J. Ind. Geophys. Union (January 2007)
Vol.11, No.1, pp.29-45

Diagnostic study of monsoon depression and examination of energetics produced by two schemes (2-D NVA and 3-D NVA) over Indian Region

S.G.Narkhedkar, S.K.Sinha, P.L.Kulkarni, J.R.Kulkarni and P.N.Mahajan
Indian Institute of Tropical Meteorology, Dr. Homi Bhabha Road, Pashan, Pune – 411 008
E-mail : narkhed@tropmet.res.in

ABSTRACT
Following Sasaki (1958) two objective analysis schemes viz. two dimensional Numerical Variational Analysis (2-D NVA) and three dimensional Numerical Variational Analysis (3-D NVA) have been developed by Sinha, Narkhedkar & Rajamani (1998); Sinha et al., (2003) and Narkhedkar & Sinha (2000) over India and adjoining region. NVA is the scheme that produces the analysed data in balance. The 2-D NVA uses geopotential height and wind data simultaneously to produce analysed height and wind field at grid points whereas 3-D NVA allows temperature data to influence the analysis of height and wind fields. Both the schemes have been tested for two to three synoptic situations and have performed well in depicting the systems. In this study the performances of these two analysis schemes in context with energetics have been assessed in depicting the features of the synoptic scale systems viz. Tropical Easterly Jet, Sub Tropical Westerly Jet etc. prevailing over Indian and adjoining region in the monsoon season. The analyses produced by these two schemes have been examined to study the energetics of a monsoon depression which formed over head Bay of Bengal. The energy terms viz. available potential and kinetic energy (both zonal and eddy part) and their conversion terms have been computed. The analyses of these terms for both schemes showed that they are in well accordance with the earlier studies made by other researchers over Indian region. The analyses produced by both the schemes were able to depict the system very well in context with the energy terms that have been computed from the analysed field produced by them. However, due to the inclusion of temperature field 3-D NVA scheme has produced higher values of energy terms compared to 2-D NVA scheme. The influence of analysed upper and lower tropospheric temperature fields on the energy terms in generation of the energy and maintaining the circulation patterns have been studied critically. It has been observed that during the period of depression the north-south temperature gradient was prominent at upper levels.

INTRODUCTION

The characteristics of atmospheric disturbances are generally determined by large-scale environment and energy sources. Since the tropics receive the major portion of solar energy on the earth, the condensation heating released by cumulus convection constitutes the main energy source of synoptic disturbances in the tropics, Wiin-Nielsen & Chen (1993). During the monsoon season, a number of monsoon disturbances (monsoon lows and depressions) move westward across India from the Bay of Bengal. Godbole (1977) constructed the composite three-dimensional structure of five monsoon depressions during July-September 1973 over India, where observations were available. However, because of lack of quality observational data, the energy analysis of a monsoon depression did not produce consistent results. Krishnamurti et al., (1976) used a multi-level primitive equation model to perform a 48-hr forecast of a well-developed monsoon depression over India during 4-8 August 1968. They carried out the energy analysis with the forecast simulation. They concluded that structure and energetics of monsoon depressions over the land may differ from those over the Bay of Bengal during the formation stage.

The correlation between the thermal structure and the vertical motion in the monsoon depressions is well established and suggests that warm air rises to the west and cold air sinks to the east of the depressions. Saha & Chang (1983) pointed out that the geopotential and temperature fields of the monsoon depressions have a phase lag such that the afore mentioned secondary divergent circulation can be related to warm-air advection from the northwest sector of the depression and cold-air advection from the southeast sector. The release of available potential energy by the thermally direct overturning is one of the important energetics processes maintaining the monsoon depression. To maintain the thermal structure of monsoon depression a supply of available potential energy through its generation by condensation heating may be one of the possible sources to counterbalance the release of available potential energy by the thermally direct overturning.

Taking into account the studies and the outcomes of the research carried out by different researchers mentioned above an attempt has been made here to test and study the analyses produced by 2-D and 3-D NVA for their consistency in context with energetics. The Numerical Weather Prediction (NWP) models require the data at equally spaced grid points that are generated with the help of objective analysis methods. There are at least two objective analysis methods in which the mass and motion fields are used to produce the balanced analysed data. One is Multivariate Optimum Interpolation scheme (MOI), multivariate version of the Optimum Interpolation scheme first formulated by Gandin (1963). The other method is Numerical Variational objective Analysis (NVA), which was first formulated by Sasaki (1958) by applying the technique of calculus of variation by subjecting the meteorological variables to dynamical constraints. The 3-D NVA analysis used here has its own importance because i) it was produced at regional level, ii) was able to capture the regional synoptic features of the monsoon depression and moreover iii) the height, wind and temperature fields were in balance.

DATA AND SYNOPTIC SITUATION

The wind and height analyses produced by 2-D NVA and 3-D NVA have been used to compute different energy terms and the conversion terms. The station data and initial guess data used were same for both the schemes. The analyses were produced by both the schemes using NCMRWF grid point (2.5° x 2.5°) data as first guess and available radiosonde station data over the domain under study (0° to 35°N and 60° to 110°E). The analyses were produced for all standard isobaric levels viz. 1000, 850, 700, 500, 300, 200, 100 hPa. The period of the study chosen was 26 to 30 July 1991. The temperature field at the grid point for all levels was derived from the analysed geopotential height data. This temperature data was used to compute the energy terms.

The energy terms, viz. zonal available potential energy (A_Z), eddy available potential energy (A_E), zonal kinetic energy (K_Z), eddy kinetic energy (K_E) and the energy conversion terms (A_Z, K_Z), (A_Z, A_E), (A_E, K_E), (K_Z, K_E) for the above period were computed using the objectively analysed balanced height and wind data produced by 2-D NVA and 3-D NVA schemes.

During the period 26 to 31 July 1991 a cyclonic circulation extending up to the mid-tropospheric level was observed on 25 July over the North Bay and the adjoining Central Bay. Under the influence of this cyclonic circulation a low pressure area was formed over the Northwest Bay and surroundings on 26 July. It concentrated into a depression with its center at 20.5° N and 89.5° E on 27 July. On the next day, it further intensified into a deep depression with its center about 150 km Southeast of Kolkata (21.5°N, 88.0°E). It crossed the Orissa coast near Paradeep on 29 July and lay over North Orissa, adjoining Bihar Plateu and East Madhya Pradesh. It moved in westnorthwest direction and on 30 July it was lying over the central parts of Madhya Pradesh (centred at 22.5° N, 80.0° E). It weakened into a depression with its center at 21.5° N, 76.5° E on 31 July.

NUMERICAL VARIATIONAL ANALYSIS SCHEME

Following Sasaki (1958), a 2-D NVA scheme was developed by Sinha, Narkhedkar & Rajamani (1998) over Indian region to analyse height and wind field using geostrophic relation as diagnostic constraint. The scheme has been tested for couple of synoptic situations, Sinha, Narkhedkar & Rajamani (1998) and Narkhedkar & Sinha (2000). 2-D NVA has been further extended to include temperature (3-D NVA) based on the assumption of quasi-geostrophic and thermal wind conditions, Sinha et al., (2003).

Variational scheme

In regard to variational optimization of meteorological parameters the functional constraints considered were quasi-geostrophic and thermal wind equations. The geopotential increment (ϕ') can be obtained by solving the following equation (for details refer Sinha et al, 1998).

$$\nabla^2\phi' - \left(\frac{\beta_1}{\alpha_1} f\right)^2 \phi' = f\,\zeta^0 + \left(\frac{\gamma_1}{\alpha_1} f\right)^2 \frac{\partial T^0}{\partial p^*} - \nabla^2\phi^0$$

For two dimensional case, above equation reduces to

$$\nabla^2 \phi' - \left(\frac{\beta_1}{\alpha_1} f\right)^2 \phi' = f\,\zeta^0 - \nabla^2 \phi^0$$

where α_1, β_1 and γ_1 are weights and

$$\zeta^0 = \frac{\partial v^0}{\partial x} - \frac{\partial u^0}{\partial y}$$

is the relative vorticity of the observed wind and the three dimensional Laplacian operator is given by

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \left(\frac{\gamma}{\alpha} f\right)^2 \frac{\partial^2}{\partial p^{*2}} \quad \text{where} \quad p^* = -R \ln\left(\frac{p}{P}\right)$$

where f is the coriolis parameter, ϕ^0 is observed geopotential and P is the pressure at some reference level. u^0, v^0 are observed u and v-component of wind and observed temperature is denoted by T^0.

DISCUSSION

Energetics of monsoon depression

To study the maintenance of the monsoon depression, the energy and the energy conversion terms were computed using the wind analyses produced by both the schemes described above. The computations were made over a limited region. There are several researchers viz. Krishnamurti et al., (1976); Murakami (1977); Rajamani (1985); Rajamani & Kulkarni (1986); Rajamani & Sikdar (1989) who studied the energetics of limited regions during the summer monsoon. Following Murakami (1977); Lorenz (1955); Oort (1964); Smith (1969); Tripoli & Krishnamurti (1975) the energy terms viz. available potential and kinetic energy (both zonal and eddy part) and their conversion terms have been computed. The necessary equations for computations of energy terms and energy-transformation terms are:

$$A_Z = \frac{C_p}{2} \int_M \gamma \left[(T) - \{T\}\right]^2 dM$$

$$A_E = \frac{C_p}{2} \int_M \gamma \left[T^{*2}\right] dM$$

$$K_Z = \frac{1}{2} \int_M \left([u]^2 + [v]^2\right) dM$$

$$K_E = \frac{1}{2} \int_M \left(\left[u^*\right]^2 + \left[v^*\right]^2\right) dM$$

$$C(A_Z, A_E) = -C_p \int_M \gamma \left\{ \left[v^* T^*\right] \frac{\partial}{\partial y}[T] + \left[\omega^* T^*\right] \frac{\partial}{\partial p}[T] \right\} dM$$

$$C(A_Z, K_Z) = -R \int_M \frac{1}{p} \left([\omega] - \{\omega\}\right)\left([T] - \{T\}\right) dM$$

$$C(A_E, K_E) = -R \int_M \frac{1}{p} \left[\omega^* T^*\right] dM$$

$$C(K_Z, K_E) = -\int_M \left\{ \left[u^* v^*\right] \frac{\partial}{\partial y}[u] + \left[u^* \omega^*\right] \frac{\partial}{\partial p}[u] + \left[v^* \omega^*\right] \frac{\partial}{\partial p}[v] + \left[v^* v^*\right] \frac{\partial}{\partial y}[v] \right\} dM$$

where $\gamma = -\frac{\theta}{T} \frac{R}{C_p P} \left(\frac{\partial \theta}{\partial p}\right)^{-1}$

C_p = *Specific Heat at constant pressure*
R = Gas constant
P = Pressure in hPa
T = Temperature over the limited region which is considered for the study.
u = x component of wind vector (eastward)
v = y component of wind vector (northward)
ω = *Vertical wind component (dp/dt) in isobaric coordinates*
A = *Total Available Potential energy (APE)*
A_Z = Zonal APE
A_E = Eddy APE
K_Z = Zonal Kinetic energy
K_E = Eddy Kinetic energy
C (A_Z, A_E), C (A_Z, K_Z), C (A_E, K_E), C (K_Z, K_E) are the corresponding energy conversion terms.
M is mass of the atmosphere over the area under study, square brackets are the zonal mean and a star(*) represents the deviation from the zonal mean.

Fig.1 (a-d) and Fig.2 (a-d) depict the vertical cross-sections of mean A_Z, A_E, K_Z, K_E for 3-D NVA and 2-D NVA scheme respectively. From Fig.1 (a) it can be clearly seen that the A_Z was concentrated between 8 to 18° N and between 24 to 32° N at upper levels (300-100 hPa) and at lower levels (1000-850 hPa). Fig. 1(b) depicts the A_E where it was observed that energy maxima at 200 hPa and 1000 to 850 hPa between 20 to 32° N. The figure was able to show the significantly high values over the region of monsoon trough and around the latitudes where the depression formed and moved. Fig.1(c) shows K_Z. This figure was able to show the existence of low level jet at 850 hPa at 12° N, easterly jet around 10 to 15° N and subtropical westerly jet between 300-100 hPa levels. The low level jet and easterly jets are characteristic features of monsoon circulations. Fig.1(d) suggests that in the lower troposphere over 16-18° N and at 200 to 100 hPa between 18 to 30° N there were high values of K_E. In lower troposphere also the higher values were seen in the region where the system was formed (around 15° N). The presence of higher values at 300 hPa may be due to extra tropical systems in the westerlies and the movement of the monsoon depressions respectively. Almost similar features were seen for 2-D NVA scheme for kinetic energy terms but for available potential energy there were marked differences in the magnitudes of the energy terms for

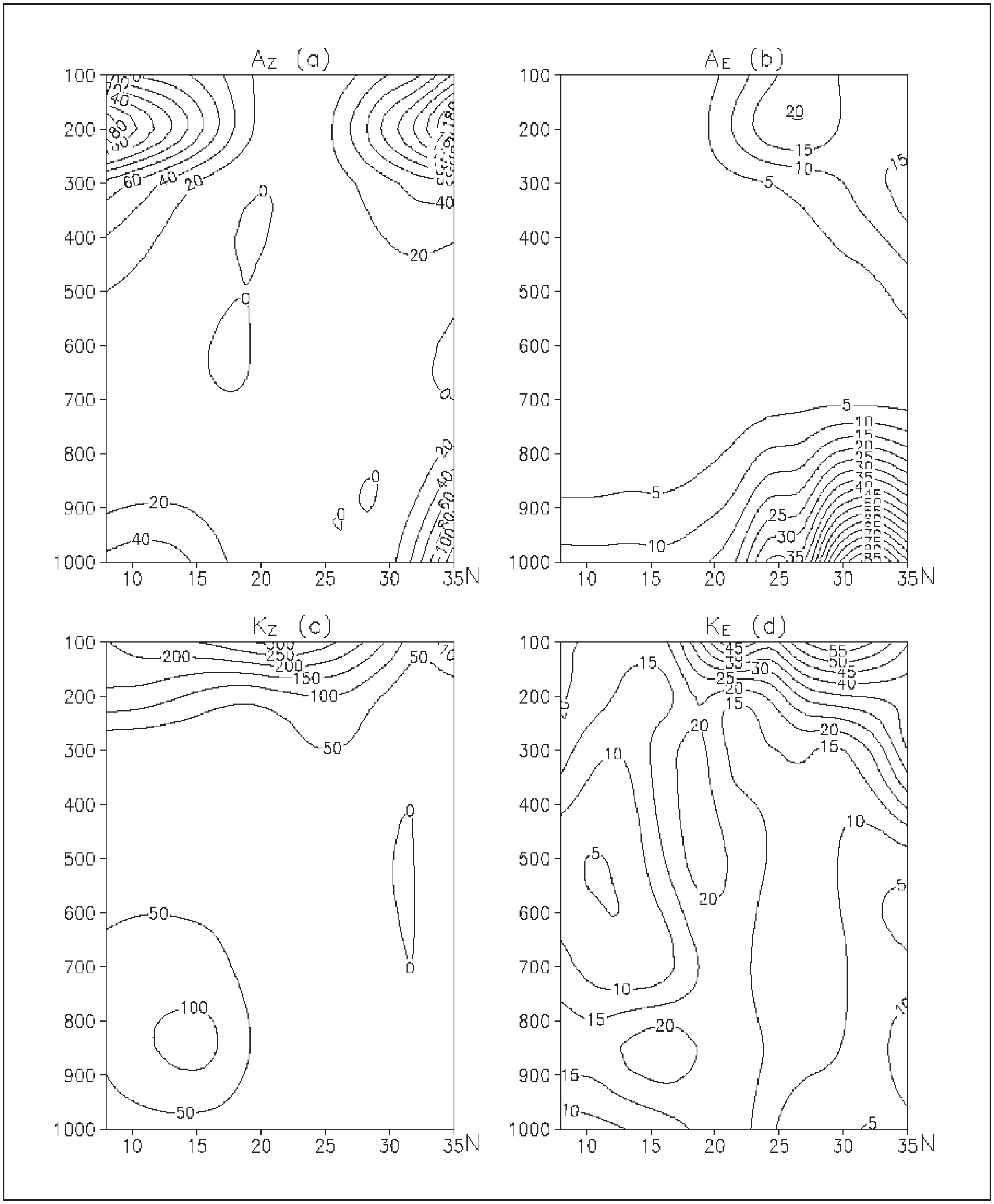

Figure 1 (a-d). Analysis for different energy terms a) Zonal available potential energy, b) Eddy available potential energy, c) Zonal kinetic energy, d) Eddy kinetic energy for 3-D NVA in m^2/s^2.

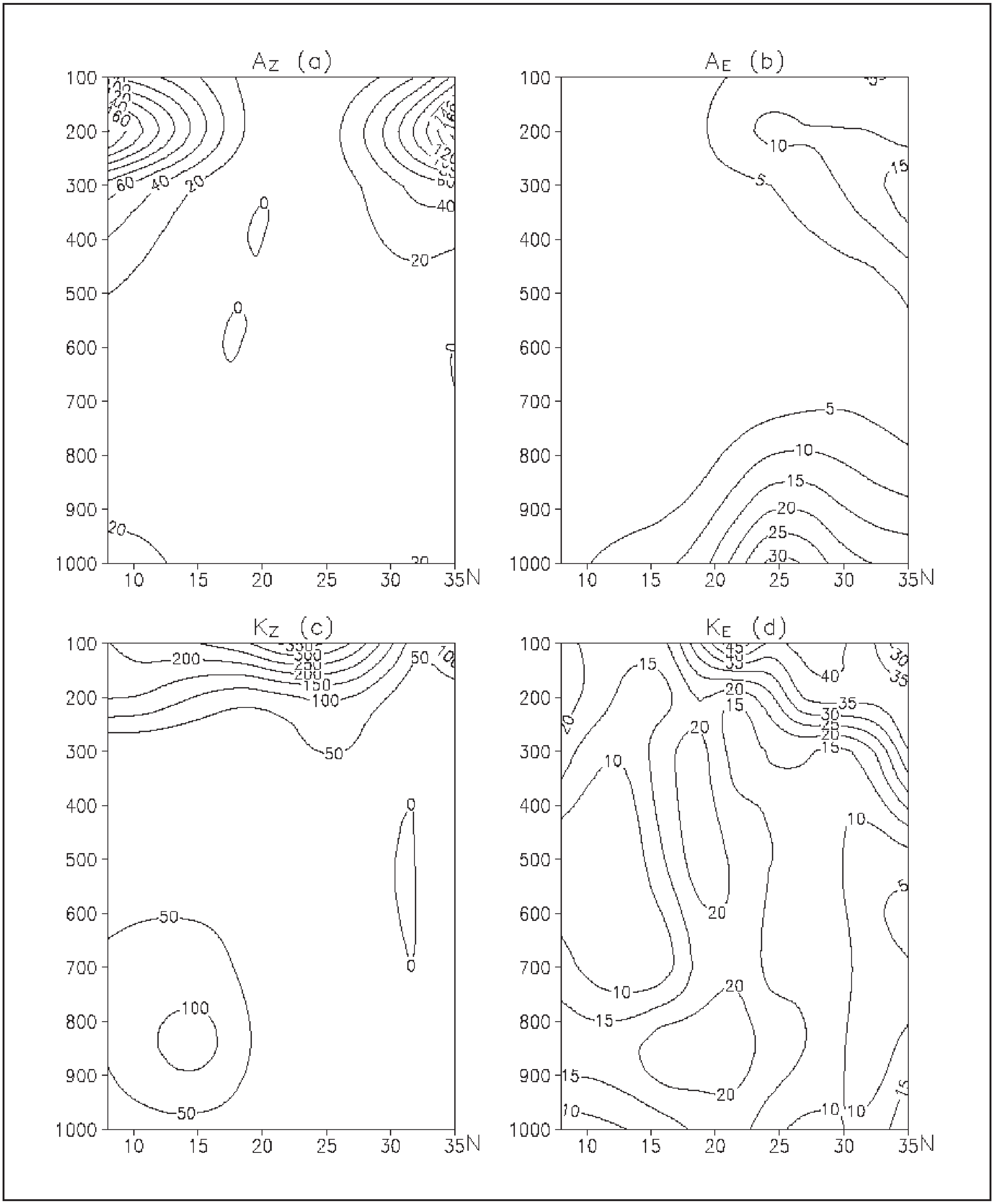

Figure 2 (a-d). Analysis for different energy terms a) Zonal available potential energy, b) Eddy available potential energy, c) Zonal kinetic energy, d) Eddy kinetic energy for 2-D NVA in m^2/s^2.

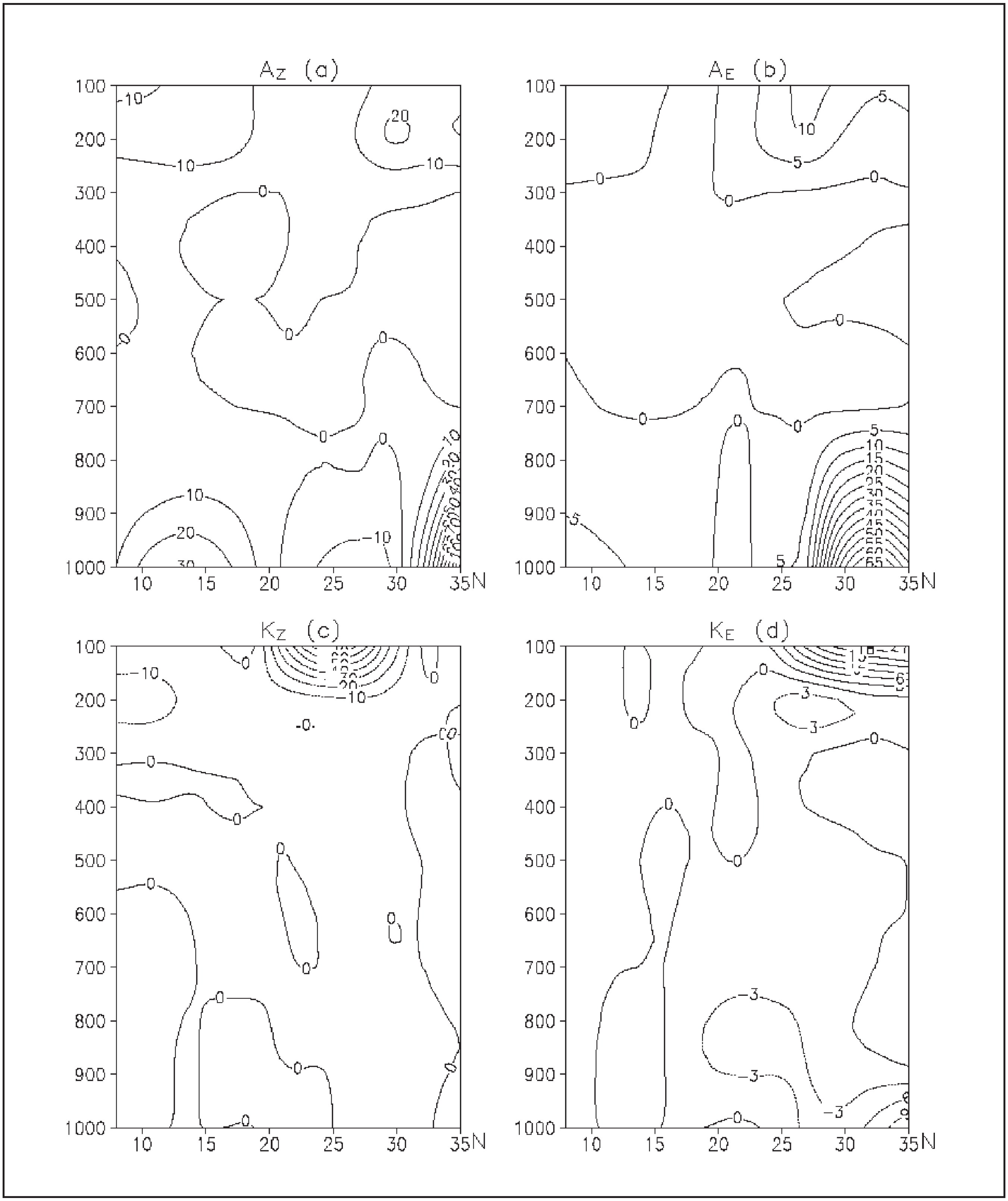

Figure 3 (a-d). Difference between the analysis of 3-D NVA scheme and 2-D NVA scheme for different energy terms a) Zonal available potential energy, b) Eddy available potential energy, c) Zonal kinetic energy, d) Eddy kinetic energy in m^2/s^2.

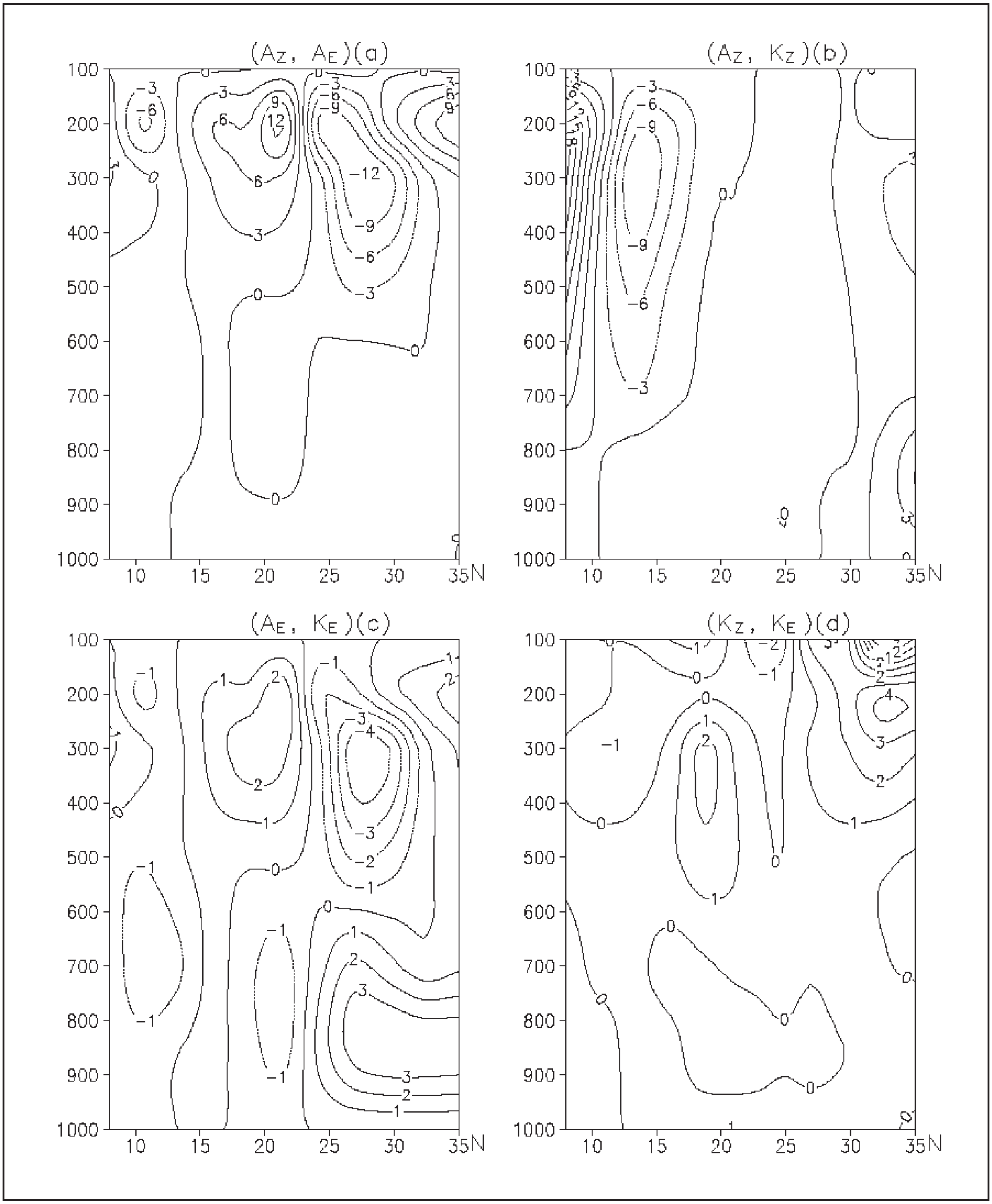

Figure 4 (a-d). Analysis for the conversion rate for energy terms a) (A_Z, K_Z), b) (A_Z, A_E), c) (A_E, K_E), d) (K_Z, K_E) for 3-D NVA in m^2/s^3*10^{-5}.

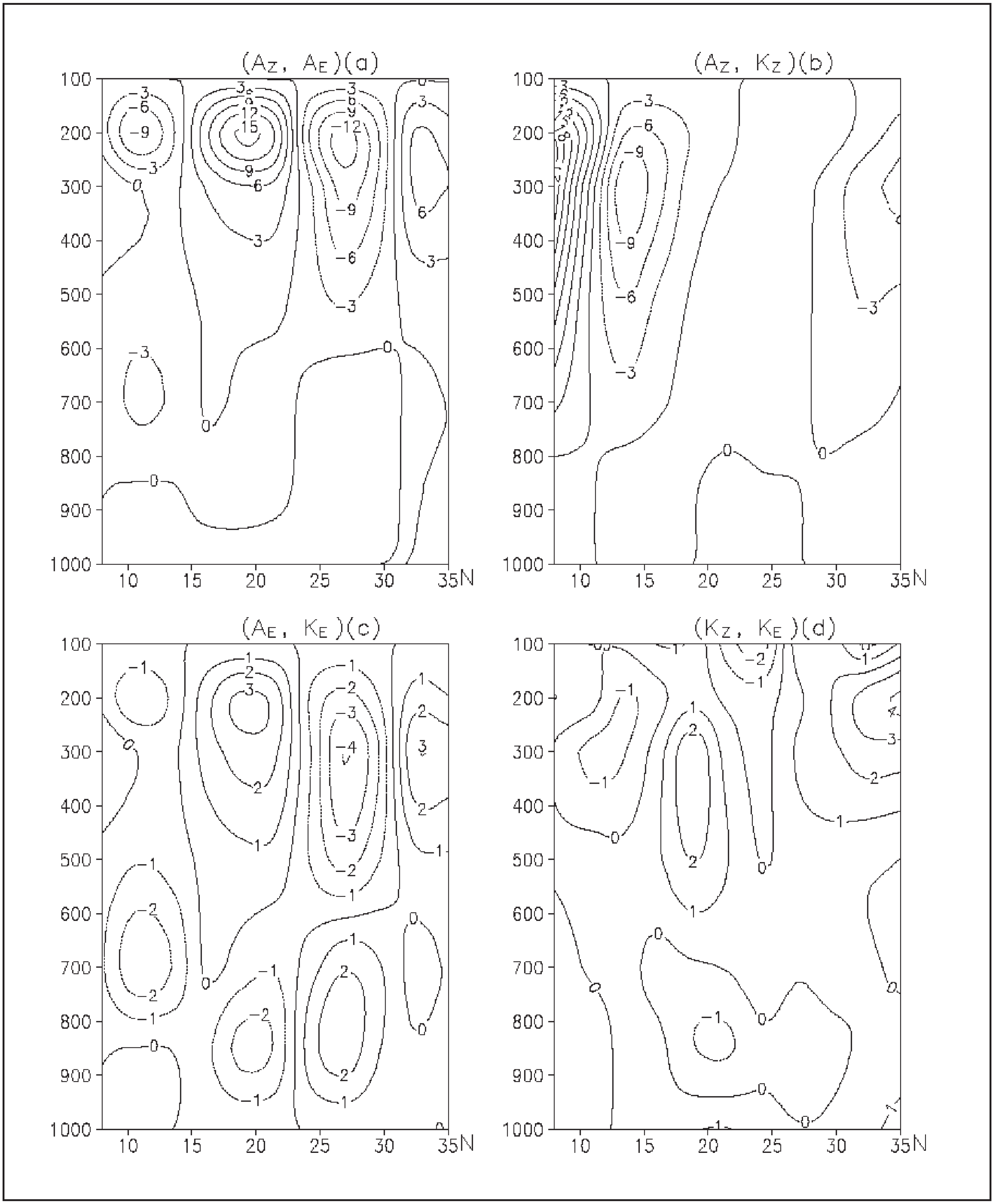

Figure 5 (a-d). Analysis for the conversion rate for energy terms a) (A_Z, K_Z), b) (A_Z, A_E), c) (A_E, K_E), d) (K_Z, K_E) for 2-D NVA in m^2/s^3*10^{-5}.

both zonal and eddy parts (Fig. 2(a-d)). Fig. 3 (a-d) depicts the analysis of difference between the analyses of the energy terms of 3-D NVA and 2-D NVA scheme. The difference was the subtraction of 2-D NVA from 3-D NVA analysis. Inclusion of temperature field in 3-D has added more depth in the analysis of available potential energy. This was expected as the equations for computing A_Z and A_E contains temperature terms. The contour difference (positive) was between the range 5 to 100 which proved the usefulness of the 3-D scheme over 2-D scheme.

Fig. 4(a-d) and Fig. 5(a-d) represent the vertical cross section of conversion rate of different energy terms for 3-D and 2-D NVA scheme respectively. The terms mentioned in the bracket as (A_Z, A_E) represent the conversion of energy from A_Z to A_E and if the sign is positive then there is conversion from A_Z to A_E. But if the conversion is from A_E to A_Z then negative is assigned for this type of conversion. Fig. 4(a) is conversion of (A_Z, A_E). The conversion is due to meridional transport of heat. The figure shows that in most parts between 12 to 22° N and 26 to 32° N, there has been conversion from A_Z to A_E and between 8 to 10° N and 22 to 28° N there has been conversion of A_E to A_Z. The maximas were seen at upper levels, one at 300 hPa (A_E to A_Z) and another at 200 hPa (A_Z to A_E). The available potential energy was converted into kinetic energy when the warm air rises and/or cold air sinks and kinetic energy was converted into available potential energy when the warm air sinks and/or the cold air rises due to dynamical or orographical forcings. Fig. 4(b) shows that there is conversion of (A_Z to K_Z) over the entire region except the region between 10 to 14° N from 700 to 150 hPa level. Fig. 4(c) shows that A_E was converted into K_E over the region 12 to 16° N and 22 to 32° N. The two maximas of this conversion were seen at 300 hPa (around 18° N) and at 850 hPa (26° N). There was conversion of K_E to A_E over the region 22 to 28° N. The maxima of this conversion was seen at 300 hPa level. From this figure it was seen that there were mixing of conversion from both sides. This may be due to the dynamical forcing which might have forced the rising of cold air or the sinking of warm air or both. Fig. 4(d) shows the conversion of (K_Z to K_E) which prominently depicts the positive conversion of (K_Z to K_E) over the entire region. The two maximas were seen at 400 and 300 hPa level. In the entire region zonal current looses kinetic energy to eddy current. Fig. 5(a-d) depicts the conversion rates for energy terms of 2-D NVA scheme. The figure shows the similar analysis features as Fig. 4(a-d). Fig. 6(a-d) shows difference between the analyses produced by two schemes for the energy conversion terms. As can be seen from the Fig. 6(a, b, c), there are positive contour values suggesting the impact of inclusion of temperature field in the 3-D NVA scheme. Fig. 6(d) did not show noticeable difference as it shows the conversion between the K_Z to K_E which did not contain any temperature term.

Fig. 7(a-d) shows the vertically integrated values of different energy terms and conversion terms for both the schemes. It shows the daily variation of the energy terms and the conversion terms. It can be seen that the values of zonal available potential energy were maximum and carried much more energy over the region of monsoon depression. On 26 July when it was low the values of A_Z were maximum and decreased when it became depression for both the schemes, Fig. 7(a). The values for K_Z increased on 27 but again decreased by 29 July. On 30 July it again increased. The maximum values of K_Z [Fig. 7(c)] on 27 (depression) were supported by the lowest values of OLR, Fig. 10.

The variation of the vertically integrated energy conversion terms with time for the period 26 to 30 July 1991 has been presented in Fig. 7(e-h). When the conversion terms were compared it was observed that the magnitudes of these conversion terms for 3-D NVA were more than 2-D NVA in the case of (A_Z, A_E) and (A_E, K_E).

The conversion of available potential energy is mostly from zonal current (which was proportional to the north-south temperature variance) to the eddies due to sensible heat transport down the gradient. Rajamani & Sikdar (1989) studied some of the dynamical characteristics and the thermal structure of the monsoon depressions formed during July-August 1979 in the Bay of Bengal. On the basis of the computational study of the energetics they showed that the A_Z was the source for A_E. This in turn, was converted into K_E on most of the days during the life cycle of monsoon depression. K_E was converted into K_Z on many days, thus maintaining the monsoon current. They also found that the monsoon systems contain maximum energy at the 300-200 hPa levels with a secondary maximum at the 850-700 hPa levels. The A_E, K_Z, K_E and energy conversion rates all increase with the strengthening of the monsoon depression and then start decreasing during weakening of the systems. The analyses of the energy terms produced by 3-D NVA and 2-D NVA were able to show the similar features as mentioned above.

In the present study it was observed that, frequently eddy available potential energy was converted into eddy kinetic energy by the rising of warm air and sinking of cold air. But sometimes it was observed that there was conversion from zonal

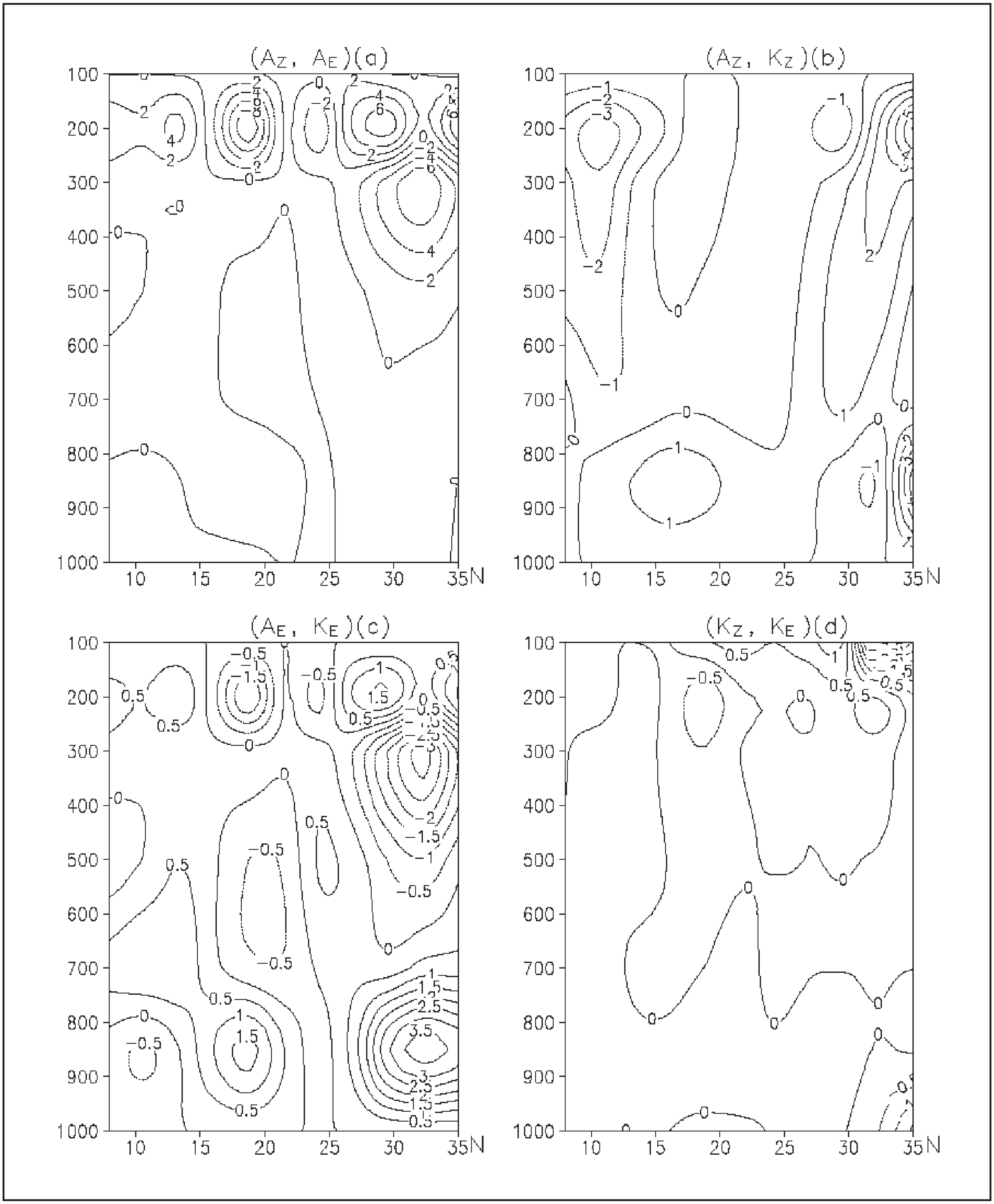

Figure 6 (a-d). Difference between the analysis of 3-D NVA scheme and 2-D NVA scheme for the conversion rate of energy terms a) (A_Z, K_Z), b) (A_Z, A_E), c) (A_E, K_E), d) (K_Z, K_E) for 2-D NVA in m^2/s^3*10^{-5}.

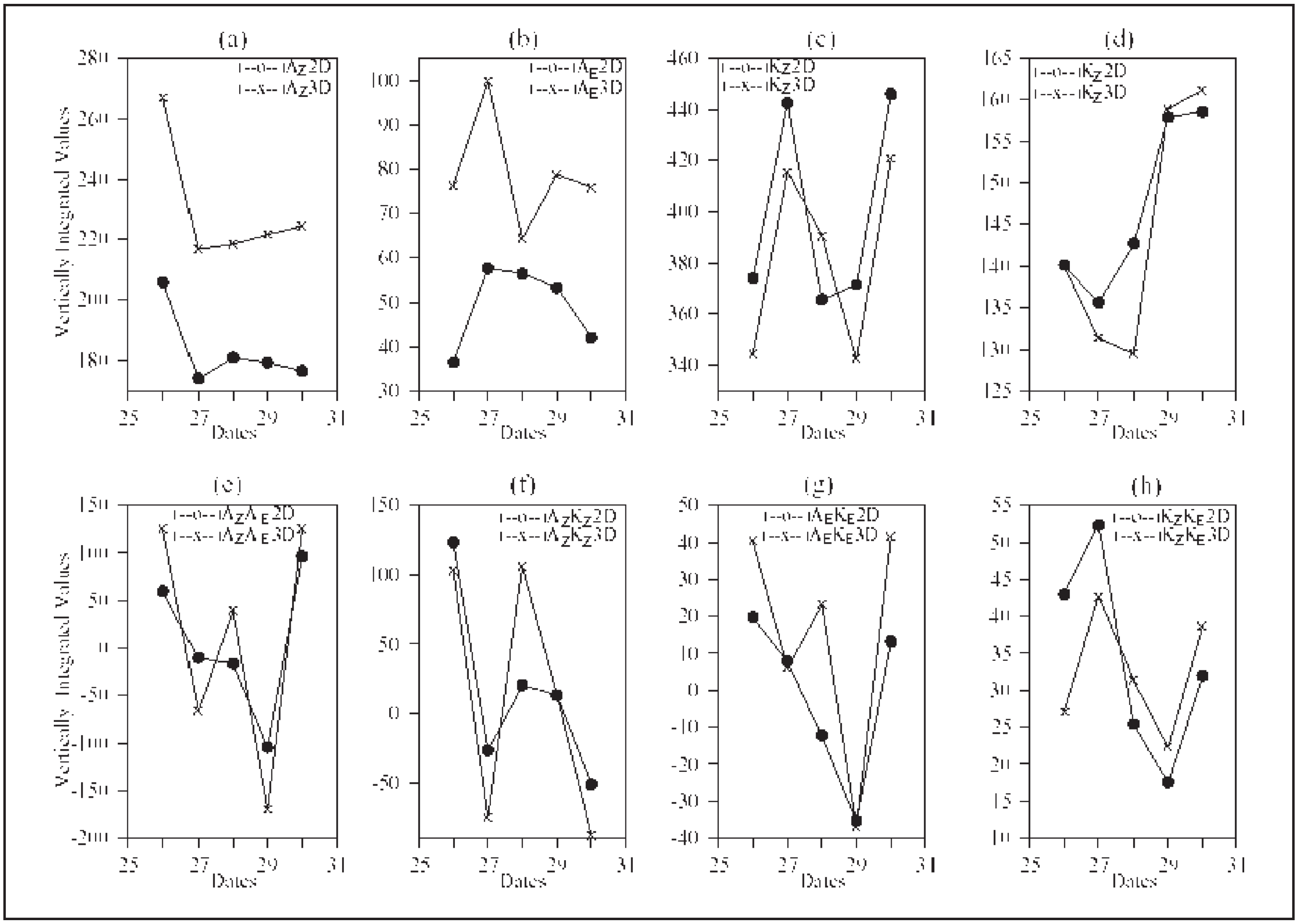

Figure 7 (a-h). Plot for the vertically integrated values with the time axis for energy terms and conversion terms for both the schemes.

kinetic energy to zonal available potential energy. Moorthi & Arakawa (1985) have also investigated theoretically baroclinic instability with cumulus heating for basic zonal flows similar to the summer monsoon flow. They found the conversions to be from zonal available potential energy to eddy available potential energy and from eddy available potential energy to eddy kinetic energy.

Temperature Field

After studying the energy terms, temperature field was looked into during the formative stage of monsoon depression. From the climatological point of view in July an anticyclone at 500-200 hPa level plays a very important role in the development of the depression over head Bay of Bengal provided they are at their normal positions. In the present study the grid point temperature data at 500 to 200 hPa levels were obtained from NCMRWF, Noida. Changes in the upper air temperature during formation, development and maintenance of the system were studied using this data.

Narkhedkar & Kulkarni (2000) studied the upper air temperature analysis produced at various research centers (NCMRWF, NCEP/NCAR) for different synoptic situations (2-8 August 1988, 26-30 July 1991, 15-18 July 1993, 6-10 August 1999). They concluded that the analyses were able to bring out the favorable shift of the Tibetan anticyclone and strong meridional temperature gradient before the formation of monsoon depression and also the development and maintenance of the system consistent with the synoptic observations.

While studying the temperature field emphasis is given on the formative stage of monsoon depression therefore only analysis of 26 July 1991 has been discussed here. On 26 July 1991 temperature analysis showed that the highest temperatures at 500, 300 and 200 hPa levels were at normal positions and their magnitudes were above normal i.e. 274°A at 500 hPa, 250°A at 300 hPa and 229°A at 200 hPa [Figure 9(a-c)]. As already mentioned earlier, on 26 July the low was formed, which supports the observation of favourable shift of position of Tibetan anticyclone before the formation of depression. On 27 July (depression) the temperature distribution was such that there was warm air advection from north and cold air advection from south. There was indication of system formation in north Bay. This has been reflected in the increase of rainfall amounts. These features were supported by the observational studies i.e. low level cyclonic vorticity, moisture convergence and vertical motion which leads to cloud formation, heavy rainfall and release of latent heat (diabatic heating) and these were responsible for development and maintenance of the system. This was observed in cloud pictures. It also shows that the upper tropospheric flow has profound influence on lower troposphere from the point of view of cyclogenesis.

It was seen from the cloud pictures and in Indian Daily Weather Report (IDWR) that since 21 July 1991 disturbed weather conditions were prevailing over Bay of Bengal region. Fig 8 shows the daily variation of the all India daily rainfall value along with daily long term normal values. These values were taken from the Indian daily weather summary published by India Meteorological Department (IMD). The number of observations is not same for all days. The plot suggests that there was lot of rainfall activity over the region which has caused release of latent heat which might have increased the upper air divergence over the region and ultimately may become the source of energy in the generation of next cyclonic disturbance over the region.

OLR analysis

The analysis of OLR data acquired from NCEP/NCAR was looked into to support the analysis of energy terms. OLR analysis was able to pick up the convective areas where the low OLR values were observed (Fig.10). There was clear cut movement of these convective areas with the movement of weather disturbance. The lowest OLR values in W m^{-2} observed are: on 26 July (LOW)-120, 27 July (Depression)-100, 28 July(Deep Depression)-120, 29 July (Depression)-120, 30 July (Depression)-120. There was one day lag between the maximum convective activity (27 July) and maximum intensity of the depression (28 July). These were supported by the cloud picture which showed more brightness on 27 July. The cloud pictures of INSAT [Fig.11(a-e)] and OLR analyses match very well in space and time with the movement of the system.

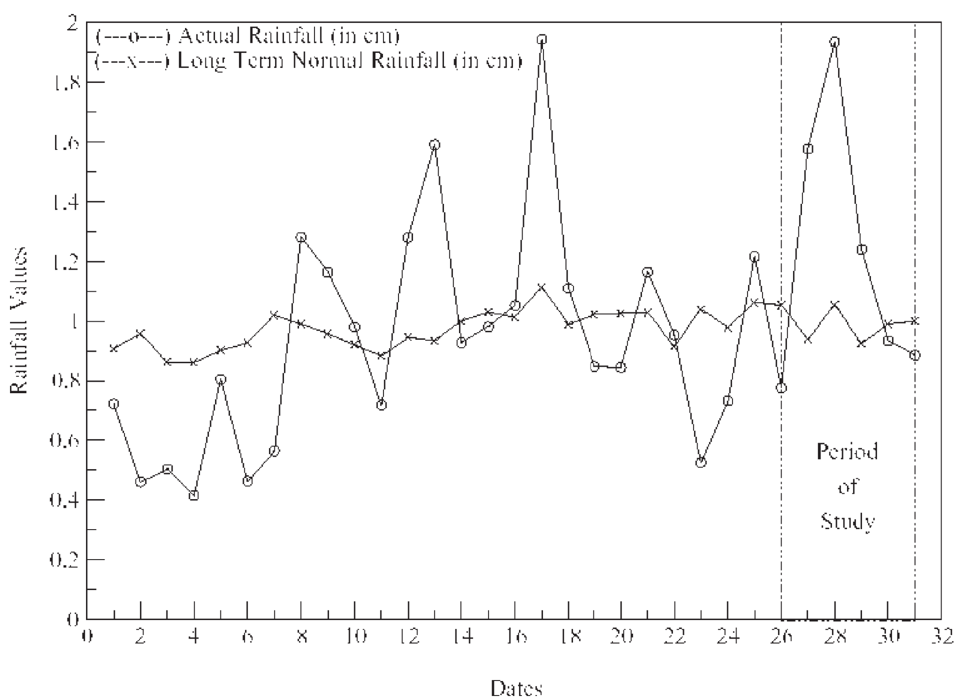

Figure 8. Plot for the all India daily rainfall value along with the long term daily normal values for the July 1991.

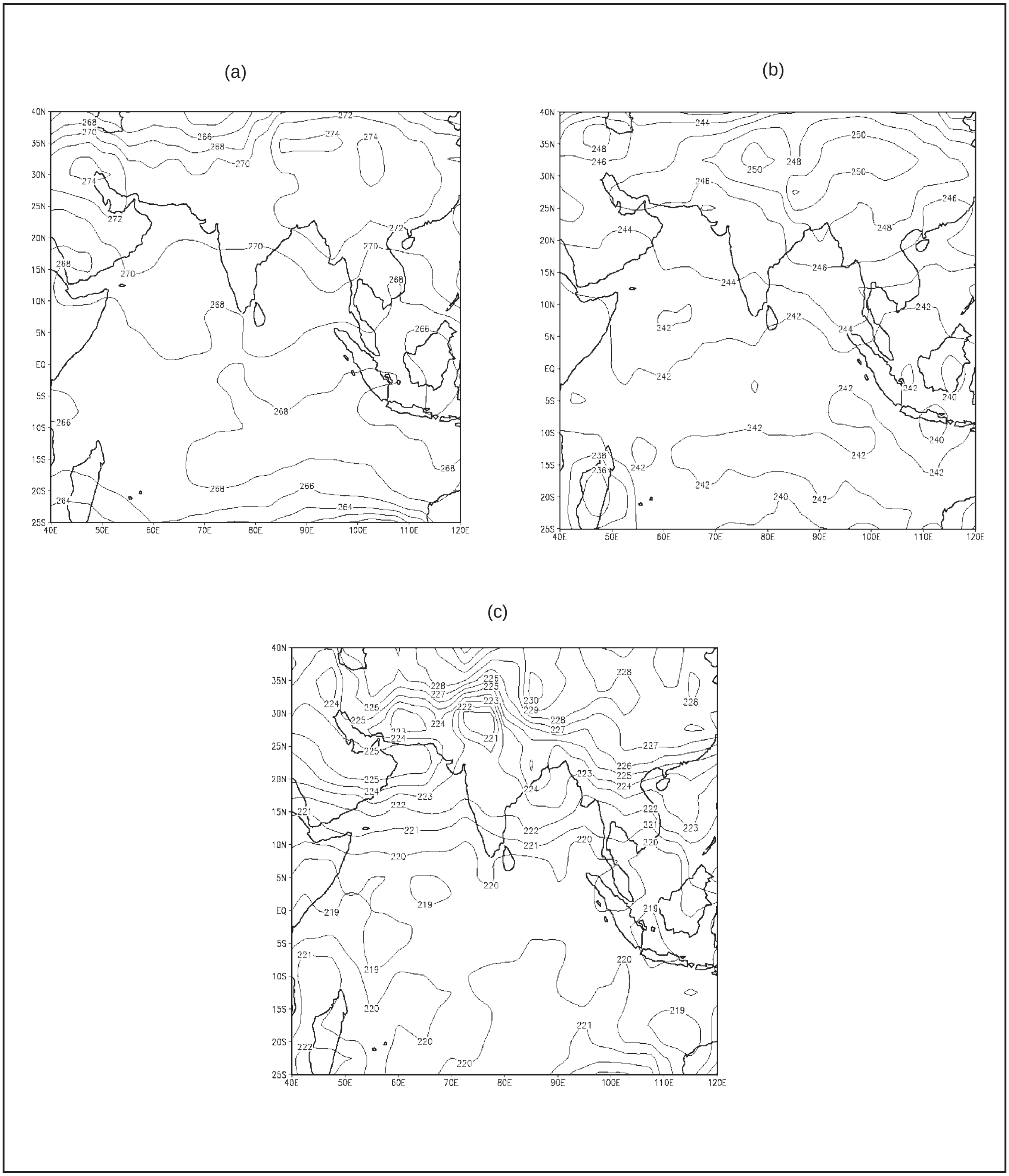

Figure 9 (a-c). Temperature analysis for 26 July 1991 at 500, 300 and 200 hPa levels.

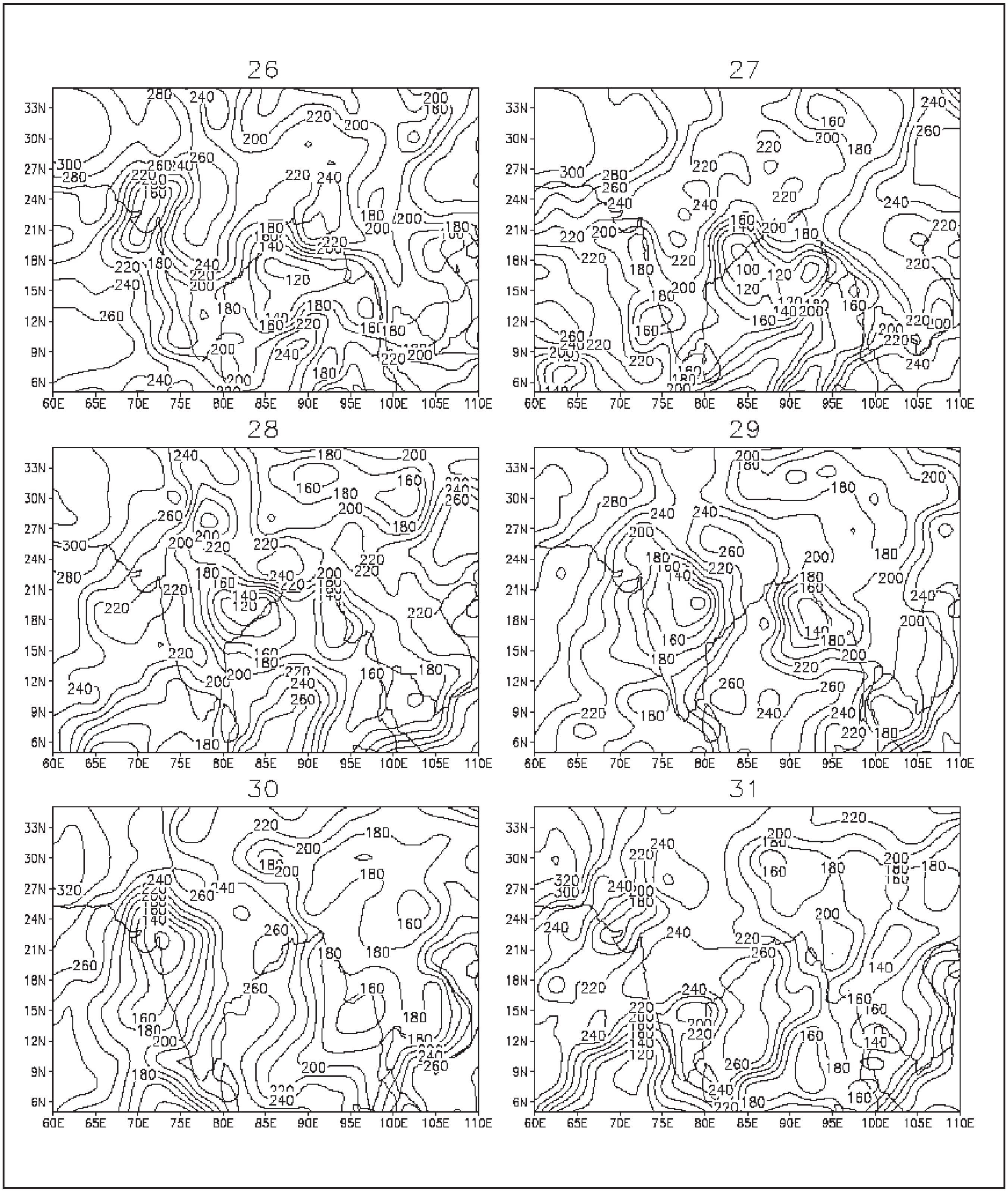

Figure 10. OLR (W m^{-2}) analysis for 26-31 July1991.

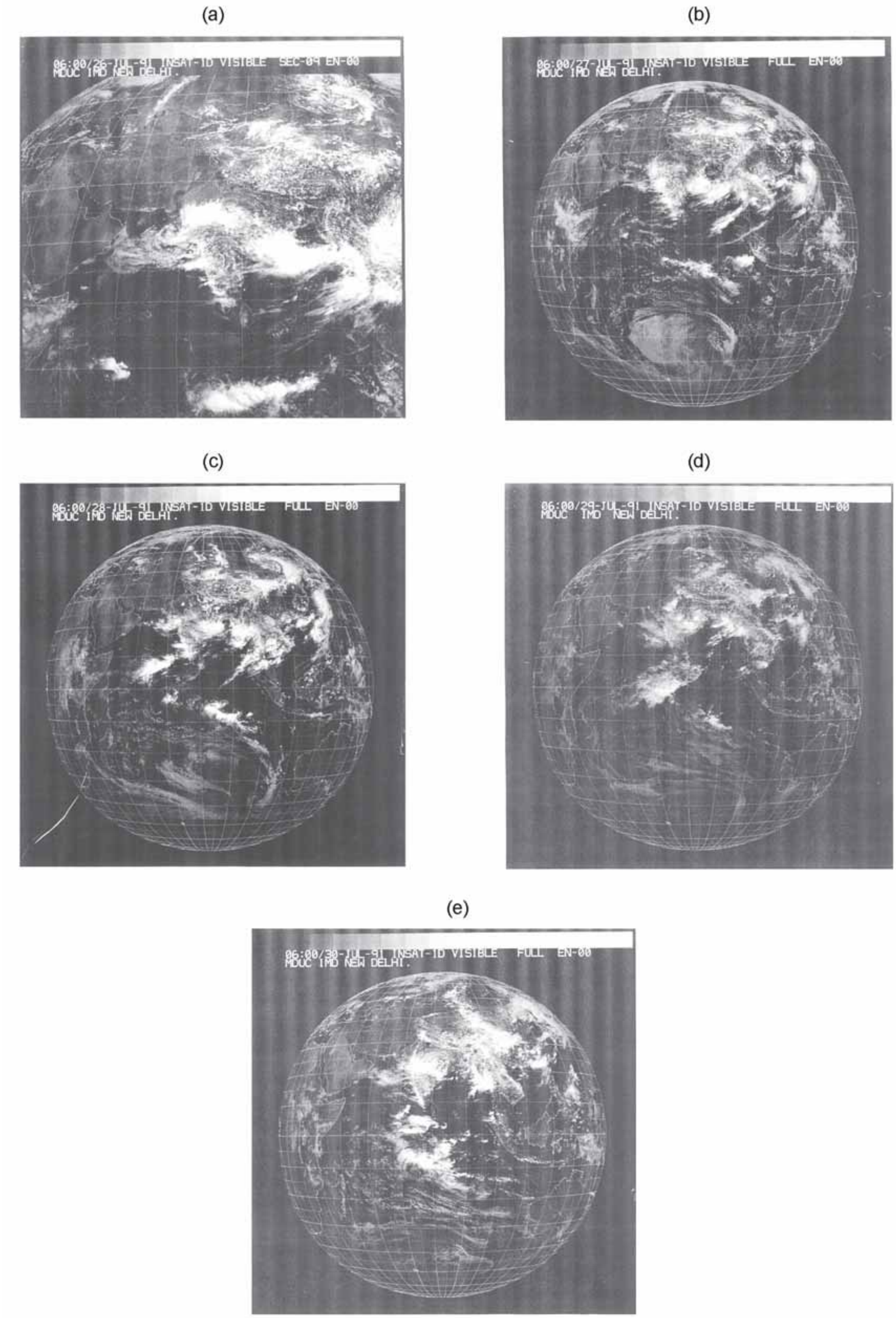

Figure 11 (a-e). INSAT- 1D cloud imageries for 26-31 July1991.

CONCLUSIONS

• The analysis of energy terms for both schemes are comparable but the analyses produced by the 3-D NVA are having marginally higher magnitudes compared to 2-D NVA. Although both schemes have produced equally good analyses, 3-D NVA can be considered to be better choice for diagnostic study as in the numerical weather prediction techniques based on the quasi-geostrophic and thermal wind assumptions it was felt that the initial map should be constructed objectively by a method based on the same assumption.

• Although on 27 July it was just depression and not deep depression as per IMD, the maximum kinetic energy was present and which incidently has been picked up very well in the OLR analysis of NCEP. Cloud features of 27 were also supportive for this showing better convective activity.

The study of life cycle of the monsoon depression by two schemes brings out the following features that are in well accordance with earlier researchers.

1. The monsoon system (1991, depression) contains maximum kinetic energy at the 300-200 hPa levels with a secondary maximum at the 850-700 hPa levels.

2. The zonal available potential energy, which is proportional to the north-south temperature variance is the main source of energy.

3. The zonal kinetic energy is more often converted into zonal available potential energy.

ACKNOWLEDGEMENTS

The authors express their gratitude to the Director, Indian Institute of Tropical Meteorology, Pune for his keen interest in this study and providing us with the necessary facilities.

REFERENCES

Gandin, L.S., 1963. The objective analysis of meteorological fields, Israel program for scientific translations, Jerusalem, 240 pp.

Godbole, R.V., 1977. The composite structure of the monsoon depression, Tellus 29, 25-40.

Krishnamurti, T.N., Kanamitsu,M., Godbole, R.V., Chang, C.B., Carr, F. & Chow, J.H., 1976. Study of a monsoon depression, II. Dynamical structure, J. Meteor. Soc., 54, 208-226.

Lorenz, E.N., 1955. Available potential energy and the maintenance of the General Circulation, Tellus, 7, 157-167.

Moorthi, S. & Arakawa, A., 1985. Baroclinic instability with cumulus heating, J. Atmos. Sci., 42, 2007-2030.

Murakami, T., 1977. Regional energetics over the north Pacific, south China Sea and the Indonesia seas during winter, Monsoon Dynamics (ed. T N Krishnamurti) PAGEOPH, 15 1283-1301.

Narkhedkar, S.G. & Kulkarni,P.L., 2000. Examination of upper tropospheric warming associated with the monsoon depression over Bay of Bengal from the upper air temperature analysis at operational NWP Centres, The J. Ind. Geophys. Union, 4, 161-176.

Narkhedkar, S.G. & Sinha, S.K., 2000. Numerical variational objective analysis of height and wind field over Indian and adjoining region, The J.Ind. Geophys. Union, 4, 177-184.

Oort, A. H., 1964. On estimates of the atmospheric energy cycle, Mon. Wea. Rev., 92, 433-443.

Rajamani, S., 1985. Energetics of the monsoon circulation over south Asia – part II: Energy terms and energy transformation terms, Mausam, 36, 405-412.

Rajamani, S. & Kulkarni ,J. R., 1986. On some energy aspects of the monsoon depression during its life cycle, Mausam, 37, 9-16.

Rajamani, S. & Sikdar,D.N., 1989. Some dynamical characteristics and thermal structure of monsoon depressions over the Bay of Bengal, Tellus, 41A, 255-269.

Saha, K. & Chang, C. P., 1983. The baroclinic processes of monsoon depression, Mon. Wea. Rev., 111, 1506-1514.

Sasaki, Y., 1958. An objective analysis based on the variational method, J. Meteor. Soc., 36, 77-88.

Sinha, S. K., Narkhedkar, S.G. & Rajamani S., 1998. Application of Sasaki's numerical variational technique to the analysis of height and wind fields over Indian region, Mausam, 49, 1-10.

Sinha, S. K., Narkhedkar, S. G., Mahakur, M. & Mahajan P. N., 2003. Meteorological objective analysis using three-dimensional numerical variational technique, Atmosfera, 16, 173-191.

Smith, P. J., 1969. On the contribution of a limited region to the global energy budget, Tellus, 21, 202-207.

Tripoli, G. J. & Krishnamurti, T. N., 1975. Low-level flows over the GATE area during summer 1972, Mon. Wea. Rev., 103, 197-216.

Wiin-Nielsen, A. & Chen, T. C., 1993. Fundamentals of Atmospheric Energetics, Oxford University Press, 376 pp.

(Accepted 1st August 2006. Received 2nd July 2006; in original form 7th February 2006)

Mr.S.G.Narkhedkar presently working as Scientist-B at the Indian Institute of Tropical Meteorology, Pune. He has obtained M.Sc. (Physics) degree from University of Pune in 1993. He has to his credit twenty five (25) scientific papers in national and international journals. He has been working since last 20 years in the field of objective analysis.

Dr.S.K.Sinha presently working as Scientist-D at the Indian Institute of Tropical Meteorology Pune. He did his M.Sc. (Mathematics) in 1968, Ph.D. (Applied Mathematics) in 1975, Ph.D. (Atmospheric Science) in 1992. He has to his credit 25 scientific papers in international and national journals.

Dr.(Miss) P.L.Kulkarni has obtained post-graduate and Ph.D. in Physics from University of Pune. She has 38 years Research experience in Meteorology After attaining the age of superannuation she retired from the Indian Institute of Tropical Meteorology as Scientist C in 2005. She has to her credit 30 scientific papers in renowned international and national journals.

Mr.J.R.Kulkarni, Scientist-E working in the Indian Institute of Tropical Meteorology, Pune is having 33 years of research experience in the field of tropical meteorology. His areas of research are: Climate and Global Modelling, Monsoon Variability, Boundary Layer Meteorology, Nonlinear dynamic and Choas. He has 75 publications. He is adjunct professor University of Pune, Physics Department since last 18 years.

Dr.P.N.Mahajan presently working as Scientist-E and Head, Forecasting Research Division at the Indian Institute of Tropical Meteorology, Pune. He did his M.Sc. (Physics) from Nagpur University and Ph.D.(Physics) from University of Pune. He has visited various countries viz. USSR, Australia, U.K., Belgium, Finland etc. in connection with the collaborative programs and/or attending symposia/seminar/ conferences. He has published 45 scientific papers in renowned international and national journals and also contributed 37 papers in proceedings/books. He has handled various collaborative projects as Principle Investigator/Co-Investigator. He has been a recipient of IITM Silver Jubilee Award during 1994. His field of specialization is satellite Meteorology.