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Long term modelling of the dynamical atmospheric flows over SIRTA site

A. Chahine [a], E. Dupont [b,*], L. Musson-Genon [b], C. Legorgeu [a], B. Carissimo [b]

[a] *CEREA (Atmospheric Environment Teaching and Research Center, Joint Laboratory École des Ponts ParisTech-EDF R&D, Université Paris Est), ENPC, 6-8 Avenue Blaise Pascal, Cité Descartes, Champs-sur-Marne 77455 Marne la Vallée Cedex 2, France*

[b] *CEREA (Atmospheric Environment Teaching and Research Center, Joint Laboratory École des Ponts ParisTech-EDF R&D, Université Paris Est), EDF-R&D, 6 quai Watier, 78401, Chatou Cedex, France*

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ABSTRACT

The atmospheric flow knowledge is important for its role in pollutant dispersion and wind energy. In this work, the hourly atmospheric flow output (8760 states) from Weather Research and Forcasting (WRF) model for the year 2011 over SIRTA (Site Instrumental de Recherche par Télédétection Atmosphérique) are analyzed and clustered into a finite number of representative atmospheric states using two clustering methods: non-controlled clustering and controlled clustering. The resulting representative situations of those clusters are used to specify boundary conditions for flow downscaling over the heterogeneous SIRTA. For flow downscaling, the CFD code Code_Saturne is used to simulate each representative atmospheric state. To assess the efficiency of WRF clustering and Code_Saturne downscaling, the measurements in SIRTA over the same year are used as reference. The Mean Absolute Error (MAE) and the Kullback-Leibler divergence (KL) metrics were computed for the distributions of the atmospheric flow features in order to: (i) compare the difference between the performance of the two clustering procedures, and (ii) compare the distribution of flow properties between WRF mesoscale model and Code_Saturne. It is clearly demonstrated that the two clustering methods are comparable in benefit, and that Code_Saturne improves considerably the flow features modeling in comparison to measurements.

1. Introduction

Atmospheric flows and their turbulence structure at local scale have an important role in the pollutant dispersion and the wind energy fields. In fact, the dispersion processes, and the performance of wind turbines are directly related to the spatial and temporal flow properties, such as the mean wind speed and direction and the turbulence statistics. Atmospheric flows over complex site are known for their spatio-temporal variability. As a consequence, the processes are variable and depend on the meso and microscale atmospheric conditions defined by the turbulent wind flow features and the thermal stability state.

For short periods, the atmospheric flow at the microscale is usually characterized by in-situ measurements or with Computational Fluid Dynamic (CFD) codes (Zaidi et al., 2013; Wei et al., 2016; Pieterse, 2013). However, for the long term prediction, such as the yearly averaged performance of wind turbine in the wind energy field, performance of the continuous operating open cooling tower, or long term assessment of risk exposure to pollutant from continuous source, numerical simulation of all atmospheric states becomes fastidious and costly because the large variability of the atmospheric states over the year must be taken into account.

An alternative to overcome this difficulty related to the large number of atmospheric states, consists in grouping the different states in clusters using a clustering procedure (Jain et al., 1999). The large number of atmospheric states is reduced to a small number of clusters (typically some hundreds). This renders the use of CFD simulation reasonable and efficient from a CPU time point of view.

An important feature of the atmospheric flows is the stratification which has been an obstacle in the physical modelling in wind tunnels and in numerical simulations. Fortunately, with the improvements in CFD tools and a better understanding of the stratified turbulence processes, it has become feasible to simulate atmospheric flows whatever the stability conditions. Zaidi et al. (2013) have simulated the atmospheric flow over SIRTA under the condition of neutral stratification for 36 wind direction sectors, and Wei et al. (2016) have simulated the flow over the same site in a stably stratified atmosphere. Moreover, many authors as for example Wyngaard and Cote (1974), Yamada and Mellor (1975) and Musson--Genon (1987) have simulated the diurnal cycle of the atmospheric flow within the whole atmospheric boundary layer over a period of one day.

* Corresponding author.
E-mail address: eric.dupont@edf.fr (E. Dupont).

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Their results agree well with in-situ measurements for all atmospheric stability states. Similarly, Milliez and Carissimo (2007) have used the same code to simulate the atmospheric pollutant dispersion over an idealized site.

For local scale long term CFD computations, the main need is the definition of the boundary conditions around the simulation domain and flow field initialization. For this purpose, the use of output of a mesoscale model is becoming increasingly used in the atmospheric CFD studies. Tewari et al. (2010) have proved that the use of the output of the mesoscale model as boundary conditions for the microscale modelling improves the accuracy of the microscale model output. Similarly, Liu et al. (2012) have coupled a Large Eddy Simulation (LES) CFD model with the WRF mesoscale model to investigate the wind field and pollutant dispersion at the scale of the city. In addition, Miao et al. (2013) and Zheng et al. (2015) have used the CFD model OpenFOAM coupled with the mesoscale model WRF to predict the local atmospheric flow and pollutant dispersion. While Gao et al. (2017) have coupled Code_Saturne with the Meso-NH model to study the atmospheric flow and dispersion over the local city. Here, we use the same approach; the inputs of the CFD model come from the large scale WRF output. This allows the downscaling of the atmospheric flows over the microscale land cover.

In the next section we describe the SIRTA over which the atmospheric flow downscaling is performed and the instrumentation set-up that will be used for numerical model validation and comparison with the mesoscale WRF model output. Next, in the section 3, we present the WRF data set used in this study for the clustering procedure followed by the description of the methods used for the clustering of the WRF data set in the section 4. The section 5 is dedicated to the description of the CFD code (Code_Saturne) and the numerical methods. The CFD numerical simulation of the clustered WRF data and comparisons between WRF data and CFD simulations will be presented in section 7. Finally, the average annual wind flow properties will be considered in the section 8, followed with discussions and conclusions in section 9.

2. SIRTA experiment

SIRTA is a french observatory located in a suburban environment on the campus of the Ecole Polytechnique in Palaiseau (Haeffelin et al., 2005), created by the Institut Pierre-Simon Laplace (IPSL). It is dedicated to the atmospheric conditions monitoring and meteorological research. The site is characterized by a strong heterogeneity of the land cover due to the presence of buildings, water surface, low vegetation and forests, as this can be seen in Fig. 1. As a consequence, the geometry and roughness of the site are very variables.

Two instrumented zones of the site (denoted Z1 and Z4) are used for this study (Fig. 1). The first period retained for our study corresponds to the years 2007–2009, used for the validation of Code_Saturne with regard to the atmospheric flows under near-neutral and stable conditions,

Fig. 1. SIRTA satellite view showing the two instrumented zones used in this study.

corresponding respectively to the almost nil and positive vertical gradient of the potential temperature. Whereas the measurements during 2011 are used for comparison with the corresponding mesoscale WRF data set and Code_Saturne results. In zone 1 a mast is set with one sonic anemometer at height of 10 m (z1_10m). Whereas in the zone 4, another mast is set with two sonic anemometers at heights of 10 m and 30 m respectively (z4_10m and z4_30m). The measurement frequency of each sonic anemometers is 10 Hz. The sonic anemometers measurements were averaged over 10 min. The wind statistics computed for each 10 min segment are the mean wind velocity U and its direction, the variances of the three components of velocity (σ_u,σ_v,σ_w) and the friction velocity U_*. Besides, the vertical variation of wind speed is obtained up to 800 m, with a vertical step of 50 m, using a SODAR wind profiler. The SODAR profiles are averaged over 20 min for the year 2011, as in (Tse et al., 2014).

3. WRF data set description

WRF (Weather Research and Forcasting) is a non-hydrostatic mesoscale numerical weather prediction model designed for both atmospheric research and operational forcasting. The model solves the equations of transport of momentum, heat and water at scales ranging from about tens to thousands kilometers. The transport equations are solved with the finite difference method and with a terrain-following pressure-based vertical coordinate.

The WRF model is used to predict the atmospheric flow conditions at regional scale around the SIRTA over the year 2011. The model run is transient on a uniform grid in the horizontal direction and variable in the vertical direction. The grid resolution in the horizontal direction is 3 km. In the vertical direction 39 levels were considered. The first level over the ground is at the height of 6 m and the last is at the height of 17 km. As the horizontal resolution of the grid in WRF model is large, the ground details (presence of buildings and forests) are not accounted for, but their effect on the ground-atmosphere exchange is represented by the roughness length approach.

The outputs of the model are stored every hour. The output variables are numerous, among which we have the three components of the wind velocity, pressure, potential temperature, water content, turbulent kinetic energy and ground friction velocity. The vertical profiles of the variables for the grid point closest to the SIRTA site were extracted for the downscaling and clustering procedure.

Overall, each hourly WRF output represents an individual state of the atmospheric flow. So, the number of the WRF atmospheric states over the year is 8760. In the microscale modelling with CFD tools, considering all those states becomes costly and is replaced by clustering.

4. Clustering of the WRF data

In order to reduce the number of the atmospheric states to be simulated with CFD code Code_Saturne, clustering procedure is a technic usually invoked. It consists in a reduction of the high number of states to a limited number of clusters (representative states) (Kalkstein et al., 1987; Romero et al., 1999; Bargaoui et al., 2008; Drevet et al., 2012). Each individual state is classified within an appropriate cluster according to its features. The clusters features are chosen according to the measured and simulated variables having a meaningful physical interest. As stated previously, the data set to be clustered is provided by WRF model with the temporal frequency of one hour. In our study the features of interest are mainly the magnitude and direction of the wind and the Richardson number characterizing the atmosphere stability at an altitude sufficiently high ($z = 50$ m) where the ground details do not influence the wind flow. Our choice is motivated by the role that the wind direction and atmosphere stability play in the wind organisation, turbulence structure and pollutant dispersion over a complex site.

To evaluate the performance of the clustering procedure and the representativeness of the clusters, we compute two statistical parameters