Centre for Atmospheric Research

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Edited by A.B. Rabiu and O. E. Abiye

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PREFACE

The Centre for Atmospheric Research was established in January 2013 with a compelling mission to improve our understanding of the behaviour of the entire spectrum of the Earth's atmosphere; promote capacity development in relevant atmospheric sciences as a way of facilitating international competitiveness in research being conducted by atmospheric scientists; and disseminate atmospheric data/products to users towards socio-economic development of the Nation. CAR's extant core research focus includes: space weather, tropospheric studies, atmospheric research software and instrumentation development, microgravity and human space technology, and atmospheric chemistry and environmental research.

Pursuant to the above, The *Monograph of Atmospheric Research* published by the Centre for Atmospheric Research (CAR), is a collection of peer-reviewed manuscripts in Atmospheric Sciences and closely related fields. This maiden edition comprises articles presented during two separate workshops; *1st National Workshop on Microgravity and Environmental Research* (26 - 29 November, 2017) and *1st National Workshop on Air Quality* (13 - 16 March, 2018). Such workshops are integral part of CAR's capacity building program and they were primarily aimed at advancing the course of atmospheric research in Nigeria towards sustainable development. The Microgravity workshop was geared towards introducing new research opportunities in space life science by simulating microgravity conditions here at the earth's surface as a means of investigation space biological environment. The Air Quality workshop was organized in collaboration with Ministry of Environment and Nigerian Meteorological Agency (NIMET). The workshop analysed current Air Quality scenario in Nigeria, explored new opportunities for collaborative research and offered novel means of improving the present quality of life of the populace without jeopardizing the chance of the future generation. Cumulatively 196 participants participated in these two workshops and about 52 articles were eventually submitted for publication consideration in this monograph. The twenty-one articles in this very monograph are the articles that eventually made it through the rigorous peer-review process. We remain grateful to the reviewers for doing thorough work on the articles.

Thus, we are very pleased to present the *2018 Monograph of Atmospheric Research* which contains twenty-one articles, including some review papers, to readers in all spheres of interest across Nigeria and beyond. It is our hope that this effort will continue and will serve as a reference to atmospheric researchers in Nigeria.

Prof. A. B. Rabiu and Dr. O. E. Abiye,
Editors

Centre for Atmospheric Research

Potential effects of hot-buoyant air pollution plume emitted from an industrial volume source on near-source and near-surface atmospheric stability

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ABSTRACT

This study investigated the potential effect of hot-buoyant air pollution plume emitted from a volume source configuration on atmospheric stability around a scrap-iron recycling factory. High resolution (10 sec, averaged over 10 min) *in-situ* measurements of surface meteorological parameters were used to estimate atmospheric stabilities over a period of six months covering both dry and wet seasons. Normally, atmospheric stability stratification is known to be driven primarily by solar heating of the ground's surface, especially in a low wind regime characterizing our study location (mean wind mostly below 2 ms^{-1}). That is, the diurnal variation of the solar heating modulates the transitions between frequently encountered daylight unstable and nighttime stable atmospheric conditions. But, our results revealed *U*nusual *N*octurnal *I*ncreases in ambient air *T*emperature *P*rofile (UNIT-P) up to 2 ^{o}C (mostly prior to and after midnight) coupled with inconsistent but strong reversals in atmospheric stability at a location near the industrial source. Approximate time intervals between the start and dissipation of the UNIT-P's were found to be 4 hours with well-defined diurnal-likes cycle on some days. Signals of other meteorological parameters measured within UNIT-P and non-UNIT-P (calm) periods indicated varied degree of responses to the pollution induced temperature forcing with relative humidity being the fastest. On the average, fluctuations between 15 - 35 W/m^2, 22- 33 W/m^2 and ~ 15% were induced on net radiation flux, soil heat flux and relative humidity respectively for a 1 ^{o}C increase in ambient air temperature. The occurrences of UNIT-P's coupled with reduced wind speed and prevalence of atmospheric stability G (up to 42%) during daylight clear sky condition were linked to characteristic releases of hot-buoyant air pollution plume from the industry. Enhanced build-up of pollution plume and likelihood of nocturnal thermal inconvenience in home micro-environment for near-source residents were implied from these findings.

Keywords: air pollution plume, atmospheric stability, hot-bouyant, near-source, near-surface

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INTRODUCTION

Air pollution problem is a growing concern globally *(Kara et al., 2013; Pandey et al., 2013; Zhou et al., 2014; Knippert et al., 2015; WHO, 2014*) and foremost environmental challenge in developing countries of Africa (*Assamoi and Liousse, 2010; Knippertz et al., 2015*) partly due to their rapid rate of urbanization and industrialization which outpaces the urban infrastructural planning process (*Adon et al., 2016; Knippert et al., 2015; Liousse et al., 2014; Evans, 2015*). Urbanization and industrialization are however an unavoidable process in the world. According to the United Nations, more than 90% of urbanization is taking place in the developing countries (*UN-Habitat, 2006*). The urban populations in the developing countries will reach 2 billion in the next 20 years, increasing about 70 million per year. The population in the urban areas of Africa is estimated to have doubled at that time. By 2030, 80% of the total world's urban population will be living in developing countries. It is estimated that 57% of the population will be living in the cities in 2050 compared to 20% in 1990, putting more pressure on the atmospheric environment (*WHO, 2014*). In line with the projections above, Nigeria is experiencing an upward surge in human population (*United Nations, 2017*) and consequently an increase in the numbers of medium-scale industrial establishment over the past few years. Mostly located in semi-urban areas (for beneficial fiscal factors), these emerging industries have over time transitioned the erstwhile background atmospheric condition of their host communities into similar scenarios in a mixed-source polluted urban atmosphere. It is therefore in no sense a rude awakening given a recent report that Nigeria accounts for the highest premature death due to air pollution in Africa (*Roy, 2016*). A typical example and fast growing among these industries are scrap-metal recycling factories; huge availability of its feedstock material (i.e. scraps) being a major driver. In the recycling process, charging and melting of the scrap metals in an electric arc furnace (EAF) could vary between an operational temperature of 1500 K to well above 1600 K (*Ohimain, 2013*) depending on the mix characteristics. The entire recycling processes, from melting to refining, are accompanied with substantial release of air pollutants. As such, air pollution plume emitted from these industries are often released into the atmospheric environment with some initial buoyancy which depends largely on the extent of thermal input along the production line. While the atmosphere is highly efficient in dispersing and diluting such air pollution plumes, near-source and near-surface atmospheric characteristics may be susceptible to transient but significant changes. On a diurnal to sub-diurnal timescales, transitions from one category of atmospheric stability to another could trigger sudden rise or fall in the range of threshold concentrations values of air pollutants than varying the source emission strength (*Chambers et al., 2015; Grundstrom, 2015; Williams et al., 2016; Wang et al., 2016*). This is because the degree of atmospheric stability or instability, as the case may be, is a function of superimposed thermal and mechanical turbulence in the atmospheric boundary layer (ABL). By its nature, the ABL is mostly turbulent due to the earth's frictional drag on the motion of air mass and daylight convective heating near the ground surface (*Arya, 1999*). The release and dispersion of air pollutants taking place within the ABL plays crucial role in modifying safe background atmospheric conditions. A clue on near surface atmospheric stability is thus helpful in understanding the probable scenarios of air pollution episodes that may play out at a particular location. In practice, most air pollution dispersion models (the widely used Gaussian models for example) employed for predicting downwind pollutant concentrations uses atmospheric stability as a defining parameter for determining appropriate algorithm in dispersion calculations (*Mohan and Sadiqui., 1998*). As such, atmospheric stability is a key parameter for consideration when meteorological forcing are reviewed regarding air pollution management strategies (*Yoshie and Hu, 2013*). The objective of this study is thus aimed at investigating possible effect of characteristic hot-buoyant emissions on atmospheric stability in a semi-rural community hosting an isolated but typical scrap-iron recycling factory in Nigeria.

MATERIALS AND METHODS

The Study Area

The study site (7° 29'N, 4° 28'E, 262 m a.s.l) is located at Fashina, Ile-Ife, a rural settlement in Ife-Central Local Government Area (LGA), Osun State, southwestern Nigeria (Figure 1). Located off a high-traffic Ife-Ibadan expressway, Fashina is an agrarian community surviving on subsistence farming, animal husbandry and cottage industry like palm oil and cassava processing. The Obafemi Awolowo University Campus is about 7 km (as the crow flies) in the NE direction from the industry. The scrap-iron recycling factory is sited across the expressway, southwest of the study area is a private smelter facility established in 2011 and it is the only industrial activity within a radius of 20 km. It is situated on a terrain at about 256 m a.s.l. Details of the location and prevailing climate has been presented elsewhere (*Abiye et al., 2017*).

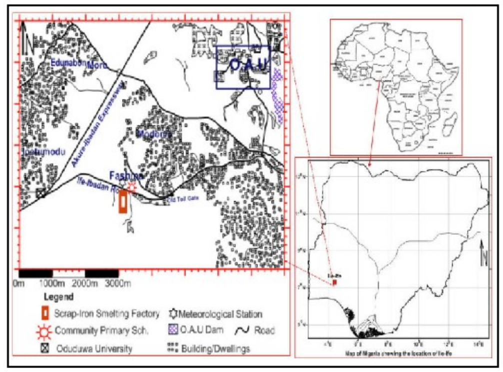


Figure 1: Map showing study location in Ile-Ife, Southwestern Nigeria (source: Abiye et al., 2017)

Data Source

Near-surface meteorological parameters measured at a near-source location about 200 m from the scrap-iron recycling industry were obtained from a previous filed experiment conducted by *Abiye et al., (2017)*. The datasets include ambient air temperature and relative humidity measured at 1 m and 5 m with a HMP45 sensor. Net radiation flux (at 1.5 m), soil heat flux and soil temperature (both at 5 cm below surface) measured with NR-LITE net radiometer, HFP01 heatflux plate and T108 soil temperature probe respectively. Details of the sensor specifications, mast configuration and data archiving has been given in *Abiye et al., (2017)*. High resolution (10 sec, averaged over 10 min) diurnal variations of the measured parameters and estimated static atmospheric stabilities over a period of six months were analyzed.

Atmospheric Stability Estimates

For the atmospheric stability conditions, a more general classification known as Pasquil-Gifford-Turner (PGT) scheme proposed by Pasquill (1961) and later modified by Gifford (1961) and Turner (1970) was adopted in this study. The PGT turbulent stability typing includes classes A, B, C, D, E and F denoting extremely unstable, moderately unstable, slightly unstable, neutral, moderately stable and extremely stable conditions respectively (*Beychok, 2005*) . Meteorological conditions defining PGT stability schemes have been given severally (*Mohan and Sadiqui, 1998; Yoshie and Hu, 2013, Edokpa* (Γ_a)
and Nwagbara, 2017). Air temperature lapse rate (Γ_a) were estimated following the simple logarithmic finite approximation method of *Arya (2001)* :

$$\Gamma_a = \frac{\delta T}{\delta z} \cong \frac{1}{z_m} \frac{\Delta T}{\left(Z2/Z1 \right)} \qquad (1)$$

Where the geometric mean height $z_m = \sqrt{z_1 \times z_2}$ and is the change in ambient air temperature between two levels (z_1 = 1.0 m and z_2 = 2.0m). To compute the dynamic atmospheric stability index (i.e standard deviations of horizontal wind direction fluctuation,), an in-built function in Campbell Scientific CR1000 datalogger was executed. The Limits of the obtained lapse and were associated with P-G-T stability scheme (Table 1) following

Sedefian and Bennett (1980) as cited in Mohan and Sadiqui (1998). R-based openair pollution analysis tool (*Carslaw and Ropkins, 2012; Carslaw, 2014*) was used to investigate polar distribution of daylight and nighttime at the location.

RESULTS AND DISCUSSIONS

Occurrences of atmospheric stability classes

Diurnal variations of atmospheric stability from September 2012 to April 2013 at near-source location of the scrap-iron recycling industry are presented in Figure 2 (10 sec intervals) and Figure 3 (1hr (circles) and monthly (solid lines) averages). On a monthly basis, the near-surface atmospheric stability in September (Fig 3a) depicts mostly an extremely unstable condition at all hours of day with a diurnal range of -0.466 ⩽ C_a ⩽ -0.089. In October, stabilities D (8%), E (4%), F (46%) and G (42%) were estimated to occur and bounded within the limits -0.057 ⩽ C_a ⩽ 0.840. For both night and day, the atmospheric stability in November (-0.0143 ⩽ C_a ⩽ -0.0761) was bounded between two classes; moderately and extremely stable conditions contributing 79% and 21% respectively.

The stability characteristics in December (Fig 3d) with values

Table 1: Limits of associated with P-G-T and stability classes (scaled-down from Sedefian and Bennett, 1980)

P-G-T stability classes	Γ_a (°C/m)	Atmospheric stability condition	σ_θ (°)
A	$\Gamma_a < -0.019$	Extremely unstable	$22.5 < \sigma_\theta$
B	$-0.019 \leq \Gamma_a < -0.017$	Moderately unstable	$17.5 < \sigma_\theta \leq 22.5$
C	$-0.017 \leq \Gamma_a < -0.015$	Slightly unstable	$12.5 < \sigma_\theta \leq 17.5$
D	$-0.015 \leq \Gamma_a < 0.005$	Neutral	$7.5 < \sigma_\theta \leq 12.5$
E	$-0.005 \leq \Gamma_a < 0.015$	Moderately stable	$3.75 < \sigma_\theta \leq 7.5$
F	$0.015 \leq \Gamma_a < 0.04$	Extremely unstable	$2.0 < \sigma_\theta \leq 3.75$
G*	$\Gamma_a > 0.04$		$\sigma_\theta < 2.0$

**Pasquill said that in light winds on clear nights the vertical spread may be less than for category F but excluded such cases because the surface plume is unlikely to have any definable travel. However, they are important from the point of view of the build-up of pollution and category G (nighttime, ⩽1 okta of cloud, wind speed ⩽ 0.5 m s^{-1}) was included.*

ranging between -0.0475 ⩽ C_a ⩽ 0.165 were similar to those obtained in October (Fig 3b) except for the prevalence of moderately stable conditions (class E) which contributes 58% and less of class G (8%) stability. March recorded a stability range of -0.074 ⩽ C_a ⩽ -0.0111, differing from April (-0.061 ⩽ C_a ⩽ 0.0285) only in the frequency of stable conditions. The highest occurrence of neutral atmospheric condition (29%) was in April followed by 17% in March, 13% in November and 8% in each of the remaining months. The months of October, November and December (OND) were observed to have predominantly daylight stable stabilities (a situation that is rather unusual, see blue plots in Figure 2). On a normal day, incoming solar radiation (short-wavelength) are generally opaque to the atmosphere thus reaching directly to the ground surface. The ground rapidly absorbs the solar thermal input and transfers some of it to the surface air layer. The surface air warms up in response, expands, becomes less dense and then rises (*Vaucher and Raby, 2013*). In the process, cooler and denser air from above is drafted downwards. The cooler air,

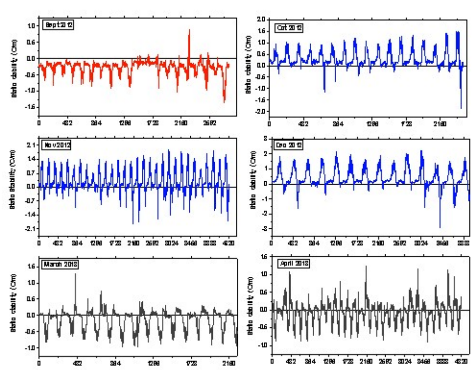


Figure 2: Diurnal variations (instantaneous values at 10 secs interval) of static atmospheric stability at near-source location of the scrap-iron recycling industry

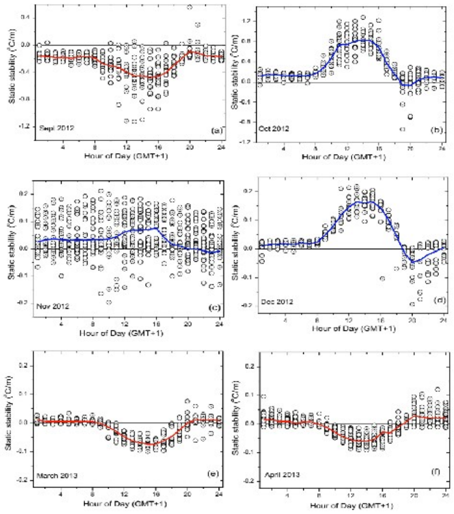


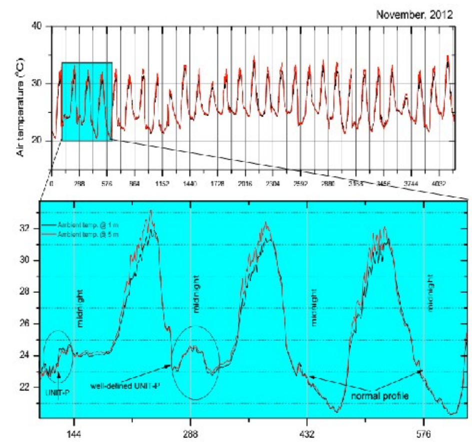
Figure 3: Hourly (black circles) and monthly mean (solid line) variations of static atmospheric stability at near-source location of the scrap-iron recycling industry

in turn, becomes heated by the ground surface and begins to rise. This process leads to random dynamic atmospheric motion which enhances vertical motion and considerable atmospheric mixing in both directions i.e. updraft and downdraft. Hence the atmosphere is unstable and turbulent, being driven by thermal buoyancy of the daylight air mass (*Harrison, 2006; Lanigan et al., 2016*). As such, unstable conditions are most commonly developed on sunny days when strong solar radiation is present and the temperature profile in near-surface layer is consequence of the radiative balance and the convective transport of energy from the surface to the atmosphere (*Liou, 2002*). While daylight stable atmospheric condition is not unusual, the consistent observed trends in OND were strong indications of a persistent atmospheric situation forcing the lapse rate to remain positive and thus making the atmosphere stable.

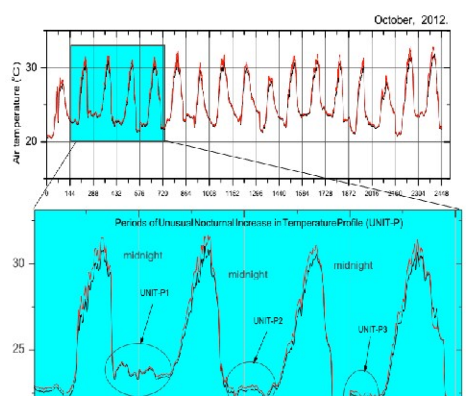
Unusual nocturnal increase in air temperature profile (UNIT-P)

Time-series investigation of air temperature values revealed the occurrence of Unusual Nocturnal Increases in ambient air Temperature Profile (UNIT-P) up to 2 °C within the OND periods (see Figures 4 and 5). This unusual increase was sensed simultaneously at the two measurement levels (1 m and 5 m). The UNIT-P was found to occur mostly prior to and after midnight coupled with inconsistent but strong reversals in atmospheric stability conditions. The Well-defined and diurnal-like cycle of UNIT-P (Figure 4, which mimics the diurnal effects of solar heating on the

surface in a nighttime atmosphere completely contradicts the physical laws of surface energy balance at midnight when air temperature is expected to drop continuously until about sunrise the following day. Interestingly, night time values of lapse rates obtained during hot-buoyant plume releases were mostly within unstable atmosphere categories in the range of slightly unstable and neutral stability conditions. In the absence of strong surface wind which may arise due to disturbed weather and precipitation, unstable stability condition at night are quite unusual. This is because nighttime is predominantly characterized by stable atmospheric condition (*Jegede et al.,, 1997; Edokpa and Nwagbara, 2017*) due to radiative cooling of the earth's surface which makes the underlying air-mass cooler than those above. It was envisaged that at night, particularly after midnight, the hot buoyant plume is emitted into a highly humid (mostly above 85 % in moisture content) atmosphere. The sharp temperature gradient between the humid ambient air-mass and the incoming dry and hot-buoyant plume allows for quick absorption of moisture by the latter thus becoming denser and subsequently drafted downwards. Meanwhile, radiative cooling occurring at night serves as a net thermal input for air-masses just below the plume centerline. This dynamics promotes



near- source and near-surface location.



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small mixing which results in a slightly unstable atmosphere and can be attributed to the range of static stability values obtained at night in OND. During daytime, the effect of the hot-buoyant plume was superimposed on the incoming insolation from the sun. Although superimposed on incoming insolation, the persistence and dominance of daytime stable atmospheric condition in OND (Figure 3b-d) fingerprints the presence of an overriding thermal input into the atmospheric condition at the location. This is because contrary to the previous discussion on expected diurnal trend of atmospheric stability, the continuous injection of hot-buoyant air pollution plume from the industry into the background atmospheric condition was inducing a significant thermal change. In this scenario, the air pollution plume is released with huge thermal buoyancy from an electric arc furnace maintained at a temperature not less than 1650 ^{o}C. As the plume disperses from the source in the direction of mean wind, it is temporarily subjected to the existing turbulence in the ambient environment. Over a short distance and time, the surface becomes well mixed with the hot plume through updraft and downdraft of air masses. As this occurs, existing positive temperature gradient of the surface air mass begins to collapse. With time, the air mass above becomes much warmer than those below as a result of the continuous thermal energy input from the hot-buoyant plume arriving at the location. Within short distances from the source, the plume is still sufficiently buoyant to override the effect of atmospheric instability which is driven by the maximum possible insolation that may be received under a clear sky condition on a sunny day. This explains the daylight stability conditions observed in OND which are a combination of wet-to-dry transition and dry months.

Effects of the UNIT-P

With reference to the UNIT-P's (Figures 3 & 4), responses of other meteorological parameters to nocturnal releases of hot-buoyant plumes from the industry are presented in Figure 6. We examined predominant periods of continuous releases between sunset (18:00 GMT+1) and sunrise (06:00 GMT+1). Although generally true, sunset and sunrise as defined in this study are for the purposes of time interval rather than actual setting or rising of the sun at the industry location. During calm periods i.e. no plume release, air temperature decrease continuously from about 27 ^{o}C at sunset to about 23 ^{o}C before sunrise. Relative humidity increases correspondingly from 80% to 98% in the same period. The diurnal cycles of air temperature and relative humidity were altered shortly (~ 1hr) after sunset as indicated by the sudden reversals in further decrease and increase of air temperature and relative humidity respectively. The maximum variance between the two levels of air temperature measurement was barely 0.8 ^{o}C on UNIT-P days as against 3.0 ^{o}C on calm days. These values indicated a forcing of net thermal input into the atmospheric air mass on UNIT-P days. Within the same period, relative humidity ranges between a minimum of 75% and maximum of 92% as against 80% and 98% respectively on calm days. In essence, a thermal discomfort associated with 15% dryness in air moisture may be experienced at near source environment. Also, the two trough-crest trends shown by the air temperature (*see Figure 5, UNIT-P1*) is a clear footprint of the forcing of two different batch cycles of scrap-metal processing in the industry. Interestingly, the time span of each UNIT-P (~ 4 hrs) corresponds to the estimated average batch cycle duration previously reported by *Abiye et al., (2016)* i.e. time taken from charging scrap-metals into the electric-arc furnace to the time when molten metals are cast into molds in the foundry. During the UNIT-P's, an increase in air temperature of about 1 ^{o}C induces an upward change of 15 – 35 W/m^2 in net radiation flux. Although the study location is predominantly a southwesterly low wind regime, calm days have slightly higher wind speeds compared to hot plume release periods. This is because the increased stability of the surface air-mass due to hot plume above hinders the turbulent mixing of air masses which brings down stronger wind at higher level more than on calm days. Soil temperature and air temperature fall steadily from about 31 ^{o}C and 27 ^{o}C at sunset to a minimum of 25 ^{o}C and 23 ^{o}C respectively around half-hour before midnight. Thereafter, both maintain fairly steady values till about sunrise. The maximum variance between the two falls from 5 ^{o}C during UNIT-P periods to 3 ^{o}C on calm days while soil heat flux minimum-maximum amplitude was 38 W/m^2 and 45 W/m^2 respectively, indicating more retention of heat in the soil on UNIT-P periods.

Dynamic stability

Key insight revealed by the diurnal investigation of dynamic stability index in Figure 7 is the tendency for high values of at nighttime. The extremely enhanced unstable ranges of (50^{o} – 90^{o}) are more prominent within a narrow wind direction sector (< 20 degrees) and wind speeds below 3 ms^{-1}. This clearly indicates that the instabilities recorded at nighttime were not driven by occurrences of strong winds at the location. For extreme near-calm conditions, *Van der Hoven (1976*) have shown that high values of at nighttime with light wind ($0.2 < u < 1.9$ m s^{-1}) are probably caused by wind direction meander induced by minor atmospheric perturbations. Hanna (1981) linked the perturbations to terrain-induced mesoscale eddies at a site in Geysers for stable nighttime conditions. At the site used in this study, the obvious condition that could be linked to the atmospheric perturbation at nighttime is the dynamics induced by the continuous released of hot buoyant air pollution plume from the industry. The site is located in a flat terrain free from the shear of roughness elements which could have been another source of perturbation arising from wind flow.

CONCLUSION

Unusual nocturnal increases (up to 2 ^{o}C) in ambient air temperature, persistent daylight stable conditions (extremely stable), and nighttime atmospheric instabilities during periods of weak mechanical turbulence (wind shear mostly < 2 ms^{-1}) were found to occur at a near industrial-source location. Timescales of the unusual nocturnal increases in ambient air temperature corresponds with predetermined average batch-cycle duration of recycling process at the site and are prolonged during intensive activity periods. Although responses of relative humidity at the two heights were more consistent than net radiation and soil heat fluxes in tracking the nocturnal increases in temperature, the signals of all parameters showed some alterations in their diurnal trends. The findings in this work suggest a mix of potentially

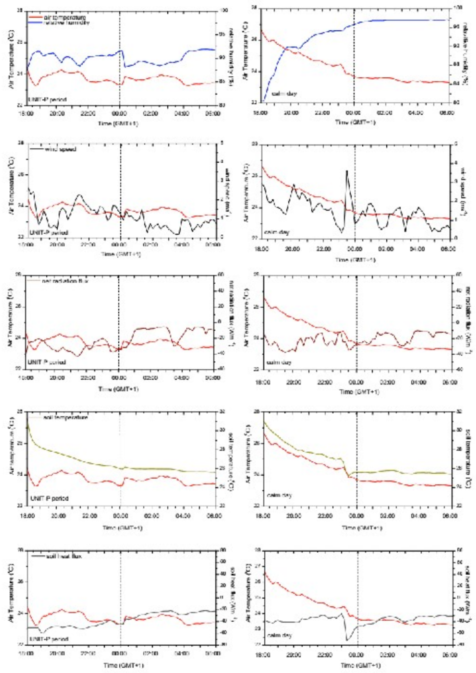

Figure 6: Comparative trends of meteorological parameters during UNIT-P and calm periods

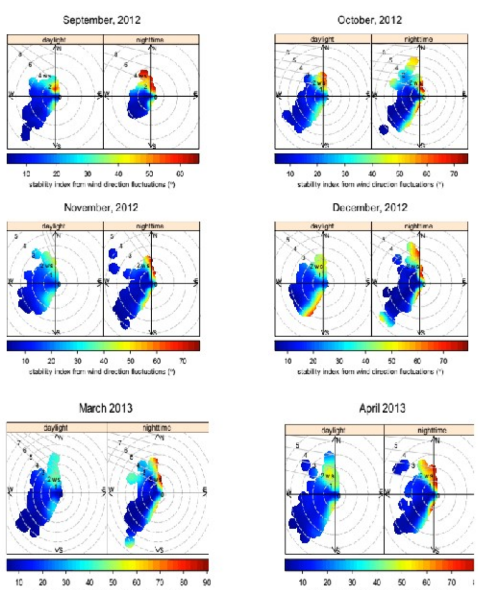

Figure 7: Polar distribution of daylight and nighttime dynamic atmospheric stability at the near-source location.

unfavorable air pollution scenarios for near-source locations coupled with possibilities of induced thermal discomfort for near-surface residents due to the hot-buoyant plumes.

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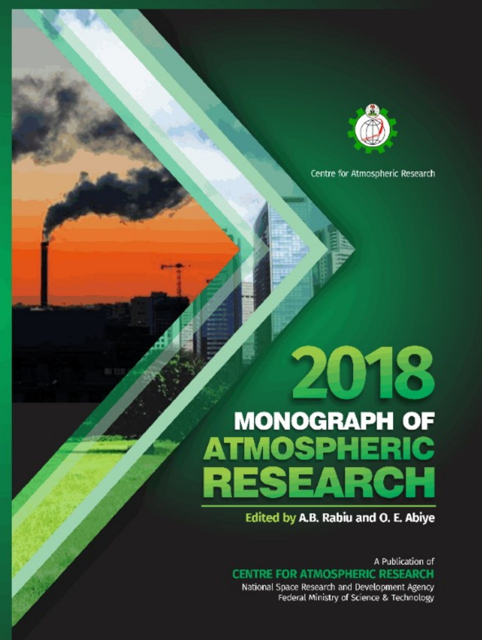

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The Center for Atmospheric Research, CAR, is a research and development center of NASRDA committed to research and capacity building in the atmospheric and related sciences. CAR shall be dedicated to understanding the atmosphere—the air around us—and the interconnected processes that make up the Earth system, from the ocean floor through the ionosphere to the Sun's core. The Center for Atmospheric Research provides research facilities, and services for the atmospheric and Earth sciences community.

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