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Research Article

The Budget of Turbulent Kinetic Energy during Premonsoon Season over Kharagpur as Revealed by STORM Experimental Data

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Turbulent kinetic energy (TKE) budget variations during thunderstorm days (TD) and nonthunderstorm days (NTD) of premonsoon seasons of 2007, 2009, and 2010 have been investigated at a tropical station Kharagpur (22°30′N, 87°20′E) using the surface layer turbulence data obtained during severe thunderstorms-observations and regional modeling (STORM) experiment. Significant variations in the contributions of the TKE budget parameters with respect to stability are observed on these contrasting days of weather activity. In highly unstable conditions, smaller dissipation rates are seen on TD compared to NTD, while approaching near neutral conditions, higher dissipation rates are found in TD. New relationships between TKE dissipation rates with respect to atmospheric stability are proposed at Kharagpur for TD and NTD.

1. Introduction

Evolution of turbulence in atmospheric surface layer (ASL) assumes special importance, as it plays major role in the transportation of heat and moisture from near the surface to higher levels in the atmosphere. Turbulent kinetic energy (TKE), which is a measure of turbulence in the atmosphere, is directly related to the transport of momentum, heat, and moisture through the boundary layer [1]. Thus, understanding the variation of the individual budget components is crucial for energy exchange mechanism from atmospheric surface layer to upper atmosphere and vice versa. TKE budget has been studied during various field campaigns based on Monin-Obukhov similarity theory (MOST) [2–6]. TKE budget equation is still an uncertain relation in the quantitative case and is commonly used to parameterize turbulent properties of the surface layer in atmospheric models of larger scale [7]. TKE budget associates the local storage of turbulence to the shear production, buoyancy production, dissipation, and the transport processes and has numerous applications in both empirical and computational modeling in boundary-layer meteorology [8–10].

Study of TKE budget under unstable conditions and convective conditions is important for understanding the timely response of ASL. It was found in [11] that in the unstable surface layer, all terms in the TKE budget are considerable, and TKE generated through buoyancy forces is transported out of the layer, while the dissipation rate can be regarded as an approximation of the sum of mechanical production and the residual, with the unmeasured pressure term. Results at different sites about TKE budget and dissipation are emphasizing the importance of various TKE terms during convective situations and the necessity to be included in numerical weather prediction models, particularly in models that resolve mesoscale structures in storms (e.g., [12–16]). Dissipation rate of the TKE is an important nondimensional parameter to study the kinetic energy evaluation in atmospheric boundary layer [17, 18] and is reported by researchers over the years in various parts of the world [1, 10, 18].

However, detailed studies of TKE budget variations are absent over Gangetic West Bengal region due to lack of surface layer observational network, where the premonsoon (March–May) thunderstorms occur every year [19]. To overcome the scarcity of available data over the region, a multi-institutional and international co-coordinated observational program known as severe thunderstorm-observations and regional modeling (STORM) has been launched by Department of Science and Technology (DST), Government of India [19]. Kharagpur (22°30′N, 87°20′E) is one of the experimental sites for STORM experiment, and data collected during premonsoon seasons of 2007, 2009, and 2010 as a part of this experiment are used in the present study. Highly convective conditions existing over this study region conduce to the occurrence of thunderstorms existing during premonsoon months over the study region. But these storms occur over a few days only. Hence, the present study aims to discern the variations and differences in the energy transport mechanisms in TD and NTD by studying the contributions of various physical forcings to total TKE during the premonsoon period over Kharagpur. This study is not looking into the dynamics of thunderstorm activity but rather looking into the turbulence transport during the whole day of thunderstorm.

2. Site Description, Data, and Quality Check of Data

The data for the present study are obtained from a 50 m instrumented tower, situated in an agriculture farm at the Indian Institute of Technology, Kharagpur region of West Midnapore, Gangetic West Bengal, India. The site is flat and grassy. The soil is sandy loam with a mixture of sand (64.1%), silt (20.1%), and clay (15.8%) and with a bulk density of 1.65 $\mathrm{Mg\,m^{-3}}$, volumetric heat capacity of 2.960×10^6 J $\mathrm{m^{-2}\,K^{-1}}$, field capacity of 26.7%, and wilting point of 9.3% [20, 21]. The mean sea level height of the station is 39 m. The data comprise air temperature (K), relative humidity (%), wind speed ($\mathrm{ms^{-1}}$), and wind direction (degrees) at six different levels (namely, 2, 4, 8, 16, 32, and 50 m) obtained from the 50 m micrometeorological tower. At 10 m level a sonic anemometer (Manufactured by R. M. Young) has been installed to measure the turbulent components of wind and temperature with 10 Hz frequency. For the present study, the fast response data averaged for 30 min are used. Complete description of sensors, with their manufacturer and model, is given in [22]. In the present study, both slow response data (SRD) of 1 Hz and fast response data (FRD) of 10 Hz (sonic data) of atmospheric variables for TD and NTD have been used for 2007, 2009, and 2010. Eight thunderstorm days (TD) and twelve clear nonthunderstorm days (NTD) are selected. The information about selected TD cases (time of thunderstorm, and associated rainfall) and NTD cases is given in Table 1.

Thunderstorm events over Kharagpur during premonsoon season are delineated using the log book information at the tower site and information obtained from cyclone detection radar at Kolkata, India Meteorological Department for the region. The classification of a thunderstorm day at Kharagpur is based on occurrence of a thunderstorm event at any time of that particular day [23] which says that if any thunderstorm event occurred within 24 hours of a day that day is termed as TD. And if there is no activity for whole day 24-hour period, that day is termed as NTD. Data sets have been subjected to quality check before analysis. Steps of quality checks employed in the present study are the same as those employed in [24]. For the present study, after employing steady state test in quality check of data, only those data sets which are satisfying the steady state assumption are used in analysis. This is essential as MOST can only be valid for the steady state. A total of 960 half-hourly data sets of FRD have been analysed for NTD (576) and TD (384), out of which 608 data sets have been finally considered into analysis (394 for NTD and 214 for TD) after quality check. The rejected data sets also include the rain hour's data sets because of the possible effects of water droplets on transducer heads of sonic anemometers significantly influencing the data quality.

3. Methodology

Assuming a steady state and horizontally homogeneous conditions and choosing a coordinate system aligned to mean wind, the turbulent kinetic energy (TKE) budget equation can be written as (e.g., [3, 25]):

$$\frac{g}{\overline{\theta}_v}\left(\overline{w'\theta_v'}\right) - \overline{w'u'}\frac{\partial \overline{u}}{\partial z} - \frac{\partial\left(\overline{w'e}\right)}{\partial z} - \frac{1}{\overline{\rho}}\frac{\partial\left(\overline{w'p'}\right)}{\partial z} - \varepsilon = 0. \tag{1}$$

From the left hand side of (1), the first term is buoyant production term which acts as a source (sink) term during day- (night-) time. The second term is shear production term, which is always a source term. The third term is a divergence of vertical TKE flux, which can be a source or sink term depending on whether there is a flux convergence or divergence. The fourth term is a pressure correlation term that describes the redistribution of TKE by pressure perturbations. The fifth and last term is viscous dissipation of TKE, which is always a sink term, where u', v', w' are zonal, meridional, and vertical components of wind fluctuations; $\overline{u}$ is the mean wind speed; p' and θ_v' are turbulent parts of pressure and virtual potential temperature; g is acceleration due to gravity; z is log mean height; $\overline{\rho}$ and $\overline{\theta}_v$ are mean density and mean virtual potential temperature; $\overline{e}$ is turbulent kinetic energy per unit mass; ε is dissipation; $\overline{w'\theta'}$, $\overline{u'w'}$, $\overline{w'e}$, and $\overline{w'p}$ are vertical kinematic eddy fluxes of heat, momentum, energy, and pressure, respectively. $\overline{e}$ will be computed as

$$\overline{e} = 0.5\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right). \tag{2}$$

During the pilot experiment at Kharagpur, the fast response turbulence measurements using sonic anemometer are available at 10 m height only, making it not possible to estimate the flux divergence following the methodology suggested in [3]. We make estimates of the magnitudes of flux divergence following [25] under the guidelines of Monin-Obukhov similarity theory (MOST). MOST is proven to be a

Table 1: Information about thunderstorm cases and associated rainfall at Kharagpur during premonsoon seasons of 2007, 2009, and 2010.

S. no.	Thunderstorm cases			Nonthunderstorm cases
	Date	Local time of thunderstorm event (h)	Rainfall during thunderstorm (mm)	Date
1	26 April 2007	1530–1632	14.39	16 April 2007
2	27 April 2007	1703–1800	18.80	19 April 2007
3	18 May 2007	1300–1425, 1500–1603	10.67, 17.27	03 May 2007
4	06 May 2009	1448–1512	5.9	04 May 2007
5	11 May 2009	1721–1809	16.7	06 May 2007
6	05 May 2010	1500–1615	19.6	15 April 2009
7	09 May 2010	1540–1700	4.0	10 May 2009
8	22 May 2010	1503–1554	1.1	04 May 2010
9	—	—	—	08 May 2010
10	—	—	—	11 May 2010
11	—	—	—	12 May 2010
12	—	—	—	15 May 2010

good tool for understanding and explanation of the turbulent characteristics of lower atmosphere at any observational site. Buoyancy and shear terms are computed from slow response as well as fast response data.

Dissipation term is calculated from the high-frequency end of spectra obtained by available fast response turbulence measurements of sonic anemometer. The following equations are used in calculating dissipation (e.g., [26]):

$$\varepsilon = \left[nS_{u,v,w}(n)\right]^{3/2}\left(\frac{2\pi n}{U}\right)A^{3/2}, \quad (3)$$

where n is natural frequency ($s-1$), S is spectral density, u, v, and w are zonal, meridional, and vertical velocity components, U is mean wind speed, and A is a universal constant for the inertial subrange (0.55 chosen for u and 0.73 for v and w), following [27]. Pressure transport term of the budget equation (1) is estimated as a residual, which is likely to contain any possible errors in all the remaining terms of TKE budget equation.

The nondimensional form of dissipation rate (ϕ_ε) of TKE is assumed to follow MOST and therefore can be expressed as a function of the stability parameter, z/L [17]; that is,

$$\phi_\varepsilon = \frac{k \cdot z \cdot \varepsilon}{u_*^3} = f\left(\frac{z}{L}\right), \quad (4)$$

where k is von Kármán constant (0.40), and u^* is frictional velocity (ms^{-1}).

4. Results and Discussion

4.1. Mean TKE Variation. Mean TKE ($\overline{e}$) has been computed using (2) for all TD and NTD cases at the site. It is noticed that diurnal variation of $\overline{e}$ is different during TD and NTD at the site. Diurnal variations of mean TKE at Kharagpur during 26 April 2007 (TD) and 6 May 2007 (NTD) are presented in Figure 1. Mean TKE values are generally higher on TD than NTD. The gap in the curve for TD is due to data removal by the quality checks. It is noticed that even after rainfall, there exists a high value peak in TD TKE curve at around 17:30 h, which may be attributed to the presence of high winds. Even in nighttime, value of TKE remains higher on TD (Figure 1). This shows presence of highly turbulent atmosphere on TD compared to NTD. Similar kind of variation has been noticed with higher values of TKE during individual TD cases compared to those of NTD at Kharagpur.

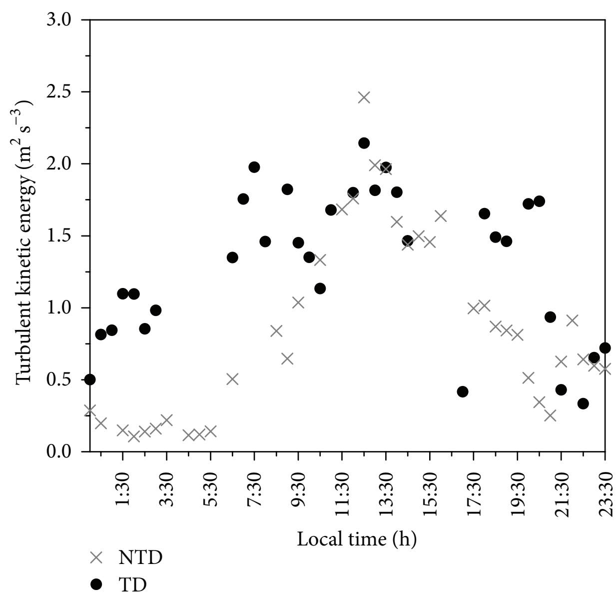


Figure 1: Mean TKE variation for 26 April 2007 (TD) denoted by filled black circles and 06 May 2007 (NTD) denoted by grey crosses.

4.2. Variation of TKE Budget Terms. The contribution of different terms of TKE budget during TD as well as NTD is analysed. Diurnal variations of TKE budget parameters on one TD case (26 April 2007) and one NTD case (6 May 2007) are depicted in Figure 2, with general variations observed on all other TD and NTD discussed. The daily daytime (0600 to 1800 h LST) and nighttime (0000 to 0600 h LST and 1800 to 2330 h LST) averages of all TKE budget terms during each of the TD and NTD cases as well as respective cumulative averages are presented in Tables 2 and 3. The variation and significance of each term of (1) have been explained for the present study.

4.2.1. Shear Term. Higher value of shear production is observed on TD compared to NTD, as seen in Figure 2(a). Shear production values in the early morning and late evening compared to daytime are more for TD, but less for NTD. The reason for such high shear production values on TD can be attributed to high winds throughout the day. During NTD, until 06:30 h the winds are of the order of 1 to 2.5 ms^{-1} and then picked up to the order of 4.5 to 6.5 ms^{-1} during the rest of the day. This can be attributed to the higher shear production values from 06:30 h onwards in NTD. On the close examination of the shear term (Table 2), maximum shear production is observed on 26 and 27 April 2007. As expected, the shear term is the main source term of the TKE budget.

4.2.2. Buoyancy Term. The daily averages for 26 April (Figure 2(b)) as well as other days (Tables 2 and 3) reveal higher buoyancy generation during TD compared to NTD. It acts as source during daytime (which shows active thermal convection up into the atmosphere) and sink during nighttime (tends to suppress or consume TKE) to the generation of TKE, during TD as well as NTD cases. Negative nighttime buoyancy values can be explained on the basis of static stability present in the atmosphere. Day to day variability of buoyancy term is noticed during TD.

4.2.3. Flux Divergence Term. Flux divergence and buoyancy terms vary opposite to each other. Variation of this term for 26 April (TD) and 6 May (NTD) is shown in Figure 2(c). Daytime negative flux divergence means upward transportation of TKE from the surface layer, whereas positive flux divergence in nighttime indicates downward transportation of TKE into the surface layer. In general, the magnitude of the term is more during daytime as well as nighttime in TD compared to NTD except on 16 April, where high values of flux divergence have been observed. Table 2 shows more upward transportation of TKE in the TD cases compared to the NTD cases (Table 3). On 3 May 2007 (NTD), the value of flux divergence is very low, and daytime value is showing the downward transport of TKE while nighttime value shows upward transport.

4.2.4. Dissipation Term. Dissipation acts opposite to shear production during the present study. Dissipation values are higher on TD than NTD (Figure 2(d)) during both daytime and nighttime. Higher dissipation in TD varies in accordance with higher shear production in those days. Dissipation of TKE can be a significant source of heat in storms, and it increases the efficiency of the storm [16]. Existence of higher dissipation values on TD can be attributed to availability of high heat availability in ASL, making the atmosphere suitable for thunderstorm happening.

4.2.5. Pressure Transport Term. Negative pressure transport term with higher magnitude is seen during the entire TD than NTD (Figure 2(e)). Negative values of pressure transport term during daytime as well as nighttime were found during TD days whereas during NTD cases, they are positive during daytime and negative during nighttime except on 16 April 2007 (NTD) when the negative pressure transport term value is observed in daytime and during nighttime. It was found in [4] that pressure transport is greater than flux divergence term, and pressure transport is always negative. We have also got similar results during TD and with change of magnitudes in nighttime in case of NTD. It is difficult to interpret this result, since this term is estimated as a residual which possibly contains the errors of all the other terms of the budget equation. The analysis of all the terms of the TKE budget equation reveals that shear term is source for both daytime and nighttime; buoyancy term is source during daytime and sink during nighttime; flux divergence term is sink during daytime and source during nighttime; dissipation term is sink during both daytime and nighttime; and finally pressure transportation term is sink during both daytime and nighttime for TD and sink during daytime and source during nighttime for NTD.

As reported in [25], our results show buoyancy and flux divergence terms are of opposite signs but the magnitudes of both terms are not equal. It is seen from Tables 2 and 3 that the magnitude of flux divergence term is higher than that of buoyancy term during TD, but it is less during NTD, with opposite sign. This is one of the characteristic differences observed between TD and NTD cases. Higher dissipation values during TD provide more heat availability for the thunderstorm initiation [16].

4.3. Kinetic Energy Dissipation Rates (ϕ_ε). The nondimensional dissipation functions for TKE (ϕ_ε) using eddy correlation method and following MOST are computed. Thus, ϕ_ε can be expressed as a function of the stability parameter ζ [17], where $\zeta = z/L$, z is reference height, and L is Obukhov length. It is suggested by various researchers [2, 3, 28] that in the nearly neutral conditions the mechanical production term equals the dissipation one. that is, ϕ_ε is equal to 1. In [29] a relationship of ϕ_ε with ζ during unstable conditions was proposed

$$\phi_\varepsilon(\zeta) = (1 - 3\zeta)^{-1} - \zeta, \quad \zeta \le 0. \tag{5}$$

It was proposed in [28] that ϕ_ε relationships based on Kansas results are as follows:

$$\phi_\varepsilon(\zeta) = \left(1 + 0.5\zeta^{2/3}\right)^{3/2}, \quad -2 \le \zeta \le 0. \tag{6}$$

And for stable conditions,

$$\phi_\varepsilon(\zeta) = 1 + 5\zeta, \quad 0 \le \zeta \le 1. \tag{7}$$

Relationship of ϕ_ε given by [29] has been widely used for unstable conditions and have been further modified by [30]

TABLE 2: Variation of TKE budget terms during TD cases at Kharagpur. The number of half hour runs is given in brackets.

Date	$-\overline{w'u'}\ (\partial\overline{u}/\partial z)\ (\times10^{-5}\ \mathrm{m^2s^{-3}})$			$(g/\overline{\theta_v})\ (\overline{w'\theta_v'})\ (\times10^{-5}\ \mathrm{m^2s^{-3}})$			$-\partial(\overline{w'e})/\partial z\ (\times10^{-5}\ \mathrm{m^2s^{-3}})$			$-\varepsilon\ (\times10^{-5}\ \mathrm{m^2s^{-3}})$			$-(1/\overline{\rho})(\partial(\overline{w'p'})/\partial z)\ (\times10^{-5}\ \mathrm{m^2s^{-3}})$		
	Daily avg.	Day	Night	Daily avg.	Day	Night	Daily avg.	Day	Night	Daily avg.	Day	Night	Daily avg.	Day	Night
26 April 2007	2877.2 (33)	2907.1 (17)	2845.4 (16)	247.8 (33)	584.4 (17)	−109.8 (16)	−351.5 (33)	−828.7 (17)	155.6 (16)	−2367.6 (33)	−2597.2 (17)	−2123.8 (16)	−405.9 (33)	−65.6 (17)	−767.4 (16)
27 April 2007	3729.3 (33)	4717.1 (18)	2543.9 (15)	189.3 (33)	424.3 (18)	−92.7 (15)	−236.7 (33)	−530.6 (18)	115.9 (15)	−2602.1 (33)	−3202.0 (18)	−1882.1 (15)	−1079.9 (33)	−1408.8 (18)	−685.1 (15)
18 May 2007	548.8 (22)	607.6 (16)	77.8 (6)	398.1 (22)	450.1 (16)	−19.0 (6)	−118.5 (22)	−134.0 (16)	5.7 (6)	−436.1 (22)	−487.1 (16)	−28.7 (6)	−392.2 (22)	−436.7 (16)	−35.7 (6)
6 May 2009	1636.6 (36)	2071.7 (14)	1201.4 (22)	143.6 (36)	330.3 (14)	−43.1 (22)	−171.1 (36)	−394.2 (14)	52.0 (22)	−1406.6 (36)	−1452.9 (14)	−1360.3 (22)	−202.5 (36)	−555.0 (14)	150.1 (22)
11 May 2009	1290.4 (33)	1692.8 (17)	887.9 (16)	197.2 (33)	440.1 (17)	−45.7 (16)	−293.7 (33)	−655.0 (17)	67.6 (16)	−1209.1 (33)	−1762.8 (17)	−655.3 (16)	15.2 (33)	284.8 (17)	−254.4 (16)
5 May 2010	2310.1 (29)	2957.6 (15)	1662.6 (14)	112.6 (29)	332.2 (15)	−106.9 (14)	−96.0 (29)	−283.6 (15)	91.7 (14)	−5831.7 (29)	−2742.7 (15)	−8920.8 (14)	3504.9 (29)	−263.4 (15)	7273.3 (14)
9 May 2010	1882.0 (30)	1140.3 (15)	2623.7 (15)	277.4 (30)	375.2 (15)	179.5 (15)	−373.2 (30)	−505.6 (15)	−240.9 (15)	−1319.3 (30)	−1473.8 (15)	−1164.8 (15)	−466.9 (30)	463.9 (15)	−1397.6 (15)
22 May 2010	915.2 (25)	1621.4 (11)	209.1 (14)	87.6 (25)	200.2 (11)	−25.0 (14)	−86.1 (25)	−196.6 (11)	24.5 (14)	−3883.7 (25)	−6064.7 (11)	−1702.7 (14)	2966.8 (25)	4439.6 (11)	1494.1 (14)
Average	1995.9	2320.3	1569.7	221.1	410.9	−41.0	−219.8	−452.3	45.7	−2265.9	−2397.4	−2052.8	268.8	118.4	478.5

TABLE 3: Variation of TKE budget terms during NTD cases at Kharagpur. The number of half hour runs is given in brackets.

Date	$-\overline{w'u'}\ (\partial\overline{u}/\partial z)\ (\times10^{-5}\ \mathrm{m^2s^{-3}})$			$(g/\overline{\theta_v})\ (\overline{w'\theta_v'})\ (\times10^{-5}\ \mathrm{m^2s^{-3}})$			$-\partial(\overline{w'e})/\partial z\ (\times10^{-5}\ \mathrm{m^2s^{-3}})$			$-\varepsilon\ (\times10^{-5}\ \mathrm{m^2s^{-3}})$			$-(1/\overline{\rho})(\partial(\overline{w'p'})/\partial z)\ (\times10^{-5}\ \mathrm{m^2s^{-3}})$		
	Daily	Day	Night	Daily	Day	Night	Daily	Day	Night	Daily	Day	Night	Daily	Day	Night
16 April 2007	1853.1	2174.2	1496.4	206.3	432.7	−73.4	−463.7	−972.6	164.8	−1566.9	−1860.1	−1204.7	−28.8	156.0	−257.0
	(38)	(20)	(18)	(38)	(20)	(18)	(38)	(20)	(18)	(38)	(20)	(18)	(38)	(20)	(18)
19 April 2007	1579.5	2124.2	938.6	239.2	480.8	−45.1	−6.8	−13.9	1.6	−1465.2	−1706.8	−1181.0	−346.6	−884.2	285.9
	(37)	(20)	(17)	(37)	(20)	(17)	(37)	(20)	(17)	(37)	(20)	(17)	(37)	(20)	(17)
03 May 2007	1252.5	1529.5	975.4	139.4	325.0	−69.4	1.1	2.7	−0.6	−1231.6	−1317.0	−1135.6	−161.4	−575.9	304.8
	(34)	(17)	(17)	(34)	(17)	(17)	(34)	(17)	(17)	(34)	(17)	(17)	(34)	(17)	(17)
04 May 2007	583.1	656.7	528.0	52.2	179.3	−57.9	−54.9	−188.2	60.7	−566.5	−566.1	−566.9	−14.0	−158.2	111.1
	(28)	(12)	(16)	(28)	(12)	(16)	(28)	(12)	(16)	(28)	(12)	(16)	(28)	(12)	(16)
06 May 2007	1309.5	1879.7	868.8	136.5	372.5	−65.7	−24.0	−65.5	11.6	−1151.5	−1535.9	−822.0	−270.5	−708.4	104.8
	(39)	(17)	(22)	(39)	(17)	(22)	(39)	(17)	(22)	(39)	(17)	(22)	(39)	(17)	(22)
15 April 2009	1529.2	2510.6	547.9	218.5	502.8	−65.8	−342.9	−747.7	62.0	−1626.8	−2241.0	−1012.5	221.9	−24.7	468.5
	(23)	(12)	(11)	(23)	(12)	(11)	(23)	(12)	(11)	(23)	(12)	(11)	(23)	(12)	(11)
10 May 2009	1094.1	1566.5	621.7	128.9	313.2	−55.4	−145.9	−354.9	63.1	−1260.6	−1691.8	−829.4	183.5	167.0	200.0
	(34)	(11)	(23)	(34)	(11)	(23)	(34)	(11)	(23)	(34)	(11)	(23)	(34)	(11)	(23)
4 May 2010	1057.6	1072.4	1042.7	102.7	272.5	−67.2	275.1	729.7	−179.6	−1271.7	−1178.9	−1364.5	−163.7	−895.8	568.5
	(32)	(13)	(19)	(32)	(13)	(19)	(32)	(13)	(19)	(32)	(13)	(19)	(32)	(13)	(19)
8 May 2010	394.4	434.8	354.1	72.6	168.1	−22.9	−90.8	−210.8	29.2	−960.9	−1215.1	−706.7	584.7	823.1	346.3
	(32)	(15)	(17)	(32)	(15)	(17)	(32)	(15)	(17)	(32)	(15)	(17)	(32)	(15)	(17)
11 May 2010	1603.8	1130.7	2076.9	106.5	255.9	−42.9	−230.3	−553.2	92.6	−1514.7	−1295.8	−1733.5	34.7	462.5	−393.0
	(46)	(23)	(23)	(46)	(23)	(23)	(46)	(23)	(23)	(46)	(23)	(23)	(46)	(23)	(23)
12 May 2010	1952.4	1978.4	1926.3	140.9	342.3	−60.5	−373.4	−908.8	161.9	−1740.7	−1825.4	−1656.0	20.9	413.5	−371.8
	(41)	(18)	(23)	(41)	(18)	(23)	(41)	(18)	(23)	(41)	(18)	(23)	(41)	(18)	(23)
15 May 2010	804.8	816.2	793.4	88.4	252.7	−75.9	−140.7	−401.7	120.4	−1031.8	−960.5	−1103.1	279.3	293.3	265.2
	(37)	(21)	(16)	(37)	(21)	(16)	(37)	(21)	(16)	(37)	(21)	(16)	(37)	(21)	(16)
Average	1287.4	1589.6	994.7	140.6	335.9	−59.2	−134.0	−312.6	47.9	−1284.3	−1476.2	−1087.3	−9.7	−152.9	140.0

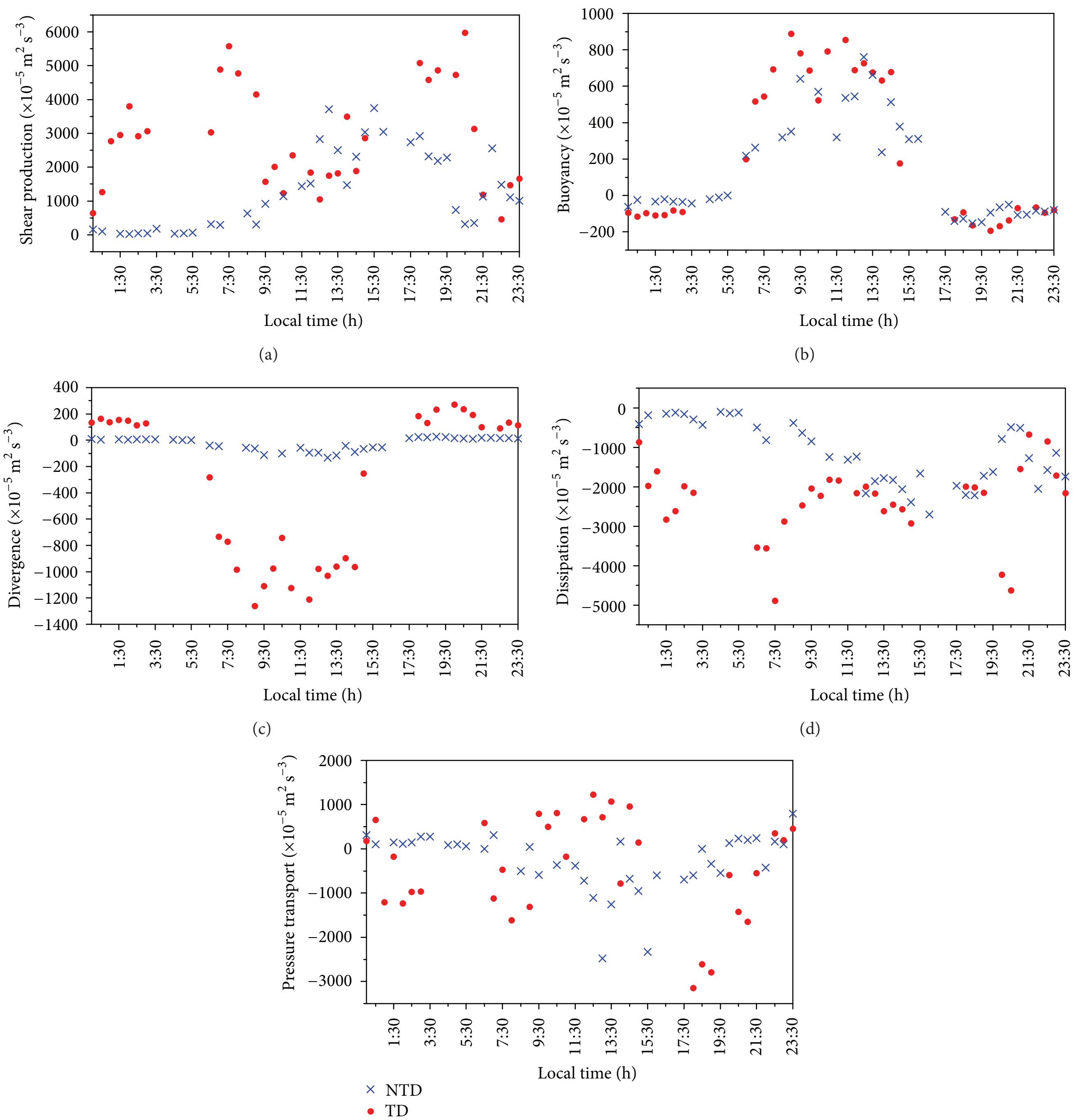


FIGURE 2: Diurnal variation of TKE budget parameters for TD (26 April 2007) denoted by filled black circles and NTD (06 May 2007) denoted by grey crosses for (a) shear production, (b) buoyancy, (c) divergence, (d) dissipation, and (e) pressure transport term.

for marine ASL. Relationships for both unstable and stable conditions provided in [30] were as follows:

$$\phi_\varepsilon(\zeta) = \frac{(1-\zeta)}{(1-7\zeta)} - \zeta, \quad \zeta \leq 0, \tag{8}$$

$$\phi_\varepsilon(\zeta) = 1 + (e-1)\zeta, \quad \zeta \geq 0, \tag{9}$$

where $e = 6$ for [30], and thus, the relationship for stable conditions comes out the same as (7). It was suggested in [17] that (9) can be written in a general form as

$$\phi_\varepsilon(\zeta) = A + \gamma\zeta, \quad \zeta \geq 0. \tag{10}$$

Equation (10) has been followed in [31] for $A = 0.61$. For very high stability, the A is negligibly small and $\gamma = 5$ in

[31], and 3.7 in [32]. Hence it was proposed in [17] that during stable conditions (nighttime), when the ground is colder than the air, TKE dissipation rate can adopt the z-less stratification behavior, while under unstable conditions (during daytime) dissipation rates are not following any specific behavior.

For the present study, normalized dissipation rates of vertical wind $\{\phi_\varepsilon(w)\}$ with respect to ζ for stable and unstable conditions during TD and NTD are estimated. Bin quartiles are computed for equal log spaced bins from data points to fit the empirical relationships in both TD and NTD. It has been found that the earlier proposed relationships for unstable or stable conditions are not satisfying the present study at both sites, and hence, there is a need for new relations in the present study for TD and NTD. Relations are different for TD and NTD at both sites, which is showing different dissipation during TD compared to NTD cases. Relations of dissipation rates at Kharagpur are based on relations of [28] and are as follows.

During NTD:

$$\phi_z(\zeta) = \left(0.28 + 0.5\zeta^{2/3}\right)^{3/2}, \quad -1 \le \zeta \le -0.001, \tag{11}$$

$$\phi_z(\zeta) = 0.28 + 6\zeta, \quad 0.001 \le \zeta \le 1. \tag{12}$$

During TD:

$$\phi_z(\zeta) = \left(0.36 + 0.09\zeta^{2/3}\right)^{3/2}, \quad -1 \le \zeta \le -0.001, \tag{13}$$

$$\phi_z(\zeta) = 0.25 + 0.7\zeta, \quad 0.001 \le \zeta \le 1. \tag{14}$$

These empirical relations, along with relations of EF and TG, $\phi_\varepsilon(w)$ with respect to ζ, bin quartile points for unstable and stable cases during both TD and NTD, are shown in Figure 3. Interestingly, the dissipation rates of TD are lower than that of NTD in the unstable region of $-\zeta > 3$ but higher than that of NTD for $-\zeta < 3$. These results are showing different behaviors of two dissipation rates in the free convection sublayer ($-\zeta > 2$) as proposed in [33]. However, in the stable region, the dissipation rates for NTD are higher than TD. The effect of highly convective atmosphere and higher production rates can be attributed to the higher dissipation during unstable conditions of TD.

4.4. Variation of Budget Parameters with Stability. Based on the stability (ζ), the period of the study is divided into three stability groups: near neutral ($-0.09 < \zeta < 0.09$), unstable ($\zeta < -0.09$), and stable ($0.09 < \zeta$) during TD as well as NTD. Table 4 provides the information of the stability ranges chosen, TKE budget parameters during TD and NTD separated individually into different stability groups, and their averages computed under each stability group. All the TD and NTD cases (of 2007, 2009, and 2010) have been taken into account for dividing them into stability groups. The variation of TKE budget parameters with respect to stability is shown in Table 4 and discussed here under for Kharagpur.

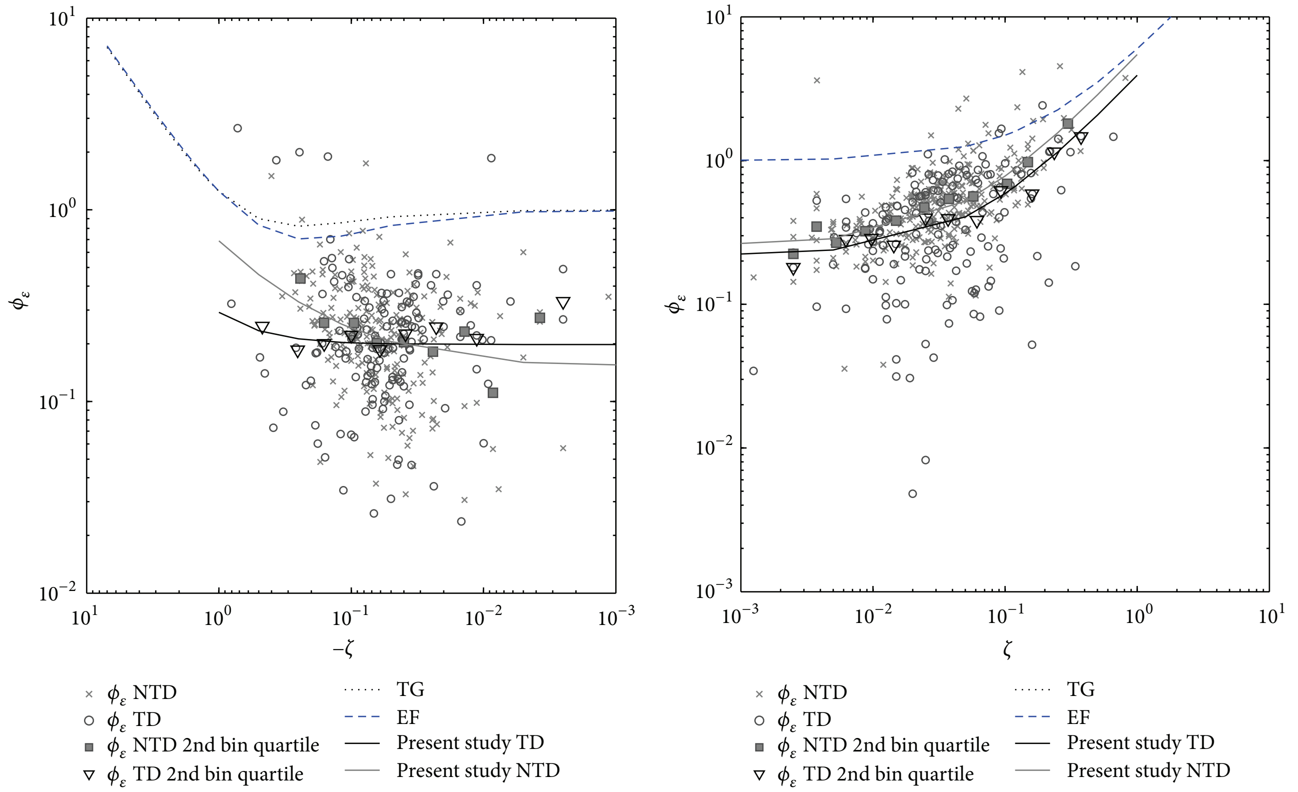
4.4.1. Unstable Case. Mean stability is showing that TD cases are more unstable (−0.172) compared to NTD cases (−0.154). In unstable conditions, shear production, buoyancy, and pressure transport terms act as source terms, while flux divergence and dissipation terms act as sink terms in both TD and NTD. Flux divergence and dissipation together compensate the other terms of the budget equation. Magnitude of terms in TD is higher than that of NTD during unstable conditions. The buoyancy production is always a strong function of stability. Availability of sufficient moisture in the lower layers of the atmosphere and rapid increase of convection in terms of sensible heat flux play an important role in occurrence of the thunderstorm, and hence, more buoyancy production during TD compared to NTD can be explainable. Higher wind speeds during daytime in TD can be attributed to higher values of shear production. Flux divergence is showing that the transportation of TKE is more up in the atmosphere during NTD. Because of higher production, high values of dissipation in TD during unstable conditions are explainable.

4.4.2. Near-Neutral Case. Generally, near-neutral conditions are associated with overcast sky and strong winds resulting in more shear production in TD cases compared to NTD cases. Mean stability is almost the same for both TD and NTD cases (−0.005 for TD and −0.002 for NTD). In the near neutral stability, it is seen that shear production and flux divergence terms are source terms, while buoyancy and dissipation terms are sink terms during both TD and NTD. Pressure transport term is source term during TD and sink term during NTD. Magnitude of terms in TD is higher than that in NTD. During premonsoon season, higher sensible heat flux and high winds can be attributed to the higher order of buoyancy and shear production during both TD and NTD.

4.4.3. Stable Case. Mean stability values are higher during TD (0.187) compared to that of NTD (0.170) for stable conditions. For stable region, shear production and buoyancy terms have higher magnitudes in NTD compared to TD. As expected, buoyancy is negative and acts as sink term. In the stable case, buoyancy and dissipation together compensate all other terms.

Higher shear production, buoyancy, and dissipation term values for TD compared to NTD during unstable and neutral conditions are showing highly convective atmosphere supporting the thunderstorm activity. During stable conditions also, dissipation values are higher for TD, but shear production and buoyancy values are high for NTD. This shows the availability of more heat in the atmosphere during TD cases. Flux divergence values are almost of the same order.

4.5. Comparison with TKE Budget Variations during Monsoon Season. TKE budget terms variations for monsoon season over the same site have been studied in [14] using data sets recorded during 1990. Their results showed that dissipation term and flux divergence term together compensate other terms of the TKE budget equation during active as well as nonactive days of summer monsoon at Kharagpur. In the present study during premonsoon season, shear production term and buoyancy term together compensate the other terms of the budget equation. This variation is in agreement with the findings of [3, 14] which found that flux divergence



(a) (b)

FIGURE 3: $\phi_\varepsilon(w)$ as a function of ζ for (a) unstable conditions and (b) stable conditions.

TABLE 4: Variation of TKE budget parameters at Kharagpur during TD and NTD cases with atmospheric stability.

Stability (z/L)	Mean stability		$-\overline{w'u'}\ (\partial\bar{u}/\partial z)$ ($\times10^{-5}$ m^{2}s^{-3})		$(g/\overline{\theta_v})\ (\overline{w'\theta_v'})$ ($\times10^{-5}$ m^{2}s^{-3})		$-\partial(\overline{w'e})/\partial z$ ($\times10^{-5}$ m^{2}s^{-3})		$-\varepsilon$ ($\times10^{-5}$ m^{2}s^{-3})		$-(1/\bar{\rho})(\partial(\overline{w'p'})/\partial z)$ ($\times10^{-5}$ m^{2}s^{-3})	
	TD	NTD	TD	NTD	TD	NTD	TD	NTD	TD	NTD	TD	NTD
Unstable (<−0.09)	−0.172	−0.154	946.33	804.50	486.27	395.41	−488.61	−511.08	−1189.78	−1045.59	245.79	356.76
Near neutral (−0.09–+0.09)	−0.005	−0.002	2691.12	1489.82	172.69	92.70	−205.96	−93.47	−2690.48	−1460.82	32.64	−28.23
Stable (>+0.09)	0.187	0.170	160.74	169.28	−29.44	−42.94	33.99	30.09	−1500.78	−423.06	1335.49	266.63

term is significant close to ground and the term is getting insignificant while moving to higher heights. Higher values of flux divergence term have been found on the days of nonactive phase of monsoon. In the present study, the flux divergence term is significant during days of TD and negligibly small during NTD. For the monsoon season, it has been found in [14] that mechanically generated turbulence dominates the thermally induced turbulence in active phase. For the present study, it has been found that during TD, both mechanically and thermally induced turbulences are higher than those of NTD. These results are bringing out the major difference in the contribution of the production/sink terms in generating the TKE during summer monsoon and premonsoon season over Kharagpur.

5. Summary

The present study aims to discern the variations in the atmospheric surface layer turbulence transport and the processes that contribute to the total TKE during the days of thunderstorm and nonthunderstorm (no weather activity) within the same premonsoon period at Kharagpur. In the present study the hours during thunderstorm event are discarded because of not following steady state condition and hence MOST. The study is useful over the site as the transport of energy such as fluxes of heat, moisture, and momentum from surface layer to above is through turbulence mechanism only. A higher magnitude of TKE is noticed during TD than NTD. TKE budget analysis reveals buoyancy and shear production processes (mechanical and thermal forcing) together contributing to the total TKE in TD and NTD, but more in the former case. It is found that the transportation of TKE from the surface layer to upper layers of the atmosphere in TD is almost twice stronger than that in NTD. Highly unstable conditions were noticed in TD, while during nighttime, highly stable stratification was noticed in NTD. Shear production is main source term which compensates other budget terms along with buoyancy during unstable conditions and with flux divergence during near neutral and stable conditions in both TD and NTD. In TD higher dissipation is noticed. TKE dissipation rates for unstable and stable conditions on TD and NTD are different, with higher rates in TD during unstable conditions and in NTD during stable conditions. New relationships for surface layer dissipation rate with respect to stability for TD and NTD are proposed. Under stable conditions, dissipation rate presents a z-less stratification behavior. This study reveals the difference in contribution of various TKE budget terms during monsoon (reported in the literature) and premonsoon period at the same site. During the monsoon season, mechanically generated turbulence dominates the thermally induced turbulence in active phase, whereas for the present study both mechanically and thermally induced turbulences are higher in TD than in NTD.

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References

[1] H.-S. Zhang and S.-U. Park, "Dissipation rates of turbulent kinetic energy and temperature and humidity variances over different surfaces," *Atmospheric Research*, vol. 50, no. 1, pp. 37–51, 1999.

[2] J. A. Businger, J. C. Wyngaard, Y. Izumi, and E. F. Bradley, "Flux profile relationships in the atmospheric surface layer," *Journal of the Atmospheric Sciences*, vol. 28, no. 2, pp. 181–189, 1971.

[3] J. C. Wyngaard and O. R. Cote, "The budget of turbulent kinetic energy and temperature variance in the atmospheric surface layer," *Journal of Atmospheric Sciences*, vol. 28, pp. 199–201, 1971.

[4] G. A. McBean and M. Miyake, "Turbulent transfer mechanism in the atmospheric surface layer," *Quarterly Journal of Royal Meteorological Society*, vol. 98, pp. 383–398, 1972.

[5] D. Pino, J. Vilà-Guerau de Arellano, and P. G. Duynkerke, "The contribution of shear to the evolution of a convective boundary layer," *Journal of Atmospheric Sciences*, vol. 60, pp. 1913–1926, 2003.

[6] X. Li, N. Zimmerman, and M. Princevac, "Local imbalance of turbulent kinetic energy in the surface layer," *Boundary-Layer Meteorology*, vol. 129, no. 1, pp. 115–136, 2008.

[7] P. Frenzen and C. A. Vogel, "The turbulent kinetic energy budget in the atmospheric surface layer: a review and an experimental reexamination in the field," *Boundary-Layer Meteorology*, vol. 60, no. 1-2, pp. 49–76, 1992.

[8] J. Han, S. P. Arya, S. Shan, and Y. L. Lin, "An estimation of turbulent kinetic energy and energy dissipation rate based on atmospheric boundary layer similarity theory," Tech. Rep. 23681-2199 NASA/CR-2000-210298, National Aeronautics and Space Administration Langley Research Center Prepared for Langley Research Center, Hampton, Va, USA, 2008.

[9] F. Holzäpfel and R. E. Robins, "Probabilistic two-phase aircraft wake-vortex model: application and assessment," *Journal of Aircraft*, vol. 41, no. 5, pp. 1117–1126, 2004.

[10] M. Frech, "Estimating the turbulent energy dissipation rate in an airport environment," *Boundary-Layer Meteorology*, vol. 123, no. 3, pp. 385–393, 2007.

[11] J. Caughey and J. C. Wyngaard, "The turbulent kinetic energy budget in convective conditions," *Quarterly Journal of Royal Meteorological Society*, vol. 105, pp. 231–239, 1979.

[12] D. V. Viswanathan, A. N. V. Satyanarayna, S. Mishra, and P. Partha Sarthi, "Turbulent kinetic energy budget parameter over Varanasi from MONTBLEX-90," *The Proceedings of the Indian National Science Academy*, vol. 63, pp. 403–412, 1997.

[13] D. V. Viswanathan, A. N. V. Satyanarayna, M. K. Srivastava, and S. Mishra, "Surface layer turbulent kinetic energy budget over Kharagpur," *Journal of Scientific Research*, vol. 47, pp. 11–20, 1997.

[14] M. K. Srivastava and P. Parth Sarthi, "Turbulent kinetic energy in the atmospheric surface layer during the summer monsoon," *Meteorological Applications*, vol. 9, no. 2, pp. 239–246, 2002.

[15] M. Bister and K. A. Emanuel, "Dissipative heating and hurricane intensity," *Meteorology and Atmospheric Physics*, vol. 65, no. 3-4, pp. 233–240, 1998.

[16] S. Businger and J. A. Businger, "Viscous dissipation of turbulence kinetic energy in storms," *Journal of the Atmospheric Sciences*, vol. 58, no. 24, pp. 3793–3796, 2001.

[17] S. Yahaya, J. P. Frangi, and D. C. Richard, "Turbulent characteristics of a semiarid atmospheric surface layer from cup anemometers—effects of soil tillage treatment (Northern Spain)," *Annales Geophysicae*, vol. 21, no. 10, pp. 2119–2131, 2003.

[18] O. K. Hartogensis and H. A. R. De Bruin, "Monin-Obukhov similarity functions of the structure parameter of temperature and turbulent kinetic energy dissipation rate in the stable boundary layer," *Boundary-Layer Meteorology*, vol. 116, no. 2, pp. 253–276, 2005.

[19] STORM Science Plan, "Severe Thunderstorms-Observations and Regional Modeling (STORM) programme," Science Plan, Department of Science and Technology, Government of India, 118 pp., 2005.

[20] B. Panigrahi and S. N. Panda, "Field test of a soil water balance simulation model," *Agricultural Water Management*, vol. 58, no. 3, pp. 223–240, 2003.

[21] D. Roy, *Development of software for the design of the on farm reservoir under rain fed farming system [M.S. thesis]*, Department of Agriculture and Food Engineering, Indian Institute of Technology Kharagpur, 2006.

[22] B. Tyagi and A. N. V. Satyanarayana, "Modeling of soil surface temperature and heat flux during pre-monsoon season at two tropical stations," *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 72, no. 2-3, pp. 224–233, 2010.

[23] C. A. M. Morales Rodriguez, R. P. da Rocha, and R. Bombardi, "On the development of summer thunderstorms in the city of São Paulo: mean meteorological characteristics and pollution effect," *Atmospheric Research*, vol. 96, no. 2-3, pp. 477–488, 2010.

[24] B. Tyagi and A. N. V. Satyanarayana, "Assessment of turbulent kinetic energy budget and boundary layer characteristics during pre-monsoon thunderstorm season over Ranchi," *Asia Pacific Journal of Atmospheric Science*, vol. 49, no. 5, pp. 1–15, 2013.

[25] G. A. McBean and J. A. Elliott, "The vertical transports of kinetic energy by turbulence and pressure in the boundary layer," *Journal of the Atmospheric Sciences*, vol. 32, no. 4, pp. 753–766, 1975.

[26] J. C. Kaimal, J. C. Wyngaard, Y. Izumi, and O. R. Coté, "Spectral characteristics of surface layer turbulence," *Quarterly Journal of Royal Meteorological Society*, vol. 98, pp. 563–589, 1972.

[27] M. Roth, J. A. Salmond, and A. N. V. Satyanarayana, "Methodological considerations regarding the measurement of turbulent fluxes in the urban roughness sublayer: the role of scintillometery," *Boundary-Layer Meteorology*, vol. 121, no. 2, pp. 351–375, 2006.

[28] J. C. Kaimal and J. J. Finnigan, *Atmospheric Boundary Layer Flows: Their Structure and Measurement*, Oxford University Press, New York, NY, USA, 1994.

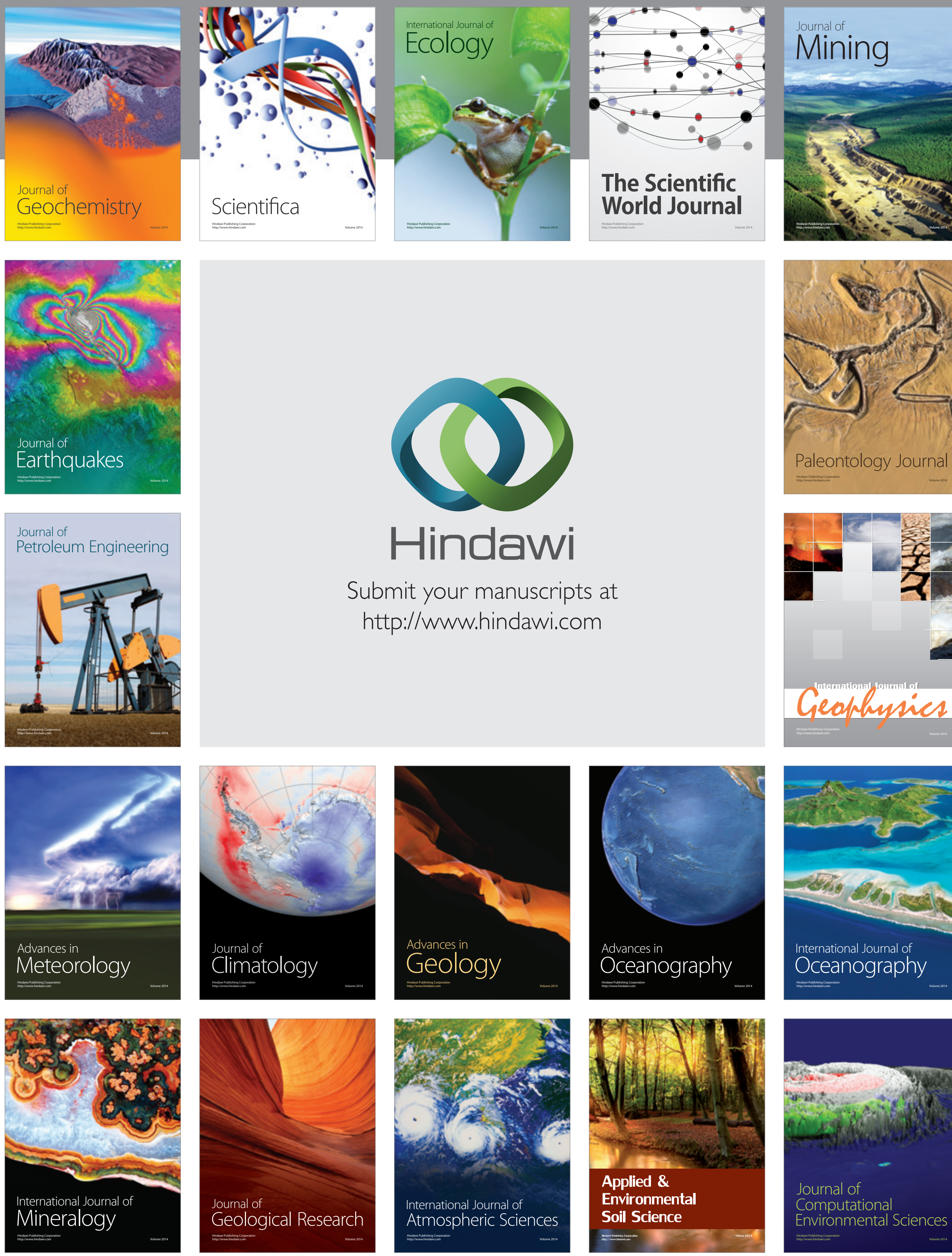
[29] V. Thiermann and H. Grassl, "The measurement of turbulent surface-layer fluxes by use of bichromatic scintillation," *Boundary-Layer Meteorology*, vol. 58, no. 4, pp. 367–389, 1992.

[30] J. B. Edson and C. W. Fairall, "Similarity relationships in the marine atmospheric surface layer for terms in the TKE and scalar variance budgets," *Journal of the Atmospheric Sciences*, vol. 55, no. 13, pp. 2311–2328, 1998.

[31] M. Pahlow, M. B. Parlange, and F. Porté-Agel, "On Monin-Obukhov similarity in the stable atmospheric boundary layer," *Boundary-Layer Meteorology*, vol. 99, no. 2, pp. 225–248, 2001.

[32] R. B. Stull, *An Introduction to Boundary Layer Meteorology*, Kluwer Academy Press, Dordrecht, The Netherlands, 1988.

[33] J. D. Albertson, M. B. Parlange, G. Kiely, and W. E. Eichinger, "The average dissipation rate of turbulent kinetic energy in the neutral and unstable atmospheric surface layer," *Journal of Geophysical Research D*, vol. 102, no. 12, pp. 13423–13432, 1997.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