Himalaya air quality impacts from the COVID-19 lockdown across the Indo-Gangetic Plain

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November 26, 2022

Abstract

Starting in January 2020, the novel coronavirus, now known as acute respiratory syndrome coronavirus (SARS-CoV-2) and the disease that it causes (COVID-19) has had significant impacts on human health, the environment and the economy globally. The rapid lockdown that occurred as well as its well documented timing in various locations allows for an unprecedented opportunity to examine the impact of air pollution from densely populated regions has on adjacent and pristine environments. Here we use in-situ and satellite observations to show that there was a step function decrease in two key indicators of air quality, nitrogen dioxide and airborne particulates, in locations within the Indo-Gangetic Plain (IGP) as a result of the Spring 2020 lockdown. Based on anomaly patterns, we find a dipole response with a statistically significant reduction in air pollution along the western IGP and Himalaya and an increase in air pollution in the eastern IGP and Himalaya. We show that spatial variability in the reductions in economic activity across northern India and the adjoining countries of Nepal, Pakistan and Bangladesh contributed to this dipole as did a persistent atmospheric circulation anomaly across the region during the lockdown.
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Key Points:

- The COVID-19 lockdown provides an opportunity to assess the impact of air pollution from the Indo-Gangetic Plain on the Himalaya.
- Air pollution levels in cities in the western Indo-Gangetic Plain experienced marked drops that coincided with the lockdown.
- Across the Indo-Gangetic Plain and Himalaya, there were reductions in air pollution in the west and increases in the east.
Abstract

Starting in January 2020, the novel coronavirus, now known as acute respiratory syndrome coronavirus (SARS-CoV-2) and the disease that it causes (COVID-19) has had significant impacts on human health, the environment and the economy globally. The rapid lockdown that occurred as well as its well documented timing in various locations allows for an unprecedented opportunity to examine the impact of air pollution from densely populated regions has on adjacent and pristine environments. Here we use in-situ and satellite observations to show that there was a step function decrease in two key indicators of air quality, nitrogen dioxide and airborne particulates, in locations within the Indo-Gangetic Plan (IGP) as a result of the Spring 2020 lockdown. Based on anomaly patterns, we find a dipole response with a statistically significant reduction in air pollution along the western IGP and Himalaya and an increase in air pollution in the eastern IGP and Himalaya. We show that spatial variability in the reductions in economic activity across northern India and the adjoining countries of Nepal, Pakistan and Bangladesh contributed to this dipole as did a persistent atmospheric circulation anomaly across the region during the lockdown.

1 Introduction

The densely populated IGP that includes much of northern India, eastern Pakistan and Bangladesh, is one of the most polluted regions of the world (Lau & Kim, 2010). For example, based on fine particle pollution data from 29 U.S. diplomatic posts across the world, New Delhi ranks as the most polluted city with median air quality rated as being unhealthy with the frequent occurrence of hazardous conditions (Dhammapala, 2019). Common sources of air pollution in the region include transportation, construction, industrial activity, electricity generation and biomass burning (Ghuide et al., 2011; Dhammapala, 2019). There is evidence that this pollution has the potential for increasingly dramatic impacts, as the IGP continues to industrialize, on the population, environment and climate in the relatively pristine Himalaya that form the northern
boundary of the IGP (Dentener et al., 2006; Moore & Semple, 2009; Ghude et al., 2011; Bonasoni et al., 2012). Please refer to Figure 1 for place names in the region of interest.

One common characteristic that spans most research topics in the geosciences is the inability to undertake large-scale controlled experiments that help identify processes and pathways. The existence of events characterized by step changes in external forcing often allow unique opportunities that mimic the sort of experiments that are common in laboratory-based scientific disciplines. Examples include: volcanic eruptions that result in large inputs of aerosols into the stratosphere that subsequently impact the earth’s radiative balance leading to a widespread cooling (Brasseur & Granier, 1992); total solar eclipses that result in a transient reduction in incoming solar radiation that can impact meteorological processes throughout the atmospheric column (Aplin et al., 2016). There is also evidence that the cessation of air travel across the United States after September 11 2001 resulted in a reduction in contrails that impacted surface temperatures (Travis et al., 2004). However, the relatively short period, 4 days, of the cessation limited the ability to definitively attribute the presence of a signal (Hong et al., 2008).

In a similar vein, the COVID-19 related lockdown (Chamas, 2020; Ellis-Petersen et al., 2020) that occurred across the IGP in March 2020 offers a unique opportunity to assess the impact of pollution sources across this region on the Himalaya. We will focus attention on Nitrogen Dioxide (NO₂) an important component of air pollution (WHO, 2006) in and of itself as well as being a precursor species to ozone, a pollutant and oxidant that has been shown to impact lung function (Lippmann, 1989). We will also consider airborne particulate matter with diameters smaller than 2.5μm (pm2.5) that have also been shown to impact human health (WHO, 2006).

Based on anomaly patterns, we find a dipole response during the Spring 2020 lockdown with a statistically significant reduction in air pollution along the western IGP and Himalaya as
well as an increase in air pollution in the eastern IGP and Himalaya. We show that spatial variability in the reductions in economic activity across northern India and the adjoining countries of Nepal, Pakistan and Bangladesh contributed to this dipole as did a persistent atmospheric circulation anomaly across the region during the lockdown.

2 Data and Methods

Data on surface concentrations of NO$_2$ for the period 2017-2020 were accessed from OpenAQ Platform. Data on surface concentrations of NO$_2$ in Delhi for the period 2005-2016 were accessed from the archives of the Central Pollution Control Board. There are multiple reporting sites within Delhi and these were averaged to obtain the time series for this city. There are individual reporting sites with the other three locations discussed in the paper: Ludhiana, Singrauli and Asansol.

Data on surface pm2.5 concentrations were obtained from United States Embassies or Consulates in Delhi India, Lahore Pakistan, Dhaka Bangladesh and Kathmandu Nepal as archived by the Environmental Protection Agency.

To characterize the impact of the lockdown on the spatial and temporal variability in air quality across the IGP and the Himalaya, we use daily tropospheric NO$_2$ column retrievals from the OMI instrument (Boersma et al., 2011) on NASA’s Aura satellite as well as higher spatial resolution data from the TROPOMI instrument (Veefkind et al., 2012) on ESA’s Sentinel 5P satellite.

Daily tropospheric NO$_2$ column retrievals from the OMI instrument on NASA’s Aura satellite, available from 2005-2020 at a spatial resolution of $\frac{1}{4}$° or $\sim$25km(Boersma et al., 2011), as well as the TROPOMI instrument on ESA’s Sentinel 5P satellite, available from 2018-2020 at a spatial resolution of $\sim$4km (Veefkind et al., 2012) were used to characterize the spatial...
distribution of pollutants. For each dataset, the cloud cleared retrievals were used. The longer length of data availability for the OMI instrument allows for the development of a climatology. This is not possible for the TROPOMI.

Information on the spatial distribution of particulate matter is also available from the OMI instrument through the so-called Aerosol Index (AI) that uses differential absorption of upwelling ultra-violet radiation to indicate the presence of aerosols associated with dust, smoke and volcanic ash (Torres et al., 2007). It is available at a spatial resolution of 1° daily from 2005-2020 (Torres et al., 2007).

Mass-weighted wind data from the European Centre for Medium-Range Weather Forecasts’ ERA5 Reanalysis (Hersbach et al., 2020) were used to characterize the atmospheric circulation during April 2020. The data is available at a spatial resolution of ~30km for the period 1979-2020.

3 Results

Figure 2 shows time series of the daily mean surface concentration of NO$_2$ at selected sites across the IGP. Please refer to Figure 1 for the locations of these sites. The data in this figure shows a step function reduction in surface NO$_2$ concentration occurred in both Delhi (Fig 2a) and Ludhiana, (Fig 2b), large urban centers in the Indian sector of the IGP, around March 23 2020 that coincided with the lockdown in the region (Chamas, 2020; Ellis-Petersen et al., 2020). The reduction in surface NO$_2$ concentrations persisted through the end of April in these cities. Climatological surface NO$_2$ data is available for Delhi back to 2005 and shows a seasonal decline in values during the transition from winter through the spring (Mohan & Kandya, 2007) that can also be seen in Figure 2a. A 31-day moving window smoother was applied to the climatological time series to reduce high frequency signals that are the result of their short length so as to allow
a clearer picture of the seasonal cycle and its variability. This inter-annual variability in surface NO$_2$ concentration confirm that values recorded in Delhi during the lockdown were two standard deviations below the mean indicating highly anomalous conditions. Indeed, the monthly mean surface NO$_2$ concentrations observed in Delhi during April 2020 were the lowest observed in the 16-year climatology.

However, the marked reduction in surface NO$_2$ concentrations observed in Delhi and Ludhiana were not uniform across the IGP. Singrauli, a city with a number of large coal-fired power plants in its vicinity (Singh et al., 2018), recorded no reduction in surface NO$_2$ concentrations suggesting that the emissions from these plants were not reduced during the lockdown (Fig 2c). Asansol, a major industrial city with significant coal mining and steel production activities (Reddy & Ruj, 2003), in West Bengal showed a reduction in surface NO$_2$ values suggesting a more modest lockdown than what occurred in Delhi and Ludhiana.

Time series of pm2.5 concentrations from U.S. embassies and consulates throughout the IGP (Figure 3) indicates the presence of step function reductions in both Delhi as well as Lahore Pakistan, confirming that a lockdown also occurred in the Pakistani region of the IGP. Dhaka also showed a reduction however no indication of a step function change. This is most likely a reflection of the strong seasonality in air quality in the region with a winter peak associated with kiln production (Begum et al., 2011). There was also evidence of a step function response in Kathmandu although there was significant variability throughout April indicating either an incomplete shutdown of industrial activity or the long-range transport of pollution into the area (Bonasoni et al., 2012).

The climatological distribution of monthly mean tropospheric NO$_2$ column densities from OMI during April (Fig 4a) shows elevated levels across the IGP with lower levels over eastern
India, southwestern India and Tibet. There is a gradient in density across the Himalaya that
approximately follows the 3000m height contour suggesting that topography plays a role in the
distribution of air pollution across the region. A number of localized maxima associated with
urban centers, like Delhi, Lahore and Dhaka, or regions of industrial activity, such as Singrauli
and Asansol are evident. The distribution during April 2020 (Fig 4b) shows generally lower values
across much of the IGP with a marked absence of local maxima in the vicinity of Delhi and Lahore.

More information on the spatial variability on tropospheric NO$_2$ column densities
associated with the lockdown is provided by the monthly mean anomaly during April 2020 (Fig
5a), i.e. the difference between the monthly mean during April 2020 and the April climatological
monthly mean for the period 2005-2020. The widespread reduction across the northwestern IGP
as well as adjoining foothills of the western Himalaya, i.e. to the west of Kathmandu, is evident.
The region around Singrauli stands out as one in which there was a marked increase in column
density during April 2020. Throughout much of the eastern IGP, including much of Bangladesh,
eastern India, eastern Nepal and Bhutan, there was an increase in column density with the
exception of region around Dhaka.

There is of course variability from year to year in air quality that is a function of variability
in sources as well as meteorological conditions (Fishman et al., 2005; Pawar et al., 2017). One
way to assess the magnitude of the anomalous tropospheric NO$_2$ column densities during April
2020 is to compare it to the expected variability from year to year during April. This so-called
normalized anomaly is constructed by dividing the April 2020 anomaly by the standard deviation
of the tropospheric NO$_2$ column density during April and expressing it as a percentage (Fig 5b).
Normalized anomaly values on the order of +/- 200% indicate that such an anomaly has a
magnitude of 2 standard deviations and should, assuming normally distributed data, occur
approximately 2-3% of the time. Across much of the western IGP, including Delhi, Ludhiana and Lahore, as well as the western Himalaya, the normalized anomaly was on the order of 200% confirming the extreme reduction in air pollution in this region, a result in agreement with the surface observations of surface NO$_2$ concentration (Fig 2) and surface pm2.5 (Fig 3) across the western IGP. In contrast, the normalized anomaly across much of the eastern IGP and the eastern Himalaya was positive with values between 100% and 200% indicating that air pollution values in this region were anomalously high, although with significance levels lower than that in the west of the region of interest. This result is also in agreement with regional surface NO$_2$ concentrations during the lockdown (Fig 2) that show lower concentrations in Delhi and Ludhiana as well as higher concentrations in Singrauli and Asansol. We will refer to this feature, reduction in air pollution in the western IGP and Himalaya and an increase in the corresponding eastern regions, as an air pollution dipole anomaly.

Figures 4 & 5 indicate that there is evidence of spatial gradients in tropospheric NO$_2$ column densities along the Himalaya that may be under resolved by the OMI instrument. A comparison between TROPOMI monthly means for April 2019 and 2020 (Fig 6a&b) show clear evidence of a reduction in tropospheric NO$_2$ column densities across much of the IGP, including in the vicinity of Delhi, Lahore, Asansol and Dhaka, as well as pronounced spatial gradients along the Himalaya. The difference between the two Aprils (Fig 6c) highlights the aforementioned dipolar nature of the changes that occurred with reductions across much of the western IGP and the western Himalaya and increases in the eastern areas of these regions.

Observations of surface particulate matter (Fig 3) also indicated the presence of step function responses across the western IGP and Nepal that were associated with the lockdown. The climatological monthly mean AI for April (Fig 7a) indicates the presence of aerosols across
the western IGP with lower values over Tibet. This pattern is characteristic of so-called Atmospheric Brown Clouds, polluted tropospheric layers characterized by high values of anthropogenic aerosols (Ramanathan et al., 2007; Bonasoni et al., 2012). The monthly mean AI for April 2020 (Fig 7b) shows reduced AI values across the IGP, consistent with the in-situ observations of surface pm2.5 (Fig 3). The normalized anomaly for April 2020 (Fig 7c) indicates that the reduction in AI across the western IGP and the western Himalaya was between 1 and 1.5 standard deviations below the mean. Unlike the case for the tropospheric NO2 column density, these is no evidence of a coherent dipolar pattern with higher values of the AI in the eastern regions of the IGP and the Himalaya.

Atmospheric circulation patterns play a role in the long-range transport of pollutants into relatively pristine regions such as the Himalaya (Bonasoni et al., 2012). As such is it important to characterize the degree to which the atmospheric conditions contributed to the spatial distribution of the air pollution anomalies associated with the COVID-19 lockdown across the IGP. Figure 8 shows the April 2020 monthly mean anomaly in mass weighted velocity field, representative of circulation in the lower troposphere, over the region of interest as represented in the ERA5 reanalysis (Hersbach et al., 2020). It indicates the presence of a cyclonic (i.e. counter-clockwise) circulation anomaly over the region. A cyclonic circulation anomaly would have acted to mitigate the transport of pollutants from the IGP towards the western Himalaya and enhance this transport towards the eastern Himalaya. As such, it would have acted to support the existence of the dipolar pattern in the distribution of pollutants along the IGP and Himalaya during April 2020.

4 Conclusions

High mountainous regions of the world, traditionally, have been considered some of the most pristine environments and the least likely setting for hazards related to air pollution. However
unique communities in high-altitude regions, such as those in the Himalaya, are unexpectedly exposed to pollution levels that are similar to, if not higher than, those reported in industrialized cities and other polluted environments (Saikawa et al., 2019). However little is known about the sources for this pollution and its pathways (Bonasoni et al., 2012). In addition, hypoxia and other unique characteristics of this high altitude ecosystem have compounding consequences for those who reside in and work in this region (Pandey, 1984; Korrick et al., 1998; Semple et al., 2016).

The COVID-19 lockdown within the heavily polluted IGP provides a unique opportunity to assess the impact of pollution from this region on the Himalaya. The lockdown produced a dipolar signature in pollution levels across the IGP with reductions in the west, that were 2 standard deviations below the climatological mean during April 2020 and a more modest increase in the east. This was most likely the result of differences in the local response to the lockdown with large cities such as Delhi and Lahore experiencing a reduction in activities such as transportation and construction that are sources of urban air pollution (Mohan & Kandya, 2007; Dhammapala, 2019); while industrial emitters such as those associated with steel production and power generation in the east continued (Reddy & Ruj, 2003; Singh et al., 2018). A similar pattern was seen along the Himalaya with decreases in the west and increases in the east.

This pattern is also consistent with anecdotal observations indicating that, for the first time in recent history, the visibility of Himalayan peaks from India’s National Capital region (Chamas, 2020; Ellis-Petersen et al., 2020). A persistent atmospheric anomaly characterized by cyclonic (counter-clockwise) air flow throughout the lower troposphere during April 2020 contributed to the dipolar pattern seen in both the IGP and Himalaya. These results confirm the importance of characterizing the spatial distribution of emissions across the IGP as well as the background atmospheric circulation when assessing the impact of pollution on the Himalaya. They also
provide an important test case that can be used to assess the ability of chemical transport models
to capture regional patterns in air quality in the presence of large-scale changes in emissions
(Moorthy et al., 2013; Sharma et al., 2017).

Acknowledgments

G.W.K.M. was supported by the Natural Sciences and Engineering Research Council of
Canada.

All satellite data was accessed through the NASA Goddard Earth Sciences (GES) Data and
Information Services Center (disc.gsfc.nasa.gov). Surface NO₂ data is available from the OpenAQ
Platform (openaq.org) and the Indian Open Government Data Platform (data.in.gov). Data on
pm2.5 concentrations is available through the U.S. Environmental Protection Agency
(airnow.gov/international/us-embassies-and-consulates). ERA5 data is available through the
Copernicus Climate Data Store (cds.climate.copernicus.eu).

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**Figure Captions**

**Figure 1**) Topography (m) and place names in the region of interest. The locations of New Delhi (‘+’), Ludhiana (‘#’), Singrauli (‘o’), Asansol (‘x’), Lahore (‘l’), Kathmandu (‘k’) and Dhaka (‘d’) are indicated. Political boundaries are shown by the thin black curves with the 3000m topographic height shown by the thick black curve.

**Figure 2**) Time series of surface NO2 concentration (µg/m3) across the region of interest for the period December 1 2019-May 1 2020. Results are shown for: a) Delhi; b) Ludhiana; c) Singrauli and d) Asansol. The blue dashed lines represent the means over Feb 15-March 15 and April 1-30. In a) the red curve is the climatological daily mean...
concentration based on available data 2005-2019 with the red dashed/dotted curves representing one/two standard deviation above and below the climatological mean. A 31 day moving window smoother has been applied to the climatological data.

Figure 3) Time series of surface pm2.5 (µg/m³) at selected sites in the region of interest for the period December 1 2019-April 24 2020. Results are shown for: a) Delhi; b) Lahore; c) Dhaka and d) Kathmandu. The blue dashed lines represent the mean over Feb 15-March 15 and April 1-30. In a) the red curve is the climatological daily mean concentration based on available data 2016-2019 with the red dashed curves representing one standard deviation above and below the climatological mean. A 31 day moving window smoother has been applied to the climatological data. Also shown with the dashed blue line is the WHO standard for acceptable daily mean concentration (25 mg/m³).

Figure 4) Column tropospheric NO2 density from the OMI (m mol/m2) across the region of interest. Results are shown for: a) April 1-30 climatology over 2005-2020 and b) April 1-30 2020. The locations of New Delhi (‘+’), Ludhiana (‘#’), Singrauli (‘o’), Asansol (‘x’), Lahore (‘l’), Kathmandu (‘k’) and Dhaka (‘d’) are indicated. Political boundaries are shown by the thin black curves with the 3000m topographic height shown by the thick black curve.

Figure 5) Anomalous column tropospheric NO2 density from the OMI across the region of interest during April 2020. Results are shown for the: a) anomaly (µ mol/m²) b) the normalized anomaly (%). The locations of New Delhi (‘+’), Ludhiana (‘#’), Singrauli (‘o’), Asansol (‘x’), Lahore (‘l’), Kathmandu (‘k’) and Dhaka (‘d’) are indicated.
Political boundaries are shown by the thin black curves with the 3000m topographic height shown by the thick black curve.

Figure 6) Column tropospheric NO2 density (µ mol/m²) from the TROPOMI across the region of interest. Results are shown for: a) April 1-30 2019; b) April 1-30 2020 and c) the difference between April 1-30 2020 and 2019. The locations of New Delhi (‘+’), Ludhiana (‘#’), Singrauli (‘o’), Asansol (‘x’), Lahore (‘l’), Kathmandu (‘k’) and Dhaka (‘d’) are indicated. Political boundaries are shown by the thin black curves with the 3000m topographic height shown by the thick black curve.

Figure 7) The Aerosol Index from OMI across the region of interest. Results are shown for: a) April 1-30 climatology over 2005-2020; b) April 1-30 2020 and c) the normalized anomaly (%) for April 1-30 2020. The locations of New Delhi (‘+’), Ludhiana (‘#’), Singrauli (‘o’), Asansol (‘x’), Lahore (‘l’), Kathmandu (‘k’) and Dhaka (‘d’) are indicated. Political boundaries are shown by the thin black curves with the 3000m topographic height shown by the thick black curve.

Figure 8) The tropospheric circulation across the region of interest during April 2020. The anomaly in the mass weighted wind (m/s) is shown. The locations of New Delhi (‘+’), Ludhiana (‘#’), Singrauli (‘o’), Asansol (‘x’), Lahore (‘l’), Kathmandu (‘k’) and Dhaka (‘d’) are indicated. Political boundaries are shown by the thin black curves with the 3000m topographic height shown by the thick black curve.
Figure 1) Topography (m) and place names in the region of interest. The locations of New Delhi (‘+’), Ludhiana (‘#’), Singrauli (‘o’), Asansol (‘x’), Lahore (‘l’), Kathmandu (‘k’) and Dhaka (‘d’) are indicated. Political boundaries are shown by the thin black curves with the 3000m topographic height shown by the thick black curve.
Figure 2) Time series of surface NO2 concentration (µg/m³) across the region of interest for the period December 1 2019-May 1 2020. Results are shown for: a) Delhi; b) Ludhiana; c) Singrauli and d) Asansol. The blue dashed lines represent the means over Feb 15-March 15 and April 1-30. In a) the red curve is the climatological daily mean concentration based on available data 2005-2019 with the red dashed/dotted curves representing one/two standard deviation above and below the climatological mean. A 31 day moving window smoother has been applied to the climatological data.
Figure 3) Time series of surface pm2.5 (µg/m³) at selected sites in the region of interest for the period December 1 2019-April 24 2020. Results are shown for: a) Delhi; b) Lahore; c) Dhaka and d) Kathmandu. The blue dashed lines represent the mean over Feb 15-March 15 and April 1-30. In a) the red curve is the climatological daily mean concentration based on available data 2016-2019 with the red dashed curves representing one standard deviation above and below the climatological mean. A 31 day moving window smoother has been applied to the climatological data. Also shown with the dashed blue line is the WHO standard for acceptable daily mean concentration (25 mg/m³).
Figure 4) Column tropospheric NO2 density from the OMI (μ mol/m²) across the region of interest. Results are shown for: a) April 1-30 climatology over 2005-2020 and b) April 1-30 2020. The locations of New Delhi (‘+’), Ludhiana (‘#’), Singrauli (‘o’), Asansol (‘x’), Lahore (‘l’), Kathmandu (‘k’) and Dhaka (‘d’) are indicated. Political boundaries are shown by the thin black curves with the 3000m topographic height shown by the thick black curve.
Figure 5) Anomalous column tropospheric NO2 density from the OMI across the region of interest during April 2020. Results are shown for the: a) anomaly (μmol/m²) b) the normalized anomaly (%). The locations of New Delhi (+), Ludhiana (#), Singrauli (o), Asansol (x), Lahore (l), Kathmandu (k) and Dhaka (d) are indicated. Political boundaries are shown by the thin black curves with the 3000m topographic height shown by the thick black curve.
Figure 6) TROPOMI column tropospheric NO$_2$ density ($\mu$ mol/m$^2$) for: a) April 1-30 2019; b) April 1-30 2020 and c) the difference between April 1-30 2020 and 2019. The locations of New Delhi (+), Ludhiana (#), Singrauli (o), Asansol (x), Lahore (l), Kathmandu (k) and Dhaka (d) are indicated. Political boundaries are shown by the thin black curves with the 3000m topographic height shown by the thick black curve.
Figure 7) Column tropospheric NO2 density (\( \mu \text{ mol/m}^2 \)) from the TROPOMI across the region of interest. Results are shown for: a) April 1-30 2019; b) April 1-30 2020 and c) the difference between April 1-30 2020 and 2019. The locations of New Delhi (‘+’), Ludhiana (‘#’), Singrauli (‘o’), Asansol (‘x’), Lahore (‘l’), Kathmandu (‘k’) and Dhaka (‘d’) are indicated. Political boundaries are shown by the thin black curves with the 3000m topographic height shown by the thick black curve.
Figure 8) The tropospheric circulation across the region of interest during April 2020. The anomaly in the mass weighted wind (m/s) is shown. The locations of New Delhi (`+`), Ludhiana (`#`), Singrauli (`o`), Asansol (`x`), Lahore (`l`), Kathmandu (`k`) and Dhaka (`d`) are indicated. Political boundaries are shown by the thin black curves with the 3000m topographic height shown by the thick black curve.