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Heavy rainfall in Pakistan during 27-29 July 2010: Role of atmospheric energy conversion characteristics

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सार – हाल के दशक में खराब मौसम की घटनाएँ एशिया महाद्वीप में विशेष रूप से पाकिस्तान में अत्याधिक होने लगी हैं। इसकी वजह से इस क्षेत्र में रहने वाले लोगों की तकलीफों में वृद्धि हो रही है। इस शोध पत्र में संपूर्ण ऊर्जा प्राचल *E* को वायुमंडलीय ऊर्जा–विज्ञान सिद्धांत से प्राप्त किया गया है। 27–29 जुलाई, 2010 की अवधि में पाकिस्तान में हुई भारी वर्षा के दौरान वायुमंडलीय ऊर्जा परिवर्तन के लक्षणों पर भी चर्चा की गई है। इससे प्राप्त हुए परिणाम बताते है कि वायुमंडलीय परिसंचरण और भू–भाग की स्थितियों के प्रभाव के कारण भारी वर्षा होने के दौरान गतिज ऊर्जा और स्थिर लहर के रूप में स्थितिज ऊर्जा में परिवर्तित हो जाती हैं। गतिज ऊर्जा और स्थितिज ऊर्जा के बीच परिवर्तन भारी वर्षा की अवधि के दौरान होता है। उच्च ऊर्जा के मान इस क्षेत्र में भारी वर्षा को दर्शाते हैं।

ABSTRACT. Extreme weather events over Asia particularly in Pakistan are becoming more frequent in the present decade or so. This is contributing to the ever increasing human suffering of the region. In this study the whole energy parameter *E* from atmospheric energetic theory is derived. The characteristics of atmospheric energy conversion during the heavy rainfall in Pakistan for the period 27-29 July, 2010 are also discussed. The results show that due to the impact of the atmospheric circulation and terrain conditions, the kinetic energy is converted into potential energy, in the form of standing wave, during heavy rainfall development period. The conversion between kinetic and potential energy is significant in heavy rainfall spell. High energy value corresponds to the heavy rainfall region.

Key words – Heavy rainfall, Energy conversion, Atmospheric energy.

1. Introduction

The heavy rainfall during monsoon is one of the most serious hazards in Pakistan (Rasul *et al*., 2004 & 2008). In 2010 Pakistan was hit by the worst flood ever in the history. It began in July, after heavy rains in different parts of the country, particularly affecting the Indus river basin. This flood affected almost 50 million people, and at one point of the time one fifth of the Pakistan's total land was under water. It is estimated that about 20 million people were affected directly by the flood. It killed 3000 people, destroyed 1 million houses, displaced 10 million people and millions were affected by water-borne diseases, lack of food, drinking water and shelter. The flood also affected Pakistan agriculture, almost 130 million hectare of croplands had been inundated. It destroyed 80 per cent of cotton crops and 30 per cent of sugarcane and rice. The flood destroyed million of tons of wheat which were kept in government storages and farmers' houses (Akhtar, 2011). According to Pakistan Meteorological Department (PMD) report, the heavy precipitation occurred on 27-29 July. Further, more than twenty stations reporting precipitation in excess of 200 mm was in Azad Kashmir and the provinces of Punjab and Khyber Pakhtunkhwa, during the three day wet spell, 27-29 July.

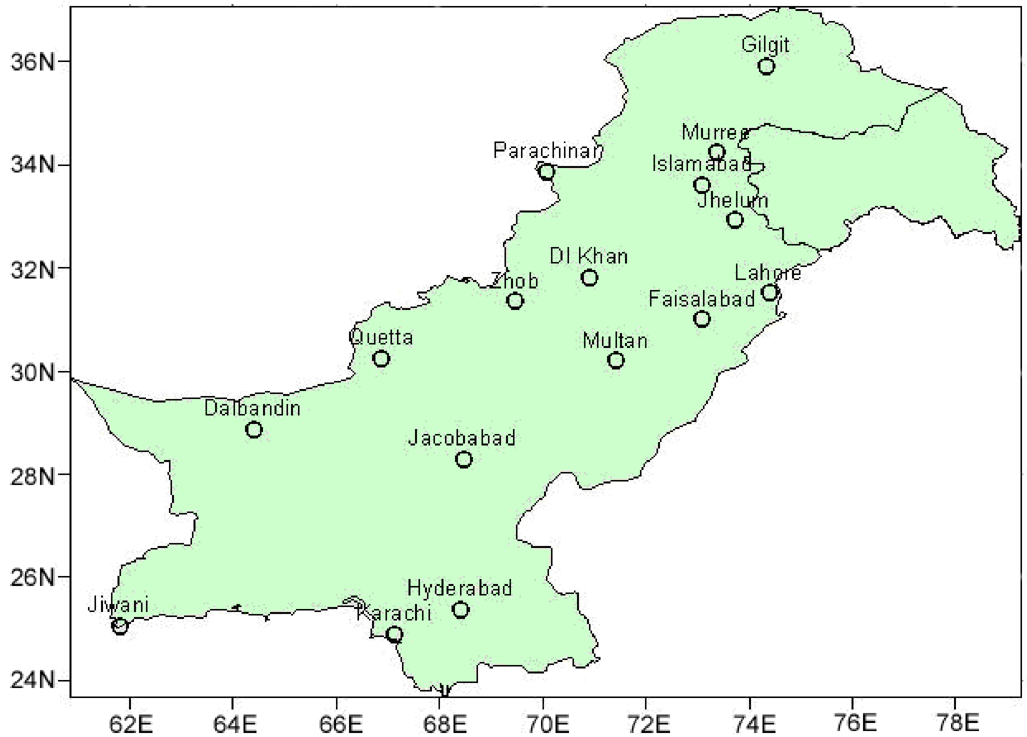


Fig. 1. Distribution of the meteorological stations

Rainfall is the main cause of flash as well as river floods. Particularly in south Asia, heavy rainfall causing severe floods, landslides, and debris and mud flows are very common (Mohapatra *et al.*, 2008 & 2011).

In the recent history, Indus basin had experienced two super floods. The first one occurred in 1929 and the second one in 1976. The strong monsoon rainfall over catchment area is the main factor of these two super floods. The recent flood in July 2010 was the worst flood in the history. The heavy torrential monsoon rainfall concentrated on the western part of Pakistan. It was the direct cause of this super flood.

These kinds of weather phenomenon are closely monitored by meteorological departments at a cost of large amount of manpower and material resources. However they are still struggling to have an efficient forecast for extreme weather events with considerable lead time.

Occurrence of severe rainfall is highly depending upon the strength of moisture content and tracks of monsoon wind. The Indus river plain is the most vulnerable region of heavy rainfall hazard. There have been many studies on heavy rainfall over India and Pakistan. Rahmatullah (1952) have discussed the flow and precipitation patterns over north India and Pakistan during one month of the summer monsoon and find out the extent to which they deviate from steady conditions. Awade *et al.* (1982) have documented large-scale wave to wave interactions of monsoon rainfall over India. However, some scientific questions as atmospheric energy characteristics of heavy rainfall in the Indus river plain regions and Pakistan still remained unanswered. We consider that it is tentatively discussed atmospheric energy conversion and distribution characteristics of heavy rainfall in our work.

According to atmospheric energetics, heavy rainfall system is the process of energy accumulation and release. Presently more and more meteorologists are becoming concerned with the role of atmospheric energy in heavy rainfall phenomenon (Yeh, 1949; Zeng, 1983 & 1985). Recent studies have some interesting results. For example, baroclinic waves in the mid-latitude storm tracks tend to be organized in localized wave packets that clearly exhibit downstream development (Chang, 1993; Lee and Held, 1993). Subsequently, Chang and Yu (1999) extend the analyses of the Southern Hemisphere and also the summer seasons to examine the seasonal and hemispheric dependence of wave packet characteristics. Recently,

TABLE 1

Geographical location of the meteorological stations

Station	Lat.	Long.	Elev. (m)
Dalbandin	28.88	64.40	848.00
DI Khan	31.82	70.92	173.00
Faisalabad	31.43	73.10	183.00
Gilgit	35.91	74.33	1459.00
Hyderabad	25.38	68.42	40.00
Islamabad	33.62	73.10	507.00
Jacobabad	28.30	68.46	55.00
Jhelum	32.93	73.72	232.00
Jiwani	25.06	61.80	56.00
Karachi	24.90	67.13	21.00
Lahore	31.52	74.40	215.00
Multan	30.20	71.43	122.00
Murree	33.91	73.38	2167.00
Parachinar	33.86	70.08	1725.00
Quetta	30.25	66.88	1600.00
Zhob	31.35	69.47	1405.00

Song *et al*. (2006) have examined the relationship between wave-packet propagation features and West Pacific Subtropical High (WPSH) pressure. More recently, Guo *et al*. (2010) have analyzed the propagation and accumulation of wave-packet in Tibet heavy snowstorm.

Previous studies have primarily focused on the influence of kinetic energy or potential energy on weather and climate system. In this study, we derive the whole energy parameter E from atmospheric energetic theory and discuss the characteristic of atmospheric energy conversion during heavy rainfall in Pakistan. This study may prove helpful for heavy rainfall diagnosis studies. Paper is organized in different sections. Section 2 describes the data and the methods of analysis used in this study. The rainfall distributions and the characteristics of atmospheric energy conversion are separately presented in Sections 3 and 4. The characteristics of vapor transportation and energy propagation are discussed in Section 5. A conclusion will follow in Section 6.

2. Data and methodology

This study uses the data of sixteen different geographical stations (Table 1 & Fig. 1) which are established by the National Weather Forecasting Center of the Pakistan Meteorological Department (PMD). The data from these stations have gone through the quality control procedures of the PMD.

For the calculation of E, the NCEP/NCAR FNL (Global Final Analyses) data is used. This dataset has 82 variables, including air temperature, relative humidity, geopotential heights, wind etc. Four-times daily (0000, 0600, 1200 and 1800 UTC) 700 hPa meridional wind and zonal wind on a 1° × 1° grid, for the period of 27-29 July, 2010 are analyzed in this study.

In terms of atmospheric energetics, the energy can be shown as (Xie, 1978).

$$E = C_v T + gz + \frac{1}{2}V^2 + Lq \tag{1}$$

where C_vT is atmospheric internal energy, gz is gravitational potential energy, (½) V^2 is kinetic energy and Lq is latent heat energy.

The heavy rainfall system can be approximated as an energetic system. Internal energy and latent heat is equivalent to the elastic potential energy of wave-packets. In the period of heavy rainfall system development, the characteristics of atmospheric energy conversion are very significant. Hence, the energy E can be expressed as

$$E = E_k + E_a = \frac{1}{2}\left(u^2 + v^2\right) + \frac{1}{2}A^2 + W^* \tag{2}$$

where u, v are zonal and meridional component of wind speed, (½) A^2 is the elastic potential energy of wave-packets. W^* is perturbation potential energy which compared to kinetic and elastic potential energy can be ignored, and therefore the energy is

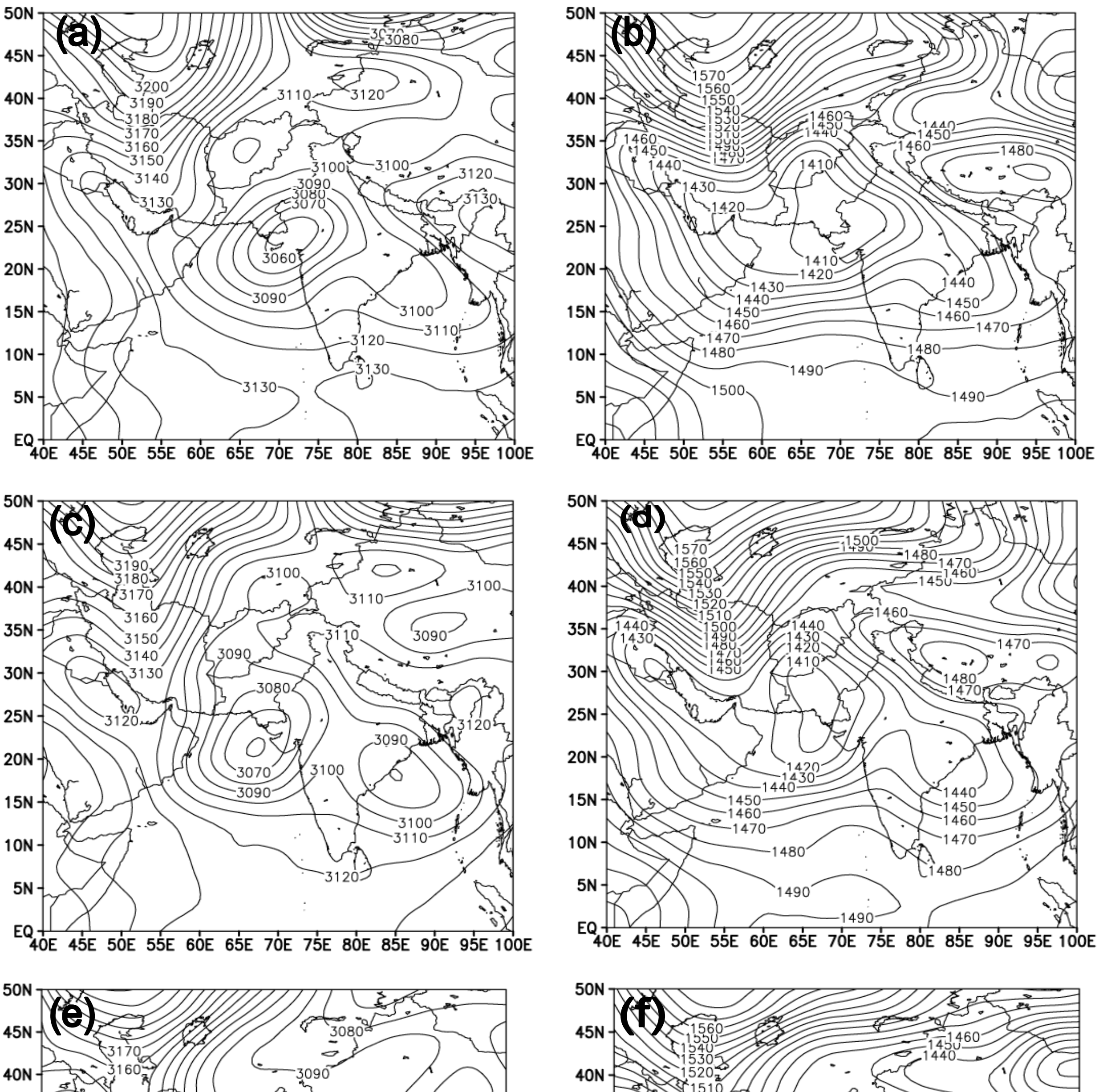
$$E = \frac{1}{2}\left(u^2 + v^2\right) + \frac{1}{2}A^2 \tag{3}$$

If the kinetic energy (E_k) and elastic potential energy (E_a) can be calculated, the characteristics of atmospheric energy conversion during heavy rainfall spell can be analyzed.

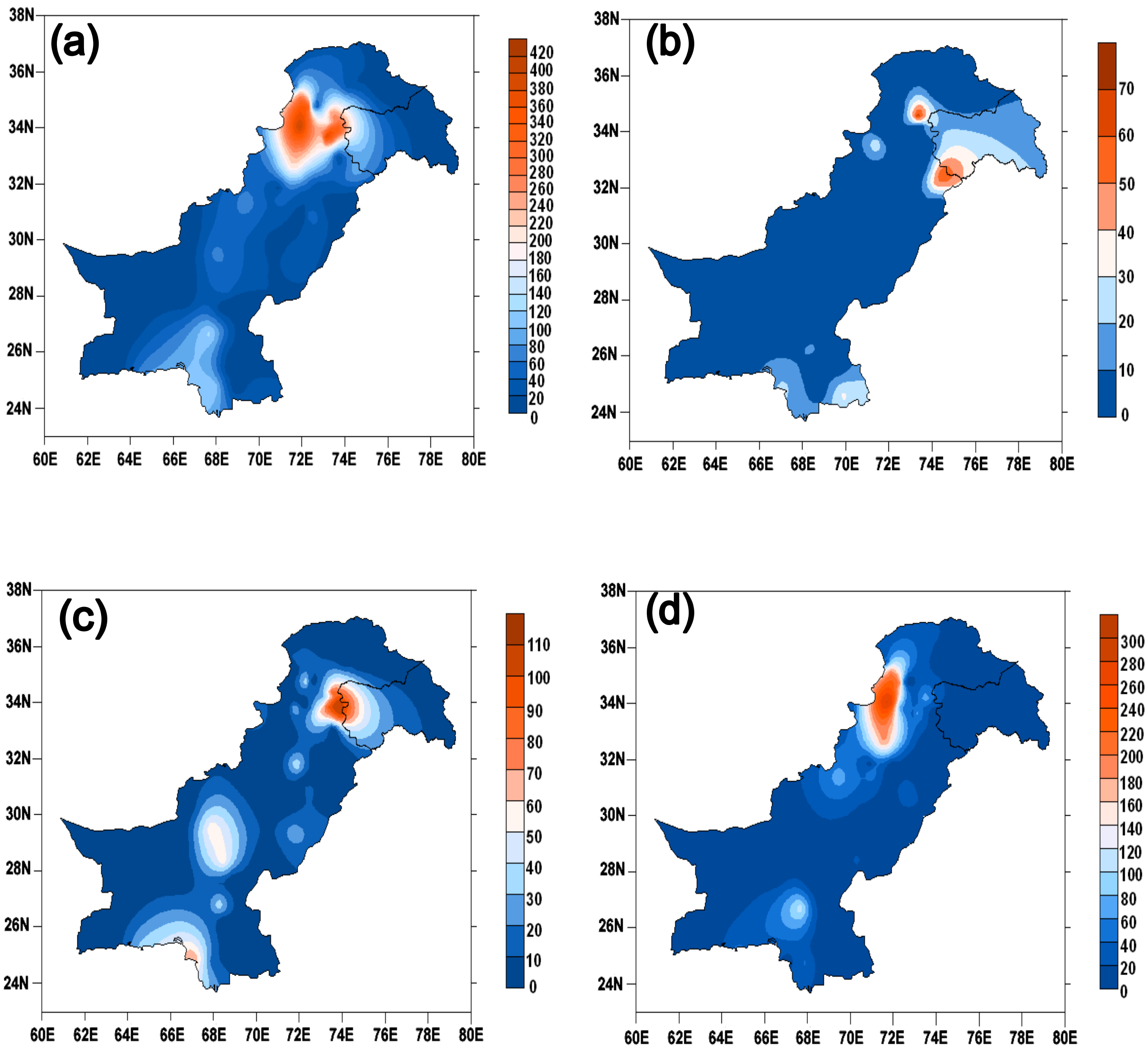
From the atmospheric energetic theory and the wave-packet propagation diagnosis (WPD) method (Chang and Yu, 1999; Miao *et al*., 2002), we know, the wave energy is propagating by wave packet envelopes. Thus, the wave amplitude A_i (x, y, z, t) represents elastic potential energy E_a.

Meteorological data can be regarded as combination of different waves. Based on the WPD method, the data can be written as

$$P(x,y,z,t) = \sum_{i=1}^{\infty} A_i(x,y,z,t)\cos\left(k_i x + l_i y + m_i z + \omega_i t + \varphi\right) \tag{4}$$



Figs. 2(a-f). Geopotential height patterns in 27-29 July, 2010 (a) 700 hPa 27th July 2010, (b) 850 hPa 27th July 2010, (c) 700 hPa 28th July 2010, (d) 850 hPa 28th July 2010, (e) 700 hPa 29th July 2010 and (f) 850 hPa 29th July 2010



Figs. 3(a-d). Distribution of total rainfall and daily rainfall in Pakistan 27th -29th July 2010 (a) total rainfall, (b) 27th July, 2010, (c) 28th July, 2010 and (d) 29th July, 2010

where, *A* (*x*, *y*, *z*, *t*) is the wave amplitude of *P* (*x*, *y*, *z*, *t*), *k*, *l*, *m* represents the wave number of *x*, *y*, *z* directions respectively, ω is the angular frequency, φ is the argument.

By using Hilbert transformation (Miao *et al.*, 2002; Zimin *et al.*, 2003), the signal *P* (*x*, *y*, *z*, *t*) can be transformed to analytic signal $\hat{P}$ (*x*, *y*, *z*, *t*).

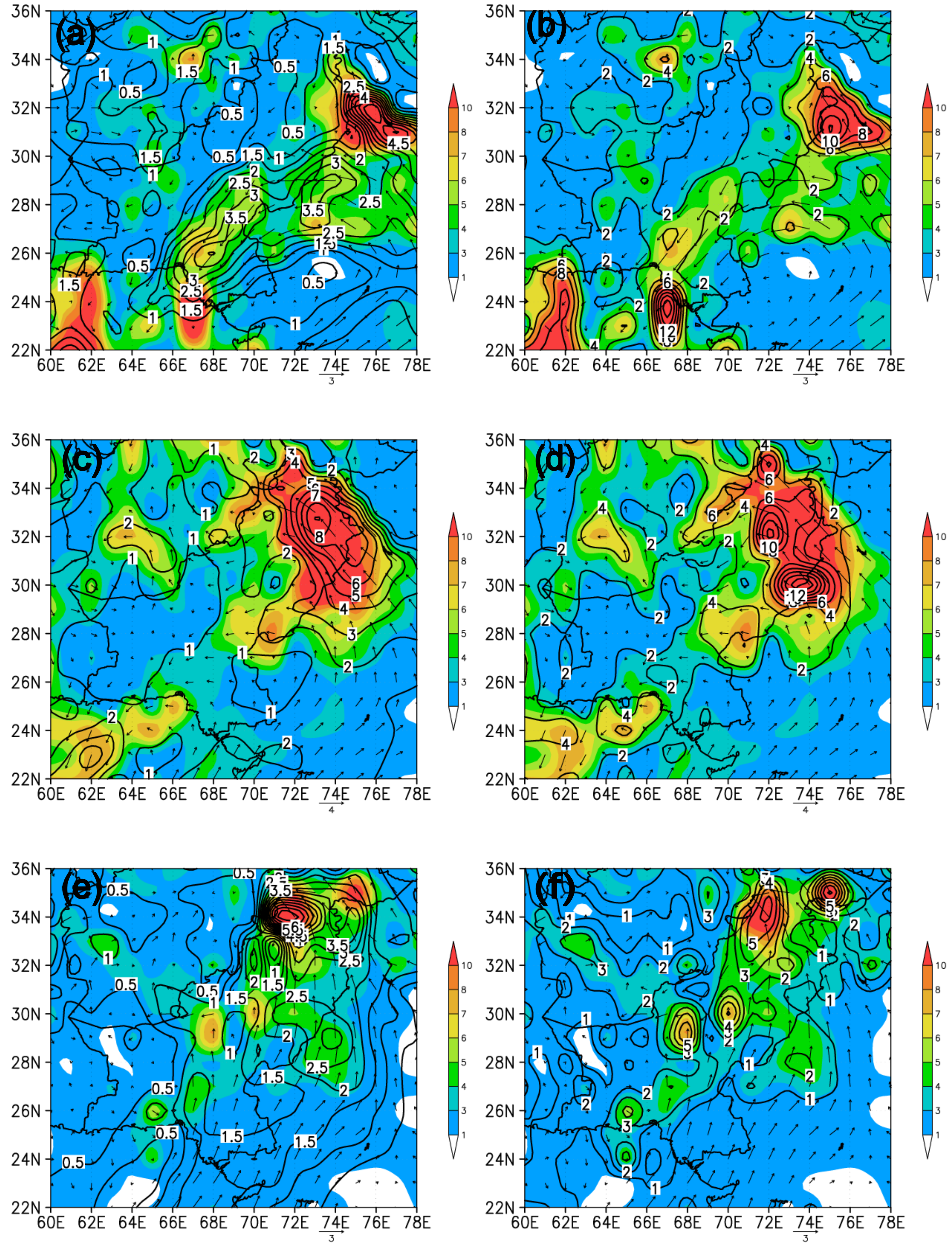
Thus, the amplitude

$$A(x,y,z,t) = \sqrt{P^2(x,y,z,t) + \hat{P}^2(x,y,z,t)} \tag{5}$$

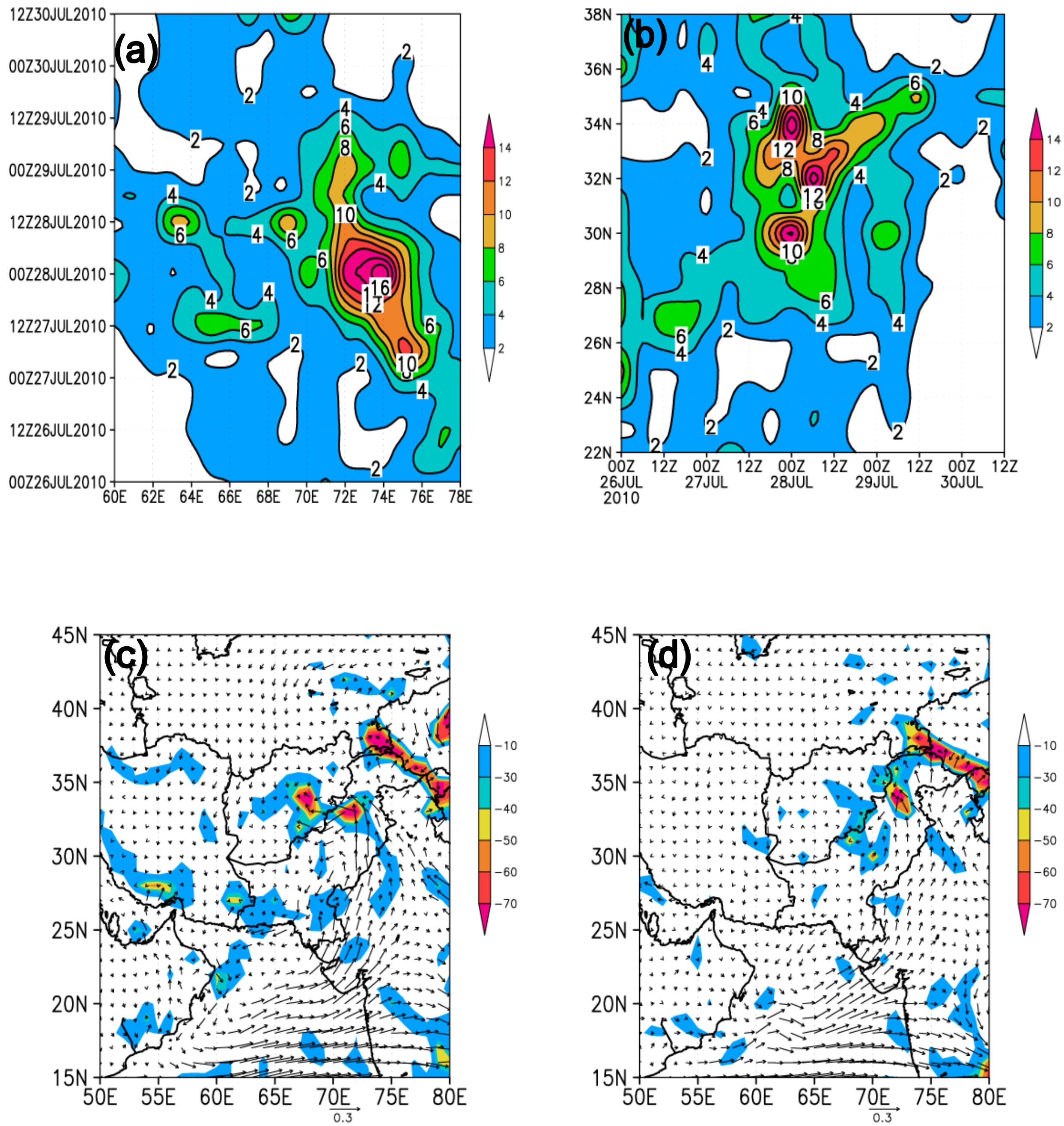
The elastic potential energy can be written as

$$\begin{aligned} E_a &= \frac{1}{2} A^2(x,y,z,t) \\ &= \frac{1}{2}\left\{P^2(x,y,z,t) + \hat{P}^2(x,y,z,t)\right\} \end{aligned} \tag{6}$$

So, from Eqns. (3&6), the energy *E* can be calculated and the characteristics of atmospheric energy conversion may be discussed during heavy rainfall spells.



Figs. 4(a-f). The kinetic energy E_k and potential energy E_a of 700 hPa wind field in the rainfall spells (a) 27th July, 2010 E_k (c) 28th July, 2010 E_k (e) 29th July, 2010 E_k (contour: E_k, shadings: E, vector arrow: 700 hPa wind field) (b) 27th July, 2010 E_a (d) 28th July, 2010 E_a (f) 29th July, 2010 E_a (contour: E_a, shadings: E, vector arrow: 700 hPa wind field)



Figs. 5(a-d). 22°-38° N time-longitude and 60°-78° E time-latitude profile map of energy *E* in 700 hPa wind field (a) time-longitude (26th July to 30th July, 2010) (b) time-latitude (26 July to 30 July, 2010) 850 hPa moisture flux divergence [shadings, unit: $\times 10^{-5}$g/ ($cm^2 \cdot hPa \cdot s$)] and vapor flux (arrow) (c) 28 July, 2010 (d) 29 July, 2010

In this study, the data have been standardized before calculation, hence the obtained value of energy parameters are dimensionless. As the heavy rainfall spell is not adiabatic process, the system energy is not conserved. Usually, the internal energy and latent heat energy may be the substantial reason in the rainfall spell. Moreover, the moisture characteristics of monsoon rainfall are better represented in the lower level, such as 850 hPa and 925 hPa etc. Thus, the moisture flux divergence of 850 hPa is analyzed in this spell. Compared to other low levels such as 850 and 925 hPa, moisture level at 700 hPa is considerably less. Thus, the potential temperature and pseudo-equivalent potential temperature are approximately equal in this level and they are all conserved physical parameters. Thus, the heavy rainfall spell can be approximated as a pseudo-adiabatic process. Heavy rainfall system can be approximated as a conserved energetic system. Hence, the conversion characteristics of energy E are better represented in 700 hPa level.

3. Synoptic situation and precipitation distributions

Figs. 2(a-f) shows the geopotential height patterns in 27-29 July, 2010. These circulations are quite prominent on both 700 and 850 hPa charts as can be clearly seen in the Figs. 2(a-f). The low pressure area present over Indian Gujrat coast seemed to be merged with the heat low present over the Balochistan region of Pakistan. Due to the presence of a strong westerly wave it took a North South orientation. This caused the moisture from Arabian Sea to be shifted to northern parts of the country. Thus adding to the moisture already being pumped in from the Bay of Bengal to the upper parts of the country. This happened due to the presence of another strong cyclonic circulations located over Bay of Bengal. The trough in strong westerly wave to the west of Pakistan with cold and relatively dry air provided all the necessary ingredients for a heavy rainfall spell. The enhanced moisture flow over the region was also evident from the prevailing wind conditions on 27th and 28th July, 2010 at 700 and 850 hPa (not shown). It endorses the earlier findings that usually in Pakistan during the monsoon low level flow from the Arabian Sea is capped by the dry flow from Afghanistan (Houze *et al*., 2007; Medina *et al*., 2010), the strong southeasterly flow during 27-29 July, 2010 produced stratiform raining cloud systems, resulting in devastating rains in the region.

Figs. 3(a-d) indicates distribution of total rainfall and daily rainfall in Pakistan 27-29 July, 2010. During the summer of 2010 Pakistan experienced the most extraordinary pattern of precipitation. Particularly the western parts of the country received heavy rainfall which is quite unusual [Fig. 3(a)]. Precipitation of more than 200 mm was recorded in Azad Kashmir and the provinces of Punjab and Khyber Pakhtunkhwa. Northeastern part of Pakistan received about 50-60 mm of rainfall on 27th July [Fig. 3(b)]. Northeastern and northwestern part of Pakistan received about 100 and 280 mm of rainfall on 28th and 29th July respectively [Figs. 3(c&d)].

4. Characteristics and distributions of atmospheric energy conversion in the rainfall spell

Figs. 4(a-f) shows the distributions of kinetic energy E_k, potential energy E_a and energy E during 27-29 July, 2010. Compared with the precipitation distributions Figs. 3 (a-d), it is obvious that high energy value corresponds to the heavy rainfall region. Moreover, it is apparent that the value of E (shadings) is very high in northwest of Pakistan, yet the distributions of E_k and E_a is different. The value of E_k is much less than E_a in the rainfall area and its distribution is influenced by 700 hPa wind field [Figs. 4(a, c&e)]. The distributions of E_a is similar to E and the heavy rainfall also occurred in this area [Figs. 4(b, d & f)]. It can be concluded from the figure that value of E greater than or equal to 7 corresponds to heavy rainfall.

By analyzing the distributions of E_k and E_a, we can infer that the occurrence of heavy rainfall is associated with energy conversion process. The rainfall area remained under the grip of high energy values. Atmospheric energy is unstable due to moisture transport from Arabian Sea and the Bay of Bengal to Pakistan. The E_a accumulated to a certain extent, through conversion process start releasing through heavy rainfall occurence. The release of potential energy may cause local oscillations, which lead to the heavy rainfall process continued for a considerable amount of time. Hence the conversion of mid level atmospheric energy may be the substantial reason in these heavy rainfall spells.

5. The characteristics of energy propagation and 850 hPa moisture flux divergence in rainfall spell

It is well known that adequate moisture presence has a major role in heavy rainfall occurrences. Figs. 5(c & d) show the characteristics of energy propagation and 850 hPa moisture transportation. The value of 850 hPa moisture flux divergence is above -70×10^{-5} g / cm$^{2}\cdot$hPa$\cdot$s and the ascending motion is also intensive in rainfall area [Figs. 5(c & d)]. As seen in the profile map of E [Figs. 5(a & b)], the energy level is always high and its propagation characteristic is obvious in the heavy rainfall spells. For instance, we can see energy E with zonal distribution shown in Fig. 4(a), where the value of E is above 16 on 28 July. The extremely heavy rainfall has also occurred during this time. With E propagating in the northeasterly direction, moisture is transported to Pakistan constantly which became a continuous source for heavy rainfall in the region.

6. Conclusion

In this study, based on atmospheric energetics theory, we have derived a new energy parameter *E*. Meanwhile, the characteristic of atmospheric energy conversion during heavy rainfall in Pakistan is examined. Atmospheric energy inter-conversion played a significant role during the heavy rainfall period. In the rainfall spells, under the influence of the circulation and terrain conditions, the kinetic energy is converted into potential energy in the form of standing wave. The local oscillation of potential energy also enhanced precipitation. The distributions of E_a was similar to *E* with high energy value corresponds to the heavy rainfall region.

From the energy analysis it can be concluded that when the value of *E* is greater than or equal to 7, the atmosphere jumps from stable to unstable condition thus causing heavy rainfall during monsoon. Energy *E* at 700 hPa, wind field and moisture flux divergence at 850 hPa, all indicate that moisture of this heavy rainfall spell mainly came from Arabian Sea and the Bay of Bengal. It also provided a favorable condition for the continuous occurrence of prolonged duration of heavy rainfall.

The energy factor *E* can be considered as a new parameter of weather analysis. The mechanism of energy conversion requires further extensive research and may prove a significant component for future forecasting of heavy rainfall events.

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