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Impact of urban parameterization on high resolution air quality forecast with the GEM – AQ model

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Abstract

The aim of this study is to assess the impact of urban cover on high-resolution air quality forecast simulations with the GEM-AQ model. The impact of urban area on the ambient atmosphere is non-stationary and short-term variability of meteorological conditions may result in significant changes of the observed intensity of urban heat island and pollutant concentrations. In this study we used the Town Energy Balance (TEB) parameterization to represent urban effects on modelled meteorological and air quality parameters at the final nesting level with horizontal resolution of ~5 km over Southern Poland. Three one-day cases representing different meteorological conditions were selected and the model was run with and without the TEB parameterization. Three urban cover categories were used in the TEB parameterization: mid-high buildings, sparse buildings and a mix of buildings and nature. Urban cover layers were constructed based on an area fraction of towns in a grid cell. To analyze the impact of urban parameterization on modelled meteorological and air quality parameters, anomalies in the lowest model layer for the temperature, wind speed and pollutant concentrations were calculated. Anomalies of the specific humidity fields indicate that the use of the TEB parameterization leads to a systematic reduction of moisture content in the air. Comparison with temperature and wind speed measurements taken at urban background monitoring stations shows that application of urban parameterization improves model results. For primary pollutants the impact of urban areas is most significant in regions characterized with high emissions. In most cases the anomalies of NO_2 and CO concentrations are negative. This reduction is most likely caused by an enhanced vertical mixing due to elevated surface temperature and modified vertical stability. Although the outcome from this study is promising, it does not give an answer concerning the benefits of using TEB in the GEM-AQ model in an operational configuration. Additional long term evaluation would be required to better estimate the anthropogenic heat flux and to assess the urban impact in longer time scales (seasonal and annual average).

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1 Introduction

Impact of urban environment on meteorological processes is a well-known phenomenon and in consequence has an impact on pollutants concentration patterns in proximity to conurbations. Measurements-based studies over different cities allowed formulation of a general concept describing differences in atmospheric structure between urban and rural areas. Due to high spatial and temporal variability of emissions sources as well as complex flow patterns, concentrations of air pollutants are characterized by large gradients. Advective transport of pollutants emitted over a city may also impact suburban areas.

Representation of urban process in complex meteorological and air quality models is an active area of research (Fisher et al., 2005; Baklanov, 2006; Baklanov et al., 2010). Results from a 1-D model of energy balance over a city show very good agreements with observations. However, applications in complex 3-D operational models are still challenging (e.g. Hamdi and Schayes, 2007; Baklanov et al., 2008; Oleson et al., 2008).

In the case of simulations with grid resolution of a few kilometres, urban structures became grid-scale features which indicated the need for more accurate description. However, the applicability of many physical parameterizations is questionable at that resolution, and increasing complexity of parameterizations leads to additional uncertainties. In addition, the lack of high resolution emission inventories, problems with proper estimation of anthropogenic heat fluxes, and an insufficient number of representative measurements for model evaluation can introduce significant discrepancies between modelling results and observations.

The aim of this study is to assess the impact of urban cover on a high-resolution semi-operational meteorological and air quality forecast calculated with the GEM-AQ model (www.EcoForecast.eu). The main purpose of the forecast is to provide information to relevant authorities and to society on possible exceedances of pollutants concentration levels. The focus is on urban areas due to population density and highest exposure.

In the previous high-resolution simulations undertaken with the GEM-AQ model over Europe/Poland and North America, the city area was represented in terms of enhanced emission fluxes only. As the host meteorological model treats urban area as one of the landuse categories taken into account, aerodynamic effects were also included. Presented work is a pilot study for the GEM-AQ model. The purpose is to assess whether the impact of urban parameterisation in the on-line air quality simulations is interpretable in the meteorological context and could be anticipated based on theory. Changes in meteorological and air quality parameters due to urban effects were analysed extensively.

2 TEB (Town Energy Balance) parameterization

To represent urban effects the TEB (Town Energy Balance) parameterization (Masson, 2000) implemented in the GEM model (Lemonsu et al., 2009) was used. The TEB parameterization coupled with the MESO-NH model was tested for selected cities in France (Lemonsu and Masson, 2002; Lemonsu et al., 2005, 2006). The GEM model with the TEB parameterisation was tested only for Oklahoma City with the resolution of 300 m against the dataset from the Joint Urban 2003 field experiment (Lemonsu et al., 2009). Also, the TEB parameterisation was tested for Montreal Urban Snow Experiment (MUSE) 2005, but as an off-line urban model (Lemonsu et al., 2010). To the knowledge of the authors, there are no published experiments related to applications of GEM with TEB in the resolution of a few kilometers. Also, such configuration has never been used in the on-line air quality simulations. The authors introduce a number of changes to the original model code to improve consistency between the description of the aerodynamic roughness in the GEM model with the predefined values used for urban classes in the TEB parameterization.

The TEB scheme describes a city as an ensemble of idealized urban canyons formed of roofs, walls and streets (Oke, 1987). Separate surface energy budgets are solved for each of these three different canyon surfaces. TEB takes into account the 3-D geometry

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of urban surfaces for radiative trapping and shadow effects, heat storage, mean wind, temperature and humidity inside street canyons, and water and snow on roofs and streets. Additional assumptions are the isotropy of the street orientations and no crossing streets.

The TEB parameterization accounts for twelve categories of urban morphology. Some of the default parameters hardcoded for the GEM model for each urban-land-use class are summarized in Table 1.

3 EcoForecast.eu air quality forecasting system

The forecasting system is based on the GEM-AQ model (Kaminski et al., 2008). GEM-AQ is a comprehensive chemical weather model in which air quality processes (chemistry and aerosols), tropospheric chemistry are implemented on-line in the operational weather prediction model, the Global Environmental Multiscale (GEM) model, developed at Environment Canada (Côté et al., 1998).

The regional forecast is computed on a global variable grid with a total of 200 by 182 grid points. The core part of the grid has 110 by 110 grid points and covers Europe with the uniform resolution of 25 km (0.22°) (Fig. 1). In the vertical there are 28 hybrid levels, with the top at 10 hPa. The forecast horizon is 78 h (starting 18:00 UTC the day before, spin-up period 6 h) with a time step of 600 s. For the self-nested high resolution simulation a limited area mode is used. Boundary conditions are provided every 1 h. A limited area high-resolution forecast is calculated on a 100 by 100 grid with a resolution of 0.0625° (rotated computational equator). The forecast is calculated for 75 h (starting 21:00 UTC the day before, spin-up period of 3 h, starting from third hour of the regional forecast) with a time step of 120 s.

As the presented work is a first stage of testing of the potential applicability of the TEB parameterisation in the operational high-resolution air quality forecast, the configuration setup and boundary conditions are exactly the same as in operational configuration.

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4 Urban land-use – simplified description

The nested computational domain covers the region of approximately 800 × 800 km. It would be difficult to make more detailed analysis for all cities in the domain. Moreover, the resolution of 0.0625° is relatively coarse in terms of urban morphology representation. The authors propose to represent the urban land-cover in a simplified way, assuming that at that resolution any urban area can be represented with only three mutually exclusive urban cover categories – representing city centre, middle suburbs and outer suburbs.

4.1 Morphology of selected cities in the modelling domain

To select the TEB land cover categories that best represent the features of major cities within the domain, an analysis of their built-up structure has been undertaken:

- In Warsaw (500 km^2) there are different types of buildings, including single houses and skyscrapers. In the city centre there are ~40 buildings higher than 65 m. Dominant building height is 20 m on average (ranging from 15 to 30 m in different suburbs);
- In Lodz (300 km^2) the dense built-up areas dominate. The average height of buildings is ~15–30 m;
- Average built-up height in Krakow (327 km^2) is in the range of 15–30 m. In the city centre the buildings are lower (2–3 stories), with a height of 10 m. Buildings in surrounding suburbs are higher (15–30 m);
- In Katowice (165 km^2) the average building height is 10–15 m. In the city centre and surrounding suburbs there are single buildings as high as 70 m; however, most dominant are sparse buildings;
- Wrocław (293 km^2) built-up area is dominated by 3–4 storey buildings, with the average height of 15–30 m;

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– The centre of Poznan (262 km^2) is characterized by 3–5 storey houses and single high buildings (70–80 m). The average height of the buildings in surrounding suburbs is 15–30 m.

4.2 Urban land-cover for GEM

In the GEM model used without TEB parameterization, urban areas are treated as sand with a large roughness length. Land cover in the GEM model is represented by twenty six classes, including water bodies, ice, and various kinds of soils and vegetation covers (Loveland et al., 2000). The urban class is defined as a fraction of built-up area in the grid cell (Fig. 2). For most of the cells the built-up area is in the order of 30 %. The information on the urban fraction in a grid cell was used to define the input data for the TEB parameterization. Two approaches were tested (Table 2).

In the first approach (UF_1), the TEB class "mid-high buildings" represented city centre. The default average building height is 25 m, and the anthropogenic heat flux (taken as a sum of traffic and industrial sources) is 30 W m^{-2}. Middle suburbs ("very low buildings" in the TEB classification) are characterized with the same value of anthropogenic heat release, but average building height is lower and set at 8 m. To represent outer suburbs, a "low-density suburbs" class was used. The average building height is the same as for very low buildings, but the value of the anthropogenic heat flux is reduced by half (15 W m^{-2}). The thresholds assumed to distinguish the three classes were 35 % and 5 % of built-up area, which indicated that for most urban regions the higher value of anthropogenic heat flux was assumed. Also, the aerodynamic effects were different in city centre and surrounding suburbs due to a significant difference between assumed average building heights.

For the second approach (UF_2), based on the grid resolution, it was assumed that in most cases the average building height in towns in the computational domain is lower. For the city centre a "low building" TEB class was attributed, characterized with the average built-up height of 13 m and the anthropogenic heat flux of 30 W m^{-2}. Middle

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suburbs were described as "sparse buildings" with very similar average building height (12 m) and anthropogenic heat flux reduced by half. The outer suburbs are described as "mix of built/nature" class, characterized with average building height of 8 m and no anthropogenic heat flux.

In the first approach the anthropogenic heat flux is more significant, but strong aerodynamic effects will be limited to urban centre. Major differences are connected with city centre, which should have the most significant impact. In the case of Katowice and Krakow, in UF_2 approach there is no "city centre" category.

5 Analysis

The impact of urban area on the ambient atmosphere is non-stationary and short-term variability of meteorological conditions may result in significant changes of the observed intensity of urban heat island (e.g. regional wind speed, cloudiness). In the operational setup the GEM-AQ model starts every 24 h from analysed meteorological fields. Objective analysis is prepared on a global grid with resolution ~35 km using the 4D-Var system (Gauthier et al., 2007). Thus, fine scale meteorological characteristics that result from the TEB parameterization are not carried between simulations. As the purpose of the study is connected with application to operational forecast, the focus is on the interpretation of the short term variability.

Three one-day cases representing different meteorological condition were selected:

- 6 November 2010 (frontal passage),
- 3 January 2011 (low wind, clear sky conditions, cold air mass)
- 29 March 2011 (moderate wind and cloudiness).

For each case study three model simulations were undertaken – a reference run without TEB parameterization and "urban scenarios" taking into account the two urban land cover approaches (UF_1 and UF_2).

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5.1 Urban cover description sensitivity study

Despite the differences in urban land cover description, the results from UF_1 and UF_2 scenarios are very similar. Most significant differences were found for 3 January 2011 case (Fig. 3). Comparison of the fields of temperature anomalies shows that there are a few differences in local structures, which is probably caused by smaller value of anthropogenic heat flux prescribed for the "middle suburb" class in UF_2. Wind speed anomalies are slightly lower in UF_2 scenario; there are also more locations with small positive anomalies.

The discrepancies in spatial pattern of primary pollutants concentration anomalies obtained for two alternative scenarios are insignificant and result from slight differences in average wind speed and vertical stability in the lowest model layers.

Assuming that the spatial distribution of anomalies for all analysed parameters and the magnitude of the differences is very similar in both urban scenarios, further analyses are presented only for UF_1 approach. To analyze the impact of urban parameterization on modelled meteorological and air quality parameters, the anomalies in the lowest model layer for the temperature, wind speed and pollutants concentrations were calculated.

5.2 Results for 6 November 2010

On 6 November 2010 meteorological conditions over Central Europe were dynamically changing. Low pressure system located over Germany moved eastward. Frontal systems crossing the area of Poland caused an inflow from the southern direction in the morning (warm front) and the rapid change of the wind direction associated with cold front passage. The average wind speed was in the range of 3–5 $\mathrm{m\,s^{-1}}$. The sky was overcast, with a wide zone of precipitation (Fig. 4).

Analysis of temperature anomalies (calculated as a difference between "urban" and "non-urban" scenarios) shows that in this case the impact of the TEB parameterization on model results was not significant. A weak urban heat island developed in

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the morning over the largest cities, but during the daytime, due to relatively strong wind speed, the temperature differences between urban and rural sites were insignificant. UHI effect appeared again during night time after frontal passages. In the case of wind speed, the average wind module was lower over most urban areas by about 0.5–1.5 $m\,s^{-1}$ (Fig. 5). The magnitude of wind anomalies was connected with the regional wind speed. For specific humidity the model showed a decrease of water vapour content over the largest cities.

Due to strong advection, the spatial pattern of the anomalies for NO_2 and O_3 are not related to the location of cities, although the largest differences occurred over Warsaw agglomeration. In general, NO_2 concentrations are slightly lower for "urban" scenario (up to 5 ppbv) and in consequence, over the same regions O_3 concentration are slightly higher (Fig. 6).

5.3 Results for 3 January 2011

On 3 January 2011 the meteorological situation over central Europe was influenced by a high pressure system centred over France. Light/moderate cloud cover as well as low wind conditions favoured temperature decrease – depending on the location – from −10 °C to −5 °C (Fig. 7).

In this case, the impact of urban areas is significant and spatial pattern of anomalies for meteorological and air quality parameters is closely related to the location of the urban mask. Temperature anomalies are positive over most cities in the domain and the differences between rural and urban area increased over the day by up to 5–6 °C. Also, there are negative anomalies, but this effect was non-systematic and usually the anomalies were close to zero. Wind speed reduction over city areas is on average 1–1.5 $m\,s^{-1}$. In contrast to the 6 November 2010 case, where the magnitude of anomalies was connected to the regional wind speed, the largest differences are located over areas with the biggest built-up fraction (Fig. 8). The pattern of specific humidity anomalies is very complex. Positive and negative differences in the range of ±0.5 $g\,kg^{-1}$ were present not only over the cities but over the entire domain.

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The analysis of pollutants concentration anomalies is ambiguous. Over most of the domain the differences of NO_2 concentrations are in the range of ±1 ppb (Fig. 9). Small positive anomalies (~2 ppbv) are located over Warsaw and downwind from Katowice agglomeration. However, over Katowice the difference between "urban" and "non-urban" scenario is negative and ranges up to 10 ppbv. Similar pattern is observed in the case of CO concentration fields. The spatial pattern of anomalies seems to be connected with the location of emission sources in the cities or nearby, rather than with the built-up density and height.

5.4 Results for 29 March 2011

On 29 of March 2011 a weak high pressure region established over Central Europe. The wind pattern was governed by a low trough from over Scandinavia (Fig. 10). The inflow of air masses was from the north-west direction and the average wind speed was in the range of 3–4 $m\,s^{-1}$. Moderate cloudiness dominated over the modelling domain.

In this case the model generated urban heat island effect over the biggest cities in the north-western part of the domain. The temperature anomalies for Warsaw, Poznan, Lodz and Wrocław over city centre reached 10 °C. It is not clear if lack of this effect is due to the assumed urban land cover or differences in meteorological situation between the north-western and southern parts of the domain. Differences in modelled average wind speed between the analyzed scenarios were relatively small – in the range of ±0.5 $m\,s^{-1}$. The pattern of anomalies is only partly related to cities locations. Over the centre of Warsaw, Lodz and Poznan there is local increase of the average wind speed. However, over the surrounding suburbs, average wind speed was lower as compared to the reference run (Fig. 11). Specific humidity anomalies were negative over the entire domain and the spatial pattern was related to the location of urban areas.

Anomalies of air pollutants concentrations are negative over Warsaw, Lodz, Wrocław, Katowice and Krakow. NO_2 concentration decreased by ~5 ppbv and CO by ~50 ppbv (Fig. 12). O_3 anomalies are closely related to the NO_2 pattern – in regions where NO_2 decreased, the ozone concentrations were higher by ~2–5 ppbv.

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5.5 Comparison with measurements

For the preliminary evaluation the measurements taken at urban background air quality monitoring stations were used. The meteorological measurements were available for all analysed days only at three stations: Warszawa-Targowek, Krakow Nowa-Huta, Wroclaw-Bartnicza. The location and characteristics of the stations is given in Table 3. It should be noted that these stations are located not in the city centers but in the suburbs.

Modelled temperature and wind speed taken for the comparison represent the average value calculated for the lowest model layer (the average thickness is ~27 m).

In the case of Warszawa-Targowek and Krakow Nowa Huta modelled temperature (both urban and non-urban scenarios) is underestimated in all three cases. For Wroclaw-Barnicza station the model tends to overestimate the near-surface temperature (Fig. 13). The impact of the TEB parameterization on modelled temperature depends on the weather during the analysed day and on the properties of the city. On 6 November 2010 the difference between temperatures calculated with urban and non-urban scenarios is very small for Warszawa-Targowek and Krakow NowaHuta. In Wroclaw-Bartnicza the positive anomaly for the TEB scenario is noted during nighttime. On 3 January 2011 the differences between the two scenarios are most significant, and for the simulation period the temperature is systematically higher for urban scenario than for non-urban at each monitoring site. The average slope of temperature changes is reproduced correctly. On 29 March the observed temperature shows diurnal cycle due to radiation. For two stations (Warszawa-Targowek and Wroclaw-Bartnicza) some phase shift in the morning temperature increase between modelled and observed series is noted (Fig. 14). Differences between urban and non-urban scenario are noticeable during early morning and evening/nighttime. In Krakow-Nowa Huta the impact of urban parameterisation is not significant for that day.

Comparison with measurements shows that the impact of the TEB parameterisation (with the default settings) is visible in the situation when solar radiation has no impact

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on surface heating – case of winter weather on 3 January or night hours on 29 March. In some cases, modelled slope of the temperature increase in the morning is stronger than observed, while in the afternoon modelled temperature decrease was more rapid. This requires further analysis of modelled surface fluxes variability in different regimes.

For the wind speed, at two stations – Warszawa-Targowek and Krakow-Nowa Huta – the modelled wind speed is overestimated and application of urban parameterisation reduces the bias (Fig. 15). In most cases the general variability pattern is reproduced correctly. At Wroclaw-Bartnicza station the agreement between modelled and observed wind speed is good.

6 Conclusions

The GEM-AQ model was used in a high resolution configuration with urban parameterization taken into account. Although the urban structure representation was simplified, the model response was correct in terms of magnitude of the anomalies and the relation to meteorological conditions. All three case studies were selected for a cold period, hence the modification of radiation budget due to differences in albedo and emissivity of the urban surface was minimized.

To assess the urban heat island effect the differences between "urban" and "non-urban" scenarios for the air temperature in the lowest model layer were calculated. In each case the spatial distribution of UHI was different. Plausibly there are two independent factors:

- regional wind speed,
- magnitude of anthropogenic heat flux.

For the 6 November 2010 case, the wind speed was strong enough to prevent the accumulation of warmer air mass over the city. For the 3 January 2011 case, in the low-wind

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conditions many local UHI structures developed, especially over cities described with "city centre" and "middle suburb" built-up classes. On 29 March 2011, characterized with moderate regional wind, the UHI developed only over the largest cites.

The average regional wind speed is reduced in the presence of urban areas. This reduction is more significant in the case of strong wind speed (6 November 2010 case). The built-up structure seems to have a smaller impact.

The analysis of specific humidity anomalies indicate that the use of the TEB parameterization leads to a reduction of moisture content in the air. The difference is small but systematic over the entire domain. It should be noted that during spring or summer this effect could be more significant.

Concerning the primary pollutants concentrations, the impact of urban areas is most significant in regions characterized with high emissions. In most cases the anomalies of NO_2 and CO concentrations are negative. The reduction is probably caused by the enhanced vertical mixing due to elevated surface temperature and modified vertical stability. In some cases the increase of concentrations is probably due to accumulation related to a reduced wind speed in weak UHI conditions. Over the cities area, the O_3 concentration pattern is closely related to the spatial variability of NO_2 concentrations. The negative anomalies of NO_2 correspond to increase of ozone concentrations. During spring and summer, when photochemical processes are active, the O_3 variability would probably be more complex. The impact of TEB parameterization on pollutants concentration is not constrained to urban areas, but also influences regions located downwind and near industrial area.

Concerning the urban land cover description, in the given spatial resolution the differences between the two alternative surface description approaches were relatively small. This might indicate that in the resolution of a few kilometers, the simplified description of urban structure would be sufficient and changes of the properties, such as building height or the anthropogenic heat flux, do not change the results substantially.

Preliminary comparison with temperature and wind speed measurements taken at urban background monitoring stations shows that application of urban parameterization improves modelled results. In the case of temperature, the temperature increase related to anthropogenic heat flux release and modified surface radiative properties is present in low-wind conditions and limited solar irradiance. In case of 29 March case study, during the daytime the TEB parameterization does not have impact on modelled maximum temperature as compared to non-urban scenario. Time shift in the morning temperature rise requires further analysis. For the wind speed the pattern is more consistent. For all analyzed monitoring sites the modelled wind speed for the configuration with urban parameterization was reduced as compared to non-urban scenarios.

Although the outcome from this sensitivity study is promising, it does not give an answer concerning the benefits of using the GEM-AQ model with the urban parameterization as an operational configuration for EcoForecast.eu. Additional experiments will be undertaken to better estimate the anthropogenic heat flux and to assess the urban impact in longer time scales (seasonal and annual average).

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Table 1. Urban land-use categories in TEB – default settings for selected parameters in the GEM model.

No	TEB urban cover	Average building height	Anthrop heat flux	Built-up fraction	Grass fraction	Tree fraction	Bare soil fraction
1	High buildings	39	30	0.95	0.03	0.02	0.00
2	Mid-high buildings	25	30	0.90	0.05	0.05	0.00
3	Low buildings	13	30	0.90	0.05	0.05	0.00
4	Very low buildings	8	30	0.85	0.10	0.05	0.00
5	Industrial areas	8	50	0.85	0.00	0.00	0.15
6	Sparse buildings	12	15	0.40	0.30	0.30	0.00
7	Roads and parking areas	5	30	0.98	0.02	0.02	0.00
8	Road borders	5	30	0.70	0.15	0.15	0.00
9	High-density suburbs	5	15	0.44	0.28	0.28	0.00
10	Mid-density suburbs	5	15	0.27	0.37	0.36	0.00
11	Low-density suburbs	8	15	0.18	0.35	0.47	0.00
12	Mix of built/nature	8	0	0.25	0.38	0.37	0.00

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Table 2. The definition of TEB classes based on default GEM model input information (urban fraction in a grid cell).

Approach	Build-up style	TEB class	TEB building height	Anthropogenic heat flux	GEM urban fraction
UF_1	City centre	Mid-high buildings	25	30	>=35
	Middle suburbs	Very low buildings	8	30	[5, 35)
	Outer suburbs	Low-density suburbs	8	15	<5
UF_2	City centre	Low buildings	13	30	>=50
	Middle suburbs	Sparse buildings	12	15	[10, 50)
	Outer suburbs	Mix of built/nature	8	0	<10

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Table 3. Location and characteristics of monitoring sites.

Station name	Longitude	Latitude	City	Station type
Warszwa-Targówek	21.039	52.285	Warsaw	Urban background
Krakow-Nowa Huta	20.052	50.068	Krakow	Urban background
Wrocław-Bartnicza	17.141	51.116	Wrocław	Urban background

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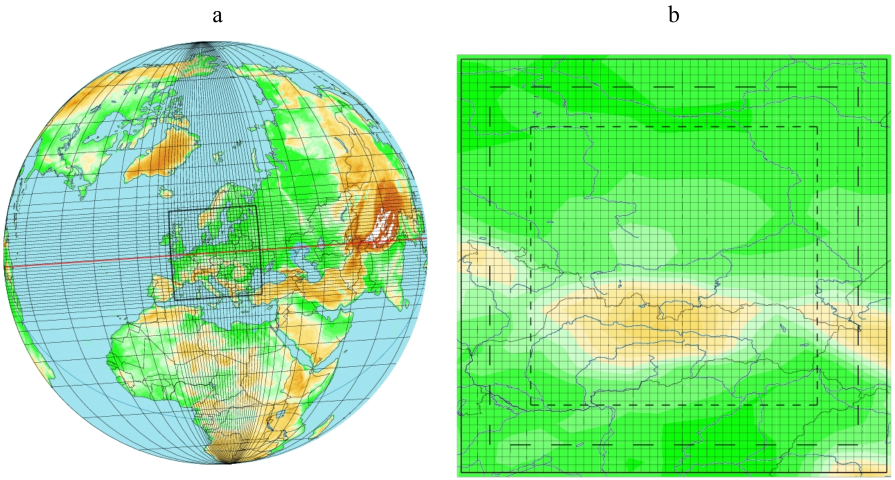

Fig. 1. GEM-AQ grid setup for EcoForecast.EU: **(a)** global variable grid – 0.22° over Europe; **(b)** nested LAM grid 0.0625°.

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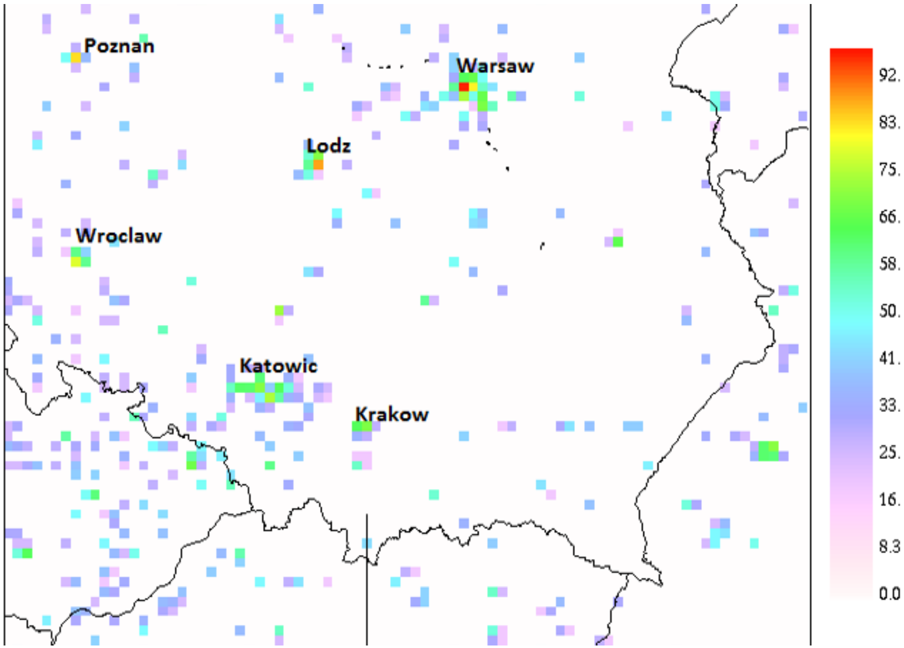

Fig. 2. Urban fraction class – default GEM input data generated from GenGeo interface for the nested LAM grid.

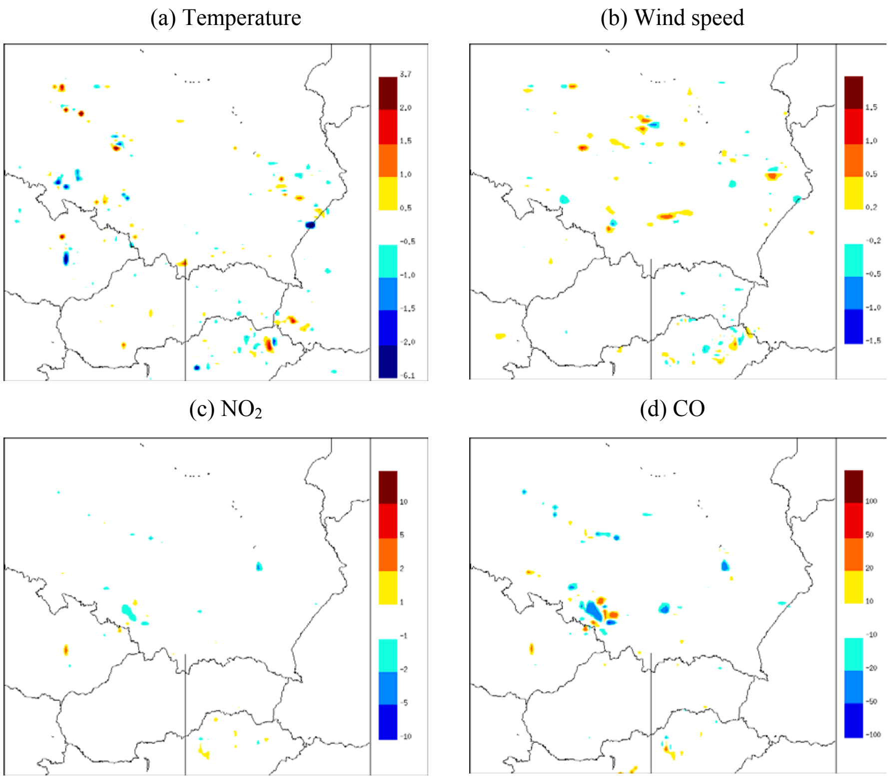

Fig. 3. Differences (UF_2–UF_1) of the anomalies calculated for two alternative urban land-use descriptions for 3 January 2011, 12:00 UTC.

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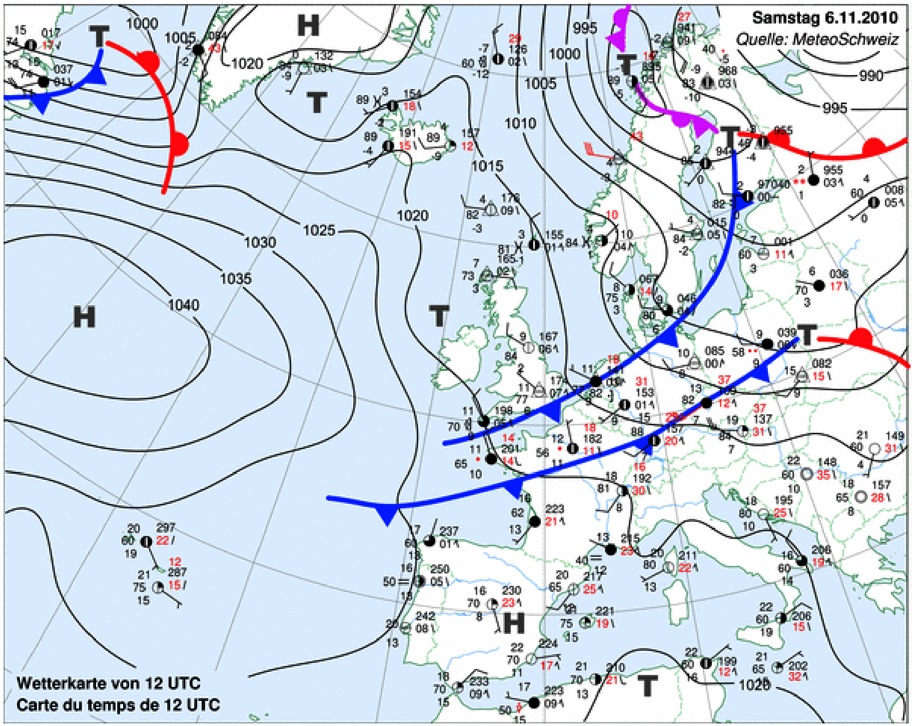

Fig. 4. Meteorological situation on 6 November 2010, 12:00 UTC (source: MeteoSchweiz).

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(a) Temperature anomaly (b) Wind speed anomaly

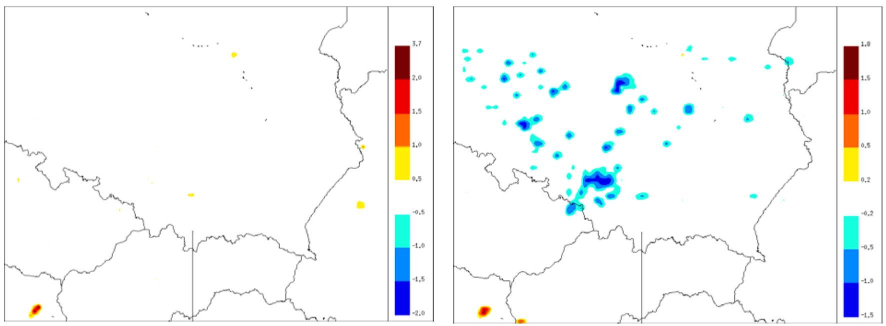

Fig. 5. Temperature **(a)** and wind speed **(b)** anomalies calculated as a difference between "urban" and "non-urban" scenarios – 6 November 2010, 05:00 UTC.

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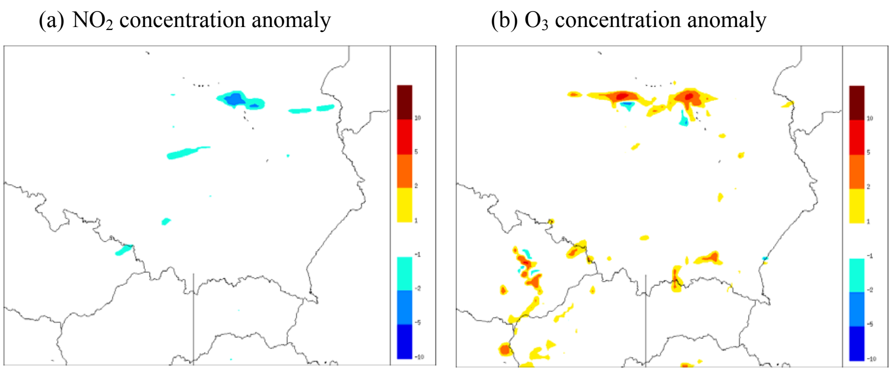

Fig. 6. NO$_2$ **(a)** and O$_3$ **(b)** concentration anomalies calculated as a difference between "urban" and "non-urban" scenarios in the lowest model layer – 6 November 2010, 15:00 UTC.

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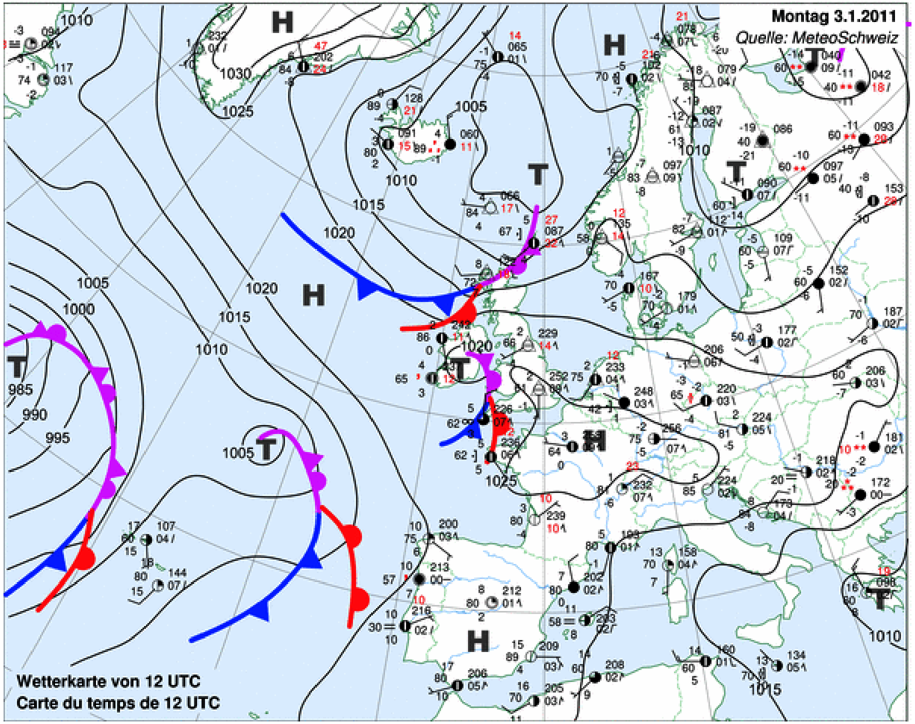

Fig. 7. Meteorological situation on 3 January 2011, 12:00 UTC (source: MeteoSchweiz).

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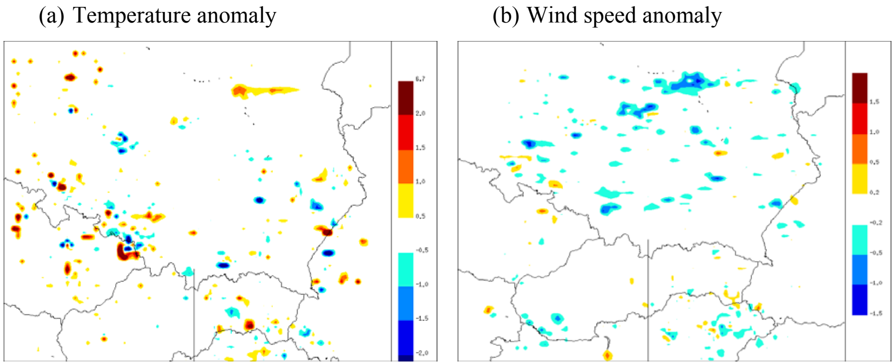

Fig. 8. Temperature **(a)** and wind speed **(b)** anomalies calculated as a difference between "urban" and "non-urban" scenarios – 3 January 2011, 12:00 UTC.

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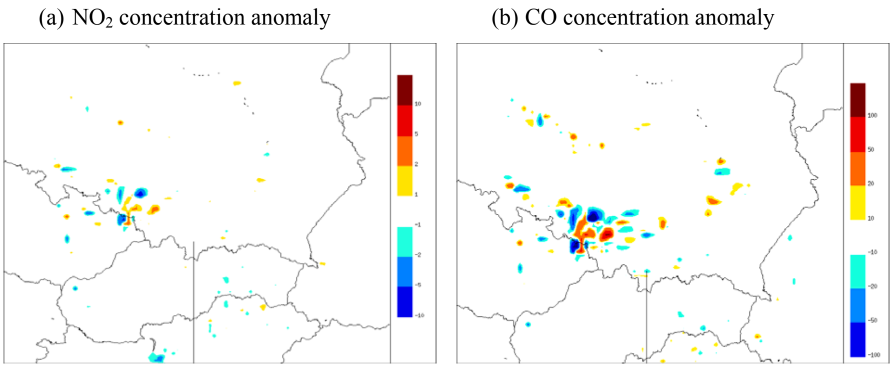

Fig. 9. NO_2 **(a)** and CO **(b)** concentration anomalies calculated as a difference between "urban" and "non-urban" scenarios in the lowest model layer – 3 January 2011, 12:00 UTC.

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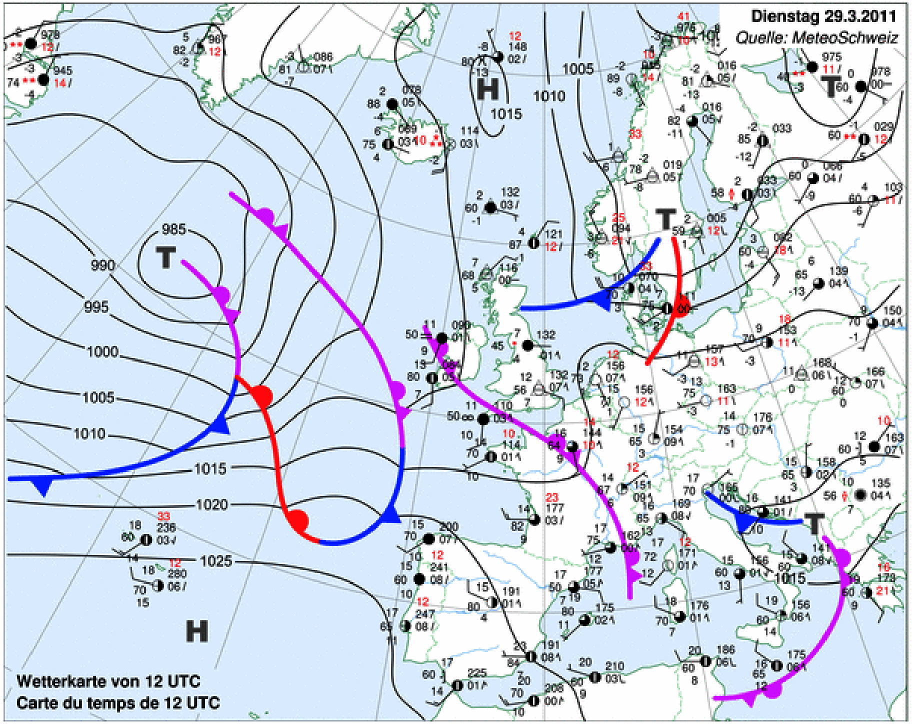

Fig. 10. Meteorological situation on 29 March 2011, 12:00 UTC (source: MeteoSchweiz).

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(a) Temperature anomaly (b) Wind speed anomaly

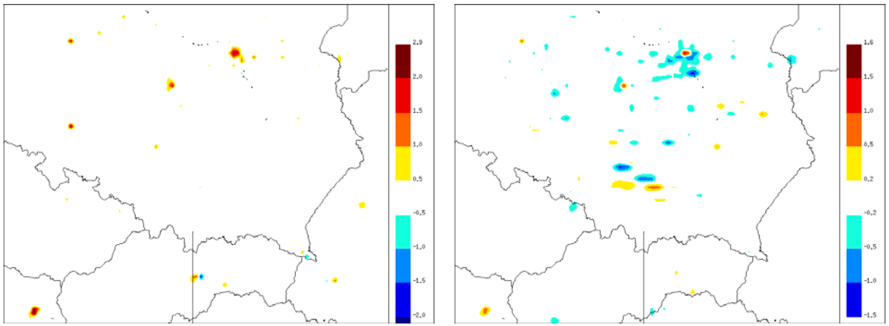

Fig. 11. Temperature **(a)** and wind speed **(b)** anomalies calculated as a difference between "urban" and "non-urban" scenarios – 29 March 2011, 18:00 UTC.

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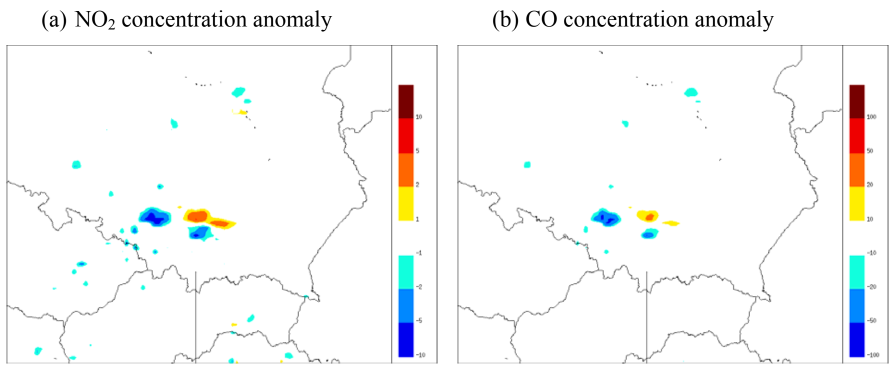

Fig. 12. NO_2 **(a)** and CO **(b)** concentration anomalies calculated as a difference between "urban" and "non-urban" scenarios in the lowest model layer – 29 March 2011, 18:00 UTC.

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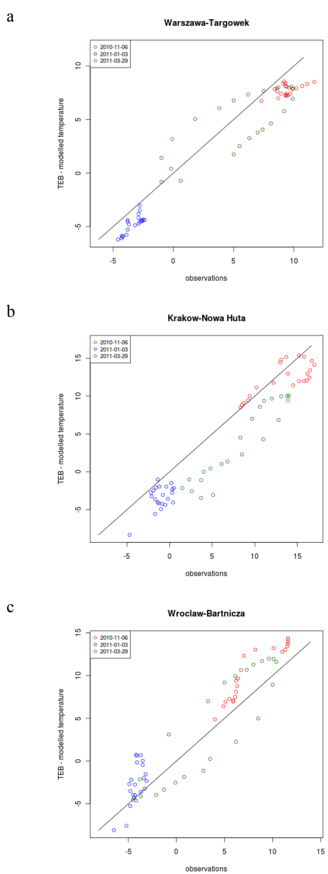

Fig. 13. Near surface temperature measured at air-quality monitoring stations and calculated with the GEM-AQ model with TEB parameterization (red: 6 November 2010; blue: 3 January 2011; green: 29 March 2011).

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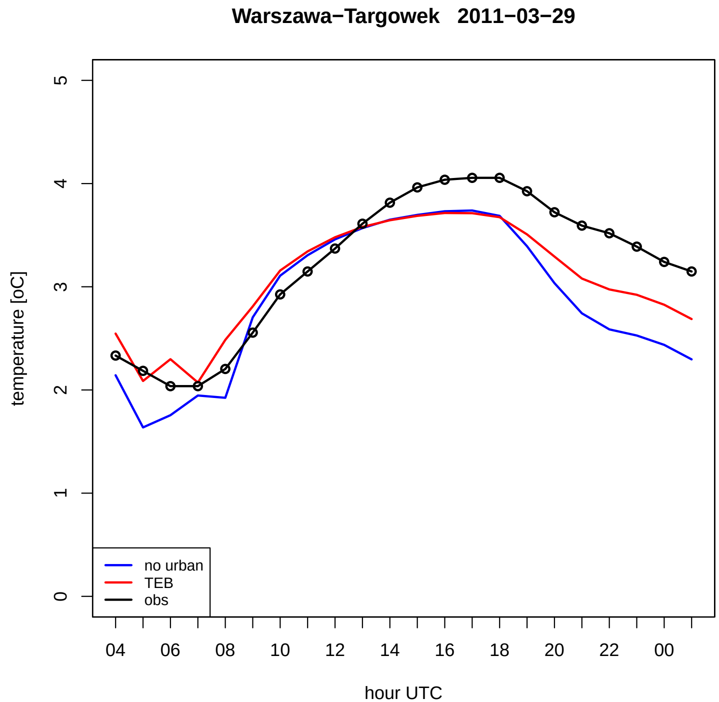

Fig. 14. Observed and modelled near surface temperature at Warszawa-Targowek monitoring station on 29 March 2011.

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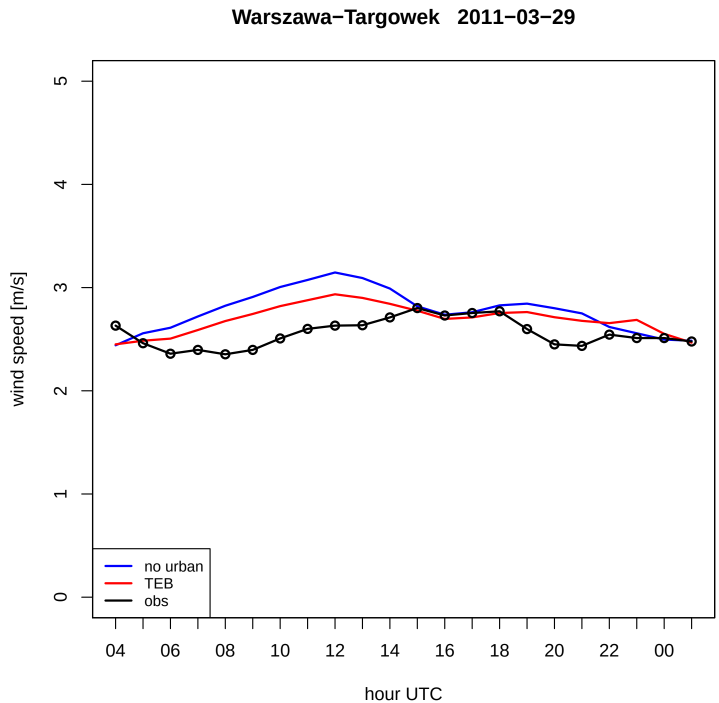

Fig. 15. Observed and modelled near surface wind speed [$m\,s^{-1}$] at Warszawa-Targowek monitoring station on 29 March 2011.

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