6.2. MEASURING AND MONITORING THE MESOCLIMATE OF TROPICAL LOCATIONS. FIELD OBSERVATIONS FROM THE SOUTH AMERICAN ALTIPLANO DURING THE SALLJEX.

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1. ABSTRACT

Most regions of the tropics are poorly sampled by conventional meteorological measurements. Thus, direct inferences of the mesoscale climatology of many tropical locations is difficult, especially those in mountainous areas. Similarly, explaining the atmospheric dynamics associated with the observed mesoclimatology is likewise not simple. One such region with a poorly understood mesoclimatology is the altiplano region of South America. This region includes two very large features that affect the mesoclimatology: Lake Titicaca (~140 km long) and a similarly large dry lake or salt flat, the Salar de Uyuni.

An enhanced upper-air network, involving mostly pilot balloon stations, was established near and over the Altiplano of Peru and Bolivia as part of the South American Low Level Jet Experiment (SALLJEX) held during the rainy season of 2002-2003. In addition, a network of about 200 simple raingauges was installed across the Peruvian Altiplano. The motivation for these activities was to investigate the relationship between rainfall, synoptic-scale circulations and local topographic effects. The region is characterized by complex terrain and the rainfall shows large spatial gradients and a strong diurnal cycle.

This talk will describe the observing networks and the analysis of the raingauge and pilot balloon data. The structure and importance of the Lake Titicaca and Salar de Uyuni breezes in modulating the rainfall will be described from both observations and simulations using the WRF model. Implications for developing observing networks to diagnose the mesoscale climate in poorly sampled regions of the tropics and extratropics will be described.

An extended version of the present study has been made available at: **http://www.nssl.noaa.gov/projects/pacs/web/ALTIPLANO/NF/** .

2. INTRODUCTION

The South American Altiplano is an elevated plateau (~ 3700 m ASL) and also a closed basin located in the Central Andes between 14°S and 22°S. It is surrounded by the Amazon Rainforest to the east and northeast, by the Chaco to the southeast and by the Atacama Desert to the west. Many lakes and dry salt flats (so called “salares”) shape the landscape. The two largest features, in which this talk will focus, are Lake Titicaca and Salar de Uyuni.

Unfortunately, as most of the regions located in the tropics and subtropics, the meteorological networks that operate continuously in this part of South America are sparse and encounter numerous problems that affect the quality of the information collected. Furthermore, the complex terrain and diverse land-surface scenarios that characterize the Altiplano are responsible for several distinct mesoscale circulations and sharp climatological rainfall

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gradients that cannot be described with the temporal and spatial density of the conventional meteorological measurements.

Interested on describing the low-level moisture transport in the poorly sampled lowlands east of the Andes, the South American Low Level Jet Experiment (SALLJEX) was programmed for the rainy season of 2002-2003. The primary goal of the experiment was to investigate the variability of the low level jet in the lowlands of Central South America, which plays a key role on the transport of moisture from the tropics into the extratropics. The SALLJEX strategy was to temporarily increment the temporal and spatial density of the meteorological measurements in Central South America through an enhanced raingauge and sounding network (Figure 1), and through soundings using the NOAA P-3 Research Aircraft. The region in South America where the existing networks were enhanced covered sectors of Peru, Brazil, Bolivia, Paraguay, and Argentina.

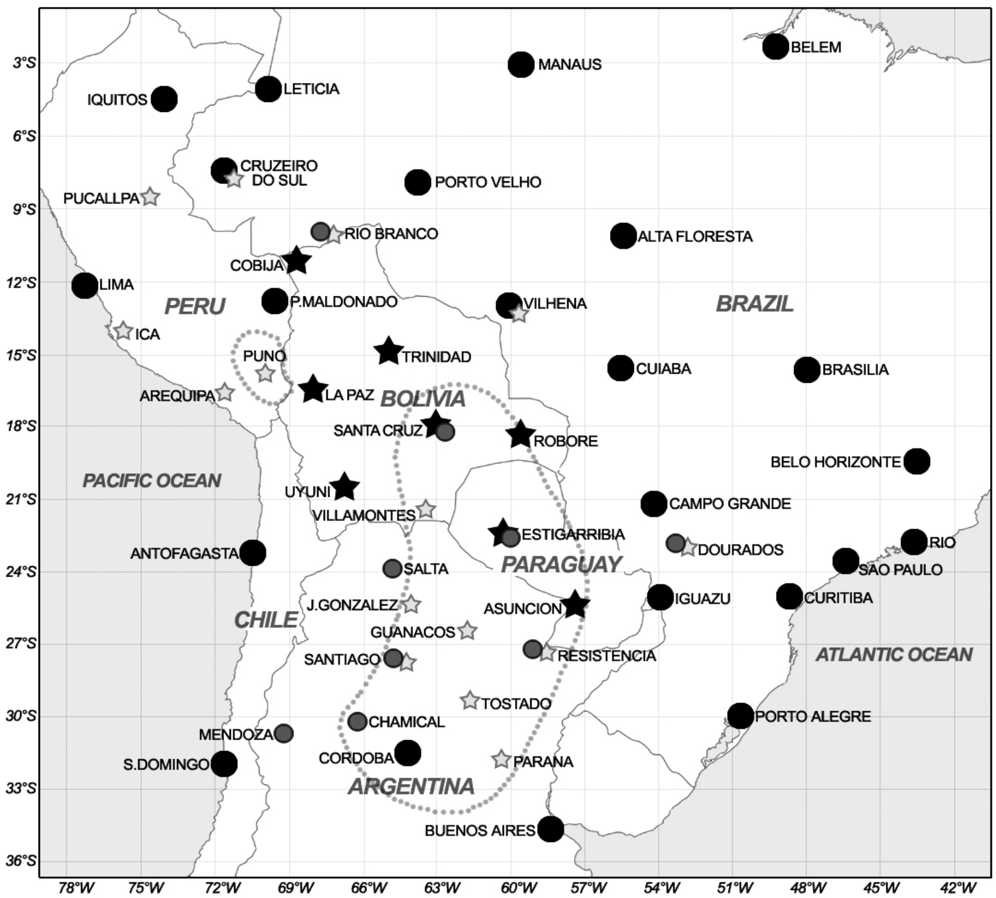

Figure 1. SALLJEX enhanced networks that operated during the Special Observations Period (SOP). The large black circles represent the operational radiosonde stations before the SALLJEX; the black stars the operational PACS-SONET pilot balloon stations before the SALLJEX; the small lighter circles represent the temporary SALLJEX radiosonde stations and the small light stars represent the temporary SALLJEX pilot balloon stations. The dotted line represents the regions where the enhanced raingauge networks were installed and successfully collected after the campaign. The Altiplano network included 116 raingauges and the SALLJEX main raingauge network included about 1000 raingauges. The research flights carried out by the NOAA-P3 Aircraft, not indicated in the figure, covered eastern Bolivia, Paraguay and northern Argentina.

The large number of observations scheduled for the SALLJEX served as a motivation to study the mesoclimatology of the Altiplano. This was done by installing a temporary daily-measuring simple raingauge network and through two short field experiments based mainly on pilot balloon soundings and surface observations.

3. SCIENTIFIC GOALS

The overall main goal was to study the mesoclimatology of the Altiplano by investigating the relationship between rainfall, synoptic-scale circulations and local effects, in particular the role of the breezes induced by Lake Titicaca and Salar de Uyuni in modulating the precipitation.

The specific scientific goals that motivated the Altiplano studies resume to:

1) Measure the diurnal variability of the horizontal and vertical motion fields near Lake Titicaca and Salar de Uyuni during the warm season.

2) Measure the diurnal variations of certain surface properties such as temperature, wind and albedo in the same region and during the same period of time.

3) Map the precipitation fields during the warm season with higher spatial density over selected sub-regions and relate them to the motion fields.

4) Describe the diurnal variations of cloudiness and relate them to the motion and rainfall fields.

5) Compare satellite-estimated cloudiness fields with rainfall measurements.

4. BACKGROUND

Several studies have been carried out in the past regarding the climate of Central South America, and some of them have been centered in the Altiplano.

Fuenzalida and Rutllant (1987) concluded that the water vapor that precipitates over the Altiplano originates in the troposphere to the east of the central Andes from where is it transported by easterly flow. Garreaud (2000) confirmed this relationship. He mentioned that mean easterly flow in the middle and upper troposphere favors the moisture transport from the interior of the continent toward the central Andes. He also indicated that moisture and rainfall variability over the Altiplano is strongly dependent on the intensity of the moisture transport over the eastern slope of the Andes rather than the precise low-level conditions on the central part of the continent.

Precipitation over the Altiplano exhibits a pronounced annual cycle, with more than 70% of the rain concentrated in the austral summer (Aceituno and Montesinos, 1993). During this season an upper level anticyclone is established to the southeast of the central Andes, and means easterly flow prevails over the Altiplano (Garreaud, 2000). The rainy season is longer in the northern Altiplano, where periods of easterly flow start as early as October and end as late as April. In the southern Altiplano, however, these periods are less frequent and constrained to the months of December through March.

Vertical moisture flux convergence due to the local orography is the leading mechanism governing the precipitation over the Altiplano (Lenters and Cook, 1995). This mechanism leads to deep moist convection during some afternoons. The occurrence of deep, moist convection is largely controlled by the availability of water vapor in the local boundary layer (Garreaud, 2000). Furthermore, Garreud found that the daytime lower troposphere is on the average conditionally unstable over the western Altiplano. The instability, however, can only be released in days in which the near-surface mixing ratio reaches high values (~7 g Kg^{-1}) yielding near-surface air parcels positively buoyant at about 400 m above the ground (Garreaud, 2000). This explains why the storms develop only during particular days when, on the other hand, the mesoscale low-level circulations and associated convergence are present on a daily basis.

Regarding the formation of lake-effect storms, prior studies in the Great Lakes have indicated that strong surface heat fluxes appear to have a major role in the formation development of mesoscale vortices over lakes in the absence of any synoptic scale dynamic forcing (Pease, 1988).

Forbes and Merritt (1984) found that mesoscale cloud vortices were associated to convergence over the lake due to land-breeze circulations. They also indicated that during vortex generation days the temperature of the lake was warmer than the temperature of the land suggesting the importance of diabatic heating in this process.

Passarelli and Braham (1981) strongly suggested that differential surface heating fluxes and resulting land breezes played a major role in the organization of the low level convection in lake effect storms. They also found that under stable conditions in the lowest layers of the atmosphere convective clouds might still form but their development would not be deep enough as to produce significant precipitation.

Lavoie (1972) found that heating coming from Lake Erie's surface was the primary factor for the generation of a convective disturbance in his model.

Gross and Estoque (1978) concluded that upward mixing of heat and moisture from the surface of Lake Ontario was the dominant physical process involved in the generation of lake-effect disturbances. He described this process as one in which intense warming and moistening of the mixed layer over the lake set up a surface pressure trough. This pressure gradient induced low-level convergence, and vertical fluxes of heat and moisture result in condensation and further latent heat release.

5. ALTIPLANO OBSERVING NETWORKS

The Altiplano observing networks consisted on a simple 200-station raingauge network and two short field experiments based mainly on 5 to 7 pilot balloon station networks that were operated during periods from 5 to 7 days. The part of the SALLJEX budget designated for the Altiplano activities approximated to a relatively low-priced USD 8000.00. This amount covered the purchase and shipping of the materials, the cost of the gas used to inflate the balloons, the entire installation and collection campaigns, and both the transportation and meals for the participants. Other minor but many details regarding the logistics were covered using this sum.

Raingauge Network

The raingauge network was installed in late October 2002 with the purpose of measuring the precipitation fields during the warm season with a higher resolution than the one of the operational networks. It covered sectors of Peru and Bolivia, with higher resolutions near Lake Titicaca and the Salar de Uyuni. The collection campaign was carried out in early June 2003, and a number of raingauges were left since some observers were interested in keeping collecting the data. The Peruvian side of the network was successfully collected and made available by local authorities and personnel from the National Weather Service (SENAMHI) as well as from the Instituto Geofísico del Perú (IGP). The Bolivian component of the network, in contrast, was not made available due to internal problems between local individuals in charge of the logistics.

Initially, the Peruvian side of the network included almost 200 raingauges distributed among an area of 50000 km^2. From these raingauges, 153 were successfully installed and 116 successfully

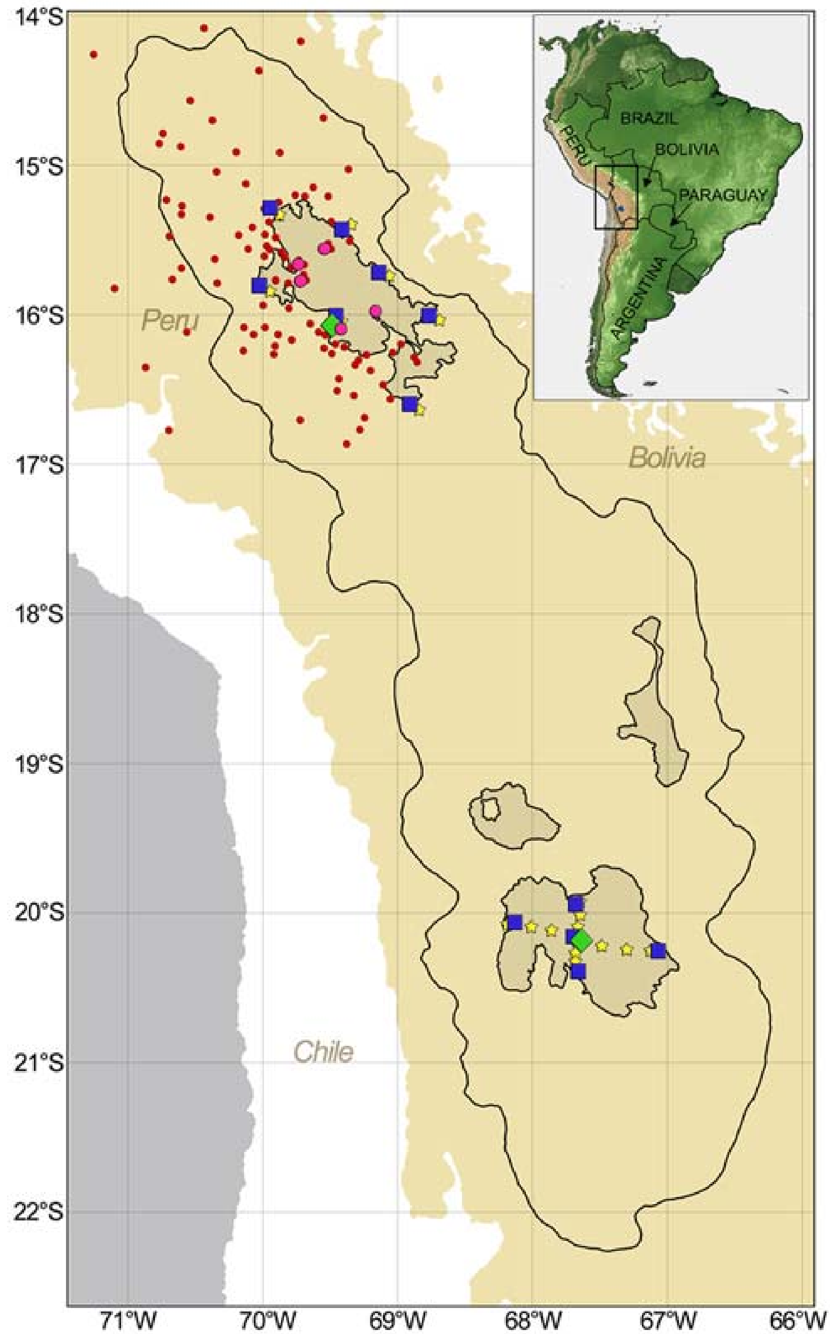

Figure 2. Enhanced networks that operated in the Altiplano during the SALLJEX. The Altiplano basin is indicated with a solid black line. From north to south, Lake Titicaca, Lake Poopó, Salar de Coipasa and Salar de Uyuni are indicated with solid black lines and shaded in gray. The terrain higher than 3000 m ASL is shaded in light brown. The 98-data point raingauge network available after quality control procedures is indicated with small red dots. The five digital raingauges installed in Lake Titicaca are indicated with large pink circles. The pilot balloon stations operated during the Titicaca and Uyuni Experiments are indicated with blue squares. The tetheredsonde and radiosonde stations are indicated with green diamonds. The yellow stars indicate temperature measurements.

collected after the SALLJEX. The data from an additional 50 stations from SENAMHI were made available, adding to a total of 166 data points. After quality control procedures a final network of 98 data points was selected for the analyses (figure 2).

The daily-measuring raingauges utilized for the Altiplano network consisted on about 200 simple 4.4 USD transparent plastic raingauges (figure 3). The installation of the raingauge network was carried out by 2 separate teams at an approximate rate of 7 raingauges per day. It was a challenge given the rural nature of the Altiplano, and the different dialects found in certain locations. The procedure followed per gauge was (1) find a voluntary observer; (2) install the raingauge; and (3) train the observer using a detailed graphic manual, which included the forms to write down the rainfall observations.

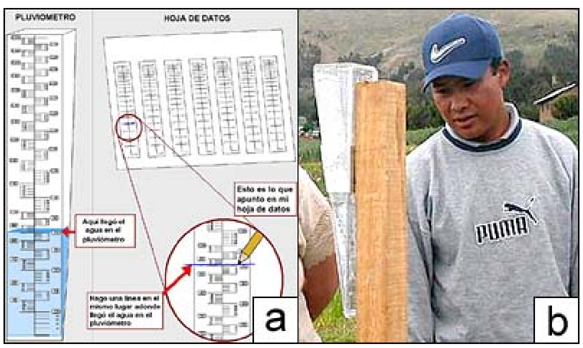

Figure 3. The left panel (a) displays part of the raingauge operation manual handed to the voluntary observers during the installation campaign. The right panel (b) shows a picture of an observer from Conima, Peru being trained about how to operate the raingauge.

The Salar de Uyuni Field Experiment

The Salar de Uyuni Field Experiment was carried out the last week of November 2003, during the first stages of the SALLJEX Field Campaign. The main goal of the experiment was to measure the salar-induced breezes and relate them to the rainfall variability over and around the salar. Unfortunately the rainfall data was not made available, but we could collect the scheduled wind observations successfully as well as some of the measured surface data.

The experiment consisted 5 days of regular observations with a higher frequency during the day than during the night. The network (figure 2) included 5 pilot balloon stations, a tetheredsonde lifted with a mechanical winch designed using a bicycle (figure 4), a network of 8 maximum and minimum thermometers installed among the salar, and temperature readings at 25, 40 and 100 cm over the ground. Additional measurements of solar radiation were made on the central site.

The pilot balloon observations were made using optical theodolites and therefore reading the elevation and azimuth angles of the balloon with respect to the theodolite. The angles were read every 30 seconds during the first 8 minutes and every minute afterwards. The maximum duration of the sounding was set to 1 hour. The sounding frequency was scheduled hourly during the day and every three hours during the night with the aid of special lights to follow the balloons.

Tetheredsonde observations were made only during the mornings since strong low-level winds caused problems every afternoon and evening. The lenticular shaped of balloon used initially (figure 3) could not be raised far away from the surface due to its limited buoyancy. We discovered that even though the zeppelin-type balloon appeared to be more sensitive to strong wind conditions, it could attain more buoyancy and therefore allow for deeper soundings. The zeppelin-type balloon has been our choice for all the experiments carried out after the Salar de Uyuni Experiment.

Temperature, surface wind direction, and sky observations were also made every 15 minutes during both day and night. The maximum and minimum temperature thermometers were installed along the salar.

The Lake Titicaca Field Experiment

The Lake Titicaca Field Experiment was carried out the first week of January 2003 with the purpose of measuring the lake-induced circulations and to investigate their characteristics as well as their relationship with rainfall in the area. The experiment lasted 7 days with continuous observations at 7 locations around the lake. Fortunately, rainfall observations are available for this period, even though the synoptic conditions induced a dry spell during most of the experiment and the rainfall amounts measured were relatively low.

Figure 4. Lenticular-shaped tethered balloon and the mechanical winch used first during the Salar de Uyuni Experiment and then during the Lake Titicaca Experiment. The mechanical winch was constructed by John Mejía using a bicycle.

The material utilized for the field campaign included 7 optical theodolites and tripods, 1 zeppelin-type tethered balloon, a mechanical winch, radiosondes, 5 digital raingauges, two cameras for cloud photography and about 12 digital thermometers among other materials.

The pilot balloon sounding schedule was similar to the Salar de Uyuni Experiment one. The nighttime observations were more successful than the ones made during the Uyuni experiment since the winds were weaker. Temperature, surface wind direction and sky observations were also made every 15 minutes. A network of 5 digital raingauges was installed on the islands near the center of the lake but unfortunately the data has not been made available yet.

Problems with the radiosonde system and the loss of one of the tethered balloons affected the quality and frequency of the thermodynamic soundings. Additional problems encountered before and during the experiment arose from the fact that the installation campaign was scheduled too close to the New Year's holiday. Many entities were closed for vacations most of the time, which particularly complicated the transport of the equipment from Bolivia to Peru, since the material was stored in El Alto, Bolivia. This lead to delays on the wind observations in Taraco and Conima, the two stations located the furthest from the Bolivian border.

6. ANALYSIS AND RESULTS

Rainfall Data

After the collection campaign, data from 166 sites was available. 50 of these stations were conventional meteorological raingauges operated by SENAMHI-Peru made available for the SALLJEX. 20 of the SALLJEX raingauges were installed in SENAMHI stations for comparison.

The quality control procedures applied to the data set included an initial selection based on comparisons between the SALLJEX and the SENAMHI stations, a secondary selection based on a correlation matrix constructed using the 166 stations, and a final selection in which some of the stations that were located too close too each other were removed based on their

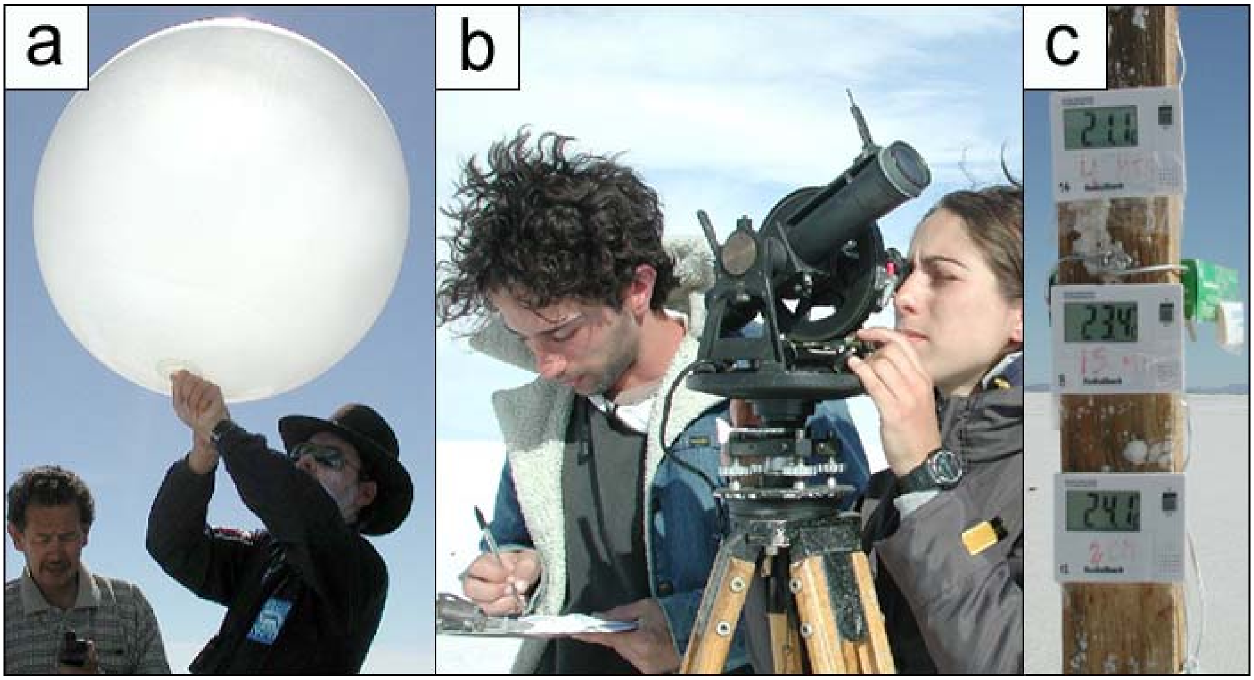

Figure 5. 30-gram pilot balloons utilized during the field experiments (a). Students using an optical theodolite to follow a balloon (b). Set of 3 thermometers used in each site to measure the temperature at .25, 1.5 and 4.0 m AGL every 15 minutes during the Salar de Uyuni Experiment (c).

correlations with nearby sites. This led to a total of 98 raingauges used for the analysis.

The results confirmed that the largest rainfall totals occur in the islands to the northeast of Lake Titicaca extending to the northeastern shore of the lake. This area of high rainfall can be associated to nocturnal low-level convergence (figure 6) since lake-induced divergence and associated cloud free skies dominate the region during most of the day. The rainfall field over the central lake and eastern shore, however, was not resolved due to the lack of islands and the lack of data in the Bolivian side.

The rest of the features recognized on the high-density rainfall analysis can be associated to afternoon and evening convection. These include (a) a region of low rainfall (less than 350 mm) extending just west and along the northeastern Altiplano mountain range associated to down slope easterly flow; (b) a region of large rainfall (larger than 550 mm) in the western side of the domain associated to low-level convergence induced by the orography; (c) a region of low rainfall (less than 250 mm) located to the southwest of Lake Titicaca, associated to low-level divergence from the upslope flow.

In order to describe and select the lake-effect storm events the stations were initially separated into lake stations and land stations. The lake stations were those located at 5 km from the lakeshore at the most, and that recorded a 3-month total of at least 400 mm. The land stations were those located within at least 20 km away from the lakeshore and within the Altiplano basin.

The rainfall time series averaged over all the stations (figure 7) showed rainfall rates as high as 14 mm.day^{-1} during the rainiest days. The rainfall averaged over the lake stations reached rates as high as 37 mm.day^{-1}. Most of the rain fell from late October through early April in the form of wet spells of 5 to 20 days long interrupted by dry spells that lasted 5 to 10 days.

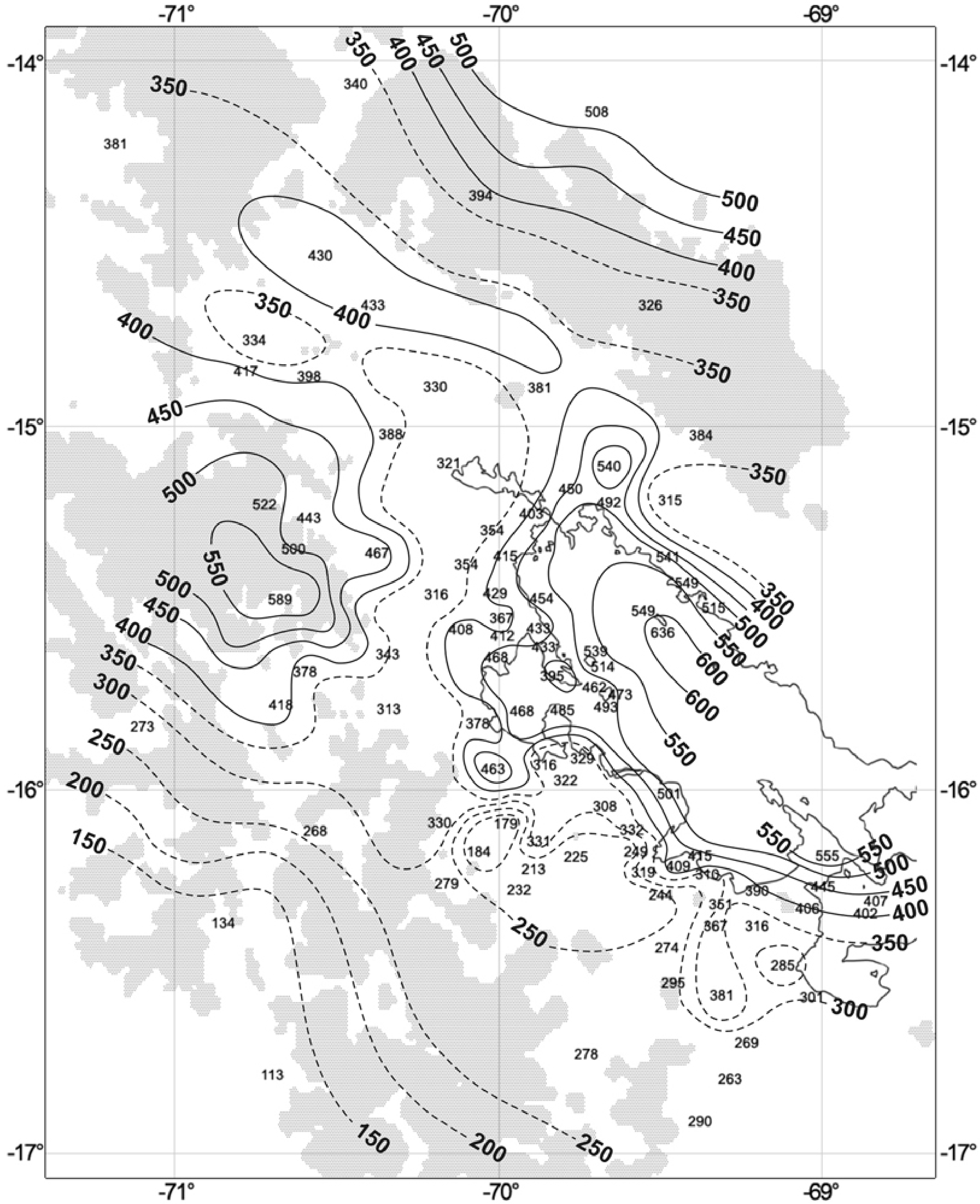

Figure 6. Rainfall collected by the SALLJEX Altiplano Enhanced Raingauge Network from December 1, 2002 though February 28, 2003. Lake Titicaca is indicated with a solid line and shaded in very light gray. The terrain above 4500 m ASL is also shaded in very light gray.

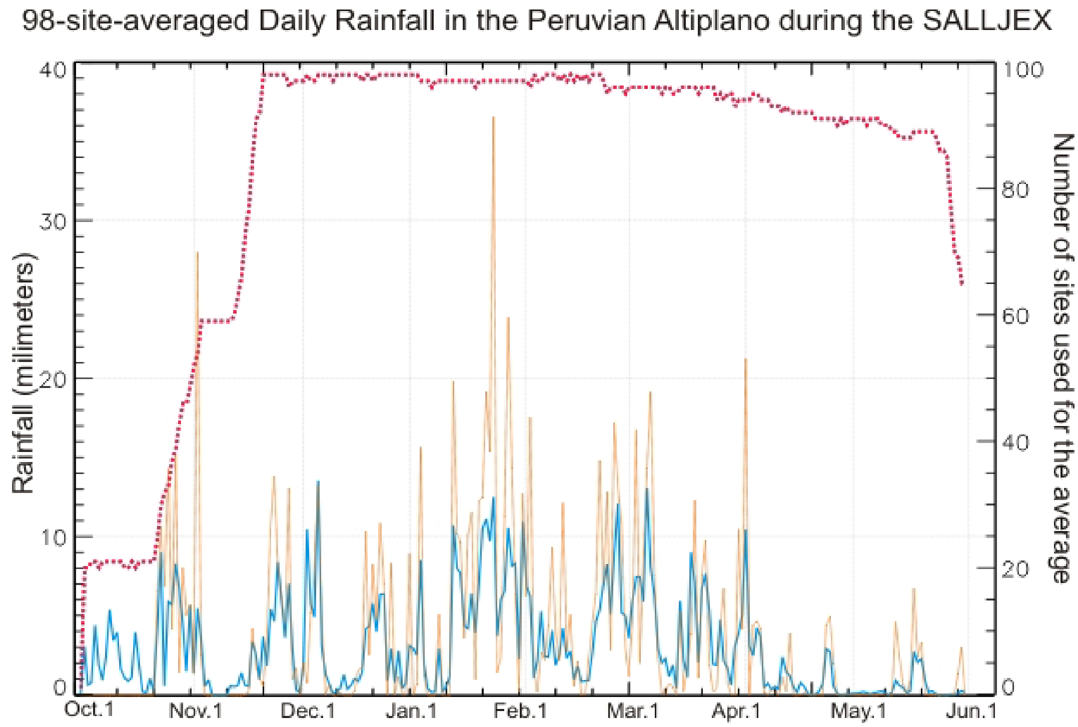

Figure 7. Timeseries of the rainfall averaged over the 98 selected sites (blue line) and over the lake stations (orange line) in mm.day^{-1}. The dotted red line indicates the number of stations used to calculate the average.

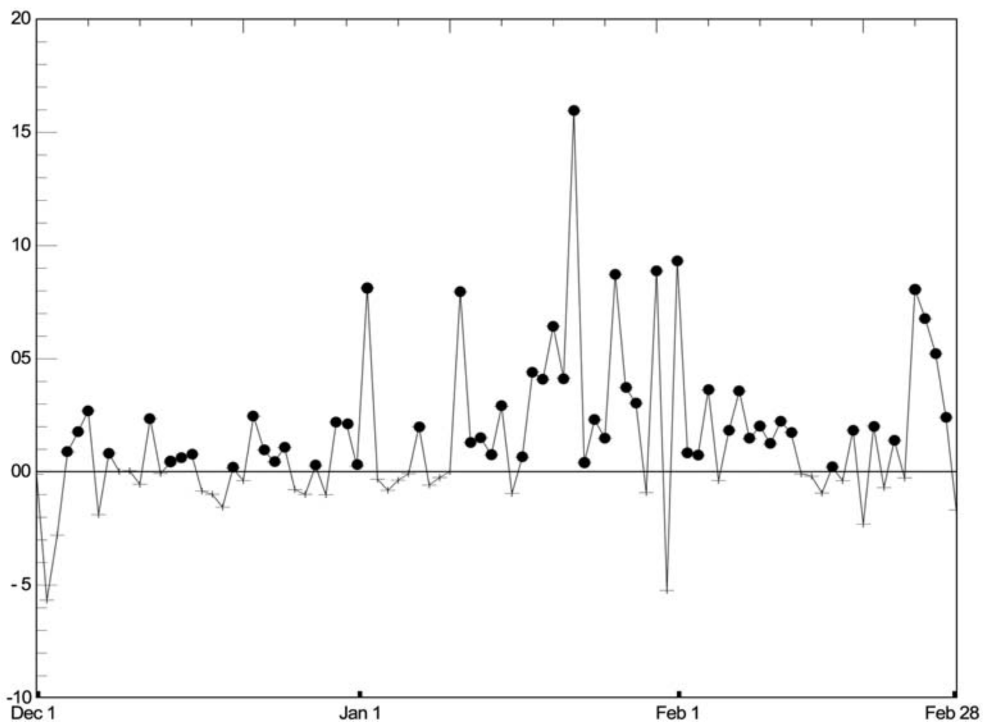

Figure 8. Timeseries of the rainfall averaged over the lake stations (RALK) minus the rainfall averaged over the land stations (RALN) in mm.day^{-1}.

To analyze the periodicity of lake-effect storms the rainfall averaged over the land stations (RALN) was subtracted to the rainfall averaged over the lake stations (RALK) and compared. During 63% of the days the RALK was larger than the RALN (figure 8). The observations also suggested that nocturnal lake-effect storms are conditioned to the amount of rainfall in the Altiplano since the days in which the largest rainfall rates were observed on the lake stations coincided with days with large rainfall rates in most of the stations located over land as well. Figure 8 also suggests that the lake-effect storm events do not follow a clear periodicity. Strong events can sometimes be followed by very weak events or by days in which more rainfall was collected by the land stations than by the lake stations.

Rainfall data and satellite imagery were also related on this study. IR4 satellite images were utilized to obtain the daily frequency of cloud tops colder than different thresholds and then correlated with the rainfall data. The largest correlations were on the order of 0.4 – 0.54 and located in the region of the highest rainfall (i.e. the islands located to the northeast of Lake Titicaca).

Pilot Balloon Data

Two types of balloons were used for the pilot balloon soundings and they were filled with helium. Initially the pilot balloon data was stored in forms containing the time and position of the balloons with respect to the observer. The data was stored in the form of elevation and azimuth angles captured by the optical theodolites. The ascent rate was assumed to be a constant equal to 3.2 m/s for the 30g balloons and 1.6 m/s for the small "party" balloons. These constants were previously found using data from many double theodolite tests carried out in Norman, Oklahoma.

For quality control, the data was processed using the "CORRIGE". This software was created by Jose Luis Carrasco (Mexican Weather Service) and later modified by Doug Kennedy (NSSL) in the 1990's. CORRIGE is a user-friendly interface that converts azimuth and elevation angles into wind data assuming a constant ascent rate. It allows the user to view the angle curves and wind profiles in order to visualize obvious errors in the data and correct them.

Before performing calculations and plots, the wind data was interpolated in the vertical and in time. A linear vertical interpolation routine was applied for data collected after 8 minutes from the launch, which corresponds to an elevations higher than ~1536 m AGL. This routine was applied since the frequency of the observations was reduced from every 30 minutes during the first 8 minutes to every minute after. A linear interpolation routine was applied in time whenever a gap of 1 or 2 observations was found on the data. The main purpose of this interpolation was to add continuity to the observations, especially for the calculations of divergence and horizontal plots, the duration and position of the time gaps varied per station. The interpolation routines were applied using IDL programming language. This tool was also used for the plots.

Salar de Uyuni Experiment

The Salar de Uyuni Experiment was held during the onset of the rainy season. The prevailing synoptic flow had a westerly component during most of the experiment. At 500 mb the wind was initially weak and variable but by the first evening – November 26 - it became westerly. It varied from westerly to northwesterly during the rest of the experiment and gained strength towards the end reaching 40 kt during the morning on November 30. No rainfall was observed during this field campaign since westerly synoptic flow over the Altiplano causes the advection of dry air from the western slopes of the Andes. This translates into clear skies and low relative humidity readings, which was the case. This situation was not unusual for November since the season when low-level moisture is available in the southern

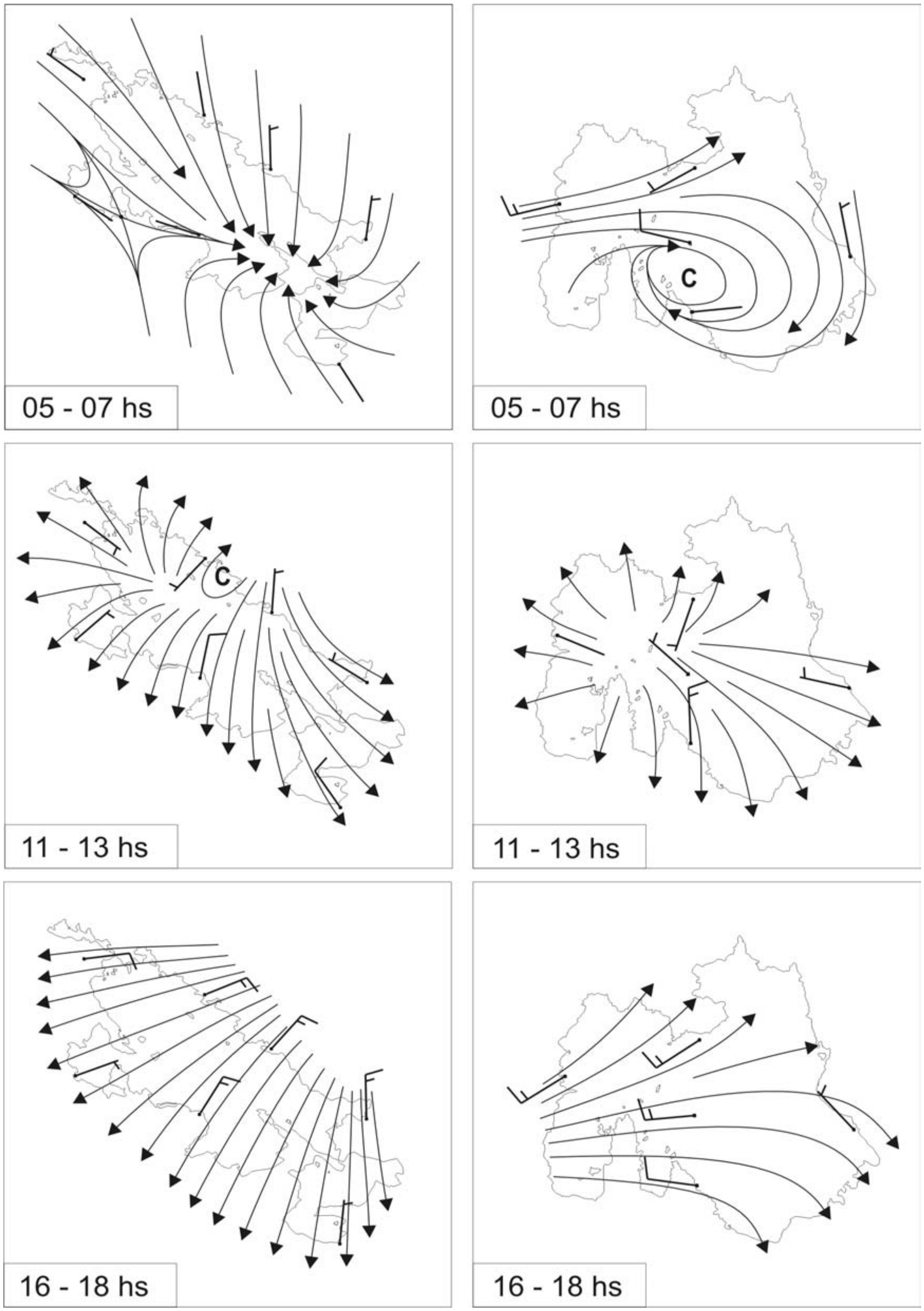

Figure 9. Wind field observed during the Lake Titicaca (left) and the Salar de Uyuni (right) Field Experiments averaged over all the days and over the observations made between 05:00 and 07:00 hs (top), 11:00 and 13:00 hs (middle) and 17:00 and 19:00 hs (bottom).

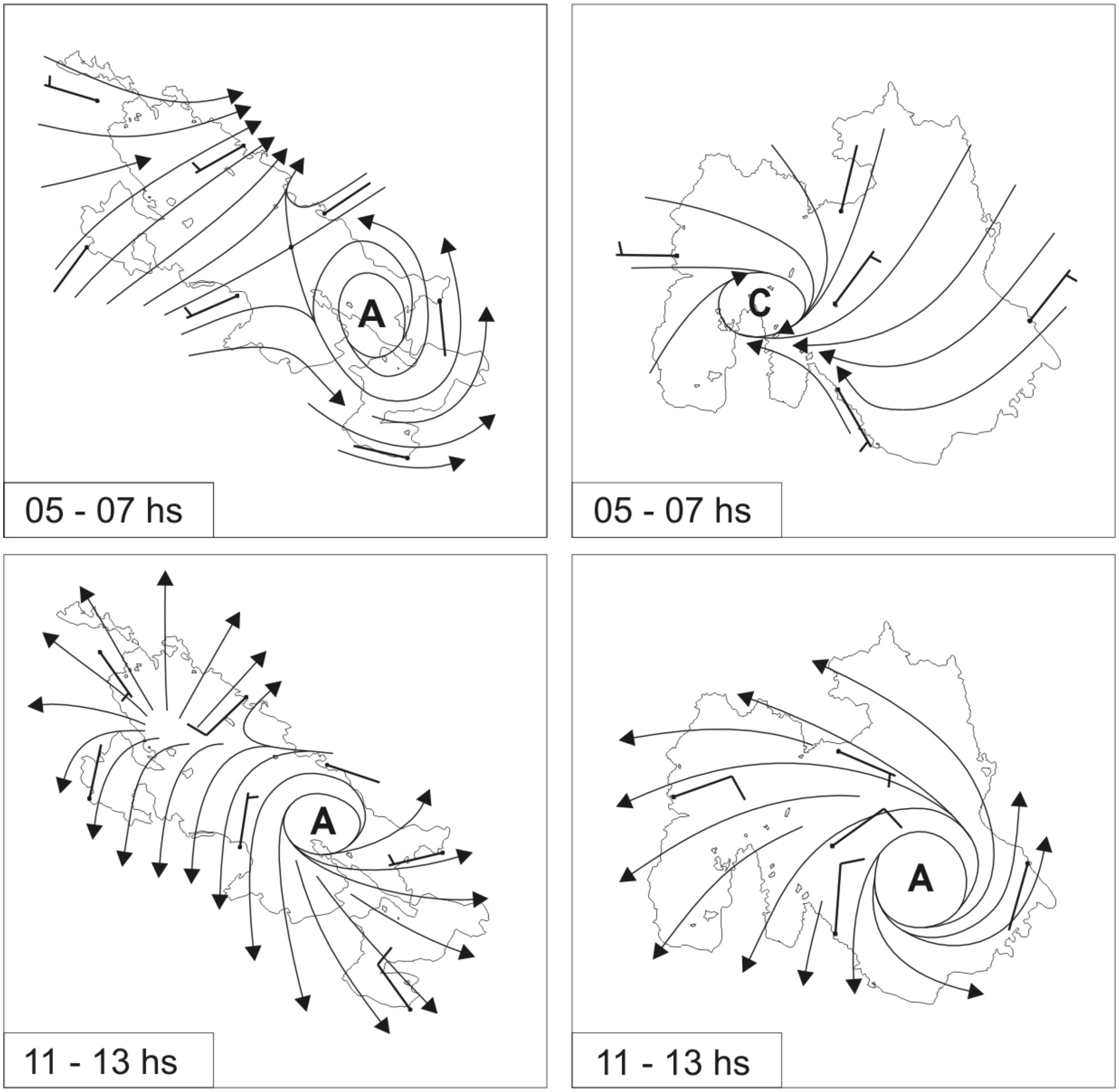

Figure 10. Anomalies of the wind field with respect to the average over the entire experiment calculated per site observed during the Lake Titicaca (left) and the Salar de Uyuni (right) Field Experiments. The panels correspond to the 05:00 - 07:00 hs period (top), and the 11:00 and 13:00 hs period (bottom).

Altiplano, so called rainy season, generally starts in December.

The wind field analyses (figure 9) show that the prevailing flow observed over the Salar de Uyuni was diffluent most of the time, particularly near noon when the salar onshore breeze mechanism was well established. The depth of the onshore breezes varied between 700 and 1500 m AGL over the stations located near the edges of the salar. A slightly shallower breeze was observed over the central station with depths that varied between 500 and 1000 m AGL. Nocturnal offshore breezes with a similar depth were also depicted. These breezes, however, appeared to be deeper at the central station when compared to the ones of the rest of the sites.

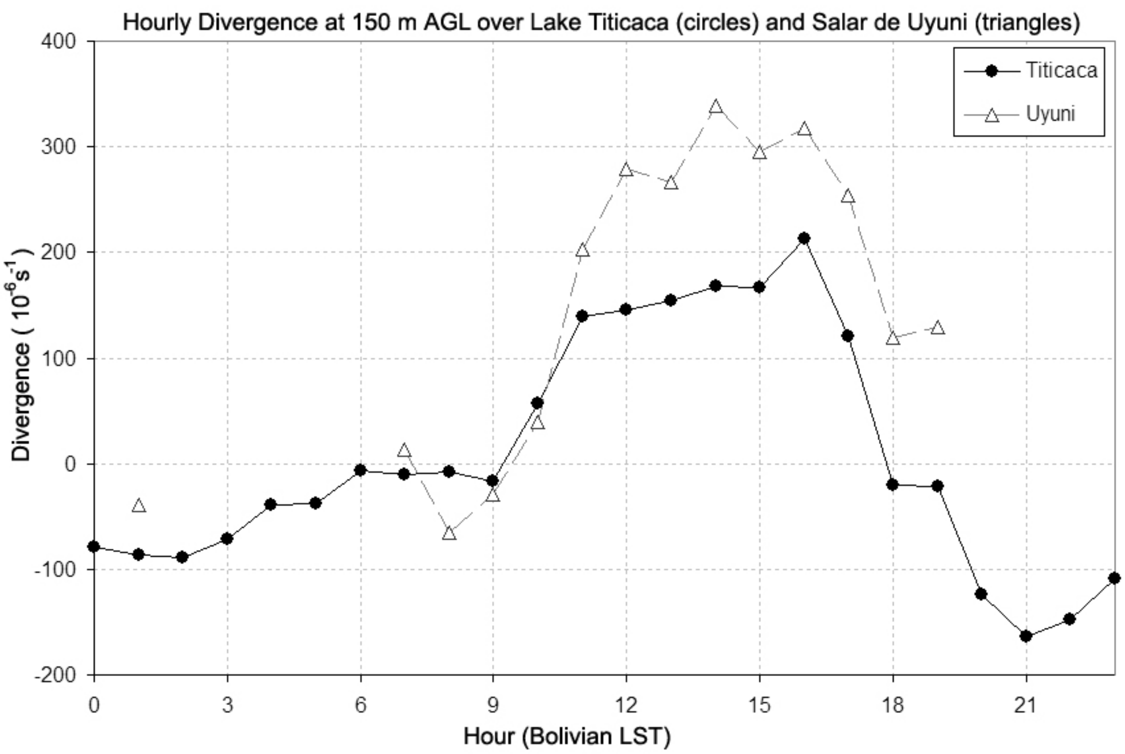

Figure 11. Diurnal cycle of horizontal divergence at 150 m AGL calculated over Lake Titicaca (circles) and the Salar de Uyuni (triangles). The calculations were made using polygons with the pilot balloon observations and assuming a homogeneous wind field (Davies-Jones, 1993).

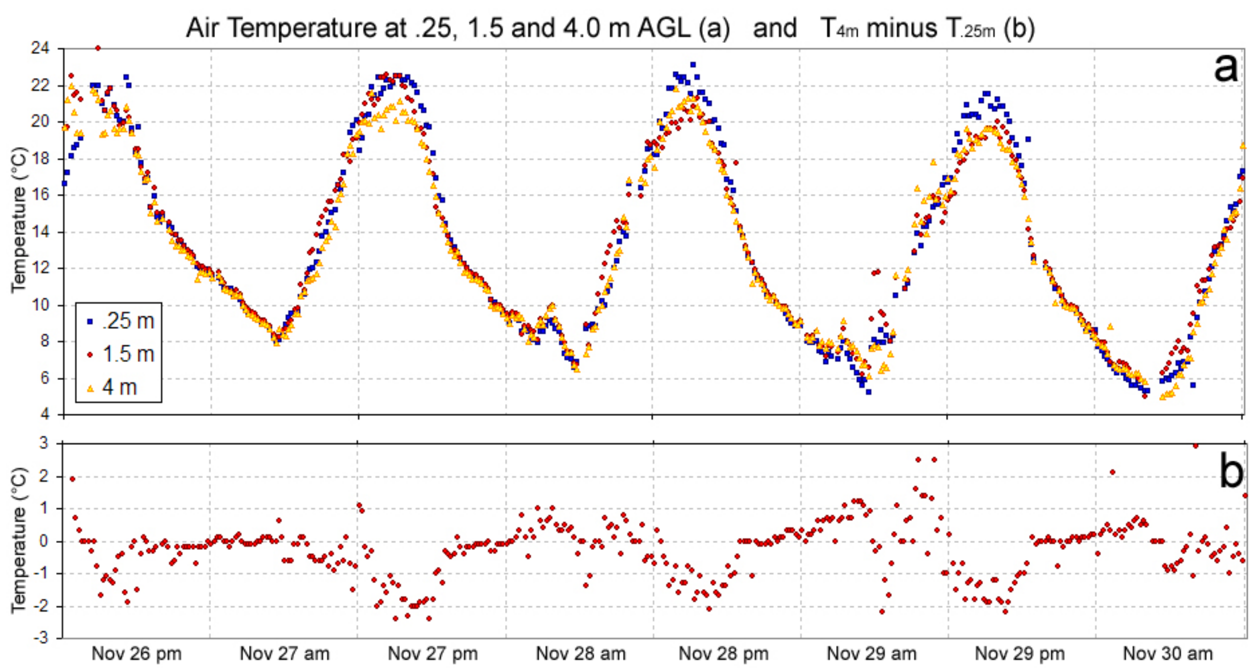

Figure 12. Timeseries of air temperature at 3 different levels (.25, 1.5 and 4.0 m AGL) at the Central Site during the Salar de Uyuni Experiment (a) and timeseries of the difference between the temperature observed at 4 m AGL minus the one observed at .25 m AGL. This is an indicator of the direction of the heat flux: Whenever the difference is negative the ground heats the atmosphere and viceversa.

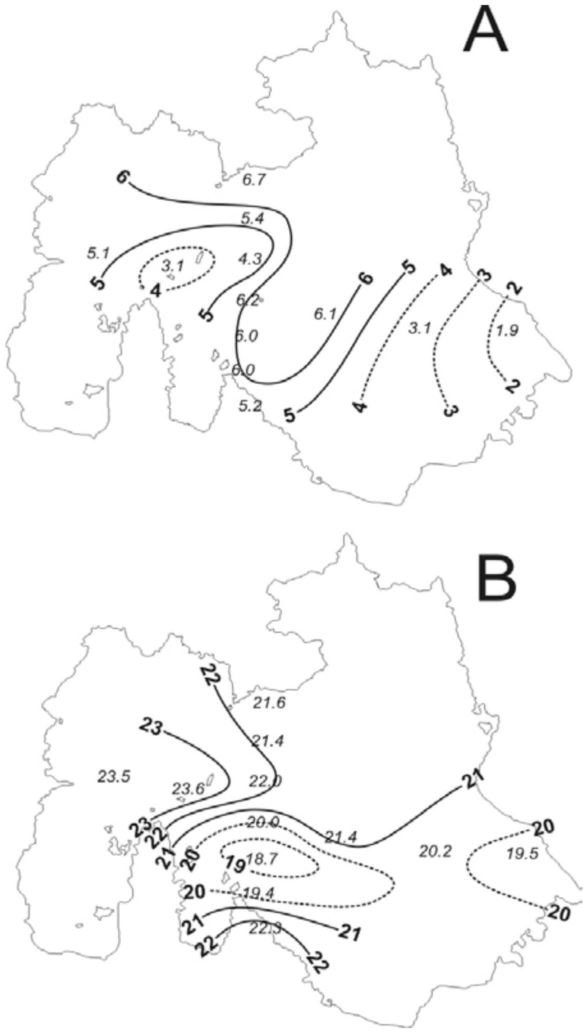

Figure 13. Maximum (a) and minimum (b) temperatures at 1.5 m AGL measured during November 29, 2002 over the Salar de Uyuni.

Divergence was calculated using polygons sketched with the pilot balloon stations. The method utilized is described by Davies-Jones (1993) and consists on fitting the a linear windfield to the observations in order to calculate the divergence and vorticity. Unfortunately, the lack of nocturnal observations in all the sites at the same time as a result of the strong winds limited the calculations of divergence during between 20 LST and 06 LST.

The results (figure 11) show the hourly divergence at 150 m AGL averaged over the 5-day period when the Salar de Uyuni Experiment took place. They show weak convergence at 1am, 8am and 9am. During the rest of the time the flow was divergent as expected. Strong divergence – in the order of 200 to 350 $10^{-6}s^{-1}$ - developed between 11 and 17 LST associated to the establishment of the onshore salar breeze mechanism.

Wind anomalies were calculated by subtracting the 24-hours averaged wind to the hourly winds for each station. The purpose was to remove the synoptic flow and therefore ease the analysis of the breezes. The results are displayed in figure 10. They show that during the early morning (upper right panel) the flow was confluent and cyclonic with the center of circulation located to the west of the central site. Near noon (lower left panel) the flow was diffluent and anticyclonic with the center of circulation located to the southeast of the central site. This same pattern of circulation was observed at about 620 mb during a NOAA-P3 Aircraft flight carried out in 28 January 2003, during the end of a wet spell characterized by weak synoptic flow over the southern Altiplano.

The diurnal cycle of temperature at 1.5 m AGL showed to be larger than expected with a amplitude of about 14°C in the central site, which is located near the center of the salar (figure 12a). Figure 13 shows the extreme temperature field observed during November 29 at 1.5 m AGL. The temperatures oscillated between 1.9°C at the eastern shore and 23.6°C near Isla del Pescado. These variations suggest that the radiative and thermodynamic properties of Uyuni's salty surface still allow for larger heating and cooling rates than those observed over water.

The difference between the temperature observed at 4 m AGL and the temperature measured at 0.25 m AGL was also plotted (figure 12b). This difference suggests the direction of the land-atmosphere heat flux with positive values for downward fluxes and negative values for upward fluxes.

Finally, using the wind observations and studies carried out by previous authors six mechanisms involved on the circulation patterns observed over the Salar de Uyuni region were identified. These mechanisms are: (1) The onshore and offshore breezes induced by the salar, (2) the anabatic and katabatic winds that originate in the surrounding terrain, (3) the arrival of strong and shallow westerly winds originated over the western slopes of the Andes, (4) the effects of boundary layer friction on decreasing the intensity of the flow during daytime, (5) downward transport of momentum from the upper troposphere and (6) isolated effects of convection in the form of local outflow boundaries.

Lake Titicaca Experiment

The Lake Titicaca Experiment coincided with a prolonged dry spell that ended two days after the conclusion of the field campaign. During the early morning of January 7, however, small lake-effect storms developed over the central edge of the lake after the large scale flow over the area changed from westerly to easterly. The rainfall averaged over the lake sites exceeded by almost 3 mm the one averaged over the land sites, which classifies January 7 as a lake-effect storm event day (figure 7).

The methodology applied to the pilot balloon data was identical to the one used with the Salar de Uyuni Experiment data. Wind anomaly and divergence calculations were made. Fortunately, several nighttime soundings were made allowing for a complete dataset after minor linear interpolation-in-time passes were applied. The results obtained with the Lake Titicaca Experiment wind data are displayed together with the Salar de Uyuni Experiment results for comparison (Figures 9, 10 and 11).

The low-level divergence observed over Lake Titicaca was weaker than the one observed over the Salar. Between 11 and 17 LST the magnitude of the divergence oscillated between 100 and 200 $10^{-6}s^{-1}$, about 100 $10^{-6}s^{-1}$ weaker than the one observed over Uyuni.

Low-level convergence prevailed for a longer period of time than low-level divergence starting at 18 LST and ending at 09 LST. The magnitude of the convergence was almost in the same order as the magnitude of the divergence. The strongest convergence, about -160 $10^{-6}s^{-1}$, was reached at 21 LST. This suggests that the main mechanism for the generation of low-level convergence over the lake is not the lake-breeze mechanism, since the breezes are expected to be the strongest near sunrise.

Satellite imagery and wind observations suggest that during the evening the easterly flow generated in the eastern slopes and transported through the canyon east of the lake collides with low-level westerly flow produced by the cooling of the land west of the lake. This westerly flow is enhanced during wet spells by the eastward propagating outflow boundaries generated by the afternoon storms that develop over the western mountain range. The late evening is the time of the day when the frequency of deep convection that develops over Lake Titicaca reaches a maximum.

The depth of the breezes observed over Lake Titicaca was shallower than the depth observed over the Salar de Uyuni. They reached depths of 400 – 700 m AGL. The flow was confluent during the morning (figure 9) with the center of confluence located in the southern part of Lake Chucuito, or the largest lake. Near noon the flow was clearly diffluent. Only the site of Challapata, the closest one to the gap in the mountain range located east of the Lake, showed offshore flow suggesting the presence of incoming flow from the eastern slopes. The wind anomalies (lower left panel in figure 10) show an anticyclonic center of circulation to the southwest of Challapata and diffluent (onshore) flow all over the lake.

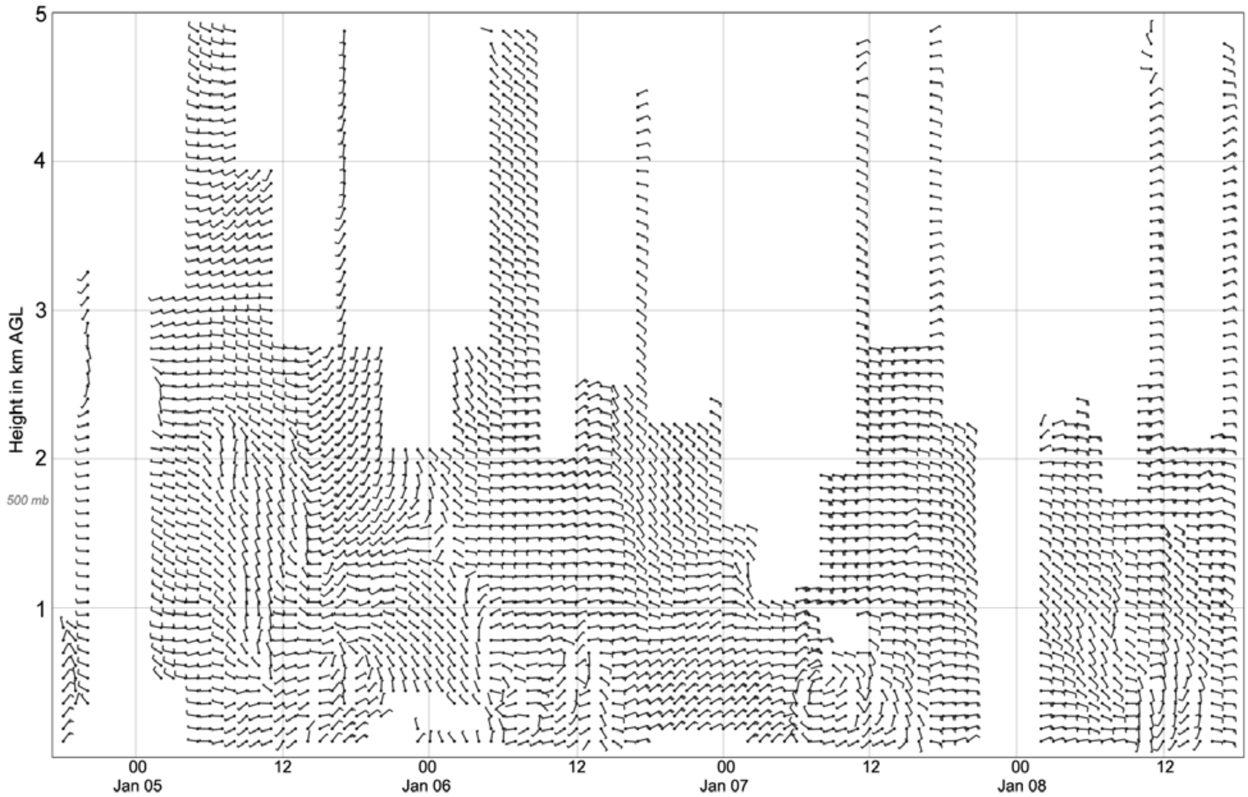

Figure 14. Timeseries of the wind profiles observed at Conima, Peru during the Lake Titicaca Experiment. This station is the northernmost site of the eastern shore.

Strong easterly flow generated in the eastern slopes of the Andes arrives in the afternoon and appears visible on the bottom left panel of figure 9. This arriving upslope flow mechanism was also observed over Uyuni.

Numerical Simulations

The numerical simulations performed using the Weather Research and Forecasting (WRF) Model served as a key tool to understand what may be occurring in the region during lake-effect storm events.

The WRF Model is a next-generation numerical model designed for weather prediction purposes with a major focus on the simulation of mesoscale processes. It is the result of a multi institutional effort as it has been developed by the Mesoscale and Microscale Meteorology Division of the National Center of Atmospheric Research (NCAR/MMM), the National Centers for Environmental Prediction (NOAA/NCEP), the Forecast Systems Laboratory (NOAA/FSL), the University of Oklahoma Center for the Analysis and Prediction of Storms (CAPS) and the U.S. Air Force Weather Agency (AFWA).

The design of the WRF started in 1998, targeted for the 1-10 km grid-scale and intended for operational weather forecasting, regional climate prediction, air-quality simulation, and idealized dynamical studies, with the idea of eventually replacing the existing mesoscale numerical models such as the MM5, ETA and RUC.

The WRF initial design allowed for multiple dynamical cores, one based on height coordinates, and one based on mass coordinates. The horizontal staggering was

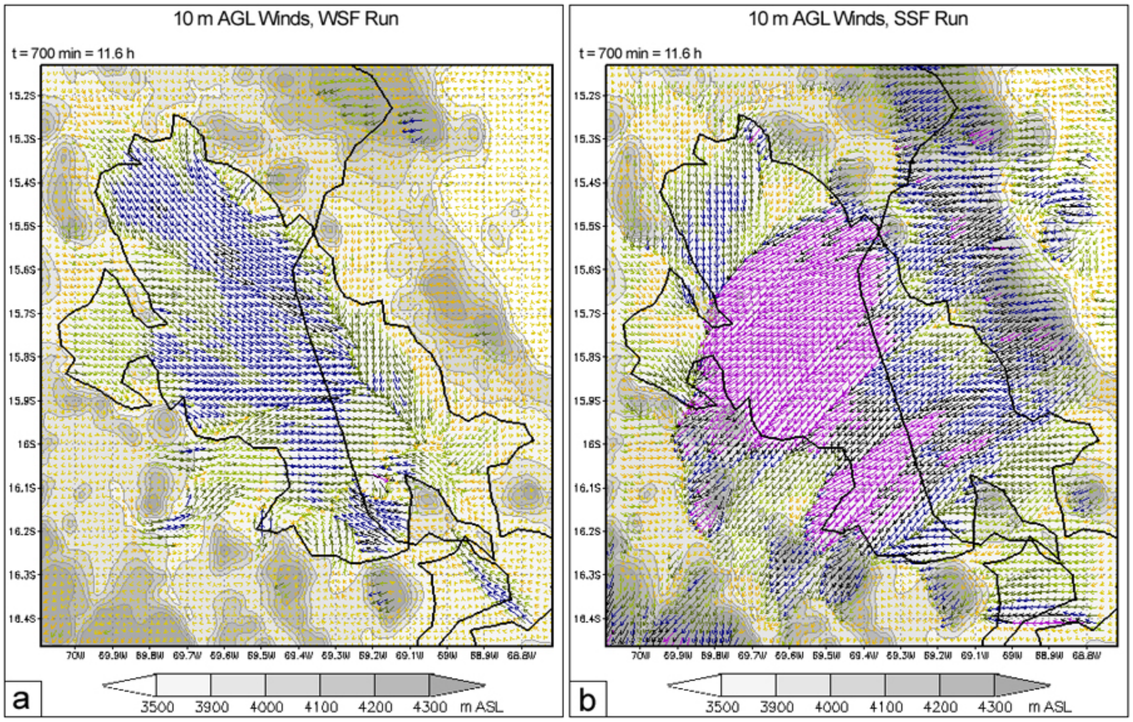

Figure 15. 10 meters AGL winds at 6:40 am LST (11.6 hours from the initialization) simulated using the WRF Model for two different cases. The difference between the panels (a) and (b) are the initial and boundary conditions. Simulation (a) was initialized with a weak easterly synoptic flow below 500 mb and a moist atmosphere as well (relative humidity of 50% to 70% below 500 mb in the entire domain); simulation (b) was initialized with a strong easterly synoptic flow and higher relative humidity values (60% to 80% over the Altiplano and 80% to 90% over the eastern slopes).

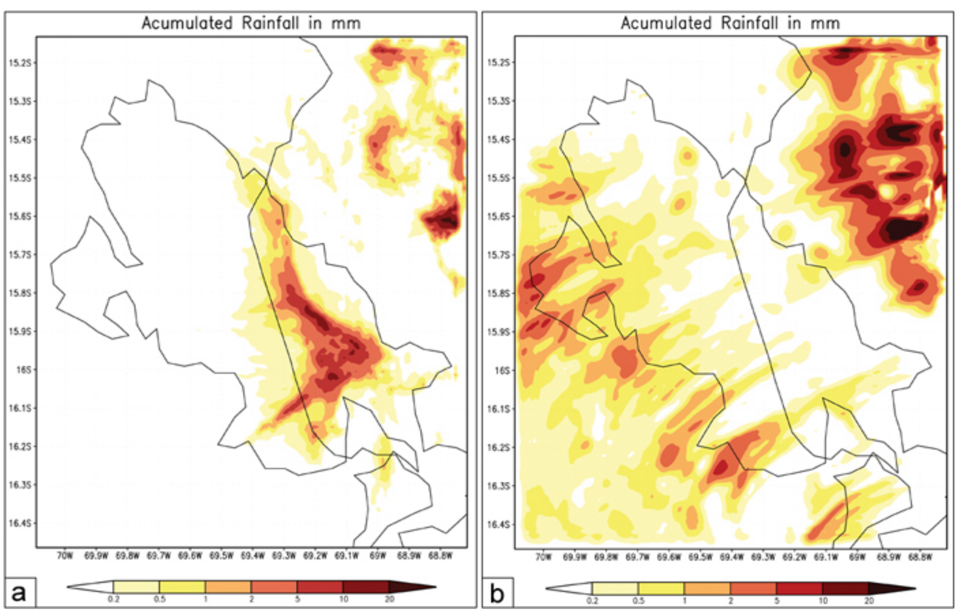

Figure 16. Rainfall accumulated during 12 hours. These images correspond to the ones presented in figure 16. The simulations were initialized at 00 UTC (19:00 LST). The left panel (a) corresponds to the weak synoptic flow simulation and the right panel (b) corresponds to the simulation initialized with larger moisture content but stronger synoptic flow.

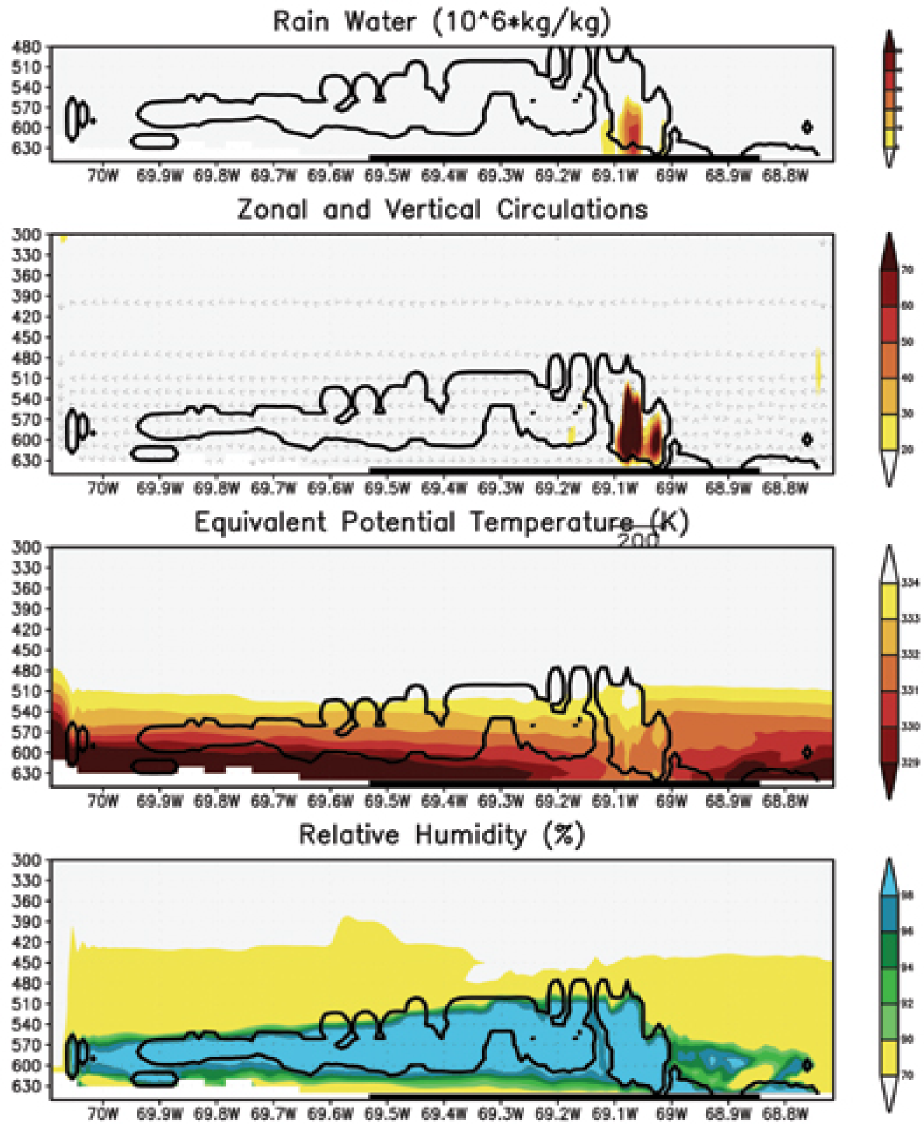

Figure 17. East-west cross-section at 16°S (near the center of Lake Titicaca) at 01:00 LST on 26 January 2003, after 6 hours from initialization. Lake Titicaca has been indicated in all the panels as a thick black line running from 69.55°W to 68.85°W. Clouds have also been indicated in all of the graphics from the cloud water field using a thick solid line. The top panel shows rainwater in shaded. The second panel from the top shows the zonal/vertical wind vectors and the vertical velocity (cm/s) in shaded. The third panel shows the equivalent potential temperature in °K and the panel in the bottom relative humidity.

the Arakawa C-grid. The large time steps utilized a third-order Runge-Kutta scheme, and second to sixth order advection operators could be chosen to solve the advection equation. The main effort when developing the WRF Model was improving the numerics.

The FNL analyses from the Aviation Model (AVN) were utilized as initial and boundary conditions. They are analysis created later than the operational analyses, therefore they take into account a larger number of observations and are closer to reality.

These analyses have a horizontal resolution of 1 degree and 24 pressure levels in the vertical. The variables contained are surface pressure, sea level pressure, geopotential height, temperature, relative humidity, zonal wind, meridional wind, vertical velocity, vorticity, sea surface temperature, ice cover and ozone content.

In order to explicitly simulate the lake-effect convective storms, a fine horizontal resolution not larger than 1 km was necessary. At this resolution the model was able to reproduce the land-lake nocturnal breezes and the lines of low-level convergence that form over the lake and lead to the convective storms (figure 16a). These features were not reproduced when using a horizontal resolution of 2 km.

Based on the numerical simulations and on analyses put together using satellite images the nocturnal lake-effect storms seem to be sensitive not only to the amount of moisture available in the Altiplano boundary layer but to the moisture advected through the canyon located to the east-northeast of the Lake. This connection could not be established only from the pilot balloon, surface and rainfall observations, which implies the applicability of the simulations and satellite data as additional tools to study the atmosphere in regions with poor observing networks.

Even though the weak synoptic flow simulation located the region of largest rainfall over the lake, a broader area was affected by precipitation in the windy and higher moisture simulation (figure 17a) which supports the hypothesis that rainfall in the Altiplano is dependent on the amount of moisture within the boundary layer.

Further experiments modifying the initial and boundary conditions are being carried out.

5. CONCLUSIONS

A short but successful study of the mesoclimatology of the Altiplano, a poorly sampled rural region of South America, was carried out with a relatively cheap budget of near USD 8000.00. This amount allowed for the installation of near 200 raingauges as well as the completion of two short – 1 week long - field experiments based mainly on 5 to 7 pilot balloon stations and surface observations. The networks permitted to study the effects of Lake Titicaca and Salar de Uyuni on the mesoscale circulations and rainfall of their environments.

The main problems that arose from the temporary observing networks were related to the logistics. The most important loss was the rainfall information from the Bolivian side of the Altiplano, the largest component of the network. The information from the digital raingauges and some surface data could not be recovered as well.

Numerical simulations and satellite information proved to be a very useful tool to complement the understanding of atmospheric processes that occur in areas with poor conventional meteorological observing networks.

The scientific results showed that Lake Titicaca does affect the distribution and amount of rainfall in the area leading to almost twice as much rainfall over the eastern islands (~200 $mm.month^{-1}$) than over the surrounding terrain (~110 $mm.month^{-1}$). The raingauge network also captured the northern Altiplano north-south rainfall gradient, from ~120 $mm.month^{-1}$ north of Lake Titicaca to ~80 $mm.month^{-1}$ south of the lake, which can be associated to the gradient of moisture available within the Altiplano boundary layer.

The density of the SALLJEX temporary raingauge network also allowed the recording of mesoscale features that the Peruvian operational raingauge network was unable to describe. Some of these features are a region of low rainfall just west and along the eastern mountain range associated to downsloping easterly flow, a region of high rainfall located over high terrain to the west of Lake Titicaca, and areas of relatively low rainfall in the valleys and flat regions of the Altiplano.

The wind field showed to be confluent and convergent for both Lake Titicaca and Salar de Uyuni during the first hours of the morning (5 to 7 Bolivian LST). The convergence was weak in both locations and varied between –5 and –60 $10^{-6}s^{-1}$. Near noon (11 to 13 Bolivian LST) the flow showed to be divergent and clearly diffluent over both the lake and the salar. The divergence was larger over Uyuni by 100 $10^{-6}s^{-1}$ during most of the afternoon. The divergence observed over the Salar de Uyuni was as large as 350 $10^{-6}s^{-1}$. During the late afternoon (16 to 18 Bolivian LST) strong easterly (westerly) flow was observed over the lake (salar) that resulted from the arrival of the afternoon upslope breeze that developed every day over the eastern (western) slopes of the Andes. At this time the formerly divergent flow over the lake quickly became convergent with magnitudes in the order of –10 $10^{-6}s^{-1}$. The divergence over Uyuni also decreased abruptly but the flow did not turn convergent. It remained divergent with magnitudes in the order of +120 $10^{-6}s^{-1}$.

The strongest convergence was found over Lake Titicaca and during the late evening. The magnitude of the convergence was in the order of – 150 $10^{-6}s^{-1}$. This period of strong convergence coincided with the period of the highest frequency of deep convection generated over Lake Titicaca, suggested by GOES-8 IR4 satellite imagery. This maximum in the convergence is associated to a boundary formed by the collision between the strong easterly flow generated in the eastern slopes and westerly flow generated west of the lake. This westerly flow is associated to either radiative cooling of the low-levels of the Altiplano troposphere or to the cooling combined with the eastward-propagating outflow boundaries that form during afternoon convection in the western mountain range and approach the lake during the evening.

Additional convective development occurs during the early morning hours associated to the convergence of the lake breezes with magnitudes that vary from -30 to -90 $10^{-6}s^{-1}$. This convection, suggested by satellite imagery and numerical simulations, generally develops in a line located near and east of the northwest-southeast lake axis. This secondary maximum of convection explains why the largest rainfall rates occur in the northeastern region of the lake since this region receives rainfall twice during a rainy night.

The divergence over the salar during the night could not be described due to the lack of nocturnal soundings, given the large wind speeds near the surface. A calculation near 1 LST suggests that the nocturnal convergence is weaker than the one observed over Lake Titicaca, which partly explains the lack of nocturnal convection over the salar. The main reason, however, may be the lack of moisture in the region, especially considering that the low-level westerly flow advects dry air. Further numerical simulations are needed to support this hypothesis.

Some recommendations for future field experiments similar to the ones described follow. It would be useful to measure temperature at different levels in locations around the salar, not only over the salt, for comparison. The same type of temperature measurements should be repeated over the lake, again, for comparison.

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