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 the system became classed as a hurricane and peaked as a category 3 hurricane system 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. The system 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. Eireann issuing a red weather warning for strong winds 48h before the event. In southern Ireland wind speeds of over 190kmh^{-1} were 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 the 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 showed 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 has shown 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 many instances of pulses of Saharan dust being observed over the mid-Atlantic Ocean (Earth Observatory, 2017). The majority of these events expelled dust in a westward direction towards the Gulf of Mexico, although mixing within the *Ophelia* system dragged dust-laden air up towards northwestern Europe.

A measure called 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

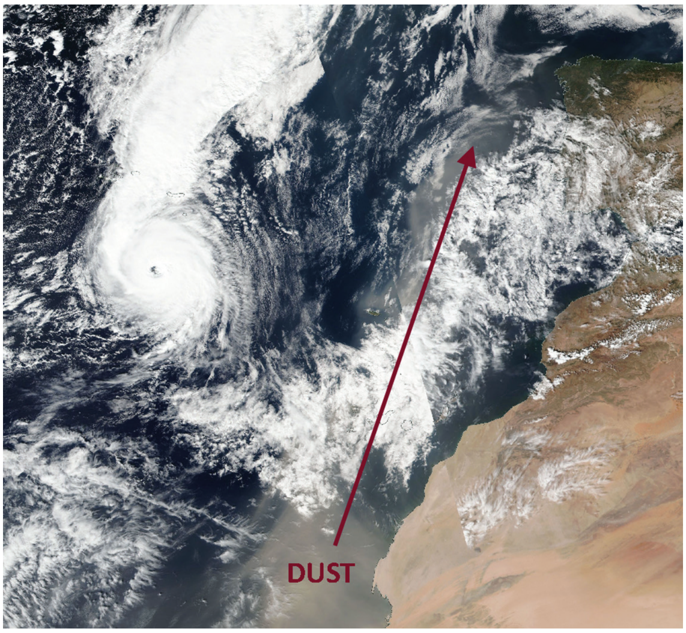

Figure 1. VIIRS (Suomi NPP) satellite image of RGB-composite images taken between 1300 and 1500 UTC on 14 October 2017 showing Saharan Desert dust being transported towards the UK ahead of the Ophelia weather system.

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particles in the 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; the dust was transported northward due to interaction with the *Ophelia* system, 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 areas of the world and, as well as the local hazards such as loss of life and damage to property, the largest fires can send aerosol and trace gases high into the atmosphere that can then readily be 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 still 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 unwanted 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' due to the 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). Coupled with the Saharan dust, the particles from the fires became entrained with the *Ophelia* system, and as the system tracked northwards towards southern Ireland, the trailing cold front within the weather system acted as a conveyor belt to feed the combination of smoke and other pollutants directly from the fire region up towards the UK.

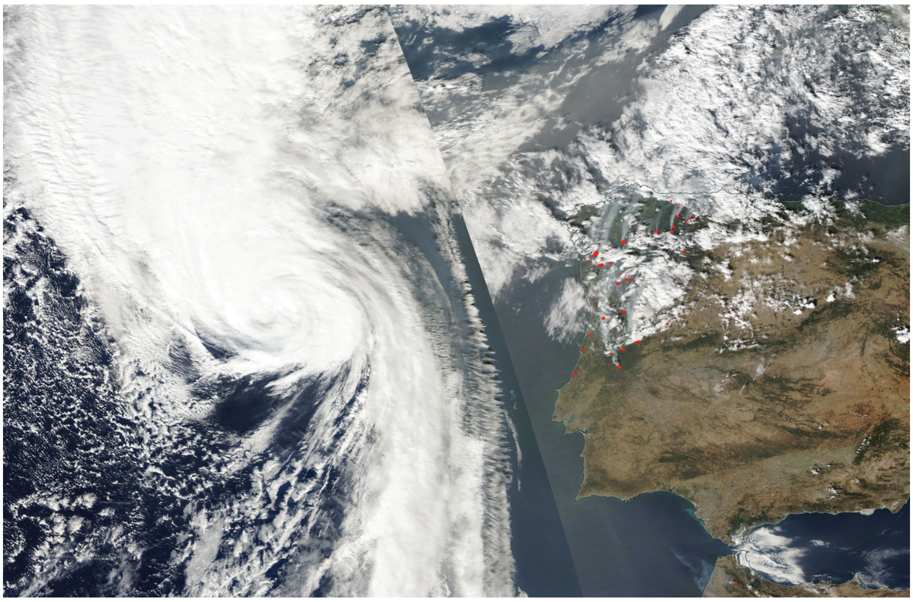

Figure 2. An Aqua MODIS true colour composite (15 October 2017) showing the evolution of Hurricane Ophelia to an intense post-tropical cyclone. Red dots indicate fire hotspot detection.

Table 1.

The largest fires across Portugal during October 2017. (The data used here are from the EFFIS burnt area locator, see http://effis.jrc.ec.europa.eu/static/effis_current_situation/public/index.html)

Start date	*Area burnt (ha)*	*Province*
14 October 2017	67521	Pinhal Interior Norte
15 October 2017	64321	Pinhal Interior Norte
15 October 2017	34844	Pinhal Interior Sul
15 October 2017	24183	Baixo Mondego
15 October 2017	18900	Pinhal Litoral
15 October 2017	10701	Serra da Estrela

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 rather than white?

Independent ground-based observations from the Chilbolton lidar on 16 October (not shown) showed 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.

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-

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ing aerosol is a complex task. Earth System Models incorporate satellite measurements and can be used for forecasting the evolution of particulate matter. The Copernicus Atmospheric Monitoring Service (CAMS) has been developed to address environmental concerns, aiming at supporting policymakers, business and the general public with enhanced atmospheric environmental information (Benedetti *et al.*, 2009; Morcrette *et al.*, 2009). CAMS delivers a variety of operational services which include (amongst others): (1) daily production of near-real-time analyses and forecasts of global atmospheric composition, (2) daily production of near-real-time European air quality analyses and forecasts with a multi-model ensemble system, and (3) anthropogenic emissions for the global and European domains and global emissions from wildfires and biomass burning. In the forecast initiated at 0000 UTC on 16 October (Figure 3), the model estimated that there was an aerosol split of 60% biomass burning aerosol and 40% dust aerosol across central England. In easternmost parts of the UK, dust aerosol was expected to be dominant (up to 100%).

For the post-event analyses, CAMS also produces a global real-time analysis product, with satellite observations providing a vital input to its 4-dimensional variational (4d-Var) data assimilation system, effectively combining short-range forecasts with satellite observations to produce the best fit in the model for both. The Moderate Resolution Imaging Spectroradiometer (MODIS), on the Terra and Aqua satellite platforms, is one source of aerosol information, and it is selected for its reliability and for the fact that data are available in near-real time, a vital requirement of a real-time analysis system. MODIS provides aerosol optical depth, globally, using two distinct algorithms – one for ocean and one for land (Hsu *et al.*, 2013; Levy *et al.*, 2013). The land algorithm aerosol optical depths have slightly higher uncertainties due to surface reflectance effects, with the largest uncertainty over highly reflective surfaces such as deserts or snow-covered areas. The optical depth at 550nm is assimilated into the CAMS analysis system.

CAMS also uses Polar Multi-sensor Aerosol product (PMAp) data from three instruments on both the MetOp-A and MetOp-B satellite platforms. The instruments on these satellites include the Global Ozone Monitoring Experiment-2 (GOME-2), the Advanced Very High Resolution Radiometer (AVHRR) and the Infrared Atmospheric Sounding Interferometer (IASI). Between them, they provide aerosol optical depth at 550nm and aerosol type classification for black carbon and organic matter (combined to give biomass burning aerosol), dust, sulphate and sea salt. Since February 2017 these products have been available globally over both land and ocean surfaces. The products are operational and are provided within 3h of measurement, with higher than 98% availability. Most products arrive within 1.5h, and the system is continuously monitored and quality controlled.

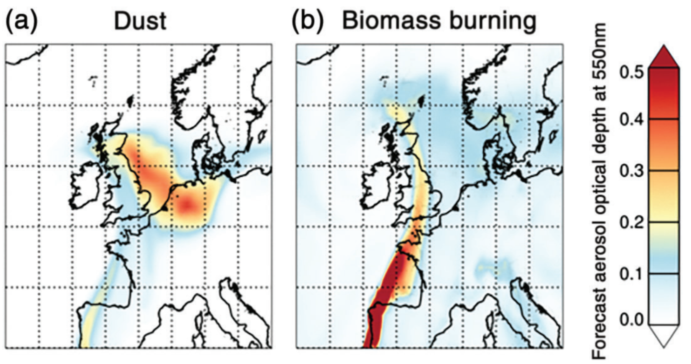

Figure 3. (a) Dust aerosol and (b) biomass burning aerosol optical depth forecasts for 1200 UTC on 16 October 2017 via the Copernicus Atmospheric Monitoring Service (CAMS), initiated at 0000 UTC on 16 October 2017. Data obtained from the ECMWF.

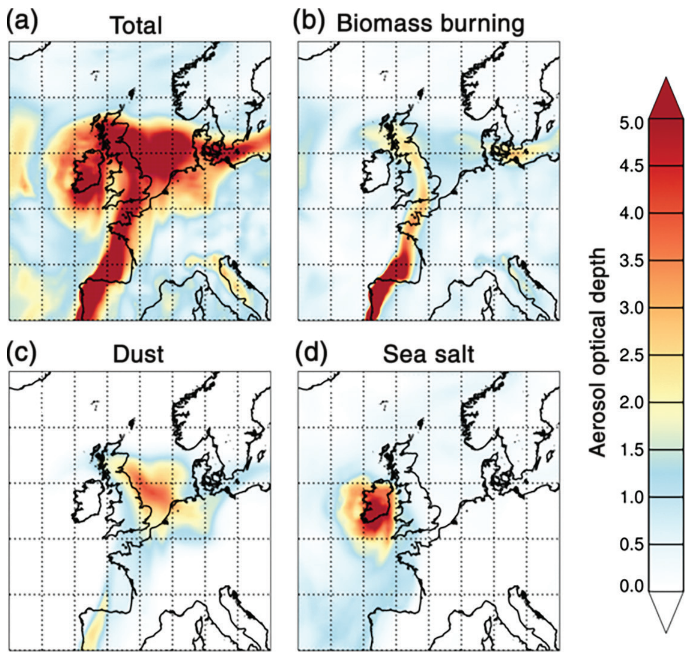

Figure 4. From the CAMS analyses product, the (a) total aerosol optical depth (AOD), (b) biomass burning AOD, (c) dust AOD, and (d) sea-salt AOD for 1200 UTC on 16 October 2017. Plot generated using Copernicus Atmosphere Monitoring Service Information [2017; https://confluence.ecmwf.int/pages/viewpage.action?pageId=58131166].

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 England was from biomass burning over central and southern regions, with a large proportion of desert dust around the English east coast 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

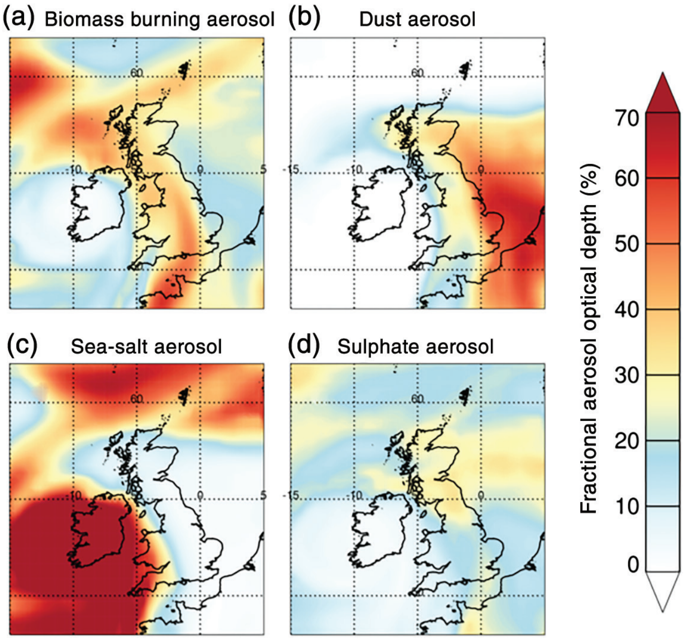

Figure 5. Fractional aerosol optical depth from the CAMS analyses product for 1200 UTC *on 16 October 2017, showing (a) biomass burning aerosol, (b) dust aerosol, (c) sea-salt aerosol, and (d) sulphate aerosol. Plot generated using Copernicus Atmosphere Monitoring Service Information [2017; https://confluence.ecmwf.int/pages/viewpage.action?pageId=58131166].*

Table 2.

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

			Aerosol fraction (%)			
City	*Latitude (°N)*	*Longitude (°W)*	*Biomass burning*	*Dust*	*Sea salt*	*Sulphate*
London	51.5074	0.1278	42	33	4	21
Birmingham	52.4862	1.8904	39	29	13	19
Liverpool	53.4084	2.9916	38	27	16	19
Nottingham	52.9548	1.1581	45	31	5	19
Sheffield	53.3811	1.4701	43	30	5	22
Bristol	51.4545	2.5879	31	25	32	12
Glasgow	55.8642	4.2518	37	26	7	30
Leicester	52.6369	1.1398	46	30	6	18
Edinburgh	55.9533	3.1883	33	29	4	34
Leeds	53.8008	1.6491	41	29	4	26
Cardiff	51.4816	3.1791	27	20	43	10
Manchester	53.4808	2.2426	40	30	9	21

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, the *Ophelia* system moved up towards Norway, and the associated cloud front bringing the red sky haze moved across France and travelled east across 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 $12km^2$, 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

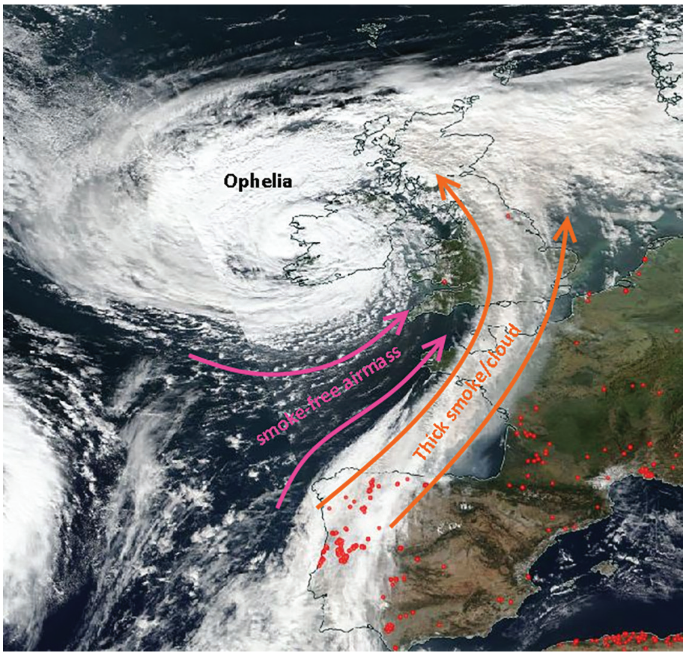

Figure 6. Composite true-colour VIIRS images (between 1230 and 1430 UTC) on 16 October 2017 showing strong advection of smoke from Portugal towards the UK. A clean smoke-free air mass can be seen following on behind the front.

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.

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 sky a deep brown and orange and the sun red across England, Wales and parts of Scotland. The event, colloquially dubbed '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 7km in altitude and so should have posed a low risk to health.

Using the unique vantage point of satellite instrumentation, it was possible to

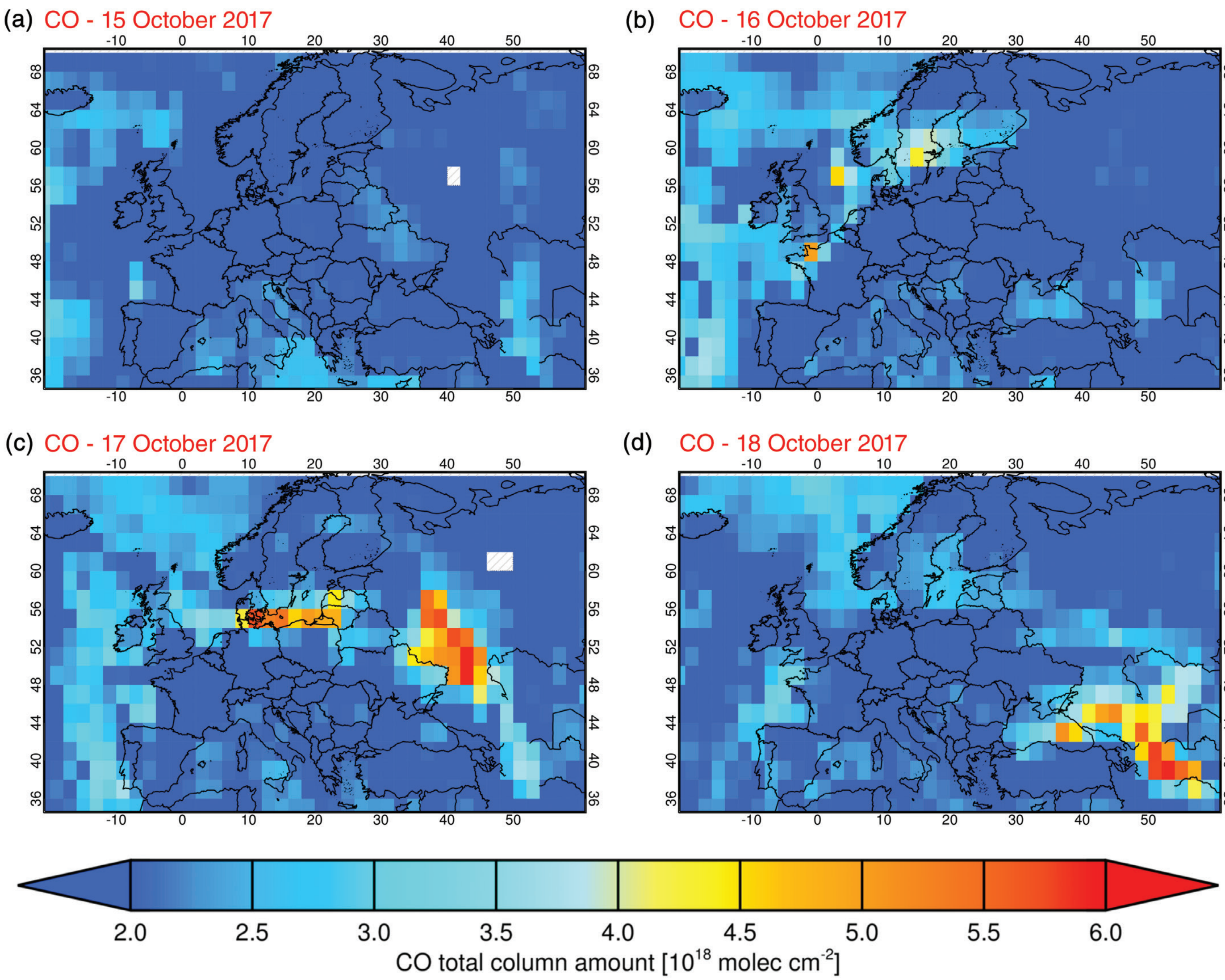

Figure 7. Night-time observations (~2130Z local time) of carbon monoxide total column amounts derived from IASI measurements from instruments on MetOp-A and MetOp-B on (a) 15 October 2017, (b) 16 October 2017, (c) 17 October 2017, and (d) 18 October 2017.

monitor the rapid spread of aerosol and pollutants such as carbon monoxide northward from the fires in Portugal/Spain.

Acknowledgements

The author is funded by the UK National Centre for Earth Observation (NCEO). This article contains Copernicus Atmosphere Monitoring Service Information [2017; https://confluence.ecmwf.int/pages/viewpage.action?pageId=58131166]. Neither the European Commission nor ECMWF is responsible for any use that may be made of the information it contains.

References

Benedetti A, Morcrette JJ, Boucher O *et al.* 2009. Aerosol analysis and forecast in the ECMWF Integrated Forecast System. Part II: data assimilation. *J. Geophys. Res.* **114**: D13205. doi:10.1029/2008JD011115

Bozzo A, Remy S, **Benedetti A *et al.*** 2017. Implementation of a CAMS-based aerosol climatology in the IFS. Technical report 801. ECMWF Technical Memorandum: Reading, UK.

Clerbaux C, Boynard A, Clarisse L *et al.* 2009. Monitoring of atmospheric composition using the thermal infrared IASI/MetOp sounder. *Atmos. Chem. Phys.* **9**: 6041–6054.

Earth Observatory. 2014. Saharan dust on the move. https://earthobservatory.nasa.gov/IOTD/view.php?id=83966 (accessed 10 March 2018)

Earth Observatory. 2017. African dust aloft. https://earthobservatory.nasa.gov/images/89944/african-dust-aloft (accessed 10 March 2018)

Fromm M, Lindsey DT, Servranckx R *et al.* 2010. The untold story of pyrocumulus. *Bull. Am. Meteorol. Soc.* **91**: 1193–1209.

Hsu NC, Jeong M-J, Bettenhausen C *et al.* 2013. Enhanced Deep Blue aerosol retrieval algorithm: the second generation. *J. Geophys. Res.* **118**(16): 9296–9315.

Illingworth SM, Remedios JJ, Boesch H *et al.* 2011. ULIRS, an optimal estimation retrieval scheme for carbon monoxide using IASI spectral radiances: sensitivity analysis, error budget and simulations. *Atmos. Meas. Tech* **4**: 269–288.

Kelly FJ, **Fussell JC**. 2015. Air pollution and public health: emerging hazards and improved understanding of risk. *Environ. Geochem. Health* **37**: 631–649.

Koren I, Kaufman YJ, Washington R *et al.* 2006. The Bodélé depression: a single spot in the Sahara that provides most of the mineral dust to the Amazon forest. *Environ. Res. Lett.* **1**: 014005. doi:10.1088/1748-9326/1/1/014005

Levy RC, Mattoo S, Munchak LA *et al.* 2013. The Collection 6 MODIS aerosol products over land and ocean. *Atmos. Meas. Tech. Discuss.* **6**: 159–259.

Morcrette JJ, Boucher O, Jones L *et al.* 2009. Aerosol analysis and forecast in the ECMWF Integrated Forecast System. Part I: forward modelling. *J. Geophys. Res.* **114D**: D06206. doi:10.1029/2008JD011235

National Hurricane Center. 2017. 2017 Atlantic hurricane season. https://www.nhc.noaa.gov/data/tcr (accessed 10 March 2018)

Prospero JM, Collard F-X, Molinié J *et al.* 2014. Characterizing the annual cycle of African dust transport to the Caribbean Basin and South America and its impact on the environment and air quality. *Global Biogeochem. Cycles* **28**(7): 757–773.

Turquety S, Hurtmans D, Hadji-Lazaro J *et al.* 2009. Tracking the emission and transport of pollution from wildfires using the IASI CO retrievals: analysis of the summer 2007 Greek fires. *Atmos. Chem. Phys.* **9**: 4897–4913.

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doi:10.1002/wea.3440