BOUNDARY LAYER STABILITY REGIME AT DACCIWA SITE USING GRADIENT RICHARDSON NUMBER

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Abstract

Meteorological data including air temperature and wind speed which were collected from DACCIWA measurement site at a tropical agricultural field site in Ile-Ife (7.55^{o}E, 4.56^{o}E), south-western Nigeria have been used to classify boundary layer stability regimes using gradient Richardson number. Three categories were considered to deduce the pattern of stability conditions namely stable, unstable and neutral conditions for 3-hourly intervals at 0.00, 03.00, 06.00, 09.00, 12.00, 15.00, 18.00 and 21.00 hours from 15th June to 31st July 2016. The data were sampled every 1sec and stored subsequently as 10 minutes averages for all the measured parameters. The data was further reduced to 30 minutes averages for easy analysis and manipulation in the calculation of gradient Richardson number used for boundary layer stability regime characterization. The results showed that the month of June 2016 had prevalence of stable regime from 0:00 – 6:00 am and 6:00 pm; 9:00 am was predominantly neutral and shared similar pattern with 9:00 pm. Unstable regime was slightly observed at 12:00 pm and majorly observed at 3:00 pm. The month of July had a little shift from what was observed in the month of June. Predominance of neutral conditions was observed from 9:00 pm to 9:00 am; Hours of 12:00 – 3:00 pm were dominated by unstable regime while 6:00 pm was dominated by stable regime.

Keywords: Richardson number, Stability regimes, Atmospheric Boundary Layer, Vertical gradient

1.0 Introductions

In the framework of the multi-institutional EU-funded research project Dynamics-Aerosol-Chemistry-Cloud Interaction in West Africa (DACCIWA) extensive ground-based measurements was conducted at Ile-Ife (7.55^{0}N, 4.56^{0}E), Nigeria during the period 13th June and 31st July, 2016. The site is a low wind tropical location where intense surface heating and net radiation is sometimes greater than 750 Wm^{-2}. Much research has been done on the processes governing the turbulent transfer of momentum, heat and water vapour in the lowest layer of the atmosphere and generalizations about the flux-gradient relationships under near neutral conditions.

In a research carried out by Edokpa and Weli (2017), atmospheric boundary layer turbulence in Maiduguri, Nigeria was assessed. Five years (2011-2015) temperature and wind speed data at 1000 mbar pressure level retrieved from Era-Interim Reanalysis Platform was used. Findings showed that the surface layer is always in a turbulent state as over 95% of Rig values were below Richardson Critical (Ric) value of 0.25 with range 0.02 - 0.94. However, all values across the hours were below the Richardson Termination (RT) value of 1. The authors observed that Laminar conditions existed at the mid layer across the hours as 99.9% of Rig values ranging 0.88 - 8.02 were greater than RT of 1. Rig values for the upper layer were largely negative and ranged between −78.71 to −724.14. This indicated robust turbulent conditions. Turbulence generated through forced and free ascents prevailed at the surface layer and upper layer respectively. This shows that wind shear is dominant at the surface while thermal buoyancy prevails at the upper level.

In another research carried out by Edokpa and Nwagbara (2018), the study examined the variation of atmospheric stability conditions in Nigeria's climate belts using the Pasquill-Gifford (PG) technique within a period of 2010 and 2015. The result showed that across climate belts in Nigeria unstable conditions increased from the coast of Port Harcourt (tropical wet climate) to Kano (tropical continental climate) in the northern part of Nigeria. There was a revered trend for the neutral conditions. It was also observed that stable atmospheric stability conditions were slightly higher in the tropical continental climate and the semi-arid zone than the coastal zone. However the climate of Nigeria was dominated by the unstable atmospheric conditions. Very stable atmospheric conditions (stability class F) prevailed during the hours of the dawn for most of the seasons in the coastal areas while less stable atmospheric conditions (stability class E) prevailed in the semi-arid region of Nigeria. During the day, the boundary layer atmosphere was slightly unstable in the coastal areas and moderately unstable in the semi-arid belt.

However, there still exist some uncertainties for boundary layer stability classification using Richardson number model. This paper presents some results of the analysis of the boundary layer stability classification at a low wind tropical site.

2.0 Theoretical Background

Atmospheric stability plays the most important role in the transport and dispersion of air pollutants. It can be defined as the atmospheric tendency to reduce or intensify vertical motion or alternatively, to suppress or augment existing turbulence (Ahrens, 2012). It is related to the change of temperature with height (the lapse rate) and also wind speed. The degree of stability of the atmosphere must be known to estimate the ability of atmosphere to disperse pollutants (Agunbiade and Adelekan, 2017). Generally, when convective turbulence predominates, winds are weak and atmosphere is in unstable condition. When importance of convection decreases and mechanical turbulence increases, atmosphere tends to neutral conditions (Schlichting and Gersten, 2000). Finally in absence of convective turbulence when mechanical turbulence is dampened and there is no vertical mixing, atmosphere is in stable condition.

The analysis of turbulent processes in the first few meters of the atmosphere is usually based upon some scheme for defining the stability regime in operation at the time the experimental data are collected. The regimes may be classified by any number of methods as long as the classification system yields the desired results (Mohan and Siddiqui, 1998). The most common classifier of stability is the Richardson number, which is quite adequate if certain precautions are observed in its calculation. To use the Richardson number effectively as an identifier of the stability regime, it is necessary to understand the turbulent processes within the surface boundary layer.

Since the numerical calculation of the Richardson number is highly dependent upon the vertical gradients of wind velocity and temperature, proper evaluation of these parameters is vital in terms of whether the data are representative or have been biased by horizontal advection or the presence of local terrain effects that lead to unsteady-state flow (Saric, *et al*., 2000).

The Richardson number, a non-dimensional parameter possessing the characteristics of dynamic similarity according to Ashrafi and Hoshyaripour, (2010), is the accepted stability indicator in most studies concerning atmospheric turbulence. Richardson (1920, 1925), while investigating the effects of gravity on the suppression of turbulence, derived a ratio of work done against gravitational stability to energy transformed from mean to turbulent motion (Abaje, *et al*., 2014). It was asserted that a motion which was slightly turbulent would remain so if the ratio were less than one and would subside if the ratio were greater than one (Garratt, 1992).

The gradient Richardson number is a turbulence indicator and also an index of stability which is defined as (Ashrafi and Hoshyaripour, 2010):

$$R_i = \frac{g\left(\frac{\Delta\Theta}{\Delta z}\right)}{T\left(\frac{d\bar{u}}{dz}\right)^2} \qquad 1.0$$

g is the gravity acceleration; $\Delta\Theta/\Delta z$ is the potential temperature gradient; T is the temperature and $d\bar{u}/dz$ is the wind speed gradient. In this equation, g($\Delta\Theta/\Delta z$) /T is indicator of convection and $((d\bar{u})/dz)^2$ is pointer of mechanical turbulence due to mechanical shear forces.

In this study, an attempt was made to classify boundary layer stability regimes. Three categories were considered to deduce the pattern of stability conditions namely stable, unstable and neutral conditions for 3-hourly daily patterns for 0.00, 03.00, 06.00, 09.00, 12.00, 15.00, 18.00 and 21.00 hours from 15th June to 31st July 2016.

3.0 Methodology

The DACCIWA measurement site chosen for the study is an agricultural farmland in Ile-Ife. The measurement surface is flat and open over an area of approximately mean roughness length of about 1.0 cm, determined for near neutral conditions and shows a variation with time and wind direction surrounded by cultivated and forested areas.

The vertical profile of temperature, friction velocity, global radiation and wind speed at 2 low levels were measured using sensitive cup anemometers and Frankenberg-type psychrometers. The data were sampled every 1 second and stored subsequently as 10 minutes averages for all the measured parameters. The data acquisition/reduction, quality control and processing programs were developed by scientists at the Obafemi Awolowo University, Ile-Ife, Nigeria. The data was further reduced to 30 minutes averages for easy analysis and manipulation in the calculation of gradient Richardson number used for boundary layer stability regime characterization.

Detailed description of the data collection methods can be found on the link (www.oauife.edu.ng/....). The meteorological station recorded air temperature (type-T thermocouple) and wind speed (cup anemometer) at 1.44 m and 12.1 m. The sensors were connected to a data logger which also served as temporary storage. The meteorological data was downloaded into a laptop for further calculation and analysis. Equation 1.0 was used to estimate gradient Richardson number and classified into 3 stability conditions for easy description.

The classification is as follows: $R_i < 0$ is typified as unstable conditions which indicates clouds growing vertically (cumuliform clouds). On the local scale, smoke plumes disperse well vertically and horizontally. There is good visibility, gusty winds, showery precipitation and sometimes thunderstorms. Air temperature decreases rapidly with height allowing vertical mixing (USEPA, 2000). The second classification is $R_i = 0$ which typifies neutral conditions showing that air temperature decreases at the rate of about 9.8^0C/km. The atmosphere has no relative tendency for air parcel to ascend or sink. The third classification is $R_i > 0$ which stands for stable conditions indicating clouds in layers with little vertical development (strati-form clouds). On the local scale, smoke from elevated stacks remains elevated and disperses mostly horizontally. There is poor visibility due to smoke, haze or fog, steady winds, usually light, drizzle or light rain. Air temperature decreases slowly with height or may increase with height (i.e. an inversion), the atmosphere is strongly resistant to vertical mixing) (USEPA, 2000).

4.0 Results and Discussion

a. Boundary Layer Stability Patterns in June 2016

The boundary layer stability patterns for the hours 0:00 am, 3:00 am, 6:00 am, 9:00 am, 12:00 pm, 03:00 pm, 6:00 pm and 9:00 pm from 15th – 30th June 2016 were shown in Table 1 and plotted in figures 1 – 8. The profiles were classified as unstable, neutral, and stable using the Richardson number estimated within the heights of 1.44 m and 12.1 m. The stable cases included all values of $R_i > 0$, while the unstable cases were in the values $R_i < 0$.

It can be clearly seen from the graphs that boundary layer stability regime is a function of insolation depicted by 3-hourly interval of stability patterns from 15th to 30th June 2016. Midnight and early hours of 00:00 – 06:00 am had prevalence of stable conditions which reached its peak by 03:00 am

Table 1: Boundary Layer Stability Patterns Depicted by Richardson Number for June 2016

	3 HOURS INTERVAL PER DAY							
Day	**0:00 am**	**3:00 am**	**6:00 am**	**9:00 am**	**12:00 noon**	**3:00 pm**	**6:00 pm**	**9:00 pm**
15	9.22	23.43	10.75	-0.05	-0.37	0.02	1.93	0.16
16	44.24	81.11	65.39	-36.17	-4.44	-1.43	1.04	0.91
17	23.69	5.48	10.96	-1.23	-0.83	-1.56	0.47	2.24
18	46.55	2.06	16.87	-5.90	-1.18	-1.63	0.71	0.57
19	2.07	2.92	37.14	-2.11	-0.42	-0.35	0.19	1.16
20	2.22	0.79	4.20	-1.47	-1.33	0.04	31.48	26.64
21	4.85	32.88	29.44	-0.46	-0.36	-0.31	0.37	25.90
22	19.83	14.03	18.89	-2.04	-2.12	-1.15	0.23	1.53
23	0.76	2.33	0.66	-0.39	-18.50	-0.86	4.31	0.85
24	1.45	3.25	1.48	-0.32	-4.54	-0.44	1.00	0.63
25	17.92	1.40	6.69	-0.31	-1.14	-0.95	0.39	0.96
26	6.30	61.17	4.21	0.08	-0.75	-1.57	3.86	1.17
27	0.29	0.76	0.69	-0.24	-0.59	-1.03	4.50	33.34
28	0.67	65.81	35.11	-0.20	-0.67	-1.47	0.39	0.57
29	2.13	2.53	1.42	-0.42	-1.00	-0.62	0.20	0.53
30	0.67	1.47	0.84	-0.31	-1.03	-1.25	1.74	48.33

Table 2: Boundary Layer Stability Patterns Depicted by Richardson Number for July 2016

	3 HOURS INTERVAL PER DAY							
Day	**0:00 am**	**3:00 am**	**6:00 am**	**9:00 am**	**12:00 noon**	**3:00 pm**	**6:00 pm**	**9:00 pm**
1	11.86	10.47	5.61	-33.70	-4.27	-1.33	0.14	0.68
2	16.17	2.33	3.86	-3.43	-4.92	-0.97	1.78	71.35
3	6.76	1.11	0.47	-0.20	-0.23	-4.69	0.60	3.39
4	32.01	0.61	3.34	-0.49	-0.50	-0.51	0.32	0.63
5	0.50	0.57	5.13	-0.11	-0.38	-0.52	0.16	0.92
6	0.49	1.10	0.35	-0.55	-0.96	-2.22	0.17	1.26
7	0.97	0.36	1.44	-0.40	-0.87	-0.92	0.32	0.66
8	0.39	0.42	0.49	-0.25	-0.66	-0.58	0.78	2.13
9	19.53	0.41	0.56	-0.08	-0.88	-0.16	0.33	1.92
10	0.53	9.32	0.31	0.23	0.04	-0.13	0.56	0.41
11	0.61	1.64	0.50	-0.05	-0.33	0.10	0.13	1.21
12	20.57	2.51	0.61	-0.29	-1.26	-0.99	0.36	0.49
13	0.83	1.40	13.09	-12.57	-0.78	-0.96	0.50	31.63
14	0.53	77.99	8.47	-0.02	-0.18	-0.31	0.60	1.09
15	68.34	5.05	1.08	0.04	-0.35	-0.84	0.15	0.53
16	2.22	45.23	2.00	0.01	-0.33	-0.55	0.18	0.15
17	0.35	0.62	0.63	0.31	-0.30	-0.10	0.38	1.31
18	1.77	2.47	64.27	-0.43	-5.91	-0.60	1.21	12.38
19	0.90	0.59	0.48	-0.10	-0.17	-0.67	1.12	18.25
20	5.89	1.69	0.56	-0.34	-1.55	-0.44	0.22	10.42
21	49.31	10.18	16.62	-2.12	-1.51	-0.28	3.26	16.34
22	21.32	13.72	2.03	-0.35	-2.80	-0.20	0.45	4.94
23	0.59	1.63	57.31	-0.34	-2.45	-1.52	0.12	0.30
24	0.38	0.42	9.88	-0.56	-1.13	-2.02	-0.14	0.27
25	0.33	0.45	0.89	-0.08	-0.33	-1.01	0.44	0.37
26	0.43	0.44	0.45	-0.02	-0.21	-1.75	0.49	0.44
27	0.57	0.79	0.35	-0.44	-0.97	-2.74	0.86	0.96
28	0.66	0.41	1.07	0.10	-0.11	-0.77	0.15	0.73
29	0.39	0.98	8.71	-0.39	-0.82	-0.74	0.43	0.87
30	0.96	0.43	0.56	0.96	-1.75	-1.18	0.06	0.24
31	0.48	0.33	0.67	-0.26	-0.87	-0.46	0.44	0.28

when highest values were observed. This was consistent with diurnal pattern of reduction in air temperature with height, cloudiness and light rain typifying the seasonal rainy characteristics prevalent in June. Morning hour of 09:00 am was apparently neutral throughout except on 16th and 18th of June. This is interface hour which marks the onset of surface layer response to insolation, during this hour, the atmosphere has no relative tendency for air parcel to ascend or sink. The neutral regime was partially observed during 12:00 noon except for extreme cases observed on 16th, 23rd and 24th June.

Unstable regime became prevalent from afternoon hour of 03:00 pm hour which coincided with the peak of net radiation from the surface layer. The stability trend gradually reverted back to stable from evening hour of 06:00 pm but greatly meandered from stable to neutral at 09:00 pm hour. Days of consistent significant upsurge in stable conditions were noticed on 16th, 20th and 27th of June 2016.

b. Boundary Layer Stability Patterns in July 2016

The boundary layer stability patterns for the hours 0:00 am, 3:00 am, 6:00 am, 9:00 am, 12:00 pm, 03:00 pm, 6:00 pm and 9:00 pm from 1st – 31st July 2016 were shown in Table 2 and plotted in figures 9 – 16. The profiles were also classified into three categories of unstable, neutral, and stable using the Richardson number estimated within the heights of 1.44 m and 12.1 m.

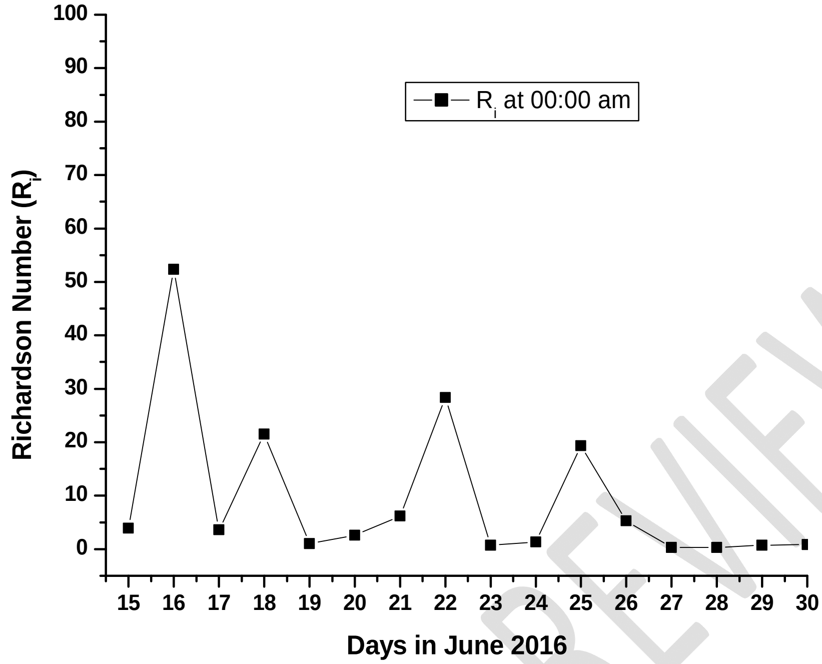

Figure 1: Boundary Layer stability Pattern at 00.00 am in June 2016

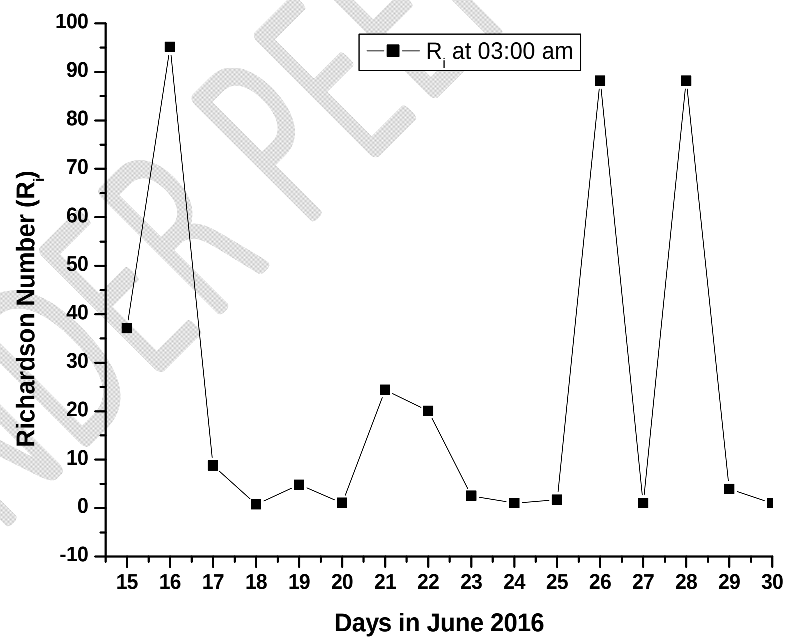

Figure 2: Boundary Layer stability Pattern at 03.00 am in June 2016

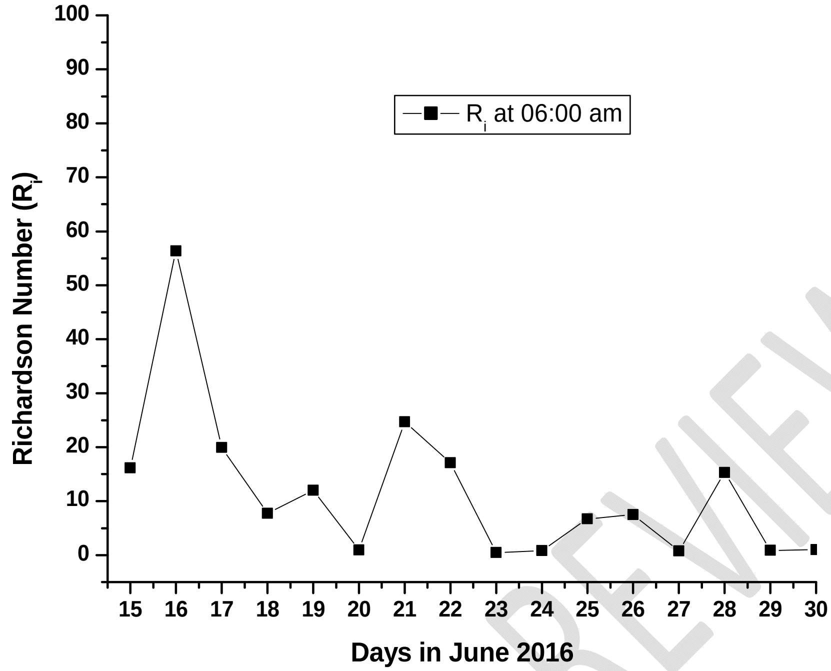

Figure 3: Boundary Layer stability Pattern at 06.00 am in June 2016

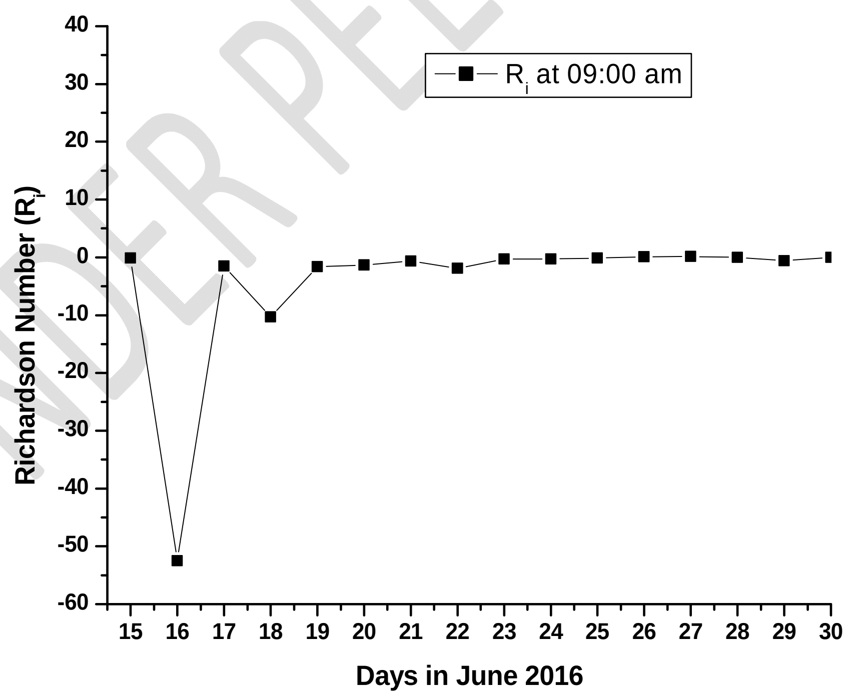

Figure 4: Boundary Layer stability Pattern at 09.00 am in June 2016

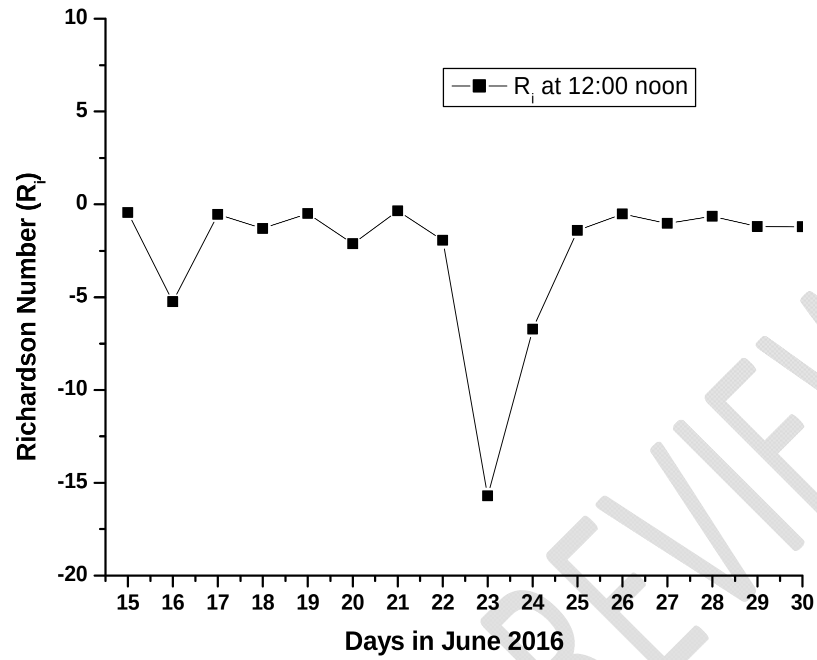

Figure 5: Boundary Layer stability Pattern at 12.00 pm in June 2016

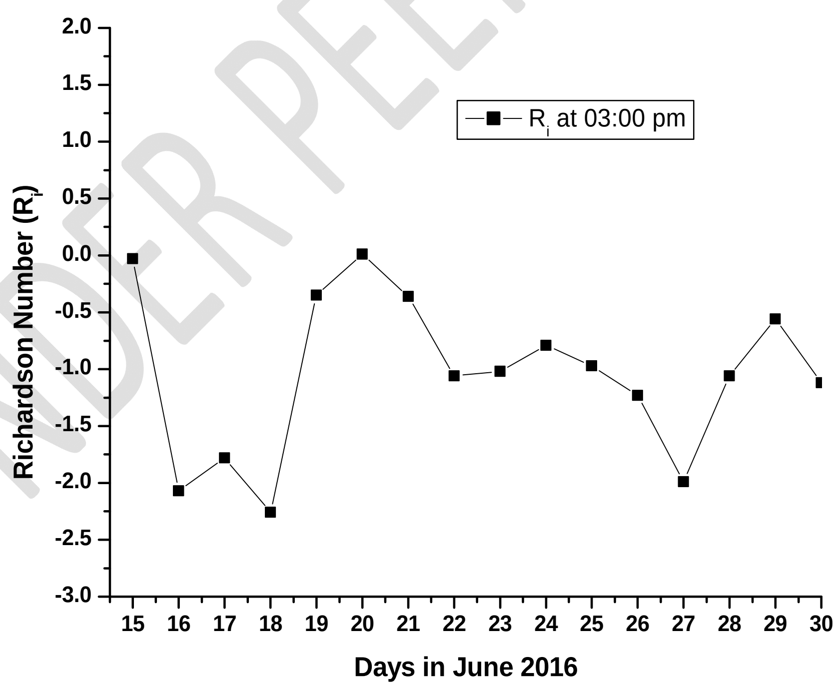

Figure 6: Boundary Layer stability Pattern at 03.00 pm in June 2016

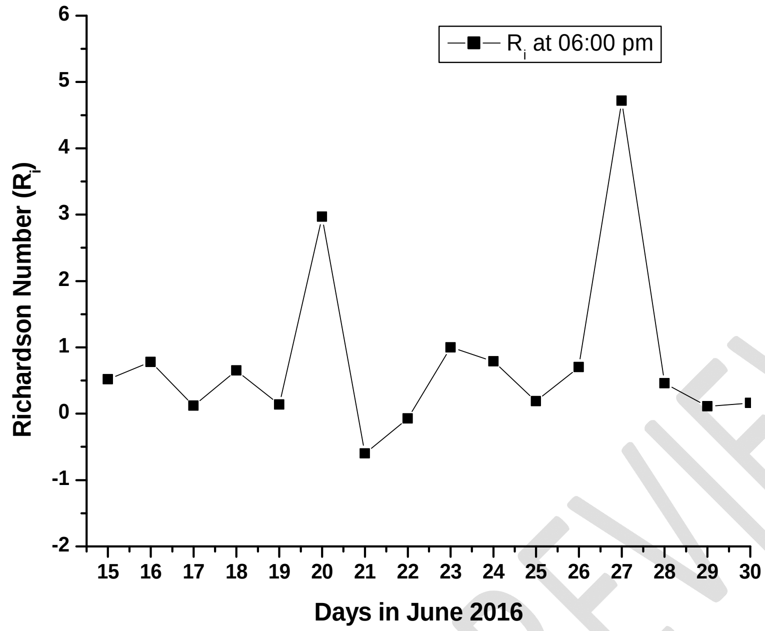

Figure 7: Boundary Layer stability Pattern at 06.00 pm in June 2016

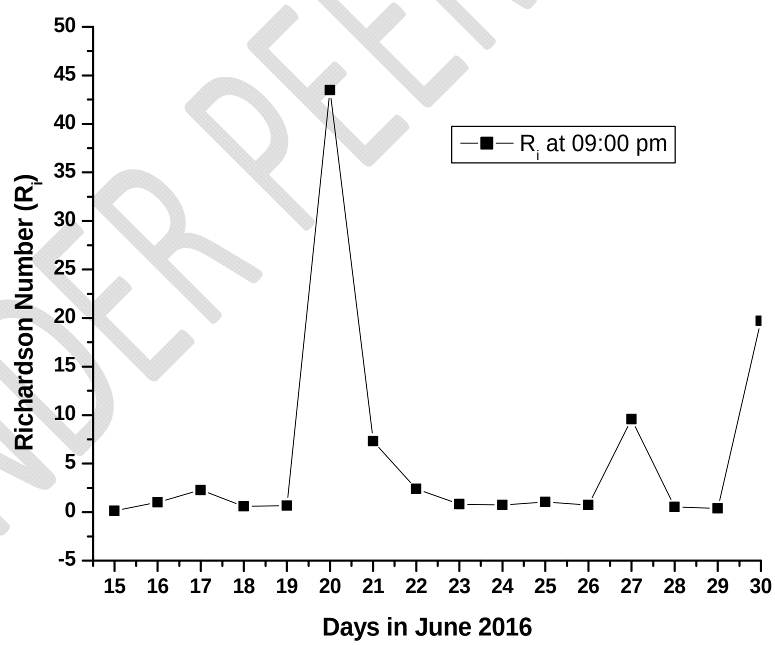

Figure 8: Boundary Layer stability Pattern at 09.00 pm in June 2016

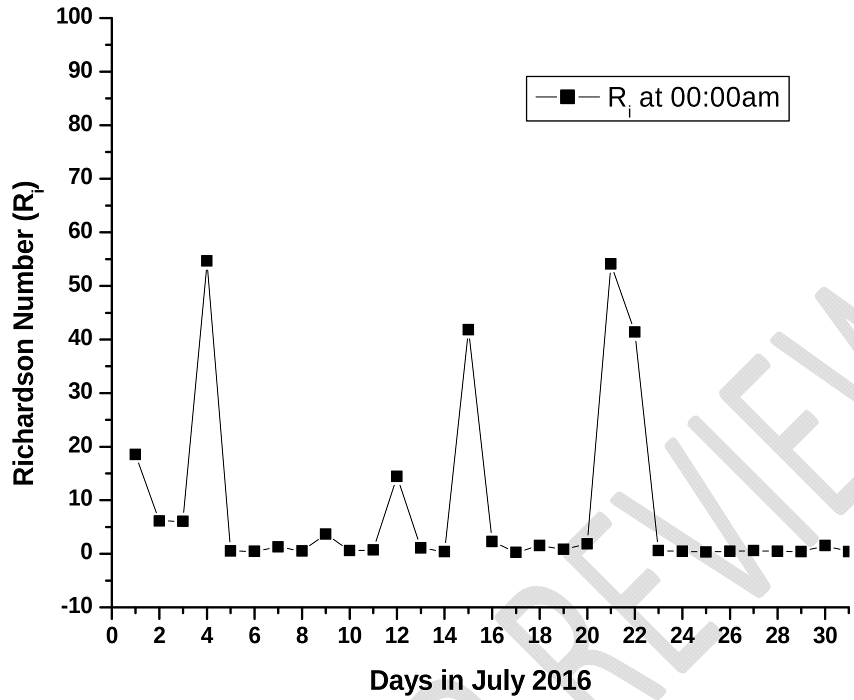

Figure 9: Boundary Layer stability Pattern at 00.00 am in July 2016

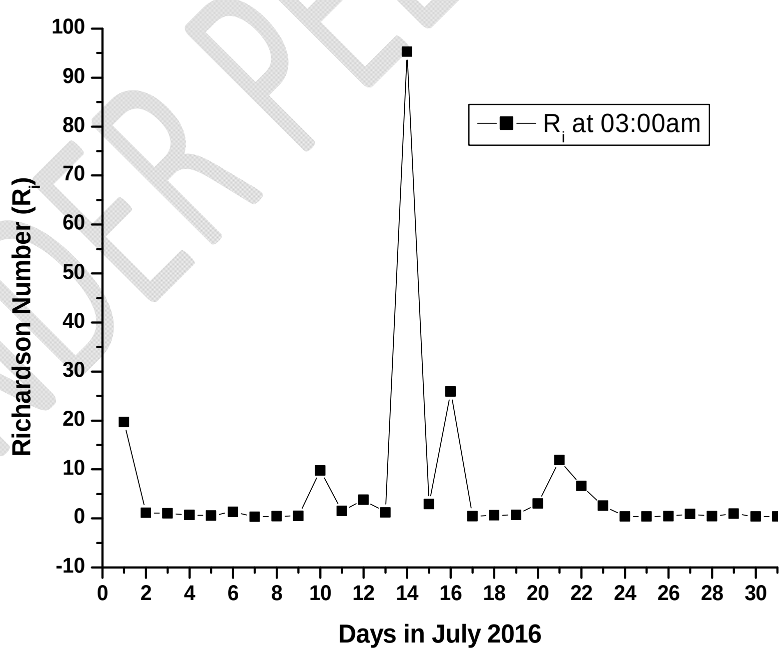

Figure 10: Boundary Layer stability Pattern at 03.00 am in July 2016

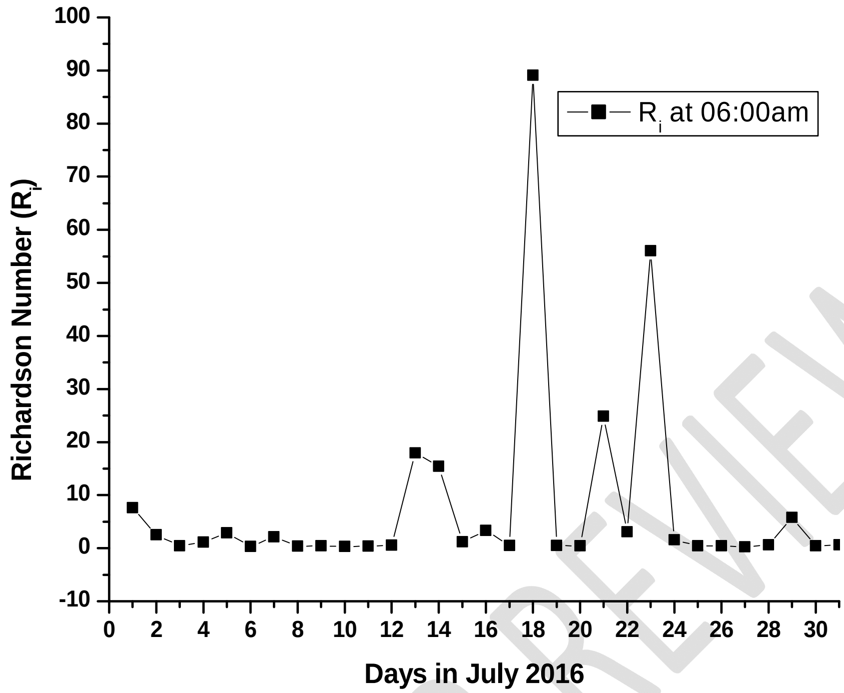

Figure 11: Boundary Layer stability Pattern at 06.00 am in July 2016

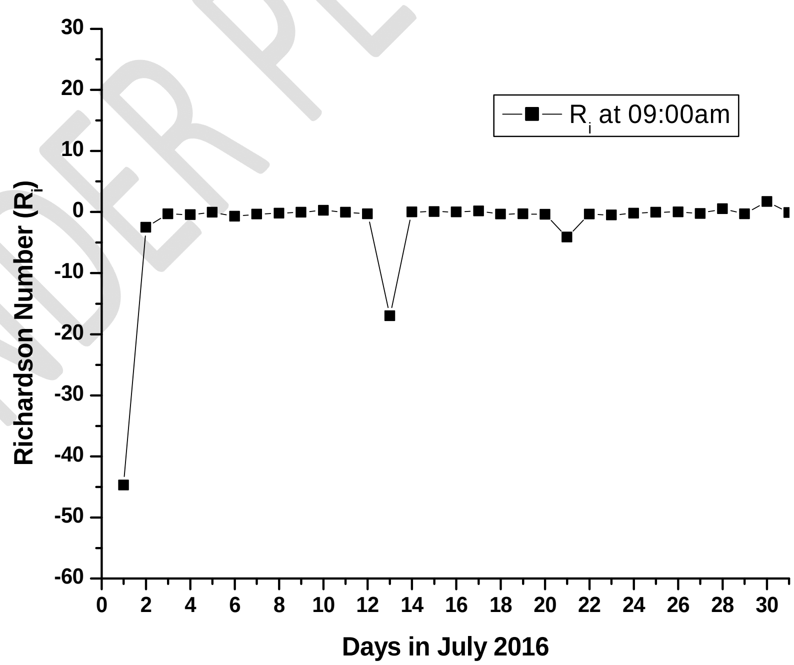

Figure 12: Boundary Layer stability Pattern at 09.00 am in July 2016

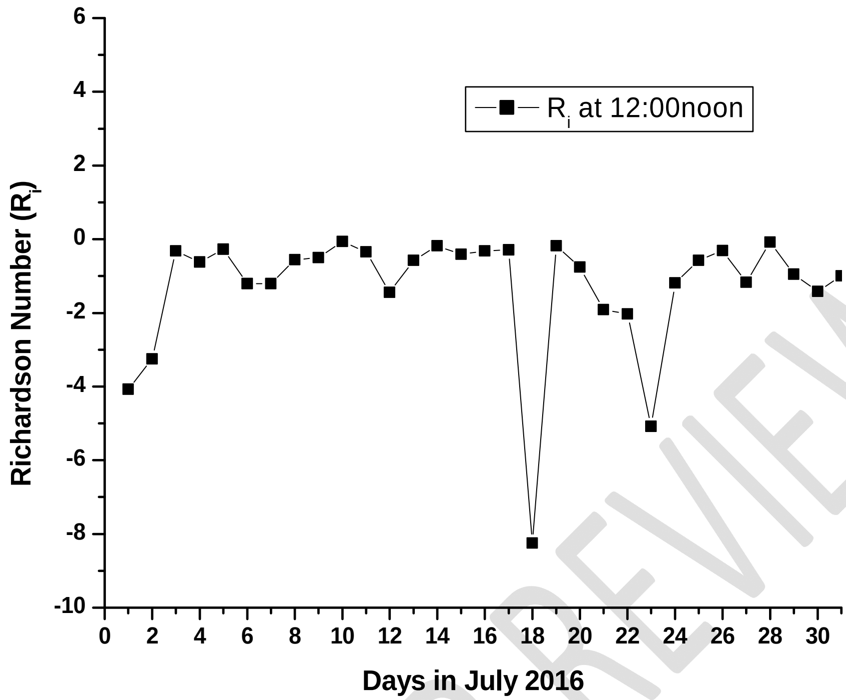

Figure 13: Boundary Layer stability Pattern at 12.00 pm in July 2016

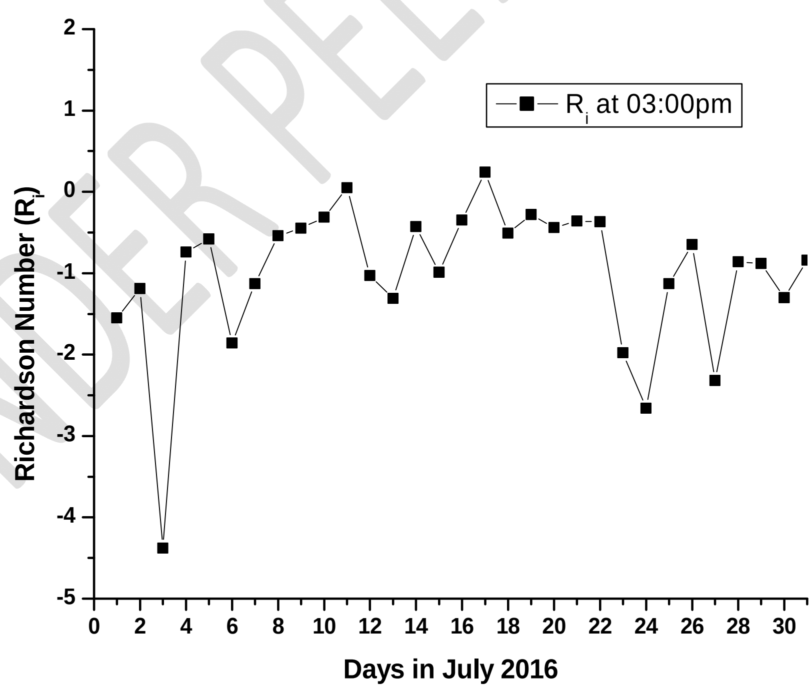

Figure 14: Boundary Layer stability Pattern at 03.00 pm in July 2016

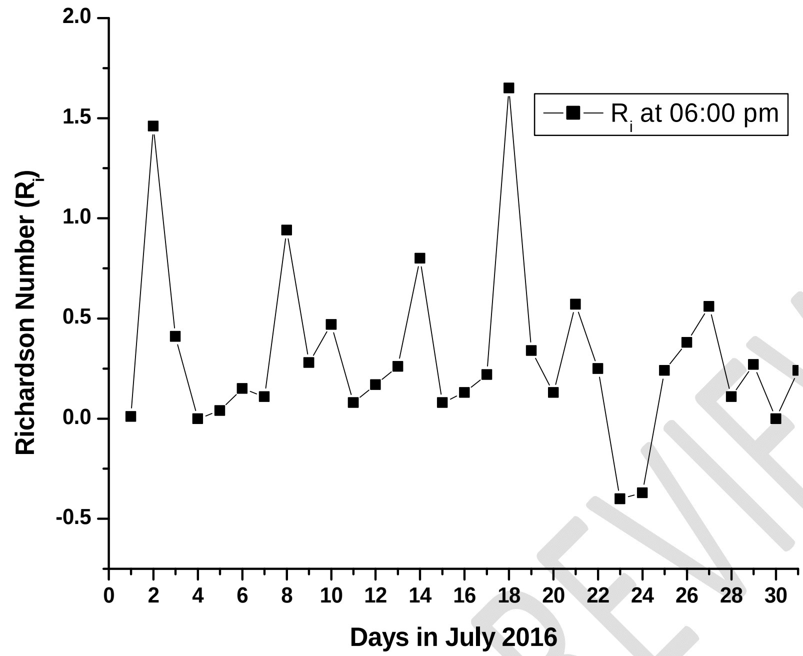

Figure 15: Boundary Layer stability Pattern at 06.00 pm in July 2016

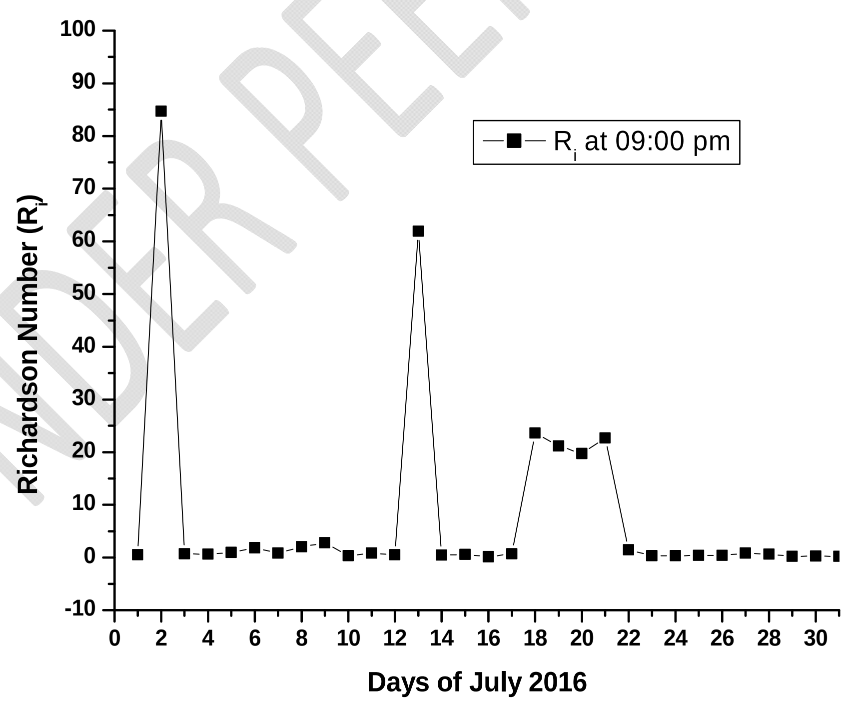

Figure 16: Boundary Layer stability Pattern at 09.00 pm in July 2016

The month of July falls within the peak of rainy season with unusual fluctuation in weather parameters most especially during the day with atmosphere mostly overcast and resulting in light showers lasting not more than 30 minutes falling intermittently. Boundary layer stability patterns in July 2016 were influenced by daily local weather phenomena as shown figures 9 – 16. Early hours of 0:00 – 6:00 am were partly stable and partly neutral unlike the pattern in June which was mostly stable. The patterns in July coincided with the peak of rainy season and were consistent with the cloudiness and wetness prevalence in the night time extending to early hours of the days.

Neutral pattern was significantly dominant at 9:00 am hour throughout July except on 1st, 12th, and 20th that were unstable thereby indicating 9:00 am to be uniquely calm in the boundary layer more than other hours of the days in July. Stability patterns during 12:00 pm in the month of July was significantly perturbed as it descended from neutral into unstable patterns, the same pattern was observed at 3:00 pm when the unstable regime was at its peak occurrence. The stability regime retracted rapidly to stable regime at 6:00 pm which also coincided with significantly reduction in insolation consistent with evening hours at the peak raining season. It was very interesting to note that 9:00 am and 9:00 pm had similar stability regimes throughout the month of July. While 9:00 am had unstable regime in only 3 days, 9:00 pm had stable regime in about 6 days; the remaining days were nearly all neutral.

5.0 Conclusion

The accurate determination of the Richardson number for micrometeorological purposes is highly dependent upon proper evaluation of the vertical gradients of wind and potential temperature in the first few meters of the atmosphere. The presence of heterogeneous processes in the planetary boundary layer leads to improper evaluation of the vertical gradients if these phenomena are not recognized and compensated for in the analysis of the data. The existence of a gap in the wind speed spectrum with a period of approximately one hour in the boundary layer indicates that commensurate averaging times are needed to provide adequate information on the stability of the lowest few meters of the atmosphere. The month of June 2016 had prevalence of stable regime from 0:00 – 6:00 am and 6:00 pm; 9:00 am was predominantly neutral and shared similar pattern with 9:00 pm. Unstable regime was slightly observed at 12:00 pm and majorly observed at 3:00 pm. The month of July had a little shift from what was observed in the month of June. Predominance of neutral conditions were observed from 9:00 pm to 9:00 am; Hours of 12:00 – 3:00 pm were dominated by unstable regime while 6:00 pm dominated by stable regime.

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