Mausam, (1987), **38**, 4, 425-430

551.557 : 551.553.21

Strengthening of extra-tropical westerlies and formation of new wind maxima at 200 hPa over Indian region during winter and pre-monsoon seasons

RANJIT SINGH

Meteorological Office, Pune

(*Received 14 May 1985*)

सार — उष्णकटिबन्ध में तीव्र संवहन के व्यवस्थापन की प्रतिक्रिया स्वरूप इतर-उष्णकटिबन्धीय पछुवाएं साधारणतः शक्तिशाली हो जाती हैं। कोणीय संवेग की अविनाशिता की सहायता से इस शोधपत्र में प्रस्तुत एक केन्द्र के ऊपर 200 मिलीबार पर पछुवा पवन उच्चिष्ठ के बनने के चार मामलों को स्पष्ट किया गया है क्योंकि मेघ के शिखर से उत्पन्न होने वाली वायुधारा अपनी उत्तर दिशा की ओर गति के दौरान अतिरिक्त पछुवा संवेग प्राप्त कर लेती है। इस वायु धारा के केन्द्र के ऊपर पक्षाभ मेघ के बाहर की ओर उड़ती हुई निरन्तरता द्वारा पहिचाना गया है। ऐसे मामलों में पछुवाएं भूमध्यीय क्षेत्र में गहराई तक बढ़ी रहती है और भारतीय क्षेत्र के ऊपर मुख्य उप-उष्णकटिबन्धीय जेट धारा के दक्षिण में एक दोहरी जेट धारा प्रकट होती है। इसके अतिरिक्त उसी शक्ति के प्रभाव में दिन के दौरान की अपेक्षा रात के दौरान पछुवाओं के अधिक तेज होने की सम्भावनाएं रहती हैं।

इस अध्ययन के करने से यह देखा गया है कि अरब सागर के ऊपर उष्णकटिबन्धीय द्रोणिका में संवहन की तीव्रता की प्रतिक्रिया स्वरूप 80° पू० देशान्तर के पश्चिम में भारतीय क्षेत्र के ऊपर पछुवाएं अधिक शक्तिशाली हो जाती हैं।

ABSTRACT. There is a general strengthening of the extra-tropical westerlies in response to the organisation of strong convection in tropics. In the four case studies presented the formation of westerly wind maxima over a station at 200 hPa has been explained with the help of conservation of angular momentum when an air stream emerging from the top of the cloud acquires an additional westerly momentum during its northward motion. The air stream was identified by the continuity of outflowing cirrus cloud over the station. In such cases the westerlies extend deep into equatorial region and a double jet stream appears south of the main sub-tropical jet stream over Indian region. Further, westerlies are likely to be stronger during nights than during day time under the same forcing.

The study conducted has shown that westerlies over the Indian region west of 80 deg. E strengthen in response to the intensification of convection in the equatorial trough over Arabian Sea.

1. Introduction

The occasional relative strengthening of the extra-tropical westerly jet stream over eastern Asia during winter has been statistically linked with the active north-easterly monsoon over Indonesia-south Malaysian region by Chang and Lau 1982 (Krishnamurti 1979). However, occasional strengthening of westerly jet stream during winter over Indian region west of 80°E and the formation of new embedded jet maxima still need explanation.

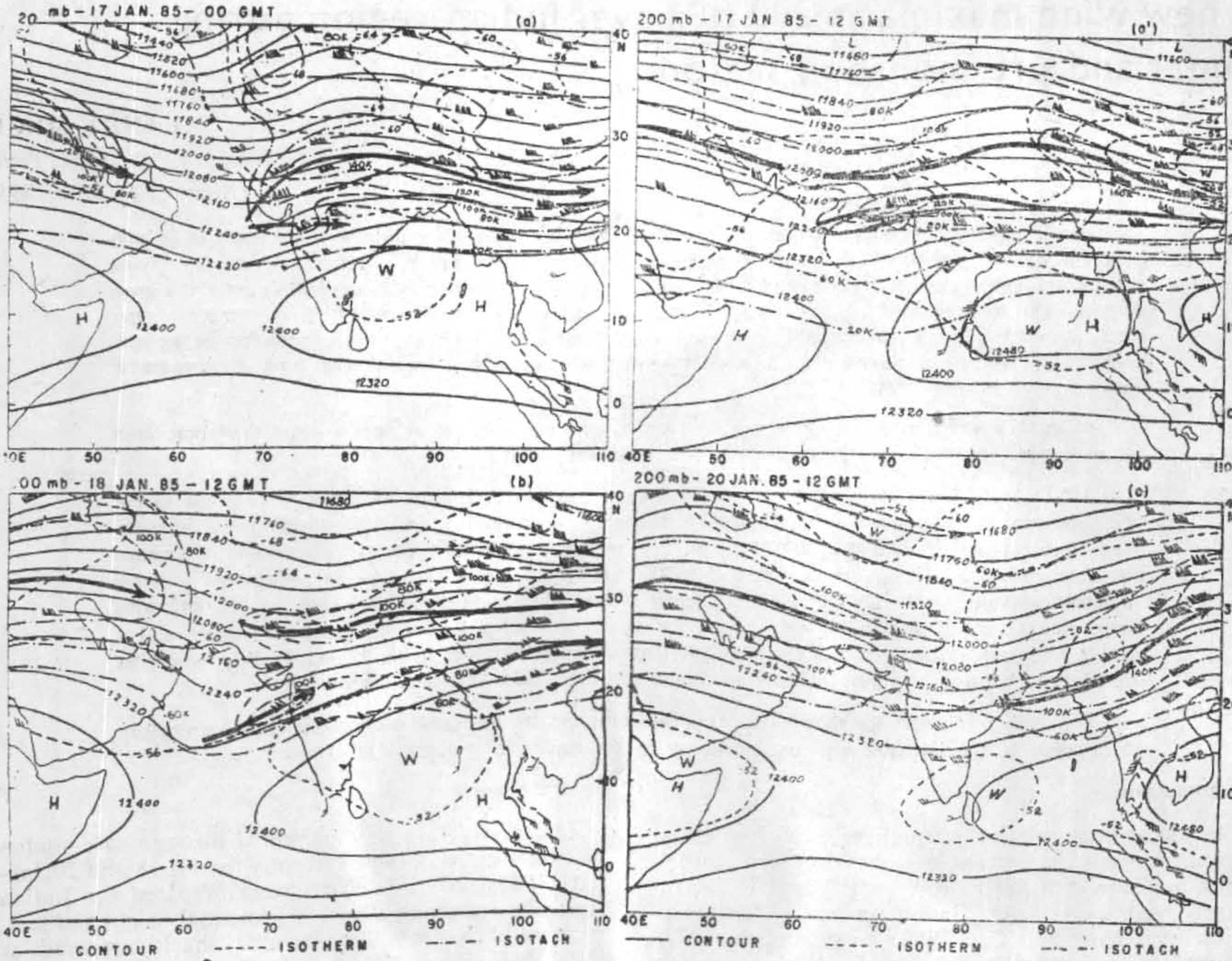
It is an observational fact that during winter, whenever an upper tropospheric westerly trough moves over India, winds strengthen over Indian stations in the forward sector of this trough due to the south-north temperature gradient (thermal wind effect). In the present paper an attempt is made to demonstrate that these westerly troughs extend southward and the jet maxima form due to an outflow in the northeast sectors of convective systems that form over the equatorial trough in the *Arabian Sea*.

2. Data source

The results have been presented through case studies of observations obtained recently for 17, 18 and 20 January 1985. 200 hPa charts were prepared for Indian region by extracting winds, geopotential height and temperature data from the extended charts prepared at INOSHAC, Pune. NOAA-9 day time satellite VIS and IR pictures were referred for the equatorial cloudiness and the cirrus outflow. In addition the atlas containing GOES-1 satellite derived winds and TIROS-N imageries for day and night prepared by Young *et al.* (1980), is consulted and occasional strengthening of westerlies east of 90° E is linked with the enhanced convective activity in Indian seas.

3. Equatorial cloudiness and the conservation of angular momentum

In January the northern hemispheric equatorial trough lies between the equator and 5°N. The tropical cloud systems mainly develop in this trough on cloud cluster



Figs. 1(a, a[1], b, c). Constant pressure charts, (a) depicts the Aurangabad wind : 120 kt, (a[1]) Ahmedabad wind : 130 kt, (b) Bombay wind : 110 kt and (c) Trivandrum wind : 26 kt coinciding with the outflow cirrus clouds scale. The trough is first activated in the region of Indonesian and Malaysian islands. This is likely to be (i) due to the effect of land sea differential heating and land sea breeze effect, (ii) advance of cold air from China around the Siberian winter high, over the equatorial warm sea waters of the region which results in the destabilisation of atmosphere there. The build up of convection over Indonesian and Malaysian islands is of quasi-stationary nature during winter. Whenever this region is active, cloud clusters occur along most parts of the equatorial troughs in the two hemispheres, westward as well as eastward. This happens (i) by process of advection in which the cloud clusters are steered westward into the south Bay of Bengal finally crossing-over into the Arabian Sea, (ii) *in situ* development of cloud clusters by the advection of gravity wave or wave CISK effect (Stevens and Lindzen 1978, Holton 1979). This happens westward as well as eastward. According to CISK concept, sinking motions in the cloud free region accentuate the convergence in the lower levels and cause further increase of upward motion and growth of convection in the form of *cb* clouds. From these *cb* clouds an upper air outflow emerges normally at 200 hPa level. Sometimes, this outflow is strong and extensive. An air particle which emerges from this outflow moves under conservation of absolute angular momentum from its original position ϕ_1 into a different geographical latitude ϕ_2. It obtains an additional angular velocity ω relative to the earth's surface. According to conservation of angular momentum:

$$\Omega\,(R\cos\phi_1)^2 = (\Omega + \omega)\,(R\cos\phi_2)^2$$

or $$\omega\,(R\cos\phi_2)^2 = \Omega\,R^2\,(\cos^2\phi_1 - \cos^2\phi_2)$$

or $$\omega\,R\cos\phi_2 .\, R\cos\phi_2 = \Omega\,R^2\,(\cos^2\phi_1 - \cos^2\phi_2)$$

Since the zonal velocity is $V_\lambda = R\cos\phi .\,\Omega$, the expression for the additional zonal velocity component $\triangle V_\lambda$ in the geographical latitude ϕ_2 reads :

$$\triangle V_\lambda = \omega\,R\cos\phi_2$$

$$\therefore\ \triangle V_\lambda .\, R\cos\phi_2 = \Omega\,R^2\,(\cos^2\phi_1 - \cos^2\phi_2)$$

$$i.e.,\ \triangle V_\lambda = \frac{\Omega\,R\,(\cos^2\phi_1 - \cos^2\phi_2)}{\cos\phi_2}$$

Here R=earth's radius $\sim$ 6370 km=63.7×10^5 m and Ω earth's angular velocity about its axis=7.29×10^{-5} rad $\sec^{-1}$ (Reiter 1963).

The outflow from *cb* clouds can be identified from the emerging cirrus clouds which normally occurs at 200 hPa in tropics. By following these cirrus cloud streaks to a radiosonde station we can add the computed additional wind component to the wind at the latitude of outflow. The resultant wind can be compared with the wind observed at 200 hPa in the station's sounding. If the two are comparable it will be suggestive of the strengthening of winds over station because of the outflow from given *cb* cloud. This is done in the next three case studies for cloud clusters formed in the equatorial trough in the Arabian Sea and the available RS/RW data.

4. Strengthening of westerlies and formation of jet maxima under the infleuce of outflow from large cloud clusters

4.1. *Case 1 — 17 January 1985*

NOAA-9 day time statellite imagery of 17 January 1985 depicts pronounced convective activity in the equatorial trough over Arabian Sea (Fig. 4a). Two important depicted cloud clusters are 'A' between Eq-10° N, 64°-76° E and 'B' Eq-10° N, 53°-59° E. The cirrus outflow emerging from the western periphery of the 'A' cloud cluster can be traced to maintain continuity up to 20°N. Similarly the southwest-northeast cirrus cloud streak 'C' between 23°-28° N & 70°-83° E also appears to be a part of outflow cirrus from the equatorial trough cloudiness. A jet maximum of 250°/120 kt is observed over Aurangabad at 200 hPa at 00 GMT of 17 January. Another jet maximum of 250°/135 kt is observed over Ahmedabad at 200 hPa at 12 GMT of 17 January. By assuming that the air particle started from the cloud cluster 'A' in the case of Aurangabad wind and from cloud cluster 'B' in the case of Ahmedabad wind, from 5° N in both the cases, the computed wind over Aurangabad$\sim$20° N comes out as 108 kt and over Ahmedabad (Lat. 23° N) as 145 kt. Both these are very close to the observed winds when we keep in view (*i*) the approximations made in relation to the position of emergence of outflow or/and zero wind there, (*ii*) difference in the timings of observed and the computed winds & (*iii*) there is intervening region of subsidence between the cloud cluster B and the cirrus streak C (Ranjit Singh 1985).

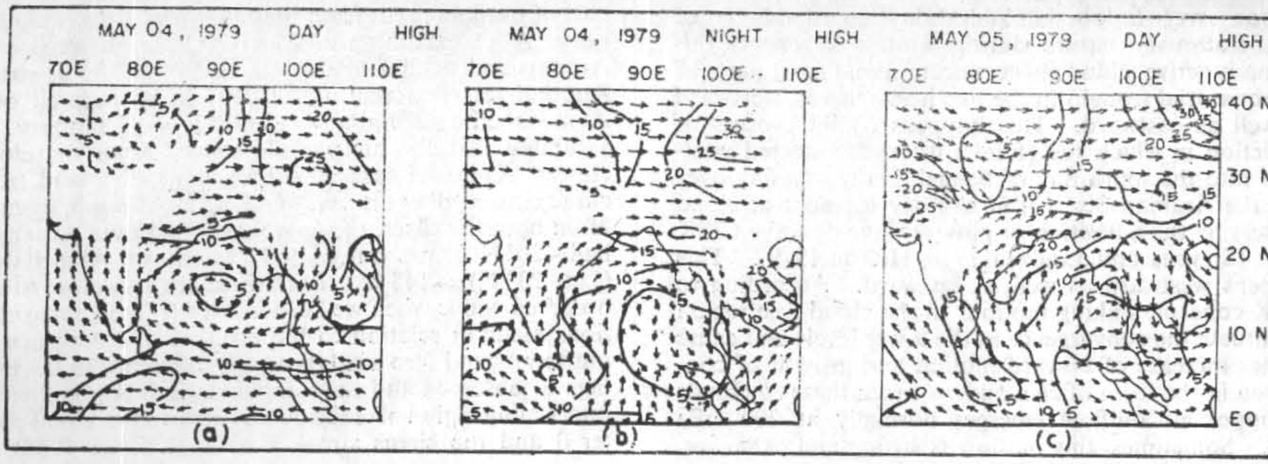
4.2. *Case 2 — 18 January 1985*

Pronounced convective activity is depicted in the equatorial trough in Arabian Sea on NOAA-9 satellite day time (IR) imagery of 18 January 1985 (Fig. 4b). It consists of several cloud clusters of different sizes between 5° S-10°N. & 61.5° E-81.5°E. Cirrus outflow emerging from the western periphery of the cloud cluster 'A' can be traced to originate at 2°N and reach the latitude of Bombay (19°N). A broad jet stream is observed between Jodhpur and Bombay at 200 hPa at 12 GMT, 18 January in which the jet core over Bombay has formed due to the outflow from equatorial cloudiness. The computed speed for an air particle which starts journey from 2° N and reaches the Lat. of 19°N preserving its absolute angular momentum comes out to be 102 kt which is close approximation to the observed wind maxima over Bombay.

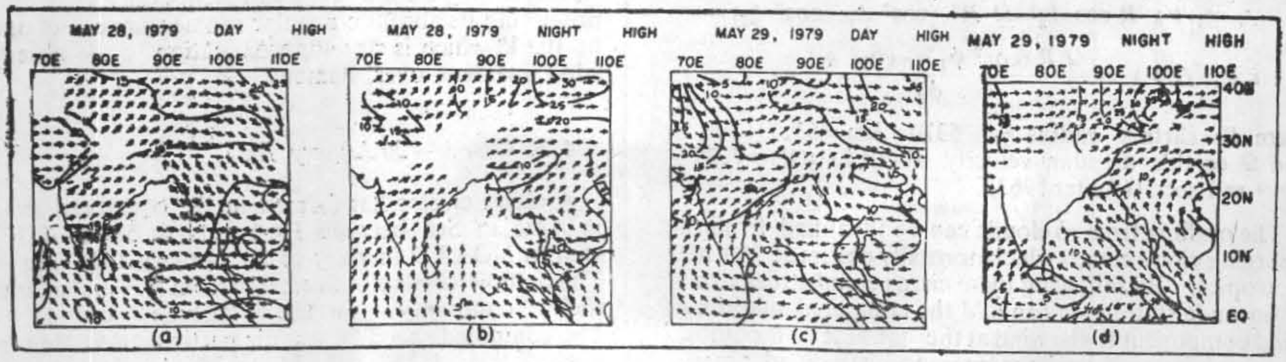
4.3. *Case 3 — 20 January 1985*

A cloud cluster has formed in the equatorial trough in Arabian Sea between Eq-10° N & 58° E-70°E as seen in NOAA-9 imagery of 20 January 1985 (Fig. 4c). The outflow cirrus clouds emerge from 5°N and maintain their continuity to the latitude of 11° N. The computed speed for an air particle traversing between 5°N & 11°N is 26 kt which is so close to the observed wind of 240°/26 kt over Trivandrum (Fig. 1c). The computed and the observed winds/wind maxima in the above three case studies are presented together in Table 1.

The three cases studied above are the ideal observations where we could trace the continuity of outflow cirrus clouds from their parent *cb* clouds and, therefore, have given an important opportunity to explain the occasional strengthening of westerlies, their deep equatorward extension and the formation of new jet maxima in them during winter over the Arabian Sea.



Figs. 2(a-c). Satellite composite windflow patterns at 200 hPa depicting strengthening of extra-tropical westerlies due to outflow from a tropical system. Arrow head shows wind direction and full lines represent isotach



Figs. 3(a-d). TIROS-N satellite imageries depicting the diurnal variation in the equatorial cloudiness

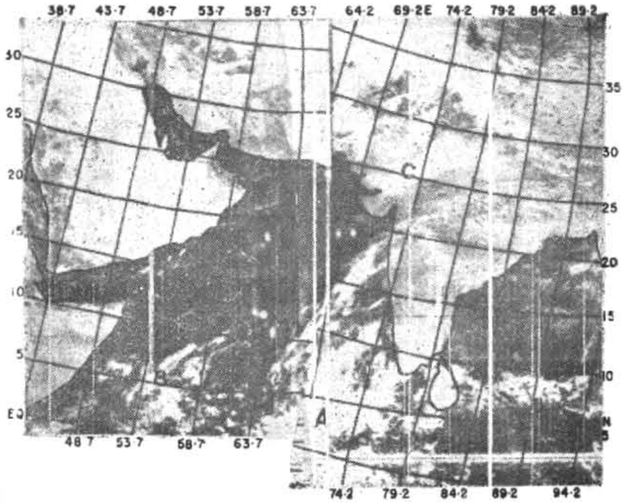


Fig. 4(a)

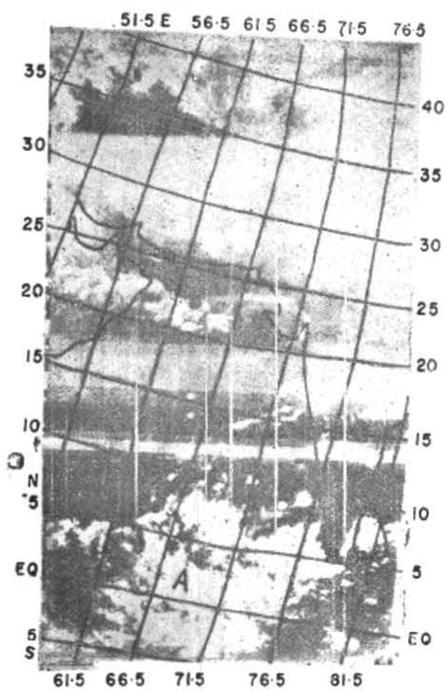


Fig. 4(b)

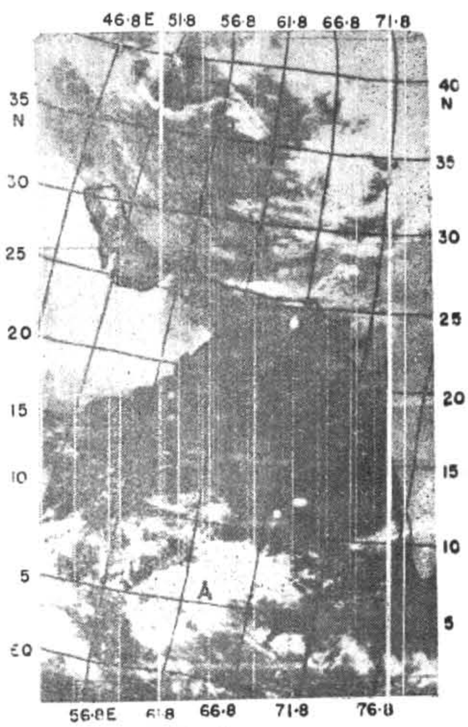
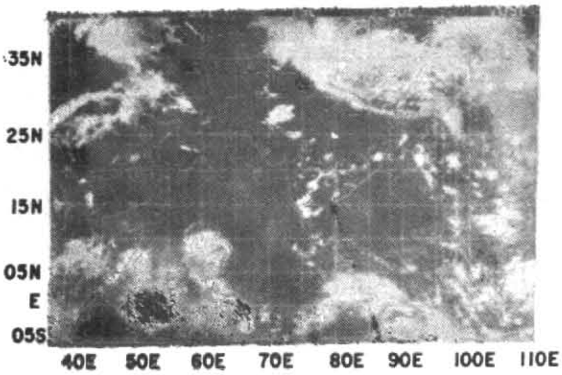


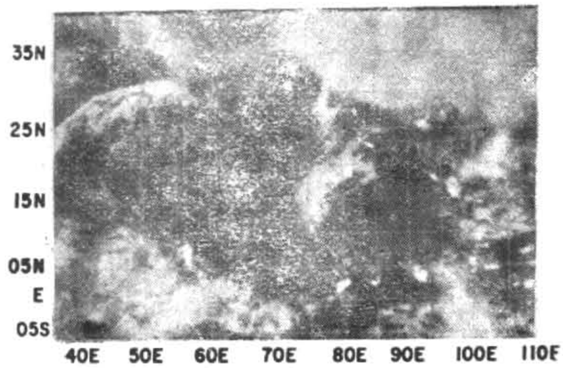
Fig. 4(c)

Figs. 4(a-c). NOAA-9 satellite imagery depicting the cloud cluster in the equatorial zone and outflow cirrus clouds over the Arabian Sea



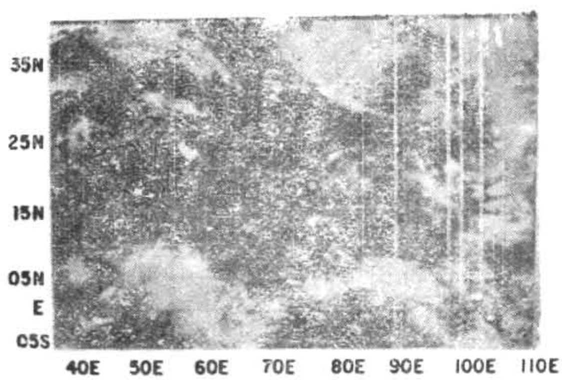
TIROS-N 28 MAY 1979 DAY IR

Fig. 5(a)



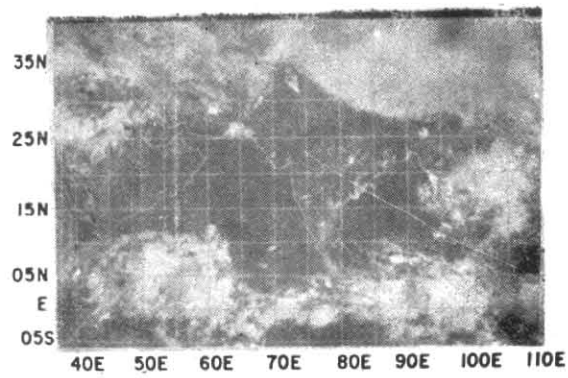
TIROS-N 28 MAY 1979 NIGHT IR

Fig. 5(b)



TIROS-N 29 MAY 1979 DAY IR

Fig. 5(c)



TIROS-N 29 MAY 1979 NIGHT IR

Fig. 5(d)

Figs. 5(a-d). Satellite composite wind flow patterns at 200 hPa depicting diurnal variation of westerlies

TABLE 1

Computed and observed wind maxima

Day & time of NOAA-9 Sat. obsn.	Lat. of the emergence of outflow	Initial wind speed (m/sec)	Lat. of wind maxima (°N) at 200 hPa	Additional zonal velocity (m/sec)	Computed value of wind Max. (m/sec)	Observed value of wind maxima (°/kt)
17 Jan. 14 hr 16 min (L)	5° N	0	20° N	53.9	53.9	250/120
Do.	Do.	0	23° N	72.6	72.6	250/135
18 Jan. 19 hr 20 min (L)	2° N	0	19° N	52.1	52.1	240/110
20 Jan. 15 hr 16 min (L)	5° N	0	11° N	13.2	13.2	240/26

5. The middle latitude westerlies during May 1979 and the linkage of their strengthening with tropical cloudiness

The method of linking the middle latitude westerlies with the tropical cloudiness may not be as simple as we have seen in section 4. There is so far only the statistical evidence that the westerlies over east Asia (Japan region) strengthen whenever the convection over Malayasian-Indonesian islands is intense. The convection in the equatorial trough forms a south-north vertical circulation known as the Hadley cell. The subsidence arm of this cell is located in the subtropical latitudes. These subsiding motions over the subtropical anticyclone diverge out and in turn, deepen the westerly trough and strengthen the jet streams embedded in them in the northeast sector of the anticyclone. We shall show the same for Indian region east of 90°E through two case studies. The second case study will also show that these westerlies may further strengthen during night in response to the night intensification of convection over Indian seas. For this satellite derived wind data from FGGE-1979 by Young *et al.* (1980) is used.

5.1. *Case of 4-5 May 1979*

On 4 May, weak easterlies formed an upper air circulation south of the subtropical anticyclone centred near 15°N and 90°E (4th day high level chart of Young's atlas). This circulation disappeared on the 4th (night) in response to the development which led to the formation of a well marked low pressure area on 5th morning. With the formation of a depression on 5th evening, a centre of divergence formed around 6°N, 89°E on the 5th (day) high level chart. The flow diverges in all directions over the system in a manner depicted by Petterssen (1956, Fig. 2.6. 1E on p. 34), turns anticyclonically in response to the environmental flow and covers an extensive area. Meanwhile the westerlies north of 20°N (Figs. 2a-c) are observed to intensify gradually from 4 May (day) to 4 May (night) and then to 5 May (day). Thus, we see a strengthening of the extratropical westerlies in response to the intensification of a convective system in tropics. However, in the present case linkage between the two phenomena through outflow cirrus clouds is not obvious from the satellite imageries of 4 and 5 May given in the Young's atlas.

5.2. *Case of upper tropospheric westerlies, 28-29 May 1979*

Comparing the cloudiness in the equatorial region over sea, it is observed that the convective cloudiness is more pronounced and covers greater area on the nights of 28 and 29 May than during the day time of 28, 29 and 30 May (Figs.3a-d, TIROS-N imageries of Young's atlas). On the night pictures of 28 and 29 May the grey tones in the cloud systems centred around 5°N, 55°E are related to the comparatively low temperatures of the cloud tops and indicate larger growth. Systems form and dissipate in the equatorial zone over sea sometimes, lasting a life span of relatively shorter duration of one to two days. It is during this period that the difference between the day *vs.* night growth of cloudiness has been brought out in the present case.

Scattered convective type cloudiness is observed over Indian subcontinent. Burma and Indo-China in day time on 28 and 29 May. Whereas during nights on 28 and 29 May cloudiness is convective-cum-stratiform and is more uniformly distributed over Burma and Indo-China. Scattered convective activity over land is a normal feature in the hot month of May wherever the moist current penetrates from the Arabian Sea, the Bay of Bengal and the south China Sea. During night this growth reaches its peak and dissipation starts. Mc Bride and Gray (1980) have explained this observed day *vs.* night variation in the growth of cloudiness by their hypothesis of radiative-cum-convective forcing. The resultant cloudiness is convective-cum-stratiform which includes outflow cirrus clouds

On examining the flow in Young's atlas (1980) corresponding to the level 200 hPa, it is noticed that the extra-tropical westerlies east of 90°E between 30° N and 40°N were linked with the equatorial outflow and they strengthened by about 5-10 m/sec on the nights of 28 and 29 May as compared to the day time on 28 and 29 May (Figs. 5a-d).

6. Discussion and conclusion

In an earlier study this author has shown that during monsoon season easterlies strengthen and accelerating wind maxima form at 200 hPa level in the southwest sector of organised convective systems over the Bay of Bengal in response to the outflow from their tops (Ranjit Singh 1985). This study gives an equally important evidence that during winter and pre-monsoon seasons extra-tropical westerlies strengthen and accelerating wind maxima form at 200 hPa in the northeast sector of organised convective systems in the equatorial trough in response to outflow from their tops. There is also an evidence that these westerlies are likely to be stronger during night than during day time since convection in the equatorial trough is more pronounced during night than day time.

Wherever the cirrus outflow maintains continuity. the value of westerly wind maximum computed under conservation of angular momentum agrees with the observed value over a station. This happens in the col region of the subtropical anticyclones. When the cirrus continuity is not present, the strengthening of middle latitude westerlies occurs due to the increased outflow from the stronger subtropical anticyclone. This anticyclone strengthens due to the subsidence from the Hadley cell.

In the present paper it has been further shown that just as the upper tropospheric westerlies strengthen over Japan region during winter in response to the intensification of convection in Indonesian-Malayasian islands region, they also strengthen over Indian region west of 80°E in response to the intensification of convection in equatorial region of the Arabian Sea. These westerlies for the same reasoning may extend deep equatorward and new wind maxima form in them south of the main subtropical jet stream.

Acknowledgement

Author is thankful to the referee for his critical and helpful comments.

References

Chang, C.P. and Lau, K.M., 1982, *Mon. Weath. Rev.*, **110**, 8, 933-946.

Holton, James R., 1979, *An introduction to dynamic meteorology*, second edition, pp. 155-159, 357.

Krishnamurthi, T.N., 1979, *Compendium of Meteorology*, WMO, No. 364, pp. 137 & 325.

Petterssen, S., 1956, *Weather analysis and forecasting*, second edition, Vol. **1**, p. 34.

Ranjit Singh, 1985, *Mausam*, **36**, 4, pp. 503-508.

Reiter Elmer, R., 1963, *Jet Stream Meteorology*, p. 16.

Stevens, D.E. and Lindsen, R.S., 1978, *J. atmos. Sci.*, **35**, 940-961.

Young, John A., Virji, Hassan and Wylia Donald, P., 1980, Summer monsoon wind sets from geostationary satellite data, Summer Monex : 1 May-31 July 1979.