Evaluation of environmental impact through computer simulations

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ABSTRACT

In this work, with the aid of advanced numerical simulation tools, we investigate the dispersion and deposition of the fine stone particles generated during working activities in three quarries located in the northern-eastern part of Friuli-Venezia Giulia (FVG) region in Italy. The numerical framework adopted for this study rely on the coupling between two numerical tools: i) the CALPUFF modeling suite, used to compute the dispersion and deposition of the stone particles; ii) the Weather Research and Forecasting (WRF) model, a next-generation mesoscale numerical weather prediction system. Present results show that the impact of the quarry activities on the PM10 concentrations in the surrounding of the extractions sites is very marginal. Large and very localized peak concentrations are only found in the close proximity of the quarries.

1. Introduction

The prediction of the suspension, dispersion and deposition of the fine particles generated during quarry activities is a complex task as it is influenced by many factors: the complex local scales of the terrain (as common in the lee of a quarry), the ever changing in space and time meteorological and atmospheric conditions, the difficulty in accurately estimating the direction, velocity, and amount of these emission, as well as many other factors (e.g. turbulence behavior, thermal radiation effects, etc.). In this context, the development of accurate air pollution dispersion models is of key importance to support decisions in air quality control and emission abatement. The development of accurate numerical models is indeed of key importance as it allows to link the emission sources with the resulting environmental impact. Specifically, the purpose of these mathematical models is to provide a quantitative assessment of the intensity of the dispersion processes and their results in the form of concentration maps. These data are in turn a tool of paramount importance to evaluate the environmental risk and support the necessary planning actions.

The complexity of air quality evaluation has led to the development of air quality models to assist with monitoring and assessment of air pollution. These models provide a cost-effective way to analyze the impacts of meteorology, topography and emissions on air quality. Many conventional plume dispersion models have been proposed and developed in recent years, such as the Industrial Source Complex Short Term (ISCST), the Air Quality Dispersion Modeling (AERMOD), the Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) and the California Puff (CALPUFF) model. While the former three models rely on a rather conventional approach and are unable to accurately model complex dispersion processes, the California Puff (CALPUFF) modeling system offers many advantages and capabilities beyond those in the current generation of straight-line, steady state Gaussian models, both in terms of its range of capabilities and use of recent advances in the modeling techniques. Therefore, the use of the CALPUFF modeling system in various studies has become increasingly popular among air pollution researchers (Song et al. 2006, Jirungnimitsakul et al. 2004).

The CALPUFF model has been employed here to study the suspension, deposition and dispersion of stone particles. To enhance the reliability of the CALPUFF predictions, the CALPUFF modeling system has been coupled with the Weather Research and Forecasting (WRF) model, a next-generation mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting applications. Thanks to the coupling with the WRF model, much more accurate predictions can be achieved as the WRF model allows for obtaining detailed information on the local meteorological conditions nearby the quarry sites.

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2. Methodology

The workflow of the CALPUFF modeling process can be divided into three main steps: i) Collection of terrain, land cover and meteorological data and generation of the prognostic files using the WRF model; ii) Estimate of the emission data (amount and size of the stone particles releases); iii) Run of the main dispersion model and analysis of the results. In the following, each of these steps will be detailed.

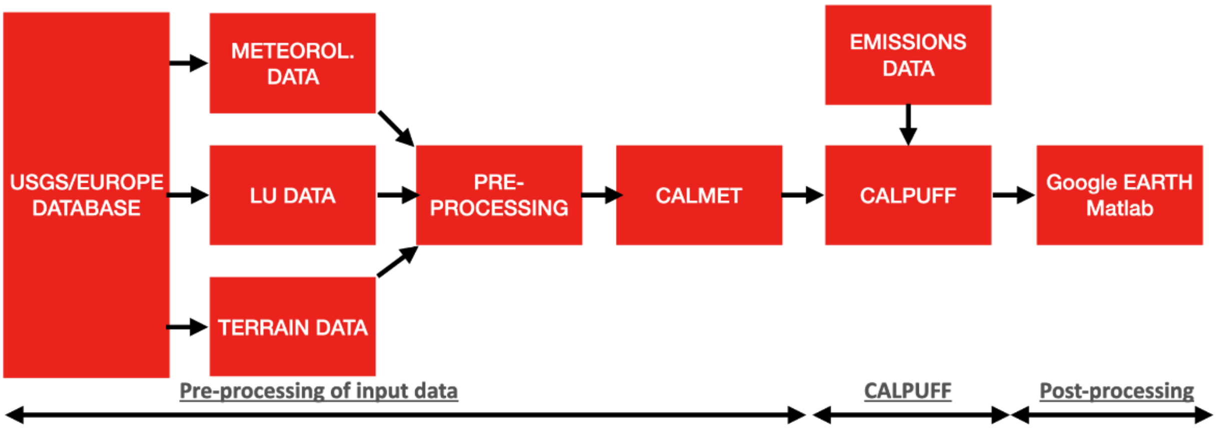

Figure 1: Workflow of the CALPUFF modeling suite.

2.1. Terrain, land use, meteorological data and prognostic files

During the first phase of the CALPUFF modeling process, the terrain, land use and cover change and meteorological data are collected and the prognostic files are generated using the WRF model. All this data represents the main input for the CALMET pre-processor. The final result of this preprocessor is the so-called CALMET.DAT file. This file contains all the relevant topographical and meteorological information for the main dispersion model (CALPUFF) in the computational domain considered. Terrain data have been acquired from the Shuttle Radar Topography Mission 1 (SRTM1) database. This data is freely available for download from the United States Geological Survey (USGS) website in GeoTiff format with a resolution of 1 arc-second (30 m). Land cover data has been acquired from the European database CORINE. Similarly to the terrain data, this data is freely available for download in GeoTiff format for the entire Europe zone with a resolution of 1 arc-second (30 m). As the categories used to classify land cover and use in the CORINE database are slightly different from those employed in the USGS database (and as well in the CALPUFF modeling suite), this data has been first processed using a Matlab script specifically written for this purpose. In particular, land use categories are first converted from the Corine levels (from 1 to 999) to the equivalent USGS categories (1-40) and then from USGS categories to the 14 CALPUFF categories.

Regarding the meteorological data, three different types of information have been collected: i) Upper air information and ii) Meteorological data at the surface. Upper air information data has been collected from the Rivolto (UD) military base and airport, which is located nearby the computational domain of interest. This data is collected with radiosonde which are launched twice a days and collect information on temperature, pressure and relative humidity at different heights from the ground level. Meteorological data at the surface (temperature, relative humidity, wind speed and direction, radiation, pressure and precipitation) has been obtained from the OSMER database of the Agenzia Regionale per la Protezione dell'Ambiente (ARPA) del Friuli Venezia Giulia in CSV format with 1-hour resolution. This data refers to the Cividale del Friuli weather station, a city located inside the computational domain of interest and very close to one of the quarries. A graphical summary (wind and precipitation) of the meteorological observations registered by the Cividale del Friuli weather station during the year 2019 is shown in figure 2.

Finally, the WRF model has been used to generate the high resolution prognostic files. These files contain finely spatial- and temporal-resolved information on many meteorological quantities of interest in a three dimensional simulation domain. In order to run the WRF model, different steps are required, from the generation of the computational domain up to the setup of the initial and boundary conditions. The WRF computational domain

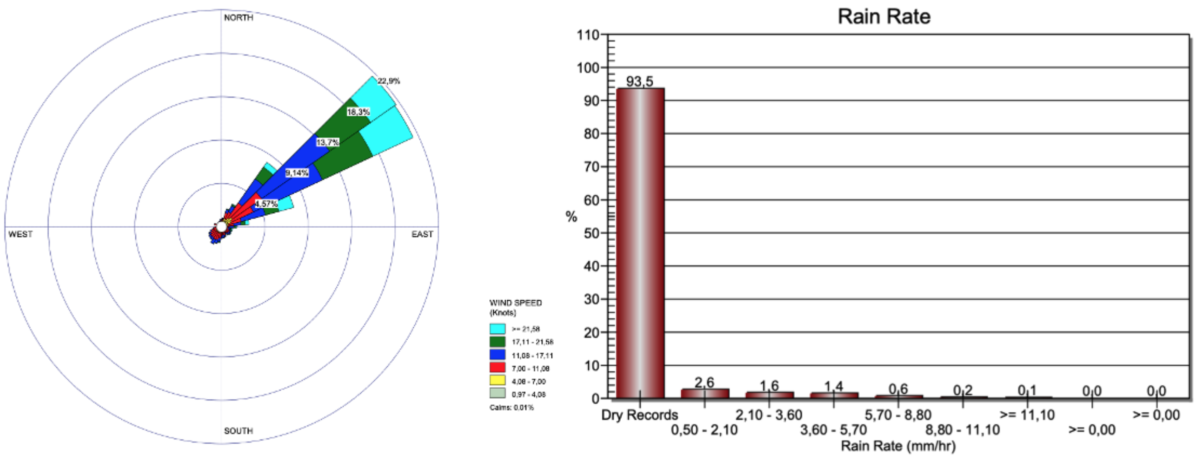

Figure 2: Wind class and frequency (left) and rain rate distribution (right) registered in the weather station of Cividale del Friuli during the year 2019. As can be appreciated from the wind rose (left), the wind is almost constant in direction (north-east) while most of precipitations are in the moderate range (less than 10 mm/h).

employed consists of two nested domains (figure 3), one with a coarser grid resolution (10 km) and one with a finer grid resolution (2 km), and is centered on the CALPUFF computational domain (see section 2.3 for details). The coarser domain is discretized using $N_x \times N_y \times N_z = 60 \times 60 \times 11$ nodes along the two horizontal directions and vertical direction, while the finely resolved domain is discretized using $N_x \times N_y \times N_z = 101 \times 101 \times 11$ nodes. The initial and boundary conditions for the model have been obtained from the Global Forecasting System (GFS) database made available from the National Center for Environmental Protection (NCEP). Nesting of the domains is required so to have a smooth transition between the initial conditions, which are provided at low resolution ($\simeq 28$ km), and the high resolution employed in the central part of the domain. As the simulations will consider the entire year 2019 (last available year not affected by the activities lockdown imposed by the Covid-19 pandemic), Skin Surface Temperature (SST) update has been enabled so to obtain more accurate predictions. SST information has been obtained from the European Center for Medium Range Weather Forecast (ECMWF). The final results of the WRF model is a large set of prognostic files that describe the weather conditions in the two computational domains considered with 1-hour time resolution. The overall size of these files is 2 TB and the wall-clock time for the run of the entire 2019 year is 1 month using a workstation with an Intel Xeon having 16 cores.

Once all this data has been collected and/or generated, the first phase of the modeling process is almost finished and the preprocessor CALMET can be used to generate the CALMET.DAT file. This file, which summarizes all the terrain, land use, meteorological data and prognostic files information will serve as the main input file for the CALPUFF model.

2.2. Estimate of the emissions

The second step of the CALPUFF modeling process involves the estimate of the type and rate of the emissions produced during the quarry activities. We focus here on the emission of stone inert particles with a size smaller than 10 microns (PM10). These particles are of particular interest for air pollution: they can remain suspended in air for very long times, can be transported over long distances by wind currents. In addition, these particles can be inhaled posing possible threats to human health. The emissions of PM10 generated during the quarry activities have been estimated using the Air Pollution Emission Factors AP-42 (US EPA) and considering the different types of vehicles, activities and operations performed in the quarries. The size distribution of the stone particles has been obtained from analysis performed on the slurries received from the quarries. In particular, the resulting size distribution, at least for small diameters, can be well approximated by a Gaussian distribution chracterized by... Once this information is defined, it is possible to generate the PTEMARB.DAT, this file will contain the location of the different sources of emissions and their rate of emissions during the 2019 year with a 1-hour resolution.

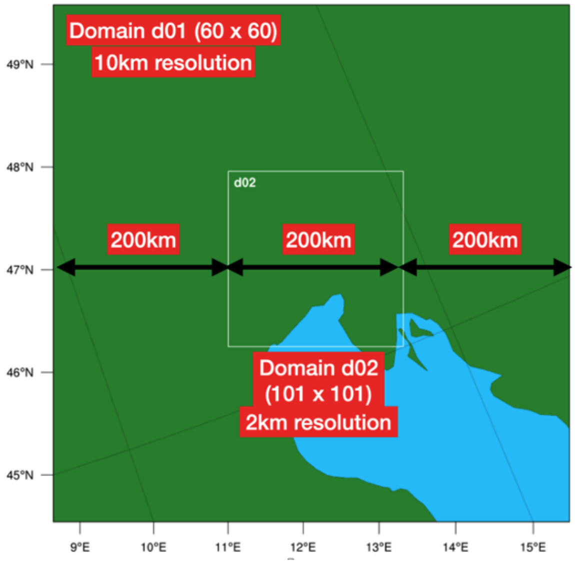

Figure 3: Nested domains used for the simulations conducted with the WRF model. The coarser grid domain d01 has a resolution of 10 km while the finer grid domain (inner part) has a grid resolution of 2 km. The two nested domains are centered in the CALPUFF computational domain.

2.3. Main dispersion model: CALPUFF

Once completed these first two steps (collection of terrain, land use, meteorological data, prognostic file and estimate of emissions), the main CALPUFF model can be run. The main input files for this model are the CALMET.DAT file (obtained from the first step) and the PTEMARB.DAT (obtained from the second step). The CALPUFF model has been run in a computational domain having dimension 24 $km \times 22$ km along the latitudinal and longitudinal directions, respectively. The southwest corner of the domain is located at 46.05 N, 13.30 E while the north east corner is located at 46.25 N, 13.60 E. The CALPUFF computational domain is discretized with Nx x Ny = 96 x 88 nodes and the corresponding grid resolution is 0.25 km. The three selected quarries are located in the central core of the computational domain: i) Noglar quarry (46.140 N, 13.456 E), Tarpezzo quarry (46.137 N, 13.503 E) and Clastra quarry (46.130 N, 13.511 E). The CALPUFF model has been run for the entire year 2019. Once the CALPUFF model has been executed (8 hours of wall-clock time), the resulting CONC.DAT file is generated. This file contains the concentration map of PM10 at the surface level with 1-hour resolution for the entire year simulated on the CALPUFF computational grid.

3. Results

The concentration maps contained inside the CONC.DAT file can be post-processed in Matlab and the results can be directly visualized using Google Maps or exported in Google Earth Pro. An example of the concentration map that can be obtained from the CALPUFF model is reported in the figure below In the figure reported above, the computational domain is shown as an opaque box and the location of the quarries have been highlighted with labels. It can be observed that the levels of concentrations of PM10 generated by the quarries are in general small. Indeed, the daily average limit imposed by the italian law is 50 $\mu g/m^3$. It can be also observed that most of the PM10 emission moves towards the southwest part of the domain (flat part of the domain), the wind is indeed frequently blowing from northwest (as can be seen from the wind rose reported above).

4. Conclusions

The CALPUFF modeling suite, coupled with the WRF model, has been used to estimate the emissions of PM10 generated by the quarry activities. The workflow of the process can be divided into three main steps: i) Collection of terrain, land use and meteorological data and generation of the prognostic files using the WRF model; ii) Estimate

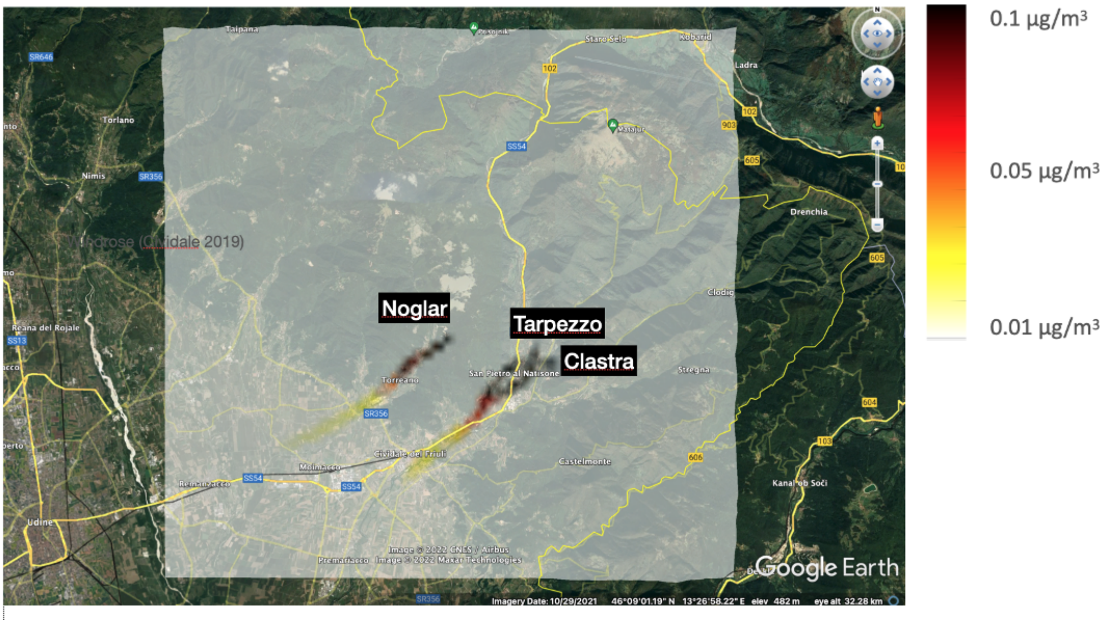

Figure 4: Concentration of PM10 in the computational domain considered for the simulations.

of the sources of PM10 emission and characterization of the size distribution of the particles; iii) Run of the main dispersion model and analysis of the resulting concentration maps. The analysis of the concentration maps reveal that most of PM10 emissions are carried along the southwest direction by the wind, which frequently blows from the northwest direction. The database generated by these simulations (WRF model results, Concentration maps obtained from CALPUFF and the main simulation code) have been deposited online and are available to other researchers.