Modeling PM10 Originating from Dust Intrusions in the Southern Iberian Peninsula Using HYSPLIT

A. F. STEIN*

Earth Resources and Technology, Laurel, Maryland

Y. WANG,+ J. D. DE LA ROSA, AND A. M. SANCHEZ DE LA CAMPA

Department of Geology, Universidad de Huelva, Huelva, Spain

NURIA CASTELL

Centro de Estudios Ambientales de Mediterraneo, Valencia, Spain

R. R. DRAXLER

NOAA/Air Resources Laboratory, Silver Spring, Maryland

(Manuscript received 4 November 2010, in final form 15 December 2010)

ABSTRACT

The Hybrid Single-Particle Lagrangian Integrated Trajectories (HYSPLIT) model has been applied to calculate the spatial and temporal distributions of dust originating from North Africa. The model has been configured to forecast hourly particulate matter ≤ 10 μm (PM10) dust concentrations focusing on the impacts over the southern Iberian Peninsula. Two full years (2008 and 2009) have been simulated and compared against surface background measurement sites. A statistical analysis using discrete and categorical evaluations is presented. The model is capable of simulating the occurrence of Saharan dust episodes as observed at the measurement stations and captures the generally higher levels observed in eastern Andalusia, Spain, with respect to the western Andalusia station. But the simulation tends to underpredict the magnitude of the dust concentration peaks. The model has also been qualitatively compared with satellite data, showing generally good agreement in the spatial distribution of the dust column.

1. Introduction

Dust particles originating from desert areas and transported around the globe are a subject of increasing scientific interest due to their effects on climate, biogeochemistry, and air quality. The Sahara Desert is a major source for crustal material that can be transported over long distances, reaching southern Europe and crossing the Atlantic Ocean (Prospero 1999; Kallos et al. 2006). In particular, the proximity of southern Spain (Andalusia) to the African continent makes it a high-impact area for air masses carrying high dust aerosol loadings. Moreover, mineral dust makes an important contribution to the levels of suspended particulate matter (PM) recorded by air quality monitoring networks in southern Spain (Querol et al. 1998; Rodríguez et al. 2001; Escudero et al. 2006).

The aim of this work is to test the Hybrid Single-Particle Lagrangian Integrated Trajectories (HYSPLIT) model's capability of predicting the contribution of Saharan dust outbreaks to surface particulate matter ≤ 10 μm (PM10) concentrations in the southern Iberian Peninsula. Toward that end, the model has been run for two consecutive years (2008 and 2009) and its results have been compared with measurements at background sites.

---

* Current affiliation: NOAA/Air Resources Laboratory, Silver Spring, Maryland.

+ Current affiliation: Chinese Academy of Meteorological Sciences, Beijing, China.

Corresponding author address: A. F. Stein, NOAA/ARL, 1315 East–West Hwy., Room 3316, Silver Spring, MD 20910.
E-mail: ariel.stein@noaa.gov

DOI: 10.1175/WAF-D-10-05044.1

2. Methodology

a. Model description

In this work, HYSPLIT (Draxler and Hess 1998) has been utilized as a tool to determine the emission, transport, dispersion, and deposition of dust originating from northern Africa. This model has previously been used to determine the specific geographic origin of particulate material emitted from the Sahara–Sahel desert region at different measurement stations located throughout the Iberian Peninsula (Escudero et al. 2006).

A model for the emission of PM10 dust has been constructed using the concept of a surface-roughness-dependent threshold friction velocity (Draxler et al. 2001). A dust emission rate is computed from each model grid cell when the local wind velocity exceeds the threshold velocity for the soil characteristics of that emission cell. The dominant mechanism for the PM10 emission is ''sandblasting,'' where the larger particles that cannot become airborne bounce along the surface (saltation) causing additional smaller particles to become airborne (Draxler et al. 2010). This emission module uses HYSPLIT's 1° land-use file (based on Wilson and Henderson-Sellers 1985) by assuming that a ''desert'' land-use grid cell corresponds to an ''active sand sheet'' roughness identification class (Draxler et al. 2001; Escudero et al. 2006). Based on HYSPLIT's land-use file, a total of 1602 sources have been identified as potential dust emitters in northern Africa. In the emission module, the flux (g m^{-2}) equation,

$$F = 0.01u^{*4},$$

from Westphal et al. (1987) is used. Dust emissions only occur during dry days and when the friction velocity exceeds the threshold value (0.28 m s^{-1} for an active sand sheet). Once the emission strength is determined, Lagrangian particles are emitted by the model with a mass computed by multiplying the PM flux by the 1° area corresponding to a desert category from HYSPLIT's land-use file. These Lagrangian particles are dispersed and transported forward in time according to meteorological fields from the National Oceanic and Atmospheric Administration's (NOAA) Global Forecast System (GFS) model with a horizontal resolution of 1°. A more detailed description of the transport and dispersion of the particles can be found elsewhere (Escudero et al. 2006). A maximum of 3 million particles are permitted. Dust particles are defined to be spherical with a diameter of 4 μm and a density of 2.5 g cm^{-3}. Emitted particles will gravitationally settle and can be removed by rainfall (see Draxler and Hess 1997 for details). In addition, the total lifetime for the particles is set to 10 days. The modeling domain covers from the equator to 60°N and from 40°E to 60°W. Two air concentration grids have been defined. One grid consists of hourly averaged air concentrations of primary PM10 dust from the surface up to 5 km (i.e., column integrated) for comparison with satellite measurements, while the other defines the layer in the lowest 100 m for comparison with surface observations.

b. Measurements

To quantify the daily dust loading, two monitoring stations have been considered: 1) Barcarrota (38.48°N, 6.92°W) representing western Andalusia and 2) Viznar (37.23°N, 3.53°W) for eastern Andalusia (Fig. 2). Although Barcarrota is not located in Andalusia, it can considered as representative of the dust loadings of western Andalusia (de la Rosa et al. 2010). These stations belong to the Spanish Ministry of the Environment and are included in the Cooperative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe (EMEP) network. The calculation of the net African dust load is performed following the methodology developed by Escudero et al. (2007) by subtracting the regional PM10 background levels contributed by anthropogenic sources from the PM10 values measured at the monitoring site. After a prior exclusion from the data of the days with African dust transport (Escudero et al. 2007), the regional background levels are obtained by subtracting a monthly moving 30th percentile value from the PM10 time series at the stations. For the remainder of the paper, all references to the PM10 measured values correspond to the net dust load.

3. Model performance

Figure 1 shows a comparison of the model prediction and the estimated dust load measured at the Viznar and Barcarrota stations. In general, the model is able to predict the occurrence of the Saharan intrusions observed at the stations. In addition, the model simulates the generally higher dust loadings observed at the station located in the eastern Andalusian region (Viznar) with respect to the one representing the background levels of western Andalusia (Barcarrota). To interpret the difference in the dust loading between the two background stations, a back-trajectory analysis has been performed using the HYSPLIT model. We calculated 5-day back trajectories to classify each day according to the origin of the air masses. We have distinguished air masses that originated from North Africa by starting at three different altitudes (500, 1500 and 2500 m MSL) and ending each day at 1200 UTC. In addition, information obtained from aerosol and dust maps and satellite images from the National Aeronautics and Space Administration's (NASA) Total Ozone Mapping Spectrometer (TOMS; information

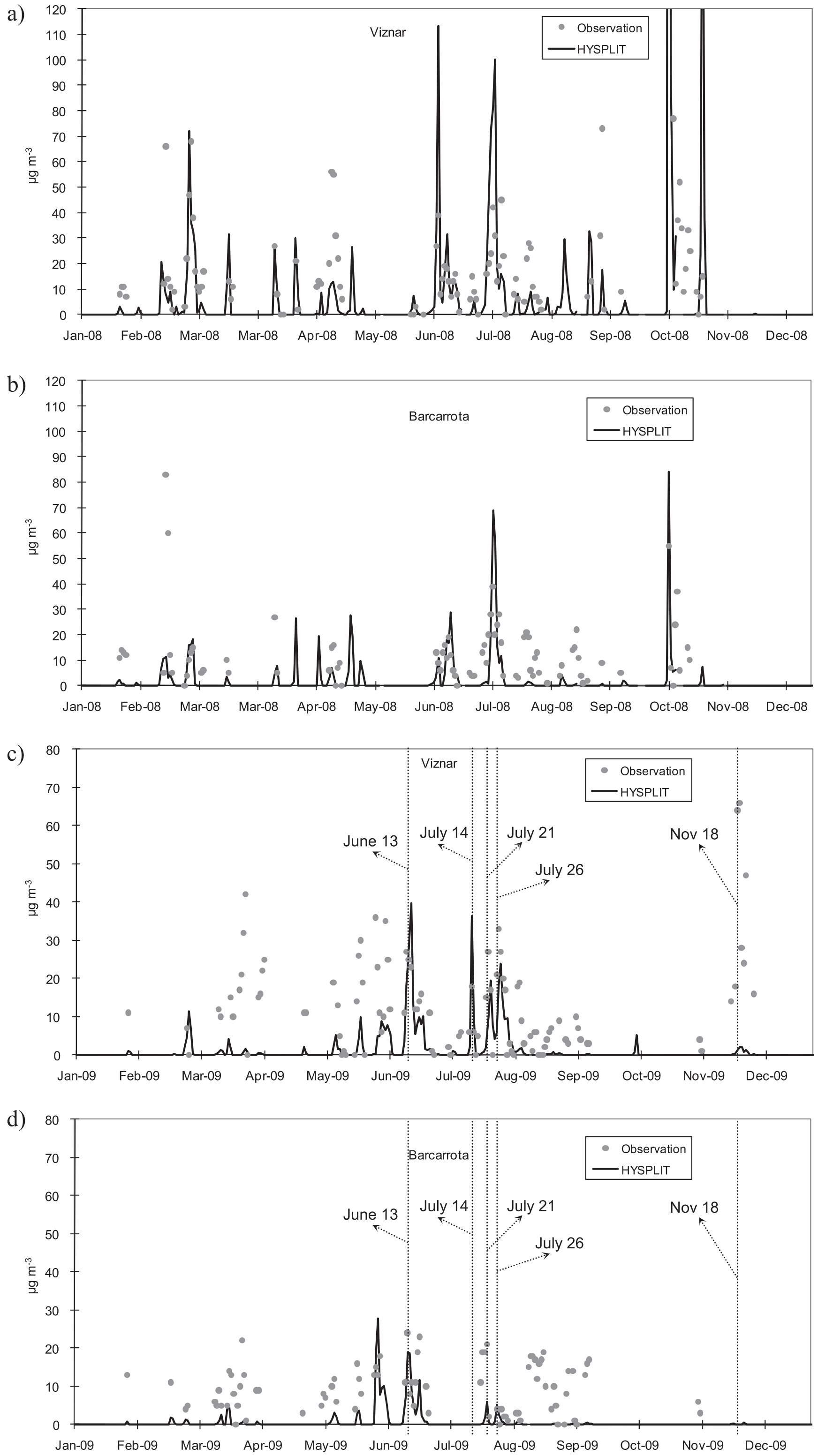

FIG. 1. Comparison of observed (gray dots) vs modeled dust loading concentrations for (a) Viznar during 2008, (b) Barcarrota during 2008, (c) Viznar during 2009, and (d) Barcarrota during 2009.

TABLE 1. (top) Discrete statistical parameters for 2008 and 2009. The units for the parameters are as follows: MB, μg m^{-3}; NMB, %; RMSE, μg m^{-3}; NME, %; and average net dust load, μg m^{-3}. (bottom) Categorical statistical parameters for 2008 and 2009.

2008			2009		
Parameter	Viznar	Barcarrota	Parameter	Viznar	Barcarrota
MB	0.93	−1.04	MB	−0.85	−3.09
NMB	31.97	−35.86	NMB	−29.41	−106.28
RMSE	30.50	7.86	RMSE	5.66	8.98
NME	228.86	95.63	NME	82.43	115.52
R	0.45	0.42	R	0.45	0.42
Avg	2.77	3.27	Average	2.77	3.27
Accuracy	79.45	83.56	Accuracy	78.08	82.19
Bias	1.52	1.16	Bias	1.46	0.79
FAR	43.06	40.45	FAR	50.88	32.86
CSI	52.23	46.90	CSI	41.18	41.96
POD	86.32	68.83	POD	71.79	52.81

online at http://jwocky.gsfc.nasa.gov), the Naval Research Laboratory (NRL; http://www.nrlmry.navy.mil/aerosol), the University of Athens's SKIRON program (http://forecast.uoa.gr), the Barcelona Supercomputing Center's Dust Regional Atmospheric Model (DREAM; http://www.bsc.es/projects/earthscience/DREAM), and NASA's Sea-viewing Wide Field-of-view Sensor (SeaWIFS) project (http://seawifs.gsfc.nasa.gov/SEAWIFS.html) have been used to help determine the occurrence of North African dust outbreaks. The analysis shows that in 21.3% and 24.9% (26.6% and 30.7%) of the days during 2008 (2009), the air masses that reached the Barcarrota and Viznar stations, respectively, originated from northern Africa. Therefore, the difference in the dust loadings can be explained by a higher frequency of air masses reaching eastern Andalusia with respect to the western portion of the territory that can be tracked back to dust sources in northern Africa.

A statistical analysis based on the discrete and categorical evaluations described in Eder et al. (2005) has been carried out to quantitatively evaluate the model performance for 2008 and 2009. Five parameters have been used for the discrete analysis: mean bias (MB), normalized mean bias (NMB), root-mean-square error (RMSE), normalized mean error (NME), and a linear regression coefficient (*R*). In addition, for the categorical statistics the following parameters have been used: accuracy (*A*), bias (*B*), false alarm rate (FAR), critical success index (CSI), and probability of detection (POD). For the categorical statistical analysis, a model threshold limit of 0.1 μg m^{-3} is used to determine the occurrence of a dust intrusion. This threshold has been determined to ensure that the ratio of observed to predicted dust events is as close as possible to one.

The discrete statistical analysis (Table 1) indicates that the model tends to underpredict the magnitude of the PM10 concentrations for the two stations during 2009 and for Barcarrota during 2008. The RMSE and NME values indicate that there is a certain degree of dispersion among the model and measurement differences that can exceed 100%. On the other hand, the categorical analysis (Table 1) shows that the model successfully predicts the time of occurrence (or not) of a dust intrusion more than 75% of the time. The false alarm rates range from, approximately, 32% to 50%. Furthermore, the probability of the detection reaches a minimum of 53% and a maximum of 86%.

a. *Case studies*

A total of five events that took place during 2009 have been selected for further study, based on several tools such as the comparison between the observed and forecasted data, the station meteorological data, and the mass and aerosol optical depth (AOD) products from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the *Terra* satellite. For this analysis, taking into account that dust storms last for several days, only a representative day has been chosen for each event; namely, 13 June; 14, 21, and 26 July; and 18 November.

The comparison between the satellite-derived AOD and the simulation provides a fundamental piece of information about the model's ability to capture the relative geographic distribution of the dust column. However, it has to be considered as a qualitative assessment since the HYSPLIT model only uses a monomodal size distribution for these simulations. To qualitatively compare the model results with the satellite data, we used the conversion of AOD to column mass from Perez et al. (2006) where AOD = 0.5 m^2 g^{-1} × column mass (in g m^{-2}). As an illustration, a concentration of 100 μg m^{-3} in the 5000-m modeled column corresponds to an AOD value of 0.25.

b. *13 June 2009*

The presence of a high pressure system over northern Africa and low pressure south of the Canary Islands constitutes an example of a Saharan intrusion episode that started on 11 June and affected the southern Iberian Peninsula. At the Barcarrota and the Viznar stations, the measured (modeled) contribution of Saharan dust to the PM10 concentration reached 24 (19) and 25 (25) μg m^{-3}, respectively (Figs. 1c and 1d). Also, the HYSPLIT model qualitatively reproduces the observed geographical distribution of dust over Spain (Fig. 2) and even into the eastern Atlantic.

c. *14 July 2009*

This is an interesting episode that illustrates the model's ability to separate air masses affecting eastern from

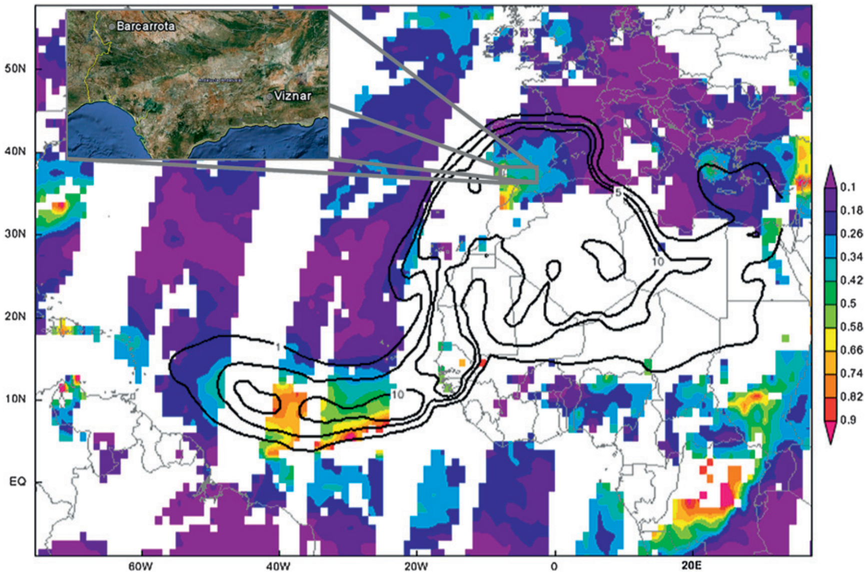

FIG. 2. HYSPLIT concentration ($\mu g\ m^{-3}$) from 0 to 5000 m at 1000 UTC (black contours) and the MODIS satellite AOD at 1030 local time (LT) 13 Jun 2009 (colored scale).

western Andalusia. In this particular case, a high pressure system located over northwestern Africa along with a low pressure system situated over the northwestern Iberian Peninsula induced the transport of dust that only affected the southeastern portion of Spain. This is consistent with the data obtained at the Barcarrota station representing the levels at western Andalusia, where no intrusion was registered while at the Viznar station a small amount of dust was observed (6 $\mu g\ m^{-3}$) (Fig. 1c). The simulation captures this feature showing 10 $\mu g\ m^{-3}$ at Viznar and no dust in Barcarrota (Fig. 1d).

d. 21 July 2009

During this day African dust entered the Iberian Peninsula and affected the southern, central, and eastern portions of the region (Fig. 3) due to the presence of a strong high pressure system located in northwestern Africa. The Barcarrota and Viznar stations registered

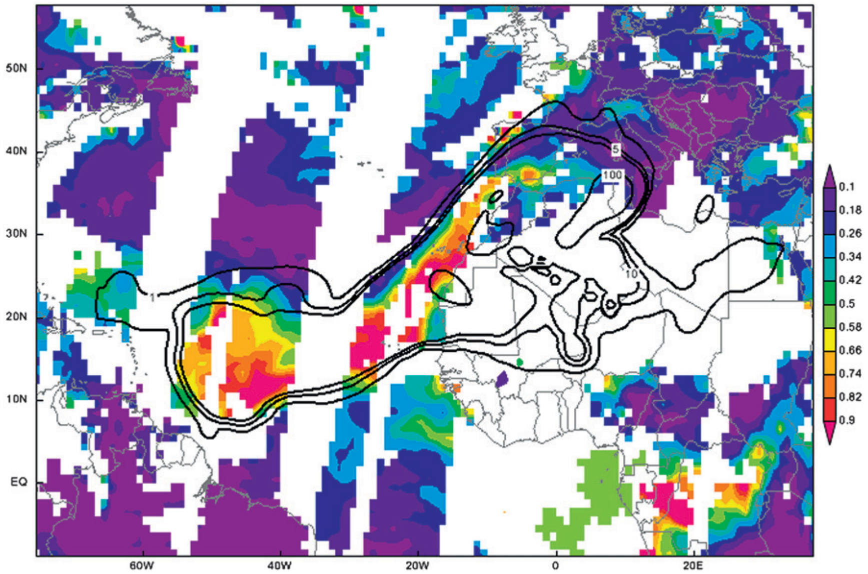

FIG. 3. As in Fig. 2, but for 21 Jul 2009.

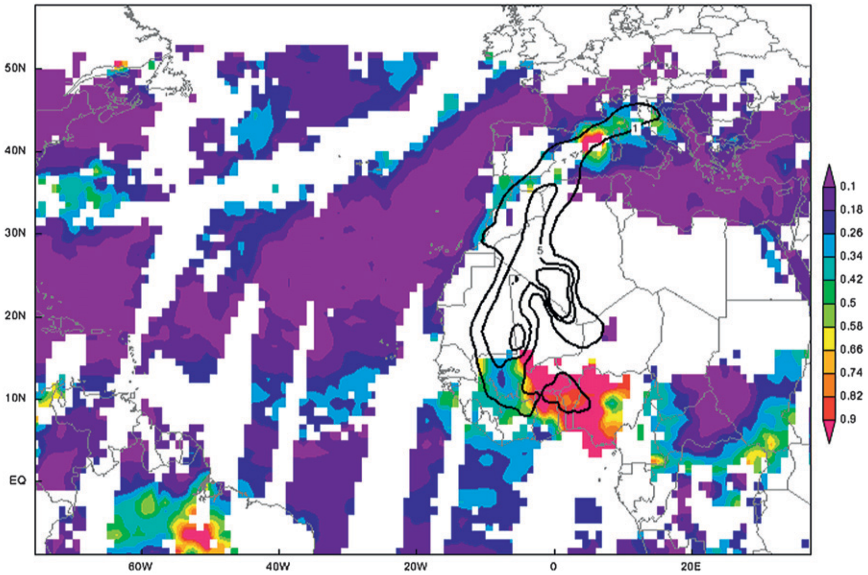

FIG. 4. As in Fig. 2, but for 18 Nov 2009.

levels of 21 and 27 μg m^{-3}, respectively. HYSPLIT predicted the dust intrusion and the geographical extension over Andalusia and the southern portion of the peninsula, but it shows values of 6 and 10 μg m^{-3} for Barcarrota and Viznar, respectively (Figs. 1c and 1d). The comparison with the satellite measurement shows good agreement with the model (Fig. 3).

e. 26 July 2009

This day can be considered to be part of the Saharan intrusion that started on 21 July. The meteorological situation dominating this episode can be attributed to an elevated high pressure system over northern Africa. A high concentration of dust was observed in southern and southeastern Spain (not shown). The HYSPLIT model simulates the intrusion over the Andalusian territory with values reaching 18 μg m^{-3} at Viznar, while the observed values at this station reached 33 μg m^{-3} (Fig. 1c). On the other hand, at the Barcarrota station (Fig. 1d) the measured levels were significantly lower (4 μg m^{-3}) than at Viznar and the model was able to capture this pattern of behavior, showing 5 μg m^{-3}.

f. 18 November 2009

During this day dust intrusions affected the coastal area of Andalusia (Fig. 4) as a consequence of the influence of a trough over the Gulf of Cadiz. The HYSPLIT simulation is able to qualitatively reproduce this feature, considering the very limited spatial extension of this episode (Fig. 4). Figure 1d shows that the Barcarrota station did not show indicate dust originating from Africa, while at the Viznar station a 6-day-long intrusion with values reaching 64 μg m^{-3} on 17 November and 66 μg m^{-3} on 18 November was observed (Fig. 1c). The HYSPLIT was not able to reproduce such elevated levels in the eastern portion of Andalusia, predicting levels of PM10 not exceeding 3 μg m^{-3}.

4. Conclusions

The HYSPLIT model has been applied to simulate the intrusion of dust that originated in northern Africa for the years 2008 and 2009. HYSPLIT output results have been compared against two surface PM background stations representing the conditions in eastern and western Andalusia. The simulation captures the main features of the spatial and temporal distributions of dust over the southwestern Iberian Peninsula. The model is able to simulate the generally higher levels observed at the Viznar station with respect to the Barcarrota concentrations. Furthermore, the model has been qualitatively compared with satellite observations for several case studies, showing its ability to simulate the relative geographical distribution of dust. This modeling approach constitutes a feasible tool for forecasting dust intrusions in the area of Andalusia due to its simplicity and low cost of implementation.

Acknowledgments. This work was supported by the Junta de Andalucía (Project 2007-RNM 02729), Consejería de Innovación Ciencia y Empresa and Consejería de Medio Ambiente (Project NET 762513/1). We also acknowledge the MODIS mission scientists and associated

NASA personnel for the production of the data used in this research effort.

REFERENCES

de la Rosa, J. D., A. M. Sánchez de la Campa, A. Alastuey, X. Querol, Y. González-Castanedo, R. Fernández-Camacho, and A. F. Stein, 2010: Using PM10 geochemical maps for defining the origin of atmospheric pollution in Andalusia (southern Spain). *Atmos. Environ.,* **44,** 4595–4605.

Draxler, R. R., and G. D. Hess, 1997: Description of the HYSPLIT_4 modeling system. NOAA Tech. Memo. ERL ARL-224, 24 pp.

——, and ——, 1998: An overview of the HYSPLIT_4 modelling system for trajectories, dispersion, and deposition. *Aust. Meteor. Mag.,* **47,** 295–308.

——, D. A. Gillette, J. S. Kirkpatrick, and J. Heller, 2001: Estimating PM10 air concentrations from dust storms in Iraq, Kuwait, and Saudi Arabia. *Atmos. Environ.,* **35,** 4315–4330.

——, P. Ginoux, and A. F. Stein, 2010: An empirically derived emission algorithm for wind blown dust. *J. Geophys. Res.,* **115,** D16212, doi:10.1029/2009JD013167.

Eder, B., D. Kang, A. Stein, J. McHenry, G. Grell, and S. Peckham, 2005: The New England Air Quality Forecasting Pilot Program: Development of an evaluation protocol and performance benchmark. *J. Air Waste Manage. Assoc.,* **55,** 20–27.

Escudero, M., A. Stein, R. R. Draxler, X. Querol, A. Alastuey, S. Castillo, and A. Avila, 2006: Determination of the contribution of northern Africa dust source areas to PM10 concentrations over the central Iberian Peninsula using the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) model. *J. Geophys. Res.,* **111,** D06210, doi:10.1029/2005JD006395.

——, and Coauthors, 2007: A methodology for the quantification of the net African dust load in air quality monitoring networks. *Atmos. Environ.,* **41,** 5516–5524.

Kallos, G., A. Papadopoulos, P. Katsafados, and S. Nickovic, 2006: Trans-Atlantic Saharan dust transport: Model simulation and results. *J. Geophys. Res.,* **111,** D09204, doi:10.1029/2005JD006207.

Perez, C., S. Nickovic, J. M. Baldasano, M. Sicard, F. Rocadenbosch, and V. E. Cachorro, 2006: A long Saharan dust event over the western Mediterranean: Lidar, sun photometer observations, and regional dust modeling. *J. Geophys. Res.,* **111,** D15214, doi:10.1029/2005JD006579.

Prospero, J. M., 1999: Long range transport of mineral dust in the global atmosphere: Impact of African dust on the environment of the south-eastern United States. *Proc. Natl. Acad. Sci. USA,* **96,** 3396–3403.

Querol, X., A. Alastuey, J. A. Puicercus, E. Mantilla, J. V. Miró, A. López-Soler, F. Plana, and B. Artíñano, 1998: Seasonal evolution of suspended particles around a large coal-fired power station: Particle levels and sources. *Atmos. Environ.,* **32,** 1963–1978.

Rodríguez, S., X. Querol, A. Alastuey, G. Kallos, and O. Kakaliagou, 2001: Saharan dust contributions to PM10 and TSP levels in southern and eastern Spain. *Atmos. Environ.,* **35,** 2433–2447.

Westphal, D. L., O. B. Toon, and T. N. Carlson, 1987: A two-dimensional numerical investigation of the dynamics and microphysics of Saharan dust storms. *J. Geophys. Res.,* **92,** 3027–3029.

Wilson, M. F., and A. Henderson-Sellers, 1985: A global archive of land cover and soils data for use in general circulation models. *Int. J. Climatol.,* **5,** 119–143.