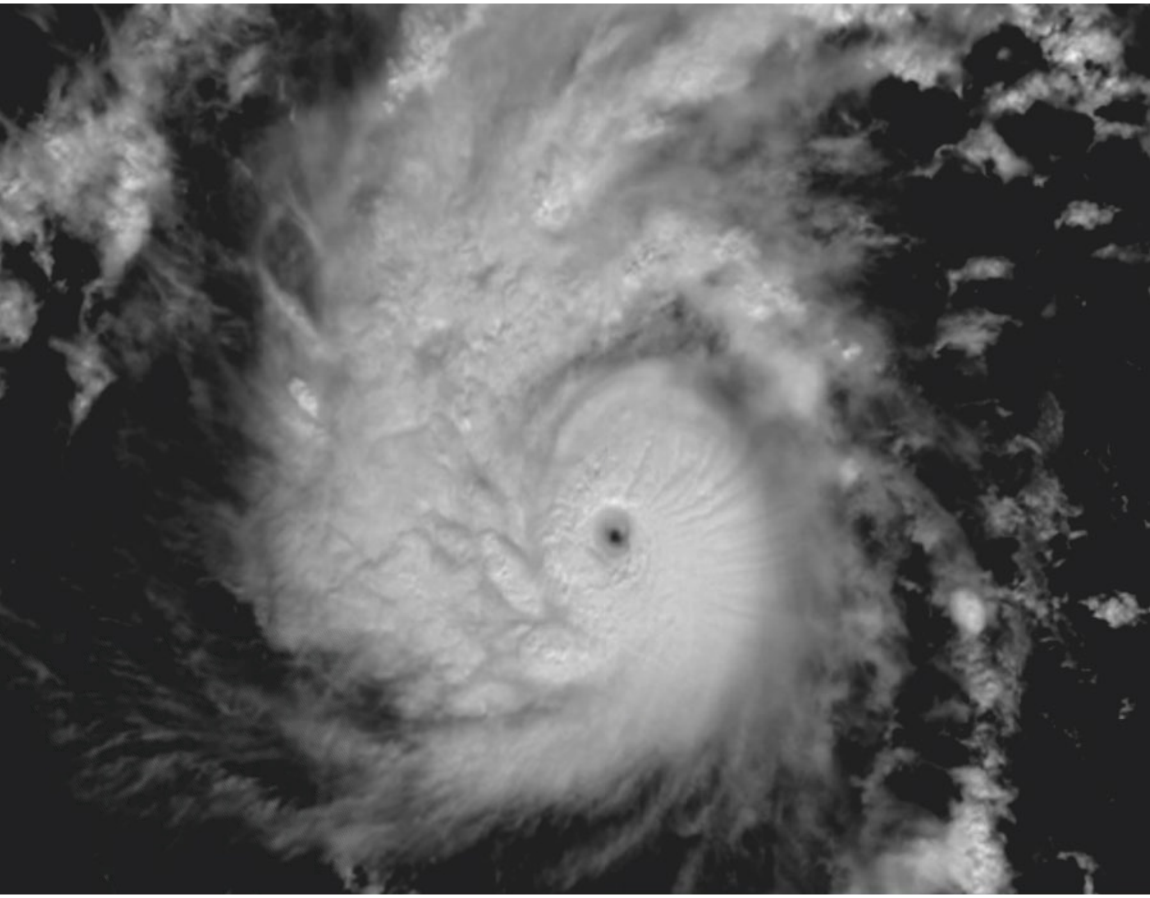
Monitoring and Prediction of Tropical Cyclones in the Indian Ocean and Climate Change



Edited by:
U.C. Mohanty • M. Mohapatra • O.P. Singh
• B.K. Bandyopadhyay • L.S. Rathore

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Preface

Tropical cyclones (TCs) are one of the most devastating natural disasters costing more than half a million lives all over the world in the last five decades. More than 75% of total TCs over the globe causing the human deaths of 5000 or more have occurred over the North Indian Ocean (NIO) during past 300 years. This high vulnerability may be attributed to various factors including geographical conditions and limitations of observations, prediction systems, understanding of physical processes, early warning systems and disaster management processes, apart from the socio-economic conditions of the region. Understanding the patterns of genesis, intensity and movement of TCs and associated adverse weather like heavy rainfall, gale winds, storm surges and coastal inundation assumed even more importance in recent years in the scenario of global climate change. In association with an increasing trend in global temperature, it is of interest to examine all the above features of TCs. The Indian Ocean region, including the Arabian Sea (AS) and the Bay of Bengal (BoB) is of particular concern because of the high population density along its coastlines.

Because of the significance of the TCs to India, the India Meteorological Department (IMD), Ministry of Earth Sciences (MoES), Government of India in collaboration with World Meteorological Organization (WMO), organised the Second International Conference on Indian Ocean Tropical Cyclones and Climate Change (IOTCCC) during 14-17 February, 2012 at New Delhi, in order to shed light on the scientific basis and the complexities inherent in combating hazardous impacts of TCs. The purpose of the Conference was to advance the science of climate change impacts on TCs, particularly for nations surrounding the Indian Ocean. The broad thematic areas of the conference were as follows:

- Climate change and TC activity over the Indian Ocean
- TC and climate change themes related to physical science
- Impact of cyclones on the economy, infrastructure and society in individual Indian Ocean countries.

About 150 delegates from different countries participated in the conference. During the conference, there were four Plenary Sessions, 14 Parallel Technical Sessions, two Panel Discussions and a Concluding Session. There were invited talks by the eminent scientists in the field of cyclone and climate change impact on cyclones over the Indian Ocean in the Plenary Sessions and in the beginning of each Parallel and Technical Session.

The main recommendations emerged in the conference are summarized as given below.

- The panel agrees that the satellite-based intensity data set indicates a significant increase in strong Cat 4-5 TCs in the South Indian Ocean (SIO) basin in recent decades, whereas the reverse trend is the case in the NIO basin. One panel member felt that it was clear that certain observed TC changes around the globe were likely due to anthropogenic factors, while others were more circumspect given the uncertain quantification of internal climate variability and other factors. The panel recommends that the IMD and regional partners continue to evaluate the TC records in the NIO and try to improve our ability to detect and attribute TC changes in the NIO to different factors. The cause for the reversal in trends of intense TC occurrence between the NIO and SIO should also be investigated.
- The panel finds that the existing NIO TC datasets are useful, but these needed to be updated and improved regularly, particularly in the Arabian Sea, e.g., go through ship records in the Indian Ocean back in time to verify and validate storm occurrence; cross compare with Joint Typhoon Warning Center (JTWC) records to identify and address inconsistencies; and cross-compare with satellite-based TC datasets.
- The panel endorses IMD's efforts to improve TC-related observations on land, with radar, and soon over the ocean with aircraft reconnaissance. The panel recommends that these improved observations be utilized to continue to improve the climate-relevant TC data sets, with an emphasis on adding information about storm size or outer wind radii of storm and gale force winds as these will be crucial when assessing impacts. The panel requests that other countries in the Indian Ocean region consider possible improvements of their observational network, especially in the coastal areas, for better monitoring and prediction of TCs.
- The panel recognized the use of new statistical analysis techniques of the climatological TC record such as employed by Holland to identify trends in changing TC behaviour. The panel recommends that IMD and others continue to explore these new techniques in the analysis of the historical record and model simulations as a means of evaluating their fidelity.
- The panel noted that the socioeconomic impact of TCs, now and in a changing climate, while significant, are not the only impacts that need to be addressed. For example, for a very strong future warming scenario, if wet bulb temperatures can possibly begin to approach human body core temperatures,

the resulting heat stress can be life threatening and cause dramatic societal impacts in such a region. The panel recommends that the TC community need to galvanize the interactions with the socioeconomic community in the region to begin the process of evaluating the relative risks of high impact weather, such as TCs, as the climate changes, together with the additional risks posed by other aspects of climate change.

- Concerning capacity building, the panel requests that the WMO organise training of Cyclone Forecasters from NIO countries in the interpretation and use of ensemble and probabilistic forecasts.

Considering the significant findings presented in the conference by various scientists and the recommendations made in the conference, it was decided to publish the selected papers presented during the conference as a book after the peer review of the manuscripts. We requested several scientists who participated in the conference for their interest in developing a volume dedicated to science of TCs and climate change over the Indian Ocean region. The response was overwhelming and these authors have generously contributed to the chapters considered in this volume.

This book is relevant to cyclone forecasters and researchers, managers, policy makers, graduate and undergraduate students. The papers presented in the book also intend to stimulate thinking and hence further research in the field of TCs and climate change, especially over Indian Ocean region. We have attempted to offer the recent progress on understanding and prediction of tropical cyclogenesis, intensification and movement as well as landfall processes like heavy rainfall, gale winds and associated storm surges based on latest observational and numerical weather prediction (NWP) modelling platforms. Further attempt has been made to include the TC management issues like early warning system, recent high impact TC events, disaster preparedness, assessment of risk and vulnerability including construction, archival and retrieval of best track and historical data sets, policy decisions etc., in view of recent findings on climate change aspects and their impact on TC activity. We hope this book will provide high quality reference materials to all the users as mentioned above and will incite further research and their applications in management of TCs over the Indian Ocean region.

As editors of this volume, we are highly thankful to all the authors for their efforts and cooperation in bringing out this publication. We are sincerely thankful to all reviewers, viz., Dr Someswar Das, Dr Ashish Routray, Dr D.R. Pattanaik, Dr. Naresh Kumar, Mr. U.P. Singh, Dr Sujata Pattanayak, Dr Osuri Krishna and Ms Monica Sharma for their continued effort in reviewing and adding values to the manuscripts. We are grateful to WMO, IMD, MoES and all the members of International Scientific Steering Committee, National Organising Committee and Local Organising Committee and Sub-Committees for successfully organising the second International Conference, IOTCCC-2012 at New Delhi. We want to place our appreciation in record to the Cyclone

Warning Division of India Meteorological Department for the tireless effort made for the organisation of the conference and significant contribution in editing and compilation of the manuscripts and publication of this volume.

U.C. Mohanty
M. Mohapatra
O.P. Singh
B.K. Bandyopadhyay
L.S. Rathore

Editors

About the Editors

U.C. Mohanty

Professor U.C. Mohanty, after about 34 years of experience in teaching and research in Indian Institute of Technology (IIT) Delhi, India, is currently serving as a Visiting Professor in the School of Earth, Ocean and Climate Sciences, IIT Bhubaneswar and President Odisha Bigyan Academy, Bhubaneswar. His research areas of interest are Tropical Meteorology, Monsoon Dynamics, Climate studies and Meso-scale Modelling of Extreme Weather Events including Tropical Cyclones. He has guided 30 PhD students and has more than 250 publications in peer reviewed national and international journals. Prof. Mohanty has received several awards for his contribution in atmospheric sciences including prestigious Shanti Swarup Bhatnagar Prize (1993), Mausam award (1982), Samant Chandrasekhar award (1999) and Sir Gilbert Walker Gold Medal (2009). He is a fellow of Indian Academy of Sciences, National Academy of Sciences, Indian National Academy of Engineering, Indian Meteorological Society and Indian Geophysical Union.

M. Mohapatra

Dr. M. Mohapatra is Head of Cyclone Warning Division of India Meteorological Department and also looks after the activities of WMO recognised Regional Specialised Meteorological Centre for Tropical Cyclones at IMD, New Delhi. His main research interests include high impact weather events including tropical cyclones. He has 20 years of experience in meteorological services and research and is the author of 49 research papers published in peer reviewed journals. He has received a number of recognitions including 25th Biennial Mausam Award and Young Scientist Award of Ministry of Earth Sciences (MoES), Government of India for his research contributions in the field of atmospheric sciences.

O.P. Singh

Dr. O.P. Singh has had an excellent academic career with a Masters and a Doctorate degree in Applied Mathematics. He joined India Meteorological

Department (IMD) in 1980. He has nearly 15 years teaching experience in meteorology at the advanced level courses conducted by IMD. His research interest covers a wide spectrum of topics in meteorology including monsoons and tropical cyclones. He has published over 80 research papers in peer-reviewed journals. He has been awarded with prestigious Dr. B.N. Desai award of Indian Meteorological Society for his research contributions in the field of meteorology.

B.K. Bandyopadhyay

B.K. Bandyopadhyay got his post-graduate degree in solid state physics in 1976 from Indian Institute of Technology Kharagpur. He joined as a Research Scholar in Indian Institute of Tropical Meteorology, Pune and during next three years, he was associated with research on microphysical characteristics of clouds. He joined India Meteorological Department in 1981 and was engaged in operational weather forecasting for past 30 years which mainly included cyclone and heavy rainfall warning services and allied meteorological research. He has made significant research contributions mainly on tropical cyclones. He has about 40 research publications in the national and international journals.

L.S. Rathore

Dr. L.S. Rathore is Director General of Meteorology, India Meteorological Department and Permanent Representative of India with World Meteorological Organization. He is Co-Vice Chairman of Intergovernmental Board of Climate Services (IBCS) and former Vice President of Commission for Agriculture Meteorology, WMO and presently on its management board. He is former President of Indian Meteorological Society and President of Association of Agro-meteorologists. He made significant contribution in setting up Integrated Agro-meteorological Service in India. He has 33 years of experience in meteorological services and research and has published about 100 research papers and seven books. He is recipient of Dr Lakhi Ram Memorial Award, 2011 constituted by Society for Recent Development in Agriculture. He has been conferred Fellowship by Indian Meteorological Society.

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Part I

Tropical Cyclones and Climate Change

Construction and Quality of Best Tracks Parameters for Study of Climate Change Impact on Tropical Cyclones over the North Indian Ocean during Satellite Era

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1. Introduction

India Meteorological Department (IMD) has the responsibility of monitoring and prediction of cyclonic disturbances (CDs) including tropical cyclone (TC) and depressions; collection, processing and archival of all data pertaining to CDs and preparation of best track data over the North Indian Ocean (NIO). A CD is classified based on the associated sustained surface wind (MSW) (IMD, 2003). The detailed classification over the NIO adopted by IMD is shown in Table 1. This classification has been used in this study for analyzing interannual variation of frequency and intensity of CDs over the NIO during satellite era (1961-2010).

Table 1: Classification of CDs over the NIO

Low pressure system	*Maximum sustained surface winds in knots (mps)*
Low pressure area (L)	< 17 (09)
Depression (D)	17-27 (09-14)
Deep depression (DD)	28-33 (15-17)
Cyclonic storm (CS)	34-47 (18-24)
Severe cyclonic storm (SCS)	48-63 (25-32)
Very severe cyclonic storm (VSCS)	64-119 (33-61)
Super cyclonic storm (SuCS)	120 (62) and above

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The process of post-season analysis of CDs to determine the best estimate of a CD's position and intensity along with other characteristics during its lifetime is described as "best tracking". The best tracking procedure has undergone several changes world-over including NIO due to change in definition and classification of TCs; monitoring and analysis tools and procedure; and physical understanding of TCs. Hence, a study has been undertaken by Mohapatra et al. (2012) to review the temporal changes in the best track procedure including changes in observational network, monitoring technique, area of responsibility for monitoring, terminology and classification of the TCs etc. over the NIO and their impact on quality of best track parameters over the NIO for the study of climate change impact on TCs. The problems and prospective with the best track data over the NIO have been presented and discussed by them.

Based on quality and availability, the whole period of best track information may be broadly classified into four phases, viz., (i) pre-1877, (ii) 1877-1890, (iii) 1891-1960 and (iv) 1961-2010 according to Mohapatra et al. (2012). The period of 1961-2010 may be further classified into (a) 1961-1973, (b) 1974-1990 and (c) 1991-2010. As optimum observational network including satellite leading to better estimation of location and intensity without missing of CDs was available since 1961, the climatology of TCs and interannual variation can be best represented based on the data set of 1961-2010 and more so since 1974 and 1982 with the advent of geostationary satellites and Indian National satellites (INSAT) respectively.

The best track developed by IMD is the consensus decision based on the available observations including satellite, radar, ships, buoys, and coastal and island observations. In this study, the characteristics of best track parameters in the satellite era (1961-2010) and interannual variation of frequency and intensity of CD over the NIO during the same period are analysed and discussed.

2. Characteristics of Best Tracks in Satellite Era

2.1 Satellite Observations of CDs

Satellites with meteorological instrumentation were first launched in the late 1950s. The first satellite completely dedicated to satellite meteorology was launched on 1 April 1960. It was called the Television and Infrared Observational Satellite (TIROS). The life span of this satellite was 79 days. The images, however, generated much excitement in the meteorological community. Nine additional TIROS satellites were subsequently launched through 1965. Nimbus 1 was launched on 28 August, 1964. Six more Nimbus satellites were subsequently launched and provided continuous coverage of the earth. This meant that tropical storms could be closely monitored for the first time from later part of 1964. The last Nimbus satellite was launched in 1978. The current NOAA polar orbiting satellites are descendents of the original Nimbus satellites. The 16 September, 1966 marked the launch of the first Defense Meteorological

Satellite Program (DMSP) and 7 December, 1966 marked the launch of the first Applications Technology Satellite (ATS)-1. The TIROS operational satellite provided nearly complete global coverage daily since 1966. The synchronous meteorological satellite (SMS)-I was launched by USA on 17 May, 1974 and SMS-II on 6 February, 1975. The Geostationary Operational Environmental Satellite (GOES)-1, initially designated as SMS-C was launched on 16 October, 1975.

2.2 IMD's Use of Weather Satellites for CD Monitoring

With the onset of satellite era in 1960, the detection of CDs with the polar orbiting satellites became more accurate and no system with a life span of more than 12 hrs could be missed. IMD's use of weather satellite commenced since the launching of TIROS-I on 1 April, 1960 (Koteswaram, 1971). While real time reception of satellite imagery commenced in December 1963 through an automatic picture transmission (APT) station at Mumbai, donated by USA, the imageries of past TCs during 1960-1963 collected from USA were investigated by several researchers. Koteswaram (1961) analysed first satellite pictures of a TC over the Arabian Sea in 1960. The intensity could be better estimated not only with satellites, but also with enhanced coastal observatory network due to augmentation in 1940s and 1950s. With the introduction of geostationary satellites for weather monitoring, the satellite products could be received more frequently leading to more accurate and frequent estimation of location and intensity of CDs since 1974. It led to relatively less smooth track and more accurate life period of the CDs. With the launch of INSAT in 1982, IMD made use of more frequently available satellite products over Indian region from these satellites. The details of Indian satellite used for cyclone monitoring since 1983 are shown in Table 2. The first and second series of INSAT had only two channels: IR channel (10.5-12.5 micrometre) and Visible channel (0.55-0.75 micrometre). INSAT II-C and II-D are only for communication purpose. Currently available meteorological satellites of special relevance to CD analysis over NIO include DMSP, INSAT, Kalpana, NOAA, METEOSAT, SSMI/S and TRMM.

Table 2 (a): Details of Indian satellite used for TC monitoring

INSAT	*1A*	*1B*	*1C*	*1D*	*II-A*	*II-B*	*II-E*
Sub-Satellite Point (SSP)	74°E	74°E	93.5°E	83°E	74°E	93.5°E	83°E
Date of launch	10-4-82	30-8-83	21-7-88	12-6-90	10-7-92	23-7-93	03-04-99
Date of operation	6-9-82	15-10-83	Lost (22-11-89)	17-7-90	Aug 92	Aug 93	1999
Period of service	–	10 yrs	–	12 yrs	07 yrs	07 yrs	07 yrs

Table 2 (b): Products available from Indian satellites

Period	*Available data*
1984-1987	3 hourly visible (VIS) and infrared (IR) radiance data without base map
1987-1993	3 hourly VIS and IR with base map
1993-2002	3 hourly regular VIS and IR, sea surface temperature (SST), outgoing longwave radiation (OLR), quantitative precipitation estimate (QPE), cloud motion vector (CMV)
2002 onwards	Water vapour (WV) imagery including above all

Table 2 (c): Resolution of satellites used for TC monitoring

Satellites	*Met payload*	*Channels*	*Spectral range (μm)*	*Resolution*	
				Spatial (km)	*Temporal (hrs)*
KALPANA-1 (Sep'02)	VHRR	VIS	0.55-0.75	2	1
		WV	5.7-7.1	8	1
		IR	10.5-12.5	8	1
INSAT-3A (Apr'03)	VHRR	VIS	0.55-0.75	2	3
		WV	5.7-7.1	8	3
		IR	10.5-12.5	8	3
	CCD	VIS	0.62-0.68	1	3
		NIR	0.77-0.86	1	3
		SWIR	1.55-1.69	1	3

2.3 Methods Used to Interpret Genesis, Location and Intensity of CDs

During satellite era (1961 to present), genesis and intensity of CDs over NIO are mainly monitored by Infrared (IR) and visible cloud imageries from geostationary satellites as surface observations over ocean are scanty (IMD, 2003; Mohapatra et al., 2012). The intensity of CDs is mainly estimated based on associated maximum MSW. During 1961-1973, the intensity estimation in mid-sea region took into consideration the once/twice daily available polar satellite imageries along with available ship observations. Initially, the MSW was calculated based on the cloud characteristics as observed in satellite imagery (Fritz et al., 1966). Timechalk et al. (1967) developed empirical technique to estimate MSW from the diameter of the dense overcast cloud mass and the cloud pattern. It was replaced by T number classification system given by Dvorak (1972). Dvorak's technique has also undergone several changes (Dvorak, 1973, 1975, 1984).

Dvorak's technique (Dvorak, 1975, 1984) is used to determine intensity of CDs using IR and visible cloud pattern taken by Kalpana and INSAT-3A satellites. The Satellite Division of IMD is estimating centre positions and intensities of CDs by the Dvorak method. The technique is subjective and imprecise as high degree of skill is required to recognize cloud patterns. During night, intensity of the disturbance is not available for want of visible cloud imagery limiting operational requirement of the technique. While the Dvorak method is the most popular technique for analyzing TCs/CDs through infrared and visible imagery, it has some known weakness and biases, especially for weaker systems. These have been described recently by Knaff et al. (2010).

Since 1970s, when system is within radar range, radar observation along with satellite, ship and coastal observations were used to estimate intensity. Since 2000s, the microwave imageries, coastal automatic weather stations (AWS) (Mohapatra et al., 2011), high wind speed recorders and buoys are in use in addition to above for location and intensity estimation. There are cases like meso-cyclone Ogni (28-30 October 2006), which could be detected only with the radar and coastal observations (Hatwar et al., 2008) and satellite failed to detect it.

Microwave imageries from NOAA series, Metop-A, DMSP satellites are used to analyze the inner structure of tropical cyclones. Several authors (Veldon and Smith, 1983) have shown a potential usefulness of microwave image products for the detection of the TC centre. However, the use of microwave data in this regard has imitation primarily because of the low spatial and temporal resolution of the microwave products. Furthermore, these methods use a limited number of channels, usually the 85.5 GHz channel which is sensitive to the ice particles, but has a higher spatial resolution than lower frequency channels, for the determination of TC centre. Recent development of the web based TC information distribution system by Hawkins et al. (2001) shows many advantages of microwave data over the current visible/IR data especially when the TC is in the development stage. Velden et al. (1989) found an objective way for centre determination of TCs using multispectral satellite imagery called the Automated Rotational Centre Hurricane Eye Retrieved (ARCHER). The algorithm finds the centre of rotation using spirally oriented brightness temperature gradients along the ring-shaped edge of a possible eye. Determination of the centre of a CD is important, as the intensity based on Dvorak's technique depends on the location of convection with respect to centre of the CD.

Several studies have been made to convert microwave-based brightness temperature of the cloud into surface wind associated with TCs (Evans and Stephans, 1993; Kummerow et al., 1996). The brightness temperature is used to determine Estimated Central Pressure (ECP) and MSW of the storm (Goodberlet et al., 1989; Bessho et al., 2006).

Currently, the intensity estimation takes into consideration (a) satellite (INSAT/METSAT, NOAA, TRMM, SSMIS, scatterometer wind etc.), (b) radar and (c) synoptic analysis. Like the location of the system, when the system is far away from the coast and not within the radar range, satellite estimated intensity based on Dvorak's technique (Dvorak, 1984) gets maximum weight. When the system comes closer to the coast, radar estimated intensity is considered along with satellite estimated intensity. When the system is very close to coast or over the land surface, the coastal observations get the highest preference followed by radar and satellite observations for estimating the intensity.

2.4 Errors in Estimation of Location and Intensity during Satellite Era

The average difference in location of a TC based on satellite estimation of IMD and best track estimates is about 55 km in the deep ocean (Goyal et al., 2013). The average error in MSW estimation has reduced over the years. During the pre-satellite era (till 1960), the average error in intensity estimation may be at least one stage in Beaufort scale (5-15 knots or 3-8 mps upto severe cyclonic storm stage). There is no classification of intensity between very severe cyclonic storm and above intensity in Beaufort scale. The error could have reduced gradually during polar satellite era. It could have been T0.5 (05-20 knots or 3-10 mps) with the introduction of Dvorak's classification of intensity since 1974. Based on seven TCs, Mishra and Hem Raj (1975) have shown large difference between wind speed inferred from synoptic data and those derived from satellite technique. According to them, the MSW could be under-estimated by 8-17 knots (5-9 mps) in depression/deep depression stage, 26-28 knots (13-14 mps) in cyclonic storm stage and 37 knots (19 mps) in severe cyclonic storm or higher stage. Based on recent years data, Goyal et al. (2013) have shown that there is a difference of T0.5 in the estimation of intensity by satellite method and best track estimates.

As there is no aircraft reconnaissance in the NIO, Dvorak's technique, which is based on one minute averaging, has not been verified. Coastal stations, equipped with cup anemometer and Dynes P.T. anemograph, use three-minute averaging in Indian region for estimating MSW. However, they have the limitation to estimate higher intensity. The high wind speed recorders along the coast of India installed in 2000s are not sufficient to cover the entire coast. The wind conversion factor for conversion of three-minute wind to one-minute wind has not been applied to the data over the NIO. Harper et al. (2008) discussed in details the issues involved with conversion of wind speed based on different averaging periods.

There are various agencies including IMD, Satellite service division of NOAA and Joint Typhoon Warning Centre (JTWC) which provide the satellite estimated location and intensity. However, there is difference in estimation of location and intensity of CDs by various operational centres due to the subjectivity involved in the estimation. However, the difference in estimation decreases with increase in intensity of CDs like other ocean basins (Lander, 2008; Nakazawa and Hoshino, 2009). The difference in intensity based on visible and infrared imageries of Kalpana-1 and INSAT 3A satellites and the microwave imageries based on polar orbiting satellites is higher in case of lower intensity of the system such as depression and CS. It then decreases in case of SCS and VSCS.

3. Frequency of CD, CS, SCS and VSCS

Comparing the genesis of depression over 2.5 × 2.5 degree blocks of the Bay of Bengal (BOB) and Arabian Sea (AS) during pre-satellite era (1891-1960) and satellite era (1961-2009), there has been increase in the frequency of genesis over the data sparse sea areas (Mohapatra et al., 2012). The frequency of genesis of depression over the head BOB has decreased during satellite era. Genesis of depression could have been over-estimated during pre-satellite era over this region due to climatological bias, as this region is prone for monsoon depressions.

The average, standard deviation (SD) and coefficient of variation (CV) of frequencies of CDs over the NIO are shown in Table 3 for the period of 1961-2010. About 11 CDs develop over the NIO during a year including nine and two over the BOB and AS respectively. Out of these about five intensify into CS or above intensity storms (wind speed of 34 knots or more) including about four over BoB and one over the AS. About three SCS or above intensity storms (wind speed of 48 knots or more) are formed over the NIO during a year. It includes two over the BoB and one over the AS. However, there is large interannual variation in the frequency of CD, CS and SCS as shown in Table 3. Due to lower frequency over the AS, the interannual variation is also higher over this sub-basin than over the BOB.

Table 3: Mean, standard deviation (SD) and coefficient of variation (CV) of frequency of (i) CD, (ii) CS and above and (iii) SCS and above intensity

Parameter	*CDs*			*CS and above*			*SCS and above*		
	BOB	*AS*	*NIO*	*BOB*	*AS*	*NIO*	*BOB*	*AS*	*NIO*
Mean	8.6	2.2	10.8	3.6	1.1	4.7	2.3	0.7	3.0
SD	3.1	1.5	3.6	1.5	1.0	1.7	1.3	0.8	1.6
CV	35.5	69.2	33.0	42.5	94.1	36.1	57.5	124.1	54.6

Considering the frequency of VSCS or higher intensity storms during satellite era (1965-2010), there have been about two VSCS per year (Table 4). The frequency is maximum during post-monsoon season (Oct-Dec) followed by pre-monsoon (March-May) and monsoon (June-September) season. As the frequency of VSCS is less, the analysis has not been carried out for the sub-basins of BOB and AS.

Table 4: Mean, standard deviation (SD) and coefficient of variation (CV) of frequency of VSCS during pre-monsoon, monsoon and post-monsoon seasons and year as a whole

Parameters	*Pre-monsoon season*	*Monsoon season*	*Post-monsoon*	*Year as a whole*
Mean	0.5	0.3	1.2	2.0
SD	0.6	0.6	1.0	1.4
CV	108	206	88	70

4. Trends in Frequency in Satellite Era

4.1 Trend in Frequency of CD

Considering the short-lived disturbances (CDs with life period of less than one day), the frequency of such systems was very high in the beginning of 19th century (Mohapatra et al., 2012). It gradually decreased to zero during 1961-1970 (Fig. 1a). It decreased from 68 during 1901-1910 to 03 during 1951-1960. It indicates over-estimation of genesis and hence frequency in the absence of adequate data during pre-satellite era. Considering the impact of frequency of short-lived systems on the long-term trends (Fig. 1b), there is significant decreasing trend in the frequency of CD when short-lived systems are included. Excluding the short-lived systems, the trend in annual frequency is insignificant.

Considering the trend in frequency of CD during satellite era (1961-2010), there is significant (at 95% level of confidence) decreasing trend in frequency of CDs over the BOB and NIO and no trend over the AS (Fig. 2a). The frequency of CD has decreased at the rate of 1.6 per decade and 1.5 per decade over the NIO and BOB respectively (Table 5). This trend is mainly due to the decreasing trend in frequency of CDs during monsoon season (not shown).

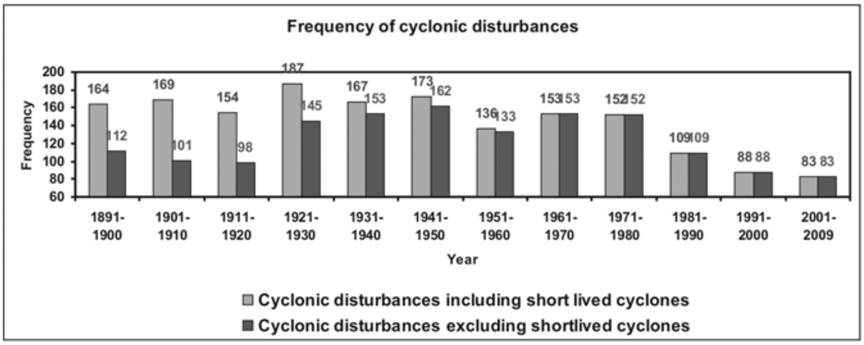

Fig. 1(a): Frequency of CDs including and excluding the short-lived CDs during 1891-2009 (Mohapatra et al., 2012).

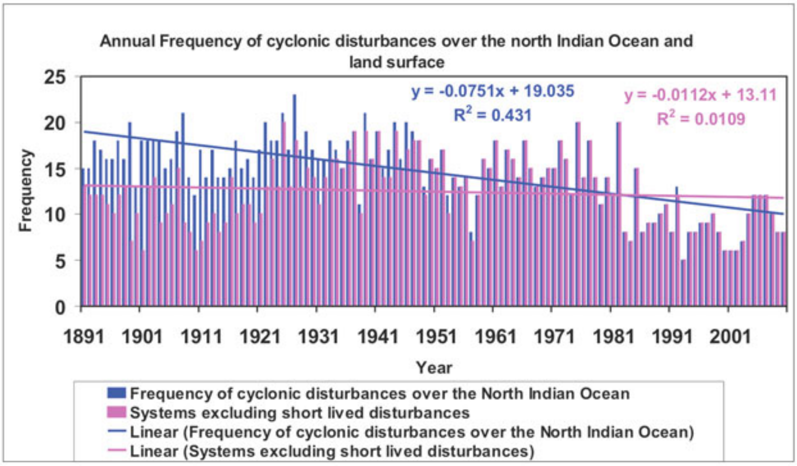

Fig. 1(b): Annual frequency of CDs over the NIO including and excluding the short-lived CDs during 1891-2009 (Mohapatra et al., 2012).

4.2 Trend in Frequency of CS or Higher Intensity Storms

Considering the intensification of cyclonic storms into severe cyclonic storms over 2.5 × 2.5 degree blocks of the BOB and AS, the frequency of such cases increased over the deep oceanic areas like the case of genesis of depression and its intensification into cyclonic storms during satellite era (Mohapatra et al., 2012).

There has been also increase along the entire east coast as well as Gujarat coast. Unlike the case of genesis of depression and its intensification into cyclones, the frequency of intensification of CS into SCS also increased over the head BOB since 1961 due to better detection. There were similar findings earlier by Mishra and Hem Raj (1975). Tyagi et al. (2010) have shown no significant trend in frequency of landfalling CDs over east and west coasts of India during 1891-2007 excluding the short-lived systems.

Considering the frequency of CS or higher intensity storms during satellite era (1961-2010), there is significant (at 95% level of confidence) decreasing trend over the BOB and NIO as a whole (Fig. 2b and Table 5). The frequency has decreased at the rate of about 0.7 per decade and 0.6 per decade respectively over the NIO and BOB respectively. There is no significant trend over the AS.

4.3 Trend in Frequency of SCS or Higher Intensity Storms

Considering the frequency of SCS or higher intensity storms during satellite era (1961-2010), there is also significant (at 95% level of confidence) decreasing trend over the BOB and NIO as a whole (Fig. 2c and Table 5). The frequency has decreased at the rate of about 0.5 per decade each over the NIO and BOB. There is no significant trend over the AS.

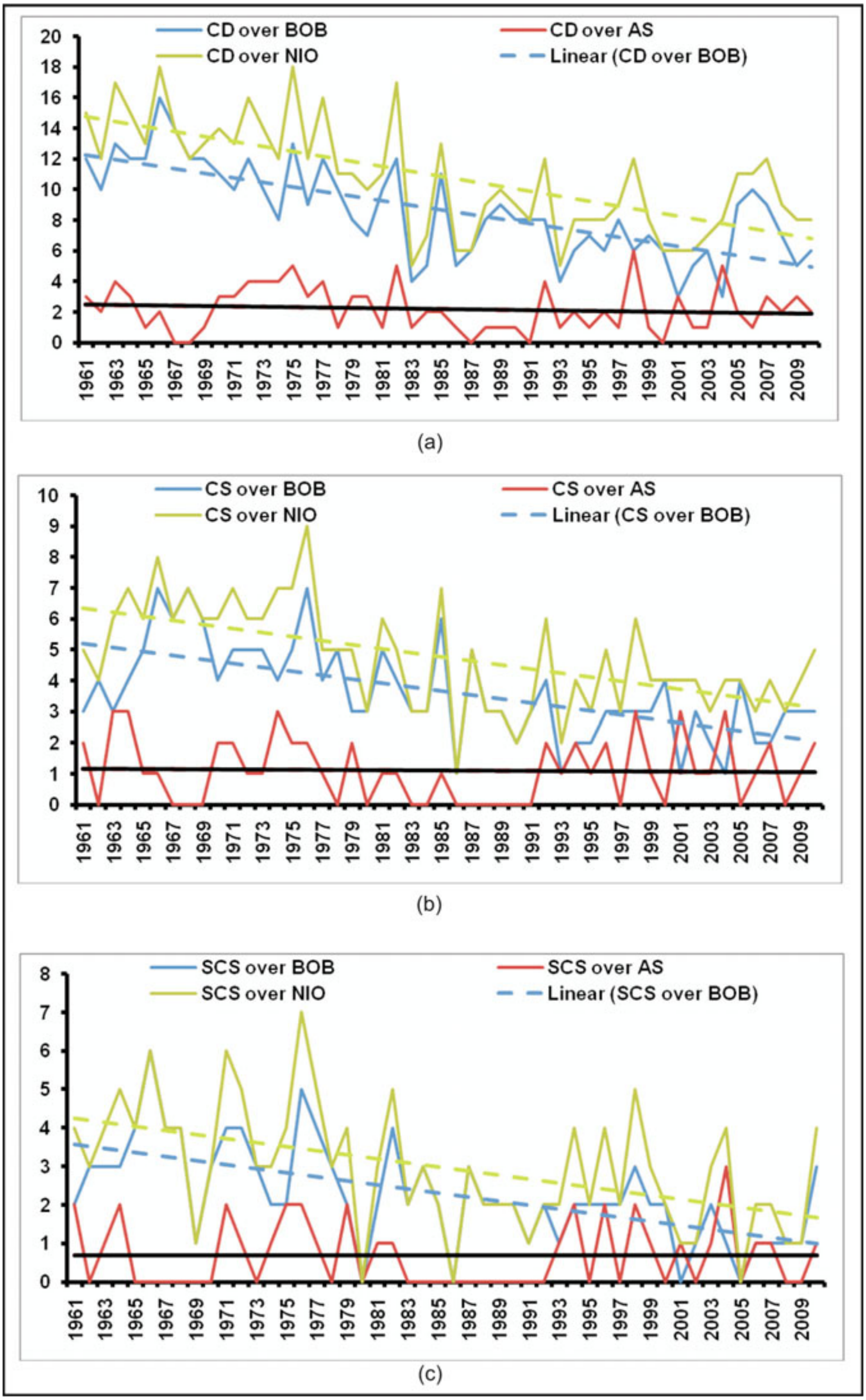

Fig.2: Trends in frequency of (a) CDs, (b) CS or higher intensity and (c) SCS or higher intensity.

Table 5: Trends (per decade) in frequency of (i) CDs, (ii) CS or higher intensity and (iii) SCS or higher intensity over BOB, AS and NIO as a whole for the period of 1965-2010

Period	*Cyclonic disturbances*		*Cyclonic storms or higher intensity*		*Severe cyclonic or higher intensity*	
	Trend	R^2	*Trend*	R^2	*Trend*	R^2
Bay of Bengal (BOB)	–1.5	0.51	–0.64	0.36	–0.52	0.33
Arabian Sea (AS)	–0.1	0.01	–0.02	0.001	0.00	0.00
North Indian Ocean (NIO)	–1.6	0.44	–0.66	0.32	0.52	0.22

4.4 Trend in Frequency of Very Severe Cyclonic Storm (VSCS) or Higher Intensity Storms

There is significant (at 95% level of confidence) decreasing trend over the BOB and NIO as a whole (Fig. 3). The frequency has decreased at the rate of about 0.56 per decade over the NIO. Further analysis indicates that the trend is significant during monsoon (June-September) and post-monsoon (October-December) seasons (Table 6). Mandal and Prem Krishna (2009) have also shown decreasing trend of frequency of very severe TCs over the NIO during 1965-2008 (satellite era) and no trend in the maximum wind associated with very severe TCs during the same period.

Table 6: Trends (per decade) in frequency of VSCS during pre-monsoon, monsoon and post-monsoon seasons and year as a whole for the period of 1965-2010

Period	*Trend (Per decade)*	R^2
Pre-monsoon season	–0.04	0.01
Monsoon season	–0.18	0.14
Post-monsoon season	–0.35	0.21
Year as a whole	–0.56	0.28

5. Conclusions

The annual frequencies of CDs, CS or higher intensity, SCS or higher intensity and VSCS or higher intensity storms show significant decreasing trend over the BOB and NIO as a whole during the satellite era (1961-2010). However, there is no significant trend over the AS during the same period.

The NIO being the data sparse region, the best track estimates are subject to errors of about 55 km in the mid-oceanic region during satellite era. There is scope for improvement, as evident from the recent past cases, due to existing and proposed buoy network over the NIO, ongoing modernization programme of IMD resulting in improved observational system like Doppler weather radar

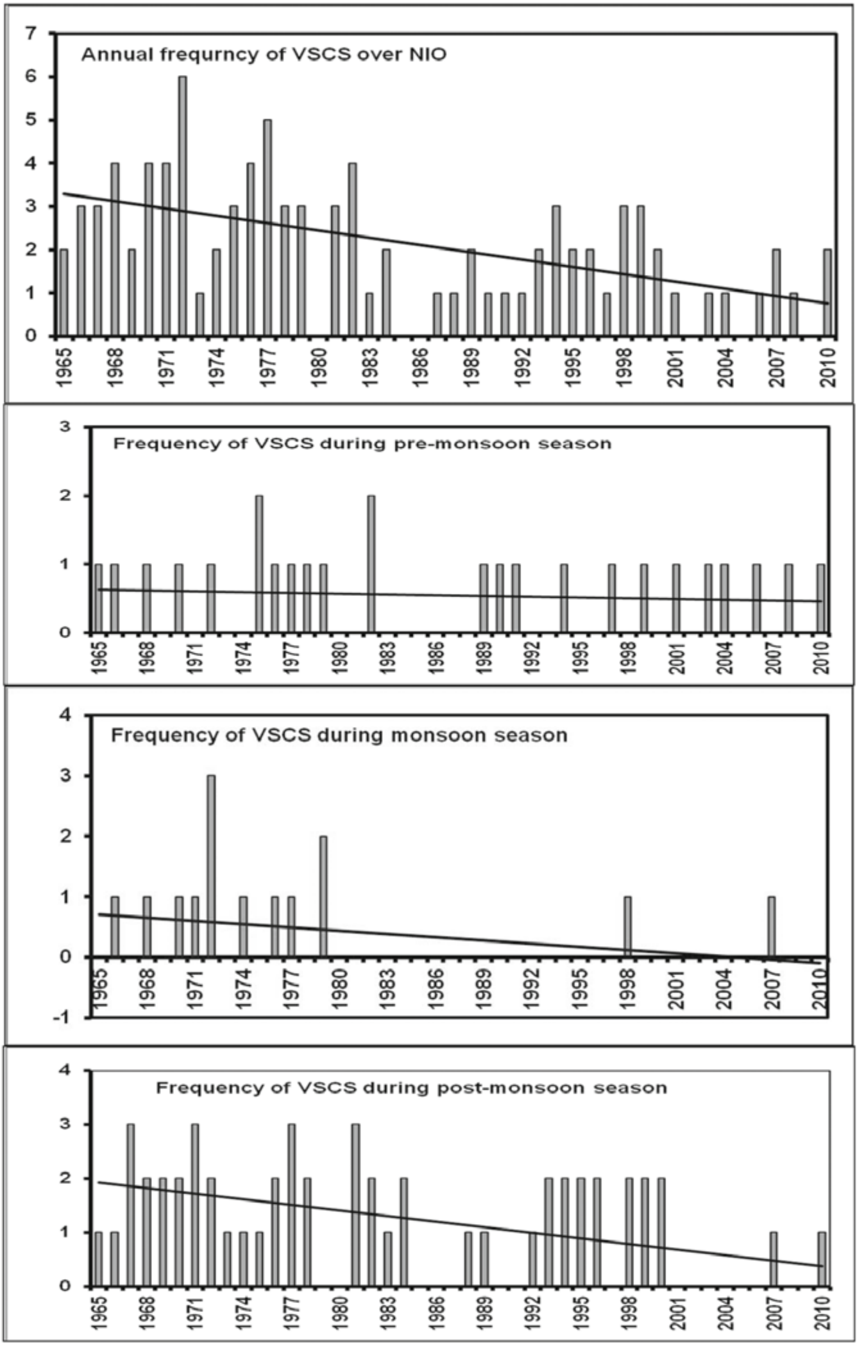

Fig. 3: Frequency of very severe cyclonic storm (64 knots or more) over the north Indian Ocean during satellite era (1965-2010).

(DWR) and automatic weather system (AWS) along the coast, ongoing forecast demonstration project (FDP) on landfalling TCs over the BOB with proposed aircraft reconnaissance. Also sea surface wind will be available on real time with launching of OCEANSAT-II along with other globally available products from polar orbiting satellites. Better satellite observations with more derived products will be available with the launching of INSAT-3D, Meghatropiques, Saral etc. The FDP on landfalling TCs over the BOB will help us further in minimizing the error in monitoring (Martin and Gray, 1993) and reanalysis of historical best tracks with modified pressure-wind relationship (Mishra and Gupta, 1976; Courtney and Knaff, 2009; Knaff et al., 2007; Koba et al., 1991), wind adjustment and modified Dvorak classification of intensity.

A complete reanalysis of CDs over the NIO during the satellite era should be taken up. There is also need for wind speed adjustments (Landsea, 1993) in the best track during periods when wind estimates were deemed to have a consistently low or high bias, especially prior to the satellite era. These are especially important for (i) accurately determining trends in frequency, intensity and track of CDs, (ii) understanding the mechanism of intraseasonal and interannual variation, (iii) prediction of genesis, intensification and movement in short range and (iv) extended range and seasonal prediction of frequency and intensity of CDs by dynamical and statistical models.

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