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Kinetic energy budget of an Arabian Sea cyclone in June 1979

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सार — इस शोधपत्र में अरबसागर में दक्षिणपश्चिमी मानसून के दौरान जून 1979 में आए चक्रवाती तूफान की गतिज ऊर्जा का नैदानिक अध्ययन प्रस्तुत किया गया है। मानसून प्रयोग 1979 (मॉनेक्स-79) के दौरान सतह और ऊपरी वायु के ड्रोपसोंदे आंकड़ों की गणना के लिए उपयोग में लाया गया है। इस अध्ययन से प्राप्त कुछ महत्वपूर्ण परिणाम निम्नलिखित हैं :—

(*i*) अध्ययन के लिए नियत सभी अवधियों में 900 मि० बार से 700 मि० बार के मध्य गतिज ऊर्जा अधिकतम रही।

(*ii*) प्रणाली में गतिज ऊर्जा के उत्पादन में आंतरिक एवं वाह्य ऊर्जा स्रोत, दोनों का समान रूप से योगदान रहा।

(*iii*) ऊर्जा का क्षैतिज सीमा अभिवाह छोटा रहा, परन्तु निचली परत में अनुप्रस्थ समदाब प्रवाह के कारण उत्पन्न स्थितिज ऊर्जा की तुलना में गतिज ऊर्जा का उत्पादन पर्याप्त मात्रा में हुआ।

(*iv*) गतिज ऊर्जा समीकरण के विभिन्न पदों के मान, बड़े आयतन से संबंधित मानों की तुलना में छोटे आयतनों से संबंधित मानों के लिए अधिक थे।

ABSTRACT. A diagnostic kinetic energy study of a cyclonic storm in the Arabian Sea of the southwest monsoon in June 1979 is presented in this paper. The surface and upper air dropsonde data especially taken during Monsoon Experiment in 1979 (MONEX-79) have been used for the computations. Some of the important results emerged from the study are following:

(*i*) The kinetic energy was maximum between 900 and 700 mb in all the period under study.

(*ii*) Internal as well as the external energy source was equally responsible for the generation of kinetic energy of the system.

(*iii*) The horizontal boundary fluxes of energy is smaller but appreciable in magnitude when compared with the generation of kinetic energy from the potential energy due to cross isobaric flow in the lower level.

(*iv*) The values of different terms in kinetic energy equation are larger in case of the smaller volume when compared with the values of larger volume.

1. Introduction

During the onset phase of southwest monsoon on 16 June 1979 a cyclonic storm developed in the east Arabian Sea. Under its influence the southwest monsoon strengthened and advanced northward over the country. Monsoon Experiment in 1979 (known as MONEX-79) provided closely spaced aerological data around the cyclone field. Mandal *et al.* (1981) studied the structure of this cyclonic storm utilising these data. In this present study various energy terms for this cyclonic storm are computed by following the observational approach in which surface and upper air data are utilized.

The cyclonic storm originated as a depression over the east central Arabian Sea on 16 June and moving in northnorthwestward direction intensified into a cyclonic storm by the morning of 18 June. Later it moved west-northwestward till it struck Saudi Arabia coast on 20 June.

2. Analysis and computational procedure

In this diagnostic study we have used the subjective method of analysis like Chien and Smith (1973). Maps of wind fields are analysed for the surface, 850, 700, 500 and 200 mb at 1730 IST of 16 June, 0530 and 1730 IST of 17 June and 0530 IST of 18 June. The values of wind at different grid points, are extracted over an area keeping the centre of the cyclone at the centre of the grid for every one degree latitude and longitude for 15×15 points. From these wind values, geopotential heights are computed by solving the

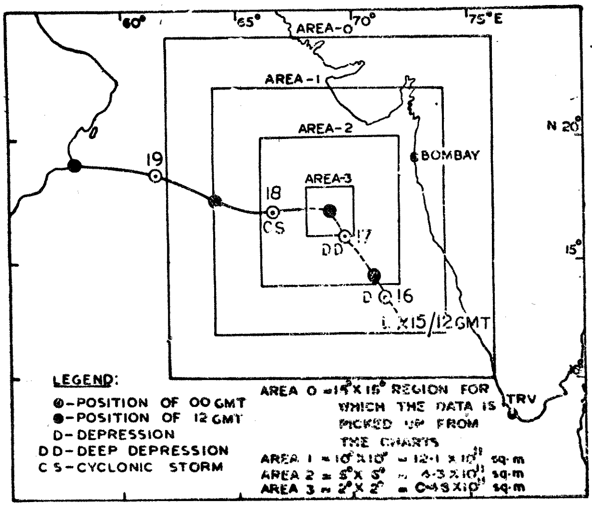


Fig. 1. Cyclonic storm of 16 & 19 June 1979 with different computational area

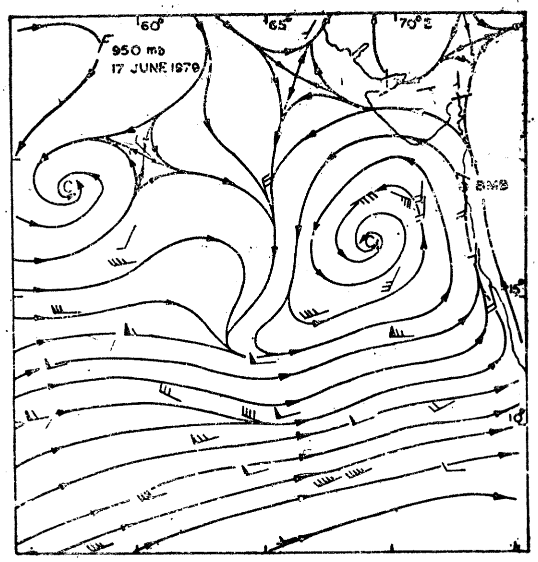
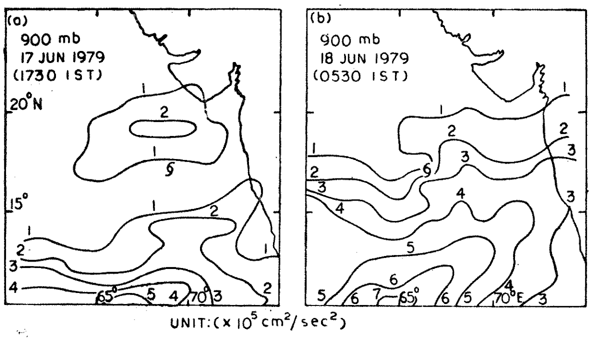
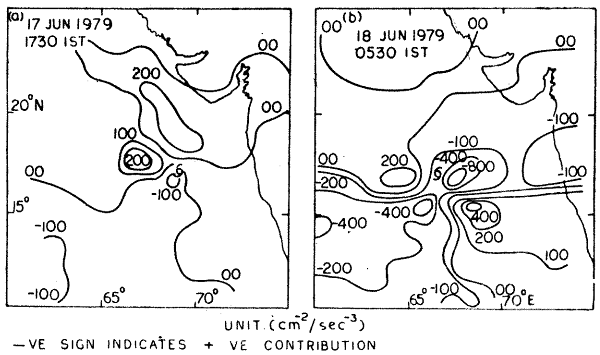


Fig. 2. Chart of 17 June 1979 at 950 mb



Figs. 3(a&b). Horizontal distribution of kinetic energy

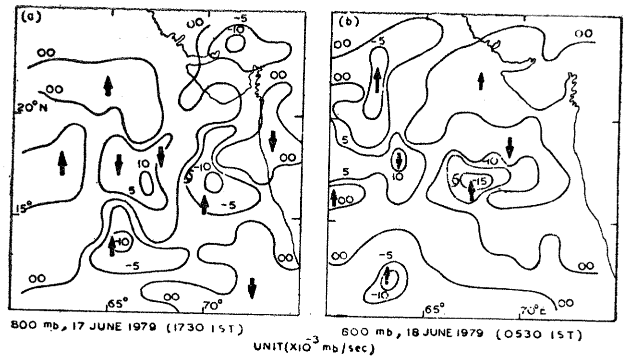


Figs. 4 (a&b). Horizontal distribution of generation term

balance equation with appropriate boundary values for the region. Such height data are further checked and suitable corrections are applied in all the levels. The height fields are interpolated at 900, 800, 700, 600, 500, 400, 300 and 200 mb, using lagrangian interpolation technique and finally these data are passed through a five point filter to avoid any spurious generation.

A simple, centred finite difference scheme is used to compute all spatial derivatives for a given synoptic time. Grid point values between two consecutive levels are linearly averaged to obtain values for the corresponding pressure layers. Values are also linearly averaged with respect to time in order to obtain terms in the kinetic energy equation.

Terms in the kinetic energy equation are computed for an area 12.1×10^{11} sq. m with the cyclone in the centre. This area lies completely within 15 degree latitude and 15 degree longitude as shown in Fig. 1.



Figs. 5(a & b). Horizontal distribution of vertical velocity

3. Synoptic situation

The cyclonic storm formed during the onset phase of the monsoon and the monsoon progressed northward along with the northward movement of the storm. Therefore the field around the storm especially in its south was monsoonal. As a result, wind field around the cyclonic storm under study was quite different from the wind field observed to be associated with the cyclonic storm formed during the pre and post monsoon periods over the Indian seas and over other oceanic region. During active monsoon condition a low level westerly jet wind appears over the south Arabian Sea (roughly around 10 to 12 deg. N). During the period under study low level westerly jet appeared as it is evident from the wind field. Thus to the south of the storm there were two wind maxima, one due to the cyclone field and other due to the presence of the low level westerly jet. At 200 mb easterly jet appeared and was passing roughly along 10 degree north latitude during this period with wind speed of 60-65 knots in the core over the Arabian Sea. At higher level to the north of the cyclone field was the sub-tropical anticyclone.

4. Kinetic energy equation

In this study following kinetic energy equation is used with the pressure as vertical co-ordinates :

$$\frac{\partial K}{\partial t} + \mathbf{V}_p.\nabla_p.K + \frac{w\,\partial K}{\partial p} = -\mathbf{V}_p.\nabla_p.\phi + \mathbf{V}_p.F_p \quad (1)$$

where,

$\mathbf{V}$ = Horizontal wind vector with components u and v

$K=\frac{1}{2}(u^2+v^2)$

ϕ = Geopotential, F = Frictional force/unit mass.

By using equation of continuity

$$\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)_p + \frac{\partial w}{\partial p} = 0$$

and integrating over the volume Eqn. (1) can be wirtten as :

$$\underset{\mathrm{A}}{\left[\overline{\frac{\partial K}{\partial t}}\right]} = \underset{\mathrm{B}}{\left[\overline{-\mathbf{V}_p.\nabla_p\phi}\right]} - \underset{\mathrm{C}}{\left[\overline{\nabla_p.K\mathbf{V}}\right]} - \underset{\mathrm{D}}{\left[\overline{\frac{\partial}{\partial p}.(wK)}\right]} + \underset{\mathrm{E}}{\left[\overline{\mathbf{V}_p.F_p}\right]} \quad (2)$$

where, $\left[\overline{\quad}\right] = \frac{1}{gA}\iiint\left[\quad\right]dx\,dy\,dp$

A = Area

The Eqn. (2) is integrated over the mass enclosed from surface to 200 mb.

The term in the left hand side of Eqn. (2) is known as local rate of change of kinetic energy per unit mass. First term in the right hand side of the Eqn. (2) represents how the kinetic energy can be changed and is known as generation of kinetic energy due to cross isobaric flow. Second term to the right represents horizontal convergence whereas third term represents vertical convergence of the kinetic energy. The last term is known as dissipation term and is calculated as residual after balancing the Eqn. (2). Sum of the terms B and E represents internal energy source.

5. Results

The contribution of various terms of the kinetic energy equation is computed and the results are shown in Tables 1 to 3. Table 1 gives computed values of different kinetic energy terms at fixed time on four occasions (1730 IST of 16th, 0530 and 1730 IST of 17th and 0530 IST of 18th).

Horizontal distributions of kinetic energy, kinetic energy generation ($-\mathbf{V}.\nabla\phi$) and vertical velocities at 900 mb for 1730 IST of 17 June and 0530 IST of 18 June are shown in Figs. 3, 4 and 5 respectively.

The unit of mean kinetic energy is 10^5 Joule m^{-2}, while the other quantities are measured in watt/m^2.

Computation shows that mean kinetic energy increased from 16th to 18th. The increase in kinetic energy is consistent with the intensity of the system and is the direct response of increase in wind speed. Computational data also reveals that kinetic energy is maximum between 900 and 800 mb in all the days and decreases upward. Horizontal distributions of kinetic energy around the cyclone field show that the peak value of the kinetic energy is located towards south of the storm centre. On 17th, a secondary maxima is also seen towards north. Kinetic energy maxima to the south of the storm centre is due to the combined effect of the cyclonic storm and strong bands of southwesterly winds in the lower levels which was the dominating flow pattern during the period under investigation.

Horizontal distribution of the vertical velocities at 800 mb indicate upward velocity to the south and eastern sector and downward velocity to the western sector of the storm. Vertical velocity is upward upto the middle tropospheric level and downward in the upper troposphere.

Horizontal distribution of kinetic energy generation in the lowest layer indicates the generation is maximum in the southwest and northeast quadrant. This we feel is due to the strong inflow over these quadrants (Mandal *et al.* 1981). Table 1 also indicates that generation is maximum in the lower level where cross-isobaric flow is maximum. In comparison to the horizontal and vertical flux this term is much larger in the earlier period but almost comparable with the horizontal transport especially in the lower level on 18th morning. This is against the facts observed to be associated with the storms of other oceanic areas and with the pre and post monsoon cyclonic storms over the Indian seas. Large contributions of the horizontal transport of energy towards the storm centre on 18th is due to the increased strength of the low level westerlies to the south of the storm.

TABLE 1

Kinetic energy terms for Arabian Sea cyclone (Area 12.1 × 10^{11} sq. m)

Pressure layer (mb)	K (10^5 J/m²)	$-[\mathbf{V}.\nabla\phi]$ (W/m²)	$-[\nabla.K\mathbf{V}]$ (W/m²)	$-\frac{\partial}{\partial p}[wK]$ (W/m²)
16 June 1979, 1730 IST				
Sfc-900	.604	2.118	.723	.025
900-800	.887	1.532	.745	.065
800-700	.727	.754	.267	—.064
700-600	.576	.405	.048	—.024
600-500	.418	.445	.129	.001
Sfc-500	3.212	5.254	1.912	—
17 June 1979, 0530 IST				
Sfc-900	1.271	2.796	1.424	.035
900-800	1.721	3.803	1.948	.006
800-700	1.733	2.316	1.410	—.034
700-600	1.454	.791	.782	—.006
600-500	1.063	.292	.778	—.001
Sfc-500	7.242	9.998	6.342	—
17 June 1979, 1730 IST				
Sfc-900	1.094	.770	1.252	.121
900-800	1.193	.620	.936	.201
800-700	1.393	1.787	1.215	.022
700-600	1.486	2.914	1.921	—.155
600-500	1.144	2.225	1.199	—.125
500-400	.711	1.129	—0.013	—.034
400-300	.497	.760	—0.246	—.025
300-200	.508	—.448	—0.364	—.005
Sfc-200	8.026	10.653	5.900	0.000
18 June 1979, 0530 IST				
Sfc-800	1.916	3.784	3.991	0.025
900-800	2.054	3.329	3.019	0.085
800-700	1.588	2.423	1.533	0.225
700-600	1.162	1.471	0.848	0.205
600-500	0.733	0.883	0.397	—0.120
500-400	0.342	0.569	0.415	—0.225
400-300	0.196	0.274	0.339	—0.175
300-200	0.429	—.173	—.045	—0.020
Sfc-200	8.420	12.560	10.497	0.000

TABLE 2

Kinetic energy budget (Area 12.1 x 10^{11} m²)

Layer (mb)	K (10^5J/m²)	$\frac{\partial K}{\partial t}$ (W/m²)	$-[\nabla.K\mathbf{V}]$ (W/m²)	$-[\mathbf{V}.\nabla\phi]$ (W/m²)	$-\left[\frac{\partial wK}{\partial p}\right]$ (W/m²)	$+D$ (W/m²)	$[\mathbf{V}.\nabla\phi+D]$ (W/m²)	$[-\mathbf{V}.\nabla\phi+D+(-\nabla.K\mathbf{V})]$ (W/m²)
16 June 1979, 1730 IST to 17 June 1979, 0530 IST								
Sfc-900	.937	1.543	1.074	2.457	.040	—2.028	.429	
900-800	1.304	1.926	1.346	2.667	.040	—2.128	.540	
800-700	1.230	2.325	.839	1.535	—.030	—.019	1.516	
700-600	0.457	2.298	.415	.599	—.030	1.314	1.913	
600-500	0.699	1.686	.403	.369	—.020	.934	1.283	
Sfc-500	4.627	9.778	4.077	7.627	—0.0	—1.927	5.681	9.758
17 June 1979, 0530 IST to 17 June, 1730 IST								
Sfc-900	1.824	—0.159	1.338	1.783	0.078	—3.358	—1.575	
900-800	1.457	—1.222	1.442	2.211	0.142	—5.017	—2.806	
800-700	1.513	—0.786	1.313	2.051	—.011	—4.139	—2.088	
700-600	1.470	—0.366	1.351	1.853	—.126	—3.444	—1.591	
600-500	1.103	—0.255	1.289	1.258	—.083	—2.719	—1.461	
Sfc-500	7.366	—2.788	6.733	9.156	0.0	—18.677	—9.521	—2.788
17 June 1979, 1730 IST to 18 June 1979, 0530 IST								
Sfc-900	1.505	1.902	2.621	1.777	.102	—2.598	—.821	
900-800	1.623	1.992	1.978	1.975	.143	—2.103	—.128	
800-700	1.491	—0.450	1.374	2.105	.095	—3.124	—1.019	
700-600	1.324	—0.749	1.384	2.192	.045	—4.370	—2.178	
600-500	0.938	—0.956	.798	1.554	—.092	—3.216	—1.662	
500-400	0.526	—0.849	.201	.849	—.157	—1.742	—.893	
400-300	0.347	—0.743	—.047	.517	—.106	—1.107	—.590	
300-200	0.468	—0.184	—.205	.137	—.029	—.087	.050	
Sfc-200	8.222	0.863	8.104	11.106	0.0	—18.347	—7.241	0.863

TABLE 3

Comparison of various terms in K. E. equation for three areas

(Area 1=12.1×10¹¹ m², Area 2=4.36×10¹¹ m², Area 3=.48×10¹¹ m²)
(Units:As in Table 1]

Pressure layer (mb)	−[V. ∇φ]			−[∇. KV]			K		
	Area 1	Area 2	Area 3	Area 1	Area 2	Area 3	Area 1	Area 2	Area 3
				17 June 1979, 1730 IST					
Sfc-900	.7701	1.898	5.174	1.2524	1.353	1.735	1.0939	1.1217	.4813
900-800	.6198	1.643	10.307	.9363	.359	1.241	1.1933	1.1991	.6563
800-700	1.7869	3.513	14.447	1.2147	1.024	.765	1.3934	1.4337	.8027
700-600	2.9138	5.025	14.602	1.9209	2.446	.414	1.4856	1.5009	.7466
600-500	2.2247	4.397	8.843	1.1990	1.974	.329	1.1440	1.0317	.3987
500-400	1.1288	3.055	4.734	—.0133	.927	.613	.7111	.5432	.1194
400-300	.7597	2.341	6.767	—.2463	.563	.617	.4975	.3913	.1315
300-200	.4478	1.693	11.802	—.3643	.340	1.118	.5081	.4181	.3564
Sfc-200	10.6516	23.565	76.696	5.8994	8.986	6.832	8.0269	7.6397	3.6929
				18 June 1979, 0530 IST					
Sfc-900	3.7844	6.021	14.554	3.9913	4.519	10.289	1.9159	1.8160	1.1801
900-800	3.3293	5.161	21.862	3.0195	4.093	13.215	2.0537	1.9438	1.3228
800-700	2.4225	3.243	9.999	1.5329	2.715	5.959	1.5878	1.5458	1.0093
700-600	1.4710	1.780	—2.010	.8482	1.093	—1.879	1.1620	1.1502	.7779
600-500	.8835	1.207	—.355	.3975	.029	—2.490	.7331	.6660	.4513
500-400	.5690	0.891	5.809	.4147	—.042	.357	.3422	.2418	.1316
400-300	.2744	0.482	7.750	.3387	—.001	.209	.1958	.1482	.1233
300-200	—.1733	0.260	10.395	—.0453	.026	—.007	.4285	.344	.3137
Sfc-200	12.5608	19.045	68.004	10.4975	12.432	25.653	8.4191	7.8558	5.3100

6. Kinetic energy budget

The computed values of the kinetic energy budget are shown in Table 2 for three different time period. The results are summarised below.

6.1. *Local change of kinetic energy*

This term shows periods of gain and loss of kinetic energy with no regular pattern. During the first time period an increase of kinetic energy at the rate of 0.98 W/m² is observed. In the second time period a slight loss of kinetic energy occurred in the lower levels. During third time period a slight gain in kinetic energy is observed in the lower levels with the compensating loss in the higher levels. The local change of the kinetic energy is maximum in the last time period.

6.2. *Generation of kinetic energy*

The generation of kinetic energy is due to the conversion of potential energy to kinetic energy due to cross-isobaric flow. Total value of this term from the surface to 500 mb shows an increase in value from the first period to the 3rd period. This is in consistent with the intensity of the cyclonic storm. Data also reveals that the energy production is maximum in the lower level of which greater percentage is produced in the boundary layer. Values decrease by almost a factor of two in the higher levels.

6.3. *Dissipation term*

The vertical distribution of the energy dissipation shows a pattern which is very similar to that of generation. This is because the dissipation is calculated as the residual in the kinetic energy budget equation and other terms are smaller than the generation terms. Dissipation is maximum in the lower levels which decreases upward.

6.4. *Boundary flux*

The vertical flux of kinetic energy is upward in the lower levels and downward in the middle and higher levels. Upward flux is maximum around 800 mb.

One interesting feature of this storm is the values of horizontal fluxes are not small in comparison to the generation and dissipation estimates. This is in contrast with the facts observed in case of the storms in the Atlantic, Pacific and the storms originated over the Indian seas during the non-monsoon months. The values of horizontal flux over a large area for the Atlantic and Pacific storms are found to be very small (Ooyoma 1969, Rosenthal 1971). During the first period there is a net influx of energy in the region with a maxima in the lower levels. Similar is the picture in the second period. During the third period there is an import of energy upto 400 mb and export in the higher levels. Large import of energy particularly in the lower levels over a larger area is due to the presence of the strong westerly low level jet to the south of the storm field away from its centre.

TABLE 4

Cases	Terms	$\partial K/\partial t$	$-\mathbf{V}.\nabla\phi$	$-\nabla.K\mathbf{V}$	D
1	Extra-tropical cyclone (matured stage) Smith 1973	3.7	18.2	23.9	—38.4
2	Present storm	—	11.1	8.1	—19.1
3	Hurricane (Celia)	—	20.1	2.3	—

6.5. *Budget summary*

The sum of the kinetic energy generation and dissipation represent an internal energy process which can cause a local change in the kinetic energy of a limited area while the boundary flux of energy is referred to as source of energy. Therefore, it is of interest to compare the internal and external source of energy to that of local rate of kinetic energy change. During the first period there is nèt internal source of energy in all the levels. In addition, there was an import of energy into the region leading to net positive local change of kinetic energy. In the second time period there is net internal sink due to the increased dissipation and the external source is not in a position to compensate the internal sink. As a result there is net loss of kinetic energy over the region. In the third time period again there is net internal sink but it is more than compensated by the external source. As a result, there is net gain of kinetic energy. This we feel, therefore, one of the reasons for the slow intensification of the system. The system became cyclonic storm in the early morning of 18th.

7. Comparison of various terms in kinetic energy equation for different areas

Computed values of various terms of the kinetic energy equation for three different areas are shown in Table 3. This table reveals that kinetic energy content decreases with the decreasing area. The contribution by the various terms of the kinetic energy equation, however, increases with the decrease in area, Significantly the generation term increases by about 6 to 7 times from a larger area to a smaller area considered here. This is due to the increase in gradient resulting increased cross-isobaric flow as we approach towards the centre of the storm. Horizontal flux term also increases by a factor of 1.5 to 2 from a larger area to a smaller area. This leads us to conclude that kinetic energy generation is maximum within the immediate vicinity of the storm centre.

8. Comparison with other storms

Due to the number of reasons like variety of approaches used by the investigators, different volumes used for kinetic energy budget, insufficient data for the complete life cycle of the storm and studies being restricted to a part of the life period of the storm, it is difficult to compare the results of the various energy studies. However, the comparative values of certain terms of kinetic energy equation of the present cyclone with the results of the hurricane *Celia* in the Atlantic and with the mature stage of an extra-tropical cyclone are shown in Table 4.

Table 4 shows the horizontal flux is lowest in case of the hurricane *Celia*. Highest value of the horizontal flux in the case of the extra-tropical cyclone (Smith's case) is due to the import of energy by the sub-tropical westerly jet stream into the storm's region whereas large value of this term in the present case compared to the hurricane *Celia* is due to the moderate import of kinetic energy from the low level jet stream in the region.

9. Conclusions

The important aspect of kinetic energy generation in this case of the cyclonic storm is the contribution by the external source as well as generation of kinetic energy due to the conversion of potential energy (internal source). They are responsible for the increase of kinetic energy content of the system. The net boundary import of energy in the lower levels is found to be almost equal in magnitude to that of internal energy source. This suggests that the present system had certain similarity in kinetic energy generation processes to that of an extra-tropical cyclone where contribution by the horizontal boundary flux towards the kinetic energy content is significant. However, this is against the facts observed to be associated with the storms in other oceanic areas as well as pre and post monsoon storms over the Indian seas where contribution by the horizontal boundary flux towards the total energy content is found to be small. A contributory factor to the energy generation and maintenance is that the lower tropospheric inflow into the south and eastern sector of the storm during this period which come directly from the low level jet over the central Arabian Sea. A comparative study of the various terms of the kinetic energy equation for a smaller and larger area leads us to conclude that the kinetic energy generation is maximum within the immediate vicinity of the storm centre. Slow intensification of the system was probably due to the excessive dissipation of kinetic energy in the boundary layer on 17th.

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