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Study of Turbulence Kinetic Energy Budget over Jodhpur, India

Review Article

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Abstract

Atmospheric turbulence plays an important role to understand the behavior of pollutants in lower atmosphere which has a large impact on surrounding environment. In the present paper, the one-dimensional Turbulent Kinetic Energy (TKE) budget in a steady and homogeneous condition is studied. The data from a 30m micrometeorological tower during Indian Summer Monsoon (ISM) of the year 1990 over a station Jodhpur (26.3° N, 73°E), which represents a dry convective station and situated at the eastern part of ISM trough over the Indian subcontinent, is used. The tower data is of Fast and Slow Response data. The Fast Response Data (FRD) sampled at (8 Hz) is collected at 4 m and 15 m levels whereas the Slow Response Data (SRD) sampled at (~1 Hz) is collected at six levels viz. 1, 2, 4, 8, 15 and 30m. The analysis of each component of TKE budget is done for active and non-active phases of monsoon at 4m and 15m levels. All terms of TKE budget show considerable variations at 4m levels. At 15m, the variations of term are not remarkable. It has been found that at both of the levels shear production term dominates over all other terms during active phase of monsoon while buoyancy dominates during day time at 4m level in both of phases. The buoyancy and shear terms influence mixing and transport of pollutants in the lower part of the atmosphere in day time during active and non active phases of ISM. TKE budget over Jodhpur, Kharagpur and Varanasi shows that buoyancy is not a major contributing factor during the summer monsoon season while major contributing factor is shear production.

Keywords: MONTBLEX; TKE; Buoyancy; Shear; Flux divergence; Dissipation

List of Symbols

g: Acceleration due to gravity; k: Von Korman constant; θ_v: Virtual Potential Temperature; e: Turbulent Kinetic Energy; u_*: Frictional Velocity; u′w′: Covariance between u′ and w′; w′θ′: Covariance between w′ and θ′; z: Height; ρ: Air Density; u′: Lateral eddy; v′: Transverse eddy; w′: Vertical eddy; ∈: TKE dissipation rate

Introduction

Increasing urban population and industrial activities causes serious air pollution problem. The pollutants emitting from stack, motor vehicles, heating and cooling systems of buildings, sudden fires, etc., can either deposit nearby source or transport to a distance depending upon the temperature and wind profile in the prevailing atmosphere. The characteristics of turbulence in the lower atmosphere control the dispersion and transport of atmospheric pollutants in the atmosphere. Therefore, TKE is one of the more important variables in lower atmosphere for the study of atmospheric pollution. The budget of TKE is directly related to the transport of heat, moisture, and momentum in lower atmosphere through atmospheric boundary layer. The tendency of TKE is important because if TKE decreases with time, the boundary layer will be less turbulent with time where as if TKE increases with time, the boundary layer will become more turbulent with time so TKE budget behaves like a source and sink.

TKE budget comprises shear production, buoyancy production, dissipation, and the transport processes which has various applications in in boundary-layer meteorology [1-3]. Panofsky [4] and Record and Cramer [5] have been studied evolution of TKE in Atmospheric Surface Layer (ASL) and found that divergence of TKE flux is important under steady condition. Busch and Panofsky [6] examined spectral characteristics of atmospheric turbulence stressed on the importance of TKE flux and found that dissipation compensates shear and buoyancy productions. Wyngaard and Cote [7] studies on the relative importance of each terms of TKE budget and found that dissipation terms were balanced by shear production, while turbulent transport and buoyant production terms were secondary important under stable condition. Under unstable condition, dissipation slightly exceeded the total production. McBean and Miyake [8] examined TKE transfer in ASL. McBean and Elliot [9] studies on divergence and pressure fluctuation terms of TKE budget and showed that divergence of pressure fluctuation was in opposite sign and of equal magnitude of the divergence of turbulent kinetic energy. Lenschow [10] examined TKE budget under unstable condition and convective condition. Champange et. al. [11] estimated TKE budget and also calculated the pressure transport terms to the dissipation terms and agreed well with Kansas results. Under convective condition, TKE budget has been studied by Caughey and Wyngard [12]. Vishawanadham et al [13] studied different terms of budget equation over semi humid station over India. Srivastava and Parth Sarthi [14] studied the TKE in the atmospheric surface layer over deep humid station and showed variation of the different terms of TKE budget in different phases of ISM over deep humid station. Dacre et al. [15] in their study said that turbulent mixing and convection processes can double the amount of pollution ventilated from the boundary layer. TKE budget variations during thunderstorm days (TD) and Nonth Tunderstorm Days (NTD) of premonsoon seasons of 2007, 2009, and 2010 over Kharagpur (22°30 N, 87°20 E) have been studies [16] using the surface layer turbulence data under STORM experiment. Variations in TKE budget parameters with respect to stability are studied in contrasting days of weather activity.

In this paper, the relative magnitudes of buoyancy, shear and flux divergence terms in day time, mean of a day and night time are computed and analyzed for active and non active phases. Section1 deals with introduction and literature survey. The data used and site are given in section2. To estimate each term of TKE budget, methodology is placed in section3. Results and discussion and conclusions are shown in section4 and 5, respectively.

Data and Site Description

Data

To probe the interaction of atmospheric surface layer with monsoon trough over Indian region, the Monsoon Trough Boundary Layer Experiment (MONBLEX) [17-20], an intense multi-institutional meteorological experiment, was conducted in 1990. As a part of this experiment, one 30 meters micrometeorological tower was erected at dry convective region named Jodhpur (26.3° N, 73°E). The various meteorological parameters were collected from the tower at six levels as 1, 2, 4, 8, 15 and 30 meters levels. The SRD were collected from all the six levels and sampled at 1Hz intervals, whereas FRD were collected at 4m and 15m heights and sampled at 8Hz intervals. The considered dates have been divided into active and non-active phases of monsoon. The classification of active and non-active is based on local conditions. The active phase is considered when cloud amount>4/8 octas and rainfall>4mm or any of them reported by Indian Daily Weather Report (IDWR) by India Meteorological Department (IMD). When the cloud and rainfall do not fulfill the above criteria, it is treated as non-active phase. The FRD were subjected to quality check before being used in the final analysis. A physical examination was made and it was decided to remove unusual spikes, which falls beyond mean ± 3 standard deviations. To confirm to be universal laws, each data set of 10 minutes duration has been subjected to spectral analysis and only those confirmed to -4/3-power law have been referred to the final analysis [21]. The details of number of runs and heights are shown in table 1. The considered dates during active and non-active phases of monsoon are presented in table 2 whereas table 3 shows prevailing synoptic weather conditions.

Site Description

The surface of the site of Jodhpur was covered with small pebbles and patches of grass. To the north of the tower, a couple of bush like trees was there. To the south of the tower, there was a water tank of about 25m height. There were several trees of 5-6 m. height in the east and west of the tower. The prevailing wind direction of the tower was from a sector between southeast and west. The land stretch between 200^0-300^0 sector was fairly flat without any obstacles on the ground. Jodhpur, Varanasi and Kharagpur comes under semi arid, humid and deep humid tropical regions.

Methodologies

The turbulent kinetic energy budget under steady and homogeneous condition can be expressed, when the coordinate system is aligned with the mean wind (ū) [22] as follows

$$\underset{\text{I}}{\frac{g}{\theta_v}\left(\overline{\omega'\theta_v'}\right)} - \underset{\text{II}}{\overline{\omega' u'}\frac{\partial u}{\partial z}} - \underset{\text{III}}{\frac{\partial\left(\overline{\omega' e}\right)}{\partial z}} - \underset{\text{IV}}{\frac{1}{\overline{\rho}}.\frac{\partial\left(\overline{\omega' p'}\right)}{\partial z}} - \underset{\text{V}}{\in} = 0 \qquad (1)$$

Where, $u', v', w', p' and\, \theta_v^{'}$ are the turbulent parts of the three winds component, pressure and virtual potential temperature, z is the log mean height, $\overline{\rho}$ and $\theta_V^{'}$ are the mean densioty and mean virtual potential temperature, g is the acceleration due to gravity, ε is the dissipation and the TKE is given by:

Table 1: Details of number of runs and height on which data collected over Jodhpur (26.3° N, 73°E).

No. of Runs	Heights(in meters)
61	4
76	15

Table 2: Details of considered dates during active and non active phases over Jodhpur (26.3° N, 73°E).

Active phase	2^{nd}-8^{th} Aug ,1990
Non-Active phase	9^{th}-15^{th} Aug, 1990

Table 3: Average synoptic conditions over Jodhpur (26.3° N, 73°E).

Stations	TKE Budget		
	Buoyancy	Shear	Flux Divergence
Jodhpur	43.0	209.4	34.4
Varanasi	16.2	125.9	10.0
Kharagpur	8.5	154.9	-2.1

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$$\bar{e}=\frac{1}{2}(\overline{u'^2}+\overline{v'^2}+\overline{w'^2})$$

The first term is the buoyant production term, which is usually a source/sink during day/night time. The second term is shear production of TKE, which is always source. The third is the divergence of vertical flux of turbulent kinetic energy, which can be a source or sink depending upon whether TKE flows into or going away from the layer. The fourth is turbulent transport of TKE by pressure fluctuations, which can again be a source/sink. The last term is dissipation, which is always a sink. Since data on pressure fluctuation are not available so pressure transport term is treated as residual term. The buoyancy and shear terms computed with the help of FRD and SRD. The vertical transport term is computed by following relation given by Mc Bean and Elliot [9].

A non dimensional form of equation (1) can be obtained by scaling it with u*³/kz, so

$$\varphi_m(z/l) - z/l - (kz/u_*^3)\partial(\overline{w'e})/\partial z - (kz/u_*^3)\,1/\rho\rho\,\partial(\overline{w'p})/\partial z - \varepsilon\varepsilon = 0 \quad (2)$$

The vertical transport can be written as,

$$\frac{kz}{u_*^3}\cdot\frac{\partial\left(\overline{w'e}\right)}{\partial z}=\frac{kz}{L}\frac{\partial\left(\overline{w'e}/u_*^3\right)}{\partial\left(\frac{z}{L}\right)} \quad (3)$$

Since $.\left(\frac{\left(\overline{\omega' e}\right)}{u_*^3}\right)$ is a universal function of z/L,

So taking, $.\frac{\left(\overline{\omega' e}\right)}{u_*^3} = F(z/L)$

This function is obtained by a least square method with number of runs. It is differentiated with z/L and multiplied by u*³/L to get for each of the runs.

Finally, the flux divergence becomes

$$\frac{kz}{u_*^3}\cdot\frac{\partial\left(\overline{\omega' e}\right)}{\partial z}=\frac{kz}{L}\frac{\partial\{F(z/L)\}}{\partial(z/L)}$$

$$\text{or, } \frac{\partial\left(\overline{w'e}\right)}{\partial z}=\frac{u_*^3}{L}\frac{\partial(F(z/L))}{\partial(z/L)} \quad (4)$$

For near neutral conditions,

$$\in = \left(u_*^3/kz\right)\left[1+0.5\left(\left|z/L\right|\right)^{2/3}\right]^{2/3}$$

For stable conditions,

$$\in = \left(u_*^3/kz\right)\left[1+2.5\left(\left|z/L\right|\right)^{3/5}\right]^{3/2}$$

In the present study, the dissipation term is computed by following Stull [22]. The pressure transport term was computed as residual, which is likely to contain any possible errors in all the remaining terms of TKE budget.

Results and Discussions

The buoyancy, shear and flux divergence of TKE budget are averaged for day time, mean of whole day and night time for the periods of active and non active respectively. The mixing and transport of pollutants depends on relative magnitudes of buoyancy and shear terms and flux divergence, mainly. The dissipation and residual terms of TKE budget do not have significant role in dispersion of atmospheric pollutants, therefore these two terms are not considered here.

Buoyancy

The buoyancy represents the generation or destruction of TKE by vertical flux of virtual potential temperature. In general, buoyancy remains positive at lower atmospheric level and decreases approximately linearly with height up to the top of the mixed layer. Hence, this term will be larger during day time and smaller or negative during cloudy days or night time. The variation of buoyancy at 4m and 15 m in day time, mean of whole day and night time during active and non active phases is shown in Figures 1a and 1b. At 4m level, during active phase (Figure 1a), the buoyancy is positive during day time while it is negative in night time but the difference between two levels during day time is more in compare to non active phase (Figure 1b). It seems that less cloudy days and clear sky during non active phase are more convective and therefore more buoyancy is found. Although the difference of buoyancy at two levels (4 and 15m) during night time in active phase is relatively large that that of non active phase. It seems that buoyancy is dominating during day time in non active phase. More buoyancy at lower level would lead more convective condition and therefore more pollutants can be dispersed in the vertical atmosphere.

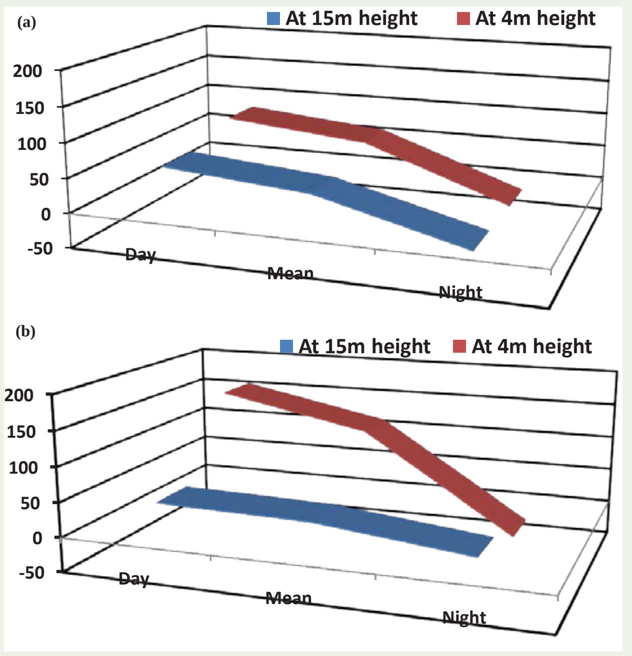

Figure 1: Buoyancy(x10⁻⁵) (m²s⁻²) in TKE budget at 4m and 15 heights in day time, mean and night time during (a) active; (b) non active phases.

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Shear

In TKE budget, shear is the interaction of the turbulent momentum flux with the mean vertical wind shear that generates turbulence. This term remains generally very large and positive near the ground and becomes larger on a windy day (larger vertical shear) and smaller on a calm day. This term shows the production of eddies by shear. The wind near the ground is generally stronger than the shear at slightly higher level. During day time, the shear is also found more than at night. Figures 2a and 2b depicts the variation of shear in day time, mean of whole day and night time at 4 and 15m during active and non active phases. At 4m level, the mean values of wind shear are more in compare to its value at 15m in active and non active phases (Figures 2a and 2b) although its values are found more in active phases due to windy condition, in compare to non active phase at corresponding level. If the source of atmospheric pollutants over this area exists, the large wind shear at 4m level will disperse or transfer pollutants, which are remaining in the lower level, in the vertical atmosphere. At each level and their phases, the day time shear is found more with respect to night time, except in active phase at 15m level, and therefore dispersion of pollutants could be more in the vertical atmosphere.

Flux divergence

The flux divergence term in TKE budget represents the vertical transport of TKE. Since it shows the flux divergence of TKE for a layer since it depends on the vertical gradient of vertical flux. So, for a given layer, if more flux in entering the layer than leaving it, there would be net convergence of the vertical flux, and therefore, the TKE of the layer will increase which may carry more pollutants in the vertical atmosphere. Figure 3a and b represents the variation of flux divergence at 4 and 15m levels in day time, mean of whole day and night time during active and non active phases respectively. In active phase (Figure 3a), the flux divergence seems to more during day time at 4m with respect 15m and therefore more turbulence in entering in the layer 4-15m during day time which in turn will increase TKE in the layer. It will lead to more dispersion of pollutants during day time in compare to night time. In non active phase (Figure 3b), the shear is found more at 4m level that that of 15m level during day time while the night time values are less. Therefore, the atmospheric pollutants will settled down during night times which have been dispersed more during day time period in the layer 4-15m. In both of the figs, more turbulence is entering during day time in compare to night time but entering of TKE in layer 4-15m is large in non active phase with respect to active phase.

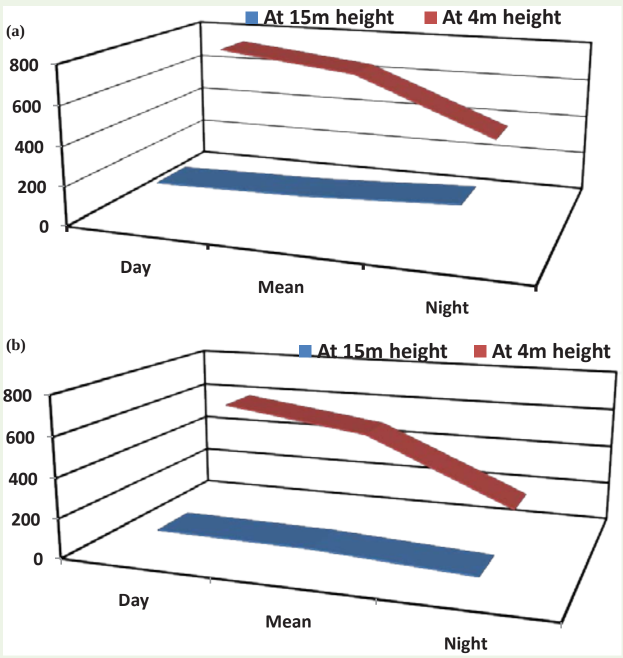

Figure 2: Shear(x10-5) m^{2}s^{-2}in TKE budget at 4m and 15 heights in day time, mean and night time during (a) active; (b) non active phases.

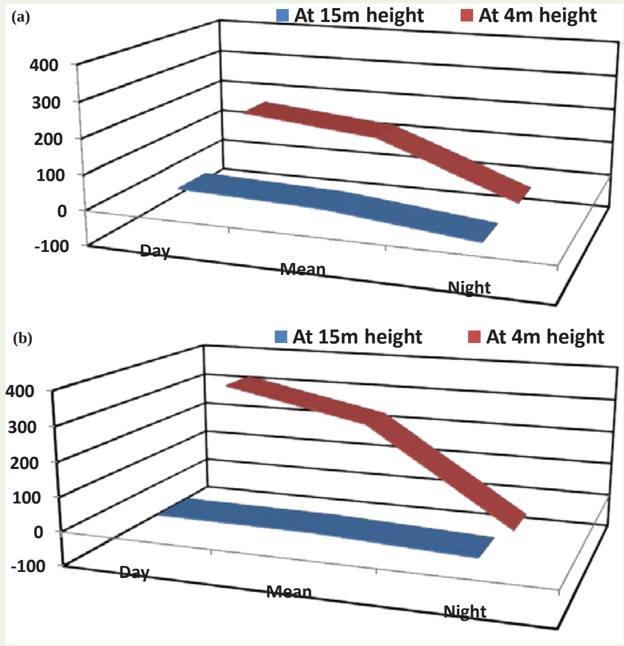

Figure 3: Flux Divergence (x10-5) m^{2}s^{-2}in TKE budget at 4m and 15 heights in day time, mean and night time during (a) active; (b) non active phases.

Comparison of TKE Budget over Jodhpur, Varanasi and Kharagpur

Tables 4 and 5 show magnitude of the budget terms for three stations namely Jodhpur, Kharagpur and Varanasi at 15m level during active and nonactive phases. The magnitude of buoyancy term over Jodhpur is more followed by Kharagpur and Varanasi, respectively. During active phase, buoyancy at Varanasi is comparable with Jodhpur. In non active phase, buoyancy is more over Jodhpur followed by Kharagpur and Varanasi. The magnitude of shear production is highest over Kharagpur during non active phase and over Jodhpur during active phase. The flux divergence shows transport of TKE away over Kharagpur while it is brought over Vanarasi and Jodhpur over both phsases. The maximum transport of TKE is noticed over Jodhpur followed by Varanasi and Kharagpur.

Citation: Sarthi PP. Study of Turbulence Kinetic Energy Budget over Jodhpur, India. J Environ Soc Sci. 2015;2(1): 104.

Table 4: TKE budget parameters during active phase at 15m height over Jodhpur (26.3°N, 73°E), Varanasi (25.2°N, 82.9°E) and Kharagpur (22.3°N, 87.3°E).

Periods	Averaged synoptic conditions
2nd-8th August, 1990	Sky was partially or completely cloud. Rain was continuing almost whole day Windy condition prevailed.
9th-15th August, 1990	Sky was either clear or partially cloudy during whole day. Wind was mild.

Table 5: TKE budget parameters during non active phase at 15m height over Jodhpur (26.3°N, 73°E), Varanasi (25.2°N, 82.9°E) and Kharagpur (22.3°N, 87.3°E).

Stations	TKE Budget		
	Buoyancy	Shear	Flux Divergence
Jodhpur	38.5	109.3	30.8
Varanasi	-5.3	181.2	-3.6
Kharagpur	26.3	267.9	-6.1

Conclusions

The study of turbulence in the atmosphere over Jodhpur helps to understand the behavior of particulate matter during monsoon season. The analysis concludes that buoyancy, shear and flux divergence of TKE budget plays significant role for the dispersion of atmospheric pollutants. The buoyancy values in mean of whole day and day time are more during non active phase at corresponding levels with respect to active phase. More buoyancy at lower level will lead more convection and therefore more pollutants can be dispersed in vertical atmosphere. Buoyancy during day time acts as source where as it behaves as sink during night time. The shear of TKE budget, at 4m level, shows that wind shear during day time is more in compare to its value at 15m in active and non active phases although its values are found more in active phases which may be due to windy condition, in compare to non active phase at corresponding level. If the source of atmospheric pollutants exists nearby by Jodhpur station, the large wind shear at 4m level will disperse or transfer pollutants remaining in the lower level, in the vertical atmosphere. In the layer 4-15m, flux divergence of TKE budget is entering more during day time in non active phase at corresponding time in active phase. Therefore, the atmospheric pollutants will settled down during night times, which has been dispersed more during day time period in the layer 4-15m. The study of relative magnitudes of buoyancy, shear and flux divergence at 4 and 15m in day and night time during active and non active phases over Jodhpur can be correlated with the vertical mixing and transport of pollutants in vertical atmosphere near the earth surface.

From the comparison of TKE budget over Jodhpur, Kharagpur and Varanasi, it is clear that buoyancy is not a major contributing factor during the summer monsoon season. The major contributing factor is shear production. Therefore, transport of pollutants may be influenced by shear production over these stations during active and non active phases.

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