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Modelling air quality impact of a biomass energy power plant in a mountain valley in Central Italy

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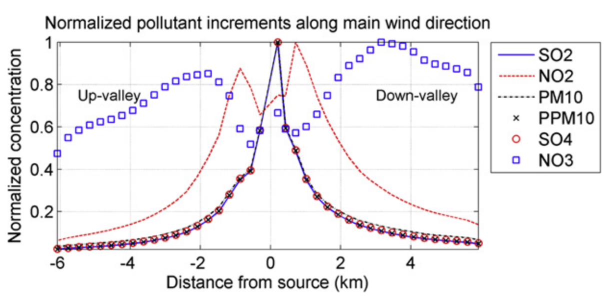
HIGHLIGHTS

- ► Pollutant increments due to a biomass power plant simulated with CALPUFF.
- ► Violations of NO_2 and SO_2 limits are predicted within 1.5 km of the source.
- ► Population exposure is greatly reduced at more than 5 km from the source.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, we investigate the potential impact on local air quality of a biomass power plant, which is planned for installation near L'Aquila, a city of 70,000 people located in a mountain valley in Central Italy. The assessment is carried out by applying a one year simulation with the CALPUFF model, following the recommendations of the U. S. Environmental Protection Agency. Meteorological input is produced with CALMET model, fed with both MM5 meteorological fields at 3 km resolution and wind observations from a surface weather station. We estimate small (<0.5 μg m^{-3}) annual average increments to SO_2, NO_2 and PM10 ambient levels over the domain of interest, but significant (up to 50% for NO_2) enhancements and several violations (up to 141 for NO_2) of hourly limits for human protection within 1.5 km from the source. These results anticipate a larger negative effect on local air quality than those published by the building firm of the plant. We also suggest that a minimum distance of 5 km from the nearest residential area would represent a significant decrease of population exposure.

1. Introduction

In the effort of mitigating anthropogenic climate change, one proposed option is to replace traditional fossil fuel power plants with those fuelled with modern biomass (IPCC, 2011). However, from an air quality point of view, a biomass power plant certainly emits short-lived substances from incomplete combustion (carbon monoxide, nitrogen oxides, volatile organic compounds, particulate matter) which are likely to affect the surrounding pollutant levels (Szarka et al., 2008; Hess et al., 2009). In this work, we investigate the effect of one such plant proposed for installation nearby a city on the Central Apennines in Italy, L'Aquila. The local impact on

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pollutant levels is assessed using CALPUFF model (Scire et al., 2000b) simulations, as recommended by the U.S. Environmental Protection Agency (EPA, 2000).

Bioenergy is an attractive mitigating solution to climate change because, in principle, it does not add carbon to the atmosphere during the vegetation life-cycle (from offspring to burning) (Jacobson, 2009; Abbasi and Abbasi, 2010; IPCC, 2011). However, the carbon neutrality of bioenergy has been recently questioned, because one must account for landuse changes, products of incomplete combustion, and energy dispatch (Howarth et al., 2009; Searchinger et al., 2009, 2010; Delucchi, 2010; Abbasi and Abbasi, 2010; Whitman and Lehmann, 2011). Moreover, although the investment in such technology is constantly growing due to decreasing production costs, it can potentially lead to an adverse impact on the environment even worse than that caused by fossil fuel consumption (Searchinger et al., 2009; Abbasi and Abbasi, 2010; Delucchi, 2010). Attention should be thus paid to specific aspects of the problem: here we focus on the impact on local air quality.

Even if properly planned for an effective abatement of greenhouse gas (GHG) levels, biomass energy may still have issues related to a negative impact on air quality. In addition to carbon dioxide (CO_2), biomass (mostly made up by cellulose, lignin, minerals and water) releases many other compounds when burned, in a proportion roughly equal to 7–8% of dry matter burned (Andreae and Merlet, 2001). Depending on the technology implemented into the power plant, major by-product of incomplete combustion such as carbon monoxide (CO), methane (CH_4), volatile organic compounds (VOC), particulate matter (PM) are released. Because of the lower burning temperatures ($\sim$800 K), nitrogen oxides (NO_x) emissions are comparatively lower than fossil fuel burning (>1500 K), but still significant. Small amounts of sulphur dioxide (SO_2) are also emitted. These species are both primary pollutants and precursors for secondary pollutants, such as ozone (Jenkin and Clemitshaw, 2000) and secondary aerosols (Raes et al., 2000). In addition to direct smokestack emissions, bioenergy exploitation includes emissions from agricultural practices, biogenic VOC emissions, biomass transport and energy distribution (Hess et al., 2009; Jacobson, 2009), but the effect of these emissions will not be assessed in the present study.

Atmospheric dispersion models have been extensively applied to the assessment of fossil fuel power plants (e. g. Hanna and Chang, 1993; Ryerson et al., 2001; Levy et al., 2002, 2003), but very few studies exist on biomass power plants, to our knowledge. Boman et al. (2003) and Jonsson and Hillring (2006) evaluated the conversion from electrical heating to pellets in Sweden, and reported that the impact on local air quality was negligible. On the other hand, Szarka et al. (2008) tested several bioenergy substitution scenarios in the Austrian–Hungarian region and found that all solutions significantly reduced CO_2 emissions, but degraded air quality with respect to fossil fuel use, because of the comparatively higher emissions factors, and increased fertilizer and machinery use for cropping.

Here we present results from a modelling study to assess the impact of a biomass power plant on local air quality nearby a city in Central Italy, L'Aquila. The CALPUFF modelling system (Scire et al., 2000b) is adopted following recommendations of U. S. EPA for modelling point sources in complex terrain, as is the case for this mountainous area. Moreover, the same model was used by the building firm (Futuris Aquilana) to make a private assessment of the power plant's emissions. Results were publicly released on a blog (http://www.collettivo99.org/site/?p=2501, in italian) and it is also our aim to compare our results to theirs. The model and site characteristics are described in Section 2 and 3, respectively. In Section 4, we use results from a base line scenario to estimate population exposure to pollutants emitted from smokestack, and make a suggestion for the location of an air quality monitoring station according to the current European legislation (EC, 2008). Robustness of results is discussed by means of model sensitivity tests. Conclusions and future outlook are given in final Section 5.

2. Model description

CALPUFF is a lagrangian "puff" model (Scire et al., 2000b) commonly used for health risk assessment from point and area sources (e.g. Levy et al., 2002, 2003). It is the Guideline Model suggested by the U. S. Environmental Protection Agency (EPA) for regulatory use for long-range transport and for local-scale applications, when the effects of complex topography or coastlines are important factors (EPA, 2000). As we shall detail in the next section, the study area (Fig. 1) is in a narrow mountain valley where winds are strongly affected by topography (Bianco et al., 2006), and thus suitable for CALPUFF application.

The meteorological driver is the CALMET model (Scire et al., 2000a), that we feed with three-dimensional meteorological fields (pressure, wind, temperature, humidity and cloud water content) simulated with MM5 model (Dudhia, 1993) and ground-based observations of wind at one location close to the plant. The domain has 40 $\times$ 40 horizontal grid-cells spaced by 250 m and 8 vertical layers (Table 2). CALMET default landuse and terrain databases are substituted with high resolution maps specific for Italy (Cinque et al., 2002), as shown in Fig. 1. The MM5 model is run on three nested domains up to a resolution of 3 km (Fig. 1), and driven with analyses issued by the National Center for Environmental Prediction (NCEP). Output from the inner domain is used to build the "first guess" fields. The CALMET diagnostic module then introduces kinematic, slope, and blocking terrain small-scale corrections to produce "Step 1" wind fields. In "Step 2", observational data from the only weather station available in the surroundings are included, by means of an objective analysis procedure (Scire et al., 2000a).

A comparison of observations with MM5 and CALMET simulations for model validation is given in the Supplementary Material. The MM5 model generally overestimates wind speeds in the first 1 km by a factor of two, it underestimates surface temperatures by 1 °C in winter and 4 °C in summer, and it reproduces well the variability of solar radiation at the ground. The wind speed bias is alleviated in the CALMET simulation through the introduction of surface observations at "S. Elia" station, while the surface temperature is not corrected in order to avoid unrealistically large vertical gradients (and thus blocking inversions) in model bottom layers.

Meteorological fields produced with CALMET are used to drive the non-steady-state puff dispersion model CALPUFF, which simulates the ground concentration increments of pollutants from the considered point source with hourly resolution. The inclusion of MM5 mesoscale model fields in CALMET calculations was shown to greatly benefit the performances of CALPUFF, because of a better representation of the upper air winds with respect to the CALMET simulation based on observations only (Protonotariou et al., 2005). The domain of application is somewhat similar to the assessment in near-field and complex terrain setting recently reported by MacIntosh et al. (2010), that found a good agreement between simulated and observed long-term air pollutant deposition. The characteristics of the simulated source are taken from the project details of the plant and are listed in Table 1. Here we focus on the impact of gaseous sulphur dioxide (SO_2), nitrogen dioxide (NO_2), and primary particulate matter (with aerodynamic diameter less than 10 μm, PM10) concentrations. In addition to gas-phase concentrations, SO_2 and NO_x emissions are used to simulate the secondary formation of particulate sulphate ($SO_4^=$) and nitrate (NO_3^-), which are

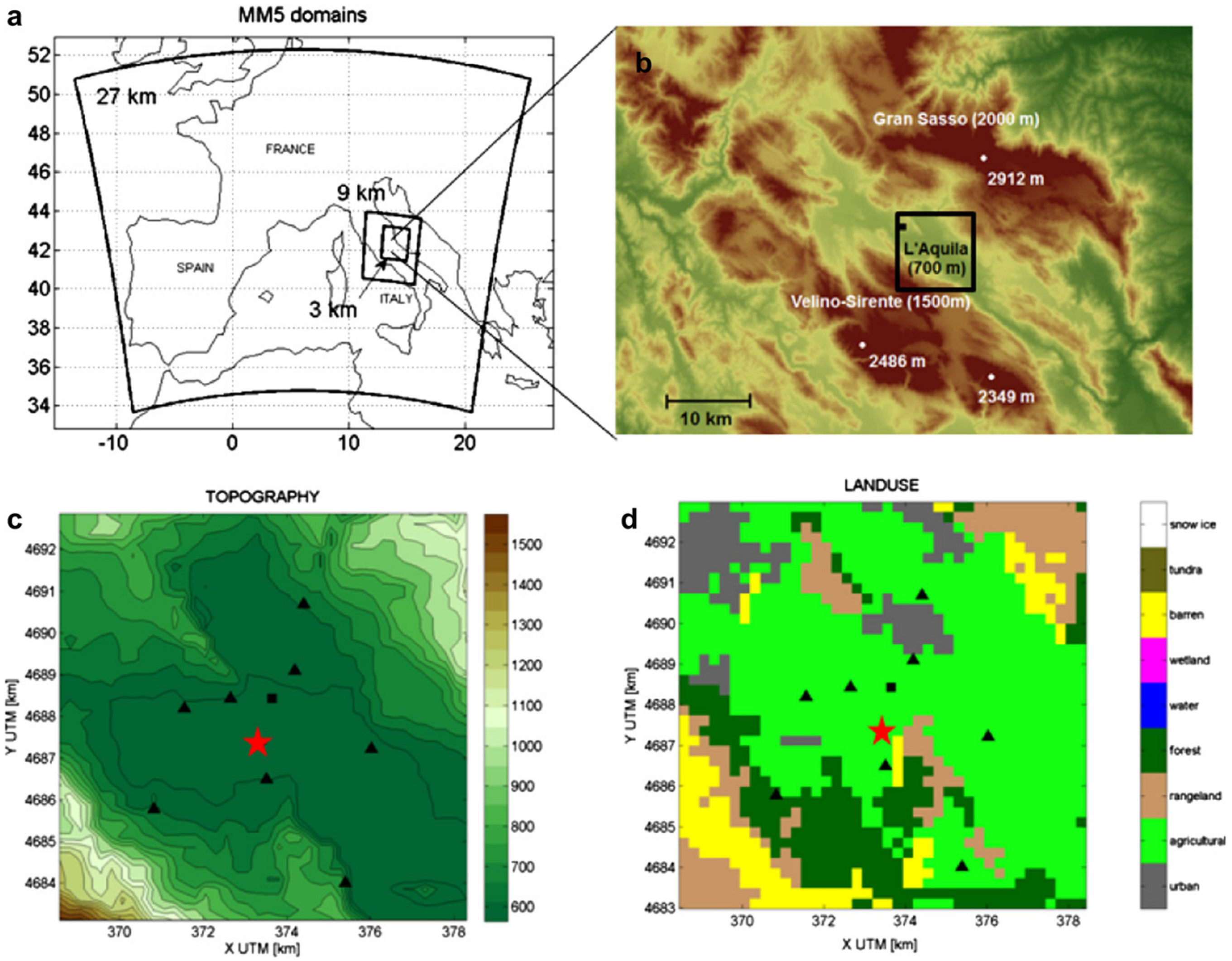

Fig. 1. Domains of the simulations. (a) MM5 mesoscale meteorological model nested domains configuration: simulations from the inner domain at 3 km resolution are used as "first guess" for CALMET. (b) Topography of the region of interest, the black square denotes the domain of the CALMET/CALPUFF simulation. (c–d) Topography (m) and landuse used for CALMET/CALPUFF simulations at 250 m resolution; the star denotes the biomass energy power plant, the square the weather station, and the triangles the main residential areas.

Table 1
Main characteristics and emissions of the simulated biomass energy power plant.

Power (MW)	5.5
Energy Production (GW $year^{-1}$)	40
Biomass Fuel (tons $year^{-1}$)	60,000
Emissions in air (g $hour^{-1}$)	
SO_2[a]	11,050
$SO_4^{=}$[a]	582
NO[b]	11,961
NO_2[b]	1330
PM10	1744
CO[c]	6645
VOC[c]	581
NH_3[c]	2492
Stack Height (m)	40
Chimney Diameter (m)	1.40
Exit Temperature (K)	403
Exit Velocity (m s^{-1})	15

[a] Estimated from total SO_x emissions assuming 95% of SO_2 and 5% of $SO_4^{=}$.
[b] Estimated from total NO_x emissions assuming 90% of NO and 10% of NO_2.
[c] Not used in the simulation, but included here for completeness.

summed to primary PM10. We point out here that, even if the aerosol model species is PM10, it is likely to be mainly representative of the particulate fine fraction (<1 μm, the most relevant for health impacts), because (1) it originates from combustion process, (2) coarse particles are more easily removed by smokestack filters than fine particles, and (3) secondary particles are produced in the fine mode.

We simulate an entire year (2008) with runs 15-days long, in order to keep dimension of data files manageable, and warranting continuity of concentrations using restart files between consecutive CALPUFF runs. For our base line scenario, we set up CALPUFF according to the regulatory guidance of EPA, and then we perform sensitivity tests changing one parameter per time to check the robustness of our results. The parameters and main options used for the reference case and the sensitivity tests are reported in Table 2. Details behind the choices of the reference configuration are provided in the auxiliary material.

3. Characteristics of the site

The city of L'Aquila (42°22′N, 13°21′E; population ∼70,000) lies in a valley of the Italian Central Apennines at about 700 m above sea level (Fig. 1). The valley has a width of ∼10 km and a length of

Table 2
Configuration of CALPUFF for reference and sensitivity simulations. For details on CALMET set up and sensitivity tests, please refer to the auxiliary material.

Model feature (option name)	Reference option	Sensitivity option *[test label]*
Horizontal grid	40 × 40 cells (250 m resolution)	–
Vertical grid	8 layers (top-heights of 20, 50, 100, 200, 500, 1000, 1500, 2500 m)	–
Meteorological fields	CALMET (MM5 + Observed surface wind)	CALMET (MM5 only) *[METEO]*
Chemical mechanism (MCHEM)	RIVAD (gaseous SO_2, NO, NO_2, HNO_3, primary PM10, secondary $SO_4^=$, NO_3^-)	MESOPUFF-II (gaseous SO_2, NO_x, HNO_3, primary PM10, secondary $SO_4^=$, NO_3^-) *[CHEM]*
Dispersion coefficients (MDISP)	3 (parameterized according to Pasquill–Gifford stability classes)	2 (estimated from micrometeorological variables) *[DISP]*
Puff shape (MSLUG)	1 (Slug)	0 (Circular puff) *[NOSLUG]*
Puff splitting (MSPLIT)	1 (Puff split allowed)	0 (No split) *[NOSPLIT]*
Background O_3	Observed monthly means (Fig. 3)	Doubled *[O3x2]*
Background NH_3	3 ppb	1 or 9 ppb *[NH3d3 and NH3x3]*

~50 km, it gently slopes to the South-East, and it is delimited by the Gran Sasso range to the North-East (average height 2000 m, highest peak 2912 m) and by the Sirente-Velino range to the South-West (average height 1500 m, highest peak 2348 m). Such a narrow and relatively deep (~800 m) valley is expected to display a strong decoupling between the synoptic (above ridges top) and the surface (at valley floor, NW–SE axis) winds, and favour the onset of a local thermally-driven circulation. Indeed, a temperature difference of less than 2 K between the two sites along the valley's axis is enough to produce a pressure difference of the same order of magnitude of a typical synoptic-scale gradient (about 0.5 hPa/100 km) (Whiteman and Doran, 1993).

In Fig. 2 we show the characteristics of winds observed at the "S. Elia" weather station (42°20'N, 13°26'E) throughout the year 2008. We choose this specific year, because currently it is the only one with PM10 observations available at the air quality monitoring site used later in this study. The simulated winds at 700 hPa are taken as representative of the synoptic flow above the valley. The wind shifts from a nighttime down-valley flow (towards south-east along valley axis) to a daytime up-valley flow (north-west) during most months (Fig. 2a), irrespective of the direction of synoptic flow, which is preferentially westerly (Fig. 2b and Di Carlo et al., 2007). This behaviour is consistent with a schematic view where daytime up-slope winds over heated valley sidewalls trigger a compensatory subsidence over the valley centre, causing temperature differences along valley axis that produce pressure gradients and eventually the reversal of the nighttime katabatic down-valley winds (Whiteman, 1990). The dominance of mountain-valley breezes was indeed confirmed by wind profiler measurements on the North-East sidewall (Bianco et al., 2006). During March, April and December the winds keep a preferential down-valley direction also during daytime, because the forcing of prevailing westerly synoptic flow is stronger than other months (Fig. 2b for March). The nighttime down-slope air masses from the mountains favour accumulation of cold air at bottom of the valley and strong thermal inversions, making L'Aquila a relatively cold city in winter (January mean temperature 2.5 °C, record low temperature −17 °C on 11/01/1985) and with fresh nights also in summer (July average minimum daily temperature 13.6 °C) (not shown).

In Fig. 3 we show pollutants' levels collected at the "Via Amiternum" monitoring site (42°22′N, 13°23′E) during 2008. The annual average ozone value is 56 μg m^{-3} (about 28 ppbv), and maximum monthly average is 85 μg m^{-3} (about 43 ppbv) in July, consistent with values previously reported by Di Carlo et al. (2007) for 2004–2005. The information threshold of 180 μg m^{-3} (EC, 2002) is exceeded only once, while the maximum 8-h average of 120 μg m^{-3} is exceeded for 45 days, more than the 25 times set as target value for the protection of human health (EC, 2008). Also the Accumulated Ozone Exposure over a threshold of 40 Parts Per Billion (AOT40)

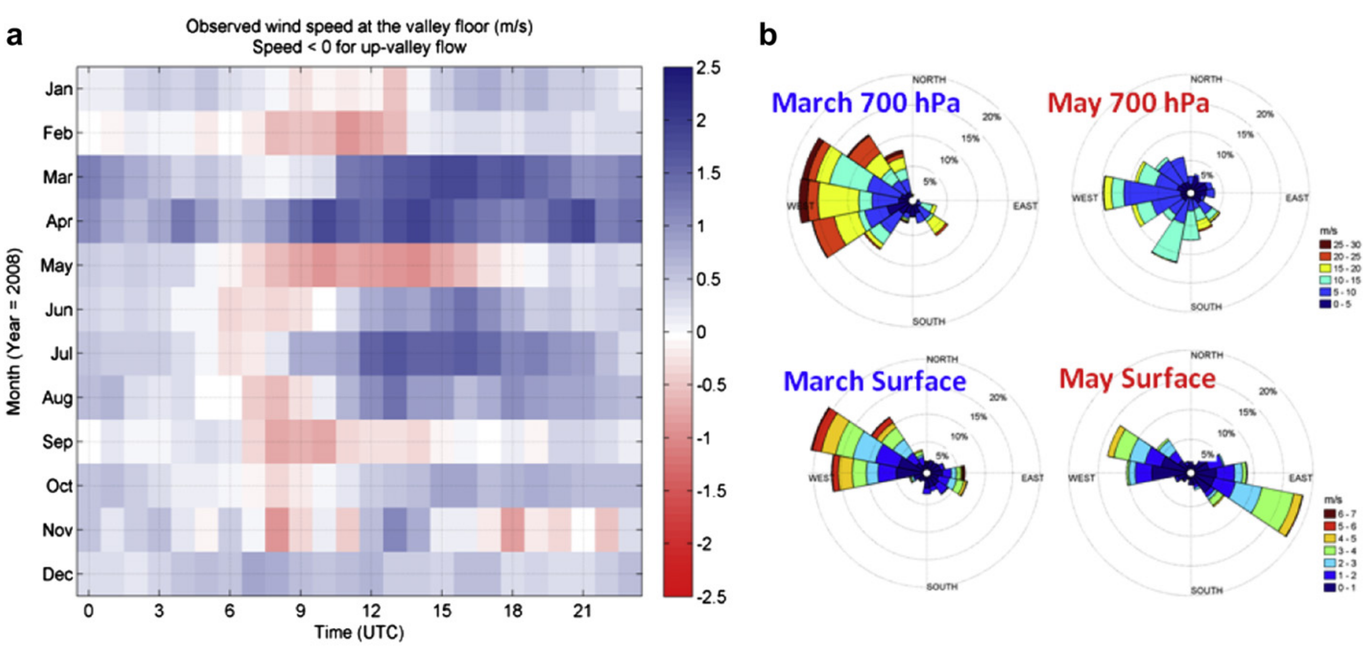

Fig. 2. (a) Monthly average of hourly surface wind observed at "S. Elia" weather station. Positive (negative) values denote down-valley (up-valley) flow or northwesterly (southeasterly) wind directions. (b) Wind rose at 700 hPa and at the surface for two selected months (March and May 2008). The upper air wind is taken as representative of the synoptic flow and it is simulated with MM5.

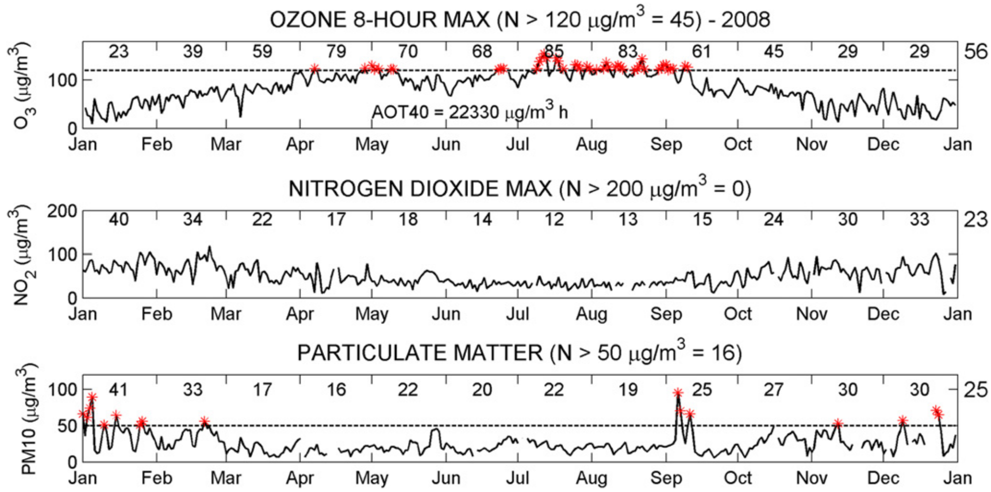

Fig. 3. Pollution levels observed in L'Aquila at the "Via Amiternum" suburban monitoring station (42°22′′N, 13°23′′E) in 2008. Red stars denote the exceedances of the limits for the protection of human health. Exceedances counts are reported in graph titles. The monthly mean concentrations are shown inset of each box, the yearly mean concentration is shown to the right of each box.

target for the protection of vegetation (18,000 μg $m^{-3} \cdot h^{-1}$; EC, 2008) is not met (22,330 μg $m^{-3} \cdot h^{-1}$). The exceedances of these threshold were neither reported by Di Carlo et al. (2007) nor are found in 2007 data (not shown). The peculiarity of the 2008 year for ozone deserves further investigation in a future study.

Nitrogen dioxide values (23 μg m^{-3} annual average) are typical of an urban station (e.g. Blond et al., 2007) and do not exceed the limit values for the protection of human health (200 μg m^{-3} hourly and 40 μg m^{-3} annual) and vegetation (30 μg m^{-3} annual) (EC, 1999). PM10 levels (25 μg m^{-3} annual average) also attain the current EU directive (EC, 2008), but exceed the target threshold of 20 μg m^{-3} annual average (EC, 1999). Moreover, the daily limit of 50 μg m^{-3} is exceeded 16 times, less than presently allowed (35 times/year; EC, 2008) but more than the future target (7 times/year; EC, 1999).

Pollutant ventilation out of the narrow valley of L'Aquila may thus be preferentially driven by the down-valley flow to the south-east exit during nighttime, and by the up-slope convective flows along sidewalls during daytime. Such dynamical control on pollutant dispersion is confirmed by the analysis of the radon budget inside the valley (Di Carlo et al., 2009). On the other hand, pollutant accumulation may be favoured by the generally weak winds and the shallow planetary boundary layer (PBL), especially in winter when the PBL height barely exceeds 600 m above ground level (Cinque et al., 2000). Indeed, despite the relatively small size of the city, measurements demonstrate that pollution episodes are not infrequent both in winter and the summer.

4. Results

In Fig. 4, we show the impact of the biomass power plant on particulate matter. PM10 includes the sum of primary particulate fraction and secondary sulphate and nitrate. The figure shows the

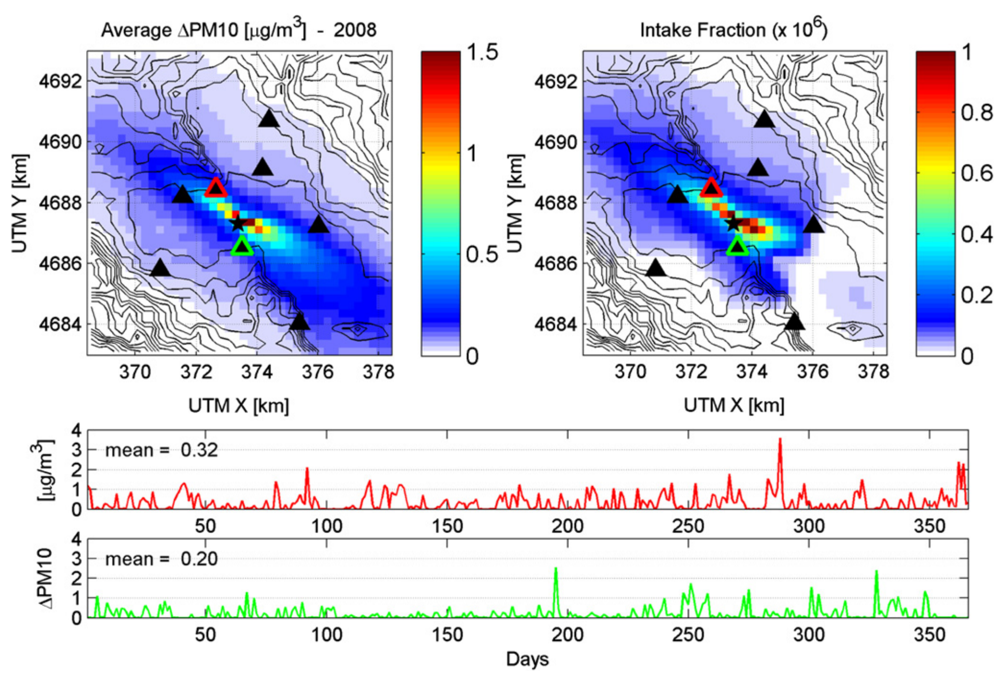

Fig. 4. Impact of power plant emissions on PM10 in reference CALPUFF simulation. Top-left: annual average total PM10 (primary PM10, sulphate, and nitrate) increment (μg m^{-3}). Top-right: annual average total PM10 intake fraction (see text for definition). Bottom: timeseries of daily PM10 increments at two receptors (red and green triangles on the maps).

spatial distribution of the annual average increments of PM10 simulated with CALPUFF in the reference simulation, and also the distribution of the intake fraction (*iF*), defined as the ratio of the breathed pollutant mass by the emitted mass (Bennett et al., 2002; Evans et al., 2002):

$$iF = \frac{BR \times \Delta C \times N}{Q} \quad (1)$$

where *BR* is the population average breath rate, assumed to be 20 m^3 day^{-1} (Levy et al., 2003), ΔC ($\mu g\ m^{-3}$) is the incremental change of the pollutant due to the selected source (i.e. CALPUFF simulation), *N* is the population, and *Q* ($\mu g\ day^{-1}$) is the emission rate of pollutant or pollutant precursors at the source. *iF* is thus a unitless quantity that measure the fraction of a pollutant mass that actually enters the lungs of people. In outdoor applications, it typically lies in the range 1–500 $\times 10^{-6}$ (Bennett et al., 2002). In Fig. 4, we also show the timeseries of daily PM10 increments simulated at two receptors, chosen at the two nearest residential areas on the two main wind directions (down- and up-valley). Similar figures for all simulated species are given in the online supplement. Numerical values associated to the impact of criteria pollutant (SO_2, NO_2, and PM10) are reported in Table 3. In the same table, we also compare our results with those published via blog by the power plant building firm (http://www.collettivo99.org/site/?p=2501). In Fig. 5, we display the impact of the power plant as a function of the distance from source.

The major burden of biomass power plant emissions are predicted to impact local air quality levels along the main wind directions (down- and up-valley), and to remain confined at the valley floor. The maximum effect is predicted at the source location for pollutants more affected by primary emissions (PM10 and SO_2) and for those that are the products of fast chemical transformation ($SO_4^=$). For those species, the impact of the power plant is reduced by 80% at a distance of 2 km. NO_2 and NO_3^-, on the other hand, take some time to build up by photochemical production and they produce the maximum impact downwind of the source. NO_2 increments reach the maximum at a distance 1–1.5 km from the power plant, and then decrease rapidly (reduced by 80% after 4 km). NO_3^- increments reach the maximum between 2 and 3 km from the source, and then slowly decrease (reduced by less than 50% at our domain edges). This peculiar behaviour is related to the chemistry of nitrate: after the formation of its gas precursor nitric acid, nitrate needs ammonia to enter the particulate phase (as ammonium nitrate). The availability of ammonia is limited by the prevailing formation of ammonium sulphate near the source, and it becomes sufficient for ammonium nitrate formation only when most of the sulphur is depleted. We note, however, that the total PM10 follows the behaviour of primary PM10, which constitutes the bulk of the simulated PM10 mass. From Fig. 5, we also estimate that the impact in the prevailing down-valley wind direction is slightly higher than in the up-valley direction.

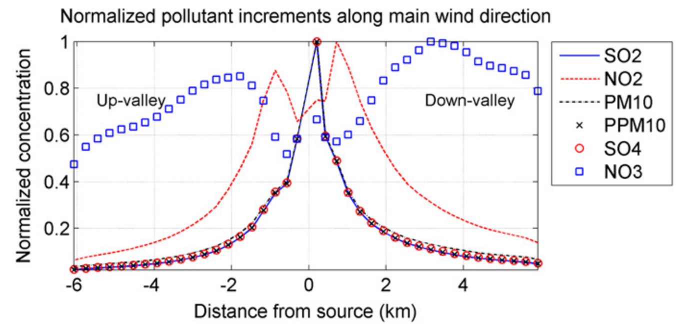

Fig. 5. Impact of power plant emissions as a function of the distance from source. Annual average pollutant increments are sampled along the main wind direction and normalized by the maximum concentration. PPM10 denotes primary fraction of PM10.

On average, the pollutant increments contributed by the plant are small (<0.5 $\mu g\ m^{-3}$) with respect to the thresholds fixed by the legislation for human protection (EC, 2008). However, they represent significant increments to ambient levels of NO_2 and PM10, especially in summer when the lowest values are observed (Fig. 3): in this season power plant emissions may locally enhance NO_2 and PM10 by 6 and 2.5 $\mu g\ m^{-3}$ (Table 3), respectively, which correspond roughly to an increase of 50% and 10%, respectively. The largest intake fraction is predicted for SO_2 and primary PM10 (both about 25 $\times 10^{-6}$), which is of the same order of typical *iF* determined for U.S. coal fired power plants (Evans et al., 2002). The *iF* of total PM10 (primary + secondary) is lower than that of primary PM10, because the source term *Q* is much larger and includes all SO_x and NO_x precursors. The *iF* is reduced to the South-East of the power plant, because of the lower population with respect to the North-West.

Hourly increments of NO_2 exceed the threshold of 200 $\mu g\ m^{-3}$ (EC, 2008) 141 times in our annual simulation, more than the allowed 18 times per calendar year, while SO_2 exceeds the threshold of 200 $\mu g\ m^{-3}$ 15 times. No violations of limits are simulated for PM10, but increments of a few $\mu g\ m^{-3}$ over the ambient levels might enhance the number of exceedances. However, assuming background PM10 levels are uniformly equal to PM10 daily observations at "Via Amiternum", this is never observed in our simulation.

Our results significantly differ from those published by the building firm, as shown in Table 3. The maximum annual average impact predicted by our simulation is about twice as much for SO_2 and PM10 (even considering only the primary fraction), while it is lower by ~60% for NO_2. Moreover, as illustrated in the previous paragraph, we calculated several limit violations due to the power plant pollutant increments only, which are not encountered in the building firm simulations. We do not have the details of the CALMET/CALPUFF configuration adopted by the building firm, and it is thus difficult to further comment on the disagreement of results.

The CALPUFF simulation also gives useful indications for the choice of an air quality monitoring site that should be installed to monitor the effect of future biomass power plant emissions.

Table 3
Impact of the power plant emissions on pollutant levels, in terms of increments ($\mu g/m^3$) simulated in the CALPUFF reference run. Results are compared with the assessment published by the building firm.

Pollutant	This study	Building firm[a]
Hourly Sulphur dioxide, SO_2		
Annual domain average	0.35	–
Max punctual annual avg.	11.7	6.3
Absolute max (alarm >500 $\mu g\ m^{-3}$)	567	–
$n > 350\ \mu g\ m^{-3}$ (max 24/y)	15	0
Max punctual annual avg. *iF* ($\times 10^6$)	25.2	–
Hourly Nitrogen dioxide, NO_2		
Annual domain average	0.52	–
Max punctual annual average	6.0	16
Absolute max (alarm >400 $\mu g\ m^{-3}$)	584	–
$n > 200\ \mu g\ m^{-3}$ (max 18/y)	141	0
Max punctual annual avg. *iF* ($\times 10^6$)	10.8	–
Daily Particulate, PM10		
Annual domain average	0.09	–
Max punctual annual avg.	2.5 (1.8)[b]	0.96
Absolute max	17.5 (12.7)[b]	–
$n > 50\ \mu g\ m^{-3}$ (max 35/y)	0 (0)[b]	0
Max punctual annual avg. *iF* ($\times 10^6$)	2.2 (25.2)[b]	–

[a] Information published on the public blog "Collettivo 99" by the building firm of the power plant (Futuris Aquilana s.r.l.): http://www.collettivo99.org/site/?p=2501.
[b] In parentheses, values for primary PM10 only.

Table 4
Sensitivity tests on CALPUFF results. For explanation of the simulation labels, please refer to the rightmost column of Table 2. Reference values are given in μg m^{-3}, while sensitivity values are given in percent difference with respect to the reference. "Winter" denotes 1–15 January 2008, "Summer" 1–15 July 2008. "avg" denotes the average annual increment calculated over the period and mediated over the domain, and "max" the maximum of average annual increment.

	SO_2				NO_2				PM10			
	Winter		Summer		Winter		Summer		Winter		Summer	
	avg	max	avg	max	avg	max	avg	max	avg	max	avg	max
Reference	8.2	188	14.2	338	3.9	240	12.6	584	1.7	8.5	3	8.6
% Diff.												
METEO	0	6	3	31	1	3	2	−11	0	6	−9	30
DISP	−20	15	−21	114	−17	30	−18	113	−21	14	−26	114
NOSLUG	0	−4	−2	−5	0	2	−1	11	0	−4	−4	−5
NOSPLIT	0	0	−2	0	0	0	−2	0	0	0	−4	0
CHEM	0	0	−2	0	−20	153	−24	35	5	1	−16	−1
O3x2	0	0	−2	0	6	30	−1	22	8	1	9	1
NH3d3	0	0	−2	0	0	0	−2	0	0	0	−11	0
NH3x3	0	0	−2	0	0	0	−2	0	0	0	5	0

According to the European legislation (EC, 2008, Annex III), "where contributions from industrial sources are to be assessed, at least one sampling point shall be installed downwind of the source in the nearest residential area". The Italian legislation (Lgs, 2010) accommodates the instance in its Annex III. In our case, there are two prevailing wind directions: up and down the valley axis. Residential areas are located within 1–2 km from the power plant in both directions. Our simulation suggests that the best choice might be the residential area to the North-West called "Bazzano" (the red triangle in Fig. 4), as opposed to "Monticchio" (green triangle). This is because (1) Bazzano is closer to the central axis of the power plant plume and will be more impacted by the power plant's emissions, and (2) Bazzano is on the side where the *iF* is higher due to its higher population.

In Table 4 we report the calculated increments for SO_2, NO_2 and total PM10 on a winter (1–15 January 2008) and a summer (1–15 July 2008) period. We note that the impact of the power plant on surface air quality levels is enhanced in summer, because of the increased vertical mixing that brings down more air masses from the 40 m high stack. In the table we also compare results of the reference simulation with several sensitivity tests, whose label were listed in Table 2. This is a useful analysis that allow us estimating the uncertainties on our results. The use of an input meteorology with wind speeds (generally positively biased) not corrected with observations (METEO test), induce both a more efficient horizontal advection and a more efficient vertical mixing due to enhanced mechanical turbulence with respect to the base case. The largest difference is an increase of ~30% of maximum SO_2 and PM10 impact in summer, and a decrease of 11% of NO_2 peak values in the same period. The use of alternative dispersion coefficients (DISP test) has the effect of lowering average values by ~20%, and increase peak values by more than 110% in summer. The use of circular puffs (NOSLUG test) yields reduced (5–10%) maximum values of SO_2 and PM10, and increased maximum values of NO_2 (up to 10%). The use of puff splitting (NOSPLIT test) has a negligible effect. Using the alternative chemical mechanism MESOPUFF-II (CHEM simulation), we obtain a significant modification to the NO_2 budget, with a reduction of ~20% of average values and an increase of ~150% and ~35% of peak values in winter and the summer, respectively, with other species left unchanged. The lack of an inter conversion between NO and NO_2 in this mechanism yield these elevated (and probably overestimated) values. NO_2 is also sensitive to a doubled ozone scenario, because more odd hydrogen radicals are available for NO to NO_2 conversion, and the net effect is an increase of 20–30% of NO_2 peak values. Finally, the choice of background level of ammonia has a negligible effect on the simulation. In conclusion, the model is found to be most sensitive to the calculation of dispersion coefficients and to the choice of the chemical mechanism. Overall, we may conservatively associate to CALPUFF results an uncertainty of 30% on the average increments and 100% on peak increments.

5. Conclusions and discussion

We presented an assessment of the impact of a biomass energy power plant proposed for installation in a narrow mountain valley in Central Italy, near the city of L'Aquila, on local air quality levels. The evaluation is carried out through a 1-year simulation with the CALPUFF model recommended by the U. S. EPA, driven with meteorological fields generated by the MM5 mesoscale model at 3 km horizontal resolution refined to include small scale features up to a resolution of 250 m using CALMET diagnostic model and observations from a surface weather station. The observations are needed to correct the MM5 positive wind speed bias.

We estimate significant increments to SO_2, NO_2 and PM10 ambient levels produced by the power plant within 1.5 km from the source. Although the average annual increments over the domain of interest are relatively small (<0.5 μg m^{-3}), we calculate 141 and 15 exceedances of the hourly limits for human protection of 200 μg m^{-3} and 350 μg m^{-3} (EC, 2008) for NO_2 and SO_2, respectively. In summer, NO_2 and PM10 ambient levels may be enhanced by up to 50% and 10%. The largest intake fraction, a measure of population exposure efficiency, is predicted for SO_2 and primary PM10 in 25×10^{-6}, similar to a typical U.S. coal fired power plant.

Our results are somewhat in contrast with those published by the building firm of the plant on the web (http://www.collettivo99.org/site/?p=2501). The maximum annual average impact is about twice as much for SO_2 and PM10 in our simulation, and we also report limit violations. The disagreement on the maximum increments is at the edge of modelling uncertainties, which we estimate to be 30% and 100% for average and peak values respectively.

We also suggest a site for an air quality monitoring station, which might be located in the nearest (<2 km) residential area on the main up-valley wind direction (Bazzano). However, our study also suggests that an optimal location of the power plant, aimed at reducing population risks from inhalation of emission products, should be at least 5 km away from the nearest residential area.

Further development of this work may include an assessment at the regional scale of the impact on additional secondary pollutants such as ozone and secondary organic aerosols, which require the use of a comprehensive Eulerian chemistry-transport model, and a complete life-cycle assessment of the power plant effect on landuse, air quality, radiative forcing, and deposition.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2012.08.005.

References

Abbasi, T., Abbasi, S.A., 2010. Biomass energy and the environmental impacts associated with its production and utilisation. Renewable and Sustainable Energy Reviews 14, 919–937.
Andreae, M.O., Merlet, P., 2001. Emission of trace gases and aerosols from biomass burning. Global Biogeochemical Cycles 15, 955–966.
Bennett, D.H., McKone, T.E., Evans, J.S., Nazaroff, W.W., Margni, M.D., Jolliet, O., Smith, K.R., 2002. Defining intake fraction. Environmental Science and Technology 36, 206A–211A.
Bianco, L., Tomassetti, B., Coppola, E., Fracassi, A., Verdecchia, M., Visconti, G., 2006. Thermally driven circulation in a region of complex topography: comparison of wind-profiling radar measurements and MM5 numerical predictions. Annales Geophysicae 24, 1537–1549.
Blond, N., Boersma, K.F., Eskes, H.J., van der A, R.J., Van Roozendael, M., De Smedt, I., Bergametti, G., Vautard, R., 2007. Intercomparison of SCIAMACHY nitrogen dioxide observations, in situ measurements and air quality modeling results over Western Europe. Journal of Geophysical Research 112, D10311. http://dx.doi.org/10.1029/2006JD007277.
Boman, C., Nordin, A., Thaning, L., 2003. Effects of increased biomass pellet combustion on ambient air quality in residential areas – a parametric dispersion modelling study. Biomass and Bioenergy 24, 465–474.
Cinque, G., Zauri, R., Di Carlo, P., Iarlori, M., Rizi, V., 2000. Sensible heat flux and boundary layer depth measurements by Doppler SODAR and sonic anemometer data. Il Nuovo Cimento 23, 331–350.
Cinque, G., Bernardini, L., de Franceschi, M., Ronconi, D., Zardi D., 2002. Study of local-scale meteorological dynamics over complex terrain by combined use of numerical models and measurements. In: Proc. ISARS 2002 11th International Symposium on Acoustic Remote Sensing and Associated Techniques of the Atmosphere and Oceans, Rome, 24–28 June 2002.
Delucchi, M.A., 2010. Impacts of biofuels on climate change, water use, and land use. Annals of the New York Academy of Sciences 1195, 28–45.
Di Carlo, P., Pitari, G., Mancini, E., Gentile, S., Pichelli, E., Visconti, G., 2007. Evolution of surface ozone in central Italy based on observations and statistical model. Journal of Geophysical Research 112 (D10316), 14.
Di Carlo, P., Pitari, G., De Luca, N., Battisti, D., 2009. Observations of surface radon in Central Italy. Environmental Geology 58, 431–436.
Dudhia, J., 1993. A nonhydrostatic version of the Penn State/NCAR mesoscale model: validation tests and simulation of an Atlantic cyclone and cold front. Monthly Weather Reviews 121, 1493–1513.
EC, 1999. Directive 1999/30/EC of the European Parliament and of the Council of 22 April 1999 Relating to Limit Values for Sulphur Dioxide, Nitrogen Dioxide and Oxides of Nitrogen, Particulate Matter and Lead in Ambient Air.
EC, 2002. Directive 2002/3/EC of the European Parliament and of the Council of 12 February 2002 Relating to Ozone in Ambient Air.
EC, 2008. Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on Ambient Air Quality and Cleaner Air for Europe.
EPA, 2000. Requirements for Preparation, Adoption, and Submittal of State Implementation Plans (Guideline on Air Quality Models); Proposed Rule. Environmental Protection Agency, 40 CFR Part 51.
Evans, J.S., Wolff, S.K., Phonboon, K., Levy, J.I., Smith, K.R., 2002. Exposure efficiency: an idea whose time has come? Chemosphere 49, 1075–1091.
Hanna, S.R., Chang, J.C., 1993. Hybrid Plume Dispersion Model (HPDM) improvements and testing at 3 field sites. Atmospheric Environment 27, 1491–1508.
Hess, P., Johnston, M., Brown-Steiner, B., Holloway, T., de Andrade, J.B., Artaxo, P., 2009. Air quality issues associated with biofuel production and use. In: Howarth, R.W., Bringezu, S. (Eds.), Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment, 22–25 September 2008, Gummersbach Germany. Cornell University, Ithaca NY, USA, pp. 169–194. http://cip.cornell.edu/biofuels/.
Howarth, R.W., Bringezu, S., Bekunda, M., de Fraiture, C., Maene, L., Martinelli, L., Sala, O., 2009. Rapid assessment on biofuels and environment: overview and key findings. In: Howarth, R.W., Bringezu, S. (Eds.), Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment, 22–25 September 2008, Gummersbach Germany. Cornell University, Ithaca NY, USA, pp. 1–13. http://cip.cornell.edu/biofuels/.
IPCC, 2011. Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN), Intergovernmental Panel on Climate Change, Working Group III – Mitigation of Climate Change.
Jacobson, M.Z., 2009. Review of solutions to global warming, air pollution, and energy security. Energy & Environmental Science 2, 148–173.
Jenkin, M.E., Clemitshaw, K.C., 2000. Ozone and other secondary photochemical pollutants: chemical processes governing their formation in the planetary boundary layer. Atmospheric Environment 34, 2499–2527.
Jonsson, A., Hillring, B., 2006. Planning for increased bioenergy use – evaluating the impact on local air quality. Biomass and Bioenergy 30, 543–554.
Levy, J.I., Spengler, J.D., Hlinka, D., Sullivan, D., Moon, D., 2002. Using CALPUFF to evaluate the impacts of power plant emissions in Illinois: model sensitivity and implications. Atmospheric Environment 36, 1063–1075.
Levy, J.I., Wilson, A.M., Evans, J.S., Spengler, J.D., 2003. Estimation of primary and secondary particulate matter intake fractions for power plants in Georgia. Environmental Science and Technology 37, 5528–5536.
D. Lgs, 155/2010. Decreto legislative 13 Agosto 2010, n. 155. Attuazione della direttiva 2008/50/CE relativa alla qualità dell'aria ambiente e per un'aria più pulita in Europa. Gazzetta Ufficiale 216 del 15/09/2010 (105pp).
MacIntosh, D.L., Stewart, J.H., Myatt, T.A., Sabato, J.E., Flowers, G.C., Brown, K.W., Hlinka, D.J., Sullivan, D.A., 2010. Use of CALPUFF for exposure assessment in a near-field, complex terrain setting. Atmospheric Environment 44, 262–270.
Protonotariou, A., Bossioli, E., Athanasopoulou, E., Dandou, A., Tombrou, M., Flocas, H.A., Helmis, C.G., Assimakopoulos, V.D., 2005. Evaluation of CALPUFF modelling system performance: an application over the Greater Athens area, Greece. International Journal of Environment and Pollution 24, 22–35.
Raes, F., Van Dingenen, R., Vignati, E., Wilson, J., Putaud, J.-P., Seinfeld, J.H., Adams, P., 2000. Formation and cycling of aerosols in the global troposphere. Atmospheric Environment 34, 4215–4240.
Ryerson, T.B., Trainer, M., Holloway, J.S., Parrish, D.D., Huey, L.G., Sueper, D.T., Frost, G.J., Donnelly, S.G., Schauffler, S., Atlas, E.L., Kuster, W.C., Goldan, P.D., Hubler, G., Meagher, J.F., Fehsenfeld, F.C., 2001. Observations of ozone formation in power plant plumes and implications for ozone control strategies. Science 292, 719–723.
Scire, J.S., Robe, F.R., Fernau, M.E., Yamartino, R.J., 2000a. A User's Guide for the CALMET Metorological Model. Earth Tech, Inc., Concord, MA.
Scire, J.S., Strimaitis, D.G., Yamartino, R.J., 2000b. A User's Guide for the CALPUFF Dispersion Model. Earth Tech, Inc., Concord, MA.
Searchinger, T.D., 2010. Biofuels and the need for additional carbon. Environmental Research Letters 5 (024007), 10.
Searchinger, T.D., Hamburg, S.P., Melillo, J., Chameides, W., Havlik, P., Kammen, D.M., Likens, G.E., Lubowski, R.N., Obersteiner, M., Oppenheimer, M., Robertson, G.P., Schlesinger, W.H., Tilman, G.D., 2009. Fixing a critical climate accounting error. Science 326, 527–528.
Szarka, N., Kakucs, O., Wolfbauer, J., Bezama, A., 2008. Atmospheric emissions modelling of energetic biomass alternatives using system dynamics approach. Atmospheric Environment 42, 403–414.
Whiteman, C.D., 1990. Observations of thermally developed wind systems in mountainous terrain. In: Blumen, W. (Ed.), Atmospheric Processes over Complex Terrain, vol. 23. Meteorological Monographs of the American Meteorological Society, pp. 5–42.
Whiteman, C.D., Doran, J.C., 1993. The relationship between overlying synoptic-scale flows and winds within a valley. Journal of Applied Meteorology 32, 1669–1682.
Whitman, T.L., Lehmann, C.J., 2011. Systematic under- and overestimation of GHG reductions in renewable biomass systems. Climatic Change 104, 415–422.