TECHNICAL MEMORANDUM

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Numerical experiments on the seasonal transition of the general circulation over Asia in summer 1979

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July 1983

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Abstract

The onset of the 1979 summer monsoon is investigated using the ECMWF grid-point model. The role of the Tibetan Plateau in this process is investigated by means of parallel model integrations with different orographies. Similarly, the relative roles of land-sea thermal contrast, latent heat release and Southern Hemisphere influence are studied. The influence of the African Highland on the onset of the Somali jet is also explored. A generally satisfactory performance of the model in representing the onset of the monsoon is documented and the various contributions to this from different model components are discussed.

1. INTRODUCTION

It has long been recognized that the onset of the southwest monsoon is that part of the seasonal transition of the general circulation from winter to summer regime over Asia. The most conspicuous features of the transition are: (1) the establishment of a huge anticyclone in the higher troposphere centred over the Qinghai-Tibetan Plateau accompanied by a northward shift of the subtropical jet and the setup of strong easterlies along and to the north of the equator; (2) the outburst of a southwesterly current in the lower troposphere over South Asia; (3) and the appearance of a flow pattern typical of the early summer raining season ("plum rain") over Asia. The significant consequences are the onset of well-known monsoon rain in India and subsequent set in of "plum rain" both in China and Japan.

The understanding and eventual forecasting of these extremely important events have received long-standing interest. The classical concept is that the monsoon circulation stems from the thermally direct overturning caused by differential heating due to land-sea contrast. As a result of this changing "heat engine" the prevailing wind systems reverse between seasons. There are some recent works which further demonstrate the fundamental importance of this factor (e.g. Webster and Chou, 1977).

Another factor which is receiving increasisng attention is the influence of the Qinghai-Tibetan Plateau (hereafter called the Plateau for brevity). Early in the 1950's, Flohn (1958) and Yeh et al (see Staff Members Academia Sinica, 1957, 1958) emphasized that the Plateau appears as an elevated heat source in the mid-troposphere. These ideas were supported by the annulus experiments of Yeh and Chang (1974); they found that, when a heated plateau was added, the "Tibetan high" appeared over the plateau accompanied by the retreat of westerlies and build-up of jet-like easterlies, etc. The study by Hahn and Manabe (1975) showed it was only when the mountains were included in their general circulation model that the onset of monsoon and the northward shift of the subtropical jet occurred abruptly rather than in a gradual way. More recently Yeh and Chen (1981, personal communication) illustrated by numerical experiment how the snow cover on the Plateau in winter and spring could influence the transition of the circulation and cause it to occur earlier or later than normal.

A further factor which has stimulated a number of studies is the interaction between the hemispheres. Although this again is a long-existing concept which can be traced back decades (Eliot, 1900), it was only after the discovery of the cross-equatorial jet off east Africa by Findlater (1969a) that there was a renewed and increasing interest in this connection.

The aim of the present study is to shed some light on how the various factors play their part in the establishment of the monsoon circulation systems and to assess their relative importance. This can be done by using GCM models which include many important physical factors and have a fine spatial resolution. These normally need a long period of integration before reaching a "steady" state, particularly when the seasonal changeover is involved, rendering the experiments very time consuming. An alternative to this is to start the integration from an observed state several days prior to the onset of the monsoon circulation; this may be considered as a satisfactorily consistent state of the real atmosphere and used as a platform from which to begin comparative experiments. This is the approach adopted in the present study.

Based on these considerations, several 10-day forecasts have been run to test the influence of diabatic heating, of the Plateau and of the Southern Hemisphere. The period from 11 to 21 June 1979 was selected, which is one of the sequences identified by WGNE (see,WGNE, 1981) as a suitable period for numerical investigation and model intercomparison studies. Table 1 summarizes the experiments described in the following sections.

The model used in all the experiments was a modified version of the ECMWF grid-point model (Burridge and Haseler (1977) and Tiedtke et al (1979)). The Kuo scheme for the parameterisation of cumulus convection (Kuo, 1974) was replaced in the tropical belt (from 20°N to 20°S) by the Arakawa-Schubert (AS) scheme (Arakawa and Schubert, 1974). This was done consistently for all model runs involving parameterisation of convection. The reason for this was that the AS scheme was shown to be more successful in representing the effects of tropical convection during the monsoon onset (see also Bengtsson and Simmons, 1983).

2. SYNOPTIC DESCRIPTION OF THE CASE STUDY PERIOD

The period from 12 to 16 June 1979 is considered as the onset phase of the SW monsoon over India for this year. On 12 June the monsoon just touched the southern tip of the Indian Peninsula and on 16 June its northern limit had reached 18°N; associated with this was a series of dramatic changes of atmospheric circulation over Asia. Also in this period, the "plum rain" set in over the Yangtze river of China on 19 June. There have been a number of papers describing the evolution of the events (e.g. Fein and Kuettner, 1980). Here only some of the main features will be described.

(1) Perhaps one of the most striking features is the build-up of a fairly strong low-level westerly jet over the south Arabian sea. A comparison between Fig. 1a and Fig. 1b clearly shows the abrupt change of situation from a rather weak and sparse current on the 11th into a strong and organized westerly jet on the 15th. Krishnamurti et al (1981) have calculated the kinetic energy of the zonal wind over this area and found an increase of an order of magnitude from the 11th to the 17th of June.

Together with the build-up of the westerlies, a redistribution of potential vorticity took place. As can be seen in Fig. 2, the pattern changed between 11th and 15th when an elongated minimum of potential vorticity appeared in the region 0-20'N at 70'E; its meridional gradient also changed sign. This seemed to satisfy the necessary condition for joint barotropic-baroclinic instability (Charney and Stern , 1962). It was on the northern fringe of the jet that the "onset" of the monsoon vortex took place.

It is also worthwhile mentioning that there was an outbreak of cold air from a mid-latitude trough (Fig. 1a) in the Southern Hemisphere at 40°E, which caused a strong southerly wind along the eastern coast of Africa. This current reached the Mozambique channel on 13th with a maximum of 24 m/sec at 850 mb, and was accompanied by a consistent development of an anticyclone to the southwest of Madagascar. This might be indicative of a dynamical connection between the two hemispheres.

(2) Another important feature of the transition was the build-up over the Plateau of a large-scale upper tropospheric anticyclone - the Tibetan high. Climatologically, its centre is at about 21°N, 101°E in May and at 29°N, 86'E

in June; thus there was a drastic north-west shift of position. In 1979 a similar transition was also observed in mid June. Before 11th of June, the position of the centre hardly reached west of 100°E. Fig. 1a also shows that on the 11th of June the anticyclone over Asia can only be defined within a rather narrow latitude belt. The dividing line between easterlies and westerlies lies at about 20°N around 80°E (see also Fig. 3). On the 19th of June the dividing line reached about 28°N and a huge anticyclone had formed covering the area from Africa to the east coast of Asia (Fig. 1c). On 21 June a centre could be defined at (85°E 28°N) near its climatic mean position for June.

Meanwhile, the subtropical westerlies over Asia shifted to the north of the Plateau. The tropical easterlies, although already established since May, increased their strength considerably. The cross-sections along 80°E (Figs. 3a-c) clearly illustrate that during this period all the zonal wind systems over Asia (upper and lower levels), experienced a process of northward shift and/or an increase in their strength.

(3) The other important feature is the setup of a "plum rain" synoptic pattern over east Asia. Three 500 mb charts for this period are shown, (Fig. 4a-c). The main changes during the period are evident and include: the northward jump of the subtropical high over the west Pacific into a favourable position, (the ridge line reading about 22°N at 120°E, on 19 June day 8); the setup of a frontal zone to the north of the Plateau in a WNW direction bringing weak cold air south-eastward, which along with the subtropical high, made up a confluence zone of flow at 30°N over east China. This was responsible for the persistent rainbelt of this area. Also noticeable is a typical "plum-rain-onset" trough at 115°E (Fig. 4c).

All these features provide evidence that the onset of the monsoon circulation in 1979 occurred, as usual, in a fairly abrupt way, and that the changeover took place over such a large area as to exhibit its planetary scale characteristics. These features will serve as the basis for comparison between experiments to illustrate the roles various factors may play.

3. THE PERFORMANCE OF THE CONTROL EXPERIMENT

In this section a description of the results from the control experiment (named H99) is given in which orography, land-sea distribution and all model physics are included.

Fig. 5a,b show the day 4 and day 8 forecast charts. The model successfully reproduces the build-up of strong low-level westerlies over the Arabian Sea, concentrated within a narrow belt near 10°N, in good agreement with the observations. It is interesting to see that a vortex occurred over the south of India as a result of the strengthening of the monsoon westerlies, even though the observed one was initiated over the adjacent sea, 6° longitude further to the west. We note that an area of extreme values of potential vorticity appears at 10°N on the 80°E cross section (figure not shown) similar to, but weaker than, the one observed at 70°E. In the Southern Hemisphere the model is successful in predicting the rapid development of the anticyclone to the southwest of Madagascar and the acceleration of the eastern African jet with a maximum of 19 m/sec near Kenya.

At upper levels, the forecast is capable of simulating the establishment of the huge anticyclone over the Plateau. The strengthening of tropical easterlies and its returning cross-equatorial flow near 60°E are also simulated, but the meridional component is weaker.

Cross-sections along 80°E, which are representative of the region roughly from 70°E - 100°E, are presented to show the general performance of the model in simulating the seasonal transition of zonal wind systems (Fig. 6).

Comparing this with Fig. 3b,c shows that the poleward displacement of zonal wind systems as a whole is well captured. The low level tropical westerlies increase in depth when moving northward and a second maximum of upper easterly wind appears over 15°N on day 4. All these features are in good agreement with the verification fields.

The model also succeeds in forecasting the setup of the "plum rain" flow pattern over China. Fig. 7b shows the day 8 500 mb forecast chart, the day when the rainy season began. Despite the apparent overdevelopment of the low over west Siberia, the chart shows a correct positioning of the subtropical high, of the frontal zone on the northern fringe of the Plateau and even of the "plum rain onset" trough at 115°E. These are all essential ingredients to the commencement of the rainy season of early summer in East China.

The defects of the forecast are equally apparent. In addition to what has already been mentioned above, the model fails to forecast the explosive growth of the "onset" vortex and its NW displacement; also the upper anticyclone is overpredicted. For a more detailed assessment of the performance the reader is referred to Shaw (1981) and Kallberg (1981).

Keeping all these advantages and drawbacks in mind, we will use the control experiment (H99) as a benchmark to test the effects of various model factors, where and when the control run shows some degree of success.

4. THE INFLUENCE OF THE SOUTHERN HEMISPHERE

The interaction between the two hemispheres is a phenomenon of planetary scale involving a number of aspects. So far as the southwest monsoon is concerned, most emphasis has recently been laid on the Somali jet (or East African low-level jet) which is considered to be a source of moisture and momentum (Findlater, 1969b) and is directly related to the rainfall over India. There is also some evidence that the influence of the Southern

Hemisphere can even be traced up to southern mid-high latitudes, although the extent of such influence is not quite clear yet (Webster et al, 1977; Cadet, 1981). For the 1979 case there was also a cold air outbreak near the southern tip of Africa, somewhat prior to the build-up of strong westerlies over the Arabian Sea. To see how it influences the northern monsoon circulation, two experiments have been performed.

4.1 The experiment with modified initial condition in southern mid-high latitudes

I25 is an experiment where the initial fields south of 30°S, including wind, temperature, moisture, etc., have been replaced by their climatic zonal mean values for June and kept unchanged north of 15°S. In between there is a transition belt where linear relaxation has been used to smoothly link the two zones.

Fig. 8a shows the modified initial wind fields at 200 mb and 850 mb respectively after initialization has been performed to improve consistency between the mass and the wind fields. One can see that all the waves at mid-high latitudes of the Southern Hemisphere have disappeared and pure zonal flow now dominates. The flow pattern north of 15°S remains basically unchanged.

Fig. 8b gives the day 4 forecast produced by experiment I25. We will first concentrate on the sector between 30°E and 90°E. As a result of the modification, the cold air outbreak from southern mid-latitudes has been removed, at least in the first few days. It is evident that the southerly flow from the Mozambique channel to the north and along the east coast of Africa has been weakened compared with the control H99 (Fig. 5a,b). The strength of the cross-equatorial flow decreases as well. Nevertheless, the flow pattern over the Arabian Sea is similar to the control (i.e. fairly strong westerlies concentrated in a narrow belt near 10°N).

To see more clearly the extent of the influence, the differences between the two pairs of 5 day mean wind fields are provided in Fig. 9. Although the modification involves the whole of the southern mid-latitudes, the dominant differences in the Afro-Asian region is mainly located at the east coast of Africa. This suggests that flow along this channel is very important, though not exclusive, for the interaction between the Hemispheres in this area. At 850 mb there is a maximum difference of more than 15 m/sec over the Mozambique channel, which of course is quite large and must be persistent to give such a mean value. The northern bound of the difference approaches the equator indicating how far the influence may reach in five days. Five days later (Fig. 9b) the influence has reached the Bay of Bengal and even further east. This implies that the influence propagates at an average speed of about 10° longitude per day. According to the analysis of Findlater (1977), it may be inferred that the phase difference between the fluctuation of rainfall in west India and that of wind over Kenya is about 1-5 days.

More recently, Cadet (1981) used lag-cross-correlation techniques to analyze the wind field along the Somali jet and found a phase lag of 12-13 days between 15°S and India. The much slower speed of propagation might suggest a different kind of linkage between the two areas.

Furthermore, one can see that the difference along 10°N in Fig. 9b is not continuously distributed but is mainly over the sea. This seems to suggest that the influence can not be thought of simply as a northward transfer of momentum. Once the hydrological cycle is involved, the propagation of the influence could be quite different since the release of latent heat might in turn be converted into kinetic energy.

The difference wind field at 200 mb for the second five days is also shown in Fig. 9b. Little difference could be identified in the monsoon area, even though the modification in the Southern Hemisphere is large at upper levels. Noticeable is the much more pronounced difference over the central Pacific. A scrutiny of the initial wind field may give some hint as to the origin of this marked difference. Going back to Fig. 8a, an apparent difference (among other things) is that there are strong tropical upper easterlies over the Afro-Asian region which are lacking over the central Pacific. According to Charney (1969), a strong zonal flow would prevent wave disturbances from passing through so that it is not likely that a strong interaction between the hemispheres would occcur on a relatively short time scale. The result may serve as an illustration of the crucial effect of the basic zonal flow on the interaction between the hemispheres.

It is also of interest to see the distribution of rainfall which is believed to be very sensitive to the modification of initial circulation. Fig. 10 shows the forecast daily rainfall distribution at day 7, the value being averaged for the Asian region (60°E - 140°E). A reduction of rainfall for experiment I25 does occur at the latitude belt of interst (10°-20°N), though the difference is small. Also found is a decrease in the 30°-40°N belt, which seems to further suggest that the influence may reach well north. Nevertheless, the basic features in the Northern Hemisphere are left unaltered.

4.2 The experiment without East African Highlands

It is generally acccepted that the presence of the north-south mountain barrier in East Africa is a basic factor responsible for the occurrence of the Somali jet (Hart, 1977).

One way to examine this interaction is to remove the East African Highlands from the model by setting the height of the topography equal to zero in the region (to the westof 62°E over Africa). The results obtained by this run (I11) are shown in Fig. 11.

The difference between this run and the control is readily apparent by comparing Fig. 11 with Fig. 5. The Somali jet can no longer be defined near East Africa for I11, the strong southerly wind having disappeared. Because of the absence of the barrier the flow over the Mozambique channel has already turned freely towards the west, forming a strong easterly flow over South Africa. The position of the anticyclone to the southwest of Madagascar also shifts westward by about 5° longitude compared to the control run. A much weaker cross-equatorial flow appears west of 30°E. However, there remains a belt of strong westerlies along 10°N over the south Arabian Sea, showing little difference from the control run, even though the difference upstream is pronounced.

On day 8 at the east coast of Somali, the maximum wind speed at 850 mb is only 9m/sec which is about half that of the control run. However the flow seems to accelerate downstream to attain a value of 17 m/sec at the tip of the Indian peninsula. The immediate implication may be that the low level westerlies over South Asia can be maintained, even though the artery for the transfer of momentum from the Southern Hemisphere has ben cut.

In order to see in more detail how the influence propagates further to the east and north, the 500 mb chart on day 8 for I11 is shown in Fig. 12. The comparison with Fig. 7b shows that the main features are quite similar; for example note the position and orientation of the subtropical high, the setup of a frontal zone on the north side of the plateau and even the "quasi-steady" minor trough at 115°E. Nevertheless, discernible differences can readily be found, e.g. over Japan where the trough is located 10° to the east of the control.

Fig. 13 shows two of the daily rainfall distribution charts. No discernible differences are seen between the 10°-20°N belt until day 3. If the change of wind field due to the removal of the East African Highlands (which starts at about 40°E-50°E near the equator) is considered as a disturbance, then the response of rainfall over India occcurs about three days later. From Fig. 13a it is evident that, owing to the weakening of the cross-equatorial flow, a decrease of rainfall in the Asian tropical belt (10°-20°N) does occur, even though the decrease only accounts for 15% of the total. On day 7 (Fig. 13b) a change of rainfall appears even up to 30°-40°N, but the basic features of the two curves in Fig. 13b are similar.

To conclude this section it is worth pointing out that, although the interaction between hemispheres must be highly variable from case to case, the above results illustrate that the change of circulation in the Southern Hemisphere influences both the Indian Peninsula and also the area to the north. This may serve as evidence of some kind of connection between the circulations over east Africa and over east Asia. The nature of this connection has, however, yet to be explored. In any case, the influence seems not strong enough to change the basic features and evolution of the northern circulation, even though the disturbances in the Southern Hemisphere are fairly strong.

5. THE INFLUENCE OF DIABATIC HEATING

An adequate description of energy supply and dissipation is important for numerical forecasts of up to a week, and this is particularly true for forecasts in the summer season. Part of the reason for this is that the mechanical energy available in a given initial state of the atmosphere in summer is far less than that in winter.

Vigorous convective activity may greatly enhance the momentum transfer in the vertical, thus increasing the dissipation rate of energy in the upper troposphere. With regard to a special period like the setup of the monsoon circulation, two kinds of differential heating attract particular attention. The first is one due to the land-sea contrast which is believed to play a fundamental role. Krishnamurti et al (1981) have performed a comparative numerical forecast to demonstrate the impact of differential heating on the setup of the low level westerly jet over the Arabian Sea. The other is the differential heating between the Plateau and contiguous plain areas which has also been emphasized recently.

In this Section we will discuss the overall effect of diabatic heating. Two numerical experiments have been conducted: (1) neglect of the latent heat release in the model; (2) removal of all diabatic heating, with only a small amount of friction corresponding to a sea-surface-type friction being retained.

5.1 The experiment without latent heat release

Comparison of the scores for the control run (H99) and I03 (no latent heat release) readily shows the superiority of H99 over I03 (Fig. 14). For the tropical area the difference is already apparent in the first few days, though not very large. Also notable are the major differences which appear in the zonal part of the RMS scores which might be an indication that the basic features of the variation of latent heating distribution are more latitudinal than longitudinal.

The build-up of the low level westerly jet over the Arabian Sea is an important measure of the success of the forecast. As can be seen in Fig.15 no organized and strong westerly wind at 850 mb occurs over the Arabian Sea in the absence of latent heat. However, the cross-equatorial current off east Africa, as in the control run, still accelerates from day 0 to day 4 - the maximum wind speed at the equator being 18 m/sec. However it continues flowing northward instead of turning sharply to the west as observed. This suggests that the downstream turning of the cross-equatorial flow can not be ascribed only to this effect, but to the differential heating by land-sea contrast as well. On day 8 (Fig. 15b) the experiment, like the control, fails to forecast the strong development of the vortex over the Arabian Sea. However, the differences between the two still give some hint of the physical process involved. In Fig. 15b westerlies appear over the Arabian Sea but are located further to the north, which is probably caused by differential heating due to surface sensible heat transfer (we will return to this point later).

Similar pronounced differences are also present at upper levels. On day 4 (Fig. 15a) the anticyclonic circulation at 200 mb over South Asia for I03 is weaker than that of H99 (Fig. 5a) in terms of the strength of zonal flow at both northern and southern fringes. Westerly flow stagnates at near 20°N in the Bay of Bengal, while for H99 (as well as the observed) the subtropic westerlies have retreated to the north of the Plateau. The most salient feature in this figure is the deceleration of the tropical easterlies taking place instead of their acceleration (hence, a well-defined easterly jet no longer exists).

On day 8 (Fig. 15b) the tropical easterly flow remains weak. Also an anticyclone appears centred right over the Plateau, while for the control run a more pronounced anticyclone is centred to the north of India. This suggests that the distribution of large scale heating might to some extent influence the position of the huge Tibetan High. This is more likely when the prevailing westerlies have retreated north of 40°N.

The cross-section along 80°E (Fig. 16b) also illustrates the overall deceleration of the zonal flow compared with Fig. 6. In particular the tropical westerlies are confined to a rather shallow layer in the absence of latent heat release.

5.2 The adiabatic run

I12 is an adiabatic run which removes from the model all diabatic effects, including latent heat release. The comparison of I12 with the control (H99) shows the ensemble effect of diabatic effects and the difference between I12 and I03 (the last section) may be mainly related to the surface sensible heat transfer.

The most striking feature presented in Fig. 17 (I12) is that the decline of circulation appears even faster than in experiment I03. The total kinetic energy of the tropical zone (32.8°S - 32.8°N) is reduced by a factor of two thirds in ten days. No strong jet-like westerly flow is set up over the Arabian Sea and the established upper tropical easterlies over the area weaken considerably. An immediate inference can be drawn that the momentum transfer from the Southern Hemisphere alone is not sufficient to account for the onset of the southwest monsoon in the absence of diabatic heating. Here again one comes to the same conclusion as in Section 4.

Fig. 18 shows the difference of five-day mean wind field between I03 (no latent heat) and I12 (adiabatic). The differences are mainly confined to the low levels for the first five days. There is a difference of 4 m/sec in the westerly wind over the Bay of Bengal at 850 mb on day 4 but hardly any at 200 mb (Fig. 18a). This might be due to the fact that the difference mainly comes from the sensible heat from the surface which takes time to accumulate and transfer upward.

Up to the second five day period it is speculated that the sensible heat transfer accumulates to bring about a discernible difference between the two forecasts both at lower and upper levels. The difference fields show westerlies extending from the Arabian Sea to the Indo-China Peninsula (Fig. 18b). The maximum is located at about 17°N, which is 7° further north than in H99.

At upper levels, there is an anticyclonic wind flow difference right over the Plateau; the horizontal scale is around two thousand kilometres, indicating the differential heating due to mountain plain contrasts might be responsible for this part of the difference. Further to the south the differences gradually disappear. In particular there is no sign of easterlies along 10°N, which means that the sensible heat transfer alone might not be crucial to the upper tropical easterlies on a relative short time scale. In other words, the latent heat makes the main contribution.

It is also interesting to see how the diabatic heating influences the setup of the "plum rain" flow pattern over eastern Asia. As can be seen from Fig. 19, even in the absence of both latent and sensible heating, an intensification and rapid north-westward shift of the west Pacific subtropical high at 500 mb still occurs. This might be an indication that the behaviour of this branch of the subtropical high is more of a dynamical process. On the other hand, since the monsoon westerlies have been greatly weakened, this seems to rule out a direct connection between the northward jump of the subtropical high and the setup of monsoon westerlies. A possible factor responsible for this may be the strong ridge at 200 mb to the east of the Plateau, which can be seen in Fig. 17b. This effect, although in agreement with established synoptic experience, has yet to be clarified.

The obvious deficiency in Fig. 19 lies in the failure to simulate the retreat of the subtropical westerlies to the north side of the Plateau; the typical "plum rain onset" trough at 115°E is totally absent. To see the consequence more clearly, cross-sections along 115°E are shown (Fig. 20) for day 8, the day when the "plum rain" sets in. The conspicuous feature in both Fig. 20a and Fig. 20b is a convergence zone in the wind field at 20°-30°N. To the north, WNW flow along tne Plateau brings weak cold air southward and the southerly winds related to the subtropical high move northward, resulting in persistent upward motion at about 30°N, which is typical of the meridional circulation associated to the "plum rain" flow pattern. But the adiabatic simulation (Fig. 20c) fails to produce the typical convergence zone. Particularly, one can hardly recognize the northerly wind north of 30°N which is obviously due to the failure of the adiabatic run to simulate the set-up of the fairly strong westerly flow along the northern fringe of the Plateau.

To conclude this section, the above results illustrate the significance of differential heating, mainly due to convection, in the setup and maintenance of the monsoon circulation as a whole, particularly the setting in of the "plum rain" in Eastern Asia. Murakami et al (1970), in their numerical simulation based on a simplified two-dimensional model, confirmed that the inclusion of a condensation cycle is crucial to the formation of the upper easterly jet. Also Krishnamurti et al (1981) demonstrated the importance of differential heating in the build-up of low level westerlies. The results here might serve to show how effective the latent heating is. Even on a time scale of a week it may exert so pronounced an influence that all components of the monsoon circulation and the evolution of the events are considerably changed.

On the other hand, the hydrological cycle and diabatic heating, in turn, are highly sensitive to, and depend on, the wind field. Therefore the effectiveness of differential heating shown in this section seems to suggest that for any explanation of the onset of the planetary monsoon circulation to be satisfactory, one must take into account the triggering and feedbacks of large scale organized convection.

6. THE INFLUENCE OF THE QINGHAI-TIBETAN PLATEAU

In summer, the Plateau not only remains (as in other seasons) a huge barrier exerting a direct dynamical effect on the atmosphere, but it also produces thermal effects as an elevated heat source. This is an aspect which has received increasing attention in recent years. According to the estimate by Yeh and Chang (1974 and 1979), the latent heat release over the Plateau in summer may warm up the air between 600-150 mb by about 2.0°C per day; the sensible heating is of the same magnitude. The heating is so strong that one may consider that even during the seasonal transition period of a few weeks, the Plateau might have a thermal influence. In this section attention will be focussed on an experiment (I02) in which the height of orography in the plateau area (65°-180°E and north to 7.5°S) has been set equal to zero. In oder to highlight the effect of the Plateau alone we retain the Iranian and east African highlands. Some smoothing has been performed in the junction areas.

Fig. 21 shows the day 4 and day 8 forecast produced by I02. Comparing them with Fig. 5 (the control) it is apparent that some main features characteristic of the transition are also reproduced here. At the upper levels one can see the setup of the Tibetan high over the plateau area and the intensification of the easterly jet over the equator. At the lower level the run is also successful in simulating the build-up of the westerlies along 10°N over the Arabian sea. It is interesting to see that a vortex appears to the west of the Indian peninsula, at a position even closer to the observed one. This result, combined with those described in Section 5, strongly suggests that differential heating due to land-sea distribution plays a fundamental role in governing the basic features and evolution of the monsoon circulation even in the absence of the plateau. Fig. 22 shows the cross-section along 80°E, which is representative of the plateau region. In addition to the northward shift of the zonal wind systems similar to the control run, a noteworthy difference is that the tropical westerlies are confined to lower levels, and are much shallower in comparison to the control (Fig. 6). To further clarify this phenomenon, a cross-section at the equator is shown in Fig. 23. Comparing it with Fig. 6 one can see that the 10 m/sec isotach reaches up to about 600 mb at 10°N (Fig. 6b) while it remains below 700 mb near the equator (Fig. 23). This means that there is a rapid increase of depth of the tropical westerlies when the flow crosses the equator, which is not likely to be accounted for in terms of the influence of the Southern Hemisphere. In this connection, the Plateau seems to play a role in changing the strength, position and particularly the depth of the westerlies. However, since there are easterly winds separating the tropical westerlies from the continent, the result can not simply be explained as part of the thermal low over the continent.

The differences at upper levels seem to be more striking. The core of the subtropical jet associated with a zone of intense baroclinity located at 30°N (Fig. 22b) is about 5 degrees to the south of that in the control run (Fig. 6b). The implication is that the Plateau greatly influences the northward shift of the subtropical jet. This result is consistent with results by Hahn and Manabe (1975). Also noticeable is that, during the period from 11 to 18 June, another maximum of upper easterlies appears at about 15°N (Fig. 3c and Fig. 6b). This feature can be seen even more clearly in cross-sections along other longitudes in this region. The control experiment largely succeeds in capturing this feature. In Fig. 6b another branch of easterly wind also appears with a maximum of 25 m/sec, but not in the experiment without the Plateau (Fig. 22b). The thermal contrast between the Plateau and the surrounding plain area is likely to be responsible for these differences.

Further to the east the difference seems to be equally, if not more, pronounced. Fig. 24 shows the 500 mb chart for I02 on day 8. Comparing with

Fig. 7b one can see that the "plum rain onset" trough at about 115°E disappears in the absence of the Plateau. If we adopt the conventional definition of the subtropical high at 500 mb using the contour of 588 dkm, its western end only reaches 125'E, lagging 10 degrees behind the control run, or 15° behind the observed. This might provide support to the idea that the subtropical high over the Pacific is not only maintained by the Hadley cell but also by a circulation in the east-west direction (Walker-type circulation) which in turn is closely related to the thermal effect of the plateau.

The longitudinal cross section along 25°N on day 8 is shown in Fig. 25 as supporting evidence to this speculation. The latitude 25°N is chosen where the basic zonal flow is weak and the centre of Tibetan High is located. Apart from minor details, the general impression is that the vertical motion for H99 is stronger than it is for I02 over most parts of the Pacific. Particularly over 140°E and 160°-180°E, (the former corresponding to the subtropical high over the west Pacific) the control run H99 presents more systematic and stronger descending motion. One of the overall consequences is the drastic reduction of the "plum rain". From Fig. 26 one can see that the typical rain belt along 30°N in eastern China is less well defined in the experiment without the plateau (Fig. 26b).

7. CONCLUDING REMARKS

1. The results show an optimistic prospect for a sophisticated GCM to be able to predict, on a time scale of ten days, the setup of a monsoon circulation or, more generally, the seasonal transition of circulation over Asia. This is a complex problem involving the interaction between different latitude zones and even between the two hemispheres.

2. The field of differential heating (mainly due to different convective heat release between land and sea) seems to be of primary importance, not

only from a long term viewpoint, but also on the relatively short time scale. It seems to be mainly responsible for the establishment and maintenance of the major components of the monsoon circulation even in the absence of the plateau. Therefore a better understanding of the interaction between the large scale flow and organized convection seems to be required to provide a satisfactory explanation and simulation of the rapidity of the transition.

3. In summer, acting as an elevated heat source, the influence of the Plateau may be thought of as two fold: firstly as part of a still larger scale heat source, the one due to land-sea contrast; secondly, as a differential heating between the plateau and surrounding plain areas. Both seem to reinforce but not radically change the basic feature of the events. These two aspects evidence themselves in increasing the depth of the SW monsoon and drawing the whole zonal wind systems northward; in particular only if the Plateau is included can the subtropical westerly jet be setup in its correct summer position. This, in turn, is crucial to the "plum rain" flow pattern over east Asia.

4. There is a phase lag relationship between the distribution of the jet off the east coast of Africa and the rainfall in the northern monsoon area. A connection between the flow over East Asia and that at the southern mid-latitudes is therefore likely, but the influence seems insufficiently strong to mainly account for the drastic change of the northern monsoon circulation.

A direct influence of waves in the upper troposphere of the southern mid-latitudes seems unlikely, probably due to the existence of strong easterlies.

Acknowledgements

The authors gratefully acknowledge Dave Shaw's and Bob Riddaway's careful readings of this report. Chen Shou-Jun's help in editing the figures was deeply appreciated.

References

Arakawa, A., 1974: Interaction of a cumulus cloud ensemble with the large-scale environment. Part I, JAS, 31, 674-701.

Bengtsson, L., 1983: Long-range weather prediction - Operational experience at ECMWF. To appear in Large-scale dynamical processes in the atmosphere, Ed. B.J. Hoskins and R.P. Pearce, Academic Press.

Burridge, D.M.and Haseler, J., 1977: A model for medium range weather forecasting. ECMWF Tech.Rep.No.4, 45p.

Cadet, D., 1981: Interaction between the Southern Hemisphere and the monsoon circulation. International conf. on early results of FGGE and large-scale aspects of its monsoon experiments. Tallahassee, Florida, USA, 12-17 Jan.1981. Condensed papers and meeting report 5,17-24.

Charney, J.G.and Stern, M.E., 1962: On the stability of internal baroclinic jets in a rotating atmosphere. J.Atmos.Sci., 19, 159-172.

Charney, J.G., 1969: A further note on large-scale motions in the tropics, J.Atmos.Sci., 26, 182-185.

Eliot, J., 1900: Handbook of cyclonic storms in the Bay of Bengal.

Fein, J.and Kuettner, J., 1980: Report on the Summer Monex Field Phase, Bull.Amer.Meteor.Soc., 61, 461-474.

Findlater, J., 1969a: A major low level air current near the Indian Ocean during the northern summer. Quart.J.Roy.Meteor.Soc., 95, 362-380.

Findlater, J., 1969b: Interhemisphere transport of air in the lower troposphere over the western Indian Ocean, Quart.J.Roy.Meteor.Soc., 95, 400-403.

Findlater, J., 1977: Observational aspects of the low-level cross-equatorial jet stream of the West Indian Ocean. Pure and Applied Geophysics, 115, 1251-1262.

Flohn, H., 1958: Recent investigations on the mechanism of the "Summer Monsoon" of Southern and Eastern Asia, Symposium on the mechanism of the "Summer Monsoon" of Southern and Eastern Asia. Symposium on Monsoon of the World, New Delhi, Feb.19-21, 1958.

Hahn, D.G.and Manabe, S., 1975: The role of mountains in the south Asian monsoon circulation, J.Atmos.Sci., 32, 1515-1541.

Hart, J.E., 1977: On the theory of the East African low level jet stream. Pure and Applied Geophysics, 115, 1063-1282.

Kallberg, P., 1981: Onset of the 1979 summer monsoon - ECMWF level III-b analysis and forecast experiments, Workshop on tropical meteorology and its effects on medium range weather prediction at middle latitudes, 11-13 March 1981, Available at ECMWF.

Krishnamurti, T.N., Ardanuy, P., Ramanathan, Y.and Posch,R., 1981: On the onset vortex of the summer monsoon, Mon.Wea.Rev., 109, 344-363.

Krishnamurti, T.N.and Ramanathan, V., 1981: Sensitivity experiments on the monsoon onset to differential heating. Ibid. 163-206.

Kuo, H.L., 1974: Further studies of the parameterization of the influence of cumulus convection on large-scale flow. J.Atmos.Sci., 31, 1232-1240.

Murakami, T., Godbale, R.V.and Kelkar, R.R., 1970: Numerical simulation of the monsoon along 80°E, Proceedings of the Conference on the Summer Monsoon of Southeast Asia (ed.C.S.Ramage), Navy Weather Res.Facility, Norfolk, Virginia, 39-51.

Shaw, D.B., 1981: ECMWF operational forecasts in the SW and NE Monsoon regions, Workshop on tropical meteorology and its effects on medium range weather prediction at middle latitudes, 11-13 March, 1981.

Staff Members Academia Sinica, Inst.Geophys.Meteor., Peking, 1957-58: On the general circulation over Eastern Asia, I-III, Tellus, 10, 58-75 and 299-312.

Tiedtke, M., Gelyn, J.-F., Hollingsworth, A.and Louis, J.-F., 1979: ECMWF model parameterization of sub-grid scale processes. ECMWF Tech.Rep.No.10, 46pp.

Webster, P.J., Lang Chou and Ka Ming Lau, 1977: Mechanism effecting the state, evolution and transition of the planetary scale monsoon. Pure and Applied Geophysics, 115, 1335-1356.

WGNE Working Group on Numerical Experimentation, 1981: Selection of FGGE cases for numerical experimentation. JSC-II Report, Annex G, Appendix C, WMO, Geneva.

Yeh, T.C.and Chang, C.C., 1974: A preliminary experimental simulation on the heating effect of the Tibetan plateau on the general circulation over Eastern Asia in summer, Scientia Sinica XVII 397-420.

Yeh, T.C., Y.X.Gao and others, 1979: Meteorology of the Qinghai-Tibetan plateau. Science Press, Peking, 278pp.

SUMMARY OF EXPERIMENTS

Experiment	Comments
Analysis	FGGE
H99	Control
I02	No Tibet 65^{o} - 180^{o}E > 7.5^{o}S $h_{*}=0$
I03	No precipitation
I12	Adiabatic
I11	No African Highland
I25	Modified S.H. < 35^{o}S climate zonal mean 15^{o} - 35^{o}S transition zone Orography < 15^{o}S $h_{*}=0$

TABLE 1

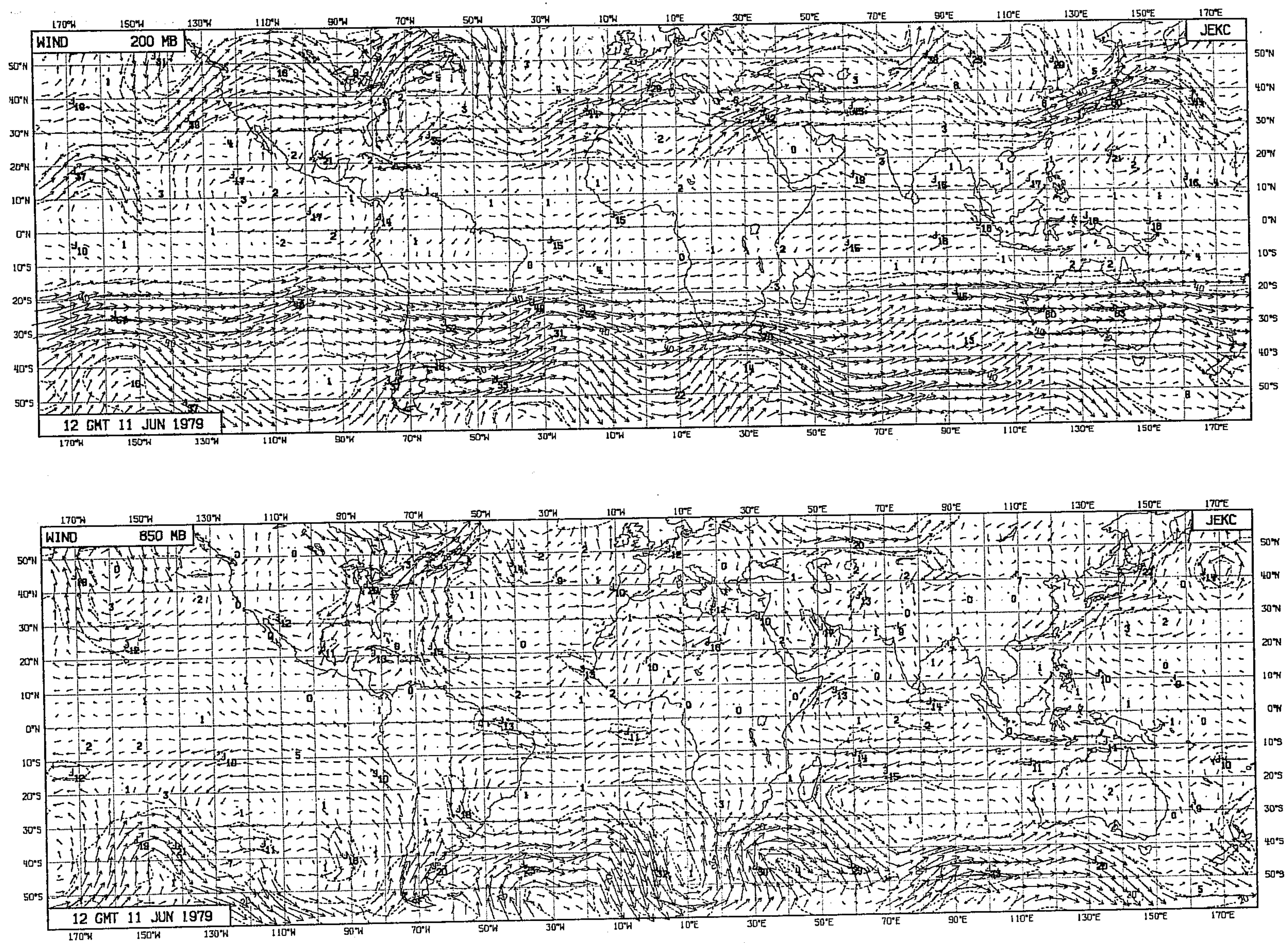
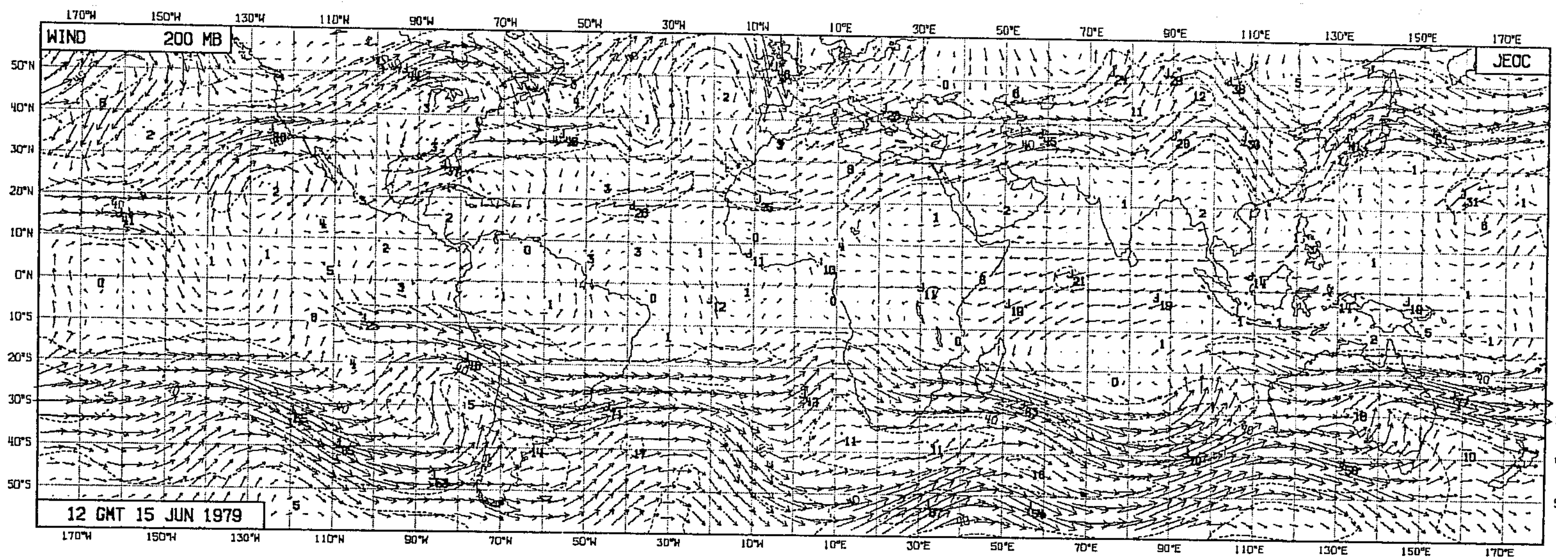


Fig. 1 200 mb (top) and 850 mb (bottom) wind analysis, Isotach interval 10 ms^{-1}
(a) 12GMT 11 June 1979 (b) 12GMT 15 June 1979 (c) 12GMT 19 June 1979.


WIND
200 MB
JEOC
12 GMT 15 JUN 1979

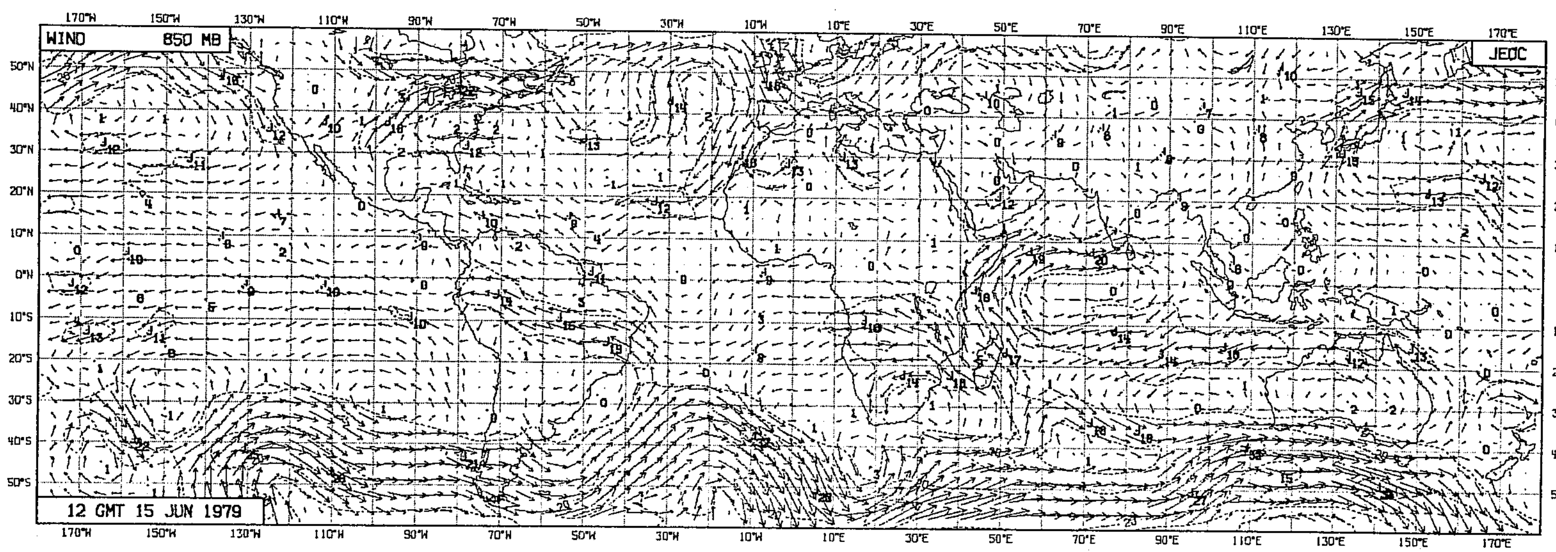
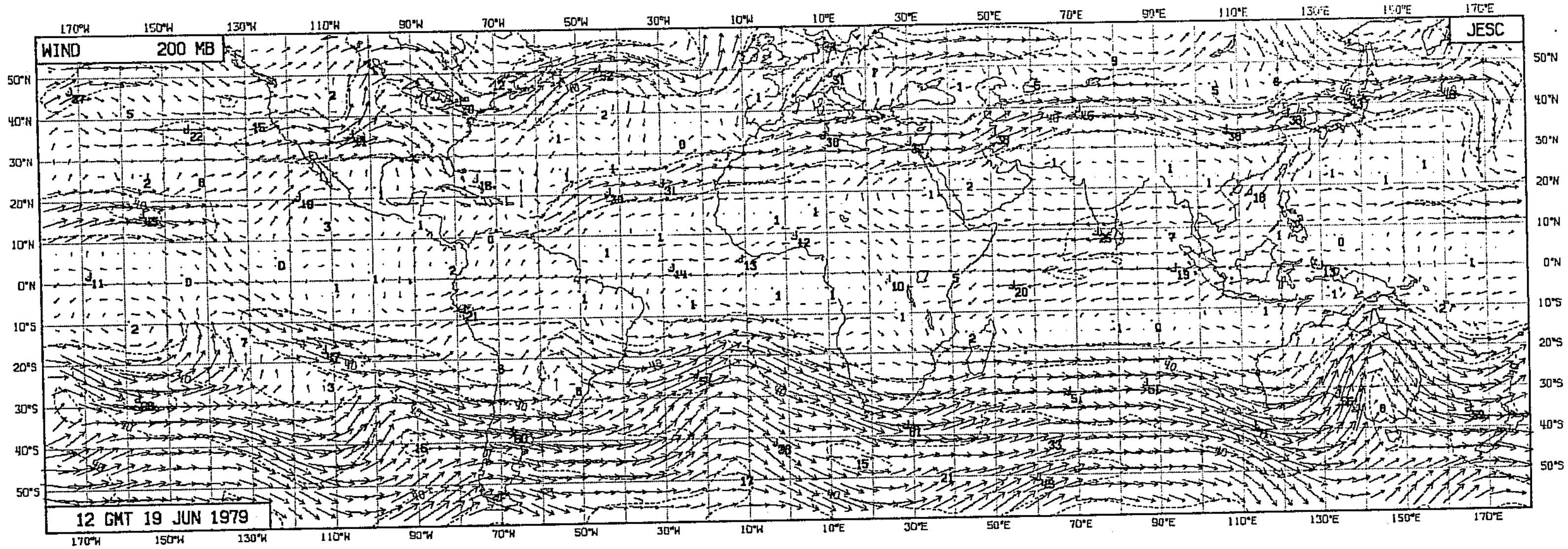

WIND
850 MB
JEOC
12 GMT 15 JUN 1979

Fig. 1(b)


WIND 200 MB
JESC
12 GMT 19 JUN 1979

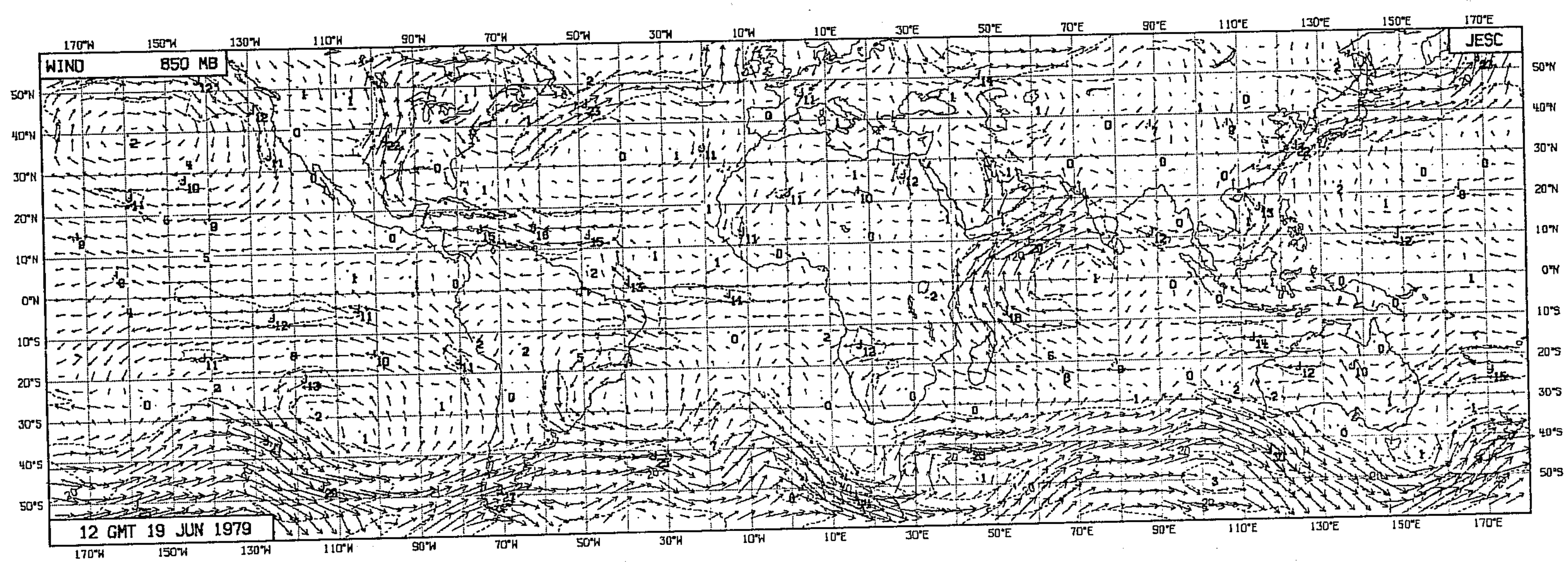
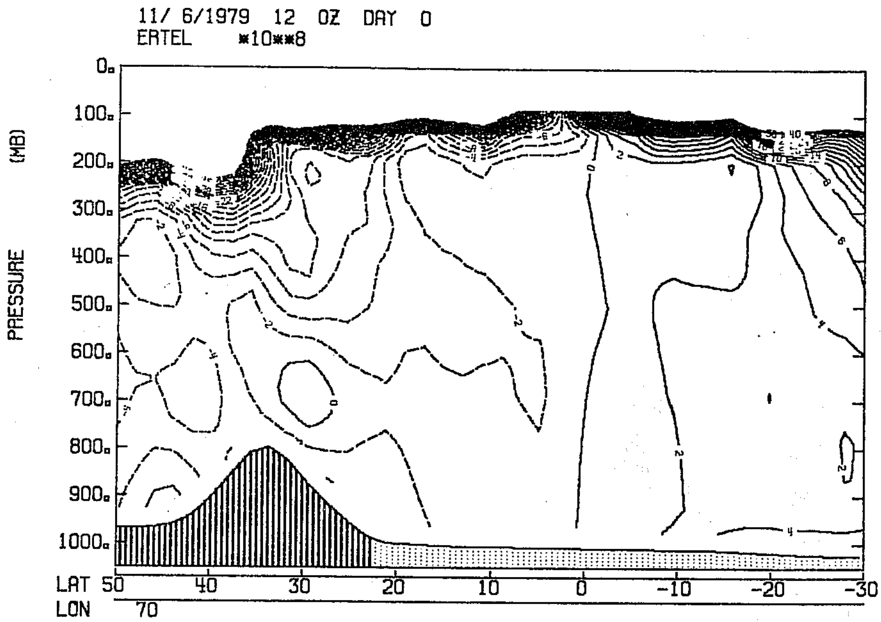
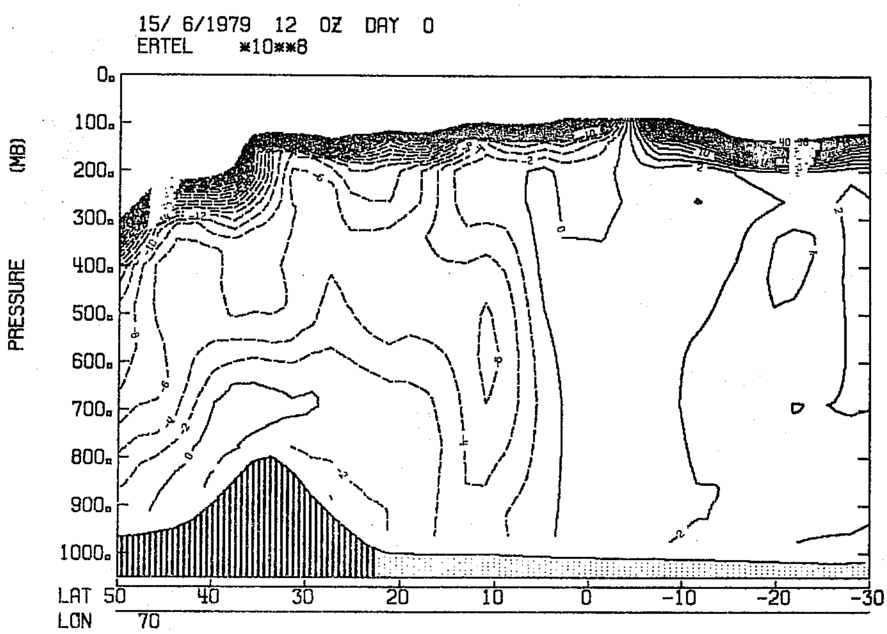

WIND 850 MB
JESC
12 GMT 19 JUN 1979

Fig. 1(c)



(a)



(b)

Fig. 2 Distribution of potential vorticity along 70°E units : $PaKs^{-1}$ (a) 12GMT 11 June 1979 (b) 12GMT 15 June 1979.

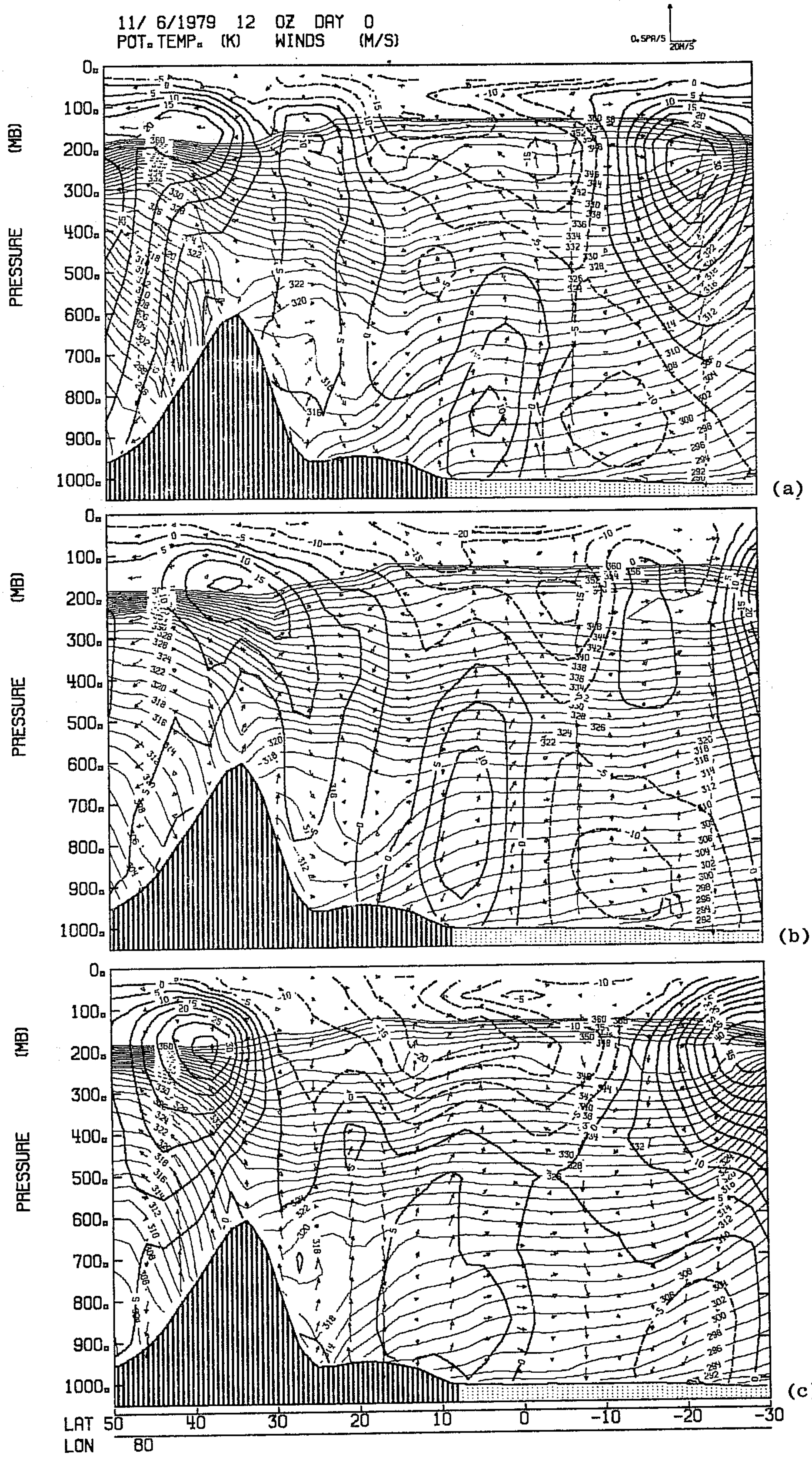


Fig. 3 Cross-section along 80°E, analysis. Thin lines potential temperature. Thick lines isotach (dashed for easterlies). The arrows denote resultant wind of vertical and horizontal velocities, the proportion shown at top right of the map. (a) 12GMT 11 June 1978 (b) 12GMT 15 June 1979 (c) 12 GMT 19 June 1979.

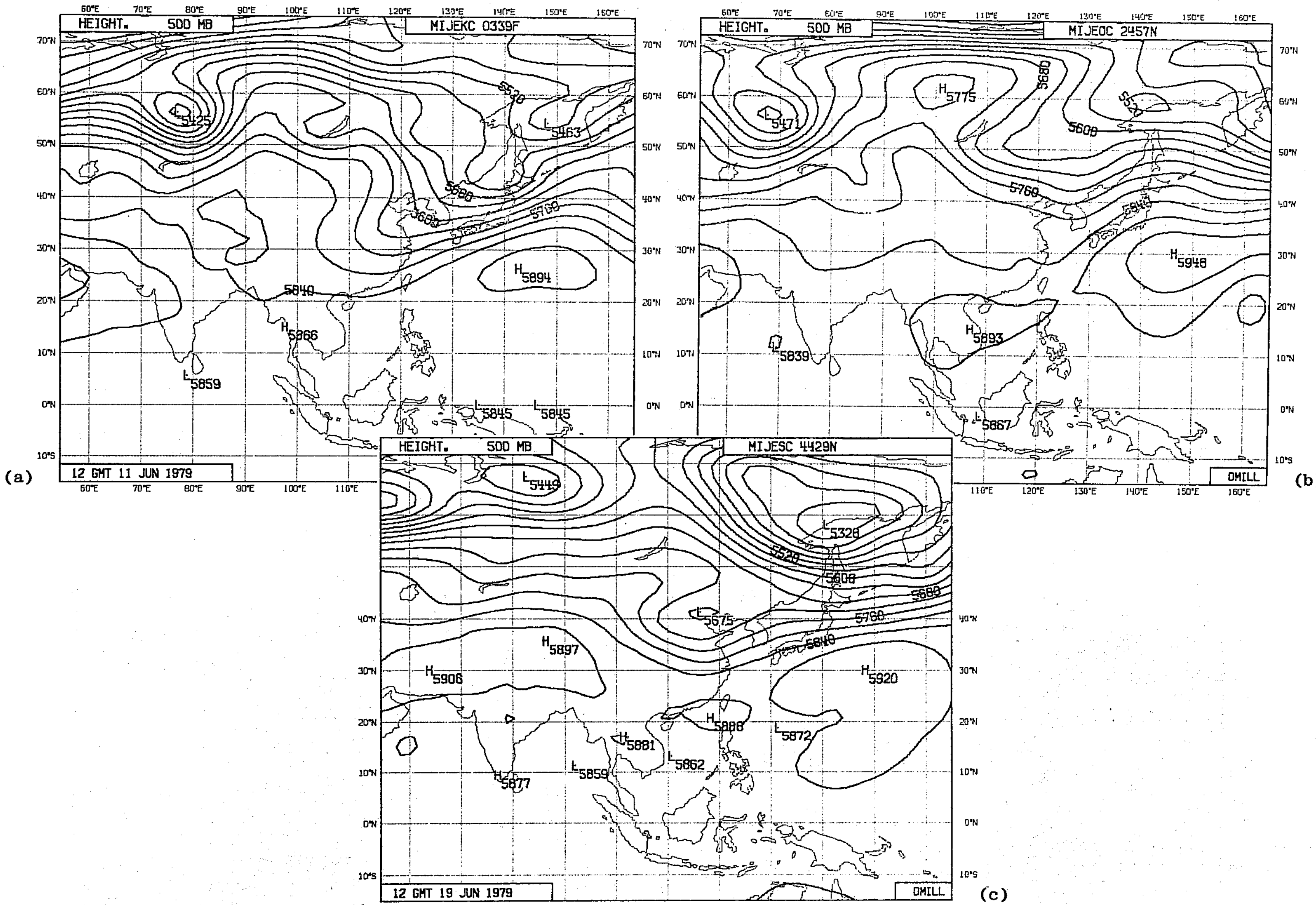


Fig. 4 500 mb geopotential fields for Asia. Contours for every 4 dkm. (a) 12GMT 11 June 1979. (b) 12GMT 15 June, (c) 12GMT 19 June.

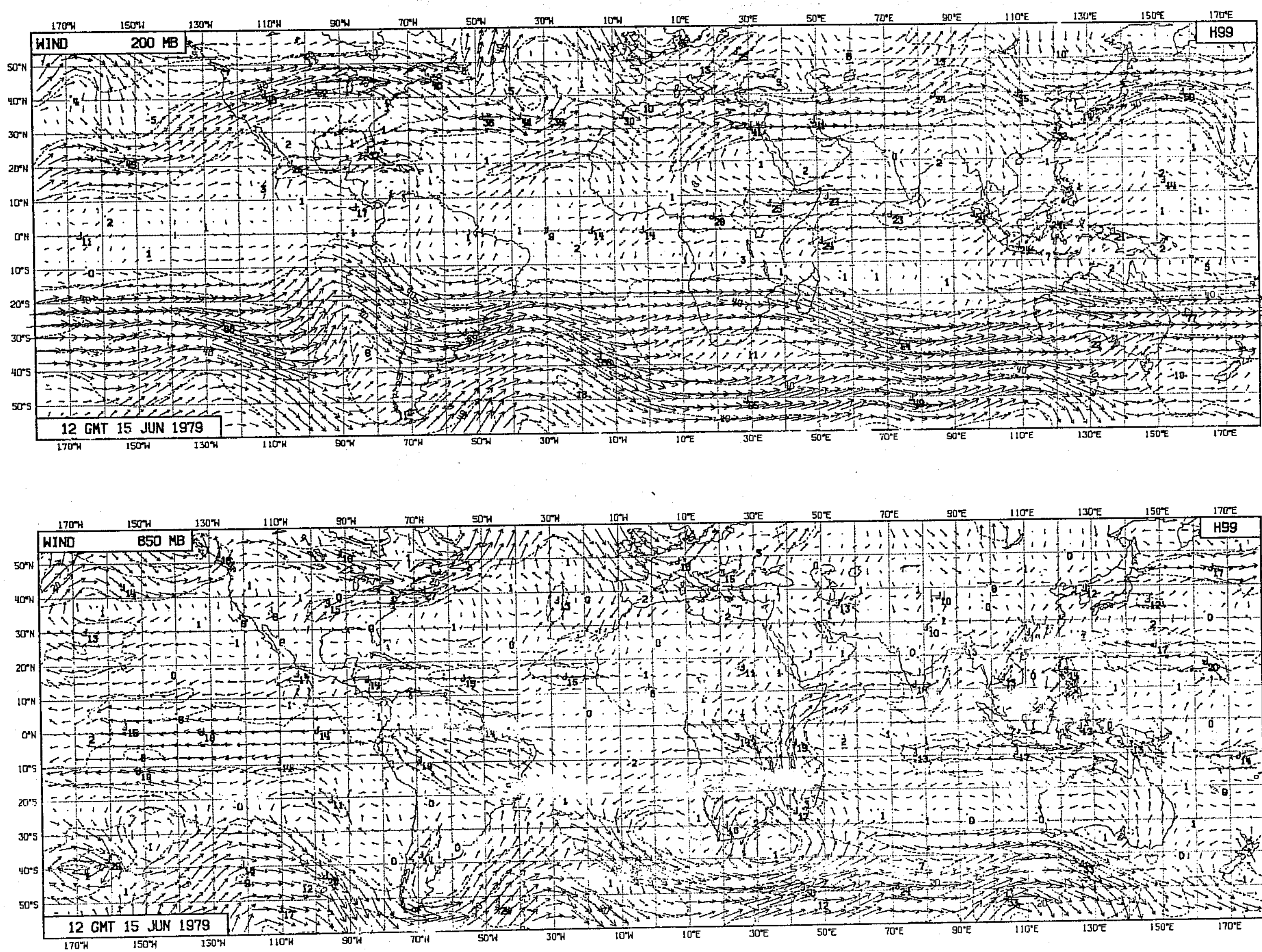
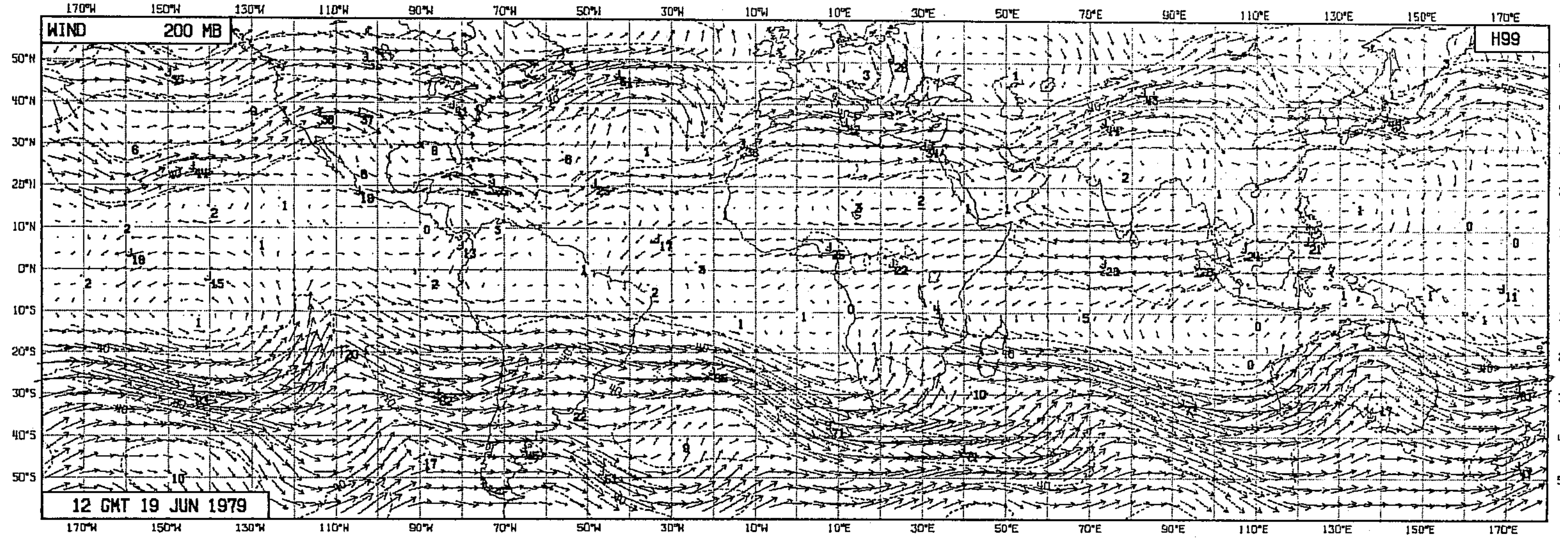


Fig. 5 Same as Fig. 1 but for exp.H99 the control. (a) 12GMT 15 June 1979 (day 4).
(b) 12GMT 19 June 1979 (day 8).


WIND
200 MB
H99
12 GMT 19 JUN 1979

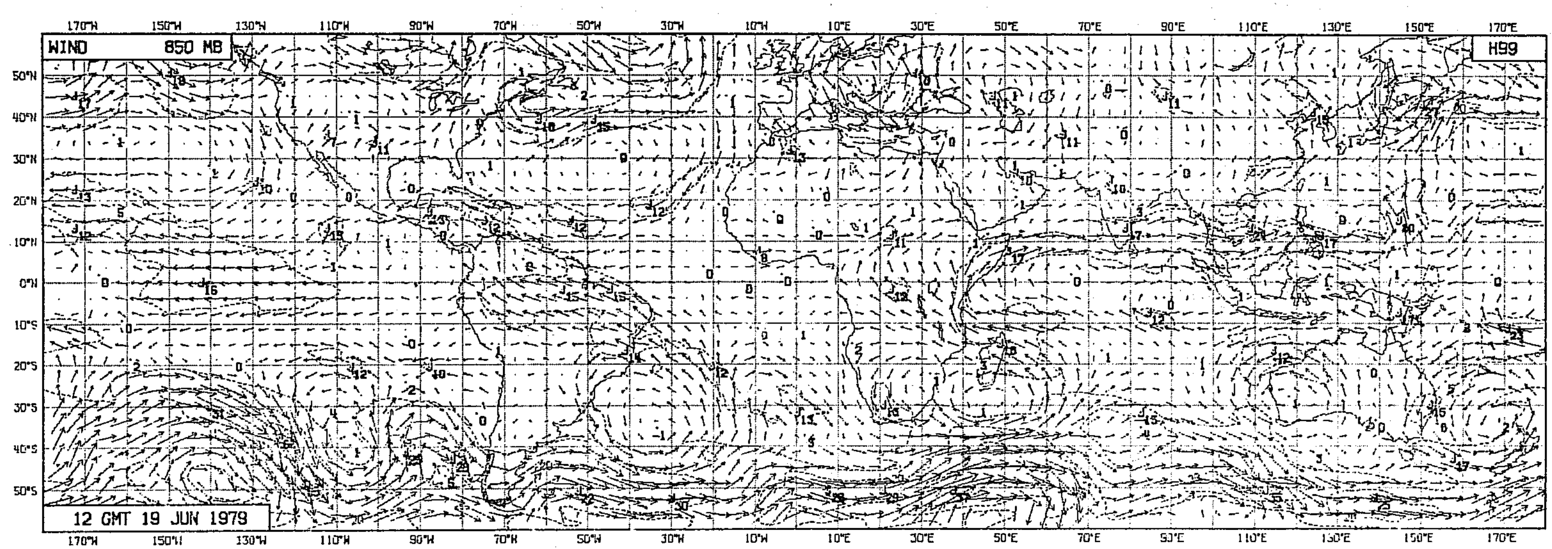

WIND
850 MB
H99
12 GMT 19 JUN 1979

Fig. 5(b)

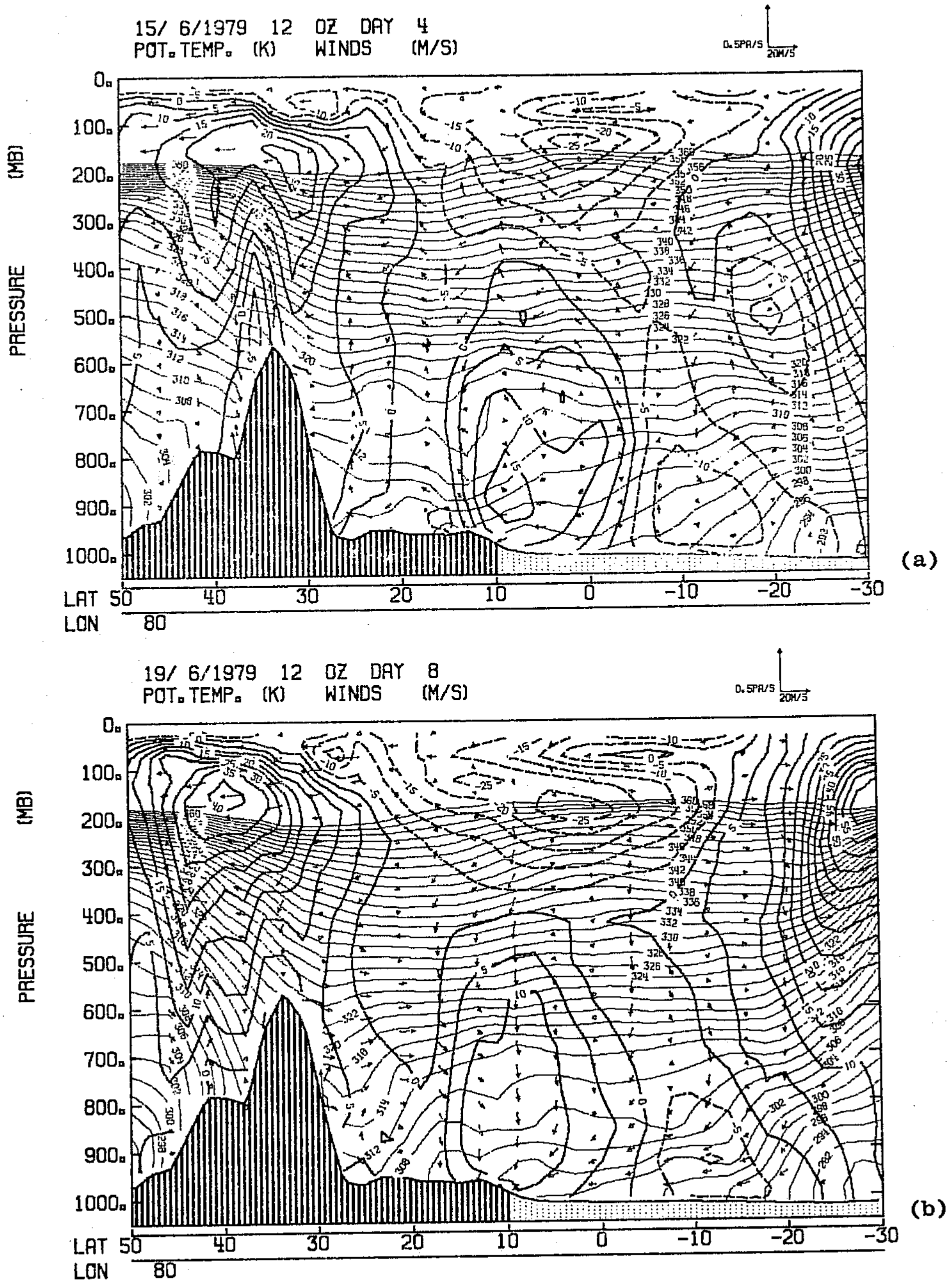
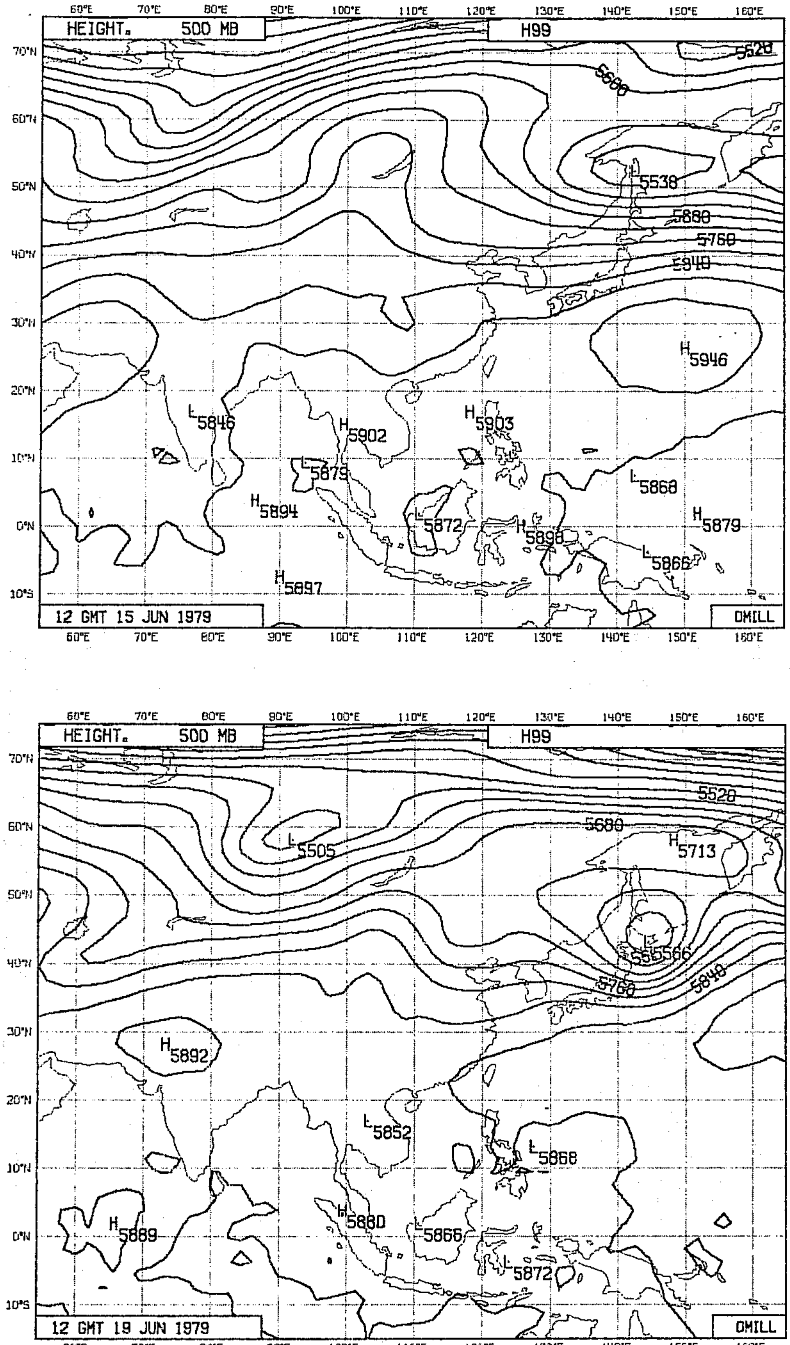


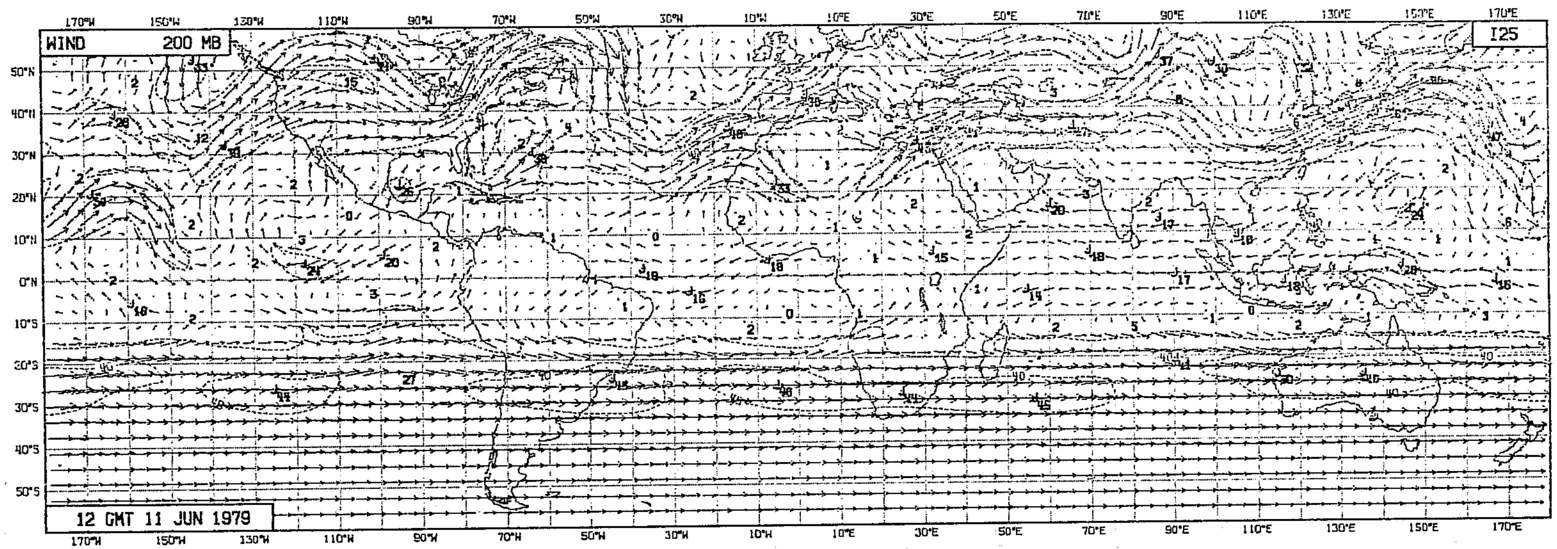
Fig. 6 Same as Fig. 3 but for exp.H99 the control. (a) day 4 (b) day 8.



(a)

(b)

Fig. 7 500 mb geopotential fields. Same as Fig. 4 but for exp.H99 the control.
(a) day 4, (b) day 8.



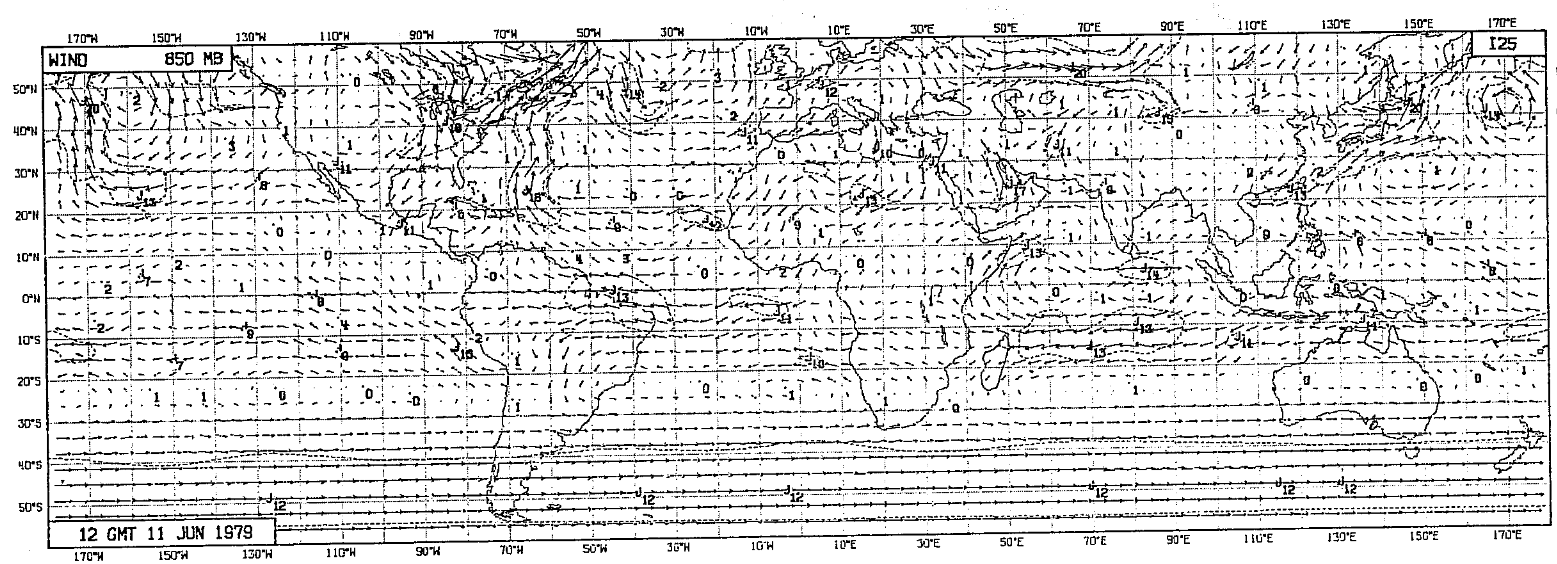


Fig. 8 200 mb and 850 mb windfields. Same as Fig. 1 but for exp.I25 (modified Southern Hemisphere). (a) The modified initial wind fields. (b) day 4, (c) day 8.

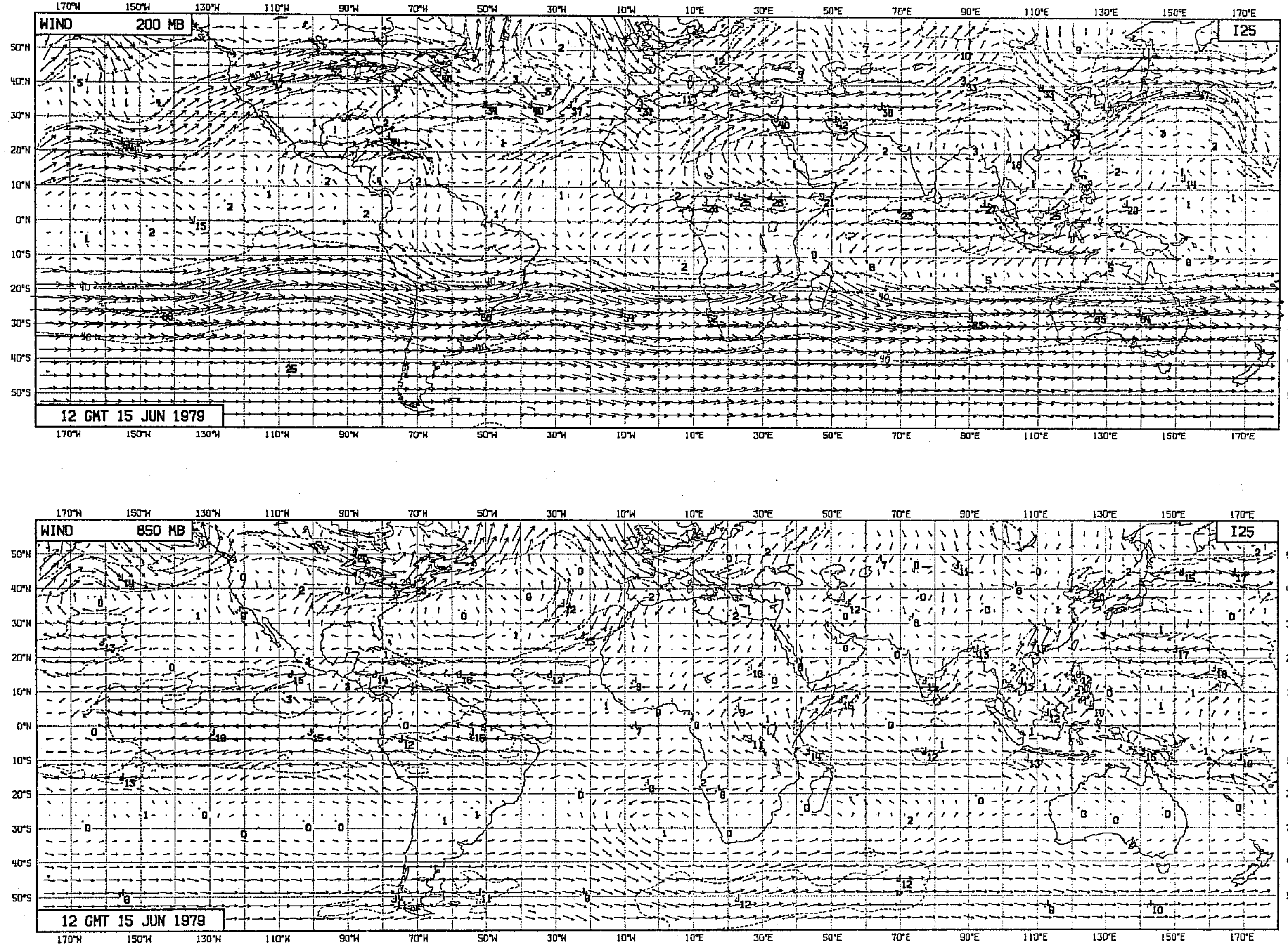
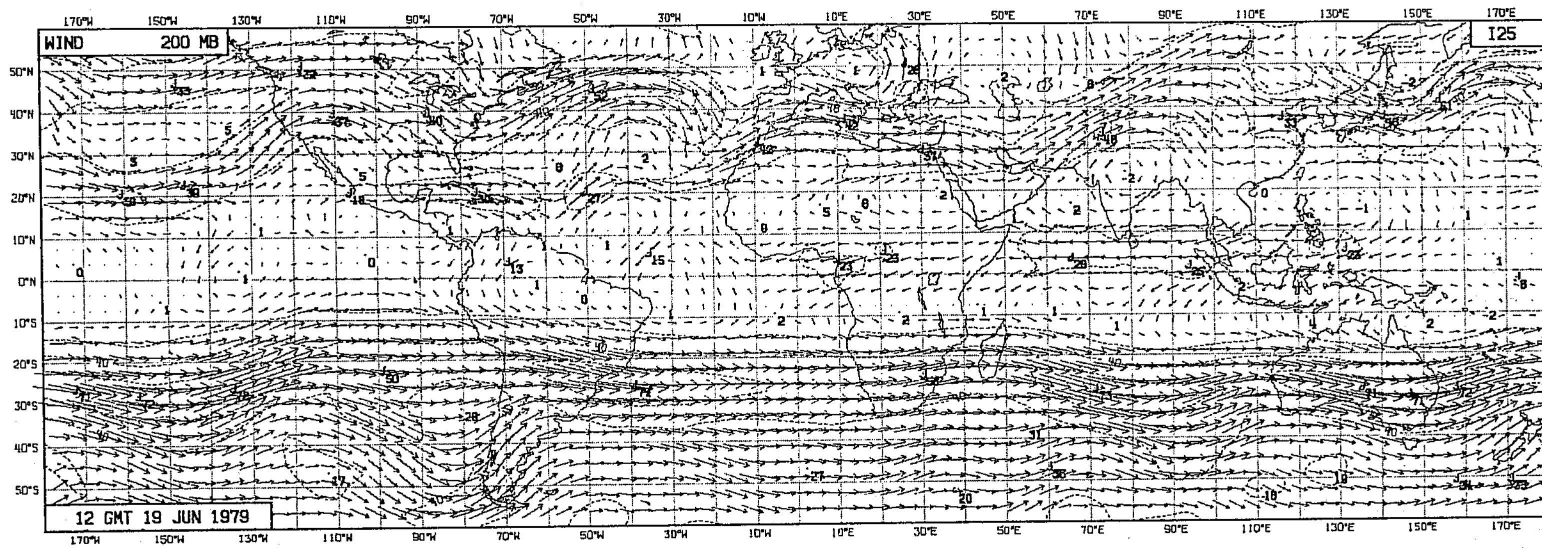

WIND 200 MB
I25
12 GMT 15 JUN 1979
WIND 850 MB
I25
12 GMT 15 JUN 1979

Fig. 8(b)


WIND
200 MB
I25
12 GMT 19 JUN 1979

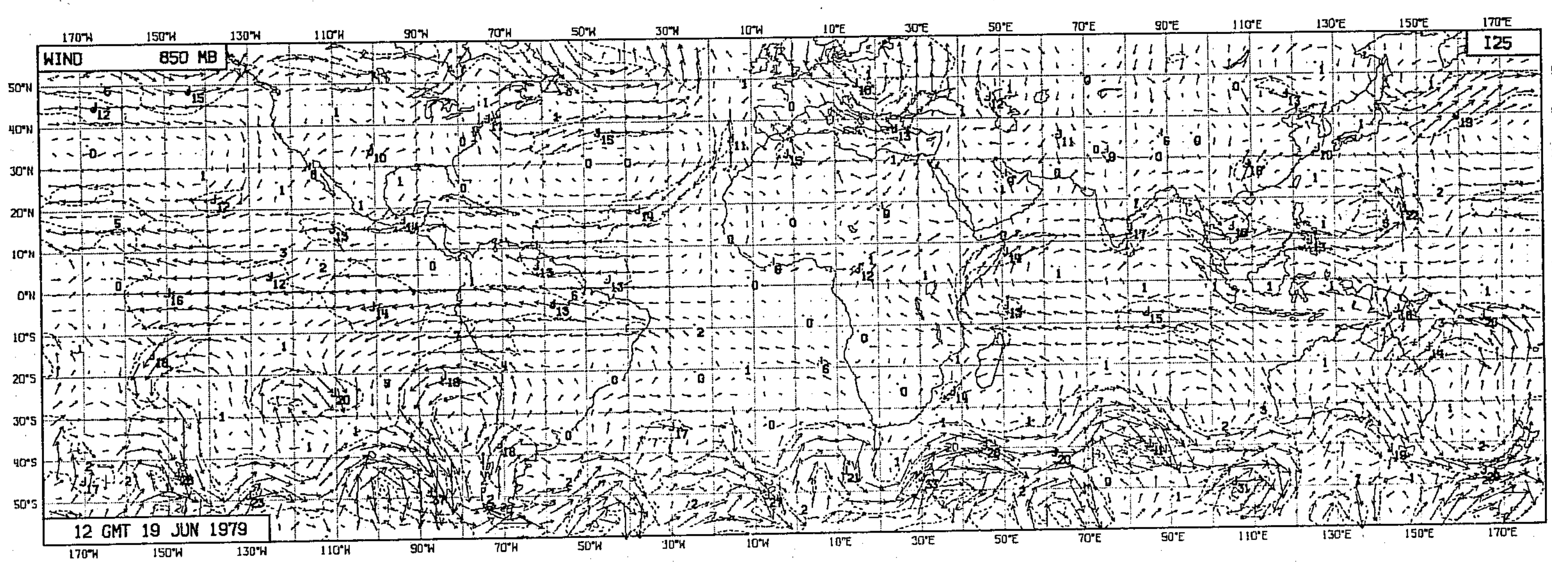

WIND
850 MB
I25
12 GMT 19 JUN 1979

Fig. 8(c)

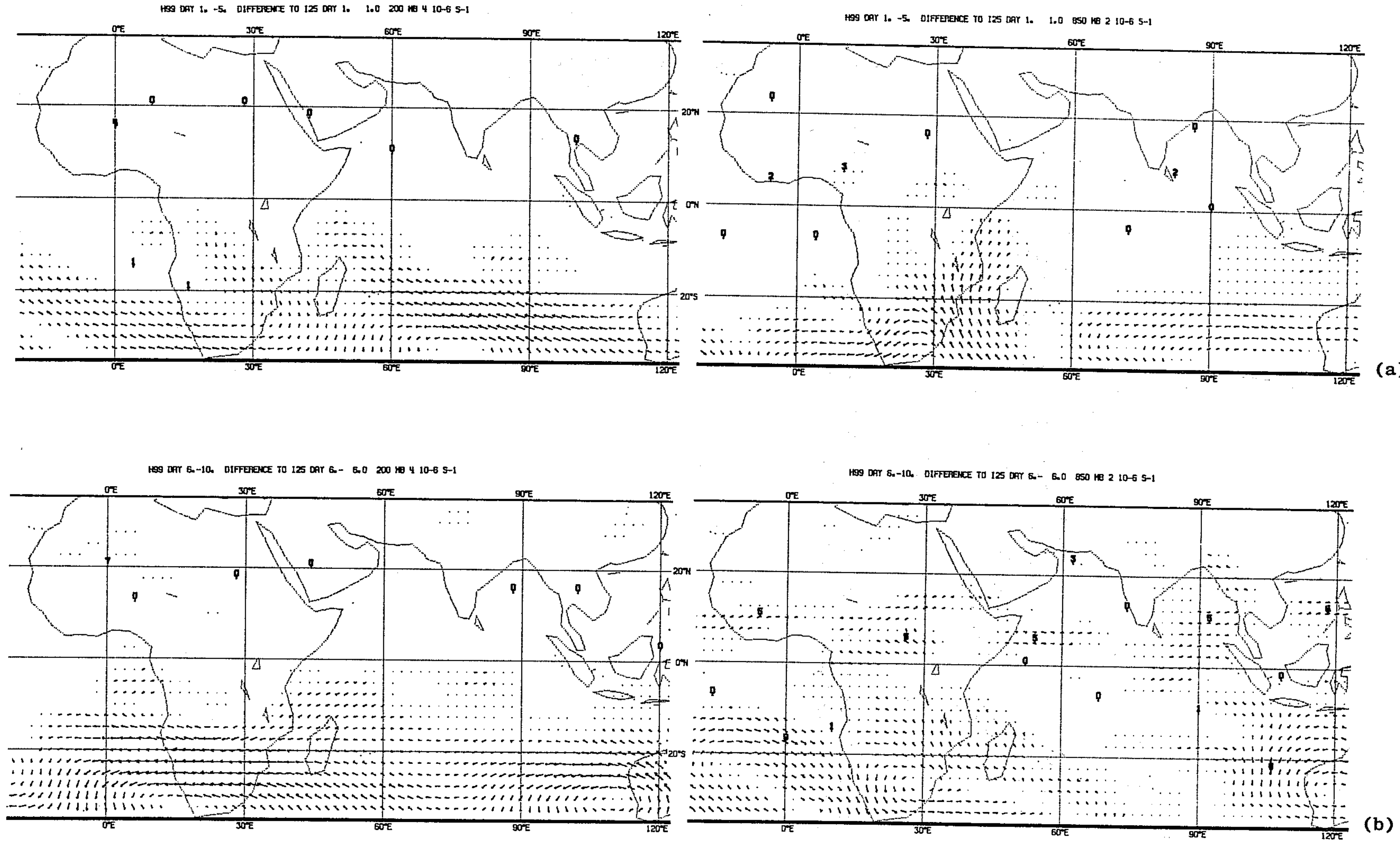


Fig. 9 Mean difference of wind vectors between exp.H99 and exp.I25 (a) for the first five days. (b) for the second five days.
Left: 200 mb; right: 850 mb.

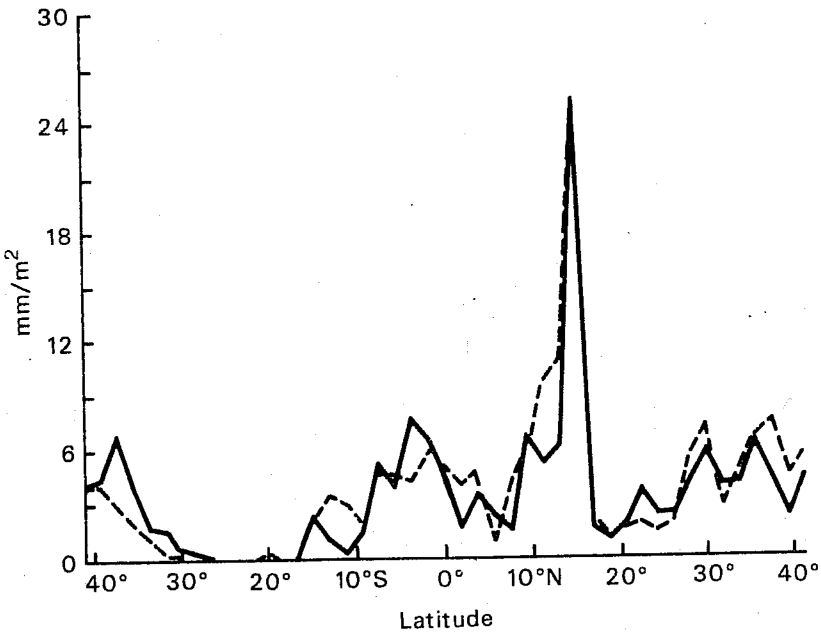


Fig. 10 Latitudinal distribution of daily rainfall averaged for 60^{o}–140^{o}E. Day 7. Solid line for Exp. I25. Dashed line for exp.H99.

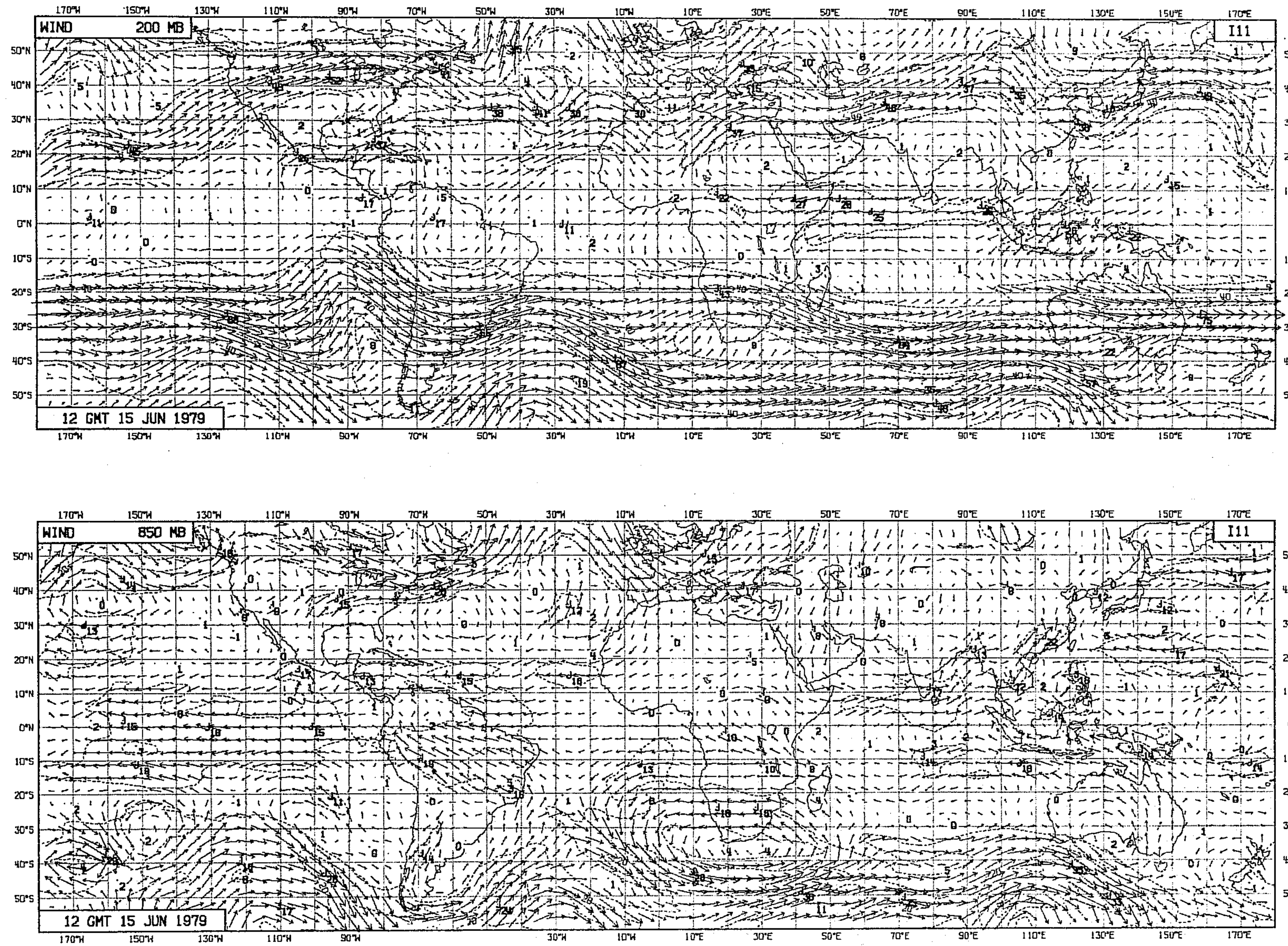


Fig. 11 As Fig. 1 but for exp.I11 (no African Highland). (a) day 4, (b) day 8.

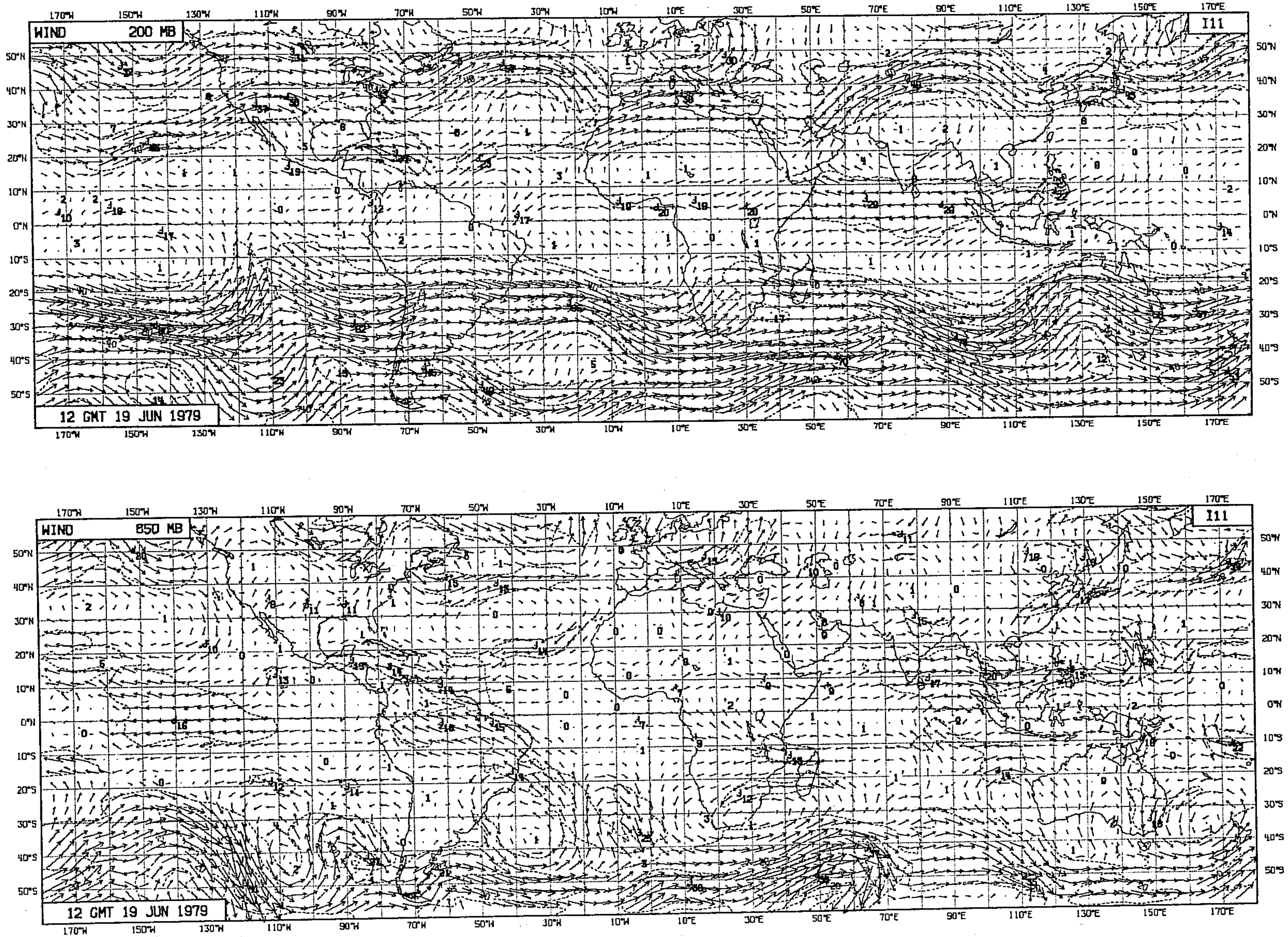

WIND 200 MB
I11
12 GMT 19 JUN 1979
WIND 850 MB
I11
12 GMT 19 JUN 1979

Fig. 11(b)

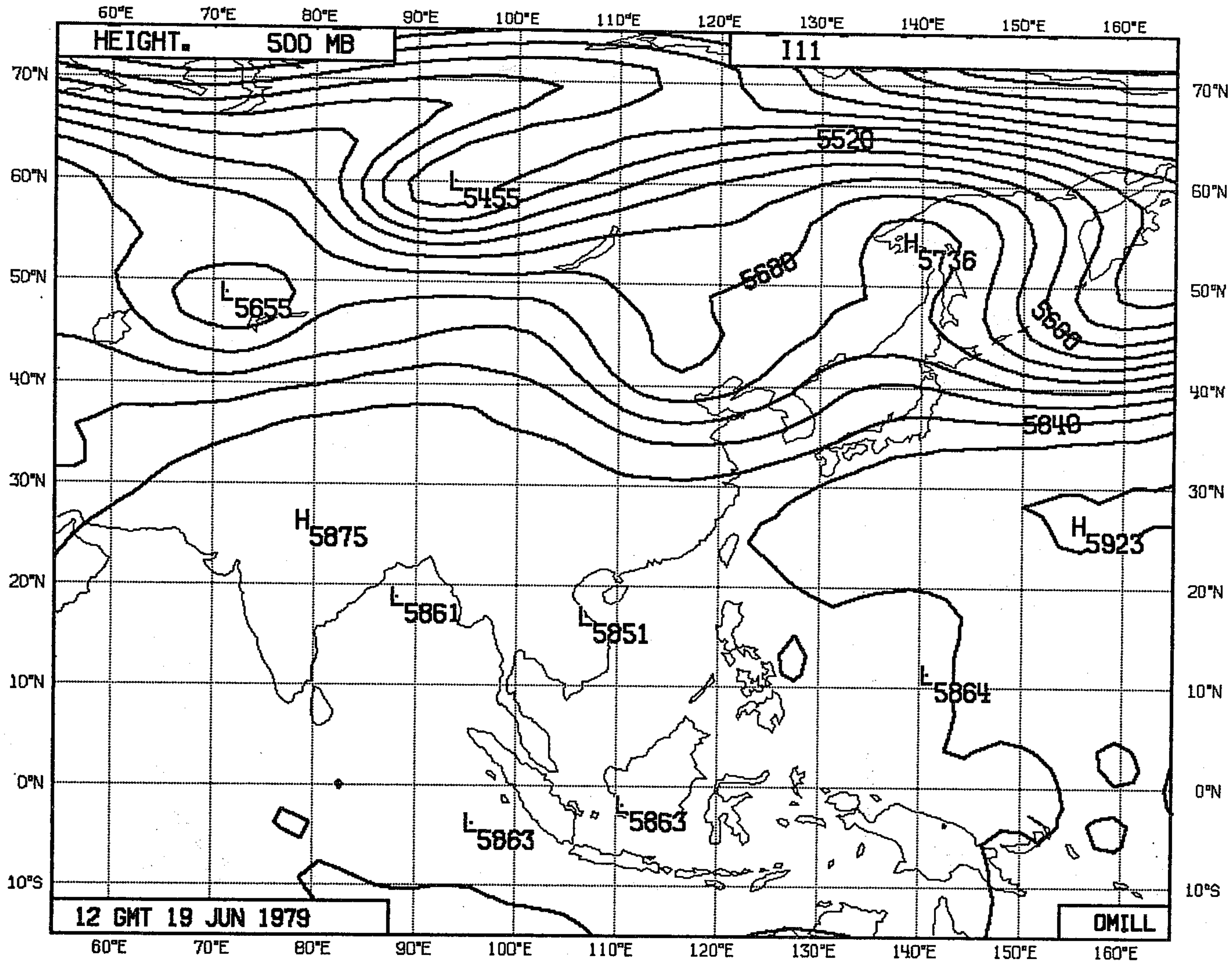
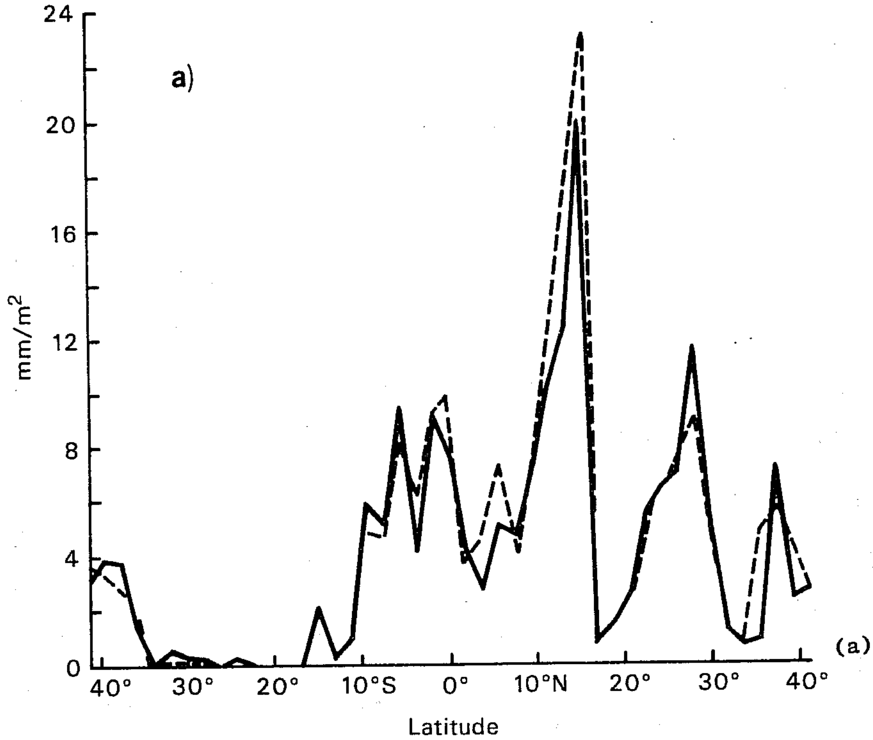


Fig. 12 As Fig. 4 but for exp.I11, day 8.



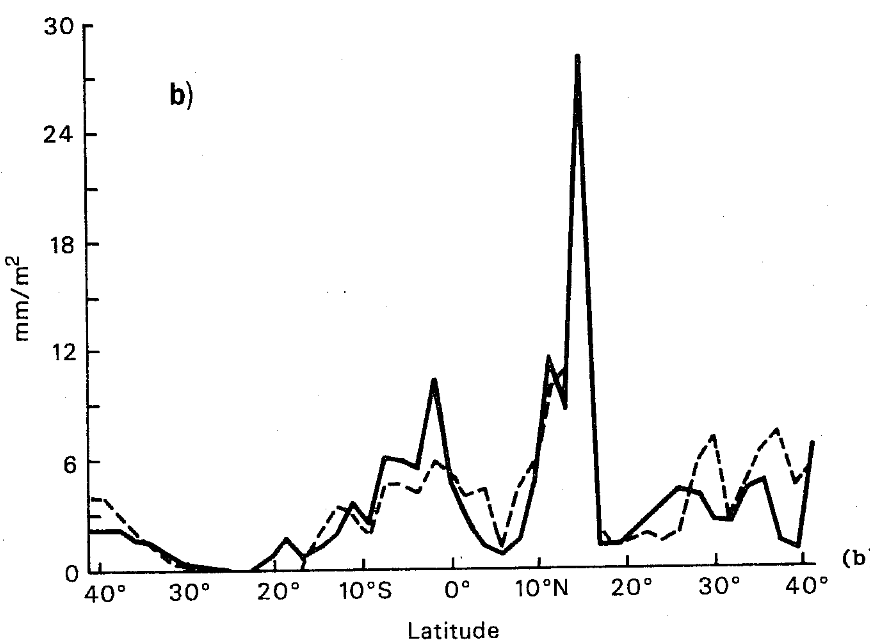


Fig. 13 As Fig. 10 but for exp.I11 (solid line) and exp.H99 (dashed line). (a) day 4, (b) day 7.

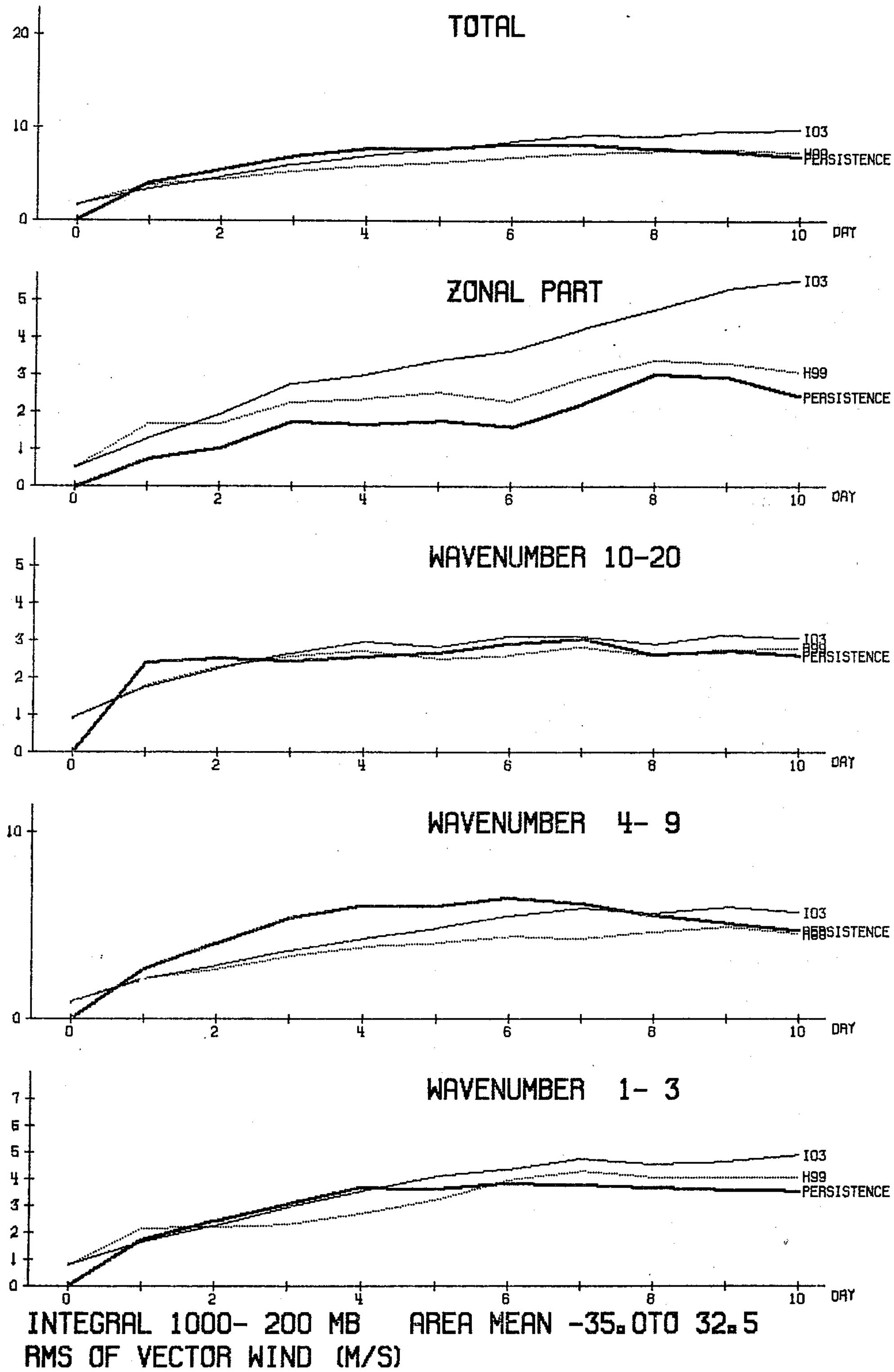
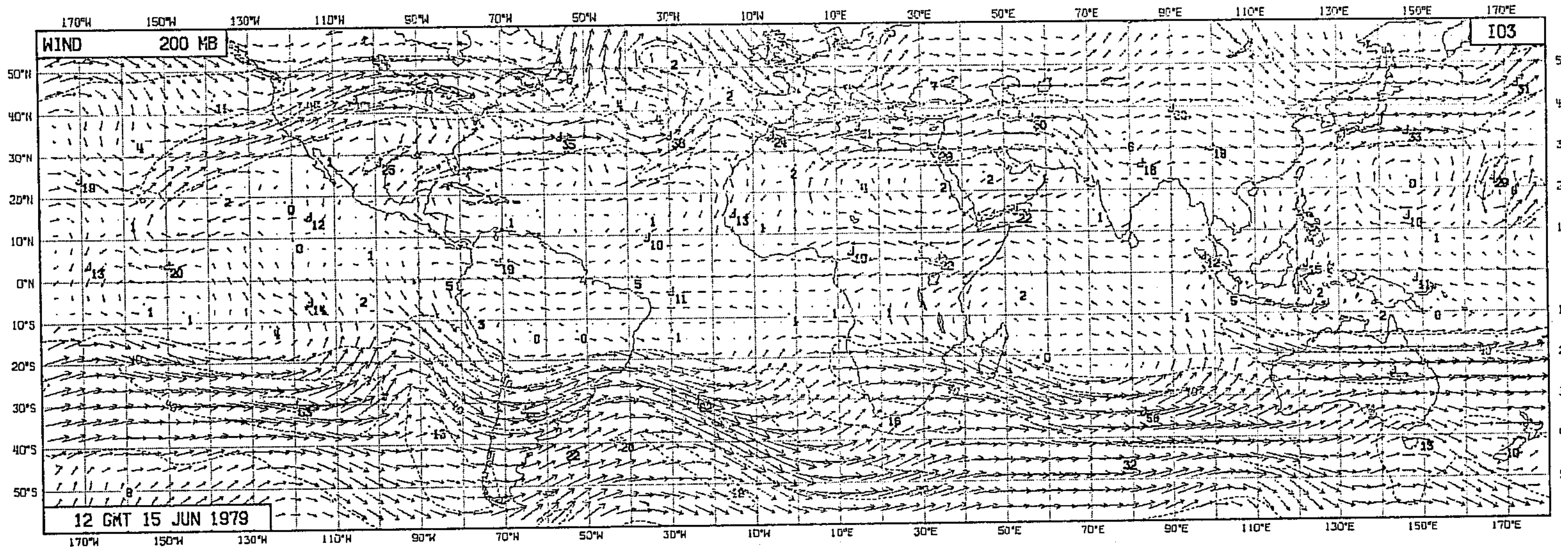


Fig. 14 RMS of vector wind for area of 35° S - 35°N. Thin solid line for exp.I03. Dotted line for exp.H99.



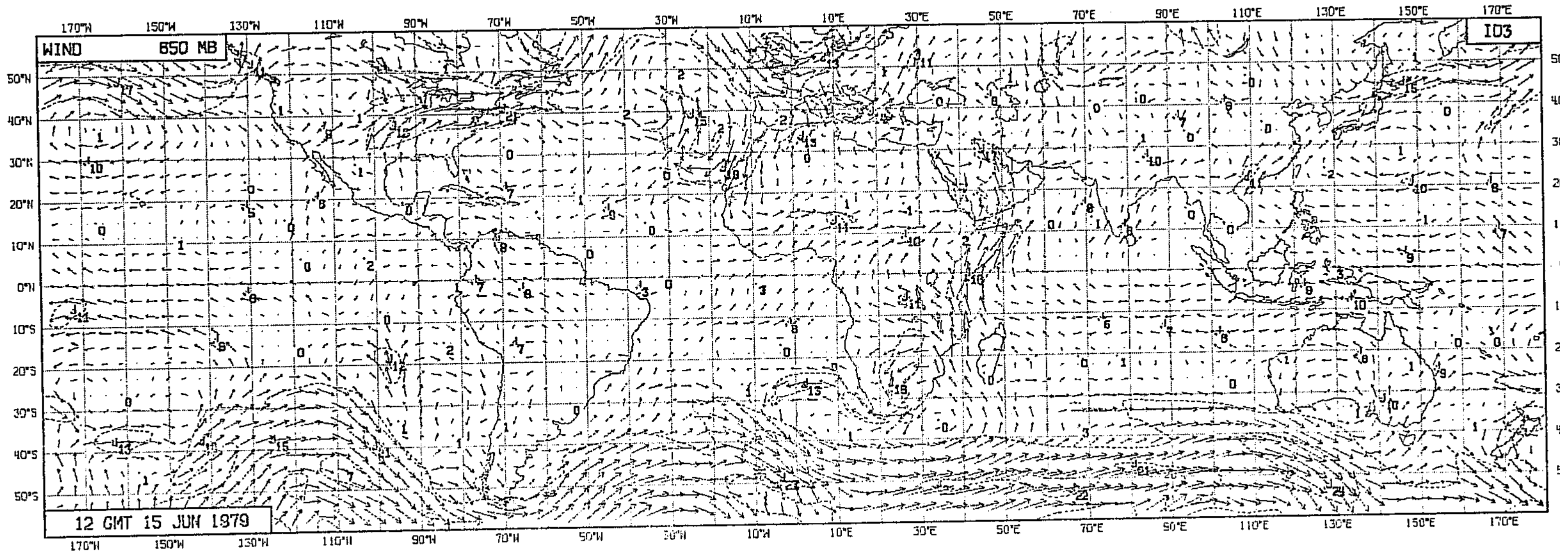


Fig. 15 As Fig. 1 but for exp. I03 (no condensation) (a) day 4, (b) day 8.

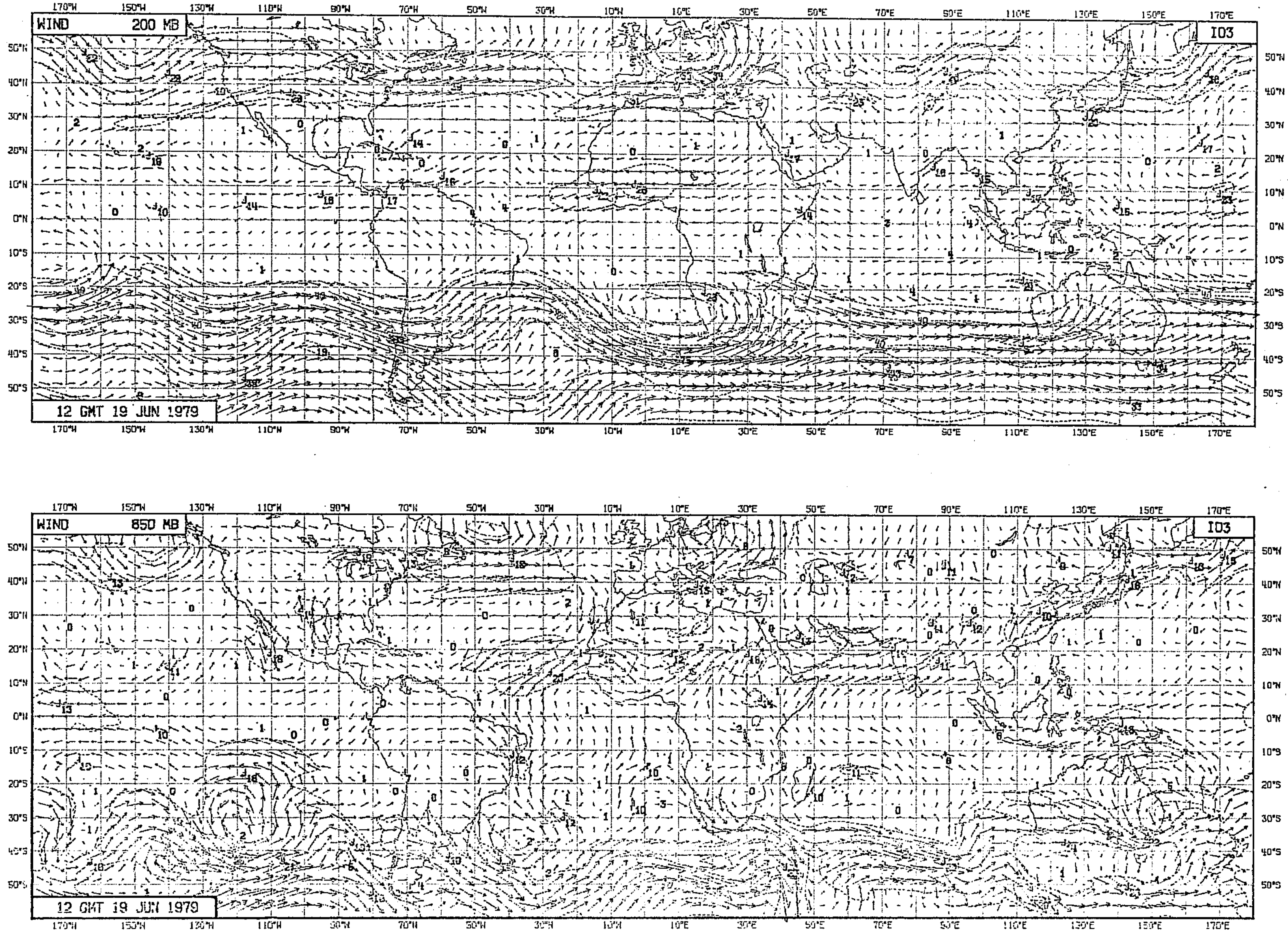

WIND 200 MB
I03
12 GMT 19 JUN 1979
WIND 850 MB
I03
12 GMT 19 JUN 1979

Fig. 15(b)

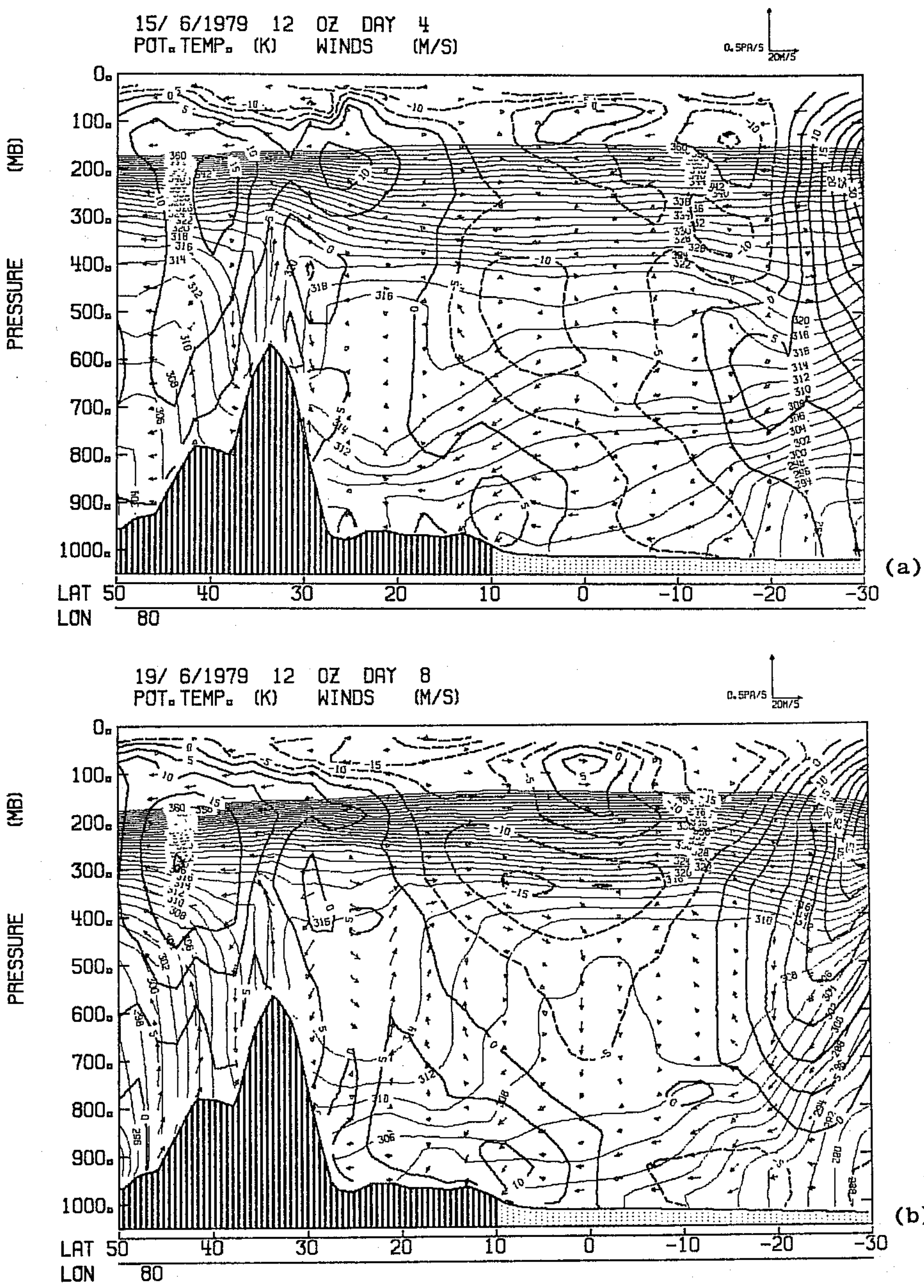
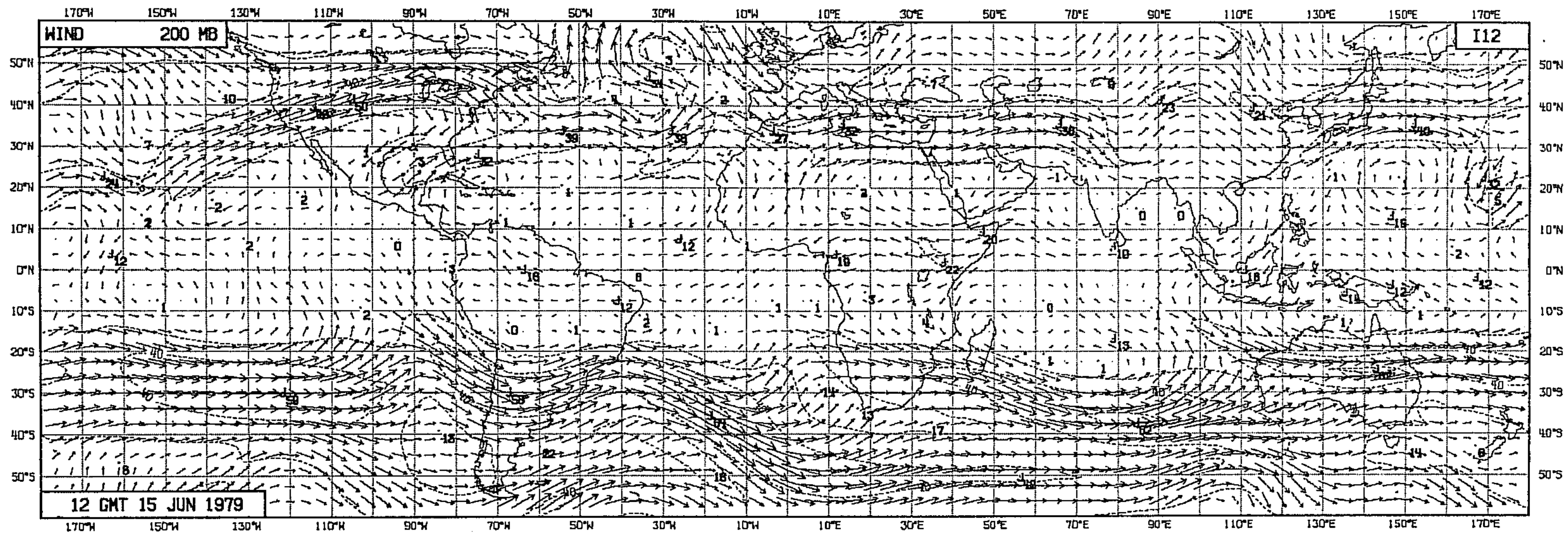


Fig. 16 Cross-section along 80°E as Fig. 3, but for exp. I03 (a) day 4, (b) day 8.



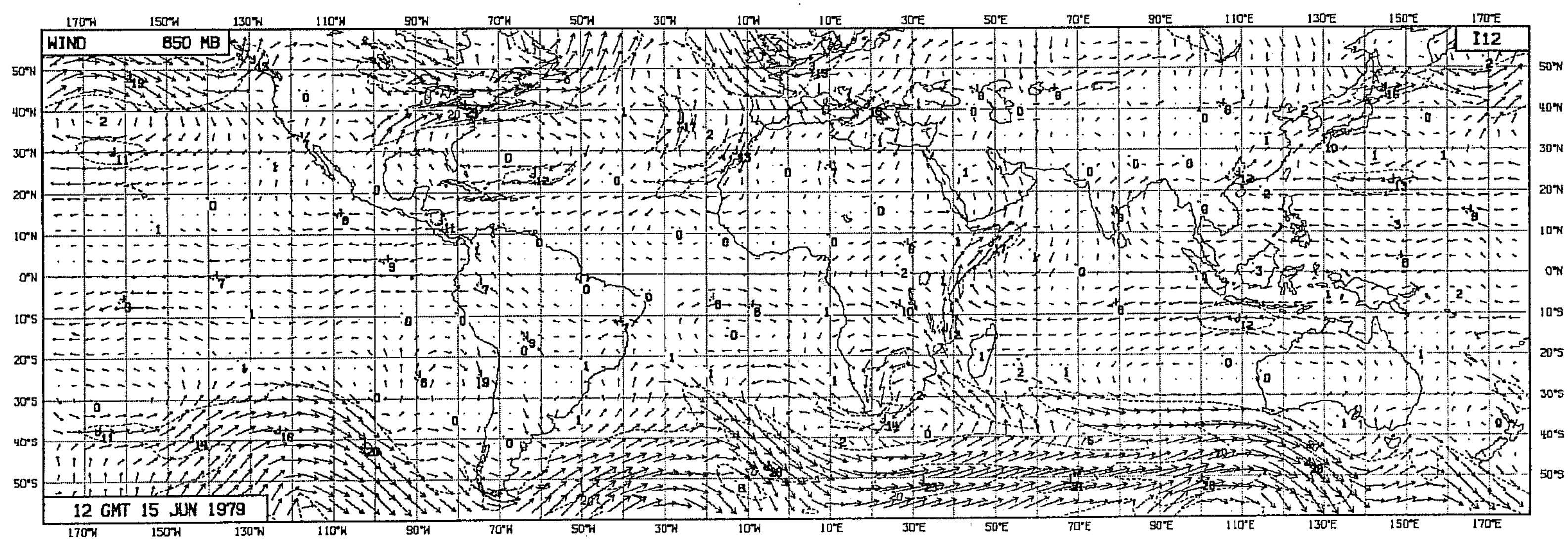
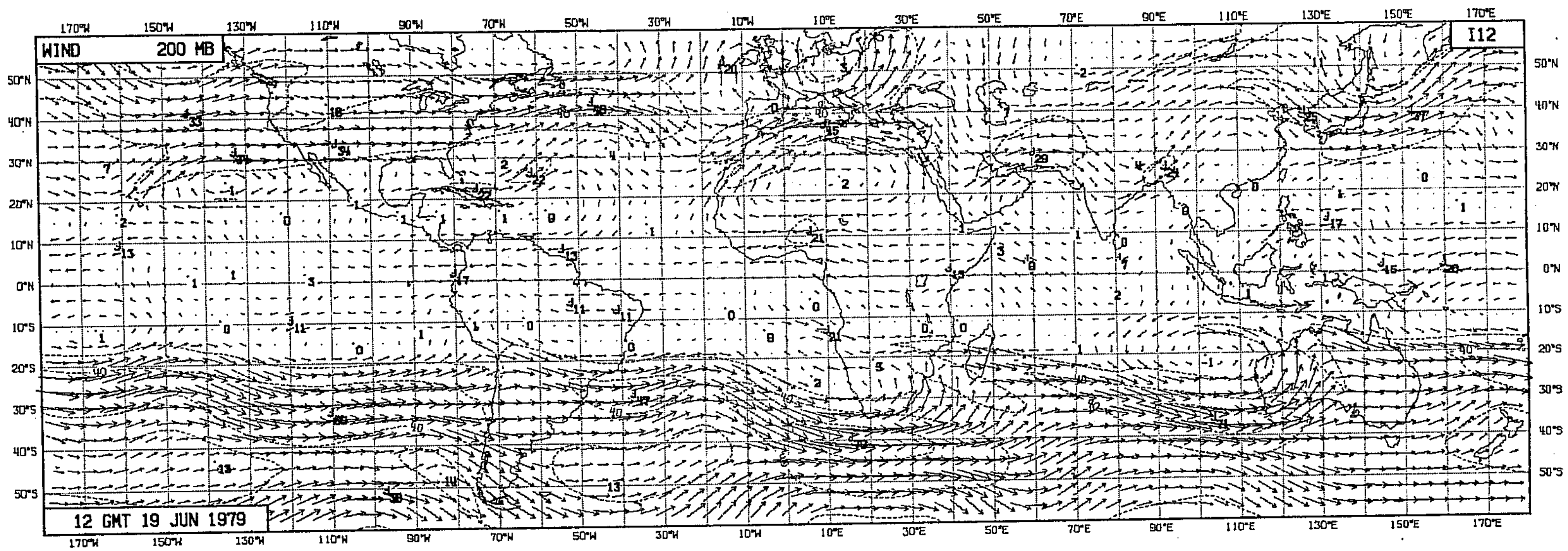


Fig. 17 As Fig. 1 but for exp.II2 (adiabatic run). (a) day 4, (b) day 8.


WIND 200 MB
I12
12 GMT 19 JUN 1979

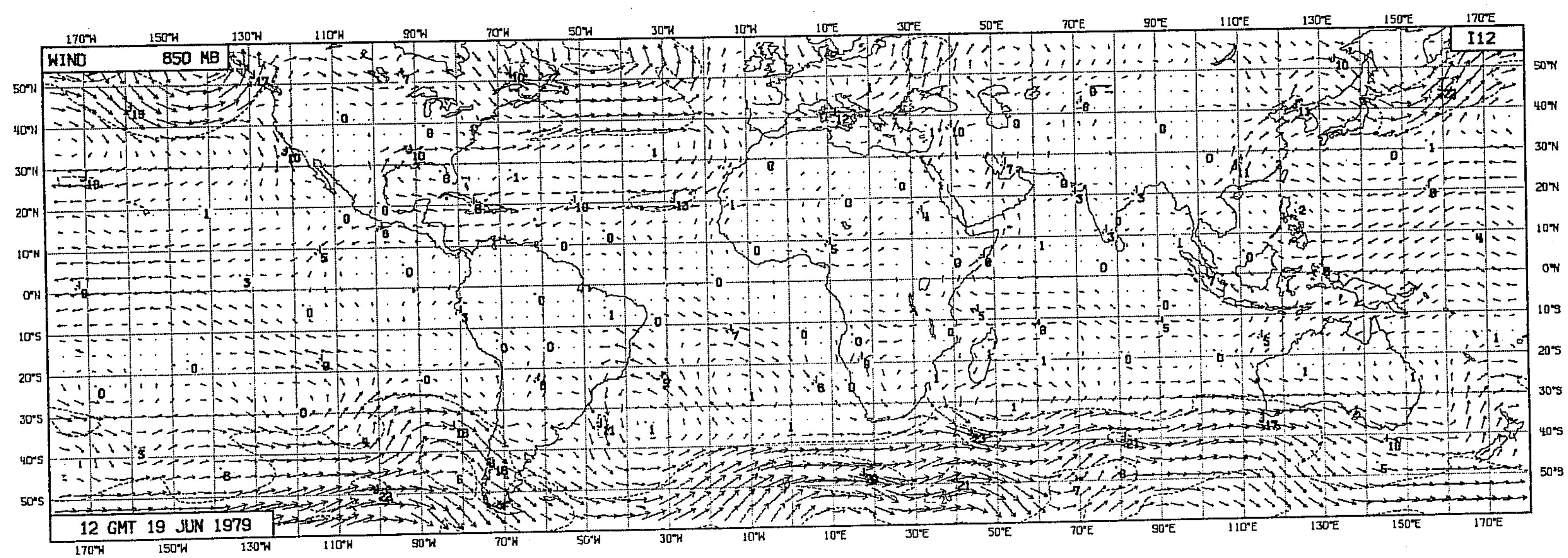

WIND 850 MB
I12
12 GMT 19 JUN 1979

Fig. 17(b)

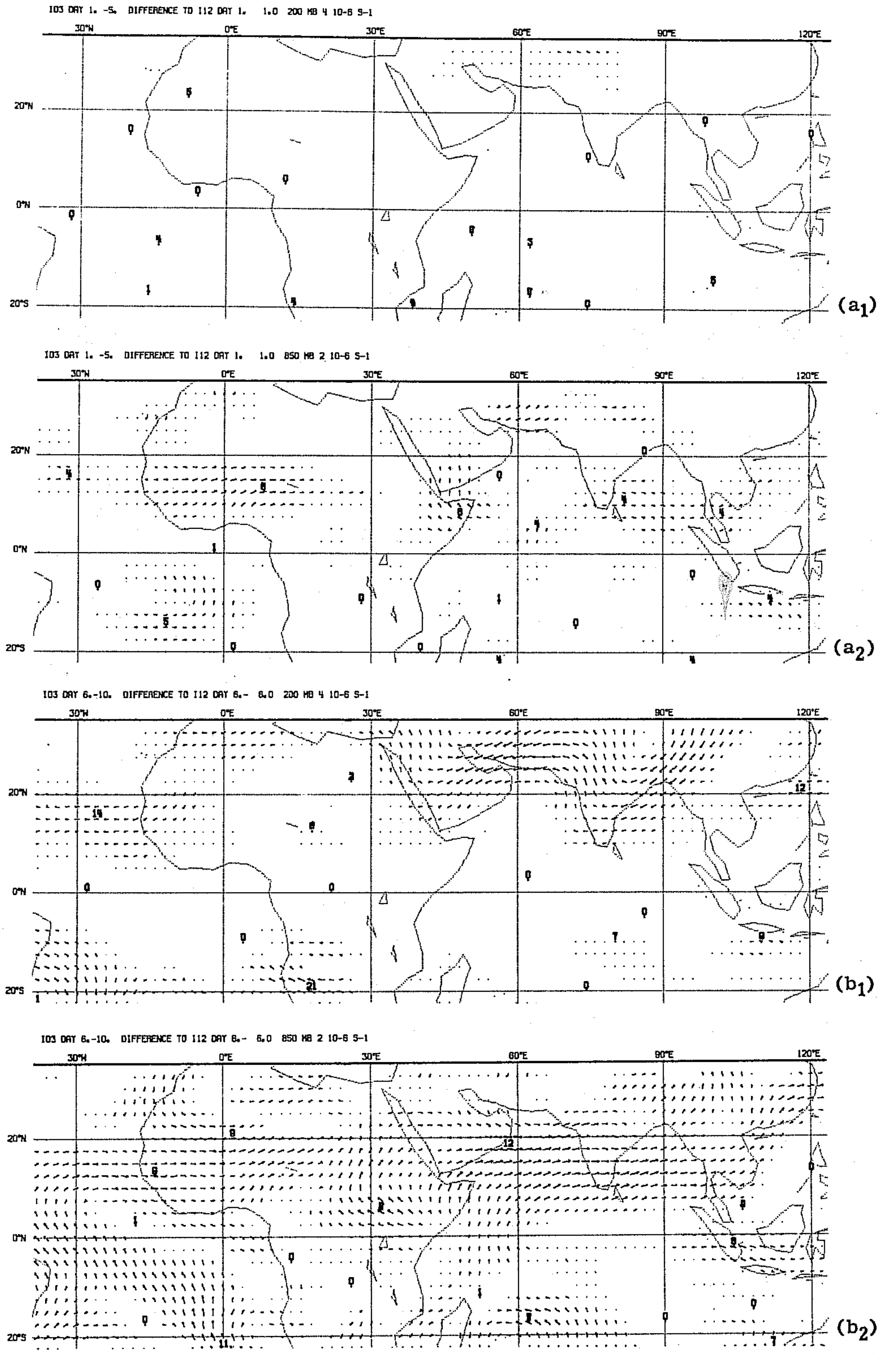


Fig. 18 Mean difference of wind vectors between exp.I03 and exp.II2 (a) for the first five days. (b) for the second five days.
Top: 200 mb; bottom: 850 mb.

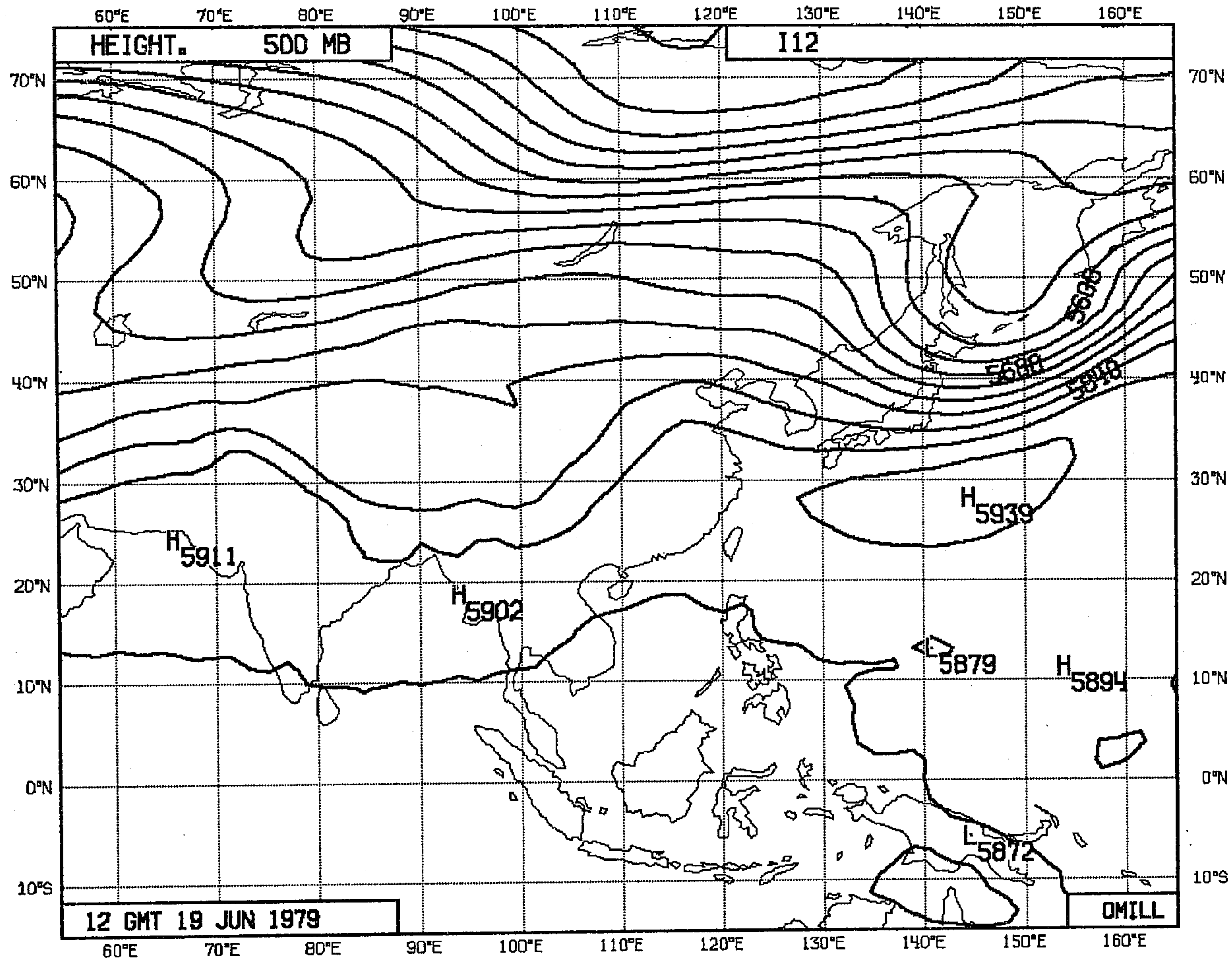


Fig. 19 As Fig. 4, but for exp.II2, day 8.

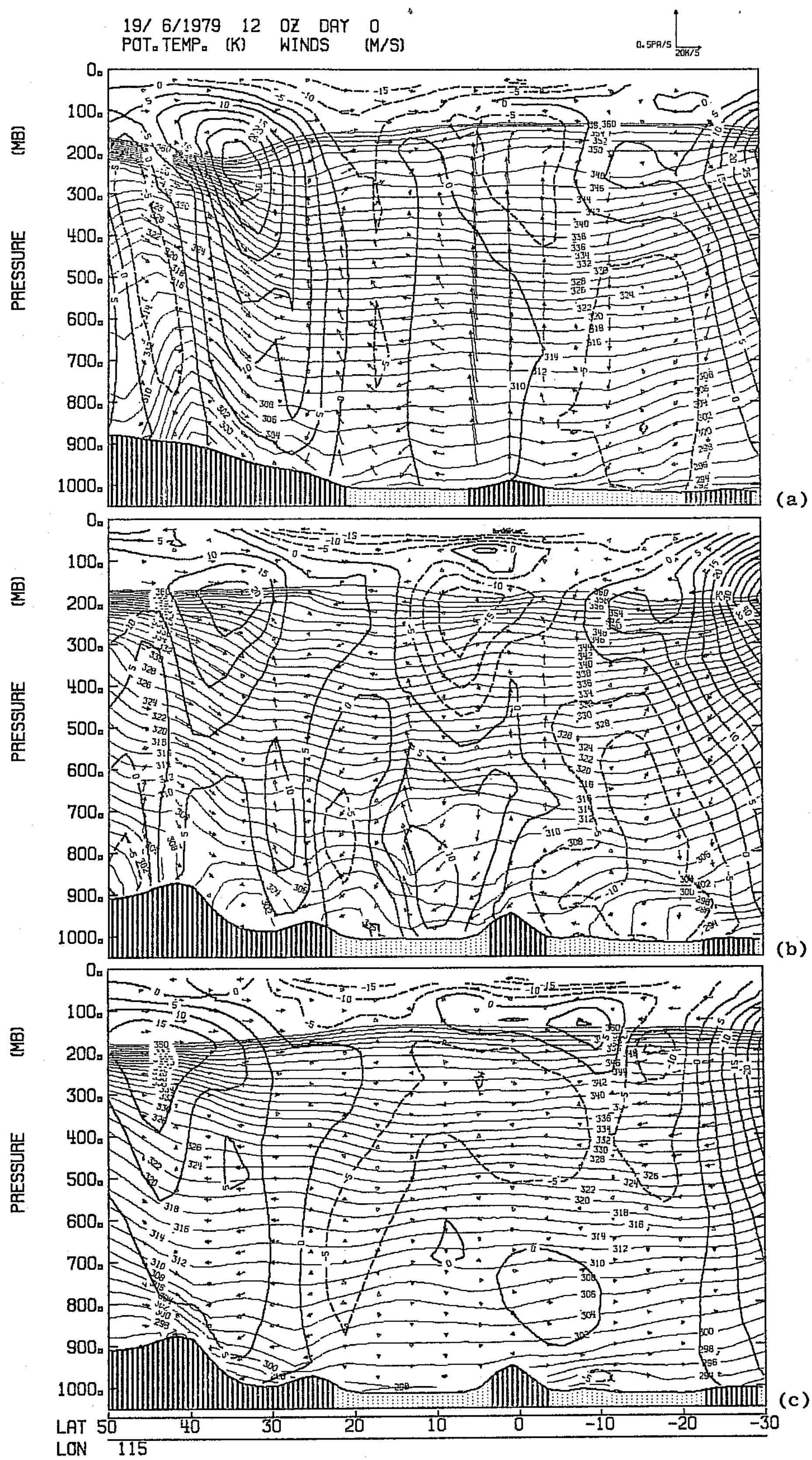


Fig. 20 Cross-section along II5^{O}E for day 8. (a) FGGE analysis, (b) exp.H99 (c) exp.II2.

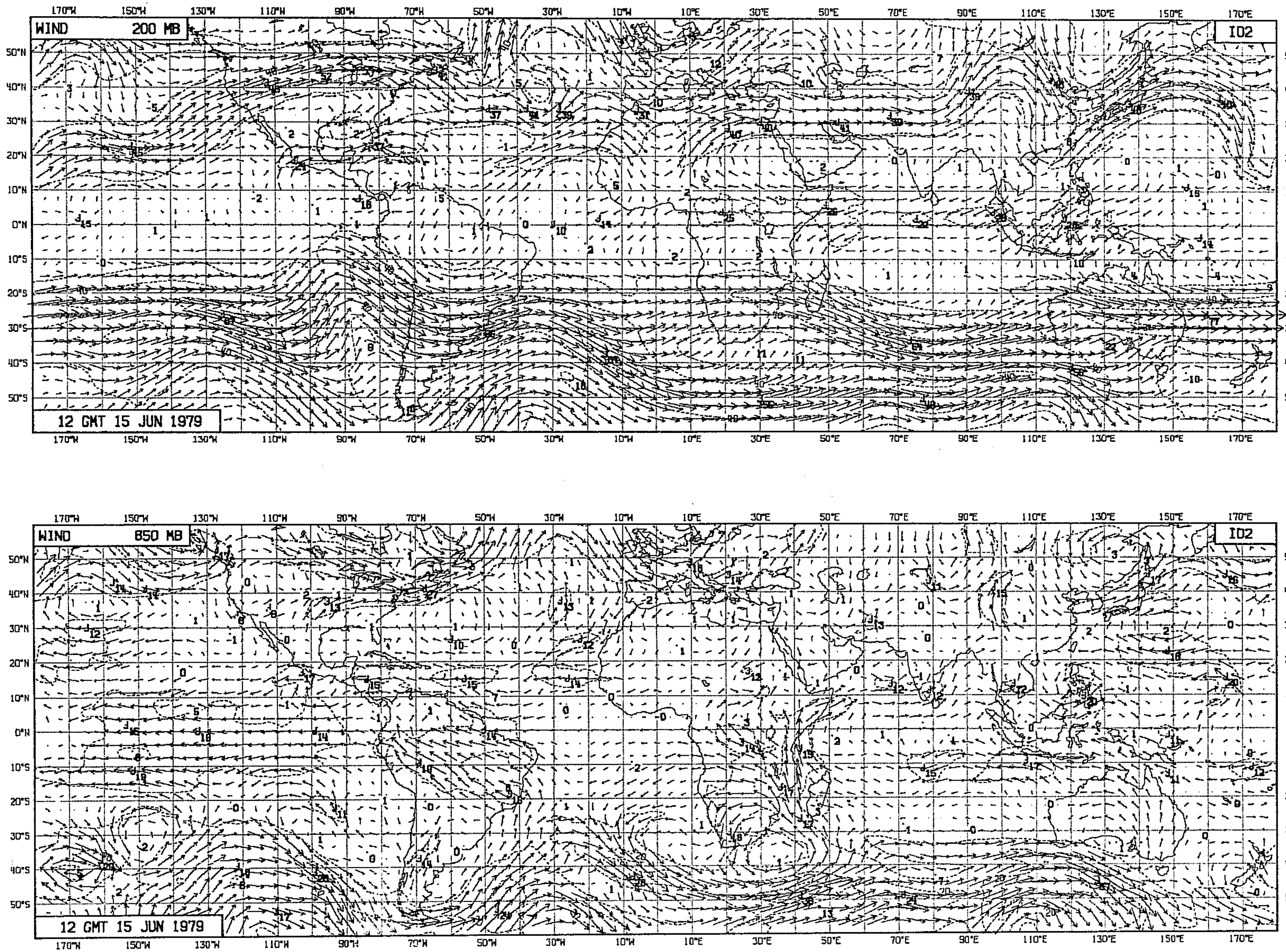


Fig. 21 As Fig. 1 but for exp.I02 (No Tibet run). (a) day 4, (b) day 8.

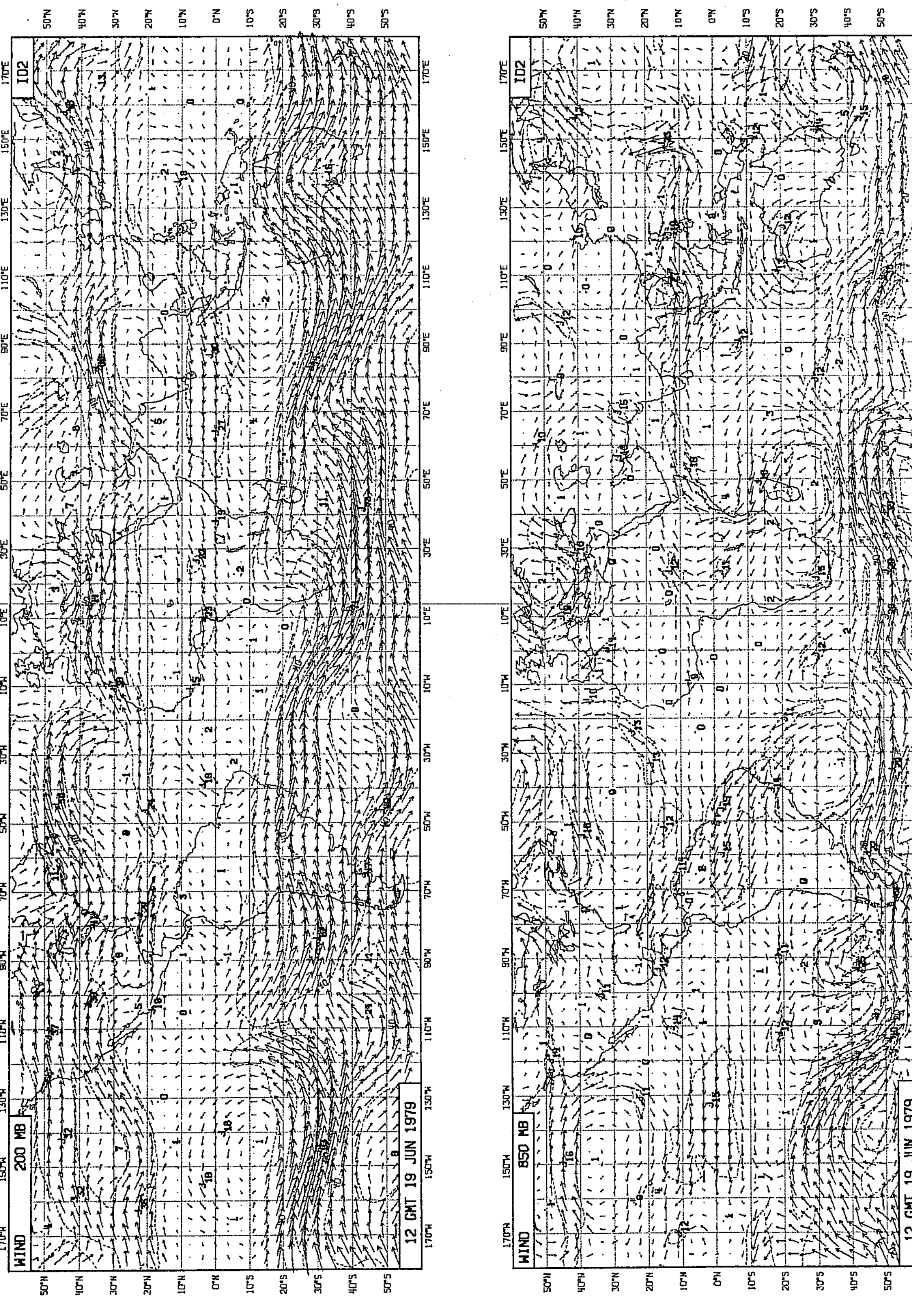

WIND 200 MB
ID2
12 GMT 19 JUN 1979
WIND 850 MB
ID2
12 GMT 19 JUN 1979

Fig. 21(b)

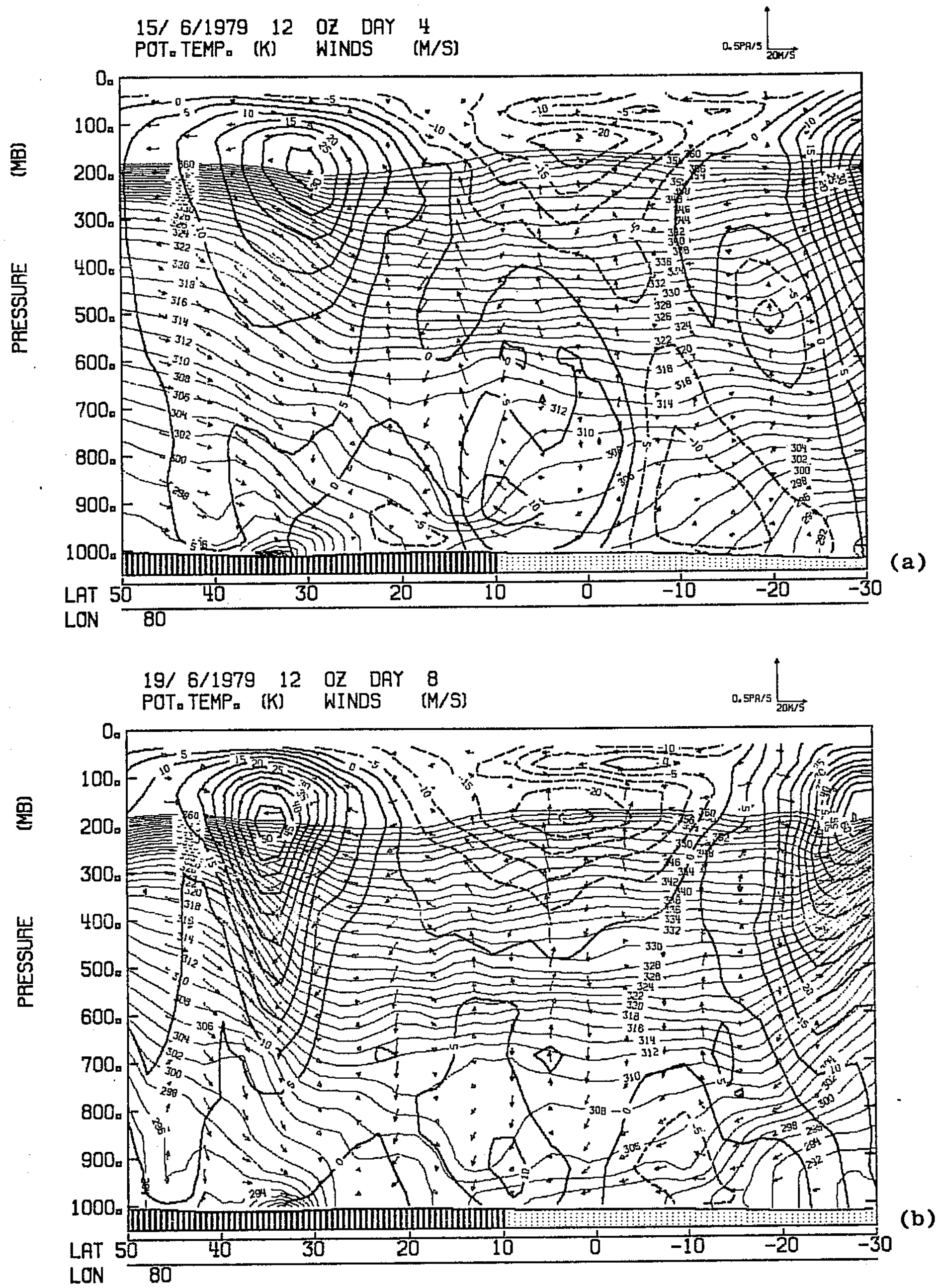


Fig. 22 As Fig. 3 but for exp.I02. (a) day 4, (b) day 8.

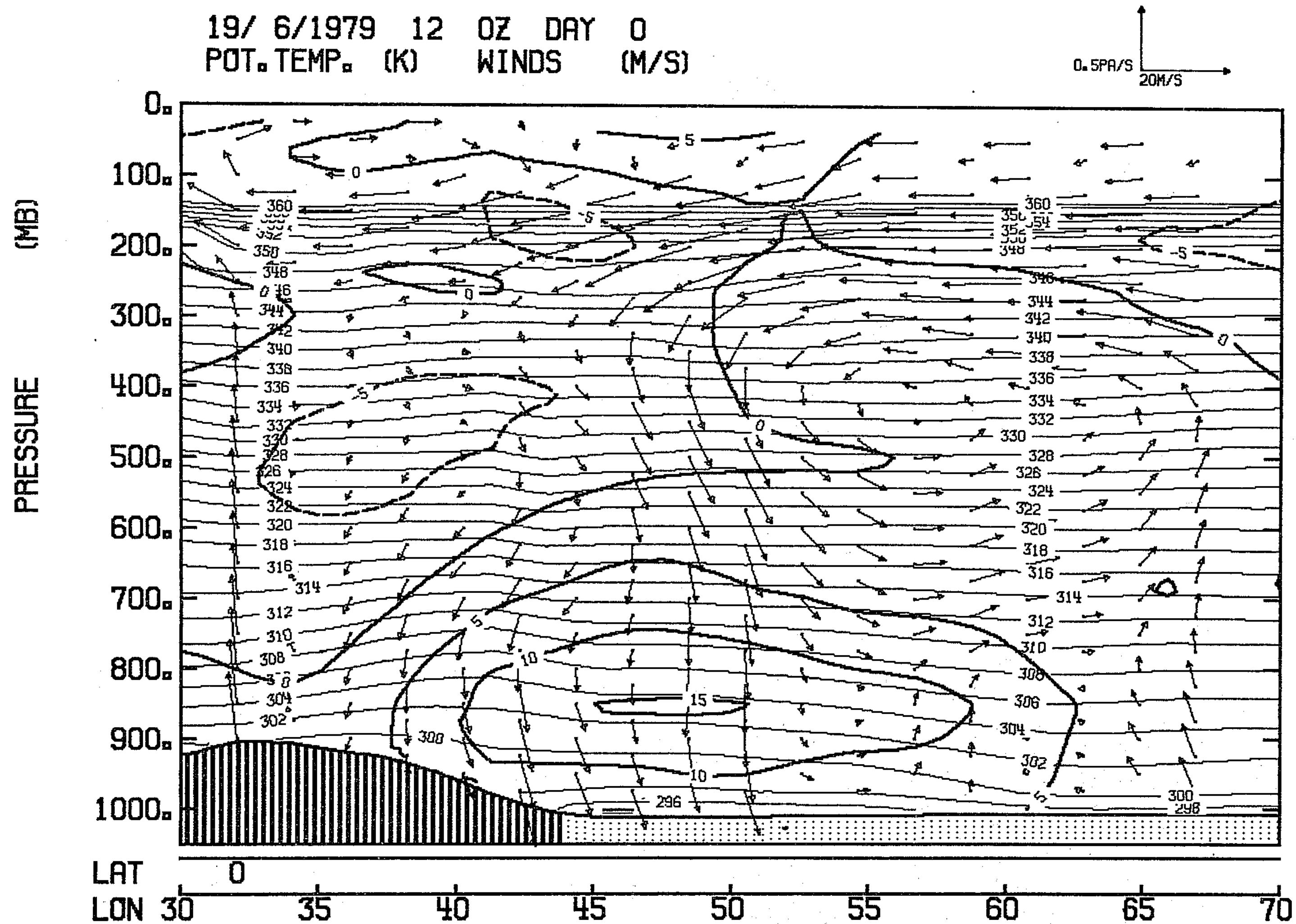


Fig. 23 Cross-section along the equator for FGGE analysis for day 8.

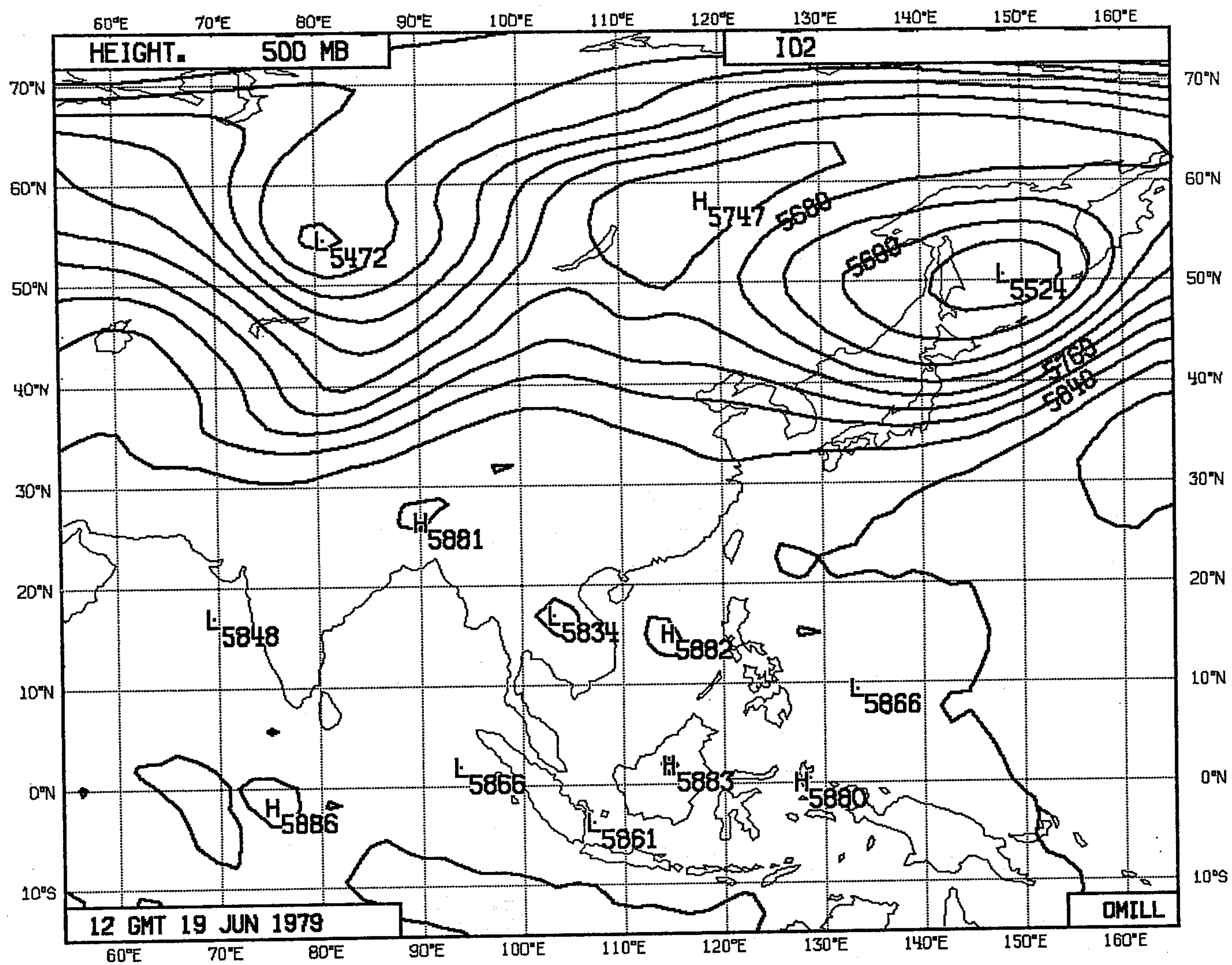


Fig. 24 As Fig. 4 but for exp. 102 day 8.

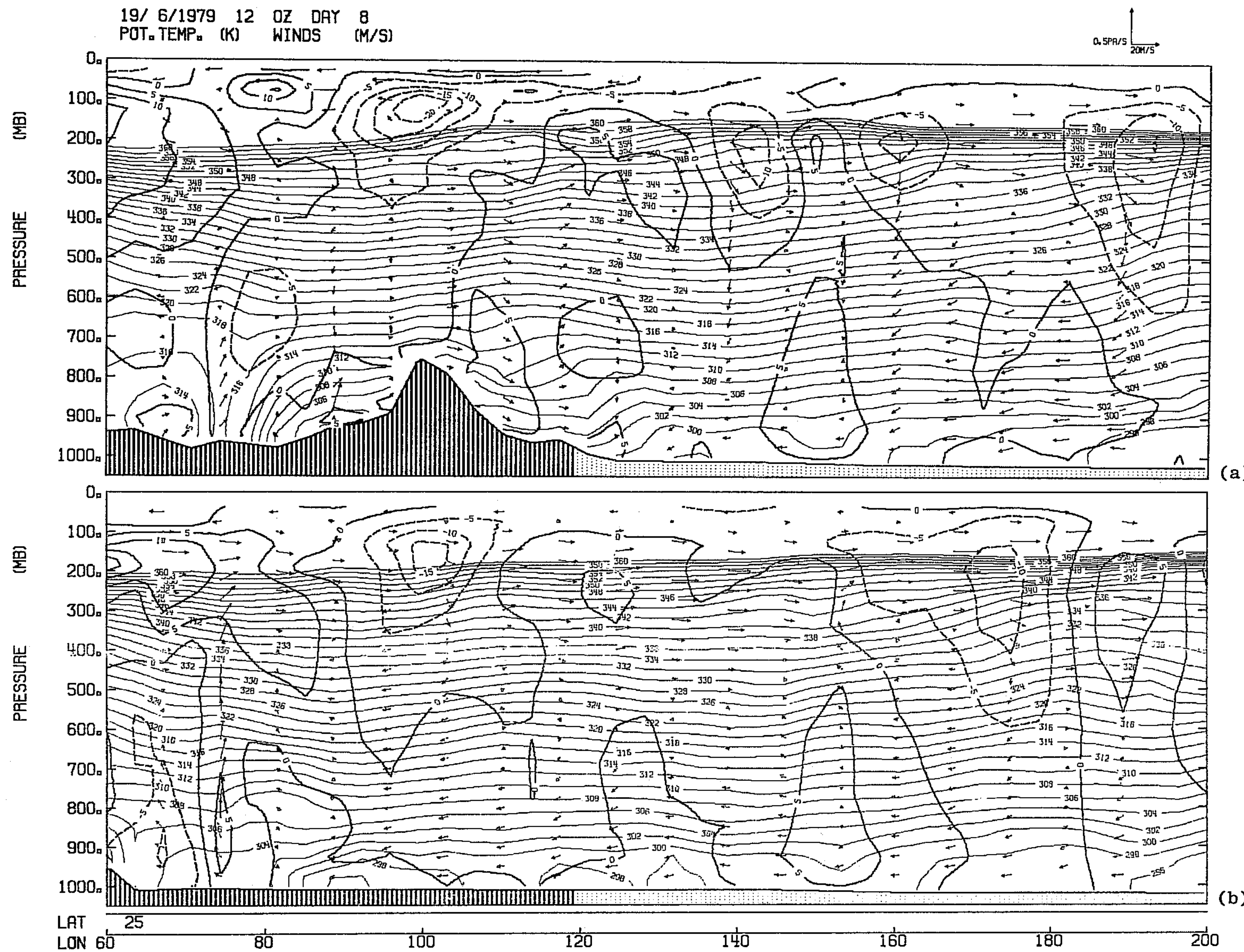


Fig. 25 Cross-section along 25^{O}N for day 8. (a) exp.H99, (b) exp.I02.

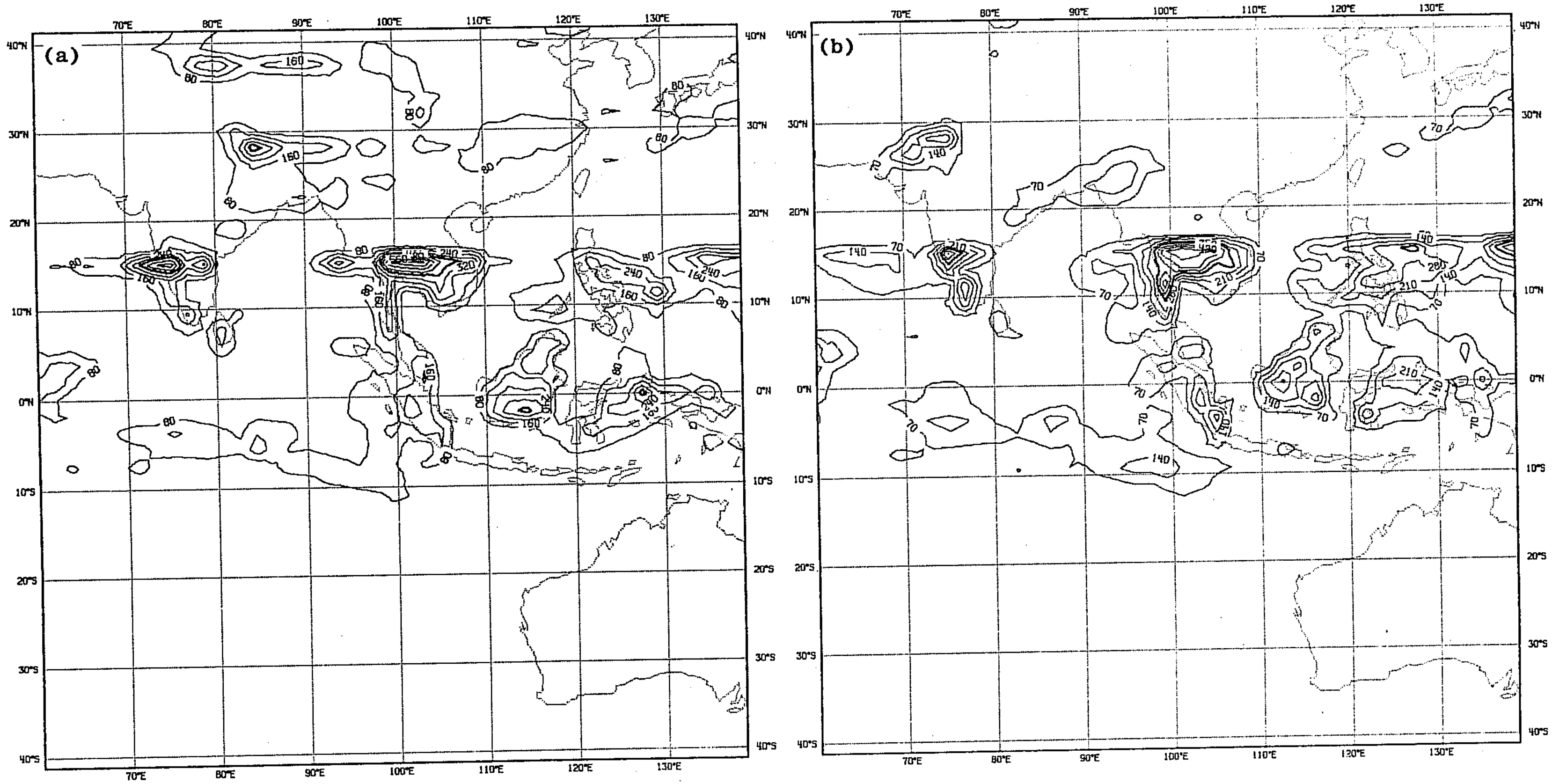


Fig. 26 Ten days accumulated total rainfall distribution. (a) exp.H99. (b) exp.I02