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Impact of COVID-19 induced lockdown on land surface temperature, aerosol, and urban heat in Europe and North America

Bikash Ranjan Parida a,*, Somnath Bar a, Dimitris Kaskaoutis b, c, Arvind Chandra Pandey a, Suraj D. Polade d, Santonu Goswami e

a Department of Geoinformatics, School of Natural Resource Management, Central University of Jharkhand, Ranchi 835205, India
b Institute for Environmental Research and Sustainable Development, National Observatory of Athens, Palaia Penteli, 15236 Athens, Greece
c Environmental Chemical Processes Laboratory, Department of Chemistry, University of Crete, 71003 Crete, Greece
d Finnish Meteorological Institute, Helsinki, Finland
e Earth and Climate Science Area, National Remote Sensing Centre, Indian Space Research Organisation (ISRO), Hyderabad 500037, India

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A B S T R A C T

The outbreak of SARS CoV-2 (COVID-19) has posed a serious threat to human beings, society, and economic activities all over the world. Worldwide rigorous containment measures for limiting the spread of the virus have resulted in unprecedented temporary decreases of aerosols and atmospheric pollutants (NO2, CO, SO2, and PM), mainly due to the confinement of combustion of fossil fuels and fumes from sclerotic traffic (Marinello et al., 2021; Muhammad et al., 2020; Wang & Li, 2021; Xu et al., 2020). Therefore, a large decrease in air pollution and positive environmental implications are reported for the first time since World War II due to the worldwide lockdowns in the wake of the COVID-19 pandemic (Evangelio et al., 2021; Grivas et al., 2020; Singh et al., 2021). Several studies demonstrated a considerable decrease in atmospheric pollutants across urban areas worldwide due to national lockdowns (Bauwens et al., 2020; Latif et al., 2021; Wang & Su, 2020). NO2 concentration has dropped by 20–30%, or even more, in urban centers of China (Bao & Zhang, 2020), India (Mahato et al., 2020), and Europe and North America (Singh et al., 2021). Several studies demonstrated a considerable decrease in atmospheric pollutants across urban areas worldwide due to national lockdowns (Bauwens et al., 2020; Latif et al., 2021; Wang & Su, 2020). NO2 concentration has dropped by 20–30%, or even more, in urban centers of China (Bao & Zhang, 2020), India (Mahato et al., 2020),

1. Introduction

COVID-19, a severe acute respiratory syndrome Coronavirus 2 (SARS-CoV-2) disease, caused worldwide panic since late December 2019. The World Health Organization (WHO) has declared COVID-19 as the latest “Public Health Emergency of International Concern (PHEIC)”. The health emergency has led to rigorous nationwide containment measures (lockdowns) over more than 100 countries. Such extreme measures in social distancing, limitations of transportation, industrial production and human activities have resulted in unprecedented temporary decreases of aerosols and atmospheric pollutants (NO2, CO, SO2, and PM), mainly due to the confinement of combustion of fossil fuels and fumes from sclerotic traffic (Marinello et al., 2021; Muhammad et al., 2020; Wang & Li, 2021; Xu et al., 2020). Therefore, a large decrease in air pollution and positive environmental implications are reported for the first time since World War II due to the worldwide lockdowns in the wake of the COVID-19 pandemic (Evangelio et al., 2021; Grivas et al., 2020; Singh et al., 2021). Several studies demonstrated a considerable decrease in atmospheric pollutants across urban areas worldwide due to national lockdowns (Bauwens et al., 2020; Latif et al., 2021; Wang & Su, 2020). NO2 concentration has dropped by 20–30%, or even more, in urban centers of China (Bao & Zhang, 2020), India (Mahato et al., 2020),

* Corresponding author.
E-mail address: bikashrp@gmail.com (B.R. Parida).

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Malaysia (Abdullah et al., 2020), Italy (Collivignarelli et al., 2020), France (Pazmiño et al., 2021), Spain (Tobías et al., 2020), Greece (Grivas et al., 2020), Brazil (Nakada & Urban, 2020), and the USA. Based on the efficacy of lockdown, it was reported that cities with complete lockdown in Europe and USA have shown a higher reduction in NO$_2$ concentration (18–40%), whereas cities with partial to no lockdown have shown no significant drop in NO$_2$ concentration (3–7.5%) (Bar et al., 2021). Similarly, the concentrations of PM$_{2.5}$, PM$_{10}$, SO$_2$, and CO were significantly decreased due to traffic restrictions in urban areas as summarized in recent studies (Benchirif et al., 2021; Kumar et al., 2020).

CO$_2$ emissions from fossil fuels combustion are a major source of greenhouse gases (GHGs) and constantly emitted into the atmosphere. It was found that anthropogenic CO$_2$ emissions have decreased temporarily due to the pandemic (Le Quéré et al., 2020; Parida et al., 2020) and this reduction had rather negligible effects on the concentrations of GHGs that are accumulated in the atmosphere for decades. The global CO$_2$ emissions fell by 17% and half of this decrease was from the transport sector, due to a decline in fumes from sclerotic traffic, and the remaining from the industry and power sectors (Le Quéré et al., 2020; Safarani et al., 2020), although global data show that this was rather parodic (Weber et al., 2020).

Aerosols significantly affect air quality, weather and climate by perturbing the Earth’s radiation budget, cloud properties and water cycle processes (Boucher et al., 2014; Bougiatioti et al., 2014). Aerosol particles are either emitted directly to the atmosphere through the combustion of fossil fuels, biomass burning, volcanic eruptions, dust storms, sea spray, etc. or formed in the atmosphere by secondary chemical reactions (Hansen & Nazarenko, 2004). The radiative effect of aerosols and their contribution to climate change primarily depend on aerosol amount and composition, and so the presence of different aerosol types, such as mineral dust, black carbon (BC), organic carbon (OC), sea-salt, sulfate may impose large uncertainty in interpreting their radiative effects (Pani et al., 2016; Srivastava et al., 2018). The Aerosol Optical Depth (AOD) is a proxy of atmospheric pollution level, which measures how light is attenuated by suspended particles through the atmosphere. During the COVID-19 lockdowns, satellite-derived AOD data revealed that the aerosol levels reduced substantially by 40–60% across urban areas in south and southeast Asia (Kanniah et al., 2020; Pathakoti et al., 2021; Ranjan et al., 2020). Recent works also revealed a large reduction in BC levels, as well as significant modulations in aerosol scattering and absorption properties enabling to modify the radiation budget and temperature at the surface and in the lower atmosphere (Anil & Alagha, 2020; Kaskaoutis et al., 2021; Wang et al., 2021).

Urban areas have faced large environmental degradation due to uncontrolled urbanization and land use land cover changes (LULC), leading to changes in urban microclimate and Urban Heat Island (UHI) (Barat et al., 2018; Ghetti et al., 2020). Typically, the UHI depicts higher surface and air temperatures over urban environments than the nearby rural areas (Voogt & Oke, 2003) due to alternation in the land surface energy budgets and the hydrological cycle. Several studies have reported that human activities are the main driving forces for the UHI effect over major cities across the world (Baralianti et al., 2018; Yao et al., 2021) in addition to other factors, such as LULC and urban geometry (Soltani & Sharifi, 2017). Consequently, UHI affects human comfort and health due to heat stress (Patz et al., 2005), thus demanding higher energy consumption from indoor air conditioning (Priyadarshini, 2009) and leading to detrimental effects on environmental quality (Ghunim et al., 2020), as well as with a retrofit effect on the outdoor temperature. Thus, the United Nations included Sustainable Development Goal (SDG-11) for making cities resilient and sustainable. As urban temperatures are rising, any insights towards reducing the intensity of UHI would be beneficial for urban dwellers and the urban environments.

Typically, Land Surface Temperature (LST) is a fundamental aspect of urban environmental quality and an indicator of urban climate, which directly controls the UHI (Li & Weng, 2007; Rajasekar & Weng, 2009). Anthropogenic emissions, aerosols and pollutants play a significant role in temperature rise in urban areas (Ma et al., 2017), so the reduced concentrations during the lockdown would result in a larger difference in thermal radiation between urban and rural areas (Shikwambana et al., 2021). However, there is no quantification of the impacts of lockdown measures on temperatures at local to regional scales due to changes in GHGs, air pollutants, and modifications in atmospheric water vapour. First analysis about the impact of reduced air pollutants and aerosols on the LST during the lockdown period was performed in India, indicating substantial negative LST anomalies (Parida et al., 2021).

The COVID-19 lockdown offers an opportunity to examine the impacts of reduced heat emitted from surface transportation along with decreased air pollutants on LST and the UHI intensity. However, to study this hypothesis at various scales, it requires observational data which are generally limited. The earth observation satellite data provide advantages to characterize the variability of LST and UHI at spatial scales. In this work, satellite-derived LST and AOD (as representative of atmospheric aerosols) data and station-based air temperature measurements were analyzed over Europe and North America aiming to quantify changes in LST during the lockdown periods. These regions have been selected since the first effective lockdown period was mostly during March–May 2020 and also witnessed the largest COVID-19 infections during spring 2020 (1st pandemic wave). The overarching objectives of this study are to: (1) analyze changes in LST during the lockdowns (March–May 2020 vs. 2015–19) by using both satellite and ground-based station measurements, (2) analyze satellite-derived AOD levels and atmospheric water vapor content to link with LST and air temperature, and (3) to understand the coupling between cessation of anthropogenic activity and urban microclimate (e.g. UHI) and land-cover effect during the lockdown across major urban cities in Europe and North America.

## 2. Materials and methods

Satellite-derived measurements of LST and ground-based data of air temperature are used to provide a comprehensive estimate of the impact of lockdown on temperature over Europe and North America. Similarly, satellite-derived measurements of AOD and water vapour content are employed to study the impact of lockdown on environment along with the meteorological data. Table 1 summarizes the datasets used in this study, which are described in the following sections.

### 2.1. Land Surface Temperature (LST)

The daily Terra-MODIS derived LST product (MOD11A1, V6) (Wan, 2008) provides day and night LST estimates using the split-window algorithm. Both daytime (LST$_{Day}$1km) and nighttime (LST$_{Night}$1km) data were obtained from the Google Earth Engine (GEE) repository in March–May of the period 2001 to 2020 (LPDAAC, 2020) (Table 1). Daytime and nighttime LST layers have been separately masked by quality control (QC) Day and QC Night flags, respectively. Data quality flag was also used to define the quality indicator of LST product.

### 2.2. Aerosol Optical Depth (AOD)

The daily MODIS-derived AOD product (MCD19A2, V6) with 1-km spatial resolution is available globally. It is a combined product of Terra and Aqua satellites with Multi-angle Implementation of Atmospheric Correction (MAIC) (Luljet, 2018). The AOD data were obtained from the GEE repository ("MODIS/006/MCD19A2 - GRANULES") (NASA LPDAAC, 2020) and are available at blue (0.47 µm) and green (0.55 µm) channels with improved cloud detection and atmospheric correction. In this study, the 0.55 µm AODs are used along with the quality assessment (QA) band for cloud masking (Luljet, 2012) over spatial domains covering Europe and North America. AOD values contaminated by clouds or snow and sun glint have been excluded from the analysis.
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et al., 2017). For the current study, the total precipitable water vapor dataset of several atmospheric variables (Gelaro et al., 2017; Randles-2.3. Total precipitable water vapor and aerosol sources from MERRA-2

Details of satellite and ground data used over Europe and North America for the period March–May from 2015 to 2020.

| Data used                        | Resolutions                        | Source                          |
|----------------------------------|------------------------------------|---------------------------------|
| **Land Surface Temperature (LST)** | Spatial: 1 km; Spectral: 36 bands   | (LPDAAC, 2020)                  |
| (Terra MOD11A1 version 6; Daytime & Nighttime LST) | Temporal: daily                    |                                 |
| **LULC (MCD12Q1 version 6 based on IGBP classification scheme)** | Spatial: 500 m; Temporal: annual   | (LPDAAC, 2020)                  |
| **Aerosol Optical Depth (AOD) (MCD19A2 version 6)** | Spatial: 1 km; Temporal: daily     | (NASA LPDAAC, 2020)             |
|                                  | Spectral: Green band (550 nm)       |                                 |
| **MERRA-2**                      | Spatial:0.5° x 0.625′ (PWV) and 2.5°x2.5° (aerosols) | MERRA-2 (Gelaro et al., 2017)  |
| Variables: total precipitable water vapour, aerosol emission sources | Temporal: monthly                  |                                 |
| **ERA-5 Reanalysis**             | Spatial: 30 km; Temporal: daily     | Copernicus Climate Data Store [https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-5-press-ure-levels-tab-4000-form] |
| Variables: Humidity, Wind, precipitation, boundary-layer height |                                |                                 |
| **Vertical Wind Velocity (omega)** | Spatial:2.5°x2.5′; Temporal: daily | [https://psl.noaa.gov/data/ta/gridded/data.ncep.reanalysis.pressure.html] |
| **Ground station: Air temperature** | Location: Vienna, Munich, Chattanooga, Pierre, and Lloydminster (Canada) | (Weather Underground, 2020) |
| Variables: Daytime Tmax, Nighttime Tmin |                                | [https://www.wunderground.com/ & Ground station, Alberta, Canada [https://climat.meteo.gc.ca]] |

**2.3. Total precipitable water vapor and aerosol sources from MERRA-2**

NASA’s Modern-Era Retrospective analysis for Research and Applications (MERRA-2) is an atmospheric reanalysis that provides a global dataset of several atmospheric variables (Gelaro et al., 2017; Randles et al., 2017). For the current study, the total precipitable water vapor (PWV, 0.5°x0.625′) and aerosol types (2.5°x2.5′) were obtained from the Giovanni platform ([https://giovanni.gsfc.nasa.gov/giovanni/]) during 2015–2020 (March–May months). Aerosol types such as BC, OC, mineral dust, sea-salt and SO2 were acquired and used in the analysis. The MERRA-2 model has been simulated with the coupled edition of Goddard Chemistry, Aerosol, Radiation, and Transport model (GOCART) along with meteorological observations. The MERRA-2 reanalysis data is produced using a state-of-the-art analysis/forecast system to perform data assimilation using past data via the Global Modeling Assimilation Office (GMAO), NASA and the Goddard Earth Observing System, version 5 model (GEOS-5). In this study, the MERRA-2 data reprocessed in September 2020 have been downloaded and used in the analysis.

**2.4. Meteorological parameters**

Meteorological variables such as relative humidity (RH), precipitation, wind vector and boundary-layer height (BLH) were obtained from the fifth-generation global atmospheric reanalysis (ERA-5) of the European Centre for Medium-Range Weather Forecasts (ECMWF). The wind vector and RH are taken at 1000 hPa to represent the near-surface meteorological conditions during the study period. The atmospheric BLH is the lowest part of the atmosphere, where the response of the surface layer due to changes in moisture and temperature can be felt in less than an hour, while its variations highly affect the pollution levels

(Dumka et al., 2019).

Furthermore, the vertical wind velocity or omega (Pascal/s) at 850 hPa (~1.5 km above sea level) was used to explain the atmospheric capability to disperse the pollutants (Acharya et al., 2021). This product was downloaded from NOAA/OAR/ESRL PSD (USA) website at 2.5°x 2.5° spatial resolution and was derived from NCEP/NCAR reanalysis (Kalnay et al., 1996). Positive value of omega indicates the downwards airflow or divergence (↑), i.e. increase in pressure gradient with time, while negative values indicate an upward airflow (↓) or convergence. Therefore, areas dominated by positive omega values are characterized by subsidence that generally leads to atmospheric stability and facilitates the accumulation of aerosol and pollutants within the lower boundary layer.

**2.5. Air temperature (AT) measurements from ground-based station**

Surface-based air temperature (AT) measurements were collected over the period 2010 to 2020 (March–May months) at five stations, namely, Vienna International Airport (48.12°N, 16.56°E), Austria, Munich Airport (48.35°N, 11.79°E), Germany (Weather Underground, 2020), two stations in USA, Chattanooga Metropolitan Airport (35.01°N, 85.21°W), Tennessee and Pierre Regional Airport (44.37°N, 100.35°W), South Dakota and one station in Alberta, Canada (Lloydminster Airport: 53°18′33″N, 110°04′21″W) (GC, 2020). All the ground-station data comprise two fields, such as maximum day temperature (Tmax) and minimum night temperature (Tmin). These five stations were located in the periphery (outskirts) of the urban areas and were selected to verify the tendency of temperature changes over large spatial domains around the cities.

**2.6. Methods**

As mentioned above, the spatial and temporal distributions of LST were derived from Terra MODIS day and night temperature data (MOD11A1) over Europe and North America. The standardized temperature anomalies during the lockdown period (March–May 2020) have been analyzed with respect to the previous five years (2015–2019) averages. In these calculations, only the effective lockdown window was considered based on the policies implemented by governments. For example, the period 10th March–10th May was taken for Europe, whereas 21st March–18th May was taken for North America.

**2.6.1. Category of the lockdown**

The level of lockdown has been categorized into four levels (0, 1, 2, and 3) based on the policies of respective governments (Le Quéré et al., 2020). Level 0 indicates no restrictions whereas level 1 indicates policies targeted at long-distance travel. Level 2 indicates regional policies that restrict about 50% of normal daily routines, whilst level 3 indicates national-level policies that significantly restrict the daily routines. The majority of the European countries had adopted level 2 lockdown in the 2nd week of March 2020, whereas level 3 started in the 3rd week of March that continued until 2nd week of May 2020. Similarly, most cities in the USA had started level 2 lockdown from 3rd week of March, and then adopted level 3 from 4th week of March that remained until 3rd week of May. In Canada, level 2 was initiated on 24 March whilst level 3 initiated in 2nd week of April. The detailed city-scale lockdown levels can be seen in Le Quéré et al. (2020).

**2.6.2. Standardized anomaly calculation**

Mathematically, the LST standardized anomaly can be expressed as:



\[
LST\,\text{anomaly} = \frac{x - \bar{x}}{SD}
\]

(1)

Where \( \bar{x} \) and SD are the mean and standard deviation from the previous five years (2015–2019) averages. In this study, the anomalies in LST,
AOD and aerosol types (i.e. BC, OC, mineral dust, sea-salt, SO\textsubscript{2}) in 2020 have been derived with respect to the 2015–2019 mean and standard deviation over the period March–May, using Eq. 1. In a complementary analysis, we also re-assessed the robustness of the LST anomaly using the long-term dataset (2001–2019). In addition, the meteorological station-based air temperature (AT) data, such as maximum day temperature (Tmax) and minimum night temperature (Tmin) were used to derive a standardized anomaly of AT as per Eq. 1. The percentage (%) differences in total precipitable water vapor (PWV) and meteorological parameters (RH, wind speed, BLH and precipitation) during the lockdown periods were derived with respect to the mean conditions over 2015–2019 (March–May) and tabulated for comparisons.

3. Results

3.1. Nighttime and daytime LST during the lockdown over Europe and North America

The spatial distribution of nighttime and daytime standardized LST anomaly (°C) across European countries during the lockdown period in 2020 (10\textsuperscript{th} March–10\textsuperscript{th} May) with respect to 2015–2019 mean is shown in Fig. 1 (a, b). The standardized LST (nighttime) anomaly in 2020 against the reference data (2015–2019) reveals that the anomaly ranged between −5 °C (in the eastern part of Europe, Ukraine) and +5 °C (Western Europe, mostly in France, Ireland and in Alpine region). The negative anomaly was profound (−1 to −5 °C), especially over central and eastern parts of Europe, as well as over the Balkans, while moderate negative anomaly was found over the Iberian Peninsula and the Mediterranean area (Fig. 1a). On the contrary, positive daytime LST anomalies were observed in the vast areas of central-western Europe and UK, while the negative LST anomalies were limited over the northern European countries (i.e. Scandinavia), as well as over the Baltic countries and the Iberian Peninsula (Fig. 1b). The LST anomalies over Europe are in general consistency with the respective anomaly of air temperature (Evangelou et al., 2021), which revealed LST positive anomalies over France, UK, Belgium, the Netherlands and west part of Germany and mostly negative anomalies over the rest of Europe i.e. Russia, east Europe, Italy and Balkans.

The European countries that exhibited mostly negative nighttime and daytime LST anomalies are shown in Table 2. Negative anomaly of LST (nighttime) was ranged from −0.11 °C over Austria to −2.6 °C over Belarus in Europe, whilst it ranged from −0.7 °C over USA to −0.27 °C over Canada. The nighttime LST anomalies over the urban areas of Vienna and Munich also showed widespread negative values during the lockdown period (Table 3). Conversely, daytime positive LST anomaly over many countries of Europe could be associated with decrease in aerosols and pollutants and less attenuation of solar radiation reaching the ground (Huang et al., 2014; Yang et al., 2016), and/or may be partly

| Major countries | LST anomaly °C (± SE) |
|-----------------|----------------------|
| Austria         | −0.11 (±0.003)       |
| Germany         | −0.33 (±0.0009)      |
| France          | 0.62 (±0.0001)       |
| Spain           | 0.04 (±0.0001)       |
| Italy           | −0.67 (±0.001)       |
| Ukraine         | −2.18 (±0.001)       |
| Belarus         | −2.60 (±0.002)       |
| Poland          | −1.97 (±0.001)       |
| Latvia          | −1.50 (±0.003)       |
| USA             | −0.70 (±0.0004)      |
| Canada          | −0.27 (±0.0004)      |

Mean nighttime LST anomaly Mean daytime LST anomaly
Austria 1.23 (±0.002)                1.40 (±0.001)
Germany 0.61 (±0.0008)              0.04 (±0.0002)
France  0.77 (±0.0009)              −0.07 (±0.0009)
Spain   0.78 (±0.0002)               −1.18 (±0.0002)
Italy   −1.19 (±0.0002)              −1.18 (±0.0002)
Ukraine −0.48 (±0.0004)             −0.22 (±0.0003)
Belarus −0.98 (±0.0008)             −1.11 (±0.0008)
Poland  −0.07 (±0.0009)             −0.07 (±0.0009)
Latvia  −1.19 (±0.0002)             −1.19 (±0.0002)
USA     −0.48 (±0.0004)              −0.22 (±0.0003)

Fig. 1. Standardized nighttime (a, c) and daytime (b, d) LST anomaly (°C) during 2020 with respect to 2015–2019 mean over Europe (10\textsuperscript{th} March–10\textsuperscript{th} May) and North America (21\textsuperscript{st} March–18\textsuperscript{th} May).
explained by the synoptic meteorological variability between the lock-
down and reference periods. For instance, the positive LST anomaly
(both in daytime and nighttime) that was persistent in Ireland and
France, was also associated with a reduction in precipitation by 25–50%
during the lockdown period and a decrease in RH by 10–20% in Western
Europe (Fig. 2). In contrast, an increase in precipitation by 25–50% over
the Iberian Peninsula (Fig. 2) seems to have a strong linkage with the
negative anomaly of LST, especially during daytime (Fig. 1) and may
mask the lockdown effect on the concentrations of air pollutants. Day-
time positive LST anomaly over the vast areas of central and southeast
Europe could be also attributed to drier days (lower RH), while the
precipitation was reduced by > 25% (Fig. 2). Although the lower pre-
cipitation and RH over the most part of Europe during the 2020 lock-
down period may partly explain the positive anomalies in LST, implying
for reduced cloudiness, larger amounts of solar radiation in the ground,
and therefore, increased temperatures. The negative nighttime LST over
the region evidences for a different cause mechanism that may be
related to the reduced anthropogenic emissions and GHGs. On the other
hand, the anomalies in wind speed are consistent with those in BLH,
indicating that stronger winds facilitate increase in BLH and better
dilution and dispersion processes (Dumka et al., 2019), thus reducing
the aerosol radiative effects. However, the contrasting meteorological
anomalies between the different European regions may only partly
explain the variability in LST anomalies, which also differ between
daytime and nighttime. Apart from prevailing meteorology and associ-
ated changes between the lockdown and the reference period in
2015–2019, the LST anomalies are also sensitive on several factors
related with soil characteristics, topography, surface albedo, land cover
type and related surface-atmosphere fluxes (i.e. sensible and latent
heat). This results in the large spatial heterogeneity of LST anomalies

| Major cities | LST anomalies°C (± SE) | AT anomalies°C (± SE) |
|--------------|------------------------|-----------------------|
|               | Mean nighttime LST anomaly | Mean daytime LST anomaly | Tmax (Day) | Tmin (Night) |
| Chattanooga, USA | −2.85 (±0.019) | −2.63 (±0.034) | −0.73 (±0.27) | −0.83 (±0.33) |
| Pierre, USA | −1.65 (±0.019) | −0.44 (±0.009) | −0.11 (±0.19) | −0.46 (±0.17) |
| Lloydminster, Canada | −1.33 (±0.011) | −2.26 (±0.011) | −0.61 (±0.18) | −0.96 (±0.31) |
| Vienna, Austria | −2.27 (±0.013) | 1.52 (±0.023) | −0.10 (±0.21) | −0.68 (±0.24) |
| Munich, Germany | −1.62 (±0.011) | 1.83 (±0.02) | 0.41 (±0.17) | −0.65 (±0.28) |

Fig. 2. Percent changes in meteorological condition over Europe between 2020 and 2015–2019 (i.e. March–May) based on the ERA-5 for (A) relative humidity, (B) wind speed at 1000 hPa pressure level, (C) boundary-layer height, and (D) precipitation. The overlaid wind direction was from 2020.
over Europe and North America.

The LST analysis from satellite data has been validated with AT measurements from ground stations in Vienna (Austria) and Munich (Germany), and the corresponding anomaly bar plot is shown in Fig. 3. The ground-based AT measurements revealed that most of the days experienced negative anomalies for both Tmax and Tmin, except Munich for Tmax (Table 3). The Tmin was about $-0.65 \degree C$ in Vienna and Munich (Europe), $-0.46 \degree C$ in Pierre (USA), $-0.83 \degree C$ in Chattanooga (USA), and $-0.6 \degree C$ in Lloydminster, Canada. The negative AT anomalies at least for night in Vienna and Munich are consistent with those observed from satellite observations over the central Europe, while the positive daytime LST from satellite retrievals are consistent with the meteorological data in Munich (Tmax anomaly of 0.41 $\degree C$), while in Vienna only a marginal negative Tmax anomaly ($-0.1 \degree C$) was found (Fig. 3). The positive Tmax anomaly in Munich might be attributed to exceptional strong regional positive anomalies observed in the first week of April, which apart from lesser aerosol-radiative effect can be attributed to synoptic meteorological forcing, especially dry atmosphere and sunny weather (Table 3; Fig. 2).

The analysis of LST anomaly during the lockdown period (21st March–18th May 2020) in North America revealed a significant drop-down of both nighttime and daytime LST across most parts of USA and Canada (Fig. 1) and high spatial heterogeneity, as also observed over Europe. The nighttime LST map revealed a significant negative anomaly ($-1$ to $-5 \degree C$) across the USA except for few southern states (i.e. Arizona, New Mexico, Texas, and Florida) that exhibited positive anomaly (Fig. 1c). The daytime LST anomaly map also depicted similar negative anomalies across the USA (Fig. 1d) except for some southern states. The spatial-averaged LST anomaly in nighttime and daytime was mostly negative over the USA territory and Canada (Table 2). Furthermore, the LST anomaly over the urban areas of Chattanooga and Pierre (USA), and Lloydminster in Canada also exhibited a negative anomaly (Table 3), in general consistency with satellite observations. The positive LST anomalies in south/western USA states (Fig. 1c, d) were found to have a correspondence with a negative anomaly in precipitation (25–50%) and RH (10–20%) during the lockdown period (Fig. 4), likely facilitating high solar irradiance at the ground and increase in LST during the lockdown period. Furthermore, the lower wind speed by 5–20% and the reduced BLH by about 5–10% over the southwest USA facilitate stable and stationary air conditions that are favorable for increasing pollutant concentrations (Fig. 4b, c). Therefore, meteorological variability might also be an additional contributing factor for the LST anomalies over the southern states, since it presents large spatial heterogeneity, as observed both for daytime and nighttime LST (Fig. 4).

Furthermore, the LST anomaly analysis from satellite observations was validated from ground-station measurements in Chattanooga (Tennessee) and Pierre (South Dakota) in the USA, and Lloydminster, Alberta (Canada) (Fig. 3). The results showed that the three ground stations revealed negative AT anomalies for both Tmin and Tmax in most of the days, as well as period means (Table 3), which are consisted with the negative daytime and nighttime satellite-derived LST anomalies around these stations (Fig. 1c, d). Additionally, the standardized nighttime LST anomalies in the pandemic year (2020) were compared with the long-term LST dataset (2001–2019) over the examined regions to confirm the robustness of changes in LST (Fig. 5). These results depicted a large reduction in LST with a similar spatial pattern as seen in

![Fig. 3. Standardized nighttime and daytime air temperature anomaly (°C) at daily-scale as represented by histogram during 2020 (March–May) over ground stations located in North America and Europe.](image-url)
Fig. 1 for both Europe and North America. This finding confirms that the LST anomaly during the lockdown period with respect to the short-term period (2015–2019) was not different from the anomaly retrieved considering the long-term period (2001–2019).

3.2. Standardized AOD anomalies during the lockdown and vertical air flow

The AOD spatial distribution over Europe and North America showed both positive and negative anomalies during the lockdown period with respect to the 2015–2019 mean (Fig. 6a, b). The spatial distribution of the AOD anomalies is highly heterogeneous, with negative ones in central eastern Europe and positive around coastal areas, such as Portugal, Spain, south France, Italy, that could be related to other regional contributions, such as an increase in mineral dust (Fig. 7), as well as to changes in meteorological conditions (Pandey & Vinoj, 2021). Furthermore, MERRA-2 reanalysis revealed a slight positive anomaly in mass concentrations of carbonaceous aerosols over central Italy, parts of France and Iberia, but the most important increases correspond to SO$_2$ concentrations and dust over parts of western Europe that contributed to the increase in AOD over these areas (Fig. 7). Therefore, it is shown that the AOD differences over several parts of Europe during the lockdown period were not negative, as would have been expected due to decrease in anthropogenic emissions, but AOD variations are also sensitive to changes in natural aerosols (i.e. dust events) leading to higher AODs at specific areas, as also shown in India and southeast Asia (Dumka et al., 2021; Kanniah et al., 2020).

Previous analysis revealed an important meteorological variability during the lockdown period, as RH decreased by 10–30%, along with a decrease in precipitation and contrasting variability in wind speed, over most parts of Europe except Spain (Fig. 2). The contrasting anomalies in wind speed, BLH, RH and precipitation may strongly affect the changes in AOD in a contradictory way, depending on which variable affects more the regional AOD variability, while the effect of each meteorological parameter in AOD anomaly is rather impossible to be quantified. The end result is a large heterogeneity in the AOD anomalies during the lockdown period (March–May 2020), although the well-defined declining trend in anthropogenic emissions all over Europe and mostly over the urban agglomerations and densely populated and industrialized areas (Evangeliou et al., 2021). Therefore, several parts of Europe (in Spain, Portugal, Germany, Austria, and Italy) showed a positive anomaly in AOD, which could be also attributed to higher positive omega values that facilitate a downward airflow and subsidence during spring 2020 (Fig. 6b). Typically, these conditions prevent an efficient dilution and dispersion of air pollution and aerosols and thereby, facilitate their accumulation and the higher AODs. However, over other parts of Europe like central-east and southern Sweden, positive omega and subsidence are not associated with an increase but with a decrease in AOD, implying...
that AOD variability mostly depends on other factors like less anthropogenic emissions due to lockdown, and an increase in wind speed and BLH (Fig. 2), indicating the difficulty in apportioning the aerosol variability and AOD trends over Europe to a single factor. The AOD anomaly over Vienna (Austria) and Munich (Germany) cities during the lockdown period with respect to the 2015–2019 mean is shown in Table 4, indicating contrasting trends, supporting the large heterogeneity in satellite AOD anomalies.

Similarly, the AOD anomalies over North America showed both positive and negative values, which are difficult to be directly related to variability in emissions and/or to a single meteorological factor (Fig. 6a). The negative AOD anomalies were prevalent over several areas in USA, whilst the positive anomalies were found mostly over the central and western states. The negative AOD anomalies could be associated with lower emissions of anthropogenic aerosols during the lockdown period and/or favorable meteorological conditions for aerosol dilution. Moreover, it was also evident that the negative anomaly of AOD was coincident with a negative omega (upward airflow) in 2020 that can result in dilution of aerosols in the lower troposphere (Fig. 6b). However, the positive AOD anomalies, especially over California and central-west states, could be attributed to other factors, such as long-range dust transport and local carbonaceous-aerosol (OC+BC) emissions (Fig. 7). A decrease in precipitation and RH was also seen in the central-western states (Fig. 4a, d), which may influence the changes in AOD, while increasing BLH during lockdown (Fig. 4c), could have resulted in suitable conditions for dispersion of atmospheric pollutants, justifying the complex processes and the large spatial variability in the AOD anomalies. On the other hand, some parts of the USA have shown positive anomalies of AOD, which were related with positive omega (downward airflow) and subsidence in spring 2020 (Fig. 6b) that might have facilitated the aerosol accumulation. The AOD anomaly over the urban areas of Chattanooga and Pierre (USA) and Lloydminster (Canada) present contrasting negative and positive trends (Table 4).

3.3. Changes in total precipitable water vapor (PWV) during the lockdown

Fig. 8 shows the percentage (%) changes in total precipitable water vapor (PWV) during the lockdown period in 2020 against 2015–2019 mean over Europe and North America. Although changes in PWV are attributed to natural reasons, they may affect the overall trends in LST, and in AOD as well, via modifications (attenuation) in solar irradiance reaching the ground (Sanchez-Lorenzo et al., 2009; Yang et al., 2018). The current results showed that atmospheric water vapor content decreased widely over Europe (15–25%) – but not in Iberia – and North America (10–20%) during the lockdown period in 2020 (Fig. 8; Table 4). This decrease in water vapor could be associated with lower RH and precipitation over Europe (Fig. 2), as well as over North America (Fig. 4), which are positive feedbacks for an increase in LST. In addition, changes in outgoing longwave radiation (OLR) are very sensitive to water vapor in the troposphere (Held & Soden, 2000) and changes in PWV can induce modifications in radiative forcing, which can be linked to LST variations. Negative anomalies in PWV over central-eastern Europe are associated with negative nighttime LST anomalies, while the same generally occur over North America. On the contrary, the positive PWV anomalies in the Iberian Peninsula are linked to negative LST.
**Fig. 6.** Standardized AOD anomaly during 2020 with respect to the mean of 2015-2019 in Europe and North America (A) during the effective lockdown period. The average vertical airflow (omega in Pascal/s) at 850 hpa (~1500 m above sea level) during lockdown period in 2020 (B).

**Fig. 7.** Standard anomaly between 2020 and 2015-2019 (i.e. March-May) based on the MERRA-2. (A) Organic and black carbon (OC + BC), (B) SO$_2$, (C) mineral dust, and (D) sea-salt over North America and Europe. The corresponding units are mass concentration (kg m$^{-3}$) for A and column mass density (kg m$^{-2}$) for B-D.
3.4. Temperature difference over urban and rural areas during the lockdown

The changes in nighttime LST anomaly around 12 selected cities in Europe and North America are plotted in Fig. 9. The urban areas are defined with the vertical red bars, while the LST anomalies in the nearby rural areas are also plotted (values outside the red bars). The results show a clear distinction of LST anomalies between urban and rural areas during the lockdown period, with higher reduction of nighttime temperature in the urban downtown areas. For instance, cities such as Vienna, Milan and Madrid have shown temperature anomalies by 2.3 °C and 0.4 °C or less. The same pattern is observed over all cities, except Pierre, South Dakota, where the negative LST anomaly was lesser above the urban area compared to the surroundings. This is likely attributed to the dominance of farmlands and water bodies in the periphery of city and/or to other local topographic characteristics, since land cover and topography plays a major role in LST variations around the cities (Harmay et al., 2021; Xiang et al., 2021). Similarly, other cities such as Munich and Hamburg have also shown temperature differences between urban and rural areas, albeit at lower magnitude. Similar characteristics are also shown in cities in North America since the maximum negative LST anomalies were found in downtown Calgary (–2.3 °C), Lloydminster (–1.5 °C), and Chattanooga (–3.6 °C), whereas other cities such as Washington (–0.5 °C), Nebraska (–0.4 °C), and Lincoln (–0.5 °C) have shown lower sensitivity of urban temperature differences relative to rural temperature.

Overall, the LST anomaly during the lockdown period is negative in all examined cities and this decrease is more pronounced over the city center compared to the surroundings and outside rural areas. This indicates a clear lockdown effect on LST variations over urban areas and a larger decrease in nighttime UHI, which can be attributed to lesser aerosol and pollutant emissions that absorb thermal ongoing radiation and increase the temperature over the cities (Halder et al., 2021). Therefore, although the results of LST anomaly during the COVID-19 lockdown period exhibited large spatial variability over the European and North American domains due to several factors influencing changes in LST, emphasis over urban agglomerations of various sizes revealed a similar tendency in all the cases, with negative nighttime LST due to less thermal radiation absorbance by aerosols and GHGs, which was more intense that the LST variation in the surrounding areas.

LST changes over a specific area are highly variable and also sensitive to many parameters such as topography, altitude, slope, vegetation cover, type of vegetation, soil moisture, roughness, surface albedo and absorptivity, which are closely related to LULC type (Harmay et al., 2021; Portela et al., 2020). Therefore, LST anomalies during the lockdown period may be sensitive to several factors beyond the effect of less anthropogenic aerosols and pollutants in the urban areas. In this respect, figure 10 shows the variations of nighttime LST anomaly with respect to five major LULC types (built-up, croplands, forests, grasslands, and water bodies) in major cities in Europe and North America during the lockdown period. Except of few outliers, all the LULC types demonstrated a consistent negative LST anomaly during the lockdown (March–May 2020) with respect to 5 years observations (2015–2019). The results revealed that the reduction of LST and its magnitude depends on various LULC types within the urban areas. For instance, urban green vegetation (forests, croplands and grassland) and built-up showed cooling by 0.93–2.23 °C and 0.95–2.57 °C, respectively in major cities across Europe, whilst water bodies depicted cooling by 0.7–2.19 °C (Fig. 10a). A similar pattern was also found in urban areas of North America (Fig. 10b), except the Washington where croplands and forests showed a positive LST anomaly. So, the large variability in the LST anomalies over Europe and North America during the period of the lockdown can be also ascribed to LULC types, which depend upon the associated geographical conditions like, elevation, slope and aspects (Peng et al., 2020). However, significant changes in the magnitude of the negative LST anomalies with respect to LULC are observed between the cities, supporting the complex associations between LST anomalies and LULC types.

![Fig. 6. Percentage changes in total precipitable water vapor (%) during 2020 (March–May) with respect to the mean over 2015–2019 over Europe (A) and North America (B).](image)
4. Discussion

4.1. Implications of the lockdown on atmospheric pollutants and AOD in the pandemic year 2020

The most affected countries from COVID-19 pandemic in numbers of infections and deaths are the USA, India, Brazil, Russia, United Kingdom, and other European countries, such as Spain, Italy and France (JHU, 2021). To limit the spread of the coronavirus, rigorous containment measures, such as partial-to-total lockdowns of industrial production and citizen mobility, were adopted worldwide mostly during March–May of 2020. Consequently, the lockdown measures have led to a large reduction of atmospheric pollution (NO<sub>2</sub>, SO<sub>2</sub>, CO, PM<sub>2.5</sub>, PM<sub>10</sub>, etc.) across the world (Cadotte, 2020; Dutheil et al., 2020; Otmani et al., 2020). The lockdown measures not only declined the spread of infections over majorly affected countries but also improved the total environment (Mahato et al., 2020; Sharma et al., 2020; Tobías et al., 2020). In Europe, about 2190 (1960–2420) premature deaths have been prevented and projected a reduction between 13600 and 29500...
depending on the efficacy of lockdown (Giani et al., 2020). Globally, it was projected about 0.78 (0.09–1.5) million premature deaths were averted in 2020 (Venter et al., 2020).

To investigate the impacts of the lockdowns on the environment, especially on the changes in LST and AOD over Europe and North America, various satellite-derived data were analyzed in this work, along with ground AT measurements. The key findings revealed a notable reduction in AOD during the period March–May in the pandemic year (2020) compared to the mean of non-pandemic years (2015–19). However, several regions exhibited positive AOD anomalies, which could be attributed to the contribution of natural phenomena like dust events, biomass burning that may increase significantly the AODs during the lockdown period (Kanniah et al., 2020; Kokkalis et al., 2021). Positive omega values could be also associated with positive AOD since a downward airflow was found over some areas in 2020, which usually preventing an efficient dispersion of air pollution (Acharya et al., 2021; Ogen, 2020). Furthermore, large changes (decrease) in ozone content over southeast Europe during May 2021 (Raptis et al., 2021) may highly affect the levels of solar irradiance reaching the ground, as well as the LST, which seems to be dependent on several parameters with contrasting feedbacks in LST anomaly. Therefore, the large heterogeneity in spatial AOD anomaly indicates the difficulty in apportioning it to a single factor (Floutsi et al., 2016; Papadimas et al., 2008).

Our findings are consistent with several studies that addressed declined AOD levels by 40–60% in south Asian countries, Europe and America in 2020 as compared to the mean of non-pandemic years (Gautam, 2020; Lonati & Riva, 2021; Ranjan et al., 2020; Sannigrahi et al., 2021). Lower levels of emissions, including the reduced concentrations of the light-absorbing OC and BC (Ramanathan & Carmichael, 2008; Tiwari et al., 2016), might have significantly altered the radiative forcing and consequently changed the LSTs. Some studies have also demonstrated decreased aerosol radiative forcing values (–24.3 W m$^{-2}$ at surface and –16 W m$^{-2}$ at TOA in the short wave) due to lower AODs during the lockdown period in Madrid (Barragan et al., 2020) and considerable decreases in carbonaceous aerosol (BC and Brown Carbon) absorption in Wuhan (Wang et al., 2021) and Athens (Kaskaoutis et al., 2021). In addition, a decrease in the radiative forcing in East Asia was attributed to reductions in AOD, with one-third of the reduced anomalies to be attributed to the lockdown, while the remaining was attributed to natural factors, such as meteorological variability and surface heterogeneity (Ming et al., 2021).

4.2. Implications of the lockdown on urban temperature

The negative anomaly in LST that was observed across Europe and North America during the lockdown period was more pronounced during nighttime, while for daytime satellite observations, large spatial heterogeneity in the LST anomalies was observed, indicating influence from several contradictory factors i.e. changes in anthropogenic emissions, LULC types and local/regional meteorology. Our findings of the dropdown of nighttime temperatures concluded that this pattern could be attributed to partial-to-total lockdown measures during COVID-19, when all anthropogenic emissions were minimal. The magnitude of declined LST was also similar to several urban agglomerations in India, which showed LST anomaly ranged from –0.63 °C to –2.1 °C in nighttime and –0.16 °C to –1 °C in daytime (Parida et al., 2021). In Gauteng Province of South Africa, declined LST was found to be about –3 °C during the lockdown, which was mostly attributed to seasonal variation,
while the lockdown effect could have a smaller role (Shikwambana et al., 2021). Other studies have found lower anthropogenic heat flux during the lockdown, which resulted in less LST change (−4 °C) (Pal et al., 2021). In Montreal, Canada, a decrease in the near-surface temperature was found to be about −1 °C, associated with about 80% reduction in traffic (Teufel et al., 2021). Two climate models were applied to study the impacts of the lockdown and related emission changes (mainly BC and sulphate) on LST over USA, revealing a positive aerosol effect on LST by 0.1 °C to 0.3 °C; however, this effect was negligible for the global temperature (+ 0.03 °C) (Gettelman et al., 2021). The main findings from several latest studies that examined the effect of lockdown on surface LST and UHI have been summarized in Table 5.

Moreover, CO₂ is the standard tracer of air pollution from complete combustion sources (Hanaoka & Masui, 2020) and the global CO₂ emissions of the pandemic year have plunged to the 2006 levels due to lockdowns (Le Quéré et al., 2020). Consequently, the atmospheric CO₂ concentrations fell by 18–39% in India (Parida et al., 2020) and by 1.8% in Peninsular Malaysia during the lockdowns (Yusup et al., 2020). Therefore, during nighttime more thermal radiation was able to escape to space due to reduced thermal absorption by CO₂ leading to negative LST anomalies over major parts of Europe, while during daytime, the reduced aerosol and pollution levels, attenuated less solar irradiance (Collaud Coen et al., 2020; Dumka et al., 2016; Qian et al., 2006), thus facilitating the increased LST over the major part of Europe and several parts in North America (Fig. 1). In addition, negative anomalies in OC and BC concentrations, which are emitted from fossil fuel combustion and biomass burning (Bond et al., 2013; Kanakidou et al., 2005), were also noticed over Europe (Evangelou et al., 2021) and North America (Fig. 7), and the spatial pattern was co-located with the negative anomaly of LST.

The negative nighttime LST anomalies during the lockdown weakened the UHI effect (Fouda et al., 2015; Gaffin et al., 2008; Sahani et al., 2020). This is justified by the larger reduction in LST (by about 1–2 °C) that was found in the urban areas (Fig. 9) compared to the surrounding regions (mostly rural setup or agriculture landscapes). Notably, the lockdown provided a natural experiment to capture the coupling between urbanization and local microclimate. Therefore, the important outcomes of this study may incorporate in urban planning for sustainable urban development because lower temperatures in urban areas would offer thermal comfort and reduce anxiety and heat-stress related health problems.

### Table 5

| Study area                  | Key findings                                                                 | Source                                      |
|-----------------------------|------------------------------------------------------------------------------|---------------------------------------------|
| Dwarka river basin, India   | PM₁₀ has reduced from 189-278 to 50-60 μg/m³ after 18 days of lockdown.   | (Mandal & Pal, 2020)                        |
|                             | The LST was significantly dropped by 3–5 °C.                                |                                             |
| Indo-Gangetic Basin, India  | More than 10% columnar air pollution during the lockdown. Daytime LST      | (Chakraborty et al., 2021)                  |
|                             | decreased by −1.96 K in rural areas and by −1.76 K in urban areas.        |                                             |
| Major cities of India       | Satellite-derived NOₓ and AOD were dropped by 18–43% and 4–34%. Both day  | (Parida et al., 2021)                       |
|                             | and night time LST exhibited a negative anomaly by 1 °C and 2.1 °C,         |                                             |
|                             | respectively.                                                               |                                             |
| Major cities of India       | The majority of the cities experienced an improved air quality Index (AQI,  | (Nanda et al., 2021)                        |
|                             | 18–151 units). LST decreased by 0.27°C to 7.06°C (except Kolkata).         |                                             |
| Pakistan                    | The electricity demand was declined by −1786 GWh which causes a considerable| (Ali et al., 2021)                          |
|                             | reduction of air pollution (NOₓ, CO, SO₂ and AOD) was observed during the   |                                             |
|                             | lockdown. In megacities, surface UHI decreased by 18–29%.                  |                                             |
| Major cities of the         | A significant decrease in atmospheric NOₓ, SO₂ and CO. The night-time      | (El Kenawy et al., 2021)                    |
| Middle East                 | surface UHI was dropped up to 1 to 2 °C, whilst in case of daytime, some   |                                             |
|                             | of the cities exhibited a slight positive surface UHI.                      |                                             |
| United Arab Emirates (UAE)  | The average atmospheric concentration of NOₓ and AOD decreased by 23.7%     | (Alaposemi et al., 2021)                    |
|                             | and 3.7% due to decreasing automobile and industrial emissions. The surface|                                             |
|                             | UHI intensity has reduced up to 2 °C (or 19.2%).                           |                                             |
| Gauteng Province of South   | The tropospheric column density of NO₂ fell by 31% during the lockdown.    | (Shikwambana et al., 2021)                  |
| Africa                      | LST and surface UHI exhibited a reduction up to 3.7 °C and 3 °C, respectively,|                                             |
| Montreal city, Canada       | Around 80% reduction of traffic during lockdown which resulted in a decrease in LST up to 1 °C | (Teufel et al., 2021)                       |
| Osaka city, Japan           | Lockdown resulted in reduction of temperature and electricity consumption by 0.13 °C and 40%, respectively. | (Nakajima et al., 2021)                    |

4.3. Significance of meteorological conditions and other factors linked temperature changes in the lockdown period

This study has addressed considerable changes in surface temperature both in Europe and North America during the lockdown. The lower surface temperatures, which have been observed mostly over the urban areas during nighttime, seem to have been related to the large decrease in emissions of anthropogenic aerosols and GHGs during the lockdown. Nevertheless, the changes in surface temperature could be also modulated by changes in meteorological conditions, precipitation and atmospheric water vapor content. The latter plays a major role in the earth’s radiation budget through its complex interaction with clouds and large-scale atmospheric circulation patterns (Wild et al., 2013; Wu et al., 2018; Zhao et al., 2020). Water vapor absorbs incoming solar radiation and through positive climate feedback, causes heating in the climatic system (Dessler & Sherwood, 2009; Obregón et al., 2021). A high increase in precipitation over the Iberian Peninsula during March–May 2020 compared to 2015–2019 mean, resulted in contrasting trends in LST (i.e. decrease in daytime LST) compared to the rest of the European continent, which has mostly witnessed dry conditions and sunny weather patterns (van Heerwaarden et al., 2021) that could have resulted in positive LST anomaly (Fig. 1). Moreover, several exceptionally dry days and lower cloud fractions were also reported in Western Europe (van Heerwaarden et al., 2021) that may facilitate the LST increase (both in daytime and nighttime) during the lockdown. Thus, the dry atmosphere and weather patterns backing sunny weather could be leading to persistent positive LST anomaly in Western Europe. Similarly, over North America, significant variations in meteorological conditions may affect the LST changes in a contradictory way. Therefore, the results in LST and AOD variations between lockdown and non-lockdown periods are more difficult to be quantified due to masking effect of changes in local, regional meteorology (Baldasano, 2020; Goldberg et al., 2020; Schiermeier, 2020) and several other related parameters examined above like LULC types.

The influence of decadal climate variability, such as El Niño-Southern Oscillation (ENSO) might not be the cause of LST drops since the Oceanic Niño Index (ONI) values ranged only from −0.5 to 0.4 during the 3-month running mean from February to July 2020 (NOAA, 2021). Notably, such widespread negative nighttime LST anomaly across Europe and North America cannot be explained only by either small-scale natural variability (local meteorology) or large-scale decadal climate variability (ENSO), and therefore, it has to be apportioned to other sources/causes. Thus, it can be deduced that large-scale nighttime
reduction of temperature during the lockdown period was mostly attributed to minimal emissions by human activities (Srivastava et al., 2021) and the weakening of the UHI effect, while it can be also modulated by changes in meteorology, surface characteristics and natural aerosol variability (Pandey & Vinoj, 2021). A 3-D atmospheric numerical modeling approach is required to quantify the contribution of different sectors (transport, industry, etc.) and the role of meteorological variability in the reduction of atmospheric pollutants and changes in LST during the lockdown period.

Changes in LST at city scales during the lockdown could have been also modulated by the LULC types (Halder et al., 2021; Liu et al., 2021) and extreme in weather conditions (temperature, precipitation, wind) (Xiang et al., 2021). Typically, urban structures are associated with increase in density of buildings and roads, whilst decrease in water bodies and green cover (Dewan et al., 2021; He et al., 2019). LULC types have been found to be strongly related to the LST pattern, and especially buildings, rooftops, roads, and bare soil in urban areas contribute to higher LST, whereas urban greenery (i.e. forests, agricultural lands) and water bodies were associated with lower temperatures (Chen & Lin, 2021). Thereby, characteristics of urban surfaces are the main driving factors for either increment or mitigation of LST due to alternation in albedo, emissivity, thermal conductivity and radiative fluxes (Filtria et al., 2019; Portela et al., 2020). Urbanization also alters the LULC, and consequently, the UHI is significantly higher in cities leading to detrimental effects on human health associated with heat stress (Patz et al., 2005). With increasing urban structures in Melbourne, it was found that UHI intensity has increased by 1.2 ± 0.2 °C and moreover, the variations of UHI intensity found to be driven by climate variations (e.g. drought, heavy rainfall and ENSO) (Harmay et al., 2021). Therefore, urban heat stress can be managed through proper land use planning and designing cities along with the SDGs. Some of the existing urban heat mitigation approaches are the increasing of green (i.e. including vegetation cover in rooftop) and blue spaces, increasing the albedo of urban materials (Touchaei & Akbari, 2013), decreasing heat from surface transportation and energy savings in buildings (Costanzo et al., 2016). Furthermore, climate change is leading to deterioration of urban microclimate and hence, long-term sustainable policies are required as a mitigation strategy towards urban heat, since the negative LST anomalies during the COVID-19 lockdown was rather parodic.

5. Conclusions

The COVID-19 pandemic has caused temporary improvement of air quality at a global scale and thereby, a silver lining of the environment owing to large-scale reductions in human activities, such as transport, industrial production, and energy consumption. The results of the current study revealed a general decreasing tendency in nighttime LST, in AOD and atmospheric water vapor content over the major part of Europe and North America during the lockdown period (March–May) of the pandemic year (2020) compared to the same periods in 2015–19. Negative (nighttime) surface temperature anomalies were noticed in Europe, ranging from −0.11 °C over Austria to −2.6 °C over Belarus. Similarly, negative LST anomalies were mostly seen over USA (−0.7 °C) and Canada (−0.27 °C). Moreover, a large drop in nighttime LST was seen in urban areas compared to rural areas (difference of about 1–2 °C). These negative LST anomalies were corroborated with the station-based measurements of negative air temperatures (Tmin) anomalies in major cities in Europe and North America. On the other hand, in vast areas in Europe and North America, the daytime LST anomalies were positive, indicating an increase in surface temperature during the lockdown period, as a result of the higher amount of solar irradiance reaching the ground due to less attenuation by aerosols and pollutants.

The temperature changes were mainly attributed to reduced levels of aerosols and pollutants during the lockdown period associated with the shutdown of vehicular, power plants and industrial emissions. However, the significant variations of spatio-temporal distributions of LST over a region could be due to the combined influences of natural (e.g. topography, LULC types, cloud, rainfall, wind, etc.) and anthropogenic factors (population, gross domestic product, etc.). Nevertheless, these temporary dropdowns in temperature have shown some evidence in minimizing the UHI effect over selected cities in Europe and North America that may potentially improve thermal comfortability and well-being of people in urban environment.

The anthropogenic emissions and LST again returned to standard levels as per the business as usual scenarios when the governments terminated the lockdown measures. Nevertheless, this study provided an insight that an improvement in air quality could be achieved if all countries adopt to optimize usages of citizen transport, industrial production and energy consumption with some strict air quality measures. By adhering to sustainable transport plans and clean air policies, especially the urban environment could be improved due to declining atmospheric pollutants and less urban heat stress.

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Declaration of Competing Interest

The authors declare no conflict of interest.

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