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# Major advances in understanding and prediction of tropical cyclones over north Indian Ocean : A Perspective

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**सार** – उत्तरी हिन्द महासागर में उष्णकटिबंधी चक्रवातों पर किए गए अनुसंधान गत 150 वर्षों में विभिन्न चरणों से गुजरे हैं और अधिक तथा बेहतर प्रेक्षणों को विकसित करने के लिए प्रौद्योगिकी के रूप मे इसका विकास किया गया है। 20वीं शताब्दी के मध्य तक समुद्र में इस आपदाकारी परिघटना के बनने और इसके तीव्र होने की जानकारी पोतों में ही कुछ हद तक विरलता से प्राप्त होने वाले प्रेक्षणों के माध्यम से मिलती थी और इसलिए 1960 के दशक तक भारत में किए गए अधिकांश अनुसंधान अध्ययनों में चक्रवातों के जलवायु विज्ञान, उनकी धरातलीय संरचना, उनकी गति और समुद्र में जहाजों को पहुँचानें वाली क्षति को अनदेखा करने वाले नियमों पर अधिक बल दिया गया था। मौसम रेडार, उपरितन वायु परिज्ञापनों, अनुसंधान वायुयान सर्वेक्षण मौसम उपग्रहों और कंप्यूटरों के माध्यम से प्राप्त की गई नई वायुमंडलीय प्रोद्योगिकी के प्रस्तुतीकरण से 1950 के दशक से लेकर 1980 के दशक के दौरान विभिन्न देशों के उष्णकटिबंधी चक्रवात अनुसंधान में आश्चर्यजनक रूप से परिवर्तन आया है। इस अवधि में उष्णकटिबंधी चक्रवातों के संपूर्ण उत्पत्ति चक्र का प्रतिरूपण करने के लिए सैद्धांतिक अध्ययनों और कंप्यूटर निदर्शों के विकास में सुधार देखा गया है। इस अवधि में उष्णकटिबंधी चक्रवात के मार्ग का पूर्वानुमान लगाना भी अनुसंधान का एक क्षेत्र बन गया है और 1950 के दशक से लेकर 1980 के दशक के दौरान जलवायु विज्ञान, सिनाप्टिक सांख्यिकीय और गतिकीय पद्धतियों पर आधारित तकनीकों के प्रकारों में निरंतर विकास हुआ है तथा इन्हें मान्यता मिली है। गत 10 वर्षों की अवधि के दौरान विकसित देशों में भूमंडलीय परिचालन निदर्शों में निहित परिष्कृत उच्च विभेदन के निदर्शों का विकास किया गया है और पारस्परिक क्रियाओं की प्रक्रिया के रूप में इस पद्धति का विकास करने और इसकी गति का पूर्वानुमान लगाने के लिए इनकी जाँच की गई है। ये पूर्ण रूप से सही पाई गई हैं। भारत में भी इस प्रकार के विकासों को अपनाया गया है। इस शोध–पत्र में उष्णकटिबंधी चक्रवात के विकास और इसकी गति में सन्निहित प्रत्यक्ष प्रक्रियाओं के संबंध में किए गए प्रमुख विकासों की सूची उपलब्ध कराने का प्रयास किया गया है। सामान्य रूप से भूमंडलीय अनुसंधान के क्षेत्र में किए गए प्रयास हिंद महासागर बेसिन में किए जा रहे अध्ययनों पर केंद्रित रहे हैं। उत्तरी हिंद महासागर में उष्णकटिबंधी चक्रवातों के अन्तः दस वर्षीय भिन्नताओं की जाँच की गई है और 1980 के दशक से इनकी गतियों में अक्सर अत्याधिक कमी देखी गई है। हिंद महासागर बेसिन में उष्ण/शीत इनसों की घटनाओं के मध्य कोई संबंध नहीं पाया गया है। प्रचंड उष्णकटिबंधी चक्रवातों के विकास और गति के लिए आवश्यक वृहत मान स्थितियों की प्रकृति से संबंधित प्रेक्षणात्मक और सैद्धांतिक मॉडलिंग पद्धतियों में कंप्यूटर प्रतिरूपणों सहित प्रेक्षणात्मक और सैद्धांतिक पद्धतियों से भिन्न भिन्न विचारों का पता चला है। उत्तरी हिंद महासागर बेसिन में किए गए और अधिक अनुसंधान की ओर विशेष ध्यान देने की दिशा में कुछ सुझाव दिए गए हैं।

**ABSTRACT.** Research on tropical cyclones in the north Indian Ocean has passed through different phases in the last 150 years and progress was made as the technology for more and better observations evolved. Till the middle of the $20^{th}$ century, the only way of knowing about the formation and intensification of this disastrous phenomenon, while out at sea, was through rather sparse ship observations and hence the climatology of the cyclones, their surface structure, movement and the rules to avoid the damage to shipping at sea were emphasized in most of the research studies in India till 1960s. Introduction of new atmospheric technologies through weather radars, upper air soundings, weather satellites and computers have brought a phenomenal change in tropical cyclone research in different countries during 1950s to 1980s. The period also witnessed break-through in theoretical studies and the development of computer models to simulate the complete genesis cycle of tropical cyclones. Predicting the track of tropical cyclone also became an area of active research in this period and a variety of techniques were increasingly developed. During the last 10 years sophisticated high resolution models embedded within global circulation models have been developed in advanced countries and tested for predicting the development and movement of the system as an interactive process. In India, too such developments have been adopted. Within the scope of global research effort in general, the focus of the article is on the studies in north Indian Ocean basin. Inter-decadal variation of tropical cyclones in the north Indian Ocean has been examined and the frequency of their formations have shown drastic decrease since 1980s. No connection is found between the warm/cold ENSO events in the Indian Ocean basin and tropical cyclone frequency in the basin. Observational and theoretical approaches with computer simulations have brought a convergence of views concerning the nature of large-scale conditions needed for development and movement of severe tropical cyclones. Some suggestions are provided for directing special attention toward further research in this area in the north Indian Ocean basin.

**Key words** – Tropical cyclone development, Track prediction, Simulation and modelling. Inter-decadal variability, Relationship with El-Nino.

## 1. Introduction

The havoc caused by the tropical cyclones to shipping on the high seas and coastal habitats have been known since millennia. Tropical cyclones have caused sinking of many ships and countless disasters along coastal environments of several countries. They have also decided the fate of wars like the destruction of the armada of Kublai Khan in the 13$^{th}$ century ACE, built on the shores of Korea for conquering Japan, and the defeat of French near Chennai at the hands of British during the conflict between France and England to control peninsular India in the early part of the 18$^{th}$ century.

The tropical Indian Ocean and the tropical western north Pacific Ocean are two very important areas for the formation of severe tropical cyclones. The trade by the western nations through marine routes in these two oceanic areas dominated during the 16$^{th}$ to the mid 19$^{th}$ centuries. As such valuable informations about tropical cyclones were obtained by scientists in the Atlantic (Reid, W., 1849), missionaries in the Philippine Sea (Deppermann, 1939), and the pioneers interested in the progress of weather science in the north Indian Ocean during the 19$^{th}$ century like (Piddington 1864). Those early days were exciting, as with few scattered observations as well as patterns of shipwrecks, these pioneers unlocked important observational facts about tropical cyclones. With an expanding horizon of meteorological science in general and tropical meteorology in particular, after the second world war, and thanks to successive introduction of new observational technologies and high speed computing not only many secrets of the phenomenon have been uncovered but the knowledge is being used for better prediction of tropical cyclones. No tropical cyclone can now escape the watchful eye of the satellite and diagnosis of its intensity changes are also kept under continuous surveillance. The prediction capabilities have also enormously increased such that the predictions 72 hrs in advance are now considered to be quite skillful. This has been amply demonstrated by the forecast made on the recent hurricanes Katrina, Rita and Wilma in August, September and October 1999 respectively in the Gulf of Merico in USA. Even though the predictions about changes and tracks of these hurricanes were quite accurate, which helped in giving early warning of the area likely to be hit hardest, there was widespread disasters in all the three cases. The reduction of tropical cyclone disasters depends on several factors, besides the skill in their prediction, which include short and long-term preparedness measures to tackle cyclone-related disasters, readiness of the people for evacuation and the public perception about the crediability of the official predictions. In this article we would devote ourselves to the major advances in the tropical cyclone research since early days of the mid 19$^{th}$ century to the end of the 20$^{th}$ century with special emphasis on the north Indian Ocean. We focus in section 2 on the climatological aspects, which remained dominant till mid 1950's and are being pursued even today. Section 3 in concerned with the observational facts on tropical cyclones on global and regional scales and their synthesis as the quantity, quality and the scope of observations improved during 1950's to 1980s. We particularly cover the role played by the weather radar, weather reconnaissance aircraft and weather satellites in providing new observations, which have become operationally so relevant that no weather service can now function without adequate observational support from weather radars and weather satellites. Section 4 traces the progress with respect to a very important area in cyclone track prediction and section 5 covers the fundamental difference made to the understanding of the dynamics of the tropical cyclogensis by the theoretical ideas beginning from mid 1960s. These ideas which ultimately have led to successful simulation of tropical cyclone formation and its intensification processes, in symmetrical and asymmetrical frameworks, on computer and testing sensitivity of the processes on various factors like initial vortex strength, SST and land fall etc. Also are provided brief discussion on the application of highly resolved numerical dynamical models, embedded within the global general circulation models, introduced since 1990's in predicting the complete interactive problem of intensification and movement of the cyclonic vortex. Recent advances on the subject and suggestions for further work for the Indian Ocean basin are covered in section 6. Conclusions are offered in section 7.

## 2. Early history, definitions and climatological aspects of tropical cyclones

### 2.1. *Historical perspective of the north Indian Ocean tropical cyclones*

Ancient mariners over the trade-rich north Indian Ocean must have known the fury of storms over the seas but they left little account of their experience in a documented format. During the early period of the domination of this trade by the Portuguese, the Dutch, the English and the French from the $16^{th}$ century to the middle of the $19^{th}$ century, the position had not much changed and the shipping suffered major losses when caught accidentally in a blowing storm over the seas as there was hardly any means to detect the storm and inform the shipping about impending danger. To Henry Piddington, an employee of the English East India Company, we owe the earliest scientific studies of the storms of the north Indian Ocean. Piddington had come to India in 1838 and he first served as a curator of the Calcutta Museum of Geological History and later became the President the Marine Court of Calcutta. He had himself met with the horrible experience of passing through a hurricane and as such had devoted himself for nearly 15 years to the study of tropical storms over the north Indian Ocean with the data available from ship logs at the Calcutta Marine Court. He published a series of 23 Memoirs (Piddington 1839-1858) consisting of 50 papers, dealing with the storms, which occurred during 1839-1851 in the Journal of the Asiatic Society of Bengal, which was the only scientific journal available then in India. He had coined the term "Cyclone" from a Greek word "Kuklos" (meaning coils of snake) and the word since then has been used to describe the tropical storms over the north Indian Ocean just like local words like typhoon, Willy and hurricane describe the phenomenon over the north Pacific, the Australian and the north Atlantic regions respectively Piddington (1864) in his book on the "Sailors handbook of storms" had stated that terms like gale, storm and hurricane, other than cyclone, used to describe the phenomenon were not apt as these terms refer to the Beaufort wind strength scale, rather than the characteristic structural feature of spiraling of strong winds in the vicinity of the center of a tropical cyclone. Meldrum and Alexander Thom, who were contemporaries of Piddington, had engaged themselves with the study of the tropical storms over the south west Indian Ocean, based on the records then available at the Mauritius Observatory.

The destructions caused by a severe cyclone which had struck Calcutta in October 1864 and had sent a huge storm surge up the Hooghly river destroying over 80000 human lives with colossal loss to shipping and followed by another severe cyclone along coastal Orissa, had prompted the Bengal Chamber of Commerce to recommend to the Government of Bengal and the Government of India to establish a regular scientific system of storm warning for the Bay of Bengal. This action in a way, along with other considerations, led to the establishment of the India Meteorological Department (IMD) in 1875 under the Central Government of India. The storm warning system was first established for the Bay of Bengal storms at Calcutta in 1865 and for the Arabian Sea storms in Mumbai by 1882. The notorious False Point Cyclone of $22^{nd}$ September 1885, which had caused terrible destruction of life and property along Orissa coast, had led Blanford, the first Head of the IMD, to introduce a system of storm warnings to all the Indian ports including those in Myanmar Coast in 1886. The system underwent several improvements over the years and in 1970s Dr. P. Koteswaram, the then Director General of Meteorology of the IMD, revamped it. Now three storm warning centers at Calcutta, Chennai and Mumbai are operating with assigned area of responsibility for national and international requirements and a centre for tropical cyclone research functions at Chennai under the IMD. These centres have access to data from powerful storm warning radars all along the east and the west coasts of India. Besides online weather satellite data, data from deep Ocean Meteorological Buoys as well as conventional observational systems of the IMD help in keeping operational watch. Public address system for distribution of storm warnings through press, radio, TV and even a satellite-based address system are also in place. In spite of all these aids, although no tropical storm goes undetected or hits the coast without warning, precious lives are still lost along the different coasts of the north Indian Ocean. There have been over 20 tropical cyclones in the historical period since 1737 which have struck the coasts of Bangladesh and India in which death toll has exceeded 5000 which had gone up to even 300,000 and 1,40,000 in two Bangladesh cyclones of 1970 and 1991 respectively. The super cyclone of Orissa (India), on 29 October 1999 took a toll of over 15,000 lives in which the maximum wind touched 140 kt and the lowest estimated - central pressure was 912 hPa. An estimated storm surge reached about 7.5 m above the astronomical tide on the sea level (several papers in this special volume of Mausam have dealt with the scientific study of this cyclone).

The study of tropical cyclones of the north Indian Ocean became an important area of investigations from the beginning of IMD. Blanford (1877) published a catalogue of 112 recorded cyclones in the Bay of Bengal for the period October 1737 to November 1876 and he also included the results of his studies in his book (Blanford, 1883) "The Indian Meteorologist's Vade-

**TABLE 1**

**Definitions used internationally to describe the intensity of tropical weather disturbances out at Seas**

| Definition the system | Maximum sustained surface wind in circulation at sea |
|---|---|
| Low (L) | Less than 17 kt or 31 km/hr |
| Depression (D) | 17-33 kt or 31 – 60 km/hr |
| Cyclonic storm (CS) | Between 34 and 47 kt or 62-82 km/hr |
| Severe cyclonic storm (SCS) | Between 48 and 63 kt or 89 to 117 km/hr |
| Very Severe Cyclonic Storm or hurricane/typhoon (VSCS) | Above 64 kt on 117 km/hr (≥118 km / hr) |

Mencum". Chamber (1882-85) published a list of 70 cyclones that had formed in the Arabian Sea for the period May 1848 to July 1881, which was subsequently updated by Dallas (1908) up to 1889 with tracks of the cyclones included. Normand (1925, 1926) also published storm tracks in the Bay of Bengal and the Arabian Sea. Since then IMD has published two atlases of the storm tracks (IMD 1964 and 1979). The tracks for the period 1970 onward are published every year in the IMD's Journal, MAUSAM. A Major pioneering attempt was made by Eliot during 1870 to 1890 to study tropical cyclones and the results of his earnest labour were published in several papers in different volumes of the Memoirs of the India Meteorological Department. He also published major results in a book form (Eliot 1900) for information and guidance of sailors navigating in the Bay of Bengal and a second and improved version was published in 1905. As the subject of tropical cyclone was still in its infancy, Eliot wrote, "We have still too much theory and too little accurate information of the details of cyclonic phenomenon. Progress, therefore, depends more upon accurate registration of phenomenon by sailors than upon discussion of theories". Eliot had recognized the role of convergence in the large scale horizontal winds near the center of disturbed weather with associated vertical motion in the formation of tropical cyclone over sea as he wrote "Where the supply of moisture was abundant and friction to air flow was least". He further emphasized when such a disturbance is started, the air at or near the earth's surface reverts toward the center from all directions and the actual motion which result from such a rush toward the central area of disturbance is always rotatory. The air is drawn into the center, but heat is not drawn directly to it. The air particles move by a spiral path to the center. Every cyclonic storm that is investigated in whatever part of the world it occurs furnishes fresh evidence and confirms the spiral theory of the motion of air in cyclones. Such a motion of air is called a cyclonic circulation and may be very feeble or it may be violent as to constitute a dangerous storm". Eliot also estimated the source of energy of the cyclone as "Forty times as much water would be condensed and poured down as rain as the Sun is able to evaporate in the same interval. Hence also forty times as much energy would be given out by the condensed aqueous vapour to the surrounding air as could be given by the direct action of the Sun. This action might be twenty, fifty or even one hundred sun powers". Thus, Eliot clearly considered latent heat of condensation of water vapour as the chief motive power of cyclonic storms.

### 2.2. *Definitions*

Under the WMO an international system of definitions about tropical weather disturbances (Table 1) has been adopted, based on the maximum sustained surface winds in their circulation when a disturbance lies on the sea. In India an intermediate strength between depression and cyclonic storm, is categorized as deep depression with sustained wind strength between 28 and 33 kt. Besides another category has been added for the Indian region defined as Super Cyclonic Storm (SUCS) in which the sustained wind strength exceeds 120 kt. The cyclone of 29 October 1999, which had hit Orissa, belonged to the highest intensity category of SUCS, which is of very rare occurrence in north Indian Ocean. SUCS is analogous to super hurricane in the Atlantic and super typhoon in the western north Pacific regions respectively. Cyclone potential scale ascending between category 1 to category 5 have been defined by Jayanthi (1999) with maximum wind strength lying between less than 36 kt for category 1, between 36 to 75 kt for category 2, between 76 to 115 kt for category 3, between 116 to 155 kt for category 4 and more than 155 kt for category 5. This is the same as followed in USA. Orissa super cyclone belonged to category 4 at its peak intensity, whereas the super hurricane Katrina of August 2005 in the Gulf of Merico had even reached the highest intensity of category 5 prior to its landfall. Jayanthi (1999) has also defined the coastal vulnerability scale for different sections of the Indian coast in terms of the likely damage. According to this criterion the highest category of cyclone disaster coastal risk zones lies over the coastal belt of West Bengal and Bangladesh as well as a long south

**TABLE 2**

**Number of tropical cyclones crossing coastal states of India (1981-1996)**

| State | Category of System | April | May | October | November | December |
|---|---|---|---|---|---|---|
| West Bengal | CS | 0 | 0 | 3 | 1 | 0 |
| | SCS | 0 | 5 | 3 | 1 | 0 |
| | Total | 0 | 5 | 6 | 4 | 1 |
| Orissa | CS | 0 | 0 | 5 | 1 | 0 |
| | SCS | 0 | 4 | 7 | 2 | 0 |
| | Total | 0 | 4 | 12 | 3 | 0 |
| Andhra Pradesh | CS | 1 | 3 | 16 | 5 | 1 |
| | SCS | 0 | 4 | 10 | 13 | 1 |
| | Total | 1 | 7 | 26 | 18 | 2 |
| Tamil Nadu | CS | 1 | 2 | 3 | 9 | 2 |
| | SCS | 1 | 1 | 2 | 8 | 6 |
| | Total | 2 | 3 | 5 | 17 | 8 |

Tamil Nadu coast. Bulk of the east coast of India between Orissa and Andhra Pradesh falls in the second most hazardous zone. North Konkan and Gujarat-Saurashtra coasts fall under the third most dangerous category and the coastal Kerala, Karanataka and Goa fall in the fourth most dangerous category.

### 2.3. *Climatological studies on north Indian Ocean tropical cyclones*

The period 1877 to 1970 has witnessed several important studies on constructing the climatology of the cyclones and using the collected information for objective track prediction as well as for vulnerability analysis to the threat of cyclones. Besides the climatological studies already mentioned by Blandford, Chambers, Dallas Eliot and Normand upto 1925 and the storm tracks atlases of the IMD (1964 & 1979) four other important climatological studies appeared in 1950s to 1970s (Rai Sir car 1956, Rao and Jayraman 1958 and Roy Choudhuri *et al.* 1959 and Raghvendra 1973) which highlighted several important aspects such as the places of genesis and intensification of the cyclones, movement of the cyclones and their re-curvature positions and land fall points on 1°×1° scale on the Indian coasts etc. Climatological tracks information, in combination with persistence was used for the first time in an objective manner by Sikka and Suryanarayana (1972a&b) for forecasting the movement of cyclonic disturbances with a fair degree of success up to 48 hrs. They also built probability ellipses for the potential land fall zones. Later (Dutta and Gupta 1975) provided a computer-based analogue forecasting technique. Both these techniques, by Sikka and Suryanarayna, Dutta and Gupta and were in operational use in IMD till 1980s, before a dynamical forecasting system was put in place. Mooley (1980, 1981a&b) applied the climatological information to validate the Poisson probability model to severe tropical cyclones striking the Bay of Bengal coast and also showed the increase in the annual frequency of severe cyclones in the Bay of Bengal between 1960s to 1970s. However as the present study, shows this increase has not been sustained and instead a decrease in frequency of total systems, cyclonic storms and severe cyclonic storms have occurred in the recent decades since 1980s inspite of the fact that the north Indian Ocean has shown a small increasing trend in the SSTs in the last three to five decades.

**TABLE 3**

**Number of tropical cyclones crossing different countries surrounding the Bay of Bengal (1981-1994)**

| Country | Total Number of | | |
|---|---|---|---|
| | CS | SCS | VSCS |
| India | 256 | 113 | 54 |
| Bangladesh | 68 | 41 | 26 |
| Myanmar | 33 | 17 | 10 |
| Srilanka | 5 | 0 | 0 |
| Dissipated over the Bay | 78 | 21 | 12 |
| Total | 490 | 192 | 102 |

It is a well known fact of climatology that the cyclonic storms occur prominently in the Indian seas during the pre-monsoon season (March-April-May) and the post-monsoon season (October-November-December)

**TABLE 4**

**Decaded average of cyclonic disturbances (Depressions and higher intensity systems) that formed in north Indian Ocean on annual basis period (1891-2000)**

| Decade | North Indian Ocean disturbances | | | Bay of Bengal disturbances | |
|---|---|---|---|---|---|
| | All cyclonic disturbances above depression category | C.S. | SCS and higher intensity | Disturbances above depression category | All cyclonic storms and above |
| 1891-1900 | 164 | 58 | - | 118 | 49 |
| 1901-1910 | 169 | 58 | - | 130 | 43 |
| 1911-1920 | 154 | 52 | - | 124 | 42 |
| 1921-1930 | 187 | 67 | - | 155 | 56 |
| 1931-1940 | 167 | 61 | - | 133 | 50 |
| 1941-1950 | 173 | 51 | - | 139 | 42 |
| 1951-1960 | 136 | 41 | - | 111 | 32 |
| 1961-1970 | 153 | 63 | - | 124 | 49 |
| 1971-1980 | 161 | 69 | 45 | 103 | 51(30) |
| 1981-1990 | 104 | 36 | 18 | 75 | 32(16) |
| 1991-2000 | 63 | 40 | 16 | 33 | 28(9) |

*Note* : Before the operational satellite era till 1970, the intensity of systems of SCS and above category was uncertain and hence the number are not given in the 4$^{th}$ column for the decades upto 1961-1970

and the maximum frequency is in the two months of October and November. The Bay of Bengal cyclones most frequently strike the Andhra Pradesh coast with a second maximum in Tamil Nadu coast. Recurving storms mostly strike Orissa and West Bengal coasts and some of them even hit Bangladesh coast. On country-wise basis nearly half the number of cyclones forming in the Bay of Bengal have struck the coastal states of India (Table 2). Table 3 shows the numbers striking different countries in the Indian Ocean basin. It is also noteworthy that a significant number of cyclones dissipate on the Bay of Bengal itself, particularly those forming in late November to end of December period. This could be due to influence of upper tropospheric troughs which advect cold air into northwest of the storm position and the storms also traveling over waters of the north Bay of Bengal which have cooled significantly by December.

Table 4, prepared on the basis of data by IMD (1979) and subsequent updates by them in their annual storm season reports, provides decadal averages of the total number of cyclonic depressions and higher intensity systems on annual basis that formed in the Arabian Sea, Bay of Bengal as well over land (in the monsoon season).

This list includes systems forming in the monsoon season (June to September) as well, which mostly attain intensity of depressions and only occasionally reach CS category. Data on SCS have been provided after 1971 during the operational satellite era as the intensity identification became more reliable. Table 4 shows the following :

(*i*) Marked inter-decadal variability in the total number of cyclonic systems and number of cyclonic storms for the entire north Indian Ocean basin and for the Bay of Bengal as well.

(*ii*) Inter-decadal fluctuations within reasonable limit for the nine decades between 1891-1980 with the maximum occurring the decade of 1921-1930 for both areas for the total number of cyclonic disturbances as well as those that reached the cyclonic storm or higher category.

(*iii*) A drastic decrease in the number of total cyclonic disturbances to less than even 50% of the average of earlier 10 decades (1891-1990) in the last standard decade of 1991-2000. This decrease is, however, noticed from the decade of 1981-90 and has continued into the first five years (2001-2005) of the on going decade.

(*iv*) Not only the total number of cyclonic disturbances have drastically decreased but the number of cyclonic storms and severe cyclonic storms on the decadal basis have also shown significant decrease in the last two standard decades. Although significant inter-annual and inter-decadal changes in the frequency of tropical cyclones are noted in other tropical ocean basins too, but a systematic decrease over two or three past decades has perhaps only happened over the north Indian Ocean. The

**TABLE 5**

**Frequency of landfalls of C.S. and higher intensity system over Myanmar coast on multi-decadal basis**

| Multi-decadal period | No. of CS and higher intensity systems that struck Myanmar coast |
|---|---|
| 1891-1930 | 27 |
| 1931-1970 | 08 |
| 1971-2000 | 08 |

cause for this is yet unexplained. Long-term changes in the frequency of monsoon depressions/storms in the Indian region has been reported in number of studies in India. (Srivastava *et al.* 2000, Kumar & Dash, 2001 Sikka 2005 has shown that although number of monsoon depressions have decreased, the number of low pressure areas forming in the monsoon season has not shown any trend. What has happened is that since 1970s several monsoon lows are not intensifying into depression stage. Understanding the cause for this is also a matter of urgency for Indian researchers. Tropical cyclones in the Bay of Bengal are important water resource for the states along the east coast of India and this huge reduction in their frequency should be a matter of concern for the water resource managers in the lean seasons. There is scope for the meteorologists to look into the possible causes of this reduction. It could as well be that the tracks of cyclonic storms in the west Pacific basin have changed such that the incipient disturbances, which track along SE Asia into the Bay of Bengal, no longer enter the Bay with normal frequency. It could also be due to general circulation change over the Indian region, which would not promote intensification of incipient lows into depressions or cyclonic storms. Further research is urgently needed as the data are now available through the NCEP/NCAR re-analysis (Kalnay *et al.,* 1996) and through ERA-40 re-analysis by the ECMWF.

Another significant fact is reduction in landfall of tropical cyclones along Myanmar coast. This was brought to our notice by Kulshrestha (personal communication) and we have verified it on multi-decadal period basis as given in Table 5. A preliminary analysis of the storm tracks show the drastic reduction to one third of the number for the four decades 1891-1930, four decades 1931 to 1970 in the frequency of land falling storms along Myanmar coast which is maintained in the three decades of 1971-2000 also. Table 5 would suggest some change in the prevailing circulation in the two cyclonic storm seasons such that storms since 1960s have avoided hitting Myanmar coast. The causes for this reduction must be examined by the researchers more carefully. However, May in 2004 a severe cyclonic storm had struck Myanmar coast. There is also considerable scope to examine the climatological records on tropical cyclones in the north Indian Oceans; particularly with respect to changes in the western north Pacific basin as well as with respect to global climatology on tropical cyclones.

## 3. Observational study of tropical cyclone genesis – conventional, radar, aircraft reconnaissance and weather satellites based studies

As mentioned earlier research on tropical cyclones in the north Indian Ocean began in India since 1839 with the pioneering work of Piddington and toward the end of the $19^{th}$ century, it was pursued with great vigour by John Eliot in IMD. Between 1920s to 1950s, during which period several Indian scientists had joined IMD, this research was carried on by several illustrious Indian investigators like K.R. Ramanathan, B.N. Desai, S. Mull, P.R. Pisharoty, P. Koteswaram, Y.P. Rao and others. Those were the days when theory of frontal instability was in development and peak stages in mid-latitude countries and as such the Indian meteorologists like. (Desai & Rao 1954), Desai (1967) and others also looked for the interplay of different air masses along the Intra-Tropical Front (ITF) [presently known as Inter-Tropical Convergence Zone (ITCZ)] for the growth of a low-pressure system out at sea into a mature cyclone. It is note worthy that the IMD, in that early period, had organized a Special Field Programe during 1930s along coastal Andhra Pradesh with special radiometer sond observations to understand the thermal structure of land falling storms. With the establishment of new synoptic meteorological concepts introduced by Malkus, Riehl and others in USA, emphasing the role of strong upper tropospheric divergence overlying lower tropospheric convergence associated with an incipient tropical low pressure area, this mechanism became the dominant one to explain tropical cyclogensis in the north Indian ocean too (Koteswaram and George, 1957). Also Koteswaram and Gaspar (1956), examined the surface level structure of cyclones in the north Indian ocean by composting surface meteorological data. For want of observations they could not have done similar work with upper air data as was done in several studies in USA by Jordan (1952, 1958a&b and 1961) for the Atlantic hurricanes. Such a work on the composting of upper air data in the vicinity of developing, non-developing and dissipating cyclones for the north Indian Ocean needs to done now as not only the radio-sonde network around the Bay of Bengal has improved since then but satellite data have also become available in large quantity in the last two decades.

### 3.1. *Life cycle and structure of tropical cyclone*

Genesis of tropical cyclones in the regional context has attracted the attention of many researchers worldwide

**TABLE 6**

**Best track position and other parameters for Bay of Bengal super cyclonic storm (25-31 October 1999) after Kalsi (2003)**

| Date | Time (UTC) | Centre Lat. °N / Long. °E | Cyclone intensity in T-number | Estimated central pressure (hPa) | Estimated maximum sustain surface wind (kts) | Estimated pressure drop at the center | Grade |
|---|---|---|---|---|---|---|---|
| 25 Oct 1999 | 06 | 12.0/98.5 | 1.5 | 1004 | 25 | 2 | D |
| | 09 | 12.5/98.5 | 1.5 | 1004 | 25 | 2 | D |
| | 12 | 12.5/98.0 | 1.5 | 1002 | 25 | 4 | D |
| | 18 | 12.5/98.0 | 1.5 | 1002 | 25 | 4 | D |
| 26 Oct 1999 | 00 | 13.5/96.5 | 2.0 | 1002 | 30 | 4 | DD |
| | 03 | 13.5/95.5 | 2.0 | 1002 | 35 | 6 | CS |
| | 06 | 13.5/95.0 | 2.5 | 1002 | 35 | 6 | CS |
| | 09 | 14.0/94.5 | 2.5 | 1002 | 35 | 6 | CS |
| | 12 | 14.5/94.0 | 3.0 | 998 | 45 | 10 | CS |
| | 15 | 15.0/93.5 | 3.0 | 998 | 45 | 10 | CS |
| | 18 | 15.0/93.5 | 3.0 | 998 | 45 | 10 | CS |
| | 21 | 15.0/93.0 | 3.0 | 998 | 45 | 10 | CS |
| 27 Oct 1999 | 00 | 15.5/943.0 | 3.0 | 998 | 45 | 10 | SCS |
| | 03 | 16.0/92.0 | 3.5 | | 55 | 16 | SCS |
| | 06 | 16.5/91.5 | 3.5 | 992 | 55 | 16 | SCS |
| | 09 | 16.5/91.0 | 3.5 | 992 | 55 | 16 | SCS |
| | 12 | 17.0/90.5 | 3.5 | 986 | 65 | 16 | VSCS |
| | 15 | 17.0/90.5 | 4.0 | 986 | 65 | 20 | VSCS |
| | 18 | 17.0/90.5 | 4.0 | | 65 | 20 | VSCS |
| | 21 | 17.0/90.0 | 4.0 | 986 | 65 | 20 | |
| 28 Oct 1999 | 00 | 17.5/90.0 | 4.0 | 986 | 65 | 20 | VSCS |
| | 03 | 18.0/89.0 | 4.5 | 978 | 77 | 30 | VSCS |
| | 06 | 18.0/88.5 | 5.0 | 968 | 90 | 40 | VSCS |
| | 09 | 18.0/88.0 | 5.5 | 956 | 102 | 52 | VSCS |
| | 12 | 18.0/88.0 | 6.0 | 940 | 115 | 66 | VSCS |
| | 15 | 19.0/87.5 | 6.5 | 928 | 127 | 80 | SuCS |
| | 18 | 19.3/87.0 | 7.0 | 912 | 140 | 98 | SuCS |
| | 21 | 19.3/87.2 | 7.0 | 912 | 140 | 98 | SuCS |
| 29 Oct 1999 | 00 | 19.6/87.0 | 7.0 | 912 | 140 | 98 | SuCS |
| | 03 | 19.9/86.7 | 7.0 | 912 | 140 | 98 | SuCS |
| | 06 | 20.5/86.0 | 7.0 | 912 | 140 | 98 | SuCS |
| | | **Crossed Orissa coast near Paradip between 0430 and 0630 UTC** | | | | | |
| | 12 | 20.5/86.0 | | Not estimated as on land or dissipating stage | | | SuCS |
| | 18 | 20.5/86.0 | | | | | SCS |
| 30 Oct 1999 | 00 | 20.5/86.0 | | | | | SCS |
| | 03 | 20.5/86.0 | | | | | CS |
| | 06 | 20.5/86.0 | | | | | CS |
| | 12 | 20.5/86.0 | | | | | CS |
| | 18 | 20.5/86.0 | | | | | DD |
| 31 Oct 1999 | 00 | 20.5/86.0 | | | | | DD |
| | 03 | 21.0/87.0 | | | | | D |

since 1950s. Excellent accounts about such studies are available in several books and monographs like Dunn and Miller (1964), Riehl (1979), Anthes (1981), Asnani (1991) Lighthill *et al.* (1993) and others. Dunn (1940) was among the first to investigate tropical cyclone genesis in the Atlantic. WMO (1993, 1995a&b) have also published reports/guide for work on tropical cyclone genesis and track prediction.

By 1950 tropical cyclone was recognized to be an important transient scale intense tropical weather system, which was associated with extremely hazardous weather events of great concern to society. Since then our understanding of this phenomenon has enormously grown due to increased and improved surveillance by radars, aircraft satellites as well as numerical modeling and simulation and theoretical studies. Mechanisms for vorticity intensification in lower and middle troposphere that lead to the generation of SCS, VSCS and SUCS have been examined through observational, theoretical and modeling approaches and each approach helped the other to build our present knowledge-base on the phenomenon. Studies of this kind have helped not only operational forecasters but also have brought a consensus among the observational points of view and that of the modelers concerning the structure and nature of large scale and meso-scale conditions favourable to SCS development.

A tropical cyclone develops from an incipient low pressure system over a period of a few days existing over warm tropical ocean with the SST exceeding 26° C (Palmen 1948). Many many incipient lows from in the ITCZ but only a few could develop into a tropical depression with an organized central area and sustained winds in circulation between 17 to 33 kt at a distance of about 150 - 200 km from the central region of the depression. The pressure drop at the center from a "low" stage to the stage of a depression is about 5 to 10 hPa and takes 2-3 days. However due to some special large scale and meso scale conditions hardly 50 percent of the lows develop into the depression stage. About 50 percent of the depressions develop into the CS storm stage and only 40-50 percent of CS would develop into SCS/VSCS stage. Further intensification to SUCS is rather rare as hardly 10 - 15 systems could reach the SUCS category in the north Indian Ocean during the last 300 years or so; the last one being the Orissa SUCS. A SUCS, like the Orissa one of 29 October 1999, passes through different stages beginning with a pressure drop of 5-10 hPa (central pressure about 1000-995 hPa) in 2 to 3 days from a low-pressure area to a depression. Further pressure drop by another 10 hPa (to a value of 990-985 hPa) in subsequent 12-24 hrs and drastic pressure drop by a further 15-20 hPa (to a value of 975-965 hPa) occurs to reach SCS stage in the next 12 hours. Ultimately intensification occurs to VSCS and even to SUCS categories with central pressure dropping between 965 to 910 hPa. The process of intensification from a depression stage to VSCS/SUCS stage is accomplished in (barely) about 48 hours time span. This rapid intensification of the vortex in matter of hours, observed only in about 10-20 percent of the total number of low-pressure areas in the storm season, makes the prediction of intensification very hard. What exactly happens in this process remains a mystery though meso-scale convective organization coupled with intensification of air sea fluxes could be responsible for the merger of deep convective cells to form the eye wall convection (Simpson *et al.*, 1997, Ritchie and Holland (1999). Venkatesh (in this volume) has examined the possibility of vortex merger on meso-scale in the intensification of the Orissa SUCS of October 1999. Table 6 illustrates the intensifications process, as estimated by the IMD in Post-Orissa Super Cyclone analysis, which could be taken as a typical one for intensification from Depression to SUCS category. At the stage of a depression the maximum sustained winds are about 150-200 km away from the center of the depression and as the intensification proceeds, the maximum wind belt shifts toward the center as well as squeezes in width such that at the VSCS/SUCS stage the maximum wind is within about 30-50 km of the center and the "eye" of the cyclone has a width of about 20-40 km. Also as intensification proceeds, spiraling cloud bands with surging winds approach the central region and a wall cloud develops near the maximum wind zone. Characteristics eye of the storm is observed at the center in mature stage. A mature cyclone has a multi-scalar structure consisting of environmental flow 1000 km away from its center, an outer core area spanning about 500-1000 km and an inner core area of about 100 km radius. The dynamics in each region is different but interacting one. Carrier *et al.*,(1971) have examined different aspects of the dynamical structure of a mature SCS/VSCS/SUCS which consist essential of a primary swirling circulation in the near inner core region with strong updraft in the wall cloud region and a secondary inflow spiraling from 500 km toward the inner core with meso-scale organized updrafts and downdrafts. At the upper troposphere level there is cyclonic motion over the small central region with strong outflow coming out of asymmetrically placed anticyclonic circulations around the centre (Shea and Gray 1973, Willoughby 1988). The cyclonically swirling winds are strongest just above the frictional boundary layer and are not much reduced till about 500-400 hPa. Observations also show that eye wall updrafts slopes upward and hence the eye wall is not exactly vertical. The meso-scale vertical velocities in the inner core area are typically a few meters per second and could be obtained from air-borne/ground based Doppler radars. It is the radial inflow or secondary circulation which controls radars reflectively coming out of different

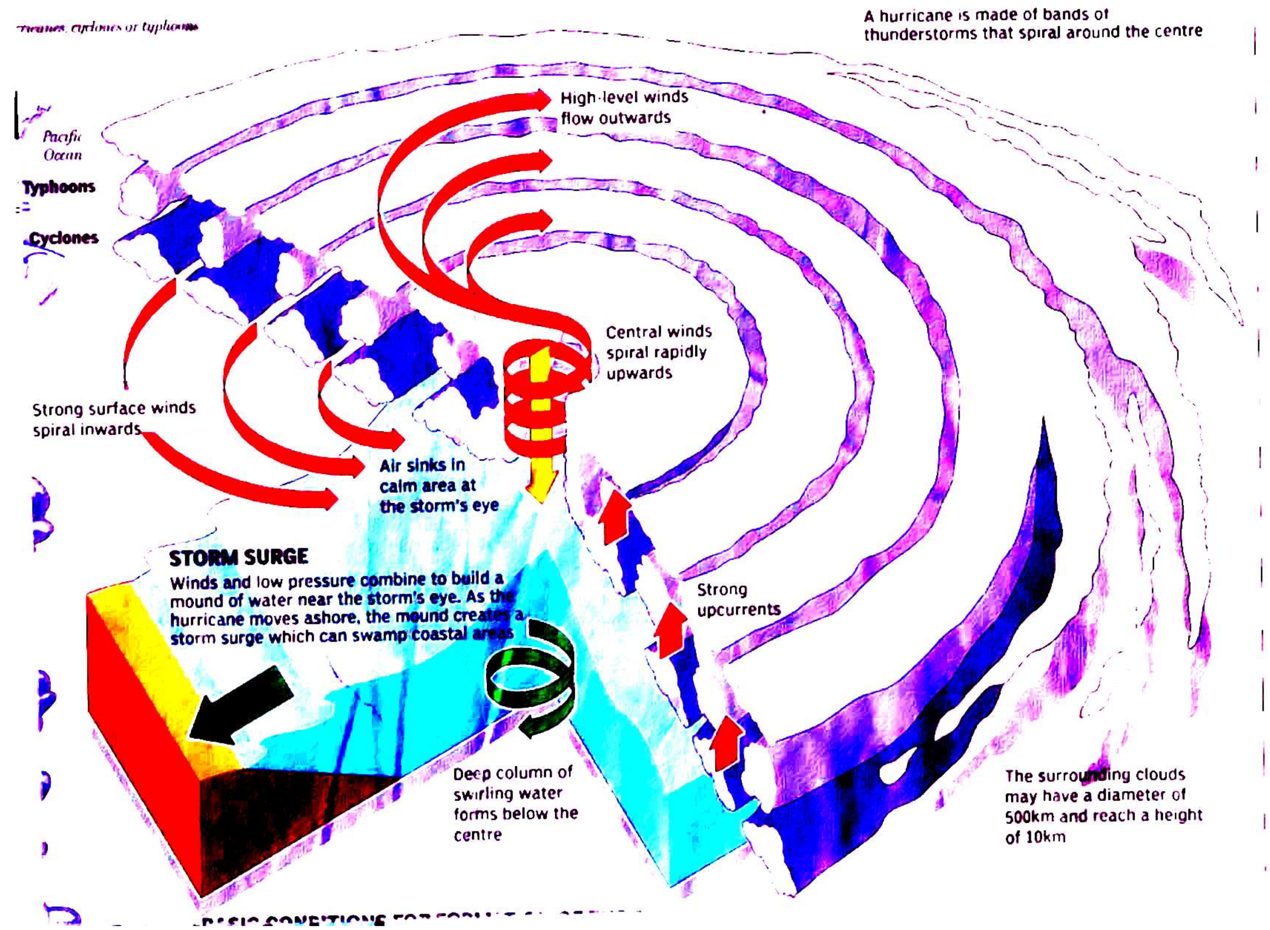
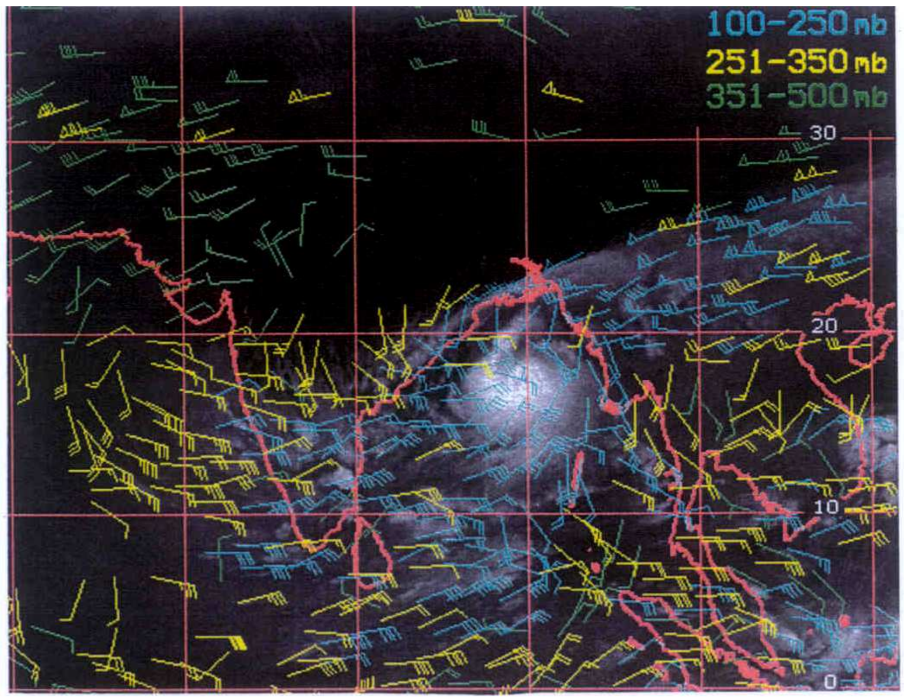


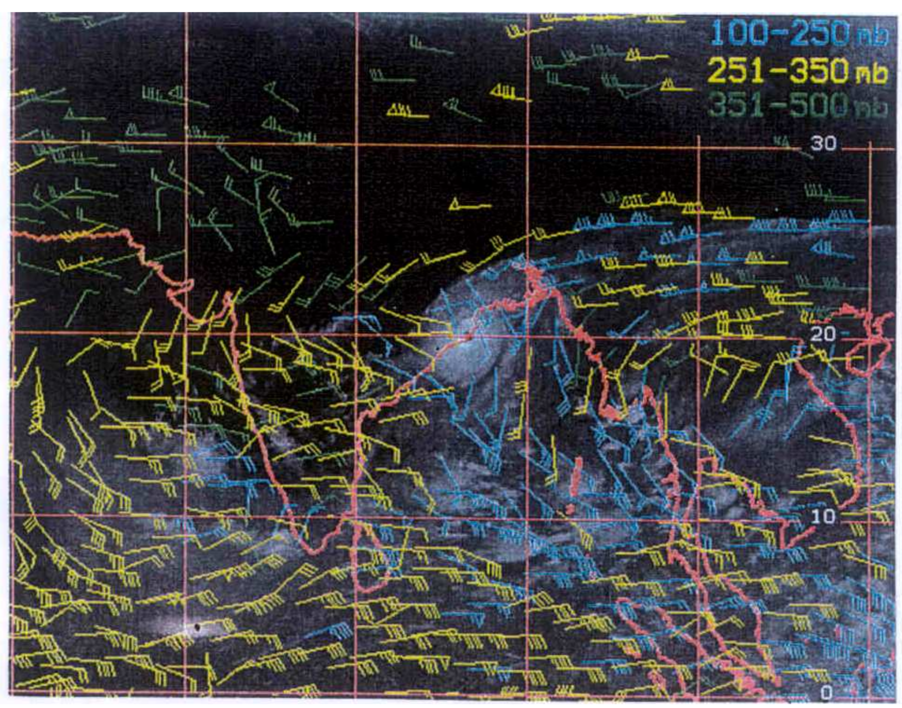

**Fig. 1.** Schematic view of structure of a matured tropical cyclone

types of hydrometeors (liquid water, ice particles, grapples etc.). Radar studies also show (as in the case of Orissa SUCS discussed by Kalsi and Srivastava in this Volume), the eye diameter undergoes dynamic changes on the scale of hours along with changes in radar reflectivity. Eye wall accounts for 25% to 50% of the rainfall in the inner core area where vertical velocities in the highly convective clouds reach even up to 5 to 20 meters per second. Ring like structures are also observed in the inner core region. Any hydrometeors which do not fall as rain in the inner core regions are distributed horizontally by the strong upper tropospheric outflow. These plus several other features of the storm structure, intensity of convection and rainfall were determined through exhaustive studies done in USA by airborne Doppler and ground-based Dopplar radars. They have been also validated in several radar investigations in India as reviewed by Ragahvan (1997). The introduction of Doppler radars is very recent in India covering 4 stations on the east coast and since then no severe cyclone has approached close to any of these radar stations. At mature stage of a VSCS/SUCS, a warm core structure develops and further drop in central pressure no longer takes place. Maximum wind speed reaches above 64 kt reaching even up to 175 kt At the terminal stage (either on landfall or over sea) transformation takes place to cold core structure with central pressure rise of about 20 to 50 hPa in 24 hours. All lows do not pass through all these four stages. Important stage is the drastic fall of pressure from 20-100 hPa and rise of maximum sustained wind from 40 to over 150 kt within about 30-50 km of the center with the cloud-free eye of the storm becoming visible. Pressure gradients near the storm center may even exceed 2 hPa/km within about 50 km of the centre in the region of the eye wall cloud, with penetrative convection even piercing the tropopause and finally descent of air in the eye region with cloud free eye or with suppressed convection. A mature cyclone has a central characteristics "eye" structure but is not completely in steady state or stopped changing with time as irregular changes in eye structure (width, shape) continue to take place and maximum winds also change irregularly with time within about 10% of the

(a)




(b)




**Figs. 2(a&b).** Water vapour channel view of the Orissa cyclone and its near peak intensity (after Kalsi 2003), (a) 0000 UTC of 28 October 1999 and (b) 0600 UTC of 29 October 1999 mean. This is discussed in the case of Orissa SUCS by Kalsi and Srivastava in this Volume. Terminal or dissipation stage of mature cyclone occurs mostly on landfall. However, there are observations over the north Indian Ocean as well as in other ocean basins too which show that SCS do weaken over oceanic areas

(*i*) under the influence of mid-latitude troughs which bring intrusion of colder air from the northwest,

(*ii*) storm traveling over colder SST region and

(*iii*) storm changing into a sub-tropical cyclone pole ward of 30° latitude in the south Indian Ocean, western north Pacific Ocean and north Atlantic Ocean basins.

Asymmetry in the near-surface distribution in tropical cyclones is characteristics of tropical cyclones of the north Indian Ocean (Koteswaram and Gaspar 1956) inward spiraling of streamlines is a very marked feature and radial component of the wind is strong in the lower troposphere. Other features which have come out of studies in India are like tangential winds do not much decrease from top of the boundary layer to 400 hPa level and the spiraling-out flow in the upper troposphere is also marked. Fig. 1 shows the schematic of a mature tropical cyclone, Fig.2, after Kalsi (2003), shows the upper tropospheric outflow pattern of the Orissa super cyclone.

Much of the structural features of the SCS were known as a result of data collected in the research aircraft reconnaissance on the Atlantic hurricanes, assembled and analysed in many studies (Simpson 1952, Malkus, 1958, Riehl & Malkus, 1961, Malkus and Riehl 1960, Malkus *et al*. 1961 La Seur & Hawkins 1963 Senn and Hiser 1959, Yanai 1961, Shapiro 1977, 1992, Sheets (1967, 1968 & 1980 Willoughby 1988, Mark & Houze 1987 and others). During 1960’s to 1980, Prof. Willian Gray and his collaborators pursued a series of observational studies on the tropical cyclone genesis and intensification which now from our basic knowledge on the subject. Gray (1968) provided a global view of the origin of tropical storms with statistics about their formation in different basins. North Indian Ocean contributes nearby 15% and the adjoining western north Pacific contributes over 30% of the global tropical cyclone formations. Gray (1975) defined a mature cyclone as a closed circulation warm core system of at least 5 degrees in diameter which extends vertically through most of the troposphere with little vertical slope and where relative vorticity at lower levels and inner 100-200 km radius is greater than $10^{-4}$ $sec^{-1}$. Frank (1977) and Shea & Gray (1973) used observations to examine hurricane inner core region and prepared a composite structure of tropical storms in the western north Pacific basin based on over 18000 soundings around nearly 248 storms, 143 of which had attained typhoon intensity.

The structure was examined in terms of several fields like pressure, temperature, tangential and radial winds, (symmetric and asymmetric), vertical motion, relative vorticity field and budgets of moist static energy with ocean atmospheric fluxes, sectorial angular momentum in different zones of the storm and kinetic energy, Gray (1979) and Mc Bride (1981) have summarized several observational inferences on the tropical cyclones Mc Bride and Zehr (1981) have analyzed vast amount of data on non-developing *vs* developing systems. The non-developing cloud clusters remain in the large-scale environment with lower cyclone genesis potential (GP) such as relative vorticity, lower level convergence at 850 hPa, vertical shear of the wind, which allows greater ventilation of convective heating etc. The opposite takes place in the case for the developing could clusters, which intensify into mature tropical storms. It is important to recognize that GP is quite high in the Bay of Bengal in the pre-and post-monsoon seasons. Roy Bhowmik (2003) has examined the changes in the GP during intensification of the north Indian Ocean cyclones from computer-based analyses and found that the GP attains a peak value 24 to 36 hours prior to the cyclones reaching their highest intensity. However a high value of GP is not always necessarily associated with the intensification process. All these studies have strengthened the hypothesis that once the troposphere favourably arranges its surrounding large-scale circulation, it is the relative frequency and intensity of rain band formation (convective bursts in the eye wall) or meso-scale convection, which is the most critical feature for the development of a mature cyclone. The rain bands help in producing the extra ocean-atmospheric fluxes of energy (sensible and latent heat) which also help in the intensification process. The observations on cloud cluster support this hypothesis as most of the non-developing cloud cluster die within 1 – 2 days and those which develop into mature tropical storms take about 2 to 3 days to reach their peak intensity on warm sea surface. Recognition during 1970s to 1980s that large-scale environmental factors and meso-scale processes play crucial roles in tropical cyclone genesis was a major step in understanding the intensification process. Venkatesh in this Volume discusses the possible role of meso-scale convection in the case of the Orissa SUCS.

### 3.2. *Role of aircraft reconnaissance, radars and weather satellites in tropical cyclone studies*

#### 3.2.1. *Research aircraft reconnaissance*

Soon after the World War II, US Weather Bureau and US researchers began to use research aircraft to probe into developing hurricane disturbances in the Atlantic. Simpson (1954) and Simpson and Street (1955) were the pioneers in this field. After the establishment of the US National Hurricane Project in 1950's, which later gave further stimulus to the establishment of the US National Hurricane Research Laboratory and the US National Hurricane Centre at Miami, many studies were undertaken by the researchers in these two organizations and US Universities, using aircraft probes of the immature and mature hurricanes (Simpson and Street 1955, Colon and Staff NHRP 1961, La Seur and Hawkin 1963, Houze and Colon 1970, Sheets 1967, Erickson 1967, Hawkins and Rubsam 1968, Hawkins and Imbembo 1976 and several others). Palmen and Riehl (1957) and Pfeffer ( 1958) discussed balance of angular momentum in hurricane and emphasized he role of eddy processes in hurricane mechanics. Riehl (1963) studied relation between wind and thermal fields in a steady state hurricane. Aircraft reconnaissance of typhoons in the western north Pacific was also introduced in 1960's and several observational facts, similar to those discovered earlier in the Atlantic hurricanes, were confirmed (Holliday 1977, Weatherford and Gray, 1988).

During the IIOE (1963-65), the very first aircraft reconnaissance mission into a developing tropical cyclone in the SE Arabian Sea was organized during May 21 to 28 1963 (Colon *et al*., 1970). This study revealed several interesting facts about the intensification processes in the pre-monsoon tropical cyclogenesis in the Arabian Sea. In this study the radar structure and other structural features in the wind, pressure and thermal fields were found to be similar to those observed in the Atlantic hurricanes. This study also revealed that the dynamics of the tropical cyclone formation in the north Indian Ocean, at the time of the onset of monsoon, is very similar to as observed in other tropical ocean basins. Earlier work by Elliot, half a century ago, had shown that tropical cyclones develop in north Indian Ocean at the forward edge of advancing monsoon during the pre-monsoon season or of the retreating monsoon in the post-monsoon season. A similar monsoon onset storm (monsoon onset vortex) was probed by aircraft missions during the summer MONEX field program in June 1979 (Krishnamurti *et al*., 1981). In both aircraft reconnaissance missions in May 1963 and June 1979, undertaken over the Arabian Sea, radar and satellite pictures as well as dropsonde data were used. The U.S. Joint Typhoon Warning Centre, Guam, Philippines also organized some aircraft reconnaissance in the north Indian Ocean during 1970's but the data have not much been used in research. Apart from these few studies, no regular aircraft missions are possible for the probing of tropical cyclones of the north Indian Ocean. Lack of such a facility is a great handicap to the Indian meteorological community interested in tropical cyclone research and it would be helpful to operations if aircraft reconnaissance into tropical cyclones in the north Indian Ocean could be organized on regular basis. Data from aircraft probes into the eye of cyclonic storm in the north Indian Ocean would help in the scientific break-trough Indian scientists need to learn more about the storm intensification process.

### 3.2.2. *Radar studies of tropical cyclones in north Indian Ocean*

Weather radar, a major aid to meteorological research and operations, was introduced in USA soon after the World War II. Wexler (1947) pioneered research in this field. Weather radars were soon installed along the US coast affected by hurricanes. Since then S-band (10 cm) and Doppler weather radars have become important tools for tropical cyclone research and operations in USA. India introduced C-Band (3cm) weather radars in 1950's for aviation. Currently a network of 6 overlapping 10 cm cyclone detection radars (CDR) are available on the east coast of India (Kolkata, Paradip, Visakhapatnam, Masulipatnam, Chennai and Karaikal) and 4 stations along the west coast of India (Bhuj, Mumbai, Goa and Cochin). Recently India has also installed four Doppler Weather Radars (DWR) at Kolkata, Sriharikota, Chennai and Masulipatnam on the east coast. More DWRs are under planning Indian researchers, mostly from the IMD and also those who have operational control on data accessibility of their radar network, have used radar data for tropical cyclone research. The pioneering work in this area was begun by De and Sen (1959) and since then several investigators have diagnosed individual cyclones with radar data striking within the range of different stations (Bhattacharya and De 1965, 1976, Raghavan 1990, Raghavan and Veeraraghavan, 1979, Raghavan and Rajgopalan, 1980a, Raghavan *et al*., 1981b, Pande *et al*., 1989, Subramanian 1981 and others). The radar echoes have been studied for a variety of purposes for understanding the genesis of tropical cyclones like the role played by (*i*) pre-cyclone squall line, convective activity in the outer cyclone domain, spiral bands and rain shield in the inner cyclone area, convective bursts in the eye wall area, radar reflectivity pattern, eye wall structure etc. Spiral bands, which are characteristic of deep convective lines, were also associated with developing cyclones in the north Indian Ocean similar to as they were found in the radar studies of the Atlantic hurricanes. Some time a double eye wall has been also noticed in the eye wall convection and the radius of maximum winds is found to almost coincide with the eye wall penetrative convective cloudiness. Smaller eye diameter is associated with VSCSs or SUCSs. The eye diameter found in the case of Orissa Super Cyclone, in its most intense stage, was about 15 km. (Kalsi, 2003 and Kalsi and Srivastava in this Volume). Radar reflectivity in the eye wall zone of the north Indian Ocean storms is also often unsymmetrical around the centre and corresponding asymmetries have been found in the rainfall and wind speed in the inner core region of cyclones. It is also observed that the tightness of the spiral bands is related to higher intensity SCSs. The number of spiral bands, the decrease of eye diameter and the occurrence of double eye wall are also positively correlated with the intensity of the cyclone. Kalsi & Jain (1992) have also found double eye wall structure in satellite pictures of the cyclones in visible channel satellite imagery. Raghavan (1997) has provided and exhaustive account of the radar features of the tropical cyclones found over the north Indian Ocean. The extensive radar studies on individual tropical cyclones in the Indian region validated the findings about the hurricanes of the Atlantic and showed that structurally the radar features observed in hurricanes and Indian Ocean cyclones are quite similar. Mark and Houze (1987) have studied the inner core structure of a hurricane with a Doppler radar. Such a study has not so far been done for the north Indian Ocean cyclones as no cyclone has so far come in the range of Doppler radars in India.

3.2.3. *Satellite studies of tropical cyclones*

Since the introduction of weather satellites in early 1960's, tropical cyclone research and operations have gained immensely from this technological innovation. Fett (1964, 1966 and 1968) was among the pioneers of application of satellite photographic data in understanding tropical cyclone formation and movement. Dvorak (1975), in his very first paper, developed criteria for intensity analysis of tropical cyclones and for forecasting from satellite imagery. He subsequently (Dvorak 1984) refined his technique which is used in India for assigning intensity category to a cyclone, depending upon the diameter of the central overcast cloud area, category of banding etc. Kalsi (in this volume) shows the changes that have been noted as the Orissa super cyclone intensified in satellite imagery. Kalsi (2002) has also provided an excellent account of use of satellite imagery in India in tropical cyclone intensity analyses and forecasting. Satellite imagery for tropical cyclone intensity determination and tracking has become the major products of INSAT being used by the weather forecasters in India and operational tropical cyclone work at present cannot be conceived without this product. Many many studies on hurricanes and typhoon have been made in USA and Japan with satellite data. Valden *et al*., (1998) have even developed a technique for objective estimation of storm intensity by analysis of satellite infrared imagery. An assessment of such a technique in the case of north Indian storms is provided in this Volume by a paper by Loe *et al*.

Considerable number of studies on the application of satellite data (imagery and radiation data) to the study of tropical cyclones in the north Indian Ocean have been published in different Journals since 1970's by Indian researchers. As already mentioned Colon *et al*., (1970) used TIROS composite NEPH analyses for the study of a pre-monsoon season storm. Nedungadi (1962) and Sikka (1971a&b) were the first among the Indian meteorologists to use the US Satellite data for evaluation of its use in determining development process and location and intensity changes of tropical cyclones in the north Indian Ocean. According to study by Sikka (1971a), the location error with respect to the best tracks of the IMD, for cyclones was more than 100 km in the early genesis period but as the system intensified it was reduced to 30 – 50 km. With visible eye in satellite imagery the center's location had no uncertainty at all. Almost same results hold good today. Other important research papers using satellite imagery over the north Indian Ocean are by Mishra and Raj (1975), Mishra & Gupta (1976), Narayanan & Rao (1981), Kalsi & Jain (1992), Pal *et al*., (1989), Kalsi (1999), Kelkar (1997) and others. Operational meteorologists since 1980's in the post - INSAT era have depended more and more on the satellite imagery for locating the centre of the storm out at sea and used radar fixes to fine-tune the location as a storm approaches the coast. India has spent considerable money on the installation of storm detection radars and operational INSAT system. Most of the research work, using radar and satellite data, in India has been done either by the IMD scientists or scientists of the Space Application Centre (SAC) Ahmedabad as they alone could have access to the radar or satellite data. It is a sad commentary that neither radar nor satellite data are easily accessible to broad Indian meteorological research community and as such these vital data sources, obtained through high technology and cost, are very much under utilized for research in India. Even for the IMD researchers radar and satellite data are normally accessible to those who function in these very units. Unavailability of radar data is partly due to lack of availability of photographic materials at the operational stations. This needs to be set right as data used for research, after the operational work, adds value to the data.

The best track position and other parameters for the Orissa super cyclone of 26-31 October 1999, as given in Table 6, after Kalsi (2003), are entirely based upon satellite information. Table 6, clearly shows that the T-number was below 2.5 (depression stage) up to 0000 UTC of 26 October 1999. It remained between 3.0 to 3.5 (CS or SCS category) for the next 24 hours with central pressure value varying between 998 to 992 hPa. The system intensified to T- 4.0 category in the next 3 hours (1500 UTC of 27 October 1999), reaching VSCS category (hurricane speed winds). The pressure drop from 1200 UTC of 27 October to 0300 UTC of 28 October (15 hours) was 14 hPa. Further intensification of the cyclone to SUCS stage occurred rapidly between 0600 UTC of 28 October to 1800 UTC of 28 October, *i.e*., within 12 hours when it intensified from T 4.5 to T 7.0 category with further pressure drop of 66 hPa from 978 hPa to 912 hPa. This was a very high pressure drop rate of 66 hPa in barely 12 hours when maximum deepening of the super cyclone had occurred and estimated maximum sustained winds reached 140 kt. Apparently considerable cross-isobaric flow would have occurred in the vicinity of storm centre in this short period of time through eddy angular momentum transport as well as through changes in the inflow angle as convective bursts occurred in the eye wall region. A study on these aspects would be rewarding from observations and model products. As the super cyclone remained almost stationary for nearly 36 hours after landfall there is scope to study such features and other budgets around this system following approach adopted by Gangopadhyaya and Riehl (1959) in the case of a hurricane and Anjaneylu *et al*., (1965) in the case of a tropical cyclone in the Bay of Bengal. Such studies are needed.

It may not be out of place to mention that the Indian research with radar as well as satellite data is mostly concerned with the approaches followed in USA. Researchers in USA were the first to have access to data from new observational tools and obviously made first use of these tools for research on tropical cyclones. As India acquired these observational tools much later than USA, our researchers were mostly left to merely validate the techniques developed in USA. We could still have done some original work provided the broad meteorological research community, outside the IMD and SAC, were encouraged for research with free access to data. There is still scope for this.

## 4. Progress in tropical cyclone track and storm surge prediction over the north Indian Ocean

Prediction of the track of tropical cyclone, its land fall point and the rise of sea water in association with the storm surge, which inundates the coastal areas at the time of landfall and results in terrible loss of human and animal lives, are the two important functions of operational meteorology. Both are linked with the changing dynamics of a cyclone in its life history. Storm surge prediction depends critically on the track of the cyclone at landfall and its intensity at the time of landfall. Considerable work has been done in India in these areas in the last 30 years for the north Indian cyclones, which is summarized below.

### 4.1. *Track prediction*

A variety of observational data have been used in India till 1960's to forecast the track and landfall points of tropical cyclones as public warnings depend on the accuracy of such forecasts. A conceptual framework was built in the early period that a cyclone follows the path along the region with maximum fall in 24 hours sea level pressure and also it is steered by the upper tropospheric flow, which in turn is dictated by the position of the sub-tropical anticyclone. A cyclone would move along its westward path so long as it is located south of the ridgeline in broad upper tropospheric easterly flow. The beta effect is responsible for a pole ward component in the movement. The storm would recurve north-to-north eastward under the influence of an approaching westerly trough in the upper troposphere. The direction in which the cirrus cloud streamers propagate ahead of the storm were also used as aids to track-prediction.

In USA Riehl and Shafer (1944), Simpson, (1946) and Riehl *et al*., (1956) were among the first to study recurvature of tropical storms. George and Gray (1976 & 1977) also examined recurvature of hurricanes relating to its surrounding wind field and Chan and Gray (1982) studied hurricane movement in relation to surrounding flow. The role of beta effect on the general poleward directed motion was examined analytically by Chan and William (1987).

Colon (1953) was the first among those in USA who used climatological hurricane tracks as objective aid to track prediction. Holland (1983 & 1984) provided theoretical back ground for storm motion. Based on the role of SST in tropical cyclone genesis, Riehl and Shafer (1944), Palmen (1948), Riehl (1956), Fisher (1958), Mc Pudov (1967), Leipper, (1967) and Brand (1971) argued that tropical cyclones follow the path of maximum SST so as to tap the energy required for their development and maintenance. As a cyclone produces considerable upwelling, the following cyclone would avoid the path followed by the previous cyclone. In the Bay of Bengal too during the MONEX Field Phase in May a Soviet research ship had shown considerable upwelling (Sikka *et al*., 1980) to the right of the intensifying storm and it had taken nearby two weeks for the waters to regain their pre-storm SSTs. U.S. research aircraft drop Aircraft Expendable XBTs (AXBTs) to study the impact of a cyclone on the ocean and *vice versa* and the data from AXBTs have produced vital information about air-sea interactions under the influence of a hurricane. Pudov (1993) discussed further ocean's response to tropical cyclones. Lighthill (1997) has provided a theoretical framework by which evaporation from the sea surface would cool the SST in the vicinity of strong winds around the storm.

At the NHRL, Miami considerable efforts have been devoted since 1960 to develop objective techniques for forecasting tracks by using synoptic, climatological and statistical (linear regression and screening regression) procedures (Miller *et al.,* 1968, Neumann *et al.,* 1972, Neumann 1981 and Neumann & Lawrence, 1975. Neumann & Pellisier (1981) examined various storm-track prediction techniques and found hardly 10 percent change in the statistical accuracy for predicting hurricane motion in the Atlantic over previous two decades (1961 – 1980), inspite of enormous efforts. With the introduction of numerical weather prediction (NWP) in meteorology in 1950's considerable efforts have been devoted since then to use NWP methods for storm-track predictions. Mc Adies and Lawrence (2000) have discussed the improvement in the track prediction from 1970 – 1998. Their estimates have shown that there is some improvement in the track prediction; particularly for periods between 48 to 72 hours, as the observational data through radars and satellites have become available and either bogus or analytical vortex (synthetic vortex) is used to define the flow patterns over the storm region which along with large scale flow would provide the dynamical interactions within a prediction model to take care of the interactions between the vortex and the large scale flow. The paper by Gupta in this Volume discusses the present status in track prediction.

The very first NWP technique for track-prediction was based on a single level barotropic model. Several papers by the Japanese and the US scientists appeared in journals with different versions of barotropic model between mid 1950's to early 1980 (Kasahara 1957, Vanderman 1962, Soyono and Yamasaki 1966, Sanders and Burpee 1968, De Maria 1985 and others). By mid 1970's it was thought that a model integrated with vertically averaged winds rather than winds at a single level would provide a better estimate of the track. Similarly statistical dynamical models like NHC-73 were developed (Neumann & Lawrence 1975). However, marginal success over the single level barotropic model was noticed. Multi-level baroclinic models also did not give significantly better track forecast. Flateau *et al.* (1991) have theoretically discussed the role of baroclinic processes in tropical cyclones motion. Mathur (1974 & 1975) developed a semi Lagrangian version of a multilevel P.E. model with parameterization of physical processes for predicting hurricane movement. After a further period of intense research for over 20 years at the US National Met. Centre. Mathur (1991) developed the model further by including a synthetic vortex in the data over the hurricane. A complex system was developed in GFDL, USA and tested on a large number of cases by Kurihara *et al*., (1995 & 1998). Krishnamurti *et al.*, (1997) applied physical initialization procedure at the initial time in their hurricane model to make the parameterized cumulus heating agree with the rainfall estimated by satellite data. Their results for 24 – hour prediction for a typhoon were much superior but deteriorated beyond 24 hours as the predicted model-derived heating deviated from the observed rainfall. Moving grid-multiple nested PE models have been also tested in Japan as well as in USA. Elsberry and Carr (2000) provide an evaluation of the application of multi-level PE models. Aberson and Simpson (2003) have discussed the predictability of tropical cyclone track.

In India development of objective techniques for forecasting track of tropical cyclones began in 1972 (Sikka and Suryanarayana 1972 a&b) by using a computer oriented half persistence and half climatology technique. Through the forecasts with this simple technique had useful skill for 24 hours, their performance deteriorated at 48 hours period. Dutta and Gupta (1975) adopted an analog method in climatological tracks for forecasting a cyclone movement and their results were broadly similar to those reported by Sikka and Suryanarayana. Shukla and Saha (1970) developed a non-divergent barotropic model with 500 hPa winds as input for dynamical weather prediction in India. Sikka (1975) used this model for several case studies for predicting tropical cyclones but the results for 24 – hour predictions were similar to those of earlier method based on persistence and climatology. Ramanathan and Bansal (1977) examined the track prediction with a quasi-geostrophic baroclinic model. Singh and Saha (1978) used case studies for forecasting movement of monsoon depressions and tropical cyclones by adopting a primitive equation barotropic model. Singh and Sugi (1986) adopted a multi-level P.E. model for dynamical weather prediction over the Indian region for the first time. In recent years Mohanty and Gupta (1997), Gupta and Mohanty (1997) and Gupta and Bansal (1997) have used multi-level P.E. models with parameterization of physical processes for the purpose. Gupta and Bansal (1997), who used the operational global T-80 NCMRWF, Delhi model to assess its performance for tropical cyclone prediction did not find highly skillful predictions since the initial position of the vortex was not well represented in the coarse resolution T-80 model. Prasad (1997) and Prasad *et al.* (2000) have reviewed application of numerical models to cyclone track prediction in India. They also used a high resolution limited area model (LAM), adopted from the limited area model of NMC USA, and found fairly good predictions up to 48-hours when a synthetic analytical vortex was used for defining the storm circulation based on satellite information. Recently Prasad and Rama Rao (2003) have evaluated the quasi-Lagrangian limited area model, (QLM) after Mathur (1991) and its performance is found to be even better. Rama Rao *et al*., (in this Volume) discuss the statistical performance of these two models in operational environment. Abraham *et al*., (1995) used synthetic data for tropical cyclone simulation. With the easy accessibility of MM5 and Regional Atmospheric Model (RAM) to the Indian researchers since 1995 several research groups have done experiments on tropical cyclone development and track predictions, (Santhanam *et al.* 2001, Potty *et al*. 2001, Trivedi *et al*. 2002, Mohanty and Mandal 2004, Singh *et al.* 2005 and others). In this volume too several papers appear on the use of MM5 model for predicting the genesis and movement of the Orissa super cyclone. It is too early to say anything definitive about the improvement in skills as the model has been used for only a few case studies. Both track and intensity predictions are found be highly sensitive to initial data, resolution of the model, lateral boundary conditions, cumulus parameterization technique, boundary layer parameterization etc. As is evident from the papers in this Volume on simulating the Orissa cyclone of 29 October 1999, the results differ widely. Hence many cases have to be run to establish the success of these high-resolution models in predicting tropical cyclones geneses and tracks in the north Indian Ocean. It is very clear that introduction of a synthetic vortex and assimilation of satellite/radar data are must for proper simulation of a cyclone in an operational model. The success of a model also appears to depend on the initial large-scale flow in the global model and its evolution with time. There could be occasions when a global model is not very skillful in predicting the large-scale flow, which may have implications on the skill of the cyclone forecast. In the cases discussed in this Volume on the use of MM5 or a GCM on the Orissa Super Cyclone, most of experiments are done under idealized conditions with initial data obtained from NCEP, ECMWF and NCMRWF models and the lateral boundary condition based on post-analyses from the same source in the case of MM5 model. As such their application to operational system still needs to be tested. Obviously more critical testing is needed and a program may be evolved for such a purpose such that both developing, non-developing and storms dissipating on the sea could be tested to evaluate the skill of high-resolution regional or global models.

### 4.2. *Storm surge prediction in India*

The severe tropical cyclones that struck Bangladesh coast in 1970, resulting in loss of over 300,000 human lives caused by a huge storm surge, led to efforts in India for the development of storm surge prediction models. The lead in this direction was taken by Das (1972). Das and his coworker (Das *et al.* 1974, Das *et al.* 1983 and Das 1994) have made several investigations in this direction. The work was vigorously followed by Dube and his coworkers at the IIT, Delhi (Dube *et al.*, 1985, 1994, 1997 & 2000 & Dube and Gaur 1995) and now a P.C. version of their model is available at several places in India. John and his group (John and Ali 1980, John *et al.*, 1981, 1983) have also made important contributions in this area. Investigations by these three groups in this area are highly recognized. At the IMD Ghosh (1997) adopted the SPLASH model, after Jelesniaski (1972), for storm surge prediction and monograms are available in the IMD for quick calculation of the storm surge along different coastal belts of India. Rao *et al.*, (1997) have also made frequency analysis of storm surges for the Andhra coast of India, which is a most vulnerable region. Even though the problem of modeling of the storm surge in the Bay of Bengal is adequately solved, the skill of the model in prediction critically depends upon three factors *viz.*, (*i*) predicted intensity of the cyclone in terms of central pressure and radius of maximum wind, (*ii*) predicted landfall point of a cyclone along the coast and (*iii*) near-coastal bathymetry. With improvements in availability of these prediction parameters, the skill of the storm surge prediction models in India is bound to improve further.

## 5. Theoretical advances and computer simulation of tropical cyclone

### 5.1. *CISK mechanism*

A tropical cyclone is a complex system of interacting physical and multi-scale processes in which the genesis of the system is controlled to a large extent by large-scale processes interacting with air-sea fluxes, meso-scale cloud formations and penetrative convection within them. Organized convection supplies the energy for maintaining the system. For a long time there was a conceptual theoretical barrier, which would not allow supportive feedback between the cumulus scale and the large scale needed for the growth of the incipient low-pressure system. The biggest step to overcome this barrier was taken by the work of Charney and Eliassen (1964) who propounded the theory of Conditional Instability of the Second Kind (CISK) in which the large scale incipient vortex was thought to organize frictional, convergence as a result of cyclonic relative vorticity at the top of the boundary layer, which would lead to cumulus convection on the cloud scale. The two motions are considered to support each other. The large scale motion results in cloud formations and the latent heat released in smaller scale cumulus convection leads to increase in the temperature of the tropospheric vertical column which in turn results in further surface pressure fall on the large scale thus leading to enhance cumulus heating. The loop goes on till the incipient low intensifies and further organizes itself into a mature tropical cyclone with enhancement of cumulus heating in the column. Thus, the large scale and cloud scale motions support each other in the formation of a tropical cyclone vortex structure. The theory emphasizes on a scale selection process in which the large scale gains from the cumulus scale. The criticism to the theory as propounded by Gray (1979) was directed on the observations that only small portion of the incipient disturbance inflow is driven by boundary layer convergence and the majority of the disturbance outflow occurs in the upper troposphere, which cannot be explained by Ekman pumping at the top of the boundary layer. Gray (1979) argued that the real energy gain of the tropical cyclone can come from a mass balancing through vertical up-moist and down-dry re-cycling circulations which result from surface energy fluxes in the vicinity of a cyclonic vortex rather than from horizontal convergence of energy. Gray suggested that it is the relative frequency and intensity of rain band formations, which is a characteristic feature distinguishing between developing and non-developing cloud clusters. However, CISK theory allowed a way to parameterize cumulus convection in terms of the presence of positive relative vorticity at the top of the boundary layer. In reality tropical cyclone intensification consists of a series of events in the life history of an incipient disturbance, which allow the probability of the intensity of a disturbance gradually increasing as it proceeds to the next stage of organization from low pressure area up to VSCS/SUCS with enhancement of convective heating. Thus, the synoptic/climatological conditions within the warm ocean ITCZ region help the possibility of intensification through a scale selection process based on CISK theory or through the so-called scale-dependent dynamics. Small-scale free cumulus convection does not occur uniformly everywhere within the ITCZ but is modulated in cloud cluster scale in patches under certain conditions. It is only on a small percentage of the frequency of cloud clusters that the energy of a cloud cluster scale grows till it becomes a self-regulating fully blown SCS/VSCS/SUCS. Thus, cumulus scale, meso-scale and large-scale processes cooperate with each, due to certain peculiar circumstances, perhaps controlled by the large scale, which ultimately lead to the formation of the self-regulating tropical cyclone. The time scale of the cyclone-scale disturbance (a few days and 1000 km in horizontal extent) is much larger than the cumulus scale up and down drafts (a few hours duration and a few km in extent) or the meso-scale bursts in convection (6-12 hours duration and on the scale of 100 km in horizontal extent). Thus, at the beginning of a cyclone's genesis moist convection is modulated and sustained by the dynamics of cloud clusters or meso-scale systems in which the vertical shear (preventing ventilation of the updraft or cumulus heating), the presence of CISK and air-sea fluxes over warm ocean waters all contribute to the increased probability of an incipient disturbance to develop into a mature tropical cyclone. CISK allowed quantification of cumulus heating, starting from the presence of moist convective instability, which would cooperate with the cyclonic relative vorticity at the top of the boundary layer of the large scale incipient disturbance to intensify into a mature cyclone. In other words cooperation between the primary (incipient low's cyclonic motion) and the secondary circulation inflow (cumulus clouds) is made possible under special circumstances and hence the rarities of the occurrence of tropical cyclones even though many cloud clusters develop over warm tropical oceans. Several forms of cumulus parameterization schemes are now available, which were developed by different researchers. However it is not yet clear as to which scheme would work best on a large statistical sample of cyclone unless they are tested vigorously

5.2. *Computer simulation of tropical cyclones*

Once the CISK hypothesis was propounded it became quite convenient to test it for simulation of a tropical cyclone using high-speed computers. By mid 1960's and into 1970's several investigators successfully simulated the intensification of an incipient low into a very severe tropical cyclone or hurricane stage vortex. By that time special numerical techniques like space differencing, time differencing, computational damping at the lateral and vertical boundaries etc. were available. An investigator on tropical cyclone simulation research would generally use an axi-symmetrical and balanced weak vortex in cylindrical coordinate system with a domain (usually 2000 – 4000 km in extent) and parameterize cumulus heating in terms of CISK. The result of all simulations showed that an incipient vortex would remain in quasi-steady state for a couple of days of computer simulation time. At some stage the pressure would fall drastically and pressure gradients increase close to the central region. The wind strength correspondingly increases and maximum wind belt shifts close to the centre. All such features are typical of what are observed in observations when tropical cyclones develop from low pressure areas into a mature cyclones. A stage would come in the simulation when further fall in central pressure stops and the simulated cyclone reaches a quasi-steady state. Important researchers, who worked in this field are Ooyama (1964 & 1969), Kuo (1965), Yamasaki (1968), Rosenthal (1970, 1971 a & b, 1978 and 1979), Anthes (1972 & 1977), Black and Anthes (1971), Tuleya and Kurihara (1978), Harrison (1973), Kurihara (1975), Kurihara and Tuleya (1974), Sundquist (1970 a & b), Willoughby (1978 & 1990) and others. Willoughby *et al*., (1982) & Davis and Bosart (2001) were also successful in simulating asymmetries in a 3 – dimensional model of the tropical cyclone. Earlier Yamasaki (1977) had even succeeded in simulating the tropical cyclone in a non-hydrostatic version of model with explicit cumulus scale resolution or without parameterising the effect of cumulus convection. Thus by 1980's the problem of computer simulation of the tropical cyclone in 2 – dimensional axis-symmetric frame work as well as in three dimensional asymmetric frame work was fairly well solved. Even it was demonstrated that a non-hydrostatic model with explicit resolution of cloud scale could be also handled for computer simulation of the cyclone. Most of these investigators performed sensitivity experiments to unfold the role played by strength of the initial vortex, boundary layer processes, cumulus parameterization, domain of the model, displacement and enhancement of latent heat release, SST, coastal friction on landfall leading to rapid filling of a cyclone etc., in modulating intensity changes in the simulated cyclone. The results were found to be very close to observations. If the initial vortex strength at the beginning of simulation was stronger, the intensification on the computer occurred faster and if it was very weak it would take many days of integrations before the simulated cyclone intensified. However a problem with these idealized simulation experiments was that every simulation showed intensification sooner or later whereas in observations only a small percentage of incipient lows would strengthen to tropical cyclone stage. Also symmetric tropical cyclone models were clearly not useful for operational work. Since 1980's, intensive efforts have been directed, particularly in USA, to devise a high-resolution model, which could be used under operational conditions for predicting the intensification and movement of topical cyclones. These efforts succeeded in early 1990's with the formulation of high-resolution models, which could be integrated within the framework of a global model. One version of such a model is known as Mesoscale Model Version 5 (MM5), developed jointly by the NCAR and Penn. State University in USA. The model has been amply tested for tropical cyclones and other tropical/mid-latitude meso scale phenomena with choice of different physical processes and cumulus parameterization schemes including rain, ice, and graupple microphysics etc. The model can be used in both hydrostatic and non-hydrostatic frame-work. The model computer code and initialization scheme were freely distributed on the internet and the code was so user friendly that even research scholars with some training could use it. This has given power in the hands of the Indian researchers who are using it extensively for diagnosing meso scale organizations like heavy monsoon rainfall spells, severe thunderstorms, tropical cyclones etc. In this Volume there are several papers on the simulation of the Orissa super cyclone. Obviously, as already mentioned, more extensive work is needed to validate the applicability of model in the Indian domain, particularly as the large scale atmospheric data are sparse, aircraft reconnaissance is not available and the documentation on land surface/vegetation, land features, water bodies etc. are needed to be quantified for inclusion in the model. NCAR, in cooperation with the global research community, has also developed a more sophisticated model for weather research forecast (WRF) for meso-scale and high impact weather predictions and the computer code for this is also available with some organizations in India. Before we conclude this sub-section, it is worth mentioning that computer simulation using a Japanese model was successfully done in India by Bhaskar Rao (1997 a & b) and he and his collaborators have also performed several sensitivity experiments with this model.

## 6. Recent progress in research on tropical cyclones of Atlantic and Pacific ocean basins and scope for the north Indian ocean basin

In spite of enormous research on understanding and prediction of the tropical cyclones between 1940 to 1990, spanning half a century, by introduction of weather reconnaissance, weather satellites and computers, research on tropical cyclones continues to attract the attention of researchers. Field experimental campaigns like Typhoon-90 and TCM-90 and tropical cyclone programme of the WMO have provided great stimulus to further research. International workshops on tropical cyclones have been held like in 1985 at Bangkok, 1991 in China, 1992 in Mexico and 1995 in Australia. Also excellent monographs have been published by the WMO on Global Perspective in tropical cyclones. In India, the Journal Mausam (1997) also issued a special Volume on the subject and its present Special Issue is being published in less than 10 years interval. During the last 10-15 years research on different aspects of tropical cyclones has made further progress. This progress has been particularly impressive with respect to hurricanes and typhoons of the Atlantic and the Pacific basins in terms of climatology, observation at aspects on formation, track and intensity prediction as well as on theoretical understanding. We provide in the following a brief summary of recent advances and through that explore the scope of undertaking further research on different facets of the subject in the north Indian ocean basin.

### 6.1. *Advances in climatological aspects*

Besides carefully documenting the year-to-year frequency in tropical cyclone formation and intensification, several investigators have examined the inter decadal variability in the frequency of formations of cyclones. Aoki (1991), Chan and Shi (1996). Yumoto and Matsmura (2001) have attempted to account for observed variability. Yumoto *et at*., (2003), used a 50 year long integration of a high resolution ocean-atmosphere general circulation model. Matsura and Yumoto (2003) have found modulation in decadal frequency with occurrence of extended periods of considerably higher than long-term average frequency of formation interspersed with

**TABLE 7**

**Average Frequency of annual formations of tropical cyclones in the north Indian Ocean in 22 warm El Nino and 18 cold La Nina years. (Period 1891 – 2004)**

No of Tropical Cyclones Per Year in different quarters of the year. Figs in bracket give the standard deviation.

| | Jan to Mar | Apr to Jun | Jul to Sep | Oct to Dec | Tropical cyclones | Annual + All cyclone depression |
|---|---|---|---|---|---|---|
| Warm El Nino Years (22 years) | 0.1 | 1.4 | 1.0 | 2.6 | 5.3 (2.0) | 16.3 (3.3) |
| Cold La Nina Years(18 years) | 0.1 | 1.5 | 0.9 | 2.3 | 5.2 (1.6) | 16.5 (3.0) |

extended periods of low number of formations. Their results showed that in the model simulations of tropical cyclones occurred more or (less) frequently over extended periods than normal. Thus, the environmental conditions favorable for the formation of tropical cyclones are more realistically simulated in this model. Elsner *et al.*, (2000 a) examined spatial variability and shift in the frequency of U.S. hurricane activity and Elsner *et al.*, (2001) studied the relationship between the U.S. hurricane and ENSO. We have also seen in Table 4 that there is considerable inter-decadal variability in the formation of tropical cyclones in north Indian ocean and particularly the frequency has significantly decreased since 1980 inspite of the increase in SSTs of the north India ocean. This enigmatic change needs to be examined with respect to other environmental factors such as the strength (weakening) of westerlies south of the ITCZ in the north Indian Ocean, reduction in 850 hPa relative vorticity, increase in vertical wind shear between 850 and 200 hPa etc. As 50 years of NCEP/NCAR or ERA-40 analyses are available, such parameters could be easily examined to understand the possible associated causes for the decrease in decadal frequency of north Indian Ocean cyclones since 1980. There is also scope to document the decadal variability in the observed tropical cyclones in the north India Ocean basin with regard to the neighboring basins like the western north Pacific Ocean, south Indian Ocean and the Australian areas as well as with respect to the global fluctuations on the decadal frequency of tropical cyclones. It appears that the frequency has increased in the north Atlantic basin but it has decreased in the north Indian Ocean basin.

Another aspect which has been examined in other basins is with respect to the influence of southern oscillation and El Nino phenomena on the formation of tropical cyclones. It is observed that the ENSO has impact on the inter-decadal frequency of formations in the north Atlantic (Elsner *et al*., 2001,) north Pacific (Yumoto and Matsmura 2001) and the Australian basins (Dong 1988). Some preliminary work with regard to north Indian Ocean basin was done by Rajeevan (1989). We now examine the formation of the north Indian Ocean tropical cyclones in 22 warm El Nino Years and 18 cold La Nina years from 1891 to 2004. Table 7 shows the results. Warm El Nino years are mostly associated with negative Southern Oscillation Index (SOI) and the cold La Nina year in the positive SOI. The annual range of tropical cyclones in warm El Nino years (cold El Nino years) was 7(6) with the maximum of 9(8) occurring in 1976 (1967) and minimum of 3(2) occurring in 1997 (1983) respectively. Thus, from the incidence of warm or cold events it is not able to discriminate between the annual frequencies of tropical cyclones in the north Indian Ocean basin. Neither there is any significant difference in the frequency of tropical cyclones between two extended episodes of more frequent ENSO events in 1901-1930 and 1961-1990 and one less frequent ENSO episode during 1931-1960 period, except that the number in the period 1961-90 have decreased due to the falling trend as mentioned earlier. Given the lack of any strong relationship between the number of tropical cyclones and the warm El Nino or cold La Nina events, we tend to conclude that it would be difficult to make any prediction about the possible modulation of frequency of tropical cyclones on long-term basis as well as under climate change scenarios in the north Indian Ocean purely from the rise in the episodes of the warming signal of SST in the central equatorial Pacific (ENSO signal). Again Bengtsson *et al*., (1996), using general circulation model simulations, attempted to examine the question of changes in tropical cyclone activity in different basins under the green-house induced warming scenario. Since then several numerical simulation experiment have been done by other researchers (Vitart and Anderson 2001, Druyan *et al*., 1999) using even coupled models under global warming scenarios, but the results are not conclusive. It would be interesting to examine the frequency of formations of tropical cyclone-like vortices in these models, with respect to the north Indian Ocean basin. As already mentioned, in the last 2 decades inspite of the ongoing global warming, the number of tropical cyclones in the north Indian Ocean basin has shown decrease. This could be due to natural causes or multi decadal variability. In the presence of this it would be hard so make any definitive statement about the role of global warming on the likely change in the frequency or intensity of tropical cyclones on regional or even global basis.

6.2. *Advances in work on formation of Tropical Cyclones*

Since the work of Gray (1968 & 1981) and his group (Mc Bride and Zehr 1981, Frank 1977 and Frand & Ritchie 2001), it was recognized that tropical cyclone formation is controlled by combination of complex processes in which large scale environmental factors provide favourable conditions for cyclogenesis and meso-scale processes cooperate for rapid intensification (Richie and Holland 1999, Simpson *et al*., (1997). Further evidence has been built in recent literature that tropical cyclone formation (Tropical Cyclogenesis - TCG) involves convective and dynamical interactions that occur on scales that are not easily resolvable in operational forecast models. Studies by Briegel and Frank (1997), Emanuel (1993 & 1999), Bracken and Bosart (2002), Demaria *et al*., (2001) and Hanon and Hobgood (2003) have confirmed that the daily TCG could provide useful probability forecast for cyclogenesis to occur from cloud cluster stage to tropical cyclone stage. Thus a large degree of predictability of tropical cyclone genesis could be derived from a simple analysis of satellite observed cloud clusters and associated diagnosis of large scale factors within observational framework and without any complicated and computer intensive dynamical model integrations. A study by Takeda and Ooyama (2003) has shown that analysis of aerial coverage of time variations of the low black body temperatures (TBB) (lower than -60° C) in satellite IR imagery could give clues about the intensification process. This is supported by other studies too by examining the organization of deep convection in the rain bands of tropical cyclones (May 1996). Venkatesh in this Volume, has also found merger of mesoscale convective organization within the storm circulation which occurs prior to the intensification of the storm This type of work could be pursued further in the north Indian Ocean basin by examining changes in cloud cluster stage to tropical cyclone stage in visible IR satellite imagery along with using daily NCEP/NCAR analyses for the last 20 years and combining the analyses with coverage of low TBB values in the vicinity of the central area of the clusters having T-1.0 to T 2.5 intensity categories. The INSAT data have not been so far much used in such type of investigations and there is enough scope to use that data for promoting research in tropical cyclogenesis in the north Indian Ocean basin. Liebmann *et al.* (1994) had investigated the role of MJO in overlapping formation or clustering of tropical storm formations in the Pacific basin. Since the MJO is an east ward moving low frequency signal in near-equatorial tropical convection, its relationship with formations of storms in the Bay of Bengal is worth investigation.

6.3. *Advances in prediction of intensification process, track and land fall points*

The recent upswing in the hurricane activity in the Caribbean sea and the Gulf of Mexico (Goldenberg *et al*., 2001) is related to warmer ocean waters and less tropospheric vertical shear in these areas. Researches on land falling hurricanes (Harr and Elsberry 1991, Lander 1994, Elsner *et al*., (2000 a&b) Franklin *et al*., 2003, Elsner 2003) have emphasized that for understanding and better prediction of climatic factors that are connected with hurricane tracks must be examined in detail. In these studies hurricane tracks were divided into straight moving and recurving ones and separately modeled statistically. It has been found that north Atlantic Oscillation activity climatologically controls the tracks in the Atlantic basin. Earlier in the north Indian Ocean Joseph (1976) and Joseph *et al.*, (1981) had examined the tracks and relative frequency of tropical cyclones with the activity of sub-tropical westerlies over the Indian region. There is scope to re-examine this issue by stratifying the track data with respect to the straight and recurving types. Such a study on multi-decadal basis may also provide clue with regard to the decrease in the frequency of cyclones striking Myanmar coast. Also there is a scope to investigate variability the tracks of storms.

It is claimed that with the improvement in dynamical models for tropical cyclone prediction and by adoption of bogussing data technique (Krishnamuri *et al*., 1989, Lord 1991, Kurihara *et al.*, 1993, Leslie and Holland 1995) as well as introduction of a synthetic vortex (Mathur 1991), to better define the position and structure of the cyclones, the mean vector error of the track prediction has reduced significantly for 48 and 72 hours forecasts (Aberson 2001, Goeros 2000). However the paper by Ashrit *et al.* in this Volume, although indicates reduction in track prediction error with bogussed data compared to the non-bogussed data, it is surprising that the Orissa cyclone, in their papers did not show much intensification (rather it filled up) with initial conditions of 27 and 28 October 1999) with bogussed data. There are different global models being run operationally at different centres such as the regional model of the Geophysical Fluid Dynamics Laboratory, USA, the Global model of the UK Met. Office, Florida State University Global Model, ECMWF Global Model, the NCEP global model, the US Navy Operational Global Atmospheric Prediction System (NOGAPS) and Japanese Met. Agency Global Model, whose forecasts about the tropical cyclones are available through meteorological communication channels. Experience shows that the accuracy in prediction of individual cyclones among different models differ considerably (perhaps because of data availability or the method of using synthetic vortex bogus data or not using it). Therefore, it becomes difficult for operational forecasters to select a particular forecast for application in warnings. To overcome this difficulty Aberson (2001) has suggested the use of ensemble mean of tropical cyclone track forecasting models in the north Atlantic. Krishnamurti *et al*., (1997), Zhang and Krishnamurti (1997 & 1999), Weber, 2003) and others have also proposed use of ensembles for forecasting tropical cyclone tracks. Even in the case of Orissa cyclone an ensemble average track prediction of different models, reported this Volume, with gives a better result. Recently Vijay Kumar *et al*., (2003) have gone a step further and have formulated a technique for preparing a multi-model super ensemble forecast for typhoons in the Pacific ocean. The technique provides a forecast for intensity as well as track of a cyclone, after objectively removing the bias of different models. According to them the proposed multi-model super ensemble gives improved forecasts compared to forecasts obtained from individual models in a statistical sense. However use of such a super ensemble in operations would need huge computational facility

Track forecasting in the north Indian Ocean is considered as relatively easy compared to other basins as most of the tracks are straight and the number of recurving or looping storms is considerably less compared to other basins (Pike and Neumann, 1987). However there is one difficulty as the average 24 hours travel of a cyclone in north Indian Ocean basin is much less compared to in the other ocean basins. As such the ratio of the actual distance traveled in 24-hours to the forecast could be large. Thus vector error in the two positions is a better measure of the skill of a forecast The following approaches could be attempted by researchers in the north Indian Ocean basin to quantify the errors.

(*i*) Operationally keep preparing half persistence-half climatology (Sikka & Suryanarayana 1972 a&b) or analog technique (Dutta and Gupta 1975) for each storm and keep a record for verification against other dynamical model forecasts for assessing improvement, if any, quantifiatively.

(*ii*) Use non-divergent barotropic model also operationally as guidance for track prediction and keep a record of these forecast or adopt a nested barotropic model like VICBAR after Aberson and De Maria (1994) for the purpose as suggested in (*i*) above.

(*iii*) Keep a record of forecast issued by the IMD QLM and RLM as well as forecast by the NCMRWF model.

(*iv*) Also obtain the forecasts from other global modeling centers like NCEP, UKMO, JMA, NOGAPS, super ensemble from FSU etc. in case of past cases as well as for each case in the future and make annual comparisons between each of these model forecasts and those made in India with IMD and the NCMRWF models.

(*v*) Obtain records on (*i*) to (*iv*) above separately for assessing improvement in prediction accuracy for 24-hours/48-hours prior to landfall, so that the skill of the prediction on land falling point is quantitatively determined. This would help in building credibility of predictions in the public eye.

A relative comparison between the past records of the operational forecasts for the next 3 to 5 years could give us well informed indicators about the improvement in track prediction and establish relative superiority of a particular model for operational use. There is need to evaluate the skills of real-time operational tropical cyclone forecasts as has been done in other ocean basins It must be, however, kept in view that 24-hr forecast had to be based on regional models as the forecast from global models, particularly from those centres which make forecasts once in 24 hours, are usually available after 12-18 hrs of the initial time. There is also scope to use nested high resolution models like MM-5 or WRF on operational basis provided the boundary conditions from the global models, like NCMRWF, are good. For this purpose the performance of the operational NCMRWF global model would need improvement. Diagnostic studies could be performed with model-analyzed data to understand whether there is any relationship between tropical cyclone intensity and the depth of steering layer (Valden and Leslie 1991). Since heavy rainfall accompanied with a tropical cyclone is one of the greatest threats, the rainfall forecast in the area under the influence of a tropical cyclone obtained from global, regional and nested high-resolution models must be also examined properly. Also research needs to be directed on establishing ensemble configurations on the cyclone-related rainfall. At present such ensembles could be made in India with the NCMRWF model and with regional models in operational use at IMD (single model setup) particularly as a recent paper by Shin *et al*., (2003) has shown only marginal improvement in typhoon-associated rainfall forecast with a super ensemble.

New kind of satellite data like TMI, SSM/I and NSCAT or QuikScat winds are now being assimilated in global/regional models (Figa and Stoffelen 2000, Isaksen and Stoffelen 2000, Leinder *et al*., 2003). Since such data are shown to improve the surface depiction of a tropical cyclone and are also available on operational basis on meteorological communication channels. An attempt in this direction was made NCMRWF by Kar *et al.,* (2003) in the case of the analysis of the Orissa SUCS and the results were found to be positive. The paper by Rambabu in this Volume has shown the used of QuikScat data for the simulation the Orissa cyclone of October, 1999. Indian operational centres would benefit if the technique of assimilating such data are adopted in India. Similarly with Doppler radars available on the east coast of India, the wind information from these radars be also assimilated in prediction models. Assimilation of new type of data must receive high priority for research and application in India.

### 6.4. *Advances in theoretical approaches and modeling*

Considerable advances have been made in the theoretical ideas about tropical cyclone genesis and a re-appraisal of CISK theory has been suggested by some investigators. Inspite of the emphasis, since the early work of Eliot (1900) in India on latent heat of condensation acquired through evaporations from sea surface, being the primary energy source for the formation of tropical cyclones, there were still divergent opinions on the primary operating mechanism (Miller, 1958). Although the work of Charney and Eliason (1964), Ooyama (1964) and Soyno & Yamasaki (1966) propounded a scale selection mechanism, the CISK-related mechanisms have shown maximum growth on small horizontal scale only. However the collective effects of heating in the large scale motions (due to individual penetrative Cb clouds an mesoscale updrafts/downdrafts and anvil and radiative effects between cloudy and non-cloudy air), tropical cyclone genesis has been observationally shown to be a multi-stage process in which the primary (rotational) and secondary (divergent) circulations combine to spin-up a pre-existing cloud cluster scale disturbance. This results in the formation of the inner core region with wall cloud, maximum swirling winds and the cyclone's eye. In idealized theoretical-dynamical simulations of cyclones based on CISK, all initial vortices would intensify into cyclones, as there is no suppression possible once the rapid intensification occurs and a near-steady state is reached by the cyclone vortex after a few days of integration time. However in actual observations hardly 20 percent of the pre-existent cloud clusters could end up into a mature severe cyclone. Apparently some critical processes take place in the real-atmosphere, which combine to intensify a pre-existing cloud cluster into a cyclone and even put a check on its not reaching its full potential intensification (Emanuel 1989, Holland 1997). Thus several alternative mechanisms for parameterizing cumulus heating have been suggested. In one such mechanism, Fraedrick and Mc Bride (1995) revisited CISK and made the heating proportional to synoptic scale vertical motion which is in turn related to the ratio of Cb mass flux to synoptic scale mass flux (unlike the CISK hypothesis making it proportion to the cyclonic vorticity at the top of the boundary layer). Emanuel (1989) even considered that the CISK models are not appropriate for parameterizing convective heating. Emanuel (1993 & 1999) and Emanuel *et al*., (1994) proposed that tropical cyclones form by a mechanism known as WISHE (Wind Induced Surface Heat Exchange) as latent heat release in free atmosphere is governed by evaporation of moisture from the sea (or moist state energy of the air at the sea surface). Even though WISHE mechanism would put a check on a cyclone development, this process can also provide a positive feedback to convection and help in development of warm core structure of a cyclone.

Guinn and Schubert (1993) have introduced the idea of the role of monsoon trough/ITCZ acting as a zone of high potential vorticity (PV) and the existence of meridional gradients of PV in this zone. According to them there could be phase locking of eastward and westward propagating waves, which may lead to cyclone formation with spiral bands. This complex theoretical concept is supported by the observations in the north Indian Ocean and adjoining western north Pacific ocean basins where tropical cyclones tend to form on the leading edge of advancing monsoon or on the southern side of the monsoon trough as was suggested by Eliot (1900) about 100 years ago in the case of north Indian Ocean cyclones. A cross-equatorial monsoon surge-taking place at the time of an eastward passing MJO would also tend to facilitate the generation of a tropical cyclone. Again increase in monsoon wind shear in the horizontal would lead to the development of barotropic instability which when combined with baroclinic and CISK-WISHE type mechanisms may result in cyclone genesis. This brief discussion has shown that recent research is establishing alternative methods of theoretical understanding of tropical cyclogenesis.

As already mentioned computer modeling of tropical cyclones entered a new phase with the introduction of high-resolution models like MM-5 and WRF. Such high-resolution models need special data assimilation schemes to improve their skills. Recently Barker *et al*. (2004) have implemented a 3-dimensianal variational data assimilation scheme for MM-5 model. Also some investigators (Zou and Ziao 2000 and Xio *et al*., 2000) have used a scheme for bogus data assimilation scheme for simulation of a hurricane and for forecasting its landfall position as well, which showed improvement in 48-hr predictions. In India too a wide variety of experiments are being made at different centres and results of some of them are reported in this Volume by different investigators. There is considerable scope to make more experiments with these high-resolution models and to carefully validate their skills on large number of cases.

Bhaskar Rao (1997 a&b), for the first time in India successfully simulated evolution of tropical cyclone in an axi symmetric primitive equation model with specification of planetary boundary layer using inner area horizontal resolution of 20 km with two different cumulus parameterization schemes (Arakawa – Schubert and Emanuel). He also used the model to perform sensitivity experiments relating to SST variations, latitude of formations of the vortex etc. Also Mandal (1997) proposed a theoretical method to construct a consistent structure of a steady state symmetric tropical cyclone from SST anomaly and boundary layer parameterization in the initial vortex region. He showed that the magnitudes of radial and vertical winds in the inner core region are sensitive to the variation of eddy viscosity coefficient.

Several observational and numerical studies in the Atlantic and Pacific basins have shown that asymmetric convection with respect to the storm centre dominate in the inner core area (Bender 1997, Corbasier and Molinari 2002 and Frank and Ritchie 2001) in vertically sheared environment of the incipient disturbance. Ueno (2003) performed a series of idealized numerical simulations to enhance knowledge on the mechanism of tropical cyclone genesis and its motion in vertically sheared environment. He proposed that the weights for allowing vertical shears at different levels need to be calculated from large number of analyzed observed data. Valden and Leslie (1991) also theoretically examined the role of vertical shears in storm intensification. Braun (2002) used a cloud-resolving model to simulate a hurricane. Further modeling experiments have been also reported recently on the use of triply-nested moveable high resolution grids and sensitivity of the models to boundary layer, convection and cloud micro - physical parameterization (Wang 2002). Several other modeling studies have been also conducted with multi-level models for the evolution and motion of tropical cyclone vortices (Shapiro 1992). In some theoretical studies the motion of a vortex in a baratropic atmosphere has been examined numerically as well as analytically (Shapiro and Ooyama 1990, Wang and Li 1992, Willoughby 1990, Smith 1991 and Smith & Ulrich 1993). All these recent studies show that the theoreticians and modelers are still vigorously perusing the complex problem of tropical cyclone genesis and movement from different approaches. There is considerable scope to follow such studies for the north Indian Ocean cyclones as more modeling groups in India devote their attention to this problem and powerful computational resource is made available to them.

## 7. Concluding remarks

Meteorologists have taken giant steps, in stages, during the last 150 years or so to understand the complex observational features and processes responsible for the formation and movement of tropical cyclones. Though the storm track predictions have become more skillful on 48 and 72 hour in advance, the predictions on intensity of the storm still lack in confidence, as they appear to depend on parameterization of physical processes. Enhanced understanding through observations and modeling have contributed to our confidence in using sophisticated models for the prediction of a cyclone and the accompanying storm surge near the landfall position. Such data are also now a days being gathered through a variety of conventional, ocean-based and space-based platforms. Timely receipt of data and their quality control, before they are ingested into the models, are equally important. The Indian research community has the access to such models and have also adequate tools to run these models for predicting the future course of an incipient depression. However there is a clear need that the data from these high technology observational platforms like weather radars, weather satellites, wind profilers, deep ocean meteorological buoys etc. are allowed free access to the research community. There may be several features, peculiar in Indian area, which could be only examined if the data are analyzed by different researchers in the field. More and more use of data for research adds value to the data themselves and the results are witnessed through the quality of research publications. There is considerable scope to address different problems connected with the understanding, variability and prediction of tropical cyclones in the Indian Ocean. The problems have tremendous societal impacts on the coastal belts of India. Many problems in Indian Meteorology await the dynamism of eager and talented researchers who need facilities like high speed computing for modeling and data for model validation. It is my sincere hope that these resources would be available in greater measure in not too distant a future so that Indian meteorologists can keep pace with the fast progress of research in advanced countries in their chosen field.

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