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ANALYSIS OF THE INTERNAL BOUNDARY LAYER FORMATION ON TROPICAL COASTAL REGIONS USING SODAR DATA IN SANTA CRUZ REGION OF MRRJ

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Abstract: This paper investigates local circulation features in the industrialized coastal region of Santa Cruz given the close relevance to recent air quality problems. The topographic characteristics and the variety of micro and mesoscale phenomena acting over the area suggest the formation of Internal Boundary Layers (IBLs) during cold front and bay breeze flows, whose parameterization is often employed in air quality modeling. Preliminary results using data from acoustic atmospheric profilers shows a frequent occurrence of the IBL formation during bay breeze periods, coinciding with flow direction upstream of the major industries and having an impact on the most populated area of this region. Vertical profiles of main meteorological variables are evaluated together with surface weather station and satellite data to derive a detailed physics-based description of the various stages of bay breeze in terms of the main forces, duration and atmospheric stabilities. It is found that the development phase exhibits the largest bay/land differences and, consequently, it is the strongest condition to observe the IBL formation.

Key words: *Sea Breeze, Acoustic Soundings, Vertical Profiles, Internal Boundary Layer*

INTRODUCTION

According to Garratt (1990), the internal boundary layer (IBL) formation is associated with air mass horizontal advection over any discontinuity of surface property. Several studies interpret this surface forcing as an abrupt change of surface roughness, temperature, humidity, or surface fluxes of heat or humidity. The mechanical forcing that produces IBL derives from a shear stress change found on coastlines due of an abrupt change in roughness. Usually, the IBL height exhibits a 1 to 10 growth rate relative to the distance that the flow covers over the roughness surface (Elliott, 1958), and this height is usually dominated by the thermal forcing at surface (Raynor et al., 1979).

Propitious conditions for IBL formation are always available during sea-breeze fronts, where a simple land-water temperature difference induces a flow crossing a coastline, generated by thermal forces ranging from mesoscale to micro-scale (Leo et al., 2015). Therefore, to identify the main physical mechanisms acting over each stage of sea breeze (Cuxart et al., 2014) becomes the key to recognize IBL formation process. The main target in this work is to understand how bay breeze acts over tropical regions where the land-bay temperature gradient is not as large as expected, and to describe the effect on IBL evolution.

METHOD AND MATERIALS

Site Characteristics

The region of Santa Cruz is part of the Metropolitan area of Rio de Janeiro city where rural characteristics can be found inside the second largest metropolitan area of Brazil with a population around 12 million. Situated over a flat lowland, this region is surrounded by several mountains with a complex topography and a coastal area delimited by the Sepetiba Bay (Figure 1).

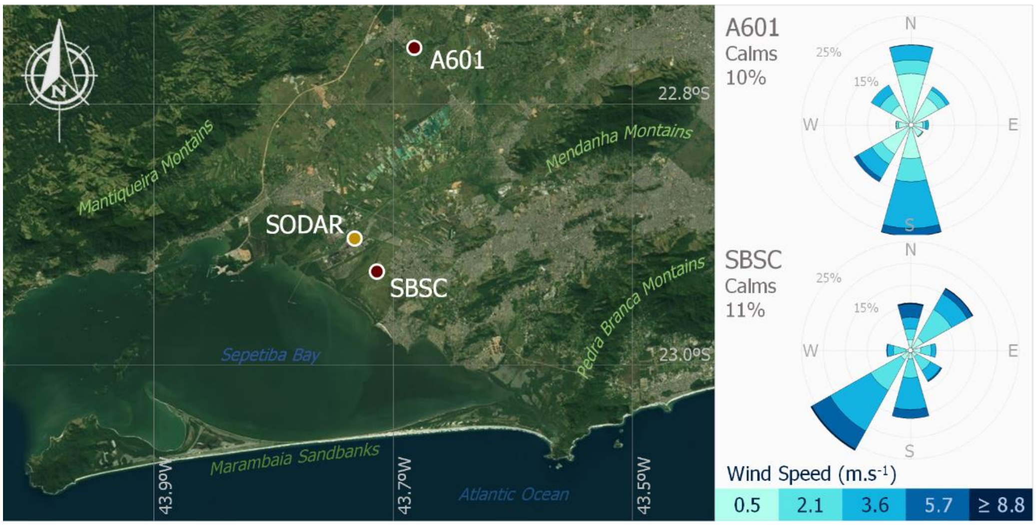

Figure 1. Satellite image of the study area highlighting the main regional topography, water bodies, and meteorological monitoring stations, and wind roses for the coastal (SBSC) and the inland (A601) surface weather stations pointing the presence of the land/bay breeze over the region of interest.

At synoptic scale, the region of interest is usually influenced by the South Atlantic Subtropical Anticyclone (SASA) and low frontal pressure systems (cold fronts), besides breeze systems on meso and local scales (sea/bay–land and valley–mountain) (Paiva, et al., 2014). The latter becomes specifically relevant considering the features of the surrounding region that is characterized by nonhomogeneous land-use and land-cover, and has the borders delimited by water bodies such as the Sepetiba Bay, and the Atlantic Ocean (Zeri, et al., 2011). On the other hand, the SASA is a semi-permanent high-pressure system (counterclockwise in South Hemisphere) with vertical subsidence winds that generates divergence at surface level and, consequently, favors calm weather and clear sky conditions over a influence area. In addition, SASA contributes to inhibit cloudiness and the advancement of frontal systems in the region of interest.

Meteorological Data

As show on Figure 1, the present study uses data from two surface weather stations (SWS). The first one is located inside an airport area named Station Base of Santa Cruz (SBSC), controlled by the National Army and positioned at 3 km from the coastline (22.93ºS and 43.72ºW) with 3 m of ground elevation and hourly measurements of wind at 10 m and air temperature at 2m. The second station, A601 Seropédica, belongs to the National Institute of Meteorology (INMET) and it is located about 20 km from the coastline (22.76ºS and 43.68ºW) at 35 m height over a very gentle slope, with hourly measurements at the same levels of SBSC. Both stations follows the World Meteorological Organization (WMO) standard and integrate the main global atmospheric monitoring systems with station codes 83115 and 86878, respectively.

An acoustic sounding profiler SODAR (SOnic Detection And Ranging) equipped with a windRASS extension (Radio Acoustic Sounding System) was used to acquire measurements of the atmospheric column over the study region. The instrument installed at the end of 2013 attend to a local government request for air quality controlling purposes, once that an important global mineral industry was established acting as the main source of pollutant emissions in the region. The SODAR model MFAS WindRASS (Scintec) is located 5 km from the coastline (22.90ºS and 43.73ºW) at 4 m above sea level, and operates in a range from 40 m up to 800 m above the ground level with 10 m of vertical spatial resolution and time integration of 10 minutes.

In order to evaluate near surface temperature gradients between bay and land, a time-compositing approach for Sea Surface Temperature (SST) was built using satellite products from Aqua MODIS. This compositing have been used to make a comparison with the land surface temperature (LST) and evaluate the diurnal cycle of the bay breeze as detailed below.

Period of Interest

The selected period for the analyses includes 72 hours starting at 00:00 (LT) of December 26 and finishing at 00:00 (LT) of December 29, 2013, where three entire and consecutive cycles of bay/land breezes circulation were observed. During these three days, air temperature oscillates between 22 and 35ºC, relative humidity between 43 and 94%, maximum wind velocities around 7 $m.s^{-1}$, no precipitation, and clear sky condition with the exception of few scattered clouds at some hours. This period was selected within 92 days between October 1st and December 31, 2013 using as criteria the simultaneous availability of data on both surface weather stations and SODAR data for, at least, three consecutive days of bay/land breezes events.

Synoptic Condition

The selected period occurs after a long period of the South Atlantic Convergence Zone (SACZ) governing the synoptic circulation over a major part of the South America between December 11 and 27, 2013. This event promoted an increase of precipitation outside of region of interest, but close enough to avoid the influence of other synoptic systems (as cold fronts, for example). Despite the SASA position was not relevant in this case, migratory high-pressure systems have influenced the region of interest during the selected period, favoring the local circulation and, consequently, the bay/land breeze evolution.

Land/Bay Breeze circulation

The region of interest present a wind field pattern well defined blowing from northeast to southwest directions, strictly perpendicular aligned to the coastline (see SBSC wind rose at Figure 2). Generally, southwest winds are associated to the bay breeze beginning close to midday (10:00-12:00 LT) with maximum wind velocities around 10 $m.s^{-1}$. On the other hand, the land breeze starts close to midnight (22:00-00:00 LT) with northeast winds and velocities up to 7 m/s. According to Pimentel et al (2014), in some occasions land breeze displays a north direction pointing out to a possible interaction with the mountain nocturnal circulation (katabatic winds). In other situations the bay breeze can be hidden by the northeast winds of SASA circulation depending of its positioning and intensity (Paiva, et al., 2014). However, it is important mention that during 92 days evaluated on the present study, 65 showed a land/bay breeze circulation (~70%), reinforcing the hypothesis of its relevance in the local circulation over the region.

RESULTS

Bay Breeze Circulation

In general terms, the time evolution of the bay breeze (Figure 2) follows a sequence of previous, preparatory, development, mature and decay phases, each one with specific patterns and duration ruled by a specific dynamics. The first phase of the bay breeze begins with sunrise, when LST is significantly colder than sea surface temperature (SST), lasting between 2 (tropics) and 4 hour (mid-latitudes) depending on solar radiation intensity. In our case, bay breeze began around 6:00LT and lasted until the previous nocturnal inversion layer break-up (between 7:30 and 8:00LT). It coincides with a land breeze intensity decreasing (NE winds) and finally suppressed by convection starting as result of land surface warming. At this point, the preparatory phase starts with LST-SST becoming positive, convective boundary layer beginning to build, and wind shifting on SW direction just near to the coastline (normal aligned). As observed of Figure1, this last condition shows a delay at Dec 27 and 28, indicating that land breeze intensity has not decreased enough to obtain a convective condition over the region.

Further, around 11:00LT the development phase starts which usually last for 3 hours. The critical period of bay breeze have the greatest temperature and pressure gradients, providing all conditions for the front breeze (wind ≥ 3 $m\ s^{-1}$) as well as the maximum turbulence (indicated by TKE on Figure2) and maximum LST-SST difference. The maximum wind speed of the evaluated period always occurs during this phase, suggesting the appropriated time to observe the IBL building up (discussed later). Close to 14:00LT it is possible to observe the bay breeze arriving at the inland station (~1 hour delayed in relation to the coast station), with an increase of wind speed and a decrease of air temperature. This is the mature phase, when the vertical circulation cell between bay and land is established with convergence winds inland. This configuration remains for 3 or 4 hours with wind speed, LST-SST difference and turbulence nearly constant, with only a slow temperature decrease. Finally, the last one called decay phase starts near to sunset (after 18:00LT) and makes the transition to the land breeze circulation. During this period, all the evaluated parameters decrease slowly until sunset, when wind speed reduces to calm winds and LST-SST difference become negative, providing the conditions for land breeze initiation.

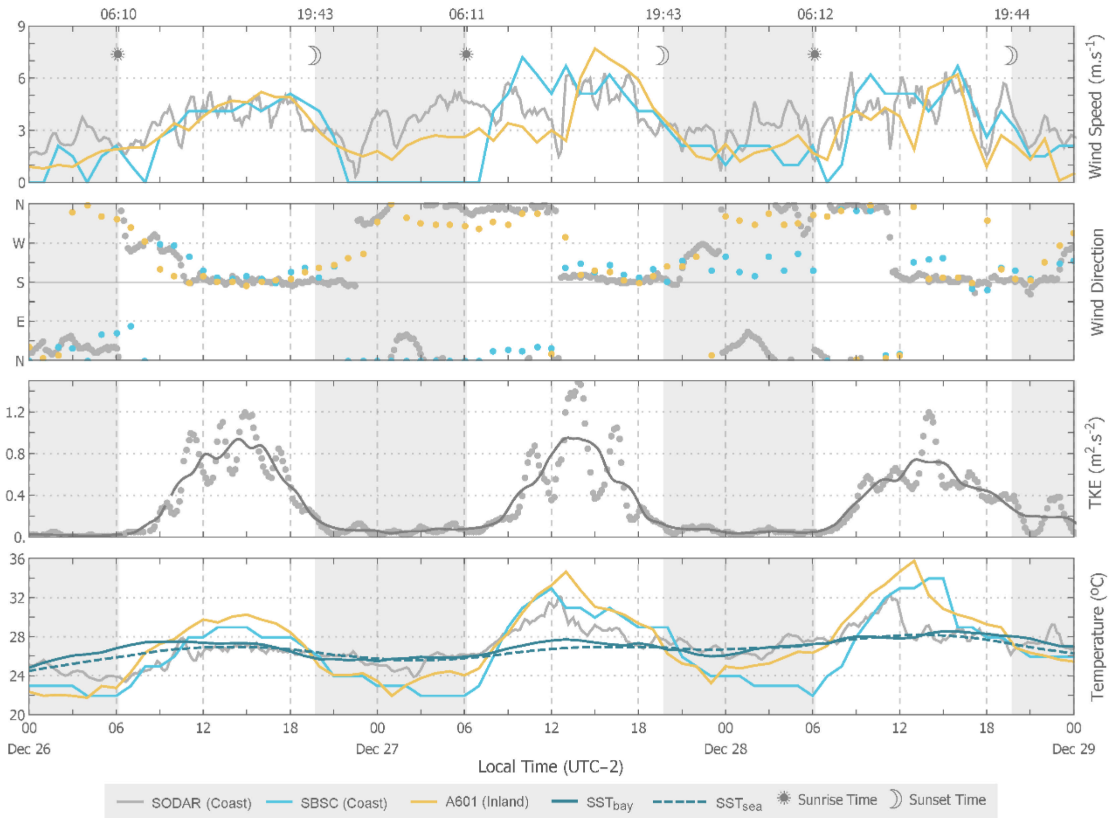

Figure 2. Meteorological data for the region of interest between 26 and 29 December 2013. Wind speed, wind direction, and air temperature measurements recorded at 10 m by surface stations. SODAR measurements are presented only for the first level (40 m), except for TKE which integrates all column (smoothed data – solid line). STT data show averages of specifc areas over the Sepetiba Bay and Atlantic Ocean.

IBL Building

Despite SODAR limitation to observe the atmospheric boundary layer height under convective condition, acoustic soundings proved to be adequate to detect the inversion height z_i (m) since it occurs inside the measurement range, for example, during nocturnal boundary layer or IBL cases (Mellas, 1993). SODAR data for the study period had z_i observations only during nighttime (stable conditions), except on Dec 26 and Dec 28, when inversions were observed for few minutes on vertical temperature profiles with heights up to 130 m (Figure 3). Both episodes occur during the development phase of the bay breeze, when the wind speed, turbulence intensity, and LST-SST reaches their maximum values, providing all the minimal conditions for a IBL building up along the coastline.

Two simple analytical formulations were applied to estimate IBL heights h_i (m) when front breezes crosses the coastline: Weisman (1976) which uses the surface heat flux H_0 (W m^{-2}) as the main term (Eq.1), and Raynor et al. (1979) which consider LST-SST ΔT_{L-B} (ºC) as principal on formulation (Eq.2).

$$h_w = \left(\frac{2\, H_0\, x}{\rho\, c_p\, |\gamma|\, U}\right)^{1/2} \qquad (1)$$

$$h_r = \frac{u_*}{U}\left(\frac{x\,|\Delta T_{L-B}|}{|\gamma|}\right)^{1/2} \quad (2)$$

where x is crosswind distance from the coastline (m), ρ is air density (1.225 kg m^{-3}), c_p specific heat at constant pressure (1004.67 m^2 s^{-2} K^{-2}), γ is the vertical gradient of temperature (ºC m^{-1}), u_* is friction velocity (m s^{-1}) and U is mean wind (m s^{-1}). The results presented in Figure 3 shows a good estimative for IBL height at 5 km (SODAR position) for both days using both models. The smaller ΔT_{L-B} on Dec 26 (1) explains the underestimation of Eq.2. Considering the wind speed during these cases (3.1 and 5.1 m s^{-1}, respectively) blowing for approximately 40 minutes, a possible IBL fetch for the region under this atmospheric conditions varies between 8 and 12 km from the coastline, impacting severely over the main emission areas suggesting a potential increase of pollutant concentration during these periods.

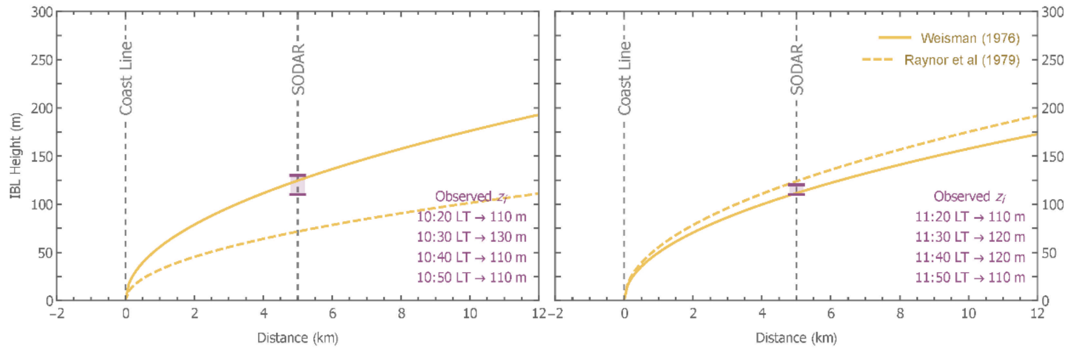

Figure 3. IBL height estimative at crosswind direction for 26 Dec 2013 at 10:00LT (left) and 28 Dec 2013 at 11:00LT (right) using Weisman (1976) and Raynor et al. (1979) formulations. Positioned 5 km from coastline, these measurements are the only one available during daytime (convective) on the study period, and both were recorded during the development phase of the bay breeze.

CONCLUSIONS

A thorough analysis over three consecutive and entire cycles of bay-land breeze was presented with a focus on the evaluation for onset of IBL and its evolution in time. The results of our analyses shows that the development phase is the critical period of bay breeze due the highest differences between air mass properties over bay and land. Furthermore, available parameterizations for IBL height estimations were tested showing good results in comparison with SODAR measurements, even when considering different approaches on formulations.

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