Climate Variability of Southern High Latitude Regions

Sea, Ice, and Atmosphere Interactions

Edited by
Neloy Khare

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Dedication

Dedicated to Late Prof Anil Kumar Jauhri

Late Prof Anil Kumar Jauhri (28.12.1947 – 08.04.2017)

Prof. Anil Kumar Jauhri was born in Lucknow (Uttar Pradesh) on 28/12/1947. He obtained his BSc in 1967 and MSc (Geology) in 1969 from the University of Lucknow. Prof. Jauhri completed his doctorate under the guidance of Prof. K.P.Vimal and later joined the department as a Lecturer in the year 1979 and become Reader in 1992. He rose to the position of Professor of Palaeontology in the year 2000. He superannuated in the year 2012 but never retired in his professional career. He continued reaching and supervising students. He maintained a rigorous research, teaching and editorial schedule throughout his academic career. Even during times of heavy administrative responsibilities as Head of the Department of Geology.

Prof. Jauhri was highly rated for his teaching ability, and commitment for research. His ability for editing was manifested when he joined the editorial board of the journal of the Paleontological

Society of India. It was his efforts that the Journal got the citation index number in 2013 and an international acclaim for its contents. Prof. Jauhri is known for his outstanding scientific contribution on Cenozoic foraminiferal biostratigraphy of Kachchh and Meghalaya, India. His long collaboration with Prof. P.K Misra, developed his interest in Coralline algae and later together they published more than 30 research papers, completed 7 research projects and guided 3 PhD theses on integrated aspects of coralline algae and larger foraminifera form the different parts of India. At the time of his death, he was working on the manuscripts of Coralline Algae form the Prang and Kopili formations of the Meghalaya and Hut Bay Formation of Little Andaman, India.

Prof Jauhri breathed his last on April 8, 2017. The void created with the demise of Prof. Jauhri in the scientific community in general and Paleontological research community in specific is difficult to be filled. All his students, colleagues and friends will always miss him and remember him for his best qualities like kind hearted, polite, soft spoken excellent human being with complete commitment and devotion to his duties. It is a great loss to all his student. Prof. Jauhri will be remembered by generations of students for advancing their careers.

As a small tribute to my teacher Prof Jauhri, I dedicate this book to him.

Contents

Foreword

The Antarctic and its surrounding ocean is a highly coupled system and plays a central role in global climate variability and change due to non-linear interactions between the atmosphere, ocean, ice, and complex links to the rest of the Earth system. Nevertheless, the sustained efforts to illuminate its critical linkages to lower latitudes are lacking. Conjunction of new observational capabilities, advances in scientific understanding, and improving numerical models highlight the global relevance of Antarctica. The Indian Ocean sector is an area that is closely coupled to the global atmosphere on a variety of time scales. The coupled air-atmosphere-ice-ocean numerical models are required for global simulations and that realistically incorporate Antarctica.

The Antarctic region is a hotspot of climate change assessment and a barometer of global climate variability. Despite such a high significance, scientific understanding about the Indian Ocean sector of the Southern Ocean and atmospheric processes over southern high-latitude regions are yet to be further augmented, and results to be collated as a ready reference to the budding researchers in the contemporary fields of high-latitude research. At the same time, significant scientific endeavours by Indian researchers in these areas need proper documentation.

The present book, *Climate Variability of Southern High-Latitude Regions: Sea, Ice, and Atmosphere Interactions,* aptly provides a comprehensive account of Indian efforts to help understand the impact of climate change on the polar atmosphere and Southern Ocean vis-à-vis the influence of the changing Antarctica and its surrounding oceans, the polar atmosphere, and sea ice on global climate change in twelve chapters.

This book begins with the assessment of ozone variability in the Antarctic stratosphere over many decades by Soni. Interestingly, the significance of “Stratospheric Dynamics in Climate over Antarctica” has been highlighted by Kishore Kumar and Koushik. On the other hand, Sunitha Devi and Maheskumar have detailed “Antarctic Weather and Climate Patterns”. Significant attempts have been made to study aerosols over the Antarctic region. Pant et al. measured Antarctic aerosols and linked them with climate change. Similarly, Sonbawne et al. detailed the Antarctic aerosol characteristics and their role in climate variability coupled with Goel and Sharma’s physicochemical characterization of Antarctic particles. The “Impact of Near-Earth Space Environmental Condition to the Antarctic Sub-Auroral Upper Atmospheric Region” has been studied by Das.

The ocean’s response to the ongoing climate variability and the associated feedback mechanisms are dealt with by Prabhu et al., who point out an “Intriguing Relationship Between Antarctic Sea Ice, ENSO, and Indian Summer Monsoon”, whereas Dwivedi and Pandey attempt to quantify the predictability of southern Indian Ocean sea-ice concentration in a changing climate scenario.

Sea ice is a critical element of the climate system, which regulates heat, mass, and momentum exchanges between the atmosphere and the oceans at high latitudes, using the sea-ice extent (SIE) data generated from a series of passive microwave sensors. The variability of SIE trends for the Weddell Sea (WS), Indian Ocean (IO), western Pacific Ocean (PO), Ross Sea (RS), and Bellingshausen and Amundsen Seas (BAS) during the past decades, along with other aspects, have been detailed by Luis. On the other hand, Chattopadhyay and Sahai explored interhemispheric teleconnection. They noticed a connection between the Southern Hemispheric climate change and the decreasing trends in the Seasonal Mean Monsoon Rainfall over the Indian region in the last century (1871–2004). At the same time, spatial and temporal variability of physical parameters in Prydz Bay, due to climate change, has been assessed by Pednekar. Altogether, this book provides a comprehensive, up-to-date account of how the physical environment of the Antarctic continent and the Southern Ocean has changed with time. Some of the findings in this volume may prepare the Antarctic environment for change over the next century due to the accelerated greenhouse gas concentrations. This book is ready with a highly cross-disciplinary approach to reflect the continent's importance in global issues.

It will be of immense value to all scientists interested in the Antarctic continent and the Southern Ocean. It will also help the policymakers and those concerned with observing systems and the development of climate models.

Shishir Kumar Dube
New Delhi, December 2021

Preface

Climate variability includes all the variations in the climate that last longer than individual weather events. In contrast, climate change only refers to those variations that persist for a more extended period, typically decades or more. In other words, climate variability refers to the climatic parameter of a region varying from its long-term mean. Sea-ice loss, accelerated sea-level rise, and longer, more intense heat waves, besides others, are consequences we have started experiencing now.

Temperature is one of the significant measures of climate variability; this is primary and can be measured or reconstructed for the Earth's surface and sea surface temperature (SST). Precipitation (rainfall, snowfall, etc.) offers another indicator of relative climate variation, including humidity or water balance and water quality.

The ocean, which covers 70% of the global surface, has a significant influence on Earth's weather and climate. The ocean acts as a great reservoir that continuously exchanges heat, moisture, and carbon with the atmosphere, driving weather patterns and subtly influencing global climates.

The atmospheric circulation is derived by absorbing solar radiation and releasing heat from the ocean. The ocean also influences climate by way of releasing aerosols. It controls cloud cover, mainly by emitting most rainwater, absorbing atmospheric carbon dioxide, and storing it for years to millions of years and thus, the oceans influence climate. The oceans absorb the maximum solar energy that reaches Earth. During the past century alone, the global temperature has increased by 0.6 degrees Celsius. Similarly, as per estimates, the average global sea level over the past decade has risen steadily.

We need to understand and recognize the warming pattern. If global warming continues, it may not be uniform. In the context of "global warming," we must address the more significant issue of "global climate variability". High-latitude regions' unique and distinctive physical features enhance change in mean surface temperature for a given perturbation of planetary heat balance. Such a physical oceanographic setting also enhances regional and seasonal environmental response due to non-uniformity in poleward heat flux and the energy relationships of phase and albedo changes connected with ice and snow cover.

India's science pursuits in climate variability over the southern high-latitude regions have been long and diversified covering, air, sea, ice, and atmosphere over the Antarctic region. Such valuable data has been collated to provide insight into the most significant topic of climate variability vis-à-vis global warming in the present book titled *Climate Variability of Southern High-Latitude Regions: Sea, Ice, and Atmosphere Interactions*. The book consists of a total of 12 chapters intensely focused on thematic topics. The book begins with a chapter on the ozone measurements over the Antarctic region by Soni et al. The atmospheric ozone is the most critical trace gas that is beneficial and harmful to human beings and the ecosystem, depending on its abundance in the stratosphere and troposphere. It plays an essential role by absorbing solar radiation and determining the stratosphere's temperature profile and atmospheric circulation. The factors controlling spatiotemporal variations of ozone in different regions of the atmosphere over the Antarctic environment provide precious information about climate change and play a crucial role in influencing weather systems around the globe. The meteorological conditions in Antarctica prompt halogenated gases to be more effective. These gases deplete stratospheric ozone. It signifies the importance of ozone monitoring in Antarctica. Ground and satellite observations show that halogen levels in the stratospheric atmosphere are declining. Several model projections suggest that stratospheric ozone will recover to 1980 levels around the middle of this century.

The next chapter discusses the "Stratospheric Dynamics and Its Role in Climate Over Antarctica" by Kishore Kumar and Koushik. This chapter provides a comprehensive view of the state of the Antarctic stratosphere and its role in modulating the Antarctic climate. Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), was used. Reanalysis of the data set during 1980–2020 for three crucial climate variables, ozone, temperature, and zonal winds, are constructed. Besides discussing the meridional cross-section of these variables in the Southern Hemisphere, their mean annual cycle in the polar cap (60–90°S) region is discussed comprehensively. Forty-one years of deseasonalized perpetrations are obtained. The same is employed to estimate the trends in the troposphere and stratosphere. Height-month sections of the annual cycle of trends in ozone, temperature, and zonal winds are discussed. In light of the present understanding of the Antarctic stratospheric ozone depletion, the degree of covariability of trends in these three parameters is also discussed. A brief discussion on the role of polar stratospheric clouds and their signatures in the space-based lidar observations is also provided. Finally, a discussion on the potential pathways through which the stratospheric structure and dynamics interact with the troposphere is discussed in detail. The results discussed in this chapter suggest that the stratospheric processes over the Antarctic impact the troposphere through both chemical and dynamical processes and play a much more vital role than anticipated.

On the contrary, Sunitha Devi and Maheskumar discussed the salient features of Antarctic weather and climate, climate change impacts, and also briefly summarized the Indian Antarctic Program. This chapter starts with the geography and seasons of the Antarctic sub-continent. Weather patterns and the variation of state parameters and significant weather producing systems are discussed later. It also summarizes the climatological aspects of all the parameters over the South Pole.

Aerosols exert direct and indirect impacts on the climate via their interaction with the incoming solar radiation and participation in cloud microphysics. These aerosol effects depend on the size range of these particles. The remote oceanic regions and Antarctica serve as background sites to assess the climatic impacts of aerosols. Pant et al. present a review of literature on the Antarctic aerosol measurements and their climatic effects. Also reported are the measurements of aerosol concentrations and number size distributions made at a coastal Antarctic station, Maitri, during January–February 2005. Some ship-based measurements of aerosols from coastal Antarctic waters near the ice-shelf region are also reported. The high-resolution aerosol size distributions were measured over a wide size range of 3 nm–20 μm. The variations in number size distributions in Aitken, accumulation, and coarse mode particles are discussed. At the Maitri station, the total concentrations of coarse particles (0.5–20 μm diameter) remained below 1.0 cm^{-3}, with an accumulation mode between 0.72 and 0.77 μm diameter. However, these particles were found to be in the range of 2–40 cm^{-3} near the ice-shelf region at Antarctic coastal waters. The total concentration of submicrometer (0.003–0.7 μm) particles varied in the range of 100–800 particles cm^{-3} in January and between 100 and 2,000 particles cm^{-3} in February at Maitri. Considerable variability was found in the magnitude and size range of different modes in Aitken mode at Maitri and ice-shelf region. The total concentration of particles over the coastal Antarctic waters near the ice shelf was double that of the Maitri station. This high concentration of ultrafine particles in the coastal Antarctic environment could be attributed to the gas-to-particle conversion in the sub-polar oceanic region around Antarctica. The cyclonic storms revolving around the Antarctic continent enhanced the aerosol number concentration at the Maitri station. The observed size distributions of aerosols at Maitri and ice-shelf locations are discussed in their generation, transformation, and climatic impacts.

Similarly, Sonbawne et al. have detailed "Transient Variations in Enroute Southern Indian Ocean Aerosols, Antarctic Ozone Climate and its Relationship with HO_x and NO_x". Recent advances in field instrumentation and remote sensing technologies have paved the way for a variety of novel approaches to study the polar atmosphere, especially aerosols and precursor gases of both land and marine origin, influencing the Antarctica climate differently. Extensive field observations have been carried out over the southern Indian Ocean on the transit journey between Cape Town to Antarctica during the 24th Indian Antarctic Expedition voyage. We used ground-based total column ozone measurements (Micro tops sunphotometer, Dobson spectrophotometer, and Brewer spectrometer) and satellites (TOMS, GOES, and SCIMACHY) data during January 2005 and December 2006 over the Indian Antarctic station Maitri (70.76°S, 11.74°E). The results revealed a short-lived ozone depletion and heterogeneous chemical effect of Antarctic aerosols. The study also points out that in addition to the ozone loss in polar regions on a seasonal time scale, the short-term ozone depletion caused by Solar Proton Events (SPEs) produced nitrate aerosols that could also have a significant impact on the Earth's biosphere. Such studies are very sparse and almost non-existint in this region, and hence the proposed measurements would help bridge this gap to a certain extent. At the same time, Goel and Mishra have studied the "Physicochemical Properties of Antarctic Aerosol Particles". They attempted to look at Antarctic aerosols' physicochemical properties (shape, size, mixing state, and chemical composition) at the individual particle level. The frequency distribution of aspect ratio and circulatory factor of the Antarctic aerosols was observed to be bimodal with their respective mode peaks at 1.3 and 1.9 and 0.3 and 0.7. The particles were rich in Al, Mg, Si, Fe, Ti, Ca, and Cr. The particles are mainly from the crustal origin with variable shapes e.g. triangular, layered, flattened, aggregated, and glass-like structure. The spectral variation of Single Scattering Albedo (SSA) shows that the particles rich in Fe_2O_3 and Cr_2O_3 are more efficient solar radiation absorbers, whereas particles rich in Al_2O_3 exhibit high scattering.

Das studied the "Impact of Near-Earth Space Environmental Condition to the Antarctic Sub-Auroral Upper Atmospheric Region". His chapter addresses the scientific interest of high-latitudinal ionospheric consequences caused by the modulation of near-Earth space environmental conditions. For better understating, this chapter is divided into three parts based on different scientific investigations. It deals with the Earth's geomagnetic perturbations due to the solar wind–magnetospheric coupling process and explores the response of the sub-auroral high-latitude ionosphere to the geomagnetic disturbances. It further explains the longitudinal ionospheric response of the Southern Hemispheric high-latitude region. This chapter elaborated that the cumulative effect of consecutive three sub-storms has been responsible for a significant increase in ring current, which triggered a moderate-type geomagnetic storm. Further, the consequences of such geomagnetic perturbations on sub-auroral as well as polar longitudinal ionospheric impact and associated phenomenon have been described.

Sea ice is a critical element of the climate system that regulates the heat exchanges between the atmosphere and the high-latitude oceans. The changed concentration of the sea ice can affect ocean circulation. It leads to changes in global climate. Sea ice also plays an intrinsic role in maintaining the energy balance of the Earth. It helps keep polar regions cool due to its ability to reflect more sunlight into space. Sea ice also keeps air cool by forming an insulating barrier between the cold air above it and the warmer water below it. Due to melting glaciers, sea levels increase. Many authors ably cover such vital aspects in this book.

While Prabhu et al. discussed the "Intriguing Relationship Between Antarctic Sea Ice, ENSO, and Indian Summer Monsoon", they demonstrated a robust relationship between Antarctic sea ice and Indian summer monsoon rainfall (ISMR) using microwave satellite data for the period 1983–2015. An in-phase significant relationship is observed between sea ice over the Western Pacific Ocean (WPO) sector and ISMR. In contrast, for the same period, an out-of-phase relationship is observed between sea ice over the Bellingshausen and Amundsen Sea (BAS) sector with that of ISMR. The underlying physical mechanism that relays southern polar variability signal to the Indian monsoon region is through the Pacific Ocean marked by El Niño Southern Oscillation (ENSO). The sea-ice variability over the BAS (WPO) sector is associated with concurrently occurring equatorial central (western) Pacific Sea Surface Temperature (SST). Anomalous meridional circulations supplemented by BAS (WPO) sea-ice variability are accompanied by an ascending (descending) motion over the central (western) equatorial Pacific. It contemporaneously impacts summer monsoon rainfall over the Indian region adversely (favorably). Though ENSO is a prime factor simultaneously modulating signatures of sea ice and precipitation, two-way interaction between sea ice over the Antarctic and SST over the Pacific is also suggested.

Furthermore, it is verified that Antarctic sea-ice variability in conjunction with ENSO could have an opposite impact on rainfall variability over central, northern, and southern parts of India. It appears that ISMR variability is linked with Antarctic sea-ice variability through large-scale atmospheric circulations. Thus, Antarctic sea ice–ENSO–Walker cell–Hadley cell–ISMR is a new channel proposed in this study.

Dwivedi and Pandey focused on the predictability of the southern Indian Ocean sea-ice concentration in a changing climate scenario using CMIP6 models. The performance of CMIP6 models in simulating the sea-ice concentration (SIC) of the southern Indian Ocean region around (10E–100E; 55S–75S) covering both the Indian Antarctic Stations Maitri and Bharati is evaluated against the corresponding satellite observations. Out of 33 CMIP6 models used for the analysis, 25 models are categorized as good and 8 as poor models. A large inter-model spread is noticed in the seasonal variability of SIC of the region, but the multi-model mean matches very well with the observed satellite data. It is found that the multi-model mean SIC time series of historical data for the period 1900–2014 as well as high greenhouse gas (GHG) concentration future projection SSP5-8.5 data for the period 2015–2100 shows a decreasing trend. The SIC will decrease at an alarming rate of nearly 0.2% per year in the SSP5-8.5 scenario. The effect of climate change on the predictability of southern Indian Ocean SIC is quantified in terms of a generalized Hurst exponent and Predictability Index. It is shown that the SIC of the south Indian Ocean is predictable. With the increase in the GHG concentration, the predictability of southern Indian Ocean SIC will decrease. The SIC of the Maitri region is more predictable compared to the Bharati region. The predictability of the SIC of the Maitri and Bharati regions shall decrease in the SSP5-8.5 projection scenario during the years 2015–2100.

Luis highlighted Decadal Sea-Ice Variability over the Antarctic region, using the sea-ice extent (SIE) data generated from a series of passive microwave sensors. The variability of SIE trends is discussed for the Weddell Sea (WS), Indian Ocean (IO), western Pacific Ocean (PO), Ross Sea (RS), and Bellingshausen and Amundsen Seas (BAS), highlighting their magnitude for each of the four decades: 1979–1988, 1989–1998, 1999–2008, 2009–2018, and the role of the atmosphere/ocean and climate indices such as Pacific Decadal Oscillation (PDO), Atlantic Meridional Oscillation (AMO), Southern Oscillation Index (SOI), and Southern Annular Mode (SAM). The WS exhibited a negative SIE trend for all seasons during 2009–2018 and 1979–1988 (except for spring). It suggests positive trends during 1999–2008 and 1989–1998 (except for summer). The IO sector exhibited negative trends for all seasons during 1979–1988 (except for spring), 1989–1998, and 2009–2018, while positive trends were observed during 1999–2008. A significant SIE trend was detected for IO in the autumn (−20.12%/decade). The negative trends during 1979–1988 were noticed in the SIE in the PO sector. It showed positive trends during 1989–1998, 1999–2008 (except for autumn and winter), and 2009–2018 (except for spring). He encountered a significant SIE trend in winter during 1989–1998 (16.38%/decade). During 1979–1988 and 1989–1998, the SIE showed positive trends in the RS sector and negative trends during 1999–2008 (except for spring) and 2009–2018. Trends significant were encountered in the RS in summer (74.48%/decade) and spring (21.26%/decade) during 1979–1988, and in winter (−11.89%/decade) during 2009–2018. With negative trends during 1979–1988 and 1999–2008, we detected positive trends during 1989–1998 (except for spring) and 2009–2018 (except for autumn and spring). He consolidates the inferences that explain the interconnection between local and remote drivers for explaining the SIE variability.

On the contrary, Chattopadhyay and Sahai detailed the “Southern Hemispheric Climate Change, Interhemispheric Teleconnection, and the Observed Trends in the Seasonal Mean Monsoon Rainfall over the Indian Region in the Last Century (1871–2004)”. The Southern Hemisphere has shown strong signatures of anthropogenic warming in recent decades. This study utilizes the available climate data from 1871 to 2004 to understand and explore the role of Southern

Hemispheric climate change on the monsoonal variability based on the definition of regional inter-hemispheric gradient indices. It is already known that inter-hemispheric gradients represent inter-hemispheric teleconnections and show strong temperature anomaly asymmetry as a result of global warming. This chapter shows that the monsoon rainfall has not increased in the past hundred years in response to global warming, as a simple theory using an increase in moisture availability (e.g. perceptible water) and warming ocean (the Bay of Bengal and the Arabian Sea) would suggest. This chapter presents how the Southern Hemispheric climate change can explain this decreasing trend in a simplistic framework. They assume that the monsoon flow, to a first-order, is a land-sea breeze circulation with the inter-hemispheric link, which is known for a long time (for example, Mascarenes high and Findlater jet induced monsoonal flow). This interhemispheric temperature gradient is inversely correlated with the Southern Annular Mode (SAM) index. SAM shows positive trends in recent decades. Thus, an increase (i.e. positive trend) in the SAM index would weaken the land-sea temperature gradient and impact the monsoon. This SAM monsoon linkage can explain the reducing trend of all India area-averaged rainfall during the peak monsoon months.

Significantly the spatial and temporal variability of physical parameters in the Prydz Bay for climate change has been dealt with by Pednekar. This chapter presents the variability of Prydz Bay's physical parameter, which is bounded by the open sea to the north surrounded by clockwise Prydz gyre and a vast polar ice sheet to the south. Instrumental Seals data supported scientific communities to describe the variability in the Prydz Bay south of the polar frontal zone. An attempt has been made to highlight the changes in space and time in Prydz Bay based on previous studies. The major water masses in Prydz Bay are briefly explained and demonstrated using a potential temperature and salinity diagram. The vertical sections of potential temperature shown the occurrence of CDW below 200 m between 65°E and 75°E near to slope of the Prydz Bay along the 66.3°S transect. The presence of mCDW flows onto Prydz Bay occurs further south below 100 m in pockets in the transect of 67°S between 72°E to 78.5°E and 74°E. Time and space analyses have shown the entrance of CDW into the Prydz Bay near the shelf break during summer having warmer and saltier water characteristics as identified. The variability in the extension of mCDW each year in both isopycnal surfaces on a spatial and temporal scale exists. The distribution of –1.7°C isotherm on potential temperature and salinity highlights the annual variability in space and time. The extent of the mCDW signal to the interior of the bay as isotherm –1.7°C extended more southward 68.5°S with small pockets up to 69°S. The continental shelf region of the bay is influenced by the signature of warm mCDW responsible for the climate change in Prydz Bay due to the strong winds blowing from northeast to southwest in the Larsemann Hills region.

This book will serve its purpose to disseminate information on the vital aspects of climate variability over southern high-latitude regions.

Neloy Khare
New Delhi, December 2021

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It is my great pleasure to express my gratitude and deep appreciation to all contributing authors. Without their valuable inputs on various facets of climate variability over the Antarctic and surrounding Southern Ocean region, the book would not have been possible. Various learned experts who have reviewed different chapters are graciously acknowledged for their timely, constructive, and critical reviews.

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Prof. Anil Kumar Gupta, Indian Institute of Technology, Kharagpur (India), Prof. Devesh Kumar Sinha, Department of Geology, Delhi University and Dr. Rajiv Nigam former adviser at the National Institute of Oceanography, Goa (India) are deeply acknowledged for providing many valuable suggestions to this book. This book has received significant support from Akshat Khare and Ashmit Khare, who have helped me during the book preparation. Dr. Rajni Khare has unconditionally supported enormously during various stages of this book. Shri Hari Dass Sharma from the Ministry of Earth Sciences, New Delhi (India) has helped immensely in formatting the text and figures of this book and bringing it to its present form. The publishers (Taylor & Francis) have done a commendable job and are sincerely acknowledged.

Neloy Khare
New Delhi, December 2021

Editor

Neloy Khare, PhD, is an adviser/scientist to the government of India at the Ministry of Earth Sciences (MoES). He has a distinct understanding of administration and quality science and research in his areas of expertise, covering a large spectrum of geographically distinct locations such as Antarctic, Arctic, Southern Ocean, Bay of Bengal, Arabian Sea, Indian Ocean, etc. Dr. Khare has almost 30 years of experience in the field of paleoclimate research using paleobiology (paleontology), teaching, science management, administration, coordination for scientific programs (including Indian Polar Program), etc.

He earned a PhD in tropical marine region and a DSc on southern high-latitude marine regions toward environmental and climatic implications. He used various proxies, including foraminifera (micro-fossil), to understand palaeoclimatology of southern high-latitude regions (the Antarctic and the Southern Ocean). These studies, coupled with his palaeoclimatic reconstructions from tropical regions, helped understand causal linkages and teleconnections between the processes in southern high latitudes and that of climate variability occurring in tropical regions. Dr. Khare is an honorary professor and adjunct professor at many Indian universities. He has an impressive list of publications to his credit (125 research articles in national and international scientific journals; 3 special issues of national scientific journals as guest editor; and edited a special issue of *Polar Sciences* as its managing editor). Dr. Khare had authored and edited many books, 130 abstracts have been contributed to various seminars, 23 popular science articles, and 5 technical reports. The government of India and many professional bodies have bestowed him with many prestigious awards for his humble scientific contributions to past climate changes, oceanography, polar science, and southern oceanography. The most coveted award is the 2013 Rajiv Gandhi National Award conferred by the honorable president of India. Others include ISCA Young Scientist Award, BOYSCAST Fellowship, CIES French Fellowship, Krishnan Gold Medal, Best Scientist Award, Eminent Scientist Award, ISCA Platinum Jubilee Lecture, IGU Fellowship, and many more. Dr. Khare has made tremendous efforts to popularize ocean science and polar science across the country by delivering many invited lectures, radio talks, and published popular science articles. He has many authored and edited books on thematic topics and has been published by reputed international publishers, which are testimony to his commitment to popularize science among the masses.

Dr. Khare has sailed the Arctic Ocean as a part of Science PUB in 2008 during the International Polar Year campaign for scientific exploration and became the first Indian to sail the Arctic Ocean.

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Glossary

Aerosol Optical Thickness: The degree to which aerosols prevent the transmission of light by absorption or scattering of light. The aerosol optical depth (AOD) or optical thickness (τ) is defined as the integrated extinction coefficient over a vertical column of a unit cross-section.

Air masses: It is a body of air extending hundreds or thousands of miles horizontally and sometimes as high as the stratosphere and maintaining as it travels nearly uniform conditions of temperature and humidity at any given level.

Air-sea fluxes: The ocean and atmosphere interact through air-sea oscillations. These fluxes, or exchanges, are the most direct ocean climate indicator of how the ocean influences climate and weather and their extremes and how the atmosphere forces ocean variability. Map of the mean net surface heat flux into the sea.

Amundsen Sea Low (ASL): It is a climatological low-pressure centr located over the extreme southern Pacific Ocean, off the coast of West Antarctica. The ASL plays a significant role in the climate variability of West Antarctica and the adjacent oceanic environment.

Aerosols: It is a suspension of fine solid particles or liquid droplets in air or another gas. Aerosols can be natural or anthropogenic. Diseases can also spread through tiny droplets in the breath, also called aerosols.

Antarctic Coastal Current: It is also known as the East Wind Drift Current. It is the world's southernmost current. This current is the countercurrent of the largest ocean current in the world, the Antarctic Circumpolar Current. On average, it flows westward and parallels the Antarctic coastline.

Antarctic sea ice: It is the sea ice of the Southern Ocean. It extends from the far north in the winter and retreats to almost the coastline every summer, getting closer and closer to the coastline every year due to sea ice melting. Sea ice is frozen seawater that is usually less than a few meters thick.

Antarctic Slope Current (ASC): It is a coherent circulation feature that rings the Antarctic continental shelf and regulates water flow toward the Antarctic coastline.

Asymmetry parameter: It is the first Legendre moment of a phase function. Anisotropy of the phase function is characterized by all moments rather than the first one. In many cases, utterly different habit mixtures return the same or very close to asymmetry parameters.

Atlantic Multidecadal Oscillation (AMO): Also known as Atlantic Multidecadal Variability (AMV), it is the theorized variability of the sea surface temperature (SST) of the North Atlantic Ocean on the timescale of several decades.

Atmospheric science: It is the study of the dynamics and chemistry of the gas layers surrounding the Earth, other planets, and moons. It encompasses the interactions between various parts of the atmosphere and interactions with the oceans and freshwater systems, the biosphere, and human activities.

Auroral Electrojet Index (AE): It is designed to provide a global, quantitative measure of auroral zone magnetic activity produced by enhanced Ionospheric currents flowing below and within the auroral oval. Ideally, it is the total range of deviation at an instant of time from quiet day values of the horizontal magnetic field (h) around the auroral oval.

Black carbon: It consists of pure carbon in several linked forms. It is formed through the incomplete combustion of fossil fuels, biofuel, and biomass and is one of the main types of particle in both anthropogenic and naturally occurring soot. Black carbon causes human morbidity and premature mortality.

Boreal summer intra-seasonal oscillation (BSISO): Asian summer monsoon (ASM) is one of the most prominent sources of short-term climate variability in the global monsoon system.

Circumpolar Deep Water (CDW): It is a designation given to the water mass in the Pacific and Indian Oceans that essentially characterizes a mixing of other water masses in the region. Circumpolar deep water is between 1°C and 2°C (34°F and 36°F) and has a salinity between 34.62 and 34.73 practical salinity units (PSU).

Climatology: Climatology or climate science is the scientific study of climate, scientifically defined as weather conditions averaged over a period. This modern field of study is regarded as a branch of the atmospheric sciences and a subfield of physical geography, one of the Earth sciences. Climatology now includes aspects of oceanography and biogeochemistry.

Cloud condensation nuclei or CCNs: These are small particles typically 0.2 μm, or 1/100 the size of a cloud droplet on which water vapor condenses. Water requires a non-gaseous surface to transition from a vapour to a liquid; this process is called condensation.

Cloud microphysics: The branch of the atmospheric sciences concerned with the many particles that make up a cloud. Relative to the cloud, the individual particles are microscopic and so exist on the 'microscale'; that is, over distances from fractions of a micrometer to several centimeters.

Coronal Mass Ejections (CMEs): These are large expulsions of plasma and magnetic field from the sun's corona. They can eject billions of tons of coronal material and carry an embedded magnetic field (frozen in flux) that is stronger than the background solar wind interplanetary magnetic field (IMF) strength.

Correlation Coefficient (CC): It is used in statistics to measure the correlation between two data sets. The correlation between two financial instruments, simply put, is the degree to which they are related.

Counter-equatorial electrojet (CEJ): Sometimes the flow of the overhead current system reverses its direction temporarily and flows westward, producing depressions in the H-field at equatorial stations in the morning/afternoon hours during magnetically quiet days. It is known as a counter-equatorial electrojet (CEJ).

Coupled Model Inter-comparison Project (CMIP): The CMIP is a standard experimental framework for studying the output of coupled atmosphere-ocean general circulation models. It facilitates assessing the strengths and weaknesses of climate models, which can enhance and focus the development of future models.

Doppler interferometry (IDI): This technique estimates the location of scattering centres and the corresponding radial velocities.

Empirical orthogonal function (EOF): In statistics and signal processing, the method of practical orthogonal function (EOF) analysis is a decomposition of a signal or data set in terms of orthogonal basis functions determined from the data. This term is also interchangeable with the geographically weighted PCAs in geophysics.

ENSO: El Niño and the Southern Oscillation, also known as ENSO, is a periodic fluctuation in sea surface temperature (El Niño) and the air pressure of the overlying atmosphere (Southern Oscillation) across the equatorial Pacific Ocean.

Equatorial electrojet (EEJ): It is a narrow ribbon of current flowing eastward in the daytime tropical region of the Earth's ionosphere.

Extreme precipitation events (EPEs): These are defined as days with precipitation in the top 1% of all days. Increases in the intensity or frequency of heavy rainfall are vital factors that affect the risk of floods and flash floods.

Fractal and multifractal dimension analysis: A multifractal system generalizes a fractal method in which a single exponent (the fractal dimension) is not enough to describe its dynamics; instead, a continuous spectrum of exponents (the so-called singularity spectrum) is needed. Multifractal systems are standard.

Geographic location: This term refers to a position on the Earth. Two coordinates, longitude and latitude, define your absolute geographic location. These two coordinates can be used to give specific areas independent of an outside reference point.

Global conveyor belt: It is a system of ocean currents that transport water around the world. While wind primarily propels surface currents, deep currents are driven by differences in water densities in a process called thermohaline circulation.

Global Positioning System (GPS): It is a U.S.-owned utility that provides users with positioning, navigation, and timing (PNT) services. This system consists of three segments: the space segment, the control segment, and the user segment.

Greenhouse gases (GHGs): Compound gases trap heat or longwave radiation in the atmosphere. Their presence in the atmosphere makes the Earth's surface warmer. The principal GHGs, also known as heat-trapping gases, are carbon dioxide, methane, nitrous oxide, and fluorinated gases.

Horizontal component: It stretches from the start of the vector to its furthest x-coordinate. The vertical part extends from the x-axis to the most vertical point on the vector. Together, the two components and the vector form a right triangle.

Hurst exponent: It is used as a measure of long-term memory of time series. It relates to the autocorrelations of the time series and the rate at which these decrease as the lag between pairs of values increases. Studies involving the Hurst exponent were initially developed in hydrology for the practical matter of determining optimum dam sizing for the Nile river‘s volatile rain and drought conditions that had been observed over a long period.

Indian Ocean Dipole (IOD): It is defined by the difference in sea surface temperature between two areas (or poles, hence a dipole) – a western pole in the Arabian Sea (western Indian Ocean) and an eastern pole in the east of the Indian Ocean south of Indonesia.

Indian summer monsoon rainfall (ISMR) or southwest monsoon rainfall: During June to September is a component of the Asian monsoon system, accounting for 70–90% of annual precipitation in India. The ISMR exhibits high temporal as well as spatial variations.

Interplanetary magnetic field (IMF): Now more commonly referred to as the heliospheric magnetic field (HMF), is the component of the solar magnetic field that is dragged out from the solar corona by the solar wind flow to fill the solar system.

Intertropical Convergence Zone, or **ITCZ:** It is the region that circles the Earth, near the equator, where the trade winds of the Northern and Southern Hemispheres come together.

Katabatic winds: A katabatic wind is a drainage wind that carries high-density air from a higher elevation down a slope under the force of gravity. Such winds are sometimes also called fall winds; the spelling catabatic winds is also used.

Lidar: Light Detection and Ranging (Lidar) is a remote sensing method used to examine the surface of the Earth. These light pulses combined with other data recorded by the airborne system generate precise, three-dimensional information about the shape of the Earth and its surface characteristics.

Mean sea-level pressure (MSLP): This is the atmospheric pressure at mean sea level (PMSL). The atmospheric pressure is normally given in weather reports on radio, television, newspapers, or the Internet. Average sea-level pressure is 1013.25 mbar (101.325 kPa; 29.921 in Hg; 760.00 mm Hg).

Microwave radiometer (MWR): This provides time-series measurements of column-integrated amounts of water vapor and liquid water. The instrument itself is a sensitive microwave receiver that detects the microwave emissions of the smoke and liquid water molecules in the atmosphere at two frequencies: 23.8 and 31.4 GHz.

Mid-latitude: The middle latitudes (also called the mid-latitudes, sometimes midlatitudes, or moderate latitudes) are a spatial region on Earth located between the latitudes 23°26′22″ and 66°33′39″ north, and 23°26′22″ and 66°33′39″ south.

Midnight sun: It is a natural phenomenon that occurs in the summer months in places north of the Arctic Circle or south of the Antarctic Circle when the sun remains visible at the local midnight. When the midnight sun is seen in the Arctic, the Sun appears to move from left to right, but the equivalent apparent motion in Antarctica is from right to left. It occurs at latitudes from 65°44′ to 90° north or south and does not stop precisely at the Arctic Circle or the Antarctic Circle due to refraction.

Monsoon: It is a seasonal change in the direction of a region's prevailing, or strongest, winds. Monsoons are most often associated with the Indian Ocean. Monsoons always blow from cold to warm areas. The summer monsoon and the winter monsoon determine the climate for most of India and Southeast Asia.

Multi-model means (MMM): It is a simple way to reduce biases in individual model outputs, and thus, it is widely used for climate change projections. The usefulness of MMM may vary from one region to the other based on the regional climate and the diagnostic variables of interest.

Northern Annular Mode (NAM): It also known as Arctic Oscillation (AO) or Northern Hemisphere Annular Mode, and is a natural form of climate variability, closely associated with the North Atlantic Oscillation (NAO), which has a similar structure over the Atlantic but when looked at from above, the shape is more annular.

Orographic terrain: Orography is the study of the topographic relief of mountains and can more broadly include hills and any part of a region's elevated terrain. Orography falls within the broader discipline of geomorphology.

Pacific decadal oscillation (PDO): This is a robust, recurring pattern of ocean-atmosphere climate variability cantered over the mid-latitude Pacific basin. The PDO is detected as warm or cool surface waters in the Pacific Ocean, north of 20°N.

Potential vorticity (PV): In fluid mechanics, potential vorticity (PV) is a quantity which is proportional to the dot product of vorticity and stratification. This quantity, following a parcel of air or water, can only be changed by diabatic or frictional processes. It is a useful concept for understanding the generation of vorticity in cyclogenesis (the birth and development of a cyclone), especially along the polar front, and in analysing flow in the ocean.

Precipitable water content (PWC): The depth of this condensed water (in millimetre) is the measure of how much water vapor is available for conversion to precipitation. This study aims to examine the potential of these PWC data to monitor precipitation systems during Indian summer monsoon.

Predictive Index® (PI®): It is a theory-based, self-report measurement of normal, adult, work-related personality that was developed and validated for use within occupational and organizational populations.

Root Mean Square Error (RMSE): It is the standard deviation of the residuals (prediction errors). Residuals are a measure of how far from the regression line data points are; RMSE is a measure of how spread out these residuals are. In other words, it tells you how concentrated the data is around the line of best fit. Root mean square error is commonly used in climatology, forecasting, and regression analysis to verify experimental results.

Sea-ice extent (SIE): Sea-ice extent is a measurement of the area of ocean where there is at least some sea ice. Usually, scientists define a threshold of minimum concentration to mark the ice edge; the most common cut off is at 15%.

Sea-ice concentration (SIC): It is a useful variable for climate scientists and nautical navigators. It is defined as the area of sea ice relative to the total at a given point in the ocean.

Sea level pressure: The atmospheric pressure at mean sea level, either directly measured or, most commonly, empirically determined from the observed station pressure.

Sea surface temperature: It is a key climate and weather measurement obtained by satellite microwave radiometers, infrared (IR) radiometers, in-situ moored and drifting buoys, and ships of opportunity. SST maps are also widely used by oceanographers, meteorologists, and climate scientists for scientific research.

Semi-annual oscillation (SAO): It is a twice-yearly northward movement (in May–June–July (MJJ) and November–December–January (NDJ)) of the circumpolar trough of sea level pressure (SLP) in the Southern Hemisphere with effects throughout the troposphere.

Single Scattering Albedo (SSA): The ratio of scattering efficiency to total extinction efficiency, is an essential parameter used to estimate the Direct Radiative Forcing (DRF) of aerosols. However, SSA is one of the large contributors to the uncertainty of DRF estimations.

Solar Proton Events (SPEs): A solar particle event or solar proton event (SPE), or prompt proton event, occurs when particles (mostly protons) emitted by the sun become accelerated either close to the sun during a flare or in interplanetary space by coronal mass ejection shocks. The events can include other nuclei such as helium ions and HZE ions. These particles cause multiple effects. They can penetrate the Earth's magnetic field and cause ionisation in the ionosphere. The effect is like auroral events, except that protons rather than electrons are involved. Energetic protons are a significant radiation hazard to spacecraft and astronauts.

Solar wind velocity: The solar wind is a stream of charged particles released from the upper atmosphere of the Sun, called the corona. At more than a few solar radii from the Sun, the solar wind reaches speeds of 250–750 km/s and is supersonic, meaning it moves faster than the speed of the fast magnetoionic wave.

Southern Annular Mode, or **SAM:** It is a climate driver that can influence rainfall and temperature in Australia. The SAM refers to the (non-seasonal) north-south movement of the strong westerly winds that blow almost continuously in the mid- to high latitudes of the Southern Hemisphere.

Southern Oscillation Index (SOI): It represents the difference in average air pressure measured at Tahiti and Darwin, Australia. More specifically, the SOI is calculated as the difference in monthly averages of standardised mean sea level pressure at each station.

Spectral refractive index: The concept of refractive index applies within the full electromagnetic spectrum, from X-rays to radio waves. It can also be applied to wave phenomena such as sound. In this case, the speed of sound is used instead of that of light, and a reference medium other than vacuum must be chosen.

TCO (Total Column Ozone): It is a measurement of the total amount of atmospheric ozone in a given column. Usually, TCO is measured in Dobson Units (DU).

Thermo-dynamical factors: The thermodynamic factor in diffusion is a parameter relating the tracer diffusion coefficient of a species in a given system to the corresponding intrinsic diffusion coefficient and may be defined for alloys as well as for oxides both pure and mixed.

Thermohaline circulation: It plays an important role in supplying heat to the polar regions. Therefore, it influences the rate of sea ice formation near the poles, which in turn affects other aspects of the climate system (such as the albedo, and thus solar heating, at high latitudes).

Traveling Atmospheric Disturbances or **TAD:** These are gusts of wind that roll through the sky, pushing along neutral atoms as they go.

Upper tropospheric atmosphere: The tropopause is the boundary in the Earth's atmosphere between the troposphere and the stratosphere. It is a thermodynamic gradient stratification layer, marking the end of the troposphere. It lies, on average, at 17 km above equatorial regions, and about 9 km over the polar regions.

Wiener process: A standard (one-dimensional) (also called Brownian motion) is a stochastic process {Wt}t≥0+ indexed by nonnegative real numbers t with the following properties: In general, a stochastic process with stationary, independent increments is called a Lévy process.

1 Antarctic Ozone
Trends and Variability in a Changing Climate

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CONTENTS

1.1 INTRODUCTION

The ozone-climate inter-relations and feedbacks are emerging as significant components that contribute to the understanding of Earth system science. The atmospheric ozone plays a fundamental role in both the terrestrial ecosystem and global climate. Although the study of the stratospheric ozone started in the early 20th century, observations strengthened in the 1980s after discovering the "ozone hole" over Antarctica. The stratospheric ozone layer extends between 10 and 40 km altitude, peaking at about 25 km and containing more than 90% of all atmospheric ozone. Atmospheric ozone has two significant effects on the temperature balance of the Earth. The ozone layer absorbs the most damaging part of UV radiation, which heats the stratosphere and plays a vital role in preventing UV radiation from reaching Earth's surface.

On the other hand, the ozone in the troposphere absorbs infrared radiation emitted by the Earth's surface, effectively trapping heat in the troposphere. Consequently, the climate impact of changes in ozone concentrations varies with

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the changes in the vertical distribution of ozone in the atmosphere. Studies have shown that the tropospheric ozone has increased globally throughout the 20th century due primarily to increased human-related emissions (Ziemke et al., 2019). Stratospheric ozone depletion has also affected the climate in the Southern Hemisphere. There exist several two-way complex interactions between stratospheric ozone depletion and climate change, such as changes in stratospheric temperature and transport affect the concentration and distribution of stratospheric ozone; changes in tropospheric climate affect stratospheric circulation; changes in stratospheric ozone influence the radiative forcing of the atmosphere, and hence surface climate, as well as the chemistry of the troposphere.

Depleting stratospheric ozone is observed in the so-called Antarctic ozone hole that appears each austral spring (September–November) over Antarctica. It occasionally develops over the Arctic (Manney et al., 2011). As a result of increased ozone-depleting substances (ODSs) in the atmosphere after industrialization, stratospheric ozone started to decline in the polar regions by the late 1970s (Bodeker et al., 2005; Farman et al., 1985; WMO, 2018). The ODSs and typical seasonal atmospheric dynamics in Antarctica led to the significant ozone loss, peaks in September. The area where total column ozone drops below 220 Dobson Unit (DU) is the ozone Hole. The TCO value 220 DU is used to define ozone hole because it is lower than pre-1980 observed TCO values and also because it is almost always a middle value in a solid spatial gradient of total ozone (Newman et al., 2004). Ozone depletion is caused mainly by anthropogenic emissions of ODSs and the subsequent release of reactive halogen gases (chlorine, bromine, etc.) in the stratosphere.

The Montreal Protocol is considered one of the most influential environmental treaties. Due to regulations of the ODSs and some hydrofluorocarbons (HFCs) under the Montreal Protocol and its amendments, not only the significant increases in UV radiation at Earth's surface have been avoided, but global warming also reduced. Most ODSs are potent GHGs with global warming potentials considerably more compared to carbon dioxide and methane. Direct evidence of the strengthening of the ozone layer due to the decline of halogen species in the Antarctic stratosphere is now available from space-borne observations. Recent scientific studies show that ozone depletion has stopped or reduced significantly, but it may take years before the ozone starts to increase again as ODSs have a long lifetime. It has been estimated that the Southern Hemisphere mid-latitude ozone is expected to return to the 1980 level around mid-century (WMO, 2018). A large variability has been observed in the ozone hole extent and minimum ozone over Antarctica. The average ozone hole area in 2019 was the smallest on record since the discovery of the ozone hole in 1985, whereas, in 2020, it was one of the largest. The Antarctic ozone hole is decreasing in size. Still, the recovery can be influenced by interannual atmospheric variability and any unanticipated changes in ODSs source emissions, such as an observed unexpected increase in total global emissions of CFC-11 after 2012 despite Montreal Protocol controls. However, a substantial decline was observed in CFC-11 concentrations during 2019 and 2020.

Accurate and uninterrupted observations of atmospheric ozone on the global scale are an essential task. The atmospheric ozone is measured using in-situ and remote sensing methods. The in-situ measurement methods require direct atmospheric air sampling into the instrument and analyzing its properties and relative amount. The in-situ measurement methods of ozone involve the use of mass or optical spectroscopy or chemical reactions with the air sample. These measurement methods can be employed either from ground, aircraft, and balloon platforms. The balloon-borne ozonesonde in-situ way is most commonly used to measure the vertical distribution of ozone from the bottom up to approximately 40 km altitude. Ozonesonde interfaced with meteorological radiosonde has electrochemical concentration cell (ECC) that senses ozone as it reacts with a dilute potassium iodide solution to produce a weak electrical current proportional to the ozone concentration the sampled air.

In the remote sensing measurement method, the amount of ozone is derived indirectly by the changes in atmospheric radiation resulting from the ozone's presence. Remote sensing instruments measure spectral radiances, from which information about light absorbers such as ozone and other trace gases can be inferred using retrieval algorithms. The Dobson and Brewer spectrophotometers are used in the World Meteorological Organization (WMO) network to measure the total column ozone (TCO). The basic measurement principle of both types of spectrophotometers is the same. The TCO is estimated by comparing the intensity of solar radiation at ultraviolet wavelengths strongly and weakly absorbed by ozone. The Dobson spectrophotometer is a manually operated instrument that utilizes a variable 'optical wedge' attenuator to measure the intensity ratio of two wavelengths. The Brewer spectrophotometer is automatic mainly, which operates unattended according to programmed schedules and directly measures the intensity of solar radiation at several different ultraviolet wavelengths. The WMO's World ozone and Ultraviolet Radiation Data Centre (WOUDC), operated by Environment and Climate Change Canada, can access more details on the global ozone monitoring network and data availability. The Dobson and Brewer spectrophotometers provide reliable TCO data at various ozone monitoring stations in Antarctica, but the ground-based measurement has limited spatial coverage. The satellite-retrieved atmospheric ozone data allows extensive spatial range but with limited temporal resolution. There are several remote sensing instruments onboard satellites for measurement of TCO and vertical profile of ozone. After the pioneer Backscatter, Ultraviolet Spectrometer (BUV) onboard Nimbus-4 operated from 1970 to 1977, a range of satellite instruments have been launched to monitor TCO and vertical profile of ozone-related species. Some necessary devices are Total Ozone Mapping Spectrometer (TOMS) aboard the Nimbus-7 and Meteor-3 satellites, Ozone Monitoring Instrument (OMI) onboard the Aura satellite, TROPOspheric Monitoring Instrument (TROPOMI) onboard Sentinel-5 Precursor (S-5P) satellite, Global Ozone Monitoring Experiment-2 (GOME-2) the European MetOp satellites, Ozone Mapping and Profiler Suite (OMPS) onboard Suomi NPP (National Polar-Orbiting Partnership) satellite, Atmospheric Infrared Sounder (AIRS) onboard the Aqua satellite, and Microwave Limb Sounder (MLS) onboard NASA's Aura Earth satellite. The satellite sounder instruments also provide the atmospheric profiles of ozone. Satellites are short-lived and, therefore, the ozone data sets from different mission observations are merged to have a consistent and homogeneous global long-term data record to study the trends analysis. The satellite data used in this