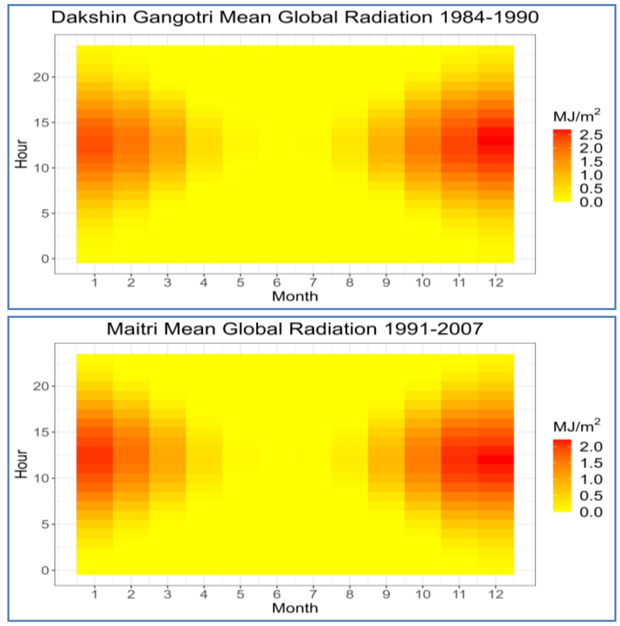


Fig. 11. Mean Diurnal Variation of Global Solar Irradiance at Dakshin Gangotri and Maitri

3.8. *Weather Forecasting System at Maitri and Bharati*

Initially, the Polar Weather Research and Forecasting (PWRF) model was employed in the Maitri region (latitude 70° 45′ S, longitude 11° 44′ E) with a horizontal resolution of 15 km. This model utilized initial and boundary conditions sourced from the India Meteorological Department's operational Global Forecast System (GFS T-382). The decision to use the Polar WRF model was driven by its superior performance compared to the IMD GFS forecasts (Kumar *et al*., 2012). This implementation was done in 2010. The performance of Polar WRF over Maitri was evaluated in comparison with Global Forecasting System (GFS) (Bhowmik *et al*., 2011). Subsequently, the Polar-WRF at 3km resolution was made operational and recently, Polar WRF model version 4.1.1 at 3 km horizontal resolution is made operational. Polar WRF v4.1.1 is a numerical weather prediction model designed for the Polar Regions and is being utilized for forecasting the East Antarctica mainly focusing over Maitri and Bharati. It uses a high – resolution grid and includes specific

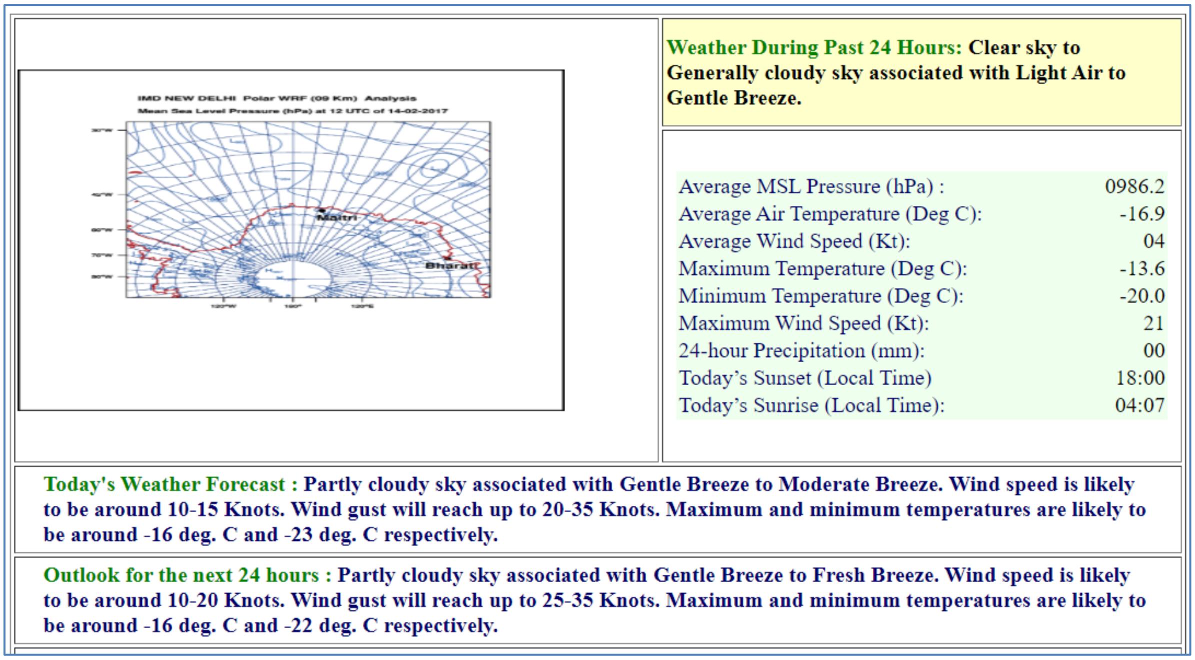


Fig. 12. Snapshot of the weather forecast bulletin for next 24 hours issued on 14 Feb 2017 for Maitri and Bharati stations

parameterizations for the unique features of polar environments, such as sea ice and snow. Currently, Polar WRF is using initial and 3-hourly boundary conditions from GFS T-1534 at a 12.5 km spatial resolution operational at IMD, Delhi. A single static domain with 1100 × 900 grids at a 3 km horizontal spatial resolution and 45 vertical levels was used for a 3-day forecast. The model employs 45 vertical model levels with a constant pressure surface at the top of 50 hPa. The WSM 5-class scheme microphysics, Goddard shortwave, RRTM longwave, Noah land-surface model, Mellor Yamada-Janjic planetary boundary layer height, and Grell-Devenyi Cumulus convection physical options were utilized in the current setup. This model is widely used for research and forecasting purposes, including studying weather patterns and climate change impacts, and for planning logistics in the Polar Regions. The observed and forecast weather bulletin as depicted in the Fig. 12 is issued regularly to support the logistic operation at the Maitr and Bharati stations.

4. Conclusion

The India Meteorological Department has been conducting consistent meteorological observations in Antarctica since its first expedition in 1981-82. These efforts have significantly improved our understanding of the complex Antarctic climate system. This paper has evaluated key meteorological parameters and their long-term variation at Dakshin Gangotri, Maitri and Bharati station. Accurate weather forecasts are crucial for logistical and scientific operations at Maitri and Bharati. These forecasts are not just convenient but essential for the success of various scientific missions in Antarctica's challenging environment. The measurement of atmospheric ozone in the Antarctic region is of fundamental importance. IMD Ozone sonde and Brewer data has confirmed ozone hole during late winter early spring (August-October). It helps us better understand global atmospheric processes and the unique climatic conditions of Antarctica. This information is vital for our broader understanding of Earth's environmental complexities.

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