Meteorology and Atmospheric Physics (2019) 131:1213–1223
https://doi.org/10.1007/s00703-018-0632-3

ORIGINAL PAPER

On the uncertainties introduced by land cover data in high-resolution regional simulations

Alexander De Meij[1] · G. Zittis[2] · T. Christoudias[3]

Received: 31 May 2017 / Accepted: 31 July 2018 / Published online: 6 August 2018

Abstract
We investigate the impact of implementing an up-to-date and detailed land cover dataset in high-resolution regional climate simulations. We used the Weather Research Forecast (WRF) model version 3.6.1 on a high horizontal resolution of 5 km × 5 km, with 29 vertical levels, covering mainland Europe. We performed simulations within the year 2050, using future Representative Concentration Pathway 8.5 mid-century projections, for 2 winter (January, February) and the 2 summer months (June, July) to investigate the seasonal dependency of the impact of the land cover datasets on and their interaction with the different meteorological conditions prevailing in summer and winter. We compare simulations using the CORINE Land Cover dataset (100 × 100 m) and the standard United States Geological Survey (USGS) (~ 1 × 1 km) land use data for the same periods. Our analysis shows that simulated meteorological variables (temperature at 2 m, wind speed, sensible and latent heat fluxes and PBL heights) differ significantly between the WRF simulations, linked to the land cover parameterization. We quantify and discuss the modelling uncertainties arising from surface-type classifications and motivate the use of high resolution, and continuously updated land use inventories in climate modelling, especially for future projections. Our findings are particularly important for the summer season and over large urban centers, and we strongly recommend the use of high-quality resolution land use data in modelling experiments studying heat waves in synergy with the urban heat island phenomenon and land–surface interactions.

1 Introduction

According to observed trends and future climate projections, global warming is expected to impact sea level, heat content of the oceans, meteorological parameters such as temperature, precipitation and wind profiles, with a likely increase in the frequency and intensity of heat waves and extreme precipitation events in some regions (IPCC 2014).

High-quality regional climate simulations are essential to assess the climate change impacts and propose adaptation strategies in the regional, national or near-local levels. The most common approach in obtaining high-resolution climate information is the dynamical downscaling through limited-area regional climate models (RCMs). Taking as input initial and lateral boundary conditions from coarse, global General Circulation Models (GCMs), high-resolution RCMs aim to spatially and temporally refine climate information over a given area of interest by describing forcings and phenomena not resolved in GCMs, such as complex topography, land use, coastlines, aerosol direct and indirect effects, and mesoscale circulations (Giorgi and Gutowski 2015).

Besides the recent developments and model improvements, climate modelling still remains a challenging task due to a number of uncertainties involved. These uncertainties are mainly related to the insufficient representation of crucial meteorological processes such as convection, microphysical or Planetary Boundary Layer (PBL) processes. These are semi-empirically described either because the complexity and small scales involved make them too computationally expensive to be modelled or because there is insufficient knowledge about a specific process to represent it mathematically (Warner 2011). Additional uncertainties can be derived from the boundary conditions (Mesinger and Veljovic 2013) and domain set-up (Mesinger and Veljovic

Responsible Editor: F. Mesinger.

✉ Alexander De Meij
info@metclim.com

[1] MetClim, 21025 Comerio, VA, Italy

[2] Energy, Environment and Water Research Center, The Cyprus Institute, Nicosia, Cyprus

[3] Computation-Based Science and Technology Research Center, The Cyprus Institute, Nicosia, Cyprus

2017 and references therein), the scenarios of future concentrations of greenhouse gases or land use cover and changes. Regarding the latter, a number of recent studies have shown the impact of high-resolution land cover and topography on calculated meteorological parameters and air quality indicators (Kim et al. 2013; De Meij and Vinuesa 2014; De Meij et al. 2015). They showed that in general wind speed, temperature, PBL, relative humidity (RH) and particulate matter (PM10) concentrations are in better agreement with the observations when the updated, high-resolution CORINE Land Cover is used compared to the standard United States Geological Survey (USGS) dataset. In light of this, the present study aims to highlight the importance of current, up-to-date high-resolution land cover datasets in climate modelling for future projections and provide quantitative estimates for the potential uncertainty resulting from using out of date land cover data in mid-century regional projections.

Land cover change has direct impacts on the radiation budget through the surface albedo. It also impacts the climate through the surface roughness (for example, changes in vegetation type) and heat fluxes. Land use change, in particular deforestation, also has significant impact on the amplification of the greenhouse effect. The climate forcing is not purely radiative and the net impact of land use change on the surface temperature depends on the latitude. There is no agreement on the sign of the temperature change induced by anthropogenic land use change (IPCC 2014). There is still significant uncertainty in the anthropogenic land cover change; in particular its time evolution (Gaillard 2010).

In this study, we investigate the potential impact of implementing up-to-date and more detailed land cover datasets in high-resolution regional climate simulations. We test the impact by comparing the high-resolution CORINE Land Cover and the USGS datasets, on future Representative Concentration Pathway RCP8.5 mid-century projections by studying a number of relevant meteorological variables, such as temperature, wind speed and heat fluxes for the year 2050. We use a future scenario to highlight the importance of high-resolution land cover datasets on climate change projections and the need to also have representative, continuously up-to-date land cover datasets throughout simulations, rather than just including a static representation. The year 2050 was selected as indicative, because (1) the greenhouse emissions start to diverge after 2050 due to different socio-economic developments leading to higher uncertainties in the global temperature rise (IPCC 2014) and (2) the United Nations (2015) project large differences in land cover classes by mid-century. The objective of the paper is to quantify and discuss the impact of high-resolution land cover on meteorological parameters arising from differences in surface-type classifications between land cover datasets and to motivate the use of high-resolution, continuously updated land use inventories in climate modelling, especially for future projections. This is particularly important as the spatial resolution of both regional and global models is continuously increasing, while in the vast majority of the current climate models the land use fields considered are static. Thus, the updates between the tested land use datasets can be used as an analogue to potential future land use changes (e.g. expansion of urbanized areas, alterations in forest cover, etc.) in an effort to quantify the impact of this uncertainty on key meteorological variables.

The paper is organized as follows: In Sect. 2, we present the model set-up (Sect. 2.1) and experimental methodology, and a comparison in land use between CORINE Land and USGS land cover datasets over central Europe (Sect. 2.2). In Sect. 3, we present and discuss the resulting differences between the two simulations for winter and summer periods. Conclusions and outlook are given in Sect. 4.

2 Methodology

2.1 Model description and experimental set-up

The Weather Research Forecast (WRF) model version 3.6.1 (Skamarock et al. 2008) is used. WRF is a state-of-the art atmospheric model designed both for research purposes and operational weather forecasting. The geographical position of the simulation domain is presented in Fig. 1. It covers a large part of Europe, including France, Benelux, England, Germany, Switzerland, Austria and the northern part of Italy. We run WRF on a horizontal resolution of 5 km × 5 km, with 29 vertical levels. For our simulations, we added additional vertical hybrid terrain following levels in the first few kilometres (first four levels closest to the surface at 27, 95, 189, 308 m) to account for a better description of surface and planetary boundary layer processes. The size of the integration domain is 299 grid points in both horizontal dimensions. Our model configuration includes the Morrison double-moment microphysics (Morrison et al. 2009), the Yonsei University Scheme (YSU) planetary boundary layer (Hong et al. 2006), the Grell 3D Ensemble Scheme Cumulus parameterization (Grell and Devenyi, 2002) and the RRTMG short- and long-wave radiation schemes (Iacono et al. 2008). For these 5-km simulations, we did not activate any WRF urban bulk scheme model. Any differences over urban grid points are a result of the different values of physical properties that are described in Table 3. For the simulations, a spin-up time of 7 days is applied in to initialize the model. Simulations over longer periods may be necessary to better quantify the uncertainties related to the dynamical variance and capture the overall impact of single weather events on averages, but fall outside the scope of the present study.

WRF uses meteorological initial and lateral boundary conditions a bias corrected version of CESM1 global earth

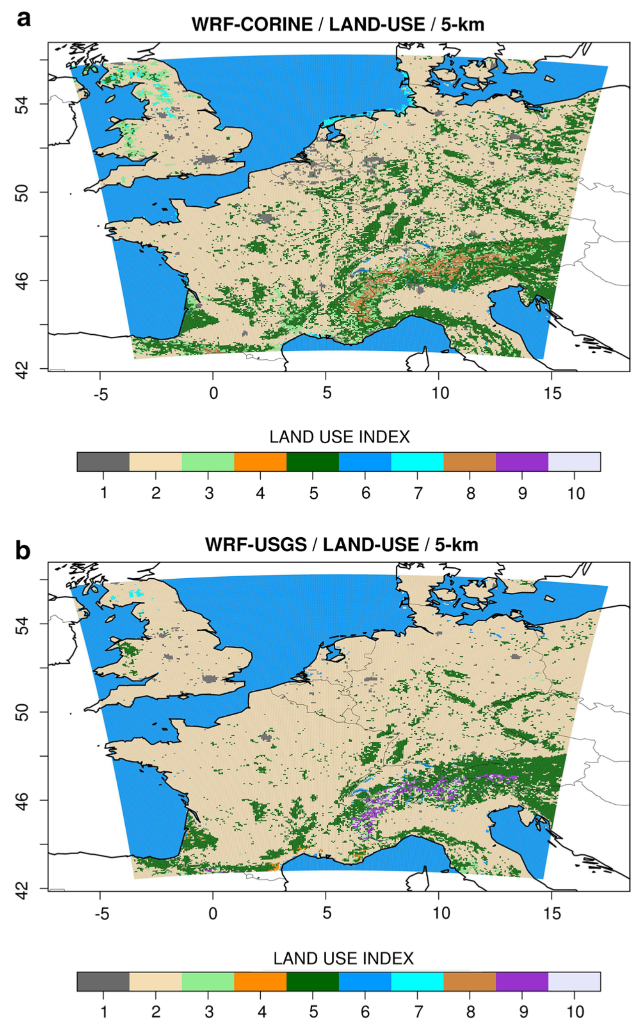

Fig. 1 Geographical representation of the main ten land use category classes in CORINE Land Cover (**a**) and USGS (**b**) land cover datasets in the model domain. USGS land use categories: (1) urban, (2) crops, (3) shrubs/grasslands, (4) savanna, (5) forest, (6) water bodies, (7) wetlands, (8) barren, (9) wooded tundra and (10) snow/ice

system model (Bruyère et al. 2015), driven by future scenario pathway RCP8.5. Dynamically downscaling global models to horizontal resolutions of this range is a common strategy in several climate downscaling experiments including the CORDEX initiative (Jacob et al. 2014; Kotlarski et al. 2014). Moreover, Veljovic et al. (2010) and Mesinger and Veljovic (2017) showed that using nesting or grid-nudging in RCM's does not necessarily improve the model results.

We performed four simulations for the year 2050. The model output was integrated for 2 winter (January, February) and 2 summer months (June, July), due to the large extent of the domain and computational cost to investigate the seasonal dependency of the impact of the land cover datasets on and their interaction with the different meteorological conditions prevailing in summer and winter. The first two simulations use the 2006 CORINE Land Cover (LC) dataset for the 2-month period January–February and June–July 2050. The third and fourth simulations incorporate the standard 1993 United States Geological Survey (USGS) 30-arc seconds land use data for the same periods. The simulations with CORINE LC are henceforth denoted as WRF_COR and the simulations with USGS 30-arc seconds are denoted as WRF_USGS. The resolution used for implementing land use in the proposed study is based on (1) the 30-arc seconds (~ 1 km × 1 km) United States Geological Survey (USGS) database and (2) the CORINE 2006 Land Cover dataset (100 × 100 m). By default, WRF uses land use categories from USGS 24-category data, which are available for different horizontal resolutions (10′, 5′, 2′, 30″; ″ denotes arc seconds and ′ denotes arc minutes). The horizontal resolution is set by the user in the pre-processing step in WPS. The highest horizontal resolution available in the USGS land use is 30″, which corresponds to ~ 1 × 1 km. The USGS land use dataset was created in 1993. Since then, urban areas have changed significantly for some regions in Europe. The CORINE LC is a European Commission program, started in 1985 by the European Commission DG Environment, intended to provide consistent localized geographical information on the land cover of the Member States of the European Community. The CORINE LC is often recognised by decision-makers as an essential reference dataset for spatial and territorial analyses on different territorial levels (Büttner et al. 2002). To make the CORINE LC categories (44) compatible with WRF Pre-processing System (WPS), they are reclassified to the USGS categories (24 land use categories, Pineda et al. 2004). The CORINE LC dataset is projected on the European Terrestrial Reference System 1989 (ETRS89) Lambert Azimuthal Equal Area (LAEA), which is not compatible with the WRF system. Therefore, the CORINE LC is re-projected to the World Geodetic coordinate System 1984 (WGS84) according to the method described in Arnold et al. (2010). Using the USGS dataset (from 1993) and the Corine Land Cover (2006), we demonstrate that updates in land cover datasets in potential future land use changes can be crucial for meteorology and air quality modelling future projections, and aim to quantify the potential resulting uncertainty, to allow comparison with the climate change signal from model simulations. Using a future scenario (RCP8.5) serves to highlight that current temperature projections by global or regional models might be underestimated due to the absence of continuously updated, more accurate and high-resolution land cover data; our results underline the importance of using the best land use description available.

Table 1 Overview of the simplified USGS land use categories

USGS land use categories
1. Urban (urban and built-up land)
2. Crops (dryland, irrigated and mixed croplands, pasture)
3. Shrubs/grasslands (mixed shrubland and grassland)
4. Savanna
5. Forest (deciduous, evergreen and mixed forests)
6. Water bodies
7. Wetlands (wooden and herbaceous wetlands)
8. Barren
9. Wooded tundra
10. Snow/ice

Table 2 USGS land use categories together with number of cells (in percent) of the land cover category class by CORINE and USGS datasets in the model domain

Legend	Land use	CORINE (%)	USGS (%)	Difference in number of cells (%)
1	Urban	2.53	0.69	1.84
2	Crops	46.77	56.50	−9.73
3	Shrubs/grass	2.78	0.53	2.25
4	Savanna	0.00	0.14	−0.14
5	Forest	16.91	11.31	5.60
6	Water	28.87	29.86	−0.99
7	Wetland	0.77	0.07	0.70
8	Barren	1.30	0.00	1.30
9	Tundra	0.00	0.75	−0.75
10	Snow/ice	0.07	0.15	−0.08
	Total	100%	100%	

In addition, the difference (in percent) in land cover classes between the CORINE and USGS datasets in the whole domain

2.2 Comparison in land use between CORINE Land and USGS land cover

In Fig. 1, we present the differences in the land cover categories between the CORINE Land Cover and the 30-arc seconds USGS databases. Large differences are observed in the geographical distribution of the land cover classes between the two datasets. For brevity and clarity of representation, we have merged similar categories that are found in the simulation domain to a total of ten as shown in Table 1. The differences between the two datasets for the simulation domain are presented in Table 2.

Clearly visible are the major differences in most categories. The differences in urban areas and the land type over mountainous regions, such as the Alps (classified as tundra in USGS which is not the case in CORINE) lead to significant differences in the model simulations. Forests in particular have expanded especially in France and Germany. Wetlands are present in the UK in CORINE data (easterly of Liverpool and Lake District), while absent in the USGS dataset.

The most significant land use alterations (about 8.3% of all grid points) are those from crop (USGS) to forest (CORINE) which are most evident over France, Germany and Poland. A significant amount of area (≅2.5% of total), has switched from forest or crop land use (USGS) to shrublands/grasslands (CORINE). This change is more pronounced in southeast France, over the Alps and in parts of Britain. About 2% of grid points are changed from crop (USGS) to urban (CORINE). As a result, large urban centers are represented more realistically when CORINE LC inventory is used. Such examples are the metropolitan areas of Paris, London, Brussels, Berlin, Milan, etc. Smaller but important alterations in LC (<1%) are also found over the higher elevation parts of the Alps (from wooded tundra/snow to barren) and in the coastal zone of Netherlands–Germany–Denmark (from water to wetlands).

3 Results

3.1 Temperature

In Fig. 2, the differences in temperatures at 2 m (T2) between WRF_COR and WRF_USGS experiments are shown for the winter January–February (Fig. 2a) and the summer period June–July (Fig. 2b). During the winter period, the differences are mainly located over the Alps. T2 in WRF_COR simulation is much higher than the one by WRF_USGS. These differences can be attributed to the alterations in LC classes between CORINE and USGS. For large parts of the Alps CORINE registers barren while USGS registers wooded tundra, resulting in ~0.4 °C difference between the two simulations (see Fig. 3). On the other hand, WRF_USGS calculates higher T2 over the Apennine mountains in Italy, due to a smaller fraction of forest classification in USGS over this area (see Fig. 1). The differences in temperatures are related to the differences in latent and sensible heat fluxes, which will be further described in the following sections. For winter time and for the rest of the domain, the differences between the two simulations are limited to ±0.2 °C.

For the summer period (June–July), the differences in temperatures are stronger than those for the winter months (Fig. 2b). These can be partially explained by the large differences in suburban built-up areas between CORINE LC and USGS. The T2 discrepancies follow the pattern of the difference in urban built-up between the two land cover datasets as seen in Fig. 3. In general, the cells which are registered as crops in USGS but are registered as urban built-up in CORINE (Fig. 3: C2U) show an average difference of

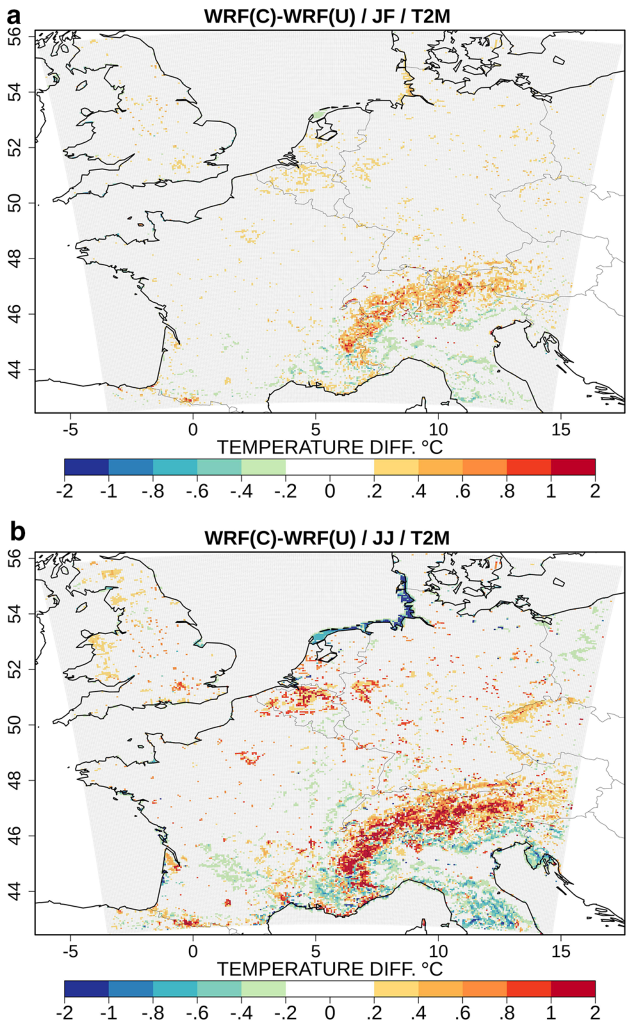

Fig. 2 Differences in temperature at 2 m between WRF_COR and WRF_USGS for the winter period January–February (**a**) and the summer period June–July (**b**)

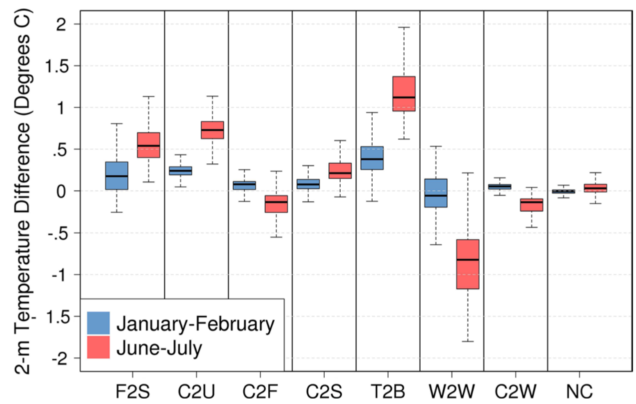

Fig. 3 Boxplot of the 2-m temperature differences for the grid cells for which large differences in land cover classifications are found between USGS and Corine datasets. *F2S* forest to shrubs/grass, *C2U* crops to urban, *C2F* crops to forest, *C2S* crops to shrubs/grass, *T2B* tundra to barren, *W2W* water to wetland, *C2W* crops to wetland, *NC* no change in land cover classifications between USGS and CORINE

about 0.75 °C. In the modelling domain, 2.5% of the total area is classified as urban built-up in CORINE, while only 0.69% in USGS, a fact that is apparently causing higher temperatures in the urban areas. This corroborates the results by De Meij and Vinuesa (2014), which have shown that higher surface temperatures over urban areas are calculated when high-resolution land cover data is used. In more detail, over Belgium, the Netherlands, Ruhr region (Germany) and around the metropolitan cities such as Paris, Berlin and London, differences in T2 temperatures are found up to 2 °C (WRF_COR higher than WRF_USGS), which coincide with the differences in urban areas between the two land cover datasets.

Interestingly, significant discrepancies in T2 (up to 2 °C) are also found over the Alps. A large part of the Alpine region is classified as tundra in USGS while for the same areas CORINE registers LC barren. In Fig. 3, we see that the land cover change from tundra (in USGS) to barren (in CORINE), (T2B) results in a difference of the 2-month average T2 of ~ 1.2 °C. The temperature discrepancies between the two simulations are smoothed during the winter months since most of the Alpine region is covered by snow (not shown). These differences are in agreement with the results of De Meij and Vinuesa (2014). They found that over the Alps T2 is in general higher by the simulation using CORINE LC than by the simulation using the USGS. We note that De Meij and Vinuesa (2014) found that calculated T2s by the simulation with the CORINE dataset are in better agreement with the observations than the simulation with the USGS dataset. For the cells which are registered as water in USGS, but registered as wetland in CORINE (W2W), result in higher temperatures by WRF_USGS, around 0.75 °C, during June–July. The differences during the wintertime are < 0.1 °C. The temperature underestimation of WRF_COR comparing to WRF_USGS over the Apennines in Italy is also enhanced during these summer months.

A consequence of high-resolution land cover and the resulting higher T2s may locally lead to changes in emission rate estimates of biogenic and anthropogenic emissions and the number of heat waves might increase.

Surface reflectivity cannot explain the increased temperatures simulated in WRF_COR. All land cover updates and shifts that are found to be related to T2 discrepancies indicate higher grid cell albedo values in the WRF_COR simulation (Table 3). Other processes related to the heat capacity of the various LC categories and latent heat fluxes through land–surface interactions that are expected to strongly affect near-surface temperatures are presented in the following sections.

Table 3 Albedo, soil moisture availability (fractions of 1), roughness length and volumetric heat capacity over selected land cover categories as described in WRF LANDUSE.TBL and VEGPARM.TBL

	Crop	Urban	Tundra	Barren	Water	Wetland	Forest
Albedo	0.16–0.25	0.15	0.15–0.20	0.38	0.08	0.14	0.12–0.16
Soil moisture availability (winter)	0.40–0.60	0.10	0.50	0.02	1	0.60	0.50–0.60
Soil moisture availability (summer)	0.25–0.50	0.10	0.50	0.05	1	0.60	0.30–0.50
Roughness length (10^{-2} m)	5–15	80	30	1	0.01	20	20–50
Heat capacity per unit volume (10^5 J/m^3/K)	25	18	9.0e20	12	9.0e20	29.2	25–29.2

3.2 Surface moisture flux

The change of water phase on the surface through evapotranspiration can affect significantly the energy fluxes and surface meteorological variables. In Fig. 4, we present the differences between the two simulations regarding the surface upward moisture fluxes. On average, these are found larger during the summer (Fig. 4b). Up to − 3 mm/day are found in the WRF_COR simulation comparing to the WRF_USGS. These differences are most pronounced over the broader Alpine region and the grid points that changed from wooded tundra (USGS) to sparsely vegetated barren land (CORINE) as shown in Fig. 4c. During the summer months, over the Alps WRF_USGS has higher (on average ~ 2 mm/day) surface upward moisture fluxes than WRF_COR (Fig. 4c). Also, discrepancies on average − 1 mm/day are also seen over the urbanized areas in CORINE LC, while smaller differences are found over north and west United Kingdom. The aforementioned discrepancies between the two runs can be attributed to the lower soil moisture availability in the urban and barren land categories that are more extended in the CORINE LC data (Table 3).

3.3 Surface heat flux

The sensible and latent heat fluxes are of great importance since they control the ground temperature and other processes such as the development of the PBL. Ball (1960) showed that over most land surfaces the sensible heat fluxes determine the convection of air in the atmosphere, and therefore, the PBL development. When there is available energy and soil water, moisture fluxes can control near-surface temperature through evapotranspiration and land–atmosphere interactions (Seneviratne et al. 2010; Zittis et al. 2014). Fraedrich et al. (1999) showed that when the latent heat fluxes are higher than the sensible heat fluxes, the temperature near the surface is lower compared to the areas where the sensible heat fluxes are prevailing, also causing to differences in the depth of the PBL.

3.3.1 Sensible heat flux

In the winter months, for most of the domain, discrepancies of about ± 10 W/m^2 are found between the two simulations (Fig. 5a). Exceptions are the higher sensible heat fluxes (up to 20 W/m^2) simulated by WRF_COR over some urban areas such as Paris, Toulouse, Belgium, western part of the Netherlands, etc., and the much higher sensible heat flux values over the Alps. The latter are in the range of up to 100 W/m^2 and represent the grid cells changed from wooded tundra to barren land. All these discrepancies can be explained from the alterations to land use categories with lower volumetric heat capacity values in the WRF_COR simulation (see Table 3). Heat capacity describes the ability of a given volume to store internal energy while undergoing a given temperature change. For example, water bodies in WRF have very high heat capacity values (Table 3) and can, therefore, internally store energy which is translated in lower diurnal or seasonal temperature range. Other land categories such as urban and barren or sparsely vegetated land are assigned to much lower heat capacity values in the model. As a result, the thermal energy that is gained during daytime is more effectively released back to the atmosphere in the form of sensible heat flux and thermal conductivity plays and important role as well in the release of energy to the atmosphere. These processes can explain the higher temperatures observed in the WRF_COR simulations and over the previously described land cover category shifts.

As expected, differences in sensible heat fluxes are much larger in summertime due to the higher amount of incoming solar radiation compared to winter. The most pronounced differences are again found over the areas for which the CORINE LC has more urban built-up than the USGS, but also over the Wadden Sea (northerly of the Netherlands) and over the Alps (Fig. 5b). For example, the differences in the sensible heat fluxes are clearly visible around metropolitan cities such as Paris, Berlin and London and the densely populated centers such as the Ruhr and other urbanized areas in Germany (Stuttgart, Frankfurt, Munich, Bremen, Hamburg) the western part of Netherlands (Rotterdam, Amsterdam), France (Lyon, Toulouse, Bordeaux), Belgium (Antwerp,

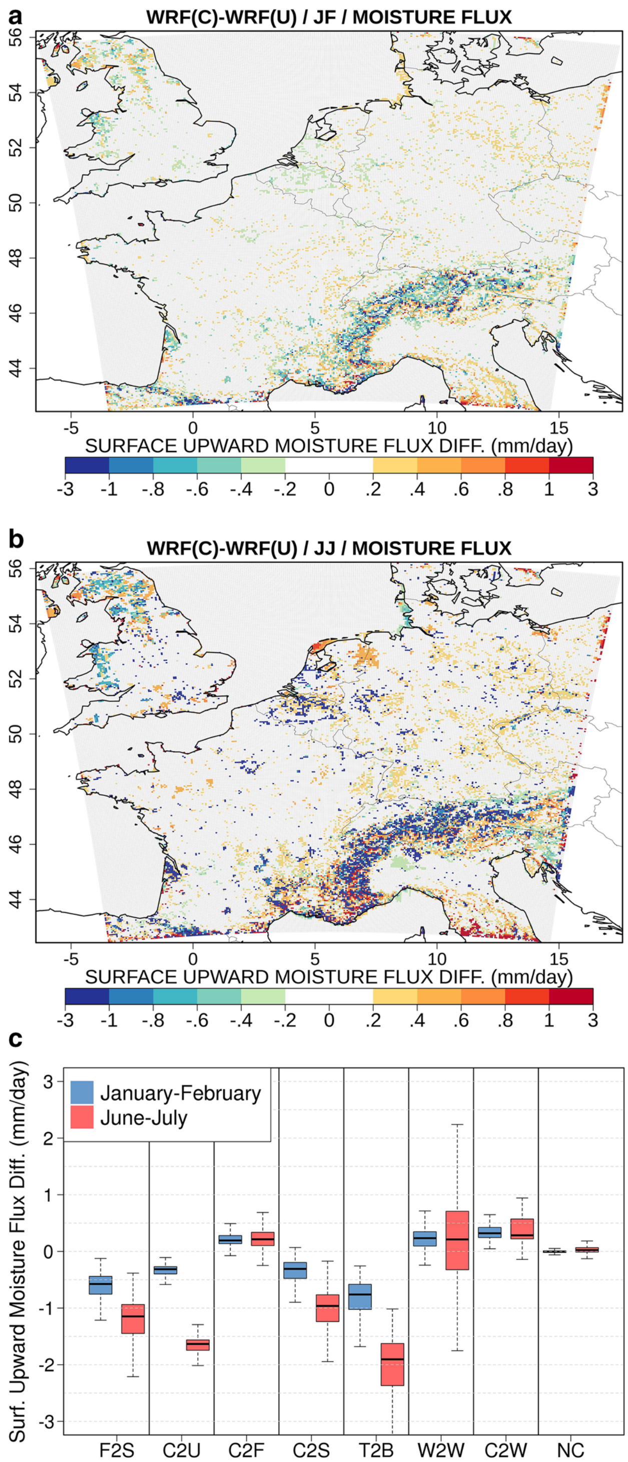

Fig. 4 Differences in the 2-month average surface upward moisture fluxes between WRF_COR and WRF_USGS for January–February (**a**) and June–July (**b**) in mm/day. Together with a boxplot of the surface upward moisture fluxes for which larger differences are found between USGS and Corine datasets. For abbreviations see caption Fig. 3

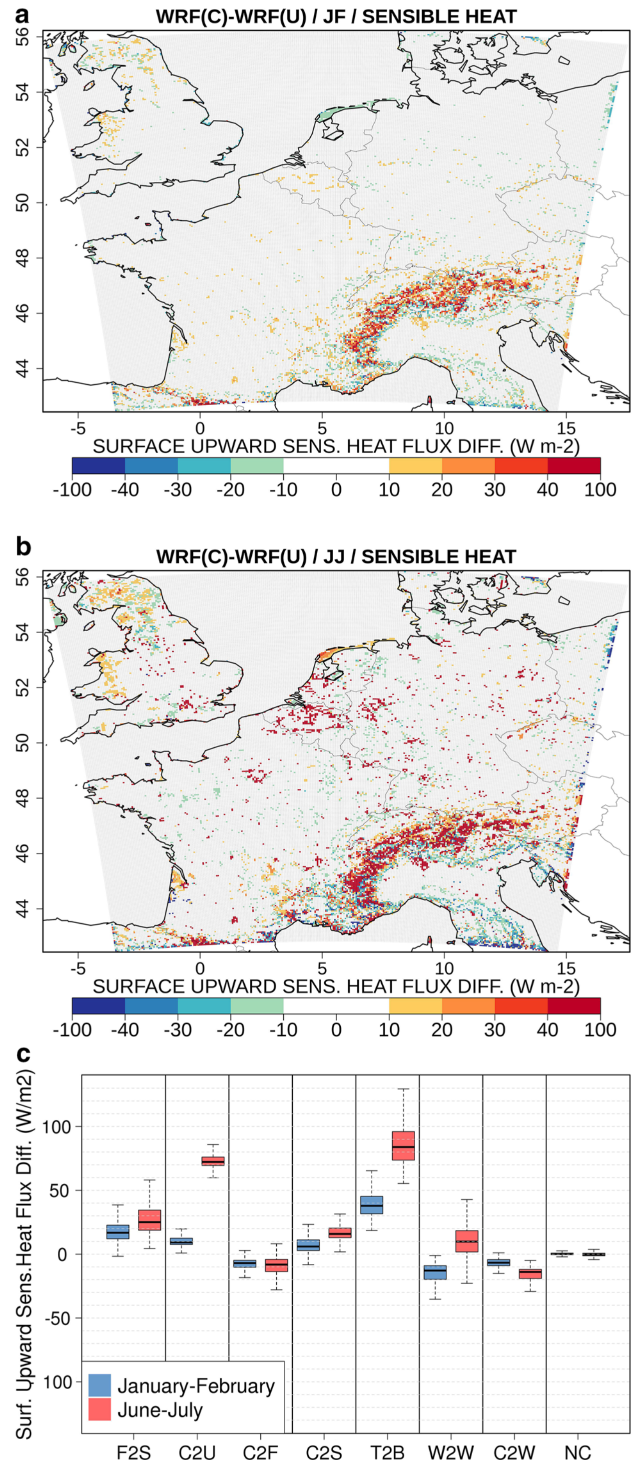

Fig. 5 Differences in the 2-month average sensible heat fluxes between WRF_COR and WRF_USGS for January–February (**a**) and June–July (**b**) in W/m^2. Together with a boxplot of the sensible heat fluxes for which larger differences are found between USGS and Corine datasets. For abbreviations see caption Fig. 3

Brussels, Ghent), for which we find also large differences in T2 (on average 0.75 °C) between the two simulations as described earlier. The CORINE Land Cover has a higher fraction of urban built-up area in the model domain than the USGS as mentioned before. This results in differences in the sensible heat fluxes on average ~ 70 W/m^2 (up to 100 W/m^2) for the 2-month June–July average, see Fig. 5c. As mentioned earlier, over the Alps, the USGS dataset registers a large fraction of the land cover as tundra while the CORINE Land cover registers mainly barren. These changes in land cover can explain the differences in sensible heat fluxes (on average ~ 85 W/m^2) as shown in Fig. 5c and the resulting differences in T2 as shown in Figs. 2 and 3.

3.3.2 Latent heat flux

The latent heat flux behaviour is expected to differentiate between the winter and summer seasons. During the winter months, sufficient moisture is available throughout the central European domain and latent heat flux is controlled mainly from the limited incoming solar radiation. The reverse occurs during summer months where the energy from solar irradiance is abundant, but moisture is not always available. This different behavior can be seen in Fig. 6.

In the winter months (Fig. 6a), latent heat flux differences are for most of the central European domain limited to ± 10 W/m^2. Exception is the Alpine region where the WRF_COR simulation produced lower latent heat fluxes (up to 20–30 W/m^2, see Fig. 6c). In general, the CORINE dataset registers the Alpine domain as "Barren or sparsely vegetated", while the USGS registers Wooded tundra or Forest over the Alps, causing differences in heat fluxes and temperature differences. There are also other areas in the Alps for which we find again differences between CORINE and USGS, leading to differences (positive or negative) in the analysed meteorological parameters. For example, in the CORINE LC several places are classified as deciduous/evergreen needleleaf forest or shrubs/grasslands while in USGS these areas are classified as Wooded Tundra.

During the summertime (Fig. 6b), WRF_COR produced much lower latent heat fluxes (up to – 100 W/m^2) over the areas classified as urban built-up in CORINE (such as large parts of Belgium, the Ruhr area and the metropolitan cities), but have different LC classes in USGS, such as crops (dryland, irrigated and mixed croplands, pasture) causing more evaporation and leading to higher latent heat value (on average ~ 50 W/m^2) by USGS, see Fig. 6c. Also, over Milan and northwestern Milan, we see clear differences in latent heat fluxes (USGS higher), caused by the absence of urban built-up in USGS. This has been described in De Meij and Vinuesa (2014) and De Meij et al., (2015). Over larger parts of the Po Valley we see also higher latent heat fluxes by USGS (indicated in blue), but the differences are

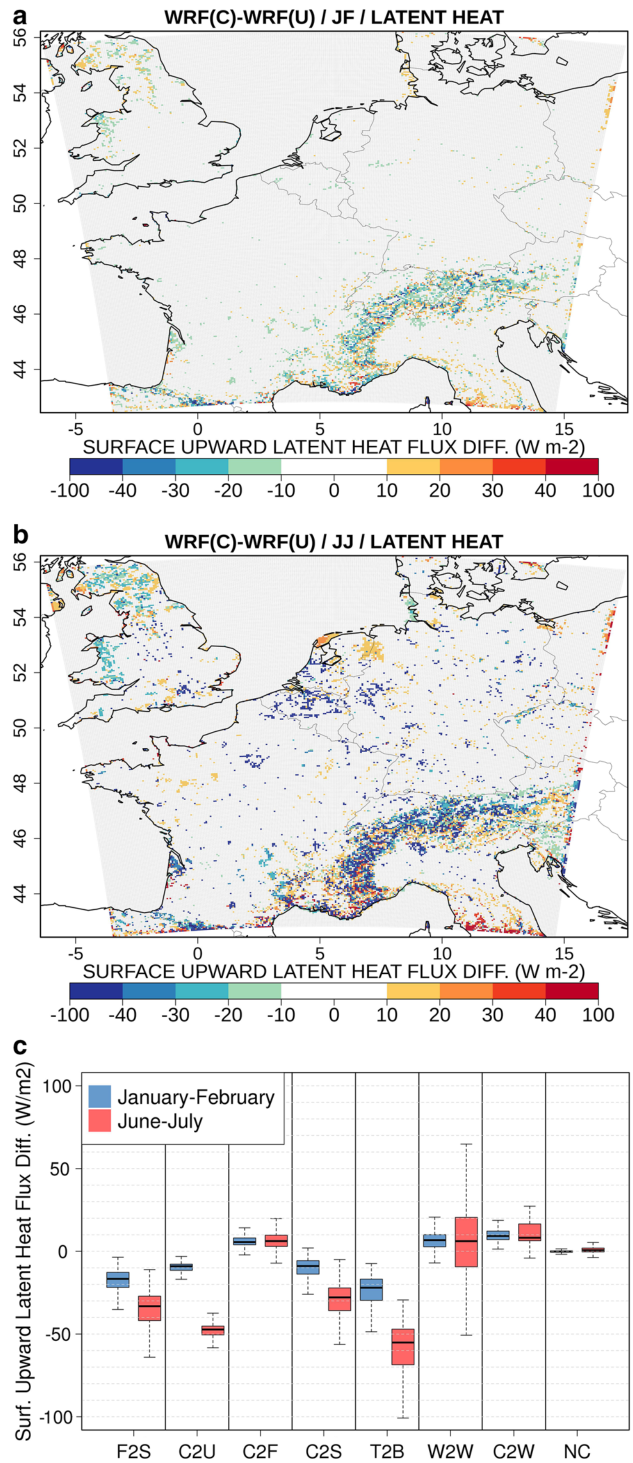

Fig. 6 Differences in the 2-month average latent heat fluxes between WRF_COR and WRF_USGS for January–February (**a**) and June–July (**b**) in W/m^2. Together with a boxplot of the latent heat fluxes for which larger differences are found between USGS and Corine datasets. For abbreviations see caption Fig. 3

smaller than over those areas classified as urban built-up in CORINE LC.

Similarly, over large parts of the Alps we see strong differences in the amount of latent heat fluxes due to the differences in land cover classes that were described earlier. For example, latent heat fluxes are on average ~55 W/m^2 higher by USGS (Fig. 6c). The surface latent heat fluxes discrepancies between the two simulations are attributed to differences in the surface moisture fluxes (see next section) that are translated in changes in the evaporative cooling of the surface.

3.4 Planetary boundary layer height

The differences in the simulated PBL heights between WRF_COR and WRF_USGS can be explained by the differences in near-surface temperatures resulting from the differences in energy and moisture fluxes as described in the previous sections. The strong effect in winter months in urban areas appears to not have the same basis in the sensible and latent heat fluxes presented. This can be rather due to the effects of wind during winter. We have seen that WRF_COR calculates higher sensible fluxes over the urban areas and over large parts of the Alps, which affect the related boundary layer development and depth. Van den Hurk (1995) showed that higher sensible heat fluxes over urban areas result in larger PBL heights, which explains the differences in the June–July average PBL heights by WRF_COR and WRF_USGS in Fig. 7b (PBL heights are in general higher by WRF_COR than for WRF_USGS). This is in agreement with the results of De Meij and Vinuesa (2014) and De Meij et al. (2015). In the latter study the authors performed two simulations with WRF-Chem (Grell et al. 2005), one with the CORINE and one with the USGS dataset. They showed that calculated PM10 concentrations by the simulation with the CORINE LC agreed better to the observations than the simulation with the USGS dataset during the periods for which large differences in the PBL heights were found. Short-term forecasts or future air quality scenarios may also benefit from a better representation of the PBL development because a deeper/shallower PBL leads to lower/higher aerosol concentrations at ground level.

3.5 Wind speed

In general, the wind speeds are lower (up to 1.5 m/s) by WRF_COR than by WRF_USGS over large parts of Europe including densely populated regions such as Po Valley area in Italy, Ruhr region, Belgium and the Rhone Valley (France). This is more evident during the winter months (Fig. 8a, c). Higher wind speeds comparing to WRF_USGS are found over some regions in the Alps (Fig. 8c). Discrepancies in near-surface wind speed values between the two model configurations can again be attributed to certain differences in land cover between the two employed datasets. For example, large parts of croplands in USGS data are replaced with forests in the updated CORINE data (Fig. 1). Forests are assigned with higher roughness length values (Table 3) explaining the lower wind speeds produced in the WRF_COR simulation. In the same context, barren land has much lower roughness length values than tundra, contributing to higher wind speed values for the Alpine region in the WRF_COR simulation. Noteworthy, for the region of north Italy, De Meij and Vinuesa (2014) found that wind speeds simulated with the CORINE LC are in better agreement with the observations than the simulation with the USGS dataset. For summer (Fig. 8b, c), the wind speed differences between the two simulations are not as pronounced.

The consequence of the differences in wind speeds and PBL height might be that the number of days for which the

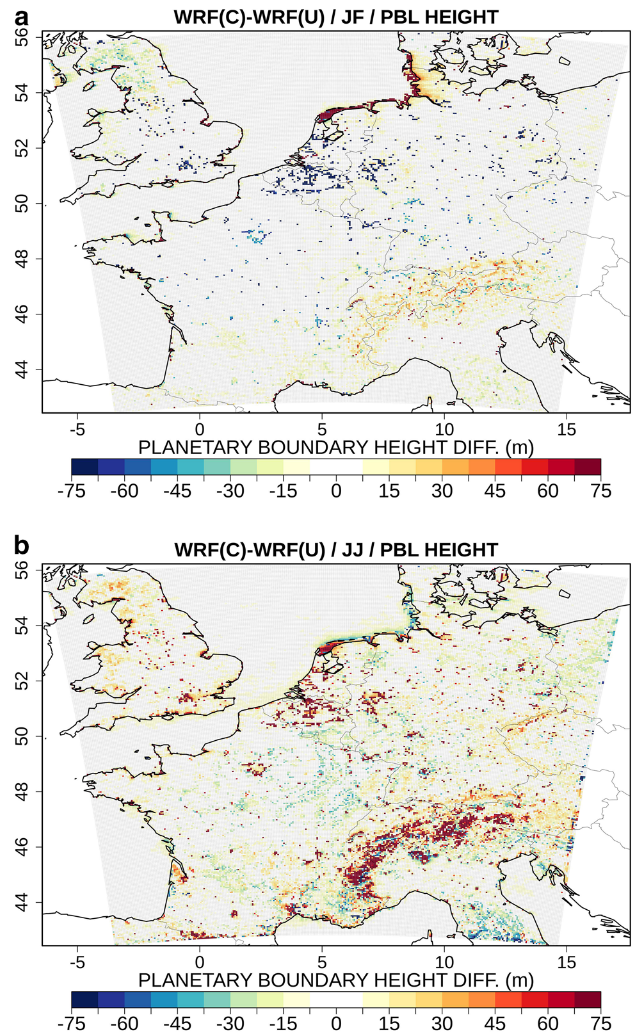

Fig. 7 Differences in the 2-month average PBL heights (m) between WRF_COR and WRF_USGS for January–February (**a**) and June–July (**b**)

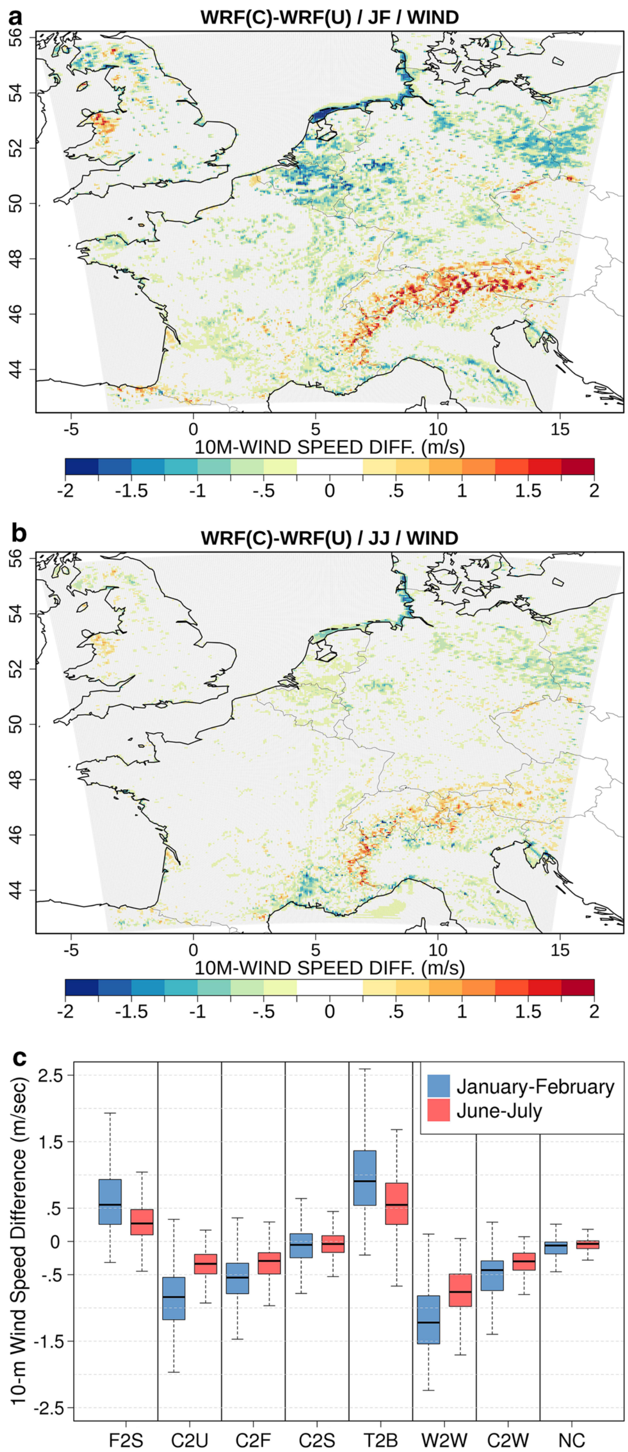

Fig. 8 Differences in the 2-month average wind speeds (m/s) between WRF_COR and WRF_USGS for January–February (**a**) and June–July (**b**). Together with a boxplot of the wind speeds for which larger differences are found between USGS and Corine datasets. For abbreviations see caption Fig. 3

European air quality standard limit values are exceeded might increase, while the calculation of wind energy potential in future climate projections can also be affected.

4 Conclusions

Our analysis shows that simulated meteorological variables (such as near-surface temperature, wind speed, sensible and latent heat fluxes and PBL height) differ between the WRF simulation using the high-resolution CORINE Land Cover and the one using the USGS dataset. The reason for this can be explained by the differences in geographical distribution of the land cover classes between the two datasets and the linked land–atmosphere interactions that are being calculated.

In general, T2 is higher by WRF_COR over urbanized areas (on average ~ 0.75 °C during June–July) and large parts over the Alps (on average ~ 1.2 °C during June–July), Germany and France due to the high-resolution land cover by CORINE. During the wintertime the largest differences in T2 are mainly located over the Alps (up to ± 0.4 °C), while over the rest of the modelling domain differences up to ± 0.2 °C are found. Land–atmosphere coupling within the model is found to control these temperature differences between the two model setups. Regional climate models might benefit from high-resolution land cover datasets as calculated surface temperatures will be closer to the observations. A consequence may be that higher temperatures could affect the emission rates of biogenic and anthropogenic emissions and volatility of aerosols, which could also affect the air pollutant concentrations at the surface. Also, as a result of the implementation of higher resolution land cover datasets, the projected number and severity of heat extremes might increase, because the criteria for events such as heat waves (number of days for which the temperature exceeds a threshold value) could be locally exceeded more often than currently projected by the global or regional climate models.

Large differences in the geographical distribution of the land cover classes between CORINE and USGS land cover datasets result in differences in moisture fluxes; on average ~ 2 mm/day over the Alps during the summer (higher by WRF_USGS) and ~ 1.5 mm/day over urban areas during the summer (higher by WRF_USGS), causing differences in sensible and latent heat fluxes, resulting in differences in PBL heights. Wind speeds during January–February over urbanized areas are on average 0.8 m/s higher by WRF_USGS, but higher by WRF_COR over the Alps (on average ~ 1.0 m/s). This is relevant for the renewable energy sector (wind energy) and air quality forecasts. The calculation of lower wind speeds might contribute to higher PM10 pollution episodes due to the more frequent stagnant meteorological conditions and shallower PBL heights can lead to higher estimations of air pollutants concentrations at ground level.

Since our findings are particularly important for the summer season and over large urban centers, we strongly recommend the use of dynamic, high-quality resolution land use data in modelling experiments studying extreme heat waves in synergy with the urban heat island phenomenon and land–atmosphere interactions. The online coupling with urban parameterization models would likely add a value in the representation of such fine-scale processes.

References

Arnold D, Schicker I, Seibert P (2010) High-resolution atmospheric modelling in complex terrain for future climate simulations (HiRmod), Vienna Scientific Cluster report 2010. http://www.boku.ac.at/met/envmet/hirmod.html. Accessed 4 Aug 2018

Ball FK (1960) Control of inversion height by surface heating. Q J R Meteorol Soc 86:483–494

Bruyère CL, Monaghan AJ, Steinhoff DF, Yates D (2015) Bias-Corrected CMIP5 CESM data in WRF/MPAS intermediate file format. TN-515+STR, NCAR. https://doi.org/10.5065/d6445jj7

Büttner G, Feranec G, Jaffrain G (2002) Corine land cover update 2000, Technical guidelines. EEA Technical report No 89. https://land.copernicus.eu/user-corner/technical-library/techrep89.pdf. Accessed 4 Aug 2018

De Meij A, Vinuesa J-F (2014) Impact of SRTM and Corine land cover data on meteorological parameters using WRF. Atmos Res 143:351–370

De Meij A, Bossioli E, Vinuesa J-F, Penard C, Price I (2015) The effect of SRTM and Corine Land Cover and SRTM data on calculated gas and PM10 concentrations in WRF-Chem. Atmos Environ 101:173–199

Fraedrich K, Kleidon A, Lunkeit F (1999) A green planet versus a desert world: estimating the effect of vegetation extremes on the atmosphere. J Clim 12:3156–3163

Gaillard JC (2010) Vulnerability, capacity and resilience: perspectives for climate and development policy. J Int Dev 22:218–232. https://doi.org/10.1002/jid.1675

Giorgi F, Gutowski WJ (2015) Regional dynamical downscaling and the CORDEX initiative. Annu Rev Environ Resour 40(1):467–490

Grell GA, Devenyi D (2002) A generalized approach to parameterizing convection combining ensemble and data assimilation techniques. Geophys Res Lett. https://doi.org/10.1029/2002GL015311

Grell GA, Peckham SE, Schmitz R, McKeen SA, Frost G, Skamarock WC, Eder B (2005) Fully coupled ‘online’ chemistry in the WRF model. Atmos Environ 39:6957–6976

Hong S-Y, Noh Y, Dudhia J (2006) A new vertical diffusion package with an explicit treatment of entrainment processes. Mon Weather Rev 134:2318–2341

Iacono MJ, Delamere JS, Mlawer EJ, Shephard MW, Clough SA, Collins WD (2008) Radiative forcing by long-lived greenhouse gases: calculations with the AER radiative transfer models. J Geophys Res 113:D13103

IPCC (2014) Climate Change (2014) Synthesis Report. In: Core Writing Team, Pachauri RK, Meyer LA (eds) Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva

Jacob D, Petersen J, Eggert B, Alias A, Christensen O, Bouwer L, Braun A, Colette A, Déqué M, Georgievski G, Georgopoulou E, Gobiet A, Menut L, Nikulin G, Haensler A, Hempelmann N, Jones C, Keuler K, Kovats S, Kröner N, Kotlarski S, Kriegsmann A, Martin E, van Meijgaard E, Moseley C, Pfeifer S, Preuschmann S, Radermacher C, Radtke K, Rechid D, Rounsevell M, Samuelsson P, Somot S, Soussana J-F, Teichmann C, Valentini R, Vautard R, Weber B, Yiou P (2014) EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg Environ Change 14(2):563–578

Kim Y, Sartelet K, Raut J-C, Chazatte P (2013) Evaluation of the weather research and forecast/urban model over greater Paris. Bound Layer Meteorol 149:105–132. https://doi.org/10.1007/s10546-013-9838-6

Kotlarski S, Keuler K, Christensen OB, Colette A, Déqué M, Gobiet A, Goergen K, Jacob D, Lüthi D, van Meijgaard E, Nikulin G, Schär C, Teichmann C, Vautard R, Warrach-Sagi K, Wulfmeyer V (2014) Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. Geosci Model Dev 7:1297–1333. https://doi.org/10.5194/gmd-7-1297-2014

Mesinger F, Veljovic K (2013) Limited area NWP and regional climate modeling: a test of the relaxation vs Eta lateral boundary conditions. Meteorol Atmos Phys 119:1–16. https://doi.org/10.1007/s00703-012-0217-5

Mesinger F, Veljovic K (2017) Eta vs. sigma: review of past results, Gallus–Klemp test, and large-scale wind skill in ensemble experiments. Meteorol Atmos Phys 129:573–593. https://doi.org/10.1007/s00703-016-0496-3

Morrison H, Thompson G, Tatarskii V (2009) Impact of cloud microphysics on the development of trailing stratiform precipitation in a simulated squall line: comparison of one- and two-moment schemes. Mon Weather Rev 137:991–1007

Pineda N, Jorba O, Jorge J, Baldasano JM (2004) Using NOAA AVHRR and SPOT VGT data to estimate surface parameters: application to a mesoscale meteorological model. Int J Remote Sens 25(1):129–143

Seneviratne SI, Corti T, Davin EL, Hirschi M, Jaeger EB, Lehner I, Orlowsky B, Teuling AJ (2010) Investigating soil moisture–climate interactions in a changing climate: a review. Earth Sci Rev 99(3–4):125–161

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Duda MG, Huang X-Y, Wang W, Powers JG (2008) A description of the advanced research WRF version 3. NCAR Technical Notes-475 + STR. https://doi.org/10.5065/D68S4MVH

United Nations, Department of Economic and Social Affairs, Population Division (2015) World urbanization prospects: the 2014 revision (ST/ESA/SER.A/366)

Van den Hurk BJJM (1995) Sparse canopy parameterizations for meteorological models, Ph.D. thesis. Wageningen Agricultural University, Wageningen

Veljovic K, Rajkovic B, Fennessy MJ, Altshuler EL, Mesinger F (2010) Regional climate modeling: should one attempt improving on the large scales? Lateral boundary condition scheme: Any impact? Meteorol Z 19:237–246. https://doi.org/10.1127/0941-2948/2010/0460

Warner TT (2011) Numerical weather and climate prediction. Cambridge University Press, Cambridge, p 526

Zittis G, Hadjinicolaou P, Lelieveld J (2014) Role of soil moisture in the amplification of climate warming in the eastern Mediterranean and the Middle East. Clim Res 59(1):27–37