STRUCTURE AND COMPOSITION OF THE LOWER TROPOSPHERE OVER THE HIMALAYAN FOOTHILLS OF NEPAL

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Abstract. Atmospheric Brown Clouds (ABCs) significantly reduce radiative transfer through the atmosphere and thereby impact regional climate. Persistent ABCs form over the Indian Subcontinent during the dry (December-February) and pre-monsoon (March-June) seasons. They extend over hundreds of square kilometers, and migrate meridionally with the monsoonal circulation between the Indian Ocean and the Tibetan Plateau. While some ABC features can be characterized based on satellite- and ground-based observations, in situ measurements from aircraft are required to resolve the primary sources, physicochemical properties, and spatial evolution of ABCs, particularly over complex terrain. We report here upon the unique observational data collected from an aircraft over the foothills of the Nepal Himalayas (28°N, 84°E) during the dry and pre-monsoon season of 2011. The measurements were collected between ground-level and 4500 m asl and include ozone, carbon monoxide, nitric oxide, black carbon (BC), size-resolved aerosol number concentrations, and corresponding meteorological conditions. Aerosol and trace gas concentrations were found to be generally lower during the dry season relative to the pre-monsoon season, and were also higher during the day relative to morning. Higher concentrations of pollutants observed above the Seti River Valley relative to comparable altitudes elsewhere suggest up-slope and up-valley transport of pollutants from the city of Pokhara toward the Annapurna Himalaya. These processes may have important implications for regional variability in radiative transfer and air quality.

Introduction

Atmospheric Brown Clouds (ABCs) are optically thick haze layers of combustion-derived aerosols and associated gases. The presence and composition of ABCs is a result of extensive biomass and fossil fuel burning in Asia, which varies with seasons. ABCs significantly reduce radiative transfer through the atmosphere via absorption and scattering, causing solar dimming at the surface. The absorbed solar radiation warms the lower and middle troposphere thereby modulating the thermodynamic properties of the column. There is uncertainty in the net magnitude and sign of the aerosol forcing effect from the ABCs, and how they may affect the South Asia monsoon circulation and regional climate [Ramanathan et al., 2001].

Elevated haze layers advected toward the Himalayas with the monsoon circulation may drive a larger climate forcing in the region than surface deposition of pollutants onto snow and ice surfaces. This process may expedite the melting of the Himalayan snowpacks and glaciers [Flanner et al., 2007; Kaspari et al., 2010; Lau et al., 2010; Yasunari et al., 2010; Srivastava et al., 2012]. Advection of ABC layers into the foothills and the Himalayas has negative consequences for the health of residents [Smith, 2000; Beegum et al., 2009], damages vegetation, diminishes harvest yields [Chameides et al., 1999; Auffhammer et al., 2006], decreases visibility, impacts water resources [Menon et al., 2002; Barnett et al., 2005] and alters regional climate [Gautam et al., 2009a].

Due to political barriers, insufficient infrastructure, and remoteness of some of the regions of South Asia, only a limited number of direct observations are available prior to 1990s. Most studies of the effect of ABCs on local climate and air quality have been based on poorly constrained model calculations. In the last two decades, a large international effort established several ground-based stations in the Indo-Gangetic Plain and in the Himalayan Mountains to augment the observations during shorter-term field campaigns involving surface- and aircraft-based sampling. Satellite remote sensing has provided additional insight of brown cloud characteristics in recent years. However, the scarcity of field data prior to the 1990s limits understanding of the background/baseline atmospheric composition and regional climate and associated interannual trends. The distance between observation stations and sparse temporal sampling coupled with the coarse scale of satellite observations results in underrepresentation of the foothills and high altitude areas of the Himalayas. This creates difficulty in parameterization of models of
regional pollution and associated impacts. Aircraft campaigns carried out in the region and elsewhere in the world emphasize that neither ground stations nor satellite data alone adequately represent the spatial distribution and temporal variability of elevated pollution layers in the atmosphere over South Asia.

Ramanathan et al. [2007a] report that an extensive ABC plume is present in the region overlaying the Indian Ocean from November to March. During this time, the dry season is experienced in the Himalayan foothills with relatively clean air AOD$_{500}<0.38$ [Bomidi, 2007], as indicated by the ground-based AERONET network and space-borne MODIS and CALIPSO instruments. Based on previous studies by Chung et al. [2005] and CALIPSO Lidar measurements, the vertical extent of the ABCs is limited to 3km amsl over the Indian Ocean. Satellite and aircraft-based observations over the Himalayan foothills show that the vertical extent of the ABCs is limited to 5km amsl, and varies throughout the year (Figure 1).

The complex terrain of the Himalayan foothills necessitates onsite observations for better characterization of the overlying atmosphere and insight into understanding of the transport mechanisms that result in the observed atmospheric composition. We report upon the investigation of the composition and structure of the lower troposphere in the vicinity of the Annapurna Himalaya, located in the western region of Nepal Himalaya, using ground- and aircraft-based measurements during the dry and pre-monsoon seasons of 2011. For aerial measurements, we have created an Atmospheric Sampling package for UltraLight Aircraft (ASULA) and employed this capability to characterize chemical and physical properties of the lower atmosphere over the Himalayan foothills. The strengths and weaknesses of this platform were assessed, and improvements are proposed. ASULA-based aerial measurements have created a unique dataset using a novel platform, and are vital for assessment of the anthropogenic contribution to the deteriorating air quality and climate change in the vicinity of the Himalayas – a fragile environment located between two nations with rapidly developing economies and emissions profiles.

Methodology

Monsoon Circulation

South Asia is affected by the Indian Summer Monsoon circulation. Pollutants form ABC haze
layers over the Indian subcontinent and extend over the Indian Ocean or into the Himalayas during the dry and pre-monsoon seasons, respectively. Precipitation events during the monsoon season deposit pollutants onto the surfaces of the land, glaciers and snowpacks, altering the surface albedo.

**Pokhara Site**

Instrumented flights were based out of the city of Pokhara (28°11N, 83°58’W) (Figure 2). Pokhara is Nepal’s second largest city (pop. 200,000 in 2011), and is located in the Kaski district of Nepal, 200km west of Kathmandu. Most notable is the fact that Pokhara is situated in the Himalayan foothills, within 25 air miles of some of the tallest peaks of the Himalayan Mountains – Annapurna I (8,091m amsl), Annapurna South (7219m), Machhapuchhare (6997m), Annapurna IV (7525) and Annapurna II (7937m). The Seti River Valley is situated NNW-SSE between Pokhara and the Annapurna Himalaya. This location is ideal for measuring the chemical composition of the atmosphere overlaying the Himalayan foothills and directly adjacent to the southern slopes of the Annapurna Himalaya, and examining local pollution and long-range pollution transport mechanisms that may be leading to drastic surface and climate changes in the Himalayas.

**ASULA Instrument Package**

An Atmospheric Sampling instrument package for UltraLight Aircraft was developed with the goal of deployment in the field for air quality and atmospheric composition measurements over the Himalayan foothills. Several limitations were considered, including the weight limit and lack of a power source onboard the aircraft, as well as the range of pressure levels covered during the flight. An ultralight aircraft can transport a 120kg payload to a ceiling altitude of 5000m amsl at an average cruising speed of 32 m/s and a maximum ascent rate of 5m/s, and has a permanent window porthole through which sampling can be conducted.

The ASULA package includes a temperature/humidity probe (HOBO datalogger U23 Pro-v2, Onset Computer Corporation, USA), with a response time of less than 10 seconds at ultralight aircraft speeds. To verify the T/RH probe and acquire ambient pressure measurements in flight, a pocket weather station (Kestrel 4500, Nielson-Kellerman Co., USA) is included. Measurements of trace gases were obtained with a carbon monoxide monitor (i48-TLE, Thermo Scientific, USA), an ozone monitor (405, 2B Technologies, USA), and a NO-NO₂ tandem (410-401, 2B Technologies, USA). An aethalometer (AE51, Magee Scientific, USA) was used to measure the atmospheric black carbon aerosol concentration, however, since this is a single-wavelength spectroscopic technique, it is likely that mostly graphitic and some organic carbon is represented in the reported concentration values. Size resolved aerosol number concentrations were obtained using a DustTrak (8533, TSI, USA) and an Optical Particle Sizer...
The DustTrak employs a photometric technique that measures particle concentrations based on scattering of an incident laser beam – a function of particle diameter. The filter at the inlet eliminates particulates larger than 50μm from entering the chamber. The DustTrak measures concentrations of particulates below the thresholds of 1μm, 2.5μm, 4μm and 10μm. The Optical Particle Sizer utilizes single particle counting technology, and has 16 size bins, the parameters of which can be set by the operator. During the instrumented flights, eight bins were utilized and the size ranges were set to 0.3-0.5μm, 0.5-0.7μm, 0.7-1.0μm, 1.0-2.0μm, 2.0-3.0μm, 3.0-5.0μm, 5.0-8.0μm, and 8.0-10.0μm. The submicron particulates are generally associated with anthropogenic origins (e.g. BC), while most of the larger aerosols are from natural origins (e.g. crustal matter).

Due to potential impaction of aerosol particulates onto the sampling tube, monitors of aerosol properties were equipped with sample tubes no more than 1m in length. Additional testing was conducted on the DustTrak to determine whether aircraft speed and inlet orientation affected the size resolved aerosol number concentration measurements. A DustTrak was placed on a hilltop near Pokhara, while an identical instrument was deployed on an ultralight aircraft that conducted several overpasses within 130m of the hilltop. Measurements from the two DustTraks were within detection limits of the instrument for all size thresholds. Similar validation tests are suggested for the aethalometer.

The ASULA instrument configuration can be modified depending on the suite of measurements sought and for combination with a passenger. The instrument package contains some of the same instruments already employed at ground stations in the Himalayan foothills, which facilitates validation of the aircraft platform and cross-comparison of aircraft data with ground-based data. To satisfy the power requirements for the gas-sampling instruments, a 12V battery with an inverter to 110V AC is utilized. The ASULA setup weighs approximately 25kg with all of the required wiring. A schematic diagram of the ASULA package is shown in Figure 3. Refer to Appendix I for more detailed information regarding ASULA instrumentation.

Ultralight Aircraft

ASULA was deployed on a closed-cabin Aeroprakt A-22 two-seater ultralight airplane (manufactured in Ukraine and assembled onsite in Pokhara, Nepal), with fuel tanks in the wing compartments, a 3-blade front propeller, and a Rotax 912UL 80hp flat-4 engine. It can fly at a speed range of 70-190km/hr, up to a maximum engine service ceiling altitude of 5000m amsl, with a maximum payload of 180kg, including the pilot. The average cruising speed is 32m/s, and the maximum rate of ascent is 5m/s. The first Aeroprakt aircraft was manufactured in the 1990’s, with a debut flight in 1996, rendering this a novel platform.

The geometry of the Aeroprakt A-22 allows for instrumentation placement in the trunk space behind the seats, in the passenger seat, and in the foot area on the passenger side, with approximately 0.42m³ of total space available for placement of instrumentation. The cabin is heated, which is a benefit as this keeps the instrumentation

![Figure 4](image-url)
within operating temperatures even when the aircraft is at high altitudes where temperatures outside of the operating ranges for some of the instruments may be encountered, especially during the dry season. During the instrumented flights, all of the instruments in ASULA were operating at ambient pressure.

For instrumented flights, the ozone monitor and the NO monitor in tandem with a NO2 converter were situated behind the seats in the trunk compartment. The DustTrak, Optical Particle Sizer, aethalometer, along with a 12V battery and inverter, were situated in the passenger foot area. The HOBO datalogger and Carbon Monoxide monitor were positioned on the passenger seat in a custom-made cradle box to prevent bending or crimping of the sample tubes. All sample tubes were lead to the outside of the cabin through a 4” diameter port hole on the passenger side. The exhaust pipe on the A-22 is located below the cabin, proximal to the pilot side (Figure 3), therefore we hypothesize that during regular ascent and constant-altitude legs of flight the exhaust does not significantly affect the measurements. A particle filter head was attached to each of the gas analyte sample intake tubes. It is likely that the aerosol measurements are underestimating the actual atmospheric aerosol concentrations, yielding aerosol concentrations at lower limits, with loss due to inlet orientation.

The ceiling altitude for the A-22 is higher than the aircraft used by Tripathi et al., [2005, 2007a] for instrumented flights over the city of Kanpur, and the UAVs deployed by Corrigan et al., [2008; Ramanathan et al., 2007a] over the Indian Ocean. To date, ASULA instrumented flights have been conducted up to an altitude of 4500m amsl. Figure 4 shows the instrumented aircraft in flight, as captured by the wing-tip digital camera, as well as the haze seen over the Himalayan foothills and proximal to the Himalayan Mountains.

**Instrumented Flights**

A total of four flights were conducted during the dry season and 32 during the pre-monsoon season, spanning morning and daytime periods for both seasons. The complete ASULA instrument package was deployed on eight 1-hr flights, with partial ASULA suite utilized on the remainder of the flights. The flight duration ranged from 15-60 minutes, and the maximum altitude reached on each flight dependent of flight duration (1300-4500m amsl). Five different flight paths were conducted, obtaining measurements within the planetary boundary layer (PBL), lower free troposphere (FT), within and above the Seti River Valley, and proximal to the southern slopes of the Annapurna Himalaya. The flight paths are shown in Figure 5. A total of 21 flights were conducted along flight path A, one along flight path B (dry), three along flight path C, one along flight path D (pre-monsoon), and six along flight path E (pre-monsoon only).

![Figure 5](image)

**Figure 5.** (a) The most common 15-min flight path A. (b) Flight path B for the 60-min afternoon flight on January 8, 2011. (c) Flight path C for the 60-min instrumented flight conducted on January 9, 2011, and during the pre-monsoon season. (d) Flight path D for the 90-min instrumented flight conducted in March 2011 (blue line), and flight path E (truncated D) for the 60-min instrumented flights conducted in March, May and June 2011 (dashed yellow line).

![Figure 6](image)

**Figure 6.** O3 vs BC during dry, mid and late pre-monsoon seasons.

![Figure 7](image)

**Figure 7.** The ratio between ozone and black carbon aerosol concentrations compared across the dry and pre-monsoon seasons.
Data Correction

The aethalometer (AE51, Magee Scientific, USA) was operated at a mass flow rate of 96 mLpm and a 60-sec time base. The pump speed depends on ambient pressure, necessitating a correction to the BC concentrations to accommodate the pressure and pump rate changes in flight as follows:

\[
BC_{\text{cor}} = BC_{\text{meas}} \frac{P_2 \cdot T_1}{P_1 \cdot T_2}
\]

where \(BC_{\text{cor}}\) is the corrected BC concentration \((\text{ng/m}^3)\), \(BC_{\text{meas}}\) is the measured BC concentration, \(P_1\) and \(P_2\) are the standard atmospheric pressure \((1017\text{mb})\) and pressure at the altitude of the measurement, while \(T_1\) and \(T_2\) are standard temperature \((293\text{K})\) and temperature at the altitude of the measurement, respectively. Further discussion of the correction [Moorthy et al., 2004] and operation of the aethalometer on an aircraft platform [Tripathi et al., 2005, 2007a] are reported elsewhere.

No correction factor is needed for the trace gas concentrations, however, it was noted that the instruments were not always able to aptly adjust to pressure changes during rapid descent \((39.8\pm0.5\text{ m/s horizontal, }>4\text{m/s vertical})\), which occurred faster than the ascent \((31.1\pm0.3\text{ m/s, }<2\text{ m/s})\) or the slower descents, therefore, only the measurements collected during the ascents and slow descents were used for analysis.

Results

Preliminary results show that the ratios of pollutants observed in the lower troposphere over

![Figure 8. Concentrations of (a) black carbon aerosol, (b) ozone, and (c) carbon monoxide measured over the complex terrain of the Himalayan foothills and the Seti River Valley between Pokhara and Annapurna Himalaya. Note that a BC-rich layer was observed above the upper Seti River Valley, with coincident CO enrichment. Higher ozone concentrations were observed at higher elevations, where there is greater potential for photochemical production of ozone and less potential for scavenging reactions.](image-url)
the foothills varied with the time of year (Figure 6), indicating an array of sources and transport ranges contributing to the composition of the haze. During the mid-pre-monsoon season dissimilar ratios of CO to O$_3$ were observed over remote foothills compared to the Seti River valley that extends between the city of Pokhara and the Annapurna Himalaya (Figure 7), indicating variation in contribution of local pollution sources and up-valley transport of local pollutants within the Seti River valley toward the Annapurna Himalaya. Distribution of BC, O$_3$, and CO was not horizontally homogeneous over complex terrain (Figure 8). Relatively higher concentrations of pollutants above the ridgetops (median ozone 42ppbv) relative to comparable altitudes away from the ridges (median ozone 37ppbv) suggest PBL-top venting driven by up-slope and up-valley transport of pollutants from the city of Pokhara.

Haze layers that contained relatively higher concentrations of CO (>1000ppbv), O$_3$ (>50ppbv) and BC aerosol (>1μg/m$^3$) were observed over the Himalayan foothills at elevations up to 2700m and 4000m amsl during the dry season and pre-monsoon seasons, respectively. What is equally important, however, is the horizontal distribution of these quantities above the complex terrain of the foothills, as can be seen in Figure 8. The thermally driven up-valley transport of pollutants from Pokhara toward the Annapurna Himalaya may be responsible for the BC- and CO-rich layer encountered above the upper Seti River Valley near the southern slopes of the Himalayan Mountains. Vertical profiles of temperature and BC concentration obtained during 24 flights are shown in Figure 9. Higher concentrations of BC and significantly greater variation in BC concentrations were observed at higher altitudes during the pre-monsoon season compared to the dry season.

Significantly lower concentrations of carbon monoxide were observed during the mid-pre-monsoon season compared to the late pre-monsoon season, as shown in Figure 10, whereas the BC concentrations were on average lower later in the pre-monsoon season.

Ozone concentrations were relatively constant with height during the dry season (38.5±4.7ppbv), and were highest during the mid-pre-monsoon season (54.7±6.4ppbv) with slightly lower concentrations observed above 3000m amsl. During the late pre-monsoon season, the ozone concentrations were generally lower (47.1±8.9ppbv), with higher concentrations aloft. Slightly higher nitric oxide concentrations were observed later in the pre-monsoon season (7.7±5.6) compared to the mid-pre-monsoon season (12.2±9.5ppbv), with a larger distribution of concentrations in the afternoons than in the morning. This difference became more pronounced later in the season. Lower NO concentration were observed near-ground during the nighttime (1.8±1.3ppbv) and relatively higher concentrations of NO were observed near ground and in elevated layers during the daytime (median 15.1±10.3ppbv) in the pre-monsoon season.

**Discussion**

The pre-monsoon season in the Himalayan foothills is characterized by general air flow from the SW, S and SE [Dey et al., 2006]. The location of the Indo-Gangetic Plain – a known hotspot of sources of ABCs [Ramanathan and Carmichael, 2008] – directly south of Nepal renders the pre-monsoon season in the Himalayan foothills with greatest potential for the presence of long-range advected ABC haze. For this reason, most field observations of the current research effort were conducted during the pre-monsoon season.
Slash and burn agricultural practices are common in South Asia, and generally occur after the winter harvest. Within the pre-monsoon season, the majority of fires in the region occur during the months of March and April (Figure 11), therefore, the greatest contribution from biomass burning (higher BC and CO concentrations) was anticipated during the middle of the pre-monsoon season. In contrast, greater relative contribution from industrial sources and fossil fuel combustion was anticipated later in the pre-monsoon season (higher BC, CO, NO, O₃ concentrations). Our findings show that indeed, higher NO and CO concentrations were present near ground and in the elevated layers above the foothills during the late pre-monsoon season, as compared to the mid-pre-monsoon season.

Based on the true color images from the MODIS instrument onboard the Terra and the Aqua polar-orbiting satellites (10:30am and 1:30pm equator crossing time on the ascending node, respectively; horizontal resolution 250m), presence of haze was assessed for the region for the flight dates (Table 1). The importance of aerial measurements is evident during both seasons, as the aerosol optical thickness (AOT) measurements obtained with the ground-based AERONET Cimel Sunphotometer at the Pokhara site and satellite-based MODIS images indicated relatively clear conditions (AOT₅₀₀<0.38) [Bomidi, 2007] for some flight dates, whereas high concentrations of aerosol and trace gas pollutants were encountered in elevated layers above the Himalayan foothills. An example of this is shown in black in Figure 6 for the afternoon of January 8, 2011. The MODIS and ground-based observations, AERONET AOT measurements, and notable elevated layers with relatively high concentrations of pollutants are shown in Table 1.

The prevalence of morning haze and fog in the valleys among the Himalayan foothills has been observed (on-site, and with satellite products) during the dry and pre-monsoon season – a phenomenon that greatly affects the local air quality, visibility, and is specific to complex terrain. Local pollution is potentially trapped below the inversion within the valley, maintaining pollutants, such as CO, BC, and NO within the stable boundary layer. Although nighttime NO concentrations were relatively low, it potentially facilitated the titration of ozone, resulting in relatively low nocturnal near-ground ozone concentrations (13±10ppbv). The diurnal variability in near-ground ozone concentrations exhibited a maximum of 45-50ppbv around 3pm, and a night-time minimum. Due to increased convection during the pre-monsoon season, it is speculated that there is greater contribution of local pollution to the air quality within the lower troposphere, than during the dry season, however, further monitoring is necessary to determine the magnitude and seasonality of local contribution.

Certain instrumentation in the ASULA package is still in need of validation during flight, including the aethalometer and trace gas monitors. Validation of aerial ozone measurements may be possible during the planned release of ozonesondes at the Pokhara site in August of 2011.
In future years, the ASULA platform may be used to test the Elevated Heat Pump hypothesis proposed by W.K. Lau [Lau et al., 2006], which suggests that increased melting rates in Himalayan glaciers and snowpacks may be due to the increased heating rates in elevated layers of the atmosphere, as may be caused by the absorbing species in the ABCs adjacent to the high Himalaya during the pre-monsoon season.

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References

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### Appendix 1

<table>
<thead>
<tr>
<th>Instrument (model)</th>
<th>Variable(s) measured</th>
<th>Accuracy</th>
<th>Range</th>
<th>Time base</th>
<th>Instrument weight</th>
<th>Power requirements</th>
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<tr>
<td>2BTech (205)</td>
<td>Ozone</td>
<td>0.1 ppb</td>
<td>1.0 ppb–100 ppm</td>
<td>10 sec</td>
<td>2.1 kg</td>
<td>12 VDC</td>
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<td>2BTech (410, 401)</td>
<td>NO, NO₂</td>
<td>1.5 ppb</td>
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