Investigating atmospheric mechanisms behind the long-range transport of fire aerosols: from the regional free atmosphere to the local boundary layer in a narrow valley

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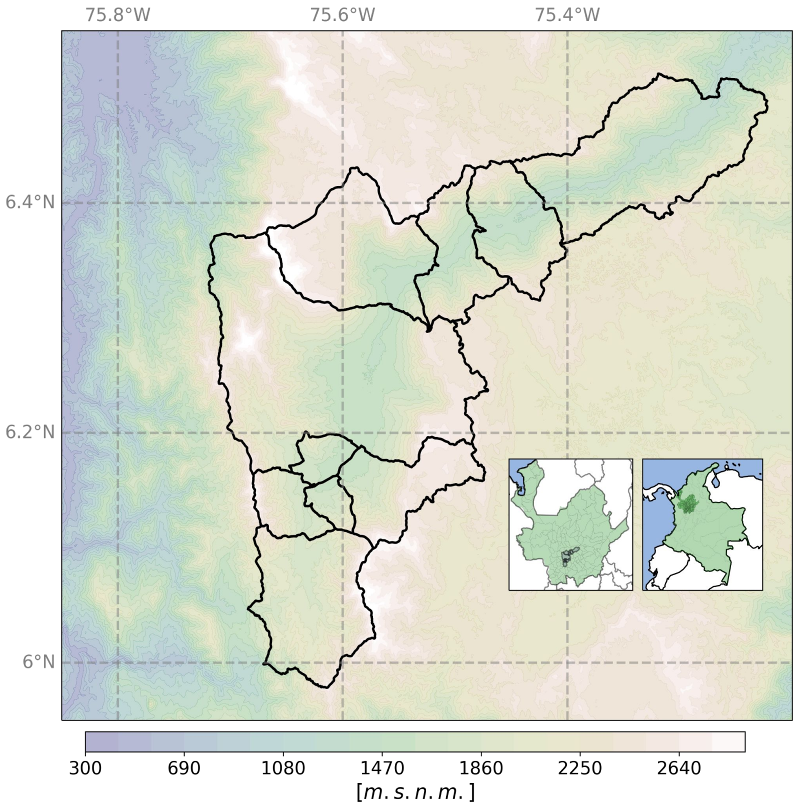
SIATA
SISTEMA DE ALERTA TEMPRANA

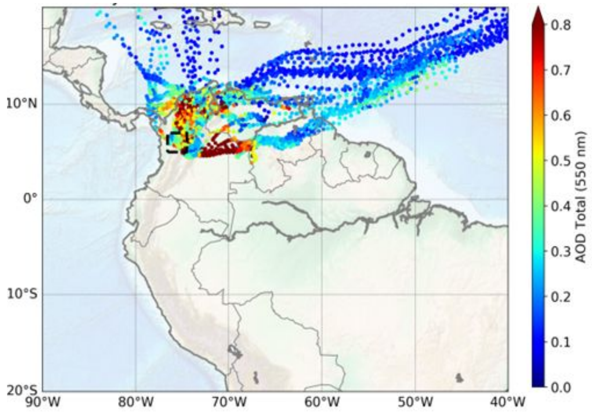
Área
METROPOLITANA
Valle de Aburrá

General context

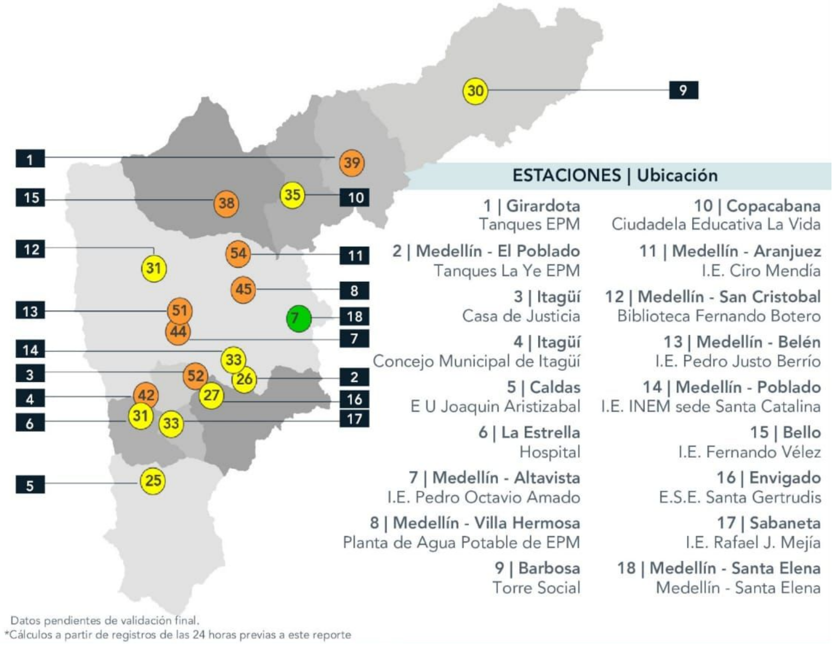
The Aburrá Valley



Regional transport (RT) events



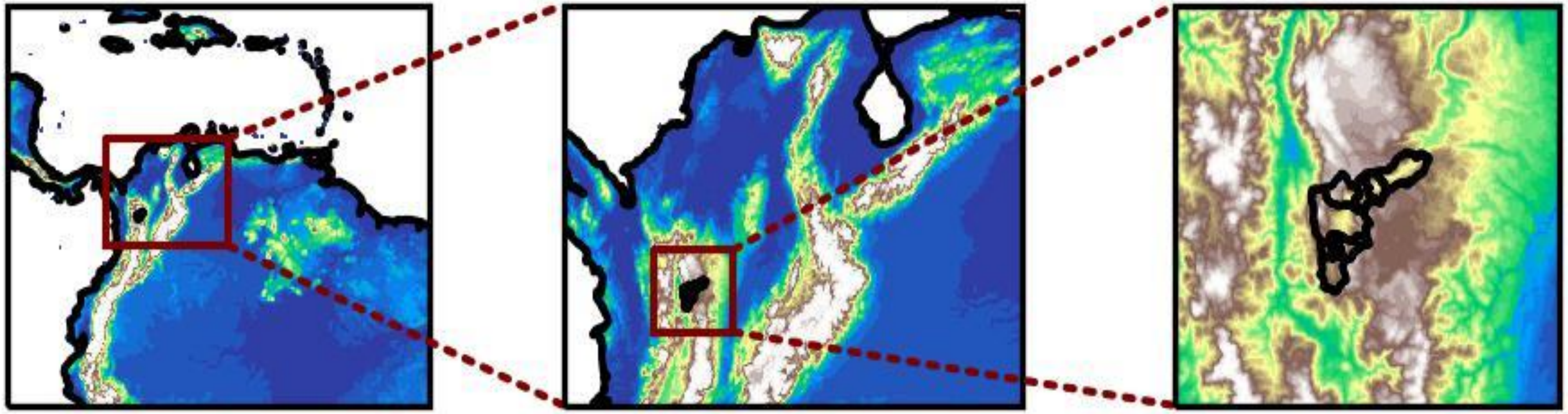
Air pollution events & early warning system (SIATA)



What are the atmospheric mechanisms behind the long-range transport of fire aerosols at different scales?

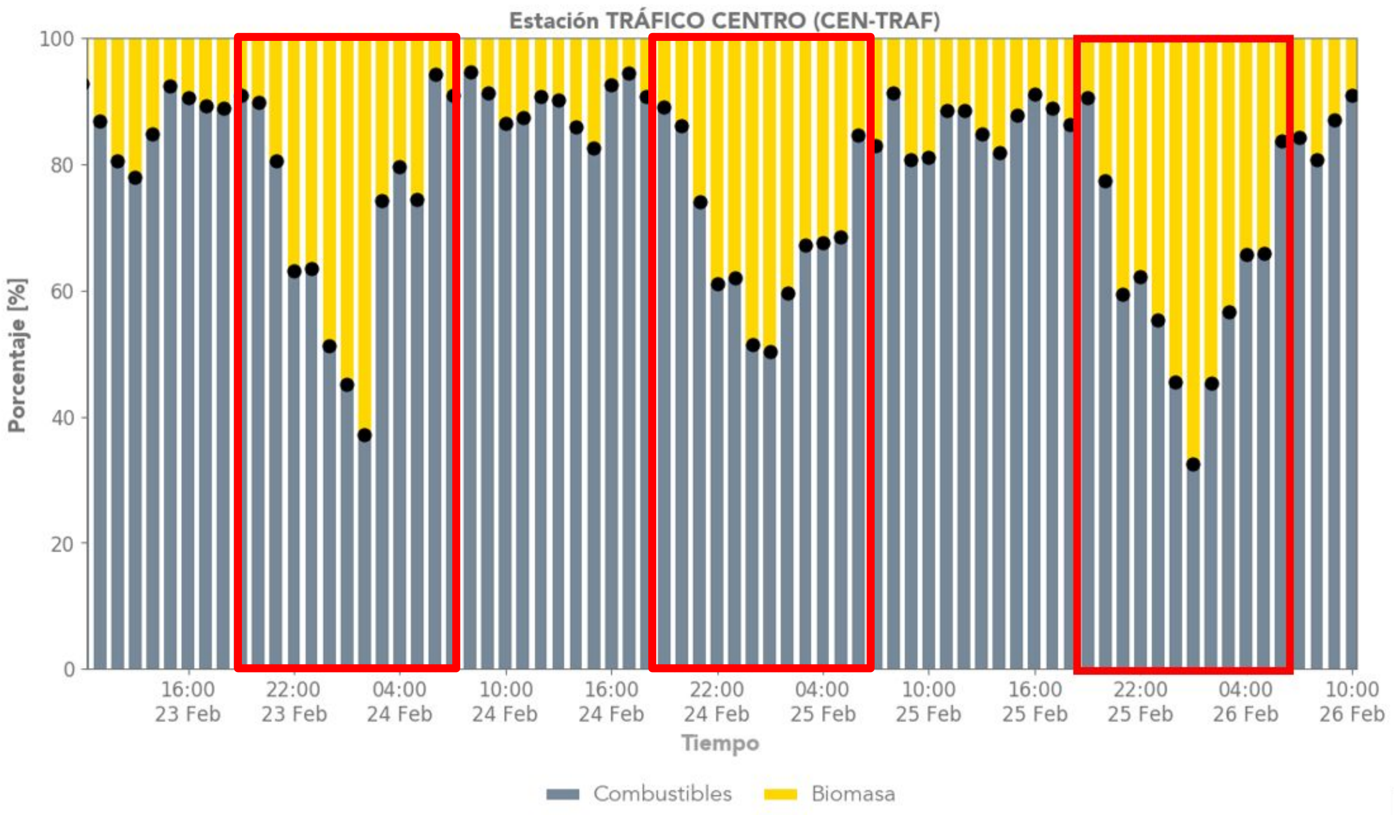
Data: modeling and observations

Synoptic to local scale (WRF simulations)



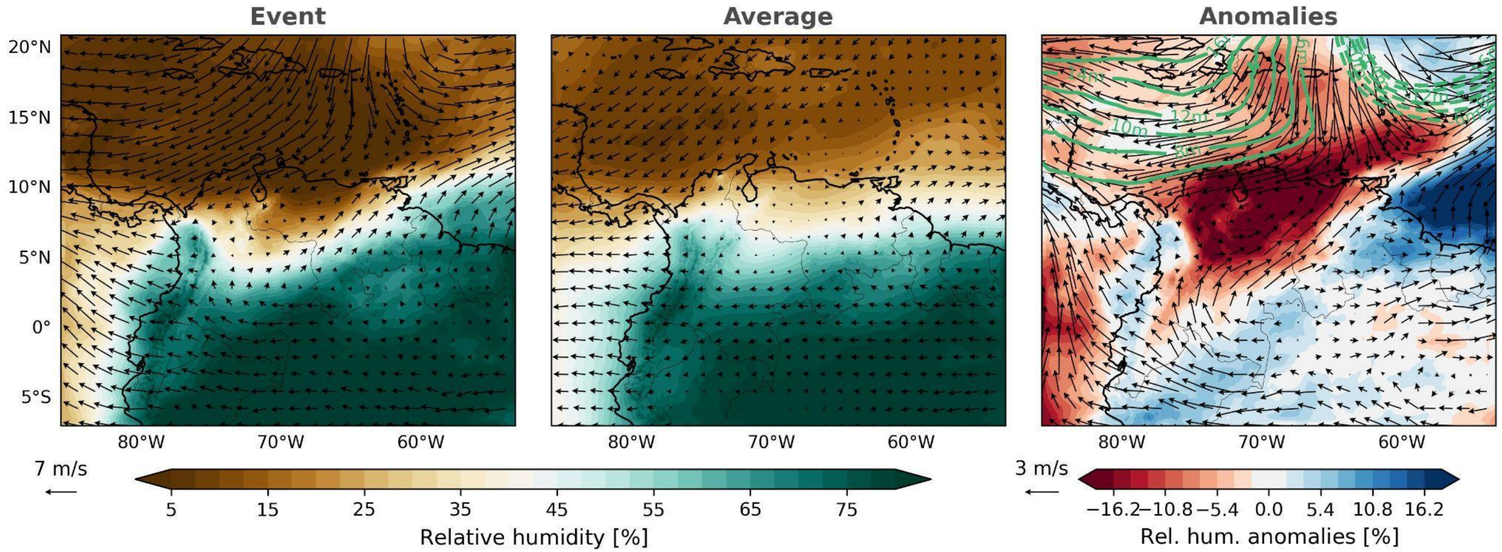
Local to microscale (observations)

Selection of RT events and composites



- As a proxy of regional transport (RT) events, we used data collected from an aethalometer located in the center of the valley.
- Days with regional fires: at least one hour having BC biomass percentage > 30%.
- This results in 7 days with RT (event) respect to 59 days in total (average).
- We computed composites of these days and compare the patterns of average days during the seasons.

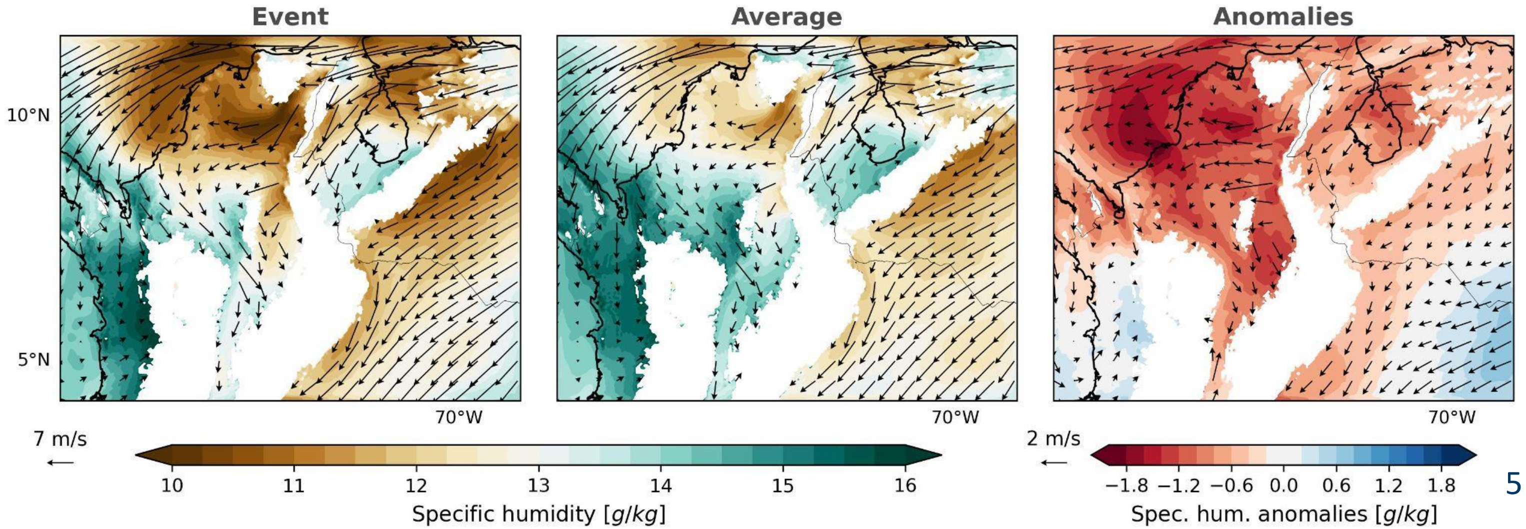
Regional winds and synoptic behavior



Winds @500hPa

- Transport of dry air masses from the Caribbean.
- Positive pressure anomalies suggest the presence of anticyclone in the Caribbean.

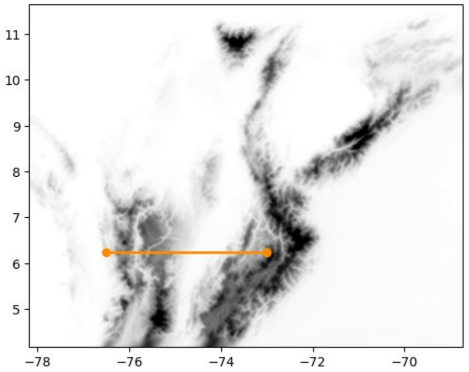
Correa et al. (2024); Arias et al. (2025)

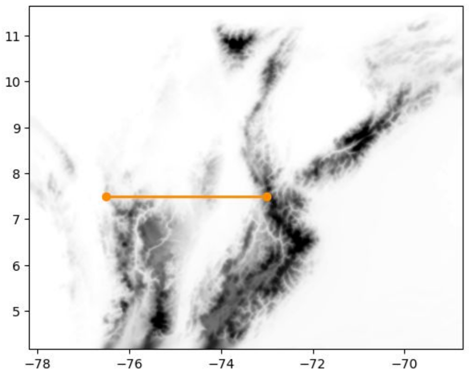


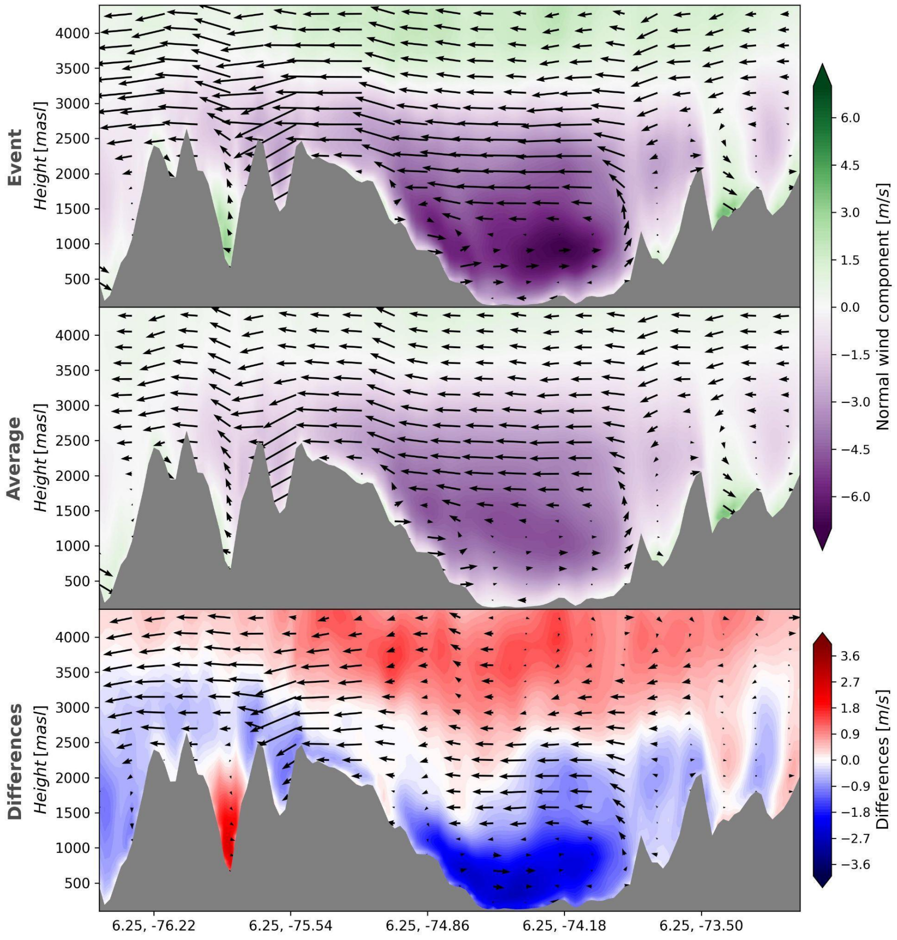
Winds @925hPa

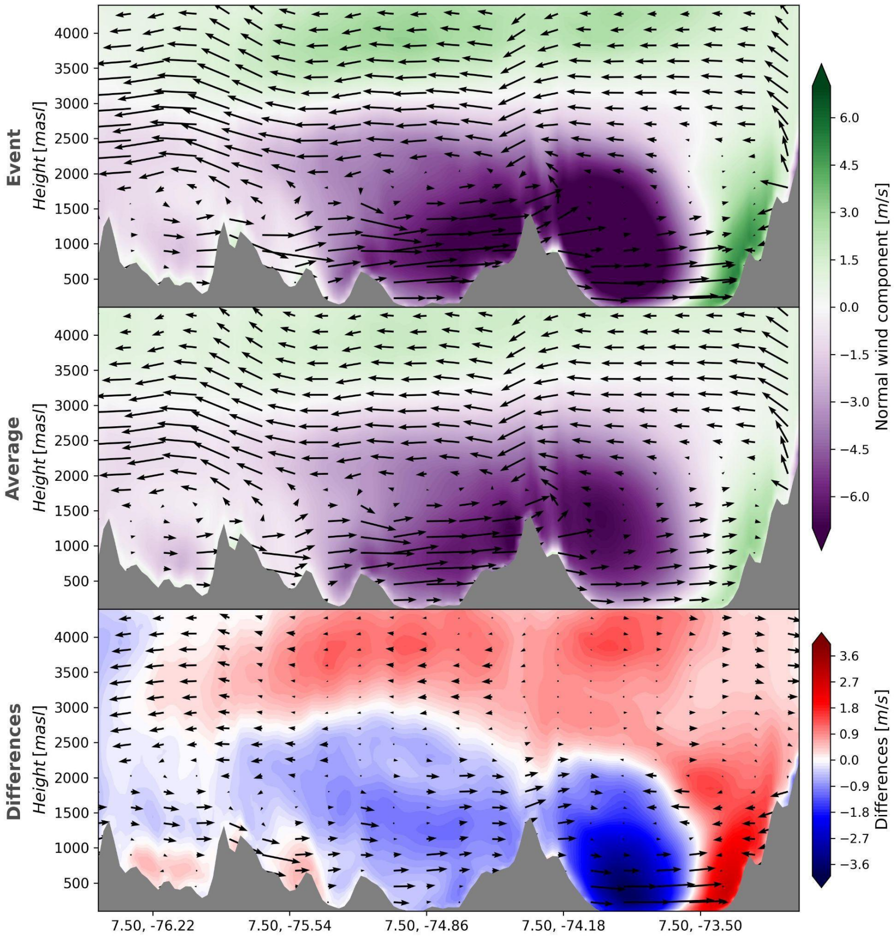
- Increase of wind intensity towards the Magdalena Valley.
- Transport of drier air toward the Andes.

Cross sections (Magdalena valley)

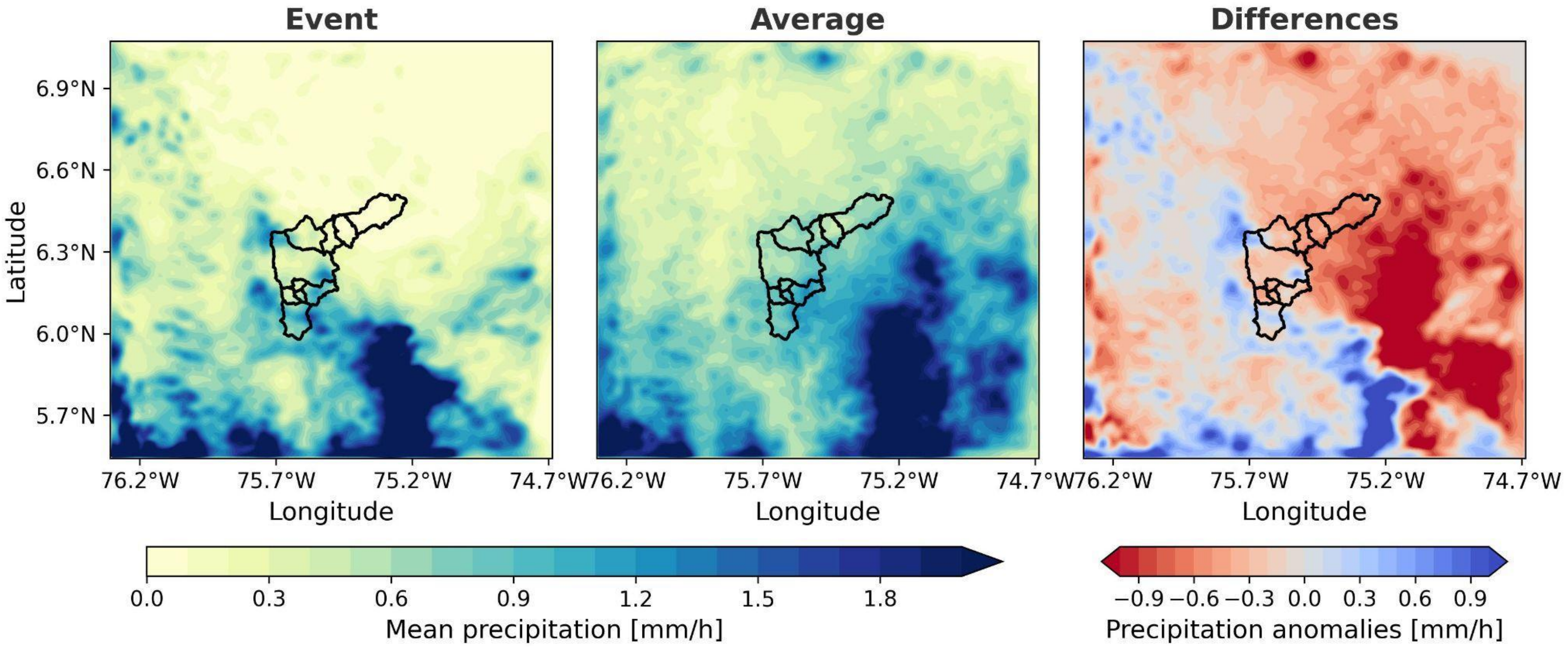








Simulated precipitation during RT events



- Marked reduction in precipitation in the north east of model domain during RT event days.
- Favorable conditions for the RT of aerosols and the income of air masses from these zones.

Velásquez-García et al. (2024)

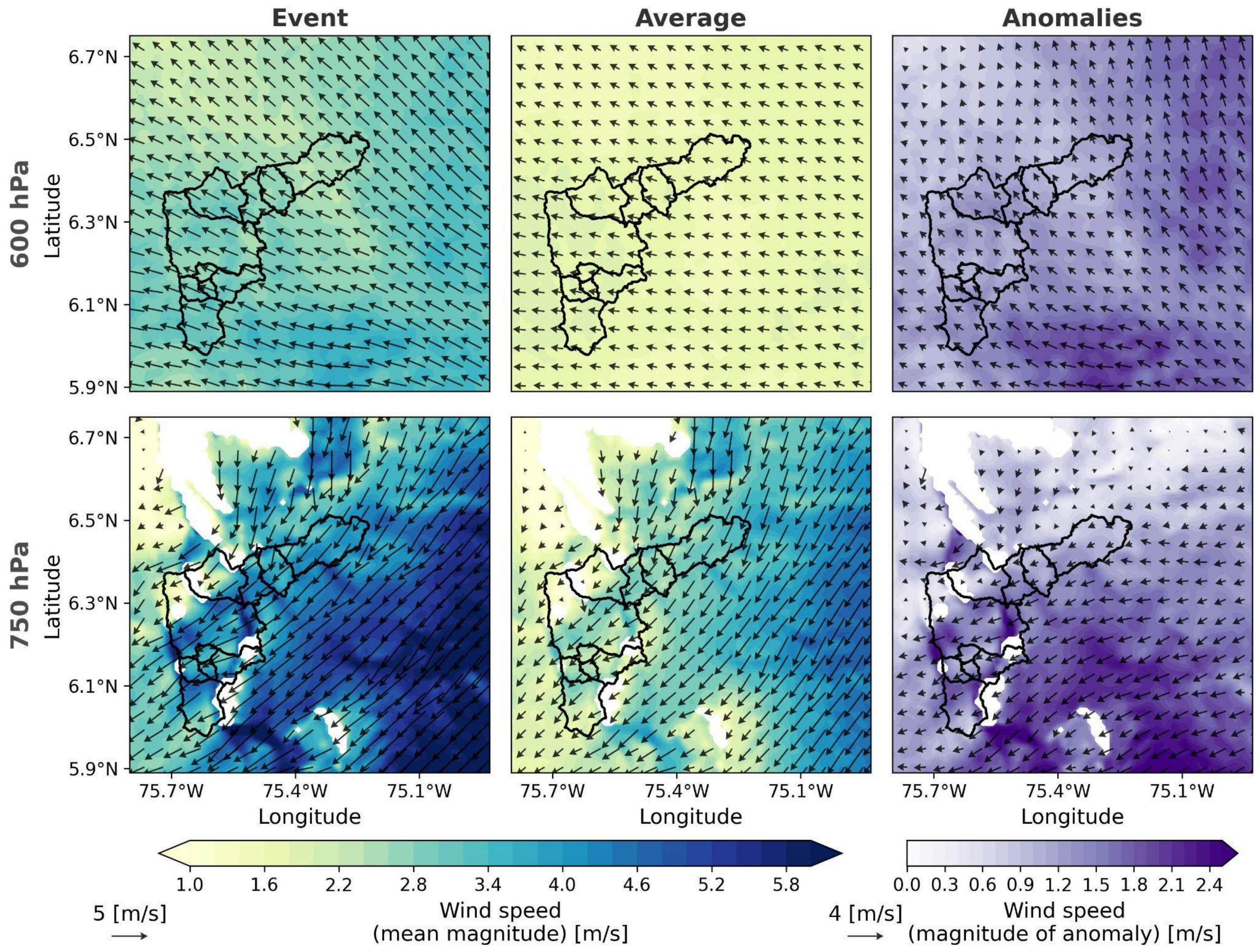
Simulated winds during RT events

600 hPa (4000 m)

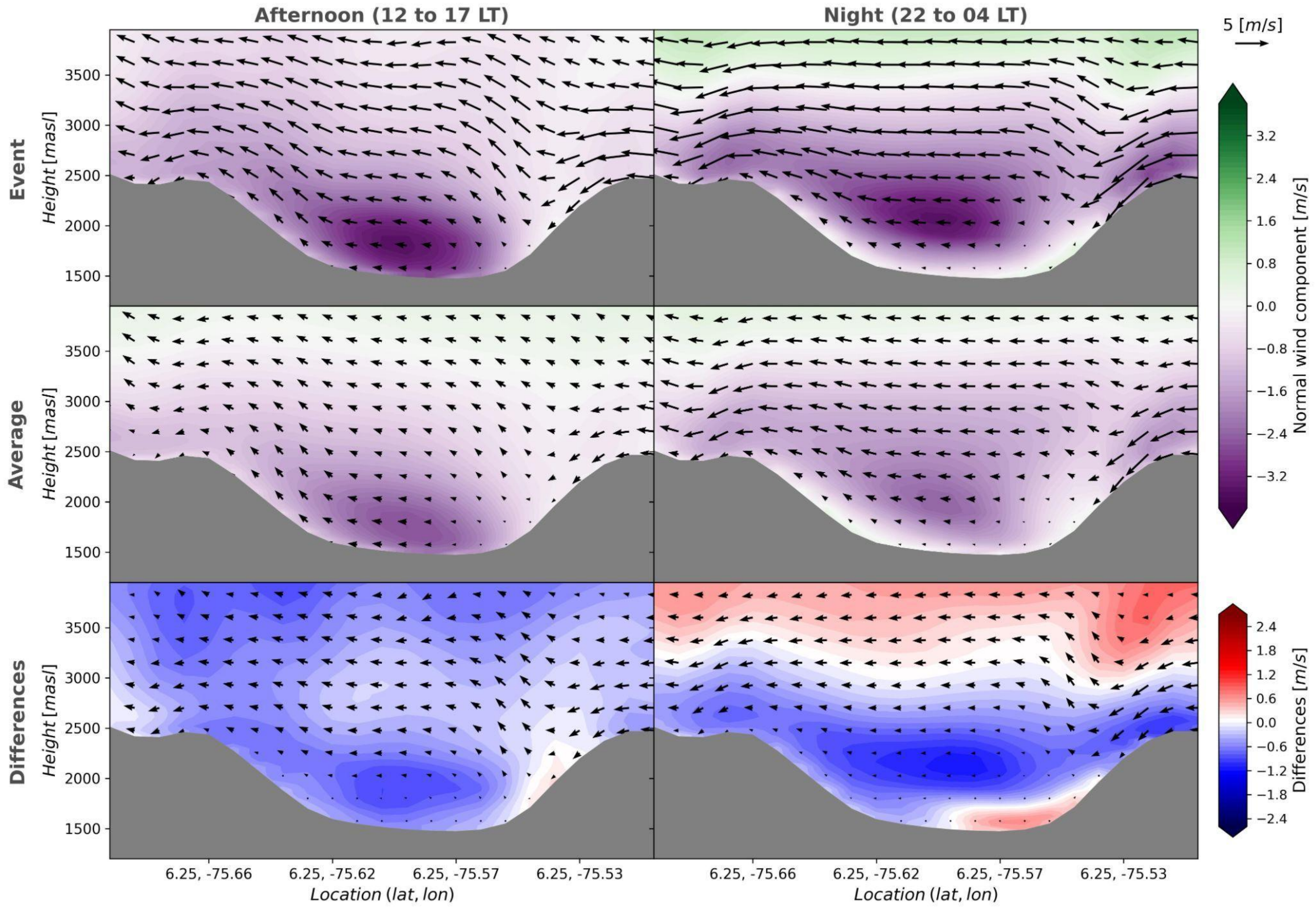
- Mostly easterly winds.
- Southeasterly winds are more marked during RT events.

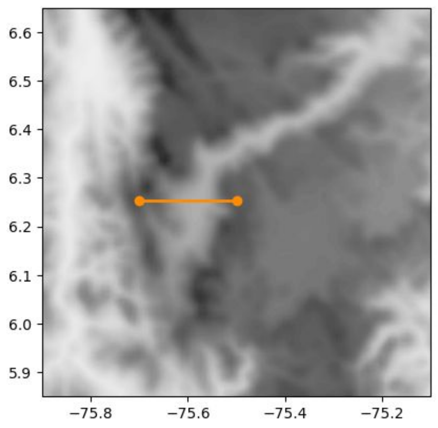
750 hPa (2500 m)

- More intense northeasterly winds during RT events.
- Wind direction is aligned with valley's axis in the north (coupling).



Cross-section in the center of the valley





- Increased wind speed in the valley, with more marked southward and westward winds.
- Large differences are evidenced during the night, with down-valley wind anomalies in the eastern slope.

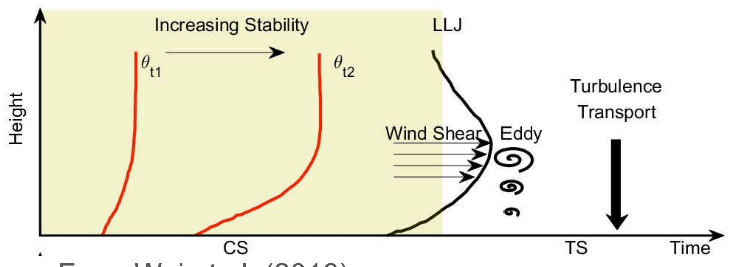
Diurnal behaviour: stability and shear

Stability

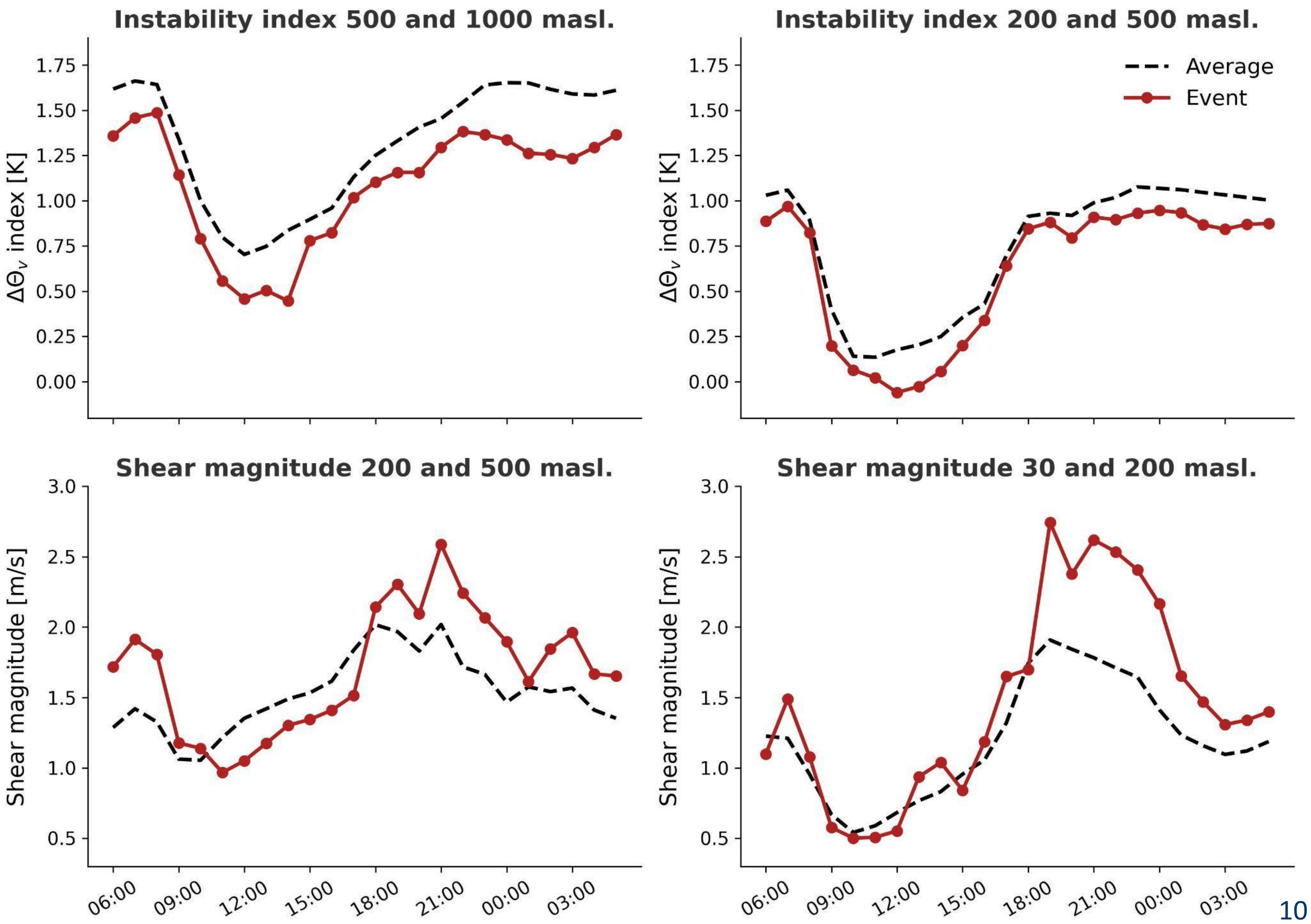
- Afternoon: more unstable atmosphere during RT events.
- Night: less marked stability.

Shear

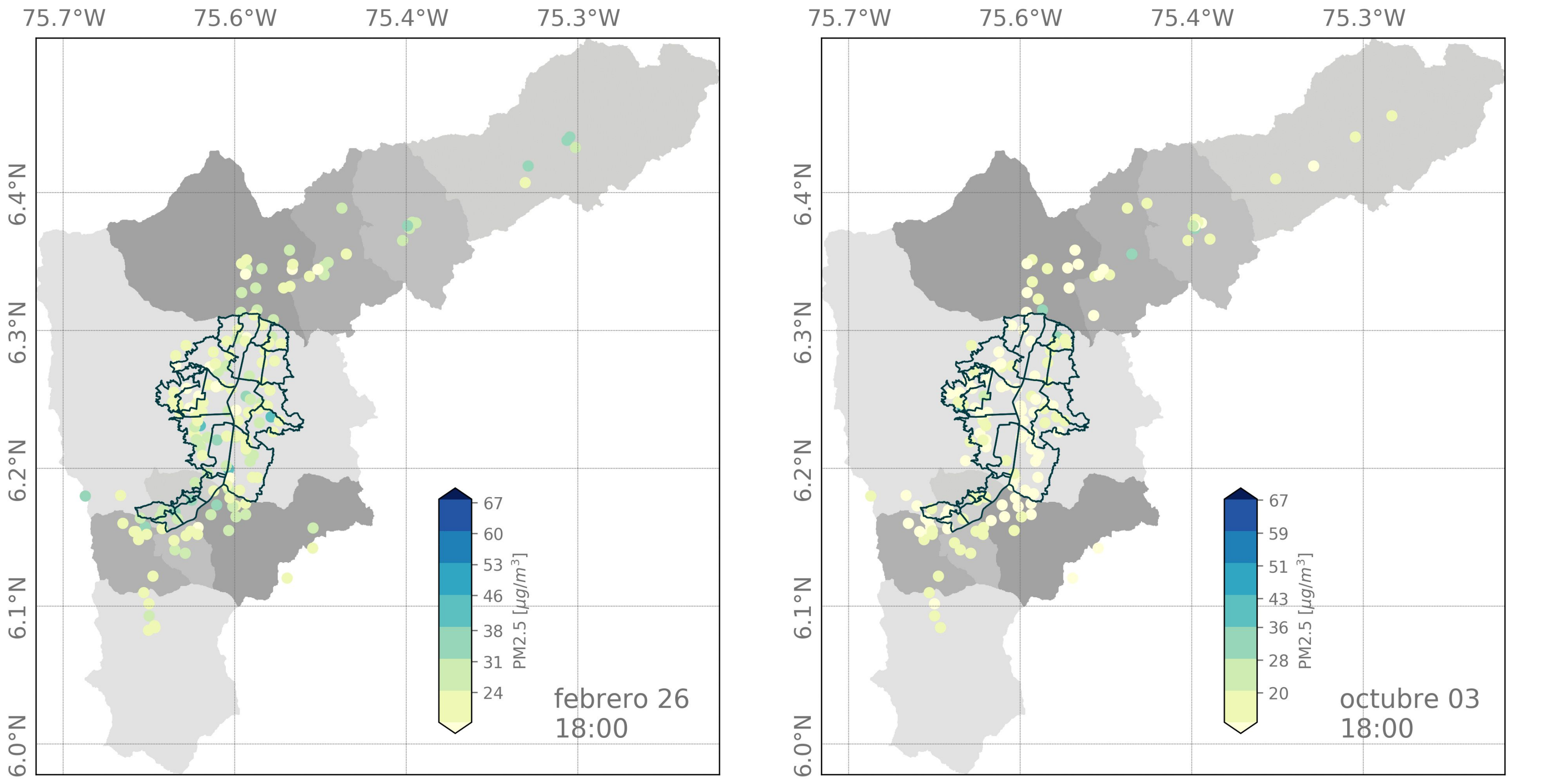
- Stronger wind shear during the nights with RT events.
- Larger wind shear differences in lower levels.



From Wei et al. (2018)

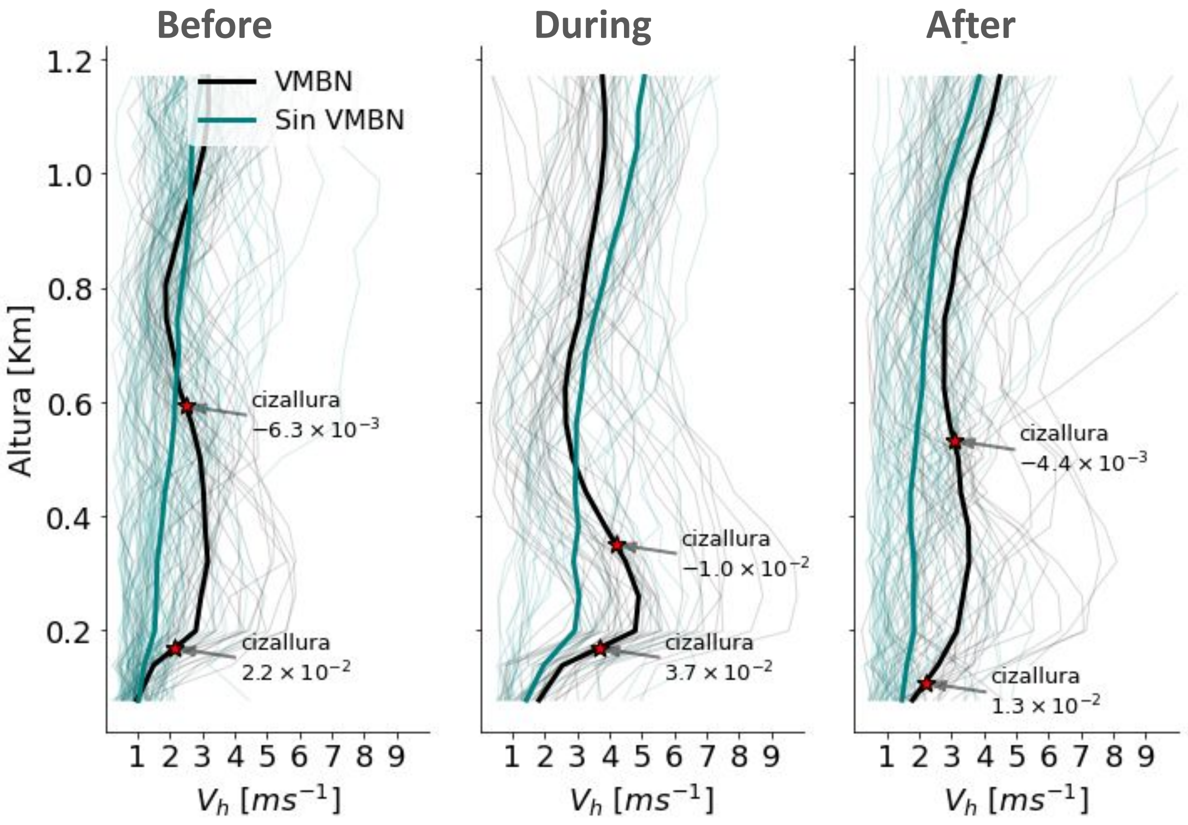


Inflow of aerosols as seen from low-cost sensors

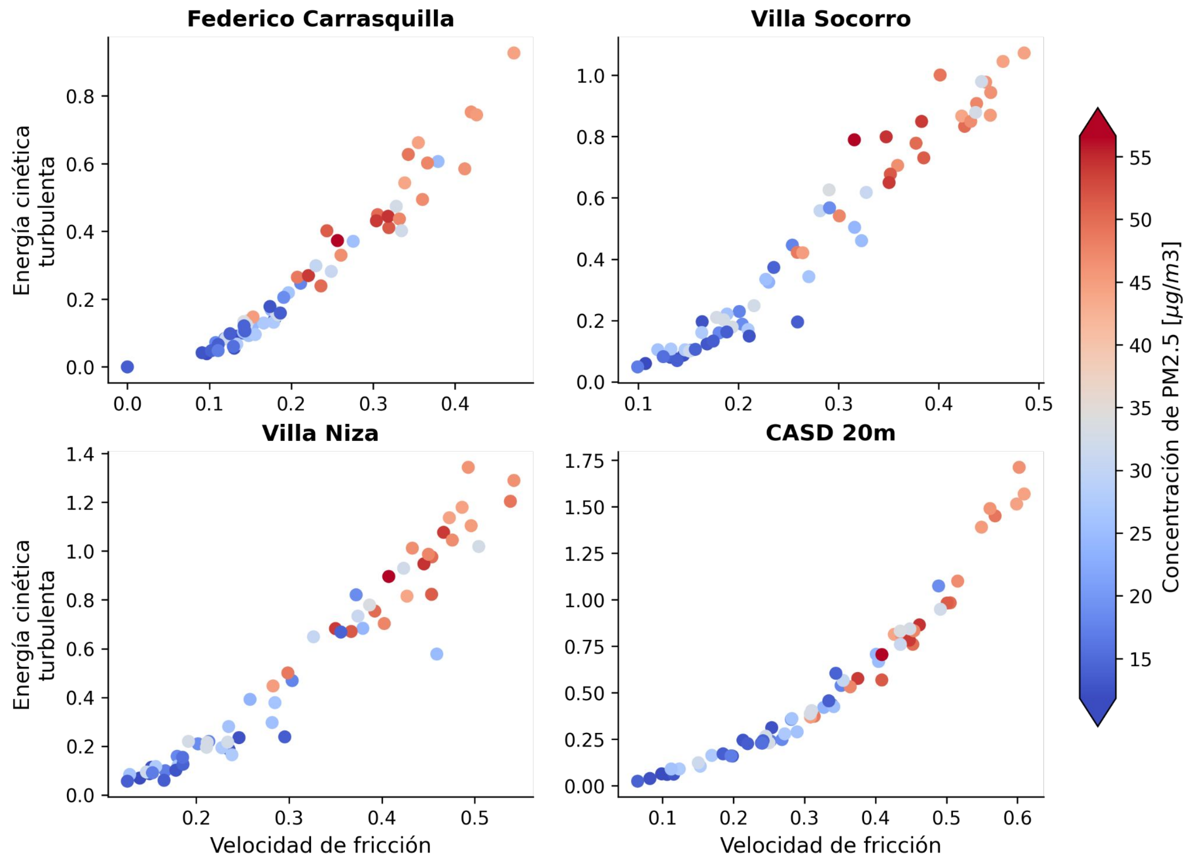


Wind inflow and turbulence production at night

Radar wind profiler

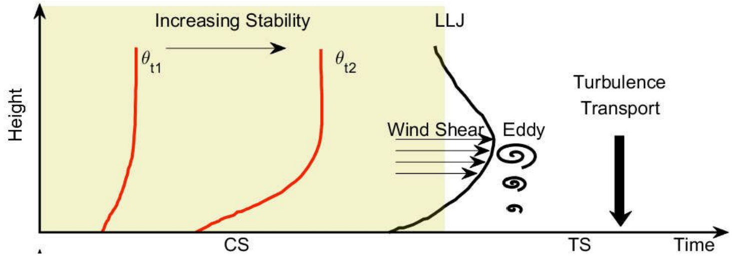


Sonic anemometer

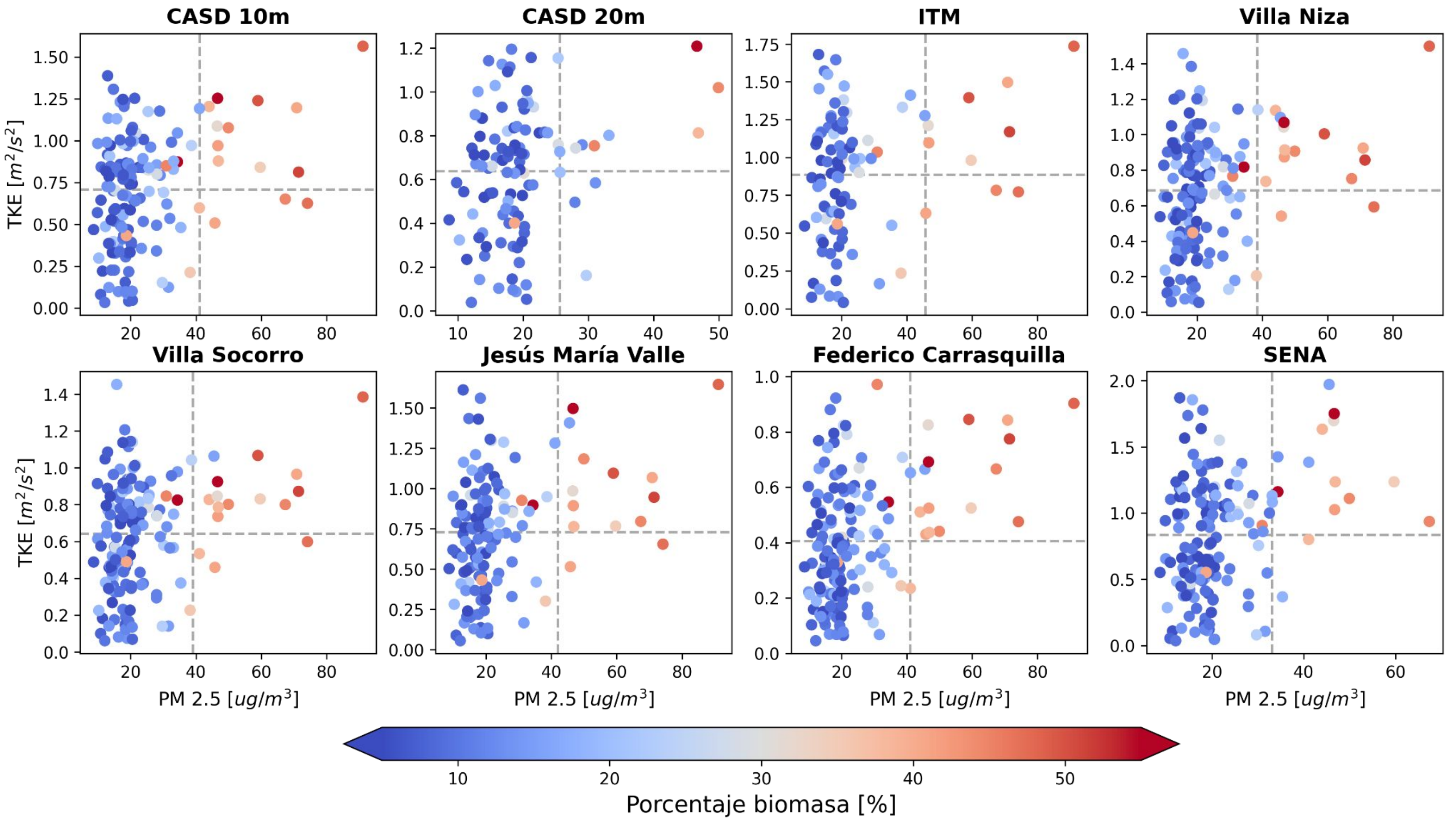


Observed turbulent kinetic energy (TKE) and PM2.5

- Higher PM2.5 values associated with greater turbulent kinetic energy (TKE).
- Observed turbulence can act as a mechanism for downward transport of PM from the upper atmosphere (aerosol RT).



From Wei et al. (2018).



Li et al. (2018); Xiong et al. (2022); Zhang et al. (2022); Zhou et al. (2022); Sun et al. (2023, 2024)

Preliminary conclusions and ongoing work

- A high pressure system in medium levels (anticyclone in the Caribbean) causes anomalous dry winds toward the continent (Magdalena valley). This condition not only favors fire occurrence but also the RT of aerosols to cities in the Colombian Andes.
- Significant reduction in precipitation both at regional and local scales during days with RT events, with a marked pattern of rainfall anomalies in the northeast and east of the simulation domain.
- The WRF simulation shows wind speed increases during the nights with RT events, with a more marked flow from the northeast at 750 hPa and from the east (easterlies) at 600 hPa. Inside the valley the model also shows noticeable increases in winds.
- During days with RT events: the atmosphere in the valley is more unstable during the afternoon; there is a higher wind shear near the surface during the night; higher TKE values are observed during nights with RT events (downward turbulent mixing).
- **Ongoing work:** we are performing and processing simulations for different years (2020 to 2024); we want to study with more detail the mechanisms associated with these events at local scale (downward fluxes, katabatic winds; BL entrainment); we will apply these findings in ML-based forecasts (Perez-Carrasquilla et al. 2023).

References

- Arias, P. A., Fernández-Berrío, A., Bedoya-Pineda, V., Acevedo-Ortiz, M. Y., & Martínez, J. A. (2025). Compound dry and hot extremes and their implications for fire activity over the Orinoco River Basin in northern South America. Climate Dynamics, 63(4), 175.
- Correa, I. C., Arias, P. A., Vieira, S. C., & Martínez, J. A. (2024). A drier Orinoco basin during the twenty-first century: the role of the Orinoco low-level jet. Climate Dynamics, 62(3), 2369-2398.
- Henao, J. J., Rendón, A. M., Hernández, K. S., Giraldo-Ramirez, P. A., Robledo, V., Posada-Marín, J. A., ... & Mejía, J. F. (2021). Differential Effects of the COVID-19 Lockdown and Regional Fire on the Air Quality of Medellín, Colombia. Atmosphere, 12(9), 1137.
- Hernández, K. S., Henao, J. J., & Rendón, A. M. (2022). Dispersion simulations in an Andean city: Role of continuous traffic data in the spatio-temporal distribution of traffic emissions. Atmospheric Pollution Research, 13(3), 101361.
- Li, J., Sun, J., Zhou, M., Cheng, Z., Li, Q., Cao, X., & Zhang, J. (2018). Observational analyses of dramatic developments of a severe air pollution event in the Beijing area. Atmospheric Chemistry and Physics, 18(6), 3919–3935.
- Pérez-Carrasquilla, J. S., Montoya, P. A., Sánchez, J. M., Hernández, K. S., & Ramírez, M. (2023). Forecasting 24 h averaged PM 2.5 concentration in the Aburrá Valley using tree-based machine learning models, global forecasts, and satellite information. Advances in Statistical Climatology, Meteorology and Oceanography, 9(2), 121-135.
- Sun, X., Zhao, T., Tang, G., Bai, Y., Kong, S., Zhou, Y., Hu, J., Tan, C., Shu, Z., Xu, J., & Ma, X. (2023). Vertical changes of PM2.5 driven by meteorology in the atmospheric boundary layer during a heavy air pollution event in central China. The Science of the Total Environment, 858(Pt 2), 159830.
- Sun, X., Zhou, Y., Zhao, T., Fu, W., Wang, Z., Shi, C., Zhang, H., Zhang, Y., Yang, Q., & Shu, Z. (2024). Vertical distribution of aerosols and association with atmospheric boundary layer structures during regional aerosol transport over central China. Environmental Pollution (Barking, Essex: 1987), 362(124967), 124967
- Velásquez-García, M. P., Hernández, K. S., Vergara-Correa, J. A., Pope, R. J., Gómez-Marín, M., & Rendón, A. M. (2024). Long-range transport of air pollutants increases the concentration of hazardous components of PM 2.5 in northern South America. Atmospheric Chemistry and Physics, 24(20), 11497-11520.
- Wei, W., Zhang, H., Wu, B., Huang, Y., Cai, X., Song, Y., and Li, J. (2018). Intermittent turbulence contributes to vertical dispersion of pm 2.5 in the north china plain: cases from tianjin. Atmospheric Chemistry and Physics, 18(17):12953–12967.
- Xiong, J., Bai, Y., Zhao, T., Zhou, Y., Sun, X., Xu, J., Zhang, W., Leng, L., & Xu, G. (2022). Synergistic effect of atmospheric boundary layer and regional transport on aggravating air pollution in the Twain-Hu Basin: A case study. Remote Sensing, 14(20), 5166.
- Zhang, L., Zhang, H., Li, Q., Cai, X., & Song, Y. (2022). Vertical dispersion mechanism of long-range transported dust in Beijing: Effects of atmospheric turbulence. Atmospheric Research, 269(106033), 106033.
- Zhou, Y., Guo, J., Zhao, T., Lv, J., Bai, Y., Wang, C., Sun, X., & Hu, W. (2022). Roles of atmospheric turbulence and stratification in a regional pollution transport event in the middle reaches of the Yangtze river. Earth and Space Science (Hoboken, N.J.), 9(1).

Thank you!

For further information: www.siata.gov.co

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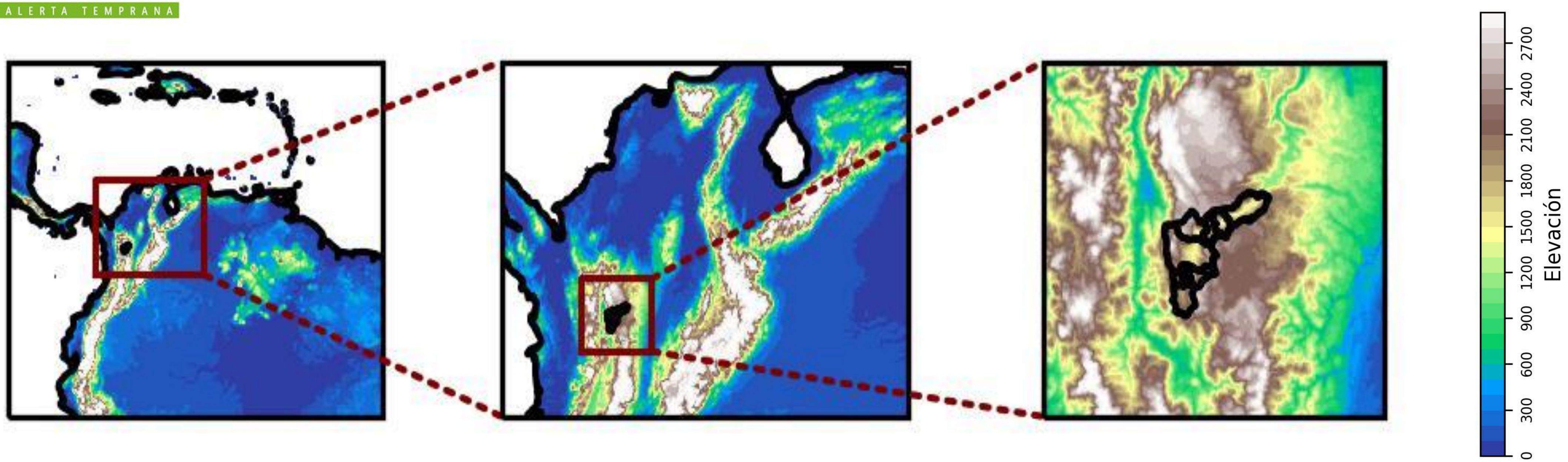
Supplementary slides

WRF model - setup



- Simulation period: February and March 2022
- 3 doms. with resolutions of 9km, 3km, 1km.
- Initial and boundary conditions: ERA5.
- 51 vertical levels (10 below 1 km).
- Nudging for d01 over the PBL (u, v, t, q, ph).
- LULC: Copernicus 300m (2022).

- Microphysics: Thompson.
- Boundary layer: MYNN (level 2.5).
- Radiation: Dudhia (SW) - RRTM (LW)
- Cumulus: Kain–Fritsch (only for 1; 2 y 3: CP)
- Land-surface: Noah-MP

Henao et al. (2020); Hernández et al. (2022)