Monsoons and the general circulation of the atmosphere — A review

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ABSTRACT. While monsoons (or seasonal changes of wind and associated weather) occur in many different parts of the world, they are most pronounced over the countries of S. E Asia, Indonesia and Australia. Upper Wind Charts in January, April, July and October were shown to illustrate the large annual movement of inter-tropical convergence zones over the Indian Ocean as contrasted with those over the Pacific and Atlantic Oceans.

In the middle and high troposphere, the maximum S—N swing of the boundary region between the equatorial easterlies and the extra-tropical westerlies occurs over the Indian Ocean and bordering continent of South Asia.

The Asiatic Monsoon with its pattern of extensive seasonal precipitation and associated heating of the middle troposphere should be considered as exercising a very significant influence on the general circulation of the atmosphere. The Indian monsoon is a geographically bound cyclonic system less than 6 km in thickness embedded in the equatorial easterlies. The monsoon strengthens and weakens ; strengthens when there is fresh input of moist air and weakens owing to friction and dispersal of water-vapour. Associated with the monsoon are longitudinally-bound strong easterlies at 200 to 100 mb levels at about 15° N over South Asia. These strong easterlies form part of the equatorial easterlies, but are regionally accentuated.

Important questions such as long travelling waves and jets in easterlies and their role in creating and steering monsoon depressions, prolonged breaks in the monsoon and why they occur, world connections of the monsoon etc have been briefly referred to.

1. The word *Monsoon* is a modification of the Asiatic word "mawsim". It was applied by seamen navigating the Indian seas to the annual alternating winds of the Arabian Sea. It is now generally applied to quasi-stationary disturbances of the average zonal circulation, particularly in the tropics, arising from temperature and humidity differences between continental and oceanic areas and between the northern and the southern hemispheres. They are best developed in the summer season of either hemisphere, *i. e.*, in July-August or in January-February. Fig. 1 shows the surface air streams and the approximate boundaries of separation between the air streams of the northern and the southern hemispheres in January and July (after Sawyer, 1952). In July, while over a large part of the Pacific and Atlantic oceans, the inter-tropical boundary lies a little to the north of equator, the southern hemisphere air-stream penetrates well into the northern hemisphere in India and southeast Asia and to a smaller extent in Africa. In January, the northern hemisphere streams penetrate farthest southward in South America (Brazil), East Africa and Northeast Australia. These areas of extensive (penetration of air from the colder into the warmer hemisphere and continents are the main monsoon areas. I am, however, not sure that the term monsoon is used in South America.

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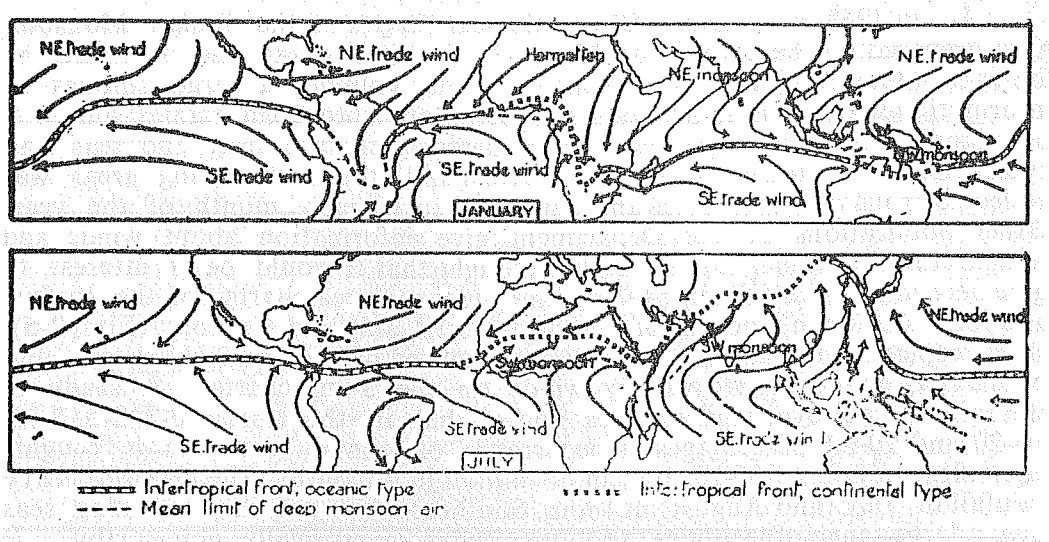


Fig. 1. Inter-tropical Fronts and Surface Air Streams in January and July (J. S. Sawyer)

2. The Asiatic monsoon is the best known of the monsoons. It is vitally important for food production in India and the countries of Southeast Asia ; a good deal of attention has, therefore, been paid to its study from the beginning of scientific meteorology in India. The space and time variations of rainfall during the monsoon, the disturbances and the storms associated with it—the breaks or failures in the monsoon, the forecasting of monsoon rains, all these have received attention. The study of upper air temperatures and humidities, and of winds up to the stratosphere, in India and neighbouring countries, have helped to link up the atmospheric circulation over India with that over the rest of the world.

3. The Indian Ocean is mostly an enclosed area with Africa on the west and Asia on the north. It is partly enclosed on the east by Australia and the Eastern Archipelago and is open towards the Antarctic. The existence of open seas right from the Tropic of Cancer to Antarctica, of Africa and Eurasia to its west and north with the lowest pressures over the region Arabia to W. Pakistan, and of the Himalayan and Burmese mountain systems are responsible for the exceptional build-up of the Asiatic summer monsoon.

In a classical paper on the Indian southwest Monsoon, Simpson (1921) treated the problem of the Indian summer monsoon as that of an extensive closed heat low, orographically bound. He laid special emphasis on the role of the Himalayas and the Burmese mountains in containing most of the moist air within the confines of India and Burma and increasing their rainfall. Pétterssen (1953) in a recent paper "On the dynamics on the Indian Monsoon" while fully realising the importance of perturbations of the monsoon, considered it worthwhile to discuss the problem of maintaining the observed large scale cyclonic system in a steady state by creation of vorticity by thermal processes and destroying it by friction within a closed system. These studies have illuminated some of the fundamental aspects of the problem.

Working meteorologists are, however, aware that the average monsoon of climatology in any particular month is a complex composite of many different kinds of weather situations. The average monsoon is continuously subject to perturbations and many of these perturbations are induced by causes originating outside the closedsystem.

4. In 1948, a volume of Climatological Charts of the Indian Monsoon Area prepared by the author and Mr. S. P. Venkiteshwaran was published by the India Meteorological Department. In that volume, a large amount of information about winds and isobars, upper winds upto 3 km, rainfall amounts over land areas, percentage hours of occurrence of rain over the seas and typical tracks of storms in the Indian Ocean and the surrounding areas was collected from various sources and put together for each month of the year. Other publications of the Department give information about winds and temperatures at higher levels. It was thought that it would be of interest to give here in a slightly modified form the monsoon area charts for the surface and for 3 km for the months of February, April, July and October (Figs. 2-5). Inter-tropical convergence boundaries are marked on the surface charts, and boundaries or regions of westerly winds on the 3-km charts. A study of the rainfall lines over land and sea shows that in the *tropics* 0-2, 2-5, 5-10, 10-20 and 20-30 percentages of occurrence of rainfall over sea is roughly equivalent to 0-2, 2-5, 5-10, etc, cm of rainfall in a month. The *extensive* heavy rainfall in July (and August) in India, Southeast Asia and the adjoining seas over a large range of latitudes and longitudes is especially noteworthy. It implies release of a large amount of latent heat in the atmosphere at the levels of condensation, and upward flux of heat at higher levels.

An important feature brought out by the upper air streamlines is that almost in all the months, the inter-tropical convergence zone over the ocean has a considerable width, the southeast trades of the southern hemisphere and the northeast trades of the northern hemisphere tending to become westerlies near the region of convergence even at 3 km. Naturally, the stream that crosses the equator has a greater tendency to become westerly.

The upper westerlies are more pronounced during the summer monsoon months July-August, when they are almost entirely on the northern side of the equator. In their northwestern part, the westerlies at 3 km have more and more of the northern hemisphere dry air in them.

In January-February, the inter-tropical convergence zone lies to the south of the equator, and the westerlies are more pronounced in the eastern half of the South Indian Ocean and the regions of East Indian Archipelago and North Australia where there is a monsoon low.

The effectiveness of the summer monsoon of India and Indonesia, from the point of view of rainfall, is undoubtedly due to the development of thick, moist columns of air (5-6 km at their thickest) before they meet stationary or moving obstacles.

All tropical monsoon circulations are topped by equatorial easterlies, but the easterlies are substantially modified by the monsoon.

5. *Upper Air conditions over the Asiatic Summer Monsoon*—From the days of the sounding balloon ascents at Agra, it has been known that the highest average air temperatures in the world between 6 km and 13 km are found during the summer monsoon over North India. It is possible that still higher temperatures may be found over Northeast Himalayas and South Tibet. From the meridional profiles of pressure in northern summer and winter over Eurasia (Fig. 6 after Bjerknes), it is evident that while in July-August, the lowest pressure at the surface is found at about 25°N with a pressure gradient

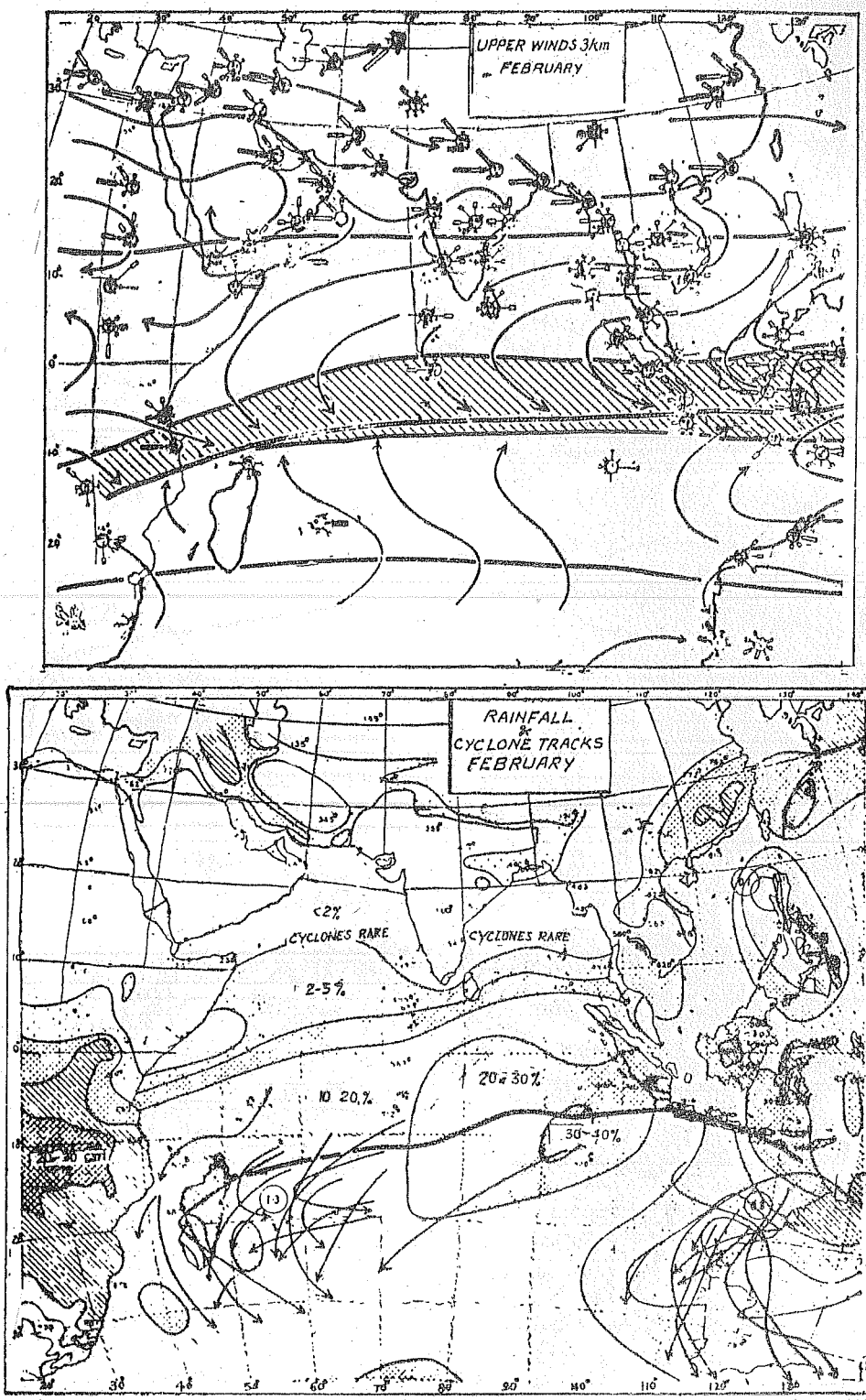
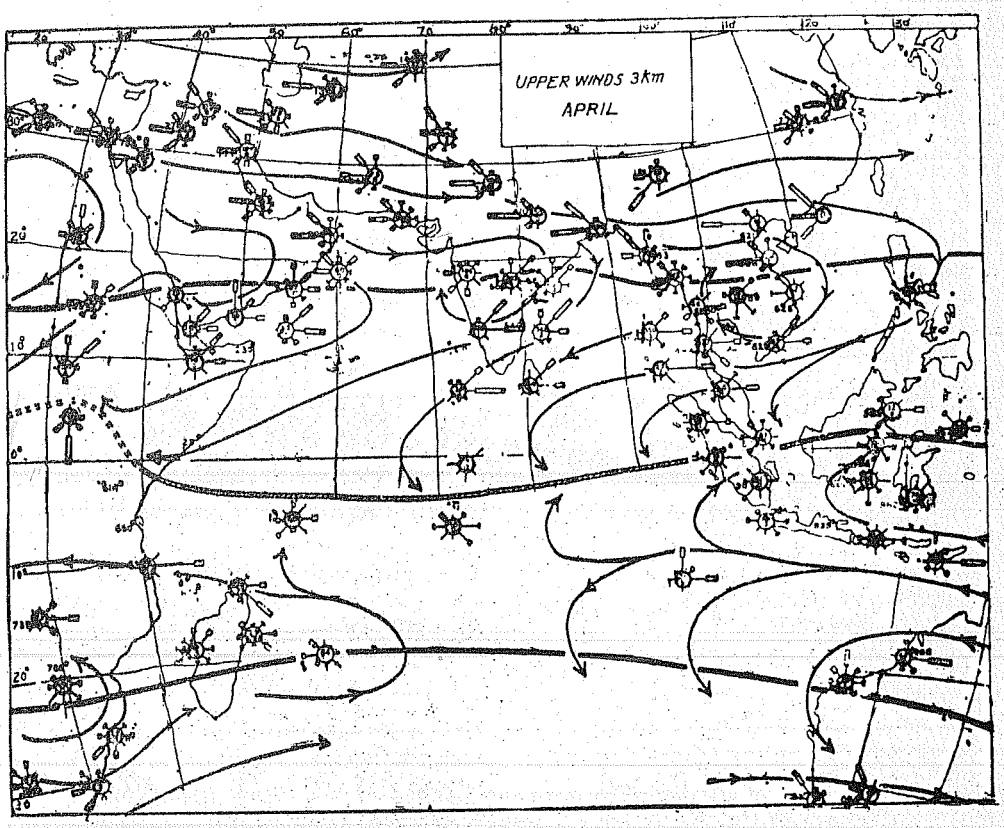

UPPER WINDS 3/km
FEBRUARY
RAINFALL
&
CYCLONE TRACKS
FEBRUARY
<2%
CYCLONES RARE
CYCLONES RARE
2-5%
10 20%
20-30%
30-40%

Fig. 2


UPPER WINDS 3km
APRIL

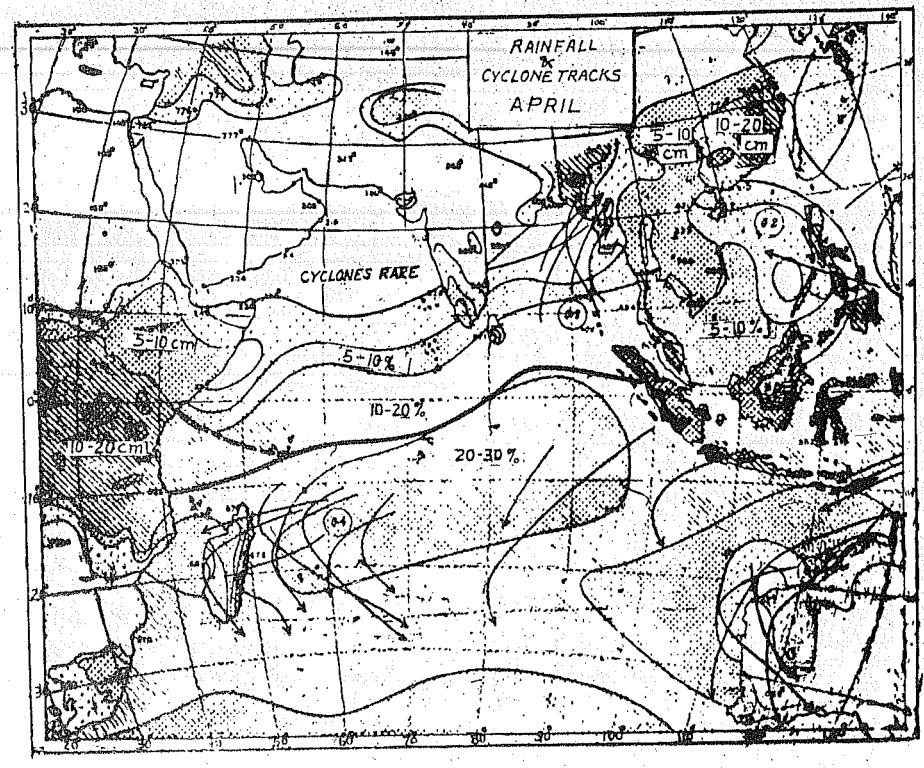

RAINFALL
CYCLONE TRACKS
APRIL
5-10 cm
10-20 cm
CYCLONES RARE
5-10 cm
5-10 %
10-20 %
10-20 cm
20-30 %

Fig. 3