Data Assimilation Schemes in Colombian Geodynamics - Cooperative Research Plan for 2017 - 2020 Between Universidad EAFIT and TUDelft, With the Help of Universidad de Antioquia and universidad Nacional de Colombia Sede Medellin

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Medellin Air qUality Initiative MAUI

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ABSTRACT

Urban air contaminants can reach distant ecosystems via atmospheric transport. Deposited contaminants can alter plant physiology, community structure, and ecosystem services. The city of Medellín within the Aburrá Valley (Colombia), presents predominantly poor air quality. It may be a source of contaminants to distant ecosystems. This branch of the cooperated project aims to contribute to the understanding of the impact that urban atmospheric pollution may be having on natural and agricultural ecosystems in Colombia, Southern Central America, Northwest South America and the Caribbean. To this end, it will contribute to the implementation of the transport-chemical model LOTOS-EUROS in the corresponding domain; optimized the use of available data products for assimilation into the model; suggest strategic areas for the acquisition of additional data; and work towards the development of measuring approaches for the acquisition of such missing data. This first Technical Report on the subject explores the prevailing global atmospheric transport dynamics over Northwest South America to identify the ecosystems with the highest risk of detrimental impacts from urban-generated atmospheric pollutants.

ERA-Interim data suggest that contaminants escaping the Aburrá Valley will travel predominantly West to the Chocó Biogeographic region, one of the most biodiverse in the world. Qualitative descriptions of satellite-based data agree with the predicted flows. Furthermore, they suggest that the release of contaminants from the Aburrá Valley may be diurnally episodic, owing to the atmospheric dynamics within the valley. As such, we conceptualize the valley, as a point source in space and time that we dub “The Volcano of the Aburraes”, paving the way for the assimilation of valley-centered, ground-based contaminant data into regional transport-chemical models that may afford a more precise estimation of distant ecosystem impacts.

We conclude with a discussion of the available satellite data, and its implication in our efforts towards modelling the regional transport of contaminants.

INTRODUCTION

Atmospheric transport of chemical species can play significant roles in the chemical dynamics of distant ecosystems. For instance, as reported by Yu *et al*. (2015), Saharan dusts transported across the Atlantic Ocean can constitute nearly half of the total Phosphorus yearly budget of the ecosystems in the Amazon basin. Despite the increasing recognition of the importance of atmospheric transport processes in ecosystem health, their role in the richly biodiverse Northwest corner of South America remains to be thoroughly explored.

Colombia is one of the 17 megadiverse countries in the world, containing the highest diversity in Bird and Butterfly species, and ranking near the top of the list of diversity of many other taxa. The development plans for the country are linked to the development of its Bioeconomy, where sustainable utilization of its biodiversity and integrated agricultural production systems are seen as major pillars of growth. Evaluating the ecological impacts resulting from long-distance transport of urban-sourced atmospheric pollutants will identify acutely vulnerable areas that may require more than local conservation effort for the preservations of their ecological functions. With this work, we aim to initiate the identification of protected areas that may be affected by distant urban pollution.

The Aburrá Valley houses the city of Medellín, constituting the second most populous urban area in Colombia. Due to its abrupt topography and its intense human activity, the valley suffers regular episodes of impoverished air quality. The top of the mountains that surround the valley preserve remnants of the native Cloud Forest ecosystem. Beyond the mountains to the West, in between the valley and the Pacific Ocean, lie the lush tropical forests of Chocó. The branch of our cooperated project that will be addressed in this report attempts to understand the regional and local transport dynamics of atmospheric pollutants as a first step towards assessing the impact of urban contaminants on natural ecosystems, keeping a regional perspective, but paying special attention to the fate of pollutants emanating from the Aburrá Valley.

The transport of urban atmospheric primary and secondary pollutants towards natural areas represents a threat to ecosystem functions. Human activities are major contributors of reactive nitrogen (N_r) species to the atmosphere (Fowler *et al*., 2013). Photochemical reactions with NO_x and NH_3 can lead to the formation of secondary aerosols (Erisman and Schaap, 2004) that may transport N_r long-distances. Atmospheric transport of nitrogen alters the ocean's nitrogen budget (Duce *et al*., 2008). Global deposition of atmospheric reactive nitrogen (Jia *et al*., 2016) accounts for over 8% of the planet's reactive nitrogen flow (Fowler *et al*., 2013). Deposition of atmospheric N_r can alters ecosystems (reviewed in Erisman *et al*., 2013), affects community species distribution (reviewed in Bobbink *et al*., 2010; see also Farrer and Suding, 2016; Maskell *et al*., 2010; Simkin *et al*., 2016; and Stevens *et al*., 2004), and in the process, alter ecosystem stability (Koerner *et al*., 2016).

Atmospheric NO_x can lead to the formation of tropospheric ozone (O_3). Exposure to ozone can interfere with photosynthesis and result in alterations of community structure (Payne *et al*., 2011). Global estimates for losses in agricultural productivity linked to ground-level ozone exposure range from 4-16% (van Dingenen *et al*., 2009).

As the opening paragraph of this section indicated, the atmospheric transport of chemical substances, is not exclusively relevant due to human inputs into the atmosphere. Aside from the interest in the impact that anthropogenic contaminants may have on natural ecosystems, we have also developed an interest on the regional transport of marine aerosols, an interest sparked by an ecological and evolutionary question. Some of the work of our Research Group on Biodiversity, Evolution and Conservation (BEC) takes place in the forests of the Darién, one of the biodiversity foci in the country. (This is in the Choco Region, in the Northwest corner of the country bordering Panama). We have learned from our contacts in the region that during certain times of the year, the salty spray can reach three to four kilometers inland. It intrigues us to understand this distribution of marine aerosols, as a guide to motivate searches of changes in plant community structures in the remote forests of the Darien.

All of the research interests on nitrogenous species, ozone and marine aerosols face the challenge of the scarcity of in situ measurements. We are looking into ways of increasing the availability of sensors in the regions of interest. In the meantime, it will be of paramount importance to maximize the use we can make of satellite data.

INITIAL IDENTIFICATION OF VULNERABLE AREAS

The native ecosystems of Colombia, richly endowed with biological treasures, have the potential to be impacted from any city upwind. As a first approximation to identifying the regions most vulnerable to impacts from atmospheric transport of urban-generated contaminants, we have begun the construction of a georeferenced database of protected areas and urban centres in Colombia. Figure 1 presents the distribution of

National Natural Parks; Paramo ecosystems; and the main urban centres. Refinements to the database will include incorporation of human population density data (as a proxy to human activity); and land-use data that may complement the list of natural ecosystems, given that National Parks and protected areas represent only 14% of the Colombian territory. This database will eventually allow geostatistical analyses of ecological risk from atmospheric pollutant transport; and it will represent a fundamental input in the ecological interpretation of results from transport-chemistry models such as LOTOS-EUROS.

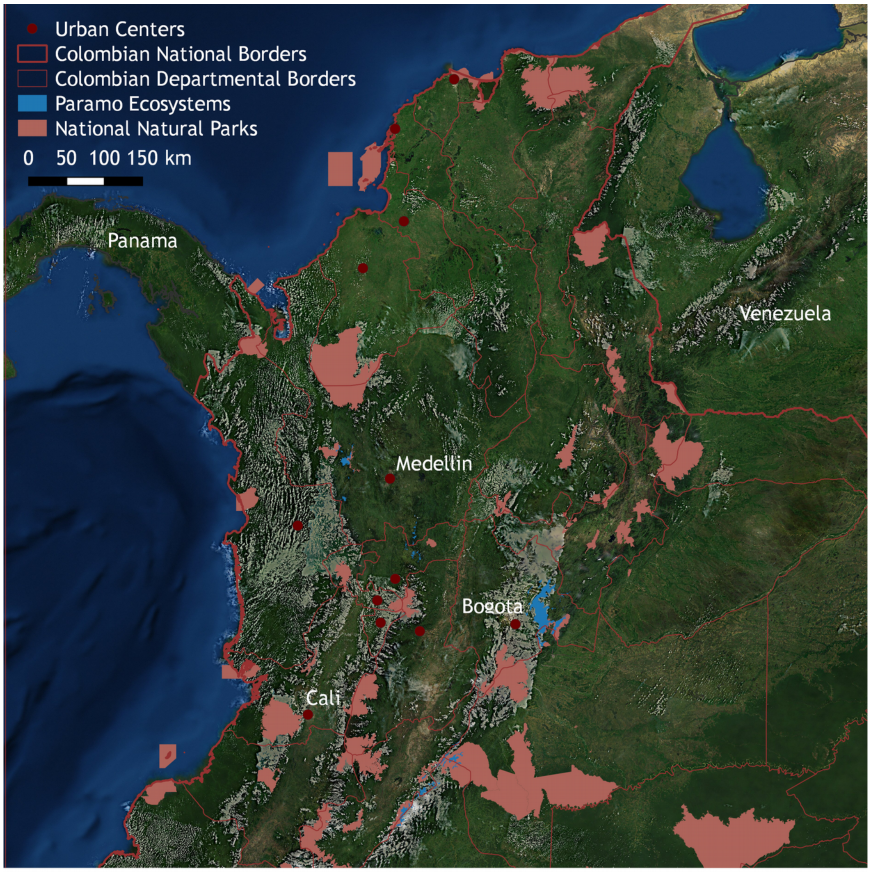

Figure 1. Distribution of National Natural Parks and Paramo ecosystems in relation to major urban centres in Colombia.

As a first approximation to understanding the transport of urban atmospheric contaminants in Colombia, we used data from the ERA-Interim reanalysis to identify the large-scale wind patterns over Northwest South America (NWSA; Figure 2) during a period of one year. We focused on the pressure layer corresponding to 750 hPa, as an approximation to the layer flowing above the mountains that surround the Aburrá Valley (2500-3100 m.a.s.l.). These analyses were contributed by our collaborators at Universidad de Antioquia.

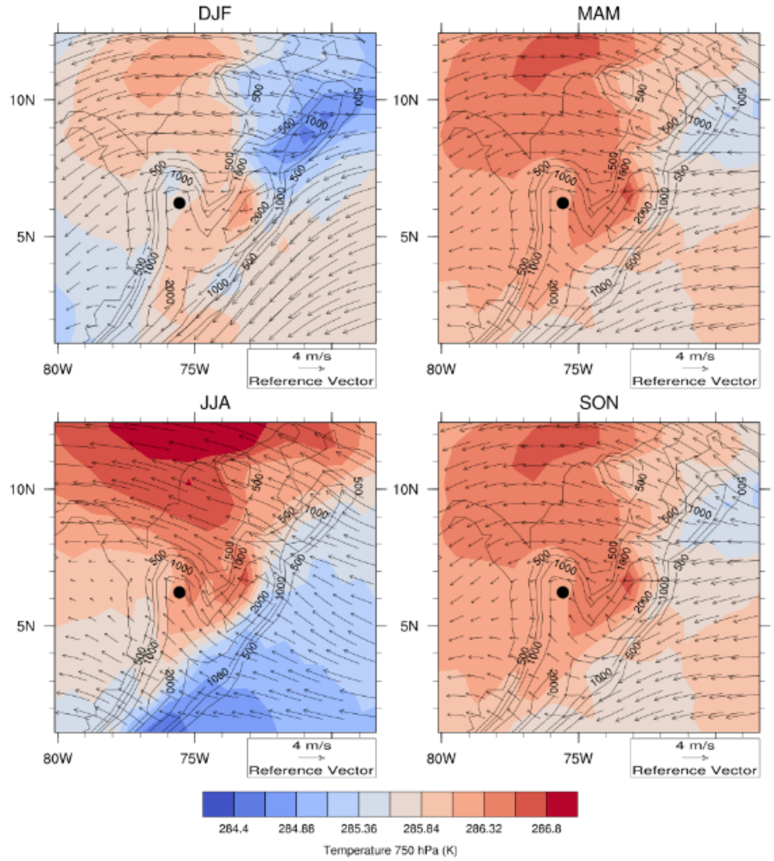

Figure 2. Long-term seasonal variations of the wind (at 750 hPa) and temperature (at the surface) fields in Northwestern South America. Data from the ERA-Interim reanalysis. Black dot indicates the location of the Aburrá Valley (Medellín and neighboring cities).

The circulation above the mountains surrounding the Aburrá valley is dominated by the trade winds (Figure 2). Assuming regional representativity for the ERA-Interim results, it could be predicted that the majority of the atmospheric pollution emanating from the Aburrá Valley heads West during the times of transition of the Intertropical Convergence Zone (MAM and SON), and it veers slightly Northward and slightly Southward during the Boreal (JJA) and Austral (DJF) summers, respectively (Figure 2).

The winds flowing above the Aburrá Valley suggest that at various times during the year, ecosystems such as Las Orquídeas National Natural Park (60-100 km NW), the Upper Atrato River (80-130 km SW), and Utría National Natural Park (170-200 km W-SW, on the Pacific coast) could be receiving contaminants emanating from Medellín (Figure 1). Depending on the strength of the flow, atmospheric contaminants may reach the tropical rainforests of the Daríen region (about 250 km NW). These ecosystems are within the Chocó Biogeographic Region, one of the most biodiverse in the world. Due West from the Aburrá Valley along the Western Cordillera lie a series of Paramos (Figure 1), high-altitude ecosystems that function as water providers for large part of the

Colombian territory. They are protected under Colombian law as providers of fundamental ecosystem services. The Paramos West of the Aburrá Valley are likely receiving pollutants from the valley through the atmospheric tele-connections depicted in Figure 2.

EXPLORING MACC DATA

We have also begun the qualitative exploration of pollutant data to identify concordance with the predicted flows. We constructed animations of data from the Monitoring Atmospheric Composition and Climate (MACC) project, as in (Rodríguez et al., 2017; see also the report MAUI-RP01).

We constructed animations of pollutant concentration data to evaluate concordance with the predicted flows. The concentration landscape of Sulphur dioxide, a proxy for urban atmospheric contamination, highlights the major foci of pollution in Colombia (Figure 3, left). The animations (external link) show a marked diurnal cycle (see also Rodríguez et al., 2017), and episodic releases into the stream of the trade winds (Figure 3, right), which are related to diurnal cycles of human activity, but also to the atmospheric stability (Herrera, 2015) that traps contaminants within the valley for extended periods.

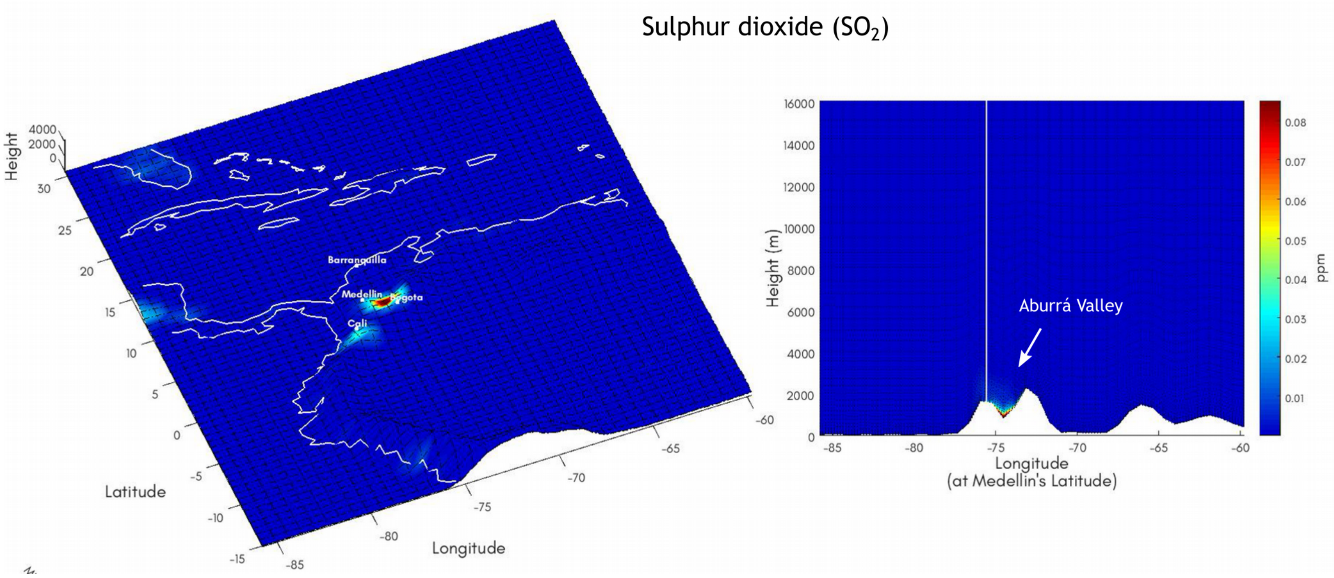

Figure 3. Sulphur dioxide concentration snapshot (June 12, 2015; 10:00) over Northwest South America (left) and the Aburrá Valley (right). Data from MACC. See Rodríguez *et al*. (2017) for a more detailed description of the contaminant dynamics in the Aburrá Valley. For an animated version of the data, visit https://www.youtube.com/watch?list=PL7DZTyo1q1YIF4cjWB0df-Au0KjIYFz07&v=20hXT-ShGAw

Work by Herrera (2015), as well as additional work presented at a recent (March 24, 2017) workshop held at Universidad EAFIT where collaborators from Universidad Nacional/SIATA presented their work, revealed that the atmosphere above the Aburrá Valley can trap contaminants within the valley for a considerable part of the day, releasing them into the trade winds only once the local atmospheric boundary layer is broken through solar heating. These dynamics are partially captured in figure 4, especially in the diurnal dynamics of Sox and PM2.5, which have low points within the valley during the day, contrary to what would expected from anthropogenic pollutants derived in large part from fossil fuel combustion in transportation. The ozone dynamics portrayed in figure 4 are opposite those described above. It's observed behavior is in accord with known chemistry, since O_3 is a secondary pollutant generated through photochemical reactions.

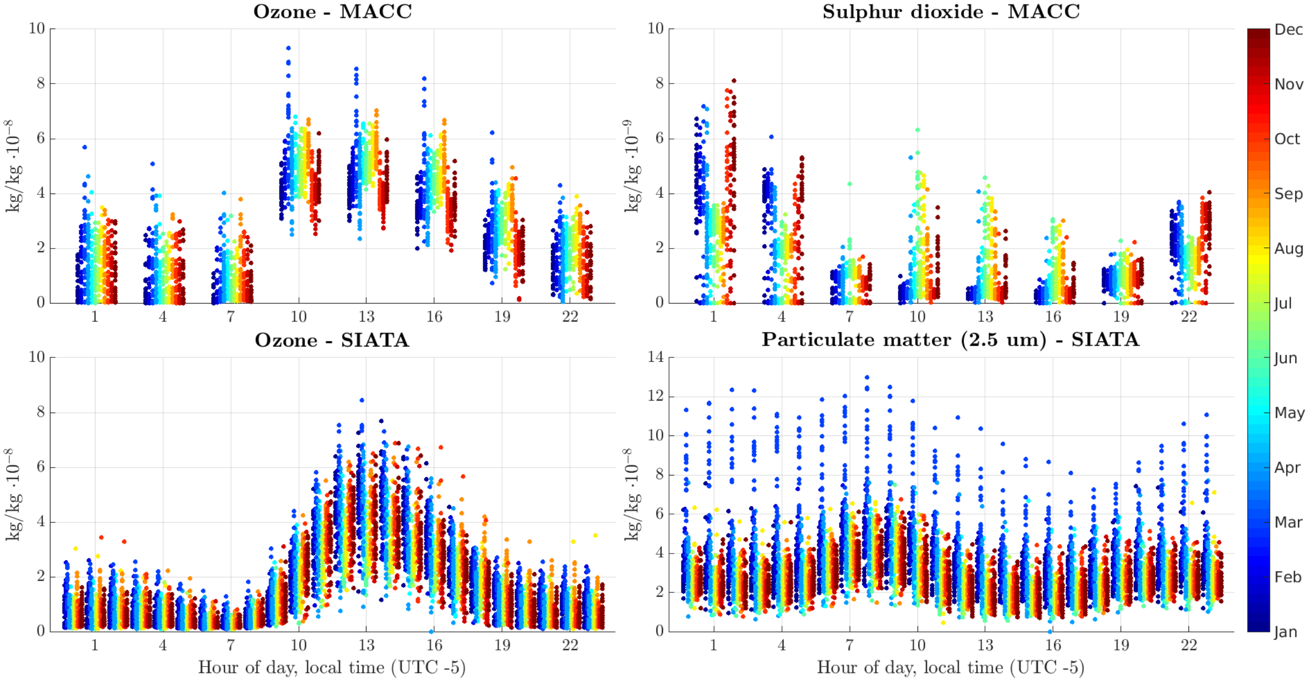

Figure 4. Diurnal dynamics of select atmospheric pollutants inside the Aburrá Valley. For a detailed description of MACC data analysis, see MAUI-RP01. For a detailed description of SIATA data analysis, see MAUI-RP03.

Based on this behavior, which is in part revealed also by the animations illustrated in Figure 3, we have come to conceptualize the valley as "The Volcano of the Aburraes". We are setting out on the endeavor of assembling the locally-generated, ground-based measurements on atmospheric conditions and atmospheric contaminants, in order to perform mass balance calculations of the amount of contaminants released daily from the valley into the trade winds, and use this as a point source to assimilate into regional transport-chemistry models (e.g., Fu *et al*., 2015).

In the process of implementing LOTOS-EUROS in the Colombian domain, one fundamental activity will be the acquisition of all available data for the region, striving towards the maximal use of existing resources while new, local ones are generated. The data described in Figures 3 and 4 were obtained from the MACC project. While this source constitutes an invaluable resource to our modelling efforts, the data products generated are not necessarily optimal to our needs. An illustration of this is given in Figure 5, where the location of the urban areas inside the valley (the sources of the atmospheric pollutants) are mapped in relation to the MACC grid areas that represents them. At the 0.7031º resolution of the data, the valley is covered by four different areas, all of which capture signals from vast areas of non-urban landscape. Figure 5 also shows a hypothetical area, re-centered on the centroid of the urban area of Medellin, that if available, could encompass the entirety of valley, and perhaps in so doing, provide a more representative monitoring of conditions inside the valley and the contaminants therefrom released into the trade winds.

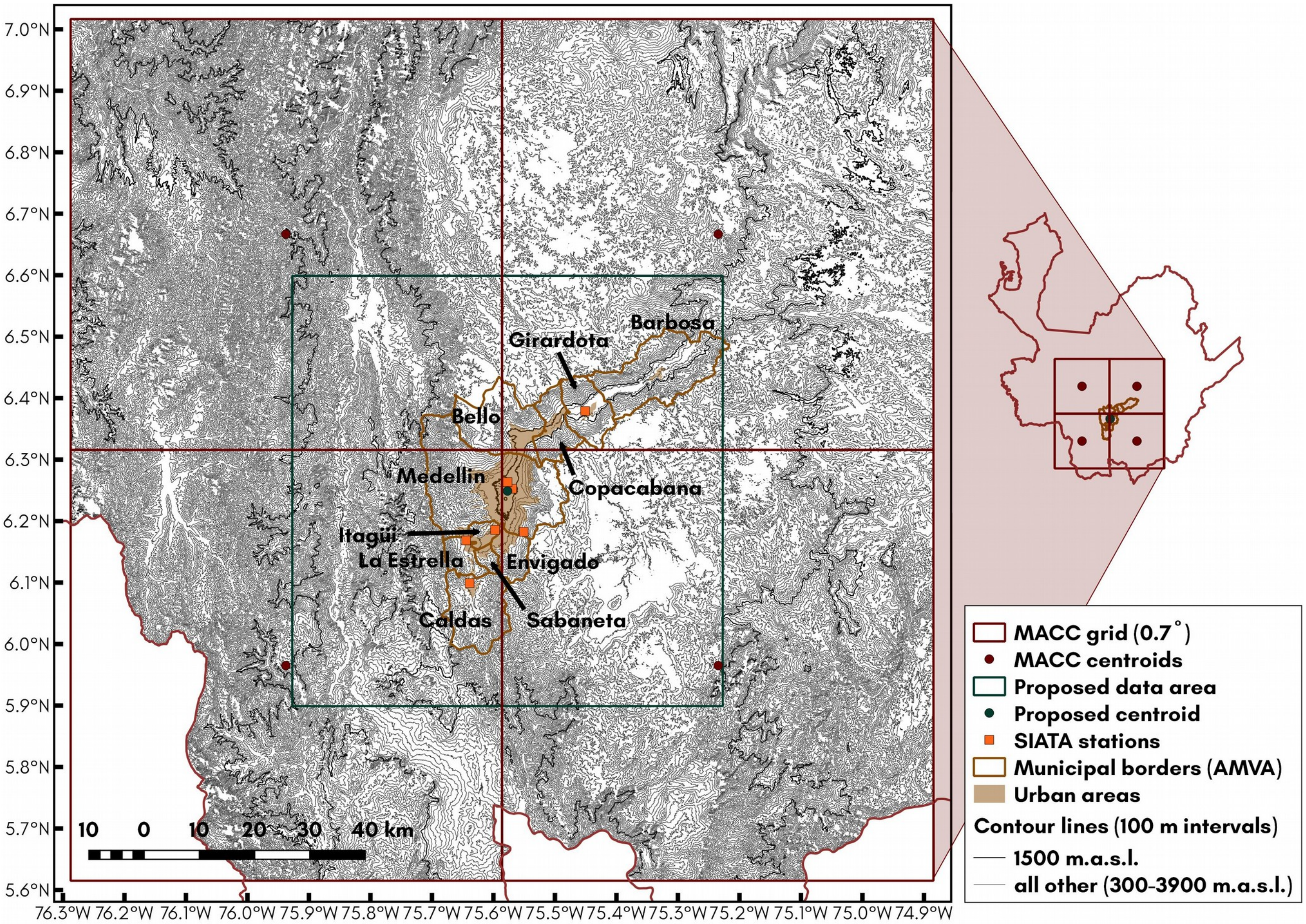

Figure 5. Location of the Aburrá Valley with respect to the MACC data centroids and areas. The proposed data area corresponds to a 0.7031ºx0.7031º polygon centered on Medellin's urban area centroid. Such a polygon could encapsulate the entirety of the valley, and perhaps be a more adequate MACC re-analysis target for the regional-scale monitoring of valley-generated pollutant dynamics. Having all of the signal from the valley contained within a single data area could facilitate treating the valley as a point source, as proposed by the concept of the "Volcano of the Aburraes."

CONCLUSIONS

Preserved, natural ecosystems may be vulnerable to impacts from atmospheric pollutants generated in distant urban centers. The prevailing wind currents blowing over the Aburrá Valley place the high altitude, Western Cordillera Paramos, the rainforests of Chocó; and the Pacific Coast at greatest potential risk from pollutants generated in the Aburrá Valley. Additional ecosystems may be at risk from pollutants generated in other urban centers. A more detailed evaluation of potential risk will require the implementation of a regional transport-chemistry model such as LOTOS-EUROS, and the refinement of available data to be assimilated into said models. Conceptualization of the Aburrá Valley will perhaps afford one such approach to incorporating local, ground-based data into regional models. Additional refinements of data derived from satellite observations, such as the MACC project data products, may come from re-localization of the data grids.

IMMEDIATE FUTURE DIRECTIONS

The preceding discussion suggests the following immediate needs:

1. Completion of the georeferenced protected areas/urban centers/population density database and GIS resources to identify possible ecosystems at risk.
2. Construction of alternative data grid systems at MACC 0.7031º resolution over the Colombian territory, and more broadly over the project's domain, to identify potentially improved grid placements. These candidate alternative grids will be selected based on their ability to encapsulate human population densities in distinct areas rather than diluting them by division over several areas; and the minimization of heterogeneity in land-use patterns within each box. The grid locations so identified will subsequently be suggested for alternative data products that could then be fed into a regional transport-chemistry model such as LOTOS-EUROS to evaluate the performance of the model against the data under each alternative grid location.
3. Development of algorithms for translating locally obtained, ground-based data on atmospheric dynamics and pollutant concentrations inside the canyon of the Aburrá Valley, into estimates of plume releases that may permit evaluation of the concept of the valley as a metaphorical volcanoe, and estimations of the pollutant load released daily into the trade winds above the mountains of the valley.

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