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Studies using wind tunnel to simulate the Atmospheric Boundary Layer at the Alcântara Space Center

Abstract: *The Alcântara Space Center (ASC) region has a peculiar topography due to the existence of a coastal cliff, which modifies the atmospheric boundary layer characteristic in a way that can affect rocket launching operations. Wind tunnel measurements can be an important tool for the understanding of turbulence and wind flow pattern characteristics in the ASC neighborhood, along with computational fluid dynamics and observational data. The purpose of this paper is to describe wind tunnel experiments that have been carried out by researchers from the Brazilian Institutions IAE, ITA and INPE. The technologies of Hot-Wire Anemometer and Particle Image Velocimetry (PIV) have been used in these measurements, in order to obtain information about wind flow patterns as velocity fields and vorticity. The wind tunnel measurements are described and the results obtained are presented.*

Key words: *Alcântara Space Center (ASC), Particle image velocimetry, Turbulence, Wind flow, Wind tunnel.*

LIST OF SYMBOLS

ALA	Aerodynamics Division
ASC	Alcântara Space Center
ACA	Atmospheric Science Division
AEB	Brazilian Space Agency
AT	Anemometer Tower
CNPq	National Council for Scientific and Technological Development
IAE	Institute of Aeronautics and Space
IBL	Internal Boundary Layer
INPE	National Institute for Space Research
ITA	Technological Institute of Aeronautics
VLS	Satellite Launcher Vehicle
PIV	Particle Image Velocimetry
MIT	Mobile Integration Tower
Re_δ	Reynolds Number based on the coastal cliff height SRB - Solid Rocket Booster
u_∞	Streamwise wind speed
δ	Coastal cliff height

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INTRODUCTION

Wind regimes and atmospheric turbulence in the boundary layer have been object of great interest in Aerospace Meteorology. Serious rocket launch failures, for example, two Titan 34Ds, an Atlas Centaur, a Delta, two Arianes and a Columbia, occurred between 1985 and 2003. Several of these losses have been weather-related. In the case of Challenger, for example, the main cause was the failure of the Solid Rocket Booster (SRB) joint, caused in part by the very low temperatures experienced.

However, it has been argued that upper-wind conditions at launch time were a significant contributing factor, since severe shear-induced turbulence may well have reopened a transient SRB metal seal (Baker, 1986). According to Kingwell et al. (1991), the main meteorological factors that affect rocket operations are lightning, since electrical surges can trigger loss of control and make rockets lose control and be destroyed; temperature and humidity fields, that affect the formation of fog and ice on the vehicle; turbulence, that can impose unacceptable stresses on key structural elements such as the attachment points of hybrid vehicles, and wind, that can affect the electronic guidance system.

Knowledge about wind flow patterns and atmospheric turbulence are important to provide basic information for Research & Development (R&D) since the rockets are designed to withstand loads due to the wind, and also trajectory, control and guidance are determined by the profile of wind near the surface. According to Fisch (1999), up to the height of 1000 m, 88 per cent of the trajectory corrections are due to the wind, while above 5000 m, this influence is only 3 per cent. In the particular case of the Brazilian Satellite Launcher Vehicle, (VLS), which is a four-stage rocket, it suffers lateral deviation in its trajectory, later compensated by the guidance system.

Sounding rockets, as they are smaller, are more affected in their trajectory by the wind flow pattern. Therefore, their take-off velocity (ballistic wind lower than 6.0 m/s) is relatively small, and produces important changes in the launch azimuth due to the lateral wind speed component (Marques and Fisch, 2005). In addition, the rockets can be also affected by turbulence when positioned at the ramp, prior to the launch. Wind data is usually obtained from meteorological stations, and vertical profile measurement devices, such as anemometric towers or masts, give details of the wind in certain places. However, valuable information can be obtained from wind tunnel experiments about the modification of the atmospheric boundary layer caused by abrupt changes in local topography.

Recently, wind tunnels have been used in Micrometeorology Science due to their advantage of flow control. Recent studies can be found in the literature, for example, Novak et *al*. (2000) analyzed the turbulent structure of the atmosphere within and above canopy. Simulations of the atmospheric wind field at a complex topography were conducted in order to plan the Naro Space Center at South Korea (Kwon et *al*., 2003). Studies on pollutant dispersion immersed in obstacles were carried out by Mavroidis and Griffiths (2003), and simulations of the air flow for complex topography were carried out by Cao and Tamura (2006).

The Brazilian Rockets, such as the VS-40, and VSB-30 sounding rockets, and the VLS, have been launched from the Alcântara Space Center (ASC), which is located on the coast of Maranhão State, at the latitude 2° 19' S, longitude 44° 22' W, 40m above sea-level and a distance of 30 km from São Luiz. As can be observed in Fig. 1, there is a coastal cliff along the shoreline in the ASC neighborhood. Consequently, in addition to an abrupt change in roughness from the smooth oceanic surface to a rugged continental terrain, a topographical variation of 40 m is added.

The Mobile Integration Tower (MIT) is located 150 m from the edge of this coastal cliff. Figure 2 shows the area of the ASC, the anemometer tower (AT) and the MIT.
This paper's objective is to describe some wind tunnel experiments that have been carried out in cooperation among researchers from IAE, ITA and INPE. These experiments have been implemented using technologies such as Hot-Wire Anemometry and Particle Image Velocimetry (PIV) in a wind tunnel, in order to investigate the wind flow pattern and turbulence at the ASC, where abrupt changes in surface roughness exist. Computational Fluid Dynamics (CFD) was also used in these investigations.

Figure 1: General view of Alcântara Space Center

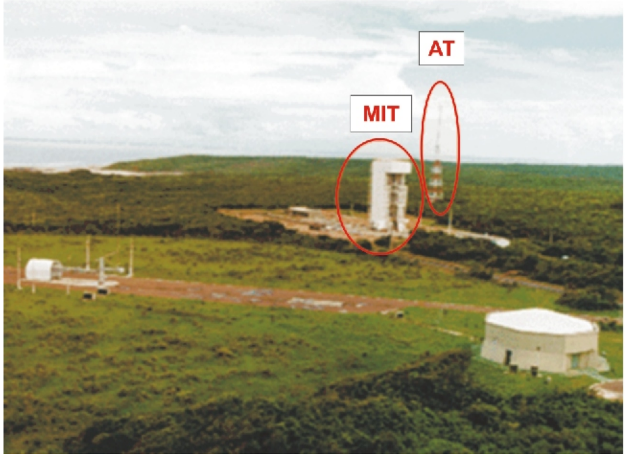


Figure 2: Detailed view of the MIT in the ASC.

Alcântara Space Center characteristics

Because of the ASC's peculiar topographical characteristics, the wind, initially in balance with the oceanic surface, interacts with the low woodland vegetation (average height of the trees is 3m), modifying itself with the formation of an Internal Boundary Layer (IBL). A schematic representation of the IBL development as it moves over a smooth surface (ocean) and then across a rough surface (continent) is shown in Fig. 3.

The terrain's influence on the flow downstream from the cliff surface depends not only on its characteristics, but also on the characteristics of the previous surface, upstream the cliff, over which the flow was in balance. So, a new equilibrium layer is formed, the vertical thickness of which increases with the distance from the edge. Above this new layer the wind profile remains in balance with the previous surface, while within it, the wind profile is adjusted to the new surface (Stull, 1988).

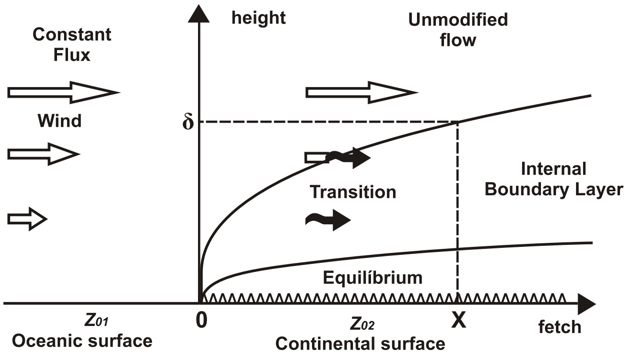


Figure 3: IBL development from a smooth surface to a rough surface (adapted from Savelyev and Taylor, 2005).

The classical work of Elliot (1958) and the following theoretical and experimental studies carried out by Pendergrass and Arya (1984), Sempreviva et *al*. (1990), Sugita and Brutsaert (1990), Källstrand and Smedman (1997) and Jegede and Foken (1998) focused on the neutral flow problem that occurs due to the change in roughness. In these studies, the development of the modified wind flow pattern, the IBL growth and the turbulent field implications were investigated. Slvelvev and Taylor (2005) did a very detailed review of published formulas following on from Elliot's pioneering work. According to Jegede and Foken (1998), non-neutral situations can be represented by adjusting empirical coefficients of the neutral cases. Subsequently, thermal stratification effects on wind flow pattern and IBL growth were introduced, as shown by Batchvarova and Gryning (1998), Liu et *al*. (2000), and Hara et *al*. (2009). It should be mentioned that atmospheric stability at the ASC can be considered to be neutral due to the high winds. Loredo-Souza (2004) took wind tunnel measurements showing that atmospheric stability can be considered neutral if the wind speed is around 10 m/s. This is the case of the ASC (Roballo and Fisch, 2008). The vegetation in the ASC area is characteristic of a region of "restinga". Average height of the vegetation is around 3 m. The climate presents a precipitation regime divided into two periods: (i) a wet period, with heavy rains from January to June, with March and April receiving the peak rainfalls, with monthly totals above 300 mm; and (ii) a dry period, from July to December, with precipitation lower than 15 mm per month (Fisch, 1999).

There are marked differences in the wind regime between the rainy and dry season. During the wet period, the east wind predominates approximately up to 5000 m, with wind speeds of 7.0 ~ 8.0 m/s at levels between 1000 and 3000 m. In the dry season, the wind is predominantly from east, and reaches up to an altitude of approximately 8000 m, with wind speeds of 7.0 ~ 9.0 m/s, being particularly strong in the layer up to 2000 m, with averages between 10.0 and 10.5 m/s, and manifesting a small south-easterly rotation. This shift occurs due to intensification of the sea breeze, which displays its maximum impact (ocean-continent thermal contrast) during this period, particularly from September to November. Air temperature and the relative humidity do not present seasonal variations and their values are typical of the tropical atmosphere due to its geographic location (Fisch, 1999).

BACKGROUND

The Atmospheric Science Division (ACA) conducts studies concerned with the atmospheric systems that occur at the ASC. In cooperation with the Aerodynamics Division (ALA) activities have begun related to the understanding of the atmospheric turbulence at the ASC using wind tunnels in another scientific project related to the upgrading of instrumentation and modernization of the aerodynamic tunnel TA-2 in order to simulate the atmospheric boundary layer. The objectives are to use TA-2 with a modern PIV system to simulate the flow at the ASC for a Reynolds number around 10^6. The TA-2 wind tunnel is a facility of the ALA and is Brazil's biggest aerodynamic wind tunnel.

Description of the experiments

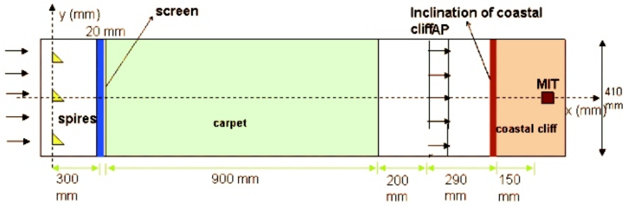
The wind tunnel experiments were carried out at the Prof. Kwein Lien Feng Laboratory at the Institute of Aeronautical Technology, (ITA), using an open circuit, closed jet subsonic wind tunnel with a square test section (465 mm x 465 mm) 1200 mm in length. The maximum wind speed through the test section is 33 m/s.

The atmospheric flow field was simulated by prolonging the test section, and by installing a screen and some spires as represented in Fig. 4. These spires consist of triangular steel plates, which were positioned at the entrance of the measurement chamber and combined with the roughness (felt carpet with a thickness of 3 mm was used) to produce the boundary layer profile similar to the atmospheric wind flow (Santa Catarina, 1999).

Average wind speed values and fluctuations were obtained through hot-wire anemometer measurements. A schematic design of measurements using the hot-wire anemometry technique is represented in Fig. 5. A coordinate system (x,y) was used as a reference system, where the negative x values correspond to the ocean (upwind of the cliff) and the positive x values correspond to the continent (downwind).

A two-dimensional PIV system was used to obtain air flow velocity fields. PIV is a very important experimental tool for fluid mechanics and aerodynamics. This technique allows instantaneous and non-intrusive measurement of the flow velocity, ranging from micro PIV to large industrial wind tunnel applications. As opposed to the more commonly used single-point measurements, PIV allows the spatial structure of the velocity field to be visualized as well as quantified. A good description of this technique is given by Raffel et *al*. (2007). The basic principle of this technique involves photographically recording the motion of microscopic particles that follow the fluid flow.

(a) Frontal view



(b) Superior view

Figure 4: Apparatus used for the experiments.

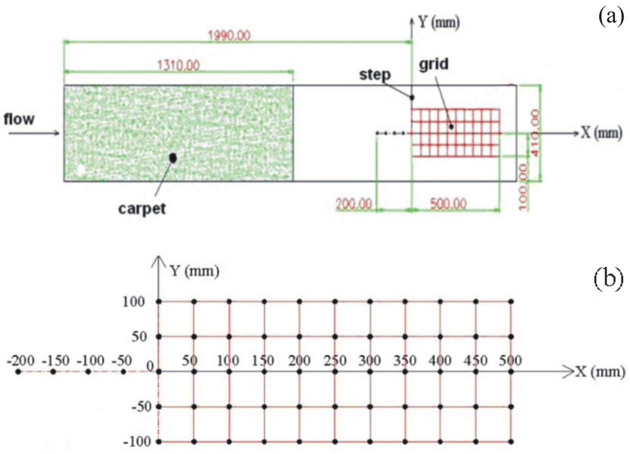


Figure 5: Overhead view of the experimental design with the coordinates *x* (longitudinal) and *y* (lateral).

To conduct the experiments, the wind tunnel test section flow was seeded with smoke particles, approximately 5mm in diameter, using a Rosco Fog generator. A New Wave Nd-YAG 200 mJ dual pulsed Nd:Yag laser, with a repetition rate of 15 Hz, was employed to illuminate the flow field. A vertical laser sheet was created using an articulated arm, as shown in Fig. 6, and a set of lenses for laser thickness adjustment. A 60 mm diameter Nikon lens was fitted to a 12-bit high-resolution digital camera HiSense 4M (built by Hamamatsu Photonics, Inc.) with acquisition rate of 11 Hz, spatial resolution of 2048 × 2048 pixels and 7.4 m pixel pitch was used to capture the flow field. The instantaneous images were processed using the adaptive-correlation option of the commercial software developed by Dante Dynamics (Flow Manager 4.50.17). A 32 pixels × 32 pixels interrogation window with 50 per cent overlap and moving average validation was used.

To enable the boundary layer formation in the region of optical access, and to allow PIV measurements, in addition to devices such as the spires and carpet, a screen was also used, as represented schematically in Figure 4.

The experimental results were compared with numerical results obtained from the computational code named *Immersed Boundary* developed by Góis (2007) and Pires (2009).

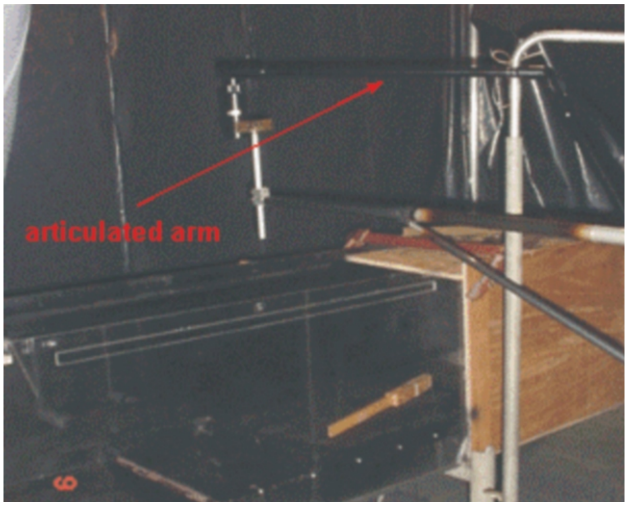


Figure 6: PIV system installed in the wind tunnel test section.

One of the models used to simulate the ASC and the MIT (represented by a wooden block of dimensions 10 x 10 x 50 mm) is represented in Fig. 7. In order to simulate the irregularity of the coastal cliffs, experiments were made with varying inclinations. These models were painted in flat black to avoid laser reflections.

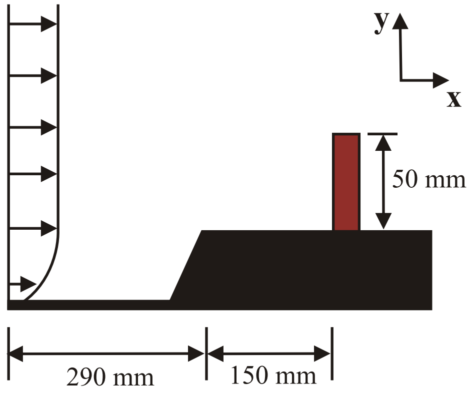


Figure 7: Wind tunnel model representation.

Comparison between experimental and numerical simulation results

Figure 8 shows a comparison between IBL height obtained from the wind tunnel experiments, for Reynolds Number based on the coastal cliff height (δ), Re_δ, equal to 7.2 x 10^4, and the IBL height obtained from numerical simulation. For the numerical simulation and for the wind tunnel measurements, the coastal cliff was taken to be 40m in height and perpendicular to the wind direction. In the numerical simulation, a 2D model was used, with vorticity-velocity formulation. High-order compact finite-difference schemes were adopted for the derivative approximations, and a 4th order Runge-Kutta method was used to integrate time (Góis, 2007). The coastal cliff was specified through the immersed boundary method (Pires, 2009). More details about this methodology can be obtained from Pires et *al*. (2009). A strong correlation between the numerical and experimental results was observed, providing a validation of the numerical method adopted.

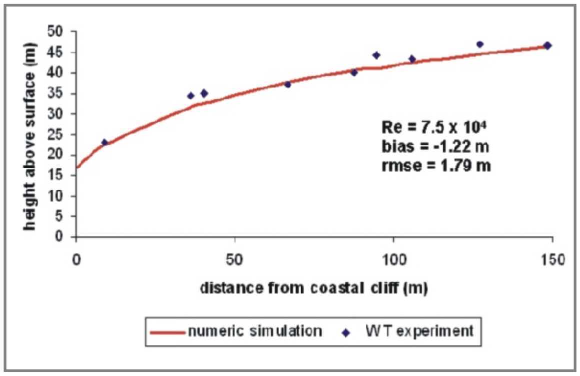


Figure 8: The IBL results from wind tunnel measurements and numerical simulation.

The streamwise wind speed (u_∞) ranged from 27 to 30m/s corresponding to a Re_δ, based on the height of the coastal cliff of 40 m varying from 7.2 x10^4 to 8 x 10^4. These were the maximum Re_δ, values obtained in this wind tunnel. In the atmosphere, the Re_δ is basically of the order of 10^6 and 10^7.

RESULTS

Figure 9 presents the wind speed profiles (or velocity) and the fluctuation (or deviation) of the wind along the central lane (keeping the position $y = 0$ in Fig. 5). It is possible to observe the modification of the profiles at the cliff (position $x = 0$). Also, it can be noticed that the wind speed values are lower after the cliff, associated with the higher values of the fluctuation, mainly close to the surface. This is an indication of the turbulence, due to the step, up to a distance around 300 mm from the discontinuity (cliff). The bigger fluctuation values for a non-dimensional height lower than 0.2 represents the influence of the surface, which creates strong turbulence.

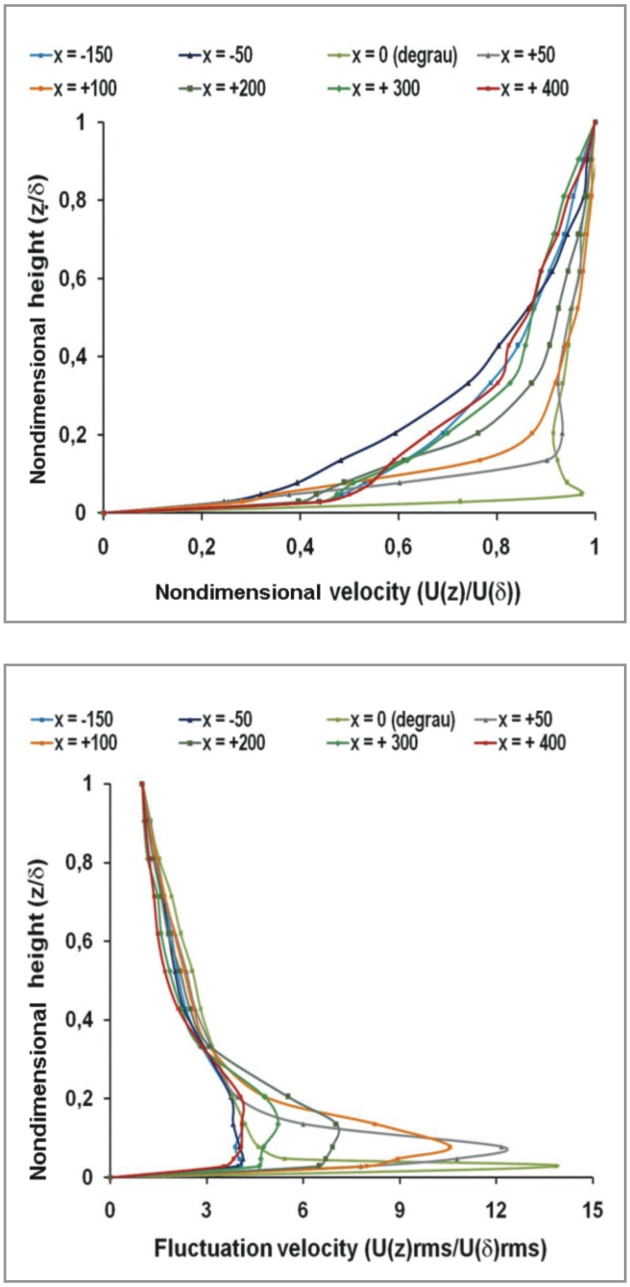


Figure 9: Average velocity profile (a) and fluctuating velocity profiles (b) along the central lane.

Figure 10 presents turbulent intensity obtained with the wind speed and deviation measured at the heights corresponding to the levels of the anemometric tower (e.g. 6, 10, 16.3, 28.5, 43 and 70 m). It is possible to observe that turbulent intensity is higher close to the ground surface, specially close to the discontinuity, reaching values of 0.7 at level 1. There is also a significant decrease in turbulent intensity with height and at level 6 (equivalent to 70 m height) the turbulent intensity is around 0.1 for all positions along the central line. The distance of 300 mm is estimated as the distance where the turbulence caused by the edge disappears (Roballo, 2007).

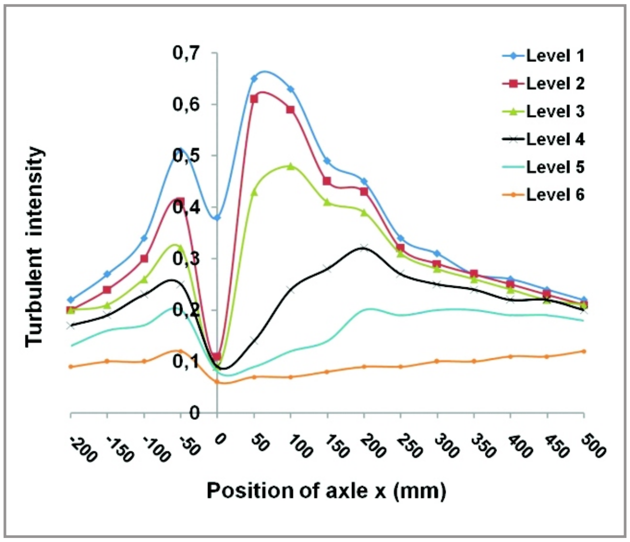
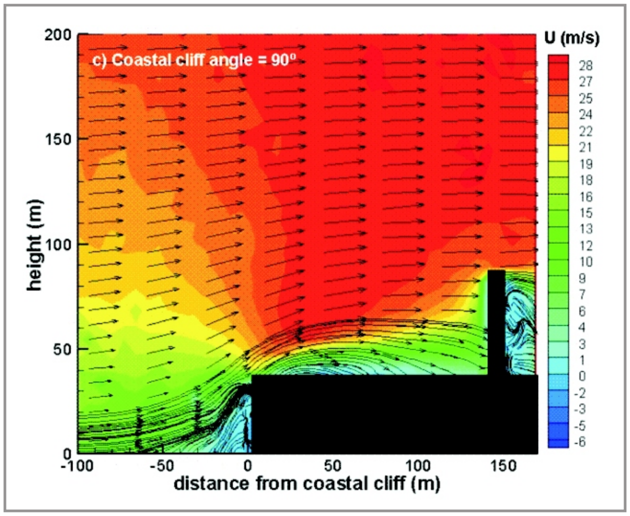


Figure 10: Turbulence Intensity distribution along the central lane (position $y = 0$).

Figure 11 shows the wind profile, the stream lines and the wind vorticity obtained from the wind tunnel measurements. The geometric structure of the coastal cliff affects the height of the IBL reaching the MIT.

It is possible to observe the formation of a strong recirculation zone downwind of the coastal cliff as described before. Theoretically, the IBL height is zero at the usual change of surface roughness. However, in this present case, the coastal cliff (40 m) causes an initial height for IBL at the discontinuity ($x = 0$), which is in the range of 7 to 10m.

The wind vorticity (Fig. 11b) ranging from -1600 to 300 s^{-1} was generated for the experiments in the wind tunnel. In each case a wind vorticity equal to 300 s^{-1} is generated by the flow when reaching the MIT and a negative vorticity (-1600 s^{-1}) is generated above the coastal cliff and the MIT (Pires, 2009).



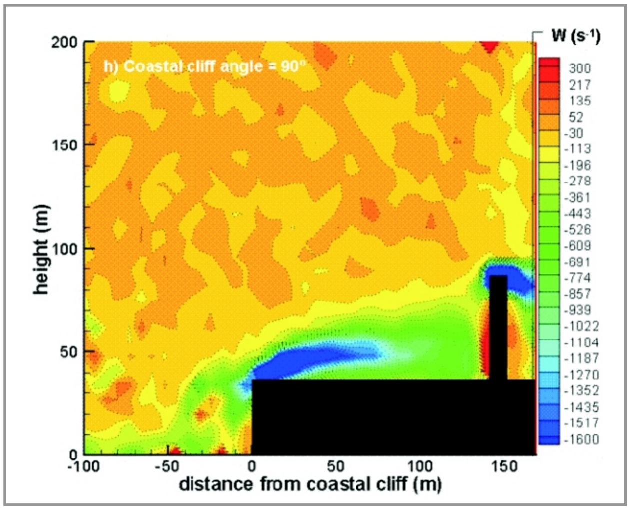


Figure 11: Wind profile, stream lines (a) and the vorticity (b).

Figure 12 shows the vorticity obtained numerically. It should be noted that this simulates the real case with Re_δ = 2.0 x 10^7. It should also be noted that the higher the *Re* the lower the IBL height. (Pires, 2009)

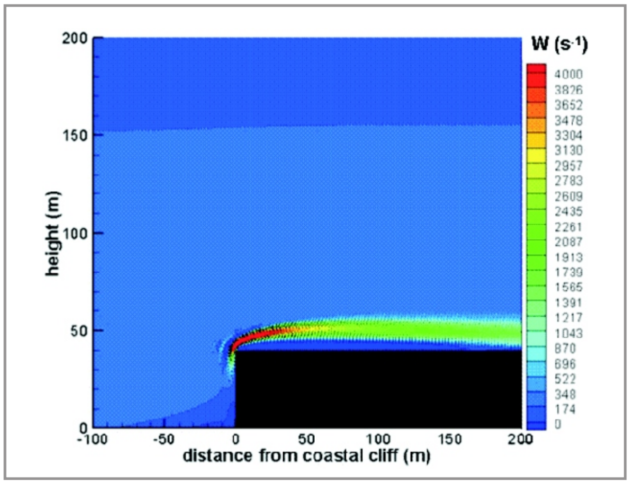


Figure 12: Vorticity obtained in numerical simulation to Re_δ = 2.0 x 10^7.

CONCLUDING REMARKS

Important information about the flow field in the region of the ASC as well as its influence on the MIT has been obtained through wind tunnel measurements in combination with numerical simulations. However, more representative results can be achieved in a wind tunnel that attains higher speeds and consequently higher Reynolds number. This will be the next step in this research, which has already commenced thanks to a grant from AEB. This project to upgrade infra-structure represents a cooperation between ALA and ACA, using the TA-2 wind tunnel facilities.

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