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

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Key Points:

- The COVID-19 lockdown provides an opportunity to the assess the impact of air pollution from the Indo-Gangetic Plain on the Himalaya.

- Air pollutions 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 (Ghude 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

43   boundary of the IGP (Dentener et al., 2006; Moore & Semple, 2009; Ghude et al., 2011; Bonasoni

44   et al., 2012). Please refer to Figure 1 for place names in the region of interest.

45   One common characteristic that spans most research topics in the geosciences is the

46   inability to undertake large-scale controlled experiments that help identify processes and

47   pathways. The existence of events characterized by step changes in external forcing often allow

48   unique opportunities that mimic the sort of experiments that are common in laboratory-based

49   scientific disciplines. Examples include: volcanic eruptions that result in large inputs of aerosols

50   into the stratosphere that subsequently impact the earth's radiative balance leading to a widespread

51   cooling (Brasseur & Granier, 1992); total solar eclipses that result in a transient reduction in

52   incoming solar radiation that can impact meteorological processes throughout the atmospheric

53   column (Aplin et al., 2016). There is also evidence that the cessation of air travel across the United

54   States after September 11 2001 resulted in a reduction in contrails that impacted surface

55   temperatures (Travis et al., 2004). However, the relatively short period, 4 days, of the cessation

56   limited the ability to definitively attribute the presence of a signal (Hong et al., 2008).

57   In a similar vein, the COVID-19 related lockdown (Chamas, 2020; Ellis-Petersen et al.,

58   2020) that occurred across the IGP in March 2020 offers a unique opportunity to assess the impact

59   of pollution sources across this region on the Himalaya.   We will focus attention on Nitrogen

60   Dioxide (NO_2) an important component of air pollution (WHO, 2006) in and of itself as well as

61   being a precursor species to ozone, a pollutant and oxidant that has been shown to impact lung

62   function (Lippmann, 1989). We will also consider airborne particulate matter with diameters

63   smaller than 2.5μm (pm2.5) that have also been shown to impact human health (WHO, 2006).

64   Based on anomaly patterns, we find a dipole response during the Spring 2020 lockdown

65   with a statistically significant reduction in air pollution along the western IGP and Himalaya as

66 well as an increase in air pollution in the eastern IGP and Himalaya. We show that spatial

67 variability in the reductions in economic activity across northern India and the adjoining countries

68 of Nepal, Pakistan and Bangladesh contributed to this dipole as did a persistent atmospheric

69 circulation anomaly across the region during the lockdown.

70 **2 Data and Methods**

71   Data on surface concentrations of NO_2 for the period 2017-2020 were accessed from

72 OpenAQ Platform. Data on surface concentrations of NO_2 in Delhi for the period 2005-2016 were

73 accessed from the archives of the Central Pollution Control Board. There are multiple reporting

74 sites within Delhi and these were averaged to obtain the time series for this city. There are

75 individual reporting sites with the other three locations discussed in the paper: Ludhiana, Singrauli

76 and Asansol.

77   Data on surface pm2.5 concentrations were obtained from United States Embassies or

78 Consulates in Delhi India, Lahore Pakistan, Dhaka Bangladesh and Kathmandu Nepal as archived

79 by the Environmental Protection Agency.

80   To characterize the impact of the lockdown on the spatial and temporal variability in air

81 quality across the IGP and the Himalaya, we use daily tropospheric NO_2 column retrievals from

82 the OMI instrument (Boersma et al., 2011) on NASA's Aura satellite as well as higher spatial

83 resolution data from the TROPOMI instrument (Veefkind et al., 2012) on ESA's Sentinel 5P

84 satellite.

85   Daily tropospheric NO_2 column retrievals from the OMI instrument on NASA's Aura

86 satellite, available from 2005-2020 at a spatial resolution of ¼° or ~25km(Boersma et al., 2011),

87 as well as the TROPOMI instrument on ESA's Sentinel 5P satellite, available from 2018-2020 at

88 a spatial resolution of ~4km (Veefkind et al., 2012) were used to characterize the spatial

89   distribution of pollutants.   For each dataset, the cloud cleared retrievals were used. The longer

90   length of data availability for the OMI instrument allows for the development of a climatology.

91   This is not possible for the TROPOMI.

92   Information on the spatial distribution of particulate matter is also available from the OMI

93   instrument through the so-called Aerosol Index (AI) that uses differential absorption of upwelling

94   ultra-violet radiation to indicate the presence of aerosols associated with dust, smoke and volcanic

95   ash (Torres et al., 2007). It is available at a spatial resolution of 1° daily from 2005-2020 (Torres

96   et al., 2007).

97   Mass-weighted wind data from the European Centre for Medium-Range Weather

98   Forecasts' ERA5 Reanalysis (Hersbach et al., 2020) were used to characterize the atmospheric

99   circulation during April 2020. The data is available at a spatial resolution of ~30km for the period

100   1979-2020.

101   **3 Results**

102   Figure 2 shows time series of the daily mean surface concentration of NO_2 at selected sites

103   across the IGP. Please refer to Figure 1 for the locaitons of these sites. The data in this figure

104   shows a step function reduction in surface NO_2 concentration occurred in both Delhi (Fig 2a) and

105   Ludhiana, (Fig 2b), large urban centers in the Indian sector of the IGP, around March 23 2020

106   that coincided with the lockdown in the region (Chamas, 2020; Ellis-Petersen et al., 2020). The

107   reduction in surface NO_2 concentrations persisted through the end of April in these cities.

108   Climatological surface NO_2 data is available for Delhi back to 2005 and shows a seasonal decline

109   in values during the transition from winter through the spring (Mohan & Kandya, 2007) that can

110   also be seen in Figure 2a.   A 31-day moving window smoother was applied to the climatogical

111   time series to reduce high frequency signals that are the result of their short length so as to allow

112   a clearer picture of the seasonal cycle and its variability. This inter-annual variability in surface

113   NO_2 concentration confirm that values recorded in Delhi during the lockdown were two standard

114   deviations below the mean indicating highly anomalous conditions. Indeed, the monthly mean

115   surface NO_2 concentrations observed in Delhi during April 2020 were the lowest observed in the

116   16-year climatology.

117   However, the marked reduction in surface NO_2 concentrations observed in Delhi and

118   Ludhiana were not uniform across the IGP. Singrauli, a city with a number of large coal-fired

119   power plants in its vicinity (Singh et al., 2018), recorded no reduction in surface NO_2

120   concentrations suggesting that the emissions from these plants were not reduced during the

121   lockdown (Fig 2c). Asansol, a major industrial city with significant coal mining and steel

122   production activities (Reddy & Ruj, 2003), in West Bengal showed a reduction in surface NO_2

123   values suggesting a more modest lockdown than what occurred in Delhi and Ludhiana.

124   Time series of pm2.5 concentrations from U.S. embassies and consulates throughout the

125   IGP (Figure 3) indicates the presence of step function reductions in both Delhi as well as Lahore

126   Pakistan, confirming that a lockdown also occurred in the Pakistani region of the IGP. Dhaka also

127   showed a reduction however no indication of a step function change. This is most likely a

128   reflection of the strong seasonality in air quality in the region with a winter peak associated with

129   kiln production (Begum et al., 2011). There was also evidence of a step function response in

130   Kathmandu although there was significant variability throughout April indicating either an

131   incomplete shutdown of industrial activity or the long-range transport of pollution into the area

132   (Bonasoni et al., 2012).

133   The climatological distribution of monthly mean tropospheric NO_2 column densities from

134   OMI during April (Fig 4a) shows elevated levels across the IGP with lower levels over eastern

135 India, southwestern India and Tibet. There is a gradient in density across the Himalaya that

136 approximately follows the 3000m height contour suggesting that topography plays a role in the

137 distribution of air pollution across the region.   A number of localized maxima associated with

138 urban centers, like Delhi, Lahore and Dhaka, or regions of industrial activity, such as Singrauli

139 and Asansol are evident. The distribution during April 2020 (Fig 4b) shows generally lower values

140 across much of the IGP with a marked absence of local maxima in the vicinity of Delhi and Lahore.

141   More information on the spatial variability on tropospheric NO_2 column densities

142 associated with the lockdown is provided by the monthly mean anomaly during April 2020 (Fig

143 5a), i.e. the difference between the monthly mean during April 2020 and the April climatological

144 monthly mean for the period 2005-2020. The widespread reduction across the northwestern IGP

145 as well as adjoining foothills of the western Himalaya, i.e. to the west of Kathmandu, is evident.

146 The region around Singrauli stands out as one in which there was a marked increase in column

147 density during April 2020. Throughout much of the eastern IGP, including much of Bangladesh,

148 eastern India, eastern Nepal and Bhutan, there was an increase in column density with the

149 exception of region around Dhaka.

150   There is of course variability from year to year in air quality that is a function of variability

151 in sources as well as meteorological conditions (Fishman et al., 2005; Pawar et al., 2017). One

152 way to assess the magnitude of the anomalous tropospheric NO_2 column densities during April

153 2020 is to compare it to the expected variability from year to year during April. This so-called

154 normalized anomaly is constructed by dividing the April 2020 anomaly by the standard deviation

155 of the tropospheric NO_2 column density during April and expressing it as a percentage (Fig 5b).

156 Normalized anomaly values on the order of +/- 200% indicate that such an anomaly has a

157 magnitude of 2 standard deviations and should, assuming normally distributed data, occur

158   approximately 2-3% of the time.   Across much of the western IGP, including Delhi, Ludihana and

159   Lahore, as well as the western Himalaya, the normalized anomaly was on the order of 200%

160   confirming the extreme reduction in air pollution in this region, a result in agreement with the

161   surface observations of surface NO_2 concentration (Fig 2) and surface pm2.5 (Fig 3) across the

162   western IGP. In contrast, the normalized anomaly across much of the eastern IGP and the eastern

163   Himalaya was positive with values between 100% and 200% indicating that air pollution values

164   in this region were anomalously high, although with significance levels lower than that in the west

165   of the region of interest. This result is also in agreement with regional surface NO_2 concentrations

166   during the lockdown (Fig 2) that show lower concentrations in Delhi and Ludhiana as well as

167   higher concentraitons in Singrauli and Asansol. We will refer to this feature, reduction in air

168   pollution in the western IGP and Himalaya and an increase in the corresponding eastern regions,

169   as an air pollutuion dipole anomaly.

170   Figures 4 & 5 indicate that there is evidence of spatial gradients in tropospheric NO_2

171   column densities along the Himalaya that may be under resolved by the OMI instrument. A

172   comparison between TROPOMI monthly means for April 2019 and 2020 (Fig 6a&b) show clear

173   evidence of a reduction in tropospheric NO_2 column densities across much of the IGP, including

174   in the vicinity of Delhi, Lahore, Asansol and Dhaka, as well as pronounced spatial gradients along

175   the Himalaya. The difference between the two Aprils (Fig 6c) highlights the aforementioned

176   dipolar nature of the changes that occurred with reductions across much of the western IGP and

177   the western Himalaya and increases in the eastern areas of these regions.

178   Observations of surface particulate matter (Fig 3) also indicated the presence of step

179   function responses across the western IGP and Nepal that were associated with the lockdown.

180   The climatological monthly mean AI for April (Fig 7a) indicates the presence of aerosols across

181   the western IGP with lower values over Tibet. This pattern is characteristic of so-called

182   Atmospheric Brown Clouds, polluted tropospheric layers characterized by high values of

183   anthropogenic aerosols (Ramanathan et al., 2007; Bonasoni et al., 2012). The monthly mean AI

184   for April 2020 (Fig 7b) shows reduced AI values across the IGP, consistent with the in-situ

185   observations of surface pm2.5 (Fig 3). The normalized anomaly for April 2020 (Fig 7c) indicates

186   that the reduction in AI across the western IGP and the western Himalaya was between 1 and 1.5

187   standard deviations below the mean. Unlike the case for the tropospheric NO2 column density,

188   these is no evidence of a coherent dipolar pattern with higher values of the AI in the eastern regions

189   of the IGP and the Himalaya.

190   Atmospheric circulation patterns play a role in the long-range transport of pollutants into

191   relatively pristine regions such as the Himalaya (Bonasoni et al., 2012). As such is it important to

192   characterize the degree to which the atmospheric conditions contributed to the spatial distribution

193   of the air pollution anomalies associated with the COVID-19 lockdown across the IGP. Figure 8

194   shows the   April 2020 monthly mean anomaly in mass weighted velocity field, representative of

195   circulation in the lower troposphere, over the region of interest as represented in the ERA5

196   reanalysis (Hersbach et al., 2020). It indicates the presence of a cyclonic (i.e. counter-clockwise)

197   circulation anomaly over the region. A cyclonic circulation anomaly would have acted to mitigate

198   the transport of pollutants from the IGP towards the western Himalaya and enhance this transport

199   towards the eastern Himalaya. As such, it would have acted to support the existence of the dipolar

200   pattern in the distribution of pollutants along the IGP and Himalaya during April 2020.

201   **4 Conclusions**

202   High mountainous regions of the world, traditionally, have been considered some of the

203   most pristine environments and the least likely setting for hazards related to air pollution. However

204 unique communities in high-altitude regions, such as those in the Himalaya, are unexpectedly

205 exposed to pollution levels that are similar to, if not higher than, those reported in industrialized

206 cities and other polluted environments (Saikawa et al., 2019). However little is known about the

207 sources for this pollution and its pathways (Bonasoni et al., 2012). In addition, hypoxia and other

208 unique characteristics of this high altitude ecosystem have compounding consequences for those

209 who reside in and work in this region (Pandey, 1984; Korrick et al., 1998; Semple et al., 2016).

210   The COVID-19 lockdown within the heavily polluted IGP provides a unique opportunity

211 to assess the impact of pollution from this region on the Himalaya. The lockdown produced a

212 dipolar signature in pollution levels across the IGP with reductions in the west, that were 2 standard

213 deviations below the climatological mean during April 2020 and a more modest increase in the

214 east. This was most likely the result of differences in the local response to the lockdown with large

215 cities such as Delhi and Lahore experiencing a reduction in activities such as transportation and

216 construction that are sources of urban air pollution (Mohan & Kandya, 2007; Dhammapala, 2019);

217 while industrial emitters such as those associated with steel production and power generation in

218 the east continued (Reddy & Ruj, 2003; Singh et al., 2018) A similar pattern was seen along the

219 Himalaya with decreases in the west and increases in the east.

220   This pattern is also consistent with anecdotal observations indicating that, for the first time

221 in recent history, the visibility of Himalayan peaks from India's National Capital region (Chamas,

222 2020; Ellis-Petersen et al., 2020). A persistent atmospheric anomaly characterized by cyclonic

223 (counter-clockwise) air flow throughout the lower troposphere during April 2020 contributed to

224 the dipolar pattern seen in both the IGP and Himalaya. These results confirm the importance of

225 characterizing the spatial distribution of emissions across the IGP as well as the background

226 atmospheric circulation when assessing the impact of pollution on the Himalaya.   They also

227 provide an important test case that can be used to assess the ability of chemical transport models

228 to capture regional patterns in air quality in the presence of large-scale changes in emissions

229 (Moorthy et al., 2013; Sharma et al., 2017).

230 **Acknowledgments**

239
240 **References**
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Figure Captions

Figure 1) Topography (m) and place names in the region of intereast. 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 NO_2 concentration ($\mu g/m^3$) 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

342   concentration based on available data 2005-2019 with the red dashed/dotted curves

343   representing one/two standard deviaiton above and below the climatological mean. A 31

344   day moving window smoother has been applied to the climatological data.

345 Figure 3) Time series of surface pm2.5 ($\mu g/m^3$) at selected sites in the region of interest for the

346   period December 1 2019-April 24 2020. Results are shown for: a) Delhi; b) Lahore; c)

347   Dhaka and d) Kathmandu .The blue dashed lines represent the mean over Feb 15-March

348   15 and April 1-30. In a) the red curve is the climatological daily mean concentration

349   based on available data 2016-2019 with the red dashed curves representing one standard

350   deviation above and below the climatological mean. A 31 day moving window smoother

351   has been applied to the climatological data. Also shown with the dashed blue line is the

352   WHO standard for acceptable daily mean concentration ($25 \ mg/m^3$).

353 Figure 4) Column tropospheric NO2 density from the OMI (m mol/m2) across the region of

354   interest. Results are shown for: a) April 1-30 climatology over 2005-2020 and b) April 1-

355   30 2020. The locations of New Delhi ('+'), Ludhiana ('#'), Singrauli ('o'), Asansol ('x'),

356   Lahore ('l'), Kathmandu ('k') and Dhaka ('d') are indicated. Political boundaries are

357   shown by the thin black curves with the 3000m topographic height shown by the thick

358   black curve.

359 Figure 5) Anomalous column tropospheric NO2 density from the OMI across the region of

360   interest during April 2020. Results are shown for the: a) anomaly ($\mu \ mol/m^2$) b) the

361   normalized anomaly (%). The locations of New Delhi ('+'), Ludhiana ('#'), Singrauli

362   ('o'), Asansol ('x'), Lahore ('l'), Kathmandu ('k') and Dhaka ('d') are indicated.

363   Political boundaries are shown by the thin black curves with the 3000m topographic

364   height shown by the thick black curve.

365 Figure 6) Column tropospheric NO2 density (μ mol/m^2) from the TROPOMI across the region

366   of interest. Results are shown for: a) April 1-30 2019; b) April 1-30 2020 and c) the

367   difference between April 1-30 2020 and 2019. The locations of New Delhi ('+'),

368   Ludhiana ('#'), Singrauli ('o'), Asansol ('x'), Lahore ('l'), Kathmandu ('k') and Dhaka

369   ('d') are indicated. Political boundaries are shown by the thin black curves with the

370   3000m topographic height shown by the thick black curve.

371 Figure 7)   The Aerosol Index from OMI across the region of interest. Results are shown for: a)

372   April 1-30 climatology over 2005-2020; b) April 1-30 2020 and c) the normalized anomaly

373   (%) for April 1-30 2020. The locations of New Delhi ('+'), Ludhiana ('#'), Singrauli ('o'),

374   Asansol ('x'), Lahore ('l'), Kathmandu ('k') and Dhaka ('d') are indicated. Political

375   boundaries are shown by the thin black curves with the 3000m topographic height shown

376   by the thick black curve.

377 Figure 8) The tropospheric circulation across the region of interest during April 2020. The

378   anomaly in the mass weighted wind (m/s) is shown.   The locations of New Delhi ('+'),

379   Ludhiana ('#'), Singrauli ('o'), Asansol ('x'), Lahore ('l'), Kathmandu ('k') and Dhaka ('d')

380   are indicated. Political boundaries are shown by the thin black curves with the 3000m

381   topographic height shown by the thick black curve.

382

Figure 1) Topography (m) and place names in the region of intereast. 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.
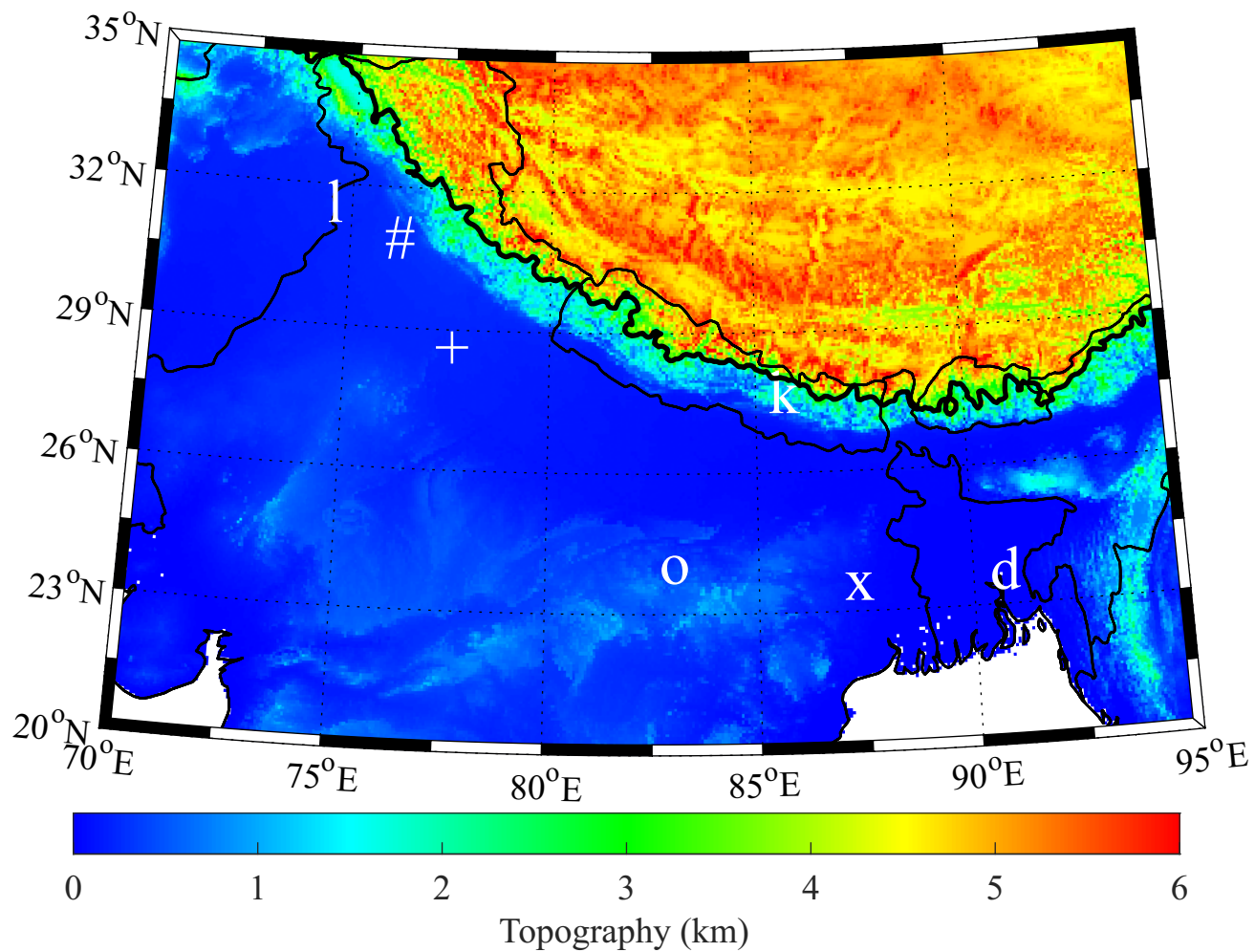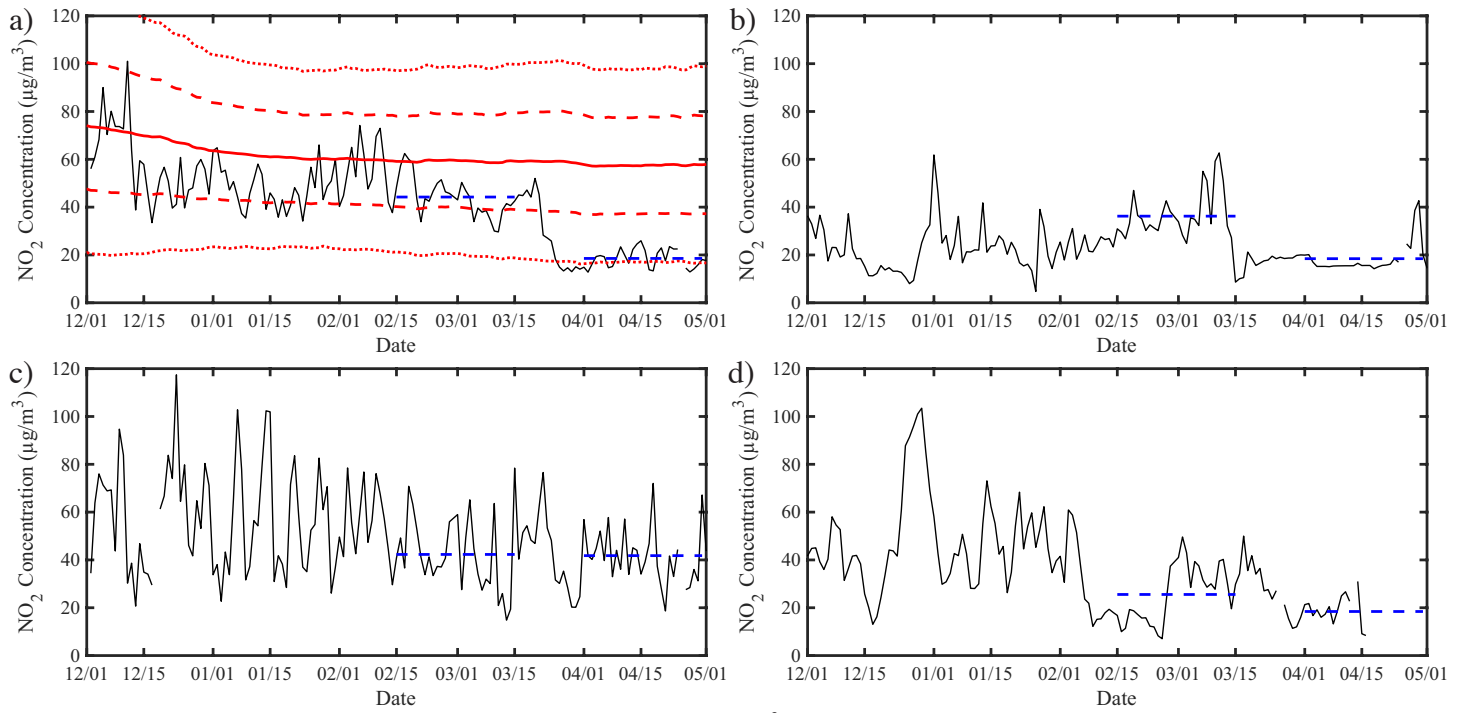
Figure 2) Time series of surface NO2 concentration (μg/m^3) across the region of interest for the period December 1 2019-May 1 2020. Results are shown for: a) Delhi; b) Ludhiana; c) Singrauli and d) Asansol . The blue dashed lines represent the means over Feb 15-March 15 and April 1-30. In a) the red curve is the climatological daily mean concentration based on available data 2005-2019 with the red dashed/dotted curves representing one/ two standard deviaiton 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/m^3) 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/m^3).

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.
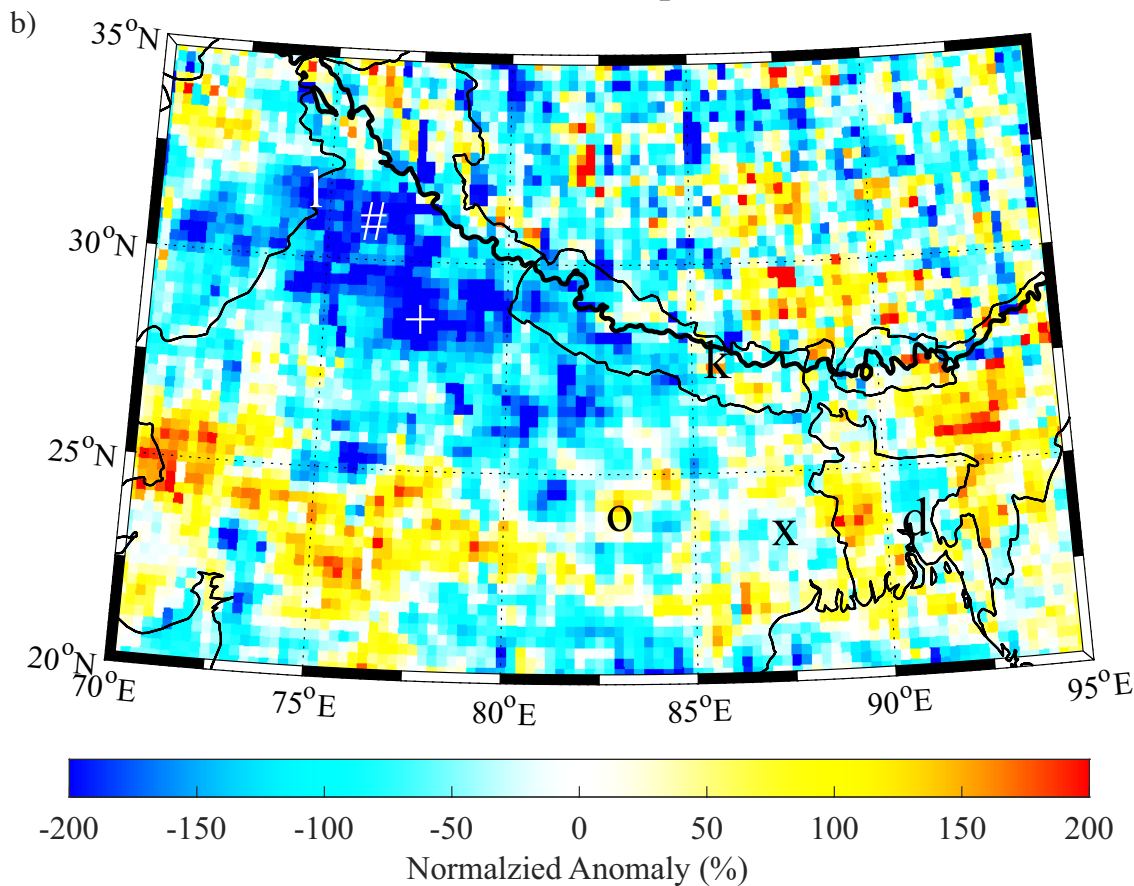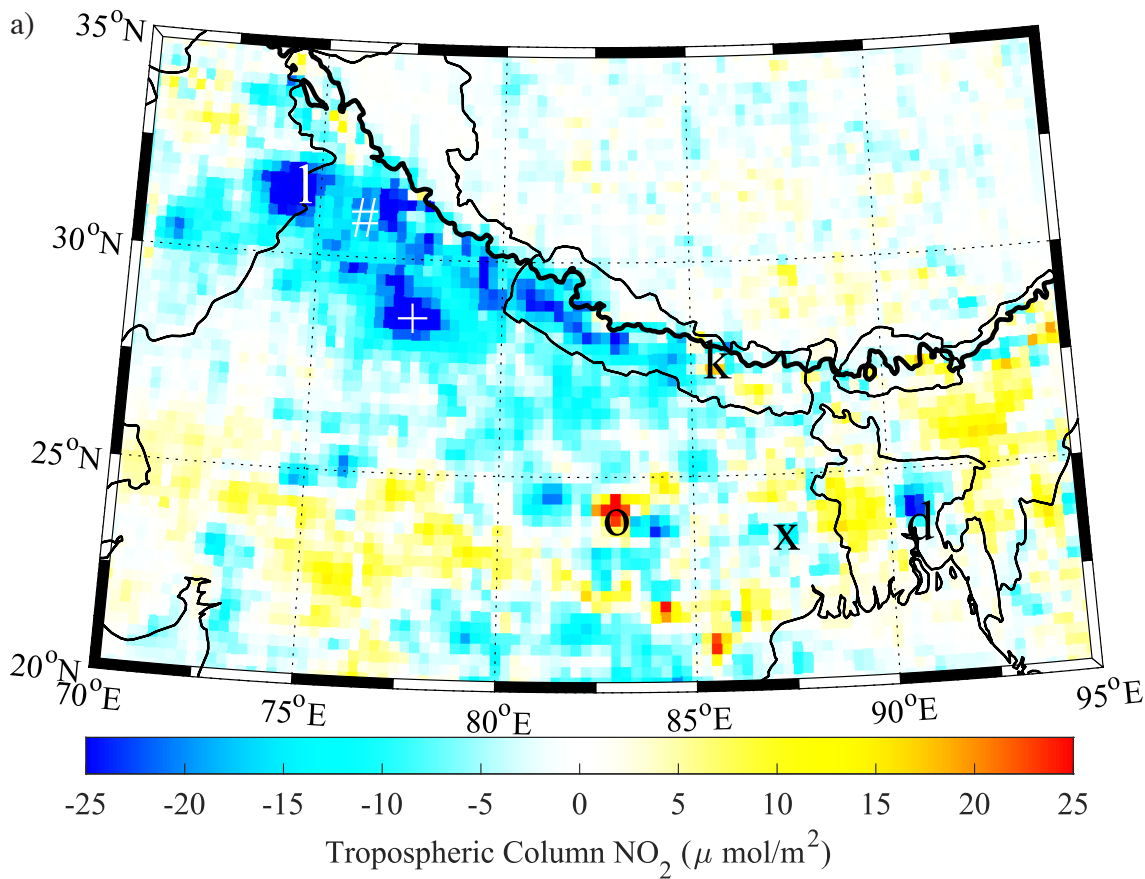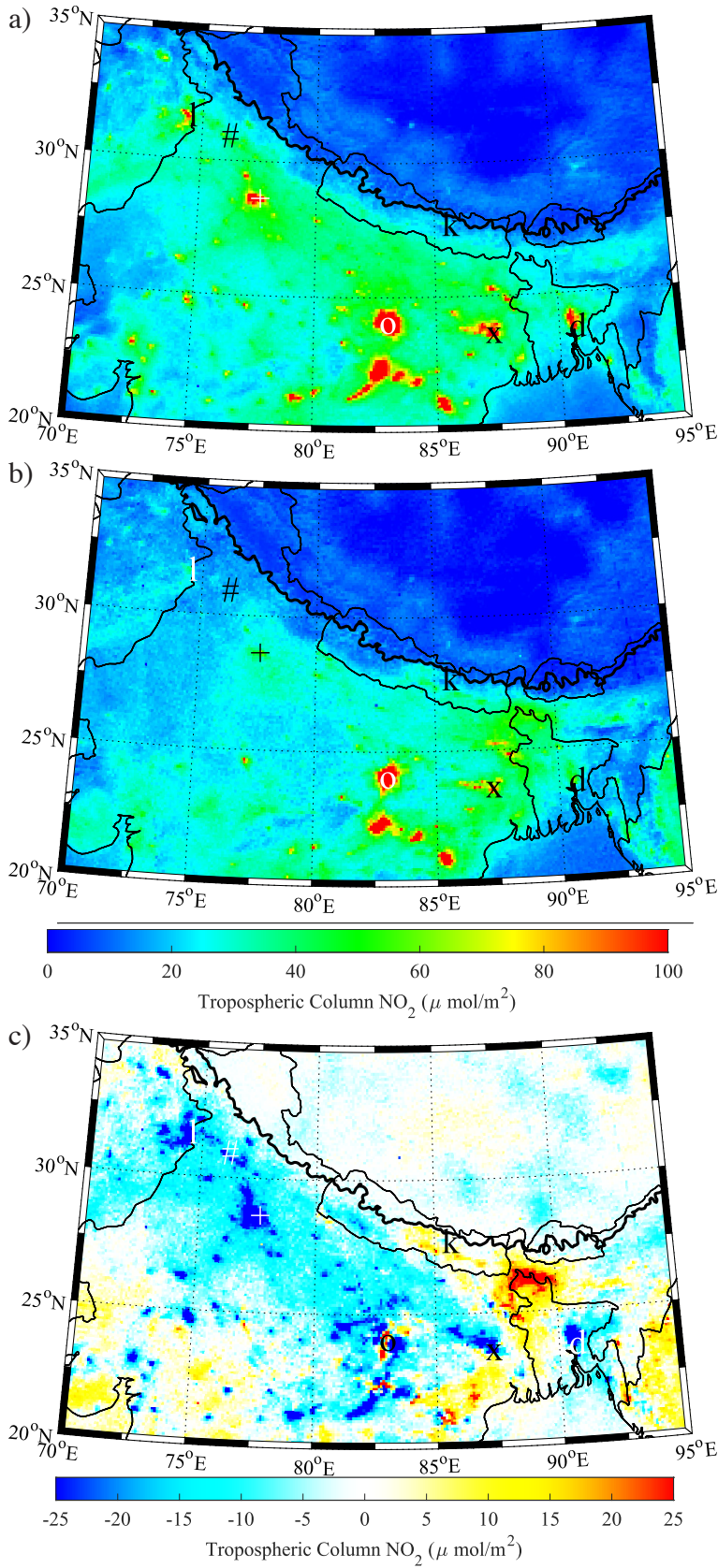
Figure 5) Anomalous column tropospheric NO2 density from the OMI across the region of interest during April 2020. Results are shown for the: a) anomaly (μ mol/m2) b) the normalized anomaly (%). The locations of New Delhi ('+'), Ludhiana ('#'), Singrauli ('o'), Asansol ('x'), Lahore ('l'), Kathmandu ('k') 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) TROPOMI column tropospheric NO$_2$ density (μ 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 topogrpahic height shown by the thick black curve.
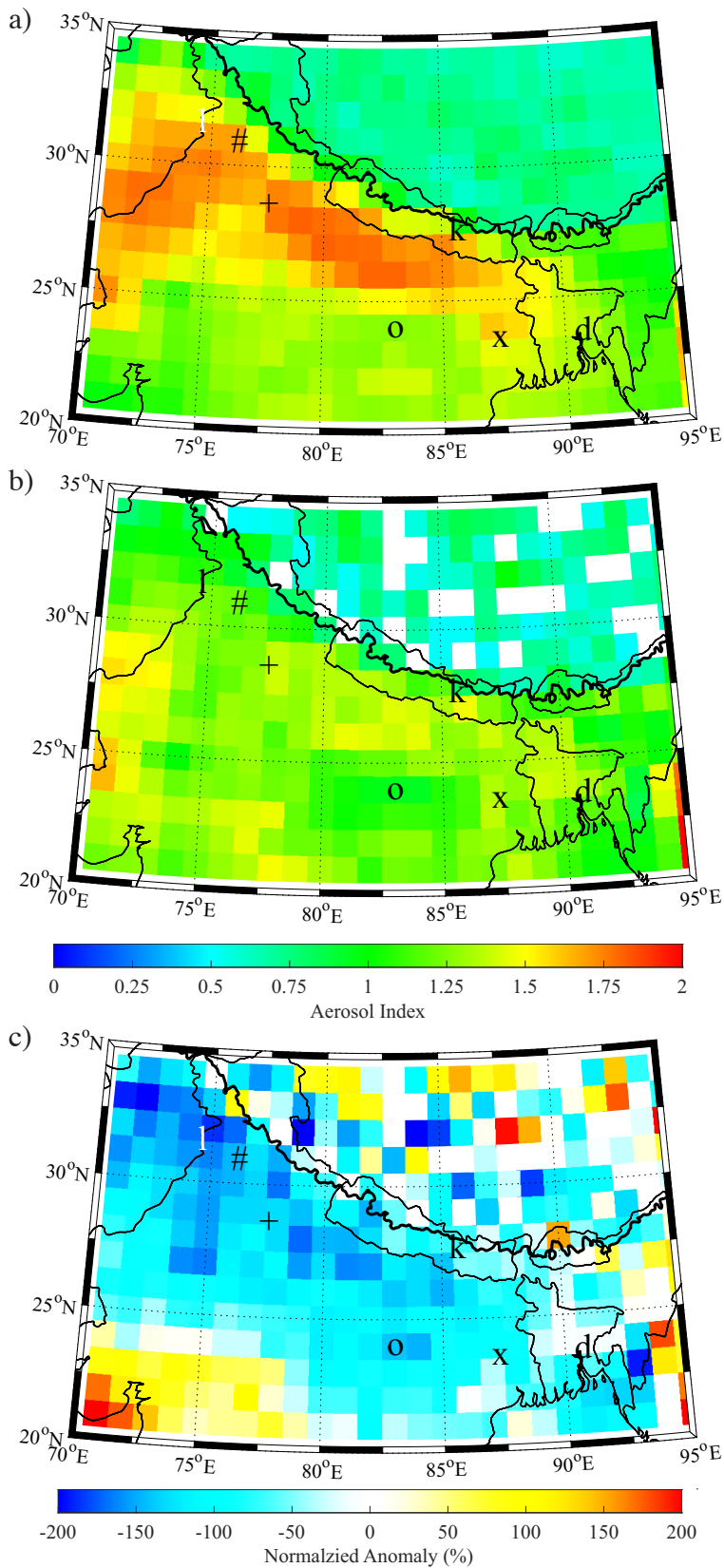
Figure 7) Column tropospheric NO2 density (μ mol/m²) from the TROPOMI across the region of interest. Results are shown for: a) April 1-30 2019; b) April 1-30 2020 and c) the difference between April 1-30 2020 and 2019. The locations of New Delhi ('+'), Ludhiana ('#'), Singrauli ('o'), Asansol ('x'), 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.
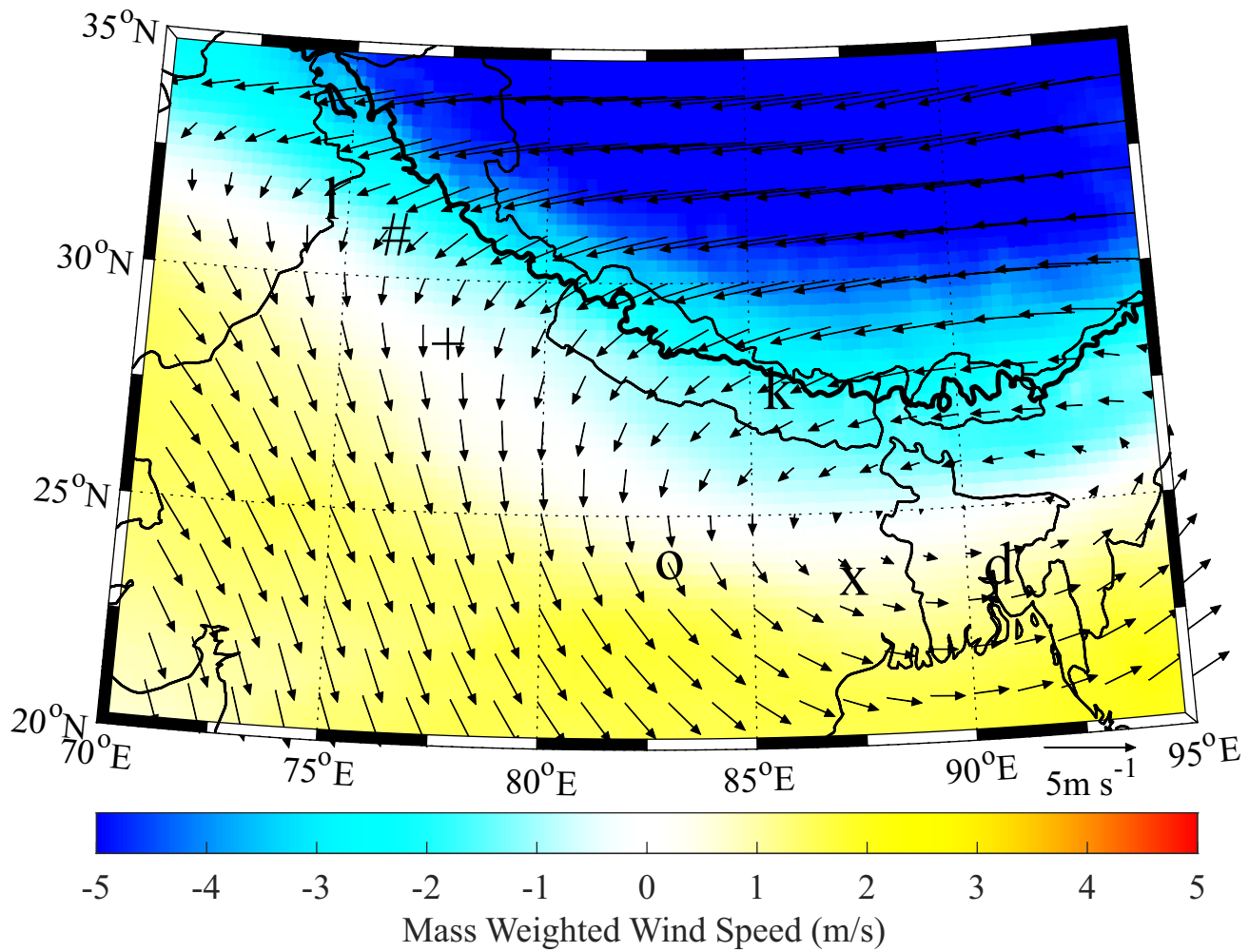
Figure 8) The tropospheric circulation across the region of interest during April 2020. The anomaly in the mass weighted wind (m/s) is shown. The locations of New Delhi ('+'), Ludhiana ('#'), Singrauli ('o'), Asansol ('x'), Lahore ('l'), Kathmandu ('k') and Dhaka ('d') are indicated. Political boundaries are shown by the thin black curves with the 3000m topographic height shown by the thick black curve.