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International Network to Encourage the Use of Monitoring and Forecasting Dust Products (InDust)

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Amongst the most significant extreme meteorological phenomena are the Sand and Dust Storms (SDS). Owing to significant amounts of airborne mineral dust particles generated during these events, SDS have impacts on climate, the environment, human health, and many socio-economic sectors (e.g. aviation, solar energy management). Many studies and reports have underlined that the society has to understand, manage and mitigate the risks and effects of SDS on life, health, property, the environment and the economy in a more unified way. The EU-funded European Cooperation in Science and Technology (COST) Action 'InDust: International network to encourage the use of monitoring and forecasting Dust products' has an overall objective to establish a network involving research institutions, service providers and potential end users on airborne dust information. We are a multidisciplinary group of international experts on aerosol measurements, aerosol modelling, stakeholders and social scientists working together, exchanging ideas to better coordinate and harmonize the process of transferring dust observation and prediction data to users, as well as to assist the diverse socio-economic sectors affected by the presence of high concentrations of airborne mineral dust. This article highlights the importance of being actively engaged in research networking activities, supported by EU and COST actions since common efforts help not only each scientist by shaping their expertise and strengthening their position, but also all communities.

Introduction

Atmospheric dust, the suspension of tiny soil-derived particles in the atmosphere, is a global player in the Earth's system. Dust influences the radiative balance of the planet in two different ways: directly by scattering and absorbing incoming solar radiation (Boucher *et al*. 2013) or indirectly by acting as cloud condensation nuclei and ice nuclei (Li *et al*. 1996), which in turn affect the optical properties and the lifetime of clouds, and consequently the precipitation patterns. Dust particles also have effects on atmospheric chemistry (Krueger *et al*. 2004), acting as a sink for condensable gases and thus facilitating the formation of secondary aerosols, which in turn contribute to particulate matter concentrations. Dust sedimentation and deposition at the surface causes changes in the biogeochemical processes of terrestrial and marine ecosystems through the delivery of primary nutrients (Jickells *et al*. 2005). It has been demonstrated that the Amazon rainforest is fertilized significantly by Saharan dust (Yu *et al*. 2015). The essential nutrient elements are iron and phosphorus oxides carried by dust on their journey through the atmosphere. Parameterizations of oxides atmospheric processing based on knowledge on geographic distribution of typical dust minerals in sources estimate their nutrition level when deposited to terrestrial systems (Shi *et al*. 2011; Baker and Jickells 2006, Nickovic *et al*. 2012; Nickovic *et al*. 2013). Airborne particles also interact with the cryosphere at far distances from the warm deserts as well as in high latitudes and mountains, where cold climate dust sources are located. The deposition of mineral dust on glaciers has the potential to lower their surface albedo and speed up their melting (Groot Zwaaftink *et al*. 2016; Dagsson-Waldhauserova *et al*. 2019).

Human exposure to airborne mineral dust represents a severe hazard to human health, causing or aggravating allergies, respiratory and cardiovascular diseases (Giannadaki *et al*. 2014; Dominguez-Rodriguez *et al*. 2020), eye infections (Goudie 2014), spreading of meningitis in Sahel region (Molesworth *et al*. 2003), valley fever (Sprigg *et al*. 2014), and the Kawasaki disease in Japan and Western USA (Frazer 2012). At the same, Sand and Dust Storms (SDS) can carry anthropogenic pollutants (Mori *et al*. 2003; Rodríguez *et al*. 2011) as well as micro-organisms and toxic biogenic allergens (Griffin *et al.* 2001; Ho *et al.* 2005). During the last decade, special attention has been given to the health effects of mineral dust particles from desert dust. However, evidence on the health effects of desert dust remains unclear. Previous reviews, systematic or no, have reported inconsistent results on the health effects of desert dust studies across different worldwide regions and methodologies applied. (De Longueville *et al.* 2013; Hashizume *et al.* 2010; Karanasiou *et al.* 2012; Zhang *et al.* 2016). The published studies differed in terms of settings, assessment methods for desert dust and sand storm exposure, lagged exposures examined and epidemiological study designs applied. Moreover, preliminary results from a systematic review commissioned by the World Health Organization (WHO) suggests that desert dust can be related, through different mechanisms, to a risk increase of cardiovascular mortality and respiratory morbidity, and especially asthma (Tobías *et al.* 2019). A potential limitation in the literature is the lack of studies conducted on the long-term health effects of desert dust.

Dust events strongly affect the air quality conditions in Asia, where the background situation is often related to high aerosol concentrations (e.g. Wang *et al.* 2014; Li X *et al.* 2018). Desert dust outbreaks over southern Europe frequently contribute to exceedances of daily and annual safety thresholds of particulate matter (PM) set by the European Union directive on ambient air quality (e.g. Barnaba *et al.* 2017; Querol *et al.* 2019; Basart *et al.* 2012; Pey *et al.* 2013). Dust also impairs air quality and affects fragile cryosphere and environments in high latitude regions (Bullard *et al.* 2016; Boy *et al.* 2019).

High dust concentrations significantly reduce visibility through increased light extinction and may affect aircraft operations and ground transportation. The high impact of SDS on the aviation industry is related to disturbances in airport operations and routes due to poor visibility associated with strong SDS that cause the closing of airports. Additionally, SDS can cause aircraft engines to deteriorate not only through long-term exposure to even small concentrations, but also by dust melting in the turbines (Clarkson *et al.* 2016). But we are still far from answering questions such as: 'How much dust is needed to significantly damage aircraft gas turbine engines?'.

SDS also have many negative impacts on the agricultural sector. The eroded material may cause mechanical injury to crops and natural vegetation by abrasion, and blown sand may bury young plants (Sivakumar and Stefanski 2009).

In addition, airborne dust is a serious problem for solar energy power plants (Schroedter-Homscheidt 2013; Kosmopoulos *et al.* 2018; Hojan *et al.* 2019). The presence of dust aerosol particles reduces the incoming solar irradiance through the direct radiative effect, and, indirectly, favouring cloud formation. In addition, in the proximity of deserts, solar energy plants suffer from dust deposition (soiling). Dust-induced soiling affects photovoltaic (PV) panels, as well as the efficiency of concentrating solar power (CSP) mirrors and water management. In brief, dust aerosol particles reduce the energy generation potential of solar power plants. The lack of forecasts, or inaccurate forecasts, results in an inefficient operation of the electricity system and can even endanger the security of supply (Kosmopoulos *et al.* 2017;

Neher *et al*. 2017). Accurate dust forecasts in this case play an important role on the operation plant's management.

Although, today, the relevance of mineral dust particles in all these fields is clear and there are several national and international scientific initiatives for studying dust-related problems, tailored products for the user communities are not yet available. Dust observations and models have nowadays reached a level of maturity to be ready for the translation into user-oriented products.

Procedure

The EU-funded European Cooperation in Science and Technology (COST) Action InDust ('International network to encourage the use of monitoring and forecasting Dust products', www.cost-indust.eu, CA16202) has the overall objective to establish a network involving research institutions, service providers and potential end-users of information on airborne dust that can assist the diverse socio-economic sectors affected by the presence of high concentrations of atmospheric dust.

Why is studying dust interesting? Why is sharing information on dust important? Why did we initiated the InDust community? The straightforward answer is that we want to bridge the gap between providers (scientists) and users, but there were many links and many possible answers discovered while getting deeper and deeper into this fascinating subject.

Through the actions taken within InDust, we are trying to harmonize data and coordinate the information exchange between the implicated communities – the benefit of EU-funded research programmes – to users and society. This interdisciplinary research stimulated innovations that are needed to solve some of the major problems facing society. In line with this main objective, the network is working on the identification and engagement of representatives of dust-affected socio-economic sectors (targeting air quality and health, aviation and solar energy) from different countries in Europe, North Africa and the Middle East. The scientists involved in InDust have been investigating current needs and future directions for airborne dust observations and applications, and also the specific needs of the users not supported by existing dust products, based on feedback obtained from user's communities.

This collaborative effort is done through a range of networking tools, such as workshops, conferences, training schools, short-term scientific missions (STSMs), and dissemination activities. Activities requiring cooperation amongst members have been accomplished mainly through STSMs. These exchanges specifically contributed to the scientific objectives of InDust, at the same time allowing the Grantees to learn new techniques, gain access to specific data, instruments and/or methods not available in their own institutions/organizations. Several researchers took the opportunity of the STMS (https://cost-indust.eu/grants/grantees) and were able to submit several scientific articles proving fruitful collaborations (e.g. Gama *et al*. 2019; Gama *et al*. 2020; Kosmopoulos *et al.* 2018; Marmureanu *et al*. 2019).

Within InDust, cooperation with institutions from near-neighbouring and international partner countries in Northern Africa and the Middle East has proved to be essential and of mutual benefit. This is because dust concentrations are markedly higher there and the adverse effects more severe near the sources than far downwind. Moreover, the participation of South African, American and, importantly, Asian partners brought the possibility of extending the application of the developed products, protocols and tools well beyond European borders. Including areas such as Asian regions, where dust particles play a significant role in the air quality and meteorological processes, was beneficial for all communities.

Outcome

The primary outcomes of the network are the identification of the needs of the user's communities and new dust-related products and services able to satisfy their needs. As a first result, the network has been working on a dust catalogue that includes an overview of the current available observations (ground-based and satellite) and model products. Moving towards the development of an open collaboration and discussion platform between scientists and users of dust-related products and services, a survey is being shared within different user communities. The results of the survey are helping us to better identify the primary needs of each particular socio-economic sector and, furthermore, the collaborations between the groups involved have been focused on the themes emerging from the survey.

The use of online models to predict airborne dust quantities for radiation calculations and cloud formation in numerical weather prediction models is being increasingly recognized as important to improve the accuracy of short-range weather forecasts (Baklanov *et al.* 2014) and air quality forecasts. Dust prediction faces a number of challenges owing to the complexity of the dust cycle (i.e. emission, transport and deposition, see Benedetti *et al.*, 2018). At the centre of the problem is the vast range of scales required to fully account for all of the physical processes related to dust emission, transport and deposition (i.e. time scales ranging from seconds to weeks). Another limiting factor is the paucity of suitable dust observations available for model developments, evaluation and assimilation, particularly over desert dust sources (Mona *et al.* 2020). Recent years have seen a considerable increase in the number and complexity of dust models used both for research and for operational purposes. Due to the increase in computer power, these models can be run at higher spatial resolutions to allow for investigations of smaller-scale meteorological processes (<5 km), such as the effects of cold outflows from thunderstorms on dust emission (i.e. haboobs, see Vukovic *et al.* 2014; Heinold *et al.* 2013; Solomos *et al.* 2018). Additionally, high-resolution model maps (<1 km) of sources are capable of recognizing dust hotspots, which in many cases have larger aerosol emissions than the other dust-productive areas. At the same time, there have been some new approaches to treating emission processes in the models at high resolution (Kok 2011; Klose and Shao 2016) as well as to including soil mineralogy

(Nickovic *et al*. 2012) and more refined size distribution parametrizations (Ryder *et al*. 2013), to better characterize varying conditions in source regions.

Coordinated work has led to better understanding of the interactions between aerosols and atmospheric processes and is thus contributing to reducing the uncertainties in modelling the chemical composition of the atmosphere and in the quantification of the direct and indirect radiative forcing attributed to natural aerosols (Granados-Munoz *et al*. 2019; Gkikas *et al*. 2018, Nickovic *et al*. 2018). Within the air quality community, there are ongoing discussions about the methodologies currently available to quantitatively report on contributions of this natural source to ambient particulate matter levels in Europe, in compliance with the EU Air Quality Directive (2008/50/CE). A matter of discussion is also how the dust forecasting models can help in the design of early warning systems (Solomos *et al*. 2018; Gama *et al*. 2019; Gama *et al*. 2020; Marmureanu *et al*. 2019; El-Nadry *et al*. 2019; Wenzhao *et al*. 2019). Mei *et al*.'s (2020) article bridges the gap between the dust modelling communities and the providers of satellite dust observations, improving data quality and ensuring data standards compliance. Gama *et al*. (2019) did a performance assessment of CHIMERE and EURAD-IM' dust modules, while Konsta *et al*. (2018) provides an analysis of the CALIPSO limitations and uncertainties on the detection of strong dust activity, contributing to the differences between the simulations (regional dust model BSC-DREAM8b) and observations above the dust sources of Bodelé and Algeria.

InDust research activities have been extended far behind the main desert areas of the world into the high latitudes and Polar Regions. Such regions respond to dust impacts to a greater extent than lower latitude regions, through interactions with the cryosphere and fragile ecosystems, which have effects on climate.

On the other side, tailored tools developed within InDust help users to exploit the positive impacts of dust information.

For aviation, all efforts are in the development of early warning systems for hazard alerting, and potentially reducing the impact of dust on air traffic and management (e.g. Papagiannopoulos *et al*. 2020).

For solar energy, Kosmopoulos *et al*. (2018) showed that under extreme dust conditions, daily energy losses can reach 60%. Such reductions can cause financial losses that exceed daily revenue values. The estimates of the impact of dust aerosols were based on reductions of surface solar radiation and solar energy in Egypt, based on Earth Observation (EO) related techniques. Soiling due to aerosol particles (mainly dust) challenges CSP plant operators to find the optimized cleaning strategy of the solar field. Low mirror cleanliness and revenues have to be balanced against higher cleaning costs, field efficiencies and water consumption. Kishcha *et al*. (2020) use a dust regional model to understand the negative effects of dust deposition on the performance of solar panels and on insulator flashover in the Israeli power electric network. Terhag *et al*. (2019) discussed the optimization potential of cleaning strategies based on dust aerosol particle induced soiling rate forecasts.

For health, Tobias and Stafoggia (2020) reviewed the exposure metric used to investigate the health effects of desert dust. Dust exposure can be defined using a binary metric and comparing the number of health events between days with and without dust events. Alternatively, dust exposure can be defined with a continuous metric quantifying the amount of mineral dust during those days with dust events and quantifying its association with the health outcome. Thus, the apparently simple question 'does desert dust impact human health?' requires a careful definition of what is the relevant dust exposure of interest and how such effects can be quantified, to identify and understand which health effects are plausible. The InDust scientists have proposed a general standardized modelling approach for investigating the short-term effects of desert dust on human health, in and near hotspots, which would allow more consistent evidence on the health effects of desert dust in future studies.

Conclusions

A large number of scientists (250) from (45) countries are working together in order to:

- enhance the collaboration among scientists, data providers and interdisciplinary end users of aerosol dust;
- find new ways to link measurements and modelling of airborne dust and its effects on climate, the environment and other socioeconomic sectors;
- work on transferring scientific knowledge about dust observation and modelling from top research institutes to various scientists and dust users from different countries;
- collaborate on publishing a number of scientific papers on airborne dust science and effects (ten papers in 2 years)

Remote areas in Europe, such as deserts at high latitudes, gain great support in dust research and monitoring through InDust, while InDust includes them as important and full partners in global dust monitoring and forecasting. This multidisciplinary network, funded by the EU COST action programme, definitely improves scientific progress due to an increase of the research into the impact of dust in different socioeconomic sectors which benefits policymakers, public decision-makers and the private sector. It also contributes to the strengthening of European research and innovation capabilities in an international context.

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