The weather's response to a solar eclipse

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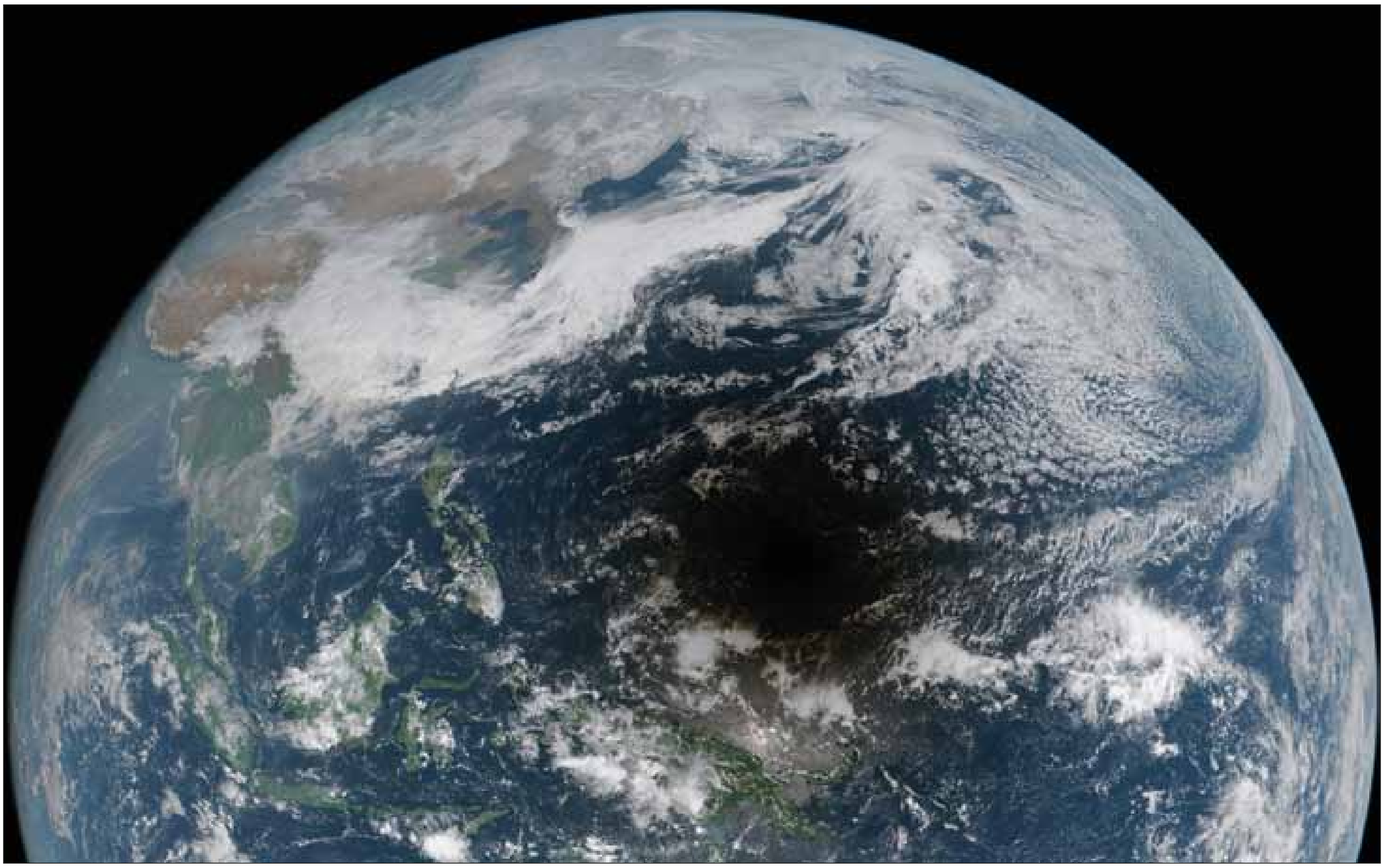


1 The lunar shadow on 9 March 2016 at 01.50 UTC, as recorded by the Japanese Meteorological Agency's Himawari-8 satellite, processed to produce a true-colour image. (CIMSS, University of Wisconsin)

The weather's response to a solar eclipse

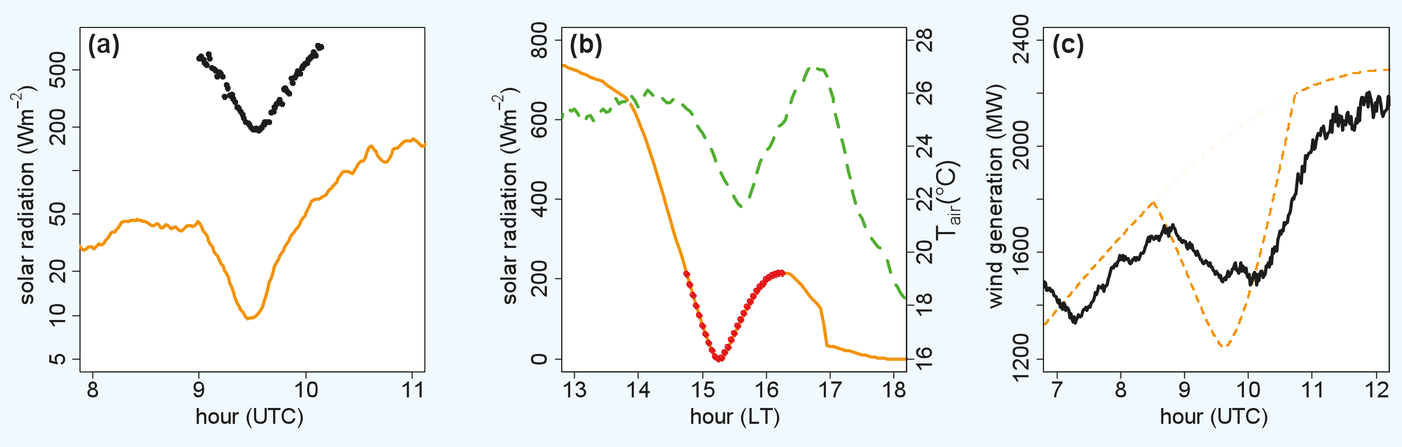
Eclipses provide a predictable transient reduction in the energy source driving the atmosphere and weather systems. **Giles Harrison** and **Suzanne Gray** examine what happened during the UK eclipses of 1999 and 2015 and what they show about detailed weather prediction models.

Solar eclipses have been studied by astronomers for centuries, providing a predictable although brief glimpse at the properties of the Sun. Their astronomical predictability decades and centuries in advance contrasts sharply with the lower atmosphere's unpredictability beyond a few days at most, especially when forecasting whether there will be obscuring effects of clouds. These weather-related problems for eclipse work are not new: for example, Edmund Halley reported just such difficulties in viewing the 1715 eclipse, noting that "My worthy colleague Dr John Keill by reason of clouds saw nothing distinctly at Oxford" (Halley 1716). But regarding meteorology solely as the obscurer of the heavens misses the rich broader geophysical research opportunities an eclipse provides, through unravelling the atmosphere's responses to the sudden removal and restoration of its energy source. By harnessing the high-resolution instrumental and numerical capabilities now available, eclipses provide a natural interdisciplinary experiment at the crossroads of meteorology and astronomy (Harrison & Hanna 2016).

"Quantitative atmospheric investigations during eclipses did not begin until the 1830s"

Eclipse meteorology

Meteorological effects of eclipses have of course long been appreciated and even indirectly recorded; for example, Edmund Halley also mentioned that "I forbear to mention the chill and damp which attended the darkness of this eclipse of which most spectators were sensible" (Halley 1716). Even without the full perspective



2 Effect of solar eclipses on surface meteorological quantities. (a) Solar radiation measured with respect to a horizontal surface at Reading during the 20 March 2015 partial eclipse, at the surface beneath cloud (solid line), and above the cloud from a modified weather balloon at 15 km altitude (black points). (Modified from Harrison *et al.* 2016) (b) Air temperature response (dashed green line) in northern Zimbabwe during the 21 June 2001 total solar eclipse, with solar radiation (solid line) against Local Time (LT). Red points mark measurements during the eclipse. (Mod. from Aplin *et al.* 2016) (c) UK wind generation during the 20 March 2015 partial eclipse. Dashed orange line shows calculated change in solar radiation for Reading, arbitrary units. (Mod. from Harrison & Hanna 2016)

on the lunar shadow now provided by satellite images (figure 1), it seems inconceivable that an observable effect would not have been foreseen in air temperature for a long time. Nevertheless, despite the ready availability of thermometers from the early 1700s, genuinely quantitative atmospheric investigations during eclipses did not begin until the 1830s. The primary change during an eclipse is that of the drop in incoming solar radiation (figure 2a), but the surface air temperature changes have historically received the most attention (Aplin *et al.* 2016), with the greatest air temperature reduction typically occurring about 10 minutes after the minimum in solar radiation (figure 2b). The temperature drop is larger in clear skies than cloudy skies (Aplin & Harrison 2003). There is also an associated eclipse-induced reduction of wind speed, which is not always appreciated. This results from a reduction in turbulence and mixing when the solar heating is removed. Figure 2c shows how the UK electrical generation from wind was reduced during the 20 March 2015 eclipse, which in some sense represents a nationally aggregated measure of the wind. As an aside, wind power generation is therefore not a good choice for mitigating the associated loss in photovoltaic power generation during eclipses.

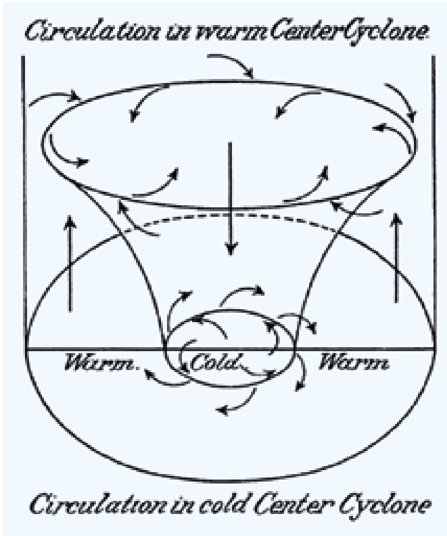
1900 US eclipse

An early defining study that recognized a broader atmospheric response was undertaken by the American meteorologist H Helm Clayton, who brought together extensive atmospheric surface measurements, particularly of the wind, using 15-minute resolution data from six measurement sites operating during the 28 May 1900 US eclipse (Clayton 1901a). Reflecting the continuation of this approach across a broad range of eclipse-related topics in atmospheric science, the term "eclipse meteorology" was firmly adopted by 1936 (Fergusson 1936).

Clayton's study concluded that atmospheric circulation changes resulted from the effect of the lunar shadow on the atmosphere, and proposed a conceptual model – the eclipse cyclone – to describe the circulation pattern associated with the umbral cooling. Clayton's perspective used the understanding of a cyclone (also known as a mid-latitude depression) from Ferrell (1889), which associated the well-known regional-scale weather pattern with wind direction and temperature changes. Minimal information above the surface was available for corroboration, but this conceptual picture of a cold-cored cyclone was pivotal to Clayton's explanation of the eclipse-induced wind direction effects observed (figure 3). Clayton's interpretation received a mixed response, in particular concerning his view of the surface data as actually representing a cold-cored cyclone (Ward 1901, Bigelow 1901, Clayton 1901b). Nevertheless, this work helped the concept of eclipse-induced wind effects to become established and others remarked on anomalous eclipse-induced wind responses around the same time, even adopting the term "eclipse wind" (Rotch 1900).

"The term 'eclipse meteorology' was firmly adopted by 1932"

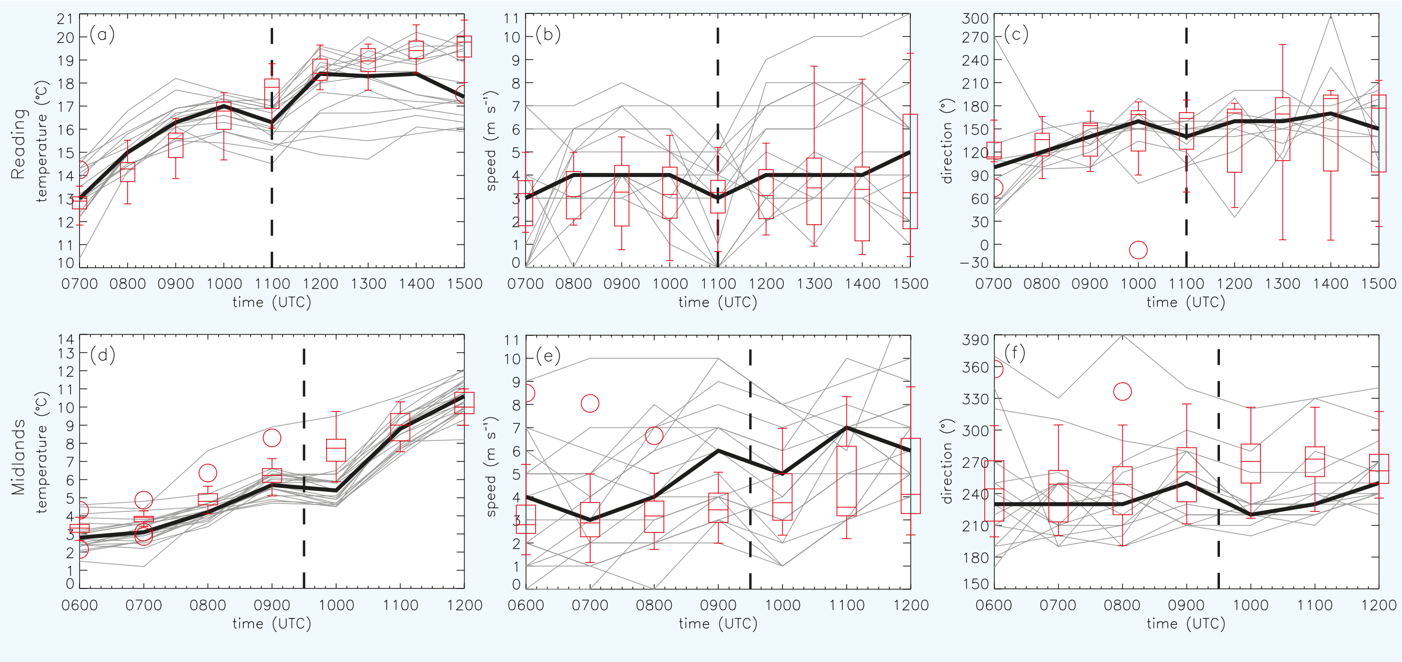
Further measurements of wind effects associated with an eclipse were reported by Kimball and Fergusson (1919), who observed a weak persistent wind anomaly along the central band of the lunar shadow. Anderson (1999) suggests that Kimball and Fergusson's work provides the basis for the idea of a cold eclipse wind, which, while debated, has become embedded in eclipse observers' folklore. Many subsequent observations of anomalous wind-changes have been made, such as a strong post-eclipse gust on 30 June 1973 in Mauritania following an anticlockwise change – known in meteorology as backing – in the wind direction (Anderson & Keefer 1975). Establishing whether these particular wind effects are a common characteristic of eclipse-induced meteorological changes is unlikely to be achieved by surface observations alone, because eclipse weather situations vary from day to day and seasonally, as do the affected locations, making it difficult to generalize. Nevertheless, changes in the wind are commonly observed as features of the atmospheric response to eclipses (Aplin *et al.* 2016).



3 Air circulation proposed by H Helm Clayton for eclipse conditions around the lunar shadow region. (From Bigelow 1901)

Numerical models

Modern computation tools provide the capability to examine the conceptual ideas and actual effects more thoroughly, in the



4 Hourly observations and model data for the 1999 (a,b,c) and 2015 (d,e,f) solar eclipses affecting the UK, for the regions identified as Reading (Gray & Harrison 2012) and Midlands (Gray & Harrison 2016). (a) and (d) show the surface air temperature response, (b) and (e) the near-surface (at 10 m height) wind speed and (c) and (f) the wind direction. In each case the grey lines show the hourly observations available from the observing sites within the region, and the black line the median of these observations. A dashed vertical line marks the time of maximum eclipse. The red outline boxplots show the median (central line) and span (interquartile range shown by edge of the box) of numerical forecast output interpolated to the observing sites, using a numerical model ignorant of the eclipse. Red points are outlier forecasts. Wind directions are conventionally recorded as angles clockwise from north that the wind is coming from. Observational data are from the Met Office Integrated Data Archive System (MIDAS) land and marine surface stations dataset. Model forecasts are made using the Met Office operational UK weather forecast model. (After Gray & Harrison 2012, 2016)

form of numerical models of the atmosphere developed for weather forecasting. Numerical weather prediction models combine the equations of motion with the laws of thermodynamics, in order to predict the atmospheric response when a quantity in one of the equations changes. To operate, they require detailed measurements of the initial state of the atmosphere, obtained from networks of measurements made by national meteorological services using surface weather stations, remote sensing of the atmosphere by satellite, and balloons and aircraft to generate vertical profiles of the atmosphere. The numerical models then advance the initial conditions forward in time using a three-dimensional gridded representation of the atmosphere, extending from the surface to typically at least 40 km altitude. One benefit of applying numerical weather prediction models to the atmospheric conditions influenced by eclipses is that the unusual set of circumstances can also be used to test the models, ultimately providing a route to improving weather prediction.

> **"Citizen science measurements showed good agreement with Met Office data"**

Modern eclipse meteorology

A fundamental question in eclipse meteorology concerns how to separate eclipse effects from atmospheric changes that were going to happen anyway. Related questions arise across the geosciences, where it is rarely possible to separate cause and effect because many related, but different, quantities co-vary. Although an eclipse provides a well-characterized and predictable change in the incoming solar radiation, weather conditions may vary so much from one day to the next that the different effects cannot be unambiguously separated. Many studies have attempted to compare changes on the eclipse day with conditions on the days before or after to identify an eclipse's effect, but this can only be effective for extracting the eclipse-induced change if the weather remains similar over the days in question.

Numerical atmospheric models provide more possibilities for such comparisons (Gray & Harrison 2012), and so far they have been used in two ways. First, by using a numerical model that does not include a representation of the eclipse, the model can provide a prediction of what the weather would have been without the eclipse for comparison with the actual observed conditions. Second, a numerical model can be extended to include representation of the eclipse-induced solar radiation changes, and the results compared with those from the same model without such an extension. The difference between the two implementations of the same core model provides a prediction of the eclipse effects, which can be compared with observations.

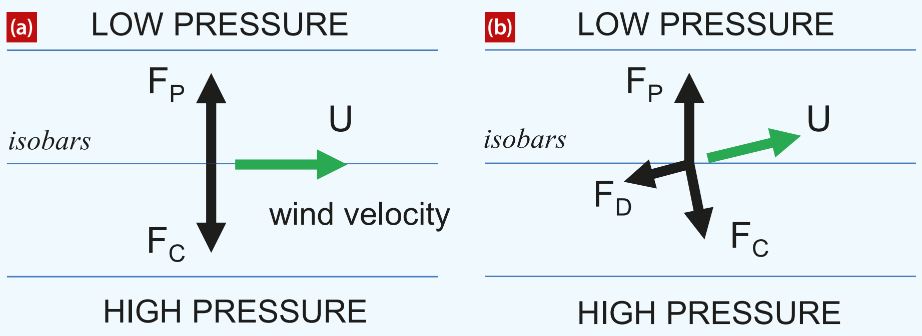
Both approaches need a network of measurements, with good spatial and temporal resolution. Eclipses passing over populated regions are increasingly able to provide such detailed measurements, thanks to the widespread use of automatic weather stations. For example, in the analysis of the weather effects of the UK's most recent total solar eclipse on 11 August 1999, the Met Office network used by Gray and Harrison (2012) had 121 measuring sites providing hourly data. In contrast, during the substantial UK partial eclipse of 20 March 2015, 331 Met Office sites providing measurements at up to 1-minute resolution were available, to which Gray and Harrison (2016) were also able to add data from a further 868 roadside weather stations.

An alternative strategy to obtain a dense network of measurements is to enlist amateur observers. The National Eclipse Weather Experiment (NEWEx) during the 2015 UK partial eclipse did precisely this as part of a science outreach activity, seeking observations via webform of wind, temperature and cloud during the eclipse at 15-minute and 5-minute resolution (Barnard *et al.* 2016). NEWEx had about 3500 participants across the UK (Portas *et al.* 2016) and the citizen science measurements obtained showed good agreement with data from the Met Office network in the reduction of temperature and wind speed (M R Clark 2016, Barnard *et al.* 2016).

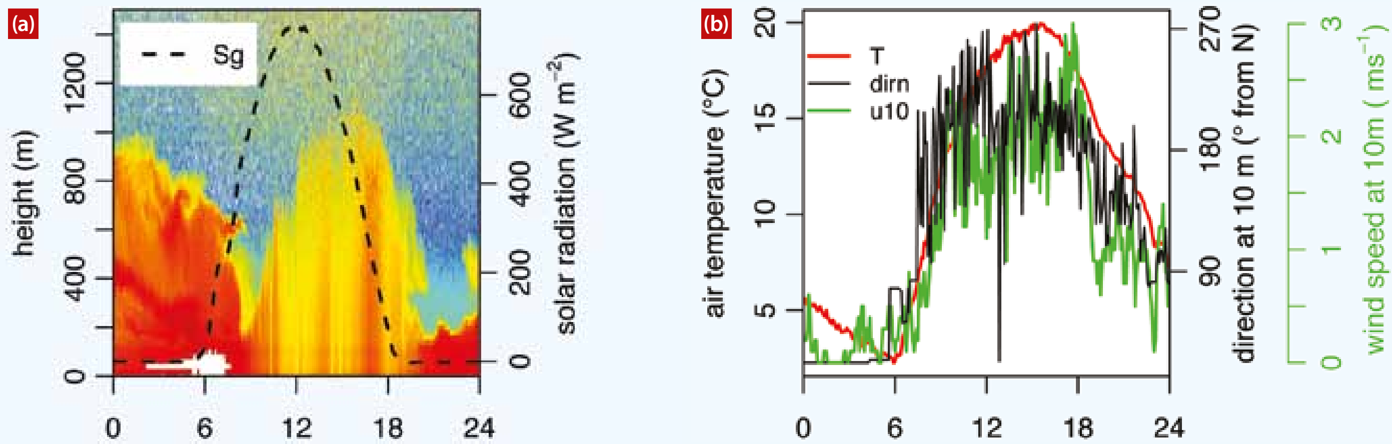
Clayton's conceptual model arose from linking a reduction in surface air pressure,

Wind speeds and wind direction

Wind speed and direction are intimately connected with horizontal differences in atmospheric pressure, with the large-scale flow direction usually immediately apparent from pressure maps showing isobars (lines of constant pressure). Flows near the surface encounter the additional effects of surface drag, modifying the wind speed and direction.



8 (a) For mid-latitudes, the horizontal forces on an air parcel aloft can be considered in balance. Looking from above in the northern hemisphere, the horizontal component of the pressure gradient force F_p balances the Coriolis force F_c. The Coriolis force arises from the Earth's rotation and acts normally to the wind direction, hence air flows along the isobars.
(b) The lowest part of the atmosphere is known as the boundary layer, where a drag force F_D also acts. For steady flow in a straight line, this modifies the force balance, and the wind direction changes.



9 (a) The depth of the boundary layer varies over a daily cycle, and can be seen in the transition from hot, coloured backscatter values to cold colours, from an upward pointing laser ceilometer, on a cloudless day at Reading. Boundary layer depth increases with vertical mixing, driven by solar radiation (S_g), with a lag of a few hours.
(b) Surface air temperature (T), wind speed (u_{10}) and direction on the same day follow the diurnal cycles in solar radiation and boundary layer depth.

wind direction changes and the circular cooling region of the lunar shadow with the meteorological structure of a cyclone. His interpretation depended entirely on surface measurements, with, despite the implications of figure 3, minimal knowledge of the upper air (i.e. above surface) conditions. Numerical models provide upper air and surface predictions, using balloon soundings and satellite-retrieved measurements for their initialization together with surface observations.

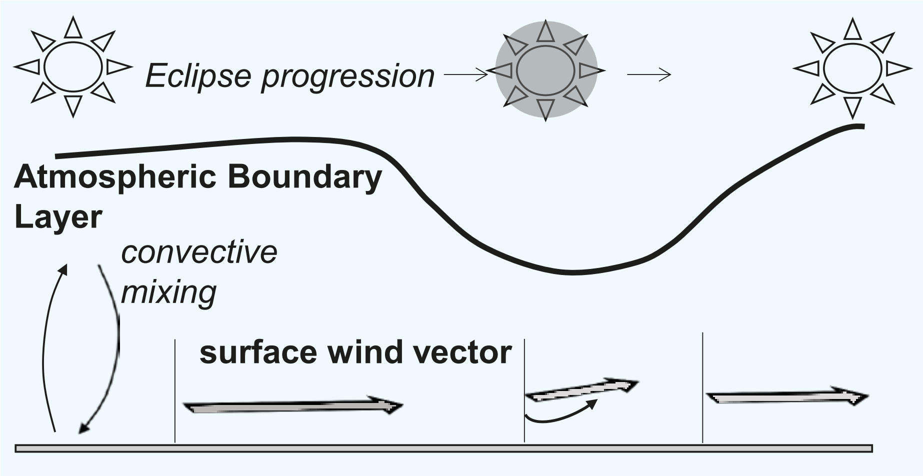
Forecast without eclipse

Adopting the first approach for using numerical models to analyse eclipse events outlined above – using a model forecast ignorant of the eclipse – Gray and Harrison (2012, 2016) compared surface observations for the 11 August 1999 and 20 March 2015 eclipses with model results from the Met Office's high-resolution numerical forecast model (known as the UKV, for UK Variable resolution), employing 1.5 km grid spacing. Figure 4 shows analyses for both events, with the data compiled in each case for inland regions away from the possible complicating effects of sea breezes. In each case, three observed (lines) and modelled (boxplot) quantities are compared: air temperature, wind speed and wind direction. For the 1999 eclipse, with light winds and substantially clear skies, the temperature reduction is clearly observable in figure 4a, beyond the range of the model predictions. A reduction in wind speed is also clearly observable (figure 4b), but within the range of forecast values. The wind direction (figure 4c) turns anticlockwise, again within the range of forecast values. For the 2015 eclipse, which was an eclipse of lesser magnitude across the UK than the 1999 eclipse and with the additional complication of more cloud, the temperature reduction is still clear (figure 4d). The wind speed reduction is also evident (figure 4e), as is an anticlockwise turning in wind direction (figure 4f). Taken together, the panels demonstrate that the temperature and wind responses observed in both UK eclipses are similar. In particular, the changes in wind yield a reduced wind speed and an anticlockwise turning in wind direction, compared with both the forecasts and the pre- and post-eclipse observed wind directions. This consistency in response occurs despite the meteorological circumstances of these eclipses being different and occurring in different seasons. The consistency in the wind responses therefore provides some corroboration for the original observations of Clayton, although in what follows we provide a simpler explanation for these changes.

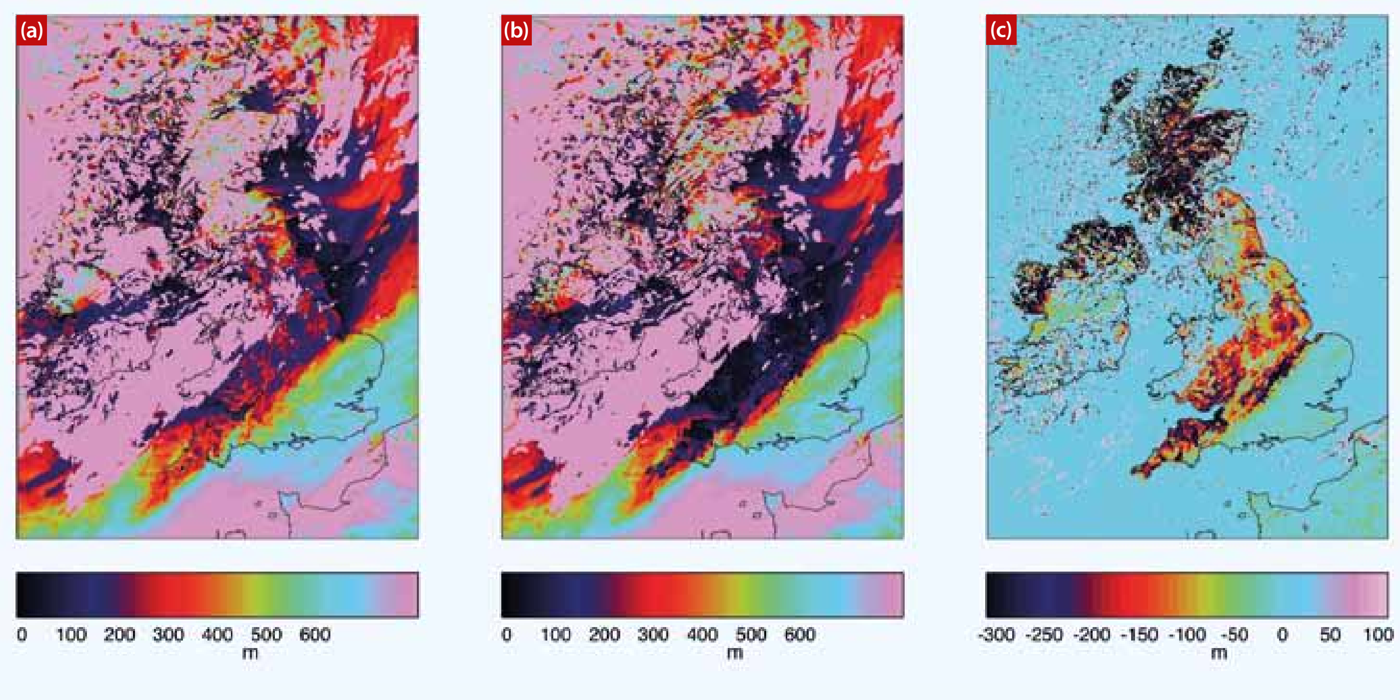
"Changes in surface drag on air flow also occur between night and day"

Surface drag

Wind direction changes can be understood in terms of the changing effect of the Earth's surface conditions on the air flow above. This is because the lower part of the



5 Suggested effect of a solar eclipse on the surface winds. Within the atmospheric boundary layer the air flow is influenced by surface properties, and the boundary layer deepens during daytime as a result of turbulence and convective motion. During an eclipse the mixing is reduced and the boundary layer becomes shallower. An associated increase in surface drag modifies the balance of forces on the moving air, changing its direction. After the eclipse, mixing re-establishes itself so that the boundary layer recovers and the wind speed and direction resume pre-eclipse properties.



6 Calculations of the boundary layer depth during the maximum of 20 March 2015 eclipse, as found by the Met Office UKV numerical model, (a) without eclipse representation and (b) with eclipse representation. (c) The difference between (a) and (b). (From P Clark 2016)

weather-forming region of the atmosphere is affected by the surface friction it encounters. For example, there is less surface drag on air flowing over an ocean compared with that flowing over a mountain range. Changes in surface drag also occur between night and day, because of the change in depth of the boundary layer, the region of the lower atmosphere where the surface properties influence the flow. These effects change the balance of the forces on the moving air, the vector sum of which determines the wind direction (see box "Wind speeds and wind direction").

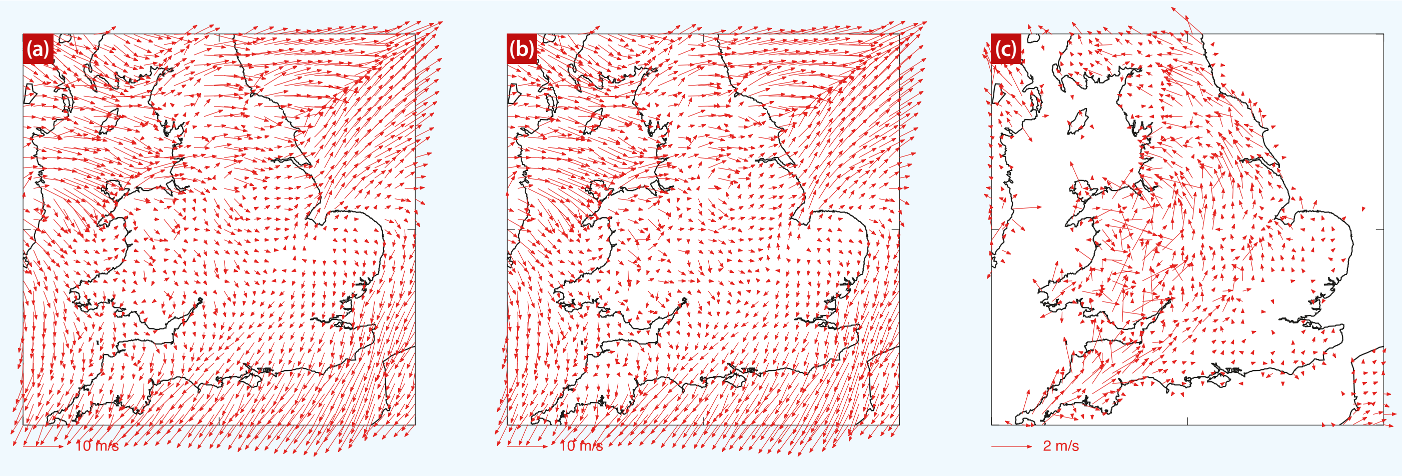
Similar effects to those after sunset might be expected as a result of transient eclipse-induced cooling, and figure 5 shows conceptually how boundary layer changes could lead to the wind speed and direction effects observed. Gray and Harrison (2016) reported wind-profiler observations from the 2015 eclipse showing a reduction in boundary layer height during the eclipse; these data informed simple calculations demonstrating that an anti-clockwise change in wind direction would be expected, together with the reduction in wind speed from reduced turbulence and mixing. However, nocturnal wind effects within the boundary layer are often complicated as the air flowing immediately adjacent to the surface can become decoupled from the air above it.

Modelling including eclipse

The second approach for using numerical models to analyse eclipse events – modifying a numerical model to include representation of the eclipse-induced solar radiation changes – can provide more detail on the wind anomalies, as the three-dimensional wind effects are explicitly resolved. The Met Office UKV model was modified to represent the 20 March 2015 eclipse, by prescribing an eclipse-induced change in the incoming solar radiation (P Clark 2016), but unmodified in other respects.

On 20 March 2015, most of the UK was covered by low cloud with light winds. There were, however, clear skies in a band from Cornwall to Leicestershire, giving good eclipse viewing conditions that were associated with the largest surface air temperature changes (M R Clark 2016). The difficulties presented by different weather conditions across the region of an eclipse provide one reason for pursuing an analysis that combines modelling and measurements, as the timing of the progression of a weather system can be important in determining the effects observed. The quantities that are observed and predicted by the model can, of course, be directly compared. But, because the model also represents physical quantities that are not directly observed, or only observed at a few sites, estimates for these can be obtained from the model calculations too.

Variations in the boundary layer depth



7 Calculations of the near-surface (10 m height) wind vectors during the maximum of the 20 March 2015 eclipse, as found by the Met Office UKV numerical model, (a) without eclipse representation and (b) with eclipse representation. (c) The difference between (a) and (b). (From P Clark 2016)

can be obtained by remote measurements using acoustic or radar techniques, or even successive balloon soundings. However, this physical quantity is measured at very few of the network of sites used for weather forecasting. The Met Office UKV model provides an alternative method of determining the boundary layer depth variation as it calculates the evolving boundary layer depth from its initialized atmospheric fields. Figure 6 shows the boundary layer depth diagnosed in the UKV model by P Clark (2016) for 20 March 2015. Figures 6a and 6b, without and with the eclipse representation respectively, clearly show the dominant feature of the clear sky region across the southern UK extending from the far southwest through the Midlands. Slight differences in the boundary layer depth between these two figures can be observed, but the difference plot (figure 6c) makes these more apparent. In the southern UK, the greatest reduction in boundary layer height is about 300 m, although reductions of 200 m persist into the northern Midlands.

Figure 7 shows the associated calculated near-surface winds from the UKV model again without the eclipse represented (figure 7a), with the eclipse represented (figure 7b) and the difference between these (figure 7c). The calculated wind speed changes are small, particularly so in the clear sky region, where wind directions changed in an anticlockwise direction by about 20°, (P Clark 2016). A consistent picture of temperature, boundary layer, wind speed and direction changes therefore emerges.

Conclusions

Clayton's cold-cored cyclone conceptual model was originally deduced from surface observations and provided significant synthesis of the measurements then available. This work correctly identified eclipse-induced wind effects. A limitation was the lack of three-dimensional atmospheric knowledge, both in a theoretical sense and in the data available with which to explain any associated phenomena. Clayton therefore quite reasonably associated wind direction changes, cooling and a reduction in surface pressure, with a cold-cored cyclone. The limitations of the surface observations alone were also apparent in the work of Aplin and Harrison (2003); high-resolution numerical modelling can now provide insight into the three-dimensional atmospheric structure, in particular for elucidating the effect on the boundary layer.

"This allows us to exploit an eclipse as a natural meteorological experiment"

Observations made during the 1999 and 2015 UK eclipses show consistency in the wind effects observed: specifically, the changes in speed and direction. More extensive observations available from the 2015 eclipse also indicated a reduction in boundary layer height at some sites, which can have important effects on the near-surface winds as illustrated by Gray and Harrison (2016). The detailed modelling work of P Clark (2016) calculated consistent changes in boundary layer height in the clear sky region, showing an anticlockwise change in wind direction. The consideration of boundary layer changes therefore provides an alternative explanation to Clayton's model for wind direction changes observed. Clayton's model may yet have validity for eclipses over large landmass regions, which has not been explored here.

The combination of high spatial resolution, detailed numerical models with dense measurement networks provides a new framework with which to investigate the predictable reduction in the incoming energy to the atmosphere presented by a partial or total solar eclipse. This not only provides new tools for planning for the changes in renewable energy generation during an eclipse, but also the means to exploit an eclipse as a natural meteorological experiment for testing and improving the weather forecasting models on which society depends. ●

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