# Direct solar ultraviolet irradiance over Nainital, India, in the central Himalayas for clear-sky day conditions during December 2004

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[1] From a high-altitude station, Nainital, India (29.4°N, 79.5°E, 1958 masl), located in the central part of lower Himalayas, the observations made during December 2004 using a pair of Sun photometers (Microtops II) at wavelengths ranging from 305 to 1020 nm are reported. The observed parameters are the direct solar UV irradiance, column ozone, water vapor, and aerosol optical depths (AOD). The results are presented for the full day clear-sky conditions that prevailed for about 16 days during the whole month. It is found that Nainital is a comparatively pristine site with average AOD at 500 nm ranging between 0.03 and 0.09 and Angstrom exponent generally close to 1. The high AOD values occurred on 2 and 25 December due to winds from populated north Indian plains as revealed by the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) backward trajectory model. The total column ozone varies between 251 and 308 DU during the entire period of observations. The maximum diurnal UV irradiance values in the 2.4 nm bandwidth centered at 305.5, 312.5, and 320.0 nm varied between 0.027 and 0.049, 0.15 and 0.20, and 0.29 and 0.37 W $m^{-2}$, respectively. The measured UV irradiances are compared with the Tropospheric Ultraviolet Visible (TUV) radiation model and show a good agreement.

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## 1. Introduction

[2] Numerous studies of UV measurements and model calculations have been done during the last few decades following the observations and predictions of the tendency of increasing solar ultraviolet radiation reaching the Earth's surface due to decrease in ozone layers [*Kerr and McElroy*, 1993; *Seckmeyer et al.*, 1994]. These studies included ground-based as well as satellite-borne measurements and model calculations for various locations around the globe [e.g., *Blumthaler et al.*, 1994; *Zerefos et al.*, 1995; *Bodhaine et al.*, 1997; *Minschwaner*, 1999; *Herman et al.*, 1999; *Dubrovský*, 2000; *Palancar and Toselli*, 2002; *Piacentini et al.*, 2002; *Xu et al.*, 2003]. However, only a few observations have been reported from the high-altitude locations [e.g., *McKenzie et al.*, 1991, 2001; *Piazena*, 1996; *Ren et al.*, 1997; *Bodhaine et al.*, 1997; *Pachart et al.*, 1999]. Most of these high-altitude stations are primarily located in the higher latitudes or in the snow covered areas. In the Himalayan region, to the best of our knowledge, only two previous studies on UV irradiance measurements have been reported, one by *Ren et al.* [1997] in the Tibet region and one by *Singh and Singh* [2004] in the Western Himalayas. In the central lower Himalayan region, however, no previous study exists. This is in spite of the fact that the region houses a wide variety of flora and fauna and its ecology are susceptible to damages due to UV and other radiation changes.

[3] Nainital (29.4°N, 79.5°E, 1958 masl), located in the central part of lower Himalayas at about 20 km inside from the plains of north India, provides an ideal site for the radiation and aerosol measurements. The site is devoid of any major pollution sources nearby and is generally free from the snow coverage during most of the time. The annual range of temperature varies between ~0 to ~30°C with generally clear-sky conditions except during monsoon season of June–September and due to light rain/snow during winter.

[4] The present observations were made during December 2004 as a part of multi-institutional land campaign experiment for aerosol and radiation measurement organized over a wide region in the Gangetic Plains of North India for characterizing the regional aerosol properties and trace gases. Nainital served as a regional background site, where comparatively pristine environment prevailed [*Sagar*

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**Table 1.** Angstrom Exponent, Aerosol Optical Depth, Column Water Vapor, and Column Ozone for Clear-Sky Day Conditions During December 2004

| Day in December 2004 | Whole-Day AOD (500 nm) | AOD (500 nm) | | Water Vapor | Total Columnar Ozone, DU | Angstrom Exponent α |
|---|---|---|---|---|---|---|
| | | Forenoon | Afternoon | | | |
| 2 | 0.09 | 0.090 | 0.070 | 0.30 | 252.8 | 0.82 |
| 3 | 0.03 | 0.026 | 0.038 | 0.20 | 264.9 | 0.37 |
| 4 | 0.04 | 0.026 | 0.049 | 0.22 | 253.5 | 0.34 |
| 8 | 0.06 | 0.046 | 0.062 | 0.28 | 251.6 | 1.10 |
| 10 | 0.05 | 0.043 | 0.064 | 0.29 | 257.5 | 1.09 |
| 11 | 0.07 | 0.062 | 0.057 | 0.36 | 257.7 | 1.02 |
| 12 | 0.07 | 0.058 | 0.059 | 0.43 | 257.6 | 1.25 |
| 13 | 0.05 | 0.039 | 0.058 | 0.34 | 252.8 | 1.07 |
| 14 | 0.03 | 0.021 | 0.052 | 0.21 | 261.1 | 0.82 |
| 15 | 0.07 | 0.054 | 0.114 | 0.29 | 262.3 | 0.95 |
| 16 | 0.07 | 0.055 | 0.098 | 0.26 | 265.0 | 1.02 |
| 22 | 0.05 | 0.033 | 0.064 | 0.22 | 308.2 | 0.67 |
| 23 | 0.07 | 0.047 | 0.072 | 0.21 | 302.6 | 0.74 |
| 25 | 0.09 | 0.048 | 0.133 | 0.17 | 313.1 | 0.44 |
| 26 | 0.03 | 0.022 | 0.033 | 0.05 | 314.0 | 0.23 |
| 27 | 0.06 | 0.038 | 0.070 | 0.35 | 285.1 | 0.69 |

*et al.*, 2004]. During this campaign period, the average monthly AOD at 500 nm was found to be ~0.06 with column water vapor ~0.26 cm.

[5] In the present study, daytime clear-sky measurements of aerosol optical depth (AOD), column ozone and water vapor were obtained using the hand held portable Sun photometer Microtops II. The column ozone measurements were compared with the satellite based Total Ozone Mapping Spectrometer (TOMS) onboard EarthProbe satellite and Ozone Monitoring Instrument (OMI) onboard EOS Aura. The measurements of UV irradiance fluxes on clear-sky days have been compared with the NCAR Tropospheric Ultraviolet and Visible (TUV) radiation model.

## 2. Observations and Analysis

[6] The observations were carried out using the Microtops II (Microprocessor-controlled total ozone portable spectrometer; Solar Light Company, USA) Sun photometer and ozonometer. Microtops II ozonometer (hereafter called ozonometer) measures the irradiance centered at 305.5, 312.5, 320, 936 and 1020 nm wavelengths and estimates column ozone, AOD at 1020 nm and column water vapor content. Similarly, Microtops II Sun photometer (hereafter called Sun photometer) provides AOD at 380, 440, 500, 675 and 870 nm wavelengths. The observations were taken during the whole month of December 2004, out of which the clear-sky conditions existed for 16 days (Table 1). The results of these clear-sky days are being reported here. During this period, the continuous black carbon data were also collected at the campaign site by using a portable Aethalometer (Maggi Scientific Inc., USA).

[7] It is to be noted that the Microtops II observations are susceptible to errors due to filter degradation and needs periodic calibration on at least an annual basis [*Morys et al.*, 2001]. In the present case, however, the instruments were procured from Solar Light Co. after proper calibration, only a month before the actual observations were taken. The calibration report from the manufacturer informs that the Sun photometer was calibrated at Mauna Loa observatory on 25 June 2004, and ozonometer was calibrated on 9 September 2004 with a reference ozonometer, which was calibrated at Mauna Loa Observatory during June 2004. As the instruments were procured only a month before the observations were made, there is little chance of any filter degradation. The calibration constants for ozonometer are $8 \times 10^{-5}$, $2.6 \times 10^{-4}$, $4.6 \times 10^{-4}$, $5.6 \times 10^{-3}$ and $7.1 \times 10^{-3}$ W m$^{-2}$/mV for wavelengths 305.5, 312.5, 320, 936 and 1020 nm, respectively and for Sun photometer, they are $2.41 \times 10^{-3}$, $1.71 \times 10^{-2}$, $2.09 \times 10^{-2}$, $1.37 \times 10^{-2}$ and $1.34 \times 10^{-3}$ W m$^{-2}$/mV for 380, 440, 500, 675, and 870 nm, respectively. The pointing accuracy of the Microtops II is better than 0.1° and long-term stability of the UV filter is better than 0.1 nm/year [*Morys et al.*, 2001]. The consistency of the observations is, however, checked periodically by taking a series of continuous measurements on clear-sky days. Great care has also been taken to avoid any manual error during pointing toward the sun. In order to check the repeatability and precision of the instrument, frequent observations were taken at about 60 s interval on a fairly clear forenoon during December 2004 for about 30 min. The repeated measurements were conducted by initializing the instruments every time for getting next data set. The results are shown in Figure 1, which indicates the average and standard deviations of 252.2 ± 0.6 DU in column ozone measurements indicating that the measurements are accurate enough in

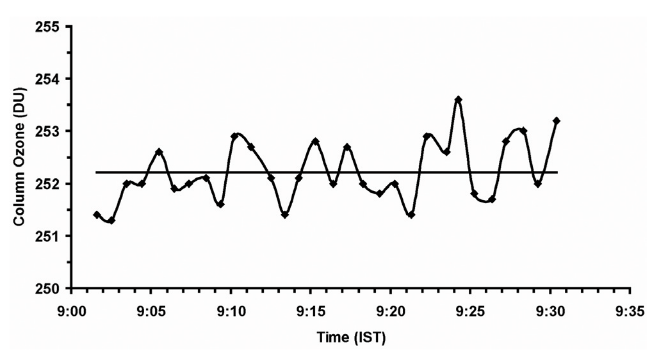


**Figure 1.** A series of consecutive measurements at about 1 min intervals by Microtops II irradiance for ozone at Nainital. The standard deviation was 0.24% with an average column ozone as 252.2 ± 0.6 DU during a total duration of 30 min.

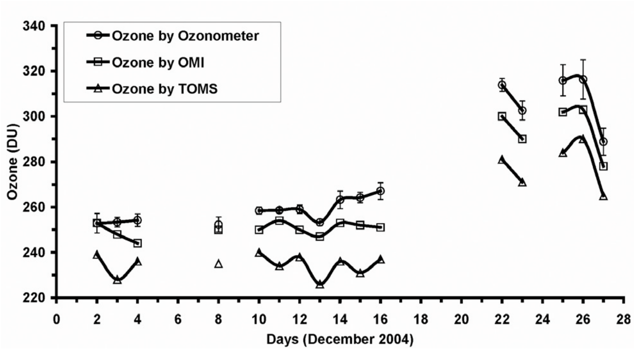


**Figure 2.** TOMS (triangles), OMI (squares), and Microtops II ozonometer derived (diamonds) daily average ozone for Nainital during December 2004. There is a systematic difference of ∼9.5% between observed and TOMS derived columnar ozone values; however, the difference between observed and OMI ozone column data is ∼3%.

comparison to the other reported consistency results [*Morys et al.*, 2001; *Singh and Singh*, 2004].

## 3. TUV Model

[8] The Tropospheric Ultraviolet Visible (TUV) radiation model developed at NCAR is a radiation transfer model extensively used to calculate solar irradiance at different layers in the atmosphere. The model gives irradiance in the UV and visible wavelength bands by using the World Meteorological Organization recommended top of atmosphere solar flux data, Rayleigh scattering by gases, and ozone profiles. The model has been run in the two-stream approach with pseudospherical correction to calculate the solar radiative transfer within the atmosphere. More details regarding this model can be found online (http://cprm.acd.ucar.edu/Models/TUV) and are given by *Madronich* [1993].

[9] For the present study, the TUV model was run to obtain the direct solar irradiance centered at 305.5, 312.5 and 320 nm (with band width of 2.4 nm). Major input parameters used for the irradiance calculations are column ozone, AOD at 550 nm, site coordinates (latitude, longitude and altitude), single scattering albedo (ssa), in addition to the date and time etc. Since the surface albedo does not affect the direct solar irradiance (as in the case of Microtops II), it has been kept at default value for the TUV model analysis. In addition, as the TUV model gives irradiances incident on a horizontal plane and ozonometer measures irradiance normal to the beam, the model values have been divided by cosine of solar zenith angle for comparison with observed data. The column ozone values as an input to the model are obtained by ozonometer. Another input parameter, the AOD at 550 nm ($\iota_{550}$) has been computed using the relation $\iota_{550} = \iota_{500}(500/550)^{\alpha}$, from the observed AOD at 500 nm ($\iota_{500}$). '$\alpha$' is the Ångström exponent [*Ångström*, 1961], which is computed from the AODs at 380, 440, 500, 675 and 870 nm by least squares fit on a log-log plot scale of the observed AOD versus wavelength. Model was run for different days taking the corresponding measured column ozone values and $\iota_{550}$. As the average AOD in the forenoon and afternoon are different, the model has been run separately for the forenoon and afternoon using corresponding $\iota_{550}$ values (Table 1).

[10] It is to be noted here that the filter transmission function for various filters in Microtops II are not available at a very high resolution for a realistic comparison with the model transmission function. The details about the UV filter specifications for ozonometer are, however, given in the paper by *Morys et al.* [2001], which indicates that the maximum out-of-band transmission relative to the peak wavelength is of the order of $10^{-6}$ for 305.5 nm filter and $10^{-5}$ for 312.5 nm filter. The TUV model, on the other hand, uses exactly unity transmission in the given wavelength band (2.4 nm in the present case) and zero outside this range. This may cause a difference of ∼1% at 305.5 nm and ∼10% at 312.5 nm in the total transmission at the bandwidth of 2.4 nm around mean wavelength.

## 4. Results and Discussion

[11] Figure 2 shows daily mean column ozone observed by ozonometer during 2–27 December 2004. These values are also compared with the Total Ozone Mapping Spectrometer (TOMS) onboard EarthProbe satellite and Ozone Monitoring Instrument (OMI) onboard EOS Aura platform. Although the observations showed similar trend as the TOMS data, the values were higher by about 9.5%, which was beyond the range of instrumental errors. The further comparison of our observation with the OMI data during the same period shows a difference of only about 3.3%. It is to be noted that the OMI data are supposed to be more reliable than the TOMS observations after the year 2004 as claimed by the Ozone Processing Team (http://toms.gsfc.nasa.gov/). Considering this, the ozonometer data seems quite reasonable as it also closely follows the trends in OMI data (Figure 2).

[12] Since the ozone column is quite consistent during high and low AOD days; an attempt is made to apply Langley extrapolation method to find the extraterrestrial irradiances at 305.5, 312.5 and 320 nm wavelengths and results are shown in Figure 3. A linear regression between logarithm of solar irradiance and the corresponding secant of solar zenith angle (∼ air mass) for less than 70° is plotted. Intercept of each linear regression (for zero air mass) is identified for the extraterrestrial solar irradiance at

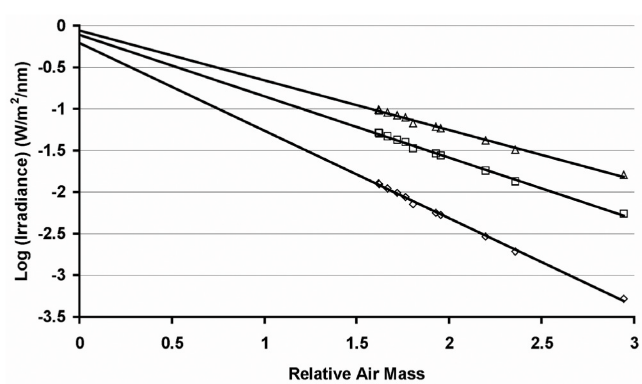


**Figure 3.** Logarithm of solar irradiance versus secant of solar zenith angle (air mass) for three wavelengths at Nainital for 3 December 2004 (diamonds, 305.5 nm; squares, 312.5 nm; triangles, 320 nm).

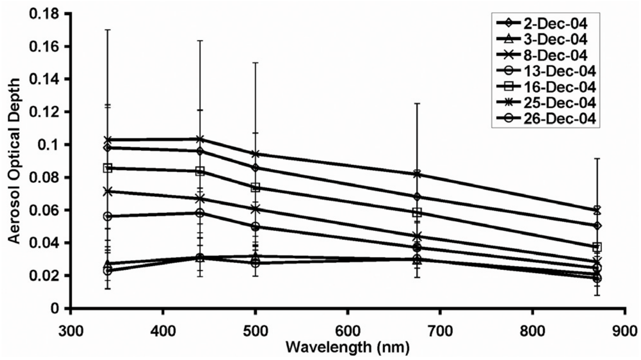


**Figure 4.** Spectral variation of daily average aerosol optical depth for few representative days during December 2004. Vertical bars show the standard deviation.

the top of atmosphere (TOA). Results show a strong linear relationship between the logarithm of the irradiance and the corresponding air mass for all the three wavelengths. The extraterrestrial solar irradiance has been obtained by this method for 3 December 2004. Obtained values are 0.627, 0.781 and 0.868 W $m^{-2}$ $nm^{-1}$ at 305.5, 312.5 and 320 nm respectively. The obtained values are in close agreement with the data reported by *DeLuisi* [1975]. It shows the irradiance at TOA at 305.5, 312.5 and 320.0 nm wavelengths to be 0.632, 0.782 and 0.858 W $m^{-2}$ $nm^{-1}$. The slight difference in our estimates from these values might perhaps be due to the errors in the observed AOD and the approximation in the air mass calculations along with the statistical error caused by small number of observed data in the present case.

[13] The general characteristics of aerosol distribution during the observation period can be studied using the Ångström exponent $\alpha$ and AOD. The average diurnal Ångström exponent, $\alpha$, shown in Table 1 indicates that on most of the days, $\alpha$ remain close to 1 except on a few occasions when it is less than 0.5. The low $\alpha$ values also coincides with the very low AOD values. Further, the total column water vapor generally has a value below 0.45 cm indicating a dry atmosphere. Another study in the Himalayan region at similar altitude also shows similar magnitude of $\alpha$, though with a higher AOD values [*Ramana et al.*, 2004]. At much higher altitude, *Singh and Singh* [2004] have reported a higher $\alpha$ value of the order of >2.1 at about 4.5 km amsl and ~1.5 at 3.4 km amsl over the Western Himalayas.

[14] The AOD spectral variations for a representative few days during the observation are shown in Figure 4. The vertical bars indicate the standard deviation values at the diurnal average. The maximum AOD is found to occur on 2 and 25 December 2005, followed by the minimum AOD on 3 and 26 December, respectively. The maximum AOD days show large fluctuation in the diurnal values. This high fluctuation is due to the intermittent winds from the plains of north Indian region with high pollutants. Minimum AOD days show a consistent values through out the day showing a small standard deviation.

[15] Figure 5 shows diurnal variation of the measured clear-sky direct solar irradiance (W $m^{-2}$ $nm^{-1}$) at 305.5, 312.5 and 320 nm during the observation (shown by scattered points). The observed direct maximum flux ranges between 0.027 and 0.049, 0.15 and 0.20, and 0.29 and 0.37 W $m^{-2}$ at 305.5, 312.5, and 320 nm, respectively. Further, the irradiances observed at Nainital exhibits an asymmetric behavior in the diurnal cycle. This may be due to a change in the TSP (Total suspended particulate matter) and BC (Black carbon) particles behavior during forenoon and afternoon at this location. To the northeast of this location there are less polluted high mountain peaks of Himalayan range (>2000 masl) and to the southwest of the site, there are highly populated plain areas (~500 masl), merely at a distance of about 20 km. During morning hours the aerosol particles are generally concentrated below the mountain peaks (in the valleys; as residual layer), consequently, the TSP concentration is less. While, by the afternoon, due to convective heating processes the subsequent atmospheric boundary layer grows with time causing updraft of contained pollutants and an increase in TSP and BC at the observation site. As most of the pollutants are confined within the atmospheric boundary layer, the lifting of atmospheric boundary layer during afternoon may be a prominent reason of the observed asymmetry.

[16] The observed diurnal irradiances have also been compared with the TUV model results in Figure 5 (shown by lines). The vertical bars indicate the standard deviation for the model values obtained on different days of observations. The comparison indicates generally similar trends in the observations and the model calculations and they are generally found to match at lower wavelengths. However, at 320 nm the observed values are generally less than the model-calculated values, particularly, in the afternoon. The reduced irradiances observed in the afternoon may be attributed to the enhanced level of black carbon (BC) particles during afternoon. Figure 6 shows the average diurnal variation in the BC concentration during the whole period of observation. Figure 6 clearly indicates that the BC concentration is almost doubled in the afternoon. This increase might be causing an additional absorption of the radiation leading to a reduced value of irradiance during afternoon, as observed. It is also to be noted that the model assumes a perfect square transmission throughout the 2.4 nm bandwidth at the central frequency whereas the Microtops II has filter transmission functions that are not exactly square in shape. A slight difference in irradiance may

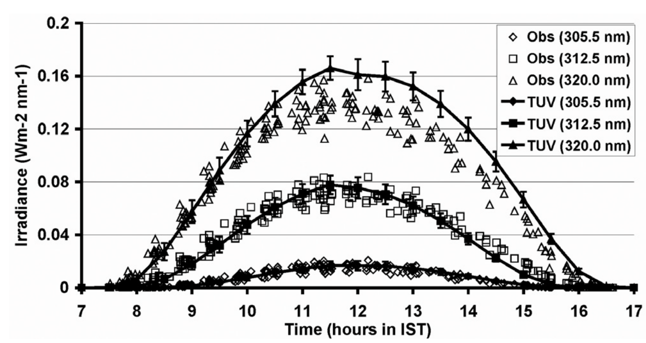


**Figure 5.** Diurnal variation (scattered points) of irradiance at 305.5, 312.5, and 320 nm wavelengths based on observations by Microtops II ozonometer for various days during December 2004. Solid lines show TUV model estimated values for corresponding wavelengths.

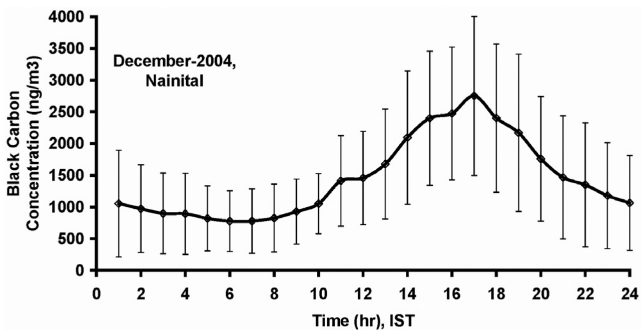


**Figure 6.** Diurnal variation of average black carbon (BC) concentration at Nainital for clear-sky days during December 2004.

also be attributed to this reason. As the solar irradiance increases sharply with increasing wavelengths in the UV region, the difference in irradiance is more pronounced at 320 nm.

[17] As discussed earlier (Figure 4) the AOD at 500 nm at Nainital shows its highest values on 2 and 25 December followed by the lowest AOD values on the following days. These days are examined in detail to explore the possible reason for their respective extreme AOD values in terms of aerosol transport from other regions. To do this, the backward trajectories derived from HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory, version 4 [*Draxler and Rolph*, 2003]) at altitudes of 2500, 3000 and 3500 masl were investigated. Figures 7 and 8 show the backward trajectories for 72 hours ending at Nainital at 1130 IST (i.e., 0600 UTC) for 3 and 25 December 2004, respectively. These backward trajectories plots are based on the FNL meteorological data. Trajectories clearly show a significant difference in the pathways of the incoming winds. It indicates that for high AOD day (25 December), the affecting southerly winds at 2500 and 3000 masl was closer to the site for a longer period and was within the mixing layer altitudes for most of the time, consequently, enhancing the concentration of aerosols. On the other hand, for low AOD day (3 December), the affecting westerly wind traveled a long distance before reaching over the observing site. Moreover, for most of the time, this wind was above the mixing layer altitudes during its pathway, minimizing the possibility of accumulation of aerosols. Similar trends in backward trajectories are also seen for the

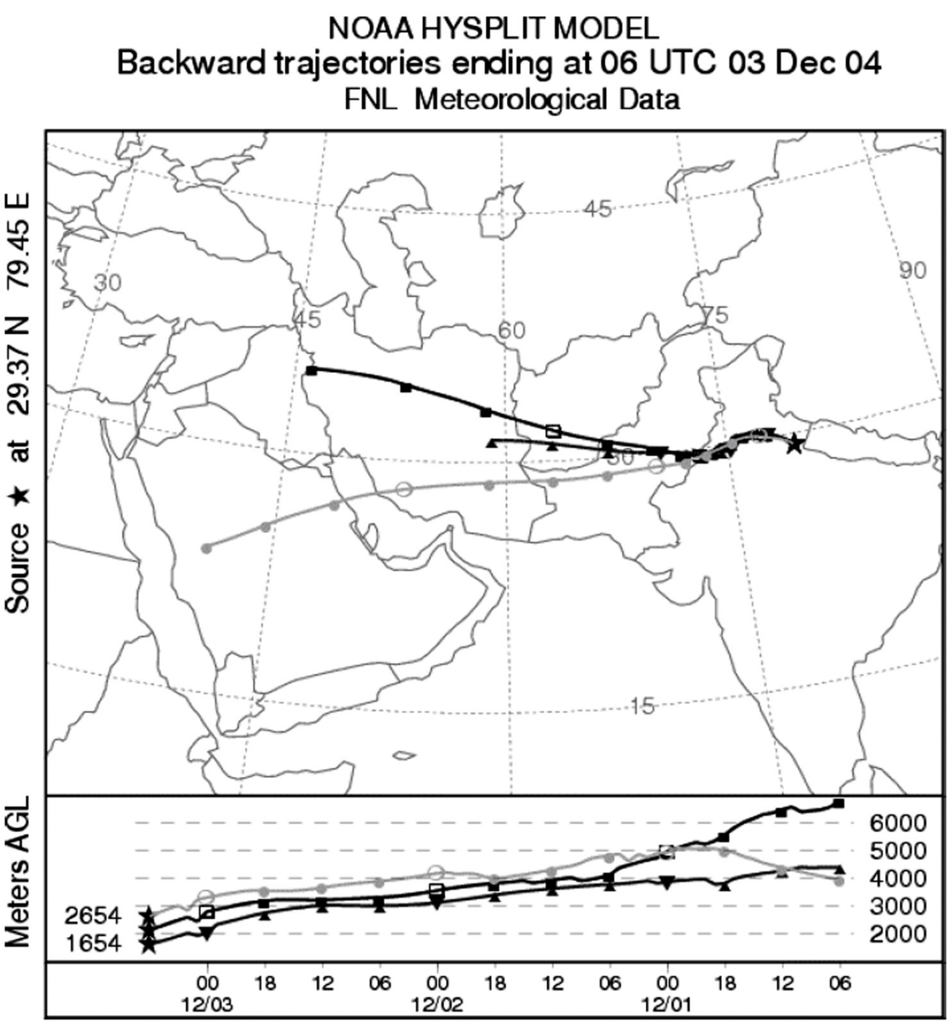


**Figure 7.** Backward trajectories at 2500, 3000, and 3500 masl for 3 December 2004 at Nainital.

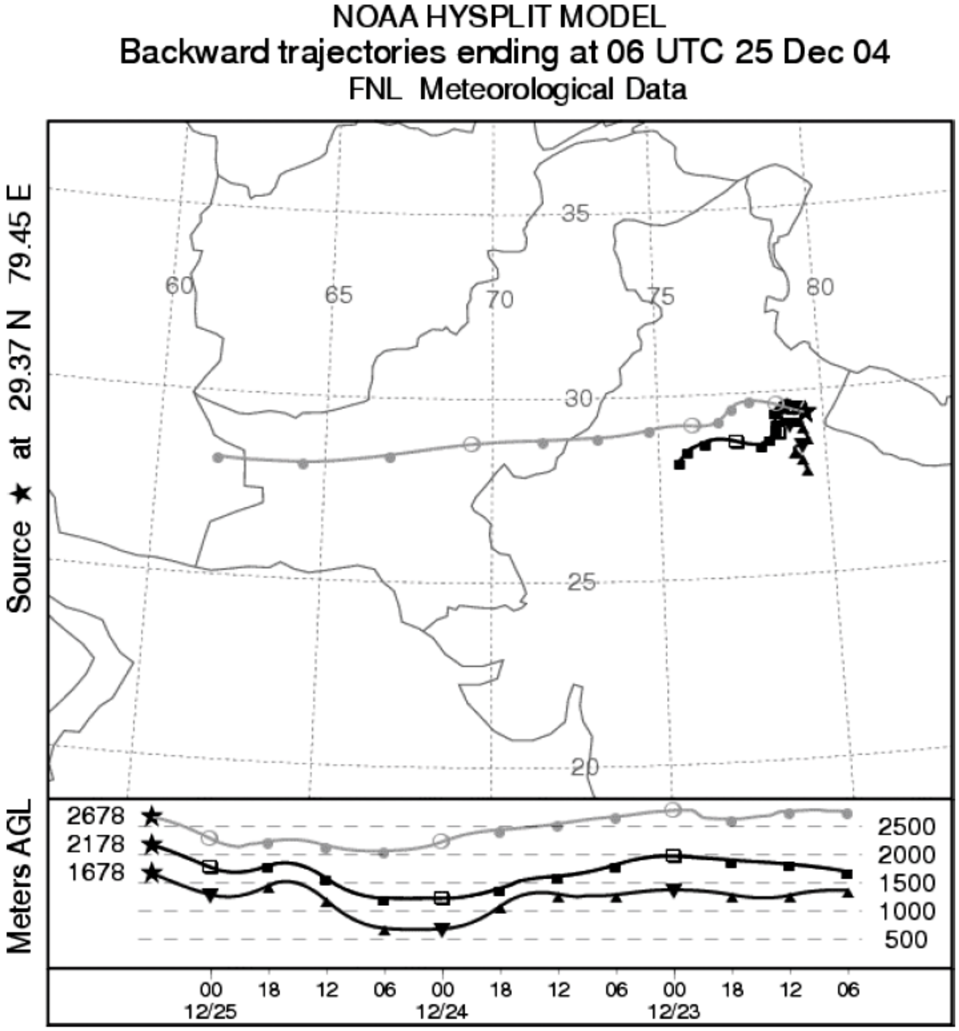


**Figure 8.** Same as Figure 7, but for 25 December 2004.

pair of days, 2 and 26 December, which are also the corresponding high and low AOD days, respectively.

## 5. Conclusions

[18] The measurements done at Nainital during December 2004 showed that the diurnal maximum direct irradiance values at 305.5, 312.5, and 320.0 nm in a 2.4 nm bandwidth varied between 0.027 and 0.049, 0.15 and 0.20, and 0.29 and 0.37 W $m^{-2}$ respectively. The observed clear-sky direct solar irradiances at 305.5 and 312.5 nm compared well with the TUV model results. At 320 nm the observed values, particularly in the afternoon, were slightly less than the model output, which is attributed to the enhancements in the afternoon black carbon concentrations. The observed average column ozone values more or less agree with the OMI measurements onboard EOS Aura satellite (within a range of ~3%).

[19] The average AOD at 500 nm during the observation period is found to be ~0.06 and shows that the afternoon AOD values are generally higher than the forenoon values. The Angstrom exponent, $\alpha$, generally lies close to 1 except on few occasions when it is close to 0.5.

[20] The maximum AOD occurred on 2 and 25 December 2005, followed by the minimum on subsequent days. The backward trajectory analysis suggest that maximum AOD occurred due to winds from populated north Indian plains, whereas the minimum AOD corresponded to winds from pristine Himalayan ranges in the west.

[21] **Acknowledgments.** The authors gratefully acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model and TOMS and OMI satellite information and Sasha Madrinich, NCAR, USA, for TUV model. One of the authors, M.K.S., is thankful to the Director, ARIES, Nainital, and CSIR, New Delhi, for the financial support.

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