J. mar. biol. Ass. India, 1975, **17** (3) : 613 - 645

HISTORY OF METEOROLOGY OF THE INDIAN OCEAN*

A. S. RAMANATHAN AND GEORGE ALEXANDER
Meteorological Office, Poona, India

ABSTRACT

After a brief introduction to the geographical features of the Indian Ocean an account is given of the seafaring activities of the ancient Arabs, Greeks, Romans and Indians in the Indian Ocean area and their knowledge of the seasonal winds and storms of this area. Interesting weather observations and ideas put forward by some of these voyagers are reviewed.

The subsequent steady progress of Indian Ocean Meteorology during the 19th century and the progress during the 20th century upto the present day is reviewed.

In conclusion some of the outstanding problems of the Indian Ocean Meteorology requiring further investigation and elucidation are enumerated and current trends in meteorological research with special reference to the Indian Ocean area are outlined.

INTRODUCTION

THE INDIAN OCEAN meteorologically as well as oceanographically occupies a unique place in the globe. Bounded in the northern hemisphere by a huge continetnal land mass and extending to polar latitudes in the southern hemisphere, it is the only unbalanced area of the globe. The lack of corresponding oceanic area in the northern hemisphere is responsible for seasonal variations of the oceanic currents and the development of marked monsoons or seasonal winds, in the region north of 10°S. The southwest monsoon of northern summer months and the rains they bring to India and adjacent countris of southeast Asia, the tropical cyclones which originate in the sea and move towards the land areas, bringing not only abundant rain but also causing occasionally immense loss to life and property on their track and the impact of the vagaries of the above meteorological phenomena on the economy of the affected countries, have given a great fillip to the study of the meteorology of this area since a long time.

To review in detail the meteorology of the Indian Ocean which have grown slowly but substantially during the past 300 years, in a few pages is no easy task. We have, therefore, attempted only to highlight the various stages through which the subject developed with particular emphasis on the turning points that ushered in new approaches to the subject.

The authors like to record their indebtedness to Environmental Data Centre of ESSA for kindly supplying some valuable reference material on tropical cyclones.

EARLY VOYAGERS OF THE INDIAN OCEAN

Centuries before the voyagers from the west came to this part of the globe, first for trade purposes, and later for successively establishing their kingdoms in

*Presented at the 'Symposium on Indian Ocean and Adjacent Seas—Their Origin, Science and Resources' held by the Marine Biological Association of India at Cochin from January 12 to 18, 1971.

the coastal belts this ocean was criss-crossed by busy maritime trade routes. The Arabs were the earliest sailores along these routes. Well before the birth of Christ, the dhows of Arabs sailed across the Indian Ocean and brought to the ports of the Red Sea and the Gulf of Oman, the spices from India and Burma, precious stones and silk from the far east, and gold, slaves, ivory and ebony from Africa. The existence of the southwest and the northeast monsoons was known to them but they did not venture to sail across midocean during the southwest monsoon months. They clung practically to the coast all along the route, to reach Calicut and returned to the Red Sea in the northeast monsoon season and sailed down to Africa taking advantage of the favourable winds during the northern winter months. Sanskrit literature and Arabic literature abound in descriptions of the trade activities in the Indian Ocean in which Arabs had the controlling influence. The Sokotra Island called Sukhatara Dwipa in Sanskrit had acquired a cosmopolitan character since all the international trades mingled in its market. It is generally believed that Hippalus a Greek Pilot of the first century sailed right across the Arabian Sea for the first time. Around 50 A.D. a Greek whose name is unknown wrote a hand book of the western coast of the Indian Ocean called 'Periplus of the Erythraen Sea' for the use of merchants and pilots. Subsequently many books were written by Arab geographers giving details about the Indian Ocean voyagers. 'Berzug' written by Abbarah, a famous Arab Captain who was the first to make regular voyages to China gives an account of a typhoon in the China Sea. The famous Pilot Shehab al Din Ahmed Ibn Majid composed a nautical directory of the Indian Ocean based on his own experiences and on previous works. Sidi Ali's 'Mohit' written round 1554 A.D. not only gives a map of the Indian Ocean area but also mentions about the occurrence of the monsoon at 50 different places.

With the appearance of the voyagers from the West, a steady effort for systematically observing the winds, weather and weather systems of the Indian Ocean commenced. In his first voyage from Melinda (near Lat. 3°S and Long 40°E) to Calicut in 1499, Vasco da Gama made use of the southwest monsoon winds which had just set in, and reached the destination in three weeks. However, no observations of scientific interest are available from his voyage accounts. William Dampier, considered as the prince among navigators, was perhaps the first to record many weather observations in the accounts of his travels round the world. He, a sixteenth century buccaneer, lived and worked with some of the roughest pirates in history, but was also an astute observer of nature in general and weather in particular. In his "Discourse on winds and breezes, storms and currents" he deals with the general wind systems throughout the world and their seasonal changes. Of particular interest is a chart of winds over the Indian Ocean where he depicts the calms near the Equator, the southeast trades of the south Indian Ocean and northeast and southwest monsoons of the north Indian Ocean. He makes special mention of the storms in the Bay of Bengal and calls them monsoons. They occur, he says, off the Coromandal Coast in April and September which according to him are the 'shifting months'. For in these months "the winds begin to shift and turn from the point on which they have blown several months before to the contrary points of the compass as from east to west or the contrary." The shift is attended with a turbulent sky which ends in a violent storm of wind or excessive rains or both. The stormy monsoons of the Malabar Coast differs from those on the Coromandal Coast in that they are more common and last longer. Dampier also mentions in this connection the common belief that when a circle 5 to 6 times the sun's diameter appears round the sun, storms of wind or much rain will ensue. If there is a break in the circle, the greatest stress of the wind will come from that quarter in which there is a break.

During the 17th and 18th centuries the military and trade activities of the European powers in the Indian Ocean waters increased considerably. Their interest in safe navigation led to the systematic recording of many weather phenomena they came across during their voyages. It is these reports by mariners that enabled James Capper to work out the first tropical cyclone climatology of the north Indian Ocean in 1801. The navigators had also recorded with care the seasonal changes of winds at different places in the Indian Ocean, the commencement and withdrawal of the monsoon at various places and a number of other phenomena, like lightning, cloud features, red sky, water spouts, etc. Halley (1686) gave a map of predominant winds during northern summer over the Indian Ocean.

Contribution of 19th Century Navigators and Meteorologists

Contributions of Capper and others during earliest part of the century

Capper's work on winds and monsoon (1801) is perhaps one of the earliest systematic enquiry into the origin of the monsoon winds and cyclones in the Indian Ocean. Basing his concepts on the works of his predecessors like Bacon, Halley, Franklin, De Apres and Volney, and on his own experiences Capper and ex-colonel in the Army wrote, "As the sun's altitude increases daily in the northern hemisphere, the extensive body of land in the northeast part of Asia, must become much hotter than the ocean and consequently a considerable degree of rarefaction will be produced over that part of the continent, whilst at the same season an immence body of cold air will come, both from the Indian Ocean and the continent of Africa in the southern hemisphere to restore equilibrium. The principal tracks of land of different temperature on the two continents bearing very nearly northeast and southwest of each other will, therefore, become alternately the two opposite extreme points of rarefaction and condensation and necessarily according to this theory be the immediaet causes of the northeast and southwest monsoons."

Following Franklin, Capper also tried to explain the difference in the performance of southwest monsoon over the Malabar Coast and Coromandal coast. According to himthe mountains act as a screen to the coast and being less electrified than the clouds coming from the seas they attract them and take away their electrical fire and cause them to precipitate the water they contain. In a similar way the clouds approaching the land in the Coromandal Coast during the northeast monsoon discharge their contents on the east coast. Capper believed that the amount of rain that falls in a place is "constantly in proportion to the height and extent of the mountains, to the length of time that the wind continues to convey the clouds towares the land and to the extent of the sea or ocean whence water which forms these clouds is evaporated". Since the Malabar Coast is much more mountainous than the Coromandal Coast, the hills on the former are more numerous than those of latter. Also the adjacent sea of the former is more spacious than that of the latter. Therefore, the rains on the Malabar Coast will be more abundant than those on the Coromandal Coast.

Explaining the formation of gales and hurricanes in the Indian seas late in the monsoon season Capper says that the monsoons do not produce them. They originate, according to him principally from some sudden violent changes in the upper regions of the atmosphere and though extremely violent are merely local and temporary. He also discusses the northwesters of Bengal and also the prevalent opinion at that time that the Bay of Bengal monsoon commences in the north and proceeds southwards. Capper discusses a few cases of post monsoon storms in the Bay of Bengal and Arabian Sea and a few in the south

Indian Ocean. Some of these are the earliest on record. He says that mariners believe that violent hurricanes never occur at the breaking up of the monsoons, nor at their commencement but rather after these changes. They are local and of short duration and are not periodic. From the limited data, he also came to the erroneous conclusion that they occur only near large bodies of land and do not occur in mid ocean. According to him no sudden changes in mid-ocean air is likely to take place as it is filled with homogenous vapours. He also discussed the commencement of the monsoons in different places in the south Indian Ocean.

One of the zealous and able contributors to the meteorology of the south Indian Ocean during the 19th century, was Meldrum of the Meteorological Society of Mauritius. To him we owe one of the earliest systematisation of all available knowledge of the winds, monsoons and hurricanes of the south Indian Ocean. He was also the earliest to study the extra tropical cyclones of the south Indian Ocean. Meldrum recognised the following divisions of the winds systems:

i. The region of the northwest antitrades or passage winds south of 25° or 30° S.

ii. The region of southeast trade winds between latitudes 10° S and 25° or 30° S.

iii. The belt of calm to the north and northwest of the southeast trades.

iv. The area of southeast and northwest monsoons between the Equator and 10°S. The northwest monsoon is characterised by a belt of westerly winds occupying the space between the Equator and 10°S in the southern summer months of November to February or March. During the opposite season the southeast trades blow over this region and is here called the southeast monsoon, but it is clearly an extension of the regular trade wind.

v. The region of southwest monsoon which blows towards the Asiatic continent in the months of April to October. It brings fair weather on the African coast but bad weather monsoon in the northern part of its course.

vi. The region of northeast monsoon which may be considered as the regular trade wind that blows over the north Indian Ocean from November to March and which constitutes the fair weather monsoon in the north.

Meldrum believed that the southwest monsoon of the north Indian Ocean and adjoining land areas is a continuation of the southeast trade winds and similarly the northwest monsoon of the south Indian Ocean is produced by the extension and deflection of the northeast trades of the northern hemisphere.

Maury (1864) in his physical geography of the seas, speaks about the cause of monsoon and says "The force exerted on the northeast trades of the sea by the disturbance which the heat of the summer creates in the atmosphere over the interior plains of Asia is more than sufficient to neutralise the forces which cause the winds to blow as trades. It arrests them and turns them back." Explaining his ideas further he says "as the equinox approaches, the heat of the sun begins to play upon the steppes and deserts of Asia, with power enough to rarefy the air and cause an uprising sufficient to produce an indraught thitherward from the surrounding regions. The air that is now about to set off to the south as northeast trades is arrested, turned back and drawn into this place of low barometer of the southwest monsoon. These plains become more and more heated as the sun becomes more and more powerful and the area of inrushing air like a circle on the water is widened and thus the southwest monsoon backing down towards the equator, drive the northeast monsoon from the land, replaces them and gradually extends itself into the sea. Thus according to Maury, the southwest monsoon commences at the north and works its way towards the south. It sets in earlier at Calcutta than it does at Sri Lanka and earlier at Sri Lanka than it does at the Equator. It takes the southwest monsoon six or eight weeks to back down from the tropic of cancer to the Equator at the rate of about 20 miles a day. Maury also gives a Table of setting in and ending of the monsoon at various latitudes. It is not till the southwest monsoon has been extended far out into the sea that it commences to blow strongly or that the rainy season begins in India. According to Maury the latent heat released due to condensed vapour in the hills adds fuel to the flame and assists the sun to rarefy the air and causes it to rise up and flow off more rapidly and to depress the barometer still more. The air which the southeast trades bring to the Equator instead of rising up there in the calm belt passes over without stopping and flows onward to the calms of central Asia, as the southwest monsoon.

Commenting on Dove's idea (1831) that the southwest monsoon is the southeast trade wind rushing forward to fill the vacant places over the northern deserts, Maury contends that the influence of the desert of Gobi and the sunburned plains of Asia is felt south of the Equator and as a consequence the southeast trades are pulled across the Equator to become southwesterlies in the northern hemisphere.

In view of the above reasons monsoon is not felt over the west coast till it is fully established over the Bay of Bengal as for as the Equator, that is till the end of May. It advances northward and reaches Bombay about a month later according to Maury.

Lack of space forbids us from giving in detail the ideas of Ferrel, Horseburgh, Dove and others. However, there was general agreement among them about the mechanism of the southwest monsoon and its rainfall. The following ideas about it were generally agreed upon by meteorologists of the 19th century: The plains of north India get very hot during the summer and the air over that region ascends and becomes light. As a result air over the sea areas where the pressure is high both in the neighbourhood of the Equator and south of it, moves towards the region of low pressure over the land. The southeast trade winds while moving northwards and crossing the Equator becomes southwest winds owing to the rotation of the earth. Again these southwest winds do not directly blow into the region of low pressure but go round it in an anticlockwise direction according to Buys Ballot's law. The copious precipitation over the west coast is due to the high mountains which run along the coast. The higher the mountains, the heavier will be the precipitation. The monsoon is sustained by latent heat released during the precipitation which adds more heat to the atmosphere and, therefore, further rarefaction takes place. Strong winds blow into the region of heavy rainfall since air from the neighbouring regions rush to occupy the space created by ascending air.

One of the important contributions of Meldrum that was given serious consideration later was that the sunspots have an influence on the rainfall and the greater the spottedness of the sun, the hotter it is and, therefore, causes greater evaporation from the sea surface and hence greater rainfall. It was this idea that later prompted the Government of India to establish the Solar Physics Observatory at Kodaikanal in South India.

While ideas about the monsoons were developing in this manner, the meteorologists and navigators of the 19th century contributed much more to the knowledge and science of cyclones in the Indian Ocean. The mariner has always dreaded these phenomena and we have already sketched the ideas of Capper about them. The first serious study of the structure of the tropical storms was made by William Redfield whose extensive experience in ocean sailing convinced him that these whirlwinds revolved in one direction moved forward at variable speed and had many similar characteristics with respect to their tracks. He collected a large amount of data collected by ships through several years and analysed them. Inspired by the writtings of Redfield, William Reid of the Royal Engineers, devoted himself to verifying Redfield's ideas by collecting ship's observations and plotting them on a large chart. The two men worked in close collaboration and exchanged ideas. Reid published several important works one of which was the famous book 'Law of Storms'. While Redfield expanded his interests to the typhoons of the western north Pacific, Reid then a Brigadier General, studied the storms of the South Indian Ocean. In this task, he needed much more detailed information of the storms of this region and, therefore, sent Henry Piddington to India, who first became curator of the Calcutta Museum and later President of the Marine Court of Enquiry at Calcutta. In the history of Indian Ocean Meteorology, Piddington's name will be written in letters of gold for his monumental contribution to the science of storms. His best seller, at that time 'Sailor's Hornbook of Storms' wherein he used hundreds of ships logs for studying the storms of the Indian Ocean, is an outstanding contribution to the science of tropical storms. He also coined the term cyclone which later gained world-wide usage. In a series of 23 memoirs presented to the Journal of Asiatic Society of Bengal, Piddington gave detailed accounts of many Indian Ocean cyclones which occurred during the period 1839–1851. His accounts reveal vast amount of patience, industry and very high ability and judgement in the arrangement of material. Glorious tributes have been paid to Piddington's work by many of his contemporaries.

In his Hornbook of storms Piddington gives an excellent review of earlier ideas of storms and their causes. He suggests that cyclones may be the common name for these phenomena and storm, hurricane, gale, etc. may be used to denote the strength of wind. From the historical point of view it will be worthwhile to mention the ideas which some of the meteorologists of the 19th century had on the formation of tropical cyclones.

William Reid believed that they are produced by the conflict of prevailing currents in different strata of the atmosphere, giving rise to circular movements. These movements later increase and dilate into storms. He also thought that electricity played the principal part at the time of formation. Epsy conceives the calm centre or lull of a cyclone to be the base of huge moving chimney circular or any other oval shape the draught of which is caused by extensive condensation of vapour above. He accounts for the production of clouds, the depression of the barometer etc. by this cause and also infers that at a certain height the rising air overflows the rest of the atmosphere. Kaemtz believed that when the N.E. winds prevail below and southwest above, violent whirlings are formed at their limits which descend to the surface of the earth and are often endowed with prodigious force. Piddington's views are that they are purely electrical phenomena formed in the higher regions of the atmosphere and descend in a flattened disc-like shape to the surface of the ocean where they progress rapidly. We shall mention more about these theories as we proceed.

Piddington enunciates the law of storms as follows: In every storm the wind blows round a focus or centre in a more or less circular form and at the same time has a straight or curved motion forward so that like a great whirlwind it is both turning round and as it were, rolling forward at the same time. Also in the north-side of the Equator the wind blows counter-clockwise and south of the Equator it blows clockwise.

He examined in detail the individual tracks of a number of storms in the Bay of Bengal and Arabian Sea and south Indian Ocean and gives several practical lessons to the navigator for finding out the centre of the storm and the direction of their motion and also for avoiding them. He also explains the use of transparent horn cards which are provided in his book for finding out centres of cyclones. He also discusses the various aspects of a tropical cyclone like the calm centre, pressure fall at the centre, winds in the various quadrants and rainfall.

One of the aspects of cyclonic storms which he discusses is the incurving of winds. Reid thought that the winds in a cyclone blow in a circle. In other words they do not spiral inwards. Redfield had recognised the spiral indraught of winds. Piddington, however, did not stress it very much so that it led to the misapprehension by some later meteorologists that Piddington along with Dove and Reid had disregarded the spiral convergence of winds in cyclones. From Piddington's writings it is evident that he believed that the central part of a cyclone consists of a series of incurving spirals. However, he had another erroneous view that when cyclones are increasing in diameter or dilating the spiral is diverging one or that the arrows curve outwardly and when it contracts the spiral is a converging one or incurving one. He hastens to add in this connection that we do not know about this but is probable or possible. It is of interest to state that all the later meteorologists recognised the incurving of the winds in a cyclone, and the present rule in use for finding out the centre was a generalisation given by Wilson, *viz.*, 'with the face to wind the direction of the centre is from ten to eleven points to the right hand side'.

Piddington gives detailed accounts of some of the most disastrous cyclones on record. Speaking of storm-surges he says that "the incurving of the wind already in a storm must also have a tendency to keep up and support a mass of water towards this part and this mass of water is borne by the direction of the path of the storm." In this connection he quotes a vivid description of the destruction of Corinja in 1789 by a succession of three great waves which rolled in upon it during the passage of a cyclone.

"The unfortunate inhabitants of Corinja saw with terror three monstrous waves coming from the sea and following each other at a short distance. The first sweeping everything on its passage brought several feet of water in the town, the second augmented these ravages by inundating all the low country and the third overwhelming everything. The sea retiring left heaps of sand and mud which rendered all search for property impossible (twenty thousand people died)."

Piddington also narrates a few cases of cyclones in the Indian Ocean when cyclones and earthquakes occurred together.

While Piddington was pursuing the study of cyclones at Calcutta, two other Englishmen Meldrum (who has already been referred to by the authors) and Alexander Thom were working on the storms of the south Indian Ocean. Meldrum systematically collected meteorological data of the South Indian Ocean for the understanding of the storms and monsoons of this region. He was perhaps one of earliest to realise the incurving of winds in a cyclone. From a study of the storms and their tracks, he came to the following conclusions:

i. The hurricanes in the Indian Ocean occur in the space between the northwest monsoon and southeast trades, the localities of these hurricanes varying with the season.

ii. Their tracks are from eastnortheast to westsouthwest simply because the equatorial calms extends from the vicinity of the equator near 85°E towards Mauritius. In other words, whatever causes the northwest monsoon to extend to Mauritius also determines the hurricane tracks. Further the temperature is more elevated on the African side of the ocean. The northwest monsoon which is on the whole stronger than the southeast trade impinges upon tne northeast quadrant of the storm with a force greater than that with which the trade impinges upon the southwest quadrant.

iii. The localities of the hurricanes of the south Indian Ocean and their laws of rotation and progression depend upon the observed relative strength and position and veering of the trade and monsoon and upon the known effects of heat.

Thom's work (1845) was more or less on similar lines as that of Meldrum. Prompted by the hurricane-damaged ships he saw at Port Louis, he analysed the Rodrigues hurricane of April 1843 especially because 14 or 15 ships were caught in it for a number of days. Thom obtained copies of their logs and interviewed Captains of these vessels and with the data obtained worked out its entire track and analysed its characteristics. Most of the work for his classical paper 'On the nature and course of storms in the Indian Ocean south of the Equator' was done fittingly during a long ocean voyage back to England. He was of the opinion that the principal cause of the rotary motion of cyclones is opposing currents of air on the borders of monsoons and trade winds which differ widely as to temperature, humidity, specific gravity and electricity. These he thinks give rise to a revolving action which originates the storm which subsequently acquires "an intense and specific action involving the neighbouring currents of the atmosphere and enabling the storms to advance through the trade wind to its opposite limits." He also gives a diagram to show how this may occur. He further believes that 'as the external motion is imparted to the interior motion of the mass and centrifugal action begins to withdraw the air from the centre and from an upcurrent the whole will be soon involved in the same vertical action.' The upcurrent he explains as being formed by the pressures being removed from the centre when the air there increases in bulk, diminishes in specific gravity and its upward tendency follows as a matter of course.

In a communication to the Bombay Geographical Society (Vol. 8, 1847–1848) Thom presented an excellent study of the Malabar Cyclone of April 1847. The preface to this study which was written in Poona is very interesting. For improving our knowledge of tropical cyclones he pleads for increased network of observatories at the coastal stations from Calcutta to Karachi round Sri Lanka. He works out the cost of such proposal and says it will be negligible when compared to the loss incurred in ship wrecks. Speaking about the inherent difficulties in the pursuit of subjects like Meteorology he says "In the study of storms, unlike other fields of science, it becomes necessary to accumulate the contemporary information of many observers who have accidentally been scattered over a vast expanse of land or sea and were often careless, ignorant or unacquainted with what they ought to notice. Hence trivial points are often carefully recorded while the more important and even more common phenomena are unheeded. The consequence is that although the theory of hurricanes is now pretty well established, it is far from possessing the exactitudy which belongs to many other branches of knowledge and can only be attained be an extensive system of observations carried out by competent persons and good instruments. This can only be achieved by the interference of one or more governments."

One of the very active contributors to the information and knowledge of storms in the Indian Ocean in the 19th century was Dr. Buist who was for some time the Director of the Colaba Observatory and later Editor of the Bombay Times and Secretary of Bombay branch of the Geographical Society. In one of his writings he says, "from 1846, I have devoted 300–400 pages of my notes on Meteorological subjects alone annually." It is to Dr. Buist we owe the earliest catalogue of cyclones for the period 1648–1854 which he extended later to some more years. He was also one of the earliest to investigate the seasonal variations of the sea surface temperature over the Arabian Sea. He collected data from the logs of vessels plying between Bombay and Aden. The water temperature was taken from 10 ft below the surface. Buist took great pains to collect meteorological information scattered in news papers. One of the subjects to which he contributed was on the occurrence of Elephanta over Bombay in autumn which marks the breaking of the monsoon. The prevalent opinion at that time was that it occurs when the sun is in the constellation Hast (elephant). In many of his writings he pays glorious tributes to Piddington. As an Editor of news paper he sometimes made frank criticism of the Meteorological organisation of the Government. Buist was so optimistic about the potentialities of the meteorological science that he thought that during the next twenty years it would be possible to predict the approach of a storm and the rate and direction of its movement with as much accuracy as we can predict the arrival of an eclipse.

Establishment of the Indian Meteorological Department and the contributions of Blanford and Elliot

The India Meteorological Department was established after a good deal of preliminary planning in 1875. A series of devastating cyclones which hit the east coast of India during the post monsoon season of 1864, causing immense loss of life and property, was to a great extent responsible for this action of the Government. Blanford who was then the Professor of Physics at the Presidency College, Calcutta and the Meteorological Reporter to the Government of Bengal was appointed as the first Imperial Meteorological Reporter to the Government of India. In addition to organising systematic meteorological observations in India, he also organised the storm warning service to ships in the principal ports of India. Dallas was specially assigned to collect and analyse the ships observations and prepare storm tracks charts for the benefit of shipping. In the wake of the draughts and famines of 1876 and 1877, Government was anxious about the prospects of monsoon in 1878 and this prompted the Department to organise research on monsoon forecasting. Blanford was the first to find a connection between the snowfall of the Himalayas and the incidence of the monsoon and he reported his results in a paper to the Proceedings of Royal Society of London. His Indian Meteorologist's Vade Mecum was for many years the best work on Modern Meteorology. Based on Blanford's ideas, tentative monsoon forecasts began to be issued by the Department. Some of these forecasts were fully verified by later observations and this increased confidence in the method.

In his Vade Mecum Blanford gave all available information on the cyclonic storms in the Indian Seas like winds, rainfall distribution, electrical phenomena, etc. Regarding movement of cyclones, Blanford said 'In the South Indian Ocean cyclones pursue a parabolic course diverging from the Equator and moving at first westward and afterwards recurving in the neighbourhood of the tropics and passing off in an easterly direction. In the Bay of Bengal the limits of the sea do not reach the tropic of cancer and the course of the cyclones is invariably between west and north. But those which attain the coast of Sunderbans generally become more or less easterly in their further course across Bengal. There are a few exceptions on record in which the course of the storm over the northern part of the Bay has been somewhat to the east, but they are rare and hence according to Blanford when the Indian Coast is greatly exposed to their ravages the coast of Arakan is but very rarely visited by them. Speaking about the origin of cyclones Blanford discusses the circular theory of Reid and the theory of parallel winds of Meldrum and Thom and points out the defects in them. Giving his own ideas which agreed well with those of Eliot, Blanford says "the Bay of Bengal cyclones originate when there is no current of wind blowing in any direction across it, when the atmosphere is calm or moved only by light and variable winds and as Eliot showed when the pressures are equal or very nearly so, all round the coasts. He agrees with Eliot's view that the primary cause of cyclone formation is the "production and ascent of a large quantity of vapour which is condensed with the liberation of latent heat over the place of its production, instead of being carried away to some distant region." The consequent lowering of the atmospheric pressure causes an indraught of air towards the place of minimum pressure. An indraught of air once set up, a cyclonic circulation will follow because of earth's rotation. As the velocity of rotation of the system increases the centrifugal force of the circulating currents will partly balance the difference of pressure between the centre and the periphery of the cyclone. The ascent of the convection currents over the vortex are kept up by the constant liberation of latent heat. According to this view the centrifugal force of the circulating currents partly neutralises the barometric gradients and retards the inflow of air to restore equilibrium. The earth's rotation also neutralises part of the gradient. Discussing the energy source in a cyclone Blanford is of the view that the vortex is maintained by the energy supplied to it by the latent heat of the condensed vapour, which overcompensates the loss due to frictional dissipation, and due to dispersal of air in an anticyclone in the upper atmosphere.

Regarding Blanford's idea on the monsoon in the Indian Ocean it may be said that he fully agreed with the ideas of his contemporaries and predecessors on its mechanism. He was in full agreement with Maury's (1866) description of the monsoon in the Bay of Bengal. As regards the monsoon in the Arabian Sea, Blanford draws particular attention to the soft place in the monsoon between the Equator around 9°N and extending from Sri Lanka to Socotra, where at the height of the south west monsoon the winds, are light and the sea smooth and says that the physical explanation of this is not known and required investigation.

It is worth mentioning at this stage that Dallas who was mainly responsible for the first compilation of monthly weather charts of cyclonic storm in the Arabian Sea and Bay of Bengal had his own views on the origin of cyclones. While presenting a paper on the upper air currents over the Arabian Sea to the Royal Meteorological Society, London in 1898 he said that he held the rather hetrodox view according to which cyclones are formed in the upper atmosphere and work down to the surface level. This according to him explains many of the observed peculiarities like (i) the advance of rainfall over regions in the probable path of progressive cyclones (ii) the semicyclonic form of a cyclone on touching coast (iii) absence of all antecident irregularities of temperature over the region where the cyclone appears, etc.

Eliot succeeded Blanford as Imperial Reporter and his work on cyclonic storms are well known. In one of his earliest papers, he gave a report on the Vizagapatam and Backergang cyclones of October 1876 in the latter of which about 200,000 people were drowned in a single half hour by a huge storm wave sweeping over the island of Sandip. In this paper Eliot developed a theory of formation of cyclones. The publication excited unusual interest both in India and England, so much so a request was made in the house of Commons for the report to be produced and laid on the table. Blanford gives glowing tributes to Eliot in his Vade Mecum for this paper and says that it is perhaps the best monograph of a cyclone that has ever been put on record. Eliot's theory of cyclone formation has already been discussed by us while discussing Blanford's ideas about it. Eliot was the first to organise systematic collection in India of weather observations made by ships in the Indian Seas. He was also instrumental in starting the Solar Physics Observatory at Kodaikanal. His article on Meteorology in Vol. I (Chapter III) of the Imperial Gazetteer of India where he has given an excellent exposition of the mechanism of the southwest monsoon is one of the most valuable contributions to the science of meteorology. His handbook of cyclonic storms in the Bay of Bengal proved to be a very valuable guide to the mariners and was widely used by them.

The achievements of the 19th century were thus quite considerable judged from what meteorology was during the previous century. A good climatology of storms and their tracks was made available mainly due to the work of Piddington, Dallas and Eliot in the northern seas and Meldrum and Thom in the South Indian Ocean. The trades and the monsoons as observed on the surface were well recognised and a theory of origin of the southwest monsoon had been put forward. Interpretation of the observed rainfall distribution on the basis of orography was also available. The presence at the upper level of an anti-trade, as a return current to the southwest monsoon was already inferred. A theroy of formation of cyclonic storms was available thanks to the efforts of Eliot and Blanford and the importance of latent heat as the input energy for the maintenance of the storm was recognised. In a way Eliot had already inferred that storms can form in a region of weak vertical shear since he has said that they develop only in a calm atmosphere. The eye of the storm was known as well as the incurving of wind in a cyclone. Further development was possible only with upper air observations which had not yet become available.

PROGRESS OF THE METEOROLOGY OF THE INDIAN OCEAN DURING THE TWENTIETH CENTURY

Contributions of Walker, Harwood, Simpson and Jeffreys

Walker succeeded Eliot in the beginning of the present century and during his period the scientific activities of the India Meteorological Department further expanded. The first upper air observations were available over Karachi by August–September 1905 and later at other places. The Dines Meteorograph became available to Indian Meteorologists in 1908 and with its observations of upper air, pressure, temperature and humidity upto several thousand feet above sea level were available for the first time. Slowly in the course of next 10 or 15 years upper air observations from several places in India became available and these formed the basis of several investigations which were published latter.

In his famous paper on the Free Atmosphere in India, Harwood (1921) said that the northeast monsoon is in all respects the exact counter-part of northeast trades. Each begins at about 30°N where it is 1 to 2 Km deep. With southward movement it progressively increases in depth to 7 to 9 Kms at latitude 10–12°N. There is a return current at the higher levels from the south or southeast at latitudes 10–12°N which progressively lowers and veers until it merges with the prevailing westerlies on the surface.

As regards southwest monsoon because Harwood could not observe any southward components in the upper easterlies, he disagreed with the view of Blanford and Eliot that they are the exact anti-monsoonal return currents. On the other hand, according to him the principal cause of the upper easterlies is the ridge of high pressure at the upper levels across north India and southern part of China and the consequent reversal of pressure gradient. He does not, however, exclude the possibility that some of the air in the upper easterlies turns southward over Arabian Sea and finds its way to the starting point of the monsoon, the south Indian Ocean. Regarding the tracks of cyclonic storms Harwood found a very noticeable coincidence between the tracks of storms and depressions as shown on climatological charts and the monthly mean directions of upper winds at cirrus level. Thus, Harwood was the first to indicate the existence of a steering mechanism in the upper levels.

Walker's contribution to the forecasting of monsoon rainfall are well known. The statistical method of forecasting monsoon rainfall was first introduced by him and replaced earlier subjective forecasts. Several correlation factors outside the Indian continent were sought for and were subjected to statistical examination by Walker. One of them was the snow fall over Himalayas and its effect on the rainfall of the next monsoon season. Walker found that it is the snowfall accumulation at the end of May and not the actual fall in May which is important for monsoon rainfall. Other factors examined by him were rainfall amounts in April and May at Zanzibar and Seychelles, pressure at Cape during the previous spring months, rainfall in Rhodesia and Java in the preceding rainy seasons, winter temperatures in the Aleutian Islands, etc. The significant parameters were picked up and regression equations derived to forecast the monsoon rainfall.

Walker's extensive investigations incidentally led to the accumulation of a great deal of information concerning world wide variations of weather. An analysis of these data led him to arrive at two important results. They are:

i. Seasonal weather variations are not controlled by variations in solar radiations (*i.e.* variations of sunspot activity). The key to variations of weather must be sought within the atmosphere itself in the previous distribution of weather anomalies.

ii. There is a swaying of pressure on a big scale backwards and forwards between the Indian Ocean and the Pacific Ocean and there are swayings on a much smaller scale between the Azores and Iceland and between the areas of high and low pressure in the North Pacific; further there is marked tendency for the highs of the last two swayings to be accentuated when the pressure in the Pacific is raised and that in the Indian Ocean lowered.

Walker's researches were published in a series of departmental memoirs and they have won high appreciation of world meteorologists.

As regards the south Indian ocean, the Royal Alfred Observatory at Mauritius continued Meldrum's work on the climatology of cyclonic storms in that area. The Observatory at Reunion Islands continued the work of Lieutenant Bridet, who was the author of an excellent memoir on the hurricanes of the Indian Ocean. Statistical data on south Indian Ocean storms were published by Suck in 1906, and Newnham and Visher independently in 1922.

Reverting to the monsoons again mention should be made of an important contribution to the understanding of the southwest monsoon by Simpson, an eminent British Meteorologist. In a classical paper on the southwest monsoon which he presented in 1921 to the Royal Meteorological Society, Simpson gave a detailed description of the mechanism of the southwest monsoon and its associated rainfall. Seeking the origin of the monsoon in the differential heating of the land and sea, Simpson said that it is brought about by a combination of circumstances involving temperature, pressure, humidity, land and sea distribution and the distribution of the mountain ranges, the last of which according to him is the most important. He stressed the important part played by the high pressure cell of southern hemisphere in driving the southeast trades upto the Equator beyond which they are caught up in the circulation around the low pressure in the northern hemisphere and move towards northeast as southwesterlies. According to Simpson the southwesterlies which reach the Indian Coast have travelled for 4000 miles over the Indian Ocean and, therefore, are highly charged with water vapour. The rainfall over the Indian region is influenced by the arrangement of mountains of India and neighbourhood which form a barrier to the north and east. The air is caught in a kind of trap out of which there is no escape except by rising. The windward side of the mountain ranges receive heavy rainfall and the leeward side is relatively dry. Commenting on the dry region over northwest India is stated that the arrangement of the mountains in the country is such as to prevent a large inflow of air into this region and also a dry upper wind and high temperature help in preventing rainfall.

The mathematical treatment of the southwest monsoon was first attempted by Jeffreys (1926). He started with an undisturbed atmosphere in which only the pressure decreased uniformly with height. He then, superimposed a strong temperature contrast on the undisturbed atmosphere and tried to find out the wind circulation that would be set up by a disturbance of this nature. Though he made a number of restrictive assumptions, he was able to demonstrate on theoretical grounds certain broad features like the reversal of the wind at the higher level.

The concept of airmasses in the tropics

During the twenties of this century, the technique of airmass analysis of weather charts was developed by Bjerknes and his school of Norway and they later extended this method to region outside Europe. The climatological concepts of the trades and monsoons fitted their prescription perfectly. Soon the temperature, humidity, typical cloud and precipitation of the trades and monsoons were examined in the light of airmasses and fronts, and were described. The Indian Meteorologists became interested in these new methods of analysis. Band on these ideas detailed studies of depressions and tropical storms were made by Roy and Roy (1930). Ramanathan and Banerjee (1931), Ramanathan and Ramakrishnan (1933), Sur (1933) and Desai (1948).

In a review article published in 1931 Normand wrote "to think or speak of Indian climate or weather in terms of air masses is no new' fashion in India. Its climate has often been described in terms of two main currents of air that traverse it in summer and winter respectively, *viz.* the southwest and northeast monsoons". The earlier view that all tropical cyclones develop within the body of a single air mass which in its lower layers has a copious supply of moisture did not according to Normand, seem to fit the facts in any tropical seas. He summarised the view of the Indian Meteorologists as follows:

a) One of the essential precursors of depressions or storms over the tropical Indian seas is the juxtaposition over the sea of two deep air masses with different properties from widely different sources.

b) One of the air masses is essentially of oceanic and the other generally of continental origin and the storms form on a diffuse boundary between the two masses.

c) The cyclonic circulation around a tropical cyclone in the Indian Seas does not possess a symmetrical structure; it has sectors possessing distinctive weather characteristics and sometimes develops sharp fronts like an extra-tropical depression.

d) The direction of movement of these storms seems to be the same as that of the warm body of air at a height between 4 and 8 km. In the final stages there is a tendency for a quasi-stationary front to develop towards the northwest and for the residual barometric depression to advance along it.

Roy (1946) in a paper on Air masses in India described the conditions associated with the onset of the monsoon as the advance of the equatorial maritime air from the south to the north. Malurkar (1950) put forward his views about the setting in of the southwest monsoon, its temporary weakening and strengthening and also the 'break' in the monsoon. He believed that the air originating in the southern hemisphere high pressure cell travels northward and gets modified by the time it reaches the Equator. At this stage it becomes equatorial maritime air and crosses the Equator in pulses in the absence of extraneous influences preventing them from crossing. If these pulses cross the Equator between 90°E and 80°E they strengthen the Bay of Bengal monsoon and if they cross into the southeast Arabian Sea the monsoon on the east Arabian sea will be strengthened. According to Malurkar if the pulses or low pressure area could not be detected as crossing the Equator or when they are seen further south the monsoon will weaken. Only when they move westward or west northwestwards and cross the Equator the monsoon will strengthen over the Indian Seas. Successive pulses crossing the Equator maintain the monsoon. During 'breaks' in the monsoon when the axis of the monsoon trough shifts northwards one of the stationary low pressure areas in West China as Chinese Turkisthan is more accentuated than usual presumably due to more southerly travel of extra tropical disturbances than usual.

For a period of about 20 years the concept of airmasses and fronts was used extensively by Indian Meteorologists for the study of tropical storms and depressions. The first doubts about the existence of fronts in depressions and storms were expressed by Pramanik and Rao (1948) who showed that there was no evidence of any front with temperature contrast either during the formation stage of a depression or later when it developed into a storm in the north Bay of Bengal during July 1945. They also showed that the zone of heavy rain in the southwest quadrant cannot be due to the upgliding of air in the region of separation of two airmasses. Also the flying activity over the tropical Pacific and Carribean areas during World War II had furnished a mass of information about the tropics which did not support the frontal theory. A change of outlook was necessary and the perturbation approach of Riehl seemed to offer the solution.

Intertropical front

Before we proceed further mention should be made of the intertropical front in the Indian Ocean, which was perhaps the first tropical phenomenon that attracted the attention of the meteorologists of the air mass school. The position and movement of I.T.F. in the Indian Ocean area during different seasons have been discussed in Weather in the Indian Ocean (1943) published by the Meteorological Office, U.K. It is the belt of separation between the air currents whose origins are respectively in the northern and southern hemispheres and reaches central Madagascar (20° S) and south of Java (15° S) in February. The outflow of the northern hemisphere air after crossing the Equator gets deflected and becomes the northwesterly monsoon flow. The easterly winds on the Equator side of the southern hemisphere anticyclone provides the opposite air flow on the southern side of the front and the necessary cyclonic shear for the formation of frontal waves some of which intensify into depressions or cyclones. Towards April the flow from the northern hemisphere anticyclone weakens and the front moves northwards and crosses the Equator and enters the northern hemisphere.

Then it tends to align itself with the east coast of the Indian peninsula. Widespread thunderstorms result in the region of the front. Surges of southerly air reaching the I.T.F. occasionally lead to the formation of premonsoon storms or depressions. During the southwest monsoon season (June–September) the seasonal monsoonal low over northwest India and adjoining Pakistan is well established. The western part of the front moves northwards and by the middle of July a quasi-stationary convergence front and associated trough extends roughly southeastwards from the monsoonal low. Most of the rain falls on the fresh monsoon air side of this front which slopes towards the south reaching to a height of 4 km or more. If this trough moves northwards to the foot of the Himalayas or even beyond, a break of the monsoon occurs over most of the Indian region and the I.T.F. now lies to the north of India and over southern Arabia. When continental air penetrates southwards, into northern India which is usually associated with formation of a monsoon depression near the head of the Bay of Bengal the I.T.F. is deflected southwards and passes through the depression. From September the I.T.F. moves southwards and post monsoon storms or depressions form on the I.T.F. in the north Indian ocean as a result of interaction between the moist S.W. monsoon air and the relatively cold dry continental air from the north. The northerly movement of the cyclonic disturbance is accompanied by a temporary northwards incursion of the southwest monsoon and associated movement of the I.T.F.

When the frontal concepts in the tropics were questioned and were gradually losing ground the name intertropical convergence zone was given to this front as it is really the zone of convergence of two air masses of different characteristics originating from the two hemispheres. We shall see more about this later.

Perturbation methods in the Indian Ocean Meteorology

One of the most serious objections to the frontal explanations of the origin of tropical storms was that some of the hurricanes that affected the west Indian and southern United States originated within a deep easterly current. As early as in 1940 Dunn drew the attention of Tropical Meteorologists to this phenomenon and showed that the easterly current in this region is subject to pressure waves which move from east to west and when they intensify and grow in amplitude they give rise to small but violent hurricanes. Subsequent workers elaborated this picture the most active of whom was Riehl. He formulated models of waves in the easterlies which under favourable circumstances intensified into typhoons or hurricanes. He also worked out the complete dynamics of his model and gave an integrated picture of the perturbation in which he correlated the field of motion, pressure and temperature. Riehl also showed that the perturbations of the wind field were of greater amplitude than those in the pressure field and that the amplitude of the former also seemed greater in the middle troposphere than at low levels. The trough axis slopes towards the east with height and the lower wind fields are positively divergent ahead of the trough and negatively divergent behind it. The distribution of cloud and precipitation could thus be readily explained. Riehl pointed out the important difference between tropical and extra tropical disturbances namely that while in the latter only tropical air rises and polar air sinks, in the former, all the air entering into the circulation rises. Thus, the fact that cyclones can originate in homogenous easterly trade winds was recognised for the firs ttime.

According to Riehl (1948, 1950) the deepening of surface tropical disturbance such as a wave in the easterlies results from the superposition of the divergence in the forward portion of a trough in the westerlies on it. Riehl gave also a second mechanism for the deepening of an incipient low, that when it comes under divergence in the upper tropospheric northerlies as the upper high level current bypasses the low level trough. This becomes all the more favourable if the northerlies are reinforced as a result of inphase superposition of a system in the westerlies and system in low latitudes in the upper troposphere. In effect Riehl brings in certain external forces, to produce the initial upper divergence, which triggers the development of the surface low.

Desai and Rao (1954) discussed the formation of nine depressions of cyclones in the Indian Seas and examined the validity or Riehl's hypothesis for their formation. While giving general support to Riehl's ideas, they contended that there may be other factors also operating in the various stages of intensification of the systems. Desai and Rao while discussing recurvature of cyclones said that in addition to the weakening of the subtropical ridge which gives the first indication for recurvature, the divergence in the forward portion of the westerly trough influences recurvature if the trough is sufficiently near.

The dynamical concepts outlined above slowly gained ground in the field of synoptic meteorology in India, since 1950. Jordan (1953) showed that the conditions of formation of the Masulipatam cyclone in October 1949, were consistent with Riehl's models. Koteswaram and Gasper (1956) in their detailed study of the surface characteristics of tropical cyclones worked out vorticity and divergence patterns in the various quarters of the storms in the Indian Seas and explained the rainfall pattern in terms of convergence. Koteswaram and George (1958) made a detailed analysis of upper and lower tropospheric peturbations leading to the formation of depressions in the southwest monsoon. They came to the conclusion that with the approach of an easterly wind maximum in the upper troposphere a pre-existing low at sea level over the north Bay of Bengal would invariably intensify into a depression. They also showed that when an area of positive vorticity advection and associated divergence in the upper troposphere is superimposed on a pre-existing trough at sea level, development takes place and this is the mechanism operating in the case of monsoon depressions in the Bay of Bengal. This is similar to what Petterson found for the development of extra tropical cyclones. In a contribution to the 75th anniversary volume of the Journal of Meteorological Society of Japan, Koteswaram and George examined the upper tropospheric conditions leading to the formation of severe tropical cyclones in the Bay of Bengal and showed that the westward movement of anticyclonic vortices over pre-existing sea level troughs is favourable for the formation of these storms. They also found that the rapid 'winding up' of the cyclones occurred with an inphase superposition of trough in the easterlies and westerlies as suggested by Riehl. The dissipation of the storms according to them occurs with the inflow of cold air from neighbouring jet streams or wave troughs in the high troposphere. They also pointed out to the close similarity in the mode of formation of cyclones in the Indian region to that of the Pacific and hurricanes of the Atlantic oceans.

During the sixties several case studies of cyclonic storms in the Indian seas were made with a view to elucidate the factors responsible for their formation, their structure and the rainfall distribution and also movements. Particular mention should be made of the work of Anjaneyulu and his co-workers (1965), Mathur and Sikka (1965), Mazumdar (1965), and Bhaskara Rao, Mazumdar and Desai (1967), Colon *et al.* (1970).

Anjaneyulu *et al.* (1965) studied the cyclonic storm of October 1963 which formed in the Bay of Bengal and examined the structure of its circulation through the entire troposphere around the storm. They also computed latent heat and sensible heat around the lateral boundary of the storm circulation and heat and moisture fluxes. They found that large tangential components of wind were noticed between 900 and 700 mb and also the energy content around the lateral boundary was found to be minimum between 600 and 500 mb. The heavy rainfall occurrence was found to have taken place under the umbrella of active upper tropospheric anticyclone. This agreed with Riehl's earlier findings in a case study. According to Riehl this upper anticyclone intensifies and is maintained by the release of latent heat of condensation. Regarding the movement of the storm, they again confirmed Riehl's ideas (1954) that it takes place as a result of interaction of vortices *i. e.* between a cyclone and an anticyclone. In this case they found that storm moved round the 300 mb anticyclones.

Mathur and Sikka examined a number of tropical storms or depressions that formed over north Indian Ocean during non-monsoon months and investigated the role of upper tropospheric flow patterns in intensification, movement and dissipation of tropical disturbances over Indian Ocean and confirmed Riehl's ideas regarding the same. Mazumdar made a detailed study of the May 1963 cyclonic storm in the Arabian Sea with aircraft winds and Tiros satellite pictures and described the structure and movement of the storm.

One of the important aspects of formation of cyclonic storms is the part played by sea surface temperature which is considered as a heat source from which the storm's energy is derived. Based on Palmer's view that cyclonic storms develops over ocean areas where sea surface temperatures are greater than 28°C several workers examined this aspect and the conclusions of these workers are varied. However, the warmer sea areas are extremely conducive to cyclone development is fairly well established now. It is also believed by some meteorologists that the cyclones move towards warmer regions in the sea. However, it has not been so far possible to establish this beyond doubts.

In a synoptic study of the Rameswaram cyclone of December 1964, Bhaskara Rao and Mazumdar (1968) examined the structure and upper air conditions associated with the intensification and the rainfall distribution. They found that the intensification took place under the influence of an upper divergent field at 300 mb and aloft in the form of a westward moving trough in the easterlies.

Climatological studies of storms and depressions in the Bay of Bengal were made by Rai Sircar (1956) and Rai Sircar and Jayaraman (1966). Statistical studies of the frequency of storms and depressions in the Bay of Bengal were also made by Rao and Jayaraman (1958).

The storm surges have also received the attention of a few Indian Meteorologists though these studies have been quite few. The contribution of Bhaskara Rao and Mazumdar (1965) has been very valuable in this respect. They developed a technique for forecasting storm waves and their height. Following Arakawa they assumed that the resultant storm wave height is made up of contributions from four individual parameters namely astronomical tide, static rise in the level of the sea surface due to reduced pressure at a point caused by the presence of the cyclonic storms or the so called Inverted Barometer Effect, the piling up effect of the wind, and the height of the individual waves. They evaluated each of these contributions and discussed the valnerability of the coast to devastation by storm surges based on the bottom topography of the sea near the coast. The variable features *viz.* the altitudes and directions of approach of cyclonic storms were discussed by them and their implications especially with reference to favourable and unfavourable pre-conditions of the sea were explained. This was the first attempt in India to give a quantitative orientation to storm wave forecasts. Storm surge study in the case of Tanjore cyclone of November 1955 was made by Nayar (1968).

Gray (1968) made a global study of the origin of tropical disturbances and storms and came to certain interesting conclusions.

He showed that most tropical storms form within a belt extending upto 20° lat. on the poleward side of the equatorial troughs where the tropospheric vertical shear of horizontal wind (*i.e.* baroclinicity) is a minimum. Over the regions of storm formation there is a frictional veering of wind in the subcloud layer (600 m) of about 10°. This enhances synoptic scale low level convergence and cumulus convection in regions of large positive relative vorticity which exist in the cyclonic wind shear areas surrounding doldrum equatorial troughs.

According to Gray large vertical wind shears do not allow for area concentration of the tropospheric distributed comulonimbus condensation. Also large shears produce a large ventilation of heat away from the developing disturbance. The latent heat released by the cumulus to the upper troposphere is advected in a different direction relative to the released heat at lower levels. Concentration of heat through the entire troposphere becomes more difficult.

Gray contends that the regions and seasons of formation of tropical storms in the north Indian Ocean can be related to the vertical wind shear. For example during the monsoon, according to Gray, development takes place only in the northern areas of the Bay of Bengal from favourable daily combinations of vertical shear values and the equatorial trough fluctuations from their mean monthly position. No developments occur over the Arabian Sea or south Bay of Bengal in the summer when a very strong easterly jet is located over south India even though large convergence

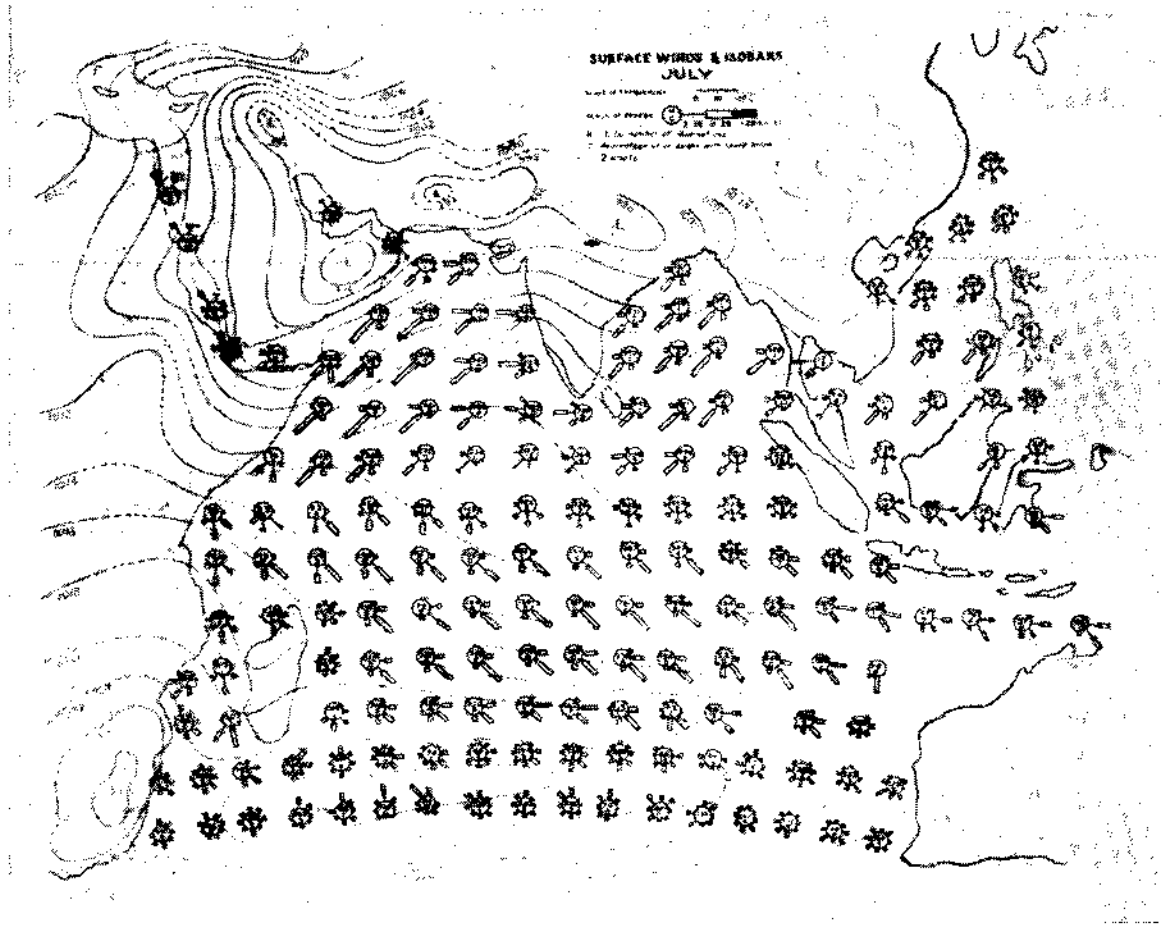

PLATE IV. Surface winds and isobars in July (from Climatological charts of the Indian Monsoon Area published in 1948 by the Indian Meteorological Department).

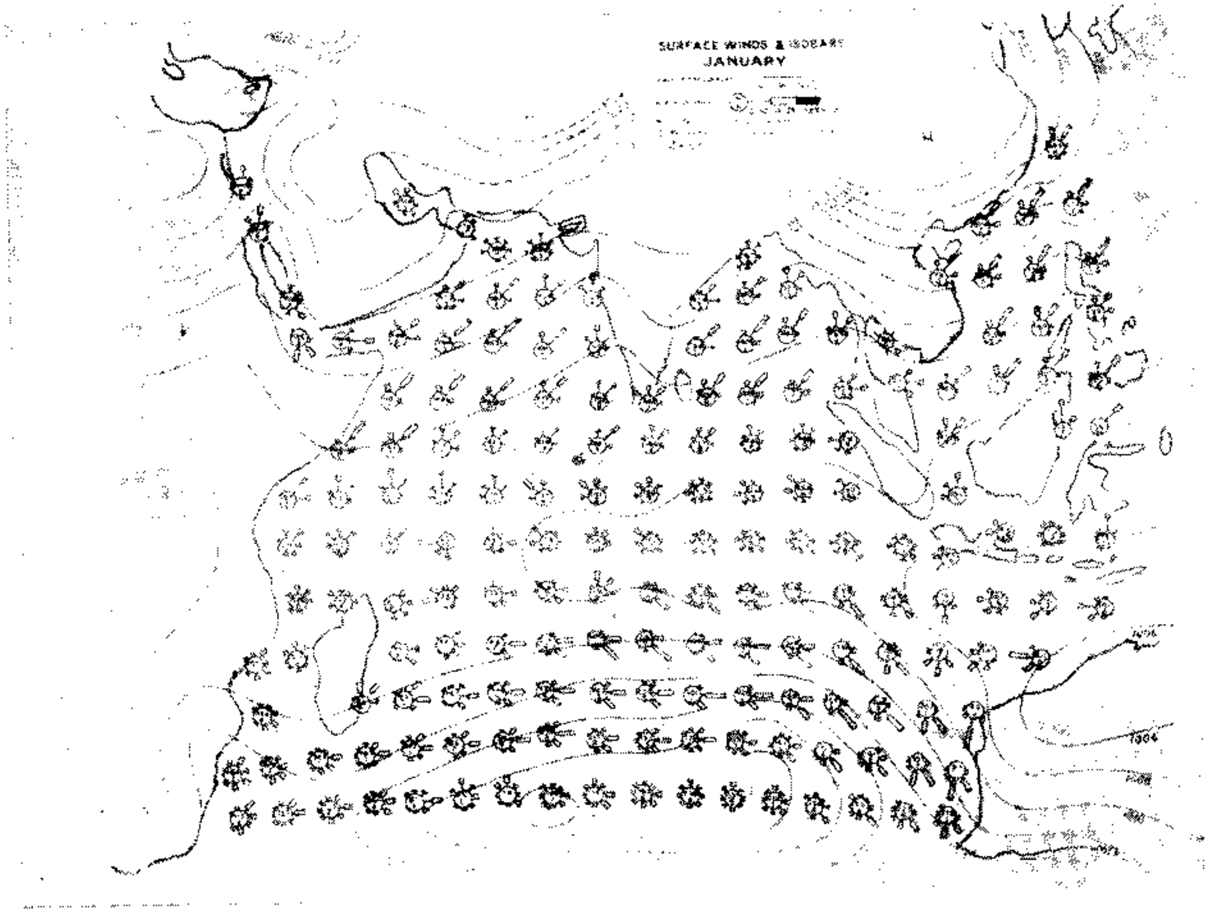

PLATE III. Surface winds and isobars in January (from Climatological charts of the Indian Monsoon Area published in 1948 by the Indian Meteorological Department).

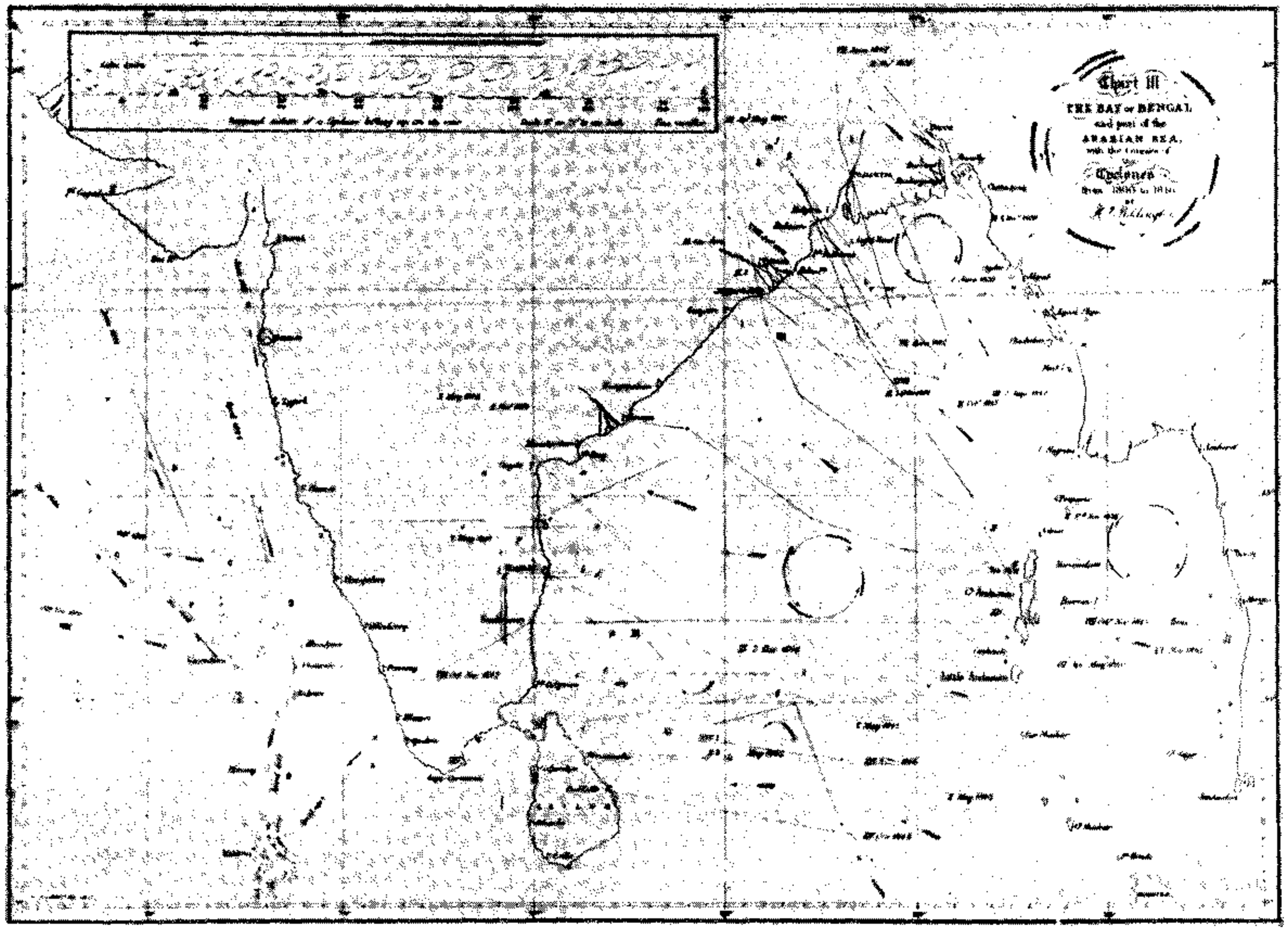
Chart III
THE BAY of BENGAL
and part of the
ARABIAN SEA,
Cyclones

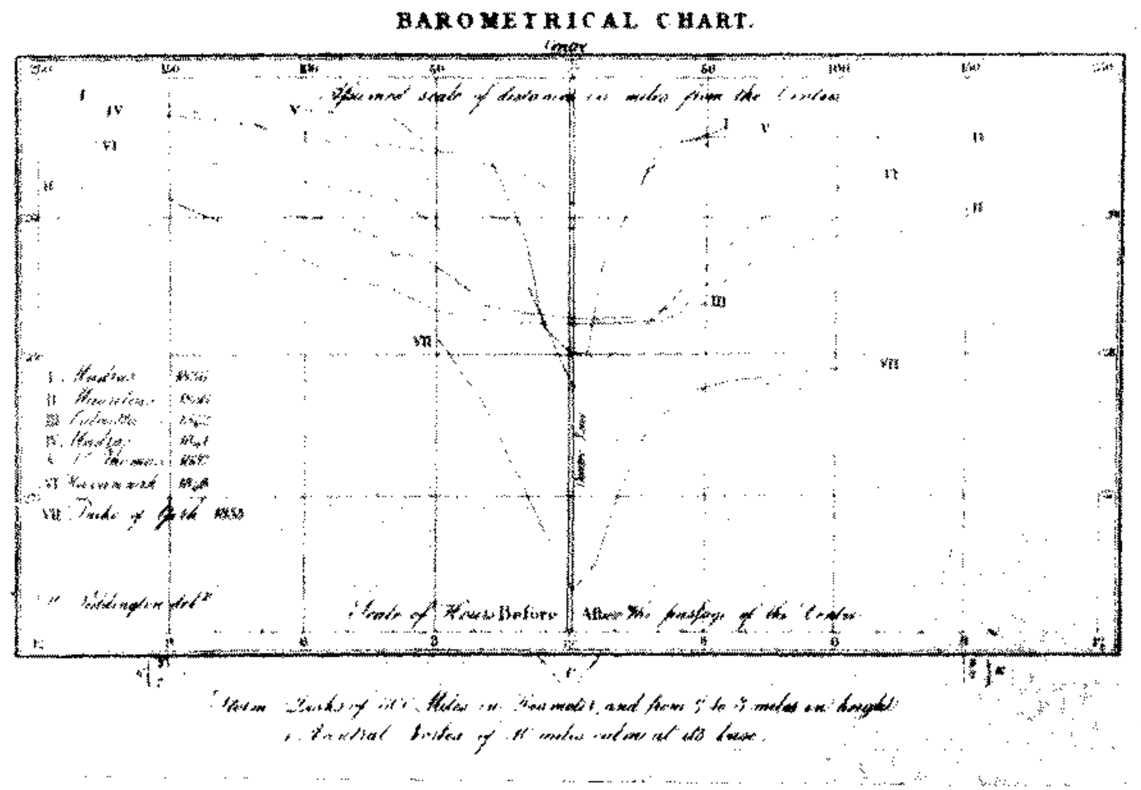

PLATE I. Barograph traces associated with the passage of storms (after Piddington).

and copious convective rainfall is intermittently present during this monsoon period. According to Gray the slightly reduced sea surface temperature over the north Indian Ocean during July and August is not a major factor in explaining features of intensification during these months.

Gray drew attention to the very high concentration of storm formation northeast of Madagascar and attributed it to the weak vertical shear present in that area during the storm season.

Commenting on storm development, Gray rejects the view of primacy of initial upper tropospheric outflow as an important genesis feature. He views development and the resulting upper tropospheric outflow as but a consequence of a lower tropospheric convergence which is frictionally forced.

In an exhaustive study of the May 1963 cyclone in the Arabian Sea, Colon *et al.* (1970) made use of aircraft satellite and synoptic data to investigate the development and structure of this tropical cyclone. They found that the warm core of the cyclone was surrounded by a ring of colder air. They also discussed the radar echoes given by the storm which showed two main precipitation bands in a spiral configuration around the north, west and south sectors of the storm. They also found that the central pressure was as low as 945 mb. Their conclusion was that all the observed features in the Indian Ocean cyclones are similar to cyclones in other areas in the Tropics, with reference to their genesis evolution and structure.

In recent years, our knowledge of tropical cyclones has considerably improved - thanks to extensive probe flights conducted mainly by U.S. At the same time, theoretical and synoptic studies of tropical cyclones elsewhere had shed much light on this subject. The maintenance of the cyclone, the source of energy, the part played by the sea surface characteristics, the important role played by initial cumulus convection and the consequent release of latent heat in the initial warming of the troposphere, which is maintained subsequently and the consequent fall of pressure have all been subjected to extensive investigation but still many of these are far from well understood.

Contribution of weather satellites

The pictures taken by the orbiting weather satellites have opened up a new vast field of research on tropical cyclones. The characteristic cloud structure of tropical cyclones as revealed in satellite pictures at various stages of formation have been extensively studied by Fritz and his co-workers. In the earliest stages an irregular cloud mass appears. Then as the low develops further spiralling cumulus clouds appear, and the solid mass organise itself into a comma shaped system the centre of circulation being just outside the cloud mass. This is the depression stage. When it intensifies into a cyclone pronounced cirrus outflow takes place and the circulation centre gets into the central overcast area which has now got a cirrus canopy over it. An eye appears in mature storms and is sometimes vitiated by the overlying cirrus shield. Making use of the fact that the diameter of the canopy is highly correlated with the maximum wind speed in the hurricane Fritz *et al.* (1966) suggested a method of inferring the intensity of the system from the cloud features in the satellite pictures. This was a remarkable achievement because over the sea areas where data are sparse we could get an idea of the intensity of the system. This classification which was first suggested by Fritz *et al.* (1966) and later adopted by ESSA for the classification of tropical disturbances all round the globe, have been of immense help to the meteorologists of the tropics all over the globe, in their operational work as well as in the research field. Today the India Meteorological Department receives satellite pictures transmitted by ESSA VIII and ITOS I daily at all the five principal meteorological centres and use them both for operational and research purposes. Satellite meteorology is now an exciting field of research where the potentialities of the pictures received by weather satellites are being gradually recognised.

Climatological Atlases

During the 20th century a number of climatological atlases of the Indian Ocean area were published by various Meteorological Services. The first Climatological Atlas of India by J. Eliot was published by the India Meteorological Department in 1906. In this Atlas the monthly storm tracks for the period 1877 to 1901 were given. The first Climatological Atlas of the Indian seas and the north Indian Ocean was prepared by W. L. Dallas and published by the India Meteorological Department in 1908. It covered the area from lat 12°S to 30°N and long. 40°E to 100°E. This Atlas contained mean monthly values of pressure, wind, sea current and tracks of cyclonic storms. In 1925–1926 "Storm tracks in the Bay of Bengal" and "Storm tracks in the Arabian Sea" compiled by Normand were published by the India Meteorological Department. The Bay of Bengal Atlas included all storms that occurred in the Bay from 1891 to 1923 and the Atlas for the Arabian Sea included thet racks of all storms upto the year 1924 whose histories were fairly definitely known.

In 1938, the U.S. Weather Bureau published an Atlas of Climatic Charts of the Oceans. Later the India Meteorological Department published the "Climatic Charts of India and Neighbourhood for Meteorologists and Airmen in 1942 and "Upper wind Roses" in 1944. The Climatological Charts of India and Neighbourhood gave the mean tracks of storms and depressions in the Bay of Bengal and Arabian Sea during the various months. A series of charts entitled "Weather in the Indian Ocean" was published by the Meteorological Office, London in 1943. Then in 1948 "Climatological Charts of the Indian monsoon area" was published by the India Meteorological Department. These charts covered the area 35°S to 40°N and 25°E to 130°E and included surface wind and isobars, upper wind roses, streamlines at 0.5, 1.2 and 3 kms above sea level, percentage number of rain hours over sea areas and cyclone tracks.

Monthly meteorological charts of the Indian Ocean were published by the Meteorological Office, London in 1949. These charts covered the area from lat. 50°S to 30°N and long. 20°E to 120°E and included information about surface winds, pressure, swell, air and sea temperatures, precipitation and cloudiness. In 1962 the Netherlands Meteorological Institute published climatological charts entitled "Indian Ocean Oceanographic and Meteorological Data." These charts covered the sea area from lat. 50°S to 30°N and long. 18°E to 116°E and contained wind roses, the general air circulation, isobars for sea level, the percentage of gales per five degree square, tracks of tropical cyclones, isotherms of air and sea temperatures, mean amount of cloud, percentage of fog duration and percentage of precipitation per five degree square.

In recent years the India Meteorological Department published in 1964 an Atlas of the track of storms and depressions in the Bay of Bengal and Arabian Sea. This Atlas contains the tracks of all depressions and storms that occurred over the area from lat. 5°N to 35°N and long. 50°E to 100°E during the period of 84 years from 1877 to 1960.

Ramage *et al.* (1968) are bringing out an Atlas which describes surface climate of the Indian Ocean as determined from 194,000 ships observations made during 1963 and 1964. From the observations, averages by individual month and by 5 degree latitude and longitude square of wind, pressure, air and sea temperature, vapour pressure, clouds, precipitation and heat exchange together with Analysis are depicted on 144 charts. Also Ramage and Raman (1968) are bringing out an Atlas of the upper air climate of the Indian Ocean incorporating information from before, during and after the IIOE period. Monthly long term averages of the resultant winds, wind steadiness, pressure height, temperature and dew point are presented on two sets of charts for several standard levels upto 100 mb.

Dynamical concept of the southwest monsoon

The dynamical concepts of the perturbation school and the availability of upper air temperature and wind observations gave impetus to the research workers whose findings have thrown considerable light on the subject. Mention should be made of the important contribution by Yin (1949), Koteswaram (1960), Rao (1960) and by Flohn (1960). Yin (1949) made a study of the onset of the monsoon in 1946 and arrived at the following conclusions:

i. The burst of the monsoon occurs as a mean low latitude upper air trough is displaced rapidly from one steady position near 90°E to another relatively steady position near 80°E.

ii. One factor that sets the low latitude trough in motion is the northward displacement of the subtropical westerly jet. As this jet begins to circle the Himalayas to its north rather than to its south an orographically imposed phase shift of low latitude mean trough and ridge position necessarily follows.

iii. The northward displacement of the sub-tropical jet correlates in time with a general rearrangement of the northern hemisphere long wave pattern that results in a replacement of a mean ridge by a mean trough over central Siberia. A polar trough then extends from Siberia to the tropics.

According to Yin contribution of the two factors *viz.* the collapse of the westerly jet to the south of the Himalayas and a rapid westward displacement of the low latitude mean trough when superimposed on the pressure gradient resulting from the large scale differential heating results in the observed violent northward advance of the equatorial convergence zone which is seen as the burst of the monsoon.

In a paper presented at the Symposium on Monsoons of the world held in India in 1958, Koteswaram (1960) examined the high tropospheric wind circulation over the tropics in northern summer and drew attention to the presence of a broad easterly flow over the Asian and African summer monsoon areas with an easterly jet stream over low latitudes between 150 and 100 mb. He associated the burst of the monsoon with the advance of the easterly jet over south India. According to him the easterly jet has an indirect vertical circulation associated with it in the left exit sector and this under favourable low level conditions causes the burst of the monsoon along Kerala Coast. Koteswaram was also of the view that the fluctuations in the rainfall activity during the monsoon could be associated with wavelike perturbations in the upper easterlies. During the break period when the rainfall is confined to the foot of the Himalayas, the easterly jet occupies a more northerly position than usual. The withdrawal of the southwest monsoon from the Indian area is preceded by a weakening of the easterly jet and a southward shift of the upper easterlies. Koteswaram also drew attention to the fact that tropical storms are conspicuously absent over Bay of Bengal and Arabian Sea during the monsoon season when they are overlaid by the easterly jet stream. To Koteswaram we owe the first systematic study of the easterly jet in the Asian region.

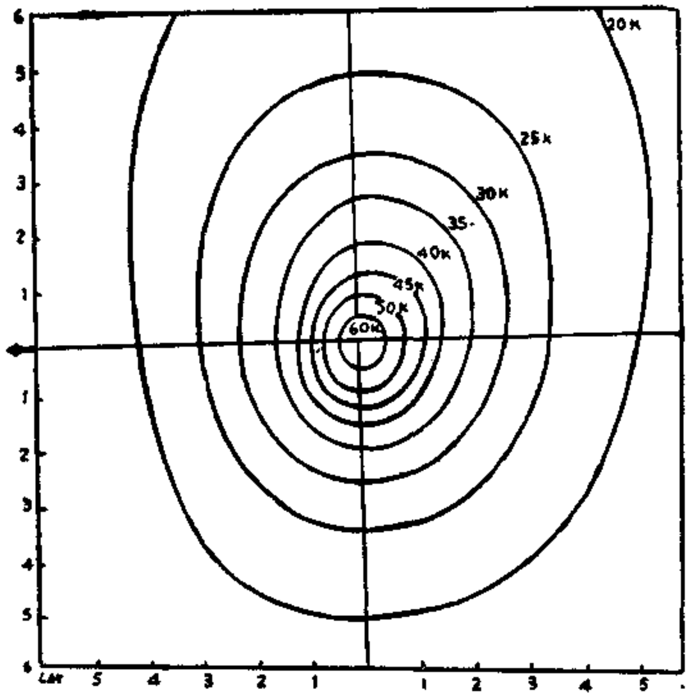

Fig. 1. Distribution of mean surface wind speed (knots) in severe cyclonic storms (after Koteswaram and Gasper, 1956).

Koteswaram (1960) also has stressed the importance of the Tibetan plateau, the thermal effects of which are responsible for the easterly jet during the Asian summer monsoon period. The equatorward branch of the outflow from the upper anticyclone over Tibet which is of thermal origin gains easterly angular momentum and for mass compensation a reverse circulation is set up in the lower troposphere and the low level poleward flow gains westerly momentum. Thus, according to Koteswaram the southwest monsoon is a return current in the lower levels of the meridional circulation system. This return current is convergent and picks up copious moisture from warm seas over which it passes. During its ascent in the monsoon trough at the rim of the Tibetan plateau latent heat is liberated and goes to augment the heat source over the plateau. The atmospheric circulation is thus completed, the engine being maintained as long as the heat source and sink are available. When during autumn the inflow of cold polar air into the subtropics quenches the heat source over the Tibetan plateau the circulation ceases and the southwest monsoon withdraws from the region. Thus a complete three dimensional picture of the southwest monsoon based purely on dynamical concepts was given by Koteswaram for the first time.

Rao (1960) discussed meridional transport of mass, heat energy and angular momentum associated with southwest monsoon circulation during July and August 1955. Advective flux of heat and angular momentum from the north into the monsoon area and northward flow of heat and angular momentum across the Equator at Singapore were noticed. Later (1962) discussing meridional components of upper air data of January and July of 1957–59 of the 12 Rawin stations of India, Nairobi, Aden, Bahrain and Tashkent, he found that the centres of direct and indirect meridional circulation cells were located at higher elevations probably to overcome the obstruction to meridional exchange, from high mountain ranges running east to west. In July the direct cell retreats northwards to near Lat. 30°N and a monsoon cell with lower southerlies and upper northerlies occupies the Indian area from 26 to 13°N. Northerlies in the lower troposphere at Colombo and Trivandrum in July suggest that the feed across the Equator into the Arabian Sea may be extremely limited.

In a series of papers, Flohn (1950–1960) showed that the warming of the Tibetan plateau during summer season causes the formation of a warm anticyclone at 225 mb giving rise to the reversal of temperature and pressure gradient in the layers between 300 and 600 mb. This reversal in turn acts like a switch for atmospheric circulation over the southern half of Asia causing almost simultaneously the following:

i. The sudden swing of the westerly jet from south of the Himalayas to the north of the Tibetan plateau.

ii. Extension of tropical easterlies towards northern India and formation of an easterly jet in latitude 15–20°N near the tropopause.

iii. Advance of I.T.C. to northern India together with a rapid extension of the equatorial westerlies (burst of the monsoon).

iv. Formation of a climatic trough near long 68°E.

v. Sharpening of the climatic trough near long. 110°E.

Flohn (1955) also pointed out that over the sea we observe only small annual temperature variations and, therefore small seasonal shift of the thermal and pressure belts. Whereas the I.T.C. travel only 5 – 10° from the Equator over the sea, over the land large temperature variations are observed causing large seasonal movements of the temperatures and pressure belts and the I.T.C. travels upto lat. 30°N over India. The pressure gradient between the Equator and the region of lowest pressure then produces a quasigeostrophic westerly current. Thus, the existence of the tropical monsoons according to Flohn is apparently not due to thermal difference between land and sea but primarily due to the seasonal movement of thermally produced planetary belts of pressure and winds under continental influences. In other words, according to Flohn the occurrence of the southwest monsoon is due to thermal response of the continental atmosphere to the annual variation of solar radiation.

While the improved network of observing stations and availability of wind and temperature observations of the upper air, have yielded better knowledge of the processes taking place over land, conditions over the vast Indian Ocean area with which we are immediately concerned here, remained unexplored due to lack of observations. Even during the International Geophysical Year, this was not given due attention. The importance of ocean atmosphere interaction processes for the understanding of the meteorological phenomena both over the ocean and over the adjoining land hardly needs any emphasis. Therefore, when oceanographers took the first initiative to organise an Indian Ocean Expedition in the late fifties the meteorologists of the tropics decided to make full use of this opportunity to get the maximum amount of information they required in the ocean area, particularly for understanding the important part played by the Indian Ocean in the operation of the monsoon engine.

The International Indian Ocean Expedition and after

A scientific committee on ocean research appointed in 1957 by the International Council of Scientific Unions decided as almost its first item of business to plan a massive multi-disciplinary investigation of the Indian Ocean. The Indian Ocean Expedition which was the result of the above decision was organised in 1959 to observe and describe and possibly explain the circulation of ocean and atmosphere and exchanges across the interface, the chemical composition and distribution of living things in the ocean and the bottom topography and coastal structure of Indian ocean which is more extensive than Asia and Africa combined.

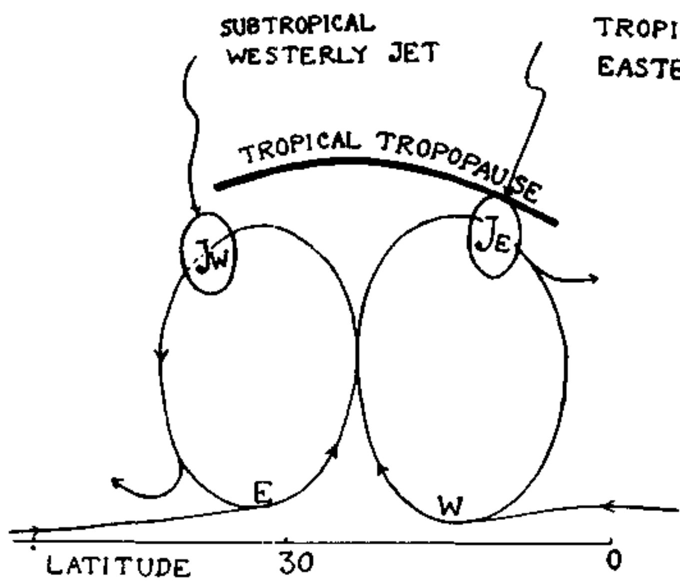

Fig. 2. Schematic model of the vertical circulation in the Asian Summer Monsoon (after Koteswaram, 1960).

A meteorology Working Group appointed in 1961 by the U.S. National Academy of Sciences Committee on Oceanography was the first to develop a plan of action for chalking out the meteorological programme to be gone through during the expedition. The committee formulated two interrelated problems for intensive study and the necessary acquisition of massive data towards the solution of the problems. The first was to study the general atmospheric circulation over the Indian Ocean region and the role of the monsoons in the circulation. The second relates to small scale measurement of the exchange of energy between ocean and atmosphere, a problem of direct interest to physical oceanographers as well. The study of the first problem demanded considerable increase in the density and number of observations made over the Indian Ocean. Many countries rose to this occasion and co-operated by providing research vessels and research aircraft to probe the ocean in all its aspects and provide meteorological observations. To collect and process the enormous amount of data that were pouring in during the observation period 1963–66, the International Meteorological Centre was set up at Colaba where not only the collection but also regular analysis of the data and also several investigations were undertaken mainly to understand the mechanism of the southwest monsoon and the role played by the ocean in it. With the above problems in view, the International Meteorological Centre collected a large amount of data of both surface and upper air over the Indian Ocean area.

The results of IIOE provided valuable data on monsoon circulation. Many investigations carried out not only by the scientists who actively participated in the meteorological programme of the IIOE but also by others working in the various offices of the meteorological department were presented in a symposium organised in Bombay in July 1965. These can be classified under the following heads.

i. Air sea exchange over the Arabian Sea during the southwest monsoon.

ii. The formation of mid tropospheric vortices off the west coast during the monsoon.

iii. Near equatorial troughs and cloudiness associated with them over Equator and neighbourhood.

iv. Synoptic studies of the southwest monsoon.

v. Meteorological Atlases.

Lack of space forbids our going into details of all these investigations. We shall very briefly touch upon them. The time and space variations in the exchange of heat and moisture between the ocean and the atmosphere is very essential for understanding the weather. The determination of this exchange was attempted by several authors during the IIOE period. Mention should be made of the measurements of momentum, moisture and temperature fluxes made by the Japanese and U. S. research vessels. Mani *et al.* (1965) computed mean monthly averages of the heat budget of the ocean surface using the empirical equations of Budyko. Bumralker (1967) used these equations in a detailed study which confirmed earlier ideas that moisture evaporated from the Arabian Sea is insufficient to supply all the summer monsoon rainfall. Pisharoty (1965) found by computation that the amount of water vapour transported into the Indian peninsula across the west coast on a day in July is two to three times the quantity transported across the equator over the longitudes of the Arabian Sea from the south Indian Ocean. According to him the mean flow pattern over the Indian Ocean on either sides of the Equator exhibits cyclonic flow on both sides of the Equator with a considerable westerly component in the flow near the Equator so that most of the air flowing eastwards across the peninsula upto about 6 km appears to be of northern hemisphere origin. All available aerological observations from equatorial acreas of Indian Ocean indicate that the atmosphere over the Equator is relatively very dry, the average relative humidity in the 800 mb level being about 40% while the corresponding value at Minicoy or Bombay is 90%. This shows that there is a dynamic process which dries up the oceanic air as it approaches the equator. So it appears that the monsoon moist air mass is produced by evaporation over the Arabian Sea and convection processes leading to the upward transport of moisture occurs over the eastern portions of the Arabian Sea, although there is some air of southern hemisphere origin in the monsoon airmass. Pisharoty came to the conclusion that "the Arabian Sea branch of the Indian southwest monsoon thus appears to be primarily a northern hemisphere trade wind system blowing from the Equator northeastwards into the peninsular India, (thus differing from the NE trades of the Pacific) rather than the deflected southeast trades of the southern hemisphere."

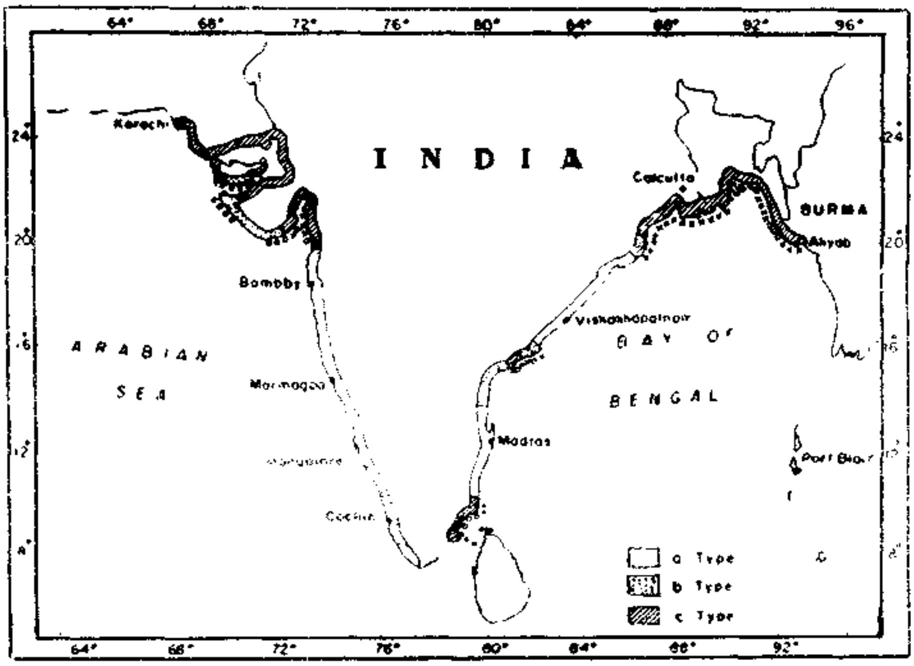

Fig. 3. Diagram showing the degree of vulnerability of different strips of coasts of India and of neighbouring countries to storm wave devastation. "a-Type" coastal areas are generally 'safe' areas where even winds with sustained on-shore component of 80 knots would not produce storm waves of height more than 2.0 metres. "b-Type" coasts are more vulnerable areas, where similar winds can produce storm waves of heights between 2.0 to 5.0 metres. "c-Type" areas are highly vulnerable areas where storm waves can reach devastating heights of 5.0 to 12.0 metres. 'X's near the coasts indicate places which experienced major storm waves in the past and 'O's where moderate surges have occurred. The figure shows a general agreement between the calculated classification and the past experiences (after Bhaskara Rao and Mazumdar, 1968).

Colon (1964) in his interesting paper showed that over large portions of the Arabian Sea there is a rapid warming of the surface water during late winter and early spring. The maximum temperature is observed in May and during the monsoon period there is cooling and temperature reaches a minimum, in August-September. This is followed by secondary maximum in October–November. This trend differs from what happens in other tropical oceans where only a single maximum

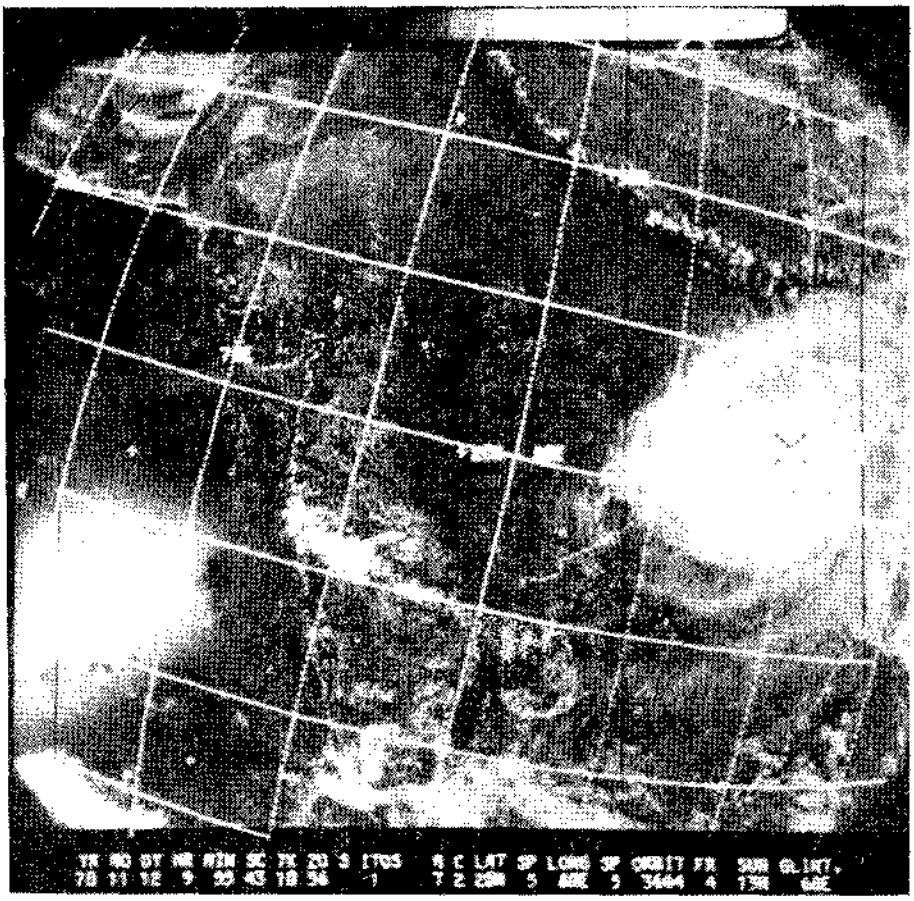

PLATE V. Satellite cloud picture of the East Pakistan Cyclone, 12 November 1970 (from ESSA, U.S.A.)

Saha, Shukla, Sikka and Ramanathan. Today 24 hr forecasts of the 500 mb level for India and neighbourhood based on height field and on the wind fieled are being tried out independently at Delhi and Poona. Other experiments for predicting the vertical velocity field and surface isobars are also in progress in the department. It is hoped that very soon the India Meteorological Department will be able to put on air 24 hour forecast charts of surface, 500 mb and quantitative precipitation over India and neighbourhood.

Conclusion

We have come to end of our long history. When we look back, we feel we have certainly made substantial progress but it should be said some of the basic problems still remain unsolved. To list only a few, we have not still a clear picture of the part played by southern hemisphere in the monsoon performance. We have not investigated the behaviour of the easterly waves in the Indian seas, and their similarity to those occurring in the Pacific and the Atlantic. We do not yet have reliable method for forecasting the movement of storms. Nor do we have a clear picture of the mechanism of intensification of a storm or a monsoon depression. The organising committee of the Global Atmospheric Research Programme are attempting to resolve these problems and they have already formulated some of the outstanding problems in tropics to be investigated during the next few years. Those that immediately concern us are:

i. The parametrisation of the monsoon convection in terms of large scale wind field.

ii. Interaction among various scales of motion and in particular the way in which comulus convection interacts with large scale environments.

iii. The study of large scale wave disturbances in the tropics and their role in energy exchanges between the tropics and higher latitudes as well as the interaction processes between both hemispheres.

Massive efforts for the acquisition of required data are planned and we hope we will have a much clearer picture of monsoon and the tropical storm in the next decade.

References

American Meteorological Society 1951. *Compendium of Meteorology.*

Ananthakrishnan, R. and A. R. Ramakrishnan 1969. *India Met. Deptt. Soc. Rep.*, **102.**

————, 1970. *Q.J.R.M.S.*, **96**: 539.

Anjaneyulu, R. *et al.* 1965. *Ind. Journ of Met. & Geophy.*, **16** : 539.

Asnani, G. C. 1968. *Journal of Atmsci.*, **25** : 133.

Badgley, F. L. and C. Paulson 1968. *IIOE Met. Monograph* 2. East West Centre Press, Honolulu.

Bhaskara Rao, N. S. and S. Mazumdar 1968. *Ind. Journ. of Met. & Geophys.*, **17**: 171.

BLANFORD, H. 1883. *Indian Meteorologist's Vade Mecum.*

BUMRALKAR, C. M. 1967. *M. S. Thesis.*

CAPPER, J. 1804. *Observations of the winds and monsoons.*

COLON, J. A. 1968. *IIOE Met. Atmograph* 3. East West Centre Press, Honolulu.

————, C. R. V. RAMAN AND V. SRINIVASAN 1970. *Ind. Journ. of Met. & Geophy.,* **19:** 1.

DAMPIER, W. *Voyages.*

DAS, P. K. 1962. *Tellus,* **14:** 212.

————, 1968. *Monsoons.*

DESAI, B. N. 1951. *Mem. of Ind. Met. Deptt.,* **28.**

————, 1967. *Journ. of Atm. Sci.,* **24:** 216.

———— AND Y. P. RAO 1954. *Proc. of UNESCO Symp. on typhoons. Tokyo,* p. 175.

DOVE, H. W. 1962. *Law of storms.*

ELIOT, J. 1890. *Cyclonic storms in the Bay of Bengal.*

FERREL, W. 1889. *A popular treatise on the winds.*

GEORGE, C. A. 1953. *Ind. Journ. of Met.,* **4:** 279.

GOVERNMENT OF INDIA 1925. *A history of the Department during the half century* 1875-1924.

GRAY WILLIAM, M. 1968. *Monthly Weather Review,* **96:** 669.

HALLAY, E. 1686. *Phil. Trans.,* **16:** 153.

HARWOOD, W. A. 1921. *Mem. of India Met. & Geophys.,* **7:** 157.

HOURANI, E. 1951. *Arab sea faring in the Indian Ocean.* Princeton.

H. M. STATIONERY OFFICE 1956. *Meteorology for Mariners.*

IND. NATIONAL COMM. FOR OCEANIC RESEARCH 1965. *Symposium on the Met. results of IIOE, Bombay.*

INDIA MET. DEPT. 1958. *Symposium on the monsoons of the world.*

JAYARAMAN, S., T. R. SRINIVASAN AND N. C. RAI SIRCAR 1966. *Ind. Journ. of Met. & Geophys.,* **7:** 157.

JORDAN CHARLES, L. 1953. *Ibid.,* **4:** 339.

———— AND B. N. DESAI 1951. *Ibid.,* **2:** 250.

KRISHNA RAO, P. R. AND P. JAGANNATHAN 1953. *Ibid.,* **4:** 22.

MALURKAR, S. L. 1948. *Current Sciences,* **17.**

————, 1951. *Mem. of India Met. Deptt.,* **28.**

MAURY, M. F. 1864. *Physical Geography of the sea.*

MULL, S. AND Y. P. RAO 1949. *Ind. Journ. of Phys.,* **23** (40): 371.

NORMAND, C. W. D. 1931. *Gerl Beitr. Zur. Geophys.,* **34:** 233.

PIDDINGTON, H. 1864. *Sailor's Horn Book of Storms.*

PIERRE PEDALABORDE 1963. *The Monsoon* (Translated by M. J. Clegg).

PETTERSON, S. 1956. *Weather Analysis and Forcecasting,* **1.**

PRAMANIK, S. K. AND Y. P. RAO 1948. *Sci. & Cult.,* **14:** 34.

RAMA, P. 1967. *Proc. NISI/INCOR Ind. Oce. Symp., New Delhi,* p. 20.

RAMAGE, C. S. 1968. *Weather,* **23:** 128.

————, 1966. *Journ. of Atmos. Sci.,* **23:** 144.

———— AND C. R. V. RAMAN 1968. *IIOE Met. Atlas 2. Upper-air.* East West Centre Press, Honolulu.

————, F. R. MILLER AND JEFFRIS 1968. *IIOE Met. Atlas 1. The surface climate,* 1963, 1964. *Ibid.*

RAI SIRCAR, N. C. 1956. *Ind. Journ. of Met. & Geophys.,* **7:** 157.

RAMAN, C. R. V. AND Y. RAMANATHAN 1964. *Nature,* **204** (4935): 31.

———— 1968. *IIOE Met. Monograph,* **8.** East West Centre Press, Honoluiu.

RAMANATHAN, K. R. AND K. P. RAMAKRISHNAN 1932. *Mem. of IND. Met. Dept.,* **26** (2): 13.

RAO, K. N. AND S. JAYARAMAN 1958. *Indian Journ. Met. & Geophys.* **9:** 233.

RAO, K. V. 1963. *Ibid.,* **14:** 143.

RAO, Y. P. 1960. Symposium on Monsoons of the World. *Indian Met. Dept.,* p. 111.

———— 1962. *Indian Journ. of Met. & Geophys.,* **13:** 157.

RAVENSTEIN 1898. *Journal of first voyage of Vasco Da Gama.*

REID, W. 1850. *Law of Storms.*

RIEHL, H. 1948. *Dept. of Met. Uni. of Chic. Mis. Rep.,* **24.**

———— 1954. *Tropical Meteorology.*

ROY, S. C. AND A. K. ROY 1930 *Beitr. Zur. Free Atmos.,* p. 224.

SIMPSON, G. C. 1921. *A.J.R.M.S.,* **47:** 151.

TAYLOR, A. D. 1874. *India Directory.*

THIRUVENGADATHAN, A. 1965. *Ind. Journ. of Met. & Geophys.,* **16:** 61.

THOM, A. 1845. *An enquiry into the nature of course of storms in the Indian Ocean south of the Equator.* Smith Elder and Co., London.

VENKATESWARAM, S. V. 1956. *Ind. Journ. of Met. & Geophy.,* **7:** 265.

VILLIERS, A. J. 1952. *The Indian Ocean.*

WAGNER 1931. *Gerl. Beitr. Z. Geophy.,* **30:** 196.

W. M. O. 1965. *Meteorology in the Indian Ocean. WMO Rep.,* 166 **TP 81,** Geneva.