



Role of wind shear, temperature lapse rate, and aerosol in assessment of atmospheric condition

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Abstract

The near-surface environment of the earth remains either in calm or in a turbulent state as per the kinetic force acts, which encourage the growth of disturbance in the atmospheric fluid. In a stable condition, mixing of the air particles at different heights reduces the overall vertical variability of the air particles in the atmosphere while unstable atmospheric condition produces the minimum shear that leads to convective situation and promotes the mixing of its composition. To analyse these types of atmospheric conditions, here two basic parameters temperature lapse rate and aerosol optical depth (AOD), has been taken into consideration. Along with these parameters, a model named hybrid single particle lagrangian integrated trajectory (HYSPLIT) has been utilised to track the air parcel or wind flow pattern. The observations were made over Guwahati (26°N, 92°E), NE region of India. It has been determined from the observations that the wind shear (WS) follows a seasonal pattern. On certain days, the shear is higher than that of the normal condition. In this context, parameters temperature lapse rate and AOD along with WS has been observed and examined to analyse the stability of the atmosphere. It is observed that on the day of high WS value, high AOD and slow decrease of temperature per km (vertically with height) shows a completely different pattern than the normal one.

1 Introduction

Atmospheric stability regulates the state of movement of gaseous fluid above the earth surface and it helps in determining an ascending air parcel that will continue to rise or fall. In a stable atmosphere, an ascending air parcel tends to sink whereas in an unstable atmosphere, it tends to rise. This motion in the atmosphere leads to the formation of clouds, it removes pollutants up and away from the Earth's surface, and supports the mixing of air in the atmosphere. Wind shear (WS) and the temperature lapse rate (the rate at which temperature decreases with height) are the two important meteorological parameters that provide an idea about the stable and unstable condition of the atmosphere (Chaudhari et al. 2010). In a stable condition where the rate

of change of the temperature with altitude is greater than environmental lapse rate (6.5 °C/km), clouds are not able to grow freely upward. But, if the temperature lapse rate is 6.55 °C/km, the atmosphere is considered to be as conditionally unstable, in which a forcing mechanism can create the initial lift which needed for clouds to grow vertically up. Once the temperature lapse rate is smaller than 6.55 °C/km, clouds are able to grow vertically on their own, with no forcing mechanism needed. However, these atmospheric conditions are of course controlled by the presence of WS and aerosols (Wang et al. 2008). Researchers found that the vertical WS qualitatively determines whether aerosols suppress or enhance the convective strength (Fan et al. 2009). Under strong WS, with the increase of aerosols, convection is suppressed and under weak WS, it is energised. Many research activities are carried out to find the role of WS in determining how aerosol affects the cloud formation (Albrecht 1989; Charlson et al. 1992; Devi et al. 2012, 2014) as well as how it controls the atmosphere which may lead to a stable or an unstable situation.

Atmospheric stability is a very significant factor that plays an important role to study the air quality. With meticulous knowledge of atmospheric stability, we can envisage the status of pollutant emission which are likely to disperse and

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the pattern of their ground level concentration of pollutants. Through the comprehensive study of atmospheric stability and on the effect it has on transport, dispersion and deposition of pollutants, it can be concluded that when and up to what extent emission can be controlled. Using this information city planners and developers can locate the best suitable place for commercial and residential zoning and the same knowledge can be utilised by various research communities for further studies related to atmosphere.

Therefore, this paper is an attempt to find out the role of wind shear, temperature lapse rate and aerosol concentration in the assessment of atmospheric condition.

2 Data and methodology

In this paper, three parameters are studied to assess the atmospheric condition over Guwahati, these are Wind shear (WS), Aerosol Optical depth (AOD) and temperature lapse rate. Therefore, seasonal variations of these parameters are first examined and then further some cases are studied. For this purpose, we have analysed eight years of radiosonde data collected during the daytime observations at 0000 UTC and 1200 UTC from the year 2006 to 2013 over Guwahati (26°N, 92°E), to find out the seasonal pattern of above mentioned parameters. The University of Wyoming is the source of our database which is available online (<https://weather.uwyo.edu/upperair/sounding.html>). The data including wind speed and temperature have been collected through radiosonde and the same data have been utilised to calculate vertical wind shear and temperature lapse rate.

Vertical WS (Chaudhari et al. 2010) is calculated using the formula,

$$\text{VWS}_{2-1} = \frac{\sqrt{(u_2 - u_1)^2 + (v_2 - v_1)^2}}{Z_2 - Z_1} \text{ s}^{-1} \quad (1)$$

where VWS_{2-1} is vertical WS between lower level (1) and upper level (2); u_2, u_1 indicate zonal component of wind at (2) and (1), respectively; v_2, v_1 indicate meridional component of wind at (2) and (1), respectively; Z_2, Z_1 indicate height of (2) and (1), respectively.

Here, u and v can be calculated using the equations given below,

$$u = U[-\sin d]$$

$$v = U[-\cos d]$$

Where, U is the wind speed and d is wind direction.

For temperature lapse rate (Γ), Eq. (2) is utilised.

$$\Gamma = -(dT/dZ) = -(T_2 - T_1)/(Z_2 - Z_1) \quad (2)$$

T_1 and T_2 are the temperatures at heights Z_1 and Z_2 , respectively.

The degree of stability or instability of an atmospheric layer is determined by comparing its temperature lapse rate, with the environmental lapse rate.

Aerosol optical depth (AOD) is the ratio of absorbed radiation to incident radiation. Physically, it refers that if an object absorbs all the radiation incident on it, its optical depth becomes 1. AOD data of 550 nm has been utilised over Guwahati in daily and monthly basis with a resolution of $1^\circ \times 1^\circ$ from Moderate Resolution Imaging Spectroradiometer (MODIS, [MOD08_D3.051]) (Barnes et al. 1998; Devi et al. 2008; Choudhury et al. 2012, 2013). These data are available in MODIS webpage, it can also be accessed from <https://disc.sci.gsfc.nasa.gov/giovanni>.

For identification of sources of aerosol contributing to the atmosphere at different seasons, we have used HYSPLIT air mass back trajectory analysis (Draxler and Hess 1998, 2004; Draxler 2006) developed by NOAA Air Resources Laboratory. The model is run using the READY interface (Rolph et al. 2017) and can calculate trajectories from multiple heights within a layer. This model is designed to support a wide range of simulations in relation to the atmospheric transport, dispersion of pollutants and hazardous materials, in addition to the deposition of these materials to the Earth's surface. Atmospheric transport, dispersion of pollutants and hazardous materials can be estimated from the forward or backward trajectory of an air mass. Back trajectory analysis is useful for ascertaining the origins and sources of pollutants, while forward trajectory analysis is helpful for determining the dispersion of pollutants. In our study, we have used backward trajectory analysis.

Other supporting data are provided by India Meteorological Department (IMD), an agency of the Ministry of Earth Sciences, Government of India.

This study is confined within two seasons: winter (December–February) and spring (March–May). In this reference, we have selected the days for observation in such a way that there is no occurrence of event like thunderstorm, rain, wind gust, etc. The event excluded days are further categorised as normal and anomaly days depending on the value of wind shear.

- (a) Here, to find out seasonal pattern of parameters, we have first extracted the respective parameters daily, then averaged the values for two seasons for a period from 2006 to 2013.
- (b) Next, we have categorised the days as normal and anomaly by considering different WS values, i.e., WS that follows seasonal pattern are taken as normal days and those days that deviated from seasonal pattern are termed as anomaly days. Likewise, we have plotted the values of respective parameter of the anomaly days with respect to normal days. After that the standard deviation (SD) and mean of the WS values are calcu-

lated and plotted as shown in Fig. 5. Here, percentage deviation (PD) is calculated using the following formula,

$$PD = \left[\left(\frac{V_1 - V_2}{V_1} \right) 100 \right]$$

Here, V_1 is the peak value of the magnitude of the particular parameter of the day and V_2 is the monthly average value of that parameter.

- (c) Next, temperature lapse rate and AOD values are collected for anomaly days (where WS value is deviated from normal days) and plotted along with normal days. With the same procedure as earlier percentage deviation is calculated for both the parameters and plotted. In both the plots (Mean + SD) and (Mean - SD) is shown to understand mainly the fluctuation of the parameters in anomaly days from the normal days.

3 Results

The atmosphere is a highly dynamic system and hence it is very difficult to point out the parameters that are responsible for stable and unstable condition (Devi et al. 2008; Draxler and Hess 1998, 2004, Draxler 2006; Kaufman et al. 2003; Levy et al. 2003). Though, in this work, we have tried to investigate the changes in AOD, WS and temperature lapse rate during different atmospheric situations. On the basis of these parameters, we examined and identified the stable and unstable conditions in the atmosphere.

To evaluate the impact of atmospheric variables such as WS, AOD and temperature lapse rate on determining the atmospheric stability condition, first the analysis of seasonal variation of WS, AOD and temperature lapse rate over our study region has been carried out and is given in the Sect. 3.1. Next, aerosol flow to this region is shown in

Sect. 3.2 and in Sect. 3.3, variation of these parameters during stable and unstable conditions are shown.

3.1 Seasonal variation of WS, AOD, temperature lapse rate

Variations of WS, AOD and temperature lapse rate in two different seasons winter (December–February) and spring (March–May) over Guwahati are obtained by analysing 8 years data from 2006 to 2013 and the results are presented in Fig. 1a–c, respectively.

From these observations, it is seen that the high value of WS are prevalent in the months of winter (December–February) with respect to the spring period (March–May). It is found that the WS value in winter is approximately 50% more frequent than that of spring. A range (0.0034–0.0043) s^{-1} of WS value is obtained from Fig. 1a for spring season, whereas in winter this range has changed to (0.0055–0.0065) s^{-1} .

In case of AOD, the AOD value in spring is found higher than that of winter as shown in Fig. 1b. It is well established that in spring season, wind flows from West and from South towards NE (Choudhury et al. 2013). It is because, during spring season, along with the local sources there is a contribution of remote sources from Western part of India and also from South, i.e., Bay of Bengal (as shown in Figs. 2, 3 and 4) in the enhancement of aerosol loading in the atmosphere. Therefore, high AOD value was observed and it was already investigated and established by Devi et al. (2008). The maximum value of AOD in winter is obtained 0.55 but in springs it increases up to 0.63 which is nearly 20% higher than that observed in winter.

Figure 1c shows that the atmospheric temperature lapse rate for winter that varies from 6°/km to 8°/km whereas in spring it lies in the range approximately 3°/km to 5°/km. The lapse rate in winter is 40–50% higher than that of spring. This means that the temperature in winter decreases slowly in vertical direction compared to spring, which emphasised

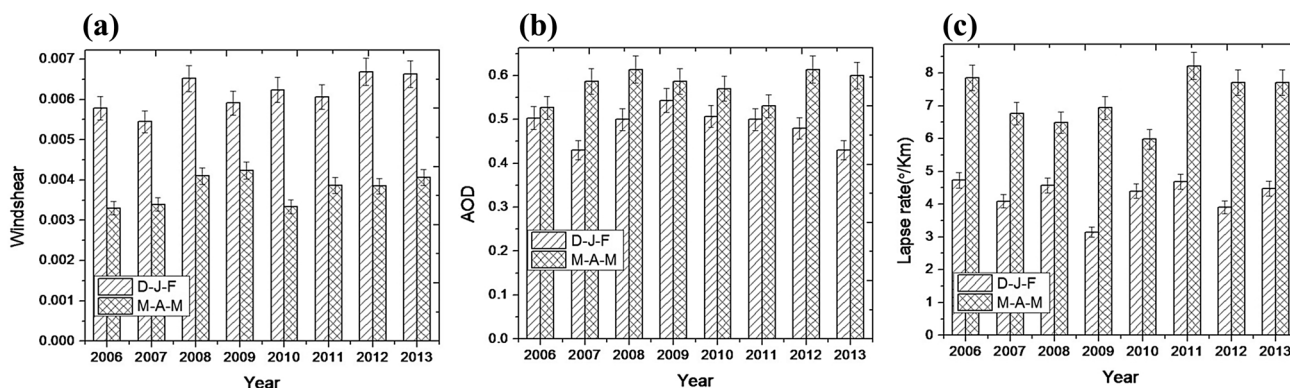


Fig. 1 a WS value (s^{-1}), b AOD, and c Temperature lapse rate ($^{\circ}C/km$) in two seasons—spring and winter—calculated over Guwahati

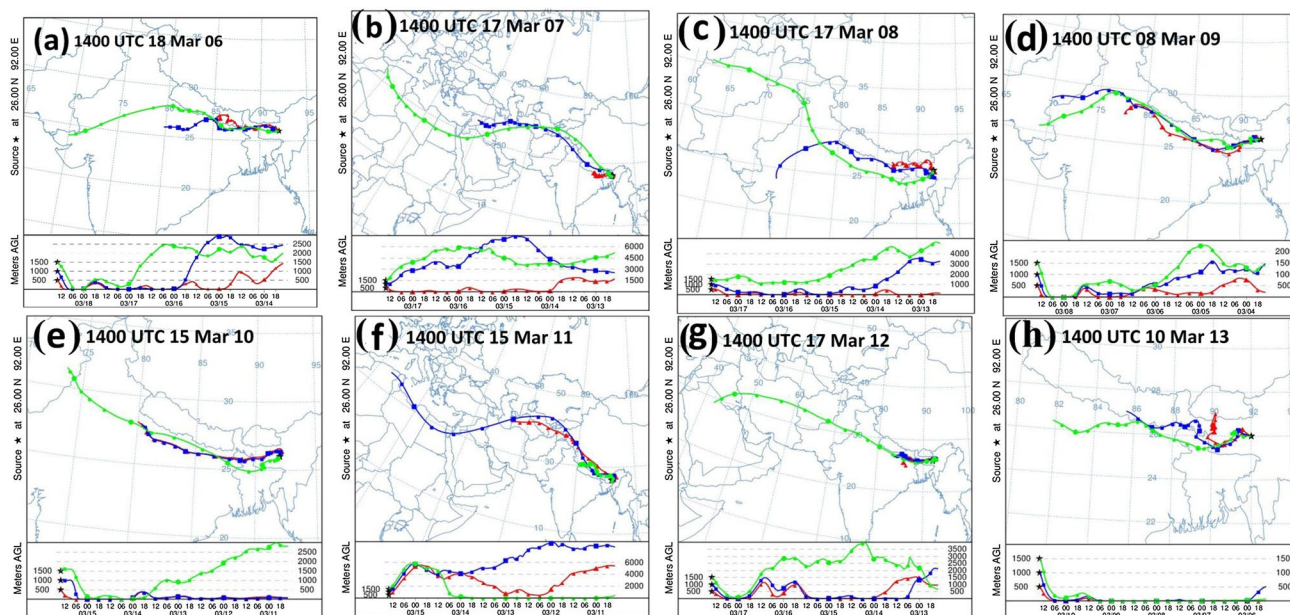


Fig. 2 Backward trajectories for air mass advection at altitudes of 500 m, 1 km, and 1.5 km is shown in the figures from (a–h) during March for the period from 2006 to 2013, indicates the transport from the western part of India to North-East

that atmosphere in winter is less unstable or nearly stable as compared to spring season.

3.2 Aerosol loading: local as well as long-range transportation over study region

HYSPLIT model has been employed here for monitoring the long-range transportation of air parcel/aerosol towards our study area, Guwahati. The 5-day back trajectories computed using HYSPLIT model are shown in Fig. 2a–h and in Fig. 3a–h and initialized at altitudes of 500 m (red), 1 km (blue) and 1.5 km (green) above ground level (AGL) for the month of March and April taking Guwahati as a source. Here, the back trajectory analysis interprets the flow of air parcel from the different parts such as from West as well as South (Bay of Bengal) as shown in figure to the source, Guwahati.

Figures 2a–h and 3a–h represent the backward trajectories of the air parcel for the month of March and April respectively in their respective region as mentioned in figure. The backward trajectories for vernal equinoxial in the month of March shows the air mass pathway from the distant west part of India (Choudhury 2014). As the pre-monsoon season comes, the direction of wind swings to south and south west directions and another wind flow from the Bay of Bengal which leads to the higher concentration of aerosol in the atmosphere leading to a high AOD value.

For further study we have analysed various HYSPLIT model output for the month of March and April to detect

the significant wind components present over Guwahati. The outcome of this analysis is plotted and shown in Fig. 4.

It can be illustrated from the figure that westerly components are significant during the month of March and south-westerly components (i.e., coming from Bay of Bengal) are significant in April over the study area.

3.3 Variation of parameters (WS, AOD, temperature lapse rate) during stable and unstable conditions

Hereafter, we illustrate the diurnal variation of WS during normal and anomaly days of month of March and April as shown in Fig. 5a.

In Fig. 5a, it is noticed that the WS values in anomaly days are quite higher than that of the normal days. It is already mentioned (in Fig. 1a) that in the year 2008, 2009, and 2010, the WS values vary approximately in the range 0.006 – 0.007 S^{-1} in normal days of spring season. The deviation in the values of WS from a normal day is calculated and plotted in Fig. 5b. A positive deviation of WS value of about 70–90% in anomaly day with respect to normal day has been obtained. This may indicate the restriction of vertical air motion in the atmosphere.

We have simultaneously observed the AOD variation for a better understanding of the stability of the atmosphere. The monthly average of AOD are presented in Fig. 6a–c including both normal and anomaly days. The figures are extracted

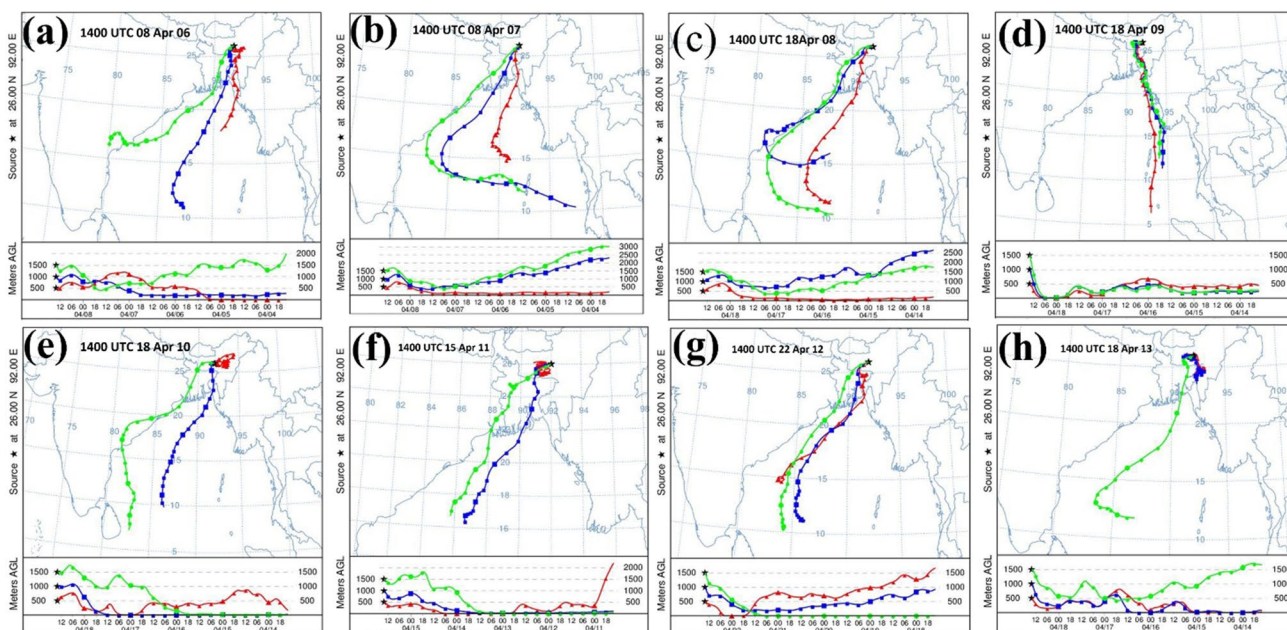


Fig. 3 Backward trajectories for air mass advection at altitudes of 500 m, 1 km, and 1.5 km is shown in the figures from (a–h) during April for the period from 2006 to 2013 indicates the transportation of the wind from the Bay of Bengal

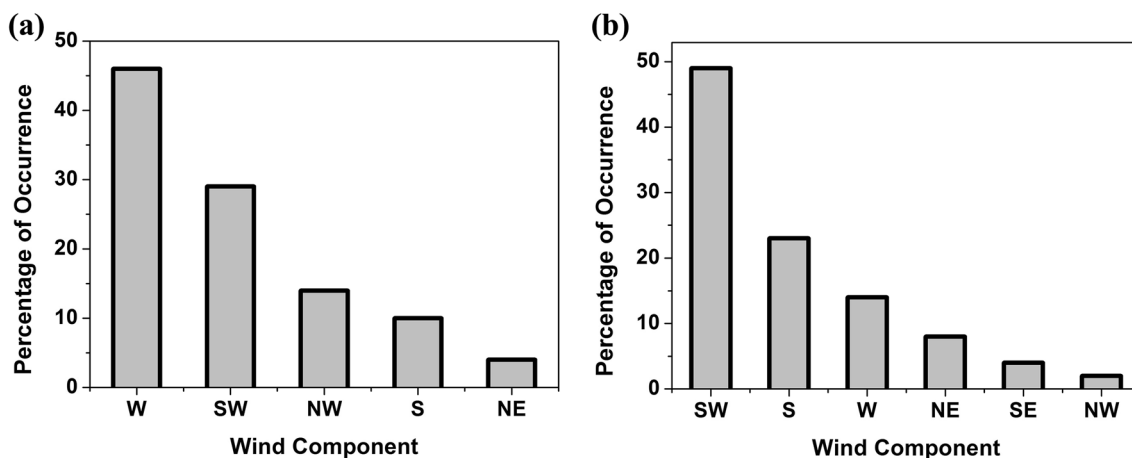


Fig. 4 Percentage of occurrence of significant wind components for the months of **a** March, **b** April

from MODIS [(MOD08_D3.051)] already explained in Sect. 2.

From Fig. 6a–c, it is seen that the monthly AOD value at 550 nm extracted for April 2008, April 2009 and March 2010 is 0.66 over the study area (marked by circle). Here the colour bar in the AOD plots indicates range of AOD strength that varies from 0.1 to 0.9. Since, both the normal and anomaly days are considered, so high AOD value is observed here. By separating anomaly days from the normal days, the average AOD of normal days is calculated and it is found to be 0.58 for April 2008, 2009 and 0.63 for March

2010. AOD value for those anomaly days has been examined where the high wind shear value is found and same has been plotted with correspondent normal days as shown in Fig. 7a.

From Fig. 7a, it is noticed that during normal days the AOD value fluctuates within the range of 3.5–5. However, in an anomaly day, the AOD value goes beyond the Mean ± SD value showing a positive deviation. The positive percentage deviation of AOD value from the normal has been shown clearly in Fig. 6b. In anomaly days, the AOD values deviate ~ 25–55% from the normal days. Such increase of AOD value during anomaly days may interpret the trapping of

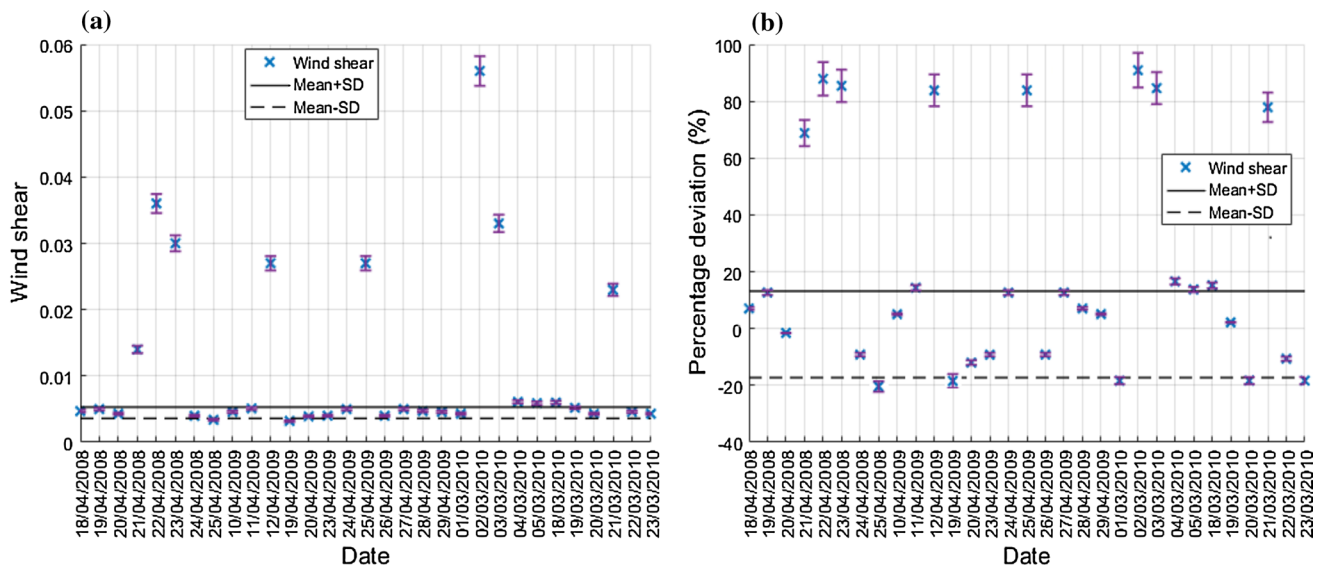


Fig. 5 **a** Variation of WS value in anomaly days along with normal days, and **b** percentage deviation of WS value from normal day value, Mean + SD and Mean – SD are shown in both the figures

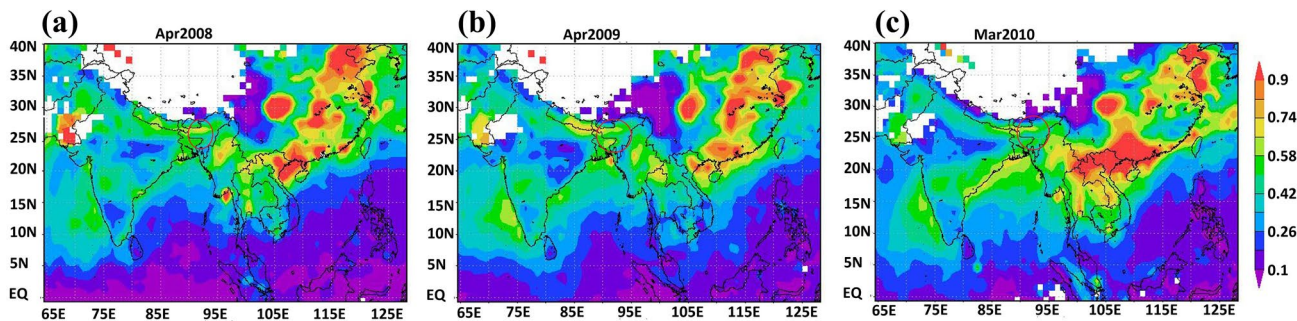


Fig. 6 Monthly variation of AOD for the year **a** April 2008, **b** April 2009 and **c** March 2010. The study area is marked by red circle

aerosol due to stable condition in the atmosphere. In the later section (Sect. 5), it is verified using HYSPLIT.

From the above analysis, a conclusion has been drawn that high WS and high AOD values lead to an anomaly situation which can be redefined as stable condition of the atmosphere, whereas the days before and after the anomaly days, in most of these cases the lower value of AOD is observed. A few representative maps of AOD during the day before and after the anomaly is shown below in Figs. 8, 9, 10. Here, anomaly days are marked by red star and study area is shown by red circle.

The lapse rates of temperature have also been calculated (as it is a basic parameter to determine the atmospheric stability condition) for these anomaly days and are found to be greater than that of the normal days. The output is shown in Fig. 11a. Temperature lapse rate values for the anomaly days are found higher than $6.5^{\circ}/\text{km}$ (environmental lapse rate) that leads to a stable situation

of the atmosphere in spring. It is generally not likely to be occurring during this season. The percentage deviation of the lapse rate from the normal days is also calculated as shown in Fig. 11b. It is noted that there is a positive deviation of 45–60% during anomaly days with respect to normal days which again is an indication of stable condition in the atmosphere.

Further, we have plotted the HYSPLIT back trajectories on the anomaly days as shown in Fig. 12a–h and figured out the actual scenario of the atmosphere. From the figure, it has been noticed that on these particular days (anomaly days), the wind is locally distributed and is not transported from remote sources (such as from Western part of India or from South) to the Guwahati. It is completely different from the wind flow pattern as shown in Figs. 2 and 3. It can be interpreted that high aerosol concentration on these particular days are mainly due to

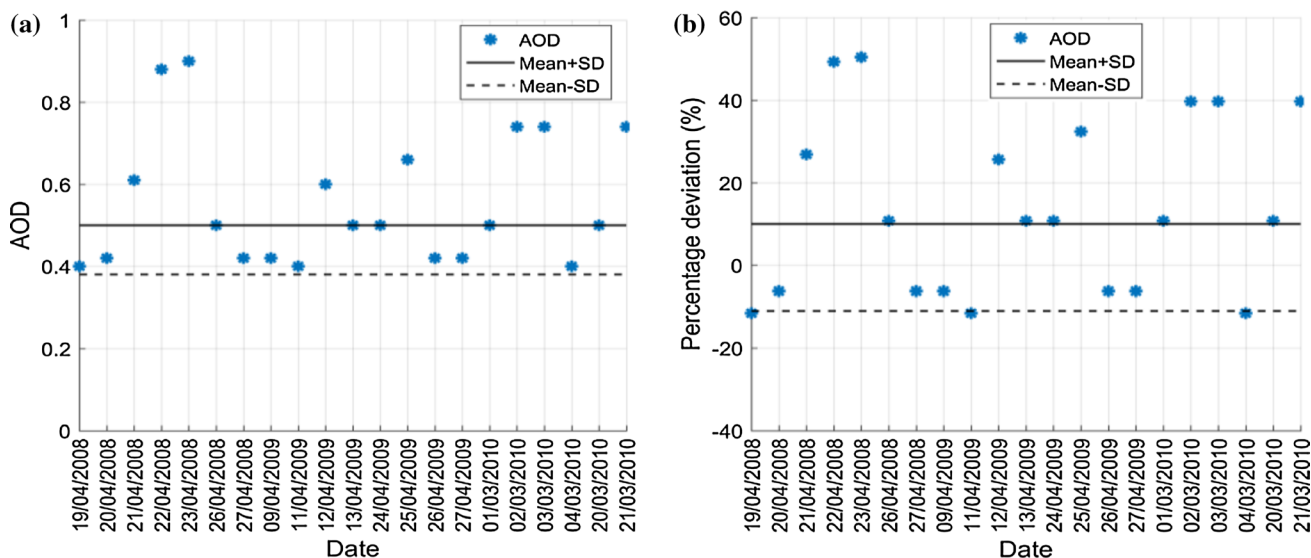


Fig. 7 a Variation of AOD of normal as well as anomaly days with Mean ± SD and b percentage deviation of AOD with respect to normal day value

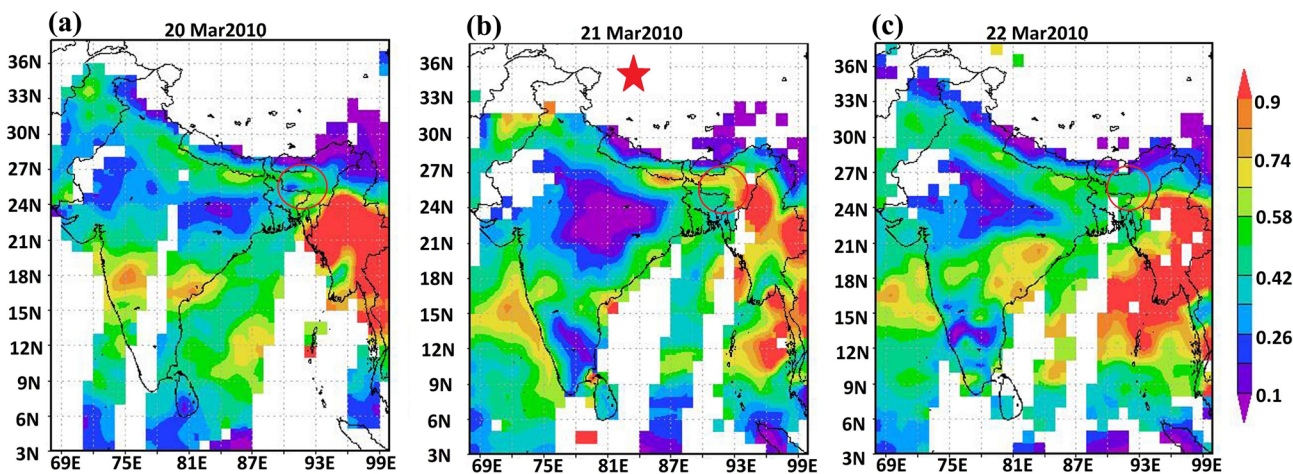


Fig. 8 AOD map of the day before and after the anomaly days (March 2010). Red star is given in figure to mark anomaly day

trapping of air, not because of aerosol contribution from remote sources.

4 Discussion

In this paper, the seasonal pattern and variations of WS, AOD, and temperature lapse rate in anomaly days [as mentioned in this paper] and normal days are studied. Here, we have first observed a positive deviation of 70–90% of WS value in anomaly days with respect to normal days which indicates that WS value is highly enhanced in anomaly

days. To find out the reason behind such observation of high WS value in the atmosphere, we examined the AOD and temperature lapse rate with air parcel trajectory or wind flow pattern over Guwahati, NE region of India. It has been obtained from the study that AOD has a positive deviation, i.e., 25–55% in anomaly days with respect to normal days and temperature lapse rate has positive deviation of 50–140% in anomaly days than that of the normal days. The high value of temperature lapse rate found in the anomaly days is an indication of slow decrease in rate of change of temperature with height which can be interpreted as stable atmospheric condition. The extreme high

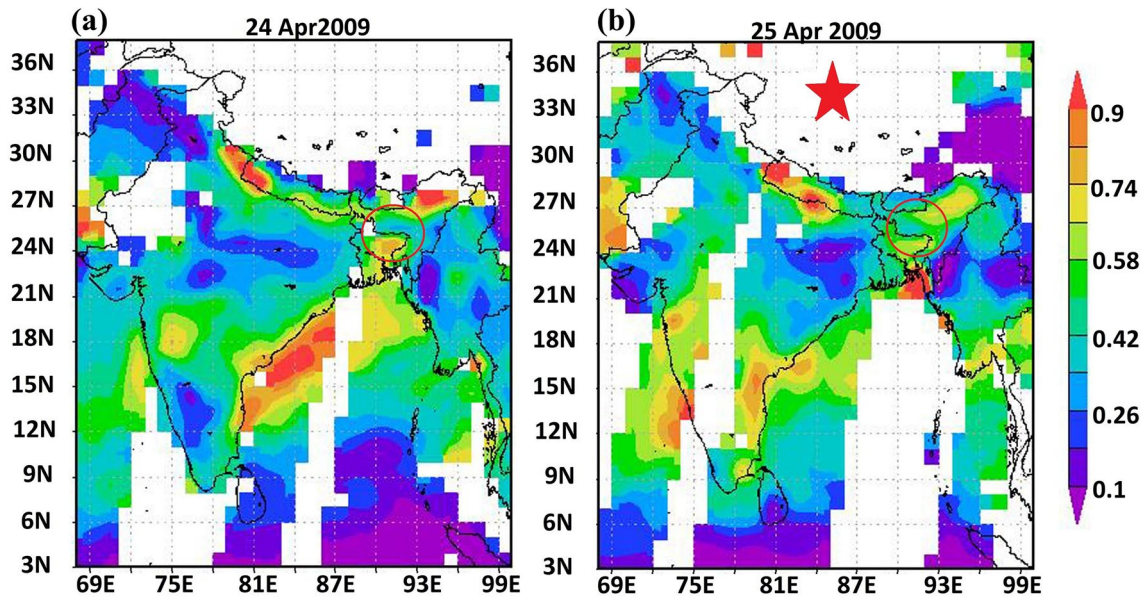


Fig. 9 AOD (at 550 nm) map of the day before and after the anomaly days (April 2009). Red star is given in figure to mark anomaly day

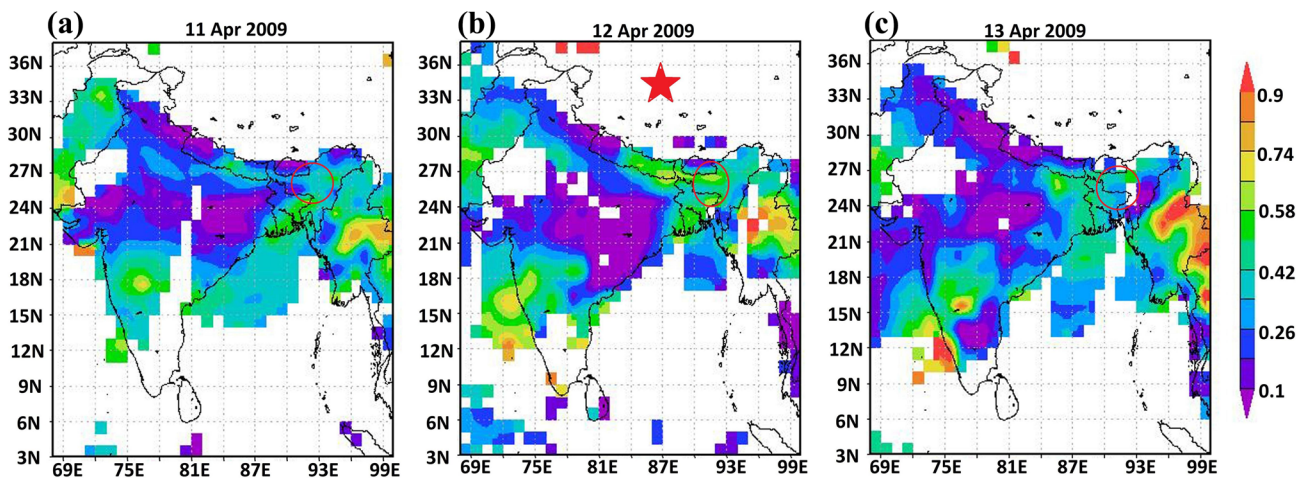


Fig. 10 AOD (at 550 nm) map of the day before and after the anomaly days (April 2009). Red star is given in figure to mark anomaly day

shear found in the study resists the vertical motion of air in the atmosphere, and, therefore, aerosols are trapped over the study region which has been observed through HYSPLIT model [Fig. 12]. Due to this trapping, high concentration of aerosols are observed.

5 Conclusion

Atmospheric stability plays an important role in determining the status of the atmosphere. The atmospheric parameters such as WS, temperature lapse rate and AOD are used

in this study which can tell about the status of atmosphere. In normal days, WS shows a definite wind flow pattern like Figs. 2 and 3 and also the mixing process in the atmosphere is found relatively intense. On the contrary, we have observed that the inflow of aerosols into this zone of NE attains a certain height above the earth's surface where the foreign pressure balances the buoyant force of the incoming stream on those particular days (anomaly days). As a result, the incoming streams do not execute a definite pattern which was observed clearly in normal days. Consequently, there would be an accumulation of aerosols at this zone increasing its optical depth. Despite the fact that,

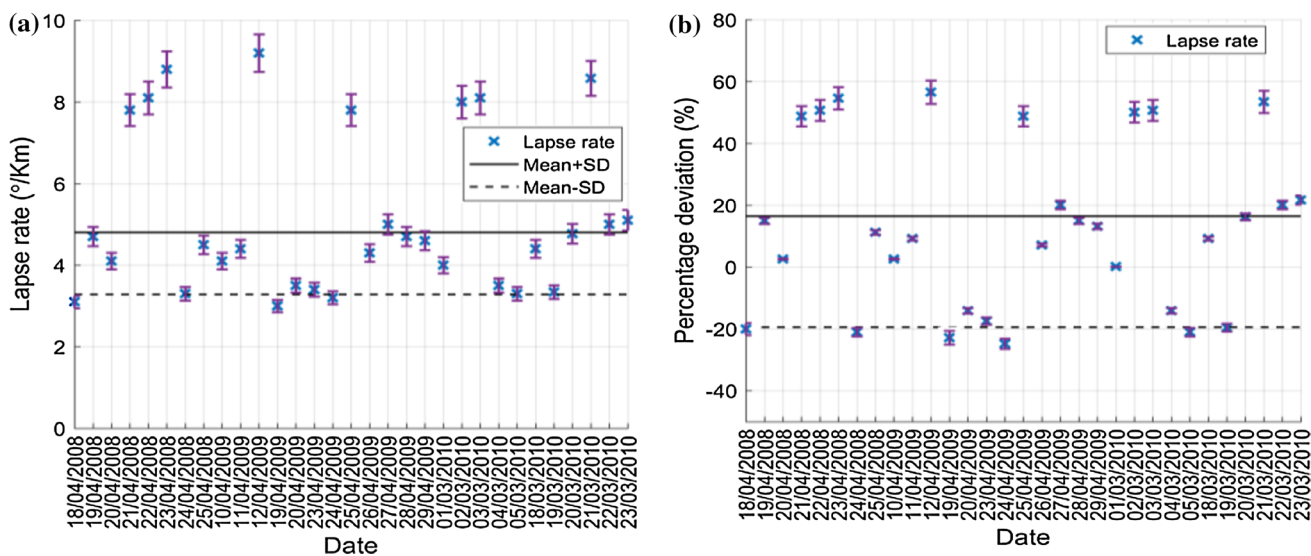


Fig. 11 **a** Temperature lapse rate of anomaly days with respect to normal days and **b** percentage deviation of lapse rate where Mean + SD as straight line ‘—’ and Mean – SD as dotted line ‘---’ are given in both figures

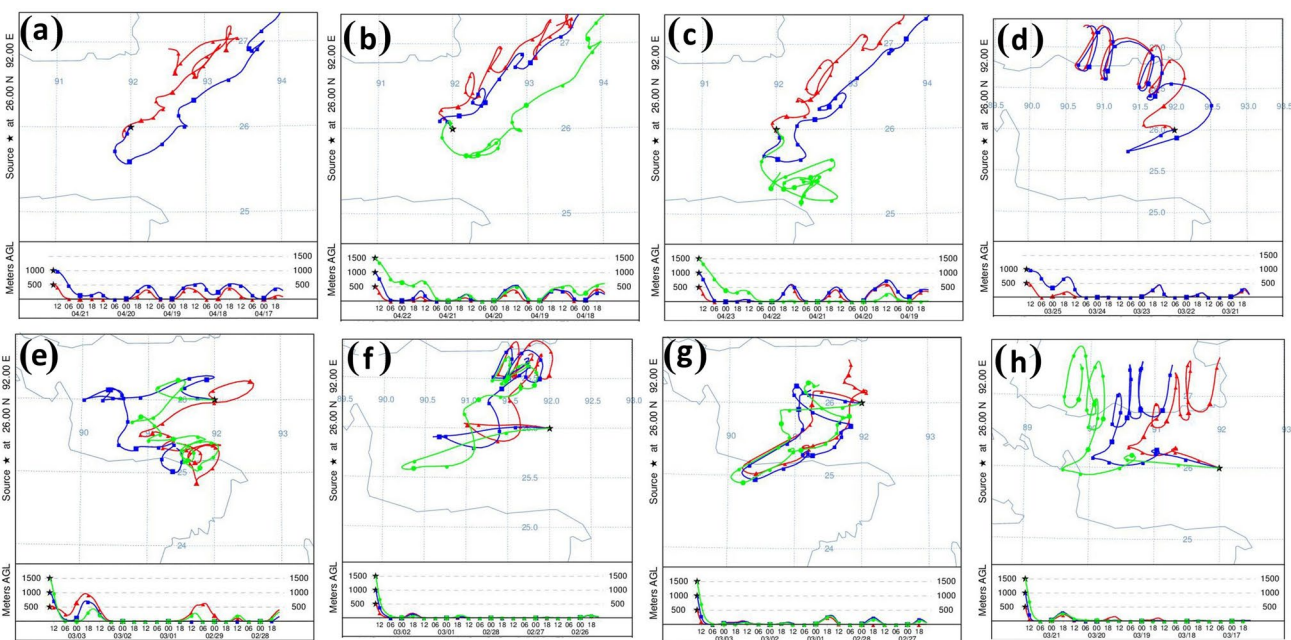


Fig. 12 Backward trajectories for air mass advection at 500 m, 1.5 km, and 2 km altitudes is shown for **a** 21 April 2008, **b** 22 April 2008, **c** 23 April 2008, **d** 25 March 2009, **e** 12 April 2009, **f** 02 March

2010, **g** 03 March 2010, **h** 21 March 2010, indicating the transportation of wind in anomaly days as defined earlier

in another case where the atmosphere is normal, aerosols have movements from one place to another. Therefore, there is no accumulation of aerosol particles to increase the AOD. Along with, a positive enhancement of temperature lapse rate over the Guwahati region during anomaly days with respect to normal days has been observed. These results clearly indicates that those anomaly days (as

hypothesised), are the stable condition of the atmosphere. Therefore, we conclude those anomaly days as stable days.

In nutshell, this paper is a comprehensive approach to define the stability of the atmosphere which has been explained through the study of atmospheric parameters viz. WS, AOD and temperature lapse rate.

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