TECHNICAL PROPOSAL

KUWAIT DUST FORECASTING SYSTEM (K-DUST)

Earth Sciences Department

Barcelona Supercomputing Center (BSC)

Barcelona, Spain

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Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Executive summary

The main goal of the present proposal is the development and implementation of a state-of-the-art dust forecasting system for Kuwait - "**Kuwait Dust Forecasting System (K-Dust)**". The system will provide routine dust storm forecasts at the **Kuwait Institute for Scientific Research (KISR)**, allowing user-oriented applications of societal and economic importance in Kuwait. K-Dust will be based on three main pillars:

1) **A research phase** to optimize the model behaviour over Kuwait. This activity will focus on the characterization of sand and dust storms over Kuwait and the refinement of the dust source term for the region in the dust forecast-modeling system.
2) The implementation of a **dust forecast-modeling system**: this will involve the design of a dust forecasting system for Kuwait, including an optimal domain and resolution configuration for the region and its operational implementation to deliver daily dust forecasts at the HPC Cluster of the **Kuwait Institute for Scientific Research**.
3) **Data management, near-real-time evaluation with observations, and visualization** of outputs and products through a website interface.
4) **Training and capacity building**: especial attention will be devoted to the transfer of knowledge and technical skills to the **Kuwait Institute for Scientific Research** to independently operate and maintain the dust forecasting system.

The project will be developed over a period of **two years**. At the end of this period the **Kuwait Institute for Scientific Research** will have the capacity to provide routine dust forecasts in Kuwait.

The Barcelona Supercomputing Center (BSC) is the Spanish National Supercomputing facility and a hosting member of the PRACE distributed supercomputing infrastructure. BSC houses MareNostrum, one of the most powerful supercomputers in Europe. The BSC also hosts other HPC systems such as MinoTauro, one of the most energy-efficient supercomputers in the world. The mission of BSC is to research, develop and manage information technologies to facilitate scientific and societal progress. The **Earth Sciences Department at BSC** (ES-BSC) has developed into a reference institution in Europe in the field of climate predictions, air quality and atmospheric composition modelling. The **Atmospheric Composition group** at ES-BSC aims at better understanding and predicting the spatio-temporal variations of atmospheric pollutants along with their effects upon air quality, weather and climate and contributes to a variety of forecasting activities. A core activity of the Atmospheric Composition group is **dust storm modelling and forecasting from regional to global scales**. As a result of its excellence, the BSC hosts both the WMO SDS Warning Advisory and Assessment System (SDS-WAS), and more recently of the first Regional Specialized Meteorological Center for Northern Africa, Middle East and Europe with activity specialization on Atmospheric Sand and Dust Forecast, the Barcelona Dust Forecast (BDFC), in a close and successful collaboration with the Spanish State Meteorological Agency (AEMET).

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1. Justification of the project

Aerosols or Particulate Matter (PM) are an important component of the atmosphere that influences the climate, environment and air quality. Air pollution by PM is of worldwide interest because of its strong social and economic impacts. PM is constituted by a complex mixture of particles emitted by natural sources (e.g. desert dust or sea salt) and anthropogenic sources (e.g. vehicle exhaust, industry or biomass burning, among others).

The major source regions of mineral dust production are found on the desert regions of the Northern Hemisphere; from the eastern subtropical Atlantic eastwards through the Sahara to Arabia and southern Asia. The Arabian Peninsula is identified as one of the major world regions where dust storm generation is especially intense (*Figure 1*).

*Figure 1. **Left pannel:** Distribution of dust sources identified by satellite retrievals in the Middle East (extracted from Ginoux et al., 2012). The white circled sources are numbered as follows: 1, Chalbi Desert of Kenya; 2, coastal desert of Somalia; 3, Nogal Valley of Somalia; 4, Danakil Desert of Ethiopia; 5, Lake Tana of Ethiopia; 6, northeast Sudan; 7, Hadramawt region; 8, Empty Quarter; 9, highlands of Saudi Arabia; 10, Jordan River Basin of Jordan; 11, Mesopotamia; 12, Urumia Lake of Iran; 13, coastal desert of Iran; 14, Hamun-i-Mashkel; 15, Dasht-e Lut Desert of Iran; 16, Dasht-e Kavir Desert of Iran; 17, Qobustan in Azerbaijan; 18, Atrek delta of Turkmenistan; 19, Turan plain of Uzbekistan; and 20, Aral Sea. **Right pannel:** Dust storm episode over Kuwait on 24 June 2015.*

Kuwait is significantly affected by severe dust storms, especially in the summertime. In the Arabian Peninsula there has been an increasing trend in dust events and dust loads in the past decade observed by visibility and satellite records (Hsu et al 2012; Solmon et al., 2015). Dust storms represent a serious hazard for health, property, environment and economy, and plays a significant role in different aspects of weather, climate and atmospheric chemistry. The main impacts are:

1. Impact on **human health**: respiratory diseases, cardiovascular diseases, infections (Kwaasi el al., 1998; Rodriguez et al., 2001; Escudero et al., 2005, 2007; Thomson et al., 2006; Gerasopoulos et al., 2006; Kallos et al., 2007; Koçak et al., 2007,. Mitsakou et al., 2008; Al-Dabbas et al., 2012; de Longueville et al., 2012 ; Pérez et al., 2013).
2. Impact on **ground and air transportation** due to visibility reduction (Shirkhani-Ardehjani, 2012).

3. Impact on **energy and industry** (El-Shobokshy and Hussein, 1993; El-Nashar, 2003; Elminir et al., 2006; Sulaiman et al., 2011; Gueymard, 2012; Ohde and Siegel, 2012; Sayyah et al., 2012; Charabi and Gastli, 2012; Schroedter-Homscheidt et al. 2012).
4. Impact on **ecosystems** (Fung et al., 2000; Jickells and Spokes, 2001; Jickells et al., 2005; Mahowald et al., 2005; Shao, 2008; Stefanski and Sivakumar, 2009; Wijayratne et al., 2009; El-Gaely, 2012; UNEP, 2012).
5. Impact on **climate** (Tegen et al., 1996, Mahowald et al., 2006, 2010; Stenchikov et al., 2011; IPCC 2007 and 2013).
6. Impact on the **hydrological cycle** (Levin et al., 1996; Miller et al. 2004, Li and Shao, 2009; Zhao et al. 2011).
7. Impact on **weather prediction** (Li et al., 1996; Moulin et al., 1997; Miller and Tegen, 1998, Pérez et al., 2006b).
8. Impact on **atmospheric chemistry** (Prospero et al., 1995; de Reus et al., 2000; Bonasoni et al., 2004; Cuevas et al., 2013).
9. Impact on **satellite retrievals** (Merchant et al., 2006 ; Amiridis et al., 2013).

2. Objectives and expected results

The BSC was contacted by Prof. Mohamed F. Yassin from the Kuwait Institute for Scientific Research to request dust forecasting capabilities for Kuwait. Based on this request, the BSC has prepared the K-Dust project whose main objectives are the **implementation of a mineral dust forecasting-modelling system for Kuwait** and the **transfer of knowledge and technical skills** to operate and maintain the system. The expected results of the implementation of the system are:

- Increased knowledge of the region in terms of dust dynamics, and particularly on the characterization of weather types and typical synoptic situations favoring dust outbreaks.
- Serving as a complement for dust observations, increased understanding of dust processes and prediction of the impact of dust.
- Better spatial identification of dust sources and dust transport paths that will help define future locations for the observational network.
- Quantification and analysis of the cross-boundary transport of mineral dust towards Kuwait.
- Provision of timely and accurate operational dust forecasts, critical for important socio-economic sectors, such as civil aviation, public health, energy, industry, etc.
- New tools to provide information to end-users about current and future dust concentration and derived parameters.
- New infrastructure for the issuance of warning advisories.

3. Development of the proposal

The project will be developed over a period of **two years** according to the three steps shown in the diagram presented in *Figure 2*. The K-Dust project is structured along three interrelated working packages. **WP1 (Sand and Dust Storm characterization)** will compile all the available dust observations over Kuwait and provide a dust climatology over Kuwait that will be used to refine the localisation of the dust sources in the model domain as well as to select the observations suitable for the near-real-time evaluation of the dust forecasting system. WP1 will feed

WP2 and WP3. **WP2 (Dust Forecasting System)** involves the implementation of a dust forecasting system over Kuwait. **WP3 (Capacity building)** will provide the necessary scientific and technical background to the staff at KISR to manage the forecasting system.

PROJECT:	Kuwait Dust Forecasting System					
Acronym	K-Dust					
Duration:	2 years					
	1st year			2nd year		
	Q1	Q2	Q3	Q4	Q5	Q6
WP1: Desert dust characterisation						
Task 1.1 Compilation of available information		**M1.1**		**D1.1**		
Task 1.2 Aerosol characterisation and desert sources indentification			**D1.2**			
WP2: Dust forecasting system						
Task 2.1 HPC resource requirements		**M2.1**	**D2.1**			
Task 2.2 Model configuration			**M2.2**			
Task 2.3 Model compilation and testing				**M2.3**		
Task 2.4 Improvement of the model performance				**D2.2**		
Task 2.5 Operational Implementation					**M2.4**	**D2.3**
Task 2.6 Data Management			**M2.5**		**D2.3**	
Task 2.7 Visualization interface						**D2.5**
WP3: Capacity building						
Task 3.1 Dust forecasting skills and observations	**D3.1/M3.1**	**D3.2/M3.2**				
Task 3.2 Implementation and maintainance of a dust forecasting system			**D3.3/M3.3**	**D3.4/M3.4**	**D3.5/M3.5**	**D3.6/M3.6**

Figure 2. Timing of the work packages and their components. M refers to milestone and D refers to deliverable.

WP1 Sand and dust storm characterization over Kuwait

This activity will focus on the compilation of available dust (ground-based and satellite) observations over Kuwait to perform the characterization of dust storms over Kuwait and the refinement of the dust sources affecting Kuwait in the modeling system.

Task 1.1. Compilation of available dust information for the study region. In-situ and ground-based remote sensing observations of aerosols and dust will allow the characterization of both natural and anthropogenic aerosols over Kuwait. This information will essential for the Task 1.2, and to implement the near-real-time evaluation included in the operational dust forecasting system (WP2). This task considers the participation of KISR to provide and get access to national and local databases.

Task 1.2. Aerosol characterization and refinement of the dust sources in the modeling system. Using the results of Task 1.2, an aerosol characterization over Kuwait based on long-term ground-based and satellite aerosol observations will be described. This aerosol characterization will include a climatology of SDS over Kuwait. This climatology will consider seasonal patterns, frequency, intensity of dust storm events (annual, seasonal and diurnal), interannual variability of dust storms, climatological trends of dust outbreaks that contributes to identify the frequency and intensity of dust production events in the region of study. These results will be used for the improvement of the model through the refinement of the localisation of the dust sources over the study domain (Task 2.2) and the implementation of the near-real-time evaluation considered in the operational forecasting system (Task 2.6). All the tests to obtain the optimal desert dust source mask for our region of interest that will be implemented in the operational system (WP2) can be run at the HPC supercomputer hosted by BSC.

Deliverables

D1.1. Report on SDS over Kuwait including the available observations that it can be used for the operational near-real-time evaluation.
D1.2. Improved desert dust source map for dust modeling of the Middle East.

Milestones

M1.1. Compilation of available ground-based and satellite observations over the Middle East.

WP2 Implementation of the dust forecasting-modeling system

The main objective of this task is the **implementation of a mineral dust forecasting system** using the NMMB/BSC-Dust model in order to perform a daily mineral dust forecast (72 hours) at high spatial resolution over Kuwait. The forecast simulations will be evaluated in near-real-time with available data from ground based stations. A comprehensive analysis will be performed. The model input data and emission parameterizations will be further adapted to the specific domain and improved.

The **NMMB/BSC-Dust model** (Perez et al, 2011; Haustein et al. 2012) has been selected to forecast the atmospheric cycle of mineral dust in Kuwait. The model is comprised of an atmospheric model (the Non-Hydrostatic Multi-scale Model, NMMB) developed at NOAA/NCEP (Janjic, 2005; Janjic and Black, 2007; Janjic *et al*., 2011; Janjic and Gall, 2012) and a dust module developed by the Atmospheric Composition Group of the BSC in close collaboration with NOAA/NCEP and other partners, including the NASA Goddard Institute for Space Studies (NASA GISS) and the University of California, Irvine (UCI) (Pérez *et al*., 2011; Haustein *et al*., 2012; Jorba *et al*., 2012; Spada *et al*., 2013; Badia and Jorba, 2014). This state-of-the-art model is designed to be efficient, flexible, and extendible. It contains advanced physics, chemistry and aerosol packages, and has the unique ability to be configured as a global model or as a very high-resolution regional model. Physical processes include dry deposition, grav-itational settling, wet deposition (including rainout and washout in and below the clouds), and radiative interaction allowing feedbacks between dust and the atmosphere. The model produces forecasts at the SDS-WAS Regional Center for a regional domain comprising Northern Africa, Middle East and Europe, where it is combined with other dust model forecasts from collaborating institutions and evaluated in near-real time. The model also runs operationally (7 days a week, 365 days a year) at the Barcelona Dust Forecast Center (BDFC; http://dust.aemet.es/) with a horizontal resolution of 10 km for the same region. At the global scale, the model contributes to the International Cooperative for Aerosol Prediction (ICAP) Multi Model Ensemble (Sessions *et al*., 2014), A detailed description of the model is presented in Section 6.2.

Task 2.1 HPC resource requirements. The modelling system needs an HPC facility to be executed. This includes a computing cluster with several nodes and a filesystem tuned to run parallel simulations. The parallel programming model implemented in NMMB/BSC-Dust is Message Passage Interface (MPI) and can be compiled with a wide range of compilers. A general-purpose architecture is required. A group of HPC experts from BSC will visit Kuwait to analyse the current capacity of the KISR cluster. The BSC can performance HPC analyses using performance tools based on hardware counters to improve the performance of the model (Tintó Prims et al., 2015). This information will be considered for the definition of the model configuration (Task 2.2).

Task 2.2 Model configuration. The model configuration (which includes the definition of the domain, resolution and the input databases for the model run) will be achieved using the results of the WP1 (the definition of the source mask) and the available HPC resources at KISR (computational and storage resources) resulting from Task 2.1.

Task 2.3 Model compilation and testing. To build the NMMB/BSC-Dust model in the KISR's cluster, BSC will need to install additional software applications (i.e. libraries and tools) for the model compilation and execution. Once the model configuration is defined (Task 2.2) and the necessary software installed, a general compilation and execution of the forecast system is required. The model outputs will be used to verify that the model has been correctly built in the KISR cluster.

Task 2.4 Improvement of the model performance. The performance of the dust forecast system will be analysed using BSC performance tools (https://tools.bsc.es/). To perform this analysis some software (i.e. Extrae) will be installed. Trace analysis of an execution in the KISR cluster will be analysed with the methodology developed by the BSC. The communication pattern of the model, the input/output of the system, the coupling of the meteorology with the chemistry and aerosols, among others will be studied. Any improvement on the model performance will have an important effect on the overall forecast time of the forecasting system. Recommendations to tune the hardware or execution parameters could be transmitted to system administrators of the cluster.

Task 2.5 Operational Implementation. The dust operational system consists in three main modules: pre-processing, model run and post-processing. The pre-processing includes a download and degrib of the meteorological input data from the global meteorological model (typically, ECMWF or NCEP). The post-processing includes the generation of the output files (in NetCDF format) and the map generation (using a programming language as Python, GrADS or R).

Task 2.6 Data Management. Output files from the dust prediction model and observational data from the air quality monitoring stations will be gathered together with other products (RGB product from Meteosat Second Generation, MSG,…) resulting from Task 1.1 and organized through a database in order to facilitate the generation of products suitable for operational monitoring and forecast. For the data storage, it would be needed a volume of approximately 1 TB per year. The storage server(s), if separated from the front-end (web interface) should be connected to this with a gigabit or (better) low latency network to make the communication between storage and visualization layer easier and not create overhead. KISR will be in charge to provide the necessary storage server and BSC will build storage infrastructure in the machine.

Task 2.7 Visualization interface. The information resulting from the operational dust forecasting system will be presented to users through a web-based application based on the current web-interface from the Barcelona Dust Forecast Center (http://dust.aemet.es), which will provide:

- Three-hourly charts of the main parameters predicted by the model (dust surface concentration, dust load, dust optical depth, dry and wet deposition, …) up to a lead time of 72 hours.
- Daily and monthly plots of model data interpolated to specific sites (e.g., air quality stations, airports, main cities) updated after every model run including the available observations.

To host the web-interface, it would be needed a server with this minimum technical requirements:

- 8 cores 3.2GHz, 64 bit architecture
- 16 GB main memory
- hard disk size minimum 0.5TB + data volume (if hosted in the same server)

It will be necessary to install all software packages to run the web server, mail server and data processing and visualization libraries. KISR will be in charge to provide the web-server and BSC will install all the necessary software and libraries and build the web-interface.

Deliverables

D2.1. Report on the available HPC resources on KISR to build the dust forecasting system.
D2.2. User Guide of the dust forecasting system.
D2.3. Report on the model performance.
D2.4. Data catalogue (model and observations).
D2.5. Web interface based on the BDFC configuration.

Milestones

M2.1. HPC visit to KISR-Kuwait.
M2.2. Model configuration.
M2.3. Compiled code.
M2.4. Implementation of the operational download of the necessary input data.
M2.5. Implementation of the storage database (modelled and observational products).

WP3 Capacity building and training

The main objective of this task is to work on the transfer of knowledge and skills on dust forecasting providing guidelines on dust products and to build capacity of the KISR staff to maintain the model.

Task 3.1. Dust forecasting skills and analysis of dust from observations. This first task will focus on providing the necessary background to the KISR staff on dust forecasting. It will provide fundamental concepts about dust forecasting models and training on the manipulation of the most common scientific formats. BSC will provide access to the forecasts products of the Barcelona Dust Forecast Center (that are based on the NMMB/BSC-Dust model) to KISR. These operational dust products will be used to provide real cases to the attendants of the courses.

Task 3.2. Implementation and maintenance of a dust forecasting system. The set of courses included in this task are oriented to prepare the KISR staff to build and maintain the dust operational system. The courses will focus on the structure of the operational system from WP2 as well as the basic concepts to configure one forecast domain and to maintain and enhance the web-server interface.

Deliverables

D3.1. Training course 1 (20h): Dust observations and forecasting models.
D3.2. Training course 2 (20h): Manipulation (read/write and visualization using programming languages as GrADs, Python, R,...) of scientific formats (NetCDF, Grib, ASCII, ...).
D3.3. Training course 3 (20h): Compilation of the NMMB/BSC-Dust model.
D3.4. Training course 4 (20h): Operational system: download input data, preprocessing, model execution and postprocessing.
D3.5. Training course 5 (20h): The NMMB/BSC-Dust model - parameterizations and main routines of the model code.
D3.6. Training course 6 (20h): Data management (storage/archive) and web-interface.

Milestones

M3.1. Announcement of the training course 1.
M3.2. Announcement of the training course 2.
M3.3. Announcement of the training course 3.
M3.4. Announcement of the training course 4.
M3.5. Announcement of the training course 5.
M3.6. Announcement of the training course 6.

4. Budget justification and payment

The total budget of the K-Dust project for **the two years is 684,069.89 €** as it is detailed in *Figure 4*. The largest part of the budget is dedicated to personnel costs, as the proposal relies on the scientific and technical skills and robust expertise of the BSC staff. The budget also includes other direct costs as:

- **Travels:** The HPC consultancy mission will include the visit to Kuwait Institute for Scientific Research of 2 HPC experts described in WP2. Additionally, this amount of the budget will include the trips of the experts that will manage the 6 trainings described in the WP3.
- **Other direct costs:** The budget includes an item to cover the organization of the 6 trainings (described in WP3) considering during the execution of the K-Dust project.

PROJECT:	Kuwait Dust Forecasting System				
Acronym	K-Dust				
Duration:	2 years				
			Personnel	Travel	Other direct
WP1: Desert dust characterisation	€ 129,444.05		€ 123,444.05	€ 6,000.00	-
WP2: Dust forecasting system	€ 310,578.54		€ 310,578.54	-	-
WP3: Capacity building	€ 244,047.30		€ 148,047.30	€ 60,000.00	€ 36,000.00
TOTAL	€ 684,069.89		€ 582,069.89	€ 66,000.00	€ 36,000.00

Figure 4. Summary of the budget by WP.

5. Conditions

The model code itself, all information and materials in the framework of the present K-Dust project will be treated by KISR as **confidential information**.

The technical support provided by BSC is limited to the duration of the current K-Dust project. Any further technical assistance beyond the duration of the K-Dust project is not considered in the current proposal. Additionally, future updates or improvements of the model, beyond the model version built in KISR during the current K-Dust project, are not considered in the current proposal and they must be discussed in the framework of a new agreement.

Prior notice of **any planned publication** resulting from the current K-Dust project shall be shared between BSC and KISR at least 30 calendar days before the publication. Any objection to the planned publication shall be made in writing to the institution proposing the dissemination within 2 calendar days after receipt of the notice. If no objection is made within the time limit stated above, the publication is permitted.

6. Information about the Barcelona Supercomputing Center

The Barcelona Supercomputing Center – Centro Nacional de Supercomputación (short named as BSC), created in 2005, has the mission to research, develop and manage information technology in order to facilitate scientific progress. At the BSC, more than 350 people from 40 different countries perform and facilitate research into Computer Sciences, Life Sciences, Earth Sciences and Computational Applications in Science and Engineering. This multi-disciplinary approach and the combination of world-leading researchers and experts in HPC (High-Performing Computing) with state-of-the-art supercomputing resources make BSC unique.

The BSC is one of the first eight Spanish “Severo Ochoa Centre of Excellence” awarded by the Spanish Government, as well as one of the four hosting members of the European PRACE Research Infrastructure FP7 project. The BSC hosts MareNostrum III (*Figure 6*), a Tier-0 PRACE system currently ranked as the #12 most powerful supercomputer in Europe (#36 in the world) with 1Pflop/s capacity. In addition, the BSC hosts other High-Performance Computing (HPC) resources, among which it is worth mentioning MinoTauro, one of the most efficient supercomputers in the world (#35 in the last ranking of the top500 green list).

The Earth Sciences Department of the BSC (ES-BSC) was established with the objective of carrying out research in Earth system modeling. The high performance capabilities of MareNostrum III and the close collaboration with the Computer Sciences department allow to increase the spatial and temporal resolution of atmospheric modelling systems, in order to improve our knowledge on dynamic patterns of air pollutants in complex terrains and interactions and feedbacks of physico-chemical processes occurring in the atmosphere. Therefore it represents an excellent infrastructure to carry the Earth system simulations on which the ES-BSC is a worldwide reference.

The ES-BSC conducts research on air quality, mineral dust and climate modelling and strongly contributes to the scientific and technological advancement in atmospheric and mineral dust modelling. In this sense, the ES-BSC develops and maintains a state-of-the-art mineral dust model: NMMB/BSC-Dust. The excellent results of the group on this field have contributed to the recently creation of the first World Meteorological Organization (WMO) Regional Meteorological Center specialized on Atmospheric Sand and Dust Forecast, the “Barcelona Dust Forecast Center”. In which the NMMB/BSC-Dust model has been selected as the reference mineral dust model. Currently the model provides mineral dust forecasts to the World Meteorological Organization (WMO) Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) Northern Africa- Middle East-Europe (NAMEE) Regional Center that is managed by a consortium between the Spanish Weather Service (AEMET) and BSC.

Figure 6. Supercomputer Mare Nostrum III hosted by the BSC in Barcelona.

6.1. Description of work expertise

The Earth Sciences Department of the BSC (ES-BSC) was established in 2006 with the objective of carrying out research in Earth system modelling. The ES-BSC inherited the activity of the Environmental Modelling Laboratory of the Universitat Politècnica de Catalunya (UPC). The main topics of research of the ES-BSC are: atmospheric modelling, mineral dust modelling, air quality modelling and global and regional-global climate modelling.

With respect to mineral dust modelling, the updated BSC-DREAM8b v2.0 and the new NMMB/BSC-Dust are the models developed and operated in the ES-BSC to simulate the atmospheric cycle of mineral dust. Two dust forecast operational systems based on BSC-DREAM8b v2.0 and NMMB/BSC-Dust models are daily available through the web page. The BSC in collaboration with AEMET hosts the WMO Northern Africa-Middle East-Europe Regional Center of the Sand and Dust Storm Warning Assessment and Advisory System (SDS-WAS NAMEE Regional Center). In which both the BSC-DREAM8b v2.0 and NMMB/BSC-Dust mineral dust forecast simulations are participating at regional scale (0.3°x0.3°). In this portal, several dust models developed worldwide are compared and evaluated in a near-real time system developed at BSC. The BSC-DREAM8b v2.0 is considered a reference model for mineral dust modelling at regional scales. However, due to the hydrostatic nature of the ETA model, the spatial resolution of the BSC-DREAM8b is limited and cannot be increased. In this sense, the availability of the NMMB/BSC-Dust model has enabled to perform mineral dust simulations at high spatial resolution.

The experience acquired with the management of the WMO SDS-WAS NAMEE Regional Center has contributed to the creation of the first WMO Regional Meteorological Center specialized on Atmospheric Sand and Dust Forecast, the Barcelona Dust Forecast Center (BDFC) which is hosted in Barcelona (Spain) and it is managed but the consortium formed by AEMET and BSC. The NMMB/BSC-Dust model has been designed as the reference mineral dust model of the BDFC which enables to perform mineral dust forecast simulations at 0.1°x0.1°.

The BSC-DREAM8b v2.0 mineral dust model (Pérez et al., 2006a,b; Basart et al., 2012a) is the updated version of the Dust Regional Atmospheric Model: DREAM (Nickovic et al., 2001). The BSC-DREAM8b model is embedded into the Eta/NCEP atmospheric model and solves the mass balance equation for dust taking account the different processes of the dust cycle (i.e. dust emission, transport and deposition). The DREAM and BSC-DREAM8b model have demonstrated their capabilities in an important number of evaluation studies (e.g. Pérez et al., 2006a,b; Haustein et al., 2009; Pay et al., 2010, 2012; Basart et al., 2012a,b; Gobbi et al., 2013) performed so far using data from observation networks such as the European Lidar Network EARLINET, the AERONET/PHOTONS sun-photometer network, and ground-level PM levels. Satellite aerosol products are used to compare and analyze the modelled dust.

On the other hand, the NMMB/BSC-Dust model is a part of the new NMMB/BSC-Chemical Transport Model (NMMB/BSC-CTM; http://www.bsc.es/earth-sciences/nmmbbsc-project; Pérez et al., 2011; Jorba et al., 2012; Spada et al., 2013; Badia and Jorba, 2014) a new chemical weather prediction system under development at ES-BSC in collaboration with with NOAA/National Centers for Environmental Prediction (NCEP), NASA Goddard Institute for Space Studies and the International Research Institute for Climate and Society (IRI) and the University of California Irvine. The NMMB/BSC-Dust model (Pérez et al., 2011; Haustein et al., 2012) is fully embedded into the Non-hydrostatic Multiscale Model NMMB developed at NCEP (Janjic, 2005, 2009; Janjic and Black, 2007; Janjic et al., 2011). The NMMB model provides an improved numerical environment for the physical and dynamical schemes, essential to be able to increase the model resolution, the forecast domain or the number of incorporated physical and dynamical processes. The NMMB is used operationally by NCEP for North America since October of 2011. The NMMB/BSC-Dust provides daily short to medium-range dust forecasts for both regional and global domains. The

NMMB/BSC-Dust model has been evaluated at regional (for Northern Africa, Middle East and Europe) and global scales (Pérez et al., 2011; Haustein et al., 2012) showing the good performance of the model to reproduce the dust cycle.

The ES-BSC group has previous experience on the generation of climatologies related to mineral dust. The ES-BSC has developed different dust climatologies over the European and North African domain. The models BSC-DREAM and NMMB/BSC-Dust models were used to generate such climatologies for 50 years (1958-2006) at horizontal resolution of 0.3° and for 30 years (1979-2010) at 0.5°, respectively. These simulations have been used in the analysis of dust trends in Alonso-Pérez et al. (2011) and Pérez García-Pando et al. (2014). Furthermore, a database with the numerical dust forecasts of both the BSC-DREAM8b and NMMB/BSC-Dust models for the period 2000-2014 are accessible from this page: http://www.bsc.es/earth-sciences/mineral-dust/catalogo-datos-dust.

Concerning air quality modelling, the ES-BSC has developed several emission inventory models for anthropogenic and biogenic emissions (Parra et al., 2004, 2006; Baldasano et al., 2008a; Guevara et al., 2013). The Department has a wide experience with air quality models that take into account photochemical interactions of the different species of pollutants (Jiménez et la., 2003, 2008a; Gonçalves et al., 2009). Several studies of the dynamics of air pollutants within the Western Mediterranean Basin, Spain and whole Europe have been carried out with CMAQ and CHIMERE models (Jorba et al., 2008b). The ES-BSC has coordinated a national initiative that aimed at developing the air-quality forecasting system for SPAIN under the umbrella of the CALIOPE project funded by the Environmental Ministry of Spain (Baldasano et al., 2008b; Pay et al., 2010; Baldasano et al., 2011; Pay et al., 2012; Basart et al., 2012b). The aim of CALIOPE stands for delivering air-quality related products with very high resolution (1 km for hot spot regions, 4 km for Spain, 12 km for Europe, 1 hr-temporal resolution) useful to a wide range of users for reducing the impacts of air pollution on human health.

Furthermore, the Department has a wide experience in the applications of lidar techniques (e.g., Soriano et al., 2001; Bösenberg et al., 2003; Pérez et al., 2004; Sicard et al., 2006; Sicard et al., 2011), participating in environmental campaigns of measurements with lidar, collaborating with Los Alamos National Laboratory (LANL), New Mexico (USA) and summer 1996 and 1997 with ERLAP (European Reference Laboratory of Air Pollution), Environmental Institute, JRC-ISPRA European Commission, and participating in the European EARLINET and ACTRIS network. Furthermore, works of the group (Pérez et al., 2006ab; Haustein et al., 2009; Gobbi et al., 2013, Amiridis et al., 2013; Mona et al., 2013) have focused on the evaluation of mineral dust models with lidar observations. Currently, ES-BSC manages a Micro Pulse Lidar and a AERONET sunphotometer located in Barcelona.

The internationalization of the research activity is guaranteed by the participation of the ES-BSC in European funded projects (e.g., APPRAISAL, FIELD-AC, IS-ENES, IS-ENES2, MACC, EARLINET, of the EU 7th Framework Programme; Excellence Network of the 6th EU Framework Programme on Atmospheric Pollution and Climate Change; ACCENT; etc.). Additionally, the Department maintains active collaborations with international groups and scientists of recognized prestige such as the Computational Sciences Laboratory of the University of California (Irvine, EEUU) directed by Dr. Donald Dabdub; Dr. Slobodan Nickovic of the World Meteorological Organization; Dr. Zavisa Janjic of the National Centers of Environmental Predictions (NCEP-NOAA), USA; the Department of Atmospheric Chemistry of the Max Planck Institute for Chemistry, Germany (Dr. Jos Lelieveld), the Norwegian Institute for Air Research (Dr. Leonor Tarrasón) and the National Center for Atmospheric Research, EEUU (Dr. Rolando García).

Also it should be mentioned that ES-BSC participates in the intergovernmental framework for European Cooperation in Science and Technology Actions (COST actions): 1) ES1004. European framework for online integrated air quality and meteorology modelling (EuMetChem); and 2) ES1002. European framework for Weather Intelligence for Renewable Energies (WIRE).

The experience gained in these research fields has resulted in numerous publications in international magazines (59 publications in JCR-SCI journal, in the period 2008-2013), and proceeding in national and international congresses (more than 150, in the period 2008-2013). These publications can be found in: http://www.bsc.es/earth-sciences/publications-and-communications. Furthermore, the group has contributed to the formation of future research scientist with the successful development of 17 PhD theses during the last 10 years.

It also may be highlighted the contracts with private enterprises (energy companies, cement companies, etc.). These collaborations have allowed technology transfer and know-how transfer between the ES-BSC and Spanish and international enterprises:

- SIEMENS
- Iberdrola
- Gas Natural
- SGS
- Enel Viesgo
- Inypsa
- PB Power
- Holcim
- SAMPOL
- GHK
- ESBI Energy Innovation
- Cementos Portland
- ENCE
- SAMCA
- PRYSMA
- Idom
- hc energía grupo EDP
- RESA

6.2. The mineral dust NMMB/BSC-Dust model

ES-BSC has a wide experience in dust modelling. At present, two operational forecast systems are maintained in the ES-BSC for the North Africa-Middle East-Europe domain: NMMB/BSC-Dust (*Figure 3*) and BSC-DREAM8b. These two models have been developed and implemented as well as extensively evaluated by ES-BSC. Both forecast systems are verified operationally in NRT (near real time conditions) against ground-based (AERONET) observations and satellites (MODIS and MSG). The daily dust evaluation plots show comparisons of AOD values from the dust forecast systems compared to the large number of AERONET stations which include desert dust source regions in the Arabian Peninsula. The MODIS and MSG images are used to qualitatively compare the desert dust load fields observed by the satellite sensors. This allows constant monitoring of the quality of the forecast systems. Additionally, works of the ES-BSC group (Basart et al., 2012a,b; Haustein et al., 2009,2012; Pay et al., 2010,2012; Pérez et al., 2006 a,b, 2011) have focused on the evaluation of dust models with lidar observations, sun-photometer data (AERONET) and satellite imagery as well as intensive experimental campaigns over desert dust source regions (i.e.

SAMUM and Bodex). Furthermore, some previous studies showed that the inclusion of dust radiative effect has shown a way to improve numerical weather prediction results through feedbacks between aerosol concentration and meteorology (Pérez et al., 2006b).

ES-BSC provides mineral dust forecasts with NMMB/BSC-CTM to European projects (Charmex, DIAPASON and EARLINET). Both models, BSC-DREAM8b and NMMB/BSC-Dust are participating in the NAMEE Regional Center of the WMO SDS-WAS Programme (sds-was.aemet.es). NMMB/BSC-Dust is also involved in the initiative International Cooperative on Aerosol Prediction (ICAP). Furthermore, NMMB/BSC-Dust is the model of the recently created **Barcelona Dust Forecast Center** of the WMO which is the first specialized center on mineral dust storm forecasting.

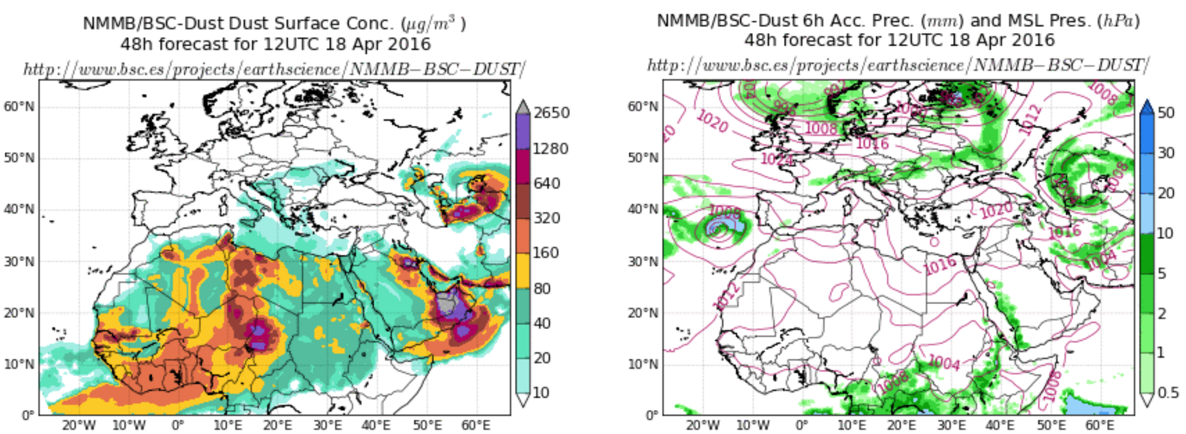

Figure 3. An example of the daily forecast product of the NMMB/BSC-Dust for 12UTC 18 April 2016. Dust load and cloudiness from the North Africa-Middle East-Europe domain.

BSC-DREAM8b is a regional dust model using as meteorological driver the hydrostatic NWP (Numerical Weather Prediction) ETA model developed in the 90's. Although the model shows its ability to reproduce the dust long-range transport from the Sahara to Europe and North Atlantic region in different model evaluation analysis (i.e. Pérez et al., 2006 a, b; Pay et al., 2010, 2012; Basart et al., 2012a,b), due to its hydrostatic core it is not able to run at high horizontal resolutions. Due to the hydrostatic capacity of the ETA model, the spatial resolution of the BSC-DREAM8b is limited and cannot be increased. Consequently, the NMMB/BSC-Dust model will be used in this project in order to perform a comprehensive dust storms assessment in Kuwait at high spatial resolution.

In this sense, the NMMB/BSC-Dust model will be the main tool used in the present research project. The NMMB/BSC-Dust model is a part of the new in-house chemical transport model at BSC (Pérez et al., 2011; Jorba et al., 2012; Spada et al., 2013; Badia and Jorba, 2014) a new chemical weather prediction system under development at ES-BSC in collaboration with with NOAA/National Centers for Environmental Prediction (NCEP), NASA Goddard Institute for Space Studies and the International Research Institute for Climate and Society (IRI) and the University of California Irvine.

The NMMB meteorological model is used by NCEP as the operational forecast system for the North America domain since October of 2011. Its most relevant characteristic is its on-line coupling with a state-of-the-art global/regional meteorological model with non-hydrostatic dynamics. This provides a unique framework to simulate/predict air quality and weather in a wide range of scales from global to mesoscale applications (from 100 to 1 km), and allows interactions among dust-chemistry-meteorology processes. At present, the NMMB/BSC-Dust model provides operational dust forecast over North Africa- Middle East-Europe (see *Figure 3*) and global regions which are daily published through the web site of ES-BSC (http://www.bsc.es/projects/earthscience/NMMB-BSC-DUST/). The NMMB/BSC-Dust model (Pérez et al., 2011, Haustein et al., 2012; Gama et al., 2015; Basart et al., 2016) incorporates different parameterizations from its predecessor the BSC-DREAM8b model. However, several improvements in the emission scheme, advection, sedimentation and deposition processes have been introduced in the new model.

The NMMB/BSC-Dust model solves the mass balance equation for dust taking into account the following processes: (1) dust generation and uplift by surface wind and turbulence, (2) horizontal and vertical advection (Janjic et al., 2005, 2007), (3) horizontal diffusion and vertical transport by turbulence and convection (Janjic et al., 2005, 2007) (4) dry deposition and gravitational settling (Zhang et al., 2001) and (5) wet removal which includes in-cloud and below-cloud scavenging from convective and stratiform clouds (Betts, 1986; Betts and Miller, 1986; Janjic, 1994; Ferrier et al., 2002). Furthermore, in order to take into account the effects of aerosols and mineral dust interactively, the rapid radiative transfer model (RRTM) (Mlawer et al., 1997) is implemented in the model. The NMMB/BSC-Dust model includes a physically-based dust emission scheme which explicitly considers saltation and sandblasting processes (White, 1979; Marticorena and Bergametti, 1995; Marticorena et al., 1997).

6.3. Project team and expertise of the staff involved.

Among other experts, the following qualified manpower will be participating in this Project. The next paragraphs summarize their experience in previous similar studies:

Prof. Dr. Carlos Pérez García-Pando. He will act as the responsible researcher for the proposed project. Dr. Pérez is AXA Professor on Sand and Dust Storms, Ramon y Cajal Fellow and leader of the Atmospheric composition Group at BSC. His research focuses on understanding the physical and chemical processes controlling atmospheric aerosols, and evaluating their effects upon climate, ocean biogeochemistry, air quality, and health. His core area of expertise is atmospheric mineral dust. He is also a model developer with a large experience in HPC and operational forecasting. Between 2009 and 2016 he worked at the NASA Goddard Institute for Space Studies and Columbia University, where he served as PI and co-PI in competitive research projects funded by the U.S. Department of Energy, NASA and NOAA, with collaborators at NOAA/NCEP, NOAA/Geophysical Fluid Dynamics Laboratory, Princeton University and Cornell University. Aside of his significant research achievements related to dust-radiation interactions, dust-mineralogy, and dust effects on health, he led an international multi-institutional initiative to develop a unique unified (regional and global) prediction model for weather, atmospheric aerosols, and chemistry that today provides operational forecasts widely used by the international scientific community, weather services, companies, and air quality managers. This is the model that will be implemented for this project. He also played a seminal role in the design, creation, and successful implementation of the WMO Regional Centres on Sand and Dust Storm (SDS) prediction in Spain, the only operational dust forecasting service in the region fully recognized by WMO.

Dr. Pérez García-Pando's work resulted in 50 peer-reviewed papers (67% in Q1, h-Index: 27, i10-Index: 42, citations: 2730, source: Google Scholar, 29-11-2016), 20 chapters in books/proceedings/reports, 150 contributions to conferences/workshops/seminars (26 as invited speaker) and the edition of a book of proceedings. He organized an international conference and a workshop on SDS. He participated in 27 international (US and EU) and national projects (in 6 of them as PD, PI or co-PI). He co-advised 3 PhD students, 3 Master students, and 1 Postdoc. His work was highlighted among others by NASA and the European Centre for Medium-Range Weather Forecasts (ECMWF), and covered by international media such as The Guardian. Dr. Pérez García-Pando was recently awarded with an AXA Chair to support an ambitious mineral dust research program at BSC.

Dr. Sara Basart. She is a researcher at the Earth Sciences Department of the BSC. Her main research background covers mineral dust modelling, and aerosols. She is scientist-in-charge of the WMO Regional Meteorological Center specialized on Atmospheric Sand and Dust Forecast, the Barcelona Dust Forecast Center and the WMO SDS-WAS NAMEE Regional Center, hosted by AEMET and BSC. She also collaborates in international projects as Copernicus and the International Cooperative on Aerosol Prediction (ICAP) initiative.

Dr. Albert Soret. He is the coordinator of the Earth System services group at BSC. For the last 8 years he has been in charge of technology transfer and research collaborations with several public and private national and international organizations, including environmental consultancy studies, emission models. He has been involved in several international projects (FIELD_AC, RETHINK-big).

MSc Kim Serradell. In charge for the system administration of all the computational resources of the department for the last five years, he's also responsible of supervising the operational runs of the NMMB/BSC-Dust model in the HPC infrastructures of the BSC and also involved in the analysis of the model to improve the performance. Furthermore, he's focused in deploying different earth system models (dust transport, climate or weather forecast) required by the department in a wide range of HPC architectures. He applied with success these skills in projects like IS-ENES (1 & 2), the WMO SDS-WAS NAMEE Regional Center or CONSOLIDER.

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