# Red snow occurrence in Eastern Europe. A case study

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## Introduction

In the second half of March 2018, the European media published in great headlines a strange occurrence. Red-coloured snow fell in Bulgaria; Romania; Ukraine; and – what most interested the media – in the mountains around Sochi (see 'star' in Figure 6), the location of the former winter Olympic Games.

As a matter of fact, this is a rare phenomenon but one that was noted even in ancient times. Red rain occurrences were mentioned by Livy, Cicero, Geoffrey of Monmouth, Pliny the Elder and learned monks in the early Middle Ages (White *et al.*, 2012; Mancini, 2018).

## Causes of Red Snow

Red-coloured snow occurs for two reasons. The first is activity of green algae, which usually occurs in summer at high latitudes (Mancini, 2018) but is not a topic of interest here. The second is red snow as result of Saharan dust storms that can occur in any season.

Dust transport occurs when an active cold trough in southern Europe with a strong southwesterly flow at its forward flank causes a dust storm in the western Sahara. The southwesterly flow transports the resulting dust northwards as shown in Figures 3 and 4. After mixing with the cold air, the dust colours the falling snow red. (Figures 1 and 2) As a matter of fact, transportation of Saharan dust occurs towards Europe and eastern America and even further (Barkan *et al.*, 2004a,b; Barkan and Alpert, 2010, 2014).

## Methodology

In this study, to explain this outstanding phenomenon, we mainly used three sources: the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay *et al.*, 1996), the Moderate Resolution Imaging Radiospectrometer (MODIS) on board the TERRA satellite and the Hysplit back trajectory model for 60h to show the origin of the dust. All the data from the former two data sources were translated to usable graphic form, for example, 700hPa geopotential and vector form (not shown) by the Grid Analysis and Display System (GRADS) programme. The development of the synoptic situation that eventually caused the transportation of an unusually large quantity of Saharan dust to south-eastern Europe (Figures 3 and 4) and caused the colouration of the snow in the area will be discussed below with reference to Figures 1 and 2.

[†]Joseph Barkan died on 7 June 2019, and consent to publish this manuscript has been given by his next-of-kin.

*Figure 1. People skiing over orange snow that is blanketing Eastern Europe. The Washington Post, 26 March 2018 (Chiu, 2018).*


*Figure 2. As in Figure 1, another E. Europe location, The Washington Post, 26 March 2018 (Chiu, 2018).*

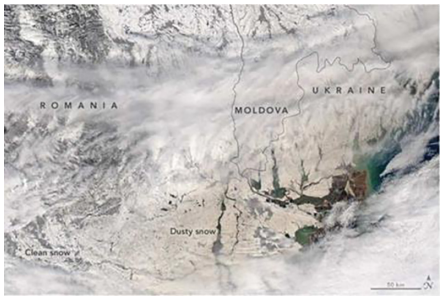


*Figure 3. Orange snow-blanketed parts of Russia, Bulgaria, Ukraine, Romania and Moldova. The coloured snow is due to sand from the Sahara Desert storms mixing with snow and rain.*

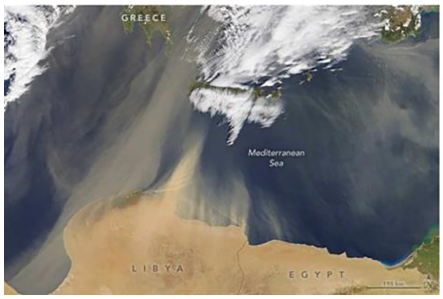


*Figure 4. Satellite picture of dust transport from North Africa to Greece corresponding to Figure 6(d). The image is taken from MODIS-TERRA on 26 March 2018.*

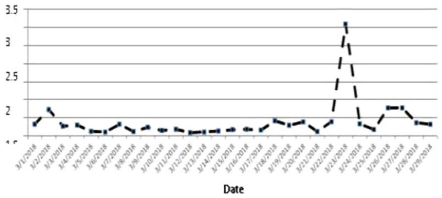


*Figure 5. MODIS Aerosol Optical Thickness (AOT) average over 30–40°E, 40–50°N, during 1–31 March 2018. PEAK AOT is observed on 23 March, while the second maximum is on 26/27 March. Note that the y-axis scale is shifted. It starts with the zero value and ends at 3.5.*

## Analysis

On 20 March, a trough extended from Scandinavia through the Gulf of Genoa towards northern Africa. The next day, 21 March, it deepened and extended into

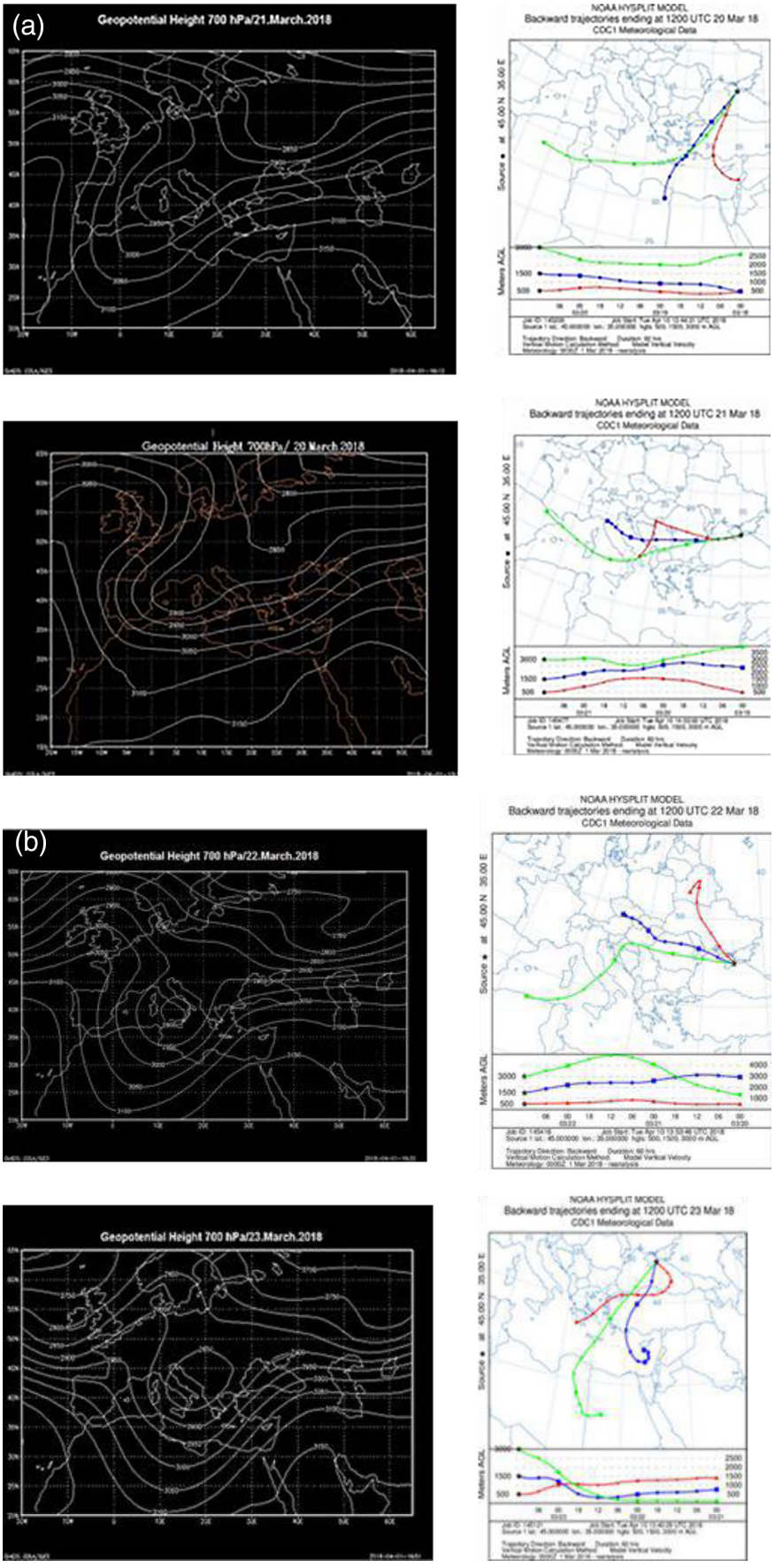


*Figure 6. (a) Geopotential 700hPa, 20 (bottom left) and 21 (upper left) March 2018. Sixty-hour back trajectories based on the Hysplit model are shown on the right panels ending at the Sochi point (denoted by star) at altitudes of 500m (red), 1500m (blue) and 3000m (green). NOAA is acknowledged for the data and model. (b) As in Figure 6(a) but on 22/23 March 2018. On 23 March 2018, peak of AOD is found in the Red Snow square. Green back trajectory from Saharan surface to 700mb within 60 hours. (c) As in Figure 6(a) but on 24/25 March 2018. (d) As in Figure 6(a) but on 26/27 March 2018*

the Western Sahara and caused a huge dust storm. At this stage, as can be seen on the eastern flank of the trough, the dust began to be transported into the central Mediterranean as shown in Figure 6(a).

On 22 March, the trough continued to deepen. A closed low formed in it, and it moved to the east.

The flow on the forward flank was definitely southwesterly, although it had not yet reached the area we are interested in. This is approximately shown by the Hysplit model (Figure 6b).

The next day, the 23rd of the month, was the crucial day for the area around Sochi. The trough deepened further, moved further eastwards and extended southward. The southwesterly gradient steepened; the flow was consequently stronger and had the potential to lift dust (Barkan *et al.*, 2004b), which reached southeastern Europe as can also be seen in the Hysplit model (Figures 6 and 7).

We can use satellite imagery to track dust plumes and their depth using the aerosol optical thickness (AOT). AOT is the measure of the column-integrated amount of the different aerosols when observing the Earth's surface from the satellite instrument. The AOT is defined as the negative natural logarithm of the fraction of light that is not scattered or absorbed on a path. If this fraction is less than about 36.7%, then optical depth is above unity. High AOT values can reach 2, and its scale runs from zero (aerosol-clean) and higher. On 24 and 25 March, the trough still existed in the central Mediterranean and northern Africa, but the westerly component of the flow became more pronounced. Consequently, the transportation of the dust to the Sochi area ceased, as can be seen in Figure 1. Contrary to 23 March with an AOT > 3, on these days, the AOT was near zero (Figure 6c).

On 26 and 27 March (Figure 6d), the trough weakened and somewhat extended to the east, while its southern part remained in the west. The closed low disappeared. As a result, the flow along the eastern flank of the trough again became more southwesterly, although the gradient was much weaker than on the 23rd. Consequently, some dust was again transported to the target area – although much less than on the peak day. In Figures 5 and 6, it can be seen that, on these two days, the AOT value rose to almost 1, contrasting with the values of 24 and 25 March. The Hysplit model also shows some transportation from the Sahara towards the target area at heights between 1500m and 3000m (Figure 6d).

## Discussion

The case of the coloured snow in southeastern Europe became a great news item

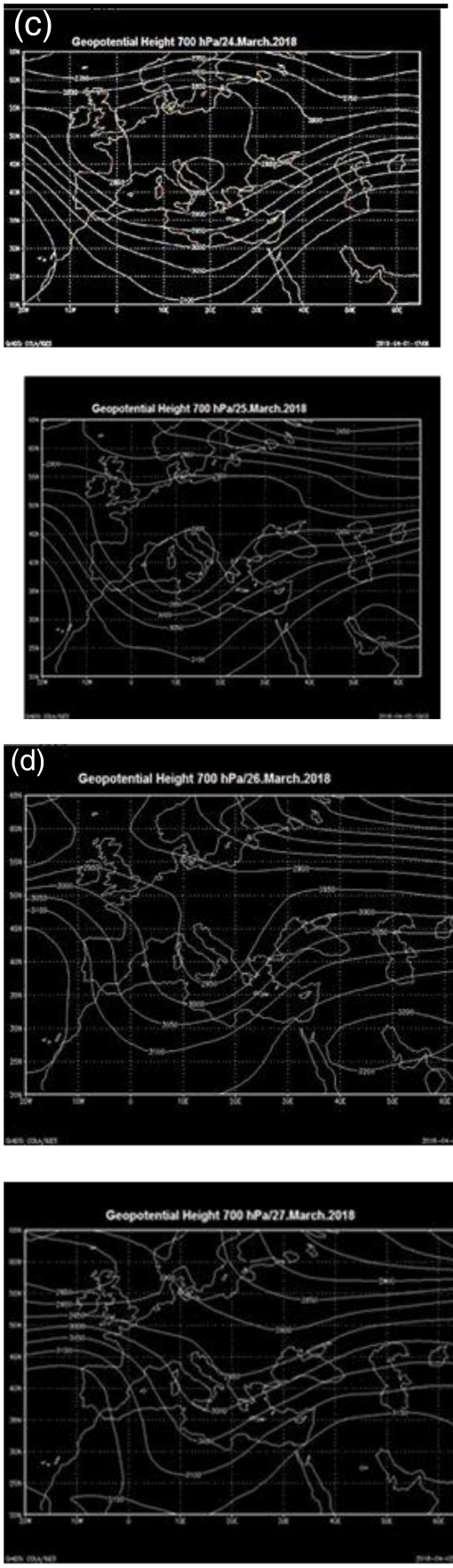


*Figure 6. (c, d) (Continued).*

*Figure 7. Satellite picture of dust transport from North Africa to Greece corresponding to Figure 6(d) on 26 March 2018.*

in the European media because of its rarity and peculiarity. As a matter of fact, transport of Saharan dust northwards is not a rare event at all (Dayan *et al.*, 1991; Barkan *et al.*, 2004a; Collaud Coen *et al.*, 2004; Barkan and Alpert, 2010). Deep cold trough penetration from high latitudes southwards towards western Africa occurs several times almost every year. At the eastern flank of the trough a strong south-southwesterly flow develops, which transports the Saharan dust to the north towards Europe. The penetration of the dust depends on the depth of the trough and, consequently, the strength of the flow (Barkan *et al.*, 2004a). The development of troughs southwards usually occurs along the western shores of Europe or somewhat eastwards. As a result, the dust is transported to western or central Europe and the Mediterranean. These areas are relatively warm, and snow is rare.

In this case, the trough developed further east, which is not a common occurrence. This caused significant dust storms in the central Sahara near the amplest dust sources (Barkan *et al.*, 2004b). In addition, the strong southwesterly flow along the eastern flank of the trough reached Eastern Europe, which is colder and snowier compared with western Europe. So, there is a high probability that the transported dust reached the Sochi area together with snow flakes and painted them with its colour, red or brown.

## Acknowledgements

We thank Ms Chiu and Mr Mancini for the important and interesting information and for the beautiful pictures in their articles. Their information is the basis of this article. We also thank the Israel Science Foundation (ISF) (grant no. 1123/17) for partial support.

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## Box 1 The late Dr Joseph Barkan

*Dr Joseph Barkan*

I knew Joseph Barkan since 1972 when I joined as a young weather forecaster under his command. Joseph Barkan was a very experienced weather forecaster and instructed several generations of young forecasters. I always admired him for being able to approach me in his late 60s in order to complete a PhD in the Department of Geophysics, Tel Aviv University. He did a comprehensive PhD study of the Saharan dust sources based on Total Ozone Mapping Spectrometer (TOMS) data and was jointly supervised by Prof. Haim Kutiel (Haifa University) and myself. His dedication, for over 20 years, to do outstanding and accurate research on dust was much appreciated by the scientific community. He continued his excellent studies in recent years on the synoptic conditions related to dust transport and the aerosol characteristics especially over the Mediterranean area. Many of his papers received worldwide attention and were frequently cited. Dr Joseph Barkan, who was born in Budapest on 3 May 1934 and survived the Holocaust, passed away on 7 June 2019 and was still able, in his last week, to provide me with his first response to the reviews of the current Red Snow paper.

Blessed be his memory.
Pinhas Alpert