ALCOA Foundation Conservation and Sustainability Practitioner Fellowship

"Transboundary air pollution in Southern Amazon of Peru"

Southern Amazon covered by smoke during burning season

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Alcoa Foundation's Conservation and Sustainability Fellowship Program

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FINAL REPORT ABOUT ALCOA'S PRACTITIONER FELLOW

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This report focus to inform about the activities developed during the research project with funding of Alcoa Foundation.

I. BACKGROUND:

During the last year, 2008, it has been developed the research project "Transboundary air pollution in Amazon of Peru", with the sponsorship of Alcoa Foundation's Conservation and Sustainability Fellowship Program where Luis Suarez was nominated as a practitioner fellow based in Instituto Superior Tecnológico de Monterrey de Mexico, and under supervision of Dr. Gerardo Mejia. In this research we evaluated the transboundary air pollution in the border of Peru and Brazil and discuss its influence in the air quality of the region. We developed sampling campaigns called INCAS (**IN**tensive **C**ampaign for **A**erosol **S**ampling). It is expected that the final results will provide basic information to policymakers for implementing a prevention plan to protect natural resources and to identify possible regional strategies (from Peru, Bolivia and Brazil) for solution. These next steps are under development and we expect have more news on the coming months.

II. INTRODUCTION

Biomass burning is the main source of pollution in the tropical region, covering huge areas in Amazon basin. Special concern exists in the border of Peru, Bolivia and Brazil where big land areas area cleared and burned every year, as part of an increase of agriculture areas for commercial crops. The pollutants resulting from this burning could travel thousand of kilometers, mainly, the related to burning in the region of Brazil, where more fire activity is identified, and that could be transported by the predominant winds to the Peruvian territory.

This transport and emission could include different gases but mainly carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), nitrogen oxides (NOx) y aerosols. Some of them has important roles in the air quality of cities, the chemical composition of the atmosphere and the climate. These gases could serve as source for the production of secondary pollutants like tropospheric ozone (O_3), main responsible of photochemical **smog**. On the other hand, but also critical, it is very important the emission of huge quantities of aerosols, small particles with diameter lower than 10 micrometer (10^{-6} m), that has special interactions in the radiative balance and the cloud formation and it is an actual research topic in this atmospheric science community because of its high uncertainty related to it role in the functioning of the Earth's system, that indeed it could have an enormous role in the greenhouse effect, backscattering the solar radiation or promoting more clouds for avoiding that rays of the sun could reach the earth. Figure 1 shows best results about this quantification and also note the possible role of tropospheric ozone in the radiative balance of the Earth.

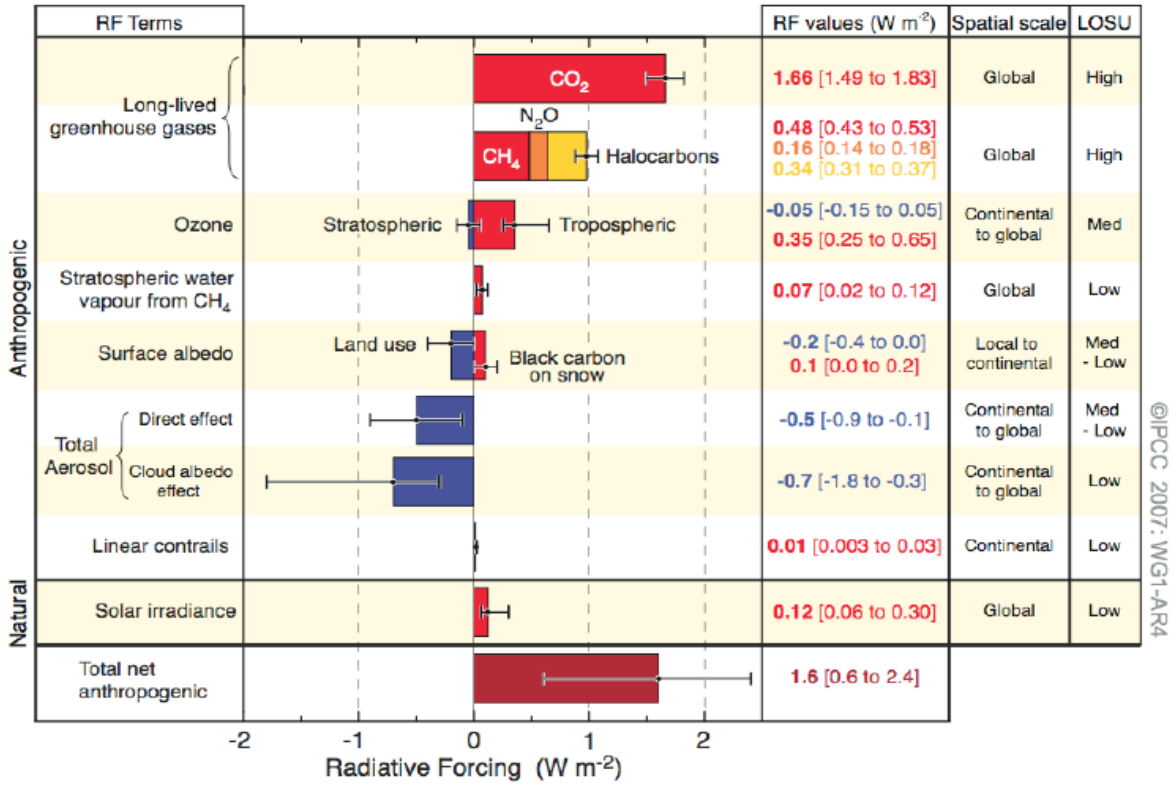

Fig. 1. Global-average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). (From IPCC, 2008). Note the high uncertainty of the aerosols and the contribution of tropospheric ozone.

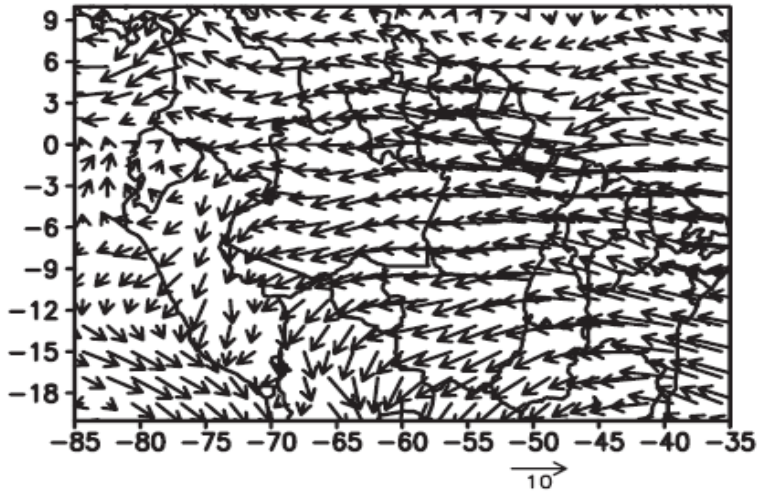

Fig. 2. Wind fields at 700 hPa of the global reanalysis from NCEP for a typical day with westward direction. Note prevailing wind from Brazil to Peru. (from Silva et al., 2002)

In this context, Amazon region also presents an intense activity for biomass burning, as part of land use change for agriculture purposes. This burning is present mainly in the dry

season (from May to October). This season also coincides with the lowest atmospheric capacity of pollutants remove because the minimum rains and with them a higher possibility that this pollutants could reach longer distances in the tropical region. In some intense periods, it is possible to identify dispersed pollution plumes along the Amazon basin, specially originating in the Brazilian region. The latter transport could input secondary pollutants and aerosols in Peruvian territory. This is done because the prevalent winds have a westward direction. (Figure 2). For that reason this work evaluates the pollution in western Amazon, with special focus on southern Peruvian Amazon. This evaluation has been done through a detailed identification of the the sources of air pollution related to the forests fires around Peru, both from ground and satellite measurements, and complemented by the determination of the trajectories of air masses coming from these air pollution sources.

This report summarize the findings and discussions about this aspect having three locations for monitoring: Oxapampa (TRAER-1), Mazamari (TRAER-2) and Manu (TRAER-3), covering the southern part of the Peruvian Amazon. Figure 3 shows the location of these sites in the Amazon and the international boundaries among Peru, Brazil and Bolivia. In these locations intensive monthly campaigns were performed for collecting aerosols (called **IN**tensive **C**ampaign for **A**erosol **S**ampling - INCAS). Also, cooperation was asked to NASA for the delivery of satellites data for detailed evaluation of temporal and spatial variation of air pollution in the region.

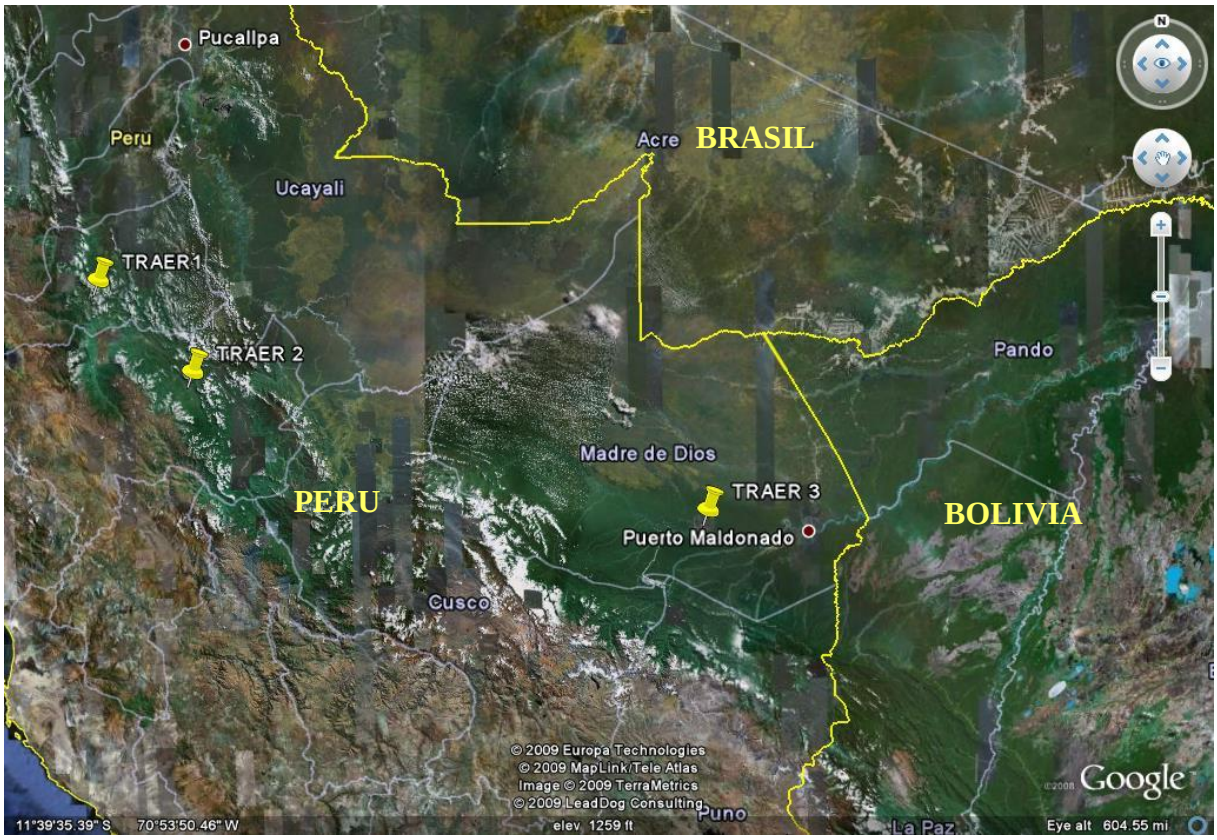

Fig. 3. The yellow pins indicate the geographical locations of the 3 sites used during this research project. Yellow lines also indicate international borders. Note the location of Brazil and Bolivia.

These three locations were implemented and prepared for specific monitoring dealing with aerosols chemical composition. Location at "TRAER1", the northern one, is

latitude 10°31'S and longitude 75°20'W, with an altitude of about 2,200 m.a.s.l., and it is located at the Yanachaga Chemillen Protected National Park. Mountainous cloud forests are the predominant ecosystem in this location where rain can reach more than 3000 mm per year and it has a mean temperature of 20ºC. Very low human activity is present in this location. A tower of about 40 meters height is used for sampling. Location at TRAER2 is 11°20'S and 74°31'W with an altitude of 640 m.a.s.l. The tower used for sampling is close to a small village and sparse secondary forests exists. It has an mean temperature of 25°C and rain of about 2,200 mm per year. The third location, TRAER3, is 12°33'S and 70°6'W with an altitude of 360 m.a.s.l., where a biological research station (Centro de Investigación y Capacitacion del Rio de Los Amigos, Madre de Dios, Peru), is located and it has fine facilities for research including a tower of 60 m height of altitude. It has a mean temperature of 27°C and rain of about 2000 mm per year. This site was used as an mining camp, during '80s, and was logged but now it is under recovery and primary and secondary forests are the dominant forest of the location. The region has very low population, but intense activity, because mining and logging purposes, is present. Also agriculture is a main activity so slash and burn is the most used method for changing land use from forest to crops. An additional treat in this region the build of the Interoceanic Road that crosses all the region from Brazil and goes to the coastal region.

III. MEASUREMENTS OF THE ELEMENTAL COMPOSITION OF AEROSOLS

Chemical composition of aerosols are key for understanding the sources of pollution, it could give us qualitative and quantitative information about the main factors of pollution in local and regional scale. Directly related to biomass burning, different research work have been done for determining the emission factors and the different compounds emitted during fires. Both have been evaluated field and lab work.

These evaluations suggested that the called black carbon (BC) is considered a tracer of combustion and the fine fraction of K is characteristic of biomass burning. Si and Ca showed a strong presence in the coarse size fraction where these species are related to crustal particles, and possibly were suspended in the air by the action of the wind and/or the strong convection generated by fires. Finally, for our results, the enrichment of K in the coarse fraction, suggests biogenic sources of K. This also could be supported for P (tracer of primary biogenic particles) in the coarse mode.

3.1. Methodology

Our work was based in collecting air samples for later chemical analysis. It was used a stacked filter unit (SFU) with two stages: in the first stage it was installed a filter with 8 um pore size for collecting coarse fraction of aerosol; and in the second stage it was installed a filter with 0.2 um pore size for the fine fraction of aerosol. It also has a 1/8 HP vacuum pump (Gast Co.), a flow meter and a digital timer. The sampling period was monthly with a flow velocity of 20 LPM and it covered close to 40 hours each sample. The sampling system was implemented at each location. If needed, an electrical generator was installed.

Pre-weighted filters of Nucleopore (Whatman co. Inc) and Teflon (Sartoriuous, Inc.) were used for the coarse and fine fraction, respectively. Each month 3 filters of each type were collected, fine and coarse fraction, respectively. At the end of the sampling both were attacked with HNO_3 and HCl for later analysis by the method of Inductively Coupled Plasma, that generates high energy intensity able to separate the elemental composition of aerosols.

At Oxapampa and Manu the system was installed above the canopy, with a height of 40 and 60 mts, respectively. At Mazamari, it was installed in the radio tower at about 40 m. In the next sections we present the results from Mazamari and Manu. At Oxapampa, did not find reasonable results, probably because pollution from using the electrical power generator

and oil fuel burning that produced pollutants that interfered with the sampling.

3.2. Results at Mazamari

Figure 4 shows the results obtained at Mazamari. The upper plot shows the results obtained for the coarse fraction of the aerosols and the lower plot shows results for the fine fraction. Results for the TRANSITION period is presented that are values registered for the months of Jun, July, and August, then the BURNING period is for September, October and November, when data is possible. The monthly value is the average of three measurements of consecutive days, each sample covering at least 40 hour.

From these results it is possible to see a moderate increase of Ca and P. A contrasting result, as expected, was obtained for P. As based on the literature there should be an increase of P related to biogenic origin and resulting from biomass burning during the "Burning period". Additional information is reviewed and discussions should be performed related to laboratory analysis that could be a bias for these values.

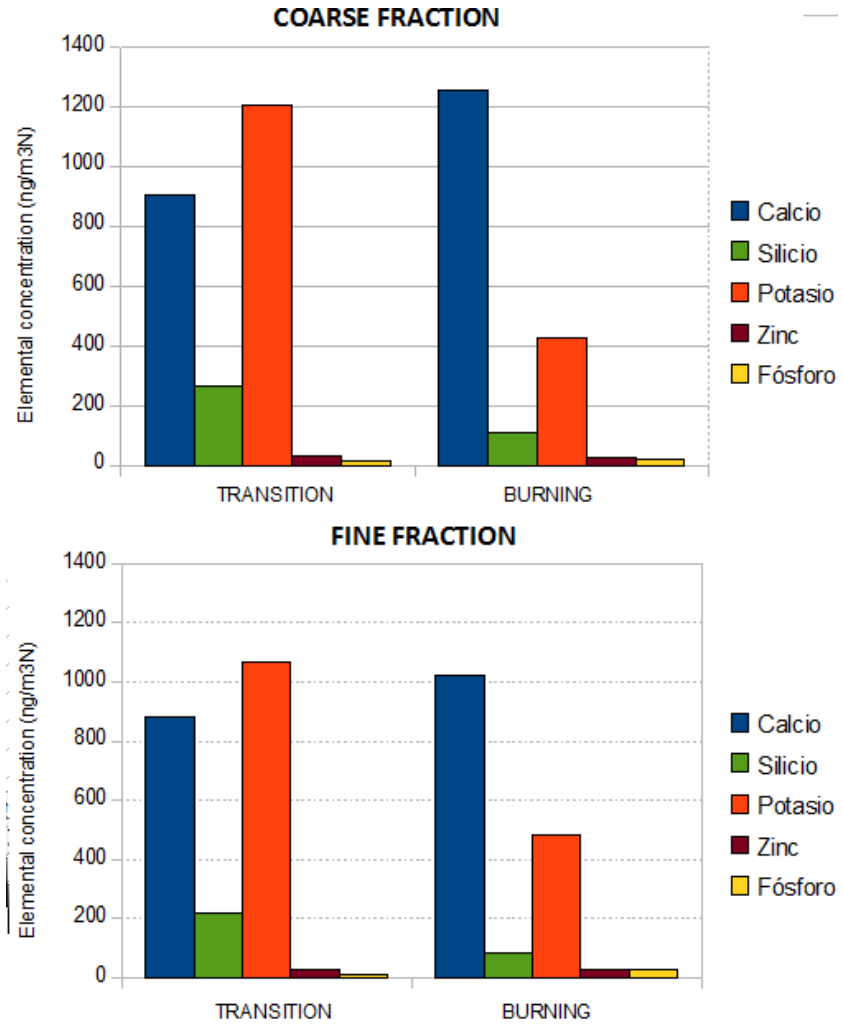

Fig. 4. Comparison of the results between transition (August and September) and burning (October and November) period for fine and coarse fraction of aerosols at Mazamari location in 2009.

3.3. Results at Manu

Figure 5 shows the results obtained at Manu location. Both fractions shows an important increase in Ca, K and P in more than 50% or more comparing the transition and

the burning period Higher values than Mazamari are obtained and this could be related to a higher influence of transboundary air pollution and local fire intensity. Specially during the last years there was an important increase of fires in northern part of Bolivia, common border with Peru and Brazil. On the other fires satellites showed a decrease in the Brazilian side. Anyway the presence of high amounts of K in both coarse and fine fraction, including an increase in the coarse fraction give us the possibility to address the biomass burning as the main modulator of pollution in this region of Peru. Complementary pollution is the appearance of P during the burning season, which could have a more sing related to strong convective emission during fire events. These increases of K and P could be higher than 50%. As additional information we should indicate that clouds of haze and smog were present. during the burning season.

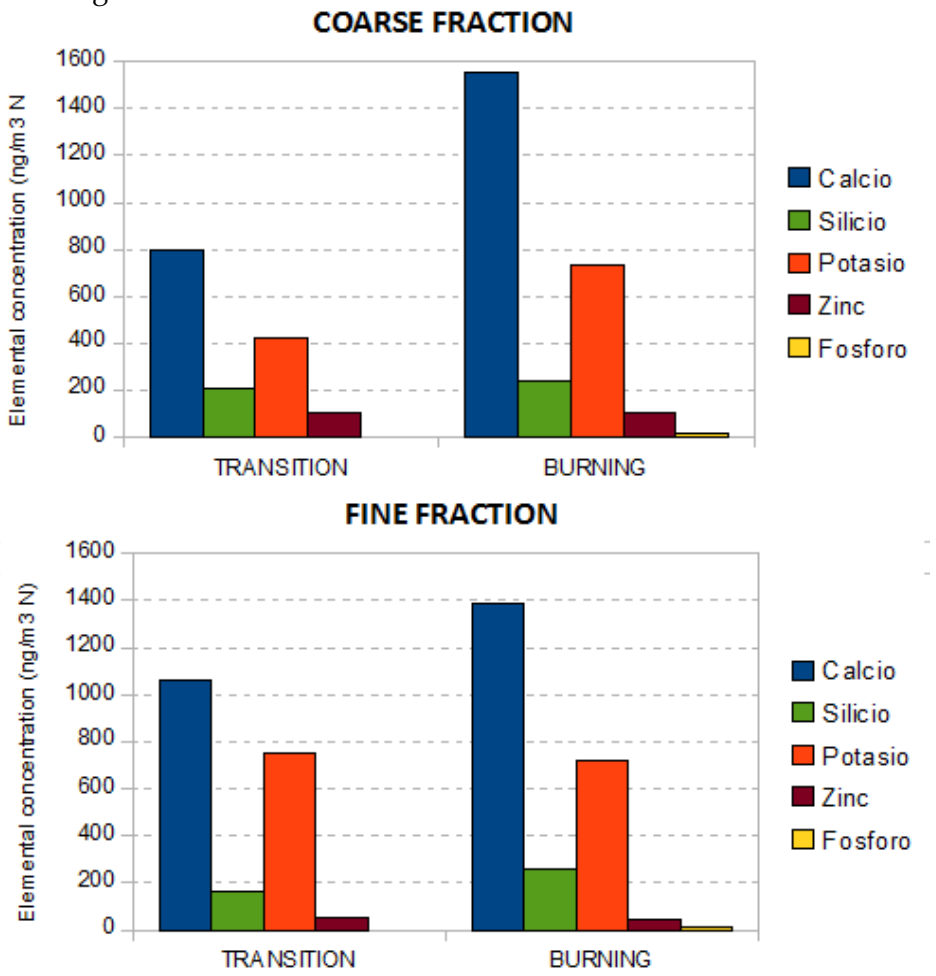

Fig. 5. Comparison of the results between transition (August and September) and burning (October and November) period for fine and coarse fraction of aerosols at Manu location in 2009

IV. SATELLITE MEASUREMENTS OF POLLUTION

During the last years important improvements have been done for the remote sensing monitoring of air pollutants. Effort were done by both USA and Europeans research groups have been involved in ambitious efforts for increasing capabilities and reducing uncertainties through exhaustive calibrations and intercomparisons of measurements. Special focus has been done to the measurement of aerosols and tropospheric ozone with the facility of the NASA satellites. These measurements give us a more spatial evaluation of our data and also let us to cover broad areas where in situ monitoring could be very difficult.

4.1. Methodology

This research project used mainly data from Ozone Monitoring Instrument (OMI) that is a nadir viewing imaging spectrograph that measures the solar radiation backscattered by the Earth's atmosphere and surface over the entire wavelength range from 270 to 500 nm with a spectral resolution of about 0.5 nm. This combination of wavelengths could be used to provide information of a high number of elements present in the atmosphere. It also has a very high spatial resolution (13 km × 24 km) and daily global coverage.

4.2. Results for aerosols

Figure 6 shows the results obtained for aerosols (reported by OMI team as aerosols index) at three locations of the research. the aerosols values are unitless. The data only consider the values from the second half part of the year, from day 183 to 366. The mean values are 0.54 (0.39), 0.50 (0.35) and 0.43 (0.38) for Oxapampa, Mazamari and Manu, respectively, indicating the standard deviation of each location in parenthesis. From there it is possible to note that Oxapampa has the highest values. The standard error for all locations is 3%. It will be needed an additional evaluation about the role of clouds in this value considering that Oxapampa site is located in a cloudy area and wetter area, where lower values were expected to be found. Finally, comparisons using Kruskal-Wallis test indicates us that there is a difference among our non-parametric data set. Evaluation using Wilcoxon test for non-parametric distribution showed that Manu aerosols data is the one different.

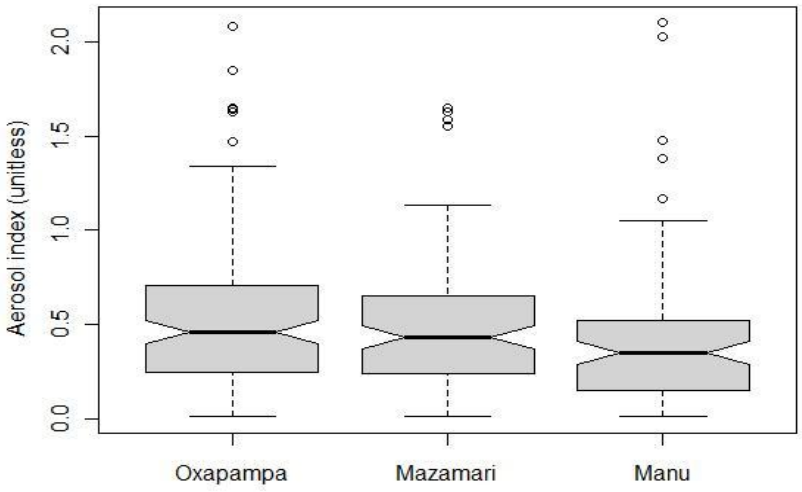

Fig. 6. Measurements of aerosol (as aerosol index) for the three locations done by the OMI satellite during second half of 2008.

4.3. Results for tropospheric ozone

Figure 7 shows the results for tropospheric ozone (reported by OMI team as ozone below the cloud). The units are in Dobson Units (1DU = 2.69×1016 ozone molecules per square centimeter). As above, the data here only considers the values from day 183 to 366 of 2008. The mean values are 3.41 (2.39), 2.99 (2.45) and 3.16 (2.83) for Oxapampa, Mazamari and Manu, respectively. The statistical evaluation with the Kruskal Wallis test did not show any significant difference among the locations. As evaluating the data is possible to note that special attention should be paid to the cloud fraction during days with high values of tropospheric ozone. Further discussion should be done on the interference of clouds on ozone measurements.

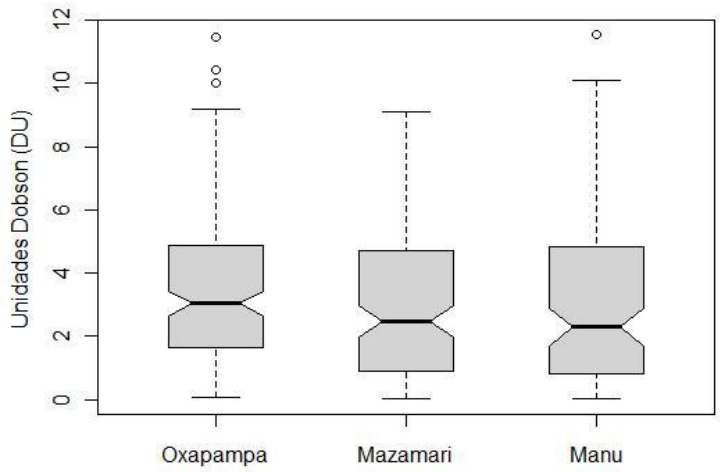

Fig. 7. Measurements of aerosol (as aerosol index) for the three locations done by the OMI satellite during the second half of 2008.

V. AEROSOLS MEASUREMENTS: MODIS AND CALIPSO INSTRUMENTS

Another important remote sensing tool for evaluating air pollution is the data obtained by MODIS sensor (Moderate Resolution Imaging Spectroradiometer) that has an special focus in aerosols and clouds. MODIS is viewing the entire Earth's surface every 1 to 2 days, acquiring data in 36 groups of wavelengths. These data will improve our understanding of global dynamics and processes occurring on the land, in the oceans, and in the lower atmosphere.

Complementary information was taken from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite that provides new insight into the role that clouds and atmospheric aerosols (airborne particles) play in regulating Earth's weather, climate, and air quality.

5.1. Methodology

The MODIS instrument provides high radiometric sensitivity (12 bit) in 36 spectral bands ranging in wavelength from 0.4 μm to 14.4 μm. It provides detailed information about aerosols where the main variable used in this study is Aerosol Optical Depth (AOD) at 550 nm. AOD is a quantitative measure of the extinction of solar radiation by aerosol scattering and absorption between the point of observation and the top of the atmosphere. It is a measure of the integrated columnar aerosol load and the single most important parameter for evaluating direct radiative forcing. MODIS was launched on May 4, 2002. On the other hand, for evaluating aerosol properties CALIPSO combines an active lidar instrument with passive infrared and visible images to probe the vertical structure and properties of thin clouds and aerosols over the globe. CALIPSO was launched on April 28, 2006 with the cloud profiling radar system on the CloudSat satellite.

Figure 8 shows the spatial variation of AOD during the burning period over the Amazon basin. It is possible to note that there is an important influence all over the region related to a source in the middle of Amazonia of Brazil. This source promotes changes along all the latitude mainly Bolivia and with a smaller influence in the southern Amazon of Peru. During 2004 there was a more intense modification of this feature. Higher values of AOD for the region of study are registered in mid-September and mid-October.

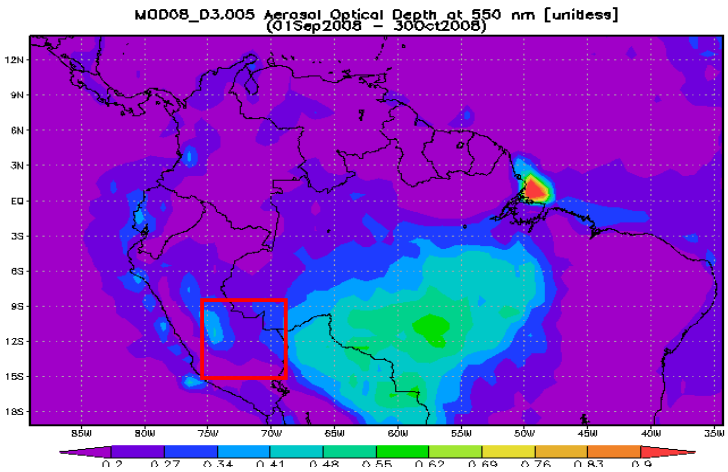

Fig. 8. Spatial variation in 2009 for the Amazon basin covering the entire study of area of this research (indicated by the red square).

Another important tool is the use of additional instruments, like CALIPSO in oder to have more information of the aerosol concentration. For example there is a need to know the vertical distribution of aerosol, and to understand the distribution of aerosol along the atmosphere. This could give us more details about the effects of local pollution but separating the components: lower (troposphere) and upper atmosphere (stratosphere). In that sense, Figure 9 represents our first attempt to evaluate this aspect over the study area using CALIPSO data. We present the results at wavelength of 532 total (perpendicular and parallel) attenuated backscatter that has a vertical resolution of about 120 m. It also shows the measurements on September 17th during the pass over our study area, and when it was recorded the highest value of AOD by MODIS instrument. It is possible to see, indicated by the red arrow, that there is mixture of clouds (white and gray colors) and aerosols (yellow and green colors).

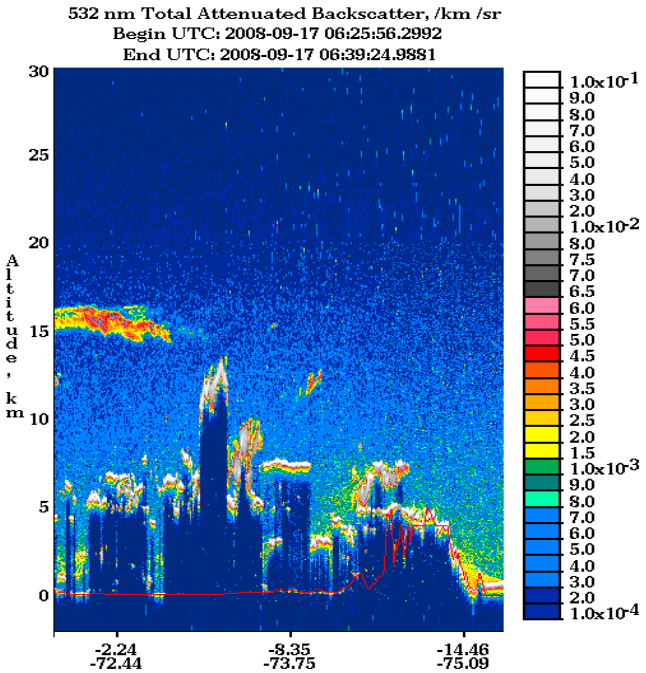

Fig. 9. Vertical variation of light dispersion in the atmosphere related to different elements (mainly low and high cloud and aerosols). The red arrow indicates pass over the study area during September 17th 2008, the day that has the highest value for AOD of MODIS (0,741).

CALIPSO is a recent instrument but we consider that it could provide high quality information about role of aerosols and the transport of them along the atmosphere in the Amazon region. There is a need to increase our knowledge about the use of this data and its final products for going in a deep understanding of the aerosols during the burning season. In addition to other satellites like MODIS and complementary measurements it could provide us a detailed and unique evaluation of physical and chemical properties of aerosols in the atmosphere during the burning season of the Amazon basin.

VI. EVALUATION OF AIR MASSES TRAJECTORIES

An effective evaluation of the transport of air masses will provide us with enough information to know about the origin and sources of pollution reaching our locations. This could be inferred from continuous meteorological data or archived information that provides the climatology of winds. In this research we used information of HYSPLIT from Air Resources Lab of NOAA that provides good capabilities for evaluating air masses.

6.1. Methodology

For this part of the project we evaluated data from Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) Model that has as main basis the use of NCEP Renalysis information for the meteorological components. The movement of air parcels is based on lagrangian transport modeling and it has the possibility of forecasting too.

6.2. Results for the study locations

In figure 10 we present the backward evaluation of air masses reaching the locations (Oxapampa at latitude 10ºS, Mazamari at 11ºS and Manu at 12ºS) of this study. The trajectories are for the last five days before September 17th. In this period, the highest AOD of 2008 was registered. It is possible to note that the trajectories all are coming from the Bolivian and Brazilian region, where the highest fire numbers are present every year. It is very clear the origin also evaluation the altitude variation of the transport of these air masses indicated below the map. It also states that air masses could collect pollutants produced in the lower parts of the atmosphere and raise these pollutants to higher altitudes or farther locations.

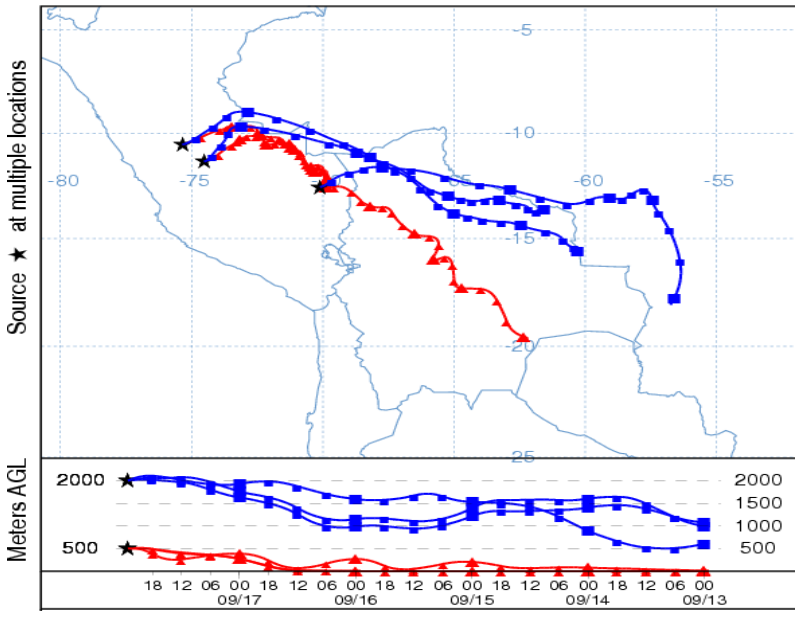

Fig. 10. Air masses trajectories for 5 days before Sep. 17th for the 3 locations used in the study. Lower box shows the variation of altitude of these masses.

VII. FOREST FIRES DETECTION

The use of satellites also could be oriented to detection of "hot pixels" for detection of the fire in the Amazon basin. Special attention was done by the group leaded by Dr. Alberto Setzer of the National Institute for Space Research (INPE) of Brazil who has been covering all South America with the detection system.
During the last years the results suggested an slight decrease of fires in the region, specially for 2005 and 2006, but then in 2007 and 2008 the high values were present. Bolivia and Brazil are the most active regions for forest and savannas types fires. Peru also has its own problems with deforestation, slash and burn agriculture. Logging does not have moderate or high values of fire pixels as we compare with the neighboring countries.

7.1. Methodology

Satellite information in the infrared region, i.e., satellites with optical sensors operating in the region of 4um, is used for estimating the fire activities of the detected pixels. Only satellites performing measurements during the nigh time were used. Therefore, we included only the next satellites: NOAA 12, NOAA 14 and NOAA 15. The collected data is from January 2000. INPE indicates that a fire of about 30 m of length and 1 m wide could be detected.

7.2. Results for the countries involved in the study

Figure 11 shows the strong seasonal variation of forest fires at the countries involved in this study: Peru, Brazil and Bolivia. It should be noted the logarithmic scale of Y axis in order to distinguish clearer the different high amounts of fire pixels at each territory. In this comparison it is not possible to consider a severe problems of fires over the Peruvian territory, around 500 or maximum 1000 fire pixels compared to Bolivia with 10 fold times those values and Brazil about 100 fold times those values. It also should be a strong evidence about the role of forest fires produced in Brazil, and maybe Bolivia, to modify air quality (in this study only was evaluated the modification of aerosols and tropospheric ozone) of the entire region, including Andean and Amazon region of Peru (see figure 8). As in the case of September 17th 2008, and noted in Figure 10, in some cases the air masses can proceed from both locations to the Peruvian territory modifying severely the aerosol (and pollutants) content.

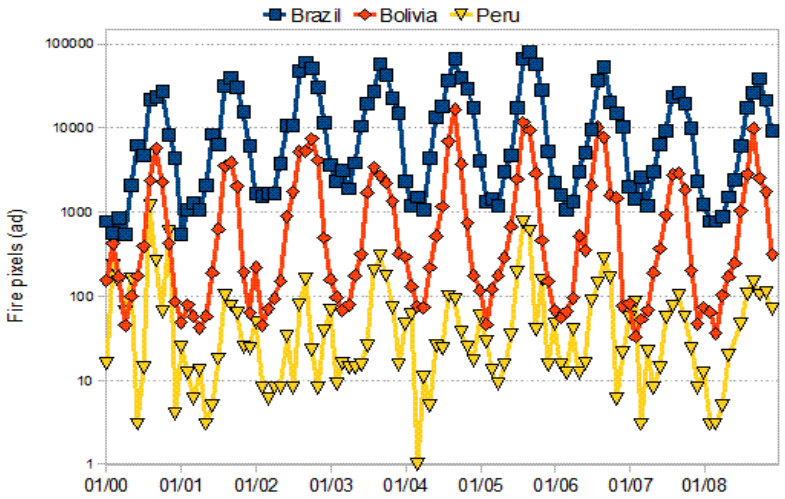

Fig. 11. Monthly variation of fire pixels in the Amazon basin covering Peru. Brazil and Bolivia from 2000. Note the logarithmic scale of Y axis.

VIII. ACKNOWLEDGEMENTS
To NGO Amazon Conservation for funding and facilities at Los Amigos Research Station. To National Geographic Society and Rufford Small Grants Foundation for additional funding to complete the fieldwork campaigns. To Damien Catchpole for tower facilities during sampling at Oxapampa. To Municipality of Mazamari for facilities for using its tower. To NASA/OMI team for making data available for the studied locations. To Enma Cortez of ITESM for helping during introductory meeting and supervision.

IX. CONCLUSIONS

- It was possible to detect the seasonal variation of aerosol and tropospheric ozone over the Amazon basin of Peru, Bolivia and Peru.
- It was completed the in-situ monitoring at three sites of the Peruvian Amazon (western Amazon) where it was possible to note the different chemical composition during burning season. This modification was detected both fine and coarse fractions of aerosols.
- There is a strong modification of elemental concentration mainly related to biomass burning tracers like P and K, and also related to crustal Ca and Si. There were contrasting results but increases of P and K of about 50% were detected.
- It was possible to note the increase in the second part of the year (from day 183 to 366 of 2008) of measurements of aerosol (named aerosol index) and tropospheric ozone (named ozone below cloud) where Oxapampa location presented the highest mean values.
- It was complemented the measurements with other satellites that could provide a deeper understanding of the aerosol content in the atmosphere: MODIS and CALIPSO. It was possible to detect the seasonal variation and peak days with high values of aerosols. Further improvements will be needed to take maximum advantage of this data and also make corrections due to clouds interferences.
- MODIS detected during September 17th 2008, the day with the highest value for Aerosol Optical Depth of MODIS (0,741).
- Evaluations of the air masses trajectories were performed using HYSPLIT in order to gain knowledge about the sources and origin of the pollution content. Results shows that for some days air masses are transported from Brasil and Bolivia and Peru modifying severely its air quality.
- The high number of fires over the region are mainly in Bolivia and Brazil. These fires can modify the entire region.

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