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Some characteristic features of the low-level jet field over the Arabian Sea during the Indian summer monsoon*

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सार–भारत – रूस मानसून प्रयोग 1973 और मानसून प्रयोग 1977 के आंकड़ों का उपयोग करके अरब सागर के ऊपर के निम्नस्तरीय जेट के कुछ अभिलक्षणों का अध्ययन किया गया है। धुर पश्चिमी अरब सागर के ऊपर याम्योतर पवन परिच्छेदिका दो भिन्न-भिन्न जेट के अधिकतमों को दर्शाते हैं। निचला अधिकतम 1.0 कि॰ मी॰ के आस पास उत्तर में और सुविख्यात व्युत्क्रमय परत के अन्दर होता है। उपरितन पवन अधिकतम 2.0 कि॰ मी॰ के आस-पास व्युत्क्रमण के ऊपर दक्षिण की ओर होता है। पूर्व की ओर परिच्छेदिका अपेक्षाकृत प्रबल निम्नस्तरीय अधिकतम और दक्षिण में उच्च स्तरीय पवन अधिकतम की अनुपस्थिति को दर्शाते हैं। इस प्रकार पश्चिमी अरब सागर पर पवन क्षेत्र में ऊपर से नीचे की ओर पवन में होने वाले परिवर्तन इस क्षेत्र में दो जेट क्रोडों में एक सम्भावित गतिक युग्म को दर्शाते हैं। अरब सागर पर निम्नस्तरीय पवन संरचना जेट क्रोड के दक्षिण की ओर शीत वायु अभिवहन और उत्तर की ओर गर्म वायु अभिवहन को दर्शाते हैं। जेट क्रोड प्रबल ऋणात्मक ऊष्मा पवन कर्षण स्पष्ट है।

ABSTRACT. Some characteristic features of the low-level jet over the Arabian Sea have been studied by using the Indo-Soviet Monsoon Experiment — 1973 and Monsoon Experiment — 1977 data. The meridional wind profiles show two distinct jet maxima over the extreme western Arabian Sea. The lower maximum occurs near 1.0 km in the north and lies well within the pronounced inversion layer. The upper wind maximum lies near 2.0 km toward the south above the inversion. Towards the east, the profiles indicate a stronger low-level maximum and the absence of the upper level wind maximum in the south. Thus, the downwind changes occurring in the wind field over the western Arabian Sea indicate a possible dynamic coupling between the two jet cores in this region. The low-level wind structure over the Arabian Sea indicates cold air advection to the south and warm air advection to the north of the jet core. Strong negative thermal wind shear is evident in the jet core.

1. Introduction

One of the most intriguing phenomena of the Indian summer monsoon is the low-level jet, which is thought to originate in the south Indian Ocean near Madagascar, penetrates inland over the flat low lying areas of Kenya, Ethiopia and Somalia and emerges in the Arabian Sea and flows across its central parts to the coast of India. The low-level jet stream was first traced by Bunker (1965) off Somalia from the International Indian Ocean Expedition (IIOE) data. Later, Findlater's (1969, 1971) analysis showed that the low-level jet seems to be a major part of the southwesterly monsoon flow over the Indian sub-continent. This jet is most pronounced at heights of 1 to 1.5 km above sea level over the Arabian Sea.

Jambunathan and Ramamurthy (1974) and Desai *et al.* (1976) studied the structure of the low-level jet over the Arabian Sea from the Indo-Soviet Monsoon Experiment (ISMEX)—1973 data. Jambunathan and Ramamurthy (1974) showed that the axis of the maximum wind generally slopes upwards from west to east and has a southward tilt between surface and 3.0 km. Desai *et al.* (1976) pointed out that jet speed winds occur simultaneously at different altitudes over the Arabian Sea between the

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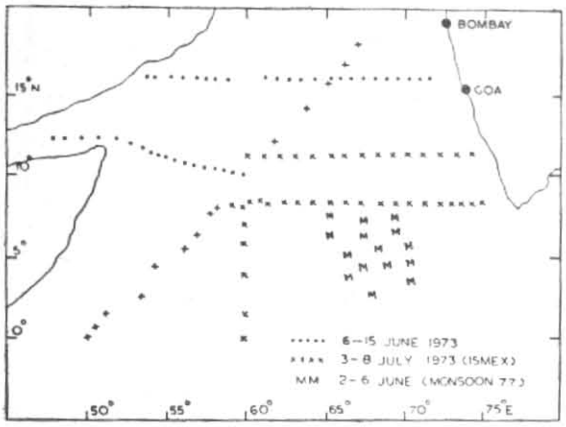

Fig. 1. Location of aerological soundings on board USSR research vessels

latitudes of 7 and 16 deg. N east of about 53 deg. E longitude. In a study of the vertical structure of the planetary boundary layer over the Arabian Sea, the author (Pant 1978) showed that the core of the maximum wind occurs well within the low-level inversion in the western Arabian Sea and within the cloud layer in the central and eastern regions and is often associated with large vertical wind shear.

More recently the author (Pant 1979) has shown that due to strong lateral shears present in a narrow belt south of the low-level jet, conditions become favourable for the occurrence of both intertially and barotropically unstable wave disturbances in this region. The phenomenon of barotropic instability may be a possible mechanism for initiating monsoon disturbances in the near equatorial region of the Arabian Sea. The dynamics of genesis of these disturbances is not yet understood.

In the present paper a more detailed study of the wind temperature and moisture structure of the low-level jet field is made by using the ISMEX-73 and Monsoon-77 data.

2. The data

The Indo-Soviet Monsoon Experiment (ISMEX) was carried out over the west Indian Ocean from 19 May to 8 July 1973. Four Russian research vessels took part in the experiment. Radiosonde and radar wind observations were taken on board the ships. Zonal and meridional cruises with observations every six to twelve hours allowed upper air observations available about one to three degrees apart in the region. During other portions of the period, stationary observation sites were chosen for a six-day period. The total area covered at various times over the Arabian Sea extended from the equator to 16 deg. N and from 50 deg. E to 72 deg. E.

The Monsoon-77 experiment was conducted under the auspices of the Global Atmospheric Research Programme (GARP) for the study of the summer monsoon over the western Indian Ocean. The experiment consisted of simultaneous sub-experiments performed independently in three separate regions during the late May through early July of 1977. One of the primary regions included the central Arabian Sea, where upto four radio and rawinsondes per day were released by a polygon of four stationary Soviet-ships centred around 12 deg. N, 65 deg. E. The other two region were (*i*) equatorial regions of eastern Africa and (*ii*) extreme western Indian Ocean.

In the year 1973, a steady (in direction) southwesterly monsoon flow established in the lower troposphere over the Arabian Sea from 4 June. Upper air observations showed occurrence of strong winds exceeding 24 mps in the layer extending from 500 m to 2000 m above sea level during the two periods (*i*) 6 to 15 June and (*ii*) 3 to 8 July. Radiosonde and radar wind observations available in the lowest 3.0 km layer in this region have been used in the present study. Data for the near equatorial region of the southeast Arabian Sea have been taken from Monsoon Experiment — 1977, as no upper air observations were available for this region during the ISMEX-73. Locations of data points is presented in Fig. 1.

Single point values of temperature and moisture were obtained by averaging the data points located within two to three degrees of one another. Similarly, single point values of winds were also obtained by vector averaging the wind data available for such data points in the region of study. Since the low-level jet stream is most pronounced in the western and central regions of the Arabian Sea, the average distributions of wind, temperature and moisture in the lowest 3.0 km layer are presented in the form of vertical cross-section for these regions along the longitudes of 55 deg. E, 60 deg. E and 65 deg. E only. Hodographs constructed from the vectorially averaged wind data for different location over the Arabian Sea are also presented and discussed in detail.

3. Vertical distribution of wind, temperature and moisture

3.1. *Zonal and meridional components of wind*

Vertical cross-section of zonal and meridional components of wind along 55 deg. E, 60 deg. E and 65 deg. E are presented in Figs. 2 and 3 respectively. A brief description of the salient features of the low-level windflow is presented in this section. A more detailed discussion of the boundary layer flow follows in the next section, where average wind hodographs for the region are presented.

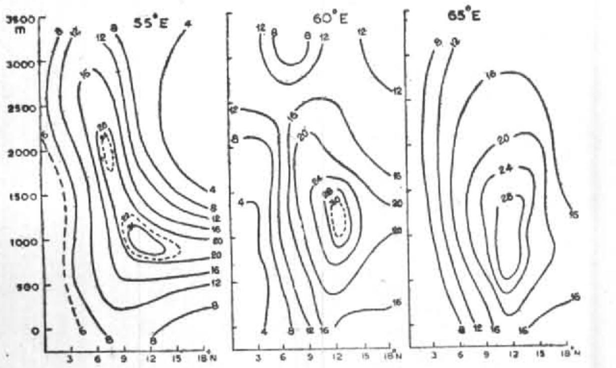

Fig. 2. Vertical distribution of zonal component of wind (mps)

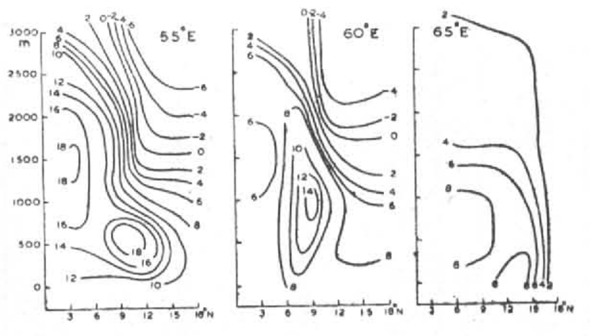

Fig. 3. Vertical distribution of meridional component of wind (mps)

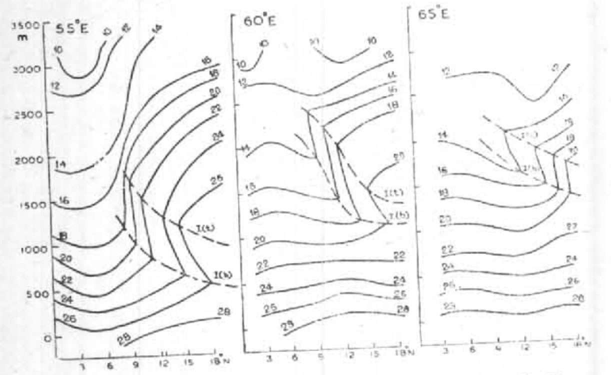

Fig. 4. Vertical distribution of temperature (° C)

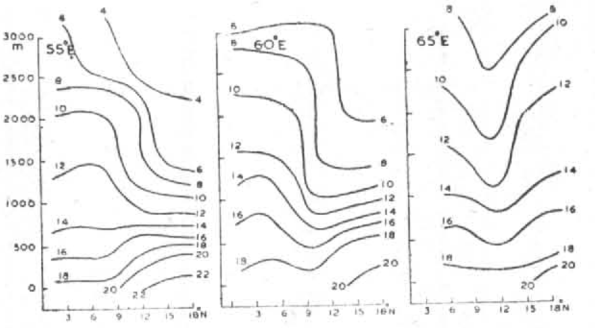

Fig. 5. Vertical distribution of specific humidity (g/kg)

The cross-sections for 55 deg. E show two distinct cores of wind maxima in both the zonal and meridional wind components. The lower zonal maximum is stronger than the upper one and occurs near 1.0 km between 9 deg. N and 12 deg. N. The upper maximum occurs near 2.0 km between 6 deg. N and 9 deg. N. Both the maxima in the meridional components are of nearly the same order but occur at relatively lower altitudes and a little south of the zonal maxima. At 60 deg. E, only one maximum is found in both the wind components, thus indicating a possible merging of the two jet cores in the downstream region. The zonal maximum shows an increase from 55 deg. E to 60 deg. E and occurs at a higher altitude near 12 deg. N. The meridional maximum shows a decrease and occurs at a lower altitude and to the south of the zonal maximum indicating that the flow is becoming zonal. The maximum occurs at 65 deg. E in a deeper layer extending from 0.5 km to 1.5 km and shows a little southward shift. The meridional components do not show any well defined maximum at 65 deg. E.

North of about 10 deg. N the meridional components become negative above about 1.5 km both at 55 deg. E and 60 deg. E but remain positive at 65 deg. E.

3.2 *Temperature and moisture*

The vertical density stratification appears to be an important factor in the dynamics of the low-level monsoon flow in this region. The temperature inversion is particularly pronounced over the western Arabian Sea north of about 8 deg. N, where it caps the lower stratified mixed layer close to the surface, thus nearly completely eliminating the cloud layer from this region (Pant 1978). The inversion in this region may not only be influenced by the local sea surface temperature distribution but also by subsidence and large scale divergence associated with the low-level jet field.

Vertical cross-sections of temperature and specific humidity at 55 deg. E, 60 deg. E and 65 deg. E are presented in Figs. 4 and 5 respectively. The low-level mamimum occurs well within the inversion layer at 55 deg. E. Eastwards, the inversion base rises more steeply in the lower latitudes as compared to that in the northern ones. The jet core occurs near the abase of the inversion at 60 deg. E. Further east, the height of the base of the inversion increases further and the broad jet core lies well below the inversion.

The specific humidity shows strong lapse in the vertical below the inversion both at 55 deg. E

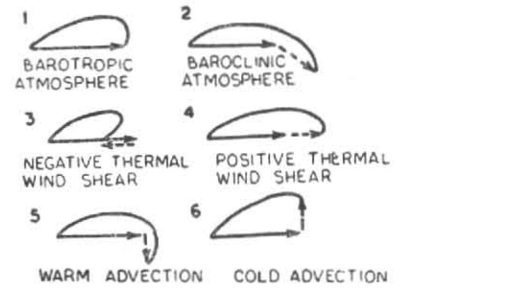

Fig. 6. Effect of baroclinity upon Ekman wind spirals, surface geostrophic wind (solid arrow), Northern Hemisphere Ekman spiral wind hodographs (curved lines) and boundary layer thermal winds (dashed arrow) [From : Lettau 1967]

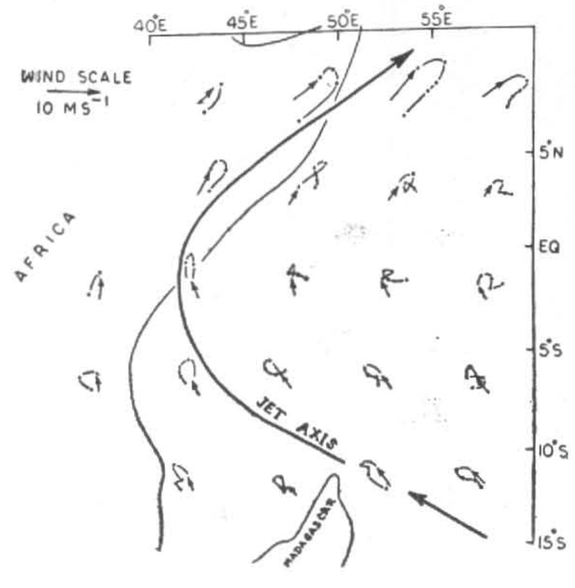

Fig. 7. Mean hodographs for cross-equatorial flow. Data point is at the tail of the arrow with arrow indicating surface wind vector. A Dots represent hts of 1000, 1500, 2000 and 3000 m. Wind scale is 10 ms^{-1} cm^{-1}

[From : J. D. Ward-1978]

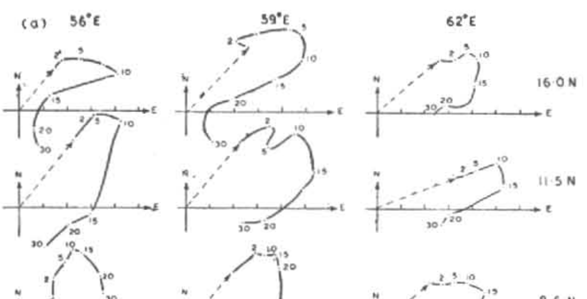

Fig. 8(a). Average hodographs of winds over Arabian Sea during June-July 1973 (Data point is at the origin, dashed arrow indicates surface wind vector, figures represent heights in hundred of metres)

and 60 deg. E. Above the inversion the lapse is weak. At 65 deg. E the humidity shows a stronger decrease in the vertical between 9 deg. N and 12 deg. N below the inversion as compared to that of in the north or south.

4. Average hodographs for the region

Hodographs constructed from the vectorially averaged wind data illustrate the average three dimensional structure of the horizontal air flow in the boundary layer over the Arabian Sea. The hodographs show large deviations from the elementary Ekman wind spiral pertaining to a barotropic atmosphere. Deviations from the idealised form of the Ekman solution can arise from many large and small scale processes occurring in the boundary layer. Some of the important processes are (a) "turbulance effects" which are complex and horizontally variable, (b) pressure gradient fields whose vertical variations depend upon baroclinity, (c) accelerations associated with local transient and horizontal variations in the wind and (d) diminishing coriolis forces near the equator. Of these, the most difficult to assess is the role of "turbulance" which represents many scales and several processes in the marine atmosphere (Roll 1965).

Some special effects of baroclinity on the Ekman spiral have been discussed by Lettau (1967) and are presented in Fig. 6. A pronounced low-level wind maximum with rapid decrease of wind above usually indicates a thermal wind directed oppositely from the surface geostrophic wind. In the northern hemisphere strong veering greater than the Ekman spiral indicates horizontal warm air advection through the layer, while veering less than the Ekman spiral (or backing) indicates horizontal cold air advection through the layer.

As the flow approaches the equator, advective terms associated with changing wind initiated by the large latitudinal variation of the coriolis parameter become important (Mahrt 1972). As the flow crosses the equator, advective accelerations may become important to the extent that the

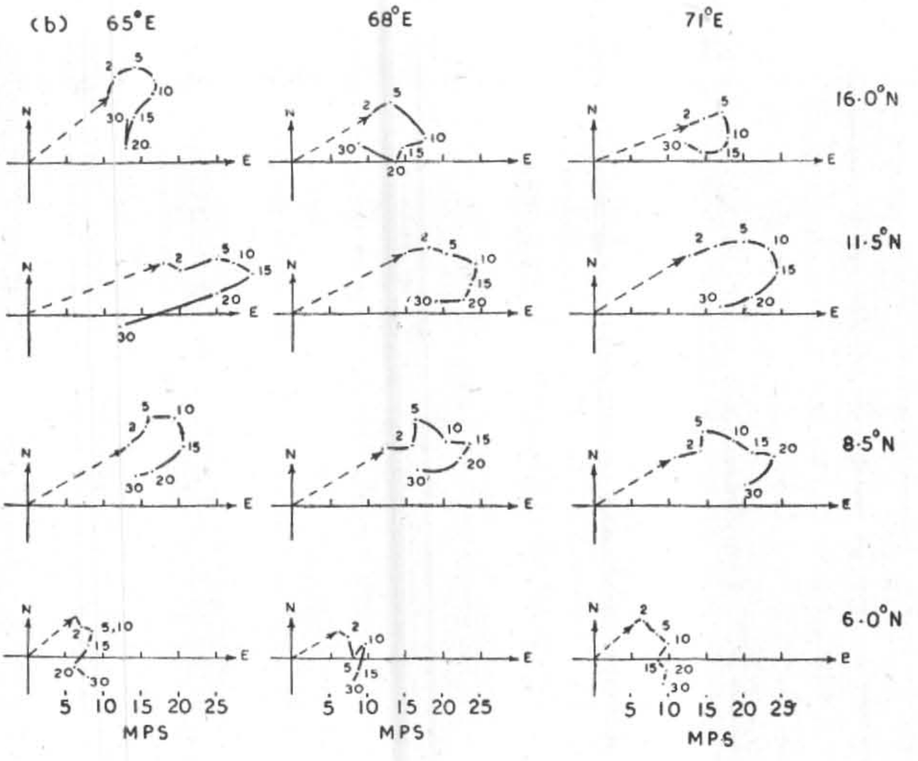

Fig. 8(b). Average hodographs of winds over Arabian Sea during June-July 1973

Fig. 9. Axes of wind maxima along 41 ° E. The scallop area indicates the minimum relative humidity [From : Ward (78)]

boundary layer downstream from the equator is radically different from the Ekman boundary layer.

Hodographs can also be affected by the local orographic features and sea surface conditions. The strong diabatic heating of the high lands of Kenya, Somalia and Arabia with the cold water upwelling along the east African coast affects the thermal wind and the turbulence. The low-level monsoon flow involves broad cross-equatorial flow in the western Arabian Sea, therefore, the three major factors which can affect the boundary layer wind profile in this region are the thermal wind, advective accelerations near the equator and orographic features.

From the mean hodographs constructed from the upper air data obtained during the Monsoon-77 experiment for the regions of Somalia, equatorial eastern Africa and adjoining ocean areas, Ward (1978) threw some light on some of the maintenance mechanisms of the jet core in this region. Mean hodographs for the above regions are presented in Fig. 7. The wind on the left flank of the jet stream south of the equator shows backing in the lower levels, implying warm air advection. Wind profiles on the right flank indicate either less backing or veering through the boundary layer, implying cold air advection. North of the equator, over the ocean area, complex loops are evident near the equator indicating a possible complex pattern of advective characteristics, temperature advection, and turbulence. Further north in the same figure a simpler pattern of veering is found on both sides of the jet, the strongest veering occurring between 2000 and 3000 m.

Average hodographs prepared from the ISMEX-73 and Monsoon-77 rawinsonde data for different locations of the Arabian Sea are presented in Fig. 8 (a&b). Some of the features which were observed in the wind cross section presented previously are evident on these hodographs also.

The major low-level maximum is evident near 1.0 km in the northern hodographs at 56 deg. E longitude, with strong veering above this height.

The hodographs to the south show a broad maximum in a deeper layer above 1.5 km. Backing is indicated below this height and veering above. At 59 deg. E, the two maxima are absent but only one deeper and stronger maximum is evident in the hodographs. Towards the east the jet core becomes sharper.

To the north of the jet either veering or less backing is observed through the boundary layer implying warm air advection. In the northwest Arabian Sea strong veering above 1000 m height may be indicative of more intense heating over the Arabian peninsula. In the eastern Arabian Sea veering considerably decreases indicating that the warm air advection becomes weaker in this region. To the south of the jet the hodographs indicate either backing or weak veering in the lower levels implying cold air advection. Strong negative thermal wind shear is evident in the jet maximum area in all the hodographs.

The two jet stream maxima found in the wind profiles over the western Arabian Sea are also clearly evident in the N-S cross-section along 41 deg. E longitude south of the equator presented by Ward (1978) from the aircraft flight data collected during the Monsoon-77 over the equatorial eastern Africa and adjoining oceanic areas of western Indian Ocean. Based on the same data Hart *et al.* (1978) have shown the existence of two jet cores, one over land at about 1.5 km altitude near 40 deg. E and the other, an oceanic lower level wind maximum toward the east found on several days. The lower wind maximum, however, was not as pronounced on days when the overland portion of the jet was extremely strong.

The N-S cross-section along 41 deg. E longitude presented by Ward is illustrated in Fig. 9. The upper jet maximum is evident only during the northern portion of the flight north of about 7 deg. S and shows a lowering of altitude as it moves northward. The lower maritime maximum remains near 1000 m height. Both the jet maxima are evident in the cross-section presented earlier along 55 deg. E longitude north of the equator. The cross-section at 60 deg. E longitude shows one stronger low-level maximum and the absence of the higher-level maximum. This suggests the occurrence of the phenomenon of dynamic coupling (subsidence) between the two maxima in the downstream region east of 55 deg. E longitude over the western Arabian Sea. The low-level temperature distribution in the horizontal, with cold temperatures to the south and warm temperatures to the north particularly in the western Arabian Sea as indicated by the wind hodographs will, however, weaken a westerly flow with height in the region. But, low-level jet is very well maintained in this region and shows even signs of acceleration downstream. At this point, a question can be asked that how is the jet stream maintained over the western Arabian Sea? One of the plausible mechanisms may be by the phenomenon of subsidence — a phenomenon which is supported by many observed features like presence of a pronounced temperature inversion, absence of clouds etc, and also by the presence of a meridional monsoon cell postulated by Koteswaram (*see* Ref.) as early as in 1958.

5. Summary and concluding remarks

This study brings out some of the characteristic features of the low-level jet field over the Arabian Sea during the summer monsoon months over India. The thermal and pressure gradient fields in the lower 3000 m appear to be quite critical in producing the sharp vertical jet core characteristics in this region. The strong vertical and lateral shears associated with the low-level jet field may be partly due to the baroclinity and advective accelerations near the equator. The coupling of the two jet cores in the downstream region over the western Arabian Sea by the phenomenon of subsidence appears to be a plausible mechanism for the maintenance of the low-level jet in this area.

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