WILEY
Publishers Since 1807

JOHN WILEY & SONS, LTD., THE ATRIUM, SOUTHERN GATE, CHICHESTER P019 8SQ, UK

***** PROOF OF YOUR ARTICLE ATTACHED, PLEASE READ CAREFULLY *****

PLEASE AIM TO RETURN YOUR CORRECTIONS WITHIN 48 HOURS OF RECEIPT OF YOUR PROOF, THIS WILL ENSURE THAT THERE ARE NO UNNECESSARY DELAYS IN THE PUBLICATION OF YOUR ARTICLE

☐ **READ PROOFS CAREFULLY**

ONCE PUBLISHED ONLINE OR IN PRINT IT IS NOT POSSIBLE TO MAKE ANY FURTHER CORRECTIONS TO YOUR ARTICLE

- This will be your only chance to correct your proof
- Please note that the volume and page numbers shown on the proofs are for position only

☐ **ANSWER ALL QUERIES ON PROOFS** (Queries are attached as the last page of your proof.)

- List all corrections and send back via e-mail to the production contact as detailed in the covering e-mail, or mark all corrections directly on the proofs and send the scanned copy via e-mail. Please do not send corrections by fax or post

☐ **CHECK FIGURES AND TABLES CAREFULLY**

- Check sizes, numbering, and orientation of figures
- All images in the PDF are downsampled (reduced to lower resolution and file size) to facilitate Internet delivery. These images will appear at higher resolution and sharpness in the printed article
- Review figure legends to ensure that they are complete
- Check all tables. Review layout, titles, and footnotes

☐ **COMPLETE COPYRIGHT TRANSFER AGREEMENT (CTA) if you have not already signed one**

- Please send a scanned signed copy with your proofs by e-mail. **Your article cannot be published unless we have received the signed CTA**

☐ **JOURNAL COPIES**

- Complimentary copies of the journal will be dispatched upon publication as follows: the correspon-ding author of a Research Article will be entitled to receive five print copies of the issue; the corres-ponding author of any other article type (including Meeting Reports and Letters, etc) are entitled to receive one print copy of the issue. Please ensure that the corresponding address on your proofs is correct for dispatch of the issue. If your address has changed please inform the Production contact for the journal – details in covering e-mail.

Additional reprint and journal issue purchases

- Should you wish to purchase a minimum of 100 copies of your article, please visit http://www3.interscience.wiley.com/aboutus/contact_reprint_sales.html
- To acquire the PDF file of your article or to purchase reprints in smaller quantities, please visit http://www3.interscience.wiley.com/aboutus/ppv-articleselect.html. Restrictions apply to the use of reprints and PDF files – if you have a specific query, please contact permreq@wiley.co.uk. Corresponding authors are invited to inform their co-authors of the reprint options available
- To purchase a copy of the issue in which your article appears, please contact cs-journals@wiley.co.uk upon publication, quoting the article and volume/issue details
- Please note that regardless of the form in which they are acquired, reprints should not be resold, nor further disseminated in electronic or print form, nor deployed in part or in whole in any marketing, promotional or educational contexts without authorization from Wiley. Permissions requests should be directed to mailto: permreq@wiley.co.uk

Synoptic analysis of a rare event of Saharan dust reaching the Arctic region

Joseph Barkan and Pinhas Alpert

Tel-Aviv University, Israel

Abstract

A rare event of Saharan dust cloud in the subArctic region north of the Scandinavian Peninsula was discovered by the LiDAR of the Arctic LiDAR Observatory (ALOMAR) on 7 August 2007 and identified by Rodriguez AQ2 *et al.* (2008). •The origin of this cloud was from the permanent dust reservoir which exists in the atmosphere above the Sahara and was not necessarily a result of a single dust storm.

The wind flow and the geopotential height at 700 hPa in the area bounded by 0°N–80°N and 100°W–40°E were examined for 1–4 August. Additionally, the 6–7-day forward trajectories from the location 28°N–0°E were computed for the same time.

It was found, that during 1/2 August, a strong southwesterly flow formed in northern Africa and western Europe, between a trough along the Atlantic coast of southern Europe and northern Africa and the eastern branch of the subtropical high. This synoptic situation was suitable to long-range transportation of the dust from the Sahara AQ3 to the Arctic. •

Introduction

Every year, huge quantities of dust are transported from the Sahara towards the American and European continents. There are well-defined areas especially in the northwestern part of the Sahara – Tunisia, Morocco, Mauritania and Mali and the Bodele depression near Lake Chad – which are the main sources of the dust (Middleton and Goudie, 1991; Prospero *et al.*, 2002; Washington *et al.*, 2003; Barkan *et al.*, 2004). The dust is raised to a height of about 3000 metres and higher due to warming of the ground in the summer season, and local winds such as the Harmatan and storm systems entering the Mediterranean and northern Africa from the north (Dayan *et al.*, 1991; Alpert and Ganor, 1993; Conte *et al.*, 1996; Prospero, 1996).

A considerable part of the dust is transported towards Europe (Papayannis *et al.*, 2005). In most cases, the dust reaches southern Europe only (Avila *et al.*, 1996; Bonelli and Mercazzan, 1996) but there are events when the dust reaches the Alps north of Italy (Collaud Coen *et al.*, 2003). In even rarer events Saharan dust has been observed in northern Europe with modern LiDAR equipment as part of the EARLINET network (Ansman *et al.*, 2003).

For effective transportation of Saharan dust to northern Europe, an unusual synoptic situation is required: a reasonably deep trough along the Atlantic coast of Europe and North Africa, and a high further east of it. If the pressure gradient between them is steep enough, a strong and long northwesterly flow will form between them, capable of transporting the dust towards northern Europe (Barkan *et al.*, 2005).

On 7 August 2007, the LiDAR of the Arctic LiDAR Observatory (ALOMAR69°N. 16°E) in northern Norway (69°N) detected a thin layer of dust at a height of approximately 2500 metres. Using several additional optical instruments like a sun photometer and a particle absorption photometer, the dust was identified as being of Saharan origin. •Rodriguez *et al.* (2008) describe this event comprehensively following the time evolution *in situ* and the instruments used. Different sun photometers and spectroradiometers were used. From the measurements, the aerosol optical depth (AOD) and the derived Angstrom exponent (alpha) were retrieved. The optical properties were analyzed jointly with air mass back trajectories to determine the aerosol types and their origin.

In this article, the synoptic situation which caused such a long-range transportation of the dust from the Saharan region to the Arctic, some 40 degrees of latitude, is investigated.

Discussion and results

As mentioned earlier, the dust which was observed in ALOMAR on 7 August originated from the western Sahara as a result of some kind of atmospheric activity several days previous. It might have been a dust storm but not necessarily. Due to the continuous activity of dust lifting in the desert for different reasons as mentioned earlier, there is always a large amount of dust available in the Saharan air (Israelevich *et al.*, 2002). If the synoptic situation is favourable, dust transportation begins. The direction and the distance of the transportation depend on the orientation and the strength of the synoptic system. In this case, the dust was transported some 5500 kilometres.

We chose to display the synoptic situation between 1 and 3 August 2007 in the area 0°N–80°N, 100°W–40°E (Figures 1–3). The variables shown are wind flow and geopotential height at 700 hPa. This level was chosen because of the average transportation of dust that takes place in this level (Prospero, 1996; Hamonou *et al.*, 1999; Alpert *et al.*, 2003). The meteorological data were taken from the NCEP/NCAR reanalysis (Kalnay *et al.*, 1996). Additionally, the forward trajectories from the western Sahara for 5–6 days were computed using the NOAA HYSPLIT model.

On 1 August, the subtropical high, which is dominant in the summer season, was weakened by a trough along the Atlantic coast of southern Europe and northern Africa. This trough actually divided the high AQ4 into two separate highs: an eastern high and a western high, the latter of which was the stronger.

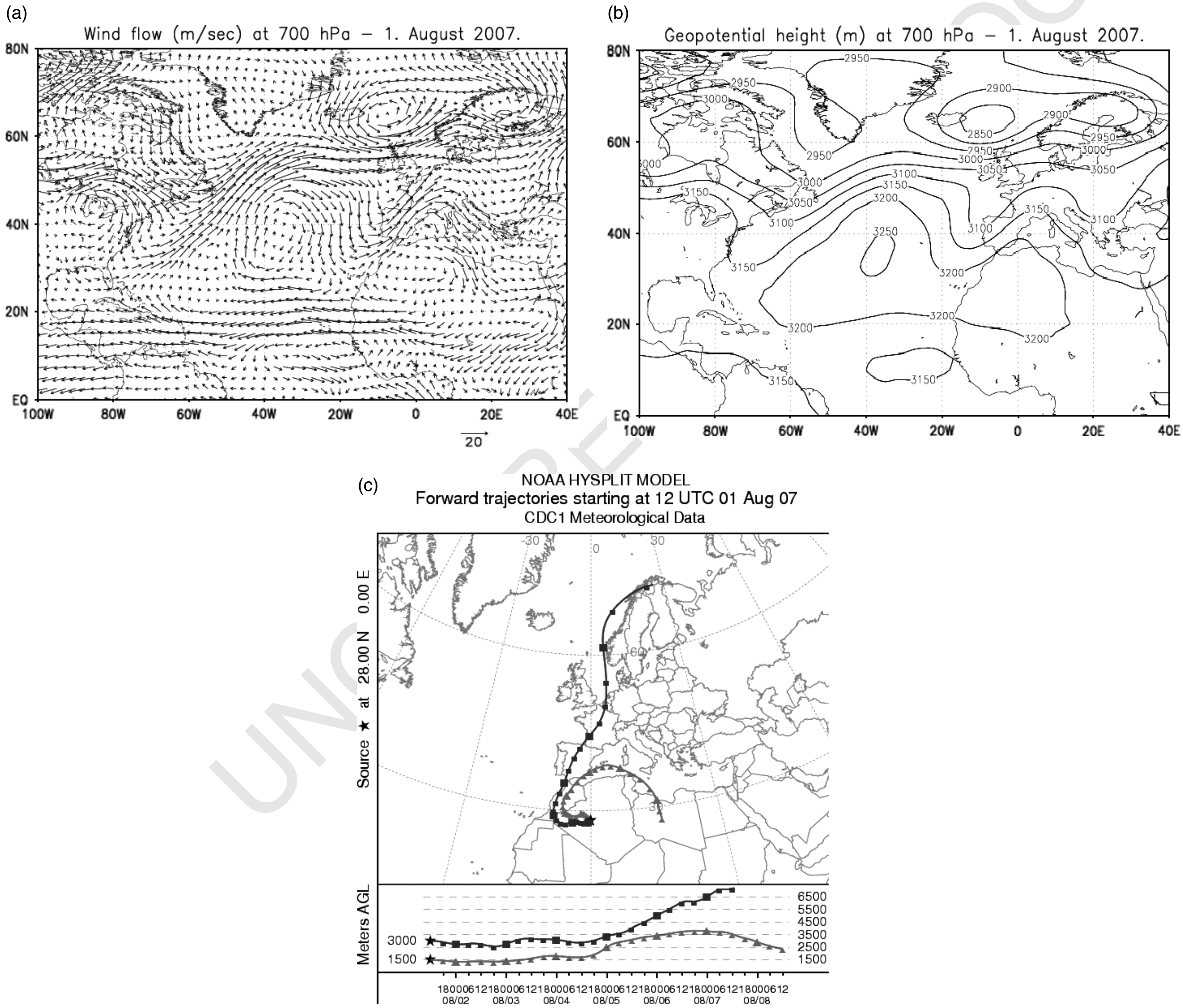
A deep Icelandic low was situated west of the Scandinavian Peninsula with two troughs emanating from it: one eastward and the other southwestward towards the Caribbean. The latter caused the strengthening of the western branch of the subtropical high which, in its part, caused the formation of the trough to the east. Between the Caribbean trough and the western high and between the coastal Atlantic trough and the eastern high a steep gradient formed causing a strong southwesterly flow. The gradient was approximately the same as the average gradient of similar situations (Barkan *et al.*, 2005). Between the Icelandic low and the subtropical high a strong westerly flow existed along 50°N. The two southwesterly flows joined the strong westerly flow around the 40°W and 0° longitudes. Easterlies at the southern flank of the subtropical high along the 20°N parallel emanated from Africa to the Atlantic and converged with the southwesterlies along the western flank of the high (Figures 1(a) and 1(b)). It is evident from these figures that the potential for dust transport from the western Sahara towards Scandinavia existed either with the flow to the north through western Europe which joined the strong flow around the eastern flank of the Icelandic Low, or with the easterlies which joined the southwesterlies along the western flank of the subtropical high and then the westerlies around the Icelandic low. The forward trajectory (Figure 1(c)) shows that the first case is the real one. The dust, originating from the source area in western Sahara and Mauritania, was transported through Spain, the Gulf of Biscay and along the European coast and then reached northern Scandinavia within five to six days, on 6 or 7 August.

The situation on 2 August was essentially the same as on the1st. The main centre of the Icelandic low moved further to the east. A trough formed in western Europe emanating from the main low and connecting to the trough across Africa which penetrated more to the south. Consequently, the southwesterly flow became stronger, smoother and continuous and the dust transportation became more effective. The trajectory was the same as on the previous day but the dust reached northern Scandinavia in less than five days (Figure 2).

On 3 August, the synoptic situation changed significantly. The centre of the Icelandic low moved a long way to the west. The trough along the African coast almost disappeared. Only a weak cyclonic circulation separated the two parts of the high (Figures 3(a) and 3(b)). In such a situation, the long transportation to Scandinavia could not happen. Although the trajectory model still shows such a transportation, we think that it takes into account the possibility that some of the dust which still moves with the southwesterly flow along the African coast can penetrate through the weak winds in the Gulf of Biscay and be injected into the strong westerlies around the Icelandic Low (Figure 3(c)).

On 4 August, the synoptic situation changed radically. Due to the strengthening of the eastern branch of the subtropical high, the gradient became steeper and more westerly preventing dust transportation northward.

We chose to show the synoptic situation for 1–3 August, although the dust in northern Norway was observed on the 7th. According to the data shown, the synoptic situation was fit for the transportation of dust out of the Sahara and northward only in the days 1-3 August while from the 4th onwards the dust supply ceased. The dust which was transported out of the Sahara in the previous days reached the area of the strong westerly flow after three days; it was injected into



AQ1

•*Figure 1. The synoptic situation 1 August 2007.*

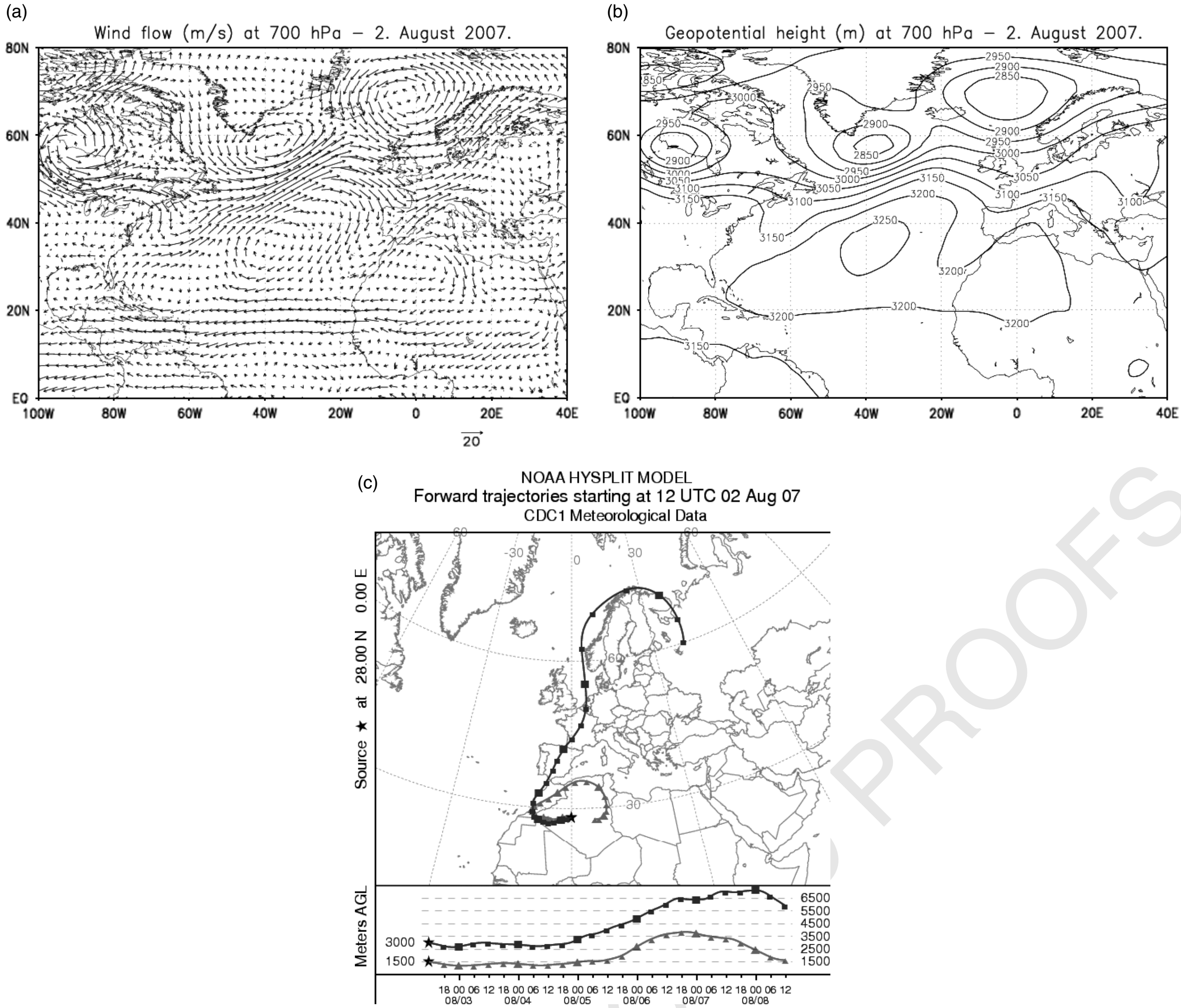


Figure 2. The synoptic situation 2 August 2007.

it and reached the north of Scandinavia some three days later.

Conclusion

An unusual synoptic situation caused the rare event of Saharan dust transportation to the far north – the northern tip of the Scandinavian Peninsula. The dust was observed in ALOMAR on 7 August 2007 but the dust transport begun about six to seven days earlier. Accordingly, the synoptic situation during the days 1–4 August was examined. A trough formed along the Atlantic coast of Africa on the first two days of August causing a strong southwesterly flow there. At the same time, the mean centre of the Icelandic low deepened and moved to the east, near the Scandinavian Peninsula. The steep gradient which formed between the low and the subtropical high caused strong westerly flow along parallel 50. The southwesterly flow in the south and the westerlies towards Scandinavia to the north together enabled the transportation of the dust from its source area in western Africa far to the north as can be seen in the computed trajectories (Figures 1(c) and 2(c)). On the 3rd and more on the 4th of August the trough in the south weakened and its contact with the northern low severed, so that the condition for long-distance transportation no longer existed.

Acknowledgment

The authors gratefully acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model (http://www.arl.noaa.gov/ready.html) used in this publication.

References

Alpert P, Ganor G. 1993. A jet stream associated heavy dust storm in the western Mediterranean. *J. Geophys. Res.* **98:** 7339–7349.

Alpert P, Kischa P, Shtivelman A, Krichak SO, Joseph JH. 2003. Vertical distribution of Saharan dust based on 2.5 year model predictions. *Atmos. Res.* **70(2004):** 109–130.

Ansmann A, Basenberg J, Chaikovsky A, Comeron A, Eckhardt S, Eixmann R, Freudenthaler V, Ginoux P, Komguem L, Linne H, Marquez MAL, Matthias V, Mattis I, Mitev V, Muller D, Music S, Nickovic S, Pelon J, Sauvage L, Srivastava MK, Stohl A, Torres Q, Vaugham G, Wendinger U. 2003. Long range transport of Saharan dust to Northern Europe. The 11–16 October observed with EARLINET. *J. Geophys. Res.* **108 (D84):** 4783.

Avila A, Querall J, Gallart F, Vide JM. 1996. African dust over Northeastern Spain: Mineralogy and source regions, in *The impact of desert dust across the Mediterranean*. Kluver Acad.: Norwell, Mass. pp 201–205.•

AQ5

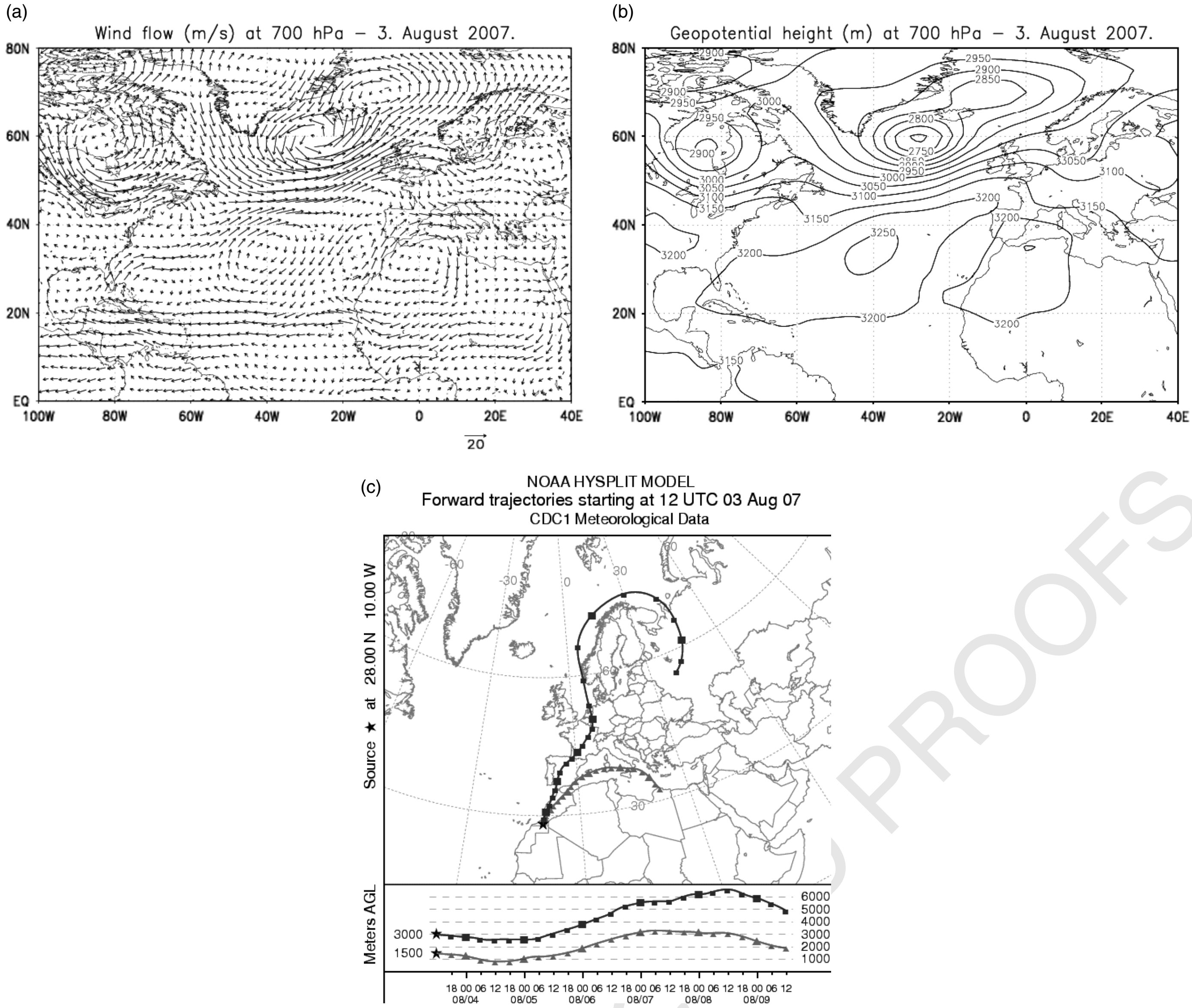


Figure 3. The synoptic situation 3 August 2007.

Barkan J, Kutiel H, Alpert P. 2004. Climatology of dust sources over the North African region, based on TOMS data. *Indoor Outdoor Environment* **13:** 407–419.

AQ7

Barkan J, Kutiel H, Alpert P, Kischa P. 2005. The synoptics of dust transportation days from Africa toward Italy and Central Europe. *J. Geophy. Res. Atmos.* **110:** DO7208.

Bonelli P, Braga Merkazzan M. 1996. Elemental composition and air trajectories of African dust transported in Northern Italy, in *The impact of desert dust across the Mediterranean.* Kluver Acad.: Norwell Mass. pp 275–283.•

AQ6

Collaud Coen M, Weingarten E, Schaub D, Hueghin C, Corrigan C, Schwikowski M, Baltspreger U. 2003. Saharan dust events at the Jungfraujoch: Detection by wavelength dependence of the single scattering albedo and analysis of events during the years 2001 and 2002. *Atmosph. Chem. Phyisic. Disc.* **3:** 5547–5594.

Conte M, Colarino M, Piervitali E. 1996. Atlantic disturbances deeply penetrating the African continent: Effect over Saharan regions and the Mediterranean basin, in *The impact of desert dust across the Mediterranean.* Kluver Acad.: Norwell Mass. pp 93–102.•

Dayan U, Hefter J, Miller J, Gutman G. 1991. Dust intrusion events into the Mediterranean basin. *J. Appl. Meteor.* **30(8):** 1188–1193.

Hamonou E, Chazette P, Bali D, Dulac F, Schneider X, Galani F, Ancellet G, Papyannis A. 1999. Characterization of the vertical structure os the Saharan dust transport to the Mediterranean Basin. *J. Geophy. Res*. **104:** 22256–22270.

Israelevich PL, Levin Z, Joseph JH, Ganor E. 2002. Desert aerosol transport in the Mediterranean region as inferred from the TOMS aerosol index. *J. Geophy. Res.* **107**(D21), 4572. doi:10.1029/2001JD002011

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woolen J, Zhu Y, Chelliah M, Eblsuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Leetmaa A, Reynolds R, Jenne R, Joseph D. 1996. The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Meteorol. Soc.* **77(3):** 437–471.

Middleton NJ, Goudie AS. 1991. Saharan dust sources and trajectories. *Weather* **50:** 313–318.

Papayannis A, Amiridis V, Rosenberg J, Chaikovski A, De Tomasi F, Freudenthaler V, Grigorov I, Mattis I, Mitev V, Munor C, Pappalarado C, Nickovic S, Pisani G, Pachalski S, Rizi V, Trickl T, Vaughan G. 2005. First systematic observations of Saharan dust over Europe (2000–2003). *Geophys. Res. Abst.* **7:** 04016.

Prospero JM. 1996. Saharan dust transport over the Atlantic Ocean and the Mediterranean : an overview, in *The Impact of desert dust across the Mediterranean* Kluver Acad.: Norwell Mass. pp 133–151.• AQ8

Prospero JM, Ginoux P, Torres O, Nicholson S, Gill E. 2002. Environmental characterization of global sources of atmospheric soil dust identified with the NIMBUS-7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product, *Rev. Geophys.* **40(1)**: 1002.

AQ9 **Rodriguez E, Mogo S, Montilla E, Berjon A, Torres B, Toledano C, Blindheim S, Cachorro V, De Frutos A, Frioud M, Gausa M, Stebel K.** 2008. Desert dust event in the sub-arctic area – ALOMAR (69N) in 2007, *24th International Conference,* Boulder Colorado 23–27 July 2008. **1:** 393–396.

Washington R, Martin T, Middleton NJ, Goudie AS. 2003. Dust storm source areas determined by the Total Ozone Monitoring Spectrometer and surface observations. *Annals of the Association of the American Geographers* **93(2):** 297–313.

Correspondence to: Joseph Barkan, Department of Geophysics and Planetary Science, Faculty of Exact Sciences, Tel-Aviv University, PO Box 39040, Tel-Aviv 69978, Israel.

Email: yossib@vortex.tau.ac.il

DOI: 10.1002/wea.503

QUERIES TO BE ANSWERED BY AUTHOR

IMPORTANT NOTE: Please mark your corrections and answers to these queries directly onto the proof at the relevant place. Do NOT mark your corrections on this query sheet.

Queries from the Copyeditor:

AQ1 please check that this is the correct postal address

AQ2 Abstract must stand alone. Please incorporate citation into text:

AQ3 information for online WIS only. Not to appear in printed or online PDF.

AQ4 please check that meaning has been retained

AQ5 Please confirm if this is the correct reference: Avila A, Querall J, Gallart F, Vide JM. 1996 African dust over North-eastern Spain: Mineralogy and source regions, in The impact of desert dust across the Mediterranean. Guerzoni S, Chester R (eds). Kluwer Academic Publishers: Dordrecht. pp 201–205.

AQ6 Please confirm if this is the correct reference: Bonelli P, Braga Marcazzan GM, Cereda E. 1996. Elemental composition and air trajectories of African dust transported in northern Italy, in The impact of desert dust across the Mediterranean. Guerzoni S, Chester R (eds). Kluwer Academic Publishers: Dordrecht. pp 275–283. If so, please change text citation to read Bonelli et al., 1996.

AQ7 Please confirm if this is the correct reference: Conte M, Colarino M, Piervitali E. 1996. Atlantic disturbances deeply penetrating the African continent: Effect over Saharan regions and the Mediterranean basin, in The impact of desert dust across the Mediterranean. Guerzoni S, Chester R (eds). Kluwer Academic Publishers: Dordrecht. pp 93–102.

AQ8 Please confirm if this is the correct reference: Prospero JM. 1996. Saharan dust transport over the Atlantic Ocean and the Mediterranean: an overview, in The impact of desert dust across the Mediterranean. Guerzoni S, Chester R (eds). Kluwer Academic Publishers: Dordrecht. pp 133–151.

AQ9 please use these edited figure captions.