Analysis and validation of Weather Research and Forecasting model tendencies for meso-to-microscale modelling of the atmospheric boundary layer

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Abstract. The different terms of momentum and energy budget simulated by the Weather Research and Forecasting model (WRF) are examined at two sites that depict diverse climate and orographic environments. The analysis focuses both on particular weather episodes of one-to-few days duration and in one-year statistics useful for the assessment of the annual wind climate of a particular location. In order to estimate their accuracy, a validation exercise is performed in the Cabauw Experimental Site for Atmospheric Research (CESAR) in the Netherlands, where a fair agreement is found when comparing the mean surface pressure gradient term extracted from WRF with the pressure-derived geostrophic winds observed by the CESAR project. This study is carried out under the New European Wind Atlas (NEWA) project as part of the effort to develop a model-chain system that connects mesoscale with microscale wind flow models with different fidelity ranges for wind resource assessment applications. Therefore the analysis deepens in the horizontal and vertical variability of the tendencies in each of the sites with the ultimate goal of providing some guidelines of their best usage as large-scale forcing of the microscale models.

1. Introduction
There is an increasing need in numerous fields of science and engineering for the accurate modelling of many local processes occurring in the atmospheric boundary layer (ABL) which are strongly affected by meso and large-scale circulations. To this end, recent advances in dynamically downscaling Numerical Weather Prediction (NWP) models have allowed to push these models beyond the mesoscale regime, typically by using Large Eddy Simulation (LES) turbulence schemes at innermost domains, allowing researchers to understand many atmospheric features unveiled only when the interaction of a wide range of scales are simulated simultaneously (e.g. [1, 2], among others).

Multiscale modelling systems however, have still several shortcomings that limit their widespread usage. The limitations range from the practical side, such as the huge computational burden or the need of running the chain of nests simultaneously; to complex technical challenges such as the appropriate turbulence development [2], or the accurate and robust simulation of complex flows produced by very steep terrain or canopy elements; of great importance for communities such as the wind energy industry.
Because of that, the meso and the microscale systems are still mostly treated separately; simulated with tools of particular physical and numerical design to deal with each application. Therefore the efficient way to obtain higher-fidelity turbulence and local-flow structures, while incorporating variability arising from the large-scale processes is by coupling the two codes.

Among different model-chain strategies recently reviewed by [3], Sanz-Rodrigo et al. [4], inspired in the work of [5, 6], proposed a coupling methodology briefly summarized in section 3. As opposed to several techniques based on driving the microscale models through boundary conditions provided by mesoscale outputs, their method focuses on using the large-scale (i.e., several kilometres, and from hours-to-days temporal scales) terms of the momentum and energy budget computed by the mesoscale model (known as tendencies) as forcing to the microscale models. These quantities are added as source terms in the microscale governing equations; i.e., as external forces in the momentum, and additional (positive and negative) heat flux in the thermodynamic equation. Through a benchmarking exercise [7], the third GEWEX Atmospheric Boundary Layer Studies (GABLS3) case study was used to prove this strategy as a reliable and consistent method for connecting the meso and the microscale codes regardless of the order of turbulence-closure or fidelity of the underlying microscale model.

The validation of the entire model-chain approach for annual integrated calculations is addressed in the publication of [8] which complements this work. The work of [8] focuses on the protocols and procedures for meaningful validations in terms of metrics relevant for the wind industry, such as the Annual Energy Production (AEP), among others. That validation is carried out in the flat site of Cabauw (Netherlands) since the application of the full coupling methodology in sites of complex terrain is still under development (up to May/2018). Besides, as argued in that work, the simulations over horizontally homogeneous terrain is a convenient starting point for the design of Atmospheric Boundary Layer (ABL) models given the simpler interpretation of results compared to a 3D setting in heterogeneous conditions.

This meso-microscale coupling method is a drastic change in the current usage of microscale models for wind resource applications; from using constant geostrophic wind and stationary solutions towards the use of realistic forcing dependent on time and space; i.e., a transient flow solution. Besides, similar to other works such as [9], they also point out the rich information contained in the tendencies useful for the understanding of the climate of a region. However, it has also been outlined that as main driving sources, their bias and uncertainty are transferred to the microscale model with their corresponding impact on the final results.

Therefore, this work mainly focuses on the mesoscale side of the coupling procedure. The objective is to get first some insights about the accuracy of one important terms of the tendencies. Then it is aimed to show some of their characteristics in both flat and complex terrain in order to define some guidelines about their further usage in the microscale models.

For the first goal, the surface geostrophic wind (tendency of pressure gradient at the surface) simulated by the Weather Research and Forecasting (WRF) model is validated against observations at the Cabauw Experimental Site for Atmospheric Research (CESAR). For the second objective, it is presented the sensitivity of the tendencies to the averaging window (spacial and temporal) applied to their processing as well as to the model resolution. It should be noted that the analysis focuses on the adequacy of the tendencies’ statistical treatment to provide adequate forcing methodology rather than the accuracy of the mesoscale model results of velocity and temperature.

2. Observational and numerical data sets
The case studies are based on two regions with different climate and orographic conditions:

(i) The region around the CESAR in the Netherlands, which is a flat not very heterogeneous land surface area. This site provides a unique data set of high-quality "mesoscale" observations of surface pressure measured at 8 surface stations within a 50×50 km squared
area. These data are employed for the validation of the WRF’s pressure gradient term of the tendencies (see section 3). Besides, wind speed and wind direction measurements from the 230 m high meteorological tower are also accessible in CESAR’s databases, so the wind speed information is employed for the correlation analysis performed in section 5.

Both data sets are available for year 2006; however as detailed below, this work aims at using a WRF configuration as close as possible to the one selected for the New European Wind Atlas (NEWA) [10] whose forcing comes from ERA-5 reanalysis [11]. Nevertheless, as of the publication of this work (May/2018), ERA-5 is only available from year 2010, therefore two case studies had to be defined for the region around Cabauw with the following simulation dates and objectives:

- Cabauw Jan/2006-Jul/2006: Validation of WRF’s pressure gradient term (section 4), and correlation study between tendencies and velocity measurements (section 5.2). WRF set-up makes use of ERA-Interim reanalysis [12] as model forcing.
- Cabauw 2016: Sensitivity to WRF’s resolution and statistical treatment of tendencies (section 5). Model is driven by ERA-5 reanalysis and makes use of high-resolution Sea Surface Temperature (SST) data.

(ii) A site located in a mountainous area in north-east of Spain, centred in the Alaiz Experiment (ALEX) which is part of the NEWA experiments [13]. The topography of the site is very complex with a peculiar wind climate of two predominant wind directions; north and south which account for approximately 90% of the records. The observations at ALEX employed for this study consist on the 2016 annual measurements of wind speed and wind direction at 80 m high of the main mast of the experiment (MP5 mast). Data coverage is about 95% for that year. These data are essentially used for the correlation analysis described in section 5.2.

The simulations at each site are performed with the WRF model version 3.8.1 [14] with the following configuration derived from the comprehensive sensitivity analysis performed by the mesoscale group in NEWA [10]. As mentioned before, ERA-Interim is employed as forcing for the 6-month period simulation of Cabauw 2006 whereas ERA-5 reanalysis data together with OSTIA SST and GLDAS/NOAH land surface information are used as forcing and boundary conditions for the annual simulations at Cabauw and Alaiz for year 2016. High-resolution elevation and land use is extracted from the SRTM and CORINE projects. NOAH model is used for land surface parameterization scheme whilst MYNN version 3.8.1, modified as detailed in [10], is used as Boundary Layer (PBL) physics scheme. Apart from the forcing for the Cabauw 2006 run, the main difference to the NEWA set-up is that domains are centred on the mast of each of targeted sites (as opposed to the regional focus of the Atlas). Thus, three nested domains are generated with horizontal grid spacing of 27(d01), 9(d02) and 3(d03) km; with 110, 100 and 88 grid points per side, respectively, and 61 vertical levels up to a height of 50 hPa at the top. In both Cabauw and Alaiz, the WRF runs are carried out by running sets of 8-day simulations with 24 hours of spin-up while performing spectral nudging in domain 1(d01). Outputs are stored in 10-min periods and then hourly averaged.

3. Definition of the tendencies

As described by [7, 9], the equation in WRF for the conservation of momentum for the zonal wind component $u_1$ in Einstein’s summation notation reads:

$$
\frac{1}{f} \frac{\partial \bar{u}_1}{\partial t} = -\frac{1}{f} \frac{\bar{u}_1}{\partial x_i} \frac{\partial \bar{u}_1}{\partial x_i} - \frac{1}{f} \frac{\partial \bar{p}}{\partial x_i} + \bar{u}_2 \frac{\partial \bar{u}_1}{\partial x_i} - \frac{1}{f} \frac{\partial \bar{u}_1'}{\partial x_i} + \bar{u}_2 \frac{\partial \bar{u}_1'}{\partial x_i}
$$

(1)
where \( u \) represents wind speed; over bars indicate the (temporal) mean value while the primes indicate departures from the mean. The index \( i \) goes from 1-3 for the zonal, meridional and vertical components respectively and \( p, \rho \) and \( f \), stands for pressure, air density and the Coriolis parameter. It is noted that for convenience, all terms are divided by the Coriolis parameter, so it is possible to read the equation (1) as a balance of different forces represented by wind speed vectors \( U \), as indicated below each term in the equation. Thus, as described in equation (2), the local change in zonal wind or tendency \( U_{\text{tend}} \), can be expressed by the contribution of advection \( U_{\text{adv}} \), mean pressure gradient force \( U_{\text{pg}} \), Coriolis force \( U_{\text{cor}} \) and the divergence of the momentum flux \( U_{\text{phys}} \) related to the turbulent mixing which is typically parameterized in mesoscale models through the Planetary Boundary Layer (PBL) schemes. Analogously, the conservation of momentum for meridional wind components is represented in equation (3). Since the pressure gradient term leads to the Geostrophic wind in ideal stationary conditions in the upper atmosphere; \( U_{\text{pg}}, V_{\text{pg}} \) are sometimes referred to as “Geostrophic” wind in this text.

\[
U_{\text{tend}} = U_{\text{adv}} + U_{\text{pg}} + V_{\text{cor}} + U_{\text{phys}} \tag{2}
\]

\[
V_{\text{tend}} = V_{\text{adv}} + V_{\text{pg}} - U_{\text{cor}} + V_{\text{phys}} \tag{3}
\]

Similarly, the terms of the energy budget in the potential temperature transport equation (4) can be represented as equation (5) where \( \theta \) is the potential temperature, \( \Theta_{\text{adv}} \) is the advection of potential temperature and \( Q_i \) (and \( \Theta_{\text{phys}} \)) stands for the contribution of the kinematic turbulent flux, radiation flux, land surface heat exchange, and other physical processes which are also accounted in the mesoscale models by the parameterization schemes.

\[
\frac{\partial \bar{\theta}}{\partial t} = -\bar{u}_i \frac{\partial \bar{\theta}}{\partial x_i} - Q_i \tag{4}
\]

\[
\Theta_{\text{tend}} = \Theta_{\text{adv}} + \Theta_{\text{phys}} \tag{5}
\]

The tendencies can be extracted from WRF as part of the standard outputs through a small modification in a routine on the of WRF’s source code as detailed by [15].

4. Validation of the tendencies
Validation is carried out with the CESAR data set. The 8 surface stations used from CESAR cover a squared region of \( L \approx 50 \times L \approx 50 \text{ km}; \) therefore, the grid points within that area in WRF are selected and averaged horizontally for each domain. The components of the pressure gradient \( U_{\text{pg}}, V_{\text{pg}} \), at the first WRF’s sigma level are considered as the surface values (first level is approximately 5 m above ground), then values are averaged over that \( L \times L \) area.

The results presented in figure 1 illustrate the time-series of magnitude \( S_{\text{pg}} = |U_{\text{pg}}, V_{\text{pg}}| \) and direction \( \zeta(U_{\text{pg}}, V_{\text{pg}}) \), of the surface gradient. For this figure, the data are averaged in daily intervals. It must be noted a missing period of 8 days due to a data loss during the model run. It can be seen however a good agreement for both WRF’s domains: d01 of 27 km (solid line) and d02 of 9 km grid spacing (dashed line), whose values are mostly contained within the 95% confidence interval of the measurements (gray shadow/points). The bias for both domains is 0.48 and 0.43 m/s whereas the mean absolute error (MAE) is 1.49 and 1.4 m/s for d01 and d02, respectively.

Given the small difference between the results at both domains, figure 2 includes a more detailed evaluation for the pressure gradient \( U_{\text{pg}} \) and \( V_{\text{pg}} \), only for d02. In order to assess diurnal accuracy of these terms, the figure shows the scatter between the hourly means of WRF and CESAR observations also with the 95% confident interval lines. Apart from few outliers in the north-south component (figure 2 right), they show a strong similarity with small offsets of less than 0.2 m/s and slope close to 1.0 in the regression line. While the bias of the magnitude \( S_{\text{pg}} \), is almost identical to the daily averages, the MAE is 2.2 m/s which is about 14% compared to the average of the period.
Figure 1. Comparison of WRF pressure gradient magnitude (above) and direction (below) at domain d01 (solid red line) and d02 (blue dashed line) versus the observations at CESAR drawn with their 95% confidence interval (gray shadow) for the period of Jan-2006 to July-2006.

Figure 2. Comparison of hourly averages of pressure gradient from WRF at domain d02 (9km res.) and observations at CESAR for the zonal \( U_{pg} \) (left) meridional wind component \( V_{pg} \) (right) for the simulation period.

5. Sensitivity analysis
5.1. Influence of WRF’s resolution
The validation at Cabauw of section 4 shows that the mean pressure gradient is relatively well captured by WRF regardless of the two model’s resolution tested; 27km grid spacing of domain 1 and 9km of d02, in a flat, homogeneous site. However, sites of higher terrain complexity introduce more challenges due to the important terrain-induced pressure gradients and their interplay with larger-scale processes and surface heat flux exchange. Within the ABL, the effects of topography on the wind flow are mostly dependent on wind direction. Therefore, with the intention of distinguishing these effects as a function of the model’s resolution, a representative day was selected from the 2016 simulations at each site. The selection criterion was that the wind direction at the WRF’s central grid point at a height of 80m remains constant (within
a range of 10 degrees) throughout that entire day. In practice the threshold is set to 90%, or more, of the records of the days within the specified wind direction range. In the case of ALEX the 6th of April was selected as very representative for northerly winds at 140 m above ground, whereas at CESAR, the 24th of April was selected as the day with an entire diurnal cycle of wind coming from the prevailing 325 degrees wind direction.

The results for the magnitude of pressure gradient term \( S_{pg} \), at the three WRF domains are shown in figure 3 for ALEX (above) and CESAR (below). The values are averaged horizontally in the squared area of \( L = 45 \text{km} \) per side, and plotted every three hours for all the sigma levels. As expected, the flat and homogeneous terrain conditions of Cabauw induce minimum surface pressure gradients, so the three resolutions provide a similar structure during the day. On the other hand, the Alaiz results, show much more variability with very high values; i.e., very strong pressure gradient force, during the night and midday which extend up to the height of the ABL. This is potentially caused by the complex mountainous system to the north of domain’s centre in Alaiz. This system also interacts with a very strong diurnal cycle of the temperature convection \( \Theta_{adv} \) as seen in figure 4. Beyond the ABL height, it is seen that the pattern becomes similar in the three resolutions; consistent with the definition of the Geostrophic level where the influence of the ground processes are vanished so model’s resolution is less relevant and variations are mostly from meso and larger-scale dynamics. It must be also noted the very strong diurnal variation of both \( S_{pg} \) and \( \Theta_{adv} \) at this level (beyond the height of the ABL) in Cabauw, and more remarkably in Alaiz. The implications is that the common assumption of constant, ideal geostrophic wind (typically used to drive stationary microscale models) is not realistic even in flat terrain sites, and can lead to unrealistic results.

Figure 3. Diurnal cycle of the magnitude of the pressure gradient \( S_{pg} \) for the three WRF’s domains on the 6th of April for ALEX (above) and 24th of April for CESAR (below). Values are averaged horizontally for every sigma level and plotted every three hours.

In order to complement the information illustrated in figure 3, figure 5 shows the standard deviation of \( S_{pg} \), along each sigma level scaled by the horizontal averages. This way it is possible to compare more consistently the variability of the pressure gradient in the different model’s resolutions and between both case studies. In this figure, it can be noticed the similar and small horizontal variability of \( S_{pg} \) along domain d01 and d02 for both sites. As a contrast,
the pressure gradient simulated by the innermost domain d03, accounts not only for meso-and-regional scale dynamics, but also for the small-scale advection potentially generated by the complex topography in first sigma levels which is then propagated vertically. Capturing these dynamics is desired in high-resolution mesoscale simulations that aim to accurately predict the surface wind flow. However, in the proposed coupling strategy of [4], the local phenomena such as the complex flow dynamics caused by the topography, should be accounted by the microscale model. Thus, in order to avoid “double counting” these processes, tendencies obtained in high-resolution mesoscale grids, such as d03, are not appropriate inputs for the model-chain method pursued by [4].

5.2. Contribution to local surface wind from the terms of the tendencies
This section explores the relative importance of several terms of the momentum and energy budget to the local wind speed measured at the CESAR (Cabauw) and ALEX (Alaiz) masts at 140 m and 80 m, respectively. The test is performed with the WRF results of the 2016 annual integration to obtain statistical significant results. The analysis is based on creating the matrix of Pearson’s Correlation $\rho_{XY}$, among these tendencies and the measured Rotor Equivalent Wind Speed (REWS). The REWS is a more convenient metric for wind resource applications because it represents the wind speed corresponding to the kinetic energy flux through the swept rotor area, when accounting for the vertical shear of wind speed and direction. Thus it provides more information than the wind speed at a single height (see [7, 8] for the detailed description). The REWS is computed from the measurements considering a hub height of 120 m with a rotor diameter of 160 m.

Only the tendencies related to large-scale dynamics are considered for the analysis; these are the magnitude of the advection term $S_{adv} = |U_{adv}, V_{adv}|$, the magnitude of the pressure gradient force $S_{pg}$ and temperature advection $\theta_{adv}$. The terms associated with the physics schemes, i.e., $U, V_{phys}$ and $\Theta_{phys}$, are excluded for the analysis (as also for inputs to the microscale models [4]) since conceptually they are used by the mesoscale model to approximate local phenomena that are
not explicitly simulated by the model dynamics. These tendencies are extracted from the domain d02 and three area extents for the horizontal averaging are included for the sensitivity analysis: squared areas of side $L = 45, 27$ and $9\text{ km}$ by side. Tendencies and REWS are normalized by their own mean $\mu$, and standard deviation $\sigma$, as $Z = (X - \mu)/\sigma$, in order to properly compute the Pearson’s correlation for all pairs of variables.

Figure 6 shows the correlation matrices resulting from tendencies averaged in the three area extents; $45 \times 45 \text{ km}$ (left), $27 \times 27 \text{ km}$ (centre) and $9 \times 9 \text{ km}$ for the Alaiz case study (above) and Cabauw site (below). It is clear from the figure that all matrices present the same patterns. Conspicuously, the pressure gradient and advection have always the highest and a positive correlation which increases when the area for averaging decreases. Interestingly to note that the correlation between REWS and $S_{pg}$, $\rho(S_{pg}, \text{REWS})$, and between REWS and advection, $\rho(S_{adv}, \text{REWS})$, are always positive and equally important as their values are in a very close range. In fact for Alaiz, $\rho(S_{adv}, \text{REWS})$ is slightly higher than $\rho(S_{pg}, \text{REWS})$ while the opposite happens in Cabauw. Regarding the area extent, no significant difference is found among the three areas considered, where, as expected, the Cabauw case study obtains almost identical results. Finally, in all the combinations, the temperature advection is weakly and negatively correlated to all the variables.

5.3. Influence of WRF’s resolution in the meso-micro coupling results

This section briefly address the effects of WRF’s resolution in the results of the full model-chain methodology. To this end, the microscale model CFDWindSCM [4] is used to resolve the fields of wind speed and temperature based on the forcing provided by the tendencies analyzed in figure 6; i.e., advection (of momentum and potential temperature) and pressure gradient terms, plus the WRF’s skin temperature imposed as boundary condition at the ground.

The case study is the Cabauw site since it complies with the current limitations of the microscale model mentioned in section 1 for the 2016 annual integration. The details of this simulation are part of the complementary publication of [8]. Following that work, the analysis
is based on binned statistics from annual quantities relevant for the wind industry, such as the REWS described above. The classification is based on bins of atmospheric stability, wind speed and wind direction.

The stability is estimated with the parameter $\zeta = z/L_{MO}$, where $L_{MO}$ is the Monin-Obukhov length and the bins are defined with the same intervals listed in the complementary publication [8], which leads to the following classes: unstable (u), weakly-unstable (wu), near-neutral (n), weakly-stable (ws), stable (s) and very-stable (vs) cases. The wind direction bins are defined by 12 sectors (every 30 deg.), and the speed bins every m/s in a range of 0 until 15 m/s.

Figure 7 illustrates the average of the REWS values that fall inside each class that combines the binning by stability classes (set in the y-axis), and wind direction (above) and wind speed classes (below) which are set in the x-axis of the plots. The black solid line, is a contour line related to the frequency of occurrence of each bin relative to the total amount of data in the annual simulation. In this manner is easy to identify that dominant wind conditions in Cabauw are associated with neutral stability and south-west direction, and the peak of the frequency wind speed distribution is $\approx 7$ m/s. The figure shows the similarity of the results among the WRF’s domains for the entire annual period. This conclusion was already expected for Cabauw given its simple terrain condition; also and given the conclusions obtained from the previous analysis of the tendencies. Nonetheless, these results show that the coupling methodology is innocuous to the mesoscale results in horizontally homogeneous conditions. Thus, it extends the conclusions obtained in the single-day experiment of GABLS3 (see [7]) to long-term simulations.
Figure 7. Heatmaps with the mean values of the REWS data that falls onto each class. The classes are created with bins of direction and atmospheric stability (above), and wind speed and stability (below). The heatmaps of binned statistics are divided by columns for the results of the three WRF domains.

6. Conclusions and outlook
The insights found throughout this work are listed below.

The validation of the WRF’s pressure gradient term is carried out at a surface level, which is not entirely suitable when the interest is the validation of WRF’s ability to simulate large-scale dynamical processes because both, model and measurements potentially include local surface effects produced by the interaction with the ground. However, the Cabauw case study minimizes this problem as the site is flat and relatively homogeneous. The outcome of the validation shows a fair agreement between the surface pressure gradient simulated by WRF and the one observed at CESAR flat terrain site. Both magnitude and direction of daily averages are very well predicted by WRF’s coarse resolution domains, d01 and d02, whose values are mostly contained within the 95% confidence interval of the measurements. Their bias and MAE are less than 0.4 m/s and 1.5 m/s, respectively. The hourly-averages of domain 2 run, show a larger absolute error of 2.2 m/s. Nonetheless, it is still close to the range of the measurements confidence intervals whose mean amplitude is approximately 1.8 m/s.

The analysis of the pressure gradient term is performed for a selected day that presents a constant surface wind direction during the entire day. From that analysis, it can be noticed that domains 01 and 02 obtain similar horizontal variability which is relatively small, even for the complex terrain site of Alaiz. Nevertheless, the pressure gradient simulated by the innermost domain d03 is potentially resolving more small-scale advection from the topographic elements. It is outlined that, while capturing these dynamics is desired in mesoscale simulations that aim to accurately predict the surface wind flow, in the proposed coupling methodology
[4], the local surface phenomena is simulated by the microscale model. Thus, in order to avoid "double counting" to some extent the local-scale processes, tendencies obtained in high-resolution grids are not appropriate inputs for this specific model-chain strategy. On the other hand, it is observed that the behaviour of the tendencies beyond the height of the ABL are far from stationary. Besides, their variability is very large with an intense diurnal pattern at the top (geostrophic level) regardless of the terrain complexity. Therefore, microscale modeling approaches that assume ideal or constant geostrophic forcing can lead to unrealistic results.

In an annual time frame, it is found that the contribution of the advection term to the momentum budget, and to local surface wind speed is as large as the one of the pressure gradient. Therefore this term should not be neglected to the forcing of the microscale model.

Finally, as for the usage of tendencies for microscale model forcing, it is found that the extent of area used to average these terms is not as relevant as the spatial resolution of the simulation. Based on the current analysis and WRF set-up, the grid-spacing of 9km is a good compromise of the resolution required to resolve important large-scale features that should be transmitted to the microscale model, without "resolving" too much of the local physical processes that should be simulated more accurately by the microscale model.

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