4.1 WIND RESOURCE ASSESMENT IN A TROPICAL REGION WITH COMPLEX TERRAIN USING SODAR AND A METEOROLOGICAL TOWER NETWORK TO MEASURE LOW LEVEL JETS AND BOUNDAY LAYER CONDITIONS

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1. INTRODUCTION

Present energy resources used for electricity production in central western Mexico are mostly based on crude oil, specifically in Colima state which produces electric power for 9 states of the 32 Mexican states in total. This energy source not only creates local health problems due to resultant air pollution near thermo-electric power plants but also is a non renewable energy source. This kind of general statement is especially true for Mexico which oil reserves are currently decreasing, and considering current extraction rates these oil reserves are expected to last 10 years at most. During the last decade efforts had been made to shift to natural gas with important infrastructure investments in the region of interest to make primary energy resource for electricity production more sustainable and environmentally more friendly. Essentially, at the time the mega-project was designed, only conventional gas was considered and contract was made with international companies for importing conventional gas from South America with cost referred to Henry Hub natural gas spot price. Due to recent evolution of extraction technique of shale gas and the expansion of non conventional gas, gas price has been very volatile and Henry Hub natural gas spot price fell down low enough to make the aforementioned contract not viable for producers to sell conventional gas to Mexican government at the referenced cost. Considering this background strategic problem, other kinds of energy sources must be considered, like solar energy and wind energy. Therefore, the accurate wind resource assessment is key in developing resources to meet the energy demands of the region.
The present study is conducted in the Colima valley, central western Mexico (19.2°N, 103.7°W), using SODAR technology combined with a specific meteorological tower network between 2010 and the present.

2. COMPLEX TOPOGRAPHY

Colima Valley, located around 40 km away from the Pacific Ocean (Fig.1), is limited to the West and South East by the Sierra Madre Del Sur, reaching 2,400 m to the west. North of the valley starts the Mexican transverse volcanic axis with the Colima volcanic complex reaching a little more than 4200 m. Between these two main features valley gaps play an important role, as well as to the South and East of the valley where the Sierra Madre gaps open toward coastal areas.

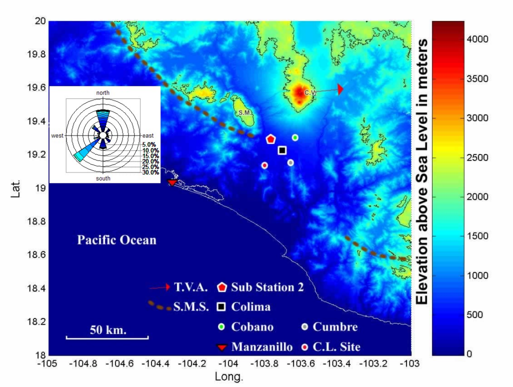

Fig.1: Topographycal map of the region showing the complex topography and the two dominant wind directions.

Therefore the topography of the region varies from sea level to more the 4000 m in less than 80 km from the coast. The aforementioned valley gaps between all theses features surrounding the Colima valley play an important role as well as land sea contrast and sloping terrain on local atmospheric circulation and on boundary layer phenomena observed in our study.

3. INSTRUMENTATION

The instrumentation used in the present study is composed of 4 classical 10-m meteorological stations made by Aanderaa, installed in 2009, measuring with 10 min intervals: wind speed, wind gusts, wind direction, temperature, pressure, solar radiation and solar duration. At one of these monitoring sites a SODAR, MFAS from Scintec, was installed in 2010. The site for the location of the SODAR was chosen to be at a sub-station of the national electricity company, the CFE (Fig.2). Since sub-stations are strategic points for energy distribution and that the current project is done with

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the goal of integrating renewable energy to the grid, the main sub-station of the capital city Colima was selected. In late 2010 a 55-m tower was installed to the North East of the study area, with measurements at 30 m and 50m.

Fig.2: Main monitoring site ant Sub-Station Colima II, with SODAR/RASS and Aanderaa 10-m weather station in the background.

The SODAR measurements done with the MFAS from Scintec range from 30 m above the ground, in 10-m layers, up to 1,000 m at full power in ideal conditions with optionally from 15 min averages to 30 min averages. In the work presented here 30 min averaged are used with maximum range set up at 750 m. The SODAR is a key feature in our network to investigate the characteristics and evolution of the planetary boundary layer. Interestingly the 10-m stations give surface data that really emphasize the necessity of remote sensing tools like SODAR or LIDAR for any realistic wind resource assessment, especially at night when stability increases (Kelley *etal.*, 2007, Banta, 2008) and at that time these stations are in the surface layer and are "blind" to what is happening at hub height of modern wind turbines, well above that relative thin surface layer. Also, these surface stations help to show how the flow observed by the SODAR is decoupled or not from the surface.
Being close to the Pacific Ocean land-sea contrasts are important and strong radiative forcing during day time influence strongly the lower troposphere. In that context, sloping terrain and low level baroclinicity play together an important role.

4. TYPICAL DIURNAL CYCLE AND LOW LEVEL JETS

As shown in previous studies in other parts of the tropics, sea breeze circulation reaches much farther inland than in mid latitudes. With the formation of dry lines, the sea breeze can reach distances of 300 to 500 km inland, making the dynamics of the dry line very specific to the tropics with formation of mesoscale phenomena during the evolution of the dry line itself during the day and the following night.

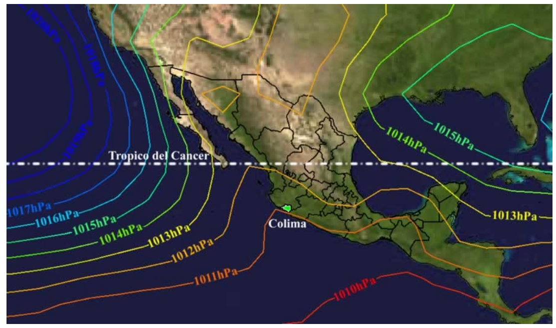

Fig.3: SLP field with major atmospheric features and location of region of interst (light green).

The sea level pressure field in central western Mexico is typically characterized by low level troughing forming between the two major sub-tropical high pressure systems that surround the region (Fig.3), these are the Pacific High and the Bermuda High. In the present study, as shown from the tower network and the SODAR data, the afternoon is characterized by a sea breeze coming from the south west. Convection and turbulent mixing helps the sea breeze flow to reach the surface and is well detected by the 10-m station network. This sea breeze flow is preceded and followed by a weak wind period. Around 03:00 LST an increase in the wind speed is typically observed with wind direction from the North North West to North North East. One would expect a land breeze phenomena to dominate with weaker winds than the diurnal sea breeze in a relative thin surface layer, typical of a gravity current, but surprisingly observations show that surface data are weak meanwhile well above that surface layer, Low Level Jets (LLJ) develop late at night an intensify in early morning, these are typically stronger than the sea breeze flow reaching wind speed maximum around sunrise (Fig.4). Considering the sea level pressure field and therefore background geostrophic state of the tropical atmosphere during these mesoscale event, the LLJs are in most cases supergeostrophic with the height of the wind speed maximum ranging from 100 m to 700 m. To be considered a supergeostrophic LLJ, as mention in other studies, the first minimum above the LLJ wind speed maximum is considered. If the SODAR cannot detect the first minimum above the wind speed maximum, the event is not considered a LLJ, but this does not mean the minimum does not exist or that it is not supergeostrophic, most of these excluded cases are due to limitations of our instrumentation or in some cases to the excess of noise to signal ratio.

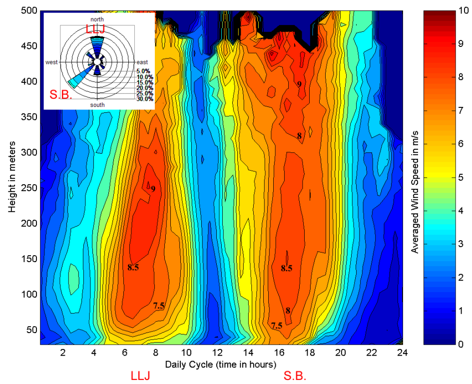

Fig.4: Typical diurnaql cycle showing the LLJ in the and Sea Breeze in the afternoon, corresponding wind direction is shown with the wind rose.

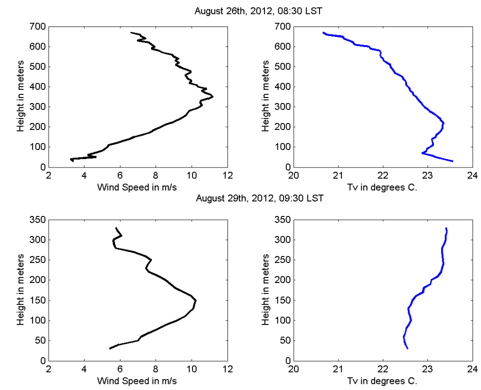

Fig.5: Difference between gravity flow from a storm (upper panels), and a typical class 0 LLJ (lower panels). Temperature profile from the RASS show position of the wind speed maximum compared to inversion layer height.

Following published classifications of LLJs, these β mesoscale phenomena are considered sub-zero category for wind speeds less than 10 m/s, category zero from 10 to 12 m/s, category 1 from 12 to 16 m/s, category 2 from 16 to 20 m/s and category 3 for wind speed greater than 20 m/s. To avoid any confusion with gravity currents resulting from storm formation up stream of the topographical gaps, LLJ profiles are studied case by case in conjunction with GOES infrared imagery and precipitation data. If the presence of any storm or precipitation during the night in the region, the mesoscale nocturnal event is not considered being a LLJ. It is important to mention that going through that selection process, profiles form typical LLJ and profiles from gravity currents that follow a storm event upstream are quite different. Meanwhile the LLJ shows a relatively smooth wind speed increase up to maximum wind speed and then a sharp but also relatively smooth decrease of wind speed toward wind speed minimum giving the LLJ a typical nose like profile, gravity currents from storms are much more turbulent and show a much more irregular profile. Surprisingly, recent installation of a RASS extension shows that meanwhile gravity currents from storms have the tendency to have their wind speed maximum above the temperature inversion, LLJs have the tendency to have their wind speed maximum just below or at temperature inversion height, but more data must be analyzed to confirm that specific point (Fig.5).

In Colima valley, LLJs that went through that selection process have a marked tendency to have their category ranging from sub-zero category up to category 3, with lower level zero- to one category jets dominating compared to sub-zero and category 2 and above. All LLJs have a consistent northerly direction from the gaps in the topography.

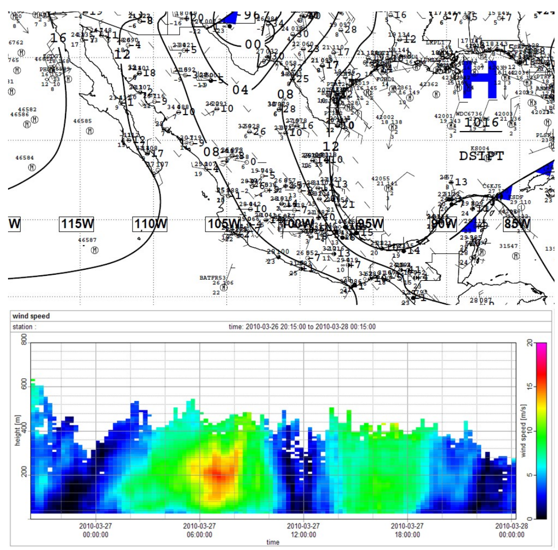

Fig.6: SLP fields (from NHC, NOAA), and corresponding LLJ (here category 2), with SODAR vertical profiles, showing LlJ typically stronger than the sea breeze and low wind speed surface observations.

These phenomena, well captured by the SODAR, are typically not detected by the classical meteorological towers with the difference of the afternoon sea breeze, obviously being due, respectively, to the presence of the night inversion and afternoon turbulent mixing. LLJs are typically observed during clear sky conditions, implying strong radiative forcing, especially the zero and category one LLJs, but is is important to mention some cases are different (Fig.6). More rarely, the presence of a high cloud deck like altostratus or cirrostratus cloud cover with corresponding large scale forcing like the Bermuda High being shifted west and extending well over the Mexican high land, pressure gradients is increased and daytime solar radiation is decreased, intensifying the LLJ that developed earlier during the night and stopping or minimizing convection that usually destroys the LLJ during the early morning. These kind of conditions are responsible for the strongest LLJs observed in the region. The most extreme case so far has been a category 3 LLJ, with maximum speed reaching 23 m/s and with a duration of more than 38 hours (Fig.7).

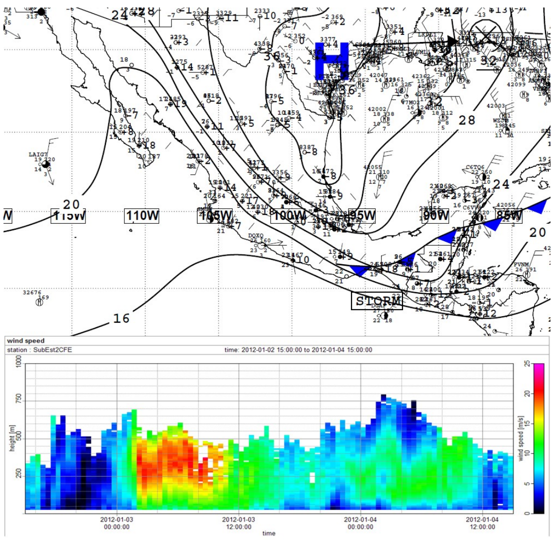

Fig.7: SLP fields (from NHC, NOAA), and corresponding LLJ (here category 3), with SODAR vertical profiles, showing LlJ typically stronger than the sea breeze and low wind speed surface observations.

5. TYPICAL WIND RESOURCE ASSESSMENTS

Still nowadays, wind resource assessment in regions not known for great winds is typically done using data from World Meteorological Organization station network. These 10-m station data are used to evaluate wind resources above the surface layer, that is at 50 m or 100 m above to surface, and wind maps are generated to be used for wind farm siting. The 10-m wind data are extrapolated logarithmically considering zero wind at the surface and the concept of friction velocity with specific surface roughness parameter usually set to 0.14 value, since most of the time local terrain conditions are not well assessed before applying that methodology. Adding uncertainty to this methodological problem, wind turbines height has evolved quite drastically farther from these 10-m measurements, with capacity of 25-60 kW and rotor diameter of 10-20 m working in the surface layer in the early 1980s to modern wind turbines of rated capacities over 3 MW with rotor diameter around 100 m. These days wind turbines hub height is soaring around 120 m AGL, well above the surface layer and well inside the Planetary Boundary Layer (PBL) where develop important mesoscale phenomena such as aforementioned LLJs. Considering evolution of wind turbines in the last few decades and as shown below this kind of methodology can really fail to evaluate correctly wind speed values at hub height. Also, total power produced by a modern wind turbine is proportional to the cubic value of the wind speed, wrong evaluation of the wind speed at hub height can really be misleading for wind resource assessment and corresponding potential power production.
As mentioned in other studies (Arfeuille *etal.*, 2012), it leads, first, to over evaluate the potential of a region with too strong winds, forcing the wind farm managers to shut down production during too strong wind events, second, to generate problems to obtain well balanced transmission lines due to high variability of the wind in the specific region were wind farms are concentrated, third, to no assess correctly the class of wind turbines that must be installed to withstand the shear created by strong LLJ events, and finally to disregard regions with lower but more consistent wind power potential for electrical production. Considering these other regions would also help to redistribute wind farms geographically and solve problems of obtaining balanced transmission lines.
To be more specific, an example is taken from a typical case observed in Colima Valley (Fig.8). Taking the corresponding half an hour average of the 10-m wind speed from the weather station located at the same site of the SODAR, the wind speed is logarithmically extrapolated from the surface up to the first wind speed minimum above the LLJ, that is 350 m in this case, and is plotted on the same graph as the half an hour average wind profile from the SODAR data. The wind speed maximum of the LLJ correspond well to the height of a modern wind turbine and for many wind turbine class the above 13 m/s wind speed corresponds to a good energy production.

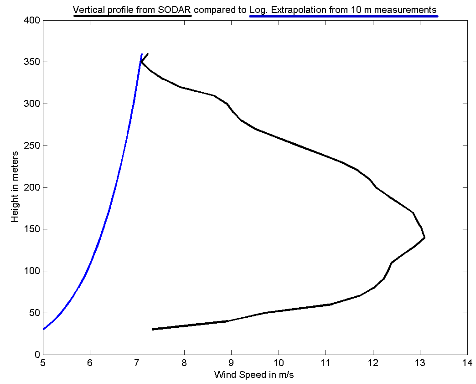

Fig.8: Logarithmic extrapolation from 10-m measurement compared with real profile from SODAR.

Meanwhile the logarithmic extrapolation form the 10-m wind speed barely reaches the first minimum in wind speed above the nose of the LLJ at 350 m and shows a speed at hub height half of the real value measured by the SODAR. This means the wind power potential is under-evaluated by a factor of 8. This fact really show how this classical methodology fails to evaluate the potential in power production and would result in easily not consider the region for wind energy production. Other studies had shown the importance of the methodology used and of these mesoscale phenomena for wind energy assessment, as they increase drastically the potential for wind power generation in the region (Kelley *etal.*, 2004, Arfeuille *etal.*, 2012).

6. DISCUSSION

Prior studies have revealed the importance to wind power generation of mesoscale phenomena such as LLJs (for example over the North American Great Plains in CASES-99, Lamar Project and ABLE studies, as well as in Northern Europe). The present results are consistent with these studies. Also, these show that logarithmic extrapolation from measurements at lower heights typically used in wind assessments grossly underestimates the early morning wind speeds at hub height of modern wind turbines, thus making this classical wind assessment technique invalid, especially in complex terrain like it is shown here. The results also support the necessity to use a methodology for wind resource assessment in complex terrain that includes SODAR or LIDAR technology.
Like in the present work these have shown that local forcing and large scale forcing influences the mesoscale phenomena formation and behavior time wise ans space wise. Additionally, it is interesting to observe that at the difference of the great plains LLJs or other regions where jets form and intensify during the evening transition due to radiative cooling and decoupling from the surface layer, the LLJs observed in this tropical region show a totally different behavior, these are still decoupled from the surface compared to the afternoon sea breeze, but after the sea breeze calms down and the dry line is far inland there is a long quiet transition period between that time after sunset (19:00 LST) and the time LLJs develop and intensify (03:00 LST) to reach their peak around sunrise (07:00 LST), similar to what has been observed in tropical regions of Australia with LLJs developing along the dry line when this comes back toward the shore in early morning; in the present case and the later one the LLJss are later destroyed by morning convection due to strong solar heating. Due to the presence of low level troughing between the two extra-tropical high pressure systems that surround the region of interest to the North, and low level baroclinicity developing due to land sea contrast, and observed pressure minimums twice a day corresponding to the sea breeze and the LLJ, similar behavior is expected.

7. SUMMARY AND FUTURE WORK

The region under study resides in the tropics (19.23°N), and most of the year the horizontal pressure gradient is typically small implying a relatively weak geostrophic back ground state in the wind field. Important topography with existing gaps, sloping terrain and low level baroclinicity that develops due to strong radiative forcing generates an interesting dynamic in the PBL with a bipolar circulation with afternoon sea breeze and early morning LLJs, these observed LLJs strongly supergeostrophic. Both sea breeze and LLJs are important for wind power potential of the region and must be considered for a relevant and realistic wind resource assessment of the region. Local and large scale forcing are important in their influence on the variability of Colima valley circulation and more specifically of the LLJs. Finally, LLJs are not only relevant to wind energy; being an important mesoscale phenomena of the boundary layer involved in many processes from dust and contaminant dispersion to mesoscale convective storm formation; the mountainous complex terrain surrounding Colima valley with the presence of an active strato-volcano and North American monsoon active phase in boreal summer months make this phenomena particularly interesting and relevant to study from many perspectives. Future work must focus on these aspects. Also, the recent installation of the RASS extension to the SODAR is giving us relevant information on the vertical temperature gradient and stability conditions. These are important to consider to be able to understand and model the dynamics of the region. Modeling of such phenomena in tropical atmosphere is very important from water resource management point of view, renewable energy strategic resources, extreme events, natural hazard and risk management.

8. REFERENCES

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