IN THE INDIAN OCEAN

WORLD METEOROLOGICAL ORGANIZATION

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METEOROLOGY IN THE INDIAN OCEAN

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tigation of the Indian Ocean during the period and covered several scientific disciplines. Its purpose was to observe, describe, and if possible, explain the circulations of the ocean and the atmosphere and the interaction between them, the chemical composition and distribution of living things in the ocean and the bottom topography and coastal structure of the Indian Ocean.

The initiative for the IIOE was taken in 1957 by the Scientific Committee on Oceanic Research (SCOR), which sponsored the Expedition together with the United Nations Educational, Scientific and Cultural Organization (UNESCO).

One of the main features of the Expedition was its meteorological programme and WMO was requested by SCOR at an early stage to co-sponsor the IIOE and readily accepted. As a consequence, the third session of the Commission for Maritime Meteorology (Utrecht, 1960) adopted several recommendations with the aim of encouraging Members of WMO to take part in different ways in the work of the Expedition. Following these recommendations, the regular weather forecasting service for the Indian Ocean was reinforced by the meteorological services bordering this ocean area, and weather charts were issued by facsimile broadcast during the period of the Expedition. In addition, surface synoptic, aerological and maritime observations were carried out and reported by means of different types of observing stations, such as land stations, ships, aircraft, rockets, artificial satellites and an automatic weather station anchored at sea. The number of synoptic reports from ships over the Indian Ocean increased appreciably during the period of the Expedition.

As regards the research aspect of the IIOE, the third session of the Commission for Aerology (Rome, 1961) adopted a recommendation urging the Members of WMO to participate to the greatest extent possible in the IIOE, which was endorsed by the Executive Committee.

An important feature of the Expedition was the establishment of an International Meteorological Centre in Bombay by the Government of India with assistance from a United Nations Special Fund project for which WMO was the Executing Agent. The IMC, which was established in 1963, provided special meteorological services to the Expedition ships ; it has been collecting, processing and analysing the meteorological data of the Indian Ocean and has been carrying out research on this special meteorological problem of the Indian Ocean. An IBM 1620 computer was installed in the Institute to facilitate this work and has been of great value.

There can be little doubt that the meteorological programme of the IIOE was a great success and much of the credit for this must go to Professor C. Ramage, who as scientific director for meteorology has played an important role in planning and implementing the programme. He is therefore admirably qualified to write this brochure which I am sure will be read widely by specialists and non-specialists.

I wish to express on behalf of WMO our gratitude to Professor Ramage for having written such a clear and comprehensive account of the meteorological work achieved during the IIOE.

D. A. Davies

D. A. DAVIES
Secretary-General

World Meteorological Organization
Geneva, June 1965

IN THE INDIAN OCEAN

1 INTRODUCTION

by the frozen mass of Antarctica, was criss-crossed by a busy maritime traffic a thousand years before seamen ventured beyond sight of the shore-lines of other oceans. Great civilizations developed around the borders of the Indian Ocean, their peoples and cultures intermingling and interacting, linked by floating caravans. Life was sustained and trade grew through the beneficent agency of the monsoons copiously watering summer crops, obligingly producing fine weather for autumn harvests, and blowing simple sailing vessels on year-long-round trips across the ocean. Farmers and sailors doubtless comprehended the reliability and occasional vagaries of monsoon weather. On the other hand, weather never seemed to interest intellectuals of the littoral civilizations. No oriental Aristotle codified or tried to explain the vast monsoon lore of peasant and fisherman.

The centuries passed, with the inhabitants philosophically taking their weather for granted. Then, in the sixteenth century, voyagers from the west appeared, heralds of modern science, restlessly determined to observe, measure, and understand their environment.

The remainder of this article outlines what the voyagers and their successors learned and failed to learn about the meteorology of the Indian Ocean realm and how today's meteorologists participating in the International Indian Ocean Expedition are trying to unravel the remaining tangled skeins of ignorance.

2 CLIMATE OF THE INDIAN OCEAN REGION

What causes the monsoons or seasonal winds and how can they be explained in terms of the large-scale processes which go to make up weather and climate? For a start, let us consider separately the effects of the changing seasons over the open ocean and over the interior of a continent. Because of the inclination of the earth's axis to the plane of its orbit around the sun, the midday sun through the year appears to march from its summer solstice, on the 22nd of June, at the Tropic of Cancer, 23.5°N, southward into the southern hemisphere to its winter solstice at the Tropic of Capricorn, 23.5°S, on the 22nd of December. At this solstice, the northward countermarch begins toward the Tropic of Cancer, where the yearly cycle is completed. The summer solstice of the northern hemisphere occurs when the sun is overhead at the Tropic of Cancer, although highest temperatures usually follow about one month later, whereas the winter solstice, when the sun is overhead at the Tropic of Capricorn, precedes the coldest weather by a month or so.

Were the earth's surface either all water or all land, temperature, averaged over say a period of one month would be constant around any latitude circle. Seasonal changes would occur more or less at the same time around this circle and we would expect the general atmospheric circulation, since it is driven by the sun's heat, to reflect this. However, the presence of huge oceans and great continents significantly alters this simple picture.

Dwellers in an oceanic environment such as the Hawaiian Islands realize that over the wide oceans the winters are not particularly cold nor the summers particularly warm. In summer the sun's rays heat the ocean's surface, but mixing of the upper layers by the wind spreads the heat through a depth of 50 metres or more, and thus the temperature rise at the surface and of the air in contact with the surface is reduced. During winter over the open ocean the surface waters lose more heat than they receive, but again, convection in the sea surface layers and wind-driven mixing spreads the heat loss through an appreciable depth and consequently limits the temperature fall at the surface. Hence the ocean acts to reduce the difference in air temperature between summer and winter.

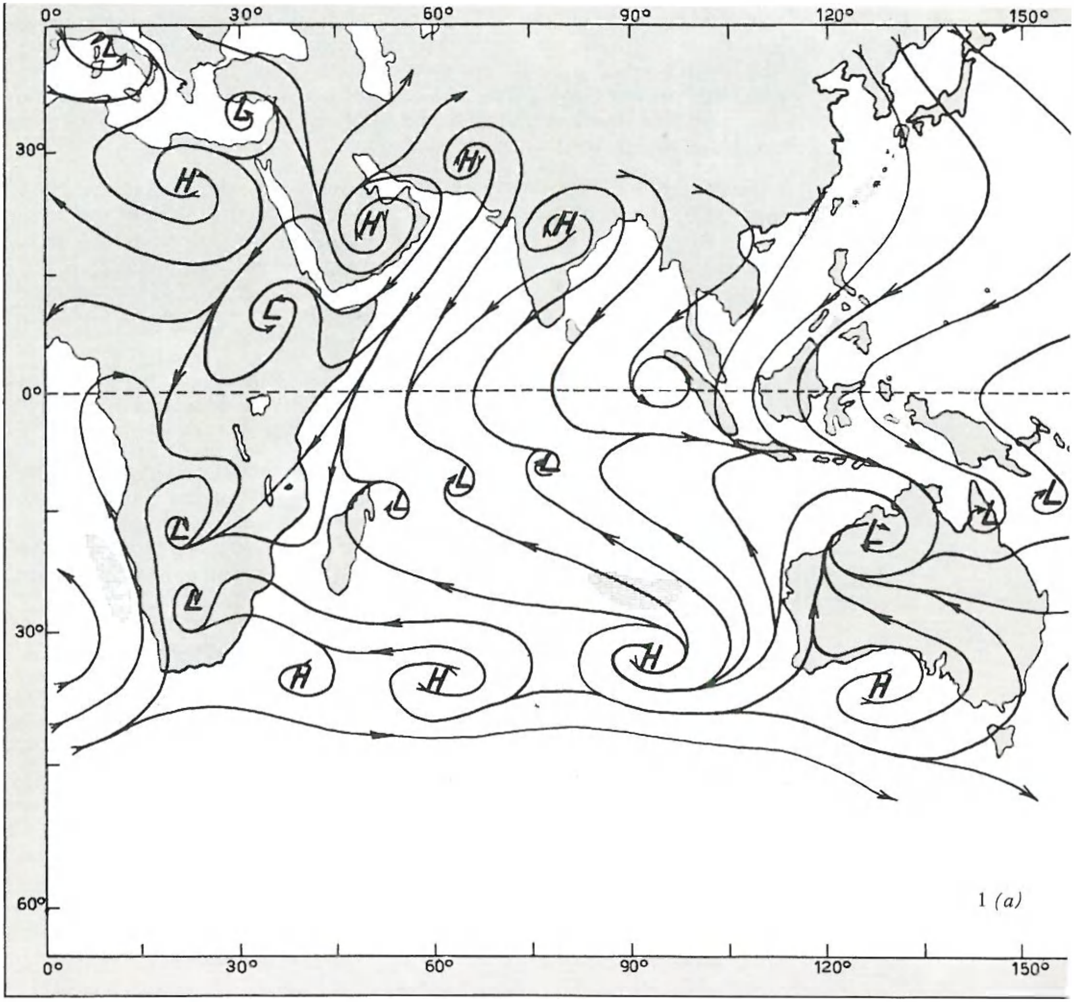
What happens over the centre of a large continent as the season changes from summer to winter? During summer the sun heats the land. However, this surface is a poor conductor of heat and is certainly not mobile in the is slow and inefficient. Most of the heat received from the sun is absorbed in the upper metre of the soil, raising its temperature and the temperature of the air in contact with it very considerably. Then as the sun begins its march south toward and across the equator and its midday rays reach the earth more and more slantingly, the land cools rapidly because of the slow rate at which heat is transferred upward from beneath.

The heat stored in the soil with its relatively low specific heat is small compared to the much greater amounts of heat stored in the considerably thicker surface layers of the ocean. Not surprisingly then, near the centre of the continental United States the average summer temperature is 30° centigrade above the average winter temperature, whereas at Honolulu near the middle of the Pacific Ocean the difference between summer and winter average temperatures is less than 5° centigrade.

Another way of expressing the difference between land and sea responses to the seasons is to say that the land has a relatively small heat capacity, whereas the ocean has a relatively large heat capacity.

The sun's heat, as received by the atmosphere, varies both seasonally and because of differences in the surface characteristics of the earth and in atmospheric moisture content. At any moment then, air is warmer, and therefore, less dense in some places than in others. Air pressure (the weight of a column of air of unit cross-section extending vertically from the point at which the pressure is measured to the top of the atmosphere) will also vary from place to place on the earth's surface, being lower where the air is warmer and higher where it is cooler. Air is subjected to a force which tends to move it down the pressure gradient from high to low pressure. The motion, however, is far from simple for it is modified by friction, by the effects of the earth's rotation and by centrifugal force if the motion is on a curved path. In combination these modifying effects produce a general gradual inspiralling or convergence of air toward zones of low pressure and a general outspiralling or divergence of air away from centres of high pressure. North of the equator, the earth's rotation causes the flow to spiral counter-clockwise into a low pressure centre or depression and clockwise outwards from a high pressure centre or anticyclone. In the southern hemisphere, the sense of rotation for depressions and anticyclones is reversed. The relationships between air pressure distribution and winds are illustrated in Figure 1.

The monsoons blow in response to the seasonal change in the difference in pressure, resulting from the difference in temperature between land and sea, and where great continents border the oceans large temperature differences might be expected. The Indian Ocean is the only ocean which does not extend from polar regions of one hemisphere into the polar regions of the other, being blocked on its northern side by the continental mass of Asia. Thus when the sun moves north of the equator in the northern hemisphere summer, the land mass of Asia with its relatively low heat capacity is rapidly warmed. On the other hand, the northern Indian Ocean between the equator and Asia stores the sun's heat within its deep surface layer. Consequently, the land more readily gives off heat than the sea, and the air over the land becomes warmer than the air over the neighbouring ocean. The warmer the air is, the less dense it is and, the less dense it is, the lower is the associated surface air pressure. A gradient of air pressure is established between the sea and the land causing surface air to flow from the sea to the land. Obviously, if this flow of air were uncompensated, the low pressure over land would soon disappear. However, it is a most persistent feature lasting from April through September every year. For this to be so, and for the distribution of pressure to remain unchanged, the air which flows into the depression at low levels must somehow be removed at higher levels. Figure 2 (a) shows a column of air over the land both hotter and less dense than a column of air over the sea. At, say, 3 kilometres above the surface the pressure gradient from sea toward land will be less than at the surface because the weight of air between the surface and



3 kilometres over land is less than over the sea. At some higher level, pressure over land will equal pressure over the sea. At still higher levels pressure over land will be greater than over the sea, and as the pressure gradient is directed from land to sea, the air will flow in that direction.

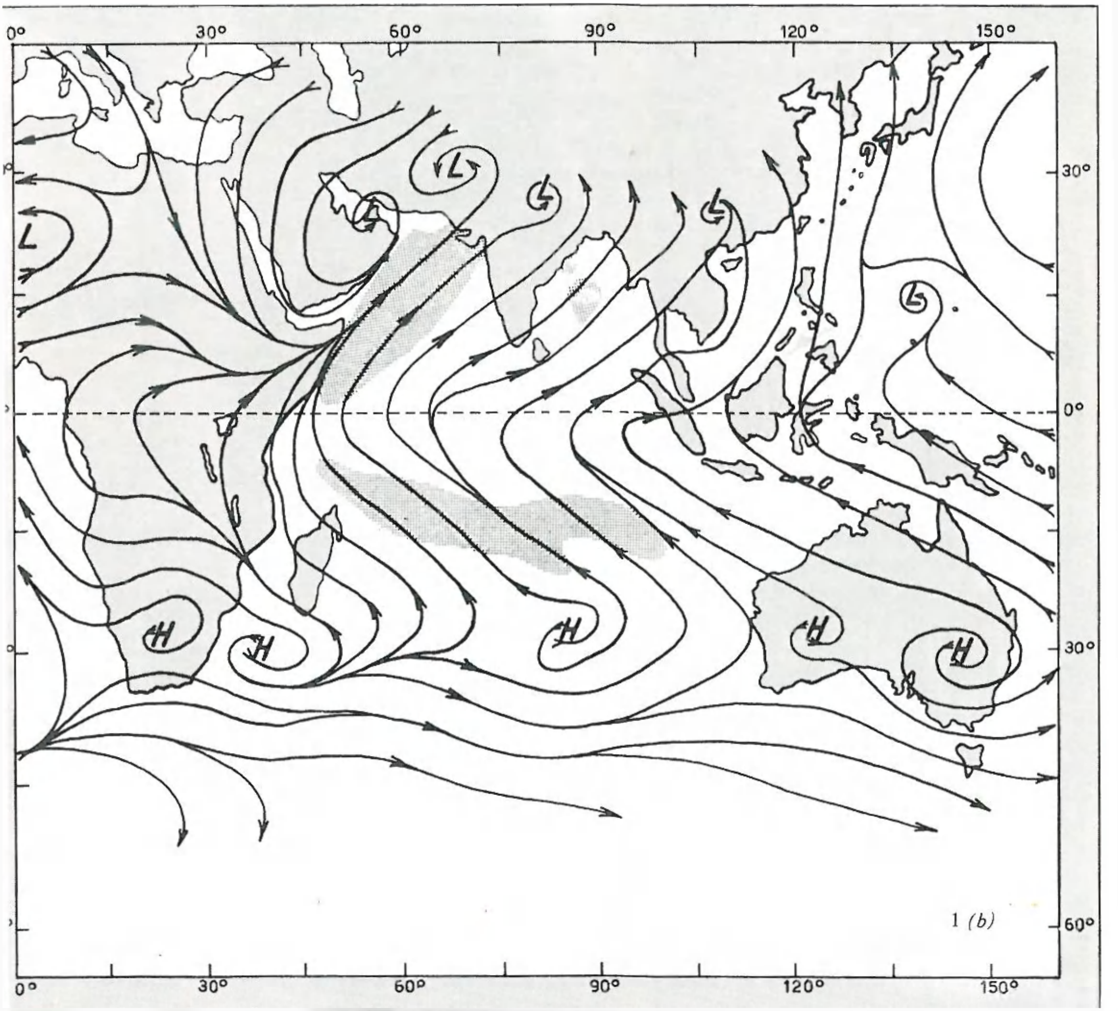
During summer, surface air flows from the Indian Ocean toward lower pressure over southern Asia, ascends as it is heated over the land until it reaches a level at which the pressure gradient is reversed, whereupon it flows on a return trajectory from land to sea, where it descends to be once more taken up by the landward directed pressure gradient. As long as the land is significantly warmer than the sea this great circulation persists. In winter the reverse occurs (Figure 2 (b)). The low heat capacity of Asia relative to the northern Indian Ocean ensures that the surface air over the land is colder than it is over the sea. We observe then the typical winter monsoon in which, at low levels, winds blow out from the continent over the sea, rise over the sea and return in the middle and higher layers of the atmosphere to the land where, sinking to the surface, they begin their travel again. Remember then, that the low-level flow in the summer monsoon is of moist air from sea to land, whereas in the winter monsoon the low-level flow is of dry air from land to sea. Later pages will show how fundamentally important this difference is for agriculture throughout the régime of the

Figu
Streamlines of the m
resultant surface wind f
for (a) January, (b) J
Portions of the tropical oce
where the mean resul
winds exceed 10 metres
second are shaded. Centre
low pressure are denoted
L and of high pressure by
Rugged terrain serio
reduces the reliability of
analysis over l

of southern Asia. During the northern hemisphere summer the desert areas of North Africa heat rapidly and surface pressure there falls in the same way as over Asia. South of the equator over Africa, during the southern hemisphere winter, cooling occurs, thus establishing a pressure gradient across Africa from south to north, which, in turn, sets up a massive flow of air, also from south to north, across the equator.

Because the deflecting force due to the earth's rotation reverses its direction at the equator and is weak in equatorial regions, air flow is more directly from high to low pressure than is the case in higher latitudes. The influence of Africa on the atmospheric circulation extends 800 kilometres east of the continent and merges with the influence of Asia farther north. In the northern hemisphere summer, at least over the low latitude portion of the Indian Ocean, a huge wind gyre flows from the south-east around the northern edge of the south Indian Ocean anticyclone and toward the coast of Africa near the equator, swings into the south across the equator and then south-west to parallel the African, Arabian, and Asian coasts and, finally, sweeps across India, Burma, and the Indo-China/Thailand Peninsula as the south-west or summer monsoon (see Figure 1 (b)).

Six months later a complete reversal takes place (Figure 1 (a)). Northern Africa is cold and southern Africa is warm and so the winds blow from the north across the equator in the western Indian Ocean. With the southward



1 (b)

ocean, as we have already seen, and winds now blow out from high pressure over Asia toward relatively low pressure over the Indian Ocean. This winter monsoon blows generally from the north-east and is much weaker than the summer monsoon. The difference is accounted for by the tremendous barrier of the Himalayas interposed between the very cold air of central Asia and the Indian Ocean. East of the mountain barrier over south China the winter monsoon is much stronger than the summer monsoon and temperatures, latitude for latitude, are much lower over south China during the winter than over India. As might be expected, Australia also experiences monsoons, but on a smaller scale.

The noted English scientist, Edmund Halley, writing in the Philosophical Transactions of the Royal Society in 1686, explained the machinery of the monsoons in terms that can scarcely be bettered even today. "Such as one (cause) is, I conceive, the Action of the Suns Beams upon the Air and Water, as he passes every day over the Oceans, considered together with the Nature of Soyl and Scituation of the adjoyning Continents : I say, therefore, first that according to the *Laws of Statics* the Air which is less rarified or expanded by heat and consequently more ponderous, must have a Motion towards those parts there of, which are more rarified and less ponderous, to bring it to an *Aequilibrium*. . ."

One way of defining a monsoon régime over the oceans is to consider as monsoonal those overwater areas where the directions of the average winds change by more than 90° between winter and summer. For this purpose we shall have to exclude the regions of very light winds or calms, the doldrums, where directions can fluctuate widely and rather meaninglessly over short intervals. A diagram (Figure 3) of this distribution points up the fact that the monsoons are essentially a phenomenon of the northern hemisphere. This is not surprising because the southern hemisphere is also known as the "water" hemisphere, and only in a few localities off the east coast of Africa and around northern Australia is the overwhelming modifying influence of the ocean on the seasons overcome by the ocean-continent interaction which produces the monsoons.

So far we have concentrated on what was probably the original connotation of monsoon, and what is certainly still the sailor's and fisherman's definition, namely, a seasonal change in wind direction. In the days of sail this change was of prime importance and in fact accounted for the very early development of considerable trans-ocean trading in the northern Indian Ocean. To the millions of peasants and farmers inhabiting the borders of the Indian Ocean, however, the monsoons signify *weather* changes associated with the seasonal changes in wind direction. Reference to Figure 2 and the following reasoning demonstrate why this is to be expected. Since the pressure at any point in the atmosphere is defined as the weight of the atmosphere above that point it follows that a parcel of air moving upwards undergoes decreasing pressure. To put it another way the air parcel expands. This expansion uses energy and the only energy available is in the form of heat. The air therefore cools as it rises. Conversely, descending air is warmed by compression. The amount of water that the air can contain as vapour is a function of the temperature of the air, so if the air is sufficiently cooled some of the water vapour condenses to form clouds, and if the clouds become thick enough, rain will fall from them. Again, should the air be full of clouds and be forced to *descend* the resultant warming could evaporate the clouds. Consequently, clouds are almost invariably associated with rising air currents and clear skies with descending currents.

Rising and descending air currents are usually linked to the patterns of atmospheric pressure as measured at the earth's surface. As pointed out earlier, air converges into areas of low pressure, and since the atmosphere acts essentially as an incompressible gas in any one horizontal level, the air must rise and consequently cool. Conversely, in areas of surface high pressure diverging air results in sinking motion and consequently atmo-

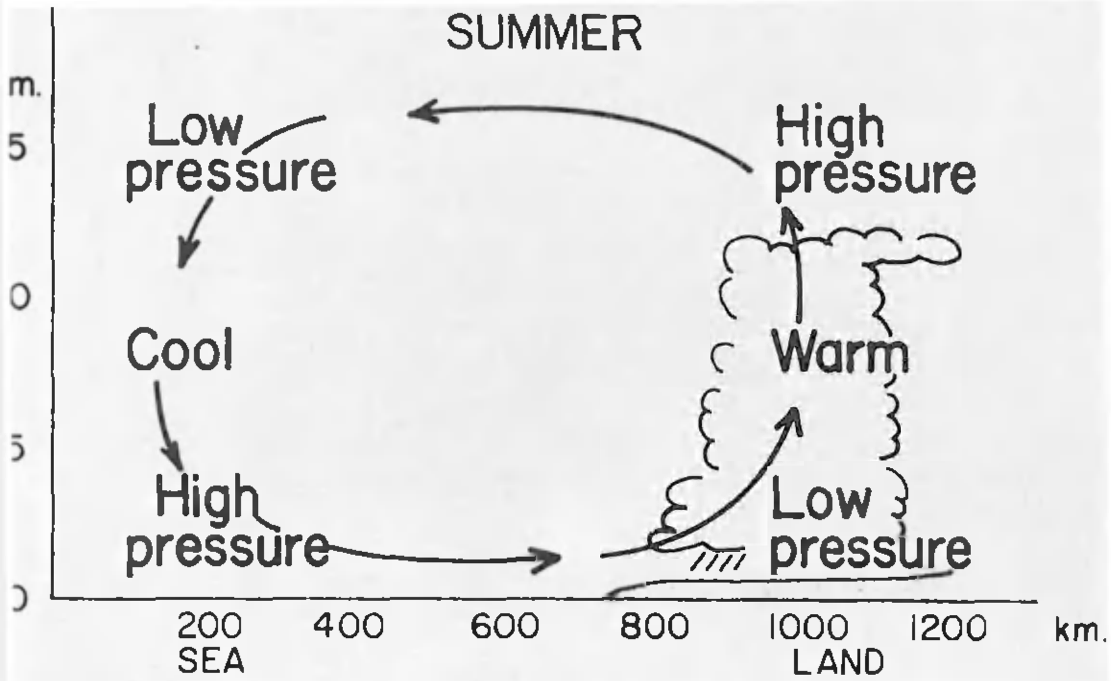
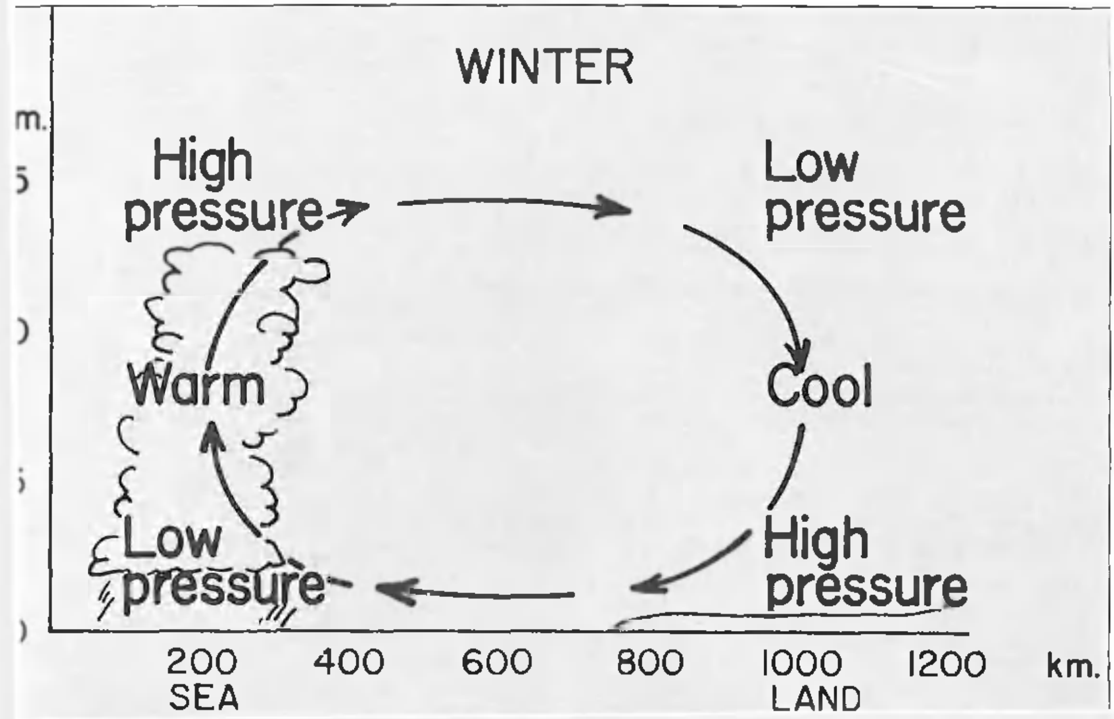


Figure 2
Schematic representations of the vertical circulations associated with (*a*) summer and (*b*) winter monsoons



layers are moisture-laden. As it is also converging into a region of low pressure, it is lifted and cooled. The winter monsoon, on the other hand, always blows from land to sea and its lower layers are dry. Besides, it diverges from a region of high pressure, sinking and being warmed in the process. Thus, the summer monsoon brings rain and the winter monsoon drought.

Were the relationship between air circulation and weather as simple as it appears here, rain would always fall from air spiralling in to the low pressure centres anchored over the heated land, droughts and famines resulting from failure of summer monsoon rains would be unknown and exact planning could ensure effective use of all agricultural land. Unhappily, although the winds change seasonally with commendable regularity, the weather by no means follows such a straightforward sequence, from which contrariness stem disasters such as the great west Indian drought of 1899. In that baleful summer the monsoon *winds* over India were stronger than normal and yet the rains that usually accompany the winds were almost entirely absent. This would suggest that although a change of the winds from winter to summer is a necessary condition, it is not a sufficient one for the development of summer rains in monsoon countries. Just as winds are the sailor's and the fisherman's monsoon criterion, rainfall is the farmer's.

Figure 4 shows the seasonal distribution of rain over the Indian Ocean and neighbouring lands. In regions with monsoonal wind régimes, we observe double maxima of rainfall in a narrow band extending from equatorial Africa to the Gulf of Thailand and Cambodia. These result from double maxima of heating corresponding roughly to the passage of the sun northward across the equator on the 21st of March and southward across the equator on the 23rd of September. North and south of this zone, around the continental periphery, rainfall possesses a single summer maximum. Areas with desert climate are located generally over the continents but toward their western edges, lying between regions of winter maximum rainfall and regions of summer maximum rainfall.

The wind diagram (Figure 3) indicates that the whole of the Arabian Sea region is monsoonal. As the summer monsoon circulation comprises air flowing at low levels from sea toward land, it is surprising to learn from the rainfall chart that the north-western portions of the Arabian Sea and Arabia have a desert climate with less than 250 millimetres of rain a year, whereas the west coast of India receives between 1,500 and 4,000 millimetres of rain in the five months of the summer monsoon. Why should a very significant rainfall discontinuity occur in apparently continuous low-level flow, and why should the convergence and consequent upward motion and cooling we might expect the monsoon air to undergo as it moves inland over West Pakistan result in little cloud and insignificant rain?

In every monsoon region rain is intermittent. After a week to ten days of frequent showers and periods of continuous rain, a lull ensues, lasting from one to two weeks when very little rain falls. The rains then resume and the monsoon is said to have strengthened.

This rhythm of the rains continues throughout the summer, a pattern quite contrary to that suggested by popular novelists who imply that the monsoon first sets in with a tremendous roar, and then the rains gush down without ceasing for periods of four to five months to be turned off like a tap when the season is over. Were such the case, monsoon rainfalls would generally total more than 25,000 millimetres in a season, rather than the 1,500 to 4,000 millimetres which, more normally, are observed in the wetter areas.

Those parts of the world possessing winter rainfall maxima lie outside the monsoon regions. There, summer is the season of dry air and few disturbances, and winter the season when moist air moves in from the sea and depressions convert the moisture to precipitation. Over the eastern United States, most of Europe, and the open oceans outside the equatorial zone,

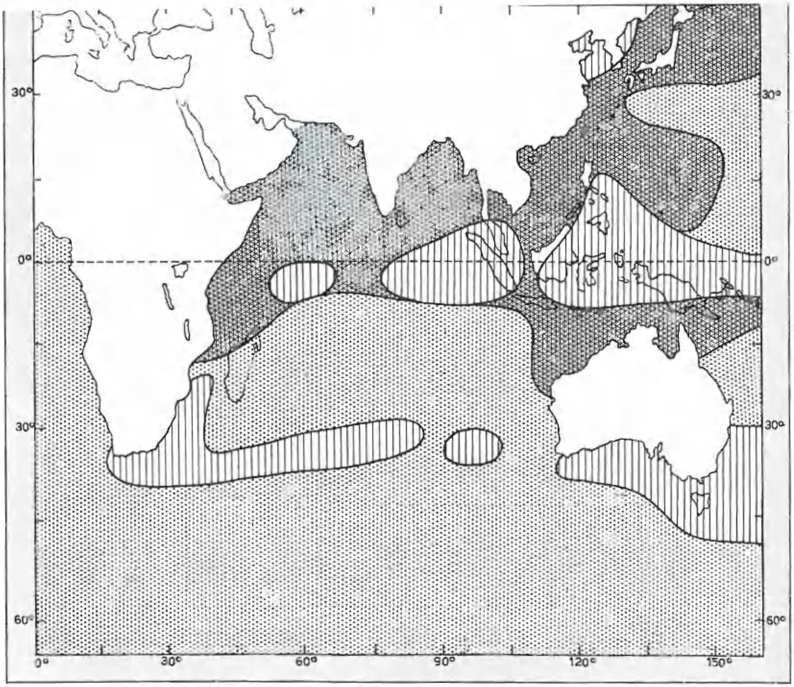


Figure 3
Wind direction as a monsoon criterion. A change in the nean resultant wind direction (as determined from ship reports) of more than 90° indicates that the ocean area)ossesses a monsoonal climate

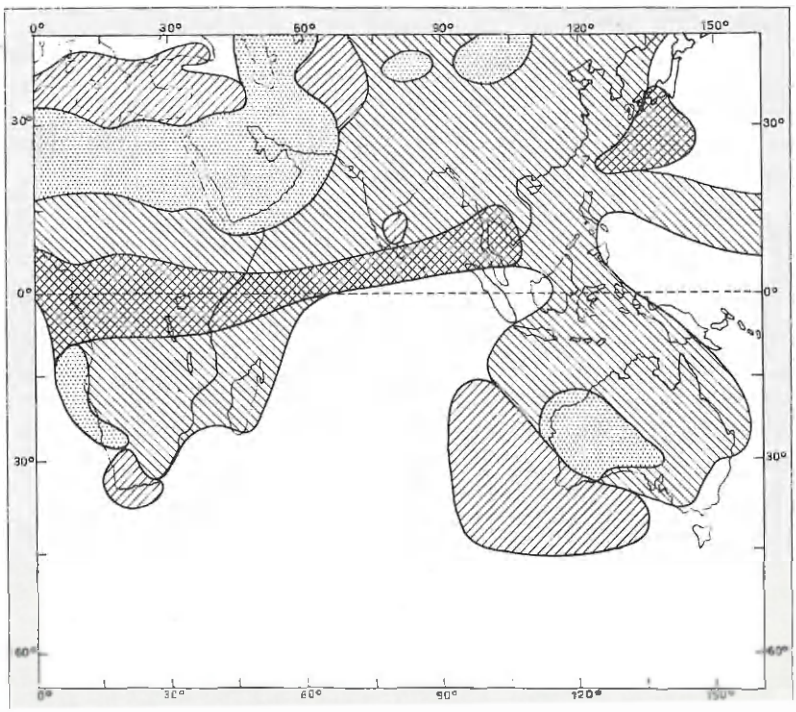


Figure 4
Rainfall as a monsoon criterion. Periods during which more than 75 % of the annual rain falls are gionally delineated. Regions ith less than 250 millimetres per year are classed as eserts ; regions accumulating 75 % of the annual rainfall in over seven months are considered to have no seasonal maximum. Ship observations of rainfall frequency are tied in to the land stations data

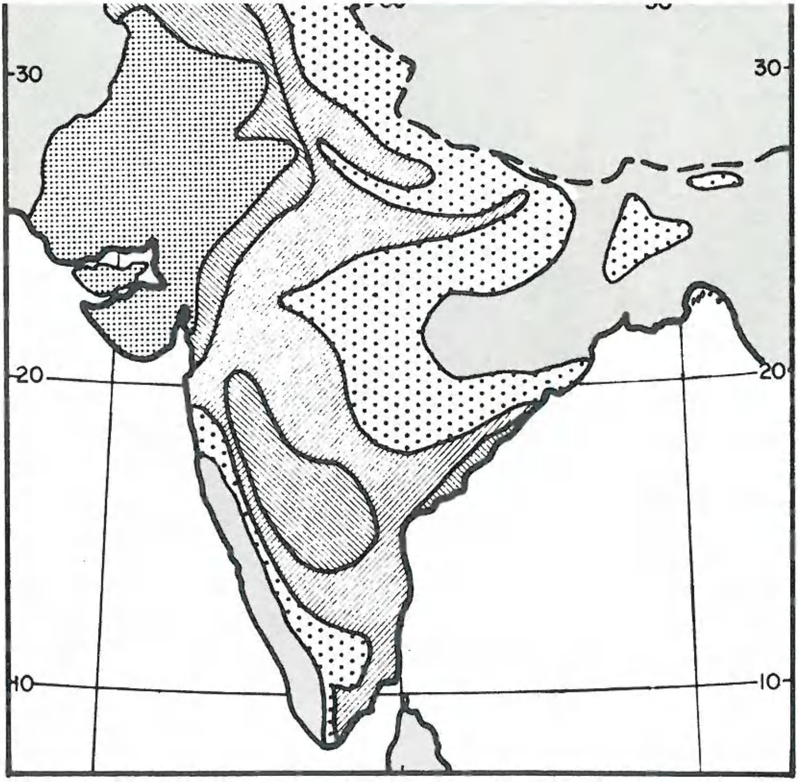


Figure 5
Per cent variability of ann
rainfall determined from
long-period records of
rainfall measured at thous
of stations in India and
Pakistan. The magnitude
of the difference between
total rainfall for each yea
at every station and the
long-term annual average
expressed as a percentage
the long-term annual aver
The average of these
percentages is the per cen
variability

It is not fortuitous that the main desert regions are sandwiched between areas with winter rainfall maxima and areas with summer rainfall maxima. The deserts are deserts because they are seldom if ever traversed either by winter or by summer rain-producing systems.

Surrounding every desert is a region where rainfall in some years is plentiful and, in others, fails altogether. The inhabitants are generally herdsmen rather than agriculturalists.

Occasionally major rearrangements in the circulation of the atmosphere, little understood as yet, suddenly turn a monsoon-rain region into a desert by causing nearly complete failure of the rains. The rhythm of rain-and-lull is completely disrupted and cloudless day follows moonlit night until the land, which should be green, begins to look like the centre of Arabia. Such relatively rare events have cataclysmic effects. Normally luxuriant rain-fed crops wither and die, and famine can be averted only by massive shipments of food from outside. Figure 5, showing variability of rainfall over India also depicts the chances of drought. Western India on the borders of the desert has high rainfall variability. Eastern India, well within the summer monsoon rain system, has low variability.

Summing up, we may delineate a summer monsoon in which moist air flows at low levels from sea to land and a winter monsoon in which dry air flows at low levels from land to sea. Monsoons result only where sharp seasonal temperature differences develop between continent and neighbouring ocean or across an equator-spanning continent. Considerably more rain falls during the summer monsoon because of the greater supply of moisture. Even so, it is an intermittently rainy monsoon characterized by lulls in which very little rain falls.

Drought may extend beyond its normal desert confines over bordering monsoon rain areas. The effect is catastrophic, particularly if such abnormal conled to the Government of India establishing a country-wide meteorological service in 1875. The India Meteorological Department and its predecessor by nine years, the Batavia Observatory, rapidly attained world renown. Meteorologists of the two services, drawing on data from superb networks of surface weather stations and assiduously analysing Indian Ocean ship logs, strove to foretell some months in advance, the intensity and distribution of monsoon rains over their countries. By the first quarter of this century their investigations, based on statistics, encompassed observations from all over the world. Success has remained tantalizingly elusive, however, and apparently is not to be won before the investigators adequately describe and understand day-to-day weather processes.

NEED TO KNOW MORE

This goal has been partially achieved over land, but, over the Indian Ocean, atmospheric conditions above the surface have remained largely unknown. Even during World War II and the International Geophysical Year, attention was fixed elsewhere.

Consequently, although time has been unkind to various theories of long-range monsoon forecasting and of significant interactions between the hemispheres, it has not favoured development of new ideas, particularly directed to explaining the large-scale seasonal variations in the monsoons, as well as the sharp differences from one week to the next and between neighbouring provinces. The ocean provides more than enough fuel for the monsoon "engine" but we are ignorant of how the fuel is used or of how surplus energy, exported from monsoon regions, may modify the general atmospheric circulation.

The first move toward filling this void in geophysical knowledge came from oceanographers, fascinated by the possible effects that a massive reversal of the atmospheric circulation between winter and summer might have on the underlying ocean.

Winds generate waves and ocean currents, and these in turn redistribute through horizontal and vertical motions the cold and warm waters of the ocean and their chemical properties. These redistributions then intimately affect the population of the ocean. In some areas wind-driven mixing of the surface layers of the ocean ensures the spread of nutrients in one season, whereas an entirely opposite wind circulation in the other season may equally ensure that no nutrients are distributed. Thus life in the Indian Ocean is probably very largely seasonally influenced and itself takes on a monsoon character.

4 THE INTERNATIONAL INDIAN OCEAN XPEDITION (IIOE)

Not unexpectedly, a Scientific Committee on Ocean Research (SCOR), 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. Two years later the International Indian Ocean Expedition as it was named got under way with the dispatching of survey vessels to the region and with joint sponsorship by SCOR and UNESCO.

The International Indian Ocean Expedition was designed to observe, describe, and possibly explain the circulations of ocean and atmosphere and exchanges across their interface, the chemical composition and distribution of living things in the ocean, and the bottom topography and coastal structure of an ocean which is more extensive than Asia and Africa combined.

A fleet of ships from many nations — ships carrying highly specialized equipment and scientists — are sailing the Indian Ocean on new voyages of discovery. More than 20 countries, contributing more than 40 vessels staffed with scientific parties, will complete more than 160 cruises by the end of 1965.

Australia, East Africa, France, Germany, India, Indonesia, Japan, Pakistan, Portugal, South Africa, the United Kingdom, the United States, and Russia are operating from 1 to 12 ships each. In addition, countries bordering the Indian Ocean provide shore stations and personnel for local observations, particularly on tidal changes and meteorology.

5 METEOROLOGY IN IIOE

In 1960 when meteorologists became fully aware of plans for the International Indian Ocean Expedition they took some time to grasp the potential significance of the programme to their discipline. 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. The group began logically, by defining what it considered were the unsolved problems of the atmosphere over the Indian Ocean, then suggested what steps should be taken to obtain data sufficient to give a good chance of solving the problems, and finally outlined ways in which the data should be processed so that a successful programme of research might be achieved. Two interrelated problems were defined. The first is 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. A study of the first problem demanded a considerable increase in the density and number of observations made over the Indian Ocean, using in the main existing instrumental techniques, and then collecting every scrap of information efficiently and quickly. In the early days WMO was asked, and readily consented, to encourage countries bordering on the Indian Ocean and countries operating large marine and air fleets to step up the quality and quantity of their observations and to make them readily available to the investigators.

Of course, to understand thoroughly the general circulation, one must eventually be able to make accurate measurement of the exchange of energy between the ocean and the atmosphere. So it is likely that final success in solving the first problem might depend rather significantly on success in solving the second, the instrumentation for which is only now being developed.

6 OBSERVATIONS FOR THE GENERAL CIRCULATION PROGRAMME

Most of the IIOE research vessels in addition to being equipped to make almost every type of biological, geological, physical, and chemical oceanographic measurement were provided with balloon-filling shelters and ground-receiving equipment to enable them to release "radiosonde" balloons at least once daily to levels up to 30 kilometres above the surface (Figure 6). Instruments carried by the balloons measure temperature, pressure, and humidity on the way up. It is fortunate that the new generation of oceanographic research vessels, many of which have made their maiden scientific voyages in the IIOE, are considerably larger than their predecessors, thus enabling multifarious interrelated experiments and measurements to be made.

Even with this important addition to observations regularly made from merchant ships, land stations and commercial aircraft, the meteorologist must remain unsatisfied. Although 40 research vessels are participating in the Expedition, at any one time fewer than 10 are making measurements. These 10, spread over 75 million square kilometres of ocean, can scarcely begin to collect a significant amount of usable information. Consequently, meteorologists have turned to other sources of data.

Commercial and military transport aircraft traverse the Indian Ocean. The weather observations and pictorial cross-sections constructed by the crews of these planes are being collected and noted. Certain aircraft have been fitted to make time-lapse movie records of the clouds on their long over-ocean flights. The technique is a relatively simple one developed many years ago and spectacularly used in science films to compress into a few

Figure 6
Release of radiosonde balloon from an oceanic weather station

movies have been taken from fixed ground stations of the changing cloud patterns in the heavens, thus allowing a complete day's sequence to be subsequently viewed in a few minutes. The next step has been to place time-lapse cameras on aircraft, have them photograph the clouds at intervals of one frame every three seconds, recording on 30 metres of 16-millimetre film every cloud which comes within camera range on a six-hour flight. When the film is developed, it is run through a projector at the normal speed of 16 frames a second and the viewer gets the rather exciting impression of flying at about 50 times the speed of the aircraft or at around 30,000 kilometres per hour. What airborne time-lapse photography does then, is record all the clouds visible in strips about 2,500 kilometres long and 60 kilometres wide, a quite considerable improvement over spot observations made from single observing points.

Even this leaves vast observational gaps, particularly when we remember that over the whole of the southern Indian Ocean only one commercial air route is operated, linking Perth, Cocos, Mauritius, and Pretoria.

Luckily for the meteorologist an even more spectacular observational tool came to hand when the first meteorological earth satellite, TIROS I, was launched in 1960 by the U.S. National Aeronautics and Space Administration. Throughout the period of maximum meteorological activity in the Expedition, during 1963 and 1964, at least one and often two weather satellites were photographing the region. A single satellite photograph taken from 700 kilometres above the surface of the earth provides a staggering amount of information. When the satellite camera points directly downward it records the cloud cover to a resolution of about 3 kilometres satellite is programmed to photograph a particular region, it generally takes a sequency of 32 of these photographs overlapping one another and extending through about 30° or 40° of latitude. Unfortunately because of readout and programming limitations, the TIROS family of satellites has photographed the Indian Ocean region only sporadically. Nevertheless the information they have provided is vital to all studies of the meteorological data from the Expedition. On 28 August 1964 the first of a new family of weather satellites, NIMBUS I, was successfully orbited. This satellite photographs every part of the earth once each day and also records the character and height of night-time clouds using infra-red radiation sensors. The implications of this tremendous advance for our Indian Ocean investigations are as yet not properly understood, but it means that at last, with these and all the other observations that have been most laboriously made, collected, checked, and processed, we now have for the first time the opportunity to attempt a complete description — at least for the period during which NIMBUS is operating — of the whole atmospheric distribution over the Indian Ocean.

placed in the Bay of Beng

Other special meteorological observations are making significant contributions to the programme. Heavily instrumented research aircraft of the U.S. Weather Bureau and the Woods Hole Oceanographic Institution (Figure 7) visited the Indian Ocean for extended periods during the summer of 1963, the late winter of 1963, and again in the summer of 1964, ranging widely over the ocean both north and south of the equator and making a bewildering variety of measurements of complex weather systems which require the most detailed probing before successful analysis of their character is possible. The planes carry time-lapse movie cameras to photograph the clouds and to record the distribution of precipitation determined by three radars, they have instruments on board for measuring temperature, humidity, wind direction and speed, liquid water content of the air, icing, altitude, air pressure, and turbulence. On some of the aircraft the information gathered by the instruments is automatically put on magnetic tape at predetermined rates which may be as often as forty times per second. Processing can then be handled by a suitably programmed electronic computer. At hourly intervals during a flight, a parachute-borne radiosonde, or "dropsonde", is released from the research aircraft, radioing back pressure, temperature, and humidity data as it descends.

Figure 7
Airplane for meteorologica
research flight

7 MEASUREMENTS OF OCEAN-ATMOSPHERE EXCHANGE

Besides giving general information about the structure of large weather systems, the equipment on the research aircraft is also designed to measure small-scale interactions between the ocean and the atmosphere.

Instruments on the Woods Hole aircraft measure the turbulent flux and short and long-wave radiation. Combining this information with photographic records of cloud and precipitation distribution and data from dropsondes may lead to determination of the energy budget of the ocean-atmosphere system.

Wind profile measurements designed to elucidate some of the aspects of atmosphere-ocean energy exchange were made in collaboration with the Woods Hole biological research vessel ANTON BRUUN. On three different days a U.S. Weather Bureau aircraft intercepted the ship en route from Madras to Bombay. At each meeting the ship was steamed slowly into wind. While the wind was continuously measured on shipboard, the plane executed a pre-set flight pattern above, first flying over the ship into wind at 1,000 metres, for about 15 kilometres, then dropping 150 metres and swinging back across the ship again ; this procedure was repeated until the plane had descended to 100 metres above the sea. All this time data from a Giannini gust probe located in the plane's nose were being recorded on magnetic tape at a rate of 40 times a second. Subsequent calculation through the atmospheric friction layer and also assess the magnitude of internal friction within the layer.

In a project timed to coincide with the second visit of the research aircraft to India in early 1964, meteorologists from the University of Washington shipped a specially instrumented buoy (MENTOR) to Bombay (Figure 8) and then, with the Dutch tug *Oceaan* acting as tender, automatically recorded continuous measurements of wind, temperature, and humidity in the layer of air from the sea surface to 10 metres above the surface in the area between 80 and 320 kilometres west of Bombay. While the fine structure of air-sea interaction was thus being recorded, MENTOR was being "boxed" by the research aircraft flying at heights between 450 and 4,500 metres collecting data from which the total energy entering and leaving the 130 × 160 × 5 kilometres box could be evaluated.

A group from the University of Michigan installed pyrheliometers, thermal radiometers, and recorders at fourteen Indian Ocean island and coastal stations to measure incident solar and atmospheric radiation. These variables as well as sea surface temperature, air temperature, relative humidity and wind are being automatically recorded on U.S. research vessels in the Indian Ocean (Figure 9). The tabulated data will be the input to a turbulent flux model now being developed.

Figure 9
Measurement of sea surfa
temperature
by bucket method

for investigations not originally connected with the Expedition. For example, special high-altitude balloons are being distributed to aerological sounding stations in the region to enable the circulation in the high atmosphere around 30 kilometres to be investigated as part of a world-wide study of a strange 26-month fluctuation of stratospheric winds. Also Expedition activities are co-ordinated with those of the International Years of the Quiet Sun. During 1964, under U.S. National Aeronautics and Space Administration sponsorship, meteorological rockets were fired from a few Indian Ocean stations as nearly simultaneously as possible to sample winds and temperatures up to 75 kilometres above the surface.

OTHER PROGRAMMES

9 THE INTERNATIONAL METEOROLOGICAL CENTRE

Data are not much use unless they can be collected, processed, and used directly in research. The vast area of the Indian Ocean, the varied observations and the sheer mass of the data demanded that some central directing organization should be established. The Government of India therefore most generously set up, equipped, and staffed an International Meteorological Centre (IMC) for IIOE on the compound of Colaba Observatory, Bombay, on 1 January 1963. From that date IMC has been the focal point for all the special meteorological activity associated with the International Indian Ocean Expedition. In addition to the more than 100 staff members provided by the India Meteorological Department, the centre has received significant contributions in men and equipment from the United States and from the WMO Special Fund project.

The International Meteorological Centre collects, processes, and distributes all types of meteorological observations made over the Indian Ocean and surrounding countries during the years 1963 and 1964. It analyses these data on horizontal charts plotted twice daily for standard meteorological levels extending from the surface to the tropopause at around 16.5 kilometres, conducting preliminary evaluation and research on the data as expeditiously as possible. In addition, IMC trains meteorologists from the region in analytical techniques and forecasting methods and also introduces them to useful research which they might profitably continue to pursue after returning home; provides special forecast and other services to the Expedition research vessels, and compiles charts incorporating the data collected in forms of value to other disciplines.

Data collection is accomplished by radio, backed up by manuscript copies mailed from meteorological centres of the region. Processing takes various forms. The WMO Special Fund project has given an IBM 1620 computer to IMC (Figure 10). The computer is used to check the accuracy of all Indian Ocean ship reports and all aerological soundings made in the region, and then to derive various averages and distributions. Of particular interest is a programme by which the computer calculates the energy exchange between ocean and atmosphere, using the data normally obtained from observations by merchant ships. The computer is also used in a diagnostic fashion to assist researchers in describing and obtaining preliminary understandings of atmospheric circulation components. At a later stage, after the Expedition is over, these rather crude qualitative models will be further refined, but for this, larger and faster computers than the 1620 will be needed.

10 A DAY AT IMC

Throughout the night, staff in the small, air-conditioned communications room have been receiving broadcast coded weather reports from the Indian Ocean region in morse code and on teleprinters. Pictures of charts analysed a few minutes before in the meteorological centres at Nairobi, Moscow, Sangley Point and Canberra unroll from facsimile printers (Figure 11). Across the compound of Colaba Observatory in the Signal Office of the western Regional Meteorological Centre, other teleprinters disgorge figure-crammed sheets of paper containing detailed information on Indian weather, and on the weather over the whole eastern hemisphere north of the equator.

This continuous stream of data flows on to the weather plotters (Figure 12), who use a graphic shorthand to enter each piece of information at its correct location on an outline map of the region. Observations made at the earth's surface are entered on one map, data from sounding balloons and aircraft on other maps assigned to specific heights above the surface. The observations recorded on this family of maps, or synoptic weather charts, were all made at the same time, at midday Greenwich Mean Time or at 5.30 p.m., Indian Standard Time, on the previous afternoon, a fact of importance in the next step — analysis.

All the information available by radio for this particular observing time having been plotted, the charts are passed to trained professionals, who attempt to construct cohesive reasonable pictures of the distribution of weather at the observing time. The analysts, as they are called, refer constantly to earlier charts, to the various charts of the family with which they are directly concerned, and to the radioed facsimile analyses depicting conditions around and beyond the borders of the Indian Ocean region, in order to maintain reasonable continuity in time and space. Analysis variable, such as pressure between the plotted observations, and relating the resulting patterns to the distribution of weather and winds. Since in low latitudes wind patterns usually can be readily related to weather, the analysts at IMC (Figure 13) construct streamlines parallel to the winds and isotachs connecting points having the same wind speed (see Figure 12 and also Figure 1).

Through the forenoon, analysis proceeds, aided by late reports, and at around noon by instant facsimile pictures of cloud patterns over millions of square kilometres of the northern Indian Ocean, received by the Automatic Picture Taking Ground Station at IMC from a NIMBUS weather satellite orbiting overhead (Figure 14).

Already a completely new cycle is under way. Observations made at midnight Greenwich Mean Time (5.30 a.m. Indian Standard Time) are being received in the communications room and are being entered on a fresh family of synoptic charts by the weather plotters.

By 2 p.m. the analysts have completed their jobs and hang the products around the wall of the analysis room, each chart directly beneath a chart showing average conditions determined for the same level for the same month in previous years. Then all the professional staff members, visiting scientists, and meteorologists under training assemble (Figure 15). The analysts lead off a general discussion by explaining and justifying their analyses, others describe and comment on details or recount a trip made the previous day on a research aircraft. In the give and take of argument, new research ideas are born and earlier ideas evaluated. With preparation of a synopsis of the overall weather situation for dissemination through the India Meteorological Department, the analysts' work for the day is done. A new team takes over and completes the next set of analyses later that evening. And so the daily routine has gone on through all of 1963 and 1964.

Figure 10
U.S. IIOE computer expert, Lt.-Col. Forrest R. Miller, at the main console of the computer

Fluctuations in radio propagation and the great distances over which some broadcasts are beamed has meant that less than 50 per cent of the weather observations made in the Indian Ocean region are received by radio at IMC. However, since research demands every scrap of available data, meteorological services mail copies of the reports to IMC, where they are "back-plotted" on the appropriate synoptic charts.

The data are both extensive and bulky. For example, over 8,000 ship reports are received, plotted, and analysed for every month, and each report contains 27 separate pieces of information. Thus, ways of condensing and making these and other data more manageable have had to be found, so that all researchers could use them. The microfilming, and the card punching and data processing units at IMC see to that.

Six hundred weather charts, each a metre square, can be photographically recorded on a single roll of 35 mm microfilm weighing only 200 grammes.

Key punch operators record all ship, island station and upper-air reports on punch cards which are then checked by the computer for errors, and processed in various ways useful to research (Figure 16). Checking and recomputation of data, from a radiosonde ascent, takes a skilled technician at least half an hour. The IBM 1620 does a much more accurate job in one minute. Dramatic weight-saving is also possible; 100,000 punch cards, containing 100,000 ship reports, weigh 250 kilograms. The reports can all be transferred electronically to a single reel of magnetic tape weighing less than 2 kilograms.

Besides performing the routine duties of a typical busy day, scientists and assistants at IMC devote much time to research, undertaking special plotting and analyses, special computer processing, and referring to earlier research and extensive weather records. Preliminary results were reported at a symposium held in Bombay in August 1963, and papers incorporating the results of investigations are being published in scientific journals.

years 1963 and 1964 will be readily able to obtain data excerpts in forms suiting their needs at the cost of materials and postage. The region of interest extends well beyond the Indian Ocean proper, ranging from 20°E to 155°E and from 50°S to 45°N. The IMC file consists of:

(*a*) Microfilm copies of all analysed synoptic charts.

(*b*) A master unanalysed synoptic chart series plotted on semi-transparent paper suitable for reproduction by ozalid or similar processes.

(*c*) Microfilm copies of all synoptic broadcasts for the region, excluding synoptic data incorporated in publications such as the Daily Weather Reports of India and the United Arab Republic.

(*d*) Microfilm copies of aircraft reports, airline meteorological logs, ship logs, etc., not available under (*c*).

(*e*) Error-checked punch card records of surface observations from ships and mid-ocean island stations.

(*f*) Error-checked punch card records of radiosonde and upper-wind observations made from ships and land stations within the region. The computer has been used to recompute soundings from the original coded messages, to interpolate significant level data, and, finally, to punch data at 50 millibar intervals on a new set of cards.

Many meteorological services in Indian Ocean countries have intensified data gathering and research. IMC helps by providing exchange and liaison facilities. In addition to the United States, the United Kingdom, Japan, the U.S.S.R., and Germany are actively participating, while WMO experts in climatology and computer methods are working at IMC under the aegis of the WMO Special Fund project.

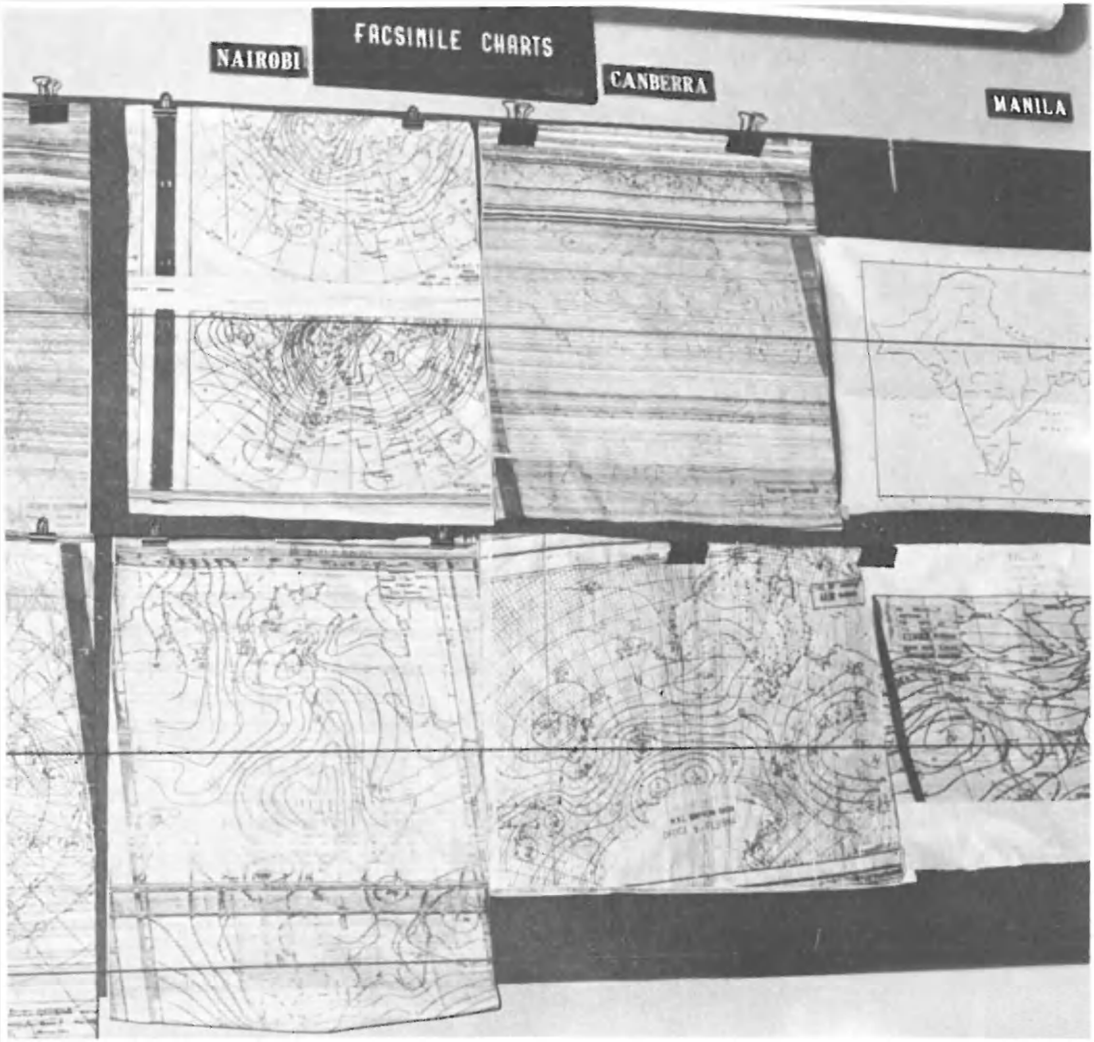


Figure 11
Facsimile charts which aid extended analysis
at IMC

igure 12
close-up of a sea-level chart under
'enaration — note coverage

Figure
Analysts at IMC discussing a weatl
situation in the southern hemisphere-Indi
Ocean aı

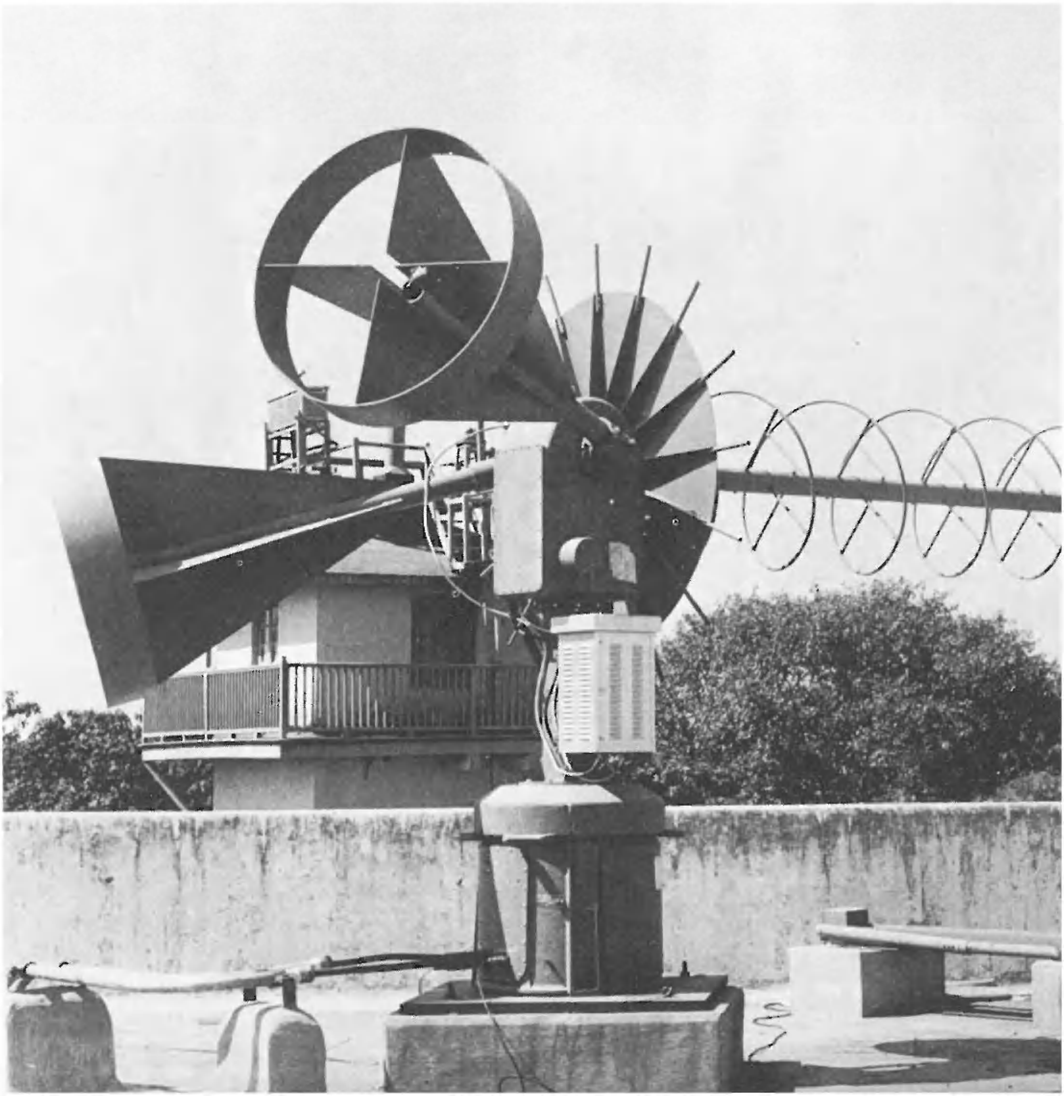


Figure 14
Antenna system of Automatic Satellite Picture Taking (APT) equipment provided by the U.S. National Science Foundation

Figure
Meteorological data being transferred
punch ca

Figure 15
Scientists at IMC attending a map discussion

be achieved by the International Indian Ocean Expedition? One tangible gain has been that scientists from widely varying disciplines, collaborating closely in a combined investigation of the problems of the ocean, have gained new insights into the disciplines of the others and also into ways in which their observations may help studies of apparently unrelated conditions. For instance, the meteorologists' observations of cloud cover and sunshine duration greatly interest the marine biologist since the amount of plant growth in the ocean is directly related to the process of photosynthesis which in turn is affected by both the amount of direct sunshine reaching the sea surface and the length of the day.

One definite result which may take several years before being finally achieved will be the compilation and publication of a series of atlases describing in as great detail as possible all the various distributions of observable quantities, physical, chemical, and biological, below, in, and above the ocean during the period of the Expedition. These atlases will provide research material for many years.

In meteorology what might we say of progress to date? Perhaps the most gratifying early discovery has been that routine Indian Ocean meteorological observations, distinct from those made for special research projects, are far more plentiful than anyone had suspected. In particular, the unexpected wealth of information obtained through the mails and in manuscript form from ships and aircraft, while straining the processing facilities at IMC, has also enabled us to begin investigations not considered feasible when the project started. Improved collection and better radio equipment could make many such concealed data immediately available to the region's forecast centres.

Certainly our data have tended to favour some existing theories of the atmospheric circulation over others but it is doubtful whether any really new theories have been developed. This is scarcely surprising in view of the way ideas on monsoon systems have proliferated over the last hundred years; ideas which unfortunately had little observational basis. Presumably, although differential heating of land and sea establishes the monsoon circulation, an additional mechanism is necessary to form clouds and to make the clouds give rain. There is little doubt that atmospheric disturbances (relatively short-lived depression or depression-like systems) lift the sea-supplied moisture hundreds of metres to saturation point then cause the deep clouds thus formed to produce rain. Over India two distinct types of summer monsoon disturbance have been identified. "Monsoon depressions" bring rain to northern Burma, and to eastern and north-eastern India. Possessing some of the characteristics of weak typhoons, they are moderately vigorous cyclonic circulations which are best developed in the atmospheric layers closest to the ground. The average monsoon depression forms over the northern part of the Bay of Bengal and then moves rather slowly west-north-westward along the general line of the Ganges Valley. Some may travel toward the north-east into Assam. As they move along, copious rain accompanies them. Over western India, rain-producing cyclones usually form just off the west coast, moving very little, and are most intense at around 4,500 or 6,000 metres above the surface. Whereas the Bay storms are frequently accompanied by thunder and lightning, the west coast storms are seldom electrical performers. Over West Africa, rain situations seem to resemble the western Indian model, but over northern Australia and south-east Asia, systems similar to the Bay of Bengal monsoon depressions bring the rains. When in the form of typhoons, they are intense and devastating.

Monsoon disturbances move slowly and often erratically and remain embedded within the monsoon régime which is itself a semi-detached part of the general atmospheric circulation system. Possibly because of this ingrown character, monsoon disturbances appear to contain within their circulations the seeds of their decay. The fine weather of the lull is just as the air is hottest and therefore least dense we find a zone of minimum surface air pressure into which the air converges from both sides. Rather surprisingly, new observations confirm that throughout the year in the winter hemisphere there is another zone of low pressure, less intense than the one in the summer hemisphere but nevertheless marked and associated with inflowing air and bad weather (Figure 1). This trough is rather weak over Africa, where, as mentioned earlier, a strong transequatorial flow occurs from the winter to the summer hemisphere. The two troughs through the course of the year participate in a double oscillation. In July the northern hemisphere trough is found lying across Arabia, Pakistan, and northern India, while the southern hemisphere trough lies just south of the equator. Between July and January both troughs move south, the northern hemisphere trough to a position just north of the equator and the southern hemisphere trough to a position about 20° or 25° south of the equator. After January the cycle reverses until the troughs once more take up their July positions. Cyclones of varying intensities frequently develop in the extensive and vigorous summer hemisphere trough with consequent severe weather. However, depressions may and do develop in the winter hemisphere trough and although they are generally weak, on rare occasions they may reach hurricane force and do unexpected widespread damage. It is not particularly uncommon especially in the spring and autumn transition seasons to observe tropical cyclones developing at more or less the same time on both sides of the equator.

Evidence is also accumulating to support the idea that there are probably many more individual monsoon régimes in the Indian Ocean than had previously been suspected. The summer monsoon of south China for example is known to be distinct from the summer monsoon of Burma. Until now there has been a tendency to lump the summer rains of the Indian subcontinent into one general category. Now it appears that there are three complexly related components to the Indian summer monsoon, dominating the north-east, north-west, and south of the country. The monsoon of north-east India is the most steady and reliable of all, depending for its rain generally on the development of monsoon depressions in the northern Bay of Bengal and on their subsequent movement west-north-westward up the Ganges Valley. The monsoon of north-western and western India on the other hand is much more variable. In some summers when middle-level depressions develop over the north-eastern part of the Arabian Sea, the rains are plentiful and widespread. In other summers, for reasons not yet understood, the meteorological conditions which produce the permanent deserts of Arabia, West Pakistan, and Baluchistan extend farther eastward than normal and bring near-desert conditions to north-west and even west India, with quite disastrous results. Such a sequence was without doubt responsible for the catastrophic drought which laid waste western India in 1899.

The third component of the Indian summer monsoon, over southern peninsular India, appears to be largely independent of the north-east Indian component and occasionally independent of the north-western Indian component. The rains here fall not always as a direct result of the development of a tropical cyclone or depression but at times in response to more subtle changes in the apparently steady, strong, low-level westerly air stream which dominates the south from mid-May to mid-September. On some days this stream converges enough to result in upward motion, condensation of the air's heavy moisture load, and heavy rain. On other days an equally subtle change in the other direction towards divergence of the low-level flow results in sinking motion, evaporation of clouds, and a spell of dry weather.

For many years meteorologists thought that events in the southern hemisphere, in particular in the region of the south-east trade winds, were somehow responsible for subsequent events during the summer monsoon in the northern hemisphere, the time lag ranging from two or three days to a week or two. Evidence we have so far accumulated indicates, however, changes in the winter hemisphere do not appear to produce or to be associated with significant changes in the summer hemisphere. Nevertheless, when the summer monsoon component over south India is weak, activity in the winter trough south of the equator seems to be greater than normal and vice versa. Weather satellite pictures must be called in to determine whether a relationship does exist.

A particularly interesting part of the Indian Ocean is receiving concentrated attention from the research vessels.

This is the region extending about 1,000 kilometres off-shore from south-eastern Arabia and Somalia, where the changes in wind and ocean conditions between summer and winter are greater than in any other part of the ocean (Figure 1). Where the south-west monsoon forces the coastal waters to upwell, research vessels have observed heavy concentrations of plankton, fish, and sea birds.

We know that in general the ocean supplies energy to the atmosphere by supplying heat to evaporate water from the ocean surface. The stronger the winds and the dryer the overlying air the more intense is the evaporation. So intense is it over the central Arabian Sea in summer that a measurable drop in temperature results at the ocean's surface. The heat required for evaporation is stored with the water vapour in the air in a latent form. Winds carry the vapour many kilometres from its source until suitable forces cause the air to rise and cool and the water vapour to condense and form clouds. Condensation releases the stored heat which goes to warm the atmosphere. Thus the ocean acts not only locally but often at considerable distances to modify significantly the temperature and therefore the density distribution in the atmosphere. Until now meteorologists and oceanographers have succeeded in measuring the rate at which the ocean adds heat and moisture to the air when the sea surface is only slightly disturbed. However, it may well be that by far the greatest amounts of heat are added to the atmosphere from the ocean by evaporation and conduction when the ocean surface is violently agitated by gale winds. And it is under these very conditions that direct and accurate measurements have so far been impossible. The three methods of measuring ocean-atmosphere exchange, mentioned earlier, using radiation equipment on islands and ships, an instrumented free-floating mast, and heavily instrumented research aircraft are opening different avenues of attack on this knotty problem.

Near the island of Socotra during the northern hemisphere summer, southerly and south-westerly winds not infrequently exceed 80 kilometres per hour. Usually, strong winds are accompanied by bad weather over the oceanic tropics, but in the region of Socotra, the weather in spite of these strong winds is almost always fine, with no rain and relatively little thin low cloud. It is, therefore, a fascinating area to study air-sea interaction.

The high winds favour extremely rapid evaporation from the ocean surface adding heat in latent form to the air, whereas at the same time the much colder ocean abstracts heat from the air. What is the net effect of these two opposing influences, as well as of the vertical circulation of the monsoon resulting in sinking motion over the same region (see Figure 2). It would seem that the stabilizing effect of the cool ocean surface and general sinking motion outweigh the destabilizing effect of heat added in latent form from that surface because, over the western two-thirds of the Arabian Sea, almost no rain falls during the height of the summer monsoon. It is only when the air sweeping from the south-west reaches the vicinity of the Indian coast that depression systems and the coastal mountain ranges lift it enough to produce deep cloud systems and copious rains. The sharp decrease of even the heaviest and most persistent monsoon rains, observed as one flies westward from Bombay, is hard to believe at first sight.

These, and other facets of the many-sided problem of the general atmospheric circulation over the Indian Ocean, are being co-operatively studied in Bombay and Honolulu by India Meteorological Department investigators and by staff members of the Hawaii Institute of Geophysics.

Ocean Expedition may turn out and what may be their impact on the lives and fortunes of the teeming peoples inhabiting the littoral of this fascinating ocean. The chances of developing a long-range forecasting system giving useful indications of the intensity and distribution of rains two or three months in advance seem as remote as ever. The atmosphere is turbulent and chaotic and it is doubtful if we can do any better than use long climatological records and detailed statistics in order to come up with a sort of odds on what the next season's rainfall will be.

However, continued study of measurements made at the interface between air and sea may lead to discovering, not only how energy is exchanged between these two interlocked systems, but also how much is exchanged. The discovery, when related to world-wide photography and radiometry by weather satellites, could help us elucidate the role of the monsoons in the total atmospheric circulation. Possessing these essential prerequisites, we would have a good chance of improving short-range weather forecasts, that is, forecasts extending over two or three days or possibly a week. The benefits to be derived from even this modest improvement could be considerable, particularly in aiding flood prevention and control and in enabling irrigation engineers to make the best possible use of stored water. Forecasts of this length could aid Indian Ocean fishermen who are forced to keep in port during much of the summer monsoon because of heavy seas. However, even at the height of the monsoon, lulls occur lasting a week or more during which a temporary resumption of large-scale fishing would be feasible. Since fish are more plentiful in summer than in winter, at least over the Arabian Sea, the advantage to the fisherman from these improved short-range forecasts is obvious. The apparently rhythmic nature of rain-and-break, rain-and-break, during the summer monsoon encourages us to delve more deeply into the underlying causes of the rhythm and in particular the causes for interruptions or changes in the rhythm. Finding the rhythm of a total season, however, seems almost certainly beyond our immediate grasp, to be achieved only as part of a global weather analysis and forecast system using a wealth of land-based and satellite observations checked and processed in the largest-sized computers.