Interactive comment on “Predicting cloud ice nucleation caused by atmospheric mineral dust” by Slobodan Nickovic et al. Anonymous Referee #1

General Comment:
My main concern is that at this stage the authors compare model ice nuclei with observations of ice water path which are not directly comparable. It would be more appropriate to calculate the corresponding modeled cloud properties and use them for model evaluation. Model results with the old version of the model should be also presented for comparison.

We agree, it would be more appropriate to compare the model against the observed cloud ice. However, in the current stage of our work, we do not predict the cloud ice but calculate the ice nuclei concentration \( n_{IN} \) and therefore compared \( n_{IN} \) against the observed ice water. Although the two variables are not directly comparable as the Referee #1 correctly noticed, they are linked through the continuity equation for cloud ice and we assumed the two variables should be correlated. Our results indeed confirm that \( n_{IN} \) in general well compares against the observed cloud ice water.

In our next paper which will represent as continuation of the current study, we will use \( n_{IN} \) as a prognostic input in the cloud microphysics scheme of our dust-atmosphere modelling system. Based on above considerations, we propose to the Editor replacement of the current manuscript title with: ’Cloud ice caused by atmospheric mineral dust - Part 1: Parameterization of ice nuclei concentration in the NMME-DREAM model’. This also takes into account the Referee’s suggestion in his/her first Specific Comment to change the article title. The second part of the current in that case will be a paper titled as: ’Cloud ice caused by atmospheric mineral dust - Part 2: Parameterization of ice water in the NMME-DREAM model’.

Specific Comments:
Page2, Line 28: To our knowledge, this is the first time that all ingredients needed for cold cloud formation by dust are predicted in the operational forecasting mode within one modeling system. Please provide more support for this statement since a variety of coupled dust-ice models seem to be already available (e.g. Zhang et al., 2012; Liu et al., 2012; Atkinson et al., 2013).

This is true there are numerous coupled dust-ice models. Articles the suggested by the Referee #1 (Zhang et al., 2012; Liu et al., 2012; Atkinson et al., 2013) are focused on studying nucleation effects in general, rather than on using dust-ice parameterization to improve numerical weather prediction. For example, \( n_{IN} \) is not online prognostic variable in none of the operational dust models within the largest two international dust forecasting projects: the WMO Sand and Dust Warning and Assessment System https://www.wmo.int/pages/prog/arep/wwrp/new/Sand_and_Dust_Storm.html; and the ICAP Multi-Model Ensemble (ICAP-MME) http://icap.atmos.und.edu/; Sessions et al, 2015). Differently from those dust models, we perform prediction of \( n_{IN} \) at every model time step to be used as input to a microphysics scheme.

We added in the text the following clarification:

... Such new parameter will be used in our future study as an input to a microphysics scheme, expecting improve the operational prediction of cold clouds and associated precipitation. Currently, \( n_{IN} \) is not used as online prognostic variable in eider of the operational dust models of two largest
international dust forecasting networks: in the WMO Sand and Dust Warning and Assessment System (SDS-WAS) (://www.wmo.int/pages/prog/arep/wwrp/new/Sand_and_Dust_Storm.html) and in the ICAP Multi-Model Ensemble (ICAP-MME) (http://icap.atmos.und.edu/ ). Unlike dust models of these networks, our modelling system predicts \( n_{\text{IN}} \) at every model time step which will be used as input to a microphysics scheme in the study of our forthcoming paper...

Page 4, Line 14 : In this study, dust concentration, atmospheric temperature and moisture as predicted by the atmospheric component of the coupled model are used to calculate. The parameterization consists of two parts applied to warmer and colder glaciated clouds. The vertical wind component is a crucial parameter for CCN/IN activation processes. Do you consider \( w \) in your calculations?

We wanted to implement the most recent parameterizations available in the community for dust-induced IN (DeMott et al., 2015; Steinke et al., 2015). These schemes require temperature, relative humidity and dust concentration as input parameters, but not vertical velocity. We added the following text:

The schemes of DeMott et al. and Steinke et al. require temperature, relative humidity and dust concentration as input parameters, but not vertical velocity as it is used in some other microphysical schemes (e.g. Wang et al, 2014).

Page 5, Line 20: to identify the different aerosol types (Papagiannopoulos et al., 2015) taking advantage of the large number optical properties they are able to provide, i.e. lidar ratio at two wavelengths, the Angstrom exponent, the backscatter-related Angstrom exponent, and linear particle depolarization ratio. This aerosol typing capability allows to classify the aerosol type acting Nin, and especially to separate mineral dust from other types of aerosol Please add Papagiannopoulos et al., 2015 in your Reference list. Also check carefully your references and edit your list in ACP format.

The reference by Papagiannopoulos et al. has been replaced by the following two as more appropriate:


Page 6, Line 15: The model resolution has been set to 25km in the horizontal. Could you please justify how you resolve cloud-scale features at this resolution?

We added the following text as a clarification:

At the horizontal model resolution used in our study (which relates to the hydrostatic type of thermodynamics), clouds are resolved by the following schemes: the parameterization of grid-scale clouds and microphysics (Ferrier et al., 2002); and the parameterization of convection clouds (Janjić, 1994, 2000).
Page 7, Line 4. On the other hand, a visual inspection shows considerable similarity between NL and the IWPL patterns (columns (B) and (C)) with respect to their shapes and locations. These two quantities are not directly comparable. Could you please show what is the NMME predicted IWP? Also show the difference between the control run (without IN parameterization) and the new run.

See please above our reply to the General Comment of the Referee #1

Figure 2. If I interpret correct the plots in Figure 2, it seems that the model predicts IN even at areas without dust. If your only aerosol source is dust (Eq.1, Eq.2) could you please explain more on this?

We think the Referee #1 is reporting to Figure 1, not to Figure 2. Figure 1 shows maps of dust C and IN integrated vertically (columns A and B respectively). The maps for same valid times indeed do not fully match because C and IN are not linearly proportional (Eq.1, Eq.2), neither their loads. However, according to Eq.1 and Eq.2 even for small C concentration there is some $n_{IN}$ if thermodynamic conditions permit it. With the used color palette scales in maps, load of small dust concentrations cannot be shown even if $n_{IN}$ is displayed.

Page 7, Line 29: The forecasts are translated horizontally over the observations until the minimum squared error (MSE) is achieved Please explain.

Figure 3 was referred by mistake to the CRA method instead to the Method for Object-based Diagnostic Evaluation - MODE. We added in the article the following correct explanation:

Additional evidence on matching between our forecasts and satellite observations has been made by applying the Method for Object-based Diagnostic Evaluation - MODE (Davis et al., 2006a; 2006b; 2009) which is based on a fuzzy-logic algorithm and which has been originally developed to quantify the errors related to spatial patterns and location of precipitation which considers various attributes of rain patterns (e.g. orientation, rain area). Factors as the separation of the object (pattern) centroids, minimum edge separation between modeled and observed patterns, model/observed patterns orientation angles relative to the grid axis, the ratio of the areas of the two objects, and the fraction of area common to both objects. MODE is used here to indicate the level of matching between NL and IWPL for a selected day of 11 May 2010. Figure 3 shows that MODE has identified three precipitation objects: two (green and red colored) showing good matching, and one (blue) with no matching.

Page 8, Line 8: Anyhow, in order to predict IWC we need to incorporate predicted Nin into a cloud microphysics scheme, which is a future task of our project. Therefore, the comparison using a semi-quantitative approach is the only available at the current stage of the analysis. Why don’t you incorporate the NMME microphysics scheme? Please show also the modeled IWC.

See please above our reply to the General Comment of the Referee #1. Incorporating the NMME microphysics scheme will be the subject of the forthcoming Part 2 of the paper, as we have indicated above.
Page 8, Line 14: Most of the ice, observed by the cloud radar below 4.0-4.5 km above ground level (AGL), is not predicted by the model. Is there any dust at these layers? If there is no dust in the model and your only IN source is dust, this could make sense.

*IN could be absent not only because dust missing but also because the other, thermodynamic conditions are not fulfilled. However, we assume that IN for lower mixed clouds is predicted because the DeMott scheme could not be extrapolated for T warmer than -36°C. See please also our detailed answer to the similar question of the Referee #2 on the same issue.*

Page 8, Line 23: Moreover, like for the case of May 2010, the model tends to under-predict the lowest ice water layers observed with the radar below 4.5 km AGL. Again it is a little confusing when you refer to IN and when you refer to ice water. Also to me it looks like there is no IN below 6km which means that the model fails to represent half of the clouds in this cross-section.

*We made corrections to avoid confusion when using model IN and ice water (following the Referee’s comment). We also included discussion addressed to the fact that the model failed to represent lower cold clouds.*

Inability of the model to predict $n_{IN}$ at lower elevations can be explained by the fact that the DeMott et al. (2015) parameterization is valid for temperatures in the interval (-20°C – -36°C). We extended this scheme to work in the interval (-5°C ; -20°C) as well but our experiments showed that lower mixed clouds could not be predicted. This result is consistent with the statement of DeMott et al. (2015) that the parameterization is weakly constrained at temperatures warmer than -20°. As these authors also claimed, this is the temperature regime that may be dominated by organic ice nucleating particles such as ice nucleating bacteria, which is aerosol not included in our parameterizations.

Page 8, Line 27 and Figure 5 caption. Replace upper and lower panel with left and right

*We did it.*

Page 9, Line 18: On the contrary, in South Italy, the volcanic layer, observed at Potenza up to an altitude of about 8 km above sea level Please provide some evidence for this argument

The paragraph at page 9 has been modified by citing the sources that can provide the requested evidence for this argument. The information has been extended also to match the most recent published version of the lidar analysis of the observation collected in 2010 freely available in the relational database at [www.earlinet.org](http://www.earlinet.org), which extend the content of the local analysis performed at the CIAO EARLINET station in Potenza to the results achieved by the whole EARLINET at the European scale. This database contains all information about volcanic layers (base, top, center of mass) and correspondingly mean and integrated values. According to what discussed above, the new paragraph has been modified as follows:

*In the period between 13-15 May 2010, both DREAM and back trajectories analysis showed that, while the transport of volcanic aerosol from Iceland (due to the Eruption of volcano Eyjafjalla 2010) was still ongoing, dust contribution was not negligible (Mona et al., 2012). In this period, the*
volcanic aerosol was mainly transported across the Atlantic Ocean, passing over Ireland and west UK, and then transported to the west off the Iberian Peninsula before reaching the Mediterranean Basin and Southern Italy. Satellite images and ground-based measurements confirmed the presence of volcanic particles in the corresponding regions (not shown). A detailed description of the volcanic layers as observed by EARLINET (European Aerosol Research Lidar NETwork) during this period is reported in Pappalardo et al., 2014. EARLINET volcanic dataset is freely available at www.earlinet.org (The EARLINET publishing group 2000-2010; (2014): EARLINET observations related to volcanic eruptions (2000-2010); World Data Center for Climate (WDCC). http://dx.doi.org/10.1594/WDCC/EN_VolcanicEruption_2000-2010). Moreover a devoted relational database freely available at www.earlinet.org contains all information about volcanic layers (base, top, center of mass) and correspondingly mean and integrated values.

The Iberian Peninsula, France and South Italy were the regions more significantly affected by the presence of volcanic aerosol (sulphate and small ash) during the considered period. For the purpose of our modelling study this might induce an underestimation of the IN (since IN due to dust only is modeled) in the above mentioned regions and can be responsible of part of the discrepancies between modeled IN and IWP provided by SEVIRI. This is particularly true for Iberian Peninsula where volcanic aerosol concentrations were quite relevant. The comparison of model predicted IN and SEVIRI IWC on 13 May shows differences that might be correlated to a larger availability of IN of volcanic origin.

On the contrary, in South Italy, the volcanic layer, observed at Potenza up to an altitude up to 15.8 km above sea level, did not enhance the formation of cold clouds due to unfavourable dry conditions in the free troposphere; this is also confirmed by the Potenza cloud radar which did not observed? clouds for the whole day (Figure 4). The absence of cold clouds over most of South Italy, including Potenza region, is also shown by the IWC reported for 13 May in Figure 1.

Page 9 Line 20: did not observed? Typo - observe

Page 9, Line 29 : The model has been validated .Avoid the use of the term validation (here and elsewhere in the text) since you are only referring to specific case studies. A validation process would require much more comparisons with observations and for a much longer time period until the model could be verified to produce validated products.

Page 9, Line 32: wormer negative temperatures Typo - warmer

Page 10, Line 6: What do you mean by “unified modelling system”

The word 'unified' is redundant and we removed it.

Throughout the text Please check again the text for grammar and spelling and provide an improved manuscript.
We made effort and improved the language with the assistance of a native English colleague.

References


Interactive comment on “Predicting cloud ice nucleation caused by atmospheric mineral dust” by Slobodan Nickovic et al. Anonymous Referee #2

Page 2 line 28: To our knowledge, this is the first time that all ingredients needed for cold cloud formation by dust are predicted in operational forecasting mode within one modeling system. Please give more evidence.

Please see our reply to the General Comment of the Referee #1

Page 4 line 25: The spread of errors in predicting IN concentrations at a given temperature has been reduced from a factor of 1000 to 10. Please give some evidence or support for this conclusion.

This statement is based on results shown Fig 3 in DeMott et al (2010); see the reference below. The spread of predicted/observed $n_{IN}$ points range from 0.001 to 10 (L$^{-1}$) in the older approach of Meyers et al. (1992); in the DeMott et al (2010) article, it ranges approximately from 0.001 to 0.1 (L$^{-1}$). We introduced in the article corresponding reference of DeMott et al, 1010.

Page 4 line 29: Why do you choose -5°C, since the underlying measurements were taken at temperatures lower than -9°C. Moreover, you set the temperatures for C1 warmer clouds range -36°C to -10°C (page 4 line 17 ). Please give more discussion.

Page 8 line 14-15: Why the model can’t predict the ice below 4-4.5km while the cloud radar can detect? Due to the temperatures you set in section 2.3 (-10 – -36°C), the vertical distribution of dust aerosols, or any other reason? You should give more discussion.

Although the DeMott et al. (2015) parameterization is for temperatures (-20°C – -36°C) we extrapolated their scheme to work in the interval (-5°C – -20°C) as well, with intention to include prediction of the occurrence of warmer mixed clouds. Our experiments however showed that the scheme could not predict such clouds. Probable reason for that is that the parameterization is weakly constrained at temperatures at temperatures warmer than -20°C as stated by DeMott et al. (2015). As these authors claimed, this is the temperature regime that may be dominated by organic ice nucleating particles such as ice nucleating bacteria. In the article we added the following text:

Inability of the model to predict $n_{IN}$ at lower elevations can be explained by the fact that the DeMott et al. (2015) parameterization is valid for temperatures in the interval (-20°C – -36°C). We extended this scheme to work in the interval (-5°C ; -20°C) as well but our experiments showed that lower mixed clouds could not be predicted. This result is consistent with the statement of DeMott et al. (2015) that the parameterization is weakly constrained at temperatures warmer than -20°. As these authors also claimed, this is the temperature regime that may be dominated by organic ice nucleating particles such as ice nucleating bacteria, which is aerosol not included in our parameterizations.
Dust is ice nucleation active surface linked to dust concentration. As we know that dust aerosols lifted to the mid and upper troposphere can serve as ice nuclei, here you use the surface value of dust. Will it affect the model results?

We wish to clarify that surface is not addressed to the dust concentration on surface but to the ice-active surface site density $S_{\text{dust}}$ [m$^{-2}$] (see also the definition of $S_{\text{dust}}$ in e.g. Connolly et al., 2009; Niemand et al., 2012). $S_{\text{dust}}$ describes the ability of a dust particle to freeze the cloud water. We added a clarification in the text.

In our IN modelling, we transit from DeMott et al., (2015) to Steinke et al., (2015) parameterization at $T= -36^\circ$C. Although one might expect some discontinuity to occur at this transitional temperature threshold, in practice a rather continuous behavior of $n_{\text{IN}}$ at this boundary has been achieved, thus not additional smoothing has been required. The following clarification has been introduced in the article in response to the Referee’s request:

Although based on two different parameterizations, the resulting $n_{\text{IN}}$ has a smooth transition across the temperature boundary of -36°C between DeMott et al. (2015) and Steinke et al. (2015) schemes. At this transitional temperature, we have not applied any mathematical smoothing.

The paragraph 1 on section 3 has been extended in the new version of the manuscript to provide a more detailed description of the ground based instruments employed in the presented study. The new paragraph is reported below for your convenience:

The model capabilities to predict vertical features of dust and cold clouds have been evaluated using vertical profiles of the aerosol and cloud properties routinely measured at the CNR-IMAA Atmospheric Observatory (CIAO) at Tito Scalo (Potenza), Italy, using several ground-based remote sensing techniques, such as lidar, radar and passive techniques. MUSA (Multiwavelength System for Aerosol) is a mobile multi-wavelength lidar system based on a Nd:YAG laser equipped with second and third harmonic generators and on a Cassegrain telescope with a primary mirror of 300 mm diameter. The three laser beams at 1064, 532 and 355nm are simultaneously and coaxially transmitted into the atmosphere in biaxial configuration. The receiving system has 3 channels for the detection of the radiation elastically backscattered from the atmosphere and 2 channels for the detection of the Raman radiation backscattered by the atmospheric N2 molecules at 607 and 387 nm. The elastic channel at 532 nm is split into parallel and perpendicular polarization components by means of a polarizer beam-splitter cube. The calibration of depolarization channels is made automatically using the ±45 method. The typical vertical resolution of the raw profiles is 3.75 m with a temporal resolution of 1 min. It is worth to stress that multi-wavelength Raman lidar measurements allow the user not only to monitor the dynamical evolution of aerosol particles in the troposphere, but also to identify the different aerosol types (Burton et al., 2013; Groß et al., 2015) taking advantage of the large number of optical properties they are able to provide, i.e. lidar ratio at two wavelengths, the Angstrom exponent, the backscatter-related Angstrom exponent, and linear particle depolarization ratio. This aerosol typing capability allows the user to classify the aerosol type acting $n_{\text{IN}}$, and especially to separate mineral dust from other types of aerosol.

CIAO, as one of the Cloudnet stations (www.cloud-net.org), applies the Cloudnet retrieval scheme to provide vertical profiles of cloud types. Cloudnet processing is based on the use of
ceilometer, microwave radiometer and cloud radar observations. For the CIAO station (Madonna et al., 2010; Madonna et al., 2011), the Cloudnet processing involves observations provided by the VAISALA CT25k ceilometer, the Radiometrics MP3014 microwave profiler, and the METEK millimetre-wavelength Doppler and polarimetric cloud radar MIRA36. In particular, MIRA36 is a mono static magnetron-based pulsed Ka-Band Doppler radar for unattended long term observation of clouds properties. In the configuration operative at CIAO, linear polarized signal is transmitted while co- and cross polarized signals are received simultaneously to detect Doppler spectra of the reflectivity and Linear Depolarization Ratio (LDR). The reflectivity is used to determine the density of cloud constituents while LDR helps to identify the target type. The radar has a 1 m diameter antenna and emits the microwave radiation at 35.5 GHz with a peak power of 30 kW, a pulse width of 200 ns and a pulse repetition rate of 5 KHz. The antenna beam width is 0.6° x 0.6° (gain 49 dBi) and the radar sensitivity is -40.3 dBZ at 5 km (0.1 sec time resolution) while the Doppler velocity resolution is 0.02 m/s. The linear depolarization ratio (LDR) accuracy is within +/- 2.0 dB. The receiver calibration is within an accuracy of less than +/- 1 dB. This system is able to provide high accurate measurements of the reflectivity factor with a vertical resolution up to 15 m, though the current configuration is set to a vertical resolution of 30 m. The radar is a 3D scanning system, but Cloudnet processing makes use of zenith pointing observations only.

Finally we add that the reference reported in the paragraph by Papagiannopoulos et al. has been replaced by the following two because more appropriate:


Page 8 line 27: The position for the pictures in Fig.5 should be left and right.
Corrected

Page 9 line 20: there is a redundant question mark.
Corrected

Figure 1: The color bar and coordinate are unclear. The compared results for the second case should also be given and discussed.

We replaced the figure with its vector image format in which the color bar can be checked by enlarging the image.

Comparison against SEVIRI for the second case: We did not include comparison model NL against SEVIRI IWPL because unfortunately EUMETSAT CN SAF products are available for the period (2009-01-01 - 2012-02-29) and do not cover September 2012. See: https://wui.cmsaf.eu/safira/action/viewProduktDetails?id=11467_14338_16270_16283_16906
Figure 3: Please give the meaning for each color and the title for x-y coordinate.

*We added the explanation for the meaning of each color and the meaning of x-y coordinate.*

Figure 5: For the first case, the mean values of IWPL are mainly greater than NL. However, for the second case, the mean values of IWPL are mainly less than NL. Please give more discussion.

*IWPL vs. NL: This is due to our mistake in inserting wrong image on the right, see graphs below which are now correctly included in the article.*

![Graph 1](image1)

![Graph 2](image2)

There are some research discuss dust aerosols effect on clouds and precipitation, please discuss more about the relationship between dust and clouds in Section 1.

*The following was added in reply to the Referee's request.*

Another study indicates that desert dust has the ability to glaciate the top of developing convective clouds, creating ice precipitation instead of suppressing warm rain; also dust invigoration effect would enhance precipitation (Rosenfeld et al., 2008). On the other hand, Teller et al. (2012) conclude from their modelling study that the presence of mineral dust had a much smaller effect on the total precipitation than on its spatial distribution, which indicates that quantification of dust effects to precipitation is still uncertain because dust could modify cloud properties in many complex ways (Huang et al., 2014); therefore impacts of dust on cloud processes requires further research.

**References:**


Cloud Predicting cloud ice nucleation caused by atmospheric mineral dust - Part 1: Parameterization of ice nuclei concentration in the NMME-DREAM model

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Keywords
ice nucleation, model parameterization, dust aerosol

Abstract
Dust aerosols are very efficient ice nuclei, important for heterogeneous cloud glaciation even in regions distant from desert sources. A new generation of ice nucleation parameterizations, including dust as ice nucleation agent, opens the way towards a more accurate treatment of cold cloud formation in atmospheric models. Using such parameterizations, we have developed a regional dust-atmospheric modelling system capable of predicting in real-time conditions dust-induced ice nucleation. We executed the model with the added ice nucleation component over the Mediterranean region, exposed to moderate Saharan dust transport over two periods lasting 15 and 9 days, respectively. The model results were compared against satellite and ground-based cloud-ice-related measurements, provided by SEVIRI (Spinning Enhanced Visible and InfraRed Imager) and by the CNR-IMAA Atmospheric Observatory CIAO in Potenza, South Italy. The predicted ice nuclei concentration showed a reasonable level of agreement when compared against the observed spatial and temporal patterns of cloud ice water. The developed methodology permits the use of...
Ice nuclei as input into the cloud microphysics schemes of atmospheric models, expecting that this approach could improve the predictions of cloud formation and associated precipitation.

1 Introduction

Aerosols acting as ice nucleating particles enhance the heterogeneous glaciation of cloud water making it freeze earlier and at higher temperatures than otherwise. Insoluble particles, such as dust and biological particles, are known as the best ice nuclei. Cziczo et al (2013), hereinafter referred to as CZ13, show that mineral dust and metallic oxide particles, found as residues in the ice crystals of aircraft measurements over North and Central America, are prevailing (61%). Concerning the other aerosol types, CZ13 show that in such regions distant from dust sources, sea salt is represented only with 3% in the regions away from the open ocean, whereas elemental carbon and biological particles represent with less than 1%. Furthermore, CZ13 demonstrate that the dominant ice nucleation (IN) is the heterogeneous immersion process in 94% of the collected samples. During IN, only a small number of dust particles, a few in a standard litre, is sufficient to trigger the cloud glaciation process at temperatures lower than -20°C (DeMott et al., 2015, 2010). Since dust in small concentrations is easily lifted to the mid- and upper troposphere, the cold clouds formed due to dust can be found at locations distant from dust deserts (Creamean et al., 2013; CZ13).

Mineral dust particles as seen have a significant impact on IN and on associated with the cloud formation and precipitation (Sassen, 2005; DeMott et al., 2003; Yakobi-Hancock et al., 2013). For example, the measurement of ice residues from in-situ cold cloud samples and precipitation measurements collected in California strongly suggest that the non-soluble aerosol originating from the Asian and Saharan dust sources (dust and biological aerosol) enhance both ice formation in mid-level clouds and precipitation (Ault et al., 2011; Creamean et al., 2013). Recent modelling experiments confirm that in the pristine environment dust and biological aerosols could increase the precipitation as well (Fan et al., 2014). In this process, there is little influence of dust chemical aging (DeMott et al., 2015). Another study indicates that desert dust has the ability to glaciate the top of developing convective clouds, creating ice precipitation instead of suppressing warm rain; also dust invigoration effect would enhance precipitation (Rosenfeld et al., 2008). On the other hand, Teller et al. (2012) conclude from their modelling study that the presence of mineral dust had a much smaller effect on the total precipitation than on its spatial distribution, which indicates that quantification of dust effects to
precipitation is still uncertain because dust could modify cloud properties in many complex ways (Huang et al., 2014); therefore impacts of dust on cloud processes requires further research (DeMott et al., 2015).

The large interest in ice nucleation research, illustrated by the exponential growth of published articles in this field (DeMott et al., 2011) has been motivated, inter alia, by the needs of the community to improve the unsatisfactory representation of cloud formation in atmospheric models, and therefore to increase the accuracy of weather and climate predictions. Older parameterizations (Fletcher, 1962; Meyers et al., 1992) considered the concentration of ice nuclei concentration ($n_{IN}$) only as a function of the temperature and ice saturation ratio, $n_{IN}$.

More recent observations, however, show that at a given temperature and moisture, $n_{IN}$ depends on aerosol concentration as well. Based on this evidence, a new generation of $n_{IN}$ parameterizations has been developed (DeMott et al., 2010; Niemand et al., 2012; Tobo et al., 2013; Phillips et al., 2013; Atkinson et al., 2013; DeMott et al., 2015), where dust is recognized as one of the major $n_{IN}$ input parameters, in which $n_{IN}$ represents the fraction of dust aerosol capable to produce cloud water ice, $n_{IN}$.

Exploiting these findings, we have developed a coupled regional real-time forecasting atmosphere-dust forecasting system (composed of the atmospheric NMME model and DREAM dust model) which predicts dust-caused $n_{IN}$ affected by dust as an online model variable. When parameterizing $n_{IN}$, the new component represents a step towards operational cold clouds prediction and associated precipitation. To our knowledge, this is the first time that all ingredients needed for cold cloud formation by dust are predicted in operational forecasting mode within one modeling system. For this study, immersion and deposition modes of freezing have been assumed to drive the dominant for ice formation process. Such new parameter will be used in our future study as an input to a microphysics scheme, expecting improve the operational prediction of cold clouds and associated precipitation. Currently, $n_{IN}$ is not used as online prognostic variable in either of the operational dust models of two largest international dust forecasting networks: in the WMO Sand and Dust Warning and Assessment System (SDS-WAS) (http://www.wmo.int/pages/prog/arep/wrp/new/Sand_and_Dust_Storm.html) and in the ICAP Multi-Model Ensemble (ICAP-MME) (http://icap.atmos.und.edu/). Unlike dust models of these networks, our modelling system predicts $n_{IN}$ at every model time step which will be used as input to the microphysics scheme in the study of our forthcoming paper.

The model description and the implemented $n_{IN}$ parameterizations are presented in Section 2. The observations used for the model evaluation and the model performance are presented in Section 3. The comparisons of model simulations against observations are described in Section 4. Conclusions are given in Section 5.
2 Modelling

The evidence on the dominant role of dust in cold cloud formation has motivated a number of research groups to link cloud microphysics schemes with the parameterizations of dust-affected $n_{IN}$ in atmospheric models. Atmospheric models which drive ice nucleation parameterizations are ranging from simplified 1-D and 1.5-D kinematic or trajectory models (Field et al., 2012; Eidhammer et al., 2010; Dearden et al., 2012; Simmel et al., 2015), to complex full atmospheric models (e.g. Niemand et al., 2012; Thompson and Eidhammer, 2014). However, only a few such models (used in weather and/or climate applications) have dust concentration as a forecasting parameter available for online $n_{IN}$ calculation. For example, in a dust event study Niemand et al., (2012) studying a dust event, used the temperature and dust particle surface area predicted by the regional-scale online coupled model COSMOART (Consortium for Small-Scale Modelling–Aerosols and Reactive Trace Gases) to calculate immersion freezing $n_{IN}$. The model has been compared against observations validated only for a dust case episode, using the chamber-processed $n_{IN}$ calculated from the ground-based aerosol concentration measurements, but not against directly observed cloud ice measurements. Furthermore, Hande et al. (2015) have implemented the COSMO model coupled to the Multi-Scale Chemistry Aerosol Transport (MUSCAT) model to compute a seasonal variability of $n_{IN}$. However, this model has not been validated against daily observations. The limited observation datasets (covering only a few weeks). A model which gets close to the real-time forecasting of glaciated clouds is a ‘dust friendly’ version of the bulk microphysics scheme (Thompson and Eidhammer, 2014), with explicitly incorporated dust aerosol. However, this model currently uses a climatological rather than predicted dust concentration for $n_{IN}$ calculations.

Following the objective of this study to develop a method for real-time $n_{IN}$ prediction, we have used the Dust Regional Atmospheric Model (DREAM) driven by the National Centers for Environmental Predictions (NCEP) Nonhydrostatic Multiscale atmospheric Model on the E grid (NMME) in which we have incorporated a parameterization of the ice nuclei concentration calculated at every model time step as a function of dust concentration and atmospheric variables. The predicted spatial and temporal distribution of $n_{IN}$ represents the fraction of dust aerosol capable to produce mass of cloud water ice due to dust.

2.1 NMME model

NMME (Janjic et al., 2001, 2010; Janjic, 2003) has been used for various applications at NCEP and elsewhere since the early 2000s. From 2006 it has been the main operational short-range weather forecasting North American Model (NAM). It is also used for operational regional forecasts in the Republic Hydrometeorological Service of Serbia. The NMME
dynamics core includes: energy/enstrophy horizontal advection; vertical advection; a nonhydrostatic add-on module; lateral diffusion; horizontal divergence damping; sub-grid gravity waves; transport of moisture and different passive tracers. Concerning the model physics, there are various optional modules: cloud microphysical schemes ranging from simplified ones suitable for mesoscale modelling to sophisticated mixed-phase physics for cloud resolving models; cumulus parameterizations; surface physics; planetary boundary layer and free atmosphere turbulence; and the atmospheric longwave and shortwave radiation schemes. NMME uses a hybrid vertical coordinate with a terrain-following sigma in the lower atmosphere, and a pressure coordinate in the upper atmosphere.

2.2 DREAM model

DREAM (Nickovic et al, 2001; Nickovic, 2005; 2006; Pejanovic et al, 2011) has been developed to predict the atmospheric dust process, including the dust emission, dust horizontal and vertical turbulent mixing, long-range transport and dust deposition. Eight radii bins in the model range from 0.15 µm to 7.1 µm. Dust emission parameterization includes a viscous sub-layer between the surface and the lowest model layer (Janjic, 1994) in order to parameterize the turbulent vertical transfer of dust into the lowest model layer following different turbulent regimes (laminar, transient and turbulent mixing). The wet dust removal is proportional to the rainfall rate. The specification of dust sources is based on the mapping of the areas that are dust productive under favourable weather conditions. The USGS land cover data combined with the preferential dust sources of dust originating from the sediments in paleo-lake and riverine beds (Ginoux et al., 2001) have been used to define barren and arid soils as dust-productive areas.

2.3 Ice nucleation parameterization

In this study, dust concentration, atmospheric temperature and moisture as predicted by the atmospheric component of the coupled model were used for $n_{IN}$ calculation. The $n_{IN}$ parameterization consists of two parts, applied to warmer and colder glaciated clouds.

For temperatures ranging in the interval (-36°C; -5°C), we have implemented the immersion ice nucleation parameterization developed by DeMott et al. (2015):

$$n_{IN} = C(n_{dust})^{(a(273.16−T)−β)} \exp(y(273.16−T)−d)$$ (1)

where $n_{IN}$ is the number concentration of ice nuclei [$1^{-1}$]; $n_{dust}$ is the number concentration of dust particles with a diameter larger than 0.5µm [$cm^{-3}$]; T is the temperature in Celsius degrees; $a = 0$; $β = 1.25$; $y = 0.46$; and $d = −11.6$. Equation (1) is applied when relative humidity with respect to ice is exceeding 100%. This parameterization scheme has been developed as an extension of DeMott et al. (2010) and Tobo et al. (2013), but applied exclusively to mineral dust $n_{IN}$ collected in laboratory and field measurements. With the DeMott et al. (2015) approach, the spread of errors in predicting IN concentrations at a given temperature has been reduced from the factor of ~1000 to ~10 (DeMott et al, 1010). Their parameterization is based on the use of observations from a number of field experiments at a...
variety of geographic locations over a period longer than a decade, demonstrating that there is a correlation between the observed $n_{IN}$ and the dust number concentrations of particles larger than 0.25 µm in radius. In DeMott et al. (2015), $C = 3$ is chosen as a calibration factor to adjust the scheme to dust measurements. Despite the fact that validity of the scheme is for underlying measurements were only taken at temperatures colder than -20°C, we extrapolated its application down to -5°C in order to test the model if it can predict the occurrence of lower mixed clouds for the temperatures range being out of the validity of the parameterization scheme than -9°C.

For temperatures ranging in the interval (-55°C; -36°C), we have implemented the Steinke et al. (2015) parameterization for the deposition ice nucleation based on the ice nucleation active surface site approach in which $n_{IN}$ is a function of temperature, humidity and the aerosol surface area concentration. In the deposition nucleation, water vapor is directly transformed into ice at the particle’s surface, occurring at the time of or shortly after the water condensation on the particle, which acts at the same time as a condensation and freezing nucleus. For deposition nucleation, water vapor is directly transformed into ice at the particle’s surface. Steinke et al. (2015) calculate the number concentration of ice nuclei due to deposition freezing as:

$$n_{IN} = pS_{dust} \exp[-q(T - 273.16) + (rRH_{ice} - 100)]$$

(2)

here $n_{IN}$ is the number concentration of ice nuclei [cm$^{-3}$]; $S_{dust}$ is the ice nucleation active surface site density [m$^{-2}$] linked to dust concentration (Niemand et al., 2012) describing the efficiency of a dust particle to freeze the cloud water; $p = 188 \times 10^5$; $q = -1.0815$; $r = -0.815$; $T$ is temperature in degrees Celsius; $RH_{ice}$ is relative humidity with respect to ice. In our experiments, $RH_{ice}$ is pre-specified to the value of 110%.

Although based on two different parameterizations, the resulting $n_{IN}$ has a smooth transition across the temperature boundary of -36°C between the DeMott et al. (2015) and Steinke et al. (2015) scheme, as our model results shown later demonstrate. Therefore, there was no need to numerically smooth $n_{IN}$ of the two schemes. At this transitional temperature, we have not applied any mathematical smoothing to secure appropriate matching.

The schemes of DeMott et al. and Steinke et al. require temperature, relative humidity and dust concentration as input parameters, but not vertical velocity as used in some other microphysical schemes (e.g. Wang et al., 2014).

3. Observations

The model capabilities to predict vertical features of dust and cold clouds have been evaluated using vertical profiles of the aerosol and cloud properties routinely measured at the CNR-IMAA Atmospheric Observatory (CIAO) at Tito Scalo (Potenza), Italy, using several ground-based remote sensing techniques, such as lidar, radar and passive techniques. MUSA (Multiwavelength System for Aerosol) is a mobile multi-wavelength lidar system based on a Nd:YAG laser equipped with second and third harmonic generators and on a Cassegrain telescope with a primary mirror of 300 mm diameter. The three laser beams at 1064, 532 and 355 nm are simultaneously and coaxially transmitted into the atmosphere in biaxial configuration. The receiving system has 3 channels for the detection of the radiation elastically backscattered from the
atmosphere and 2 channels for the detection of the Raman radiation backscattered by the atmospheric N2 molecules at 607 and 387 nm. The elastic channel at 532 nm is split into parallel and perpendicular polarization components by means of a polarizer beamsplitter cube. The calibration of depolarization channels is made automatically using the ±45 method. The typical vertical resolution of the raw profiles is 3.75m with a temporal resolution of 1 min. It is worth to stress that multi-wavelength Raman lidar measurements allow the user not only to monitor the dynamical evolution in the troposphere of the aerosol particles, but also to identify the different aerosol types (Burton et al., 2013; Groß/Papagiannopoulos et al., 2015) taking advantage of the large number of optical properties they are able to provide, i.e. lidar ratio at two wavelengths, the Angstrom exponent, the backscatter-related Angstrom exponent, and linear particle depolarization ratio. This aerosol typing capability allows the user to classify the aerosol type acting as an aerosol acting as a cloud, and especially to separate mineral dust from other types of aerosol.

CIAO, as one of the Cloudnet stations (www.cloud-net.org), applies the Cloudnet retrieval scheme to provide vertical profiles of cloud types. Cloudnet processing is based on the use of ceilometer, microwave radiometer and cloud radar observations. For the CIAO station (Madonna et al., 2010; Madonna et al., 2011), the Cloudnet processing involves observations provided by the VAISALA CT25k ceilometer, the Radiometrics MP3014 microwave profiler, and the METEK millimetre-wavelength Doppler and polarimetric cloud radar MIRA36. In particular, MIRA36 It is a mono-static magnetron-based pulsed Ka-Band Doppler radar for unattended long term observation of clouds properties. In the configuration operative at CIAO, linear polarized signal is transmitted while co- and cross polarized signals are received simultaneously to detect Doppler spectra of the reflectivity and Linear Depolarization Ratio (LDR). The reflectivity is used to determine the density of cloud constituents while LDR helps to identify the target type. The radar has a 1 m diameter antenna and emits the microwave radiation at 35.5 GHz with a peak power of 30 kW, a pulse width of 200 ns and a pulse repetition rate of 5 KHz. The antenna beam width is 0.6° x 0.6° (gain 49 dBi) and the radar sensitivity is -40.3 dBZ at 5 km (0.1 sec time resolution) while the Doppler velocity resolution is 0.02 m/s. The linear depolarization ratio (LDR) accuracy is within +/- 2.0 dB. The receiver calibration is within an accuracy of less than +/- 1 dB. This system is able to provide high accurate measurements of the reflectivity factor with a vertical resolution up to 15 m, though the current configuration is set to a vertical resolution of 30 m. The radar is a 3D scanning system, but for Cloudnet processing makes use of zenith pointing observations only.

Cloudnet processing provides the categorization of the observed vertical profiles of cloud water categories, such as liquid droplets, ice particles, aerosols and insects. This categorization is essentially based on different sensitivities of the lidar and radar to different particle size ranges. For layers identified as ice clouds, the ice water content (with the related uncertainty) is derived from radar reflectivity factor and air temperature using an empirical formula based on dedicated aircraft measurements (Hogan et al., 2005). Consistency between Cloudnet products and Raman lidar observations of clouds performed at CIAO has been also been examined (Rosoldi et al., 2016).

To complement the Potenza in-situ profiling observations and to examine how the model predicts horizontal distribution of cold clouds, the MSG/SEVIRI ice water path satellite observations were used. SEVIRI (the Spinning
Enhanced Visible and InfraRed Imager), as a geostationary passive imager (MSG) systems. The high SEVIRI spatial and temporal resolution (~4km and 15min, respectively), provides, among other advantages, high-quality products. The inputs to the retrieval schemes were inter-calibrated effective radiances of Meteosat-8 and 9. In our study, the daily averages of the retrieved ice water path of the SEVIRI cloud property dataset (CLAAS) were used (Stengel et al., 2013a; Stengel et al., 2013b) to validate the model results against there observations on the regional scale:

\[ IWP = \frac{2}{3} r I r_{eff} \tau \]

Here, IWP \([gm^{-2}]\) is the ice water path, \(\tau\) is the vertically integrated cloud optical thickness at 0.6µm derived in satellite pixels assigned to be cloud filled; \(r_{eff}\) is the surface-area-weighted radius of cloud particles [µm]; \(r_I = 0.93 \, g cm^{-3}\) is the ice water density.

4 Model experiments and validation

The model domain covers Northern Africa, Southern Europe and the Mediterranean. The model resolution has been set to 25km in the horizontal, and to 28 layers in the vertical ranging from the surface to 100hPa. At the horizontal model resolution (which relates to the hydrostatic type of thermodynamics), clouds are resolved by the following schemes: the parameterization of grid-scale clouds and microphysics (Ferrier et al., 2002), and the parameterization of convection clouds (Janjić, 1994, 2000). The initial and boundary atmospheric conditions for the NMME model have been updated every 24 hours using the ECMWF 0.5deg analysis data. The concentration was set to zero at the ‘cold start’ of DREAM launched 4 days before the period to be studied, thus permitting the model to be ‘warmed-up’, i.e. to develop a meaningful concentration field at the date considered as an effective model start. After that time point, 24-hour dust concentration forecasts from the previous-day runs have been declared as initial states for the next-day run of DREAM.

The coupled NMME-DREAM model has been run and validated against ground-based and satellite observations for two periods (1-15 May 2010, and 20-29 September 2012) during which the CIAO Potenza instruments have observed an occasional occurrence of Saharan dust accompanied with a sporadic formation of mixed-phase and/or cold clouds. These periods, characterized by modest rather than major dust transport into the Mediterranean, have been intentionally chosen to find out if non-intensive dust conditions can still form cold clouds.

For the May 2010 period, a detailed day-by-day comparison of the model against SEVIRI data is shown in Figure 1. It is important to mention that during the periods 8–9 May and 13–14 May, the Eyjafjallajökull volcanic cloud was also observed in Potenza (Mona et al, 2012; Pappalardo et al, 2013), thus potentially interfering with dust. Possible influence of the existing volcanic ash on our results is discussed later in the text.

Figure 1 shows the mapped daily averages of the following variables: the model vertical dust load (DL), the model NL = \(\log_{10} \int n_N dz\), the MSG-SEVIRI IWPL=\(\log_{10}(IWP)\), and the overlap of NL and IWPL; columns in the Figure showing these variables are marked by A, B, C, and D, respectively. From columns (A) and (B) in the Figure–1 one can...
observe a general lack of agreement between DL and NL. This difference is expected, since the cold cloud formation is dependent not only on dust but also on its complex interaction with the atmospheric thermodynamical conditions. On the other hand, a visual inspection shows a considerable similarity between NL and the IWPL patterns (columns (B) and (C)) with respect to their shapes and locations.

The maps in column (D) show how much the normalized NL and IWPL daily averages are overlapping. Hits, misses and false alarms are represented by areas shaded in blue, green and brown color, respectively. One can notice that the overlapping (hits) always represents the largest parts of the shown daily maps. Although not dominant, there are certain regions of cold clouds either observed but not predicted (misses), or predicted but not observed (false alarms). The former case should not necessarily be erroneous because it might be addressed the processes not represented by our parameterization: the clouds generated by homogeneous glaciation or the clouds made by heterogeneous freezing with aerosols other than dust.

To gain additional evidence on the matching between NL and IWPL, we used their normalized daily averages to calculate the following statistical dichotomous (yes/no) scores based on hits, misses and correct negatives (not predicted, not observed) (WMO, 2009):

- accuracy - showing what fraction of the forecasts were correct;
- probability of detection (hit rate) - showing what fraction of the observed "yes" events were correctly forecasted;
- the false alarm ratio - showing what fraction of the predicted "yes" events actually did not occur.

The scores were calculated using the values for all model/observation grid points and for all days of the considered period. Figure 2 shows the time evolution of the scores (which by definition range between 0 and 1). In average for the whole period, 63.4% of all NL were correct with respect to IWPL, 73.9% of the observed IWPL were predicted, and for 30.4% of the forecast NL, IWPL was not observed. Such result confirms a high matching level between two fields shown in Figure 1.

Additional evidence on matching between our forecasts and satellite observations has been made by applying the Method for Object-based Diagnostic Evaluation - MODE (Davis et al., 2006a; 2006b; 2009) which is based on a fuzzy-logic algorithm and which has been originally developed to quantify the errors related to spatial patterns and location of precipitation which considers various attributes of rain patterns (e.g. orientation, rain area). Factors as the separation of the object (pattern) centroids, minimum edge separation between modeled and observed patterns, model/observed patterns orientation angles relative to the grid axis, the ratio of the areas of the two objects, and the fraction of area common to both objects. MODE is used here to indicate the level of matching between NL and IWPL. for a selected day of 11 May 2010, Figure 3 shows that MODE has identified three precipitation objects: two (green and red colored) showing good matching, and one (blue) with no matching.

In order to additionally illustrate the level of matching between NL and IWPL, we have further selected one day of the considered May 2010 period to which we have applied the contiguous rain area (CRA) technique (Ebert and McBride,
2000; Ebert and Gallus, 2009) introduced in numerical weather prediction for verifying the accuracy of precipitation forecasts; the method is sufficiently general so that could be applied to other geophysical fields as well. To make CRA applicable for our analysis where there are two different physical variables, we use the normalized NL and IWPL whose patterns are compared. To match the forecast and observed entities within a CRA, the forecasts are translated horizontally over the observations until the minimum squared error (MSE) is achieved. The translation vector calculated by CRA represents the location error of the forecast. Finally, with user predefined thresholds of two compared entities, CRA decomposes MSE into three components: the displacement error, the volume error, and the pattern error. As an example of the CRA pattern matching, we show results of the technique applied to 11 May 2010 normalized daily averaged IWPL and NL fields (Figure 2). CRA recognizes two best matching pairs of entities (shaded in red and green colours), dominating over other smaller-scale patterns.

To evaluate the model performance in representing the vertical structure of the ice water clouds, we have compared with the observed IWC obtained using the Cloudnet retrieval scheme over Potenza. Figure 4 shows time evaluation of $\log_{10}(n_{IN} \cdot m_{w})$ (coloured shaded) and $\log_{10}(IWC \times 10^{-6} \text{ kg m}^{-3})$, (contour plotted) over periods 1-15 May 2010 and 22-30 September 2012. In addition, the red contours show the temperature field as provided by the NMME model. The different quantities provided by DREAM and Cloudnet to characterize the cloud ice content. Note that IWC, $n_{IN}$ are different physical variables and therefore a semi-quantitative comparison is possible, makes the comparison less punctual on a quantitative basis. Anyhow, in order to predict IWC we need to incorporate predicted $n_{IN}$ into a cloud microphysics scheme, which is a future task of our project. Therefore, the comparison using a semi-quantitative approach is the only available at the current stage of the analysis.

The comparisons reveal general good performances of DREAM in predicting the vertical structure of the observed ice clouds for temperatures below -20°C which coincides with the validity range of DeMott et al. (2015). Especially during Q1 1-15 May 2010, a remarkable agreement between patterns of the ice vertical layer retrieved using the cloud radar observation and the $n_{IN}$ predicted by the model is evident. However, noted, though the model underpredicts the vertical extent of the ice layer over most of the ice nuclei concentration for temperatures warmer than -20°C was not predicted, although mixed clouds were time series. Most of the ice, observed by the cloud radar below 4.0, 4.0-4.5 km above ground level (AGL), is not predicted by the model. This is particularly evident on 6 May when only ice cloud layer below 3 km AGL was observed only by the radar, and conditions for ice occurrence were but completely missed by the model.

On 22-30 September 2012 the model was able to indicate the deep ice layers observed on 25-27 September 2012 between about 5 and 12 km AGL (-10°C and -60°C) and it was able to partially predict a part of the thinner layers observed after 27 September above 7 km AGL (<-25°C). The model was also able to well-predict the occurrence of cirrus clouds observed by the cloud radar on 29 September in the range between 6 and 12 km. It is also worth to mention that the co-located and simultaneous Raman lidar measurements (not reported) showed some high optically thin cloudiness not detected by the radar because of its limited sensitivity to thin clouds at that height levels (Borg et al., 2013).
In particular, this is the $n_{IN}$ case of the layers predicted by the model in the second half of 27 September and on 28 September are in the range between 9 and 12 km. However, as in the case of May 2010, the model underpredicted $n_{IN}$ tends to underpredict the lowest ice water layers observed with the radar below 4.5 km AGL.

Inability of the model to predict $n_{IN}$ at lower elevations can be explained by the fact that the DeMott et al. (2015) parameterization is valid for temperatures in the interval (-20°C – -36°C). We extended this scheme to work in the interval (-5°C ; -20°C) as well but our experiments showed that lower mixed clouds could not be predicted. This result is consistent with the statement of DeMott et al. (2015) that the parameterization is weakly constrained at temperatures warmer than -20°C. As these authors also claimed, this is the temperature regime that may be dominated by organic ice nucleating particles such as ice nucleating bacteria, which is aerosol not included in our parameterizations.

In Figure 5 we also report the comparison of IWPL and NL over Potenza calculated every three hours, in the period from 1 to 15 May 2010 (left upper panel) and from 22 to 30 September 2012 (right lower panel). The outcome of the comparison confirms the good performance of the model in the prediction of $n_{IN}$ of the ice clouds over the whole atmospheric column.

The correlation between the IWPL and NL retrieved using the ground based measurements, merging the datasets from both the selected cases studies of 1-15 May 2010 and 22-30 September 2012, is shown in Figure 6. The linear-linear correlation made considering the daily averages averaged for both the quantities provides a regression coefficient of R=0.83. The scatter plot shows a large variability in the values corresponding to the higher values of the IWP and to the higher values of IL. Therefore, for optically thinner ice clouds, IL linearly increases with IWPL. For larger IWPL values, the two variables are less correlated and the second or higher order polynomial fitting could compromise the linear relationship.

In the period between 13-15 May 2010, both DREAM and back trajectories analysis showed that, while the transport of volcanic aerosol from Iceland (due to the Eruption of volcano Eyjafjalla 2010) was still ongoing, dust contribution was not negligible (Mona et al., 2012). In this period, the volcanic aerosol was mainly transported across the Atlantic Ocean, passing over Ireland and west UK, and then transported to the west off the Iberian Peninsula before reaching the Mediterranean Basin and Southern Italy. Satellite images and ground-based measurements confirmed the presence of volcanic particles in the corresponding regions (not shown). The analysis of multi-wavelength Raman lidar measurements permitted a detailed aerosol typing at the different altitude levels over Europe. A detailed description of the volcanic layers as observed by EARLINET (European Aerosol Research Lidar NETwork) LidarNETwork over Europe during this period is reported in Pappalardo et al., 2014. EARLINET volcanic dataset is freely available at www.earlinet.org (The EARLINET publishing group 2000-2010; 2014): EARLINET observations related to volcanic eruptions (2000-2010); World Data Center for Climate (WDCC), http://dx.doi.org/10.1594/WDCC/EN_VolcanicEruption_2000-2010). Moreover a devoted relational database freely available at www.earlinet.org contains all information about volcanic layers (base, top, centre of mass) and correspondingly mean and integrated values.
The Iberian Peninsula, France and South Italy were the regions more significantly affected by the presence of volcanic aerosol (sulphate and small ash) during the considered period. For the purpose of our modelling study this might induce an underestimation of the IN (since IN due to dust only is modelled) in the above mentioned regions and can be responsible of part of the discrepancies between modelled IN and IWP provided by SEVIRI. This is particularly true for Iberian Peninsula where volcanic aerosol concentrations were quite relevant. The comparison of model predicted IN and SEVIRI IWC on 13 May shows differences that might be correlated to a larger availability of IN of volcanic origin.

On the contrary, in South Italy, the volcanic layer, observed at Potenza up to an altitude up to 15 of about 8 km above sea level, did not enhance the formation of cold clouds due to unfavourable dry conditions in the free troposphere; this is also confirmed by the Potenza cloud radar which did not observed? clouds for the whole day (Figure 4). The absence of cold clouds over most of South Italy, including Potenza region, is also shown by the IWC reported for 13 May in Figure 1.

5 Conclusions

We have expanded the regional DREAM-NMME modelling system with the on-line parameterization of heterogeneous ice nucleation caused by mineral dust aerosol. We employed the recently developed empirical parameterizations for immersion and deposition ice nucleation that include dust concentration as a dependent variable for the cloud glaciation process. In our approach, the ice nucleation concentration was calculated as a prognostic parameter depending on dust and atmospheric thermodynamic conditions. To our knowledge, this is one of first attempts to predict in real time all ingredients needed for parameterization of dust-induced cold cloud formation within one modelling system. Experimental NMME-DREAM daily predictions compared against SEVIRI observations are posted at http://dream.ipb.ac.rs/ice_nucleation_forecast.html to show operational capabilities of the methodology presented in this study.

The model was applied for the Mediterranean region and surroundings for two periods: 1-15 May 2010 and 22-30 September 2012 during which several dust transport events of moderate intensity occurred. The model has been compared against both ground-based and satellite observations for two periods with the aim of checking the performance over both the horizontal and vertical cross-sections of the investigated atmosphere providing promising results. Somewhat lower performance of the model in representing ice layers at lower altitudes could have been affected by the capability of the parameterization scheme to predict mixed-phase clouds in the zone of negative temperatures.

Our study aimed to develop a methodology which lays the groundwork for further improvement of predicting clouds and associated precipitation in current atmospheric models. Namely, the operational numerical weather prediction systems today usually do not include aerosol effects in cloud formation or they do it in a simplistic way. By integrating dust and atmospheric components into an unfired modelling system we achieved to have at every time step all necessary ingredients to calculate the ice nuclei concentration
formed by dust, which will be used in our future development phase as an input into a dust-friendly cloud microphysics to predict the ice mixing ratio.

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Figure 1: Daily-averages of (A) the model dust load (gm⁻²); (B) the model NL = log₁₀ ∫ n_{IN} dz; NL = log₁₀ ∫ n_{IN} dz, (C) the MSG-SEVIRI IWPL = log₁₀(IWPL); (D) overlap of normalized NL and IWPL. Color selection: hits – blue; misses – green; false alarm – brown.
Figure 2: Time evolution of the forecast accuracy (black), the probability of detection (hit rate, red) and the false alarm ratio (green) for the period 1-15 May 2010.
Figure 3: Best matching pairs of entities identified using the MODE method: red and green colours identify objects that are matched, dark blue and gray indicates no matching; x-axe and y-axe are longitudes and latitudes, respectively, by the CRA feature matching technique when applied to normalized daily-averaged IWPL (left) and NL (right) fields valid for 11 May 2010.

Figure 4: Comparison of $\log_{10}(IWC \times 10^{-6} \text{ kg m}^{-3})$ obtained from the Doppler radar reflectivity using the Cloudnet algorithm (solid black line contour plot) versus DREAM $\log_{10}(n_{IN})$ (coloured contour plot), in the period 1-15 May 2010 (left) and 22-30 September 2012 (right). Red contours show the temperature as provided by the NMME model.
Figure 5: Time evolution of IWPL and NL over the periods from 1-15 May 2010 (left, upper panel) and from 22-30 September 2012 (right, lower panel).
Figure 6: Linear correlation between IWPL and NL retrieved using the ground based measurements merging the datasets from both the selected case studies of 1-15 May 2010 and 22-30 September 2012.