HARMO22

22nd International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
10-14 June 2024, Pärnu, Estonia

Assessing the effect of topography on the Atmospheric Flow over the Amazon Forest by means of Large Eddy Simulation and tower measurements

Daiane Brondani[1,4], Raissa Soares de Oliveira[2], Cléo Q. Dias Junior[3], Silvia Trini Castelli[1], Tony Christian Landi[1], Umberto Giostra[4], Luca Mortarini[1]

[1]*Institute of Atmospheric Sciences and Climate, National Research Council, Italy*

[2]*National Institute of Amazonian Research (INPA), Manaus, Brazil*

[3]*Federal Institute of Pará, Belém, Brazil*

[4]*Urbino University "Carlo Bo", Urbino, Italy*

Email of first author: daiane.devargasbrondani@cnr.it

Abstract:
Contrary to our intuition forest are rarely situated on uniform and flat terrain in which the horizontally homogeneity of turbulence holds. The orography of the Amazon Tall Tower Observatory (ATTO, https://www.attoproject.org/) makes no exception and this complicates the interpretation of its measurements. The spatial representativeness of anemometric tower data and the underlying hypothesis of horizontal homogeneity of the atmospheric flows have long being questioned in the literature, as it has been long known that forested canopies enhance the effects of even mild topography. Using the Parallelized Large Eddy Simulation Model (PALM) with the highly vertically resolved measurements of the two ATTO towers (19 levels from 5 m to 316 m) allowed the assessment of the influence of topography on the atmospheric flow within and above the roughness sublayer in the Amazon Forest. To totally ascribe the flow variability to spatial orography gradients, a horizontally homogeneous leaf area density was considered. Simulations considering the real topography of the ATTO site and different wind directions are compared with measured profiles and with simulations ran over flat topography. The impact of the orography on turbulence is presented. Focus is also given to the ability of the PALM model to increase the spatial representativeness of the tower data.

Key words: PALM, Amazon Forest, Orography, Horizontal inhomogeneity

INTRODUCTION

The turbulent flow dynamics within and above forested canopy across complex terrain remain a significant focus for researchers in diverse environmental fields, including studies on exchanges of greenhouse gases and biogenic volatile organic compounds, energy and momentum transfer, and wind energy distribution. However, understanding the interaction with mean flow presents a complex challenge. As revealed by Dupont et al. (2008) the forested hills alter the airflow dynamics due to the topography-induced horizontal pressure gradient. This gradient distorts the mean flow and generates turbulent eddies, disrupting the mean flow. A wake region on the lee side of the forested hills emerges, characterized by reduced wind speed and enhanced turbulence levels. Moreover, the authors identified an intermittent region that may develop, mainly if the topography is steep or the forest canopy is dense, significantly influencing scalar exchanges.

Over time, observational and modelling approaches have been used to assess the role of topography in turbulent flow. While measurements from micrometeorological towers are valuable for enhancing our understanding of the real turbulent flow and for validating numerical models, their footprint is limited to meters or a few kilometers. Additionally, forested terrain often presents challenges for installing this type of instrumentation. Conversely, the large eddy simulation technique can be used to simulate larger areas and investigate the features of turbulent flow in detail.

The Amazon Tall Tower Observatory (ATTO) in the Central Amazon in Brazil presents a unique opportunity to study turbulent flow over a dense forest canopy within a complex terrain. Situated on a broad plateau, two micrometeorological towers capture atmospheric processes and the surrounding environment, offering a wealth of data for researchers. In this preliminary analysis, our aim is to assess the role of topography in wind speed profiles and turbulent statistics at the ATTO site. To achieve this, we employ the Parallelized Large Eddy Simulation Model (PALM) to simulate a neutrally stratified atmosphere over the real topography of the ATTO site. Specifically, we investigate the influence of real topography on wind patterns by considering two prevailing wind directions from west and east. Furthermore, we contrast these findings with simulation conducted over flat terrain to elucidate how real topography influences wind speed profiles and turbulent statistics at the ATTO site.

DATA AND METHODS

Site overview

Figure 1a illustrates the Amazon biome (green line) and the Brazilian Amazon region (yellow line), where a red point marks the ATTO site. Placed 150 km northeast of Manaus, the most populous city in the Brazilian Amazon region, ATTO lies within the Uatumã Sustainable Development Reserve in the Central Amazon. Situated at an elevation of 120 m above sea level on a plateau surrounded by valleys (Fig. 1b), the area is characterized by dense forest cover, with a maximum leaf area density 5 - 6 m^2m^{-2} and a canopy top height approximately 36 m. The prevailing wind direction is from northeast.

At the plateau where ATTO is situated there are two micrometeorological towers: the ATTO tower (02° 08’ 45” S, 59° 00’ 20” W), standing at a height of 325 m, and the INSTANT tower (02° 08’ 39” S, 59° 00’ 00” W) measuring 81 m in height (Fig 1b, marked orange and green). Both towers are equipped with 3D sonic anemometers, including the CSAT3B by *Campbell Scientific*, Inc. and Ultrasonic Anemometer 3D by Thies providing measurements at nineteen vertical levels of measurements with high acquisition frequency (10 Hertz).

For a more comprehensive understanding about of this site, readers are referrered to Andreae et al. (2015).

Data Analysis

For comparison with the Large Eddy Simulation (LES), continuous measurements taken from 2021 to 2022 were considered. Data were quality controlled following Dias et al. (2023), discarding sub-data blocks with more than 1% Not a Number, removing spikes, and verifying the non-stationarity condition for the u, v and w wind velocity components.

Neutral stability was identified using the same criterium described in Cava et al. (2022). After a scrupulous selection, a subset of 18000 seconds for each wind direction was selected. This data were also used to evaluate the wind profile used as initial condition for the LESs.

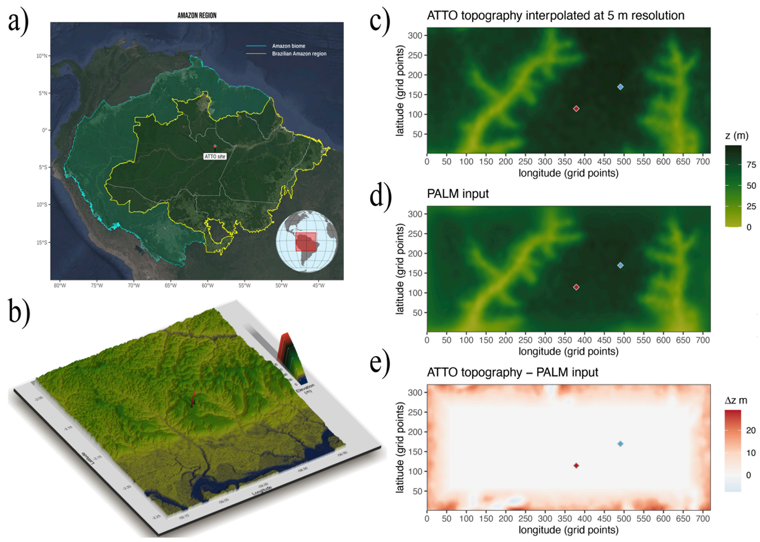

Figure 1. a) Localization of the ATTO site in the Amazon region. b) Digital elevation map (~25 km x 25 km) of the topography around the ATTO site. Panels c), d) and e) illustrate the preparation of the static input file (3600 m x 1500 m): c) original orography of the ATTO site referred to its minimum. d) palm elevation input. e) Difference between the ATTO original elevation and the PALM input. The ATTO (INSTANT) tower is depicted in red (blue).

Simulation Set up

To isolate the dynamical effects of topography on a flow over a forested canopy, neutral stratification, and a constant leaf area density profile were considered.
The PALM model was used to generate the three-dimensional velocity field within and above the forest. We conducted three simulations: prevailing wind direction from west and east for real topography and a simulation considering flat terrain. The model integration domain is a 3600 m x 1500 m rectangle with 5 m isotropic grid spacing ($dx = dy = dz$) and a vertical extension of 800 m. We neglected the Coriolis force effect, which is particularly weak near the Equator, where the ATTO site is located, and we imposed a constant east-west wind direction by setting a constant pressure gradient ($\frac{1}{\rho}\frac{dp}{dx}$) of $\pm 3 \cdot 10^{-4}$ ms^{-2}. Additionally, we also implemented a Rayleigh damping layer above 700 m, controlled by the Rayleigh damping factor set to 0.1.

Since cyclic boundary condition were considered on the frontier of the domain, the domain borders were smoothed as follow (Chen et al., 2020):

- The orography was referred to its minimum value (which is also the way PALM threats the orography) as shown in Figure 1c;
- A rectangular outside border 300 m thick was defined, outside the border the elevation was kept equal to its original values, while inside the border a two-dimensional weighted gaussian smoothing was applied (Figure 1e).

The elevation used in the PALM static file is shown in Figure 1d. The time duration required to reach a quasi-steady state was 12 hours for both wind directions.

RESULTS

Figure 2 depicts the preliminary analysis results. We chose the ATTO tower position rather than the INSTANT one to compare the simulations, since this tower would likely be less influenced by the valley ridges. Overall, the windspeed profile presents a clear inflection point at the canopy it, identifying the presence of a turbulent mixing layer (Fig. 1a). The role of the topography is highlighted by the differences between the flat simulation and the ones with orography (Figs. 1b – 1f), particularly within the first 300 m. However, a less pronounced effect of topography compared with the turbulent variables is noted for wind speed, which is reasonable given its lesser sensitivity to local topographic effects.

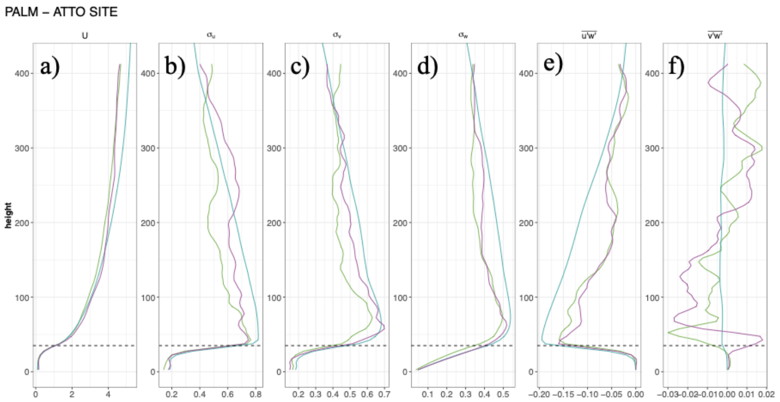

Figure 2. Mean values calculated over and area of 45 m x 45 m (81 grid points) for a) wind speed (U) in ms[-1], b) streamwise variance (σ_u), c) spanwise variance (σ_v), vertical variance (σ_w), downward vertical momentum flux $(\overline{u'w'})$, and f) crosswind-vertical turbulent momentum transport, $(\overline{v'w'})$ in m^2s^{-2}. The result is presented for simulations corresponding to the east wind direction (green color line), west wind direction (purple color line), and flat terrain (cyan color line).

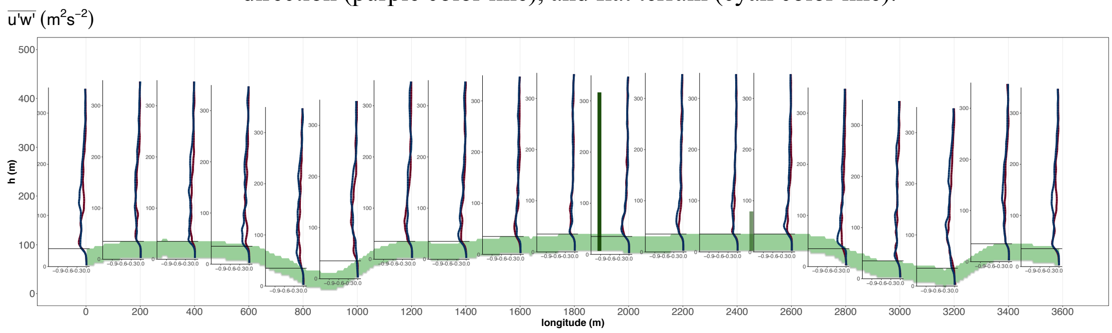

Figure 3. XZ cross-section illustrating downwind vertical momentum flux $(\overline{u'w'})$ for west (blue color line) and east simulations (red color line) at intervals of 200 m for the y-ATTO position (dark green). The INSTANT tower is shown at its corresponding x-position (light green).

On the other hand, the profiles of turbulent quantities reveal the influence of topography on altering the flow, mainly above the canopy top (Figs. 1b – 1f). Another interesting aspect is the difference between the σ_u and σ_v profiles (Figs. 1b and 1c). The simulation from the west wind direction exhibits a behaviour similar to the one performed over flat terrain. This is expected since the westerly flow has time to re-equilibrate before reaching the tower. Another noteworthy point is the behaviour of the downward vertical momentum flux $(\overline{u'w'})$ (Fig. 1e). While there are a few differences between the simulations for both wind directions, we observe a disruption of vertical momentum transport compared to the flat terrain, resulting in weaker downward transport of momentum. Less clear is the role of topography in the crosswind-vertical turbulent momentum transport $(\overline{v'w'})$ (Fig 1f). Above the canopy top, until 75 m, the simulation for the east direction presents a downward transport of momentum, while from the west, it is positive. However, from this height to 200 m, both simulations tend to have the same signal. These results require further investigation and will be analysed in the future.

Figure 3 displays an xz slice cut at the y-ATTO position (dark green) depicting $\overline{u'w'}$ for both west and east simulations at intervals of 200 m along the x-axis. For reference, the INSTANT tower location on the x-axis was added (light green). The single profiles show that the $\overline{u'w'}$ profiles tend to become more stable on the plateau (between 1400 m and 2600 m). The west and east simulation present similar values for the momentum flux at the canopy top, but they show slightly different behaviours in the roughness sublayer. These results highlight the complex interaction between topography and the turbulent flow, highlighting the need for continued investigation and analysis in future studies.

CONCLUSIONS

Three LESs were performed to evaluate and assess the effect of topography on turbulent flow at the ATTO site in neutral stratification. Specifically, a simulation over flat terrain and two simulations above the real orography of the ATTO site were carried out and their turbulence family portrait were compared. The preliminary results show the topography influence on turbulent variables, with pronounced differences in vertical momentum transport and turbulence intensity between the simulations. These findings reveal the complexity of the interaction between topography and the forested canopy at the ATTO site. However, more investigations and the comparison with the measured data are necessary to have a deeper insight.
The insights gained from studying the role of topography on turbulent flow within and above forested canopy can provide valuable insight into urban canopy studies. The complex interactions between topography, vegetation, and turbulent flow using large eddy simulation techniques can be easily applied to models like PALM for urban settings. This is particularly crucial as urban architecture becomes more complex and trees, streets, and buildings interact with the turbulent flow.

Acknowledgements: This work was partially conducted within the framework of the National Biodiversity Future Center (NBFC) at the National Research Council, Institute of Atmospheric Sciences and Climate (ISAC), Lecce. The project was funded by the European Union - Next Generation EU by PNRR, Spoke 4: "Piano Nazionale di Ripresa e Resilienza (PNRR), Missione 4 Componente 2 Investimento 1.4 “Potenziamento strutture di ricerca e creazione di "campioni nazionali di R&S" su alcune Key Enabling Technologies” finanziato dall’Unione europea – NextGenerationEU”.

REFERENCES

Andreae, M. O., Acevedo, O. C., Araùjo, A., Artaxo, P., Barbosa, C. G. G., Barbosa, H. M. J., Brito, J., Carbone, S., Chi, X., Cintra, B. B. L., da Silva, N. F., Dias, N. L., Dias-Júnior, C. Q., Ditas, F., Ditz, R., Godoi, A. F. L., Godoi, R. H. M., Heimann, M., Hoffmann, T., Kesselmeier, J., Könemann, T., Krüger, M. L., Lavric, J. V., Manzi, A. O., Lopes, A. P., Martins, D. L., Mikhailov, E. F., Moran-Zuloaga, D., Nelson, B. W., Nölscher, A. C., Santos Nogueira, D., Piedade, M. T. F., Pöhlker, C., Pöschl, U., Quesada, C. A., Rizzo, L. V., Ro, C.-U., Ruckteschler, N., Sá, L. D. A., de Oliveira Sá, M., Sales, C. B., dos Santos, R. M. N., Saturno, J., Schöngart, J., Sörgel, M., de Souza, C. M., de Souza, R. A. F., Su, H., Targhetta, N., Tóta, J., Trebs, I., Trumbore, S., van Eijck, A., Walter, D., Wang, Z., Weber, B., Williams, J., Winderlich, J., Wittmann, F., Wolff, S., and Yáñez-Serrano, A. M.: The Amazon Tall Tower Observatory (ATTO): overview of pilot measurements on ecosystem ecology, meteorology, trace gases, and aerosols, Atmos. Chem. Phys., 15, 10723–10776, https://doi.org/10.5194/acp-15-10723-2015, 2015.

Cava, D., Dias-Júnior, C. Q., Acevedo, O., Oliveira, P. E., Tsokankunku, A., Sörgel, M., ... & Mortarini, L. (2022). Vertical propagation of submeso and coherent structure in a tall and dense Amazon Forest in different stability conditions PART I: Flow structure within and above the roughness sublayer. *Agricultural and Forest Meteorology*, *322*, 108983, https://doi.org/10.1016/j.agrformet.2022.108983

Chen, B., Chamecki, M., & Katul, G. G. (2020). Effects of gentle topography on forest-atmosphere gas exchanges and implications for eddy-covariance measurements. *Journal of Geophysical Research: Atmospheres*, 125, e2020JD032581, https://doi.org/10.1029/2020JD032581

Dias, N. L., Toro, I. M. C., Dias-Júnior, C. Q., Mortarini, L., & Brondani, D. (2023). The Relaxed Eddy Accumulation Method Over the Amazon Forest: The Importance of Flux Strength on Individual and Aggregated Flux Estimates. *Boundary-Layer Meteorology*, *189*(1), 139-161. https://doi.org/10.1007/s10546-023-00829-7

Dupont, S., Brunet, Y., & Finnigan, J. J. (2008). Large-eddy simulation of turbulent flow over a forested hill: Validation and coherent structure identification. *Quarterly Journal of the Royal Meteorological Society*, *134*(636), 1911-1929, https://doi.org/10.1002/qj.328

Maronga, B., Banzhaf, S., Burmeister, C., Esch, T., Forkel, R., Fröhlich, D., Fuka, V., Gehrke, K. F., Geletič, J., Giersch, S., Gronemeier, T., Groß, G., Heldens, W., Hellsten, A., Hoffmann, F., Inagaki, A., Kadasch, E., Kanani-Sühring, F., Ketelsen, K., Khan, B. A., Knigge, C., Knoop, H., Krč, P., Kurppa, M., Maamari, H., Matzarakis, A., Mauder, M., Pallasch, M., Pavlik, D., Pfafferott, J., Resler, J., Rissmann, S., Russo, E., Salim, M., Schrempf, M., Schwenkel, J., Seckmeyer, G., Schubert, S., Sühring, M., von Tils, R., Vollmer, L., Ward, S., Witha, B., Wurps, H., Zeidler, J., and Raasch, S.: Overview of the PALM model system 6.0, Geosci. Model Dev., 13, 1335–1372, https://doi.org/10.5194/gmd-13-1335-2020, 2020.