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Atmospheric Emissions from a Fossil Fuel Power Station: Dispersion Modelling and Experimental Comparison

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In this paper, a comparative study of different dispersion models considering stack emissions from a coal-fired power plant. Modelling comparison study was performed utilizing Safe-Air II, a reliable Lagrangian model and ADMS 5adopting a skewed Gaussian representation. Fallouts were estimated starting from the statistical elaboration of meteorological data of the year 2012.Results evidenced a satisfactory agreement with measured data from monitoring stations, both in the discrete values and in the monthly and hourly averages. Furthermore, within an impact radius 40 km from the source, the areas of highest and lowest fallouts were identified in order to explore the possibility of considering lichens as potential bio-monitors, being well established their sensitivity to SO_2 and eventual damage to the thalli.

1. Introduction

This study investigates atmospheric dispersion and deposition from the emissions of a fossil fuel power station provided with two stacks and located in the Mediterranean area. Generally speaking, industrial coal utilization poses different environmental concerns and potential hazards throughout the whole cycle. The latter aspect is evidenced by historical accident statistics: from the beginning of this century to 2011, 72 accidents connected to coal were recorded: 19 with fatalities and 28 with injuries (Fabiano et al., 2014). A peculiar explosion risk to be adequately considered under confined geometry is connected to accidental releases of coke oven gas, a by-product of coal carbonization to coke which is co-generated during the dry distillation process (Palazzi et al., 2013).Even if the coal chemical composition does not contain any hazardous pollutants, wind erosion emissions during open handling is capable of producing a considerable environmental impact, particularly when crossing residential areas, causing nuisance due to dust deposition and contributing to the PM10 atmospheric concentration (Fabiano et al., 2014). The inherent safety approach, widely applied also in consolidated processes (e.g. Fabiano et al., 2012), would require applying the guideword “substitution” to the fuel, so obtaining a sharp reduction of critical pollutant emissions (e.g. SO_2, dust); however the actual feasibility of this option is clearly constrained by technical, economic and strategic burdens. Furthermore, alternative liquid, or gaseous fuels can pose additional severe hazards (e.g. thermal power and flame temperature in case of pool-fire scenario (Palazzi et al., 2012), or overpressure and possible knock-on effect in case of explosion scenario). The mitigation approach is connected to the application of the Best Available Technique, as also envisaged by the European Directive IPPC (Integrated Pollution Prevention and Control). The filtration system of a coal fired power station represent a critical section to mitigate environmental impact from the dust combustion gas, requiring high reliability and suitable technical strategies preventing malfunctions or service interruptions, even when triggered by natural events (Milazzo et al., 2013). As part of a project which studied the impact of a thermal power plant on air quality, a forecasting model for diffusion and dispersion of pollutants emitted into the atmosphere from the plant was implemented, with emphasis on the emissions from the stacks of two coal units with 330 MW nominal power each. The purposes of the modeling are mainly the identification of the zones which are affected by the fallouts of pollutants emitted by combustion, the evaluation of different impact scenarios to changes in plant productivity by integrating information from the

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provincial monitoring network (isolating the contribution of the source under test with respect to the overall local air quality). The resolution of the relevant inverse problem (starting from immission experimental data) requires a proper regularization technique (e.g. Reverberi et al., 2103), and is clearly limited to simple geometries. The selection of the proper modelling is not a trivial problem to be solved. The most common approach used for neutrally buoyant gases is the Gaussian dispersion equation for continuous releases, that can be effectively used in near-field, or short term evaluation. In view of public health protection, the decision of evacuating or sheltering people potentially exposed to an accidental release can be based, with enough reliability, on simple integral modelling such as ALOHA (US-EPA), provided that the validation is limited to the near-field and in the absence of local geometrical/orographic complications (Vairo et al., 2013). Relevant climate data of the area were elaborated starting from experimental observations, covering the whole year 2012.The cross-check modelling study was firstly performed by applying a Lagrangian model (Safe-Air 11) and a well-tested and validated quasi-Gaussian model (ADMS 5) (Riddle et al., 2003). According to this approach, dispersion under convective meteorological conditions was calculated using a skewed Gaussian concentration distribution, providing a better representation than the standard symmetrical expression. Subsequently, modelling results were compared, as a cross-check validation, with data from monitoring fixed stations. At last, we experimentally explored the possibility of considering lichens as possible bio-monitors, in a circle area of nearly 40 km^2 around the emission sources. In fact, it is amply reported that sulphur dioxide is the primary agent for lichen mortality, particularly dealing with those of fructicose structure, owing to their larger surface area.

2. Dispersion modelling

Computer models addressed to the evaluation of gas dispersion into the atmosphere have been developed and improved for many decades since the Seventies and are generally applied over space scales up to 50 km from the emission source. The main features of the models utilized for intercomparison are summarized in the following.

2.1 Lagrangian model approach

SafeAirII (Simulation of Air pollution From Emissions Above inhomogeneous Regions)is a model designed to simulate pollutants transport and diffusion on complex, non-homogeneous terrains, at different spatial scales. It is structured into three interconnected modules, namely: WINDS (Wind-field Interpolation by Non-Divergent Schemes) builds the three-dimensional wind field; ABLE (Acquisition of Boundary Layer parameters) calculates the micro-meteorological parameters which characterize the atmosphere in the zone (mainly the mixing height);P6 (Program Plotting Paths of Pollutant Puffs and Plumes) is a pollutants transportation and diffusion Lagrangian model (advection), which responds dynamically to the local weather conditions: close to the source and under conditions of prevailing transport (wind velocity) uses segments of Gaussian plume, whereas, away from the source under prevailing spread (no wind), uses Gaussian cloud (puff).

2.2 Gaussian model approach

ADMS (Atmospheric Dispersion Modelling System) is a recent generation of Gaussian dispersion model, in which the atmospheric boundary layer properties are characterized by two parameters: the boundary layer depth, and the Monin-Obukhov length, rather than in terms of the single parameter Pasquill-Gifford class. Dispersion under convective meteorological conditions uses a skewed Gaussian concentration distribution (shown by validation studies to be a better representation than a symmetrical one).The basic ADMS5 dispersion model calculates long-term and short-term concentrations and deposition fluxes from continuous point, jet (directional release), line, area and volume sources. Long-term output can be directly compared with air quality objectives and limits. Sources can be time varying on an hourly, period or seasonal basis. A meteorological pre-processor (based on the “mass-consistent” FlowStar) is part of the model and calculates values of the meteorological parameters in the boundary-layer from the input meteorological data. ADSM has been validated against a wide range of data sets and the validation has confirmed that, in particular over flat terrain, the predictions of the model are in reasonable agreement with observations (Riddle et al., 2003).

Table 1: Stack characteristics of the coal-fired power station

Stack height and diameter	200 m; 6.5 m
Volumetric flow rate	1,050,000 Nm^3/h
Average velocity	14 m/s
SO_2 emission rate	5,350 t/y

3. Case-study

The main technical data of the stack utilized in the coal-fired power station under investigation are presented in Table 1, making reference to the average values for the year 2012.

The simulations of transport and diffusion into the atmosphere are closely dependent on local meteorology. The parameters determining the extent of the ground impact are the wind field (direction and intensity) and the atmospheric stability class (conventional classification of the status of "turbulence", i.e. the degree of air layers vertical mixing). Parameters are less sensitivity to temperature, cloud coverage and air humidity. These parameters were calculated by a digital three-dimensional lattice, the surface of which consists of a digital elevation model (DEM at a resolution of 200 m) describing the topography and land cover of the portion of the investigated area The total control volume extends up to the highest atmosphere boundary layers (5,000 m).The simulation study involved the calculation of three-dimensional wind fields and all the weather variables needed for the simulation over a squared area of about 40 km on each side, as shown in Figure 1. As a main drawback of the modelling approach, it should be noted that we considered the dispersion behaviours of primary pollutants, without evaluating secondary oxidation processes in the atmosphere, which could exert a determining role in case of coastal area, by the well-known “photochemical smog cycle”.The model utilizes as input the meteorological hourly variables, which are dependent on the boundary of the wind circulation at a regional scale (7 km resolution). The detail of the space scale was refined to 200 m resolution in presence of geometrical terrain complications, suitable to affect the ground concentration profile, within the investigated area. Figure 2 shows,as an illustrative example, a comparison of the spatial scales of the wind field.By a proper calculation code, we processed all the variables of the different modules in the chain, so as to model the dispersion and propagation of the plume and to record the ground concentrations in correspondence with critical receptors. A regular grid of receptors placed at 2 m above the ground is used, covering a rectangular area of 8 x 14 km (pitch 500 m).

Figure1: Investigated area and calculation domain utilized in the modelling study

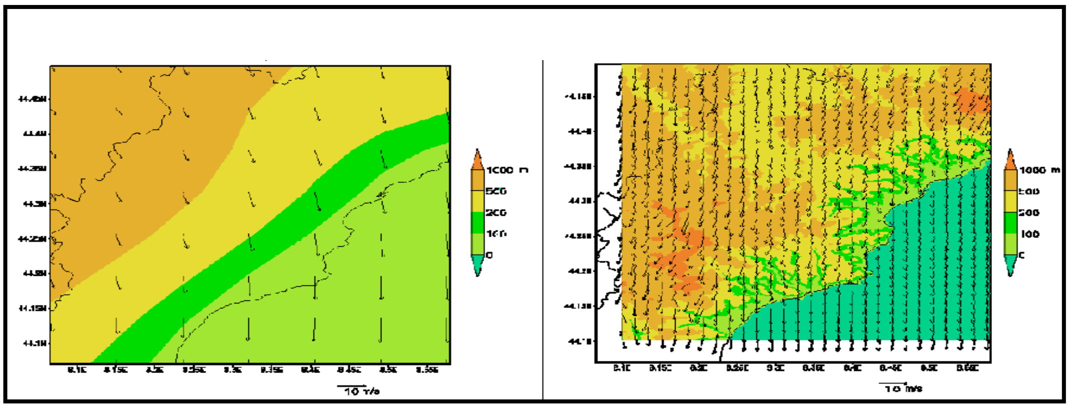

Figure 2: Wind field modelling by SafeAirII

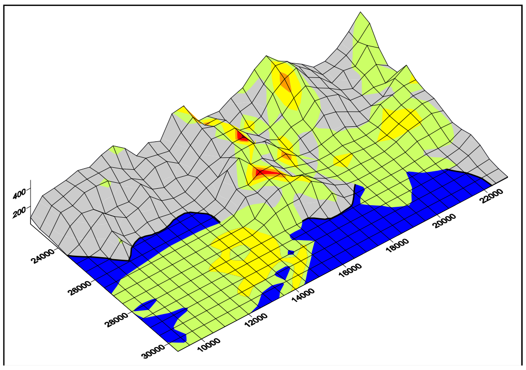

Figure 3: Ground level sulphur dioxide concentration modelling by SafeAirII

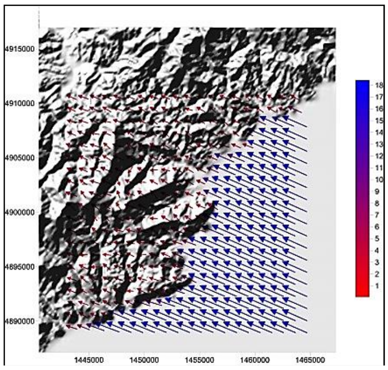

Figure 4: Three dimensional wind field simulation, performed by ADMS 5

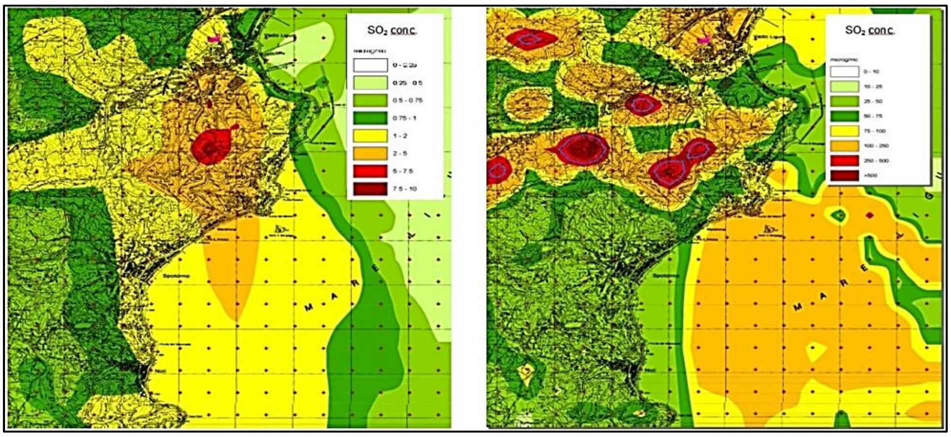

Figure 5: Sulphur dioxide ground concentration: a) annual average; b) hourly average – 99.7th percentile

Figure 3 shows an example of the output obtained by the model to highlight the three-dimensional characteristics of the results. The model provides the results of the simulation as a reference average hourly concentrations of SO_2 [μg/m^3] considered as the heuristic pollutant in the air. Fixed stations at the receptor points were utilized to compare the concentration values at different time scales, using proper statistical analysis (daily, monthly, yearly). In order to define standard vertical profiles of mean flow and turbulence, ADMS boundary layer structure is defined in terms of the Monin-Obukhov length, boundary layer height and surface roughness, An integrated data processing was performed in order to elaborate the raw data provided by the forecasting model Moloch (pertinent to the geographical area and containing information on wind intensity and direction and other thermodynamic properties) obtaining for each hour of the day the input for ADMS runs. The meteorological configuration files contain all the information related to the dynamics of the winds and other micro-meteorological parameters, properly describing the degree of turbulence / atmospheric stability. An example of wind field simulation is provided in Figure 4.

4. Results and discussion

The modelling results referred to the average hourly concentrations of the pollutant in the air (μg SO_2/m^3) at the selected receptors were elaborated at the different time scales. The simulation referred to the yearly average shows that the air-quality reference value(20 μg/m^3 for SO_2) is never attained at the ground receptors.

The results of the simulation on the extreme percentile of hourly average shows the occurrence of some peaks exceeding the threshold value set down by Italian legislation (350 μg/m^{3}for SO_2) placed, as expected, in some locations at high altitude. The areal distribution of the effects can be interpreted as the combination of the worst scenarios (as previously mentioned of rare statistically occurrence) characteristic for each of the propagation direction of the pollutants (typically connected to strong atmospheric stability and low wind effects resulting in poor air mixing and pollutant diffusion).

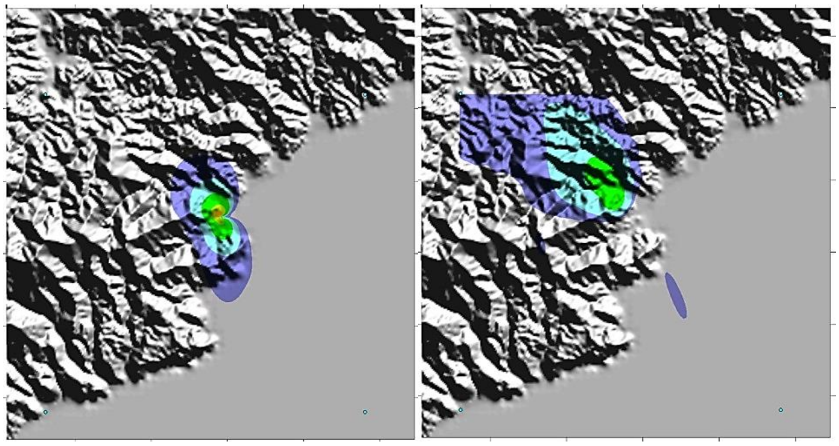

Figure 6: Average sulphur dioxide ground concentration over the time span July-August 2012.

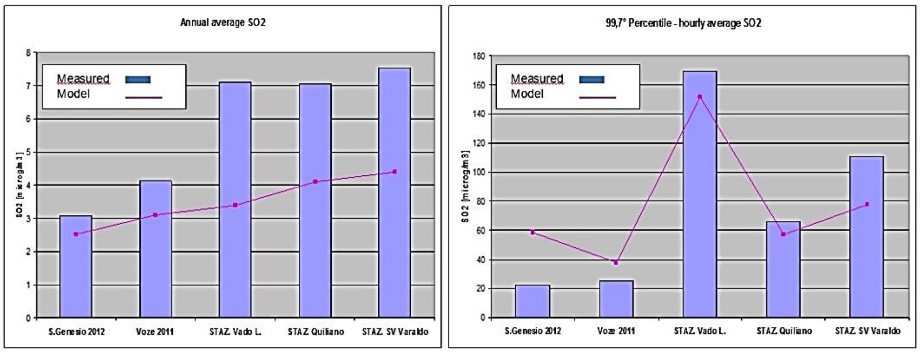

Figure 7: Comparison of calculated and measured concentration of the heuristic pollutant SO_2

ADMS modelling was carried out to obtain a map of the concentrations of the pollutants emitted by the source, on a regular grid of 100x100 receptors located at the “respiratory intake level”. Based on these assumptions and utilizing a set of meteorological data referred to July and August 2012,we performed series of modelling runs on the same pollutants previously studied, according to short term and long term-evaluation mode, in order to perform a simplified sensitivity study on

- the accuracy of the wind profile modeling, at a high resolution rate;
- the variability of ground level concentrations, as a function of the coordinates (x, y) utilized for the wind field reconstruction and of the representative wind height (Figure 6 shows an applicative example).

5. Biomonitoring

Lichens are used both as bio-indicators (Garty et al., 2002), exploiting the sensitivity of the major primary gaseous pollutants (especially SO_2 and NO_x) and, sometimes integrated with other biomonitors, as bio-accumulators of micropollutants. The studies carried out in the area and discussed by Scarselli (2014), show a picture of lichen flora depletion, with rather low values of biological indexes (IAP Atmospheric Purity Index; IBL Lichen Biodiversity Index) in an extended area where the different anthropogenic sources include SO_2 and NO_x immissions from the power plant stacks.A survey of IBL carried out on43 sampling unit (UCP)evidenced values of IBL ranging from a minimum of 0 (lichens desert), corresponding to the maximum detectable alteration, to a maximum of 106, consistent with the maximum IBL in the bioclimatic area and concurs to natural or near-natural conditions.Considering that in a complex orography area, with inhomogeneous climate, the IBL may be influenced by various natural variables(e.g., microclimate, rain) andnot only by anthropogenic factors (point source stationary emissions from industry; linear emissions from road traffic etc.) it seems possible identifying some "macro" IBL alteration areas. Figure 8 shows that, even considering other sources of pollutants, the values of IBL are in a broad sense consistent with the fallouts areas. Further studies could consider investigating possible accumulation on lichens of heavy metals (such as Fe, Co, Cr) originating from coal and ash particles.

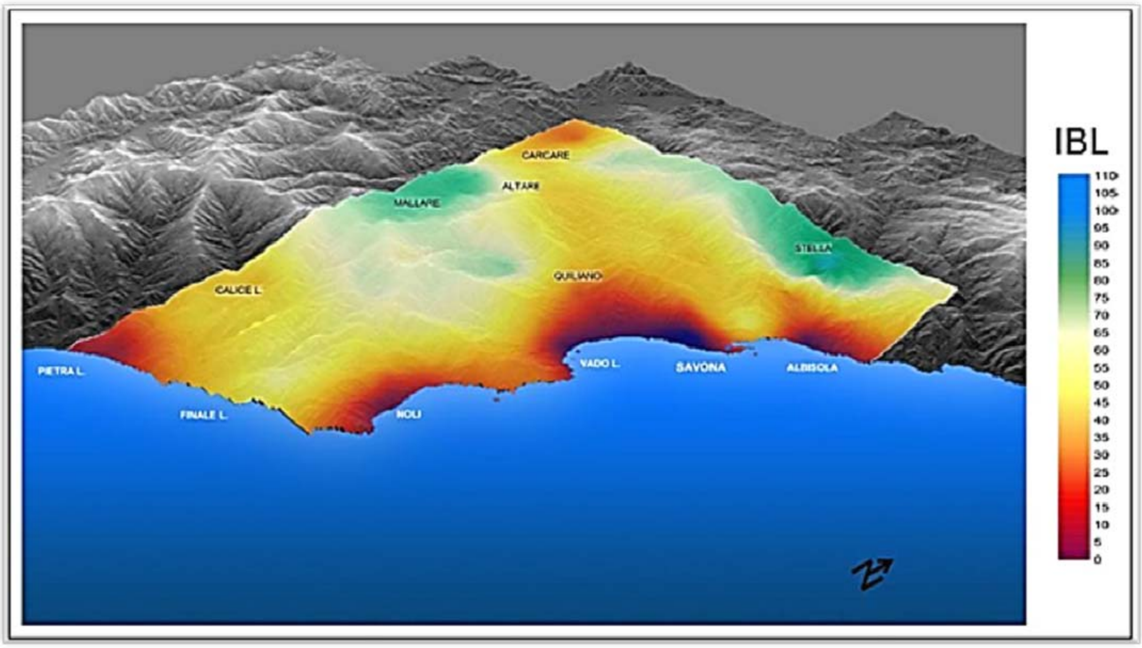

Figure 8: 3D representation of the lichen biodiversity index IBL

6. Conclusions

On the basis of the evidence of this study, the tested modeling systems are comparable in terms of distribution and values with the measured data obtained over one year observations. Overall, the simulations were satisfactory and suitable for normal atmospheric dispersion studies, without resorting to CFD simulations requiring much larger run times and higher setting –up complexity. Even considering dispersion over large temporal and spatial scales, with non-homogeneous terrains, it is possible to use an advanced Gaussian model using current understanding of the structure of the atmospheric boundary layer, instead of a Lagrangian one, allowing a significant reduction of the calculation time.

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