

Artigo

Foehn-like Wind in the Mountains of Southeastern Brazil as Seen by the Eta Model Simulation

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Abstract

The present study gives evidence of the occurrence of foehn-like wind on the eastern slopes of the mountains at Southeastern Brazil. A particular case was detected based on observational evidence on 4 July 2015 near the city of Cruzeiro, state of São Paulo, on the Serra da Mantiqueira mountains. Results obtained from numerical simulations are consistent with the foehn wind occurrence deduced from the analysis of regional patterns and time series of selected meteorological parameters.

Keywords: foehn wind, mountain weather, South America, Serra da Mantiqueira.

Vento Tipo Foehn nas Serras do Sudeste do Brasil Visto pela Simulação do Modelo Eta

Resumo

O presente trabalho evidencia a ocorrência de vento tipo foehn nas encostas orientais das serras do Sudeste do Brasil. Um caso particular foi detectado a partir de evidências observacionais em 4 de Julho de 2015 perto da cidade de Cruzeiro, Estado de São Paulo, na Serra da Mantiqueira. Os resultados obtidos por simulações numéricas são consistentes com a ocorrência de vento foehn, como pode ser visto a partir da análise de padrões regionais e séries temporais de certos parâmetros meteorológicos.

Palavras-chave: vento foehn, meteorologia de montanha, América do Sul, Serra da Mantiqueira.

1. Introduction

According to the definition of foehn wind, it consists on a wind blowing downward along the lee slopes of a mountain. Occasionally, when the content of humidity in the air is higher enough, orographic clouds are observed over the mountain. These clouds have particular features that are typical of foehn wind (Richner and Hachler, 2013). An example is given by the so called *foehn wall* which forms on the mountain crest seen from the lee side. Another example is given by the *foehn cloud* composed of altocumulus lenticularis that form above and downstream of the mountain at high levels (Vieira, 2005).

Because this type of wind occurs worldwide, both its name and classification criteria are abundant (Mayr *et al.*, 2018). In South America, it mainly develops in the Andes mountains at extratropical latitudes. On the eastern slopes, the typical wind is named *zonda* (because of Zonda valley, where usually blows) (Norte, 1988; Norte, 2015). It consists of a warm and very dry wind that blows on the eastern slopes of the Andes (Norte, 2015). It has been the subject of research with numerical models both for case studies (Seluchi *et al.*, 2003; Norte *et al.*, 2008; Mesinger *et al.*, 2012; Puliafito *et al.*, 2015; Otero and Nicolini, 2018) and to obtain a climatology (Antico *et al.*, 2017). On

the western slopes, an orographic wind from the east also exists and is locally known as puelche or raco (Rutlant and Garreaud, 2004; Montecinos *et al.*, 2017).

There are no references in scientific literature about foehn wind in Southeastern Brazil, despite personal observations of wind and cloudiness. In general, the impact of orography on the atmospheric flow becomes more evident at middle latitudes because the higher baroclinicity (i.e., winds increasing with height) and wind speed, particularly in presence of high mountains. However, personal observations suggest the occurrence of foehn effect even at subtropical latitudes and in presence of relatively low mountains. That is the case of the descending winds that are occasionally observed on the eastern slopes of the Serra da Mantiqueira. These mountains extend approximately parallel to the Atlantic coast from 20° S to 23° S with a highest elevation of almost 2,800 m (Fig. 1).

Although there are no reports of damages caused by wind velocity, the occurrence of foehn-like winds in the vicinity of the Serra da Mantiqueira may produce turbulence. This, in turn may constitute a risk for the aviation (Jones, 2010), in particular for small planes in an area characterized by intense air traffic. On the other hand, Serra da Mantiqueira is exposed to the risk of forest fires (Pereira and Souza, 2019) and the occurrence of foehn-like wind may have an impact on it (Sharples *et al.*, 2010).

The present study analyzes, for the first time in the scientific literature, an event of foehn wind in the Serra da Mantiqueira, Brazil. The objective of this study is to document the features of this type of wind by using high resolution simulations.

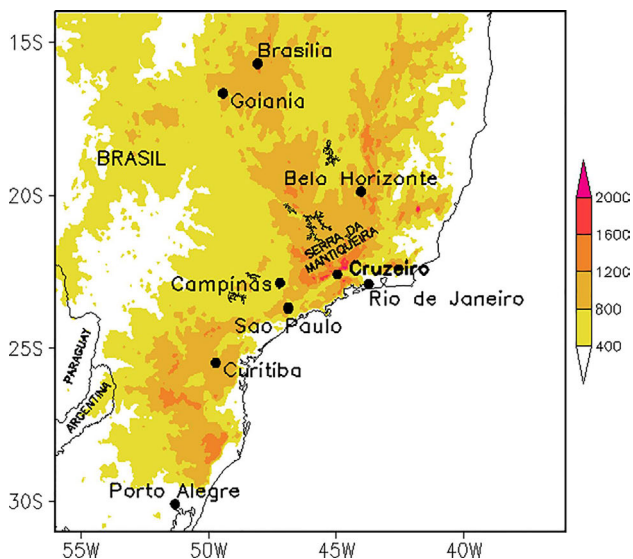


Figure 1 - Map showing the mountains at Southeastern Brazil. Terrain elevation as seen by the model in meters above sea level. Among the main cities in the area, the Serra da Mantiqueira mountains are depicted north of Cruzeiro city.

2. Material and Methods

The absence of meteorological observations along the Serra da Mantiqueira does not allow the detection of foehn-like wind from the analysis of time series of different atmospheric parameters. For this reason, the selection of the present case derives from a subjective basis given by local observations of cloudiness and wind. The selected case occurred on 4 July 2015 on the southeasterly slopes of the Serra da Mantiqueira and is documented with photographic media at 10 km northeast of Cruzeiro city, in the state of Sao Paulo (Fig. 1). In this case, the use of a numerical model to simulate the air flux over mountains results fundamental both to illustrate and to characterize the necessary conditions for the occurrence of this type of wind.

The model used in this study is the most recent version of the regional Eta-CPTec model (Mesinger *et al.*, 2012). Its name come from the Greek letter eta, used to define the vertical coordinate of the model. Unlike other numerical models that use different vertical coordinates, the use of the eta coordinate causes that the isobaric surfaces turn almost horizontal whatever the terrain slope, similar to the real atmosphere. Hence, the use of the Eta model is particularly convenient to simulate air flux over mountains. Indeed, the Eta model succeeded to simulate foehn wind to the east of the Andes (Mesinger *et al.*, 2012). The Eta model also uses sloping steps and piecewise linear vertical advection for dynamical variables as described in Mesinger *et al.* (2012). Together with the eta vertical coordinate, these features make the Eta model a very convenient option to simulate the atmosphere over terrain with pronounced slopes.

Two different simulations are performed with the Eta-CPTec model. The first one with a horizontal resolution of 5 km, and the second one with 1 km. From here in after, both simulations will be referred to as Eta-5 and Eta-1, respectively. Eta-5 uses both initial and lateral boundary conditions taken from another Eta simulation with a coarser resolution of 40 km. The initial time for Eta-5 is 3 July 2015 at 12 UTC that is 24-h prior to the photograph in Fig. 2. On the other hand, Eta-1 uses the simulations of Eta-5 to define its initial and lateral boundary conditions. It initiates on 4 July 2015 at 12 UTC that is almost simultaneously with the time of the photograph in Fig. 1. Time length is 72-h for both simulations.

3. Results and Discussions

Orographic clouds were observed over the Serra da Mantiqueira on 4 July 2015 at 12:17 UTC, as shown in Fig. 2. The photograph shows rotor type clouds as seen from the city of Cruzeiro looking towards the northeast. A cap cloud forms over the mountain crest as seen from the lee side. Another interesting feature of Fig. 2 is given by

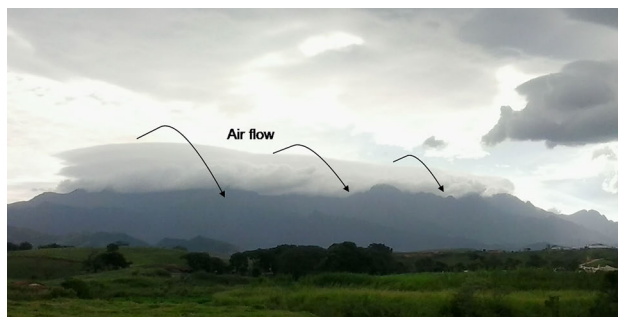


Figure 2 - Foehn wall over Serra da Mantiqueira as seen from the city of Cruzeiro heading to NE. The sharp edges of clouds suggest forced lifting of air upstream of the mountain. Descending motion of air prevents cloud formation downstream. Date & time: 4 July 2015 at 09:17 local time (12:17 UTC)

the Altopumulus Standing Lenticular Clouds (ASLC) (Jones, 2010). Together with the rotor cloud and the cap cloud, they are signs of mountain waves and flow overpassing the mountain when foehn blows on the lee side (Vieira, 2005).

The infrared satellite image of Fig. 3 reveals a cloud pattern associated with northwesterly flow over the mountains in southeastern Brazil. This would be easily seen in an animated sequence of images (not shown). This circulation is favored by the vicinity of a trough related to a cold front that approaches from the south along the Atlantic coast. Over the Serra da Mantiqueira, stationary cloud patterns are embedded into the main stream from the northwest. These patterns are consistent with the formation of orographic clouds.

The 24-h simulation of Eta-5 (Fig. 4) shows a trough axis at surface near the mountains in southeastern Brazil. This is related with the cold front observed in the satellite image (Fig. 3) and is responsible for the change in the direction of surface wind over the Atlantic Ocean. As seen in Fig. 5a, mountains are an obstacle for the flow even at

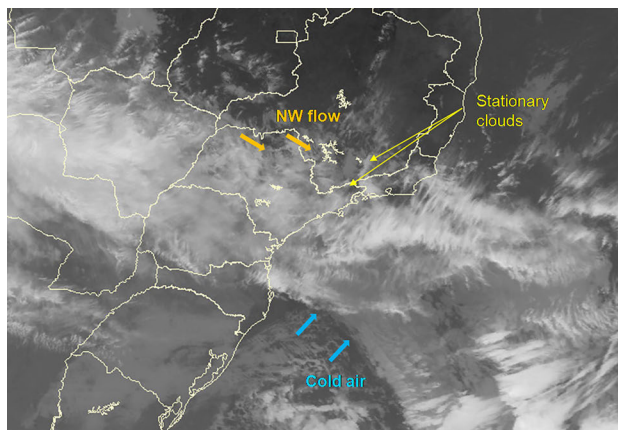


Figure 3 - Satellite imagery from GOES-13 channel 4 (IR) corresponding to 4 July 2015 at 13:30 UTC. Main features are highlighted in color, as in the case of stationary clouds pattern. See text for more details.

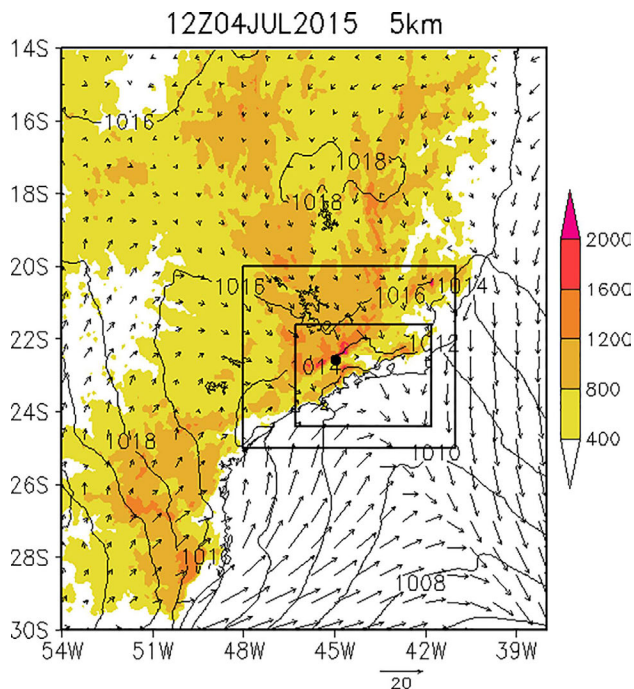


Figure 4 - Sea level pressure (contours in hPa) and surface wind (in m s^{-1}) as simulated by the Eta-5 valid for 4 July 2015 at 12 UTC (24-h simulation) and terrain elevation (colors bar in meters above sea level). The outer box encompasses the area covered in next figures. The inner box encompasses the area of the Eta-1 domain used later. The black dot within the inner box shows the location of Cruzeiro city.

the 850-hPa level since their altitude exceeds 2,000 m. In this case, the air flows over the obstacle as revealed from the analysis of vertical movement at that level (Fig. 5b). As a result of ascending and descending motion on the windward and lee sides, the corresponding pattern of cooling upstream and heating downstream is evident in the pattern of air temperature of Fig. 5c. The corresponding distribution of relative humidity at both sides of the mountain (Fig. 5d), reveals favorable conditions for clouds formation on the windward side and their dissipation on the lee side.

The dashed line in Figs. 5b-d indicates a transect along which vertical cross-sections perpendicular to the mountains were constructed. The transect intersects the mountains at the point where orographic clouds were observed in Fig. 2. The vertical cross-section of potential temperature in Fig. 6a reveals a mountain wave over the Serra da Mantiqueira (44.9° W) that propagates up to the 600-hPa isobaric level. The outstanding feature of this wave is the vertical orientation of isentropes just above the mountain crest. This feature is consistent with an abrupt descent of air associated with foehn wind. In contrast, the isentropes to the west of the mountain have a less pronounced slope which suggests a more gradual ascent of air. The corresponding pattern of windward cooling and lee warming is shown in Fig. 6b. Meanwhile, the wind component perpendicular to the mountain has a maximum

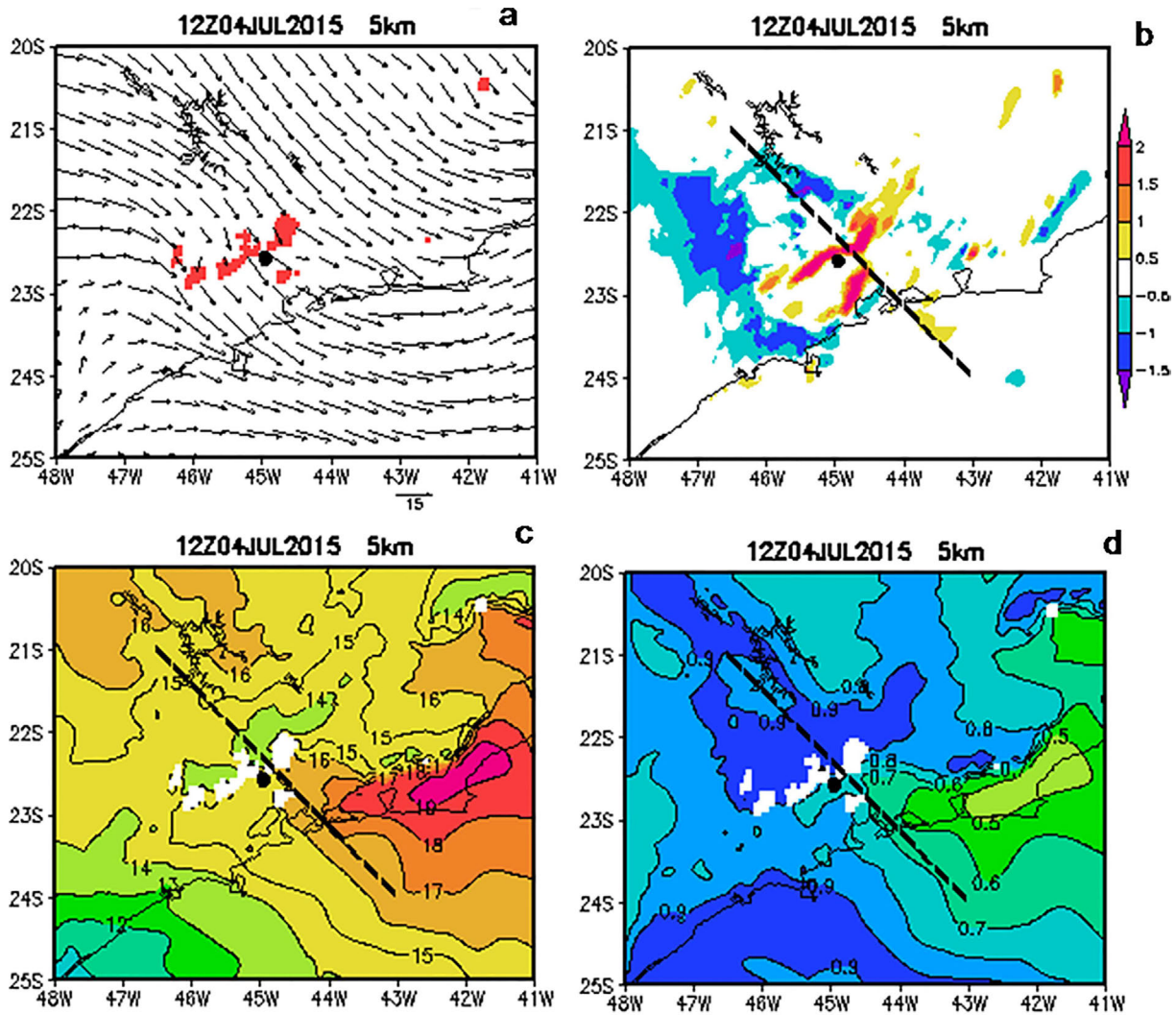


Figure 5 – Several parameters at the 850-hPa isobaric level as simulated by the Eta-5 valid for 4 July 2015 at 12 UTC (24-h simulation). (a) Wind vector in m s^{-1} , (b) omega in hPa s^{-1} , (c) temperature in $^{\circ}\text{C}$, and (d) relative humidity in fraction. Surface pressure less than 850-hPa are masked. The dashed line is a transect used for vertical cross-sections.

greater than 18 m s^{-1} just above the mountain top (Fig. 7a). It extends downward from 600-hPa to the surface onto the crest and the easterly mountain slopes. On the other hand, the wind component parallel to the mountain is weak or even null (Fig. 7b). As a result of the ascending motion above the mountain crest and because the humidity content of the air, saturation is almost reached (relative humidity greater than 95%) from the surface up to the 650-hPa level on the windward side (Fig. 8). The sharp contrast between the driest air to the lee and the almost saturated air windward, suggests clouds formation due to forced lifting caused by the flow perpendicular to the mountain.

A more detailed picture of surface circulation over mountains is given by the 1-h simulation obtained with Eta-1 as shown in Fig. 9. The simulation time almost coincides with the observation of orographic clouds in

Fig. 2. In comparison with the Eta-5 simulations, the orography features as peaks and valleys along the mountain crest are now solved in much more detail. In this sense, it can be seen in Fig. 9 that the strongest surface winds are from the northwest and blow perpendicular to the mountain crest, in contrast to weak winds from the southwest in the valley. As in the Eta-5 simulations, the mountains also constitute an obstacle for the flow at 850-hPa. In the Eta-1 simulation (Fig. 10) part of this flow is deflected around the peaks and channelized through the valleys across to the mountain crest.

The two points denoted with A and B in Fig. 10, located on the upwind and downwind slopes of the Serra da Mantiqueira, respectively are used to analyze the intensity and the evolution of the foehn-like wind. The location of point B almost coincides with the site of orographic clouds observed in Fig. 2. The time series of different

parameters obtained from the Eta-1 simulation are presented in Fig. 11. The series begin just 1-h after the

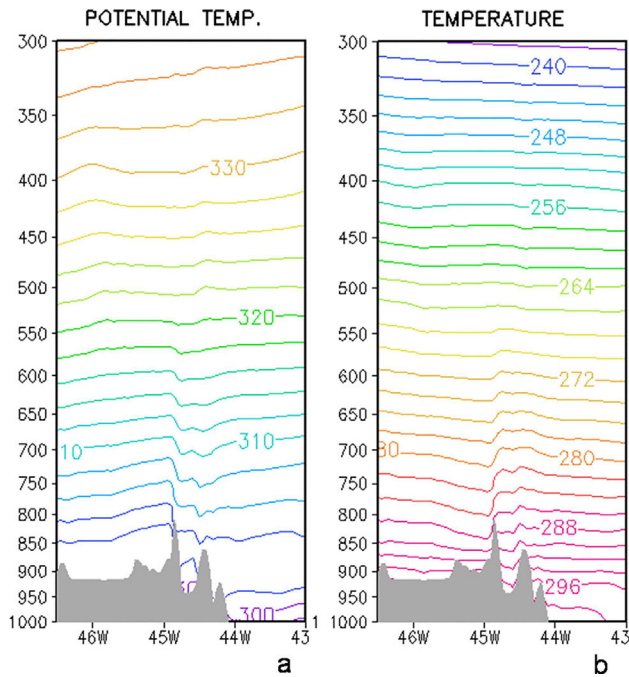


Figure 6 - Vertical cross sections of potential temperature (a) and temperature (b) (in K) as simulated by the Eta-5 valid for 4 July 2015 at 12 UTC (24-h simulation). The location of the vertical cross sections are indicated with a transect on the maps of Fig. 5. Dark shadows at the bottom represent terrain elevation.

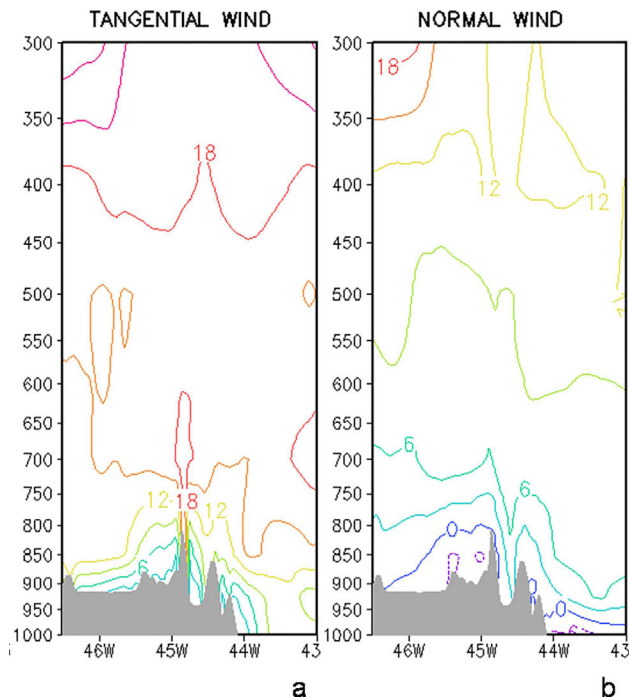


Figure 7 - As in Fig. 6 but for the wind component parallel (a) and perpendicular (b) (in $m s^{-1}$) to the transect. Positive values are northwesterly wind in panel a, and southwesterly wind in panel b.

moment when clouds were observed in the picture of Fig. 2 and end 24-h later. In the point A (Fig. 11), proper conditions for air saturation persist from 4 July at 13 UTC to 5 July at 00 UTC when the passage of the cold front occurs. The latter is confirmed by the change in the wind direction from the 300° to 150° that simultaneously occurs with the drop of air temperature. On the other hand, the maximum temperature in point B occurs at the beginning

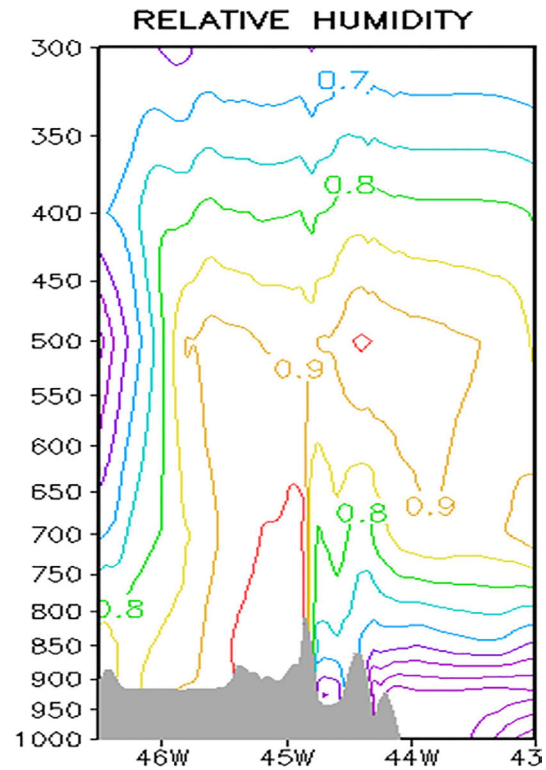


Figure 8 - As in Fig. 6 but for the relative humidity (in fraction).

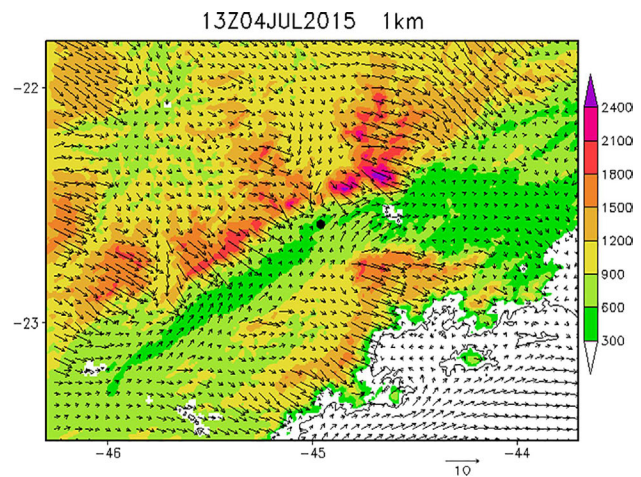


Figure 9 - Surface wind (in $m s^{-1}$) as simulated by the Eta-1 valid for 4 July 2015 at 13 UTC (1-h simulation) and terrain elevation as seen by the model (colors bar in meters above sea level). The black dot indicates the location of Cruzeiro City.

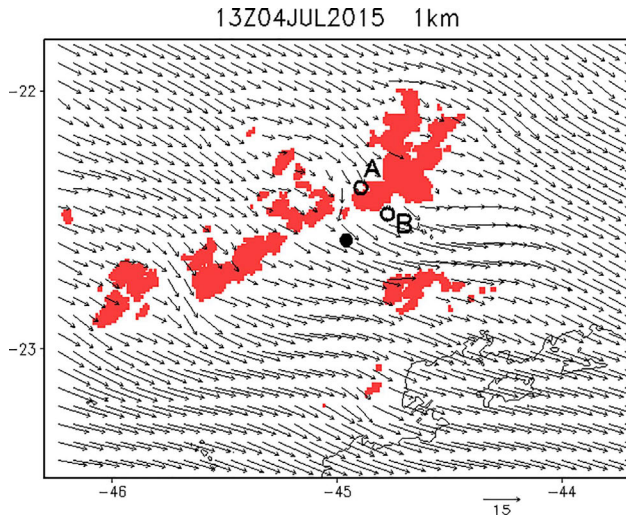


Figure 10 - Wind vector (in m s^{-1}) at the 850-hPa isobaric level as simulated by the Eta-1 valid for 4 July 2015 at 13 UTC (1-h simulation). Surface pressure less than 850 hPa are masked. The black dot indicates the location of Cruzeiro City, and the white dots denoted with A and B are selected sites upwind and downwind the mountains (see text for more explanation).

of the time series, i.e. only 1-h after orographic clouds observation. At this time, the minimum value of relative humidity also occurs and the wind is blowing from the 270° at 10 knots. These conditions contrast with those previously described in point A, suggesting that a foehn-like wind is blowing at point B. Even though its intensity reduces from the beginning of the time series, it persists up to the passage of the cold front on 5 July at 00 UTC. The latter coincides with the maximum wind intensity of 16 knots and the drop of air temperature. From there on, the air remains saturated.

4. Conclusions

The present study introduces for the first time in literature, the presence of foehn-like winds at subtropical latitudes of South America over a relatively low mountain-range (Serra da Mantiqueira) located on eastern Brazil. The article focuses on a particular case observed on 4 July 2015 that was documented just through photographs. Numerical simulations with the Eta model at horizontal resolutions of 5 and 1 km were used to describe the main atmospheric characteristics of the foehn-like wind over both slopes of

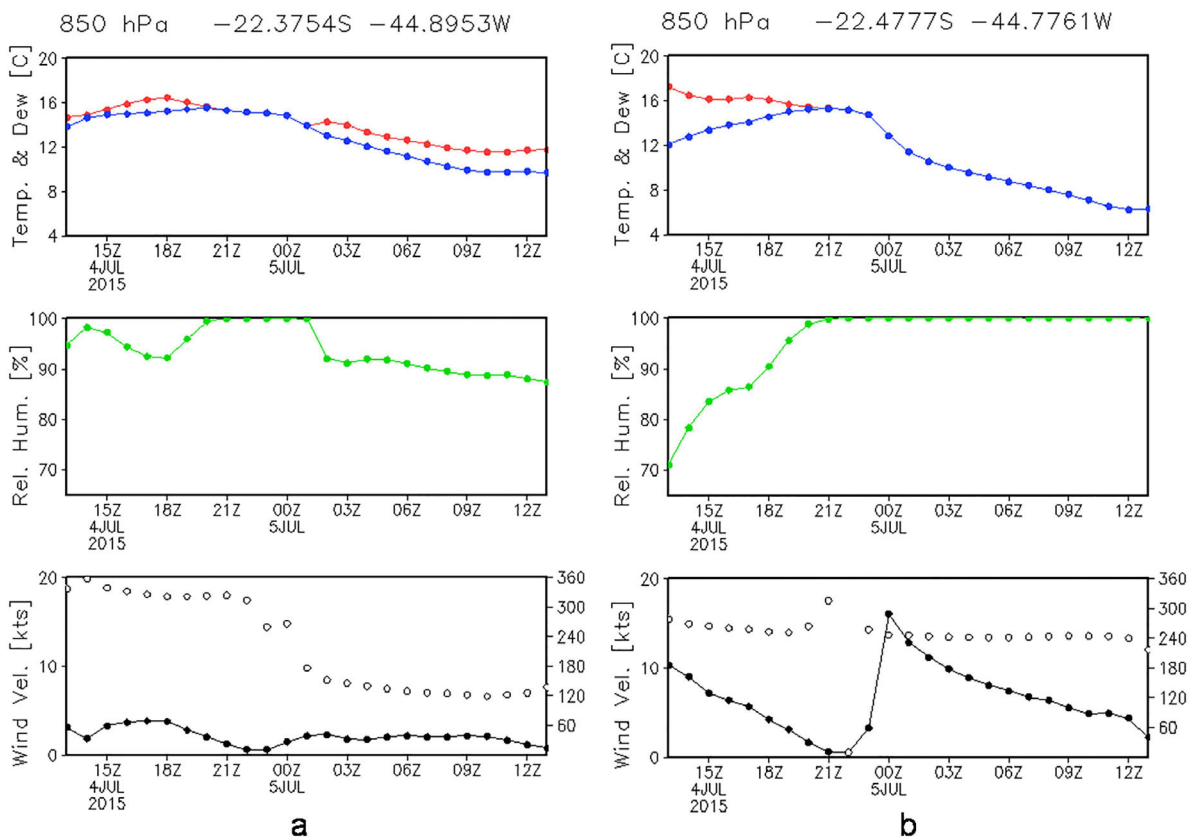


Figure 11 - Time evolution of meteorological parameters at two points in Fig. 10 as simulated by the Eta-1 from 04 July 2015 at 13 UTC to 05 July 2015 at 13 UTC. Column (a) corresponds to point A in Fig. 10; column (b) to point B in the same figure. Temperature and dew point in the upper panel (in $^\circ\text{C}$), relative humidity in the middle panel (%), and wind velocity and direction (black and white dots, respectively) expressed in knots (scale on the left) and compass degrees (scale on the right).

the Serra da Mantiqueira mountains and also to explore the proper conditions for its occurrence. This wind, that could be named as “Mantiqueiro” wind has similar characteristics in comparison to other foehn-like winds detected in other parts of the world: 1) wind direction perpendicular to mountain crest and parallel to the horizontal pressure gradient, 2) upward vertical motion over northwestern slopes (upstream) where clouds form, 3) downward vertical motion over southeastern slopes (downstream) where air dryness occurs inhibiting cloud formation.

Numerical simulations allow establishing that the wind started just before the passage of a low-level trough associated with a cold front. Due to the enhanced baroclinicity flow tends to progressively intensify and turn towards the southeast, becoming perpendicular to the mountain range, as the corresponding middle-level trough approaches the mountain crest 2,000 m above sea level. Consequently, part of the flux overpass the mountains as it was shown in the vertical cross-sections, whereas another part surrounds the mountains and passes through the valleys across the mountain crest.

The analysis of the evolution of different meteorological parameters suggests that a foehn-like wind has been blowing for at least 24-h prior to orographic clouds observation. The end of the event occurs when the cold front passes between 18 and 19 UTC on 4 July.

In addition to the analysis made in this study about the foehn-like wind, it would be necessary to provide meteorological observations in the mountains to improve the knowledge of its features (e.g., duration, frequency, intensity, etc.) as well as its impacts on surface (e.g., forest fires).

The occurrence of foehn-like wind in the mountains of Southeastern Brazil reveals the complex interaction that exists between the orography and the low and middle-level flow. This interaction takes place even at subtropical latitudes and over low-altitude mountains (below 3,000 m). The present study provides an example about the atmospheric conditions when foehn-like wind probably occurs. It demonstrates the relationship between synoptic-scale features and the occurrence of the foehn-wind. Finally, the impact of eventual atmospheric turbulence on aviation and the relationship with forest fires will be analyzed in further studies.

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