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THREE-DIMENSIONAL WIND FIELD ESTIMATES IN COMPLEX TERRAIN

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Abstract. Air pollution dispersion modelling in complex terrain is dependent upon adequate modelling of the three dimensional wind fields. This paper presents the results of the application of two different wind field models for simulating the winds in a complex terrain area with coastlines, valleys and mountains. We have applied one diagnostic and one prognostic wind field model which are currently being used at Norwegian Institute for Air Research (NILU) to estimate the atmospheric dispersion from local scale to mesoscale. The statistical performances of the estimated wind fields as against the corresponding measured values revealed that both models reasonably predict the wind field in a complex modelling area. When mesoscale circulations occur some differences are mainly encountered during transition period from e.g., the onshore sea breeze to off shore land breeze and vice versa. Comparisons have been performed with wind observation in a large number of measurement locations covering the model area for one month (November 1999).

Key words: wind field model, complex terrain, diagnostic model, prognostic model.

1. INTRODUCTION

The results of air pollution dispersion modelling in complex terrain are entirely dependent on adequate description of the three-dimensional wind field. A verification study of the model in a rather complex terrain has proven that the non-homogeneous and non-stationary winds play an important role in advecting the plumes. Several different procedures for modelling the three dimensional wind and turbulence fields have been developed and tested.

The topography strongly influences the boundary layer flow in such manner that the geographic variations either can modify the flow or in some cases generate circulations in conjunction with diurnal heating cycles.

Warming of mountain slopes by daytime sunlight or cooling by nocturnal radiation causes the air adjacent to the mountain to be warmed or cooled by conduction and turbulence. If the air near the mountain is at a different temperature than the ambient air at the same altitude over the centre of valley, then buoyant forces generate a circulation. Similar forcing occurs over flat surfaces where albedo or heat capacity differences generate a horizontally inhomogeneous temperature field.

Therefore, the effects induced by topography conduct to an inhomogeneous and non-stationary wind field, and a specific treatment is needed in this case.

By the other hand, in many real situations, ambient synoptic or mesoscale winds can modify, or even eliminate the weak geographic circulations.

This paper investigates two wind field-estimating approaches and compares the simulated results with the observed winds in the area.

One approach is based on a meteorological diagnostic model, which generates stationary wind field by interpolation of wind observations or assimilated data from mesoscale models. Algorithms describing the effects of the complex terrain are included in the diagnostic models. Such algorithms describe the blocking and deflexion of air flow by local terrain irregularities as well as the up slope and down slope flow through the heating and cooling of slopes (Ratto et al., 1994).

The second approach consist in a meteorological prognostic model that solves numerically the equations describing the atmospheric physical processes and supplies the fields of wind, turbulence and other meteorological variables in the modelling region. In the prognostic models the topography, surface characteristics, urban zones as well as the big water reservoir are taken into account. Meteorological prognostic models can be hydrostatic or nonhydrostatic (Pielke, 1986, 2000).

Despite their limitations, these approaches represent the most common way to generate consistent wind field in the majority of the advanced dispersion models that are used today (Sherman, 1978; Barna and Lamb, 1995; Pielke and Uliasz, 1998; Hurley, 2002).

The two analysed wind field models are part of two sophisticated dispersion models currently applied worldwide: TAPM (Hurley, P., 2002) and EPISODE (Slørdal, L.H., 2001).

Some verification studies regarding the performance of the two dispersion models and their meteorological components have been performed for both TAPM (Hurley et al., 2002; Physick et al., 2002) and EPISODE (Slørdal et al., 2003).

In this paper, the statistical performances of the two approaches are studied by comparing the predicted wind fields with the observed data fields in a complex terrain by making use of Boot statistical model (Hanna et al., 1991). In Section 2 the diagnostic and prognostic models are presented. The results obtained and corresponding conclusions are discussed in Section 3 and 4.

2. MODEL DESCRIPTIONS

Two procedures for generating the wind fields have been applied in this study. Short descriptions of the two wind field models are presented in the following chapters.

2.1. MATHEW Model

MATHEW (Sherman, 1978; Slørdal, L.H., 2002) is a diagnostic wind field model able to generate a three-dimensional wind field in a Cartesian grid, based on an arbitrary number of wind observations within the model domain. The model treats variable topography within the model domain, and computes a wind field that minimizes the variances between the observations and the calculated values. In addition the computed wind field is conserving the mass, e.g. a condition that is approximated in the model by requiring the flow field to be free of divergence ($\nabla \cdot \vec{V} = 0$).

2.2. TAPM Model

TAPM (Hurley, 2002) is a prognostic, incompressible, non-hydrostatic, primitive equation model with a terrain-following vertical coordinate for three-dimensional simulations.

The model solves the momentum equations for horizontal wind components, the incompressible continuity equation for vertical velocity, and scalar equations for potential virtual temperature and specific humidity of water vapour, cloud water and rainwater.

The model can run in a nested way, with a maximum number of 4 inner grids. The boundary conditions for the inner grids are provided from the course outer grids, by an interpolation procedure.

3. RESULTS

3.1. TEST AREA

The modelling area is bounded to the northeast by the sea, to the southwest by the 500 m high ridge running northwest southeast, and to the east by another ridge of similar height. A rather flat valley bottom extends about 16 km from the coastline and has an average width of about 10 km. The plain is open to the north.

The land-sea breeze is a dominant feature of the local meteorology, creates wind fields that oscillate through 180°, roughly perpendicular to coast. Historical data and estimates indicate that for more than 50% of the time the local wind field is de-correlated from the synoptic wind field.

Another type of local circulation may be represented by the katabatic winds during the nighttime and anabatic winds during daytime that blow along sloping terrain.

In the southeast of the modelling area a channelling effect in the valley between the two ridges should be presented.

The local topography and measurement sites are shown in Fig. 1 below.

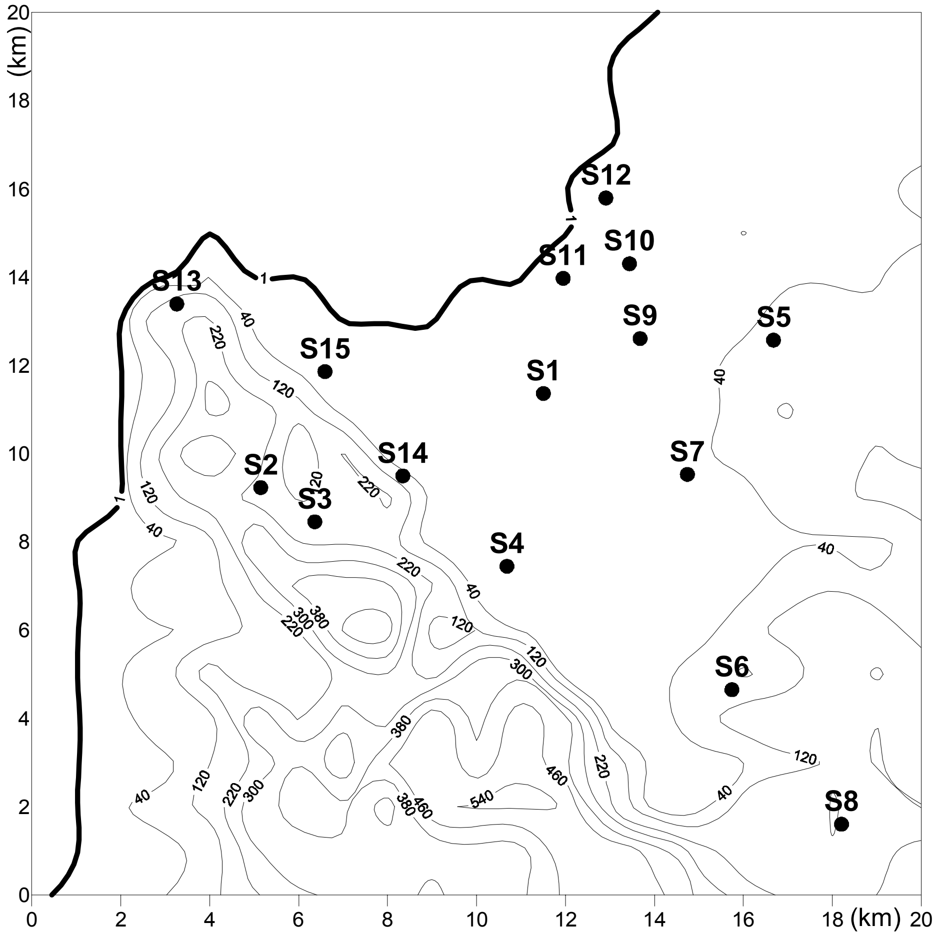

Fig. 1 – Modelling area showing land/sea and topography.
Also included are the available meteorological sites.

Due to the complex topographical features as well as the variability in surface conditions regional meteorological models cannot reproduce the local circulations.

The features of the local wind patterns will have to be estimated either by interpolation of a very dense network of local wind measurements or by local scale dynamical models. The interpolative methods can be used for diagnostic wind field estimates.

For prognostic models it will be necessary to scale down the wind field model to predict the fields on a local scale, i.e. on a scale of typical dimensions one to five kilometres. The TAPM model enables such procedures and may be used to a certain degree for this purpose.

The test area monitoring networks as presented in Fig. 1 consists of 14 air quality stations, which are also equipped with meteorological instruments for measuring wind speed, wind direction and temperature.

A detailed analysis (Mocioaca, G. and Sivertsen, B, 2003) that has included considerations regarding the position of the measurement points in the modelling area and their representativity related to different topographical effects has lead to a reduced number of 5 representative sites for surface measurements and 2 sites where upper air winds have been generated using the dynamical weather data from the TAPM model. These selected data were considered able to reproduce an average wind field in the test area and was used for the first run of MATHEW. These 5 stations were: S1– Centrally located and at 60 m is the most obvious choice, S5– Representative for Easterly inland flow, S3– Located at the top of the ridge, S13– Representative for sea breeze effects, S8– Representative for southerly flow and topographic channelling.

3.2. WIND FIELD MODELLED WITH MATHEW

For diagnostic wind field in the test area, the MATHEW meteorological pre-processor has been run in different conditions. This makes use of point measurements for wind and temperature and, through a mass-conserving algorithm that takes into account topography, converts these points into a physically consistent wind field.

As input data MATHEW requires: wind speed and wind direction at surface at least at one location, upper wind speed and wind direction, temperature gradient between two vertical levels at one location, topography field as well as a constant roughness length over the entire modelling.

When running such model, the first task should be the selection of the most representative measurement points that correctly reproduce the pattern of the wind field in the area. No strong local effects such as induced turbulence by buildings or other nearby obstacles should influence the measurements of wind speed and wind direction at the selected sites.

The MATHEW model produces more representative wind profiles when upper air data is also available. Unfortunately no such measured data are available in the test area, so instead output from TAPM dynamical weather model at 400 m was used as upper air wind data in the MATHEW at S1 and S13.

Two different runs of MATHEW including different measurement points were performed: case A includes observed data from S1, S5, S8 and S13; case B includes observed data from S1, S3 and S5.

The resolution of the model run was 1 km while the total grid size was 20 km × 20 km. In vertical a number of 10 layers with the following thickness 20, 30, 40, 50, 60, 100, 250, 500, 750 and 1200 m have been defined. The total model depth was thus 3000 m. The time period for the model run was one month, from 1 to 30 November 1999.

The model output is hourly, gridded values of wind speed and wind direction.

3.2.1. Wind direction modelled with MATHEW

The model estimations of wind speed and wind direction data have been compared with the observed data at the measurement points, which were not used as input data in the model.

The results have been divided into site locations: in the valley (S4 and S15), on the ridge (S2) or on the plain (S11).

The scatter plots in Fig. 2 show that the model (both runs) reflects well the land and sea breeze effects at the valley sites. At the station S15 (case A) the interaction between slopes flows and land or see breeze effect is partially reproduced by the model based on the measured data from S13 or S3 used as model input.

A strong channelling of southeasterly winds is generated at S4 by the model due to topographical effects along the main valley axis. However, the model cannot reproduce the local katabatic flows measured at this site during nighttimes. A small valley south of the site may influence the measured wind directions to give southerly and southwesterly winds during the night.

The sea breeze during daytime hours is well reflected at both sites by the MATHEW model.

The analysis for the elevated site S2 indicates that the MATHEW model is reflecting the measurements well at the ridge sites. This was expected, especially for Case B, which uses data from site S3, close to the S2. The sea breeze and land breeze are not as strongly channelled as at other sites, due to local and micro scale topographical effects. However, these effects are also reflected in the model.

The open plain site S11 is located very close to the shoreline. The model estimates show in both cases a fairly good agreement with the observed data and describe well both sea and land breeze effects. Small differences for onshore as well for offshore winds are still occurring. The 90 degrees observed offshore wind is turned to 120 degrees in the model, while the observed onshore winds are also slightly turned counter clockwise.

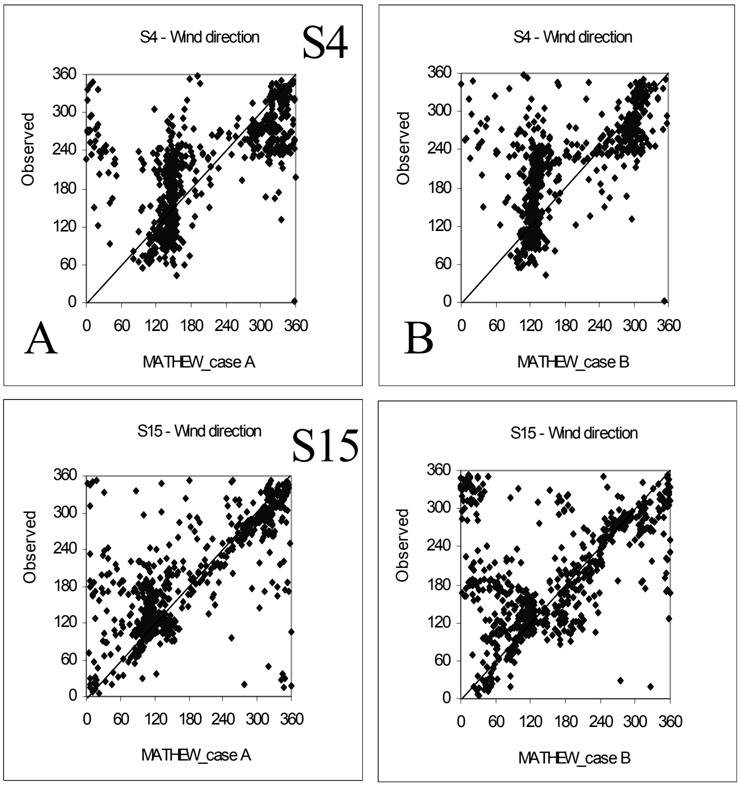

Fig. 2 – Scatter plots of the wind direction (degrees) modelled with MATHEW in case A, case B and the observations. The wind direction is measured at 10 m above ground, while the modelled wind direction corresponds to the middle of the first model layer (20 m thickness).

3.2.2. Wind speeds modelled with MATHEW

For model performance evaluation in case of wind speed a BOOT statistic model has been applied. Statistic calculated include mean, standard deviation (sigma), bias, normalised mean square error (nmse), correlation coefficient (cor), fraction of results where the modelled and observed wind speeds agree to within factor of two (fa2), fractional bias and fractional standard deviation (fs). The results are presented in Caption of tables Table 1.

The wind speeds were measured at 10 m above ground, while the modelled wind speed corresponds to the middle of the first model layer, which has a thickness of 20 m.

The MATHEW model performance in simulating the observed wind speeds depends on site.

At open plain sites S11 and valley sites S4, the cases A and B give good enough results.

Table 1 indicates better performance of the MATHEW Case A relative to MATHEW Case B for all sites. That is, MATHEW Case A has much lower fb and nmse and greater fa2 as compared to MATHEW Case B.

Table 1

BOOT statistics comparing observed and modelled wind speeds with MATHEW

Valley sites _S4

Model	Mean (m/s)	Sigma (m/s)	Bias (m/s)	Nmse $(m/s)^{-1}$	Cor	fa2	fb	fs
Observed	2.1	1.0	0.00	0.00	1.000	1.000	0.000	0.000
MATHEW_case A	2.5	1.4	0.43	0.23	0.697	0.782	0.190	0.283
MATHEW_case B	2.6	1.6	0.50	0.31	0.656	0.753	-0.218	-0.403

Plain sites_S11

Model	Mean (m/s)	Sigma (m/s)	Bias (m/s)	Nmse $(m/s)^{-1}$	Cor	fa2	fb	fs
Observed	2.1	1.3	0.00	0.00	1.000	1.000	0.000	0.000
MATHEW_case A	2.6	1.6	-0.56	0.17	0.868	0.850	-0.236	-0.167
MATHEW_case B	2.9	1.7	-0.78	0.22	0.862	0.814	-0.315	-0.221

Elevated sites_S2

Model	Mean (m/s)	Sigma (m/s)	Bias (m/s)	Nmse $(m/s)^{-1}$	Cor	fa2	fb	fs
Observed	3.4	1.8	0.00	0.00	1.000	1.000	0.000	0.000
MATHEW_case A	3.9	2.0	-0.51	0.13	0.799	0.897	-0.140	-0.132
MATHEW_case B	5.5	3.1	-2.11	0.41	0.872	0.783	-0.477	-0.533

As it may be seen the case B overestimates the wind speeds compared to MATHEW Case A and observed data.

The comparable values of the correlation coefficients indicate that wind speeds simulated by case A and case B have a dynamics similar to that of the observed wind speed data.

As an interpolation model MATHEW is strongly depending of the observed data as well as of the distribution of sites used in the model. One can conclude that the wind speeds on the open plain as well as at the valley site is better reflected than in the ridge.

3.3. WIND FIELD MODELLED WITH TAPM

The prognostic model TAPM has been operated for the area to create meteorological data such as wind speeds, wind direction, turbulence, vertical profiles and a number of boundary layer parameters. The meteorological data used as input by the model are provided by the synoptic scale analysis model (LAPS) and consists of six-hourly weather data on a longitude/latitude grid at 0.75 degree spacing (approximately 75 km).

The model has been run in the hydrostatic mode, in a three nested way starting with a 200 km × 200 km grid (20 × 20 cells, 10 km resolution), then 60 km × 60 km (3 km resolution) and finally 20 km × 20 km (1 km resolution). A number of 25 vertical layers have been defined. The total vertical model depth has been 8000 m.

The model output consists of wind field, temperature, boundary layer parameters, fluxes, turbulence field and also profile data for most of the parameters.

3.3.1. Wind direction: modelled and observed data

Using the scatter plots the modelled wind direction has been compared with observed data at different locations (Fig. 3). The wind direction is measured at 10 m above ground and the modelled one corresponds to the first model layer (10 m thickness) for all sites except for S1, which corresponds to the third model level (about 50 m above ground).

At meteorological site S1, TAPM can reflect relatively well the land breeze, while in case of sea breeze the model shows a spread of the results over a large range of wind sectors. The cases with badly corresponding wind directions are most probably due to quickly changing winds during transitional periods, which may be poorly reflected in the model.

At the elevated site S2 the model seems to be more sensitive at the see breeze effect (270 degrees) than during land breeze conditions. In the latter case the model seems to channel the wind along an axis at around 150 degrees, while the observation indicate a prevailing wind direction of around 90 degrees. At S13 the model produces in case of land breeze a similar channelling effect. Most of the land breeze cases are modelled at winds from southeast; 120-140 degrees.

At all the open plain sites the TAPM model produce a well defined land breeze, which is channelled around 120 degrees. The observations during these cases may vary from one site to another, dependent upon local influences in the observed winds. The sea breeze at S5 is very well reflected by the TAPM model, while at S11 there is a turning in the model results to blow from NNW compared to the observed more northerly winds at S11.

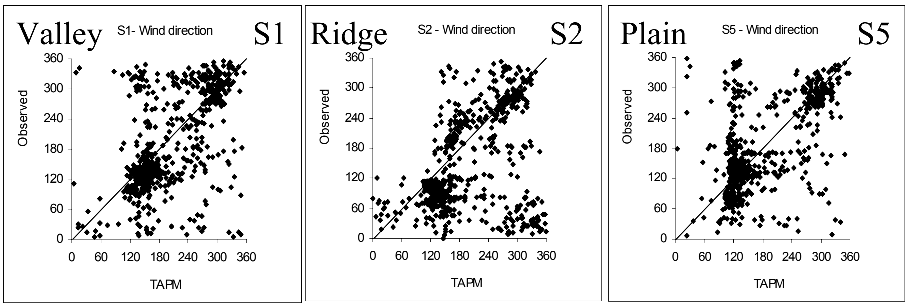

Fig. 3 – Scatter plots of the wind direction (degrees) modelled with TAPM and the observations at different sites. The wind direction is measured at 10 m above ground, the modelled wind direction corresponds to the first model layer (10 m thickness) at S4 and S15 while at S1 corresponds to the 3-rd model level, (approximately 50 m above ground).

From the results of wind field modelling using the TAPM model it may be stated that the main differences between the model estimated winds and the observed winds seem to be related to transitions periods. This especially relates to the transitional periods from sea breeze to land breeze. However, it may also relate to the morning transition from land breeze to sea breeze. It seems that the changes in wind directions occur faster in real life observations, than the model is able to reflect. The model for most of the sites adequately reproduces the prevailing wind directions related to land or see breeze.

3.3.2. Wind speed: modelled and observed data

The wind speeds estimated using the TAPM model has been compared to observed wind speeds, applying the same BOOT statistic model. The results are presented in Table 2.

The computed statistical measures given in Table 2 indicate better performance of the TAPM model for the elevated sites S2 as compared with valley and plain sites where the model simulated values significantly overestimate the observed data (fb equals to –0.22 and –0.44 as compared with –0.098). Also fa2 in case of S2 is greater than in cases of the sites S1 and S11. This means that 76% of the wind speeds are predicted within a factor of two in case of site S2 as compared with 67% and 53% for the sites S1 and S11. Also the correlation coefficient values show that the model predicted wind speeds for elevated sites S2 are more correlated with the measured wind speeds.

Table 2

BOOT statistics comparing observed and modelled wind speeds with TAPM

Valley sites _S1

Model	Mean (m/s)	Sigma (m/s)	Bias (m/s)	Nmse $(m/s)^{-1}$	Cor	fa2	fb	fs
Observed	3.7	2.1	0.00	0.00	1.000	1.000	0.000	0.000
TAPM	4.6	2.8	-0.83	0.41	0.490	0.671	-0.200	-0.283

Plain sites_S11

Model	Mean (m/s)	Sigma (m/s)	Bias (m/s)	Nmse $(m/s)^{-1}$	Cor	fa2	fb	fs
Observed	2.1	1.3	0.00	0.00	1.000	1.000	0.000	0.000
TAPM	3.3	2.3	-1.20	0.70	0.589	0.533	-0.446	-0.523

Elevated sites_S2

Model	Mean (m/s)	Sigma (m/s)	Bias (m/s)	Nmse $(m/s)^{-1}$	Cor	fa2	fb	fs
Observed	3.4	1.8	0.00	0.00	1.000	1.000	0.000	0.000
TAPM	3.7	2.3	-0.35	0.33	0.547	0.760	-0.098	-0.275

The TAPM model appears to overestimate the wind speed at most of the valley and open plain sites. This especially applies to winds stronger than about 6 m/s. At the ridge site, S2, the model more often predicts stronger winds than observed, but not as strong winds as in the valley. A study of these cases has shown that the model is generating a stronger land and sea breeze than indicated in the observations.

4. CONCLUSIONS

Both models reasonably predict the wind field in the modelling area, showing similar pattern in many cases. Differences are mainly encountered during transition period from the onshore sea breeze to off shore land breeze and vice versa.

With regard to the wind direction, the MATHEW model: (*i*) simulates well land and see breeze effect at the valley sites, (*ii*) estimates well the measured directions at the ridge site and at the site located near shoreline, and (*iii*) can not reproduce the katabatic flow measured at valley sites during the night. The MATHEW model has the possibility to reflect the sudden changes in wind direction better than the TAMP model.

As far as the wind speed is concerned, the MATHEW model skill in simulating the observed wind speed depends on sites. At the open plain and valley sites the run of cases A and B has given better results than in the ridge. The values of correlation coefficients indicate that simulated wind speeds have a dynamics similar to that of the observed ones.

The MATHEW model generates proper results as long as the observed data used in model interpolation estimates are representative and not influenced by local and micro scale effects at the measurement sites.

The TAPM model is able to predict a wind field that incorporates the physics of many processes that actually occur in the modelling area. The complete set of equations for wind, temperature and humidity field, together with the radiative scheme, cloud microphysics and boundary layer parameterisation has the capacity to describe the horizontal *unhomogeneities* in temperature fields induced by the influence of complex terrain. The effects of sea breezes and land breezes as well as any other effects that are generated by the horizontal radiative forcing have been well simulated by the model. A limitation of TAPM model is the fact that it cannot make evident the sudden changes in wind directions observed at most sites. As regard the wind speed, the computed statistical measures indicate that TAMP model has better performances for the elevated sites as compared with valley and plain sites where the model overestimates the measured values. Also the correlation coefficient shows that the simulated wind speeds for the elevated sites are more correlated with the measured wind speed values.

This study reveals the importance of the models that generate the meteorological input data for atmospheric dispersion models used for assessing the air quality as well as for interpreting the measured data in dispersion experiments.

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