Dust emission and dispersion from mineral storage piles

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ABSTRACT

Dust pollution is a complex problem of growing interest because of its environmental, health, economic and political impact. Environmental impact assessment methods for dust pollution management are often based on the simulation of dust dispersion, which requires a precise characterization of the source term and of the source parameters. The source term model should be as simple and as accurate as possible and require low time consumption in order to be easily connected to a more complex algorithm for the dispersion calculations. This work focuses on dust emissions from mineral storage piles, which are usually modelled as source terms by means of the algorithm proposed in the AP-42 US EPA standard. Unfortunately, this algorithm tends to overestimate emissions, and when coupled with a Gaussian dispersion model it leads to inaccurate results in terms of estimation of both of concentrations and spatial distribution. This paper proposes a new methodology drawn from the original standard US EPA AP-42 scheme with the purpose to account for the actual dynamics of erosion, and to enhance the accuracy of the concentration and the pollutant spatial distribution assessment, thereby considering the effects of the wind interactions. The standard EPA methodology and the new one have been compared by means of the AERMOD and CALPUFF dispersion models. Results are superimposable in terms of concentration values, leading to a quantification of the same order of magnitude, although with a different and more variable spatial distribution.

Keywords: particulate matter (PM) emission; dispersion modeling; AP-42; emission factors; AERMOD; CALPUFF

1. INTRODUCTION

The particulate matter (PM) or, equivalently, the total suspended particulate (TSP) is the ensemble of solid and liquid particles dispersed in the atmosphere with a diameter in a range from few nanometers to hundreds of micrometers. It is characterized by a very complex chemical composition, with components such as O3, CO, SO2, NO2. The PM neither constitutes a specific chemical entity, nor possesses unique composition (US EPA, 2004a, 2004b; WHO, 2004). Given the wide range of features, PM is characterized by multimodal dimensional distribution and complex composition. The emitted dust can spread over long distances because of the action of wind and atmospheric turbulence or settle down because of scavenging agents such as rain and snow (US EPA, 2004a, 2004b; Kelly and Russel, 2012). The properties of PM affect the atmospheric behaviour of the particles, the interaction with citizens and the environment; the detrimental action mechanism of the PM is still not completely understood (Kelly and Russel, 2012), although the relation between exposure to dusts and several health effects has been proven (US EPA, 2004a, 2004b). Humans' exposure to dust pollution can occur by three main ways: through respiration, ingestion and wounded skin. Exposure to pollutant agents can lead to both chronic and acute effects, strictly related to composition and particles dimensions. Considering the exposure through the airways, the typical short-term effects may include inflammatory reactions, respiratory symptoms, and cardiovascular diseases. Among chronic effects of exposure it is worth to mention reduction of lung activity, COPD (Chronic obstruction pulmonary diseases), cardiopulmonary disease and lung cancer. The susceptibility to PM pollution is closely related to genetic causes, gender, behavioural, social or environmental factors (Mage and Donner, 1995; WHO, 2004; Curtis et al., 2006; Brunekreef and Forsberg, 2005; Yang and Omaye, 2009).

Among the others, PM have an environmental impact by means of effects such as hindering of photosynthesis, alterations of the aquatic environment, solid surface corrosion and fouling. Furthermore, suspended dust particles can impair the visibility over long distances (US EPA, 2004a, 2004b; Prajapati, 2012). Dust pollution can also produce economic impacts due to the costs related to prevention and remediation technologies required to satisfy mandatory requirements. Actually, other kinds of costs should be taken into account, such as hospitalization and care expenses, damage costs resulting from deposition and chemical interaction with the surfaces, communications and corporate social responsibility costs (El Fadel and Massoud, 2000; Rohr and Wyzga, 2012).

Based on these considerations, the importance that modelling activities may have in order to prevent or reduce the impact of particulates emission can be easily understood. As already mentioned, PM may be emitted from many sources. This work focuses on mineral storage piles that are mainly present in the mining activities or heavy industry, and which can have a huge impact on health and environmental quality. The aim of this study is to propose a new and simple instrument to be used for assessing the impact of PM emission from piles when performing dispersion calculations. The accurate definition of the source term is crucial order to provide the emission data as input to a dispersion model. The estimation of dust emissions from mineral storage piles is commonly obtained by means of the methodology suggested in the section 13.2.5 of the AP - 42 U.S. EPA. This paper compares AERMOD and CALPUFF model applied to the dispersion simulation of dust emissions from storage piles estimated based on the AP-42 US EPA model as well as on a new improved scheme proposed in this work.

2. MATERIALS AND METHODS

2.1 The AP-42 emission scheme

The U.S. Environment Protection Agency (US EPA) algorithm has been developed by means of field tests with both portable and fixed wind tunnels. The main goals of that research has been to obtain a simple methodology characterized by a good degree in accuracy. However, the methodology has some inherent limitations: it tends to overestimate emissions, has empirical origin (thus being limited in application to specific situations) and analyses only the conical and the flat-topped circular base geometries, thus neglecting some other different shapes that are commonly applied in workplaces to optimise spaces. In this sense it should not be extended to different conditions although the scientific community has nonetheless extended its application to other contexts, thereby accepting the inaccuracies that can be compensated by means of environmental sampling (Axetell & Cowherd Jr., 2004; US Environment Protection Agency [US EPA], 2006).

The AP-42 emission factor can be calculated based on the following assumptions and concepts:

- Logarithmic wind profiles.
- Fastest mile: u_{10}^{+} [*m/s*]. It is the maximum value of wind speed between two disturbs of the surface corresponding to the entire mile of wind movement as detected by a reference anemometer at 10 m from the ground. It is the representative parameter of wind gusts, obtained by converting the measured values into a distance: all data greater than a mile will be effective bursts, while others will be discarded. Among all, the greater one (in terms of length) will be selected (in terms of speed).
- Threshold friction velocity: u_t^{*} [*m/s*]. It is the erosion limit which can be determined by means of a sieving procedure as stated by the ASTM-C-136 standard; above the erosion limit the detachment of the particles from the pile surface and the consequent removal by the wind action will occur.
- Normal surface velocity distribution: $u_s^{+} = \frac{u_s}{u_r} u_{10}^{+}$ [g/m^2]. It represents the fastest mile distribution above the surface, normalized with respect to the fraction of the speed detected in wind tunnel tests at 15 cm above the surface (u_s) with the speed detected by a 10 m reference anemometer (u_r) (Stunder & Arya, 1988).
- Friction velocity: $u*$ [*m/s*]. It is a representative parameter of the shear stress and is related to the mechanical wind action at surface level; for flat piles (H/B<0.2) it can be determined as $u^{*} = 0.053\ u_{10}^{+}$; for elevated piles (H/B>0.2) as $u^{*} = 0.10\ u_s^{+}$.

- Emission potential: $P = 58(u^* - u_t^*)^2 + 25(u^* - u_t^*)$ [*g/m*^{2}]. It is the maximum specific emission per surface unit. It is assumed to be zero as a consequence of a total instantaneous release when the friction velocity related to the fastest mile is above the threshold friction velocity. It is assumed to be restored whenever the surface is affected by mechanical actions (e.g., handling, supply of new material, etc.).
- Emission factor: $EF = k \sum_{i=1}^{N} P_i$ [*g/m*^{2}]. It is obtained from the erosion potential for the *i-th* period; it accounts for the particles size distribution by means of the multiplicative constant *k* obtained from experimental investigations.

By means of the emission factor it is thus possible to calculate the emission rate related to the surface under study for the simulation period (Stunder & Arya, 1988; US EPA, 2006), that is, all the dust that can be eroded from the surface is emitted in one shot in the hour of the fastest mile.

The friction velocity depends on the distribution of the wind velocity on the surface and thus it is affected by the flow conditions in proximity of the surface. Based on these premises, applications of the AP-42 standard have been developed to enhance the quantitative prediction and to extend its use to different geometries and conditions. One of the most interesting ones involves coupling the EPA algorithm with the computational fluid dynamics software (as ANSYS CFX or FLUENT). This method led an enhanced prevision for wind distribution above the surface to be used in the source term calculation for particulate dispersion modelling (Badr & Harion, 2005; Cong et al., 2012; Diego et al., 2009; Toraño et al., 2007; Turpin & Harion 2009, 2010). Particles detachment modelling would require the use of complex mathematical means to accurately describe the physics of the problem. Unfortunately, CFD application to long-term simulation is still problematic because of the computational time. Furthermore, air stability description creates issues on long term modelling, thus leading to turn toward less sophisticated instruments. Because of these considerations, the preferred available approach is the coupling of the emission factor obtained by means of the AP-42 algorithm with a simpler dispersion model. In this sense, Gaussian models (either plume or puff ones like AERMOD or CALPUFF) are a good compromises between accuracy and computing requirements and are thus the most used instruments. Based on this considerations, this study proposes an approach that uses an improved estimate of the source term and then compares the modelling results obtained both with AERMOD and CALPUFF.

2.2 Instruments used for dispersion modelling

The alternative procedure was developed for the application of the EPA AP-42 standard, drawn from the original scheme, with the aim to take into account for the actual dynamics of erosion. The last one is strongly influenced by wind intensity, directionality and randomness of the wind action. Furthermore, the emission dispersion depends on the same variables.

From these observations, the EPA AP-42 scheme was applied but assuming that also miles of lower entities are able to erode part of the mineral on the surface, according to the below explained sequential release path. The goal of the new approach is to obtain a values distribution for the source term as accurate and conservative as possible, maintaining the same general features as for the traditional application when compared to experimental data but allowing to follow in a more realistic way iso-concentration and iso-deposition profiles resulting from the dispersion calculation.

In the following chapters, the outcomes of the two source term estimation methods are compared by means of AERMOD and CALPUFF dispersion models.

The US EPA AERMOD is considered to be the most advanced among steady-state Gaussian plume models (Carrera-Chapela et al., 2014). In the stable boundary layer, it assumes the concentration distribution to be Gaussian in both the direction perpendicular to the plume axis. In the convective boundary layer, the horizontal distribution is also assumed to be Gaussian, but the vertical distribution is described with a bi-Gaussian probability density function. The plume is modelled as either impacting and/or following the terrain features. Stability conditions are described by means of the Monin-Obhukov model (US EPA 2004c, 2004d, 2004e). AERMOD also incorporates current concepts about flow and dispersion in complex terrain (Busini et al., 2012). The US EPA CALPUFF has been developed for far field (>50 km from the source) dispersion calculations (US EPA, 2008). CALPUFF is a multilayer, multispecies, non-steady-state, Lagrangian, Gaussian, puff dispersion model. It is able to account for the effects of time and space variations, meteorological conditions (3D met model), on pollutants transport, transformation, and removal. The total concentration at a receptor is obtained as the sum of the contributions of all nearby puffs averaged. CALPUFF is able to describe a 3D wind field (Scire et al., 2000a, 2000b). In this work CALPUFF was ran using a single-station meteorological dataset (AERMOD-type data) in order to make the outcomes comparable with the AERMOD ones. The choice of these two models was based on the consideration of the specificities of the case study, as well as the US EPA (2008) indications for air modelling regulatory application. The release from mineral storage piles is likely to be described as a puff release, while typically its effects are considered to be very impacting in the near field. By these considerations, AERMOD was chosen because it is the EPA recommended model for near field applications while, on the other hand, CALPUFF was selected because its puff formulation is likely to be the best suitable choice to describe the dynamics of the dispersion of a non-continuous release.

2.3 Data gathering, model set up, and basic assumptions

For the meteorological data, a realistic case was considered (data recorder at Spokane Airport, Washington, USA). Figure 1 shows the wind rose (blowing from) relevant to the meteorological data set. A preferential wind direction blowing from SW can be observed, and 5.22% of wind calms. This observation is important as CALPUFF is able to deal with very low wind conditions, whereas AERMOD neglects dispersion contributes associated with a wind velocity below 0.28 m/s. Another difference that is expected to influence results is related to the ability of CALPUFF to account for the previous hours outcomes, which is not achievable with AERMOD (Barclay & Borissova, 2013).

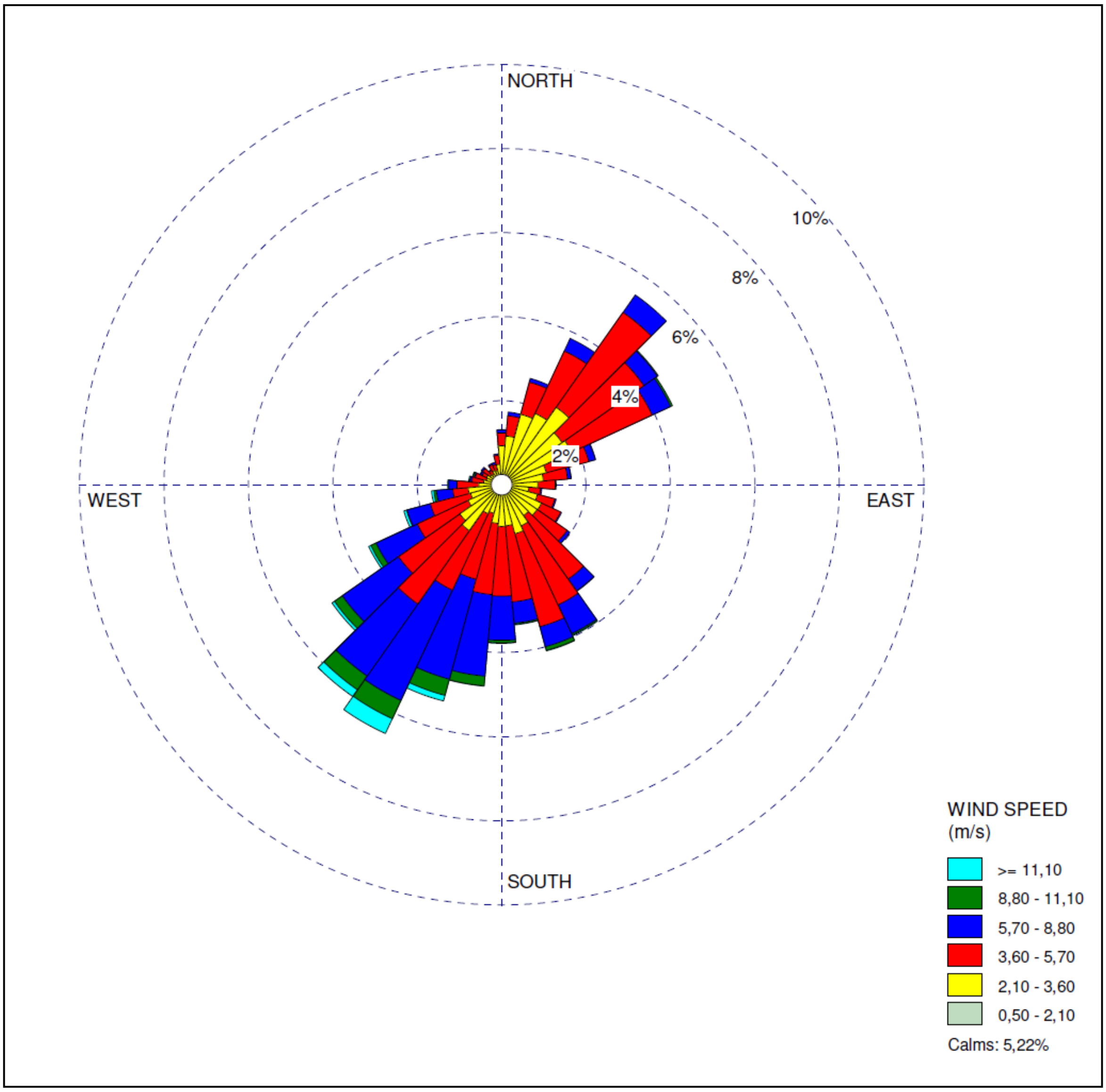

Figure 1. Wind rose relevant to the meteorological data used for the case study

DEM1-Deg model was selected to account for orographic conditions whereas a mineral storage piles yard consisting of 6 piles parallel (50m x 5m x 5m) to the prevailing wind direction was investigated. The simulation domain has an extent of 5000m x 5000m and a receptor grid spacing of 25 m was selected after a grid sensitivity analysis.

The simplest case reported in the AP-42 document, the flat-type pile (H/B<0.2, threshold friction velocity = 0.55 m/s), was selected in order to avoid some unnecessary complications in the calculations that are related to geometrical features.

AERMOD and CALPUFF require dust particle size distribution to perform dust dispersion simulations. PM10 distribution was used in order to simplify calculations. Moreover, a gusts distribution is required to produce the emission rates distribution. Given the unavailability of real field data for wind gust distribution, because the wind rose represent hourly averaged wind speed without giving any information about the gusts, an hypothesis about the velocity of the gusts was necessary. In this perspective, the behavior of a real distribution reported in the AP-42 document was taken as a reference: in this distribution, differences between the mean wind speed and wind gusts values is characterized by a 3 m/s mode; so, 3 m/s were added to the hourly averaged recorded wind speed values of the case study.

Once all the required data were gathered the source terms were calculated both by means of the above explained traditional AP-42 method and the alternative method. For the last one, the concept of daily fastest mile needs to be introduced, which is calculated considering the highest speed that occurs in a single day, and then the following procedure is adopted:

- the overall emission potential referred to the overall fastest mile (i.e., the fastest mile of the traditional method) between two disturbs is calculated by means of the traditional AP-42 approach;
- in day one: the daily fastest mile is used to calculate the daily emission potential with the same formulation of the AP-42 standard;
- the emission rate is obtained from the daily emission potential with a similar approach to the one described in the traditional method;
- in day two, and consecutives in the period, the procedure is repeated until the sum of the daily emission potential is equal to the maximum emission potential, that is the one of the traditional method;
- if residual material is still available above the emitting surface, then the updated overall emission potential is used to calculate the emission rate related to the day in which the overall fastest mile occurs.

Of course if the overall fastest mile occurs in the first day after the refreshment of the emission potential, all the material on the emitting surface is carried away by the wind gust related to this fastest mile, thus leading to the impairment of the surface emission capability unless new fresh material is still available. Otherwise, part of the available material is emitted day by day reproducing a more realistic scenario.

Once the required data have been gathered, dispersion simulations were performed under the hypothesis of bi-daily, weekly and bi-weekly disturbs of the surface. For each surface disturb, the source term was calculated using the pseudo-gusts obtained by means of the two procedures discussed above.

3. RESULTS AND DISCUSSION

3.1 Assessment of the mean specific flux of the emitted LFG

The simulations results are represented by means of iso-concentration maps, which are useful in order to compare the results obtained with the different models. In general, as expected, the extension of the averaging time led to results of the same order of magnitude for both of the dispersion models and for both of the emission schemes. Slightly higher results can be observed for CALPUFF simulations, confirming what above stated about the capability to treat wind calms and to memorize the contributes of the previous hours.

The two different emission schemes (traditional AP-42 vs. alternative/improved) for each of the three typology of disturbs (bi-daily, weekly and bi-weekly) being studied were compared. Although several considerations could be done for very short averaging period, results will be presented only for the long-term averaging period since the last one is the most interesting outcome for regulatory modelling purposes.

Figure 2 and Figure 3 show the long-term concentration isopleth for the case of bi-daily disturbs, obtained by means of AERMOD (Figure 2) and CALPUFF (Figure 3), respectively. Greater differences between traditional and alternative emission scheme can be observed for the AERMOD model. The concentration isopleth change significantly in shape with the introduction of new different plumes. This is an effect of the partial emission scheme that, for the combined application of the alternative procedure with AERMOD, led to the obtainment of an improved description of the pollutant spatial distribution. CALPUFF outcomes produce less significant differences in terms both of shapes and isopleth values. It could be an effect of the combination of a very short emission interval with the memory capability that characterize the puff model. Indeed, CALPUFF is able to redistribute the pollutant over the entire domain also accounting for the previously emitted pollutant. In the case of bi-daily disturbs the concentrations cannot be diluted very fast to negligible amounts – which would not be recorded by the model – and, as a consequence, CALPUFF is able to consider also the previous contributes. As a general consideration, the overall prediction order is conserved for both the models while both the old and the new procedure were applied.

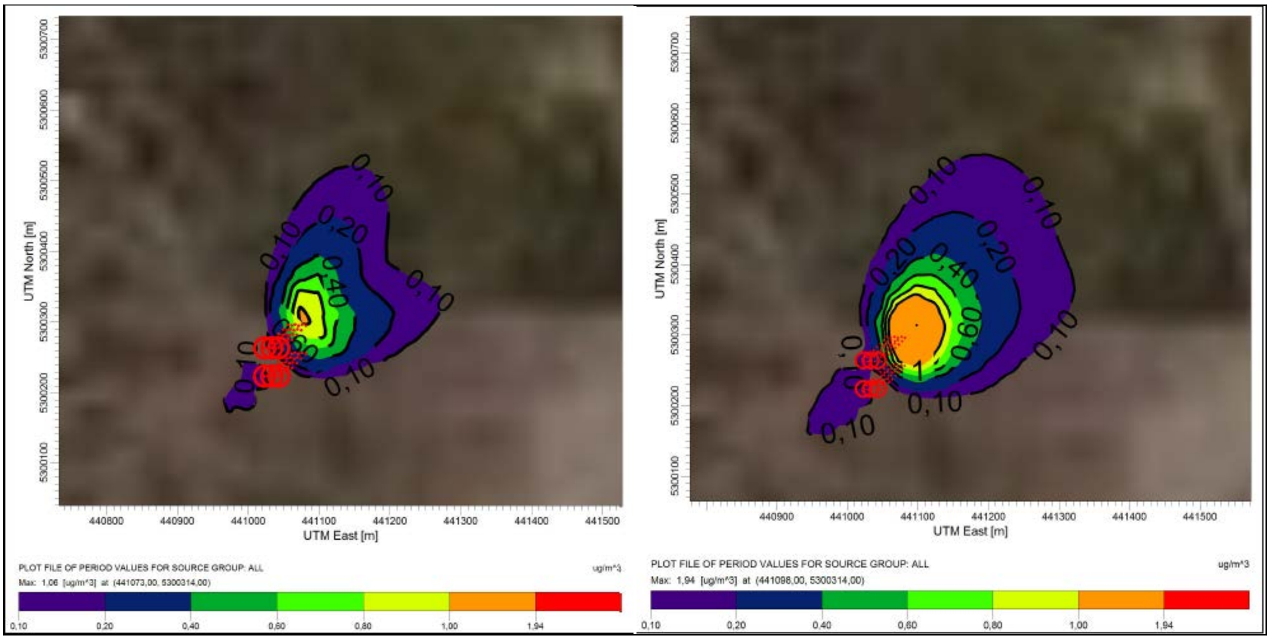

Figure 2. AERMOD long term concentrations for bi-daily disturbs: traditional scheme (left) vs. alternative scheme (right)

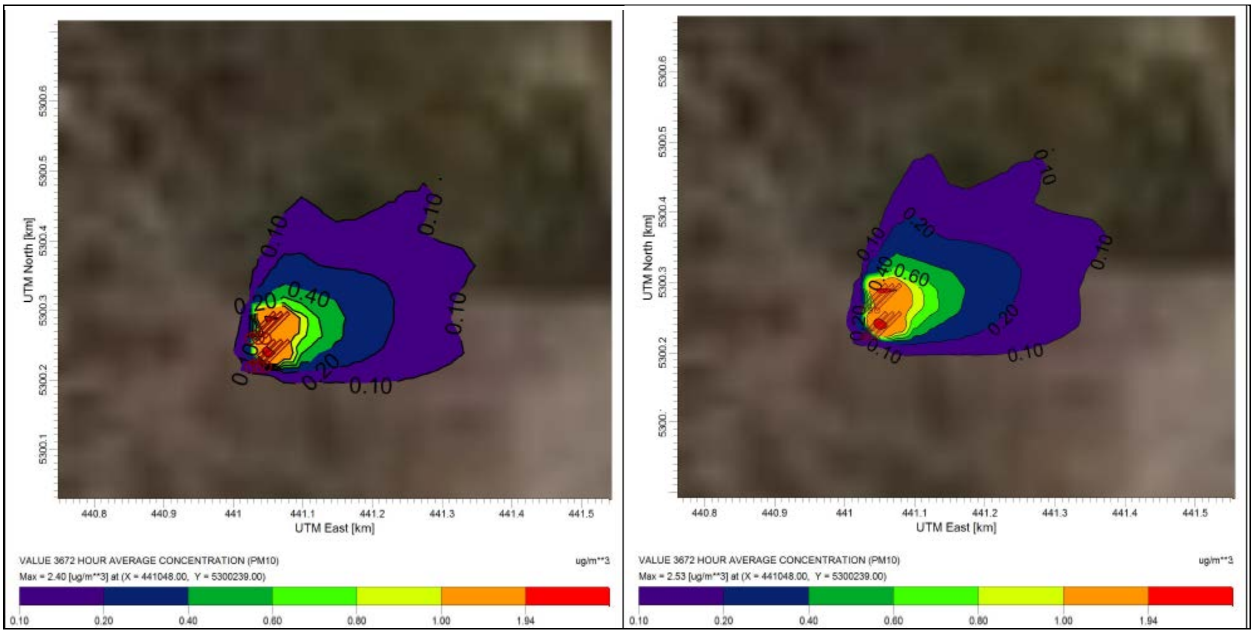

Figure 3. CALPUFF long term concentrations for bi-daily disturbs: traditional scheme (left) vs. alternative scheme (right)

Figure 4 and Figure 5 show the long-term outcomes for the traditional and alternative schemes obtained for the case of weekly disturbs, by means of AERMOD (Figure 4) and CALPUFF (Figure 5), respectively. Coherently with the prevision of the AP-42 traditional scheme, the reduction of the concentration values was obtained because of the lowering in the number of restorations of the surface emission potential. Also in this case, it can be noticed that the quantitative estimate for both AERMOD and CALPUFF maintain the same order of magnitude when applying the alternative and traditional methods. Contrarily to the case of bi-daily disturbs the CALPUFF isopleths appear more modified than in the AERMOD case, which may be explained by making a hypothesis about the CALPUFF sensitivity to the interaction between wind gusts and emissions.

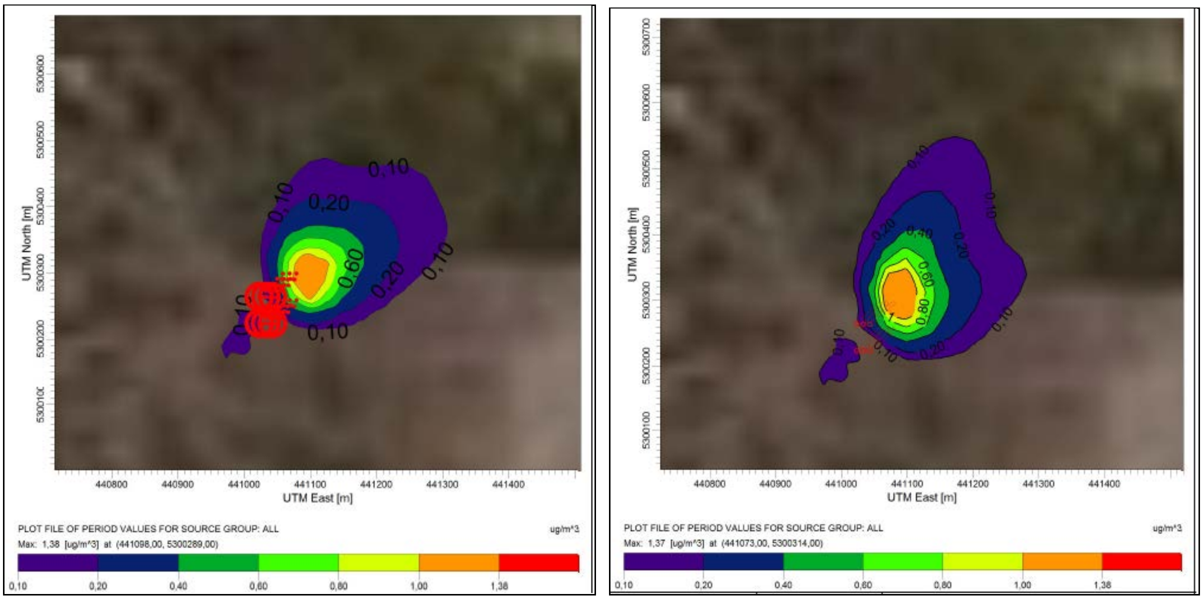

Figure 4. AERMOD long term concentrations for weekly disturbs: traditional scheme (left) vs. alternative scheme (right)

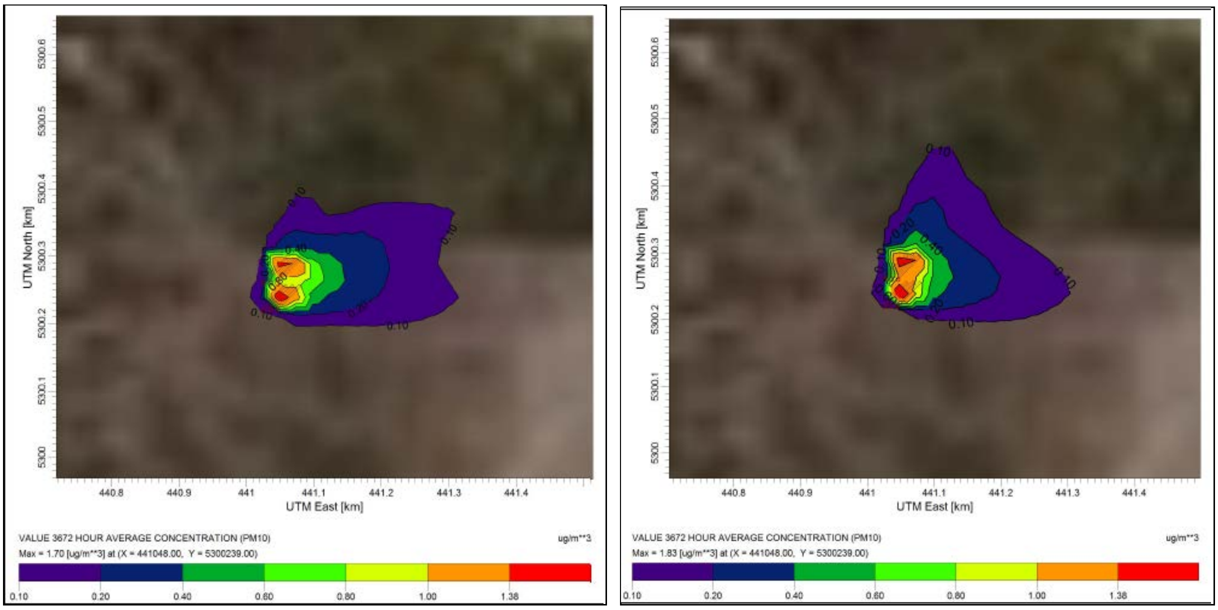

Figure 5. CALPUFF long term concentrations for weekly disturbs: traditional scheme (left) vs. alternative scheme (right)

Figure 6 and Figure 7 related to bi-weekly disturbs, obtained by means of AERMOD (Figure 6) and CALPUFF (Figure 7), respectively, maintain the general overall behaviour described above. It is worth to mention that for the CALPUFF simulations, differences between traditional and alternative scheme are more pronounced. However, the alternative scheme produces a reduction of the extent of the main plume with respect to the result obtained with the traditional scheme, while a new preferential dispersion direction appears.

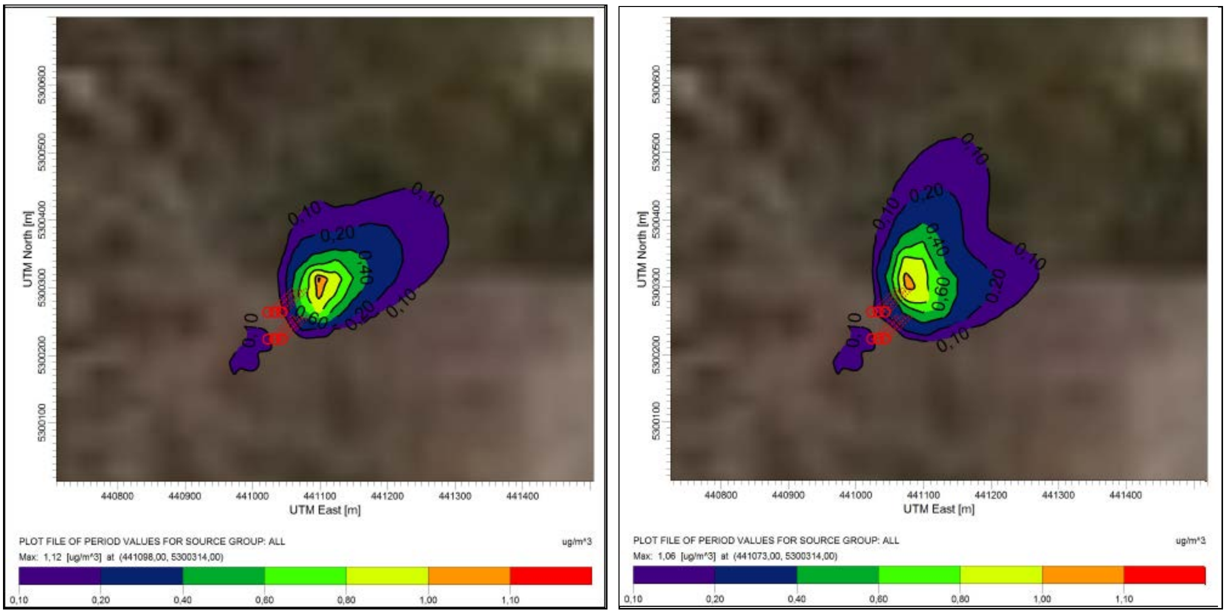

Figure 6. AERMOD long term concentrations for bi-weekly disturbs: traditional scheme (left) vs. alternative scheme (right)

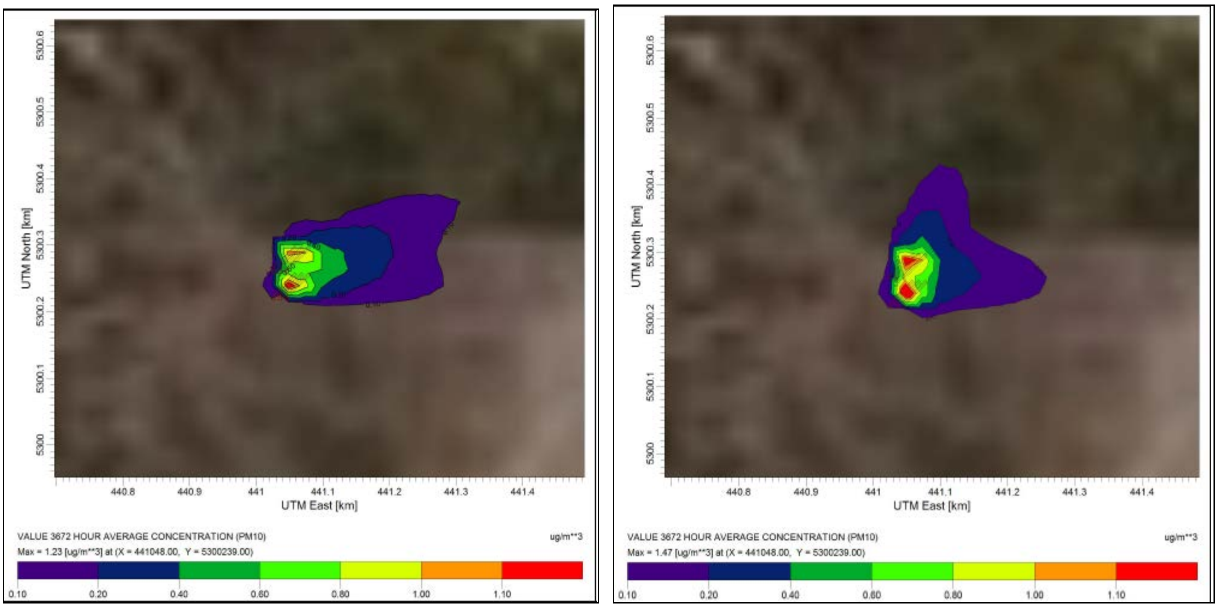

Figure 7. AERMOD long term concentrations for bi-weekly disturbs: traditional scheme (left) vs. alternative scheme (right)

4. CONCLUSIONS

Dust emissions from mineral storage piles are usually modelled by means of the AP-42 standard method. This work has discussed an alternative procedure that rely on a sequential release path and has been drawn from the original application scheme in order to get a more realistic and reliable instruments to describe emission phenomena. Both procedures have been applied in order to obtain specific emission rate data to be used as input for AERMOD and CALPUFF models. A comparison between the behaviour of the two emission schemes has been performed by means of the two dispersion models.

The results obtained with both AERMOD and CALPUFF are characterized by the same order of magnitude for the two release schemes, although with some differences in the isopleth shape. Anyway, the traditional AP-42 method is not conservative producing always shorter distance because of the higher dilution obtained with the overall fastest mile. The general results obtained from the study of the case here discussed are coherent with expectations, although CALPUFF seems to be more sensitive than AERMOD to the interaction between wind gusts and the emission scheme. A future step of this work could be a sensitivity analysis in order to investigate this aspect.

The most interesting point that emerges from this study is the achievement of significant changes in the long-term description of the spatial distribution of dusts, although only on a theoretical and modelling basis. In this sense, this work has to be considered as a first step of a process that will be completed with the application of the methodology to real case studies and possibly with the following validation of results by means of field data.

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