Chapter 4

Influence of Biomass Burning and Downward Transport on Trace Gases Over Nainital

The observations of ozone, CO and NO$_y$ have been conducted at a high altitude site Nainital (29.37°N, 79.45°E and 1958 m amsl) in the central Himalayas during 2009-2011 period. These observations were analyzed for identifying different processes controlling the diurnal and seasonal variations in the trace gases over Nainital, which has been presented in detail in the previous chapter (Chapter 3). The key processes controlling the diurnal variations of trace gases over Nainital were suggested to be the upslope and downslope mountain valley flows, boundary layer evolution and associated convective mixing. While, the seasonal changes in trace gases were mainly attributed to the influences of regional pollution during spring and arrival of southwest monsoon during summer. Additionally, it is suggested that the northern Indian biomass burning and downward transport of air masses from
higher altitudes could play very important roles in the observed variations of trace gases. Nainital site is reasonably remote from any direct anthropogenic activities and therefore it could act as a better regional representative of the northern Indian region and well suitable for understanding the role of the aforementioned processes. Further, being a high altitude location, the signatures of downward transport of the air masses from the higher altitudes can also be observed.

The knowledge of the influences from biomass burning emissions on trace gases is only limited to the surface ozone at Nainital so far [Kumar et al., 2011], which is here being extended to the ozone precursor gases (CO and NO$_y$). Moreover, the observations of surface ozone over the high altitude mountains in the southern Himalayas [Cristofanelli et al., 2010] show significant contributions from the downward transport in all the seasons except during the summer-monsoon; however measurement based studies of downward transport are non-existing over the central Himalayas so far. In view of the above, the maiden observations of CO, and NO$_y$ and meteorological parameters are analyzed along with the ongoing ozone observations which provide an invaluable dataset to identify the influences of the downward transport.

In view of the above, in this chapter, a set of case studies are conducted utilizing the unique dataset of ozone, CO, NOy and meteorological parameters in conjunction with the satellite data and model simulations to assess the role of northern Indian biomass burning (Section 4.1), downward transport (Section 4.2) and day-to-day variations in the meteorological parameters (Section 4.3) on trace gases over Nainital. Finally, a case study is conducted to evaluate the back air trajectories at Nainital simulated using different meteorological inputs to HYSPLIT model in the Section 4.4.
4.1. Influence of Northern Indian Biomass Burning

Biomass burning emissions have considerable input in the budget of several trace species by directly injecting them to the atmosphere and also by the subsequent photochemical transformations of the emissions in favorable meteorological conditions. Therefore, it is necessary to investigate the biomass burning activities in the vicinity of measurement site (Nainital). The variations in fire counts over the northern Indian region (60° to 95°E and 20° to 38°N) has been investigated using the satellite (MODIS) retrieved data of fire locations. Figure 4.1 shows the seasonal variations in the daily and monthly total fire counts over the northern Indian subcontinent during 2009-2011 period. Explicitly, biomass burning activities over this region are observed to be the maximum during spring months (April and May). The fire counts are observed to be much less during the wet season (summer-monsoon) as well as during winter. While, a secondary enhancement in the fire counts is noticed during autumn (October and November); however, it is less prominent as compared with spring. Here, it is suggested that the maximum influence of biomass burning activities on trace gases could be during spring months which coincides with the higher levels of surface ozone and precursors over Nainital (Chapter 3) and therefore the springtime observations are analyzed further to quantify these influences.
Figure 4.1: Seasonal variations in MODIS derived monthly and daily total fire counts over Northern Indian region during 2009-2011.

The spatial distribution of fires over the northern Indian Subcontinent during the spring season of the years 2009, 2010 and 2011 is shown in Figure 4.2. Clearly, the fire activities show nearly similar spatial variations during these years with the maximum density of fire locations lying towards the northwest of Nainital site.
Figure 4.2: Map showing the fire locations during spring over the Northern Indian Subcontinent during (a) 2009, (b) 2010, and (c) 2011 respectively.

Most of these fires are seen to be over the cropland areas which are suggested to be associated with the crop residue burning for field clearing [Venkataraman et al., 2006; Kumar et al., 2011]. Additionally, some fires are also observed over the mountain areas in the vicinity of Nainital site indicating some contribution from the forest fires.

In order to quantify the enhancements in ozone, CO and NO\textsubscript{y} due to biomass burning activities, an approach similar to that used by Kumar et al. [2011] has been employed here. The observations are segregated into high and low fire activity periods. In this approach, the period during which 3 days running mean of fire
counts exceeds the median fire count of April-May are classified as “High Fire Activity Period (HFAP)”, while, the remaining observations are classified as “Low Fire Activity Period (LFAP)”. In this way, the high fire activity periods are identified as 18 April to 17 May in year 2009, 14 April to 16 May in year 2010 and 22 April to 22 May in year 2011. Further, low fire activity periods are restricted to those prior to high fire activity periods i.e., 1 to 17 April 2009, 1 to 13 April 2010 and 1 to 21 April 2011 respectively, to avoid the residue influences of the prior high fire emissions. Moreover, the observations influenced by air masses from higher altitudes (see section 4.2.2) are excluded from the time series of ozone, CO and NO\textsubscript{y}. Figure 4.3 shows the time series of ozone, CO, and NO\textsubscript{y} at Nainital during April and May for years 2009, 2010 and 2011. Three days running mean of fire counts are also shown. Ozone, CO and NO\textsubscript{y} levels show enhancements during HFAP (period within dashed cyan line) in comparison with LFAP in all the three years with some inter-annual variations.
Figure 4.3: Time series of ozone, CO and NO\textsubscript{y} during High (HFAP) and Low (LFAP) Fire Activity Periods over northern Indian region during (a) 2009, (b) 2010 and (c) 2011 respectively. The green line represents the 3-day running mean of fire counts.

The enhancements in the levels of ozone, CO and NO\textsubscript{y} at Nainital during HFAP are estimated to be 4-18\%, 15-76\% and 35-51\% respectively (Table 4.1). The estimated enhancements in ozone, CO and NO\textsubscript{y} are lower during 2010 as compared with 2009 and 2011. This is mainly due to the occurrence of more rainfall during 2010, which
reduced the fire activities significantly resulting in the observed lower enhancements.

*Table 4.1:* Enhancements in ozone, CO and NO$_x$ during the High Fire Activity Period as compared to the Low Fire Activity Period for 2009, 2010 and 2011. The values in the parenthesis represent the enhancement in percentage.

<table>
<thead>
<tr>
<th>Year</th>
<th>Ozone (ppbv)</th>
<th>CO (ppbv)</th>
<th>NO$_x$ (pptv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>9.3 (18%)</td>
<td>116.9 (76%)</td>
<td>396.9 (51%)</td>
</tr>
<tr>
<td>2010</td>
<td>2.6 (4%)</td>
<td>26.4 (15%)</td>
<td>246.4 (35%)</td>
</tr>
<tr>
<td>2011</td>
<td>13.0 (16%)</td>
<td>70.3 (43%)</td>
<td>1375.0 (50%)</td>
</tr>
</tbody>
</table>

This analysis clearly demonstrates that the springtime higher levels of trace gases over Nainital have considerably large contribution from the northern Indian biomass burning. Such enhancements in the springtime maxima of ozone and CO were also reported from other high altitude sites such as Mt. Lulin [Ou Yang et al., 2012] and Mt. Mie-Feng [Lin et al., 2012a] in the central Taiwan region. The biomass burning induced enhancements in ozone and CO were reported to be 8 ppb and 45 ppb respectively at Mt. Mie-Feng during spring. Moreover, it was suggested that the pollutants emitted from Southeast Asian biomass burning could be transported and influence the air quality over the subtropical Taiwan during spring [Lin et al., 2012a].
4.2. Influence of Downward Transport

In addition to the in situ photochemical ozone production, the other key source of tropospheric ozone is the Stratosphere-to-Troposphere Transport (STT) or Stratosphere-Troposphere Exchange (STE). The downward transport of ozone has been shown to contribute significantly in the ozone variations over the Alpine sites, the Himalayas, Tibetan Plateau, United States and Europe [e.g. Stohl et al., 2003; Ding and Wang, 2006; Langford et al., 2009; Kumar et al., 2010]. Generally, the STT influences are observed more frequently on the ozone variations in middle and upper tropospheric altitudes; however, occasionally, it is found to deeply penetrate to the lower troposphere enhancing near surface ozone levels [Ludwig et al., 1977; Haagenson et al., 1981; Stohl et al., 2000; Cooper et al., 2005; Akriditis et al., 2010; Lin et al., 2012b].

The influences on surface ozone are observed more frequently over the high altitude mountain sites. However, the quantitative information on the contribution of STE in the tropospheric ozone budget contains large uncertainty mainly due to lack of sufficient measurements of ozone and chemical tracers. Over the southern Himalayas, the downward transport events have been observed more frequently during winter and spring months [Cristofanelli et al., 2010]; however, such studies are very limited/not available over the central Himalayas.

In view of this, an event of high ozone observed at Nainital during December 2010 has been investigated for the possible influence of downward transport (Section 4.2.1). In addition, the simultaneous observations of ozone, CO, NO\textsubscript{y} and wind speed conducted during 2009-2011 are analyzed in conjunction with the back
air trajectories to identify the enhancement in surface ozone associated with the downward transport of air masses at Nainital (Section 4.2.2).

### 4.2.1. High ozone Event of December 2010

Figure 4.4 shows the time series of surface ozone observations at Nainital in the central Himalayas and at a nearby semi urban site Pantnagar in the Indo Gangetic Plain (IGP) during 15-25 December 2010. Surface ozone levels at Nainital are observed to be very high (70-140 ppbv) during 18-21 December (event period) as compared with those (~50 ppbv) during 15-17 December (pre-event period). After 21 December 2010, the ozone levels are observed to be nearly similar to the pre-event observations (~40-50 ppbv).

![Figure 4.4: Time series of ozone observations at Nainital (red colour) and Pantnagar (blue colour) during 15-25 December 2010. Daily Average Relative Humidity is also shown for comparison.](image-url)
Thus, ozone levels at high altitude site (Nainital) showed an enhancement of about 160% during the event period, however, no such ozone enhancement was observed over the low altitude site (Pantnagar) in the IGP. The large enhancements in the high altitude ozone observations and lack of any simultaneous ozone enhancement in the nearby low-altitude polluted areas indicate the possibility of downward transport of ozone rich air masses from higher altitudes, which has been investigated using meteorological tracers as follows:

4.2.1.1. Variation in Water Vapor

The changes in water vapor amount e.g. relative humidity and water vapor mixing ratios are suggested to be a key tracer of downward transport of air masses as the stratospheric air masses are much drier than tropospheric air therefore sinking air masses could result in lower water vapor amount [e.g. Bithell et al., 1999]. The time series of average relative humidity for 15-25 December is shown along with the ozone observations in the Figure 4.4. Clearly, the relative humidity values are showing a significant reduction from their pre-event values in the range of 60-70% to as low as about 30% during the event period (18-21 December 2010), while after the event period, relative humidity values are seen to recover again (40-50%).

In addition to the ground-based relative humidity measurements, the satellite retrievals of water vapor mixing ratios are investigated from AIRS during the event and pre-event periods. Figure 4.5 shows the spatial distribution of water vapor mixing ratios at 850 hPa (near surface of Nainital site) over the Northern India region during 14-17 December 2010 (pre-event) and 18-21 December 2010 (during event).
Figure 4.5: The spatial distribution of water vapor mixing ratios at 850 hPa obtained from AIRS satellite during 14-17 December 2010 (pre-event) and 18-21 December 2010 (during event) over Northern Indian subcontinent. The location of observation site Nainital is shown by a white filled triangle.

The water vapor distribution shows clear reductions over Nainital and its vicinity in particular towards the north (higher altitude mountains). It is observed that water
vapor mixing ratios at 850 hPa decreased from their pre-event values of about 2.6 g/kg to 1.75-1.8 g/kg during the event. This is in agreement with the reductions in surface relative humidity measurements at Nainital.

4.2.1.2. Back Air Trajectory

The high ozone event of December 2010 is further examined for downward transport by simulating the 7-days back air trajectories at Nainital using HYSPLIT model for the event period (Figure 4.6).

Figure 4.6: HYSPLIT model simulated 7-day back air trajectories over Nainital for 19 and 20 December 2010. The altitude variations along the trajectories are also shown.

Figure 4.6 shows that during the high ozone event period (19-20 December 2010) air masses are descending from middle tropospheric altitudes (6.5 km AGL and above). This suggests that, the air mass arriving from higher heights brings ozone rich air
which penetrated into the troposphere and there is an increase in the ozone levels near surface over Nainital.

4.2.1.3. Change in the Potential Vorticity

Potential Vorticity (PV) is another key tracer used to identify stratospheric intrusions or downward transport of air masses [e.g. Cristofanelli et al., 2006]. Generally, air masses having PV values greater than 1.6 pvu, where $1\text{ pvu} = 10^{-6}\text{ m}^2\text{ K kg}^{-1}\text{ s}^{-1}$, are associated with stratospheric intrusion [Cristofanelli et al., 2006]. Stratospheric air masses are generally characterized by lower water vapor mixing ratio, lower relative humidity and reduced CO level along with high levels of ozone and PV values.

The spatial distribution of potential vorticity calculated using WRF simulated meteorology for pre-event and during event conditions are shown in the Figure 4.7.
Figure 4.7: Contour maps of potential vorticity at 200 hPa pressure level over the South Asian region on 17th December 2010 and 18th December 2010 obtained from WRF meteorology simulation. The location of observation site Nainital (NTL) is also shown as black filled triangle.

PV values are observed to be less than 1.6 pvu over Nainital on 17th December, while these are found to be substantially increased to 2.5 pvu during the high ozone period (18th December) over most of the Himalayan mountains. Such large increase in PV values during the event period clearly indicates the downward transport of the air masses from higher altitudes.

Thus the detailed investigation conducted shows reductions in relative humidity and water vapor mixing ratios, enhancement in the potential vorticity and descend in the air mass trajectories confirming the contribution of downward transport in observed high ozone event of December 2010. Following the analysis of this event, all the observations are screened for possible role of downward transport in different seasons in the next section (Section 4.2.2) and quantitative estimates of these influences are made.
4.2.2. Influence of Downward Transport on Ozone, CO and NO$_y$

Observations of ozone, CO, and NO$_y$ along with meteorological parameters have been analyzed in conjunction with the back-air trajectories to identify the influences of downward transport over Nainital. In this analysis, the observations are considered to be influenced by downward transport, when ozone and wind speed are higher than their respective 75$^{\text{th}}$ percentile values of the season, CO and NO$_y$ levels are lesser than their respective 50$^{\text{th}}$ percentile values of the season and the minimum pressure attained by the back-air trajectory is lesser than or equal to 600 hPa. In this analysis, spring season has been defined from 1$^{\text{st}}$ March to 15$^{\text{th}}$ June (spring*) in order to account for the arrival of the monsoon. The first 15 days of June are observed to be very sunny (~626±155 Wm$^{-2}$) and therefore, it is reasonable to merge these days with the spring season (571±145 Wm$^{-2}$ during 2009).

Using these criteria, the observations are classified and average values of ozone, CO, NO$_y$ and wind speed are estimated for air masses uninfluenced and influenced by the downward transport for each season as shown in the Figure 4.8. The seasonal average values calculated from all data are also shown for the comparison. The influences of downward transport have been estimated as the difference between influenced and uninfluenced values ($\Delta$O$_3$, $\Delta$CO, $\Delta$NO$_y$ and $\Delta$Wind speed), as given in the Table 4.2.
Figure 4.8: The comparison of average values of (a) Ozone, (b) CO, (c) NO$_y$ and (d) wind speed for the all data, uninfluenced from the downward transport and influenced from downward transport for winter, spring*, summer-monsoon and autumn during 2009-2011 period over Nainital is shown.

In order to identify the geographical regions, where the air masses have been descending, the 10-days back air trajectories during the downward transport events are shown in the Figure 4.9 for different seasons over the Nainital site. The trajectories are color-coded according to the pressure attained by the air masses to
show the altitude variations along the trajectory. It is observed that the air masses from the higher altitudes (pressure ~ 600 hPa and less) generally descend over the northern India, northern Pakistan and Afghanistan regions which can bring ozone rich air to the Nainital site.

**Figure 4.9:** 10-days back air trajectories showing the transport patterns during the downward transport events during different seasons over the Nainital site. The trajectories are color-coded according to the pressure along trajectory to show the altitude variations of the air masses.

Here, it can be clearly seen that the influence of downward transport are observed over Nainital in all the seasons (12 to 18 counts), except during summer-monsoon.
The result agrees well with the observations over the Nepal Climate Observatory-Pyramid (NCO-P) in the southern Himalayas [Cristofanelli et al., 2010]. Seasonal changes in the frequency of intrusions over Nainital are more-or-less similar to some of the Alpine sites (Zugspitze and Sonnblick) where the frequency is minimum during summer and higher during winter and autumn [Stohl et al., 2000]. Though, the frequency of intrusions was observed to be higher over Jungfraujoch, no clear seasonality was noticed [Stohl et al., 2000], which is in contrast to the Himalayan regions. Moreover, very large diversity is observed over the Himalayas as compared with other parts of Asian region as the stratospheric intrusions show higher frequency during summer over a high altitude location Mt. Waliguan [Ding and Wang, 2006] in East Asia. Such comparative analysis clearly demonstrates that the dynamics over the Himalayas is different from those over East Asia and the differences are attributed to the complex topography and influence of jet streams over these parts of the world [Ding and Wang, 2006].

Table 4.2: The observed changes in ozone, CO, NOy and wind speed between the air masses influenced and uninfluenced by the downward transport over Nainital.

<table>
<thead>
<tr>
<th>Season</th>
<th>ΔO₃ (ppbv)</th>
<th>ΔCO (ppbv)</th>
<th>ΔNOy (pptv)</th>
<th>ΔWind Speed (m/s)</th>
<th>Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>6.1</td>
<td>-106.0</td>
<td>-676.0</td>
<td>3.1</td>
<td>18</td>
</tr>
<tr>
<td>Spring*</td>
<td>18.8</td>
<td>-95.2</td>
<td>-1280</td>
<td>2.5</td>
<td>14</td>
</tr>
<tr>
<td>Summer</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Autumn</td>
<td>11.1</td>
<td>-77.9</td>
<td>-1026.5</td>
<td>1</td>
<td>12</td>
</tr>
</tbody>
</table>

The enhancements in surface ozone levels due to downward transport are observed to be very significant (6.1-8.8 ppbv) over Nainital, with its maximum influence during spring* (18.8 ppbv). On an average, ozone enhancement estimated over NCO-P (13 ppbv) is found to be within the range estimated for Nainital. It has also
been studied earlier that during spring the tropopause altitude increases, which entrains stratospheric air into the troposphere [Appenzeller et al., 1996]. It is suggested that the observed springtime ozone maxima at Nainital is a manifestation of complex influences of regional pollution, biomass burning and dynamical processes including the downward transport.

4.3. Influence of Meteorological Parameters

To investigate the influences of meteorology on the trace gas variabilities, the time series of ozone and CO along with daily average solar radiation and daily total rainfall are shown in Figure 4.10 for September 2010. This month has been chosen as it contains significant day-to-day variability in the solar radiation and rainfall (Figure 4.10). Solar radiation shows a systematic decrease from 15th to 18th September and minimum of solar radiation coincides with the maximum rainfall (more than 200 mm) on 18th September. Observations of ozone and CO could not be made on 18th due to heavy rain; however, during this period changes in meteorological conditions are shown. CO mixing ratios decreased from their initial level of ~250 ppbv on 15th to about 125 ppbv on 21st September. While, ozone levels reduced from about 20 ppbv to 10 ppbv. These significantly large changes caused during the cloudy rainy conditions suggest that meteorological variations play a significant role in the observed variabilities of trace gases.
Figure 4.10: Day to day variations in ozone, CO and solar radiation (0700-1700 hrs) are shown for September 2010. Daily total rainfall is also shown for the same period.

These influences are mainly attributed to the washout of some of the ozone precursors from the atmosphere through the rain supplemented with the suppression of regional ozone photochemical production due to cloudy conditions and drastically reduced solar radiation. Moreover, it is suggested that during the low insolation days, boundary layer mixing and therefore the transport of pollution from the surrounding regions could also be suppressed.

4.4. HYSPLIT Simulated Back-air Trajectories at Nainital with two Different Meteorological Inputs

The back air trajectory simulations have emerged as a key tool to trace the origin of air masses and to investigate the role of local/regional pollution [Pochanart et al.,
1999; Naja et al., 2003a; Naja and Akimoto, 2004; Kumar et al., 2010; Ojha et al., 2012] and long-range transport [e. g. Cooper et al., 2010; Lal et al., 2013]. However, the use of different trajectory models (e. g. METEX, HYSPLIT, FLEXTRA) with different meteorological inputs (e. g. NCEP, GDAS, EDAS, WRF) can lead to differences in the simulated trajectories. Considering this, a case study is conducted with one of the most popular back air trajectory model HYSPLIT (see Chapter 2 for model description) to identify the possible differences and uncertainties caused due to different meteorological inputs (NCEP and GDAS) over this region. The NCEP data has been popularly used to drive back air trajectory models; however, few recent studies [e. g. Ojha et al., 2012] have also used GDAS meteorological fields, mainly due to higher spatial resolution suggesting that it could be more suitable due to complex geographical topography of the northern Indian region.

Figure 4.11 shows the HYSPLIT simulated back air trajectories at Nainital during May and August 2011 representing spring and summer-monsoon seasons respectively. Different colors represent simulations for 1 to 10 days, 10 to 20 days and 20 to 30 days of the month.
Figure 4.11: Synoptic wind patterns simulated using HYSPLIT model for spring (May) and summer-monsoon (August) during 2011 using different data sets to drive HYSPLIT; left column (a) GDAS and right column (b) NCEP. Location of Nainital is shown by black filled star symbol. The blue color represents 1-10 days, red color represents 10-20 days and green color represents 20-30 days of the months respectively.

It is seen that the back-air trajectories simulated from both the meteorological fields are similar/consistent with each other qualitatively (Figure 4.11). During May (spring), air masses generally circulate over the continental northern and western India, Pakistan and Afghanistan regions, before arriving to the observation site,
while, cleaner marine air masses arrive to the site during summer-monsoon (August). It is suggested that during the longer residence over continental regions, air masses could be well exposed to the regional pollution during spring months. The influences of this variability in air masses are discussed more in chapter 3. The noticeable difference between the two simulations is relatively larger expansion of the trajectories in case of high resolution (GDAS) data as input in both of seasons. It is suggested that quantitatively these differences could introduce differences in the estimations of air mass residence times over the northern India and marine regions.

4.5. Summary and Conclusions

In this chapter, a set of case studies were conducted by combining the simultaneous measurements of ozone, CO, NO$_y$ and meteorological parameters with the satellite retrievals and model simulations to investigate the role of northern Indian biomass burning, downward transport, and day-to-day variations in the surface meteorology. The differences in synoptic wind simulations by a popular back air trajectory model (HYSPLIT) were also evaluated using two different meteorological inputs datasets. The influence of northern Indian biomass burning on the trace gases at Nainital have been studied by combining the trace gas measurements with satellite (MODIS) retrieved fire counts. The fire activities over northern Indian region are observed to be highest during spring, which are mainly associated with the crop residue burning supplemented with forest fires. The observations of ozone, CO and NO$_y$ are classified into High Fire Activity Period (HFAP) and Low Fire Activity Period (LFAP). The enhancements in ozone, CO and NO$_y$ at Nainital during HFAP are estimated to be 4-18%, 15-76% and 35-51% respectively.
A high ozone event (~140 ppbv) was observed at Nainital during 18-21 December 2010 with an enhancement of about 160% as compared with pre-event observations (~50 ppb). However, simultaneous observations in the nearby low altitude polluted environment of Indo-Gangetic plain (IGP) did not show any such ozone enhancement. This indicated possible role of downward transport of ozone rich air mass from the higher altitudes which has been confirmed by the analysis of several key tracers. The relative humidity values showed considerable reduction to about 30% during event as compared with pre-event observations (60-70%). This reduction in surface relative humidity was also in agreement with the satellite (AIRS) water vapor mixing ratios at 850 hPa showing reduction from 2.6 g/kg to 1.75-1.8 g/kg. This event was further corroborated using HYSPLIT simulated back air trajectories showing air masses descending from ~6km and above. Potential Vorticity calculated using WRF simulated meteorology showed significant enhancement with values as high as 2.5 pvu over most of the Himalayan region. Additionally, the observations of ozone, CO, NO$_y$ and wind speed are used with back-air trajectories to identify the air masses influenced by downward transport during 2009-2011 period. It is shown that downward transport influences Nainital site in all the seasons (12 to 18 counts), except summer-monsoon. The enhancement in surface ozone due to downward transport has been estimated to be 6.1 to 18.8 ppbv over Nainital, with maximum influence during spring*. A comparison of this result with other parts of Asian region in particular with East Asia shows large diversity associated with downward transport. The different dynamics among the Himalayas and other Asian regions are attributed to the complex topography and role of jet streams.
The effects of day-to-day changes in meteorological conditions on the trace gas variabilities have been investigated. Solar radiation decreased significantly during 15-18 September coinciding with rainfall (> 200 mm). CO and ozone levels also decreased from \(~250\) ppbv to about \(125\) ppbv and from \(20\) ppbv to \(10\) ppbv respectively. These variations in trace gases were associated with the daily changes in meteorological conditions including solar insolation, clouds, rainfall and boundary layer. To identify the differences in trajectory simulations using different meteorological fields a case study has been conducted for two contrasting seasons using HYSPLIT model. It is shown that NCEP and GDAS meteorological inputs lead to qualitatively consistent trajectories. The simulated trajectories are in good agreement with the observed seasonal variations in trace gases.