Large-scale Aspects of the "Summer Monsoon" in South and East Asia

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1. Introduction

In classical text-books of climatology the annual course of weather and climate is largely described by means of monthly averages and frequencies. In some areas of Japan this leads to considerable smoothing of the two dominant rain-periods found in early and late summer, separated by a dry season starting near mid-July. Although J. J. Rein has mentioned this threefold structure of summer weather in Japan, as early as 1876, and although the late T. Okada has thoroughly described the Baiu-Season (15) with its westerly disturbances, the fiction was widely accepted of a single rain period during the whole summer connected with a south-easterly "monsoon flow" from the Pacific. From the geographical viewpoint, climate, landscape and economy of Southern and Eastern Asia ("Monsoon Asia") were not infrequently considered as dominated by the summerly inflow of maritime moist air with rain. However, since 1930 the aerological observations have revealed a far more differentiated picture of the upper air currents. This is well-known among meteorologists of Eastern Asia, even if large gaps in the available aerological informations still are to be filled. The purpose of this contribution is to draw attention to some peculiar large-scale teleconnections, *i.e.* space- and time- correlations connected with the occurrence of the early summer rainy season in Eastern and Southern Asia.

2. Weather singularities and their teleconnections

Starting from investigations of the micro-structure of the average annual course of weather during the year on the basis of daily frequencies—known as "singularities of weather"—, the author has found some correlations between distant areas. As an example (6), the frequency of anticyclonic spells in the eastern USA and in Central Europe during late September has a maximum between 26 and 30 September, which is well-known in folklore (Indian Summer, Altweibersommer), coinciding with a peak of anticyclonic weather at Osaka. In another investigation (7) two complete examples of such a micro-structure are given for Shanghai (1920-39) and Osaka (1883-1926)—the latter with daily averages of temperature, pressure, precipitation (intensity and amount) and duration of sunshine, and with daily frequencies of precipitation, cloudy and clear days. It is not intended here to discuss the large number of investigations of these singularities; the available literature up to 1952 is summarized in (9), and Japanese contributions are mentioned by Takahashi (20). Wahl (22) has contributed much to a more general understanding of their aspects in the atmospheric circulation. Comparing the advancement of the frontal zone ("Pacific Polar Front" = PPF) over Eastern Asia towards the north, with the rapid shift of the Intertropical Convergence Zone (ITC), that causes the "onset of summer monsoon" over India,

and with the most pronounced peak of frontal rains in Central Europe, we observe the surprising fact, that these events occur, in the average, in the second decade of June (9).

Under undisturbed conditions, the time of the onset of monsoon is remarkably constant. As a result of ship-records from 30 years we obtain (Fig. 1, lower half) the frequency of precipitation observations for an area along the route Aden-Colombo, in the Arabian Sea ($8-12^{\circ}\text{N}$, $62-68^{\circ}\text{E}$). In this

Fig. 1 Annual course of precipitation frequency in two areas over the Indian Ocean, 10-day-averages (after punch-card decks from the Seewetteramt, Hamburg).

representative sample an isolated maximum occurs in the first decade of June; this peak is considered as one of the most pronounced "singularities" of weather. Secondary peaks in November and December represent the retreat of the ITC. In the upper half of Fig. 1 an even more pronounced precipitation peak is found in mid-July in the Gulf of Bengal, but the number n of available observations is far smaller, and consequently

also the statistical significance. For further investigations of this type, a fixation of the dates of start and end of large-scale (area-averaged) rain-periods, representing Baiu and similar seasons for individual years in Eastern Asia, seems to be highly desirable.

Yin (23) and Riehl (17) have considered the large-scale and disrupt shifting of the planetary jet-stream from North India to the northern edge of the Tibetan Plateau. This relationship has also been investigated recently in China (14).

In 1954 Sutcliffe and Bannon (19) demonstrated a relationship between the shift of 200 mb-winds over Arabia from W to E, the transition from polar to tropical tropopause over the Iraq and the onset of the Indian Monsoon at the Malabar Coast. Recently Suda and Asakura (18) have shown that the onset of the Indian summer monsoon coincides rather strongly with the start of the Baiu-season in Japan. However, it seems necessary to investigate this in more detail, considering individual stations or areas.

In Central Europe, the most pronounced frequency peaks of precipitation and cooling are caused by blocking anticyclones near $0-10^{\circ}\text{W}$ and subsequent upper troughs or cold pools in the area $10-20^{\circ}\text{E}$. According to the Catalogue of European Large-Scale Weather Patterns (13), the two highest frequency peaks of large-scale weather types with northerly flow at Central Europe—cf. (13), Table I, N (GT)—occur at June 11 and May 31 with frequencies of 37% and 33% respectively of all cases (1881-1951). A rather similar annual trend has been demonstrated for blocking highs in the sector $20^{\circ}\text{W}-10^{\circ}\text{E}$ (2). Their frequency exceeds 25% of all cases only in the period May 25—June 20. This situation together with its teleconnections over Southern and Eastern Asia forms part of a hemispheric circulation-pattern, which is obviously correlated with the thermodynamic and kinematic influence of the elevated mountains of Central Asia.

3. The role of the Tibetan Plateau

Yin (23) and Riehl (17) have shown, how the advance of the Indian Summer Monsoon is connected with the disintegration of the planetary jet-stream in subtropical latitudes and with the nearly contemporaneous formation of a new jet at 40–45°N, on the northern flank of the Central Asiatic Mountains. These are dominated by the vast and elevated Tibetan Highlands where the average altitude exceeds 4500 m for an area of at least $1.7 \cdot 10^6$ kms².

It is easily understood that during summer and in subtropical latitudes the Tibetan Highland with its rolling or rather flat steppe or barren land acts as an elevated heat source. All explorers from the Schlagintweits (near 1855) and Sven Hedin (near 1900) to recent times—describe at this season the high frequency of cumulonimbus, of severe squalls and showers with sleet, hail or graupel during daytime. This is confirmed by the observations of the Italian Expedition to the Caracorum (1), on which thorough hourly meteorological observations (including pilot balloons and pyrhelio-meters!) were made during the summer of 1914 at the plateau Depsang (35.3°N, 78.0°E, 5362 m). Under these conditions it may be assumed that in summer near noon the average lapse rate of the atmosphere in the ground layer (up to about 1000–1500 m above surface) will be practically dry-adiabatic and/or, above the condensation level, near moist-adiabatic, while in the lowest 100–200 m it may be slightly super-adiabatic. In addition it is allowable to assume at noon that the direction of surface winds deviates only slightly (about 20°) from the representative wind 500–1000 m above the surface. This is also confirmed by the unique pilot-balloon data of Depsang.

Now we are able to use all available meteorological observations from expeditions as a first approximation to compute the height and temperature of the 500 mb-level,

Fig. 2 Temperatures at the 500 mb-level, July and August, over the Central Asiatic Highlands.

Fig. 3 500 mb-contours, July and August

- a = aerological data
- b = fixed stations
- c = non-stationary expedition observations
- d = resultant pilot balloon winds
- e = direction of medium clouds
- f = surface noon wind direction.

the freezing level etc(11). This has been done with great care, especially by excluding series where the thermometer may be affected by radiation errors. When so treated, the result, together with the surface winds near noon, reveals the existence of a thermal anticyclonic cell in the mid-troposphere above the Highlands, slightly displaced towards east. Here the temperatures at the 500 mb-level (Fig. 2) are slightly above freezing, presumably +1 or +2°C, which is confirmed by the aerological stations of North India (about -2°C) toge-

ther with easterly winds in the north. Then the mid-tropospheric temperatures are, during summer, higher than elsewhere at the same level in the atmosphere, caused by the peculiar (but numerically unknown) radiation balance of subtropical high mountains. The southeasterly upper winds at 500 mb over Burma and Assam, the easterly flow at the southern edge of the Himalaya, together with cloud directions from NW over Eastern Tibet and from WSW in the Caracorum, confirm the existence of a thermal mid-tropospheric anticyclone (Fig. 3) in an area where up to 1956 no aerological information was available. Travelling upper troughs only occasionally are able to sweep away for a short period the warm air above the Highland; then westerly winds are observed near 300 mb over North India with a resulting "break of the monsoon" (8).

In the author's opinion, the mechanism of the large-scale shifting of the tropospheric winds over India (8) can be most easily understood if we take into account the seasonal warming of the Tibetan Highland, acting like a switch. This warming gradually weakens the westerly subtropical jet over North India, then reverses the meridional gradient of pressure and temperature up to more than 20 kms and creates a new jet north of Tibet (40-45°). As a typical example of a summer cross-section along 75°W the average conditions for July 1956 (Fig. 4) may be given, where the SW-Monsoon over India as a part of the continental equatorial westerlies reaches the 6 km-level, separated by the subtropical easterlies from the extratropical westerlies with a jet core near 45°N and a secondary maximum near the northern coast of Siberia.

The formation of a thermal anticyclone over Central and Eastern Tibet, occurring normally about 15-30 days before solstice, causes also a shifting of the orographically influenced upper troughs. The broad trough near 90°E (Gulf of Bengal), described by Riehl (17) and Ramaswamy (16), and pre-

Fig. 4 Average meridional cross-section of temperature and zonal component of wind in the troposphere along 75°E, July 1956 (drawn by H. Oeckel).

formed by the Southern fringe of the Himalayas, vanishes, and the Eastern Asiatic trough in the lee of the mountains is sharpened. The convergence of relatively cool north-westerly flow and warm moist air from the SW over Western China, described by Thompson (21), strengthens the orographically fixed frontal zone at 30-35°N and plays an important role for the Baiu-Season. Upstream, a new upper trough tends to form near 68°E, also preformed in the low-land of Turkestan between Hindukush and Pamir-Tianshan. A comparable situation of troughs and ridges can frequently be observed over North America, in summertime, on both flanks of the western mountains and highlands between 105° and 122°W.*)

So the large-scale teleconnections between

*) In Arizona, Bryson and Lowry demonstrated (3) a sudden change from NW flow to SW flow near June 15. But the development of "monsoonal" rains at the beginning of July seems to be nearly homologous to that over Bengal, since it is connected with a shift to ESE-winds at 500 mb, and to SSE-winds at 800 mbs, indicating a transport of warm moist air from the Gulf of Mexico to this desert area.

the switching of the wind distribution over the whole area from the Iraq to the southern coast of China, and the onset of summer rains over Southern and Eastern Asia—as produced by the northward movement of the ITC and the PPF respectively—are considered as result of the seasonal warming of air over the Tibetan Highlands. It seems not quite clear, however, how the contemporaneous occurrence of blocking anticyclones and the splitting of the planetary jet in the European and Alaskan sector may be linked with these events. But such a problem in a hemispheric scale generally must be studied in relationship to the intensity of the zonal circulation, as proposed by Wahl (22).

The hypothesis of an active role of the seasonal warming of the Tibetan Highlands is confirmed by some statistical studies on the onset of the Indian Summer Monsoon according to the data given in (5).

1) If June is substantially warmer (colder) than normal at Leh (34.1°N , 77.6°E , 3514m)—temperature deviations distributed into 3 equal classes—the monsoon starts at the southern part of the peninsula (Travancore-Cochin) at May 26 (30), near $18\text{--}20^{\circ}$ Latitude at June 5 (10), at Delhi (28.5° Lat.) at June 30 (July 6). The last date is correlated with the temperature at Leh in July with $r = -0.41$. The same value was found between the onset of monsoon at 20°N (Kolaba) and the temperature at Leh in June.

2) The time-relationship of the development of the monsoon from S to N is rather weak and insignificant. The correlation between the beginning of the dry season at W Java ($6\text{--}8^{\circ}\text{S}$) and the monsoon onset near 17°N is only $+0.24$; that between the latter time and the onset at New Delhi is even negative, namely -0.17 .

In addition it should be stated, that the onset of monsoon at Delhi occurs at June 28 in years when the hemispherical zonal index (500 mb) in June is above normal, while in years with normal or low zonal

index this date averages July 4.

4. General considerations

The persistence of an *anticyclonic subtropical cell* over Tibet, in July and August, must be taken into account when describing the distribution of atmospheric currents and convergence zones over Southern and Eastern Asia. At the 700 mb- and the 500 mb-level (10), a zone with easterly flow separates the extratropical westerlies from the equatorial westerlies. The so-called Bengal Branch of the Indian Summer Monsoon forms part of these subtropical easterlies, and is separated by a strong but fluctuating convergence (ITC) from the Arabian Branch, as a part of the equatorial westerlies extending from the Atlantic off West Africa over Africa and S-Asia to the Marianas in the Pacific. Having this in mind, it seems not advisable to consider the PPF over Eastern Asia—being a convergence and frontal zone within the extratropical westerlies—as a continuation of the ITC over India (10), as frequently done even in well-known textbooks and papers. Due to the strong zonal differences of surface pressure the planetary belt of subtropical easterlies is lifted from the surface to approximately 700 mbs in two regions: in the area $40\text{--}60^{\circ}\text{E}$, where winds from NW (“shamal”) are predominating, and in the area $100\text{--}120^{\circ}\text{E}$, where apparently an indistinct weak average flow from S or SW carries moist “equatorial air” towards the frontal zone. But since the easterly flow still exists in upper levels, it should be preferred not to confound two convergence zones of quite different meaning, which are normally separated by a large belt of easterlies together with the subtropical divergence.

In a recent investigation, Flohn and Oeckel (11) have demonstrated the existence of a net *water vapour transport* from W to E during July 1952 over Korea and the main land of Japan, as assumed earlier (7). Over Okinawa and Southern China (Hongkong)

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Fig. 5 Average transport of water vapour between 1000 and 700 mb (arrows) and between 700 and 400 mb (dashed arrows), July 1952 (drawn by H. Oeckel).

the water vapour flux is concentrated in lower layers (mostly below 700 mbs) and directed roughly from SW (Fig. 5). This result contrasts strongly with former textbook views, but is well in accordance with similar findings over the east coast of North America. Thus the hydrological cycle between ocean and continents is rather complex; in humid regions the annual actual evapotranspiration over land is only slightly smaller than the oceanic evaporation, and export of moisture from continent to ocean is far from being excluded.

The original meaning of the term "monsoon" is nothing else than a seasonal shifting of dominating winds. From the view-point of our present knowledge of the relations between precipitation, vertical component and convergence of wind, and the predominant flow in the layer of low and medium clouds, it seems not advisable to include in this

term the annual course of precipitation and cloudiness. This was frequently used in climatological text-books, following Woeikof, Hann and other classical authors. Independently, Chromow (4) and the author (7, 8) have demonstrated, that the physical cause of large-scale monsoons is not in each case and necessarily the differential heating of continents and oceans, but—especially in tropical latitudes—the seasonal shifting of planetary wind belts. Over the central Pacific, the ITC remains throughout the year between 0° and 10°N. But in continental sections—like Africa—the ITC travels from 18°N in July to 15°S in January, and over India it reaches even 30°N, due to the excessive warming of the elevated parts of the Asiatic continent. If the distance between ITC and equator exceeds a critical value near 10° Lat., an area of unstationary quasi-geostrophic westerlies is formed in that zone. In such sections large seasonal variations of the planetary pressure and wind belts with latitude—of course in accordance with their cellular structure—are occurring and cause, for a given station, monsoonal wind shiftings. Thus it seems justified to assume (8) that on a homogeneous land-covered earth the seasonal travel of planetary wind belts reaches its highest values, resulting in a series of zonal strips with monsoonal wind variations. Physically, this hypothetical mechanism is produced by the thermal reaction of continental surface to the seasonal variations of the radiation balance. In contrast to this, on a homogeneous water-covered earth the planetary wind belts should remain nearly constant at all seasons, as in the central Pacific.

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References

- 1) **Alessandri C. and N. Venturi Ginori**, 1931: *Meteorologia, Aerologia e Pireliometria*. In: Spedizione Italiana de Filippi, Serie I, 3, Bologna. —2) **Brezowsky, H. H. Flohn and P. Hess**, 1951: Some remarks on the climatology of blocking action. *Tellus*, **3**, 191-194. —3) **Bryson, R.A. and W.P. Lowry**, *Synoptic climatology of the arizona summer monsoon*. Scient. Rep. 1, Dept. Meteor. Univ. Wisconsin. —4) **Chromow, S. P.** 1950: Der Monsun als geographische Realität. *Sowjetwiss.* 1950, Heft 4 (russ. Orig. in: *Isv. Vses. Geogr. Ob.* 82 225-246. —5) **Data published by G. S. Bhullar**, 1952: (Ind. J. Meteor. Geophys. 1952, 25), L. V. Ramdas and Coll. (l. c. 1954, 307) and F. H. Schmidt (Verh. Meteor. Geophys. Djakarta 43, —6) **Flohn, H.** 1947: Indianersommer-Altweibersommer. *Meteor. Rundsch.* 1, 282-286. —7) **Flohn, H.** 1950: Ablauf und Struktur des ostasiatischen Sommermonsuns. *Ber. deutsch. Wetterdienst US-Zone* 18, 21-33. —8) **Flohn, H.** 1953: Wilhelm Meinardus und die Revision unserer Vorstellungen von der atmosphärischen Zirkulation. *Z. Meteor.* 7, 97-108. —, 1955: *WMO Tech. Notes* 9, *WMO-No.* 38, *TP* 13. —9) **Flohn, H.** 1954: Verbreitung und Ursache der Witterungsregelfälle. In: Witterung und Klima in Mitteleuropa, 2. Aufl. *Forsch. deutsch. Landeskd.* 78, 168-184. —10) **Flohn, H.** 1955: Der indische Sommermonsun als Glied der planetarischen Zirkulation der Atmosphäre. *Ber. deutsch. Wetterdienst* 22, 134-139. —11) **Flohn, H.** 1955: *Bemerkungen zur Klimatologie von Hochasien*. (in: *Abh. Ak. Wiss. Lit. Mainz*, in press), cf. also *Arch. Meteor. Geophys. Bioklim.* B 6, 193-206. —12) **Flohn, H. and H. Oeck**, 1956: Water vapour flux during the summer rains over Japan and Korea. *Geophys. Mag.* **27**, 527-532. —13) **Hess, P. H. Brezowsky**, 1952: Katalog der Großwetterlagen Europas. *Ber. deutsch. Wetterdienst US-Zone* 33. —14) **Koo, Ch. Ch.** 1955: A Tibeti-fennsík dinamikuss hatása a keletázsiai légkörzésre. *Idjárás* **59**, 204-211. —15) **Okada, T.** 1910: The Bai-U or rainy season in Japan. *Bull. cent. meteor. Obs. Japan* **1**, 5. —16) **Ramaswamy, K.** 1956: The subtropical jet stream and its role in the development of large-scale convection. *Tellus* **8**, 26-60. —17) **Riehl, H.** 1954: *Tropical Meteorology*. London. —18) **Suda, K. and T. Asakura**, 1955: A study on the unusual "Baiu" season in 1954 by means of northern hemisphere upper air mean charts. *J. meteor. Soc. Japan* **2**, 33, 233-244. —19) **Sutcliffe, R. C. and J. K. Bannan**, 1954: Seasonal changes in upper-air conditions in the Mediterranean-Middle East Area. *Scient. Proc. Internat. Ass. Meteor. X. Gen. Ass. Rome* 322-334. —20) **Takahashi, K.** 1955: *Dynamical climatology* (in Japanese). Tokyo. —21) **Thompson, B. W.** 1951: An essay on the general circulation of the atmosphere over South-East Asia and the West Pacific. *Quart. J. r. meteor. Soc.* **77**, 569-597. —22) **Wahl, E. W.** 1953: Singularities and the general circulation. *J. Meteor.* **10**, 42-45, 129-141. —23) **Yin, M. T.** 1949: A synoptic-aerologic study of the onset of the summer monsoon over India and Burma. *J. Meteor.* **6**, 394-400.