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Reasons for the observed tropospheric ozone weakening over south-western Europe during COVID-19: Strict lockdown versus the new normal

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HIGHLIGHTS

• Ozone reduction during COVID-19 disease over south-western Europe
• Hemispheric contributions decreased markedly
• Decrease in ozone formation from regional precursors during strict lockdown
• Air pollution is not an endemic matter.

GRAPHICAL ABSTRACT

ABSTRACT

In this work we investigate the variation in tropospheric ozone concentrations in south-western Europe in March and April 2020 in the context of COVID-19 disease, and to what extent the former situation was recovered one year after the pandemic outbreak. To carry this study, data from 15 regional background sites in Spain, from 2010 onwards, are used. Historic (2010–2019) and most recent tropospheric ozone concentrations are compared. March and April 2020 ozone concentrations declined over 15% in most cases, rising to 23–28% at sites facing the Mediterranean. Most of the decay was related to the reduction of hemispheric background concentrations, but those sites downwind continental emissions from the Iberian Peninsula and neighbouring countries experienced an additional lessening. By exploring O3 concentrations one year after, March and April 2021, the general decline with respect to 2010–2019 persist but its magnitude was substantially lessened with respect to the strict lockdown period. The pandemic situation unveiled that air pollution is not an endemic matter but it should be tackle with adequate actions. Ozone abatement plans for Mediterranean countries should need a pan-regional covenant in order to drop precursor emissions.

ARTICLE INFO

Editor: Pavlos Kassomenos

Keywords:
Long range transport
Air quality
Secondary pollutant
Meteorology
Mediterranean

1. Introduction

Tropospheric ozone is a short-lived trace gas produced by photochemical reactions involving gas precursors (nitrogen oxides, non-methane volatile organic compounds, methane or carbon monoxide), or is transported from the stratosphere, where it is formed naturally (Cooper et al., 2014). Ozone formed in the troposphere is the result of intricate transformations and reactions involving a number of chemicals released by natural and anthropogenic sources (Monks et al., 2015; Seinfeld and Pandis, 2016). As a result of increasing emissions from anthropogenic sources in last decades, ozone formation has been
substantially enhanced, especially over the Northern Hemisphere (Cooper et al., 2014).

The Western Mediterranean is one of the regions in the Northern Hemisphere more affected by ozone pollution (EEA, 2021), where it is accumulated owing to the significance of recirculation processes and hemispheric transport (Millán et al., 1997; Gangoiti et al., 2006; Jiménez et al., 2006). Ozone concentrations in this region exceed by far the new guidelines recently approved by the World Health Organization (WHO, 2021). The annual peak is usually recorded in the transition spring-summer, coinciding with the bloom of biogenic emissions and elevated anthropogenic emissions over the whole region as a result of the beginning of the touristic season, under intense sunlight conditions (Cerro et al., 2015, 2020). In addition, part of such ozone spring increase in the western Mediterranean is frequently due to tropospheric subsidence (Kalabokas et al., 2017) under specific synoptic meteorological conditions. The observed mechanism is not only occurring in the Western Mediterranean but also in the Eastern part in summer months (Gaudel et al., 2018, and references therein). A recent study by Pay et al. (2019) has focused on the source apportionment of this pollutant during summer period in the Iberian Peninsula, demonstrating that hemispheric ozone contribution ranges from 40 to 80%. According to that study, regional to local ozone formation is only significant over downwind areas towards anthropogenic emissions are carried.

To tackle air quality degradation, including ozone pollution, a number of strategies have been implemented throughout the European continent in the last two decades. Although the concentrations of some pollutants have declined significantly over the last years, those of ozone remain at the same levels or even they have augmented (EEA, 2009; Cerro et al., 2015).

COVID-19 health crisis emerged as an interesting case-study comparable to current projected atmospheric emissions in 2050 for OCDE countries (Rao et al., 2017). In this period, especially during the pandemic crisis, mobility was exceptionally reduced and millions of inhabitants were locked down at their homes. The benefits of this situation in terms of air quality have been extensively documented (Barrera et al., 2021; EEA, 2021; Querol et al., 2021; Slezakova and Pereira, 2021) but they are focused mainly on NO2 and particulate matter. Our aim is to quantify the benefit of this crisis on O3 concentrations in the Western Mediterranean, one of the Northern Hemisphere hotspots, and to infer whether this benefit is linked to local ozone production or is related to the hemispheric background. In the particular case of Spain, a strict lockdown was implemented by the Spanish Government from March 14th 2020 to April 26th 2020. From that date a progressive softening of lockdown measures was applied, but it was on June 21st 2020 when the new normal arrived (https://www.lamoncloa.gob.es/covid-19/Paginas/index.aspx). After this new normal, the regional governments adopted the necessary actions based on the evolution of the pandemic crisis. As a result, several actions were taken in different territories across Spain to contain the new COVID-19 waves, some affecting mobility in between regions, provinces or even municipalities, some others limiting the number of people in public and private spaces, or closing bars, restaurants or cultural places, but none of them comparable to the period March–April 2020.

2. Methods

For this study we have collected tropospheric ozone data from 15 regional background sites and 1 suburb site in different regions in Spain: Laza, in Galicia (https://www.metegalic.es/LaCaire/index.action?request_locale =es); Cangas, in the Principado of Asturias (https://tematico.asturias.es/CecomaWeb/index.php); Valderejo, in Euskadi (http://www.euskadi.eus/gobierno-vasco/aire-medioambiente/); El Maillo, in Castilla y León (http://servicios.jcyl.es/esco/index.action); El Atazar, in the Comunidad de Madrid (http://gestiona.madrid.org/azul_internet/run/j/AvisosAccion.icm); Galilea, in La Rioja (https://www.larioja.org/medioambiente/es/calidad-aire-cambio-climatico/calidad-aire); Torrelisa, in Aragón (http://www.aragonaire.es/index.php); Pardines, in Catalunya (http://mediambient.gencat.ca/ca/05_ambits_dactuacio/atmosfera/qualitat_de_laire/); Zorita and Pinoso, in the Comunitat Valenciana (http://www.agroambient.gva.es/es/web/calidad-ambiental/calidad-del-aire); the EMEP sites of Barcarrota and Viznar, in Extremadura and Andalucía, respectively (http://ebas.nilu.no/), Doñana, in Andalucía (https://www.juntadeandalucia.es/medio-ambiente/emisiones/emisiones/calidad.html); and Can Llompart, in Illes Balears (http://www.caib.es/sites/atmosfera/es/indice_de_la_calidad_del_aire-25433/). In the EMEP sites, NO2 concentrations were also retrieved. All data are freely available in their respective websites. Exact location of these monitoring sites is provided in Table 1.

The study period covers the interval 2010–2021. The months under study are March (the beginning of the mobility restrictions and lockdown was implemented in the different European countries from 9th to 22nd March, being applied in Spain since March 14th, see RD 463/2020) and April (most of Northern Hemisphere citizens subjected to mobility restrictions and economies severely tempered by the shut-down). The evaluation of O3 concentrations one year after the lockdown has been conducted.

2.1. Lockdown phases and COVID-19 restrictions in Spain

In Spain, on March 14th 2020 was declared the state of alarm due to COVID-19 outbreak, entering in force on March 16th (Real Decreto 463/2020). During the established period, the restriction of the movement of citizens was decreed. The supply of food and products necessary for public health was guaranteed. The Government regulated the opening of hotels, restaurants and places where cultural activities were carried out, including artistic, sports and similar. The prioritization of remote work and the suspension of face-to-face school activity were implemented. The Minister of Health had under his direct orders the civil authorities of the Public Administrations throughout the country, in particular the health authorities. The strict lockdown started on March 16th and ended on May 2nd. From this date, a progressive softening of some of the restrictions was introduced, including the allowance of 1 h per day for outdoor activity to the completion of the first new normal period on June 21st 2020 (https://www.lamoncloa.gob.es/covid-19/Paginas/plan-transicion.aspx).

The second state of alarm declared by the Spanish Government was on October 9th 2020, but only affected some municipalities in the Madrid Region, affecting mobility in the concerned area (Real Decreto 900/2020). The third state of alarm was declared on October 25th 2020 (Real Decreto 956/2020) and affected all the Spanish territory until May 9th 2021. During that period there were mobility restrictions in between Spanish regions (not inside each region) but it was allowed for professional Table 1

| Name site | Latitude (N) | Longitude | Altitude (m a.s.l) | Region | Type |
|-----------|--------------|-----------|------------------|--------|------|
| Laza      | 42,0616      | 74,089    | 767              | Galicia | Regional |
| El Maillo | 40,5697      | 62,239    | 1029             | Castilla y León | Regional |
| El Atazar | 40,9103      | 34,603    | 995              | Comunidad de Madrid | Regional |
| Cangas    | 43,1808      | 65,503    | 330              | Asturias | Regional |
| Tojos     | 43,1528      | 42,531    | 605              | Cantabria | Regional |
| Valderejo | 42,8751      | 32,318    | 905              | Euskadi | Regional |
| Galilea   | 42,3414      | 21,350    | 570              | La Rioja | Regional |
| Torrelisa | 42,2725      | 10,065    | 1006             | Aragón | Regional |
| Pardines  | 42,1213      | 22,130    | 1224             | Catalunya | Regional |
| Barcarrota| 38,4728      | 69,236    | 393              | Extremadura | EMEP |
| Zorita    | 40,7350      | 0,1694    | 619              | Comunitat Valenciana | Regional |
| Pinós     | 38,4516      | 10,664    | 642              | Comunitat Valenciana | Regional |
| Doñana    | 37,0519      | 65,553    | 35               | Andalucía | EMEP |
| Viznar    | 37,2372      | 35,342    | 1230             | Andalucía | EMEP |
| Can       | 39,8408      | 30,280    | 25               | Illes Balears | Regional |
| Llompart  | 39,8753      | 43,164    | 78               | Illes Balears | EMEP |
matters or other justified reasons; the free mobility of people between 23:00 and 6:00 was not allowed; the number of people in public and private places was controlled; and the presence of people in worship places was also limited. The extent of application of these measures and its severity was decided individually for each Region, depending on the evolution of the pandemics. This resulted in very dissimilar restrictions across Spain from November 2020 to May 2021, but without lockdowns.

3. Results

Historic ozone (2010–2019) in the selected sites ranged from 57 to 91 μg m⁻³ in March and 61–95 μg m⁻³ in April (Fig. 1, top part). In general, Northern sites displayed comparable ozone concentrations in the range 77–89 μg m⁻³, with the exception of Cangas (suburban), which is affected by nearby industrial and traffic emissions. In Central, Southern and Eastern sites, ozone concentrations were usually in the range 68–93 μg m⁻³, with the exception of Barcarrota, in which ozone concentrations were significantly lower (56–59 μg m⁻³). When regarding the situation in 2020 for the same two months, regional background sites in Northern, Central and Eastern Iberia, as well as in the Balearic Islands, reflect an ozone reduction ranging from 2% to 19% in March 2020 when compared to the 2010–2019 average (Fig. 1, central part). In April, when mobility restrictions were at their highest, the reduction ranged from 8% to 28% with respect to the 10-year average. The two sites located in the south-western part of Iberia display very low ozone variation with respect to historic values, being slightly positive in Barcarrota (from 1.7 to 2.3 μg m⁻³). The wide-ranging March 2020 variation, with still normal activity in most Europe until day 15, shows a reduction ranging from 5 to 15 μg m⁻³, being around 12–15 μg m⁻³ at 6 sites. In April, such downward trend was accentuated, rising to 7–22 μg m⁻³, commonly from 13 to 21 μg m⁻³ at 10 of the 16 sites (Fig. 1). It is interesting to observe that such April decline was more prominent in the regional background sites facing the Mediterranean coast, equivalent to −18.0 to −22.0 μg m⁻³.

These observations may advise on two main patterns: 1) most of the ozone reduction in April 2020 could be related to a decline in hemispheric

![Fig. 1. Top-maps: 10-year average ozone concentration (μg m⁻³) for March and April (2010–2019) over different regional background sites in Spain; central-maps: ozone variation (μg m⁻³) with respect to the 10-year average in March and April 2020; bottom maps: ozone variation (μg m⁻³) with respect to the 10-year average in March and April 2021.](image-url)
and regional-derived background concentrations (around \(-15,0 \, \mu g \, m^{-3}\)); 2) the extra 3–9 \, \mu g \, m^{-3} of decrease observed in the Mediterranean sites could be the ozone formation related to anthropogenic precursors emitted in the Iberian Peninsula.

Once the economic activity was partially recovered one year after the strict lockdown, ozone concentrations still displayed a general reduction with respect to the historic 2010–2019 values (Fig. 1, bottom). The reduction observed in March 2021 was significant in Northern (\(-5.2 \, \mu g \, m^{-3}\)), Southern (\(-4.7 \, \mu g \, m^{-3}\)) and Mediterranean sites (\(-4.8 \, \mu g \, m^{-3}\), with the exception of Mahó (\(+2.6 \, \mu g \, m^{-3}\)), but insignificant in Central Iberia (\(-0.3 \, \mu g \, m^{-3}\)). However, ozone concentrations in April 2021 were generally lower than the historic ones, although the difference was less marked than in April 2020. Only four sites registered an ozone decrease higher than 10 \, \mu g \, m^{-3} (they were 11 sites in 2020), while at two sites a moderate to sharp increase was observed (Barcarrota +5.8 \, \mu g \, m^{-3}, Mahó +17.6 \, \mu g \, m^{-3}). As explained previously, to battle against the different waves of the pandemic crisis, regional governments adopted a number of temporal measures which affected mainly the free movements among regions or provinces, in most cases affecting leisure trips but not professional displacements.

In an attempt to explore the origin of \(O_3\) variations, parallel \(NO_2\) data have been examined for those sites in which \(NO_2\) data quality was assured. As seen in Table 2, changes in ozone in 2020 and 2021 with respect to historic values are poorly related to \(NO_2\) variations, for example via titration of ozone, and from \(NO_2\), are prominent, varying from \(-18.8\) to \(+17.3 \, \mu g \, m^{-3}\) in the case of ozone, and from \(-19.7\) to \(+16.4 \, \mu g \, m^{-3}\) in the case of \(NO_2\). Net \(O_3\) changes are, therefore, intrinsic related to this pollutant rather to atmospheric reactions onsite.

In order to investigate in more detail the origin of the described depletions, we have calculated (individually for the period 2010–2019, and 2020 and 2021) for a selection of Northern and Mediterranean sites, the averages for the period 22 h–09 h, thus representing background values under limited photochemical ozone production (hemispheric + regional background), and those between 12 h–18 h, thus in the period in which photochemical reactions occur (added to the former the diurnal ozone formation at local to regional scale). With this procedure we should be able to quantify the variations of the regional-to-hemispheric background and the magnitude of the diurnal ozone production related to local-to-regional emissions. As seen in Table 3 and Fig. 2, the regional-to-hemispheric ozone background was reduced in March 2020 and April 2020 with respect to historic data, from 3.0 to 14.1 \, \mu g \, m^{-3} of decrease in March 2020, and from 13.5 to 16.7 \, \mu g \, m^{-3} of decrease in April 2020 in the Iberian Peninsula, dropping by 25.6 and 23.8 \, \mu g \, m^{-3} in the Balearic Islands, for March and April 2020 respectively. In general the observed decrease ranged between 6 and 20% in March and 17 to 35% in April with respect to historic values. In March 2021, the hemispheric and regional background was clearly bellowing the historic records by 8 to 24%, tumbling to 40% in Can Llompart. The observed decrease was comparable to March 2020 (\(-4.3\) to \(-25.6 \, \mu g \, m^{-3}\) of reduction), especially accentuated in Tojos and Can Llompart. The concentrations recorded in April 2021 were kept bellow historic averages in Tojos (\(-13.6 \, \mu g \, m^{-3}\), \(-20\%\)), Pardines (\(-7.0 \, \mu g \, m^{-3}\), \(-10\%\)), Can Llompart (\(-6.0 \, \mu g \, m^{-3}\), \(-16\%\)) and Zorita (\(-3.4 \, \mu g \, m^{-3}\), \(-8\%\)), but resembled those of the historic period in Torrelisa.

While the hemispheric + regional ozone background was significantly reduced during the health crisis, the diurnal ozone formation (difference between concentrations in the period 12 to 18 h local time with respect to concentrations in the period 22 to 09 h local time) was not reduced in the same amount. Actually, at the two sites located in the Pyrenees (Torrelisa and Pardines), a slightly higher diurnal ozone formation was observed in April 2020 with respect to historic data (from 2.6 to 3.2 \, \mu g \, m^{-3}\), with a tiny increase in March 2020 in Pardines (0.9 \, \mu g \, m^{-3}), and a slight decrease in March at Torrelisa (\(-3.3 \, \mu g \, m^{-3}\)). In eastern Iberia and in the Balearic Islands sites the diurnal ozone formation decreased in March 2020 (from \(-2.9\) to \(-6.5 \, \mu g \, m^{-3}\), but especially in April 2020 (from \(-6.9\) to \(-8.3 \, \mu g \, m^{-3}\)). These results could indicate that the decrease in anthropogenic emissions over the Iberian Peninsula (Querol et al., 2021), in a context of prevalent westerlies over south-western Europe in this period of the year may explain the decrease observed in these Mediterranean sites (less precursors available, less ozone formation). On the contrary, the low variation (even slightly positive) in the Pyrenees may have another explanation: prevalence of westerlies, having in mind the low anthropogenic emissions taking place westwards from the two Pyrenean sites, but an earlier arrival of the spring season in 2020 over south-western Europe (see Spanish Meteorological Agency reports from February, March and April 2020, http://www.aemet.es/es/serviciosclimaticos/vigilancia_clima/resumes?w=0) could anticipate few days to weeks the release of volatile organic compounds from vegetation, thus contributing to the slight enhancement of diurnal ozone production.

In 2021 the situation regarding diurnal ozone formation was reversed with respect to 2020. At most sites the significant improvement observed in 2020 was diminished or even overturned, especially in March 2021. Tojos, Torrelisa, Pardines and Zorita displayed higher diurnal formation with respect to historic values. March 2021 was drier and sunnier than usual (see Spanish Meteorological Agency report for March 2021, http://www.aemet.es/documentos/es/serviciosclimaticos/vigilancia_clima/resumes/resumenes_climat_mensuales/2021/res_mers_clim_2021_03.pdf). Under such circumstances an enhancement of photochemical activity could be expected. The diurnal formation of \(O_3\) in April 2021 was more important, in general, than in 2020, but still not reaching historic values.

### Table 2

|            | NO\(_2\) | O\(_3\) | Ox | \(\Delta NO_2\) | \(\Delta O_3\) | \(\Delta Ox\) |
|------------|---------|--------|----|----------------|---------------|-------------|
| March 2010–2019 | 1.82    | 59.4   | 61.2 | -0.4           | 1.7           | 1.3         |
| 2020        | 1.41    | 61.1   | 62.5 | -0.1           | -0.3          | -0.4        |
| 2021        | 1.71    | 59.1   | 60.8 | -0.1           | -0.3          | -0.4        |
| Doñana 2010–2019 | 2.31    | 70.3   | 72.6 | -0.1           | 1.3           | 1.4         |
| 2020        | 2.85    | 69.7   | 72.5 | -0.5           | -0.6          | -0.1        |
| 2021        | 2.16    | 65.6   | 67.7 | -0.1           | -0.4          | -0.5        |
| Vizar 2010–2019 | 3.94    | 87.1   | 91  | -0.1           | 1.3           | 1.4         |
| 2020        | 2.52    | 80.2   | 82.7 | -1.4           | -6.9          | -8.3        |
| 2021        | 3.42    | 79.4   | 82.9 | -0.5           | -7.6          | -8.2        |
| Zarra 2010–2019 | 3.02    | 91.8   | 94.8 | -0.1           | 1.3           | 1.4         |
| 2020        | 0.87    | 74.2   | 75.1 | -2.1           | -17.6         | -19.7       |
| 2021        | 1.1     | 84.5   | 85.6 | -1.9           | -7.2          | -9.1        |
| Mahó 2010–2019 | 4.02    | 90.9   | 94.9 | -1.5           | -5.4          | -6.9        |
| 2020        | 2.5     | 85.4   | 87.9 | -1.5           | -5.4          | -6.9        |
| 2021        | 2.3     | 93.5   | 95.8 | -1.7           | 2.6           | 0.9         |

*All values in \(\mu g \, m^{-3}\).*
4. Discussion and conclusions

The health crisis that emerged early in 2020 changed our life and societies. The pandemic crisis and the adopted limitations in mobility and social interaction to counteract SARS-CoV-2 spread brought a number of environmental benefits (Rume and Islam, 2020). Air quality was substantially improved in many European regions (EEA, 2021). In this study we have put the eye on ozone, a secondary gas pollutant subjected to complex formation mechanisms. Most of the studies have put the focus on urban variations of NO2, PM10 and PM2.5. It has been extensively shown that urban emissions were reduced up to 50 or 60% (Querol et al., 2021). However, in our study we have observed an ozone decrease in regional background sites up to 25%. Our findings are connected to those by Barré et al., 2021, who show average reductions of European NO2 concentrations of 23% (satellite monitoring), 43% (surface stations), and 32% (models). In this regard, the EEA (2021) report shows a NO2 map for April 2020 in which the NO2 decrease in Spain ranges from 15 to 60% (https://www.eea.europa.eu/data-and-maps/figures/relative-changes-in-no2-concentrations). Therefore, the lockdown provoked a real background ozone drop, partially related to a decrease in the continental background, but also affected by the lessening of regional ozone formation in the Iberian Peninsula-Balearic Islands domain. In this short manuscript we analyse the extent of this reduction from the strict lockdown in March and April 2020 to the new normal scenario one year after. In the first case, land transport was extraordinarily reduced and industrial emissions dropped substantially. Therefore, primary atmospheric pollutants from these sources decreased by around 50% (EEA, 2021). This unique situation created a low-emission scenario, but the effect on a secondary pollutant is little explored. Cuesta et al. (2021) have explored the extent of ozone changes over Europe from 1 to 15 April 2020 with respect to the same period in 2019, comparing ground based observations, satellite data and model simulations. They have observed clear changes in ozone concentrations across Europe, positive in some cases, negative in others. They have observed clear ozone enhancements in Central Europe, Northern Italy, and other hotspots, where VOC-limited chemical regimes prevail, contrasting to a general decrease where ozone chemistry is driven by NOx. In an attempt to remove the meteorological effect from their observations they used chemistry transport model simulations of each year and identical emission inventories, and corroborated that emission reduction during lockdown was consistent, and provoked ozone enhancements in the most polluted areas over Central Europe and the Po Valley, while promoted an overall reduction elsewhere over Europe and the ocean.

The health emergence caused by the COVID-19 disease has evidenced that atmospheric pollution should not be an endemic matter. In this work we have demonstrated that the decline in ozone concentrations reached over 15% in most cases, but to 23–28% in different parts (Fig. 3). One year after the pandemic outbreak, a significant part of the ozone reduction over southwestern Europe was still evident, but the magnitude was much reduced.

Almost two thirds of the decline has been found to be in regional-to-hemispheric contributions. In spite of this, our results unveil a non-negligible ozone formation from continental emissions taking place in the Iberian Peninsula and neighbouring countries, which contribute to increase tropospheric ozone downwind, that is, over the Mediterranean region. Bearing in mind the extensive knowledge about Mediterranean air-pollutants dynamics, affected by recirculation processes over the basin (see Millán, 2014 and references therein), a common strategy to offset ozone precursors in Mediterranean countries should be adopted.

4.1. Variations of the ozone background

The health crisis emerged early in 2020 changed our life and societies. The pandemic crisis and the adopted limitations in mobility and social interaction to counteract SARS-CoV-2 spread brought a number of environmental benefits (Rume and Islam, 2020). Air quality was substantially improved in many European regions (EEA, 2021). In this study we have put the eye on ozone, a secondary gas pollutant subjected to complex formation mechanisms. Most of the studies have put the focus on urban variations of NO2, PM10 and PM2.5. It has been extensively shown that urban emissions were reduced up to 50 or 60% (Querol et al., 2021). However, in our study we have observed an ozone decrease in regional background sites up to 25%. Our findings are connected to those by Barré et al., 2021, who show average reductions of European NO2 concentrations of 23% (satellite monitoring), 43% (surface stations), and 32% (models). In this regard, the EEA (2021) report shows a NO2 map for April 2020 in which the NO2 decrease in Spain ranges from 15 to 60% (https://www.eea.europa.eu/data-and-maps/figures/relative-changes-in-no2-concentrations). Therefore, the lockdown provoked a real background ozone drop, partially related to a decrease in the continental background, but also affected by the lessening of regional ozone formation in the Iberian Peninsula-Balearic Islands domain. In this short manuscript we analyse the extent of this reduction from the strict lockdown in March and April 2020 to the new normal scenario one year after. In the first case, land transport was extraordinarily reduced and industrial emissions dropped substantially. Therefore, primary atmospheric pollutants from these sources decreased by around 50% (EEA, 2021). This unique situation created a low-emission scenario, but the effect on a secondary pollutant is little explored. Cuesta et al. (2021) have explored the extent of ozone changes over Europe from 1 to 15 April 2020 with respect to the same period in 2019, comparing ground based observations, satellite data and model simulations. They have observed clear changes in ozone concentrations across Europe, positive in some cases, negative in others. They have observed clear ozone enhancements in Central Europe, Northern Italy, and other hotspots, where VOC-limited chemical regimes prevail, contrasting to a general decrease where ozone chemistry is driven by NOx. In an attempt to remove the meteorological effect from their observations they used chemistry transport model simulations of each year and identical emission inventories, and corroborated that emission reduction during lockdown was consistent, and provoked ozone enhancements in the most polluted areas over Central Europe and the Po Valley, while promoted an overall reduction elsewhere over Europe and the ocean.

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The health crisis emerged early in 2020 changed our life and societies. The pandemic crisis and the adopted limitations in mobility and social interaction to counteract SARS-CoV-2 spread brought a number of environmental benefits (Rume and Islam, 2020). Air quality was substantially improved in many European regions (EEA, 2021). In this study we have put the eye on ozone, a secondary gas pollutant subjected to complex formation mechanisms. Most of the studies have put the focus on urban variations of NO2, PM10 and PM2.5. It has been extensively shown that urban emissions were reduced up to 50 or 60% (Querol et al., 2021). However, in our study we have observed an ozone decrease in regional background sites up to 25%. Our findings are connected to those by Barré et al., 2021, who show average reductions of European NO2 concentrations of 23% (satellite monitoring), 43% (surface stations), and 32% (models). In this regard, the EEA (2021) report shows a NO2 map for April 2020 in which the NO2 decrease in Spain ranges from 15 to 60% (https://www.eea.europa.eu/data-and-maps/figures/relative-changes-in-no2-concentrations). Therefore, the lockdown provoked a real background ozone drop, partially related to a decrease in the continental background, but also affected by the lessening of regional ozone formation in the Iberian Peninsula-Balearic Islands domain. In this short manuscript we analyse the extent of this reduction from the strict lockdown in March and April 2020 to the new normal scenario one year after. In the first case, land transport was extraordinarily reduced and industrial emissions dropped substantially. Therefore, primary atmospheric pollutants from these sources decreased by around 50% (EEA, 2021). This unique situation created a low-emission scenario, but the effect on a secondary pollutant is little explored. Cuesta et al. (2021) have explored the extent of ozone changes over Europe from 1 to 15 April 2020 with respect to the same period in 2019, comparing ground based observations, satellite data and model simulations. They have observed clear changes in ozone concentrations across Europe, positive in some cases, negative in others. They have observed clear ozone enhancements in Central Europe, Northern Italy, and other hotspots, where VOC-limited chemical regimes prevail, contrasting to a general decrease where ozone chemistry is driven by NOx. In an attempt to remove the meteorological effect from their observations they used chemistry transport model simulations of each year and identical emission inventories, and corroborated that emission reduction during lockdown was consistent, and provoked ozone enhancements in the most polluted areas over Central Europe and the Po Valley, while promoted an overall reduction elsewhere over Europe and the ocean.

The health emergence caused by the COVID-19 disease has evidenced that atmospheric pollution should not be an endemic matter. In this work we have demonstrated that the decline in ozone concentrations reached over 15% in most cases, but to 23–28% in different parts (Fig. 3). One year after the pandemic outbreak, a significant part of the ozone reduction over southwestern Europe was still evident, but the magnitude was much reduced.

Almost two thirds of the decline has been found to be in regional-to-hemispheric contributions. In spite of this, our results unveil a non-negligible ozone formation from continental emissions taking place in the Iberian Peninsula and neighbouring countries, which contribute to increase tropospheric ozone downwind, that is, over the Mediterranean region. Bearing in mind the extensive knowledge about Mediterranean air-pollutants dynamics, affected by recirculation processes over the basin (see Millán, 2014 and references therein), a common strategy to offset ozone precursors in Mediterranean countries should be adopted.
Having in consideration that ozone pollution is one of the main air quality concerns in Southern European countries, the air quality benefit induced by the health crisis may persuade our politicians and policymakers to really battle against air pollution. The pandemic crisis has provided to our society the opportunity of having a healthier atmosphere. In the new normal, part of the air quality benefit arrived in 2020 still persists, and could be related to the higher prevalence of homeworking, which reduced the overall emission from vehicles. Thus, the option of homeworking in different sectors, in addition to other measures to decrease land transport, should be strategic when developing abatement plans for air pollution.

CRediT authorship contribution statement

**Jorge Pey:** Conceptualization; Data curation; Formal analysis; Funding acquisition; Methodology; Project administration; original draft; review & editing.

**José Carlos Cerro:** Conceptualization; Data curation; Formal analysis; review & editing.

Data availability

All data from this study have been obtained from public databases.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Fig. 3. % of ozone change in March and April 2020 (strict lockdown) and March and April 2021 with respect to 2010–2019 historic data.

Acknowledgements

We would like to thank all the regional administrations from Spain used in this work for the provision of their data. Furthermore, we would like to thank the co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants (EMEP) for the provision of Barcarrota and Viznar data. The Spanish Agencia Estatal de Investigación (AEI – Spain) and the European Funds for Regional Development (FEDER – European Union) are gratefully acknowledged for financial support through CGL2015-68993-R and PID2019-108101RB-I00 projects (AEI/ FEDER, UE).

References

Barre, J., Peterin, H., Colette, A., Guevara, M., Pesch, V.H., Rouil, L., Engelen, R., Inness, A., Flemming, J., Pérez García-Pando, C., Bowdalo, D., Meleux, F., Geels, C., Christensen, J.H., Gauss, M., Benedictow, A., Tryro, S., Friese, E., Struzewiska, J., Kaminiski, J.W., Dourson, J., Timmenmanns, R., Robertson, L., Adani, M., Jorba, O., Joly, M., Koznentso, R., 2021. Estimating lockdown-induced european NO2 changes using satellite and surface observations and air quality models. Atmos. Chem. Phys. 21, 7373–7394. https://doi.org/10.5194/acp-21-7373-2021.

Cerro, J.C., Cerda, V., Pey, J., 2015. Trends of air pollution in the Western Mediterranean Basin from a 13-year database: a research considering regional, suburban and urban environments in Mallorca (Balearic Islands). Atmos. Environ. 103, 138–146.

Cerro, J.C., Cerda, V., Querol, X., Alastuey, A., Bujosa, C., Pey, J., 2020. Variability of air pollutants, and PM composition and sources at a regional background site in the Balearic Islands: review of western Mediterranean phenomenology from a 3-year study. Sci. Total Environ. 717, 137177. https://doi.org/10.1016/j.scitotenv.2020.137177.

Cooper, O.R., Parrish, D.D., Ziemke, J., Balashov, N.V., Cupeiro, M., Galbally, I.E., Gilge, S., Horowitz, L., Jensen, N.R., Lamarque, J.-F., Naik, V., Oltmans, S.J., Schwab, J., Shindell, D.T., Thompson, A.M., Thouret, V., Wang, Y., Zbinden, R.M. 2014. Global distribution and trends of tropospheric ozone: an observation-based review. Elementa (Wash. D.C.) 2, 000029. https://doi.org/10.12952/journal.elementa.000029.
