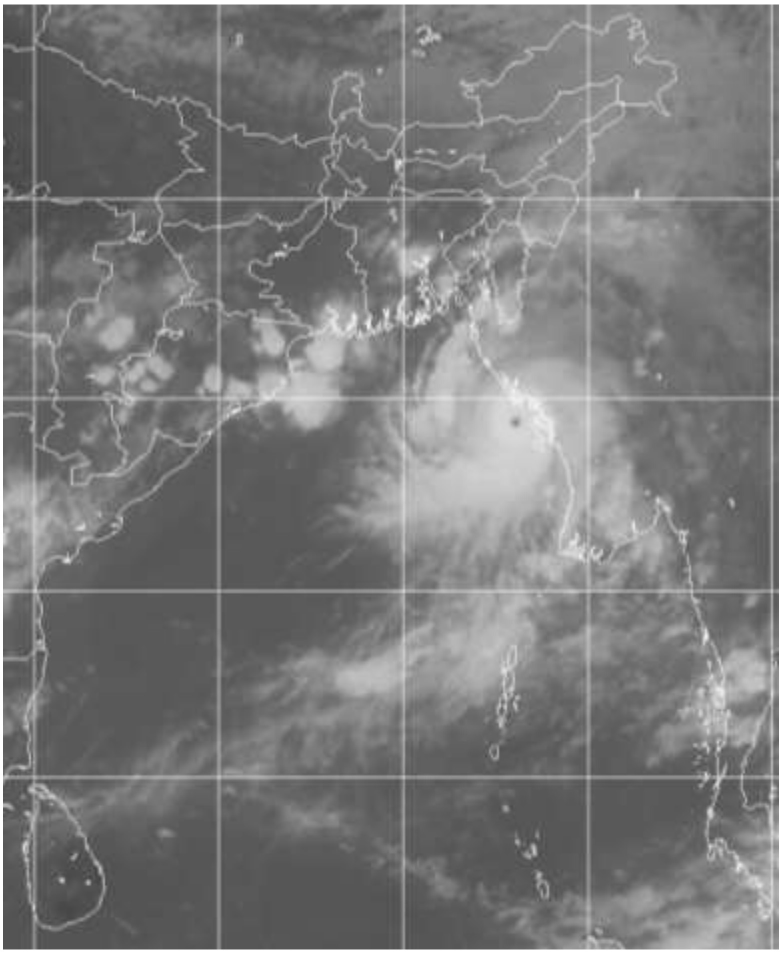
Ministry of Earth Sciences

Forecast Demonstration Project



Bay of Bengal Tropical Cyclone Experiment

(FDP-BOBTEX)

Science Plan

India Meteorological Department

Mausam Bhawan, Lodi Road, New Delhi - 110003

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Forward

During the past few years, huge technological advancements have been achieved elsewhere in the world to observe the inner core of the cyclone through aircraft probing. Accordingly, Ministry of Earth Sciences conceived a programme in 2008 for aircraft probing of tropical cyclones over the Bay of Bengal which resulted in the commencement of Forecast Demonstration Project (FDP) in 2008 with Multi-institutional mechanism and IMD as nodal agency. FDP programme is aimed to demonstrate the ability of various NWP models to assess the genesis, intensification and movement of cyclones over the north Indian Ocean with enhanced observations over the data sparse region and to incorporate modifications into the models which could be specific to the Bay of Bengal. A detailed Science Plan has been prepared to carry out the Forecast Demonstration Project (FDP) on Bay of Bengal Tropical Cyclone Experiment (BOBTEX) during 2008-2012. The Science Plan will be a first step towards an ongoing focus on impact of surface-upper air and space based observations including aircraft probing in operational cyclone forecasting and NWP modelling in the north Indian Ocean.

I am glad to inform that a volume of Science Plan for FDP-BOBTEX is brought out which will be very helpful as guidance material for further research on cyclone and planning of future FDP campaigns. I thank Cyclone Warning Division of IMD, New Delhi, for bringing out this document. I also thank Dr M. Mohapatra, Dr. K.J. Ramesh, Dr. D. R. Sikka and Dr A. K. Bohra apart from the esteemed members of the Scientific Steering Committee and project Team for their valuable contribution in preparation of this Science Plan.

IMD, New Delhi
30. October 2011

Ajit Tyagi
Director General of Meteorology

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1. Introduction:

The havoc caused by tropical cyclones (TCs) to shipping in the high seas and coastal habitats along the Indian coasts have been known since hundreds of years. The tropical warm Indian Ocean, like the tropical North Atlantic, the South Pacific and the NE Pacific, is a breeding ground for the disastrous (TC) phenomenon. TCs are accompanied by very strong winds, torrential rains and storm surges. Historically, in terms of loss to human life, the Bay of Bengal TCs have accounted for deaths ranging from a thousand to three hundred thousands. The death toll had exceeded 3,00,000 and 1,40,000 in earlier Bangladesh severe cyclones of 1970 and 1991 respectively in which the damages were beyond imagination. The recent Orissa Super Cyclonic Storm (SuCS) of 29-30 October 1999 had caused over 10,000 human deaths and resulted in destruction and damage to over 1.9 million houses in 14 districts of Orissa affected by the cyclone landfall. More than 6 villages were completely washed away and 59 villages were partly washed out (Kalsi, 2006 Mohapatra, 2002). The impact of the SuCS was more pronounced as it had struck just 11 days after a very severe cyclonic storm (VSCS) had damaged the southern districts of Orissa State on the eastern coast of India. The total damage caused to the State of Orissa by these two cyclones in Oct 1999 was more than $2.5 billion. Besides the economic problems caused by the two cyclone landfalls, within a few days of each other, they had resulted in several socioeconomic problems. The recovery from these shocks was slow due to rural nature of the affected coastal population. The damage caused by these two cyclones in Orissa in October 1999 required a large intervention for relief work from the Governments of India and Orissa, United Nations, NGOs, donors and other national and international agencies. Recently there was death toll of 1,40,000 in Myanmar due to VSCS Nargis during April-May, 2008. There are several such examples of the enormous storm-havoc along not only the Eastern Indian coast but also along the coasts of the other rim countries of Bay of Bengal, viz., Sri Lanka, Bangladesh, Myanmar and Thailand.

The reduction of TC disasters depends on several factors, besides the skill in their prediction, which include short and long term preparations to tackle cyclone-related disasters, readiness of the people to heed to the warnings, and the public perception about the credibility of the official predictions and warnings. In the last 3 decades the prediction skills have substantially improved in the north Atlantic and Pacific Ocean basins as a result of improved observations and research campaigns. The potential for such improvements exists in the Indian Ocean basin too provided a special effort is launched in observations and modeling. The purpose of this document is to present a well articulated Science Plan to achieve this goal.

2. Early History of Studies on North Indian Ocean Tropical Cyclones.

Scientific studies on the North Indian Ocean TCs can be traced back to the work of Henry Piddington between 1839-1851. Piddington was an employee of the English East India Company, who later became the President of the Marine Court of Calcutta, (now Kolkata). He had authored nearly 50 papers during this period and were published in the Journal of the Asiatic Society of Bengal, which was the only scientific journal then available in India. He also coined the word ‘Cyclone’ from a Greek word ‘Cyclos’ (meaning coils of snake) and the word since then has been used to describe the TCs over the North Indian Ocean, just like local words Hurricane, Willy Willy, Typhoons are used over the North Atlantic and Eastern North Pacific, South Pacific, and Western North Pacific basins.

The destruction caused by a Severe Cyclonic Storm (SCS) which had struck Kolkata in October 1864, within a short period of an earlier cyclone striking Orissa coast in the same month of 1864, prompted the Bengal Chamber of Commerce to recommend to the Govt. of India to establish a regular scientific system of Storm Warning for the Bay of Bengal. This led to the introduction of port warning system in 1865. Also this action, along with other considerations, led to the establishment of the India Meteorological Department (IMD) under the Central Govt. of India in 1875. Since then the Storm Warning System of the IMD has undergone several changes.

Presently Cyclone Warning centers at Kolkata, Bhubaneswar, Visakhapatnam and Chennai are operating for the Bay of Bengal region and Ahmedabad and Mumbai cater to the needs of the Arabian Sea with assigned areas of responsibly to meet national and international requirements. India also meets international requirements for the Indian Ocean tropical cyclones under the system organized by the World Meteorological Organization (WMO). Cyclone Warning Division of IMD, New Delhi acts as Regional Specialised Meteorological Centre (RSMC)-Tropical Cyclone and Issues Special Tropical Weather Outlook and Tropical Cyclone Advisories to the WMO/ESCAP Panel countries including Bangladesh, Myanmar, Thailand, Srilanka, Pakistan and Oman. As far as special observational campaigns are concerned, IMD had taken a lead in 1930s to launch a special experiment to understand the landfalling tropical cyclones along the east coast of India in which a number of radio-meter sonde stations were established along the coast to obtain information on structure of cyclones (Mohapatra etal 2011).

At present the INSAT geostationary satellite coverage over the Indian Ocean and the coverage provided by the coastal radar networks along the Indian coasts form the bulwark of TC detection over the region. Unlike in the 19th century, no cyclone can now go undetected in the Indian Ocean, based on the monitoring provided by the INSAT or go without appropriate storm warnings along the Indian coasts from the radar scanning when a TC is within striking distance of Indian coasts.

3. Climatological Aspects of the Bay of Bengal Tropical Cyclones.

The cyclonic disturbances over the north Indian Ocean are classified based on the associated maximum sustained surface wind (3 minutes average) The detailed classification is given in Table 1.

System	Associated MSW (knots)	Pressure drop (hPa)
Depression	17 and 27 kt	3
Deep Depression	28 and 33 kt	4.5
Cyclonic storm	34 and 47 kt	6.1
Severe cyclonic storm	48 and 63 kt	15.0
Very severe cyclonic storm	64 and 119 kt	20.9
Super cyclonic storm	120 kt and above	80.0

The detailed classification with respect to genesis, frequency distribution, intensity, movement etc is described in the following sub-section.

3.1 Genesis and frequency

During the period 1877 and 1980, several efforts have been made in the IMD (Blanford 1877, Chambers 1882, Normand 1925, 1926 IMD 1964, 1979, 2008) to update climatological records on TCs of the North Indian Ocean. Atlases showing tracks of individual cyclones are also available in electronic form (IMD, 2008). Analysis of storm tracks with reference to their genesis, recurvature and landfall points on 1°x1° scale along the Indian coasts have been produced in several studies (Raisircar 1956, Rao and Jayraman 1958, Roy Choudhuri et al 1959, Raghvendra 1973, Srivastava et al 2000, and Singh and Loe 2007 Tyagi etal 2010) besides others.

It is now a well known fact of climatology that TCs occur in the North Indian Ocean prominently during the pre-monsoon season (March-April-May) and the post-monsoon season (October-November-December). The maximum frequency is in the two months of October and November in the Bay of Bengal. The Bay of Bengal TCs more often strike Orissa-West Bengal coast in October, Andhra coast in November and the Tamilnadu coast in December. Over 60 percent of the TCs in the Bay of Bengal strike different parts of the east coast of India, 30 percent strike coasts of Bangladesh and Myanmar and about 10 percent dissipate over the sea itself (Tyagi etal 2010). Nearly 7 percent of the global TCs form in the North Indian Ocean. About 5 to 6 TCs occur in the North Indian Ocean annually including 4 over the Bay of Bengal and 1 Over the Arabian Sea. The monthwise distribution of TCs over the north Indian Ocean is shown in **Fig.1**. The frequencies of TCs over the Bay of Bengal and Arabian Sea are shown in **Fig.2** and **Fig.3** respectively. More than 80% of all cyclonic disturbances occur during the months June to November with a maximum in August. The monthly frequency of cyclonic storms show two maxima with primary maxima in November ad secondary maxima in May.

It is seen that the annual number of disturbances has ranged from 8 in 1957 to 23 in 1927. The number of cyclonic storms has varied from a minimum of 1 in 1949 to a maximum of 10 each in the years 1893, 1926 and 1930. The average number of cyclonic disturbances and cyclonic storms per year is about 13 and 5 respectively. Out of total cyclones, about 50% intensified into severe cyclonic storms.

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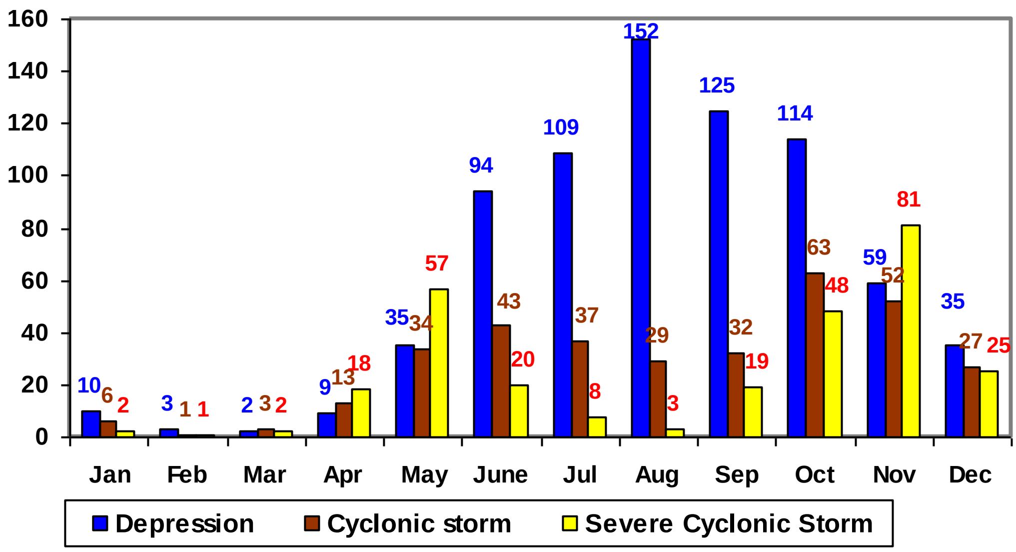


Fig.1. Monthly frequency of cyclonic disturbances during 1891-2008 over north Indian Ocean

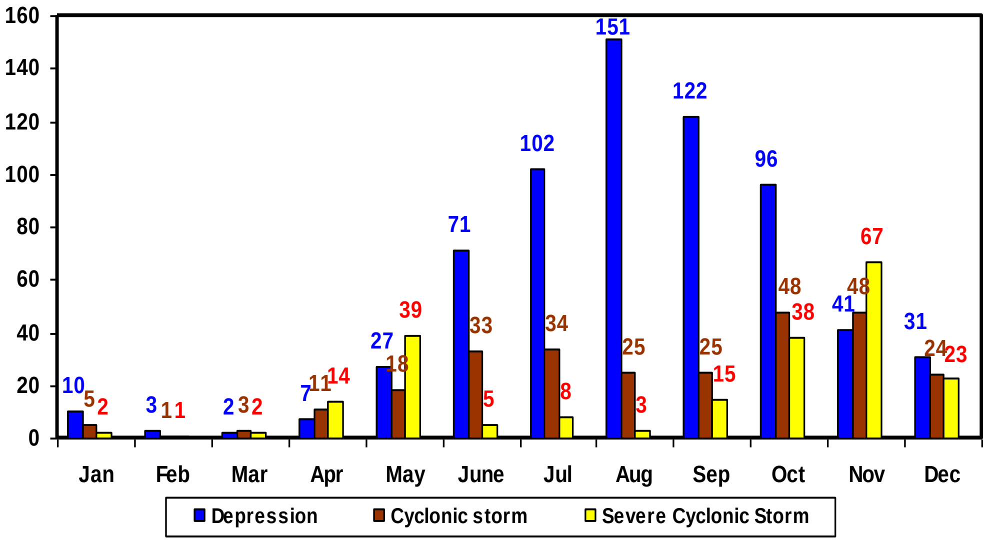


Fig.2. Monthly frequency of cyclonic disturbances during 1891-2008 over the Bay of Bengal.

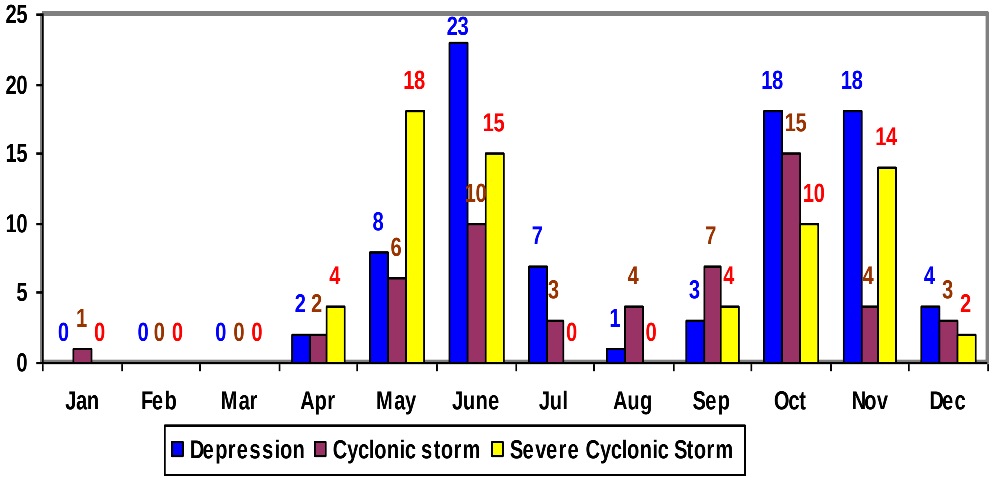


Fig.3. Monthly frequency of cyclonic disturbances during 1891-2008 over Arabian Sea.

The decadal frequency of cyclonic disturbances over the north Indian Ocean, Bay of Bengal and the Arabian Sea are shown in **Table 2 and Fig. 4**. There is significant decreasing trend in the frequency of cyclonic disturbances during last three decades.

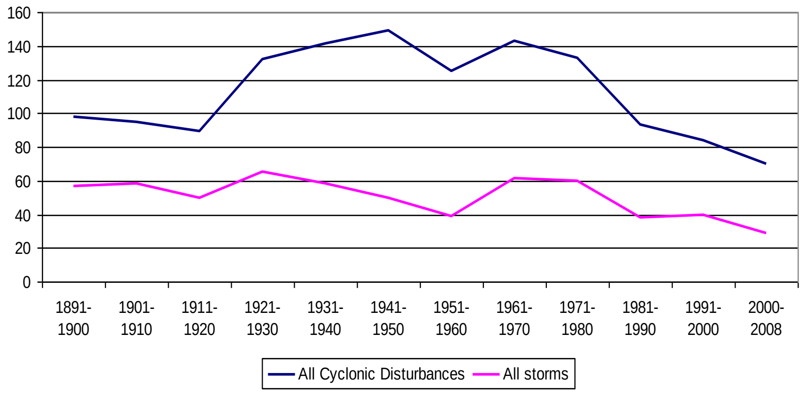


Fig. 4 Decadal Frequency of cyclonic disturbances and cyclonic storms over the north Indian Ocean

Table 2 (a). Decadal frequency of cyclonic disturbances during 1891-2008 over north Indian Ocean.

Decade	All Cyclonic Disturbances (D+C+S)	All Storms Bay of Bengal & Arabian Sea	Cyclonic storms	Severe cyclonic Storms
1891-1900	98	57	36	21
1901-1910	95	58	37	21
1911-1920	89	50	31	19
1921-1930	132	65	46	19
1931-1940	141	58	33	25
1941-1950	149	50	32	18
1951-1960	125	39	21	18
1961-1970	143	61	23	38
1971-1980	133	60	20	40
1981-1990	93	38	14	24
1991-2000	84	40	13	27
2001-2008	70	29	15	14

The frequency of depressions(D), cyclonic storms(CS) and severe cyclonic storms (SCS) based on the data of 1891-2008 over different $2.5^0X2.5^0$ lat./long. Grid in the north Indian Ocean and adjoining land region are shown in **Fig. 5.** It indicates that the Bay of Bengal (BoB) is more prone for intense systems. Further the frequency is very less over the west Arabian Sea mainly due to colder sea surface temperature (SST). Higher cyclonic disturbances(CD) over the BoB is mainly due to the depressions/deep depressions during the monsoon season developed over this region, warmer SST and the remnants from the south China Sea which may re-intensify into cyclonic disturbances.

Table 2 (b). Decadal frequency of cyclonic disturbances during 1891-2008 over the Bay of Bengal.

Decade	All Cyclonic Disturbances (D+CS+SCS)	All Storms (CS+SCS)	Cyclonic Storms (CS)	Severe Cyclonic Storms (SCS)
1891-1900	89	49	32	17
1901-1910	80	43	31	12
1911-1920	81	42	28	14
1921-1930	121	58	40	18
1931-1940	125	49	29	20
1941-1950	134	44	31	13
1951-1960	106	31	18	13
1961-1970	124	49	16	33
1971-1980	99	46	17	29
1981-1990	78	35	13	22
1991-2000	66	28	9	19
2001-2008	52	18	11	7

Table 2 (c). Decadal frequency of cyclonic disturbances during 1891-2008 over Arabian Sea.

Decade	All Cyclonic Disturbances (D+CS+SCS)	All Storms (CS+SCS)	Cyclonic Storms (CS)	Severe Cyclonic Storms (SCS)
1891-1900	9	8	4	4
1901-1910	15	15	6	9
1911-1920	8	8	3	5
1921-1930	11	7	6	1
1931-1940	16	9	4	5
1941-1950	15	6	1	5
1951-1960	19	8	3	5
1961-1970	19	12	7	5
1971-1980	34	14	3	11
1981-1990	15	3	1	2
1991-2000	18	12	4	8
2001-2008	18	11	4	7

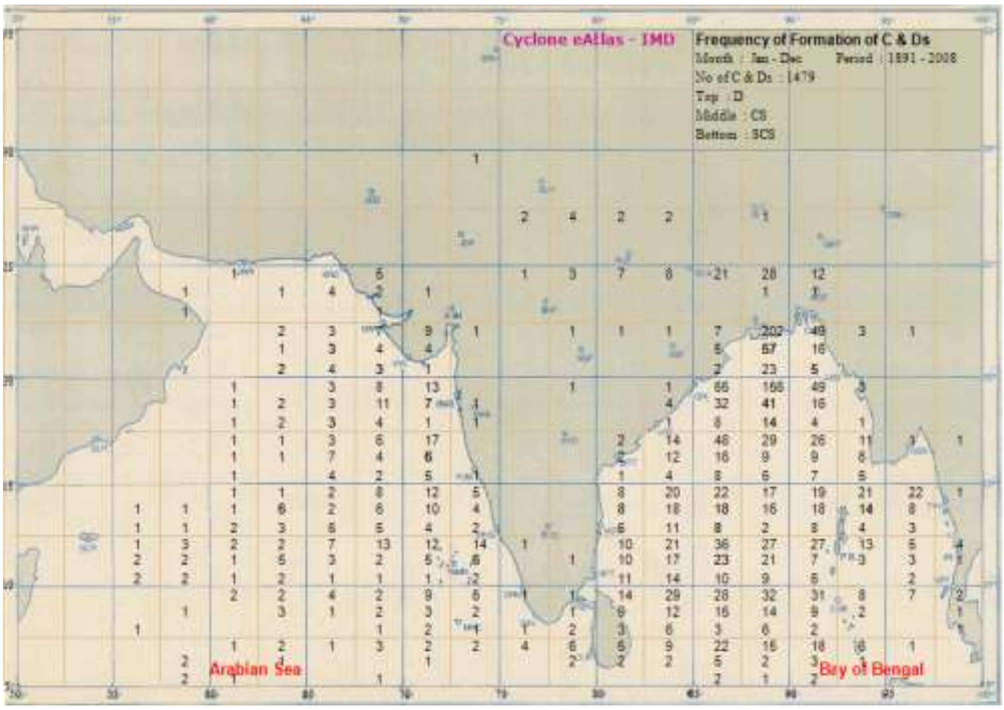


Fig. 5 Frequency of depression(D), cyclonic storm (C)and severe cyclonic storm (S) over different $2.5^0 X 2.5^0$ lat./long. Grid during 1891-2008

3.2. Intensification

More than 50% of the cyclonic disturbances that form in the months of March, April, May, November and December intensify into storms. Considering individual basins a third of the Bay disturbances and half the number of the Arabian Sea disturbances intensify into storms. The probability of intensification of a depression into a cyclonic storm or severe cyclonic storm is shown in **Fig.6.**

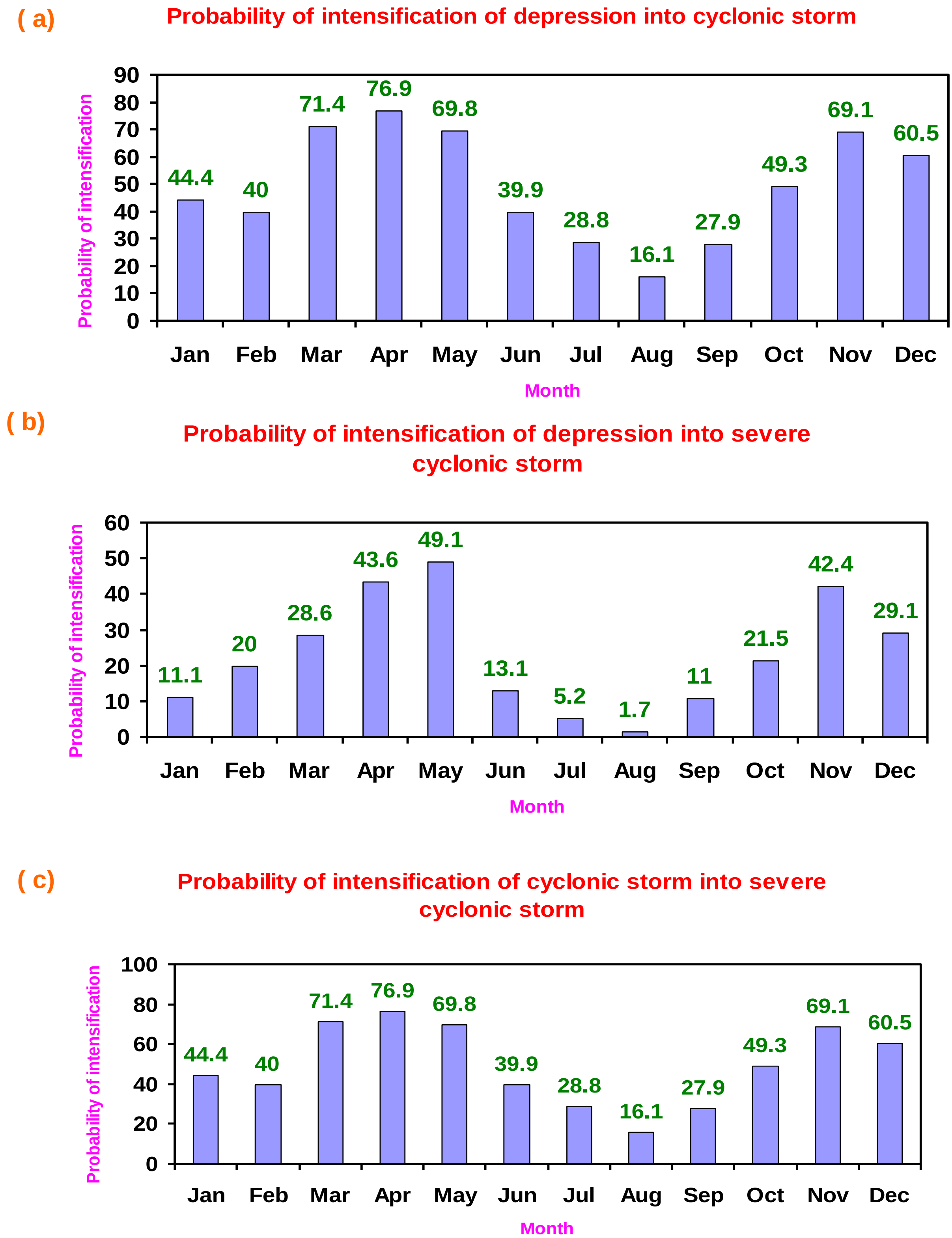


Fig. 6 Probability of intensification of (a) depression into cyclonic storm (b) depression into severe cyclonic storm and (c) cyclonic storm into severe cyclonic storm.

3.3. Movement

The tracks of TCs over the north Indian Ocean during 1891-2008 are shown in **Fig.7**. Recently an electronic atlas has been published for tracks of cyclonic disturbances over the Bay of Bengal and Arabian Sea. Analyses of storm tracks with reference to their genesis, recurvature and landfall points on 1°x1° scale along the Indian coasts have also been produced. The percentage frequency of direction of movement of disturbances are shown in **Fig. 8.** Mostly, the systems developing over the north Indian Ocean move in a north-westerly direction. However, there are cases for recurvature towards the northeast or east to southwest. The frequency of recurvature is higher towards the northeast compared to southwest or east. The probability of recurvature is higher over the Arabian when the system moves to the north of 15^0N leading to more landfall over Gujarat coast. Over the Bay of Bengal, there is no such preferred latitude/longitude for the recurvature of the system. However the probability of recurvature towards the northeast is higher during the pre-monsoon season (IMD, 2008).

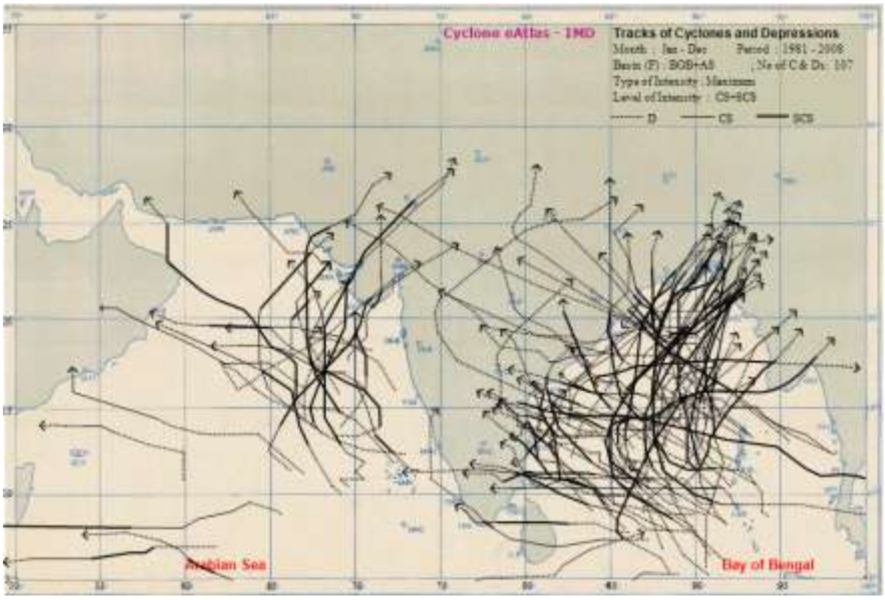


Fig. 7. Tracks of cyclones over the north Indian Ocean during 1981-2008

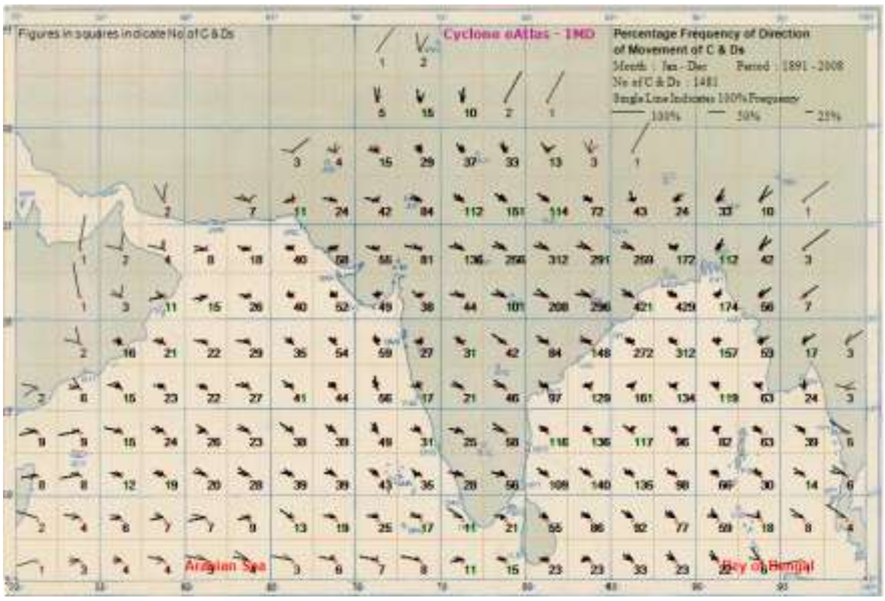


Fig. 8 Percentage frequency of Direction of movement of cyclonic disturbances over different 2.5^0X2.5^0 lat./long. Grid during 1891-2008

3.4. Landfall

The Bay of Bengal TCs more often strike Orissa-West Bengal coast in October, Andhra coast in November and the Tamilnadu coast in December (Tyagi etal 2010). Over 60 percent of the TCs in the Bay of Bengal strike different parts of the east coast of India, 30 percent strike coasts of Bangladesh and Myanmar and about 10 percent dissipate over the sea itself. The cyclones crossing different coastal states are shown in **Fig.9** (IMD, 2008)**.** About 50% of the cyclones over the Arabian Sea dissipate over the sea itself. Maximum landfall takes place over Gujarat coast.

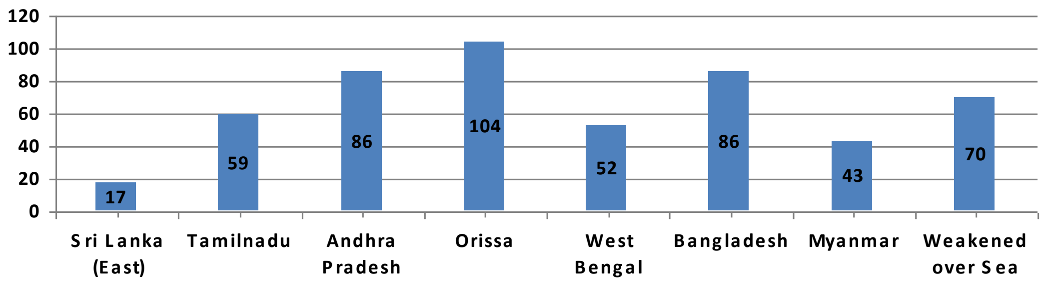


Fig.9(a). Frequency of cyclone/ severe cyclone over the Bay of Bengal landfalling over different coastal states during 1891-2008.

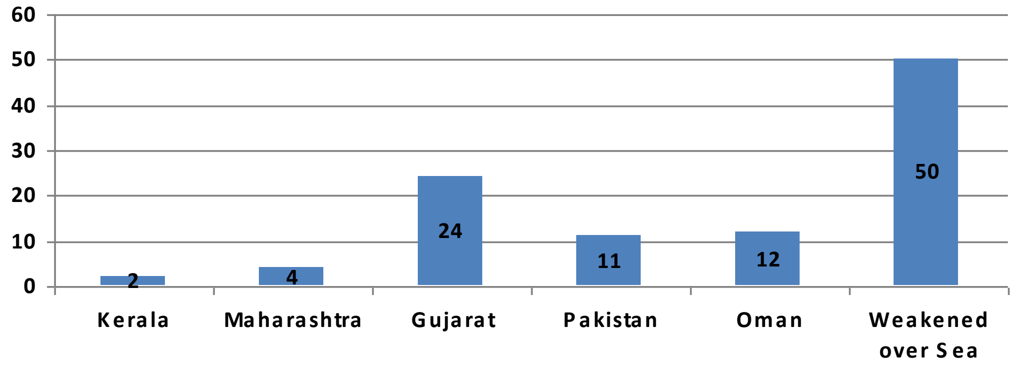


Fig.9(b). Frequency of cyclone/severe cyclone over the Arabian Sea landfalling over different coastal states during 1891-2008

3.5. Dissipation

The cyclonic disturbances mostly dissipate when they move over the land. Also when a cyclonic disturbance over the sea comes across the unfavorable conditions like colder sea surface temperature and high vertical wind shear, it dissipates over the sea itself. The frequency of dissipation of cyclonic disturbances during 1891-2008 over 2.5^0 X 2.5^0 lat/long. grids are shown in **Fig. 10** (IMD, 2008). The frequency of dissipation is significantly higher over the West Arabian Sea, mainly due to colder SST. There are also significant number of cases of dissipation along the esat cost of India , Bangladesh and Myanmar coasts.

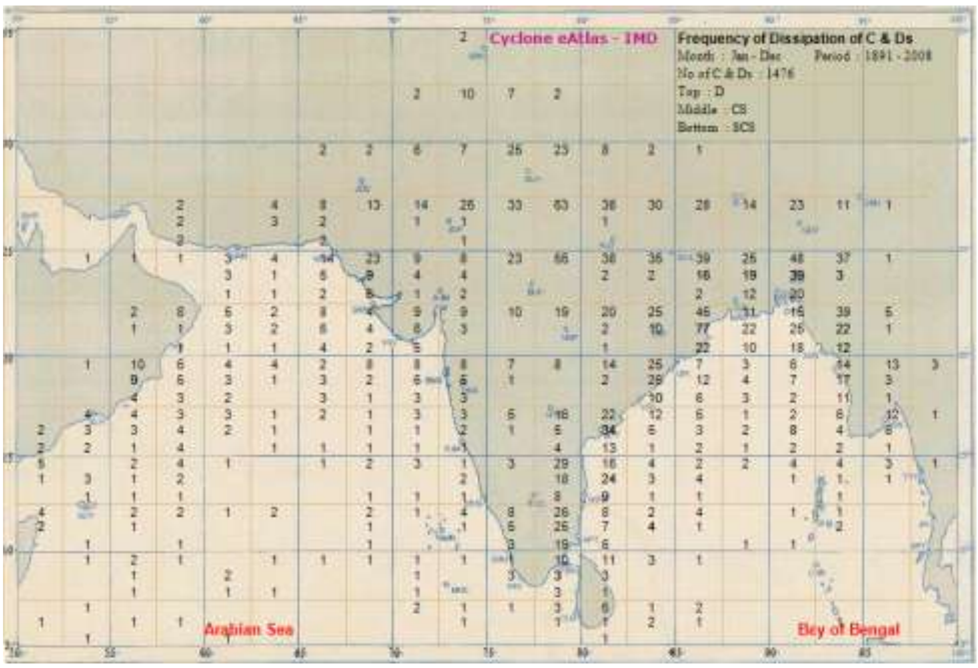


Fig. 10. Frequency of dissipation of cyclonic disturbances during 1891-2008 over 2.5^0 X 2.5^0 lat/long

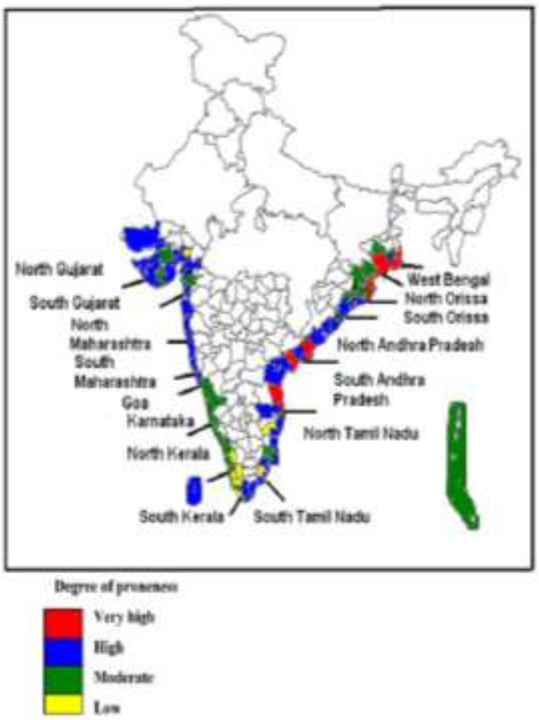


Fig.11 Cyclone prone districts map

3.6 Impact of TCs:

The disastrous impacts of cyclones due to heavy rain, strong wind and storm surge have been analysed and discussed by many authors. A recent review has been made by Mohapatra et al (2011). Many authors have also attempted to classify the coastal zones based on the impacts characteristics of the cyclone. recently Mohapatra (etal 2011) have developed the cyclone prone districts mapping (**Fig 12**) based on the frequency of TC, frequency of severe TC, associated MSW, heavy rainfall and probable maximum storm surge. It indicates north Orissa and west Bengal coastal districts are very highly prone to cyclonic activity.

3.7. Limitations:

The climatology of cyclonic disturbances presented here is based on data available in e-Atlas published by IMD. The limitation and scope of this Atlas have been discussed by IMD (2008). One of the important limitations is that it does not include the short lived disturbances (life period < 12 hours).

Further, the climatology depends on the monitoring capability to detect the disturbances. The monitoring system over the region has undergone several changes with augmentation of surface observatories, introduction of RS/RW observations during 1930's, use of satellite since 1960s and implementation of meteorological buoys since 1997. Hence all these facts should be taken into consideration while analyzing the climatological characteristics of cyclonic disturbances over the north Indian Ocean (Mohapatra et al 2011).

4. Background for Undertaking Forecast Demonstration Project Bay of Bengal Tropical Cyclone Experiment (FDP-BOBTEX)

Meteorologists world over, recognize that prediction of tropical cyclogenesis, intensification of the Cs and their tracks are some of the most challenging problems in tropical meteorology. The prediction problems become all the more complex over the Bay of Bengal, which is a data void region. A high percentage of precursors (low pressure areas) for the Bay of Bengal cyclogenesis result from the westward moving remnants of the TCs moving from Western North Pacific via South China Sea and Gulf of Thailand. These precursors (low pressure pulses) intensify over different parts of the warm and less saline waters of the Bay of Bengal. Upper air observational networks are inadequate over the South China Sea and the Bay of Bengal. These networks are also inadequate over countries of SE Asia like Cambodia, Vietnam, Laos, Thailand and Myanmar. INSAT imagery is the only way for timely detection of tropical cyclogenesis over the Bay of Bengal. Indian meteorologists, for over 3 decades, have felt that skills of prediction of intensification and tracks of the Bay of Bengal cyclones could be considerably improved if aircraft weather reconnaissance facility is provided over the Bay of Bengal. The recent availability of high resolution meso-scale models for tropical cyclones (such as ARPS, MM5, WRF and HWRF) with several Indian operational agencies (IMD, NCMRWF, IAF, Indian Navy) and research groups (IITM, IIT-Delhi, CMMACS, Bangalore, SAC, ISRO Ahmedabad, Andhra University and other organizations) have convinced the Indian meteorologists that prediction skill of TCs in the Bay of Bengal basin can dramatically improve by using such high performance models, as it has occurred over North Atlantic, provided atmospheric data from the environment and vicinity of developing cyclones in Bay of Bengal are made available from aircraft weather reconnaissance flights.

Fig 12 demonstrates the consistent improvement in the skills of annual average track forecast over the north Atlantic region in the last 20 years (1990-2009). The figure shows that the skill for 72-hr forecast has improved as error has dropped from around 500 km to 250 km, that of 48-hr forecast from 350 km to 150 km and 24-hr forecast from 200 km to 100 km. On the other hand, for the North Indian Ocean TCs, **Fig 13** (Gupta 2006) shows that the skill over the North Indian Ocean undergoes inter annual fluctuations for 72-hr, 48-hr and 24-hr forecasts and there is hardly any improvement trend in forecast skill till 2000. Partly this could be due to large error in the initial positions (time zero) of cyclones at the time of preparing forecasts which varies between 100-200 km. The fixing of initial positions of the cyclones over North Indian Ocean, while they are still far away from the coastal radars, depend chiefly on satellite information, which could be more definitive only if the ‘eye’ of a cyclone is observed in satellite photographs. Aircraft reconnaissance is helpful in precise fixation of the centre of a cyclone even when it is not in the coastal radar range. However, the analysis in recent years (2003-2010) indicate that the track forecast errors have decreased (IMD 2011). It is mainly due to the increase in observational network over the region (Mohapatra et.al 2011). The 24 hr forecast error has reduced at the rate of about 6 km per year and is about 130 km in 2010. The 48 hr and 72 hr forecasts have been introduced recently since 2009 only. The fact that the forecast error in the North Indian Ocean region is still higher compared to that over the Atlantic or the Pacific basin (table -3) calls for setting up of priorities on various operational and research issues urgently so that the benefits of potential improvement in skills in TC predictions could be demonstrated to benefit society.

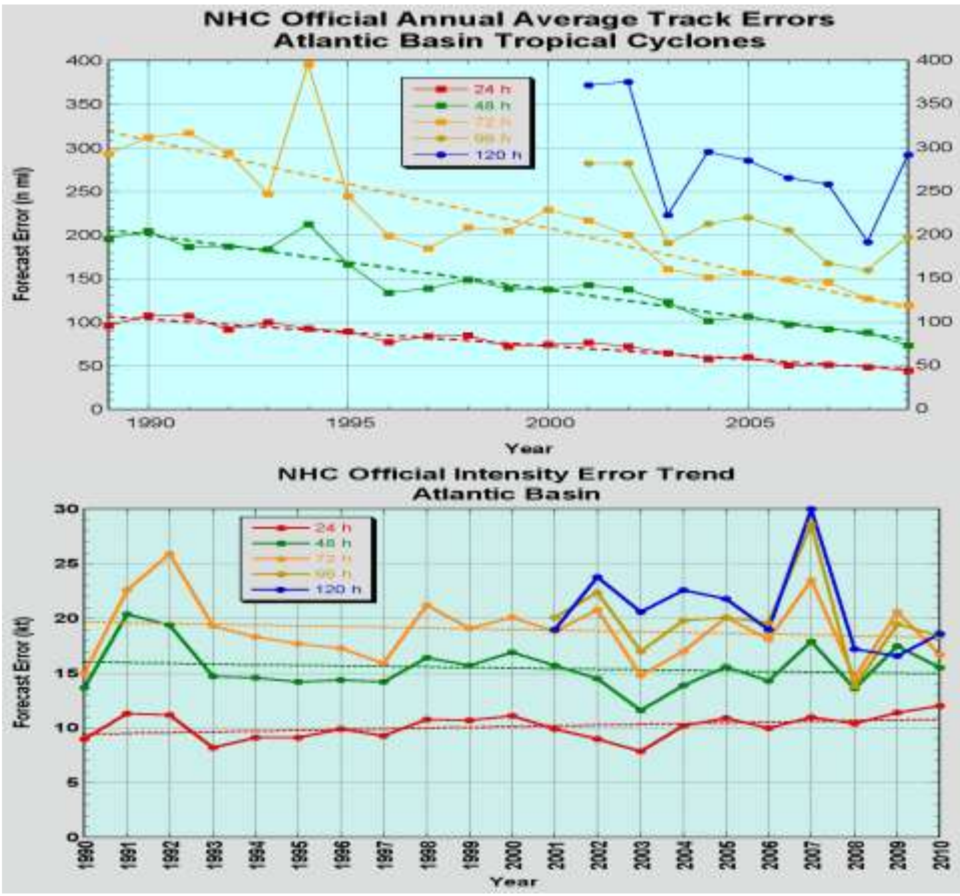


Fig. 12 Annual average Track and Intensity forecast error over North Atlantic region for the period 1970-2010

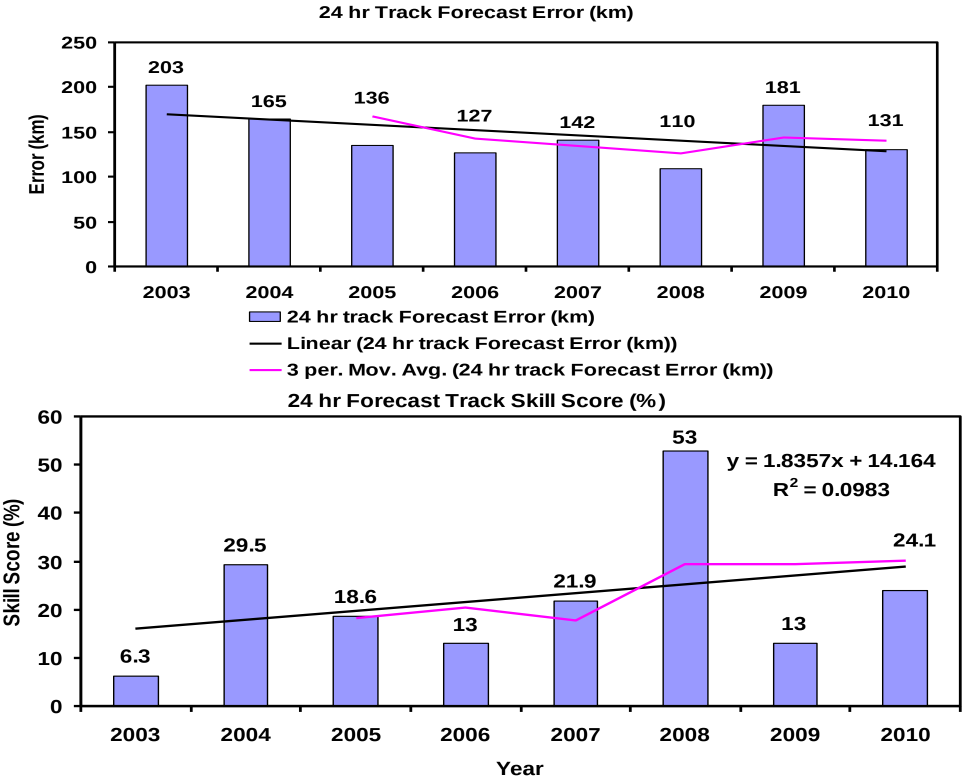


Fig.13 Mean Forecast error for North Indian Ocean

The possibility of launching a tropical cyclone Forecast Demonstration Project (FDP) was discussed at the Indo-US round table held at NCAR Boulder in June-July 2005. Both the sides agreed that the feasibility of launching of FDP in the Bay of Bengal ought to be jointly considered. It was also agreed that the NCMRWF in India and the NCAR in USA would be the lead agencies for developing this project.

Considering all the above, various attempts have been made in the past since 1871 for aircraft probing of TCs. Recently this initiative was further strengthened as WMO under their Project Tropical Meteorology Research Programme (TMRP) and the Land Falling Hurricane Project of the NCAR's Division of Micrometeorology and Meso-Meteorology (MMM) are focusing on Forecast Demonstration of land falling TCs. Following the India-US meeting of June-July 2005, the Planning Workshop of Forecast Demonstration Project (FDP) of land falling tropical cyclones over the Bay of Bengal was held between 28 Feb-03 March 2007 under the sponsorship of the Indo-US Forum. The workshop was attended by scientists from NCAR and NOAA from US side and leading scientists from India working in NCMRWF, IMD, IAF and Indian Navy from operational side as well as scientists of all prominent R&D organizations, IITs and Universities engaged in tropical cyclone research. The major recommendations of the workshop are as follows:

- Launching of FDP for the Bay of Bengal Tropical Cyclone Experiment (FDP-BOBTEX) is highly desirable and also feasible with the cooperation of India and USA. It is equally desirable that the Bay of Bengal rim countries may be involved in this initiative as their observational systems would support implementation of FDP-BOBTEX and they also stand to gain in improved prediction skills.

- India and USA will jointly prepare a well articulated Science Plan for the FDP-BOBTEX. India (NCMRWF) may send the first draft plan to NCAR by May 2007 and get it vetted by NCAR by July 2007. A joint meeting be held in New Delhi in Oct-Nov. 2007, also under the sponsorship of Indo-US Forum, to give a final shape to the draft. This meeting would also sort out and finalize action-plan on technical issues with regard to requirements in different phases of FDP which could be submitted to respective Governments by December 2007.
- Indian scientific community may to continue carrying out well focused background studies on tropical cyclone genesis, clustering of the TCs formation in the Bay of Bengal, Observing System Simulation Experiments (OSSE), role of mid-latitudes circulation regime in cyclo-genesis and tracking of TCs, targeted observations, gaps in observing systems, site surveys, cooperation with Bay of Bengal rim countries and validation of different high resolution model simulations of past cyclones to demonstrate the forecast skill of the dynamical models on a statistical sample with present data gaps.
- It is also important that two pilot experiments, one in October-November 2008 and the other in October-November 2009, be launched by the Indian side in which US scientists may be invited to participate.
- The high intensity field program (main FDP Field Campaign), with the participation of hired research reconnaissance aircraft and an Indian aircraft with two research ships and other land-space and ocean base observing systems by India and rim countries, be carried out in Oct-Nov 2011. This would allow sufficient lead-time for the main field campaign and also for full implementation of the FDP-BOBTEX in the 11th Five Year Plan (2007-2012) of India.
- The data collected in the Pilot experiments and the main field campaign would be utilized in research for several years there after.

The preparation of this Science plan is an attempt to fulfill recommendations of the Feb. - March 2007 Planning Workshop held at New Delhi.

However due to various reasons, the FDP is planned to be taken up independently without the collaboration of USA.

5 Key Scientific Objectives and Goals of the FDP-BOBTEX.

5.1 Key Scientific Objectives

The key objectives are:

- Improvements in scientific understanding of the genesis, intensification, structure and movement of the Bay of Bengal TCs through observations and modeling.
- Demonstration of societal benefits through improved skills, resulting from improved observational systems (land, ocean, space and air borne platforms) and use of high resolution meso-scale models for tropical cyclone track, landfall position and intensity predictions.

5.2 Expected Benefits on achieving the goals

The twin objectives are expected to lead to following benefits:

- Better understanding of TC movement and intensification processes.
- Improvement in the skill of 72-hr and 48-hr track predictions to less than 250 km and 150 km respectively from the present and 48 hrs landfall prediction to within 50 km.
- Better observations on rainfall intensity on TC landfall, spatial-temporal variation in coastal and inland wind strengths, data assimilation, storm surge and hydrological modeling. Landfall studies cover all these issues.
- Addressing near-and far-time observing and modeling challenges in anticipation of developing improved TC prediction system to become operational in India by 2012.
- Improved prediction system would be useful for more precise warning formulations and preparations for better evacuation of people from the threatened region of landfall. It would also help in triggering storm surge models, storm vulnerability models, inundation models and storm surge-river flood interaction models. The research work for such societal models have to be carried out by organizations other than those directly involved in the implementation of FDP-BOBTEX for this purpose. A separate plan may be formulated by Indian research organizations and organizations involved in disaster vulnerability, impact assessment, rescue and disaster management work in India.

- The benefits would arise on achieving the goals which in turn are achievable based on utilization of advanced NWP, storm surge, hydrological and risk assessment models. The proposed FDP-BOBTEX is within a framework of the functioning of a specialized forecast centre to implement new research and technology strategies. Studies would also include societal impacts and socio-economic benefit aspects. However, scientific communication between different experts may be encouraged so that the benefit of the expected improved skills could be fully used for societal benefits.
- Improvement in prediction with regard to the intensity of the cyclone at landfall in terms of expected radius or swath of the high speed winds.
- Amount and region of high intensity rainfall 24-hr prior to and 24-hrs after the landfall of a cyclone. This is required as with the collapse of an intense tropical cyclone after the landfall, deep convection and cyclone eye wall weakens in bursts which are accompanied with short-time very intense rainfall. The information would be useful in rescue work, disaster management work and impact assessment.

There is inadequate information on the above aspects in India and the FDP-BOBTEX would provide key elements in planning disaster-related management strategies by the Central and State Governments as well as district levels authorities.

For the FDP-BOBTEX priority one would be to fulfill the first objective as the second objective follows from it**.**

6. Requirements for the FDP-BOBTEX

The following key requirements are necessary and are to be met prior to the implementation of the high intensity campaign, proposed to be launched in Oct.-Nov., 2012.

6.1 Observational System

India has undertaken an ambitious plan to modernize their atmospheric-ocean Observation System in the 11th Five Year Plan (2007-2012). The present distribution of observational network over India and north Indian Ocean as on 1st January 2011 are shown in Appendix I. In order that the modernized observational system may provide full impact on the prediction of TCs of the Bay of Bengal, the following requirements ought to be met with:

- Setting up of two clusters of surface meso-meteorological networks - one along the coast of Orissa - West Bengal and the other around the coast of Andhra Pradesh. Already efforts are going on to install two meso networks under India's STORM and PRWONAM programs which are being carried out through the support of the Ministry of earth science (MoES), previously by Department of science and Technology (DST) and the Department of Space (DoS) respectively. The networks are expected to provide Automatic Weather Station (AWS) at 20 kmx20km resolution. Ministry of Earth Sciences (MoES), India is supplementing the two networks to obtain even finer resolution.

- MOES is also involved in strengthening of the deep ocean and coastal met-ocean buoys. Priority may be given to put a network of buoy at 2^0x2^0 spacing in the Bay of Bengal by 2009 (Prior to the Second Pilot Experiment.) As thermal structure of the upper ocean could influence TC genesis (Ali et al 2007), it would be highly desirable that the existing XBT lines between Kolkata-Port Blair and Chennai-Port Blair, being carried out by National Institute of Oceanography (NIO), India under MoES sponsorship be not only maintained but their frequency increased .
- Currently there are 5 radiosonde wind finding stations along the east coast of India (Kolkata, Bhubaneswar, Visakhapatnam, Masulipatnam and Chennai) and one station at Port Blair in the Andaman islands. One station at Car Nicobar is urgently needed and is under active consideration of the Indian Navy. Also three additional stations could be established by IMD - one each between Bhubaneswar and Visakhapatnam, Hyderabad and Visakhapatnam and Bangalore and Chennai. These three additional stations would enhance the utility of surface meso-network.
- There is a wind profiler at Tirupati near Chennai and a profiler is planned to be installed at SHAR centre to the north of Chennai. It would be very useful if wind profilers are installed at Visakhapatnam and Bhubaneswar and an additional mobile wind profiler is acquired to be located at the desired site during the pilot and field campaign of 2011 and 2012 respectively.
- At present five S-band Doppler radars are functional along the Indian east coast (Kolkata, Visakhapatnam, Masulipatnam, Sriharikota, and Chennai). It is required that a similar radar need to be installed at Bhubaneswar (Paradip) by April 2009. All these Dopplar radars be fully integrated by July 2009 and their scanning strategies fine-tuned so that their data could be fully used for assimilation in the high resolution meso-scale prediction models. Acquisition of one mobile radar by IMD, to be placed at an appropriate site, would be highly useful to add to radar coverage for the TCs on landfall.

- The GPS equipment for measuring water vapor content has been installed at Chennai, Kolkata and Guwahati. It should be extended to Bhubaneswar and Visakhapatnam to get over optimum network. An optimum network of lightning detectors be installed along the east coast of India and at nearby inland stations by July 2009.
- Under the Indo-French collaboration, MEGHA-TROPIQUE satellite, with capability of repeated scanning over the Bay Bengal region, has been launched recently in October, 2011. India has plans to launch INSAT-3D with multi spectral sounders and water vapor channel in 2012. . These two satellites would provide wealth of data which have bearing on the implementation of FDP-BOBTEX.
- The earth receiving stations for METOP and MODIS satellite data have been installed in Chennai, Guwahati and New Delhi in 2010. They are providing a lot of data and products useful for cyclone monitoring and prediction. However steps should be taken for assimilation of these additional data especially vertical profile of temperature and moisture in the NWP models.
- The Ocean Sat-II has been launched in 2009 and the data are available since the Phyan cyclone over the Arabian sea in November 2009. It is very useful in the absence of QuikScat for monitoring Ocean surface wind. However these data should be assimilated in the NWP models.

With the above mentioned and other possible observational platforms, the Bay of Bengal could be monitored well for tropical cyclone prediction. However the important gap over the Bay of Bengal for the FDP-BOBTEX could be filled only by pressing into service highly instrumented aircraft reconnaissance facility of NOAA and NCAR of USA, two Indian research ships with GPS –based upper wind, temperature and humidity sensing systems and at least one research aircraft from India fitted with drop-sonde system and other instruments.

6.2 Field Phase Operations Centre

Modern field campaigns for special process-oriented studies depend on the support of field scientists and also several infrastructural facilities such as access to predictions from global prediction models as well as on site running of high resolution meso-scale models. This is quite possible with the developments in India. Chennai, which lies in the southeast coast of India, provides a good choice for hosting the Field Phase Operation Centre for the Pilot and the Main Field Campaigns. Cyclone Warning Research Centre(CWRC) and the Area Cyclone Warning Centre(ACWC) of the IMD, situated in the same campus, could provide the requisite infrastructures for running the Field Phase Operational Centre. The airport at Chennai is also equipped to carry out any major repairs etc. to aircraft.

6.3 Requirements for Communication Facilities

Field phase operations are also critically dependent on the communication links for the purpose of accessing data from the observational systems, communication with the aircraft, aircraft landing and take off operations, aircraft maintenance facilities etc. To fulfill all these objectives Chennai is more appropriate because this international airport has excellent ATC facilities for take-off, landing and in flight operations as well as is equipped with aircraft maintenance facilities etc. Bay of Bengal is a relatively small basin and any TC forming in the basin can effectively be covered from this airport. Perhaps it would be more suitable if the Field phase Operations Centre is located where the research aircraft are parked. The computational facilities for running meso-scale models are also available Chennai.

Other logistic support required as well requirements of project safety overview could be jointly reviewed in July of the campaign year so as to take appropriate actions.

7. Status of Observational, Theoretical and Modeling Research on Tropical Cyclones in World and India

7.1 Status in the world

Enormous advances have been made in the world with regard to scientific understanding on hurricanes and typhoons and their prediction using a variety of dynamical models and data assimilation. These advances have come primarily through the data provided by aircraft reconnaissance probes. Setting up of the National Hurricane Research Project (NHRP), the National Hurricane Research Centre (NHRC) and the National Hurricane Centre (NHC) at Miami in 1950s, setting up of Joint Typhoon Warning Centre (JTWC) at Guam (Phillipines) in 1960s for aircraft reconnaissance facility for typhoons, establishment of the National Centre for Atmospheric Research (NCAR) at Boulder in 1960s and promotion of research in the Universities have also helped in accelerating research on hurricanes. New observational systems such as aircraft probes, weather radars, and recently hurricane balloons (SMART BALOONS) and introduction of operational satellites and weather research satellites etc. have also contributed to provide vital observations for gaining new scientific insights into the study of TCs.

Aircraft reconnaissance missions into hurricane environment had begun in 1940s by the U.S. Airforce (Sumner, 1943; Simpson 1952; Gentry 1981; Mark and Houze 1987, Houze et al 1992). At different periods new instruments like dropsonde, Doppler Weather radars were added. New types of high performance aircrafts were added into the reconnaissance fleet in 1970s. NOAA P-3 aircraft have completed 30 years of service in 2006. As a result of such observations and modeling, hurricane track prediction errors have decreased since 1980s (Burpee et al, 1994)

Detailed structural features about hurricanes were brought out between 1950s and 1980s as a result of aircraft probes through reconnaissance of hurricanes. Research is continued till the present time as a result of regular data collected in aircraft reconnaissance missions in North Atlantic and western North Pacific (Simpson 1952, Simpson and Street 1955, Malkus1958, Malkus & Reihl 1960, Reihl & Malkus 1961, La Seur and Hawkins 1963, Shapiro 1992, Hawkins and Rubsam 1968, Jorgensen 1984 a, b, Mark & Houze 1987, Willoughby 1978, 1990, Willoughby et al 1982 and many others). During 1960s to 1980s Gray and his collaborators provided a global view of TCs in respect of different aspects of developing and non-developing systems and composite structure of hurricane vortices etc. (Gray 1968, 1979, Shea & Gray 1973, Frank 1977, Mcbride and Zehr 1981 and several other papers by the group). Studies have continued in 1980-1990s (Emanuel 1999, Holland 1983, 1984, 1997, Bosart et al 2000) which have laid sound observational foundations about the formation, intensification, structure, dynamics and movement of TCs. Complex interactions of cyclones with their environments especially in respect of interactions of vertical shear-mean flow, injection of dry air into storm's environment etc. have been highlighted in recent studies of Black & Willoughby (1992), Elseberry and Jeffries (1996), Valden and Leslie 1997, Peng et al (1999), Frank & Ritche (2001), Rogers et al (2003), and Chen et al (2006) and others. Many studies using weather satellite data in 1970s to 1990s also added to substantial knowledge on TCs. Recently, the National Science Foundation (NSF), NCAR, NOAA and its other laboratories and research divisions, National Environmental Satellite Data and Information Service, the University of Washington and the University of Miami joined in a collaborative effort in August-September 2005 to undertake an intensive field campaign, called the Hurricane Rainband and Intensity Change Experiment (RAINEX). The primary objective of the RAINEX was to understand the storm's intensity derived from the eye, eye wall and rain bands interactions. RAINEX used three P3 aircraft with Doppler radar measurements, intensive airborne dropsonde coverage and high resolution meso-scale models

(Houze et al 2006). Three hurricanes, namely, Katrina, Rita and Ophelia of the 2005 hurricane season were probed and RAINEX obtained excellent data in these historic hurricanes. The flight missions targeted the eyewall structure and hundreds of dropsonde were released by three RAINEX P-3 aircraft and one NOAA G IV aircraft besides flights undertaken by the aircraft of US Air force Weather Reconnaissance Wing. Other island nations on the rim of the Caribbean Sea also cooperated in the campaign by providing their data. Innovative system of data transfer between the RAINEX Operation Centre at the ground and aircraft was employed. A mini ensemble forecast product set was provided in real time during the RAINEX with an inner domain modeling resolution of 1.67km. RAINEX data set are expected to provide a new basis for a wide range of hurricane observational studies over the next several years.

7.1.1 Aircraft Reconnaissance

The TCs have been observed by aircraft since the first flight piloted by United States Army Air Force Lt. Col. Joseph P. Duckworth on 17 July, 1943 (Sumner, 1943). The United States military conducted the first dedicated research flight into a TC (Wexler, 1945; Wood, 1945), and a subsequent flight examined the upper troposphere of a 1947 Atlantic TC (Simpson, 1954). Regular aircraft reconnaissance of the tropics by the United States military to investigate whether TCs were developing, and their locations and intensities, soon began in both the Atlantic and Western Pacific basins. With the advent of satellite data, the importance of the airborne search for developing TCs decreased, and methods to locate and estimate the intensities of TCs were derived (Dvorak, 1975; Velden *et al.,* 1998; Velden *et al.,* 2006; Olander and Velden, 2007). However, the remotely sensed satellite location and intensity data remain less accurate than in situ aircraft measurements.

In addition to operational uses, aircraft have a long history in TC research. After the disastrous Atlantic hurricane season of 1954, the United States Weather Bureau created the National Hurricane Research Project (NHRP) to advance TC science and improve forecasts. NHRP soon pioneered quantitative observations with instrumented aircraft that shaped the modern understanding of TCs (Dorst, 2007).

The. following is a discussion of the operational reconnaissance, surveillance and research aircraft that have participated in TC field programs since 1997 and the instrumentation available on them. It is aimed to summarize the types of observations available and their uses for research and operations, with broad information available in the references.

7.1.1.a NOAA P-3s

In the mid-1970s, the United States National Oceanic and Atmospheric Administration(NOAA) purchased two WP-3D (P-3) aircraft, modified United States Navy maritime reconnaissance aircraft that are versions of the civilian Lockheed Electra (Aberson *et al., 2006).* Proposed uses of the aircraft were observations of TC structure and dynamics, participation in TC modification experiments, and monitoring of TC formation, all with the goal of improving the TC forecast and warning process to limit damage and loss of life. Since then, the NOAA Aircraft Operations Center has maintained the P-3s to be among the premier meteorological research aircraft in the world.

When the P-3s were procured, only basics of TC structure were known (Shea and Gray, 1973). The hurricane was considered to be an approximately circular, axisymmetric vortex with nearly constant wind speeds extending to at least 400 hPa, and with deviations from axisymmetry considered to be gusts or largely due to vortex motion. The eyewall was thought to be vertically aligned up to 5-10 km above the surface, and funnel-shaped above. The eye was observed to have warm, moist air below an inversion, with clear, dry air above and ice clouds streaming inward near the top. Both the eyewall and rainbands were understood to have convergent airflow in low levels and outflow above. Rainbands were seen to move inward toward the eye and to cause intensification of eyewall convection. Numerical modeling of TCs was limited to idealized 2-dimensional studies due to a lack of adequate computer power and observations of the dynamic and thermodynamic fields in three dimensions, and only primitive techniques to assimilate the data into model initial conditions (Simpson and Riehl, 1981).

Partially as a result of observations from the P-3s, the description and understanding of TC behavior and structure were revolutionized. The NOAA P-3s have conducted missions into nearly 150 TCs in the Atlantic and Eastern Pacific Oceans and near Australia. Data were obtained on the micro- to the synoptic scale, and data analyses have led to many new insights about TC structure, dynamics, thermodynamics, and environmental interactions (Aberson *et at., 2006).*

Sophisticated instrumentation installed on and developed for the P-3s is unique among meteorological airborne platforms (see Jorgensen, 1984 for details of the original instrument installation). At the time of delivery, both P-3s measured flight-level temperature, pressure, and moisture and had a state-of-the-art inertial navigation system allowing for flight level wind vector calculations with 0.l-0.3 ms-1 accuracy; these data are transmitted in real-time at a rate of up to 0.1 Hz, and are available in research mode at 1 Hz. As electronic equipment and expendable probes became more accurate, smaller, faster and lighter, new instrumentation enhanced the potential to gather comprehensive TC research data sets. For example, P-3 instruments now include the airborne infrared radiation thermometer for remotely determining flight-level temperature in clear air (Barnes *et at.,* 1991; Eastin *et al.,* 2002), a stepped frequency microwave radiometer (SFMR) for estimating surface wind speed (Uhlhorn and Black, 2003), and Global Positioning System (GPS) navigation. Omega dropwindsondes (ODWs-Govind, 1975) were first used in. hurricane research in 1982 to provide wind and thermodynamic profiles, but did not report in cloudy regions nor provide wind measurements in the boundary layer. The GPS dropwindsonde (Hock and Franklin, 1999), first used in 1996, provided reliable wind and thermodynamic profiles in the TC eye wall and down to the surface for the first time, thus revolutionizing understanding of structures in the eyewall and boundary layer. Each aircraft also carries a workstation for airborne radar and dropwindsonde processing (Griffin *et al., 1992).*

Among the most advanced meteorological equipment on the P-3s are three digital radars. Two record the reflectivity signal: a 5.5-cm (C-band) wavelength (lower fuselage) radar extends below the fuselage and measures the horizontal distribution at all azimuth angles; a 3-cm (X-band) wavelength radar is in the tail (TA) and determines the reflectivity distribution along rays oriented either perpendicular to the aircraft track or at angles fore and aft within 25° of the aircraft heading (Marks, 1985). A third radar with a 5.2 cm (C-band) wavelength is in the nose and scans horizontally back and forth looking forward; the pilots use it to avoid turbulent weather, and the data have not been recorded since 1987. Important additions to the radar systems first occurred in 1980 when a prototype Doppler signal processing system was added to the TA radar on one P-3 (Jorgensen *et al., 1983)* and again in 1988-1989 when refined radar data systems were installed on both aircraft (Marks, 2003). In 2006, an automated quality control and analysis system was applied to the TA radar data, and three-dimensional wind and reflectivity analyses are transmitted in near- real time for use by operational forecasters and for testing data assimilation schemes in high-resolution regional hurricane model systems (Gamache *et al.,* 1997; Gamache, 2005).

The P-3s are also equipped with Particle Measuring System probes (a Forward Scattering Spectrometer Probe and 2-Dimensional Optical Array Probes) mounted on the wing tips to distinguish between water and ice particles and estimate their sizes (Knollenberg, 1970; Black and Hallett, 1986; Gayet *et al.,* 1993; Baumgardner and Korolev, 1997). Starting in 2008, one P-3 has a full complement of particle imaging and non-imaging probes manufactured by Droplet Measurement Technologies (DMT). These probes include the Cloud Combination Probe, imaging particles from 0.025 mm-1.6 mm in diameter and (using forward scattering methods) measuring the diameters and number concentrations of cloud droplets in the range 0.003mm-0.050 mm. The DMT Precipitation Imaging probe images particles in the diameter range 0.100 mm-6.4 mm. The DMT Cloud Aerosol Spectrometer is a non-imaging probe that measure: particles from 0.00061 mm-0.005 mm (forward scattering) and 0.001-0.I mm (backward scattering). These probes offer the capability to measure the size distribution and number concentrations of cloud particles over three decades of diameters with unparalleled accuracy. In addition, five field mills will allow for measurement of the three dimensional electric field vector. This combination of instruments will provide unprecedented observations of the role of water and ice microphysics and electrification on TC convection and structure.

In addition to obtaining atmospheric data, the P-3s have the ability to collect upper ocean observations. Each aircraft has 24 chutes in its fuselage for external ejection of airborne expendable bathythermographs (Boyd,1987; Boyd and Linzell, 1993), current profilers (Sanford, 1971), and conductivity temperature depth profilers to measure ocean temperature, current, and salinity to a depth up to 300 m. A Scanning Radar Altimeter (SRA) measures surface directional wave spectra and rain rate, and transmits these data to operational forecasters in near real-time (Walsh *et al., 2002;* Wright *et al.,* 2001). These provide important data at and near the ocean-atmosphere interface where the TC derives its energy, allowing for greater understanding and modeling of air-sea interaction processes. All these instruments make the two P-3s the most advanced and comprehensive of all meteorological aircraft currently in use.

7.1.1.b NOAA G-IV

In 1982, TC numerical modeling was in its infancy, and the most accurate track guidance available to forecasters was statistical. NOAA began to test the hypothesis that additional vertical wind and thermodynamic profiles in the TC environment (the "synoptic flow") would improve analyses and numerical model forecasts that provide operational guidance to human forecasters. The data obtained during P-3 research missions through 1996 helped to reduce errors in TC track forecasts from global and regional dynamical models significantly (Burpee *et al.,* *1996).*

The success of this research program led to the development of a new generation of dropwindsonde (Hock and Franklin, 1999) and the acquisition of a high-altitude jet aircraft, the Gulfstream-IV-SP (G-IV) as an operational platform for conducting synoptic surveillance missions. These operational flights, along with concurrent research into optimal targeting and sampling strategies and data assimilation, continue to improve National Centers for Environmental Prediction (NCEP) operational global model track forecasts significantly (Aberson, 2003). A complete G-IV flight and the required dropwindsondes cost about $40,000, far less than the estimated average of $1 million needed to evacuate just six miles of coastline for landfall (Aberson *et al., 2006).*

Because of limited flight time and dropwindsondes, optimal sampling strategies must be found. Aberson (2003) found that the most rapidly growing modes in the NCEP global model can be represented by regions of relatively large spread in the ensemble forecasting system 850-200 hPa mean wind. In testing the efficacy of this sampling strategy, the important question is whether the removal of at least one-third of the dropwindsonde data that are in non-target regions has no negative impact on subsequent forecasts. More specifically, the question is whether targeting techniques define regions where mobile platforms such as aircraft should concentrate observations and other regions in which observations will have little or no impact on subsequent forecasts. When entire regions of large ensemble spread are sampled by regularly spaced observations, a statistically significant improvement to forecast tracks above that from assimilating far more data obtained symmetrically about the storm results.

Majumdar *et al.* (2006) and Reynolds *et al.* (2006) compared this and other techniques during the 2004 hurricane season. They concluded that singular vector targets were often located within an annulus around 500 km from the storm center, and/or at long distances from the storm in locations associated with features such as mid-latitude troughs. The targets suggested by the Ensemble Transform,. Kalman Filter were localized around the storm in either upstream or downstream locations where wind or temperature errors were correlated with those near the verification region. Evaluation of these techniques with observing system experiments using data from operational missions is ongoing.

In addition to synoptic surveillance, by 2008, a TA Doppler radar and SFMR are available on the G-IV to complement those instruments on the P-3s. The radar measures reflectivity and three-dimensional wind field similar to the P-3 TA radars, but from a much higher altitude. This may allow for three-dimensional wind measurements in the TC cirrus outflow. The SFMR measures surface wind speed and rain rate .below the aircraft in a similar manner to the instruments available on the P-3 and C-130 aircraft, but at a lower resolution and with a larger footprint due to the aircraft altitude and speed. The G-IV will have the ability to transmit these data to the Global Telecommunications System (GTS) in real time.

7.1.1. c Taiwanese ASTRA SPX

At least partially due to the success of the NOAA G-IV, the Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR) began in 2003 (Wu *et al.,* 2005, 2007b). Data from dropwindsondes released from the ASTRA aircraft have substantially improved track model forecasts *(Wu et al.,* 2007b). However, the average improvement to typhoon track prediction in the Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model was insignificant, likely due to the dropwindsonde signal being swamped by the synthetic vortex data used during the. initialization. As a result, Chou and Wu (2008) devised an alternative technique to combine dropwindsonde and synthetic data in a mesoscale model in order to further boost the effectiveness of dropwindsonde data with the implanted storm vortex.

An additional targeting technique, the Adjoint-Derived Sensitivity Steering Vector (ADSSV), has been devised and .tested during these missions (Wu *et al.,* 2007a). By appropriately defining a response function to represent the deep-layer-mean (850-300 hPa) steering flow around the TC at the verifying time, sensitive locations at the observing time are clearly shown. The ADSSV relates these sensitive areas to the steering flow at the verifying time. The ADSSV direction and magnitude at a given location indicates the change in the steering flow due to a perturbation in the initial conditions at that location and the extent of the sensitivity, respectively. This adjoint sensitivity can be used to identify important regions and dynamical features affecting the TC track and is helpful in defining target regions for surveillance. The ADSSV has been used to design missions for DOTSTAR as well as for Atlantic hurricanes.

7.1.1.d. United States Air Force WC 130-Js

The United States Air Force Reserve 53rd Weather Reconnaissance Squadron operates a fleet of ten Lockheed-Martin C-130-J aircraft that are mostly used for operational hurricane fixing (finding of the center location and storm intensity) in the Atlantic and Eastern and Central Pacific basins when TCs threaten land. Like the NOAA P-3s, these aircraft measure and transmit flight-level wind, pressure, temperature, and moisture data, as well as surface wind speed measurements from SFMR and data from dropwindsondes. As the vast majority of operational flights are conducted by these aircraft, they are the workhorses of aircraft reconnaissance and provide the most fixes yearly to operational centers; the data are also frequently used for research. In addition to these tasks, these aircraft also participate in synoptic surveillance missions to augment coverage from the G-IV, and in research experiments by providing air deployment of large platforms such as buoys and floats necessary for ocean observations (Black *et al.,* 2007).

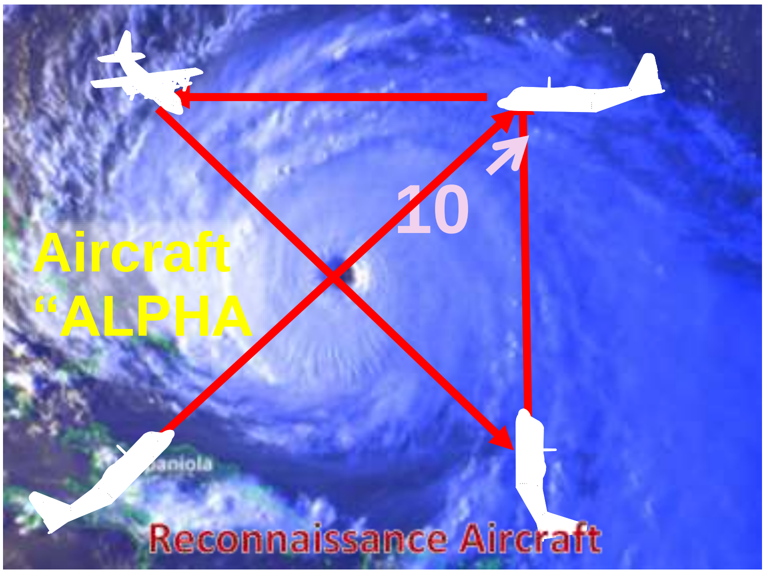
7.1.1.e Naval Research Laboratory P-3

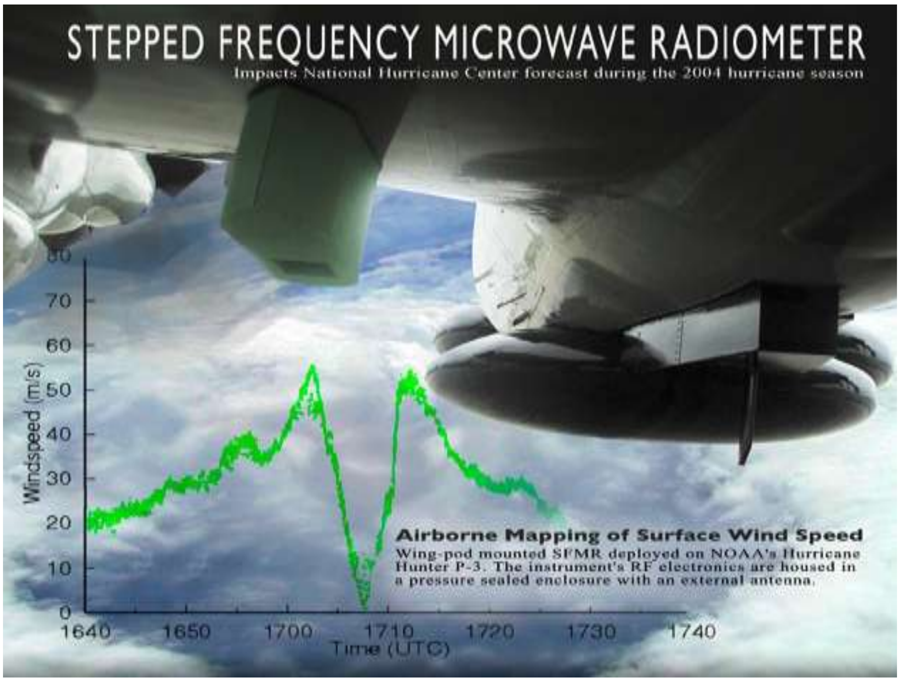
The Naval Research Laboratory (NRL) NP3D "Orion" aircraft is similar in design to the NOAA P-3s, but with a different instrumentation suite. It is maintained and deployed by the NRL Military Support Division and the Scientific Development Squadron-l (VXS-l) "Warlocks" (formerly Flight Support Detachment) for a variety of military and scientific missions. After the decommission of the National Center for Atmospheric Research (NCAR) Electra aircraft in 2001, an agreement between NRL, the National Science Foundation, and NCAR to use this aircraft as the new platform for the Electra Doppler Radar (ELDORA) was reached. An Airborne Vertical Atmospheric Profiling System (AVAPS) system was installed in 2005 to allow for dropwindsonde processing (Hock and Franklin, 1999), augmenting the radar and in situ measurements obtained from the inertial navigation system.

ELDORA is a dual beam, X-band (3.2 cm) meteorological research TA radar developed jointly by NCAR and the Centre de Recherches en Physique de L'Environnement Terrestre et Planetaire (Hildebrand *et al.,* 1994), first deployed in 1993 (Hildebrand *et al.,* 1996). It has two flat-plate, slotted waveguide antennas with oval beam widths of 1.8° x 2.0^0 that spin about the longitudinal axis of the aircraft. The antenna rotodome is a radome that rotates with the antennas. One antenna points slightly fore of the aircraft and the other slightly aft. As the P-3 flies, these two radars trace conical helixes through the atmosphere, providing three-dimensional precipitation and kinematic structure at resolutions finer than 400 m. This is similar to the NOAA TA radars using the Fore/Aft Scanning Technique (F/AST), but with approx. 4 times the spatial resolution due to the dual-transmitters and a higher antenna rotation rate (up to 24 revolutions per minute). Though the high rotation rate improves the along track resolution, it limits the number of independent samples in a radar volume necessary for accurate Doppler radial velocity measurements (i.e., the time for each beam to obtain a significant sample is shorter). The velocity statistics are improved with a complex waveform pulse within which four separate frequency sub pulses are coded, enabling the received signals to be processed individually. A dual pulse repetition frequency technique increases the maximum unambiguous velocity to greater than 60 ms-l while maintaining a 75 km unambiguous range, a highly desirable attribute in high wind regimes (Wakimoto *et al.,* 1996; Wakimoto *et al., 2004).*

The first use of the NRL P-3 for TC observations was in 2005, during the Hurricane Rainband and Intensity Change Experiment (RAINEX-Houze *et al.,* 2006). In cooperation with the three NOAA aircraft, the P-3 investigated hurricane intensity changes associated with eyewall-rainband interactions. Nine missions were flown into Hurricanes Katrina, Ophelia, and Rita, documenting many different stages of the TC life cycle and a variety of rainband configurations. One of the unique aspects of this project was the coordination among the multiple aircraft, including transmitted composite LF radar images from the NOAA P-3s to the NRL P-3 for navigation assistance. The high level of detail in TC precipitation and kinematic structure is a significant observational advancement resulting from the use of ELDORA in RAINEX.

This platform's second deployment to study TCs took place in the summer of 2008 as part of the THORPEX Pacific Area Regional Campaign (T-PARC) and Tropical Cyclone Structure 2008 (TCS-08) field programs. A Doppler wind lidar was added to the instrumentation to provide wind profiles in clear air below the aircraft, and the missions focused on the genesis, structural changes, and extra-tropical transition of TCs, extending the life cycle observed by the NRL P-3 and ELDORA.


10
Aircraft
“ALPHA
Reconnaissance Aircraft


STEPPED FREQUENCY MICROWAVE RADIOMETER
Impacts National Hurricane Center forecast during the 2004 hurricane season
Windspeed (m/s)
0
10
20
30
40
50
60
70
80
1640
1650
1700
1710
1720
1730
1740
Time (UTC)
Airborne Mapping of Surface Wind Speed
Wing-pod mounted SFMR deployed on NOAA's Hurricane Hunter P-3. The instrument's RF electronics are housed in a pressure sealed enclosure with an external antenna.

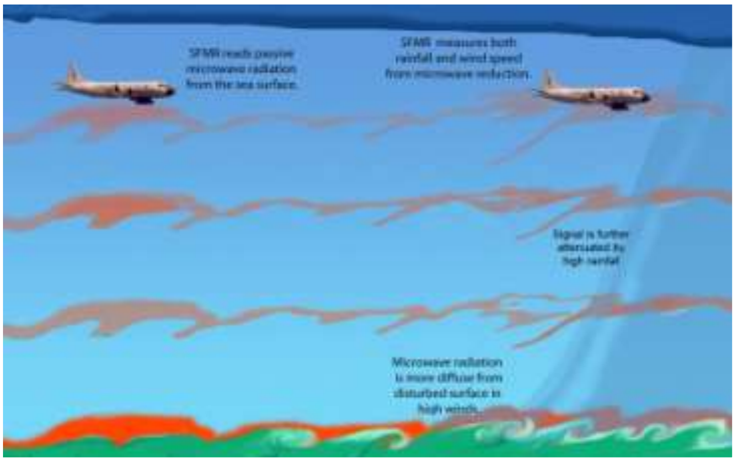

SFMR reads passive microwave radiation from the sea surface.
SFMR measures both rainfall and wind speed from microwave reduction.
Signal is further attenuated by high rainfall
Microwave radiation is more diffuse from disturbed surface in high winds.

Fig. 13. Aircraft used for TC Probing. (a) NOAA P-3 (top) and (b) G-IV (bottom), (c) AF C-130, (d) NRL P-3, (e) NASA DC-8, (f) Aerosonde, (g) DLR Falcon, (h) Canadian Convair, (i) NASA ER-2, and (j) Taiwanese ASTRA.

7.1.1.f. NASA DC-8 and ER-2

For more than a decade, the National Aeronautics and Space Administration (NASA) Science Mission Directorate (SMD) has utilized high-altitude research aircraft to conduct scientific investigations of TC genesis, intensity change and landfall impacts. The principal airborne platforms include the McDonald Douglas DC-8 and Lockheed Martin Earth Resources-2 (ER-2).

NASA began flying sorties into TCs in TC, Oliver in January, 1993**,** in the Coral Sea during the Tropical Oceans/Global Atmosphere (TOGA)Program. Since then, NASA has conducted four major hurricane research field programs. These include: the Convection and Moisture Experiments (CAMEX-3 and CAMEX-4) of 1998 and 2001 (Kakar *et at.,* 2006); the Tropical Cloud Systems and Processes experiment

(TCSP) of 2005 (Halverson *et al.,* 2007); and the NASA African Monsoon Multidisciplinary Activities (NAMMA) of 2006. CAMEX was designed to intensively study TC structure and intensity change. TCSP was focused on tropical cyclogenesis, but also sampled the unusually intense, early season Atlantic Hurricanes Dennis and Emily. NAMMA sought to investigate the metamorphosis of African easterly waves into named TCs as they emerged off the coast of western Africa.

The field experiments were jointly planned and implemented in coordination with the NOAA P-3s and G-IV aircraft. The advantages of the combined effort include the complementary nature of scientific objectives contained in both the NASA and NOAA research plans. The main advantage is that the NOAA P-3 aircraft fly low and the NASA aircraft fly high, enabling investigation of the complete TC vertical structure from 70,000 feet down through the oceanic mixed layer. Coordinated surveys involving multiple aircraft require diligent planning, real-time mission monitoring and reliable radio contact to keep as many as five aircraft arranged in a moving, vertical stack. Flights nominally last 6-8 hours with the DC-8 sampling the storm between 30,000-40,000 feet and the ER-2 operating entirely above the storm close to 70,000 feet.

The aircraft payloads consist of a diverse suite of *in situ* and remote sensing instruments varying with each field campaign. They test new technologies. some of which may undergo transition to satellite platforms. From its very high vantage point, the ER-2 can serve as a "virtual satellite" to target observations to the particular scientific objective. The DC-8 spends most of its time within the TC core and is best suited to sample electrical fields, cloud and precipitation particles, and the three-dimensional water vapor structure. Missions may be timed to coincide with one or more NASA satellite overpasses in order to provide crucial calibration/validation information.

Several classes of instruments are common to most missions on the DC-8. Instruments designed to measure the *in situ* temperature, moisture, pressure, and winds comprise the Meteorological Measurement System, and a 4-channel A V APS (Hock and Franklin, 1999) allows for GPS dropwindsonde processing. One or more hygrometers such as the Diode Laser Hygrometer (Heymsfield *et al.,*1998) and Jet Propulsion Laboratory Laser Hygrometer (May, 1998) provide precise measurements of water vapor, with high accuracy at very low ambient humidity. The Lidar Atmospheric Sensing Experiment (Miloshevich *et at.,* 2004) provides high resolution, vertical profiles of water vapor mixing ratio and aerosol scatter. A series of nadir-viewing Doppler radars (Airborne Mapping Radar [Durden *et al.,* 2003]; Precipitation Radar and the Dual-Frequency Airborne Precipitation Radar [APR-2]) provide fine-scale vertical precipitation (reflectivity) structure, particularly within stratiform rain regions, as well as radial wind measurements, and have served as prototypes of instruments flown on the Tropical Rainfall Measurement Mission (Simpson *et at.,* 1988; Kummerow *et al., 1998)* and the planned Global Precipitation Mission (Smith *et at.,* 2002). The DC-8 also typically hosts a suite of cloud microphysics probes; these include the Cloud Particle Imager (Heymsfield and Miloshevich, 2003) to measure ice particle size, Counterflow Virtual Impactor (Twohy*et al.,* 2003) to measure cloud liquid water content, and the Cloud and Aerosol Particle Characterization (McFarquhar and Heymsfield, 1997) system of probes that measures the particle size distribution from *30'Lm* to above 1 mm in 30-m(micro) increments.

Instrument payloads on the ER-2 are geared toward remote sensing and retrieval of atmospheric vertical profiles. The Advanced Microwave Precipitation Radiometer (Spencer *et al.,* 1994) uses a combination of passive microwave frequencies at high spatial and temporal resolution to map instantaneous rain rate. The ER-2 Doppler Radar (Heymsfield *et al.,* 1996) uses both nadir and forward-directed active beams to detect fine-scale precipitation structure and radial motions within convective and stratiform precipitation. Electrical field mill measurements are provided by the Lightning Imaging Package. The High Altitude Monolithic Microwave Integrated Circuit Sounding Radiometer (Lambrigtsen and Riley, 2002) obtains temperature and humidity profiles, liquid water profiles and rain rate. Vertical temperature profiles, tropopause height and high-altitude lapse rate are also retrieved using the Microwave Temperature Profiler (Denning *et al.,* 1989). The Moderate Resolution Imaging Spectro radiometer Airborne Simulator (Roskovensky *et al.,* 2004) provides multispectral visible and infrared cloud top imagery at 50 m horizontal resolution. Recent additions to the ER-2 payload suite include the fully autonomous ER-2 High Altitude Dropsonde and the Cloud Radar System (Li et al*.,* 2004; Halverson et al*.,* 2006) that provides high sensitivity radar reflectivity, Doppler velocity and derived measurements of cloud ice.

Many of these instruments are being specifically adapted for use on the Global Hawk Unmanned Airborne System (UAS) to provide long-duration, high altitude missions during the NASA Hurricane and Severe Storm Sentinel research initiative. The goal is to observe tropical cyclogenesis and intensification from tropical storm to hurricane during an extended time period, operating in surveillance rather than a reconnaissance mode.

7.1.1.g Canadian Convair-580

The first research aircraft mission into a hurricane (Michael) undergoing extra tropical transition was arranged by the Meteorological Service of Canada using the Canadian National Research Council Convair-580 aircraft on 19 October, 2000. A comprehensive description of the aircraft specifications and of experiences during the Michael flight is provided in Wolde *et al.,* (2001). At the time, Michael was near maximum intensity and undergoing rapid transition to an extra tropical storm. Since this was the first time the aircraft was being flown into a storm of that nature, the pilots chose not to fly directly through the storm center which contained vigorous convection, lightning and very strong wind in the lower levels near the boundary layer as measured by dropwindsondes and airborne conventional radar (Abraham *et al.,* 2004). The Convair-580 aircraft was equipped with cloud microphysical probes which collected information on the ice and cloud liquid water concentrations within the storm. Ice water concentrations on the western side of the storm in the stratiform precipitation region were very high, and more characteristic of concentrations seen in the center of continental cumulonimbus clouds. Data from the mission led to improved initialization techniques for numerical models (Fogarty *et al.,* 2007).

Other missions were conducted into Tropical Storms Karen (2001) and Isabel (2003), and Hurricane Juan (2003). The flight in Hurricane Juan south of Nova Scotia provided an unprecedented look at a strong hurricane making landfall in Canada with destructive effects (Fogarty *et al., 2006).*

7.1.1.h DLR Falcon

In 2008, the Falcon 20 aircraft of the Deutsches Zentrum fur Luft-und Raumfahrt (DLR) in Oberpfaffenhofen, Germany was deployed to the West-Pacific for typhoon research as part of T-PARC. The main objectives were targeted observations to improve typhoon forecasts and the investigation of extra-tropical transition of tropical cyclones and downstream impact in the mid-latitudes. In coordination with the NRL P-3, the USAF WC-130 and DOTSTAR unique typhoon observations from genesis through recurvature and extra-tropical transition, with simultaneous observations of the typhoon core and environment and sensitive areas related to the mid latitude flow or the subtropical high often highlighted by singular vector sensitivity calculations, were obtained. Typhoons Sinlaku and Jangmi were observed for 13 and 9 days, respectively. One particular focus of the data analysis will be to evaluate which observational strategies are most effective for typhoon forecasting and observations in which regions have the highest potential for forecast improvements.

Options for instrumentation include dropwindsondes, air chemistry probes, aerosol and particle probes and various lidars. For T-PARC it was configured with a dropwindsonde system, a scanning coherent wind lidar (Weissmann *et at.,* 2005) and a four-wavelength differential absorption lidar for water vapour that includes a high spectral-resolution channel to measure aerosol extinction. The individual observations are volume averages and thus seen as more useful (representative) information for assimilation in numerical models than point observations like dropwindsondes. This was pointed out by Weissmann and Cardinali (2007) using wind lidar observations during the Atlantic THORPEX Regional Campaign (A- TReC) and will be an important subject of future T-PARC research.

One restriction of lidars is that they can not penetrate optically thick clouds; if clouds are at the flight level, the aircraft must reduce its altitude to get observations. Conversely, in clear air, the wind lidar must have sufficient aerosols to determine winds or data gaps occur. The optimal mix of lidar and other observations (i.e., dropwindsondes) therefore requires further research.

7.1.1.i UASs

The interaction between the ocean and the hurricane is important, complex, and not well handled in current observing systems and models. Specifically, the TC depends on the ocean to supply the heat necessary to form and maintain the storm. The detailed process by which a storm obtains heat from the ocean and ultimately converts it into kinetic energy (i.e., strong winds) is complex and not well understood due to the limited availability of detailed observations within the storm near the air-sea interface. To dramatically improve understanding of this rarely observed region, these low-level observations must be obtained. Unmanned aerial systems (UAS) designed to penetrate and sample the violent low-level hurricane environment' can fill this critical data void.

Two groups, a NOAA/NASA team and one based in Taiwan, have used the Aerosonde (Holland *et at.,* 2001) to this end. Aerosonde missions are conducted in completely robotic mode with the aircraft monitored by a ground controller. The Aerosondes used in TC missions have measured temperature, humidity, pressure, and wind speed and direction, but they have the ability to use interchangeable instrument payloads allowing for other measurements. During a mission into hurricane Noel (2007), NOAA/NASA set endurance (17.5 h) and minimum altitude (82m) records for a UAS in a TC environment. During the missions into Typhoon Longwang (2005), four passes through the eyewall were completed, and maximum 10-min (l-min) wind speed of 58.6 ms-1 (62ms-l) were measured (Lin and Lee, 2008). The aircraft is therefore able to complete long missions into severe tropical cyclones globally.

The UAS data obtained during recent missions conducted by the NOAA/NASA team (Ophelia in 2005 and Noel in 2007) have proved to be very useful. In both cases, near-surface observations were reported to the National Hurricane Center in real-time to be used during operational warning. The UAS found the highest wind speeds in both storms despite the presence of manned aircraft at the same time. Analysis of the data from these missions is proceeding, and further missions with various UAS platforms are planned. A major goal is to transmit the data operationally for assimilation into high resolution TC model systems and to greatly expand the amount of data available at the under sampled air-sea interface in the TC core.

Sampling of TC cores is currently performed routinely only in the Atlantic basin, though reconnaissance in the eastern and central Pacific is occasionally tasked. In all other TC-prone ocean basins, in situ information is rarely obtained. Though satellites are certainly capable of some measurements similar to those obtained by aircraft, the ability of satellites to obtain the necessary data both accurately and with the necessary spatial and temporal resolution in all TC basins remains in doubt. Aircraft remain the sole platform by which data can be obtained for operations, and are a testing ground for new instruments that may be put into orbit on future satellite systems, as well as for calibration and validation of current and future satellite observing systems, not only for operational purposes, but to improve TC monitoring for the assessment of climatic changes. These data are also required for the development of high-resolution model systems, especially next generational data assimilation systems, that are necessary to provide accurate forecasts of TC intensity, rainfall and structure.

7.1.2 Theoretical and Modeling Studies:

Observational studies have established that a TC is a complex synoptic scale system (Scale = 1000 km and a few days) of interacting physical and multi-scalar processes in which the genesis of the system is controlled to a large extent by large scale processes interacting with meso-scale cloud formations, associated deep convection and air-sea interactions. Organised convection supplies the energy for maintaining and intensification of the system. The biggest step in theoretical understanding took place with the work of Charney and Eliassen (1964) and Ooyama (1968) who propounded the theory of Conditional Instability of the Second Kind (CISK) in which the co-operative mechanism between the synoptic scale incipient vortex and cumulus convection was shown to play the key role for higher and higher organisation of the synoptic scale disturbance over warm tropical ocean. The positive feedback between intensifying incipient vortex and deep convection leads to the formation of an intense vortex through scale selection process. Although existence of cloud clusters is a common feature over warm tropical oceans, only a few of them would result into an intense tropical cyclone. CISK hypothesis provides quantification of cumulus heating in tropical environment and lays sound physical foundations for the co-operation between the incipient vortex and secondary circulation in-flow (cumulus convection). It is only under special large scale environment that the incipient vortex (low pressure area) over the warm tropical waters would grow into a mature tropical storm. Once the CISK hypothesis was propounded it became quite convenient to test it for simulating TCs using high speed computers. By mid-1960 and 1970s several investigators in USA, Japan and Europe successfully simulated the intensification of an incipient low into a mature steady state cyclone (Kuo 1965, Yamasaki 1968, Rosenthal 1979, Anthes 1977, 1981, Kurihara 1975, Tuleya and Kurihara 1978, Sundquist 1970). The work has continued in 1980s and 1990s by Willoughby et al 1982, Frank and Ritchie 2001, Davis and Bosart 2001, Braun 2002 and others by using more sophisticated models. Yamasaki (1977) was successful in simulating a TC in a non- hydrostatic framework with explicit cumulus scale resolution (without parameterization of cumulus convection). These simulations were performed both in 2 and 3 dimensional frameworks producing realistic tropical cyclone genesis with symmetric as well as asymmetric structures. Sensitivity experiments such as role of SST, landfall etc. also yielded realistic results which agreed with those obtained through earlier observational studies.

Since 1980’s intensive efforts have been directed in USA to develop high resolution meso-scale models which could be used for research and operational purposes. A variety of meso-scale models such as ARPS, MM5, WRF and HWRF etc. have been developed which use the strategy of multi-scale telescopic grids with boundary conditions coming from the global high resolution general circulation models. Meso-scale models are now a days applied in understanding hurricane dynamics (Davis & Bosart 2002, Braun 2002, Yau et al 2004 and others as well as predicting hurricane intensity and movement under operational conditions. As mentioned earlier, RAINEX used such high resolution models to predict storms to support the aircraft probes in the field operations too.

7.1.3 Mesoscale and Data Assimilation and Initialization Techniques:

FGGE-related research made a big advance in using synoptic and asynoptic data to improve model predictions. Several land mark papers were produced in Canada (Daley 1978), France (Talagrand, 1981, Dimet et al, 1986, Talagrand and Courtier, 1987) and USA (Philips 1982), which explained the theoretical and mathematical problems associated with asynoptic data assimilation and initialization for global models. Newtonian nudging, an approach for 4-dimensional data assimilation, was suggested by Seaman et al (1990). Meanwhile assimilation and initialization for regional models were developed by Anthes (1974), Hoke and Anthes (1976), Ramamurthy and Carr (1987), Stauffer and Seaman (1990), Stauffer et al (1991), Wang and Warner (1988), Zou and Ziao (2000) and others and work is still being carried out. These studies established the efficacy of assimilating as much information as possible from available data sources – conventional as well as non-conventional. They were designed to take advantage of availability of high performance computing resources in USA for assimilating meso-scale data and asynoptic non-conventional data. New research findings were used to investigate the potential of various observing systems for data assimilation on different interacting scales. Later researchers used physical initialization procedures (Krishnamurti et al 1997) to adjust the observations at initial time so as to produce model predicted rainfall as close as possible to the observed rainfall at the initial time (rain gauge and satellite rainfall measurements). The Four Dimensional Data Assimilation (FDDA) schemes have come into vogue in variational dynamical framework. Current efforts have succeeded in assimilating satellite radiance data and 4-D variational framework is being operationally used in UK, ECMWF and Japan which produces highly skillful weather forecasts. Thus initialization and data assimilation schemes have passed through different development stages like balanced initialization, normal mode initialization, 3-D Variation Data Assimilation to 4-D Variation Data Assimilation and now cover even assimilation of satellite-observed radiance data. Meso-scale high resolution models such as MM5, WRF, etc use their own specific data assimilation technique to produce optimum results for hydrostatic and non-hydrostatic models (Kato 1997). 4-D variational schemes use adjoint modeling approach to fit the model produced data with the observed data. Specialized schemes for hurricane data assimilation have been introduced (Xie et al 2000, Barker et al 2004). All these far-reaching investigations have contributed to the present day skillful predictions of hurricanes in USA using high resolution meso-scale models. A wide variety of cumulus parameterization, planetary boundary layer and microphysical processes schemes, etc. have been tested to evaluate their performance for the high resolution models which can be tuned to produce the best results.

7.1.4 Recent Improvement in Hurricane and typhoon Track Prediction:

Immense thrust has been given by different investigators to improve hurricane track prediction which has shown positive results in USA as shown in Fig 1. Till 1970s track prediction of hurricanes had shown margnial improvement (Neumann 1981) though a variety of techniques like climatology and persistence (CLIPER), different versions (Flateau et al 1991) of statistical models (Miller et al 1968), barotropic models, baroclinic models and also vertically integrated barotropic model (Sanders & Burpee 1968, De Maria 1985 and Aberson and De Maria 1994 and others). Goeros (2000) and Elsberry and Carr (2000) reviewed status of dynamical models in hurricane track forecasting. Primitive equation models (Mathur 1974, 1991, Kurihara et al 1998, Leslie and Holland 1995) were tested. Schemes for introduction of synthetic vortex in place of the observed vortex were also introduced. All these efforts and use of high resolution models with good observations have reduced track prediction errors for 48-hr and 72-hr substantially (Aberson 2001). Super-ensemble model forecasts have been also suggested by Krishnamurti et al (1997), Zhang and Krishnamurti (1997), Vijay Kumar et al (2003) and others. Even though track predictions in the Atlantic and the Pacific basins have improved considerably but predictions on hurricane-associated rainfall and hurricane intensity still require improvements. The track prediction have primarily improved as a result of assimilation of dropsonde data in the environment of the hurricane and the use of TMI, SSM/I and Quickscat data from US satellites. Hurricane intensity prediction requires understanding of the complex processes taking place in the inner core region of an intensifying hurricane. Focused research with data generated through field programs like RAINEX is likely to produce positive results employing high resolution models.

7.2 Status in India

Sikka (2006) has discussed important advances which have taken place in the last 50 years with regard to understanding the tropical cyclone formation, intensification and movement in the north Indian Ocean as well as in the cases of Atlantic hurricanes and western North Pacific typhoons. Mohapatra et al (2011) have reviewed the characteristics of best track data over north Indian Ocean with respect to observational system, analysis procedure and decision making process. Here we present the most important features of the status of observational, theoretical and modeling studies in the world and India which are relevant to the development of this Science Plan.

7.2.1 Observational network

In IMD, there are 203 departmental surface observatories and out of these, 144 observatories takes 4 or 8 observations communicating daily. The details of departmental surface observatories are shown in Fig.14 and type of synoptic observations and there reporting shown in Table 3

Fig.14 Network of Departmental surface observatories

Table 3: Type of synoptic observations by departmental surface Observatories and their reporting

Type	No	No. of Syn. Obsn. & Reporting
I	144	4 or 8 observations daily Communicating in real-time
II	55	2 observations daily Communicating in real-time
III	Nil	one observations daily Communicating in non-real-time bi-monthly
IV	Nil	0ne-two sets of obsn except Pressure Communicating in non-real-time monthly
V	Nil	Daily-Rainfall observation Communication daily / bi-monthly / weekly
VI	03	Obsn. for specific purpose
FMO	Nil	two rainfall obsn daily Communicating in real-tine
EMO	01	Experimental Met. obsy.

There are 247 non-departmental surface stations, which takes two observations daily and communicate these observations in real time. The observatories, which take rainfall observations only, there are 213 non-departmental stations of type V, which takes daily rainfall observation and communicate them on daily/weekly/ bi-monthly basis.

Fig.15 Network of non Departmental surface observatories

Table 4: Type of synoptic observations by non departmental surface Observatories and their reporting

Type	No	No. of Syn. Obsn. & Reporting
I	-	4 or 8 observations daily Communicating in real-time
II	247	2 observations daily Communicating in real-time
III	02	one observations daily. Communicating in non-real-time bi-monthly
IV	10	0ne-two sets of obsn except Pressure. Communicating in non-real-time monthly
V	213	Daily-Rainfall observation Communication daily / bi-monthly / weekly
VI	04	Obsn. for specific purpose
FMO	363	two rainfall obsn daily Communicating in real-tine
EMO	06	Experimental Met. obsy.

Under FMO, there are 363 non-departmental stations, where two times rainfall observations based at 0300 UTC and 1200 UTC are taken and are communicating daily. The details of non-departmental surface observatories are shown in Fig.16 and type of synoptic observations and there reporting shown in Table 4.

The complete observational network including departmental and non-departmental are shown in given below **Fig.16**

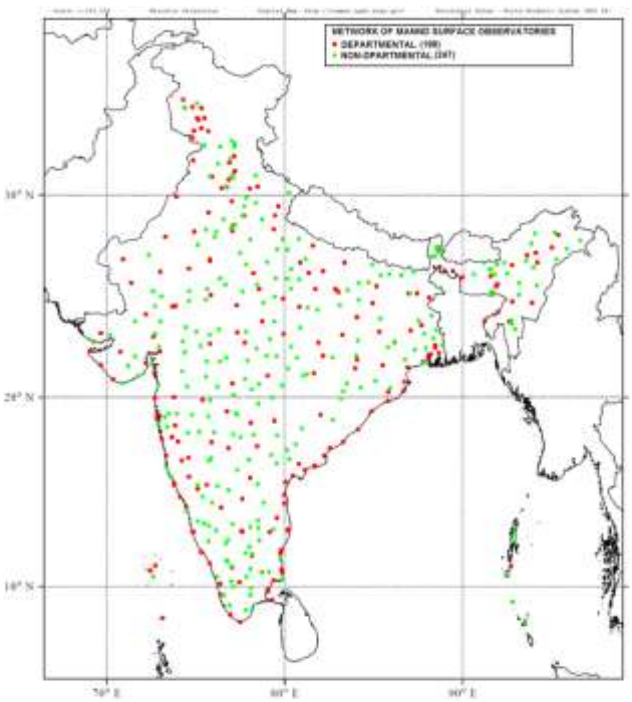


Fig.16 Network of Departmental & non Departmental surface observatories

There is also a good network of AWS uniformly distributed along the west as well as east coast of India, at present the number AWS are 550. The locations of these are shown in the following Fig.17

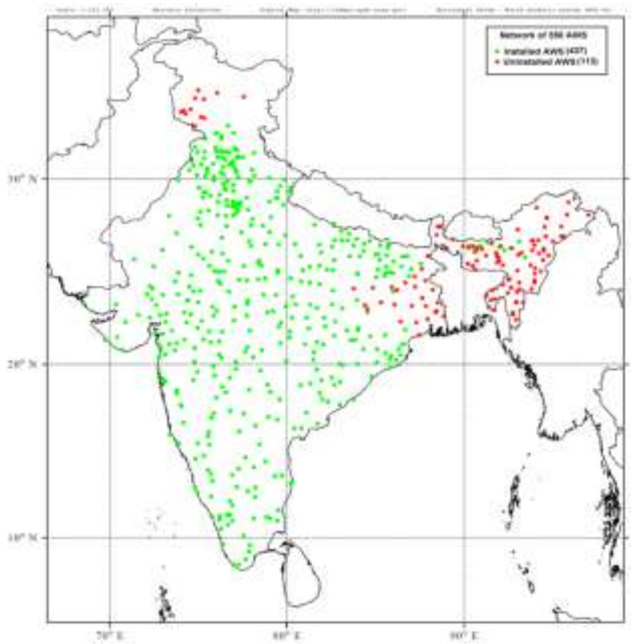


Fig.17 Network of AWS Stations

There is good network of manual as well as automatic observatories, which includes manual departmental, non-departmental and AWS. Details of all the surface network over entire country is shown in Fig 18

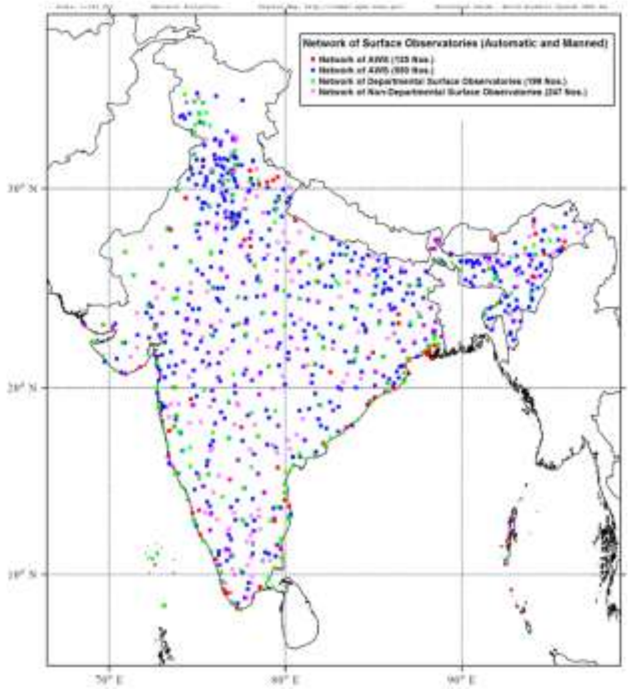
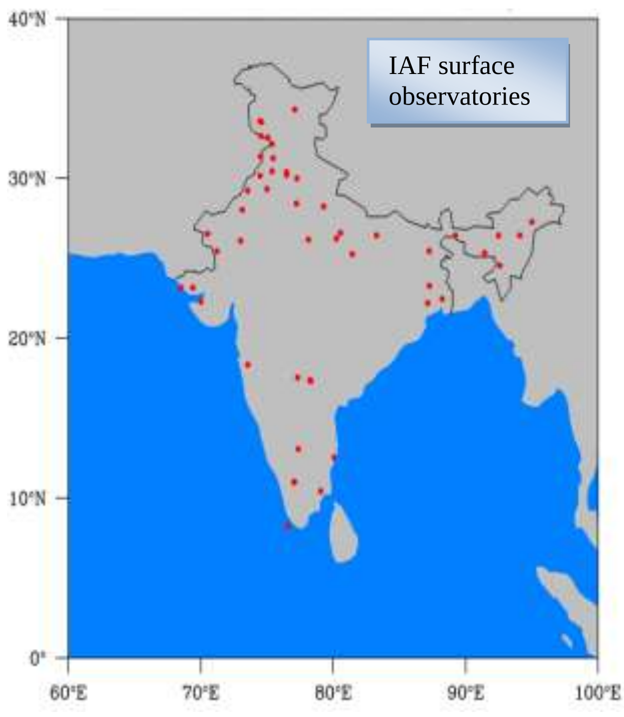


Fig.18 Network of Surface Observatories(Automatic & Manual)

So, the observatories (manual + automatic) networks along the Indian coasts are quite good. In addition, there are 11 high wind speed recorder (HWSR), these HWSR are installed at Digha, Visakhapatnam, Machilipatnam, Nellore, Chennai, Karaikal, Mumbai, Puri, Balasore, Gopalpur and Veraval. As FDP is a multi agency project, so the data of surface and upper air observatories of IAF is also used for cyclone monitoring. IAF has around 50 surface observatories and 18 IAF Pilot networks, the location of IAF surface observatories and Pilot network are shown in following **Fig 19(a) and Fig 19(b)** respectively.

Along with surface and upper air data, satellite based ocean surface wind and imageries are also used to monitor the cyclonic activities. The above product is in use since its inception in 1999. Oceansat-II launched in 2009 provides data since Phyan cyclone in November 2009. The example of the satellite based ocean surface wind is shown in the following **Fig 20** Indian Satellite imageries like IR, Visible and water vapour are also used for monitoring of the system over the sea. in addition, there are products like Cloud Motion Vectors (CMV), Water Vapour Winds (WVW), Outgoing Longwave Radiation (OLR), Quantitative Precipitation Estimates (QPE), Sea Surface Temperature (SST), Upper Tropospheric Humidity and Cloud Top Temperatures, which are derived from satellite data and disseminated through GTS. Along with above satellite based products, there are few network of Buoys over the north Indian Ocean, presently around 12 Buoys are in operational mode over Bay of Bengal and Arabian sea. The network of the Buoys are given in following **Fig 21.**



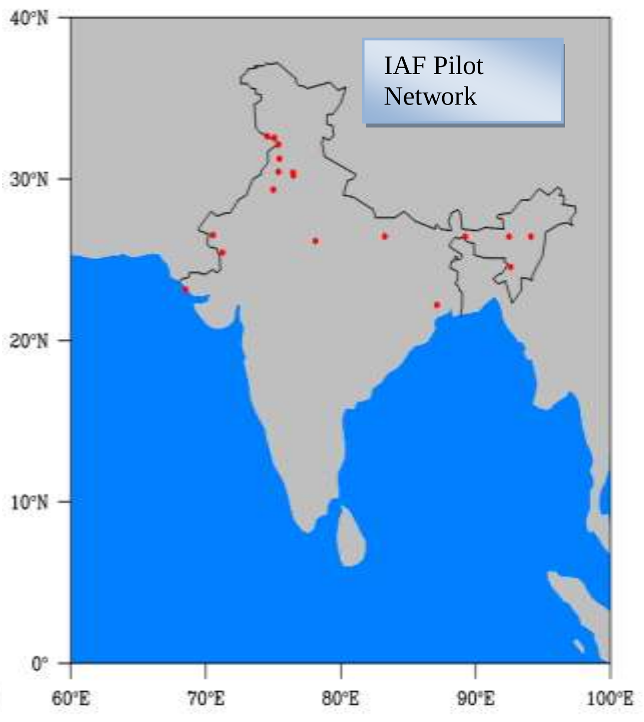


Fig.19 Network of IAF (a)surface observatories (b) Pilot Network

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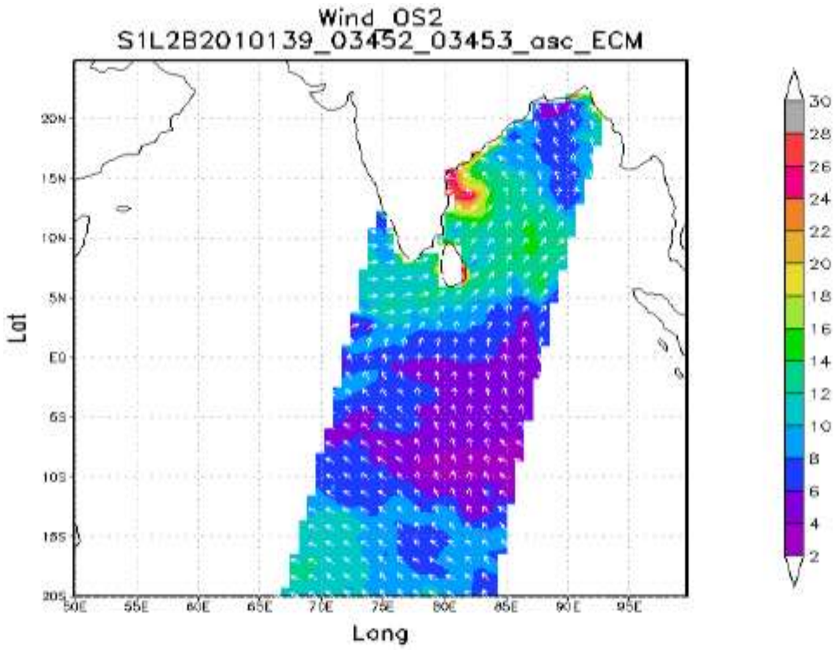

Fig.20 satellite based Ocean surface wind

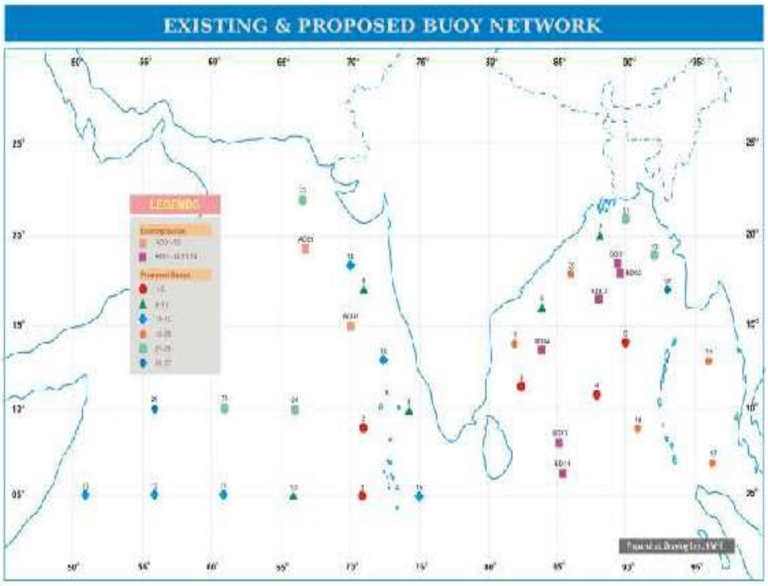

Fig.21 Buoy Network

IMD has 39 RS/RW stations network over the entire country. In 2009, 10 stations upgraded with new GPS based upper air systems. Another GPS system installed at New Delhi in October'2010. At present the network comprised of 11 GPS system,

10 IMS-1500 Radiotheodolites installed in 2002, 18 Ground System of indigenous make installed in 1992-93. Digital GPS radiosonde resulted in better data quality but due to shortage, single ascent is being taken at many stations. The network of the RS/RW stations are shown in **Fig22**…………………

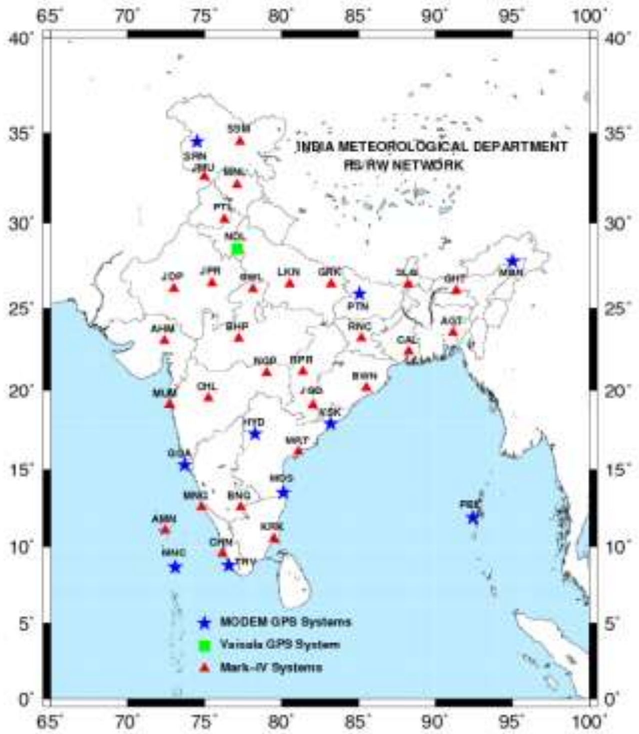

Fig.22 Network of RS/RW Stations

Radar network of IMD includes 11 S- Band and 11 Doppler Weather Radars (DWR). The DWR are installed at Chennai, Kolkata, Machilipatnam, Visakhapatnam, Sriharikota (SHAR), Delhi (Palam), Hyderabad, Nagpur, Agartala, Lucknow and Patna. Presently there are 3 conventional CDRs installed at Ganganagar Jaisalmer and Paradip. IMD has also plans to establish of National Weather Radar Operation Centre (NWROC), which will be responsible for main Centre (NWROC) which will be responsible for maintenance of IMD's radar network, archival and dissemination of data, development of algorithms for new products, network planning and Research and Development. The DWR existing and proposed network is shown in **Fig 23**…………………

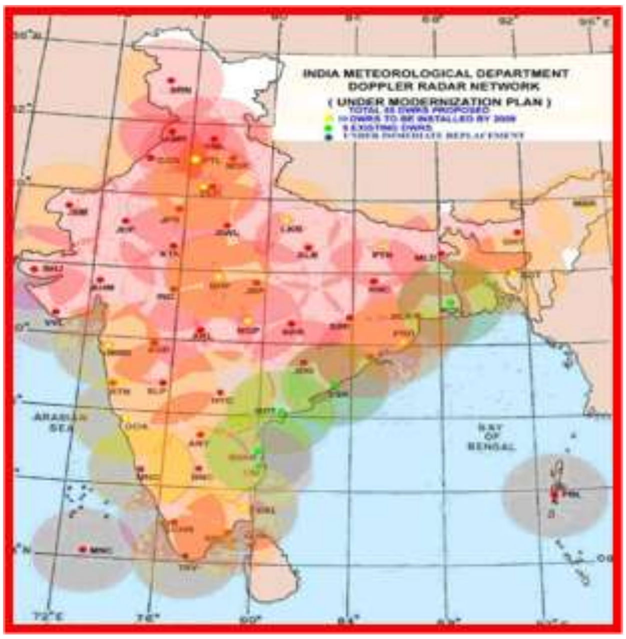

Fig.23 DWR Network

7.2.2 Observational studies

Study of TCs of the North Indian Ocean has remained an important area of meteorological investigations right from the inception of the IMD in 1875. For nearly the first 8 decades of the IMD, meteorological investigations in India were mostly carried out by the scientists working in the operational environment of the IMD as part of their scientific curiosity. Eliot (1900) was among the early pioneers of scientific study of TCs. In those early studies he had recognized role of moisture convergence and latent heat in cyclogenesis. He mentioned “At the early stage of a cyclone formation the air at or near the earth’s surface is drawn towards the centre from all directions and a rotatory motion is set up. The air particles move by a spiral path to hurricane/cyclonic motion”. He also mentioned “Forty times as much water would be condensed as rain as the sun is able to evaporate in the same interval”. Eliot clearly was referring to latent heat of condensation as motive power of TCs.

Within about two decades of India’s freedom, meteorological research began to gain impetus in more organized ways as research organizations like Institute of Tropical Meteorology, Pune and Universities (CUSAT, Andhra University, Banaras Hindu University, IIT Kharagpur, IIT Delhi, Indian Institute of Science, National Institute of Oceanography and other centres) were set-up. The period 1877 to 1970 has witnessed several important studies and the climatology of the cyclones Blanford 1877, Chambers 1882-1885, Normand 1925, 1926, IMD 1964, 1979, Raisircar 1956, Rao & Jayraman 1956, Raghvendra 1973 and others) was built up to cover their genesis, intensification, movement and landfall etc. Also synoptic studies on the evolution of several individual cyclones were undertaken by different investigators who followed the developments in frontal theory of extra-tropical cyclones in the mid-latitudes in Europe between 1930s to 1960s. They tried to involve different air masses even in the cyclone formation process (Desai and Rao 1954, Desai 1967 and others). The publication of the book ‘Tropical Meteorology’ by Riehl (1954) made a big difference as meteorologists in India began to understand tropical weather as a distinct discipline. The contact established between the US scientists working on hurricanes and the Indian meteorologists during 1950s to 1980s made a big difference in advancing research on genesis and movement of tropical cyclones in the North Indian Ocean basin (Koteswaram and Gaspar 1956, Koteswaran and George 1957, Koteswaran 1958, Gangopadhya and Riehl 1959, Anjaneylu et al 1965, Colon et al 1970, Krishnamurti et al 1981, Roy Bhowmik, 2003 and others).

Introduction of weather radars in the Indian Meteorological observational network began in 1950s and investigators have used their data for understanding the structure of several landfalling cyclones on the Indian coasts (De and Sen 1959, Bhattacharya & De 1965, 1976, Raghvan et al 1980, Raghavan & Varadarajan 1981, Raghavan 1990, 1997, Kalsi & Srivastava 2006, and others). The radar studies emphasized the role of pre-cyclone squall lines, spiral bands and rain bands in the inner core region, radar reflectivity patterns with the convective bursts in eye wall region and eyewall structure etc. Asymmetries in such structures have been observed in radar studies. With the introduction of weather satellites, Indian Meteorologists began to use satellite data in their observational studies on the TC (Nedungadi 1962, Sikka 1971, Mishra and Gupta 1976, Kalsi and Jain 1992, Kalsi 1999, 2002, Kelkar 1997, and others). These and other studies have built up a store-house of knowledge on the formation of TCs in the North Indian Ocean, emphasizing the role of SST, synoptic and convective processes in their formation and evolution of structural changes as the intensification of TCs proceeds. North Indian Ocean TCs, like the hurricanes and the typhoons, develop from an incipient low over a period of a few days. Many incipient cloud cluster-scale disturbances and low pressure areas form but only some develop as depressions (sustained wind speed 17 to 33 kt) and only about 50 % of the depressions develop into tropical cyclone intensity(wind speed 34kt or more) systems and only less than 25 % of TCs further intensify in to SCS and VSCS (wind speed over 48 kt or more). Whereas it takes about 2 to 4 days to develop a low pressure area into a depression, the intensification from a depression to VSCS can occur in 24-to 48-hrs. For example, in the case of Orissa Super Cyclone, it took only 24 hrs for intensification to occur from cyclone intensity to VSCS intensity and further rapid intensification to sustained wind speed from 65 kt to over 100 kt occurred in just about 15 hrs or so. Such cases of rapid intensification have occurred in several other cases too, which are accompanied with formation of eyewall, eye and even multiple eyewall structures with the collapse of one eyewall and the formation of another eyewall (Colon et al 1970, Raghavan 1990 and Kalsi 2002). Fig 4 after Kalsi (1999) shows multiple eyewall structures as observed in recent TCs. These structures show close resemblance to those observed in hurricanes in the North Atlantic and North East Pacific basins.

7.2.3 Studies on movement and landfall of cyclones:

A variety of observational data have been used in India till 1960s to forecast the track and landfall of TCs such as patterns of 24-hr pressure changes along coastal stations, approach of a westerly trough in mid-and upper troposphere etc.

Satellite era, since 1960s, added another feature with respect to observations in terms of the direction of major cirrus outflow away from the central region of a cyclone which indicates future direction of its movement. Development of objective techniques for forecasting tracks of TCs in the North Indian Ocean began in 1972 (Sikka and Suryanarayna 1972) by using a computer-based half persistence and half climatology technique and adoption of analogue technique by Datta and Gupta (1975). Sikka (1975) applied non-divergent barotropic model with 500 hPa wind as input and Ramanathan and Bansal (1977) examined the track prediction with a quasi-geostrophic baroclinic model. Singh and Sugi (1986) adopted a multi-level P.E. model for dynamical weather prediction and in recent years Bhaskar Rao (1997), Mohanty & Gupta (1997) and Gupta & Bansal (1997) Mohanty & Mandal (2004) and others have done further work on dynamical prediction of tracks of cyclones. With the regional quasi-Langrangian model in operational use in IMD and the T-80 atmospheric general circulation model in the NCMRWF in 1990s, TC motion is being operationally predicted in India using dynamical models. As the predictions with these models suffer from the inaccuracy of precise location of a cyclone at the initial time by as much as 200 to 300 Km, researchers began to use synthetic vortex (Abraham et al 1995, Kar et al 2003, Singh et al 2005 and others) by replacing the vortex position and structures at the initial time by an idealized vortex based on satellite observations. With this the model errors have reduced. However, data by Prasad et al 1998, Prasad & Rama Rao (2003) and Gupta (2006) show that the statistical vector error for prediction of TCs in the North Indian Ocean basin remains high (24-hr. error of 140 km, 48-hr error of 220 km & 72-hr error of over 300 km), with standard deviation approaching 50-70 percent of the respective vector errors. Recent work by Ali et al (2007 a) using neural network approach also did not show any significant improvement in 48- and 72-hr track forecast.

The challenge for the Indian researchers in the last couple of years has been to reduce the track prediction error and also, if possible, predict the intensity changes in the evolution of TCs. For this purpose several groups in India have applied high resolution meso-scale models of U.S. origin with a variety of physical parameterization in isolation and also in combination. In 2005 an exercise was undertaken to evaluate the performance of meso-scale models on the genesis and movement of Orissa Super Cyclone of 29-30 Oct, 1999. Several papers on simulation on this cyclone were published in the special issue of Mausam (2006). Sikka and Rao (2007) have found a considerable scatter in the track & intensity predictions on this cyclone as the investigators used different initial conditions

(NCMRWF, NCEP, ECMWF), synthetic vortex, parameterization schemes etc. Currently an effort is underway in which high resolution models are being used on 15 to 20 cases by different groups to determine the statistical error in track & intensity predictions. However, it is worth stressing that this exercise would not have any aircraft reconnaissance data to improve the environmental flow which is so crucial (as found by US investigators) for improving the track predictions.

Accurate track and landfall predictions are so crucial for saving life and property on and near the coastal belts as well as in triggering strategies for evacuation of cyclone-threatened coastal population. It is considered very important to acquire weather reconnaissance aircraft facility to provide information on environmental winds and thermo dynamical structures in the inner core region of TCs. The FDP- BOBTEX is an attempt in this direction to determine the possible improvements in track and land fall predictions by using aircraft data. The data provided in FDP-BOBTEX would also help in validating the Dvorak (1984) technique for application of satellite observations for determining the intensity stage of cyclones in the North Indian Ocean basin.

7.2.4 Storm surge forecasting:

The VSCS that had struck Bangladesh in 1970, resulting in loss of over 3,00,000 human lives through huge storm surge, posed a challenge for predicting storm-surges in the North Indian Ocean basin. The lead on research in this area was taken in IMD by Das (1972). The work has been followed intensively since then by several investigators (Das et al 1974, Ghosh 1977, Das 1994, Dube et al , 1994, Rao et al 1997, and others).

Storm surge models are now routinely used in India under operational conditions but their response depends on the precise predictions about the intensity and landfall position of a cyclone and the availability of high resolution coastal bathymetry. The expected improvement in these parameters, through FDP-BOBTEX, would enhance the performance of storm surge prediction and result in safety of property and life. This would be the most important gain from FDP-BOBTEX. Also the planning of FDP-BOBTEX would promote scientific investigations in developing models for vulnerability of coastal and inland regions to inundations through storm surges, flooding under heavy rainfall bursts and interactions between storm surge-coastal streams flooding.

7.3 Climatological Environment of Bay of Bengal Tropical Cyclones and Hurricanes in North Atlantic

That a tropical cyclone structure may broadly agree in the North Indian Ocean and North Atlantic Ocean was found in the study by Colon et al (1970) with respect to the Arabian Sea and Atlantic systems and other studies based on satellite and radar data. However, there could be subtle differences in their genesis and even perhaps structures as the climatological atmospheric and oceanic conditions differ over North Indian Ocean from those over North Atlantic. Differences in climatological features in the two basins manifest as follows:

- The Bay of Bengal is a vast warm pool adjoining the warm pool of the western North Pacific. Several of the precursors of the Bay of Bengal cyclones emerge from the neighboring Pacific basin as remnant of typhoons and re-intensify over the Bay after passing over rather narrow strip of SE Asian countries. The Atlantic hurricanes are born out of the easterly waves coming out of West Africa.
- Bay of Bengal TCs form in the monsoon trough with low-level equatorial (or monsoon) westerlies to their south. Prior to the genesis of a Bay of Bengal cyclone, the westerlies show strengthening. This strengthening may occur under the eastward passing Madden-Julian Oscillation in which the envelope of large scale organized convection is moving eastward as a super cluster (2000 km or more) but the intensifying meso-scale cloud cluster (200-500 km) moves westward. The convection on the super cluster scale, under large scale strengthening westerly flow, and meso-scale convection, though still unexplained processes, leads to meso-scale organsation of convection and mergers of meso-scale clusters to result in the genesis of a cyclone. Venkatesh (2006) has shown meso-scale merger of vortices takes place in the Bay of Bengal just like observed by Simpson et al 1997, Ritchie & Holland 1999 in the Western Pacific basin. On the contrary hurricanes of the Atlantic basin form in the ITCZ region of North Atlantic through processes involving interactions of the easterly waves with the large scale flow. The upper tropospheric environment over the south and central Bay of Bengal is dominated by strong tropical easterly flow in the southern Bay and strong sub-tropical westerly flow north of 18° N. The sub-tropical westerlies are channelized by the Himalayan massif north of 27° N, in the large scale environment of the Bay of Bengal TCs. On the other hand Atlantic hurricanes are generated in weak easterly flow in the upper troposphere coming out of West Africa but strong sub-tropical westerly flow existing to north of 20°N. Bay of Bengal is a narrow basin and an intensifying TC takes only 3-4 days to cover it

before land fall. Tropical North Atlantic is a much larger basin and TCs continue to strengthen into high intensity hurricanes as they enter the Gulf of Mexico after several days of travel in the ITCZ of North Atlantic. The ocean currents in the Bay of Bengal are quite complex and in the post-monsoon season low salinity warm waters begin to cover the eastern coastal waters from October to December through the East India Coastal Current. Also satellite altimetry data (Ali et al 2007 b) have shown complex eddy structures in the Bay of Bengal which may have an impact on TC genesis. Waters off the east coast of (near Florida) , are controlled by the warm Gulf stream and as such some hurricanes continue to track along the east coast of USA well into the mid-latitudes after recurvature.

The above similarities and differences in the two large scale environments also provide important scientific challenges and motivations for undertaking detailed studies on Bay of Bengal TCs under FDP-BOBTEX and compare results with the extensive studies already available in the Atlantic and Pacific Oceans.

8. Critical Scientific Issues in respect of Bay of Bengal Tropical Cyclones and approaches to tackle them through FDP-BOBTEX.

8.1 Critical Scientific Issues

Intense landfalling TCs, forming over the Bay of Bengal in post-monsoon season, with radar and satellite studies display structures such as eye, annular eye, wall convection and at time multiple eye wall structures under intense conditions. Eye wall convection, during its collapse process at landfall may produce cores of localized phenomenal rainfall with high gustiness over very short duration (3 to 30 seconds) in which the wind strength may even reach more than twice the sustained wind speed. Such features can be detected, if the observational systems near the landfall region have multiple Doppler radars, automatic high intensity wind measuring devices and rain gauges. US hurricane researchers have launched special process-studies initiatives during 2005 (RAINEX) through intensive multi-aircraft operations to understand the complex dynamical processes which operate through the life cycle of TCs. They have used refined measurement techniques that provide improved real-time monitoring of environment, structure and intensity of developing TCs. Similar experiments have been carried out over northwest Pacific Ocean also. No such studies could be carried out in the Indian region for want of such precise measurements using aircraft to improve understanding of the physical processes which could be important in intensity changes in TCs of the Indian basin at all stages of their life cycle.

Indian researchers have adopted so called ‘synthetic vortex’ technique to improve the representations of cyclones in dynamical-numerical models. However, the empirical constants needed for the purpose have not been validated under the environment of the Bay of Bengal. Also advanced data assimilation techniques have yet to be perfected for the Indian region; both for the early (incipient) stage of cyclogenesis to the highly intense stage. Even meso-scale oceanic eddies/coastal current variability may have crucial role in TC intensification and movement; particularly in these cyclones which mature close to the Indian coasts. Such observations are needed to assess the value of these features on observed and modeled intensity and structural changes of cyclones.

There is a great need for studying the ‘eye wall’ convection region and eye-region subsidence as positive feedback are likely to operate between the two regions. Inward (radial) moisture convergence with transport of angular momentum, followed by spin-up of the tangential winds, have to be much better understood for modeling of rapid intensification of a cyclone to a hurricane or a super cyclone intensity in the Bay of Bengal.

8.2 Approaches to Tackle Scientific and Societal Issues: Need for Aircraft Reconnaissance in the Bay of Bengal

As tropical cyclones generally develop over high seas, regions which do not have good observational network, special efforts/observations are required to suitably determine their intensity and location for initializing the models used for prediction.

Only research aircraft probes in the core region of an intense cyclone can provide the much needed data on landfall intensity, landfall location, locally heavy rain with the collapse of the eye wall on landfall and maximum winds needed for storm surge prediction and triggering hydrological models to predict coastal and nearby inland inundations. Refinement of observing technologies along the coastal regions (climatologically favorable landfall locations) must also be established so that these observations could be combined with aircraft probes using sophisticated technologies such as airborne Dopplar radars. There is an urgent need to intensify research on data assimilation for TC prediction in India as the improvement in prediction skill can only come through better use of all possible data. There is also an acute need to train tropical cyclone specialist forecasters who have knowledge about the state of advanced research on TCs, real-time Doppler radar analysis, uncertainty or certainty in the modeling, use of probabilistic forecasts and access to operational forecasting tools etc. Also the advances in communication technology for the dissemination of TC landfall-related warnings have to be adequately addressed. The biggest gains in using modern scientific modeling tools with improved modest success in cyclone landfall prediction can be projected to the society through effective communication skills of the forecasters. Effective decision making by users can only result if they have developed confidence in forecasts and in the communication of warnings for the impending TC landfall. Hence, in the FDP-BOBTEX program separate goals may be kept for improving communication channels and communication skills of operational forecasters. Also improved working relationships between the forecasters and disaster managers must be developed in synergetic manner so that the role of humans in forecasting and disaster management is optimized. Thus, along with scientific issues infrastructural development and skillful modeling efforts and human resource capacity building would also contribute to quality enhancement about the use of forecast products for public good.

To sum up, improved understanding of tropical cyclone intensification process, and increased preparedness, awareness through education, effective utilization of existing and new knowledge as well as use of research outcomes into operational practices would contribute to effective disaster preparedness and warning systems for India. These are great challenges which must be met during the build-up and operational phases of FDP-BOBTEX.

9. Feasibility of launching FDP-BOBTEX and Phasing of the Programme.

9.1 Feasibility of the Programme

The programme is being built on sound scientific rationale, the availability of highly improved modern Ocean – atmospheric observing system in India and the help provided by the existing WWW observing system of the Bay of Bengal rim countries. The additional air-borne observing system, consisting of aircraft research flights would definitely provide crucial environmental and inner storm-core data for improving the predictions of dynamical models in track and intensity evolution of Bay of Bengal cyclones. The details of the instrumentation required for the aircraft is shown in Appendix II. The support likely to come from the WMO initiative on fully established TMRP Land Falling Tropical Cyclones Programme. MoES has formed respective project science teams to plan strategies for implementing the program at their respective ends **(Appendix-III).**

9.2 Components of the Program

The recommendations made by two workshops held in India viz. (i) Brainstorming session on "Tropical Cyclone Observation and Prediction- Current Status and Future Challenges", held at IIT-Delhi on 6 January 2007 and (ii) The Planning Workshop on "Instrumented Aircraft for Forecast Demonstration Project of Land Falling Tropical Cyclones Over Bay of Bengal", held at New Delhi during 28 February 03 March 2007, have advocated that the BOBTEX should have the following three components :-

- Background Research on Observational Studies.
- Efficacy of Observing Systems as well as Targeted Observations along east coast of India for study of landfalling TCs
- Intensive Field Programs (Pilot and Main)

9.2.1 Background Research Phase (2007-11):

India may launch background research needed for BOBTEX by using their data bases on TCs to understand:

- Post-monsoon clustering of cyclones.
- Land fall location, associated rainfall and wind strength 24-hr prior and at 24-hr after the land fall of TCs.
- Storm surges and extent of coastal and inland inundations.
- Public response to warnings, societal impacts etc.

It would be good if data bases on the above aspects are organized as these will be very useful in formulating the implementation strategy of the FDP-BOBTEX. Also modeling groups in India are encouraged to produce about 20 forecasts of the landfalling tropical cyclones of the Bay of Bengal to provide statistical base of current state of average error against which the predictions after the final Field Phase of BOBTEX could be judged. It would be also useful if the forecast based on analogue method, quasi-Langragian regional model IMD GFS modeland the NCMRWF's AGCM model are also made by using a standard synthetic vortex replacement technique. Intensified research may also be continued in data assimilation by scientists trained in this area in USA from NCMRWF, IMD, IIT and also drawn from IAF and Indian Navy. A specialized data assimilation package for the Bay of Bengal

TCs would enhance the forecast of the cyclones during the Pilot and Main Field campaigns and result in enhancing the utility of field-phases data. The scientists may collaborate further on running WRF and HWRF models at very high resolution (5 km) so as to improve understanding and prediction of structural changes at land fall. A programme of adopting the coupled-ocean HWRF (movable fine grid) model and data assimilation for the TCs may be also initiated jointly by Indian and US scientists. Eye wall structures, eye wall temperature and moisture profiles and rain band as simulated by MM5 / WRF / HWRF could be analysed for a few highly intense Bay of Bengal TCs of the post-monsoon season. The possible organizations and institutions that are likely to participate in the programs from India is shown in **Appendix IV.**

9.2.2 Pre-pilot Phase Campaigns (2008-09)

The pre-pilot phase of Forecast Demonstration Project (FDP) on landfalling tropical cyclones over the Bay of Bengal was taken up in 2008 and 2009. It helped in minimizing the error in prediction of tropical cyclone track and intensity forecasts.

During pre-pilot phase**,** several national institutions participated for joint observational, communicational & NWP activities, like during 2008. However, there was no intense observation period during the pre-pilot phase 2009, as there was no cyclonic disturbance over the Bay of Bengal during this period. The daily reports prepared during this period will be helpful to find out the reasons for suppressed cyclogenesis over the Bay of Bengal during 15th Oct. to 30th November 2009. The pre-pilot phases in 2008 and 2009 helped in development of institutional mechanism and improvement in standard operation procedure.

9.2.3 Pilot Phase Campaigns (2010-11) :

The main field programs may be preceded by two pilot phases. Pilot Phase-1 could be launched by India in October – November 2010. Effort should be made by India to put in place the bulk of their modernized observational system along the east coast & neighboring regions. Efforts should be also made to involve the Bay of Bengal rim countries. Appendix V shows the distribution of surface as well as upper air network of the rim countries viz. Bangladesh, Myanmar, Sri Lanka and Thailand. NRSA, Hyderabad and IITM Pune are in the process of acquiring a jet aircraft for the purpose of monitoring floods and other disastrous phenomena and monsoon activity. As monsoon season is over by mid-September, this aircraft could be used by India for releasing dropsondes in the environment (not core region) of the TCs in the Bay of Bengal. On an average there may be only 10 days requirement for using this aircraft from mid-October to November for such a purpose. Also enquiries be made to acquire another suitable turboprop aircraft by India by 2011 which could be fitted with inflight meteorological measurements, cloud microphysical measurements and drop sonde systems. They may also provide 60 drop-sonde instruments for deployment in field phase in the flying missions to be organized with NRSA aircraft around the environment of developing depressions/cyclones in post-monsoon season of 2011. High resolution models be run operationally during the field phase to evaluate their performance under operational conditions.

Pilot phase may be organized also by India in October-November 2011. This must have 90 percent of the full required observational network along the east coast of India as well as the facility of aircraft reconnaissance by NRSA aircraft probing the environments of developing systems with drop-sondes. The review of the results of Prepilot phase of 2008 and 2009 the implementation plan for Pilot Phase of 2010 and 2011 may be carried out during July 2010 and 2011 respectively.

9.2.4 Main field Campaign 2012:

The fine-turning of the final version of the Science Plan and preparation of an Implementation Plan for Main Field Phase campaign-2012 will be prepared by July 2011. For this purpose one meeting of the Indian and rim-countries scientists is proposed to be held with the International Scientific Steering Group around July 2011-12. The main field campaign is to be organized during Oct-Nov. 2012 in which the aircraft would also participate to provide observations not only on the environment of the developing TCs but also on their inner core structures. Indian aircraft would fly environmental sounding as the periphery of these cyclones. A strategy of flying missions and flying patterns has to be developed for these complex flight missions and provided as an essential part of the Implementation Program. All infrastructures such as hosting of BOBTEX Operation Centre, communication links including those with flight missions etc would be provided and ATC clearances and operations safety review etc would be carried out. Appendix VI shows in detail the salient features of the operational Centre. The detailed procedure will be firmly decided upon the final procedures by April 2012. A final meeting may be held with the Scientific Steering Group in July 2012 to review the preparations.

9.2.5 Post-Main Campaign Research:

While participating scientists may produce quick field phase researches, the main research campaign to show the gains of the FDP-BOBTEX may begin in early 2013 and would remain active for another 5 to 10 years. This would require collaboration of scientific groups within a country as well as bilaterally and internationally. This collaboration may be encouraged by all concerned and scientists given opportunities to discuss the results in specially organized conferences on FDP-BOBTEX. By 2013 some results would be available and India would begin using them in operations from 2013 season onward and share the operational products with other rim countries. However, the National Conference may be held annually once to evaluate the research and outcome of pre-pilot and pilot phases even in the absence of aircraft probing.

10. Data Management

FDP-BOBTEX shall generate huge amount of observational and model-generated data, Observational data will come from:

- Atmospheric observations over the Indian and adjacent region on the large scale parameters,
- Intensified observations along the Bay of Bengal rim countries.
- Satellite observations from INSAT and other US satellites (Scat winds, TMI/SSMI/ SSMIs observations and SST, Cloud Sat etc.),
- Data from ocean observing platforms like ARGO Floats, met-ocean buoys, current meter moorings, drifting buoys etc.,
- Dopplar radar photographs, radar reflectivities and radial winds,
- Total atmospheric moisture content from GPS measurements,
- Data on lightning flashes from lightning detectors network,
- Automatic weather stations data from coastal meso-network,
- Automatic rainguage and wind data from special networks,
- Aircraft flight level data on moisture, temperature and winds and cloud microphysical data,
- Drop-sonde and other special data from research aircraft reconnaissance flights.

Thus, there would be a host of data types which would require quality control checks to make them consistent internally as well as with respect to different parameters. Like other major field programs successful implementation of FDP-

BOBTEX and effective utilization of field data will require an efficient Data Management Plan which would consist of:

- Field Data Catalogue for different data categories viz. observed and model derived parameters,
- Merged Data Sets,
- Final Quality Control Data Catalogues
- Mirrored Data Sites

Data management would be done by specialists using management tools like meta data, map servers, smoothing and quality control procedures, visualization of data etc. The project teams will in due course formulate a data policy for each type of data with respect to time schedule for the quick-look and quality control data sets as well as their distribution among project teams and for open access. An appropriate task team /working group will be constituted for the data management which is one of the most important components of the project. A web-site for the project (FDP-BOBTEX Website) should be created by October-November 2010 so that information about the approved Science Plan, observational systems etc. begin to be displayed on the web-site. By October-2010 a Data Management Plan for the Pre-Pilot phase and main campaign should be finalized by Indian project teams. The Data Management Plan will continue to develop as the project proceeds from Pre-Pilot-I phase (2008) to main field Campaign Phase (2012).

11. Tentative Time Scheduling for the Program

The following tentative time scheduling may be developed for effective implementation of FDP-BOBTEX:

- Preparation of the first draft of the Science Plan in India: Early July 2007
- Formulation of the Project teams in India: Early September 2007
- First meeting of the project teams in India: Oct-Nov2007.
- Formulation of the first Data Management Plan: Feb-March 2008
- Completion of enquiries etc. for using NRSA aircraft and for leasing/acquisition of a turboprop aircraft by India: Feb-March 2008
- Overview of the arrangement for Pre-Pilot-I Phase (2008) by India: July-Aug 2008.
- Fitting of drop sonde release device in the NRSA aircraft by India and receipt of drop sonde from NCAR: Aug 2010
- Launching of Pre-Pilot phase by India: Mid-Oct 2008

- Completion of Pilot-I field Phase : Nov 2008
- Constitution of an International Scientific Steering Group for the program: Jan-Feb 2011.
- Workshop on Pre-Pilot-II Phase and its assessment: March 2010.
- Overview of Observation Systems in India for the Main Campaign (Representatives of Bay of Bengal rim countries may be invited): June-July 2011.
- Finalisation of aircraft participation for Pilot field phase and receipt of drop sonde: June-July 2010.
- Launching of Pilot field Phase by India and its completion: Mid Oct-Mid Nov 2010.
- Dispatch of Field Phase data catalogue to all users including Rim countries: Dec.2010- Jan.2011
- Overview of the two Pre-Pilot and Pilot phases, Data Management Plan and preparation for main field phase campaigns for 2011: July-Aug 2011.
- Workshop on the findings of the pilot phases in India: – July-August 2011
- Meeting of India and Bay of Bengal rim countries Project Scientists and Meeting of the International Organizing Committee for Main Field Phase: Feb-March 2012.
- Finalization of communication channels, research flight mission planning, ATC requirements etc.: May 2012.
- Project safety overview and setting up of mechanism for the main field phase, finalization of data management plan June 2012.
- Arrival of aircraft and setting up of Project Field Operation Centre: Beginning of 2011
- Launching of the Main Field Phase campaign and its implementation: 15 Oct-15 Nov. 2012.
- Distribution of Quick Look Data sets: Jan 2013.
- Workshop on Preliminary Results of FDP-BOBTEX : July 2013.
- Research continues with data and models with 2 reviews: Till 2017

12. Project Implementation

- A steering committee would be set up who would advise on the future planning and various activities related to the FDP project. They would essentially work as the "think tank" for the project. It could comprise of members from various organizations.

- Different working groups to address various issues will be set up. These will essentially comprise of
  - ❖ Data Management
  - ❖ Observations (Field Campaigns)
  - ❖ Modeling and Research
  - ❖ Output and Diagnostics
- A coordination cell/team will be set up for effective implementation of the four working groups and the steering committee.
- A monitoring/review mechanism will be put in place.

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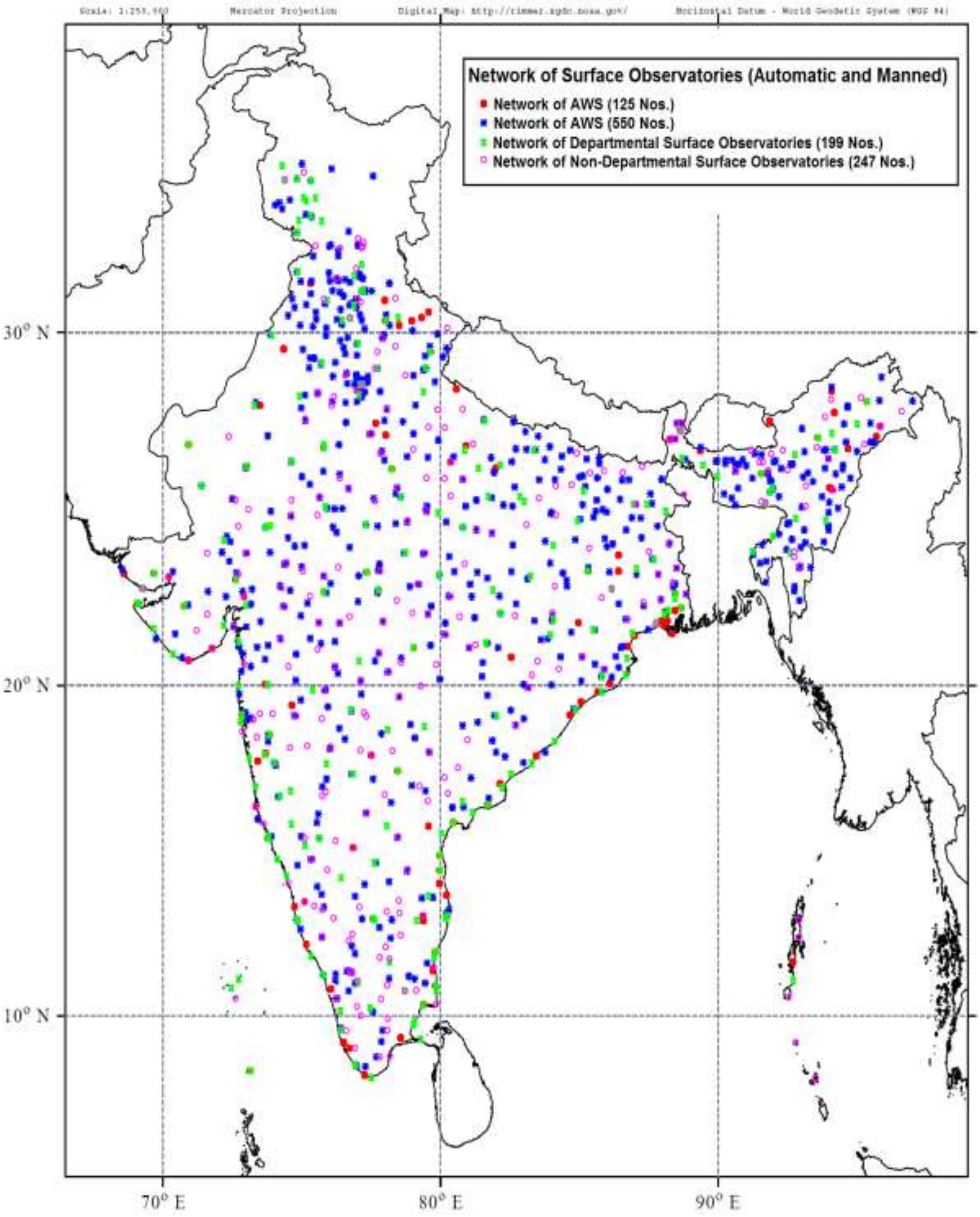
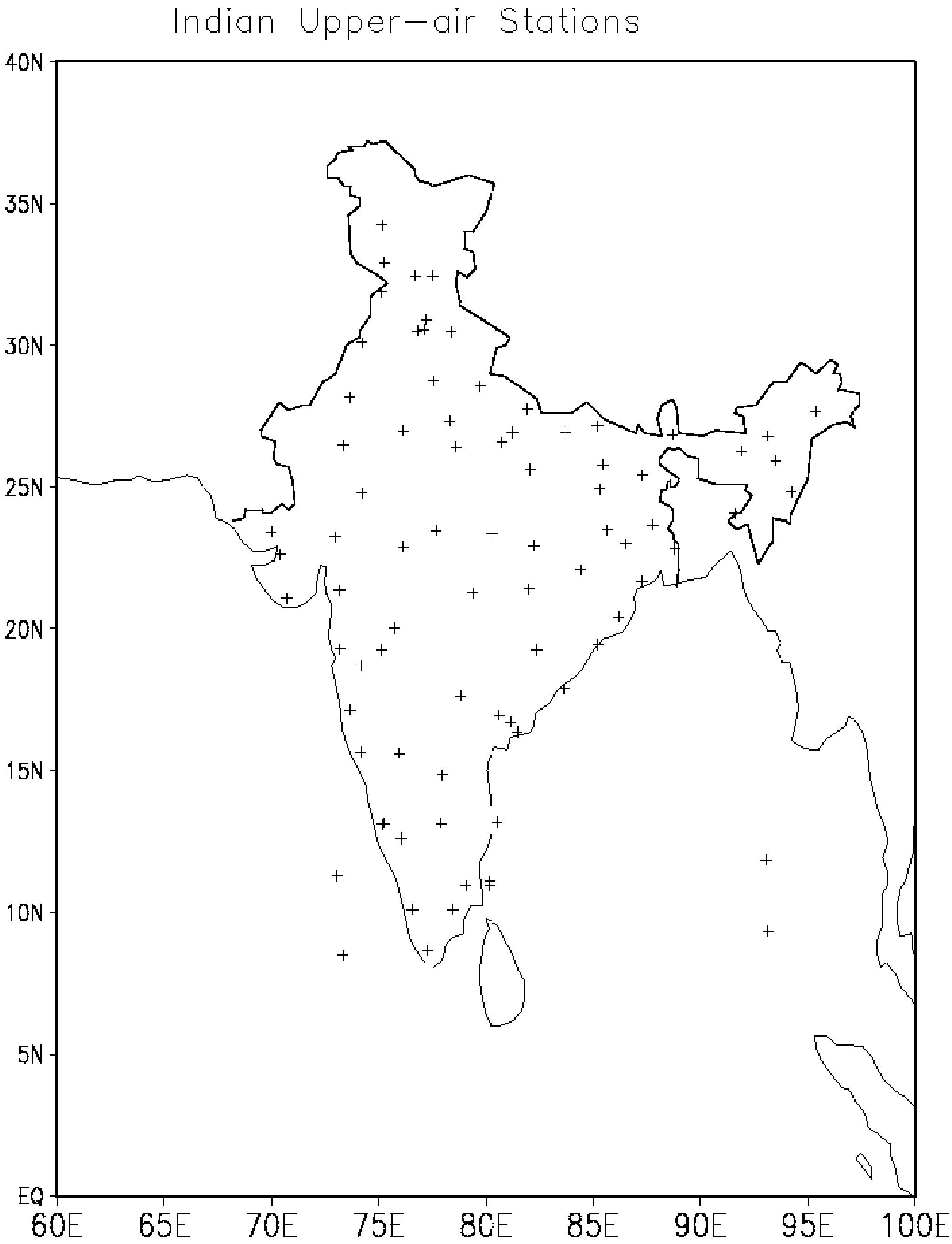
APPENDIX- I

Network of Surface Observatories(Automatic and Manned)




Indian Upper-air Stations
40N
35N
30N
25N
20N
15N
10N
5N
EQ
60E
65E
70E
75E
80E
85E
90E
95E
100E

APPENDIX- II

Details of Instrumentation required for Aircraft Probing of the Cyclone Specific Requirements for National facility For Airborne Research on tropical cyclones and other severe weather events

To achieve the scientific objectives of the programme the bidder has to provide the following services in consultation with the IMD scientists, in mutually agreement taking into consideration the flying constraints and observational requirement.

i) The aircraft must be stationed in the desired airport (Chennai, Visakhapatnam or Bhubaneswar) once IMD scientists request for the same as and when there is a cyclone formation/ genesis in Bay of Bengal.
ii) They should be available to make one or two reconnaissance flights per day depending upon the requirement or feasibility.
iii) Some of the data collected may be transmitted to IMD station on real time basis for immediate use and remaining data can be handed over using removable media after landing.
iv) Necessary analysis and visualisation software may be provided to IMD for this purpose.
v) The off-line data analysis software may be provided on hire/ retention basis till the analysis is complete.
vi) Training of IMD scientists in the data processing, data formats conversion, ingesting techniques into NWP models, and visualisation software utilisation etc should be given before commencement of the observational plan.

(i) There should be provision for the following
   a. Provision of one aircraft on hire basis with all necessary meteorological equipment and software installed. The company is responsible for all the auxiliary facilities required for moving the aircraft to the required airports, hanger facilities and necessary aviation permissions.
   b. Provision of necessary manpower to fly, fuel, maintain the aircraft and to operate the meteorological equipment on board the aircraft, including communications.

(ii) Provision of the following Meteorological Observational instruments mounted in the probing aircraft, calibration done, tested and ready for use.
   a. Pressure, temperature, humidity, wind speed, wind direction, LIDAR, drop sondes, aerosols, trace gases

(iii) Provision of online communication to the ground station located in India for real time transmission of some of the data and images collected.
(iv) Provision of off-line data storage and retrieval system with removable media like USB Drives, Memory sticks etc. for easy collection of data immediately after the aircraft each flight.
(v) Provision of necessary software for analysis and visualisation of met data collected by aircraft on near-real time basis.

SPECIFICATIONS

a) Specifications of minimum requirement of instruments to be installed on board aircraft.
   i) Rapid sampling of atmospheric pressure at every 1 km distance.
   ii) Rapid sampling of atmospheric temperature and humidity every 1 km distance
   iii) Rapid sampling of horizontal wind speed and direction (absolute values)
   iv) Rapid sampling of Vertical wind speed and direction (absolute values)
   v) Drop sondes to be taken at every 50 kms range/ or lat/long grid assigned.
b) Specifications of meteorological data collection.
   i) Resolution of atmospheric pressure up to first decimal of an hPa.
   ii) Resolution of temperature up to first decimal of a degree centigrade.
   iii) Resolution of wind speed up to one knot per hour, and wind direction 10 degrees.
c) Specifications of type and frequency of data collection.
   i) Near continuous data collection like every 1, 5 or 10 second as possible.
d) Specifications of software needed for data analysis and visualisation.
e) Specifications of type of communications to be used in data communications.
f) Specifications of off-site and on-site training for officers associated with the project.

Aircraft operation details

Sl no.	Details required
01	80 hours measurement flights to/from India
02	Number hours for bring-in and taking out of the aircraft before and after mission including fuel cost
03	fuel cost for actual hours of flight as per acutals
04	Cost of hanger, airport usage
05	39 days aircraft usage

Manpower

Man Power details
exploration trip
installation/de-installation
campaing preparation operations
campaign in India
data processing
Certifications
Miscellaneous
exploration trip
Campaign including travel
transfer of falcon

General Requirements of Aircraft for NFAR for other studies

According to past experience of aircraft observations an aircraft with following specifications will be required:

- Twin Engine, turbo prop
- Maximum Altitude: 35000 ft and minimum altitude 1500 ft over ocean
- Scientific Payload 1500 kg
- Range 2500-3000 km and endurance 6-8 hrs
- Cabin volume required for equipments and personnel 10-12 m^3
- Special arrangements- Air inlets, 2-3 instrument racks of standard size and 4 – seats for scientists and 2 pilots, toilet optional
- Stability of platform - Strong enough to go in the outer regions of conviction clouds / disturbance etc.

Detailed list of aircraft instrumentation

1. **Basic suit of instruments**
   Standard Airborne Scientific Measurements includes

1. INERTIAL REFERENCE SYSTEM
2. GLOBAL POSITIONING SYSTEM (GPS)
3. ALTITUDE AND POSITION
4. AIRCRAFT AND METEOROLOGICAL STATE PARAMETERS
5. THERMODYNAMIC MEASUREMENTS
6. WINDS

TOTAL WEIGHT : 100 KG, POWER 200 W

Cloud Physics Instruments

No.	Instrument	Mfg.	Size	Weight	Dimension	Power	Fitting
1	**Cloud Droplet Probe (CDP)**	DMT	2-50 μm	5 kg	8.5” L x 4.675” H x 5.875” H; signal-processing module is 7” L x 3.25” W x 2” H, remotely mounted	30W at 28VDC, plus 200W for anti-ice heaters Total 230 W	External
2	**Cloud Imaging Probe (CIP)**	DMT	25μm to 1550μm	12 kg		10A @ 28VDC for the system, 6A @ 28VDC for LWC power and 2 legs of 28VDC @ 10A for anti-icing 30 W	External
3	**Cloud**	DM		28 kg.	81cm high,	28 VDC	Intern

	Condensation Nuclei Counter (CCN-100)	T			48cm wide, 28cm deep Rack mountable	power, 15A 30 W	al
4	**Passive Cavity Aerosol Spectrometer Probe PCASP-100)**	DMT	0.1µm to 3.0µm	20 kg	40” long x 7” diameter (102 cm x 18 cm)	115VAC or 230VAC, 50-60Hz., <120W Anti-ice power requirements: 28VDC, Power 215W	External
5	**AIMMS-20**	DMT	Differential GPS Module (GPS),	6 kg		30 W Power +28 VDC, 100mA (Electronic System) +28 VDC, 8A Anti-ice power: 200W	External
6	**Cloud, Aerosol, Preci.Spectrometer plus Hot-Wire LWC, Temp. and RH**		0.5µm to 1550µm	21kg		: 28VDC: 10A for probe system, and 45A for anti-ice heaters 30 W + 200 W Total 230 W	External
7	**Precipitation Imaging Probe (PIP)**	DMT	100µm with a particle sizing range of 6.2mm.	12kg		+28VDC, 3A, for the system electronics. Anti-icing heaters use +28VDC at 8A. Power 230 W	External
	Total weight			104 kg	Total Power	230 W	

Aerosol Instruments

	Instrument	Mfg.	Size	Weight	Dimension	Power	Fitting
1	**Ultra-High Sensitivity Aerosol Spectrometer (UHSAS)**	DMT	55 nm to 1 micron	31 kg		100-240 VAC 47-63 Hz 200 W	External
2	**Single**		black	36 kg		100W for	Internal

	Particle Soot Photometer (SP2)		carbon			instrument, 200W for pump	
3	**Scanning Mobility Particle Sizer**	TSI	5 - 500 nm	28 kg	45.7 cm × 41.4 cm × 40.6 cm (18 in. × 16.3 in. × 16 in.)	85 to 260 VAC, 50/60 Hz, 200 W maximum	Internal
4	**Aerodynamic Particle Sizer Spectrometer**	TSI	0.5 20 micron	10 kg	38 cm × 30 cm × 18 cm (15 in. × 12 in. × 7 in.)	100 to 240 VAC, 50/60 Hz, 100 W, single phase or 24 VDC	Internal
5	**Ultrafine Condensation Particle Counter**	TSI		13 kg	24 cm × 38 cm × 25 cm (9.5 in. × 15 in. × 10 in.),	100/120/230/240 VAC, 50/60 Hz, 200 W maximum	Internal
	Total			107 kg	Power	230 W	

3.5 Chemistry Instruments

	Instrument	Mfg.	Size	Weight	Dimension	Power	Fitting
1	**LI-7000 CO2/H2O Analyzer**	LI-COR		10 kg	5" H □□9.875" D □□14.5" L (12.7 □□25 □□36.8 cm).	100-240 VAC, 50-60 Hz, or 10.5-16 VDC, 4 amp max.	Internal
	So2 H2s Analyser	AF 22		10 kg	54 *48 *13 cm	100-240 VAC, 50-60 Hz, 60 VA	
	Carbon monoxide analyzer	Co12 M		8 kg	54 *48 *13 cm	100-240 VAC, 50-60 Hz, 50 VA	
	Ozone analyzer	O242M		9 kg	54 *48 *13 cm	100-240 VAC, 50-60 Hz, 70 VA	
	Nitrogen oxide analyzer	AC32M		13 kg	54 *48 *13 cm	100-240 VAC, 50-60 Hz, 250 VA	
	CO2/CH4/H2O Flight Analyzer			12 kg	23*18*10 inch	100-240 VAC, 50-60 Hz, 370 VA	
	Total weight			62 kg	Total Power	230 W	

Radiation instruments

	Instrument	Mfg.	Size	Weight	Dimension	Power	Fitting
1	**Precision Spectral Pyranometer**	EPLAB		2 kg	5.75 inch diameter		External
2	**Precision Infrared Pyranometer**	EPLAB		2 kg	5.75 inch diameter		External
3	**Thermometer**	EPLAB		1 kg			External
	Total eight			5 kg	Total Power	230 W	

Data Acquisition System

	Instrument	Mfg.	Size	Weight	Dimension	Power	Fitting
1	16 channel data acquisition system			20 kg	19 *12*10 inch rack mounted	100-240 VAC, 50-60 Hz, 250 VA	Internal

3.8. Power Distribution System

	Instrument	Mfg.	Size	Weight	Dimension	Power	Fitting
1	Power distribution system			20 kg	19 *12*10 inch rack mounted	28V at 2.5 A 230 W	Internal

Indicative Budget Requirements during the XII Plan: Rs. 300crores

1. SPECIFICATIONS

g) Specifications of minimum requirement of instruments to be installed on board aircraft.
   vi) Rapid sampling of atmospheric pressure at every 1 km distance.
   vii) Rapid sampling of atmospheric temperature and humidity every 1 km distance
   viii) Rapid sampling of horizontal wind speed and direction (absolute values)
   ix) Rapid sampling of Vertical wind speed and direction (absolute values)
   x) Drop sondes to be taken at every 50 kms range/ or lat/long grid assigned.

h) Specifications of meteorological data collection.
   iv) Resolution of atmospheric pressure up to first decimal of an hPa.
   v) Resolution of temperature up to first decimal of a degree centigrade.
   vi) Resolution of wind speed up to one knot per hour, and wind direction 10 degrees.

i) Specifications of type and frequency of data collection.
   ii) Near continuous data collection like every 1, 5 or 10 second as possible.

j) Specifications of software needed for data analysis and visualisation.

k) Specifications of type of communications to be used in data communications.

Specifications of off-site and on-site training for officers associated with the project.

APPENDIX-III

Planning Workshop on
Instrumented Aircraft for Forecast Demonstration Project
of land falling Tropical Cyclones over Bay of Bengal

28 Feb – 03 Mar 2007

National Academy of Agricultural Sciences
NASC Complex, DPS Marg, Near Todapur,
Pusa Campus
New Delhi -110012

AGENDA

DAY 1 (28-02-2007)

9.00 AM	**Registration**	
10.00 AM	**Welcome Remarks**	**A. K. Bohra (NCMRWF)**
10:10 AM	**Address**	**Karyn Sawyer (NCAR)**
10:20 AM	**Indo-US S&T Collaborations Perspectives and Opportunities**	**A. Mitra (IUSSTF)**
10:30 AM	**Inauguration of the workshop**	**P. S. Goel Secretary, MoES**
10:40 AM	**Vote of Thanks**	**Swati Basu (MoES)**
10:45 AM	**TEA**	

Session-I

Chairman: Dr. R. C. Bhatia, DGM, IMD

11.15 AM	**A. K. Bohra**	**Scientific objectives of FDP**
11:30 AM	**D. R. Sikka (ICRP)**	**Five Decades of Indo-US collaboration in Atmospheric Sciences: Development of Partnership in FDP of land Falling TC in North Indian Ocean**
12.10 PM	**Karyn Sawyer**	**Planning and Implementing International Field Campaign**
12:30 PM	**LUNCH**	

DAY 2 (01-03-2007)

	Session –II	**Airborne Instrumentation**
	Chairman: Karyn Sawyer	
9.30 AM	**Dave Jorgensen (NOAA)**	**Using Instrumented Aircraft to Understand Physical Processes of Tropical and Extratropical Weather Systems**
10.00 AM	**Roger Wakimoto (NCAR)**	**Convective storms and frontal systems**
10.30 AM	**G. S. Bhat (IISc)**	**Aircraft observations for cloud research**
11.00 AM	**TEA**	
11.30 AM	**Al Cooper (NCAR)**	**Measuring Properties and Structures of the Atmosphere**
12.00 Noon	**Ajit Tyagi (IAF)**	**Airborne Observations for tropical cyclones**
12.30 PM	**V. Mudkavi**	**Saras -- India's First Multirole Civil Platform. A Potential Indigenous Aerial Platform for Meteorological Research**
12.45 PM	**Discussions**	
1:00 PM	**LUNCH**	
	Session –III	**Other Observation Platforms for FDP**
	Chairman: D. R. Sikka	
2.00 PM	**S. K. Kundu (IMD)**	**New Capabilities of detection and monitoring of tropical cyclones**
2.40 PM	**G. Viswanathan (ISRAD, ISRO)**	**Development of Doppler Weather Radar in ISRO**
3.10 PM	**TEA**	
3.40 PM	**K. Somasundar (MoES)**	**India's effort in Ocean observing system**
4.00 PM	**M. Mishra (Indian Navy)**	**Ship-borne observations over Indian Ocean**
4.20 PM	**Discussions**	

DAY 3 (02-03-2007)

Session –IV	**Data (Management & Assimilation)**	
	Chairman: Prof. U. C. Mohanty	
9.30 AM	**Steve Williams (NCAR)**	
9.50 AM	**Preveen Devrajan (NCMRWF)**	**Field data management at NCMRWF**
10.10 AM	**Dale Barker (NCAR)**	**WRF Data Assimilation in Indian Applications**
10.40 AM	**John P. George (NCMRWF)**	**Data Assimilation for Meso-scale models at NCMRWF**
11.00 AM	**Discussions**	
11.15 AM	**TEA**	
Session –V	**High resolution Modeling**	
	Chairman: Dr. Ajit Tyagi	
11.45 AM	**Dale Barker (NCAR)**	**WRF model**
12.15 PM	**R. Ashrit (NCMRWF)**	**TC Modelling at NCMRWF**
12.35 PM	**Y. V. Rama Rao (IMD)**	**TC Modelling at IMD**
1.00 PM	**LUNCH**	
2.00 PM	**U. C. Mohanty (CAS, IIT-D)**	**TC Modelling at IIT-D**
2.30 PM	**P. Goswami (C-MMACS)**	**TC Modelling at C-MMACS**
3.00 PM	**D. V. Bhaskar Rao (Andhra University)**	**TC Modelling at Andhra University**
3.20 PM	**Discussions**	
3.30 PM	**TEA**	
Session –VI	**Tropical Cyclone Warning & Applications**	
	Chairman: Dr. B. Bhattacharjee	
4.00 PM	**B.K. Bandyopadhyay (IMD)**	**Present TC warning system in India**

4.20 PM	**K. J. Ramesh (DST)**	**Applications of TC warnings**
4.40 PM	**Discussions**	

DAY 4 (03-03-2007)

Session –VII **Planning for Research and Field Phase**

Chairman: P. S. Goel

10.00 AM	**A. K. Bohra (NCMRWF)**	**Indian Perspective**
10.20 AM	**Karyn Sawyer (NCAR)**	**US Perspective**
10.40 AM	**Discussions**	
11.00 AM	**TEA**	
11.30 AM	**Discussions on**	

Need for aircraft probes and long term plans for procurement of instrumented weather reconnaissance aircraft

R. C. Bhatia, IMD to lead the discussion

Research Issues and strategy
USA: NOAA, NCAR
India: IMD, NCMRWF, IITM, IIT-D, INCOIS, CMMACS, IAF, Indian Navy, CUSAT (Dr. P. V. Joseph), Andhra University

1.00 PM	**LUNCH**
2.00 PM	**Panel Discussions and Recommendations**

APPENDIX- IV

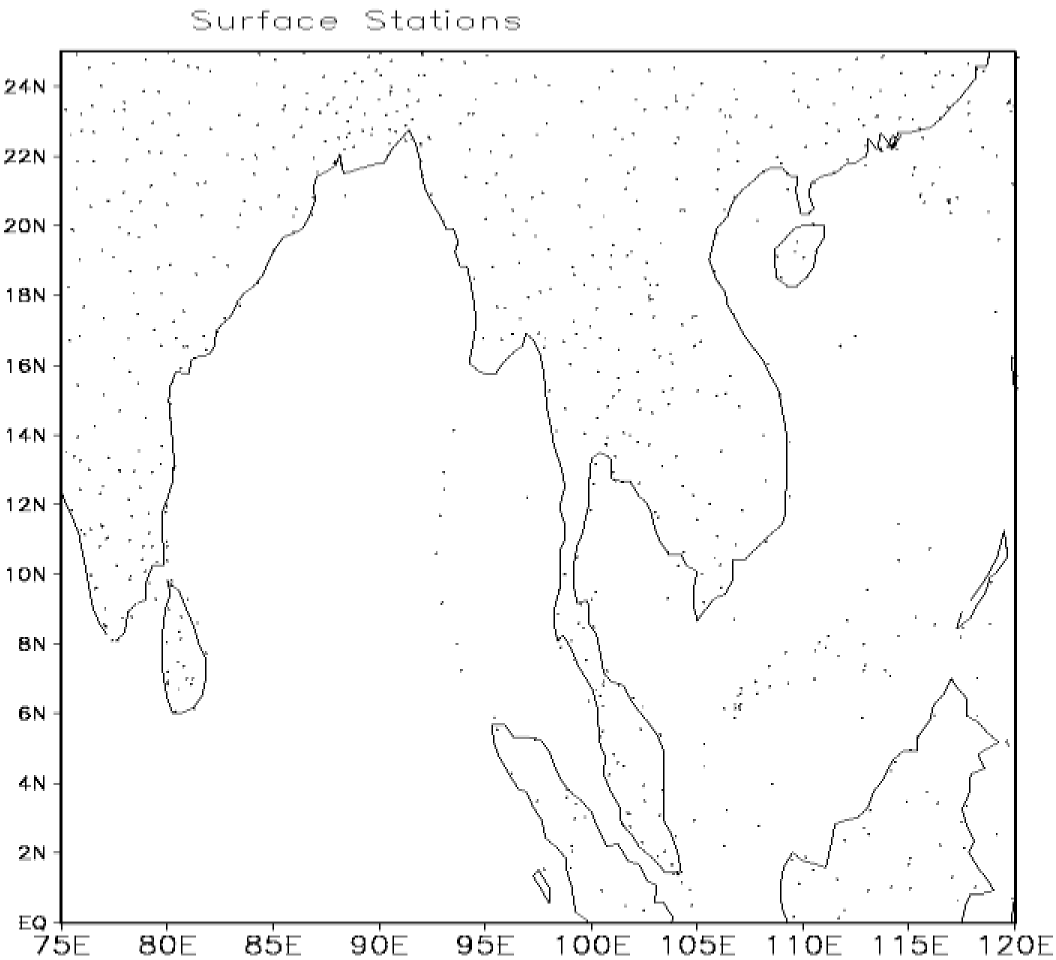
List of Indian Participating Agencies

1. Andhra University, Department of Meteorology & Oceanography
2. Department of Science & Technology, New Delhi
3. Department of Space, Bangalore
4. Indian Institute of Technology, Delhi
5. Indian Institute of Technology, Kharagpur
6. Indian Institute of Technology, Chennai
7. Indian Space Research Organization, Bangalore
8. Indian Institute of Science &, Centre for Atmospheric Ocean Science
9. Indian Institute of Tropical Meteorology, Pune
10. India Meteorological Department, New Delhi
11. Indian National Centre for Ocean Information System, Hyderabad
12. Ministry of Earth Sciences, New Delhi
13. National Centre for Medium Range Weather Forecasting, NOIDA
14. National Remote Sensing Agency, Hyderabad
15. Cochin University, Department of Meteorology & Oceanography
16. National Disaster Management Authority, New Delhi
17. Centre for Mathematical Modeling & Advanced Computing
18. National Aeronautical Laboratory, Bangalore
19. National Institute of Oceanography, Panaji
20. National Institute for Ocean Technology, Chennai
21. Andhra Pradesh State Disaster Management Agency, Hyderabad
22. West Bengal Disaster Management Agency, Kolkatta
23. Orissa State Disaster Management Agency, Bhubaneshwar
24. Tamil Nadu State Disaster Management Agency, Chennai
25. National Atmospheric Research Laboratory
26. Department of Atomic Energy
27. Department of Marine Science, University of Berhampur

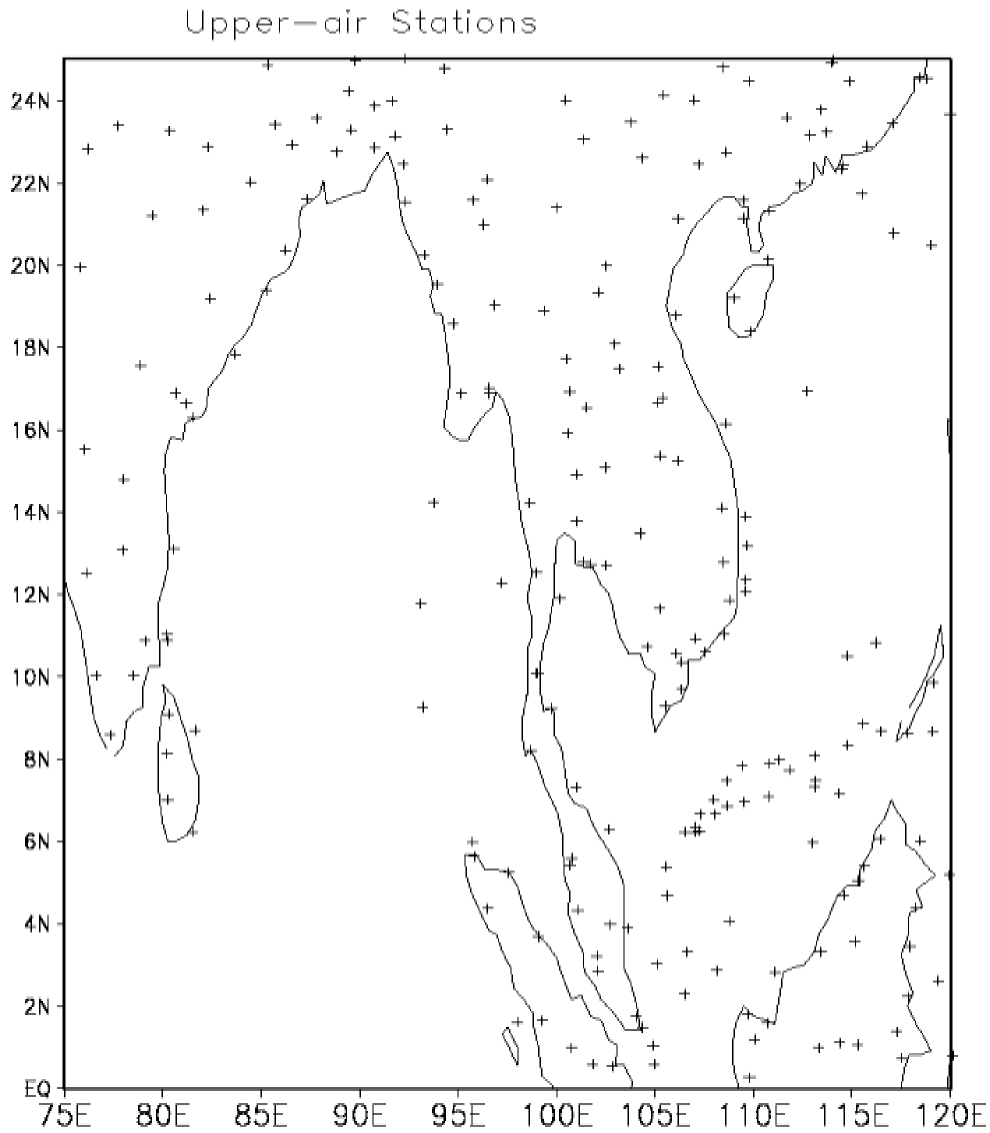
Distribution of observational network of Bay of Bengal Rim Countries to be involved in BOBTEX

1. **Bangladesh**
2. **Myanmar**
3. **Sri Lanka**
4. **Thailand**

(a) Surface Stations



(b) Upper Air Stations



APPENDIX- VI

List of Acronyms

ARPS	**Advanced Research Prediction System**
BOBTEX	**Bay of Bengal Tropical Cyclone Experiment**
CLIPER	**Climatology and Persistence**
CISK	**Conditional Instability of the Second Kind**
CMMACS	**Centre for Mathematical Modelling and Advanced Computing System**
DOS	**Department of Space**
DST	**Department of Science & Technology**
ECMWF	**European Centre for Medium Range Weather Forecasting**
FDDA	**Four Dimensional Data Assimilation**
FDP	**Forecast Demonstration Project**
HWRF	**Hurricane Weather Research Model**
IAF	**Indian Air Force**
IIT	**Indian Institute of Technology**
IITM	**Indian Institute of Tropical Meteorology**
IIOE	**International Indian Ocean Expedition**
IMD	**India Meteorological Department**
INCOIS	**Indian National Centre for Ocean Information Services**
INDOEX	**Indian Ocean Experiment**
INSAT	**Indian National Geostationary Satellite**
JTWC	**Joint Typhoon Warning Centre**
MMM	**Micro and Meso-scale Meteorology**
MM5	**Meso-scale Model Version 5**
MONEX	**Monsoon Experiment**
MoU	**Memorandum of Understanding**
MoES	**Ministry of Earth Sciences**
NCEP	**National Centers for Environmental Prediction**
NHRC	**National Hurricane Research Centre**
NHRP	**National Hurricane Research Project**
NHRL	**National Hurricane Research Laboratory**
NCAR	**National Centre for Atmospheric Research**
NCMRWF	**National Centre for Medium Range Weather Forecasting**
NDMA	**National Disaster Management Authority**
NOAA	**National Oceanographic and Atmospheric Administration**
NRSA	**National Remote Sensing Agency**
NSF	**National Science Foundation**
PRWONAM	**Prediction of Regional Weather using Observational Meso-Network and Atmospheric Modeling**
RAINEX	**Hurricane Rainband and Intensity Change Experiment**
SST	**Sea Surface Temperature**
STORM	**Severe Storm Observational Research and Modeling**
SUCS	**Super Cyclonic Storm**
TC	**Tropical Cyclone**
TOGA	**Tropical Ocean and Global Atmosphere**
TMRP	**Tropical Meteorology Research Programme**
UK	**United Kingdom**
USA	**United States of America**
VSCS	**Very Severe Cyclonic Storm**
WMO	**World Meteorological Organization**
WRF	**Weather Research Forecast Model**