**The October 2017 red sun phenomenon over the UK**

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**Introduction**
As the old saying goes, *red sky at night, shepherd’s delight*, meaning that observing a red sky at sunset is supposed to herald fair weather on the following day. On 16 October 2017 the saying needed to include a new clause as the ex-hurricane *Ophelia* reached the shores of the British Isles, bringing exceptionally strong winds and rainfall to much of the western UK, as well as a peculiar haze to the skies of central and eastern UK, with reports of the sun turning red for a time.

During early October 2017 an unusual event was happening over the Eastern Atlantic Ocean. On 6 October the United States National Hurricane Center started monitoring an area associated with a decaying cold front for possible tropical cyclogenesis, and a circulation soon developed and formed a non-tropical system which remained fairly stationary. The system began to develop a well-defined circulation pattern over the following days; by 9 October deep convection patterns were established near the centre, and the system became classified as a tropical depression – number 17 of the 2017 hurricane season (National Hurricane Center, 2017). Atmospheric conditions allowed the system to gradually strengthen, and by 11 October it attained hurricane status, peaking as a category 3 hurricane on the Saffir–Simpson scale on 14 October. By now the system had moved to 26.6°W and had become, officially, the easternmost hurricane ever recorded in the satellite era. It remained classified as a hurricane until it reached around 47°N, 13°W, where the system began to weaken over the cooler waters of the North Atlantic Ocean. Ex-hurricane *Ophelia* may have been downgraded in status, but the system maintained very high winds across much of Ireland and the western half of the UK. Forecasters were fairly confident of the track and power of the system, and this led to Met Éireann issuing a red weather warning for strong winds 48h before the event. The southern coastal counties of Ireland were worst hit by the violent storm force winds, and a gust of 103 kn was reported at Fastnet Rock off the Cork coast, and the storm claimed the lives of three people across Ireland.

During the morning and afternoon of 16 October, the rest of the UK started to notice that the sky started to turn a yellow/orange colour. What caused this to happen? Two factors: scattering of sunlight by Saharan dust and wildfire smoke.

**Transport of Saharan dust**
Under suitable weather conditions mineral dust from the Sahara Desert can be lofted and transported great distances away from their source region, and quite often this dust traverses the whole Atlantic Ocean to reach the Amazon and North American regions (Prospero *et al.*, 2014). Indeed, one such event occurred in June 2014, when the VIIRS instrument on the SUOMI NPP satellite captured dust heading toward South America and the Gulf of Mexico (Earth Observatory, 2014), being transported by the trade winds along the Intertropical Convergence Zone. It is estimated that about 40 million tonnes of dust reach the Amazon River Basin from the Sahara each year (Koren *et al.*, 2006). This has a positive impact on ecosystems as the mineral rich dust replenishes nutrients in the soil. Analysis of peat soils in southeastern America shows that this transport process has occurred for several thousand years, at least. In contrast to its ecological benefits, the dust has a negative impact on air quality and may therefore have adverse health effects, as the fine particles can irritate the lungs and exacerbate symptoms of asthma and other breathing conditions (Kelly and Fussell, 2015).

Throughout September and October 2017 there were several instances of pulses of Saharan dust being observed over the mid-Atlantic Ocean (Earth Observatory, 2017). The majority of these events exported dust in a westerly direction towards the Gulf of Mexico, although when *Ophelia* entered the scene, dust-laden air was dragged up towards northwestern Europe.

The atmospheric property known as aerosol optical depth (AOD) is used to quantify the extinction of light or, in other words, how strongly light is absorbed and scattered by dust or other particles in the atmosphere.
atmosphere. It is defined as the negative natural logarithm of the fraction of light that is either scattered or absorbed in a path. For example, an AOD of 1.0 corresponds to only 36.7% of light passing through a path which is neither absorbed nor scattered. Values above 1.0 are generally considered ‘very hazy’. Instruments such as MODIS on the Aqua satellite (Figure 1) can measure AOD, and on 13/14 October there was a very large dust event observed in the satellite imagery; dust was transported northward due to interaction with Ophelia which was passing to the west of North Africa at this time.

Severe wildfires over Portugal and Spain

During the same period, a number of severe wildfires were affecting Portugal and Spain. Wildfires affect many parts of the world and, as well as posing hazards such as loss of life and damage to property, the largest fires can project aerosols and trace gases high into the atmosphere where they can be readily transported across the globe in a matter of days to weeks. In some cases, smoke from intense fires can be injected directly into the stratosphere through pyrocumulus clouds; the effects of these smoke particles on the radiation budget and stratospheric chemistry are poorly understood (Fromm et al., 2010).

Across Europe as a whole, 2017 was a very significant year for fire activity over Europe. The European fire database – EFFIS – is one database which uses a number of satellite observations to derive both the burnt area and total number of fires. For the EU, almost 1 million ha were burnt in 2017 – an area five times larger than the 2008–2016 average. Portugal alone accounted for 60% of the area burnt, surpassing the previous record of 425 000 ha burnt in the very hot summer of 2003.

A number of large fires, allegedly started by arsonists, were reported across Portugal on 15 October. The MODIS instrument on the Aqua satellite (Figure 2) is capable of detecting fire ‘hotspots’ using the range of detector channels available on the instrument and observed a large number of fires across northern Spain and Portugal on the early afternoon of 15 October (Table 1).

**Aerosols in the atmosphere**

To account for the effects seen across central and eastern parts of the UK, it is first useful to explore optical properties of the atmosphere. The atmosphere consists of a large number of gases, aerosols and particles which all interact to a stronger or lesser degree with incoming solar radiation and outgoing longwave radiation emitted from the Earth’s surface. For incoming radiation, scattering of the sunlight occurs as it passes through the air and interacts with smoke or dust particles. The general effect is to diffuse the light, by spreading it out in all directions rather than just a single straight beam, as would be the case if there were no atmosphere. There are three different types of scattering: Rayleigh scattering, Mie scattering and non-selective scattering. The Mie scattering effect explains why clouds are white, for example. Clouds contain billions of small water droplets (which are themselves clear) that form around a nucleus that could be dust, smoke or another particle. As sunlight interacts with the newly formed droplet, the light is scattered. As the cloud contains so many droplets the light is scattered many times, an effect called multiple scattering, and this causes the colours of the light to recombine to make white light to an observer on the ground. So why was the sky yellow or orange rather than white?

Independent ground-based observations from the Chilbolton lidar on 16 October (not shown) indicated that the haze layer was actually made up of several very thin layers between 4 and 7km in altitude. As the smoke and dust particle layers were very thin, multiple scattering would likely be less important, and single scattering would be the dominant mode (i.e. there would be only one, or at least very few, interactions between the visible light and the particles). Blue wavelengths are scattered more than the red ones, and this means that many of the blue and green wavelengths will be scattered directly back into space, with only the yellow and orange wavelengths being observed at the ground.

**Table 1.**

| Start date   | Area burnt (ha) | Province                        |
|--------------|-----------------|---------------------------------|
| 14 October   | 67521           | Pinhal Interior Norte           |
| 15 October   | 64321           | Pinhal Interior Norte           |
| 15 October   | 34844           | Pinhal Interior Sul             |
| 15 October   | 24183           | Baixo Mondego                   |
| 15 October   | 18900           | Pinhal Litoral                  |
| 15 October   | 10701           | Serra da Estrela                |

**Copernicus Atmospheric Monitoring Service**

Estimating the separation between the different aerosol types involved in the Ophelia system and showing that it was caused by a combination of dust and biomass burn-
Deriving aerosol types

From the CAMS analysis products at the time of the UK ‘red sun’ on the afternoon of 16 October, the total aerosol optical depth (Figure 4(a)) was greater than 5.0, meaning that more than 99.3% of incoming solar radiation was being either scattered or absorbed by the aerosol in the atmosphere. The partition between different aerosol types shows that most of the aerosol over central and southern England was from biomass burning, with a larger proportion of desert dust around the east coast of England and over the North Sea. At the same time, the powerful Ophelia storm brought very high sea-salt AODs (greater than 4.0) to Ireland.

In fractional terms (Figure 5) biomass burning aerosol accounted for 30–50% of the total aerosol across Wales and northern, central and southern England. Across Wales, the remainder was made up of mainly sea-salt aerosol drawn up by Ophelia. Across northern England dust aerosol made up 20–40%, in central England, 30–40%, and in southern England, 20–40%. In eastern England, dust aerosol was the dominant mode, accounting for 50–70% of the total AOD, with biomass burning contributing 20–30%.

The picture across different UK cities is very interesting. As might be expected, most of the images on social media were taken in London. At the time of the red sun event (Table 2) Leicester came out as the city with the highest proportion of aerosol
due to biomass burning (46%), followed by Nottingham (45%) and then Sheffield (43%). London was fourth, with 42%. For dust, London had the highest proportion (33%), followed by Nottingham (31%) and then Sheffield, Leicester and Manchester (30%). The split between dust and sulphate aerosol was quite similar in Glasgow and Edinburgh. Across western regions, sea salt appeared to be the dominant factor within the AOD, with Bristol (32%) and Cardiff (43%) both having high fractional values. A non-negligible factor in all areas was sulphate aerosol, with levels varying between 10% in Cardiff and 34% in Edinburgh. Sulphate aerosol in CAMS, from the MODIS satellite data, comes from a variety of sources (Bozzo et al., 2017), including industrial and fossil fuel combustion, biomass burning and natural sources (volcanic and biogenic). Given the distance from active volcano sites, the high sulphate levels would likely be more attributable to biogenic sources such as marine plankton.

The VIIRS visible channel satellite data at around 1330 UTC on 16 October (Figure 6) clearly shows the smoke/dust layers as a brown feature (with clouds showing as white in the same figure). At that time, the plume extended from the Bay of Biscay up to Scotland, with a width of up to 250km; the satellite image corresponds very closely to the CAMS aerosol analyses. On this larger scale, it can also be seen that the system was occluding rapidly, and so the winds, although still strong, were beginning to abate across Ireland and Scotland. During late afternoon on 16 October, Ophelia moved up towards Norway, and the associated cold front bringing the red sky haze moved across France and travelled further east across continental Europe. On 17 October many regions across northern Europe, including Germany, Belgium and the Netherlands, reported the same phenomenon.

### Enhanced air pollution

Alongside the optical effects caused by the increased aerosol loading, satellites offered a unique perspective with which to observe the air pollution associated with the wildfires. Such events can significantly alter air quality on both regional and hemispheric scales. The Infrared Atmospheric Sounding Instrument (IASI), which was first launched onboard Metop-A in 2006, orbits the Earth in a sun-synchronous orbit at ~800km with a 0930h equator local crossing time. This results in two overpasses per day for tropical regions and up to four overpasses for the high latitudes. As the instrument is a Fourier Transform Spectrometer, it produces data with very high spectral resolution, up to 0.5cm⁻¹, and a spatial resolution up to 12km², sufficient to allow a variety of species to be measured at a high spatial resolution (Clerbaux et al., 2009; Turquety et al., 2009).

Carbon monoxide (CO) is produced from incomplete combustion of vegetation in wildfires, has a lifetime of the order of several weeks, and is a tracer of long-range transport of pollution. The gas contributes to climate change as the main atmospheric sink of CO is reaction with OH – the same sink for the greenhouse gases tropospheric ozone and methane. Using the ULIRS algorithm (Illingworth et al., 2011) it was possible to quantify total column amounts of CO during the red sun event. No enhancement of CO is seen on 15 October from the fires (Figure 7), but by 16 October a spike in CO is observed over the North Sea and southern Sweden. By 17 October the enhancement extends across to western Russia, and by 18 October the CO has mixed across an area from the Black Sea to Iran. CO values are up to five times the background values. This CO plume can be unambiguously linked with trajectory models (not shown) back to the fires over Portugal and Spain with a plume height of between 6 and 8km. As the IASI measures in the infrared part of the spectrum, clouds unfortunately pose a particular problem for the CO retrieval, and so lots of data are excluded where clouds are detected; this explains why very little CO enhancement was observed on 16 October, while ex-hurricane Ophelia was still active. By 17 October the storm had dissipated

#### Table 2.

Aerosol fraction based on the CAMS analysis product for the afternoon of 16 October 2017 for the four different aerosol types.

| City          | Latitude (°N) | Longitude (°W) | Aerosol fraction (%) | Biomass burning | Dust | Sea salt | Sulphate |
|---------------|---------------|----------------|----------------------|-----------------|------|---------|----------|
| London        | 51.5074       | 0.1278         | 42                   | 33              | 42   | 3       | 21       |
| Birmingham    | 52.4862       | 1.8904         | 39                   | 29              | 39   | 29      | 13       |
| Liverpool     | 53.4084       | 2.9916         | 38                   | 27              | 38   | 27      | 16       |
| Nottingham    | 52.9548       | 1.1581         | 45                   | 31              | 45   | 31      | 5        |
| Sheffield     | 53.3811       | 1.4701         | 43                   | 30              | 43   | 30      | 5        |
| Bristol       | 51.4545       | 2.5879         | 31                   | 25              | 31   | 25      | 32       |
| Glasgow       | 55.8642       | 4.2518         | 37                   | 26              | 37   | 26      | 7        |
| Leicester     | 52.6369       | 1.1398         | 46                   | 30              | 46   | 30      | 6        |
| Edinburgh     | 55.9533       | 3.1883         | 33                   | 29              | 33   | 29      | 4        |
| Leeds         | 53.8008       | 1.6491         | 41                   | 29              | 41   | 29      | 4        |
| Cardiff       | 51.4816       | 3.1791         | 27                   | 20              | 27   | 20      | 43       |
| Manchester    | 53.4808       | 2.2426         | 40                   | 30              | 40   | 30      | 9        |

*Figure 5. Fractional aerosol optical depth from the CAMS analyses product for 1200 utc on 16 October 2017, showing (a) biomass burning aerosol, (b) dust aerosol, (c) sea-salt aerosol, and (d) sulphate aerosol. Plot generated using Copernicus Atmosphere Monitoring Service Information (2017; https://confluence.ecmwf.int/pages/viewpage.action?pageId=58131166).*
Conclusion

On 16 October 2017, the combination of the powerful ex-hurricane *Ophelia*, wildfires in Portugal and Spain, and uplifting of desert dust from the Sahara all combined to varying degrees to turn the colour of the sky a deep brown and orange hue, and the Sun red, across England, Wales and parts of Scotland. The event, colloquially dubbed ‘the red sun’, was very unusual for the UK and caused a lot of speculation on social media at the time as to the causes. Although some people across the UK reported burning smells during the event, most of the material causing the phenomenon was between 4 and 7 km in altitude and so should have posed a low risk to health.

Using the unique vantage point of satellite instrumentation, it was possible to somewhat, allowing the IASI to observe the enhanced CO. There is ongoing work within the UK National Centre for Earth Observation investigating the possibility of obtaining CO concentration information from above cloud layers using IASI.
monitor the rapid spread of aerosol and pollutants such as carbon monoxide northward from the fires in Portugal and Spain.

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Analysis of the long-time climate data series for Turin and assessment of the city’s urban heat island

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Introduction

The historical meteorological data series for Turin is one of the longest for the whole of Italy – with observations of temperatures and rainfall extending back for about 260 years – and it is almost uninterrupted (Di Napoli and Mercalli, 2008; Acquaotta et al., 2009). The story of the Turin observatory begins in the eighteenth century, alongside the observatories at Bologna, Padua, Milan, Rome and Palermo, but despite the presence of such stations, the development of meteorology in Italy was influenced negatively by the lack of political unity and the absence of a national agency that was capable of ensuring homogeneity across measurements, as well as their publication and dissemination.

A decisive turning point in the development of Italian meteorological networks occurred around 1850, with the invention of new meteorological instruments and the enhancement of existing ones, as well as improvements to the communication networks between the different regions, following the invention of the telegraph in 1843. The Fluvial Hydrography Rain-gauge Service, founded in 1867 by the Ministry of Public Works, underwent an important development under the direction of the Barnabite Francesco Denza. In the same year a meteorological survey network was created under the supervision of the Ministry of Public Education.

With the growth of the city of Turin over the centuries, changes to the distribution of energy usage over the urban area led to development of an urban heat island (UHI). This phenomenon is a surface and atmospheric thermal modification of the climate, which has been well-described elsewhere. The urbanised areas are warmer than the non-urbanised surrounding areas, particularly at night (Voogt and Oke, 2003). The UHI is one of the most studied climatic effects relating to urban settlements, and it is evident in the characteristic warmth of a town or city due to human modifications of the surface and atmospheric properties which accompany urban development (Oke, 1995).