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Study of the exceptional meteorological conditions, trace gases and particulate matter measured during the 2017 forest fire in Doñana Natural Park, Spain

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Abstract

In late June 2017, a forest fire occurred in Doñana Natural Park, which is located in southwestern Europe. Many animal and plant species, some of which are threatened, suffered from the impact of this fire, and important ecosystems in the European Union were seriously affected. This forest fire occurred under exceptional weather conditions. The meteorological situation was studied at both the synoptic scale and the local scale using meteorological fields in the ERA-Interim global model from ECMWF (European Centre for Medium Range Weather Forecasts), the WRF (Weather Research and Forecasting) mesoscale model and ground observations collected at El Arenosillo observatory. Anomalies were obtained using records (observations and simulations) over the last two decades (1996-2016). An anticyclonic system dominated the synoptic meteorological conditions, but a strong pressure gradient was present; positive high pressure anomalies and negative low pressure anomalies resulted in intense NW flows. At the surface, wind gusts of 80 km h^{-1}, temperatures up to 35 ^{o}C and relative humidity values less than 20 % were observed. In terms of anomalies, these observations corresponded to positive temperature anomalies (differences of 12 ^{o}C), positive wind speed anomalies (greater than 29 km h^{-1}) and negative relative humidity anomalies (differences of 40

%). The forest fire reached El Arenosillo observatory approximately 8 hours after it began. When the fire started, record-setting maximum values were measured for all gases monitored at this site (specifically, peaks of 99995 µg m^{-3} for CO, 951 µg m^{-3} for O_3, 478 µg m^{-3} for NO_2, 116 µg m^{-3} for SO_2 and 1000 µg m^{-3} for PM10). According to the temporal evolution patterns of these species, the atmosphere over a burnt area can recover to initial atmospheric levels between 48 and 96 hours after an event. The impact of the Doñana plume was studied using hourly forward trajectories computed with the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model to analyse the emission source for the burnt area. The Doñana fire plume affected large metropolitan areas near the Mediterranean coast. Air quality stations located in the cities of Seville and Cadiz registered the arrival of the plume based on increases in CO and PM10. Using CO as a tracer, measurements from the AIRS and MOPITT instruments allowed us to observe the transport of the Doñana plume from the Strait of Gibraltar to the Mediterranean. Finally, after two days, the Doñana forest fire plume reached the western Mediterranean basin.

Highlights

- A massive forest fire occurred in Doñana Natural Park in late June 2017.
- Biodiversity in this protected area was seriously affected.
- The fire occurred under exceptional synoptic and local meteorological conditions.
- The fire reached El Arenosillo, and record-setting values of trace gases were measured.
- The Doñana plume affected the western Mediterranean basin.

Keywords: Forest fire, Doñana Natural Park, biodiversity, trace gases (CO, O_3, NO_2, SO_2), ECMWF-WRF model.

1. Introduction

Climate change and air pollution will be the two greatest atmospheric challenges for societies in future decades. These environmental issues are highly connected, and there are a number of factors that link air pollution and climate change, such as emissions, atmospheric processes and chemistry (von Schneidemesser et al., 2015). Climate change has led to an increase in the frequency and intensity of extreme weather events, such as floods, droughts, heat waves and wildfires (Stott, 2016).

Wildfires occur due to dry weather and the availability of fuel and ignition sources. It is well known that temperature, relative humidity, precipitation and wind speed affect fire spread rates and intensities (Parente et al., 2018). The occurrence of weather extremes, such as hot, dry and windy conditions, leads to the most severe fires (Dupire et al., 2017). Fire season length and duration can affect large areas and have increased across all vegetated continents during the late two decades due to extreme weather events and climate change (Jolly et al., 2015).

Therefore, there is a clear feedback between climate change and forest fires. Climate change induces weather extremes, which lead to forest fires, while fire emissions contribute to climate change. These emissions increase greenhouse gas concentrations, thereby increasing atmospheric radiative forcing and aerosol concentrations and changing the Earth's albedo by depositing more light-absorbing particles onto the Earth's surface (Sommers et al., 2014).

Forest fires have impacts on the biosphere-atmosphere interface, atmospheric chemistry, atmospheric circulation, the composition of the ecosystem and its distribution, environmental degradation and air quality (Chen at al., 2017). Chemical species released by wildfires include gases such as CO_2, carbon monoxide (CO), methane (CH_4), non-methane organic compounds, nitrogen oxides (NO_x), nitrous oxide (N_2O) and sulphur dioxide (SO_2). The controlled combustion of various biomass fuels under laboratory conditions has revealed the presence of more than 500 different volatile organic compounds (VOCs), which differ in terms of reactivity, health effects and the ability to form active climate constituents (Gilman et al., 2015). Moreover, the simultaneous emission of nitrogen oxides and reactive VOCs from the combustion of biomass leads to the photochemical formation of tropospheric ozone (O_3) and secondary organic aerosols (Alvarado et al., 2015). On the other hand, smoke is the main forest fire-produced atmospheric constituent that affects air quality and climate because the massive plumes can travel thousands of kilometres downwind. The monitoring of these plumes is only possible through satellite measurements, such as AIRS or MOPITT CO measurements, because CO is emitted by forest fires (Ding et al., 2015).

This work analyses the case of a large forest fire that occurred in June 2017 in an important ecological area (Doñana Natural Park, located in southwestern Europe) under exceptional meteorological conditions because it is a clear example of the connection between extreme weather events, forest fires, air quality degradation and climate change. The meteorological context, impact on biodiversity and CO, O_3, NO_2, SO_2 and PM10 levels are analysed. The regional impact of the fire plume is studied by means of space observations and transport models.

2. Area description, instrumentation, atmospheric models and satellite observations

2.1. Area description

The area of Doñana (116487 ha of a protected park) is considered to be a major hot spot of biodiversity (López-López et al., 2011) and one of the most important wetlands in Europe. It is part of the Guadalquivir River basin and is composed of highly diverse ecosystems: forests, ponds, fossil and mobile dunes, riverbanks and beaches. The Doñana area features rich flora and fauna with many endemic, threatened, and endangered species. Despite this high biodiversity, there are many threats to its conservation, such as summer tourism, the pilgrimage of El Rocio, contamination due to heavy metals and pesticides, intensive agriculture in its surroundings, aquiculture and frequent forest fires (Groom et al., 2005). At least 80 % of the forest fires detected in the area are anthropogenically induced, 50 % of which are directly provoked, and only 4 % are naturally induced (WWF/Adena, 2008). The vegetation in the area, which was intensively reforested with pines (*Pinus pinea*) and wide areas of shrublands, makes this territory highly sensitive to forest fires. These pyrophytic species facilitate the fast expansion of fires, especially in summer, when high temperatures and drought conditions predominate. Fires are natural disturbances in Mediterranean ecosystems and have contributed to landscape dynamics for thousands of years (Trabaud et al, 1993). A large number of flora and fauna species have adapted to periodic fires by developing strategies that allow them to germinate, resprouting or recolonizing their habitat after fire. However, the delicate structure of the Mediterranean ecosystem is altered when forest fires of anthropogenic origin reoccur frequently.

El Arenosillo observatory is located in the SW Iberian Peninsula in Doñana National Park, 1 km from the Atlantic Ocean coastline (Fig. 1). Surface meteorological conditions, solar radiation, surface chemistry species (CO, O_3, NO_2 and SO_2), and optical, chemical and microphysical aerosol properties are routinely monitored. The urban area of Huelva is located 35 km away from El Arenosillo in the NW direction. The Seville metropolitan area is the largest urban area in SW Europe, with more than 1.5 million inhabitants, while the Cadiz urban area has a population greater than 0.5 million inhabitants. These urban areas are near Doñana Natural and National Park (approximately 60-70 km away). The transport of Doñana forest fire plumes to these areas could have potentially impact ~2 million inhabitants.

2.2. Trace gases and meteorological instrumentation

Trace gases were measured at El Arenosillo observatory. O_3 was collected with an analyser (Dasibi 1008 RS) based on the absorption of ultraviolet radiation at 254 nm using a flow rate of 2 l min^{-1}. NO_2 was recorded with an analyser (TAPI 200E) based on the chemiluminescence method using a flow rate of 0.5 l min^{-1}. SO_2 was measured using an analyser (TAPI T100) based on the ultraviolet fluorescence technique using a flow rate of 0.65 l min^{-1}. CO measurements were obtained using an analyser (TAPI T300) based on non-dispersive infrared spectroscopy using a flow rate of 0.8 l min^{-1}. PM10 was measured at the air quality station Mazagon (7.5 km from El Arenosillo observatory) by an instrument based on the attenuation of beta radiation (FAG FH-62-N), which was equipped with a PM10 inlet outside the laboratory.

These instruments belong to the Survey and Air Quality Control Network of the Environmental Department at the Regional Government of Andalusia and follow the quality protocols defined by European Directive (Directive 2008/50/EC). The measurement threshold ranges for instrumentation were as follows: between 1 and 1000 ppb for O_3 (1.96 - 1960 µg m^{-3}), between 0.4 and 261 ppb for NO_2 (0.75 - 490 µg m^{-3}), between 0.04 and 88 ppm for CO (45.8 - 100032 µg m^{-3}), between 0.4-376 ppb for SO_2 (1.04 - 985.12 µg m^{-3}) and between 15 and 1000 µg m^{-3} for PM10. Maintenance (weekly) and calibration (monthly) operations were routinely performed to guarantee the accuracy of the instruments. Gas data were collected every 10 min; the inlet was 8 m above the ground and 2 m above the canopy. El Arenosillo observatory has available O_3 concentrations since February 2000, NO_2 concentrations since August 2007, and CO and SO_2 concentrations since November 2015.

Surface weather conditions were recorded using a Vaisala 520WXT analyser to monitor temperature, relative humidity, pressure, and wind speed and direction; the sensor was installed on the ground at a height of 10 m above ground level (a.g.l.). The data were collected at a time resolution of 10 minutes. Surface meteorological information is available at El Arenosillo site since 1994.

To investigate the impact of the Doñana fire plume on other areas, observations collected by air quality stations belonging to the previously mentioned Air Quality Network of Andalusia have been used. In Seville, data from the Bermejales and Alcala stations were used; in Cadiz, data from the Cartuja station were used. These stations have been selected because they were suitable locations downwind of the plumes and were not affected by urban emissions; furthermore, they were under the same meteorological conditions as those when the fire occurred. In all cases, the measurement techniques and maintenance and calibration protocols were similar to those mentioned previously for El Arenosillo observatory.

2.3. Atmospheric models and satellite observations

ERA-Interim model meteorological fields from the ECMWF (European Centre for Medium Range Weather Forecasts) (Dee et al., 2011) with a spatial resolution of 0.5° x 0.5° were used to generate the historical and anomaly maps. The model had 22 vertical levels from the surface to 250 mb and a temporal resolution of 6 h. To understand the local meteorological fields in detail, the WRF (Weather Research and Forecasting) model was used. Simulations were performed using the default options in the WRF model (version 3.8). The planetary boundary layer was estimated by means of the Yonsei University scheme (Hong et al., 2006), microphysical characteristics were simulated using the WRF single-moment 3-class scheme, and longwave and shortwave radiation parameterizations were carried out by the Rapid Radiative Transfer Model (RRTM) and the Dudhia scheme, respectively. The simulated area consisted of a single domain centred on the Gulf of Cadiz area (37 $^{\circ}$N, 7.5 $^{\circ}$W), which utilized a grid with 100 points and a 9 km spatial resolution. The spatial resolution was chosen following the 1:3 ratio between the inner and outer domains (Dudhia and Wang, 2014). The boundary conditions and initial inputs utilized those from the ERA-Interim fields, with a 0.25° x 0.25° spatial resolution. WRF simulations started at 00:00 UTC on 22 June 2017 and covered seven complete days, which allowed the simulation to stabilize for a few days before reaching the forest fire period.

Fig. 1.

To investigate the impacts of the Doñana fire plume, the forward trajectories of air masses were computed with the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model developed by NOAA's Air Resources Laboratory (ARL) (Draxler et al., 2009; Stein et al., 2015). Threedimensional kinematic hourly trajectories were computed with a 24-hour pathway at 100 m a.g.l. The forward trajectories were calculated using ERA-Interim meteorological fields (spatial resolution of 0.125^{o} x 0.125^{o}), which were converted into the ARL standard format using the HYSPLIT model.

The spatial distribution of the Doñana plume has been investigated using CO measurements from the Atmospheric Infrared Sounder (AIRS) aboard the Aqua satellite, which covers the entire globe from pole to pole twice a day. The AIRS instruments include an infrared spectrometer and a visible light/near-infrared photometer. The standard AIRS products include temperature, water vapour mixing ratios and trace gas concentrations (e.g., O_3, CO, CO_2, and CH_4), which are usually products or by-products of biomass-burning and forest fires (Kumar et al., 2013; Kim and Sarkar, 2017). The AIRS total column amounts of CO are obtained from the product AIRX3STD (level 3). Each file covers a temporal period of 24 hours during either a descending or ascending orbit, with a spatial resolution of 1° x 1°. In addition, continuous measurements of CO are taken by the MOPITT instrument (which measures pollutants in the troposphere) aboard the TERRA satellite (Dekker et al., 2017; Jiang et al., 2017). CO data are obtained from the product MOP03J (level 3), which has a 22 × 22 km^2 spatial resolution and a global coverage once every 2–3 days.

3. Results

3.1. Doñana forest fire: biodiversity impact

The forest fire started on the afternoon of 24 June 2017 southeast of the village of Moguer. Due to extreme meteorological conditions (Section 3.2), the fire rapidly spread towards Doñana Natural Park, an area that has been intensively reforested with pines. The fire was active for approximately 60 hours. The total affected area comprised 10339 ha (88 % of which was protected areas, primarily Doñana Natural Park). A cartographic analysis indicates that a total of 40 endangered plant species were directly affected by the forest fire (see Dávila and Hidalgo, 2017 for further details). In particular, 50 % of the total localities of *Linaria tursica*, an endangered endemic annual plant in the Doñana area, were impacted. With respect to animals, the habitats of the threatened Iberian lynx

(*Lynx pardinus*), the imperial eagle (*Aquila adalberti,* Spanish imperial eagle) and Adalbert's eagle (Spanish eagle) were also affected. Reptiles and amphibians, such as a chameleon (*Chamaeleo chamaeleon*), the red-tailed lizard (*Acanthodactylus erythrurus*), the Iberian newt (*Lissotriton boscai*) and the meridional frog (*Hyla meridionalis*), were among the animals most affected due to their limited capacity for displacement. With respect to the habitat present in Annex I of the Habitat Directive (Council Directive 92/43/EEC on 21 May 1992), a total of 1664 ha of priority habitats were affected (Fig. 1c and Table 1). The most affected habitat was the Atlantic decalcified dunes, of which more than 1000 ha were colonized by heaths in the affected area. These habitats hosted many endangered species and were especially sensitive to alterations. An intensive restoration programme is necessary to recover such extreme fragile environments, especially the Mediterranean temporary ponds and dunes, due to their sensitivity to erosion after the removal of vegetative coverage.

Table 1.

3.2. Meteorological conditions at the synoptic and local scales

The meteorological conditions in the lower atmosphere in this region are governed by both synoptic and mesoscale processes. In the warm months (May to September), the synoptic flow can have a maritime origin, and air masses can originate from the Atlantic Ocean or be continental (e.g., originate from the African continent). In this last case, dust can be transported from the Saharan Desert, which is associated with an increase in temperature and a decrease in relative humidity (e.g., Adame et al., 2015). During situations with a low pressure gradient or atmospheric stagnation, mesoscale processes develop, especially in the Atlantic area close to the Iberian Peninsula and the western Mediterranean basin. In this coastal region, two types of sea-land breezes have been identified (Adame et al., 2010): a pure sea-breeze, which has a wind direction perpendicular to the coastline in both sea and land breeze regimes, and non-pure sea-breezes, which result from the flow of pure sea-breezes and northwesterly synoptic forcing.

The mean synoptic meteorology was analysed over the last two decades for the week of 23 to 30 June (1996 to 2016) using ERA-Interim fields (Fig. 2a-c). At the synoptic scale, surface meteorological conditions were characterized by anticyclonic conditions in late June. A high-pressure system centred over the Azores region, which affects the Iberian Peninsula and western Europe, was associated with a heat low system located over northwestern Africa. The temperature SW of the Iberian Peninsula oscillates between 25 and 30 ^{o}C, with values up to 30 ^{o}C in northern Africa, while the wind speed at the surface only reaches 11-13 km h^{-1}. The highest wind speeds are observed along the coast of North Africa and originate from pressure differences between the Atlantic High and the African Low, which are induced by the Atlas Mountains, which act as an orographic barrier.

Using a similar strategy, local meteorological conditions at the surface were studied over the last twenty years using meteorological records at El Arenosillo observatory. The temperature at this time ranged from 17 to 19 ^{o}C during the nighttime and a maximum of 25 ^{o}C during the daytime. Because it is a coastal region, the relative humidity during the nighttime reached 80 %, which decreased to 55-60 % at midday. In regard to wind speed, values of $\sim$12.6 km h^{-1} were obtained during the nighttime and $\sim$19.8 km h^{-1} during the daytime. The atmospheric dynamics in the lowest troposphere were defined by the development of mesoscale processes, Atlantic flows from the W-SW and low-frequency flows from the NW.

Several days before the fire event, synoptic conditions had anticyclonic characteristics, with a high-pressure system propagating from the Atlantic Ocean to France, which covered the Iberian Peninsula (IP), and a low-pressure system over northwestern Africa. The IP had a weak gradient-baric field, which favoured mesoscale mechanisms in coastal areas, such as the sea-land breeze, which developed in the Gulf of Cadiz area.

The day before the forest fire (24 June), a low-pressure system located over North Africa deepened, and the Azores High moved away from the western Iberian Peninsula, which caused a decrease in the surface pressure in the Gulf of Cadiz and along the western coast of North Africa and an increase in the baric gradient.

These new conditions were not favourable for the development of mesoscale processes, and atmospheric dynamics were governed by synoptic flows from the NW. In the early hours on 24 June, an increase in the wind speed was observed in the coastal area of the Gulf of Cadiz, with gusts reaching 85 km h^{-1}. This change can be observed in the wind fields simulated by the WRF model at 19:00 UTC (Fig. 3a), which was when the fires started.

Fig. 2.

The observed behaviour was associated with an increase in temperature and a decrease in relative humidity. On 24 June, a maximum temperature of 39 °C and a minimum relative humidity of 15 % were measured at El Arenosillo (Fig. 3d-e). The night of 24 June and throughout the day on 25 June, the wind field showed elevated wind speeds with changing wind directions, mostly in terms of the north component (Fig. 3b).

Fig. 3.

A channelling effect occurred through the Gibraltar Strait, the Gulf of Cadiz and the Guadalquivir valley. In the fire zone, there were areas with simultaneous winds from the NW and the SW (Fig. 3c), which made fire control difficult and facilitated the spread of the fire.

On 25 June, a maximum temperature of 36 °C, a minimum relative humidity of 18 %, and wind gusts up to 80 km h^{-1} were recorded. At 14:00 UTC, the fire reached the El Arenosillo area, with 10-min average temperature and relative humidity values of 45 °C and 15 %, respectively (1-min average values of 52 °C and 10 %, respectively) and wind speeds up to 45 km h^{-1} with gusts up to 80 km h^{-1} (Fig. 3d-e). On 26 June, the anticyclone weakened, and the Iberian Peninsula was under a weak pressure gradient, which favoured mesoscale mechanisms along the coast. At El Arenosillo, this change was observed by decreases in the wind speed and temperature and an increase in the relative humidity, which were consistent with typical meteorological conditions at this time of year.

To understand how exceptional these meteorological conditions were during the Doñana forest fire, the synoptic anomalies of mean sea level pressure (MSLP), temperature and wind speed on 24 June 2017 at 18:00 and 25 June 2017 at 12:00 were evaluated and compared against historical data from

1996-2016 (Fig. 2d-l). The local anomalies of daily average temperatures, relative humidity and wind speeds on 24 and 25 of June 2017 were also evaluated.

The Doñana forest fire occurred under positive pressure anomalies over the Atlantic and negative pressure anomalies over northern Africa (i.e., the high and low were more intense than usual during this time of year). Therefore, a was observed, and NW flows with high wind speeds occurred over areas such as the Guadalquivir valley, the Gulf of Cadiz and the Atlantic Ocean, which were close to North Africa. High anomalies were obtained over the Gulf of Cadiz, with values of 29-36 km h^{-1} with respect to the historical series.

Most of the Iberian Peninsula and North Africa showed positive temperature anomalies, especially the Guadalquivir valley and the Gulf of Cadiz, with differences between 10 and 12 ^{o}C. At the local scale, based on the measurements from El Arenosillo observatory, positive temperature anomalies were also observed, with nighttime differences from 6 to 8 ^{o}C and up to 10 ^{o}C during the daytime. The relative humidity presented negative anomalies, specifically between 35 and 45 %. In terms of absolute values, the daytime values were lower than 30 % and reached a minimum of 15 %. An analysis of wind speed anomalies showed positive values during the nighttime (1.8 and 14.4 km h^{-1}) and during the daytime (with differences of 25-29 km h^{-1}).

3.3. CO, O_3, NO_2, SO_2 and PM10 measurements at El Arenosillo

Fig. 4 shows the temporal evolution of the CO, O_3, NO_2, SO_2 and PM10 values observed from 22 to 28 June 2017. In late June, CO concentrations in this area were characterized by values between 250 and 350 µg m^{-3}. Ozone concentrations varied between 60 and 80 µg m^{-3} during the nighttime, with a minimum occurring at 6:00 UTC. In the early morning, the ozone values increased to 90-100 µg m^{-3} (from 11:00 to 20:00 UTC). On the other hand, NO_2 values varied between 4 and 7 µg m^{-3}, with peaks in the early morning and during the nighttime of 25 and 40 µg m^{-3}, respectively. According to local meteorological conditions, air masses with elevated NO_2 levels arrived, which originated from marine emissions or from the industrial area of Huelva, similar to the nighttime observations from 23 to 24

June. SO_2 measurements showed background concentrations between 2 and 4 µg m^{-3} since the observatory is not near an SO_2 emission area. However, under rare atmospheric conditions (i.e., less than 5 % per year), these values can reach 15-20 µg m^{-3}. Daily and hourly SO_2 background values were recorded before the fire. PM10 records in this rural area had values between 35 and 45 µg m^{-3}, indicating a desert dust particle contribution at ground level prior to the Doñana fire. Without the impact of desert dust, PM10 levels decreased to values of 20 µg m^{-3}.

Fig. 4.

Prior to the fire, typical CO, O_3, NO_2 and SO_2 values were recorded at El Arenosillo; PM10 was excluded, although it showed an important increase (peaks of ~500 µg m^{-3}) on 24 June between 16:00 and 21:00 UTC. This particulate matter event occurred three hours before the Doñana fire began. A study was performed to investigate the origin of this increase in PM10, and it was attributed to the arrival of a plume that originated from forest fires occurring in Portugal.

At 2:50 UTC on 25 June, approximately 8 hours after the forest fire started, an increase in trace gases and aerosols was observed at El Arenosillo, which remained until ~8:30 UTC (Fig. 4). These increases occurred under NW atmospheric flows and an increase in wind speed, which doubled from 14 to 28 km h^{-1} with wind gusts of 144 km h^{-1} (1-minute data). Moreover, the temperature increased to 32 °C at 8:10 UTC, and the relative humidity dropped to values lower than 35 %.

During these nocturnal hours, the following peaks were reached: a CO peak of 8400 µg m^{-3}, an O_3 peak of 87 µg m^{-3}, a NO_2 peak of 90 µg m^{-3}, a SO_2 peak of 17 µg m^{-3} and a PM10 peaks of 880 µg m^{-3}. Not all chemical species increased simultaneously since some are primary pollutants, while others, such as ozone, are formed through reactions of fire-emitted precursors. O_3 and NO_2 did not present a continuous increasing trend, as they reached a peak at approximately 3:00 UTC followed by a decrease (Fig. 4). The PM10 nocturnal peak coincided with the relative minimums for O_3 and NO_2, which were less than 20 µg m^{-3}. These values for PM10 are attributed to the arrival of ash, which produced fast O_3 and NO_2 destruction via irreversible dry deposition onto the large ash particle surface area.

From the early morning hours to 13:00 UTC, these concentrations decreased, and they resumed their usual values. Although the wind continued to blow from the NW, a decrease in temperature was recorded (Fig. 4). After 13:00 UTC, the wind speed and temperature began to increase, and the humidity began to decrease as the fire surrounded El Arenosillo. Under the meteorological conditions mentioned in Section 3.2., the fire reached the observatory, and our facilities suffered from the fire during the next 1.5 hours (approximately until 15:10 UTC). Due to our autonomous power system, the atmospheric instrumentation continued to work and measured the direct emissions of the forest fire. Specifically, at 14:10 UTC on 25 June 2017, record-setting peaks for all gases monitored at El Arenosillo were measured: 99995 μg m^{-3} of CO, 951 μg m^{-3} of O_3, 478 μg m^{-3} of NO_2, 116 μg m^{-3} of SO_2 and 1000 μg m^{-3} of PM10 (at Mazagon station) (Fig. 4). Note that in the cases of CO, NO_2 and PM10, the instruments reached their upper limits of operation; hence, the concentrations could have been even higher. The fire directly emitted chemical species such as CO, NO_2, SO_2 and PM10. However, the presence of high levels of VOCs and NO_x associated with the fire can promote additional atmospheric pathways for ozone production (Parrington et al., 2013). O_3 production in wild fires includes the net effect of aerosols on chemical and photochemical reactions within a fire plume and the impact of oxygenated VOCs and nitrous acid on O_3 production.

The beginning of the post-fire period at El Arenosillo started at 15:30 on 25 June. The O_3 values decreased abruptly (only 7-10 μg m^{-3} between 16:00-17:00 UTC), with values below 20 μg m^{-3} during the following night. This decrease could be caused by several effects: i) due to the high ash concentrations, the solar radiation decreased, and the local photochemical activity ceased; ii) the high aerosol concentrations eliminated O_3 via dry deposition; and/or iii) the emission of VOCs and the conversion of radicals initiated the oxidation chains and removed O_3. In the following days (26 to 28 June), O_3 values did not recover; a maximum of 60 μg m^{-3} was measured, with lower values than usual during this time of year. Even though there was no smoke around the observatory, aerosol levels remained elevated, and hence, O_3 could have been removed by dry deposition on airborne particles. The O_3 concentrations did not start to exhibit normal values until 29 June (four days later), with peaks of 80 µg m^{-3} (not shown).

Once the fire passed, CO concentrations remained elevated during the following eight hours, with values between 5000 and 10000 µg m^{-3}. Almost 24 hours after the fire reached the observatory (approximately 14:30 UTC on 26 June), CO recovered to its usual values of ~300 µg m^{-3}. After the fire, NO_2 decreased, but over the next few hours, values remained between 10 and 25 µg m^{-3}, which were elevated for this region. After 1:00 UTC on 26 June (less than 24 hours later), the observed NO_2 values were below 10 µg m^{-3}, which are typical in this area and indicate recovery. SO_2 did not present an abrupt decrease similar to that of O_3 and NO_2, but a continued decrease during the next 48 hours was observed. This can be explained by the longer photochemical lifetime of SO_2 with respect to NO_2. SO_2 values below 5 µg m^{-3} were not recorded until 16:00 on 27 June. Later, a PM10 peak was observed (a second peak of 560 µg m^{-3} between 0:00 and 1:00 UTC on 26 June); this showed a decreasing trend during the next eight hours. At 9:00 UTC, the PM10 concentrations were 60 µg m^{-3}.

3.4. Regional atmospheric impacts of the Doñana forest fire

To investigate the widespread impacts of the Doñana fire emissions, hourly forward trajectories were computed for 25 to 27 June 2017 at a height of 100 m. For the analysis, a source region was defined with five points, which covered the burnt area. The results obtained can be observed in Fig. 6. At first, on 25 June, the forward trajectories showed atmospheric transport towards the Gulf of Cadiz, but later, the plumes were transported towards the SE, affecting the Seville and Cadiz areas as well as the Mediterranean area near the Strait of Gibraltar, which is in agreement with the wind fields obtained with the WRF model (Section 3.2). On 25 and 26 June, the Doñana plume continued to move toward the SE, reaching the western Mediterranean area.

Fire plumes impacted the Seville and Cadiz urban areas, which are located 60-70 km away from the Doñana National Park (Fig. 1), and the arrival of plumes was registered by air quality stations, which recorded increases in hourly CO, O_3 and PM10 values (Fig. 5). During the hours prior to the beginning of the forest fire, increases in CO and O_3 (14:00-16:30 UTC) were observed in the Cadiz area, and an increase in PM10 (18:30-20:30 UTC) was observed in both Seville and Cadiz, with a peak of 140 µg m^{-3}. Lower values were observed at this time in El Arenosillo. This increase over Seville and Cadiz could be attributed to the arrival of an air mass that originated from a forest fire that occurred in Portugal during the second half of 24 June 2017, as mentioned in Section 3.3. Therefore, this plume from Portugal not only affected the coastal area of the Gulf of Cadiz (Mazagon station) but also inland areas.

The Cadiz urban area was affected by Doñana forest fire emissions at 10:30 UTC on 25 June, which increased PM10 values to 100 µg m^{-3}. However, a later impact was more intense and occurred between 14:30 and 16:20 UTC. This later event featured a CO peak of 1600 µg m^{-3} and PM10 values higher than 240 µg m^{-3}. In addition, an increase in O_3 was recorded, reaching values of 135 µg m^{-3}. Twelve hours later, at approximately 2:30-3:00 UTC on 26 June, the plume reached both the Seville metropolitan area and the Cadiz urban area and affected this inland region over the next 8 hours until approximately 10:30 UTC on 26 June 2017. During this period, CO peaks with values of 2032 µg m^{-3} in Seville (Bermejales station) and 1300 µg m^{-3} in Cadiz (Cartuja station) were recorded, and maximum PM10 values of 110 µg m^{-3} were recorded in the Seville area (Fig. 5).

Fig. 5.

On the first night of the fire (24 to 25 June 2017), the typical nocturnal removal of O_3 was not observed, but the O_3 concentration did slowly decrease, with a minimum of 60-70 µg m^{-3}. Since the Doñana plume had not yet affected the Seville and Cadiz areas, this nocturnal behaviour could have been associated with O_3-rich aged air from Portugal. On 25 June, when the Doñana plume impacted

Seville and Cadiz, an increase in O_3 concentrations was observed, with daily maxima of 30-40 µg m^{-3}, higher than those measured on previous days (values of 125-130 µg m^{-3} compared to 90-100 µg m^{-3}). Because the Doñana plume was transported towards the east on 26 and 27 June 2017, surface observations at other air quality stations located to the east (e.g., the Malaga metropolitan area) were analysed. The recorded increases in O_3, CO, NO_2 and PM10 were not attributed to the impact of the Doñana plume. Hence, based on meteorological conditions, such as forward trajectories, wind fields, and the absence of gas concentration increases in ground observations, the Doñana plume was transported towards the Mediterranean Sea.

To understand the spatial distribution of the Doñana plume, CO was used as a tracer for space observations from the AIRS and MOPITT instruments aboard the Aqua and Terra satellites, respectively (Fig. 6). The day before the Doñana fire (24 June), the AIRS instrument measured high CO total concentrations over the maritime area of the Gulf of Cadiz, which were also observed by MOPITT on 25 June. Both instruments measured CO transport from the south of Portugal to SW Spain. These observations support the arrival of the Portuguese plume to this area. However, the air quality stations measured an increase in the PM10 concentration on the evening of 24 June but not an increase in surface CO. Based on these observations, it was determined that the CO plume was transported at upper levels; both satellite instruments measured the CO column, and it was observed that the increase in PM10 at the surface was likely due to gravitational settling processes.

Fig. 6.

On 25 June, AIRS observed a CO column of 1.7-1.8 x 10^{18} mol cm^{-2} in the Doñana area and Mediterranean area close to the Strait of Gibraltar. This column was transported towards the interior of the Mediterranean in agreement with the forward trajectories and the wind fields (Fig 3. a-c). On 27 June, both the AIRS and MOPITT instruments showed an increase in CO in the Mediterranean area near the east coast of the Iberian Peninsula. Atmospheric transport occurred on these days (24 to 27 June) in the western Mediterranean from the west to the east, which is confirmed by the forward trajectories and ECMWF wind fields. Therefore, the arrival of emissions from Europe, North Africa or the eastern Mediterranean should be neglected.

4. Conclusions

A forest fire affected the Doñana Natural Park from 24 to 26 June 2017. This fire had a strong impact on biodiversity and affected many endangered plant and animal species. Similarly, many priority habitats considered by the Habitat Directive were seriously damaged. An intensive restoration programme is necessary to recover the biodiversity in the region and avoid erosion.

The Doñana forest fire occurred under an exceptional meteorological scenario, which consisted of a strong pressure gradient, positive high pressure anomalies in the Atlantic and negative anomalies in North Africa, and areas of low pressure. The following atmospheric characteristics were also observed: intense atmospheric flows from the NW; positive wind speed anomalies, with differences greater than 8 m s^{-1}; wind gusts of 80 km h^{-1}; positive temperature anomalies, with differences between 10 and 12 °C and an absolute maximum of 35 °C; and negative humidity anomalies with a difference of ∼40 % and an absolute minimum of 15 %. Unfortunately, these meteorological conditions, i.e., high temperatures (>30°), low humidity (<15 %) and high wind speeds, with gusts up to 80 km h^{-1}, were suitable for the occurrence and spread of a forest fire.

The Doñana forest fire affected El Arenosillo observatory approximately 8 hours after it started. Despite these extreme conditions, the instrumentation continued to work, and record-setting values were observed for all gases measured at our observatory. After the fire ceased (i.e., during the post-fire period), the chemical species recovered to their usual concentration values, although some species, such as CO, SO_2 and PM10, remained at high levels for several hours. The temporal evolution shown at El Arenosillo indicated that a burnt area should recover to its initial atmospheric levels between 48 and 96 hours after the event.

Hourly forward trajectories were computed with the HYSPLIT model to understand how the Doñana plume developed. Forest fire emissions affected the Seville and Cadiz metropolitan areas and subsequently moved towards the Mediterranean Sea. One day after the fires started, the air quality stations in these urban areas observed increases in the CO and PM10 values. CO peaks of 1600 µg m^{-3} and 2032 µg m^{-3} and PM10 values of 240 µg m^{-3} and 100 µg m^{-3} were measured in Cadiz and Seville, respectively.

After these metropolitan areas were affected, the Doñana plume continued moving toward the Mediterranean. To investigate its dispersion, CO was used as a tracer via observations from the AIRS and MOPITT instruments aboard the Aqua and Terra satellites. The increase in the total column of CO was measured in the Gibraltar Strait area and later in areas farther away from the Mediterranean.

Therefore, the Doñana plume had a local impact in the first 24 hours, reaching the Seville and Cadiz metropolitan areas, and was later transported toward the Mediterranean and the Strait of Gibraltar. Two days later, the Doñana plume had a regional impact, as it affected the western Mediterranean basin (800-1000 km from emission source).

This forest fire was one of many fires that occur every year around the planet. If the fire close to Doñana Natural Park was small and had occurred under normal atmospheric conditions, it would not have caused the impacts that it had in this exceptional meteorological situation. When a forest fire occurs under extreme conditions, control of the fire is more difficult, the burnt area is greater, and the atmospheric emissions are greater. This forest fire had the potential to have a great impact on radiative forcing at a regional level. Forest fires similar to this event contribute to the occurrence of new unusual atmospheric events, leading to feedback processes.

Acknowledgments.

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Table.

Table 1. Priority habitats (according to Habitat Directive, 1992) present in the area and total area affected.

Priority habitats	Area (ha/km^2)
3170-Mediterranean temporary ponds	289.9/2.899
2250-Coastal dunes with *Juniperus* spp.	52.1/0.521
2130-Fixed coastal dunes with herbaceous vegetation (grey dunes)	102.6/1.026
2150-Atlantic decalcified fixed dunes (*Calluno-Ulicetea*)	1206.64/12.066
4020-Temperate Atlantic wet heaths with *Erica ciliaris* and *E. tetralix*	12.55/0.125
Total Area	1664.00/16.64

Figure captions.

Fig. 1. Iberian Peninsula in Europe (a); location of El Arenosillo observatory and the Seville and Cadiz metropolitan areas (b); forest fire and different priority habitat locations (Directive, 1992) (c).

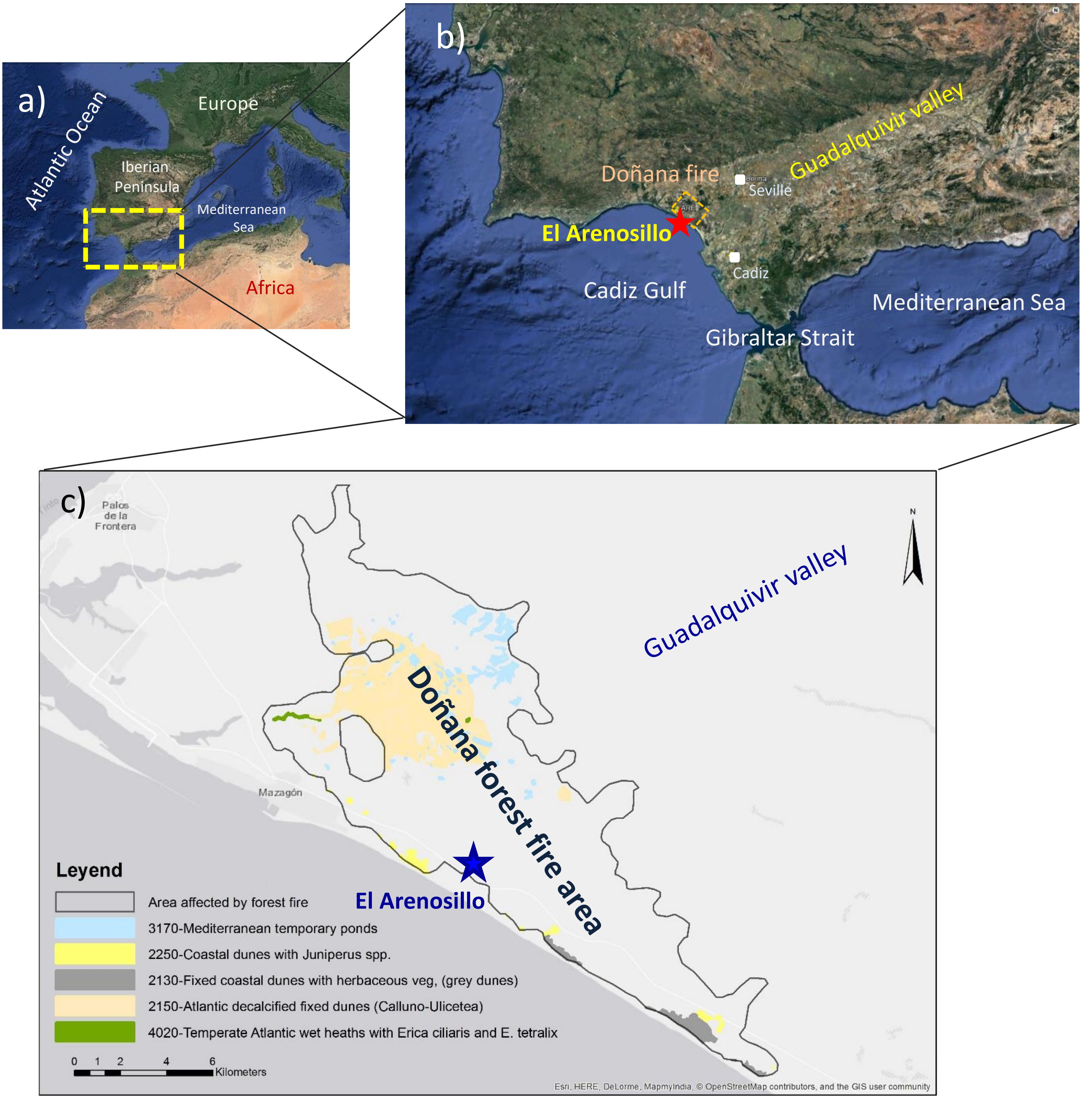
Fig. 2. Mean sea level pressure (MSLP), temperature and wind speed maps for the week of 23 to 30 June using the period 1996-2016 (a-c). MSLP, temperature and wind speed anomalies for 24 June at 18:00 UTC and 25 June 2017 at 00:00 and 12:00 UTC compared to the historical averages over the last two decades (d-l). Meteorological fields obtained from the ECMWF model using ERA-Interim files with a 0.5^o x 0.5^o spatial resolution.

Fig. 3. Wind fields obtained from the WRF model with a 9 x 9 km spatial resolution for 24 June at 19:00 UTC and 25 June at 8:00 and 17:00 UTC (a-c). Wind (direction and speed) and wind gusts (d); temperature and relative humidity (e) recorded at El Arenosillo (INTA; Huelva) from 22 to 28 June 2017. The shaded area represents the forest fire period.

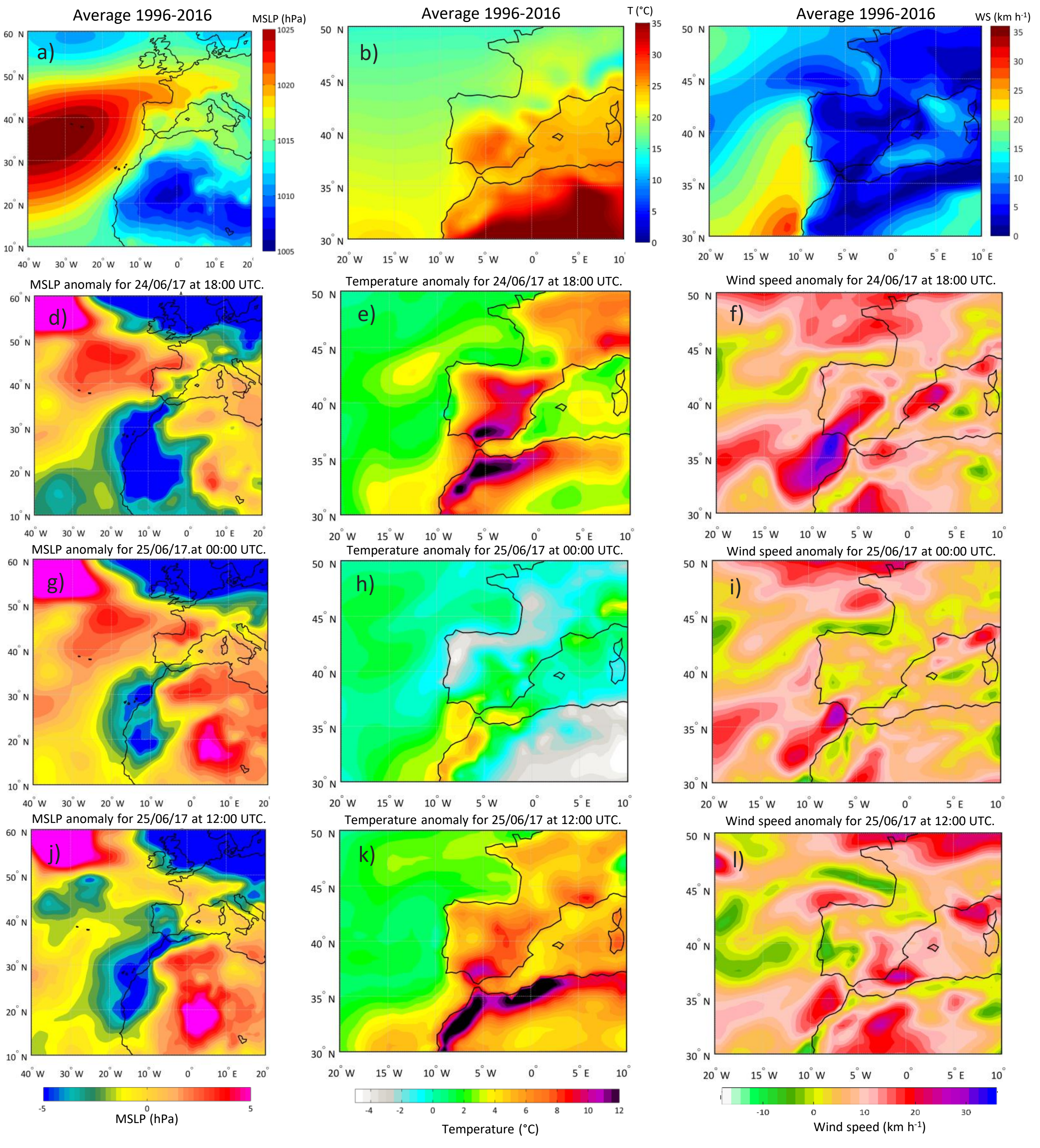
Fig. 4. Temporal evolution trends for CO, O_3, NO_2 and SO_2 measured at El Arenosillo and PM10 measured at the Mazagon station from 22 to 28 June 2017 using 10-minute data.

Fig. 5. Temporal evolution trends for CO, O_3 and PM10 measured at Seville (CO and O_3 at the Bermejales station and PM10 at the Alcala station) and Cadiz (Cartuja station) from 22 to 28 June 2017 using 10-minute data.

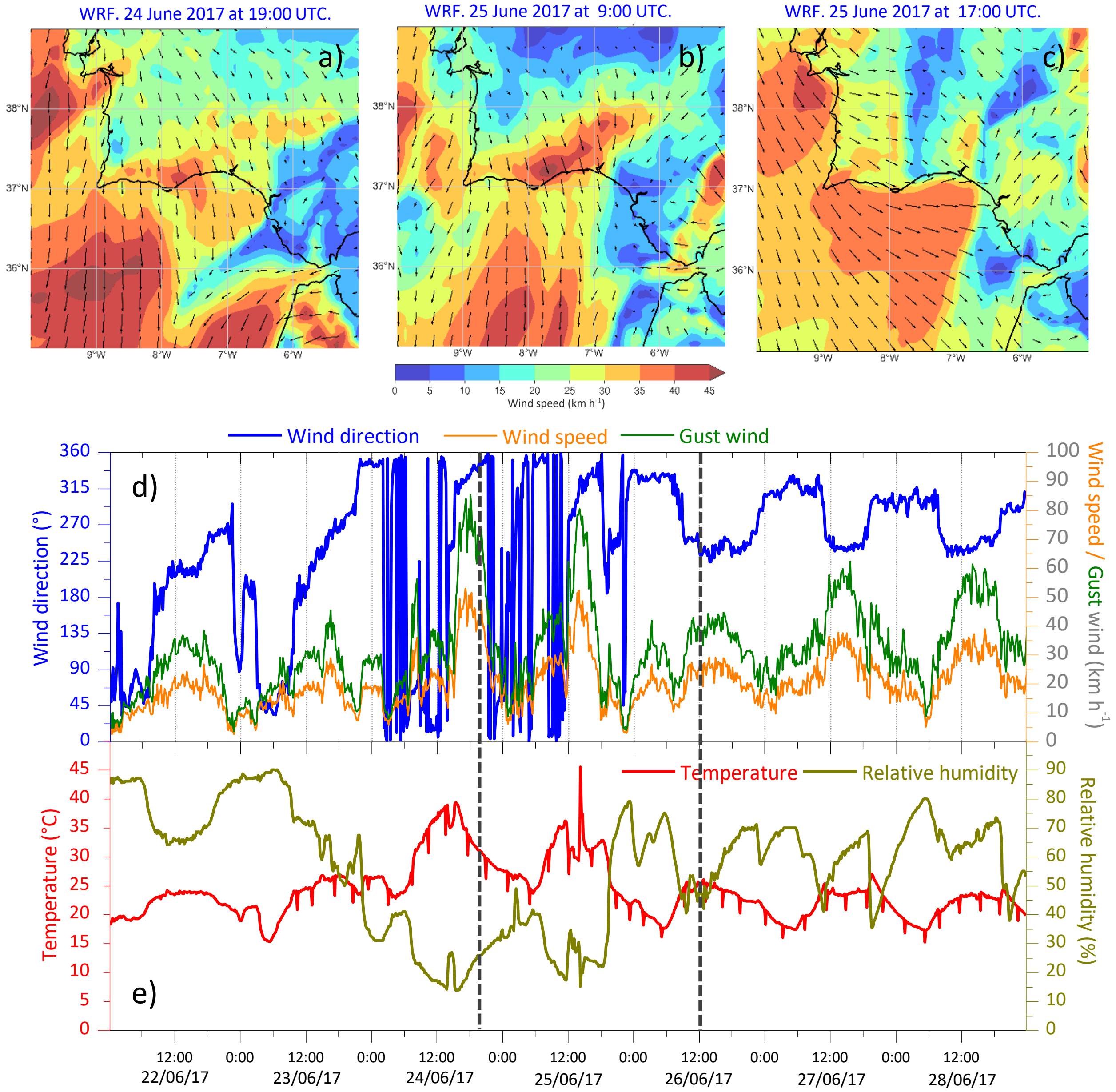
Fig. 6. Total daytime CO columns observed by the AIRS and MOPITT satellite instruments from 24 to 27 June 2017 and forward trajectories obtained with the HYSPLIT model using ERA-Interim meteorological fields (0.125° x 0.125°).



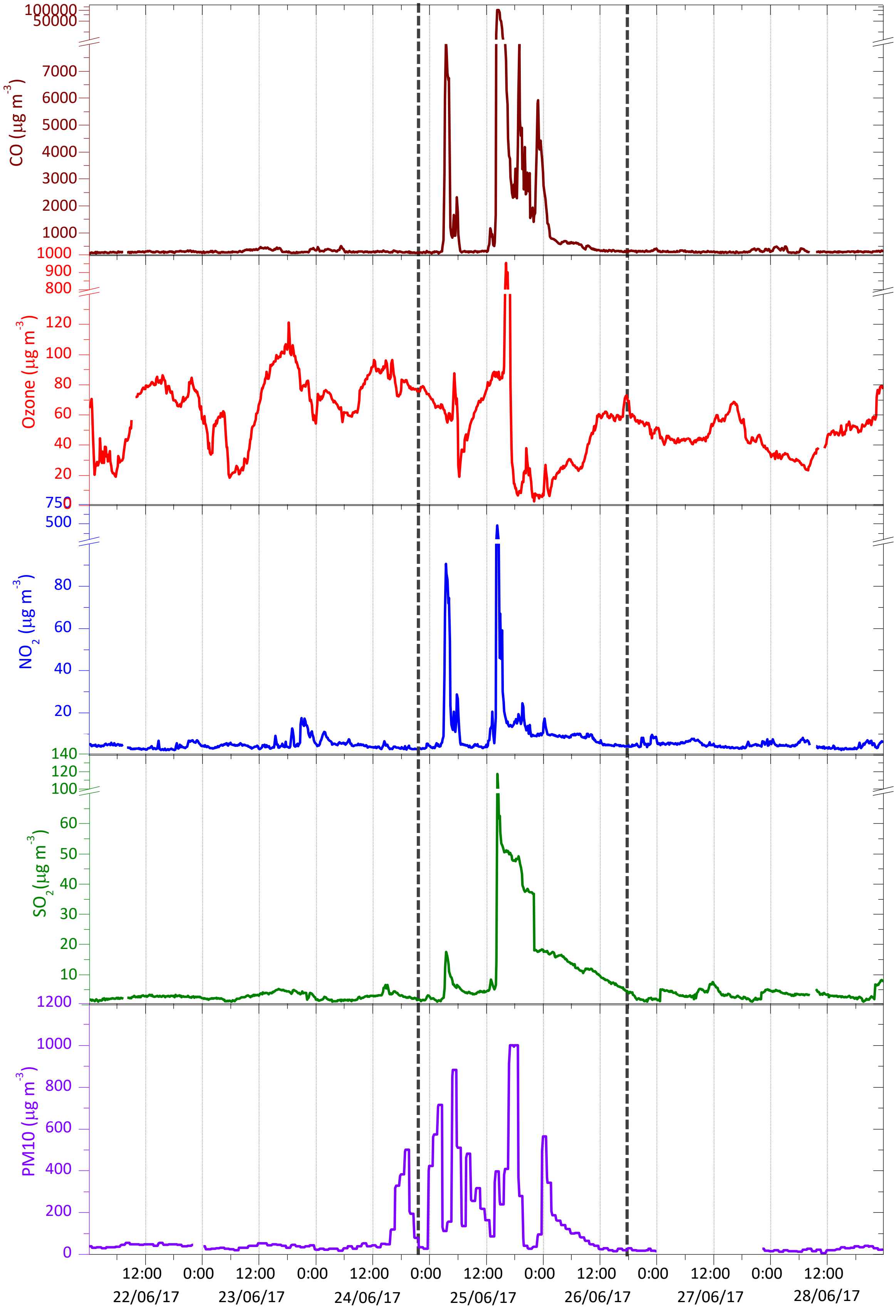
a)
Atlantic Ocean
Europe
Iberian Peninsula
Mediterranean Sea
Africa
b)
Doñana fire
Seville
Guadalquivir valley
El Arenosillo
Cadiz
Cadiz Gulf
Mediterranean Sea
Gibraltar Strait
c)
Palos de la Frontera
Guadalquivir valley
Doñana forest fire area
Mazagón
El Arenosillo
Leyend
Area affected by forest fire
3170-Mediterranean temporary ponds
2250-Coastal dunes with Juniperus spp.
2130-Fixed coastal dunes with herbaceous veg, (grey dunes)
2150-Atlantic decalcified fixed dunes (Calluno-Ulicetea)
4020-Temperate Atlantic wet heaths with Erica ciliaris and E. tetralix
0 1 2 4 6
Kilometers
N
Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community



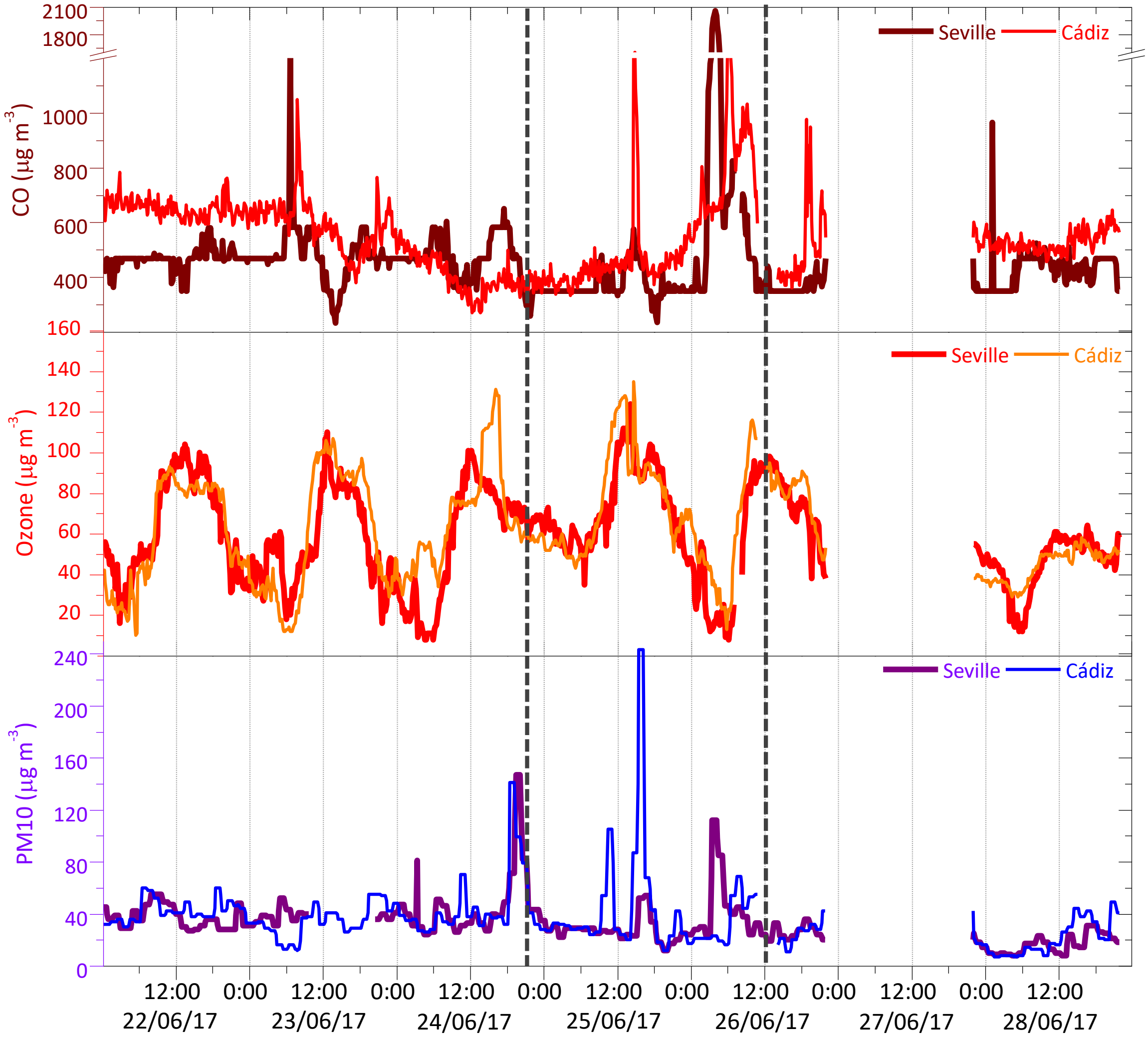
Average 1996-2016
MSLP (hPa)
a)
Average 1996-2016
T (°C)
b)
Average 1996-2016
WS (km h-1)
MSLP anomaly for 24/06/17 at 18:00 UTC.
d)
Temperature anomaly for 24/06/17 at 18:00 UTC.
e)
Wind speed anomaly for 24/06/17 at 18:00 UTC.
f)
MSLP anomaly for 25/06/17.at 00:00 UTC.
g)
Temperature anomaly for 25/06/17 at 00:00 UTC.
h)
Wind speed anomaly for 25/06/17 at 00:00 UTC.
i)
MSLP anomaly for 25/06/17 at 12:00 UTC.
j)
Temperature anomaly for 25/06/17 at 12:00 UTC.
k)
Wind speed anomaly for 25/06/17 at 12:00 UTC.
l)
MSLP (hPa)
Temperature (°C)
Wind speed (km h-1)



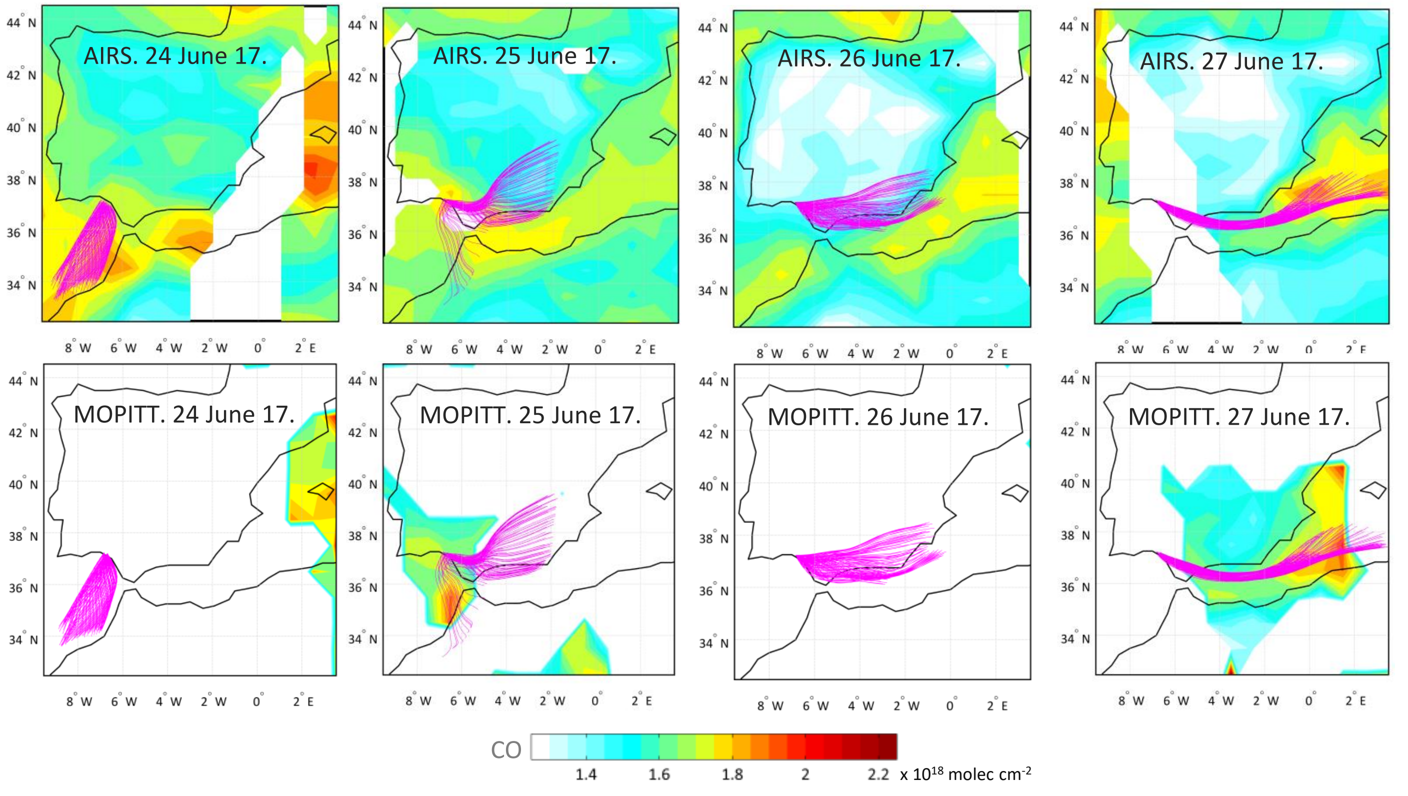
WRF. 24 June 2017 at 19:00 UTC.
WRF. 25 June 2017 at 9:00 UTC.
WRF. 25 June 2017 at 17:00 UTC.
a)
b)
c)
Wind speed (km h-1)
d)
Wind direction
Wind speed
Gust wind
Wind direction (°)
Wind speed / Gust wind (km h-1)
e)
Temperature
Relative humidity
Temperature (°C)
Relative humidity (%)
12:00 22/06/17
12:00 23/06/17
12:00 24/06/17
12:00 25/06/17
12:00 26/06/17
12:00 27/06/17
12:00 28/06/17

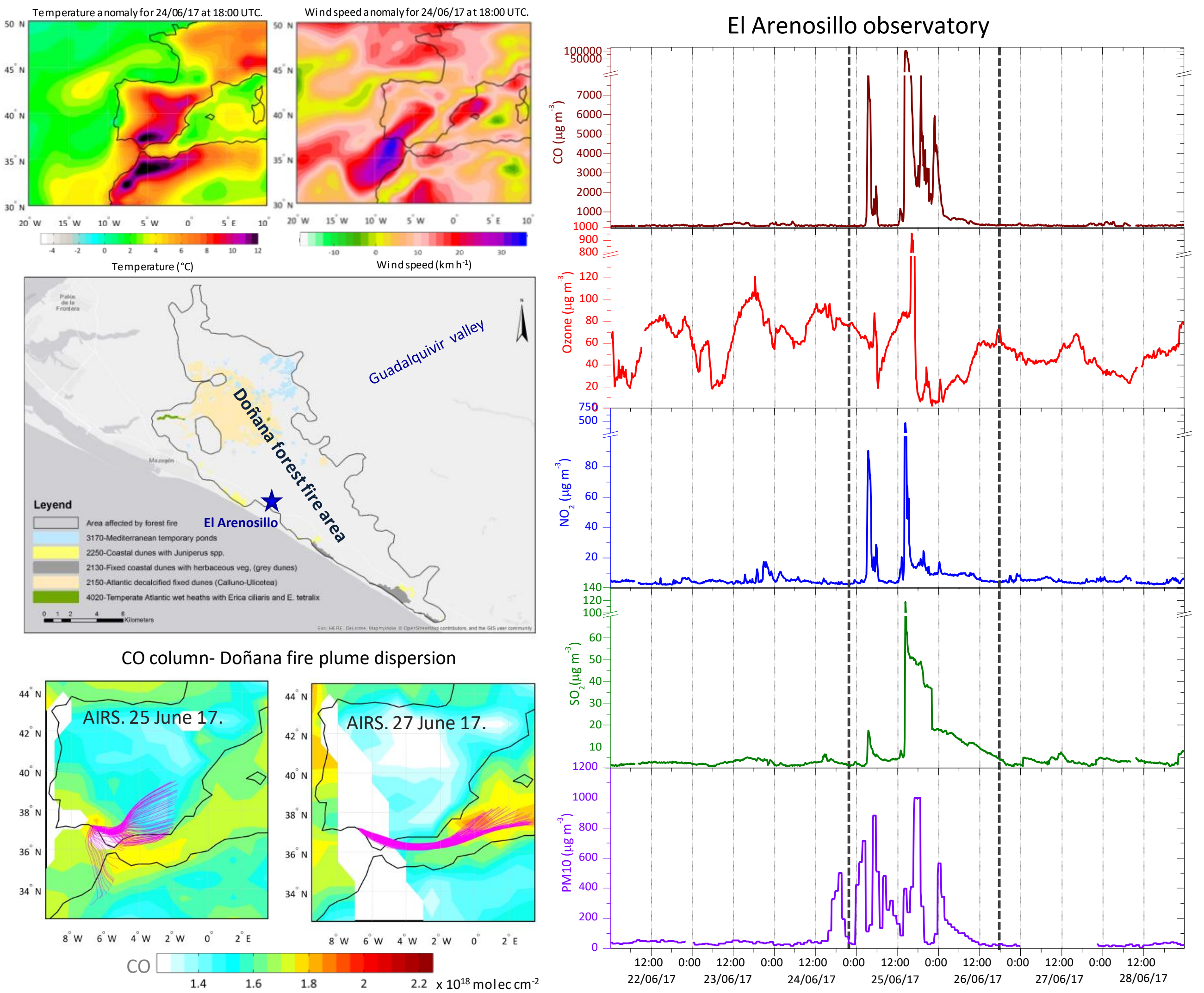


CO (µg m-3)
100000
50000
7000
6000
5000
4000
3000
2000
1000
Ozone (µg m-3)
1000
900
800
120
100
80
60
40
20
0
NO2 (µg m-3)
750
500
80
60
40
20
SO2 (µg m-3)
140
120
100
60
50
40
30
20
10
PM10 (µg m-3)
1200
1000
800
600
400
200
0
12:00
0:00
22/06/17
23/06/17
24/06/17
25/06/17
26/06/17
27/06/17
28/06/17



2100
1800
1000
800
600
400
160
CO (µg m-3)
Seville
Cádiz
140
120
100
80
60
40
20
Ozone (µg m-3)
Seville
Cádiz
240
200
160
120
80
40
0
PM10 (µg m-3)
Seville
Cádiz
12:00
0:00
22/06/17
23/06/17
24/06/17
25/06/17
26/06/17
27/06/17
28/06/17


AIRS. 24 June 17.
AIRS. 25 June 17.
AIRS. 26 June 17.
AIRS. 27 June 17.
MOPITT. 24 June 17.
MOPITT. 25 June 17.
MOPITT. 26 June 17.
MOPITT. 27 June 17.
44° N
42° N
40° N
38° N
36° N
34° N
8° W
6° W
4° W
2° W
0°
2° E
CO
1.4
1.6
1.8
2
2.2
x 10^18 molec cm^-2


Temperature anomaly for 24/06/17 at 18:00 UTC.
Wind speed anomaly for 24/06/17 at 18:00 UTC.
Temperature (°C)
Wind speed (km h-1)
Guadalquivir valley
Doñana forest fire area
El Arenosillo
Leyend
Area affected by forest fire
3170-Mediterranean temporary ponds
2250-Coastal dunes with Juniperus spp.
2130-Fixed coastal dunes with herbaceous veg. (grey dunes)
2150-Atlantic decalcified fixed dunes (Calluno-Ulicetea)
4020-Temperate Atlantic wet heaths with Erica ciliaris and E. tetralix
Kilometers
CO column- Doñana fire plume dispersion
AIRS. 25 June 17.
AIRS. 27 June 17.
CO
x 10^18 molec cm-2
El Arenosillo observatory
CO (µg m-3)
Ozone (µg m-3)
NO2 (µg m-3)
SO2 (µg m-3)
PM10 (µg m-3)
22/06/17
23/06/17
24/06/17
25/06/17
26/06/17
27/06/17
28/06/17