Summertime Precipitation Variability and Atmospheric Circulation over the South American Altiplano:

Effects of Lake Titicaca and Salar de Uyuni

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Abstract

The South American Altiplano is a high altitude plateau located between 15°S and 22°S and lying between two mountain chains of the Central Andes. Within the plateau are two large features of surface discontinuity that influence local circulations. Lake Titicaca, at the north end of the Altiplano is has an area of 8,300 square km making it the 2nd largest lake in South America. The Salar de Uyuni is the largest dry salt lake in the world with a surface area of 9000 square km. These features and their influences on local circulation can possibly change weather and climate of their surrounding areas. The aim of this study is to use pilot balloon soundings and rain gauge measurements to describe the influence of these features on their surroundings, and the impact on precipitation.

Large-scale results showed a relationship between upper-level easterly flow and wet days on the Altiplano, in addition to the opposite; westerly flow and dry days on the altiplano. On the local scale we observed a tendency for increased precipitation with proximity to the lake. The difference in flow on wet and dry days also modified the diurnal breeze circulation of the lake. Analysis of morning and afternoon near-surface winds at the lake and salar indicate morning confluence and afternoon difluence, which may be linked to increased morning convection over the lake indicated by satellite imagery. Comparison of the Salar and Lake indicated a stronger breeze signal at the Salar, possibly a result of the resistance of the salt surface to heating, and reduction of daytime surface heating surrounding Lake Titicaca due to increased vegetation.

1. Introduction

The South American Altiplano is a high altitude plateau lying between two mountain chains of the Central Andes. The Altiplano, located between 15°S and 22°S, has an area of 58,000 square km and extends 170 km across and 500 km lengthwise along the Andes, at a mean altitude of 3500-4000 m ASL. The climate of the altiplano is semi-humid, with increasing aridity to the south. The region receives the majority of its precipitation during the austral summer months of December, January, and February, in the form of convective thunderstorms (Lenters and Cook 1999; Garreaud 2000). The austral summer is composed of periodic wet episodes, with average lengths of 1-5 days, separated by dry episodes of similar length (Lenters and Cook 1999; Garreaud 2000). These wet/dry periods are coupled with complementary easterly/westerly synoptic flow, leading to the conclusion that the Altiplano receives much of its low-level moisture for convection from moist air transported from the Amazonia region of South America (Vuille 1999; Garreaud 1999, 2000, 2001). The Amazonia is not, however, the only source of moisture for the altiplano, and at times Pacific moisture or the recirculation of moisture from local sources of water (such as large lakes) can be significant.

Differences in land surface characteristics, whether due to vegetation variability, surface albedo variations, or the presence of a lake can lead to variations in heat exchanges with the atmosphere that can lead to mesoscale disturbances. These disturbances can interact with or be modified by the synoptic scale flow. The South American Altiplano, having numerous lakes and salars (dry salt lakes), is affected by these local disturbances, as well as by anabatic and katabatic flows from the eastern and western Andean ranges. These flows result in a measurable diurnal circulation overlain on the prevailing synoptic flow. Although the effects of large lakes have been studied in many locations around the world, no detailed meteorological studies have been carried out to explain the effects of Lake Titicaca on the atmosphere. Even less has been studied about the effects of the large Salar de Uyuni.

Lake Titicaca is located near the northern end of the Altiplano, on the Peru-Bolivia border. At 120 miles (190km) long and 50 miles (80km) wide, with an area of 3,200 square miles (8,300square km), Lake Titicaca is the 2nd largest lake in South America. In addition, at an altitude of 12,500 feet (3,810m) ASL it is the highest navigable lake in the world. The high specific heat of water leads to a diurnal temperature contrast between the temperature of the lake and the surrounding land surface. This temperature contrast produces the well-known lake-land breeze circulation. This type of circulation has the effect of producing convergent winds over lakes at night and wind diverging from the lake during the day (Estoque, 1981). In addition, evaporation takes place from the water, increasing the moisture content in the lower boundary layer. The combination of these mechanisms can induce or at least help to intensify precipitation events over the lake.

The Salar de Uyuni is the largest dry salt lake in the world, with a surface area of 9000 km^2. It is located near the southern end of the South American Altiplano and lies at an altitude of 3653 m ASL. The albedo of the salar is very high, leading to very low absorption of incoming solar radiation. In addition, there is a high thermal conductivity and diffusivity beneath the salt surface leading to less energy available for sensible and latent heating (Physick and Tapper 1990). This produces a diurnal surface temperature contrast with the surrounding terrain, producing salar breezes during the day and terrain breezes at night, similar to the lake-land breeze. The salar, however, lacks the large evaporative surface of a lake, and therefore does not have the effect of adding moisture to the lower boundary layer.

The effect of the lake and salar breezes on rainfall over the Altiplano can be large enough that lake-induced rainfall may modify the climate of the region. During the last glacial period (~15,000 years ago) a very large lake existed over much of the Altiplano, and had a large effect on the precipitation of the region. If smaller lakes, such as the present Lake Titicaca, have a major impact on precipitation over the lake then the transition of a salar into a lake by a small change in evaporation and precipitation could produce a large change in rainfall rates due to the lake breeze circulation that develops. The rainfall climatology over Lake Titicaca shows a maximum of rainfall over the islands at a rate of 1400 mm/year. This is twice the rate on the shore, which is 700 mm/year. Current climate models cannot incorporate such mesoscale effects, which might be important for rapid transitions from one climate state to another.

2. Data

The data for this experiment was obtained from the South American Low-Level Jet Experiment (SALLJEX), which was an international field campaign to better understand the role of the SALLJ in moisture and energy exchange between the tropics and extra tropics and the subsequent impacts on local hydrology, climate, and climate variability (Douglas). This study has explored the diurnal atmospheric circulations associated with Lake Titicaca and the Salar de Uyuni, taking advantage of relatively detailed measurements made during the SALLJEX. The Lake Titicaca Experiment and the Salar de Uyuni Experiment were done very inexpensively due to limited funding. Inexpensive pilot balloon, surface temperature, and rain gauge measurements were taken, limiting the amount and quality of the data.

The data analysis was separated into, first large-scale Altiplano circulations, and second local scale Lake Titicaca and Salar de Uyuni circulations. The wind data for the large scale was obtained from SALLJEX and the Pan-American Climate Studies Sounding Network (PACS-SONET). Eight pibal stations in and around the Altiplano were selected on the basis of their proximity to the plateau and completeness of data (Fig. 1). The data frequency was one sounding per day at 12Z with additional soundings at up to three per day. The time period of our study was limited to the austral summer ranging from November 14, 2002-April 6, 2003. The rainfall data was obtained from a rain gauge network surrounding Lake Titicaca, with data available from that same period. The spread of the stations was representative of sites on the lake (islands), on the shore, by the coast, inland, and far inland in higher terrain (Fig. 2). In our analysis we used only the stations on the Peruvian side of Lake Titicaca, because of data availability problems with the Bolivian data, and therefore the rain gauge data is incomplete and does not represent the behavior of the entire lake. The rain gauges were checked once per day. The final Large-scale dataset is satellite images over our area of study, which are available multiple times per day.

The main local scale dataset is the hourly/tri-hourly pilot balloon soundings taken during the Lake Titicaca Experiment from January 4, 2003-January 9, 2003, and the Salar de Uyuni Experiment from November 25, 2002-November 30, 2002. For the Salar de Uyuni Experiment five stations were set up on the north, south, east and west edges, as well as the center of the Salar. The Lake Titicaca Experiment involved seven sites distributed fairly evenly around the lakeshore (Fig. 3).

3. Methodology

First we determined the large-scale flow associated with wet/dry periods over the altiplano. The Lake Titicaca rainfall data, ranging from Nov.14, 2002 until April 6, 2003, were divided into wet and dry periods, with a daily average rainfall threshold of 0.05 inches determining wet or dry days. In order to determine the synoptic conditions surrounding these wet and dry periods we chose eight SALLJEX pibal stations, that represent the area of the Altiplano, and surrounding regions. The data for these stations were averaged over the wet and dry periods to determine the circulation related to these periods.

The daily pibal data associated with the Titicaca and Uyuni Experiments were averaged and anomalies obtained to depict the breezes. Also, because of the diurnal nature of the breezes, period averages were taken for morning and afternoon soundings. Using these averages we created streamline maps to depict the flow over the lake and salar at different times of day and at different levels. Using the Lake Titicaca rainfall data we determined the rainfall patterns around the Lake During the Lake Titicaca Experiment. The wettest and driest days of the experiment, January 7, 2003 and January 5, 2003, were extracted to compare circulations in the pibal data and rainfall distributions.

4. Results & Discussion

A. Large Scale Moisture Variability

Examining the average rainfall near Lake Titicaca over the entire austral summer we see distinct wet and dry periods ranging in length from a few days to a month (Fig. 4). On average they are about a week in length, agreeing with previous observations of the quasi-periodic nature of precipitation events over the Altiplano (Lenters and Cook 1999; Garreaud 2000). During this period the mean flow in the upper levels was northwesterly (Fig. 5). However, the wind anomalies of all wet periods and all dry periods exhibit a difference in the u components of the wind at upper levels. The wet period wind anomaly shows a distinct easterly flow at upper levels (Fig. 5). This agrees with previous literature, which associates this easterly flow with the transport of moisture from the inland Amazonia into the Altiplano (Vuille 1999; Garreaud 1999, 2000, 2001). This influx of moisture, combined with the dynamical processes associated with the lake-land breeze circulation, helps initiate convective precipitation over the lake. The moisture transport into the Altiplano is also affected by the downward transport of momentum of the large-scale upper level easterly flow. As this easterly flow impacts the Central Andean ridge, it accelerates the eastward upslope flow and moisture transport into the Altiplano (Vuille 1999; Garreaud 1999). In contrast, the wind anomaly for all dry periods has a large component from the west in the upper levels from 6,000-12,000 m ASL. This suggests that the drier air from the west is critical in inhibiting convection over the lake.

Streamline maps of wet minus dry anomalies at different levels confirm the impact of upper-level flow on precipitation in the Altiplano. The analysis of the 300 mb anomalies shows the expected tendency of easterly flow across the altiplano during wet periods (Fig. 6). At 500 mb, which is slightly higher than the surface of the Altiplano, we see a tendency for a more southeasterly flow that enters the Altiplano near Salar de Uyuni and moves northwestward along the Altiplano.

B. Local Scale

1. Lake Titicaca Precipitation

Rainfall climatology around Lake Titicaca shows a maximum of precipitation over the lake. Therefore, by classifying rain gauge sites both with respect to their similar behavior as well as their distance from the lake, we seek a relationship between rainfall rates and proximity to the lake. It is clear that there is a slight tendency for higher precipitation amounts near the lake (Fig. 7), however it is inconsistent, with some lake classifications receiving much less precipitation than their nearby counterparts. One reason for this is the scattered and convective nature of the precipitation in this region.

Lake Titicaca exhibits an effect on the precipitation over and surrounding it, but other factors contribute to the distribution as well. Topographical influences such as mountain-induced convection may disrupt a clear picture of the effects of the lake. With data from stations surrounding the entire lake and on islands in the lake itself we may see the more intense effects of the lake in producing precipitation.

2. Lake Titicaca Pilot Balloon Data

In the analysis of pibal data from the Lake Titicaca experiment the appearance, duration, intensity, and span of lake and land breeze circulations at each site had many similarities. However, certain areas of the lake exhibited distinctly different circulation patterns that could be a result of topographic influences.

The Lake Titicaca experiment can be divided into two sections. The first beginning at the onset of the experiment until the end of Jan.5 where a westerly synoptic flow and little precipitation is present, and the second spanning from Jan.6 until the end of the experiment where an easterly flow and more precipitation is present (Fig. 8).

The analysis of the driest (Jan.5) and wettest (Jan.7) days of the experiment exhibited distinct differences in synoptic and local flows. The most distinguishing feature is the presence of a mean westerly flow in the mid levels (1000m-6000m AGL) on Jan.5 and a mean easterly flow in the mid levels (1000m-6000m AGL) on Jan.7 (Fig. 8). This is consistent with our previous analysis east/west flow associated with wet/dry days.

The reversal in flow from wet to dry days also affects the local scale flows and diurnal breezes around the lake. In the hourly pibal soundings at Conima, located on the northeastern shore of the lake (Fig. 3), there is a distinct lake breeze and return flow present on Jan.7, while on Jan.5 this circulation is not as clear and is dominated by a more westerly flow (Fig. 9). The afternoon lake breeze at Conima comes from the west. Therefore, on Jan.5 with westerly flow, the breeze is masked by the prevailing wind. On Jan.7, however, a wind reversal is evident because of the opposition of the lake breeze to the prevailing flow.

An interesting feature on both days is the presence of increased easterlies in the late afternoon near the surface. A possible explanation for this is the upslope flow along the eastern slope of the central Andes. After reaching the crest of the ridge these winds propagate along the relatively flat surface of the Altiplano until reaching the lake. This phenomenon consistently occurs at the sites that lie on the eastern edge of the lake, but is less clear at the western sites.

There are certain similar characteristics of the breezes at all lake sites. The start of the day breeze occurs between 8 and 10 am, but the cessation is different on the eastern and western edges of the lake. The eastern edge of the lake experiences an earlier end to the day breeze of 2-3 pm because of the easterly winds discussed earlier. The western edge of the lake maintains the day breeze until 5 or 6 pm. The night breeze begins between 8 and 11 pm and continues until around 5 am with sunrise and the heating of the terrain. The depth and intensity of the day breeze is generally larger than the night breeze with the day breeze reaching about 1 km and the night breeze 800 m. This is a result of the larger temperature contrast between the lake and land after daytime heating.

In our streamline analysis of morning and afternoon wind anomalies over the lake, the lake breezes are evident. The streamline analysis of the morning at 240m over Lake Titicaca show confluence over the lake, while the same analysis in the afternoon shows distinct difluence (Fig. 10). The strength of these breezes indicates that their effect is limited to the local scale over and on the coast of the lake. It is possible that the morning confluence over Lake Titicaca is responsible for the increased precipitation amounts experienced over the lake by initiation of convection. While confluence and difluence do not imply convergence and divergence, the cloud fields around Lake Titicaca reflect morning convergence and afternoon divergence patterns near the surface. Further comparison of the lake breezes and early morning convection may confirm this hypothesis.

3. Salar de Uyuni Pilot Balloon Data

The diurnal cycle of salar-land breezes around the Salar de Uyuni is slightly simpler than for Lake Titicaca. This is a result of factors such as the roughly circular and symmetric geographical layout of the salar and the stronger and deeper salar-land breeze circulation. The flow near the surface of the salar can be divided into three time periods. First, the early morning land breeze leads to confluence over the salar (Fig. 10). Second, the afternoon salar breeze is associated with difluence over the salar. Finally, at around 5pm local time afternoon westerlies increase, overcoming the salar breeze.

Initiation of daytime breezes over the salar occurs on average around 9 am local time, consistent with the Lake Titicaca breeze circulation. The end of the day breeze at 2-4 pm occurs earlier than at the lake most likely because of the strong afternoon westerly phenomenon. This phenomenon may be a result of upslope flow along the western slope of the Andes propagating across the Altiplano. The westerly phenomenon at the Salar de Uyuni is stronger than the easterly phenomenon at Lake Titicaca. The night breeze begins at around 8 pm after the moderation of the strong afternoon westerlies and continues until 5 am. The difference in breeze depths for Salar de Uyuni is similar to Lake Titicaca, with the day breeze extending to 1 km and the night breeze to 700 m. The maximum wind speed for the breeze anomalies is much larger for the Salar, with maximums of 5-20 knots as compared to 5-10 knots for the Lake. The reason for this is unknown. Possible explanations include the large resistance of the salar surface to heating because of its high albedo and high thermal diffusivity and conductivity. Also, the terrain surrounding the lake is far more vegetated than the terrain surrounding the salar, leading to decreased daytime surface heating surrounding the lake.

In our streamline analysis of morning and afternoon wind anomalies, we depict the breezes present over the Salar. Comparing the morning streamline analysis at 240m over the salar to the afternoon there is nearly a 180-degree reversal of winds at all the sites on the edges of the salar (Fig. 10). The morning anomalies indicate confluence over the salar, the afternoon, difluence. It is clear that the salar has a distinct effect on the local circulations above surrounding it, however its extended effects on the Altiplano, if any, could only be determined by further study.

5. Concluding remarks

On the large scale we observed prevailing easterly flow anomalies in association with wet periods over the Altiplano and westerly anomalies with dry periods. This is a result of both increased moisture transport from the inland South American Amazonia and acceleration of this transport from the interaction of downward transport of momentum impacting the Central Andes.

On the local scale we found a tendency for increased precipitation with proximity to Lake Titicaca, but the limits of our dataset prevent any further analysis. Also, many other impacts such as topography and regionality also diminish the apparent impact of the lake. During dry and wet periods, however, there is a clear modification of Lake Titicaca breezes, because of changes in prevailing easterly or westerly flow. In general we observe morning confluence and afternoon difluence over the lake and salar, however the day breeze usually extends to about 1 km, while the night breeze is limited to 700-800 m. There is also a stronger diurnal breeze circulation over the Salar de Uyuni than Lake Titicaca, which may be a result of the geographical conformity of the salar as well as the resistance of the salar surface to heating and the large sensible heating of the surrounding terrain due to its lack of vegetation. An interesting late afternoon breeze phenomenon also occurred at both the lake and salar, however the lake experienced wind from the east, and the salar from the west. These could be indications of complementary upslope flows over the Central

Andean range in the case of Lake Titicaca and the Andean Cordillera at Salar de Uyuni that then propagate along the relatively flat surface of the Altiplano.

The mechanisms for precipitation identified include the increase in moisture from upper-level easterly flow and possible influences by the confluence over Lake Titicaca supporting the climatology of increased precipitation over the lake.

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Figures

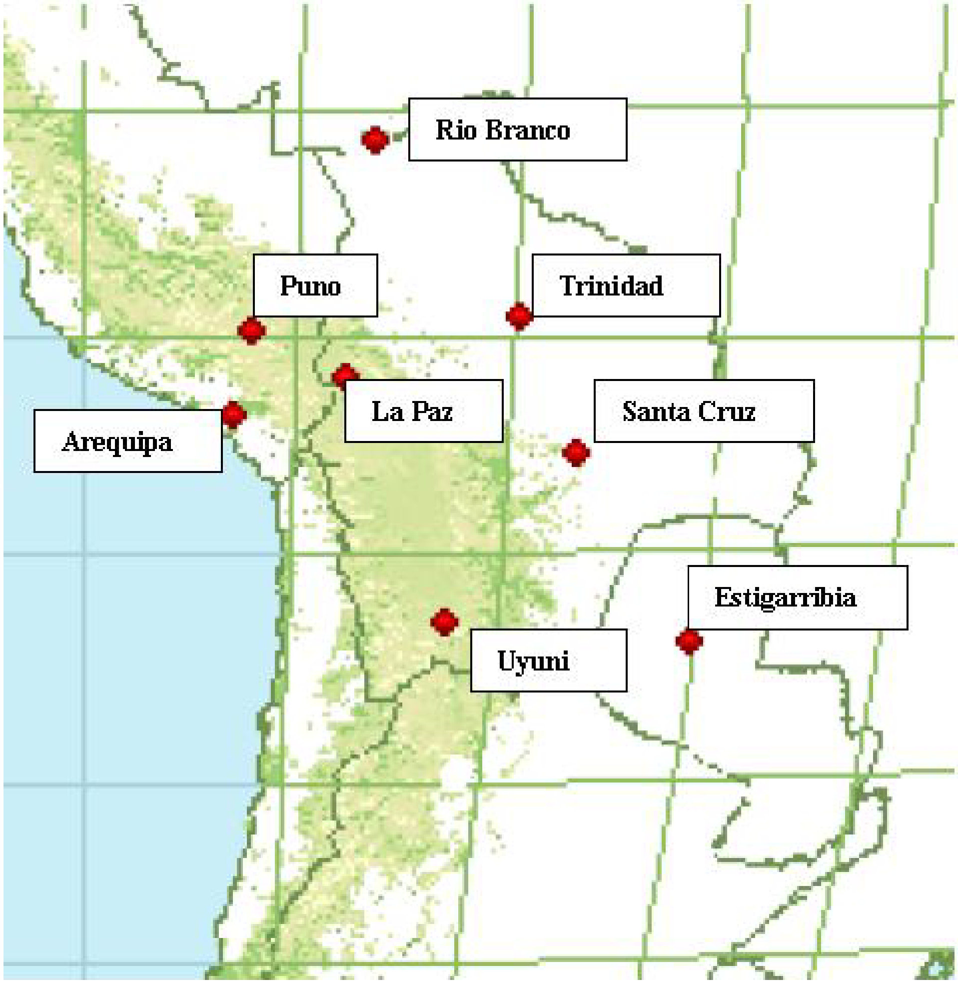


Figure 1: SALLJEX Pibal sites used for analysis of winds during wet and dry periods.

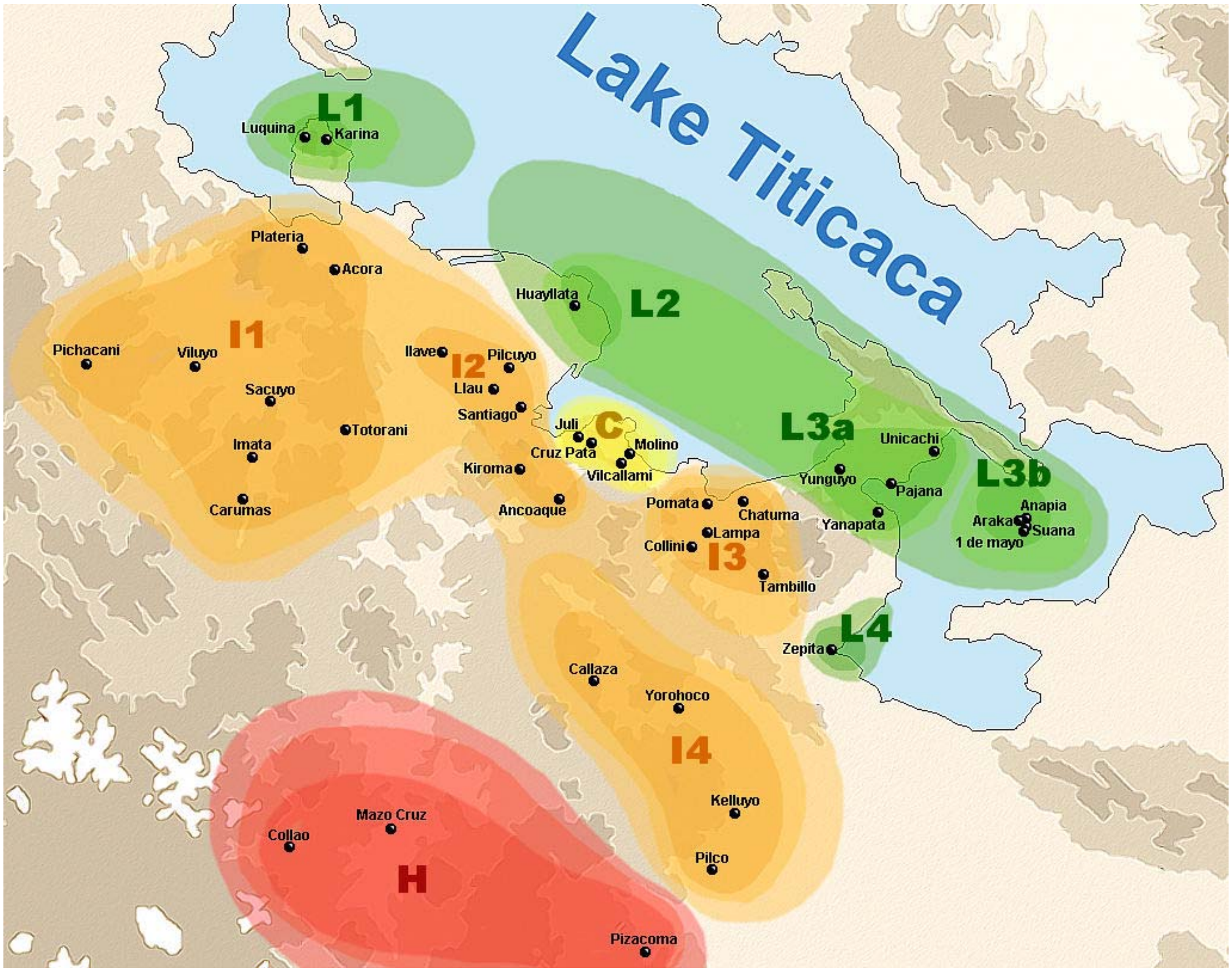


Figure 2: Lake Titicaca Rain Gauge Sites, and classifications on basis of correlation and proximity to the lake.

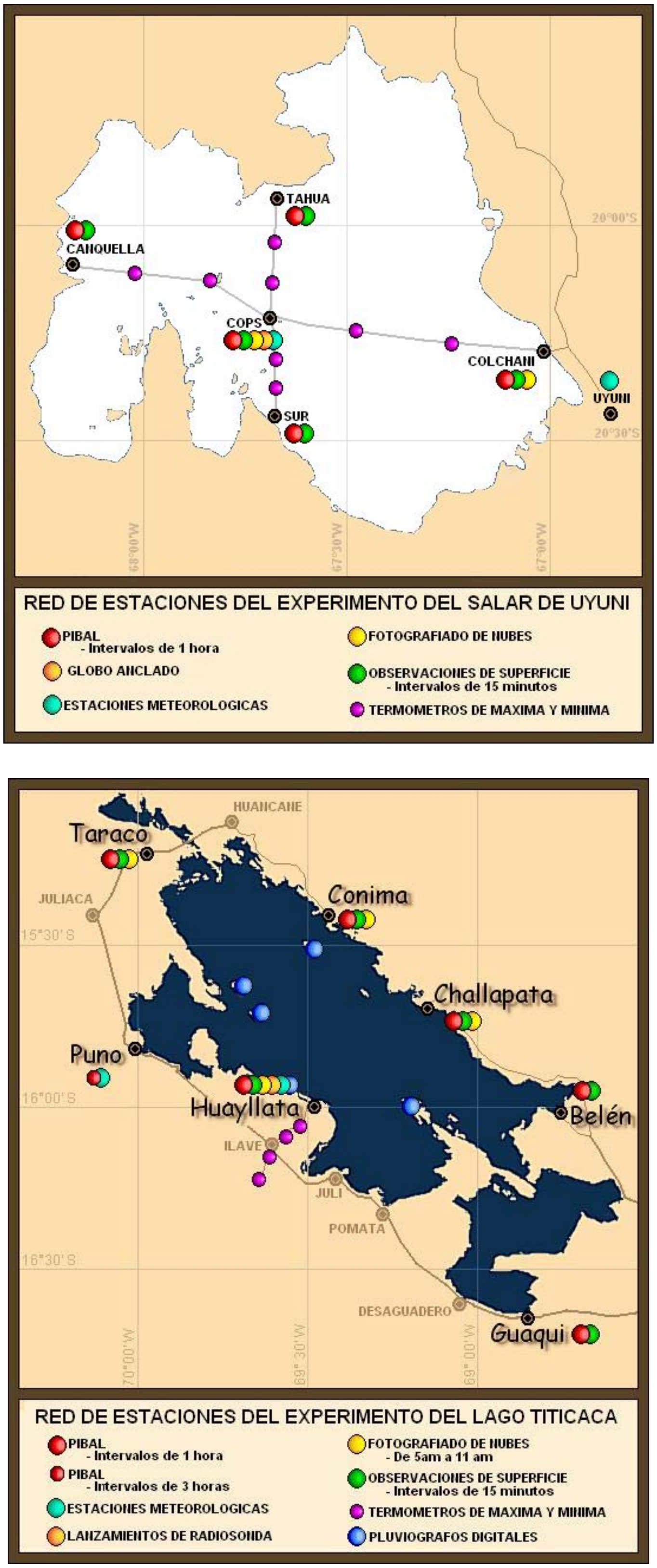


Figure 3: Map of location of Pibal Sites for the Salar de Uyuni and Lake Titicaca Experiments.

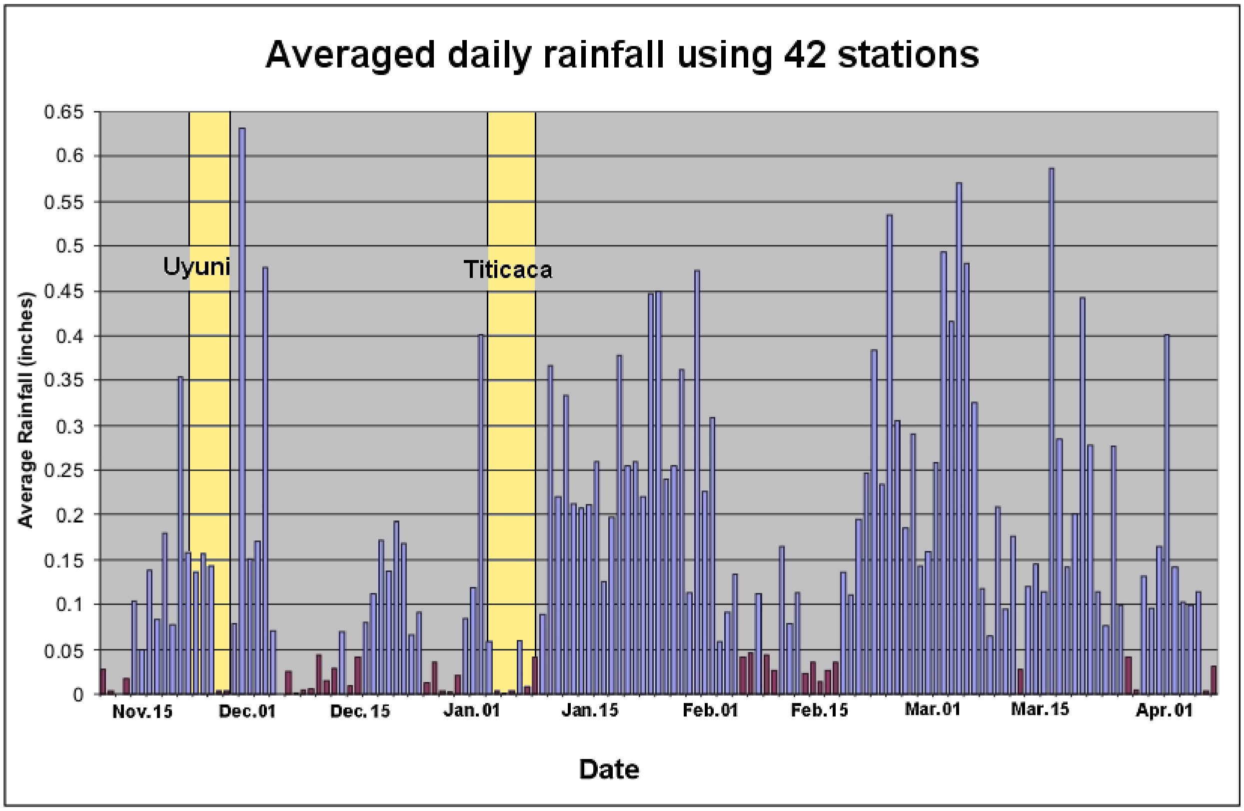


Figure 4: Timeseries from November 14, 2002 to April 6, 2003, of Average rainfall per day for all Titicaca Rain Gauge Stations, with darker bars indicating averages below the threshold of 0.05 inches and highlighted areas indicating the time periods of the Salar de Uyuni and Lake Titicaca Experiments.

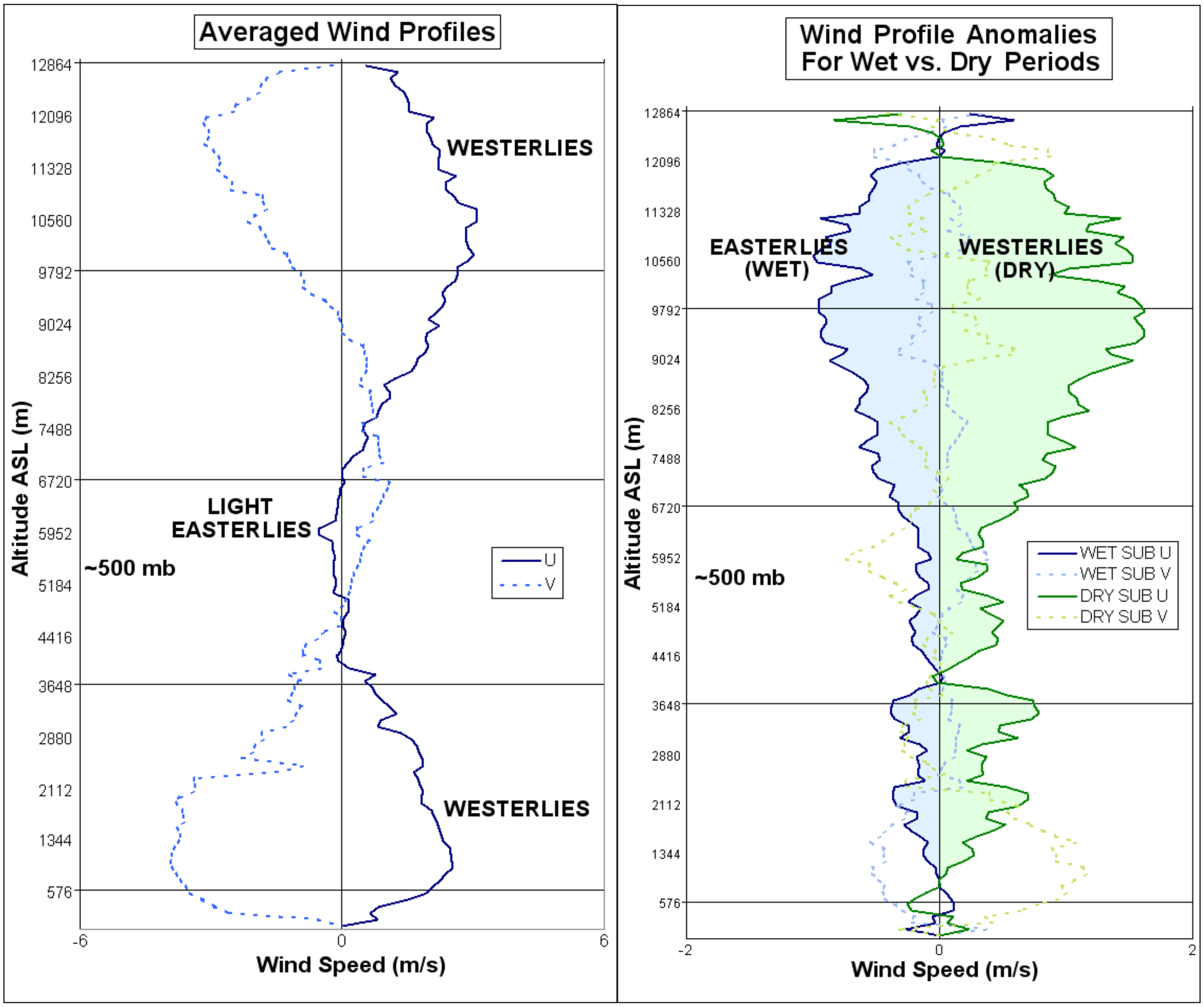
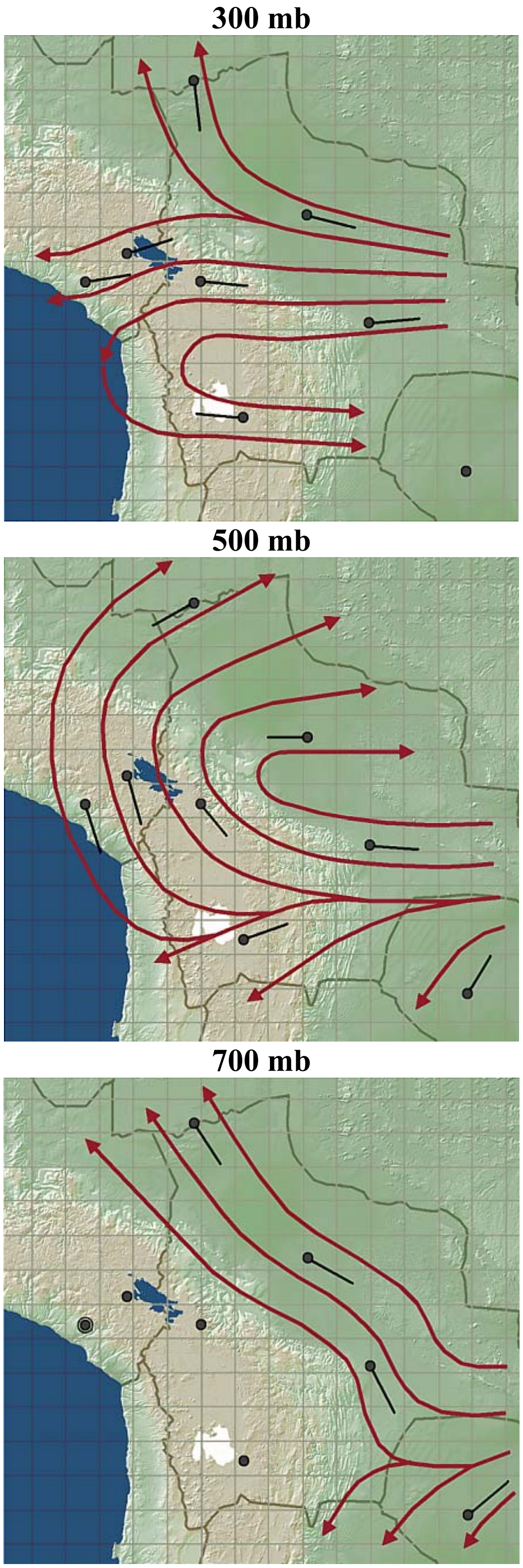


Figure 5: Averaged wind profile with u and v components in m/s, for all sounding during the austral summer from November 14, 2002-April 6, 2003. Wet and dry wind anomalies plotted with u and v components for selected wet and dry periods during the austral summer.



300 mb

500 mb

700 mb

Figure 6: Streamline analysis of anomalous flow of wet minus dry periods using eight selected SALLJEX pibal stations. Analysis at 300 mb, 500 mb, and 700 mb.

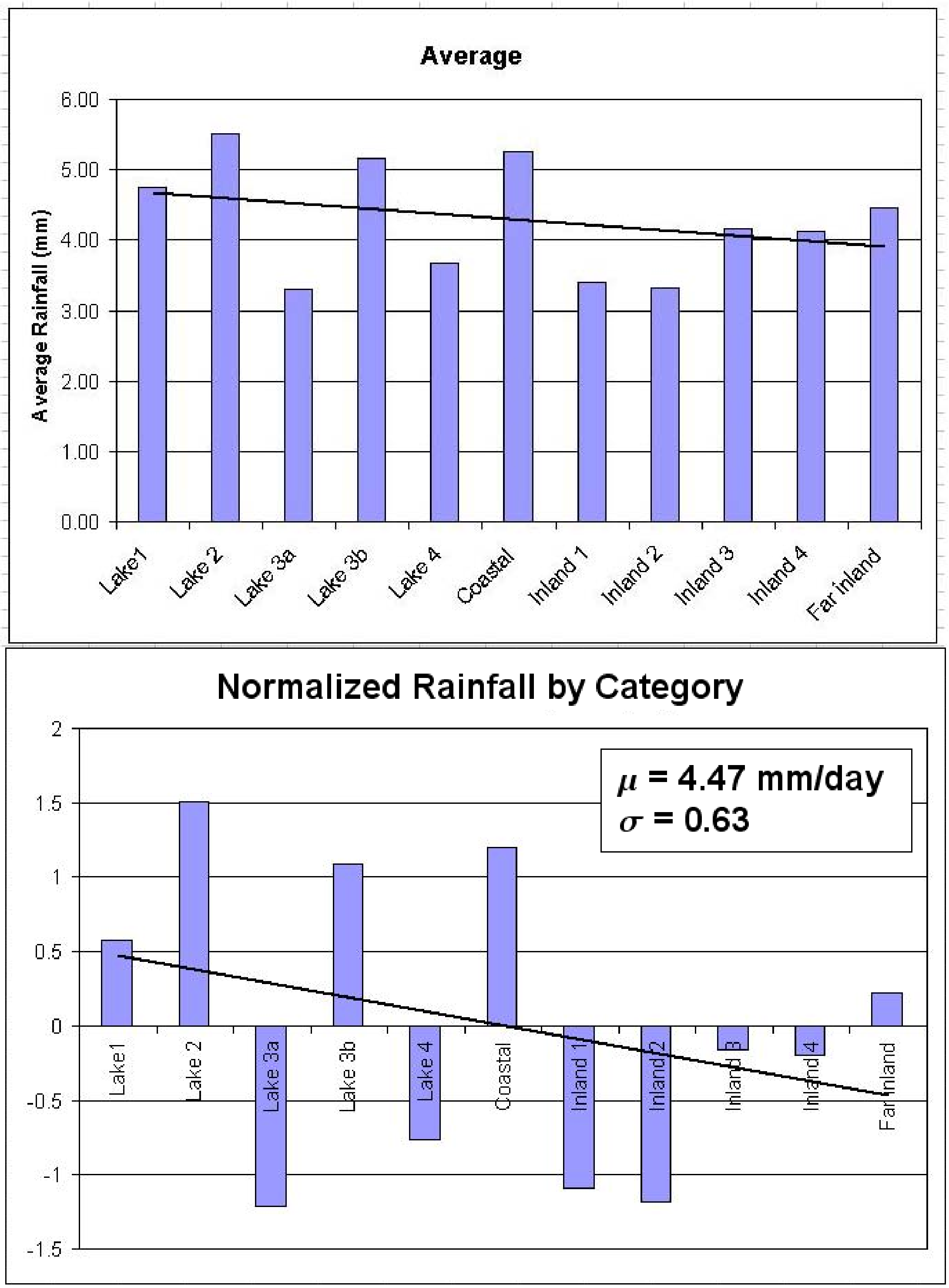


Figure 7: Average daily rainfall in millimeters and normalized rainfall by category and distance from the Lake.

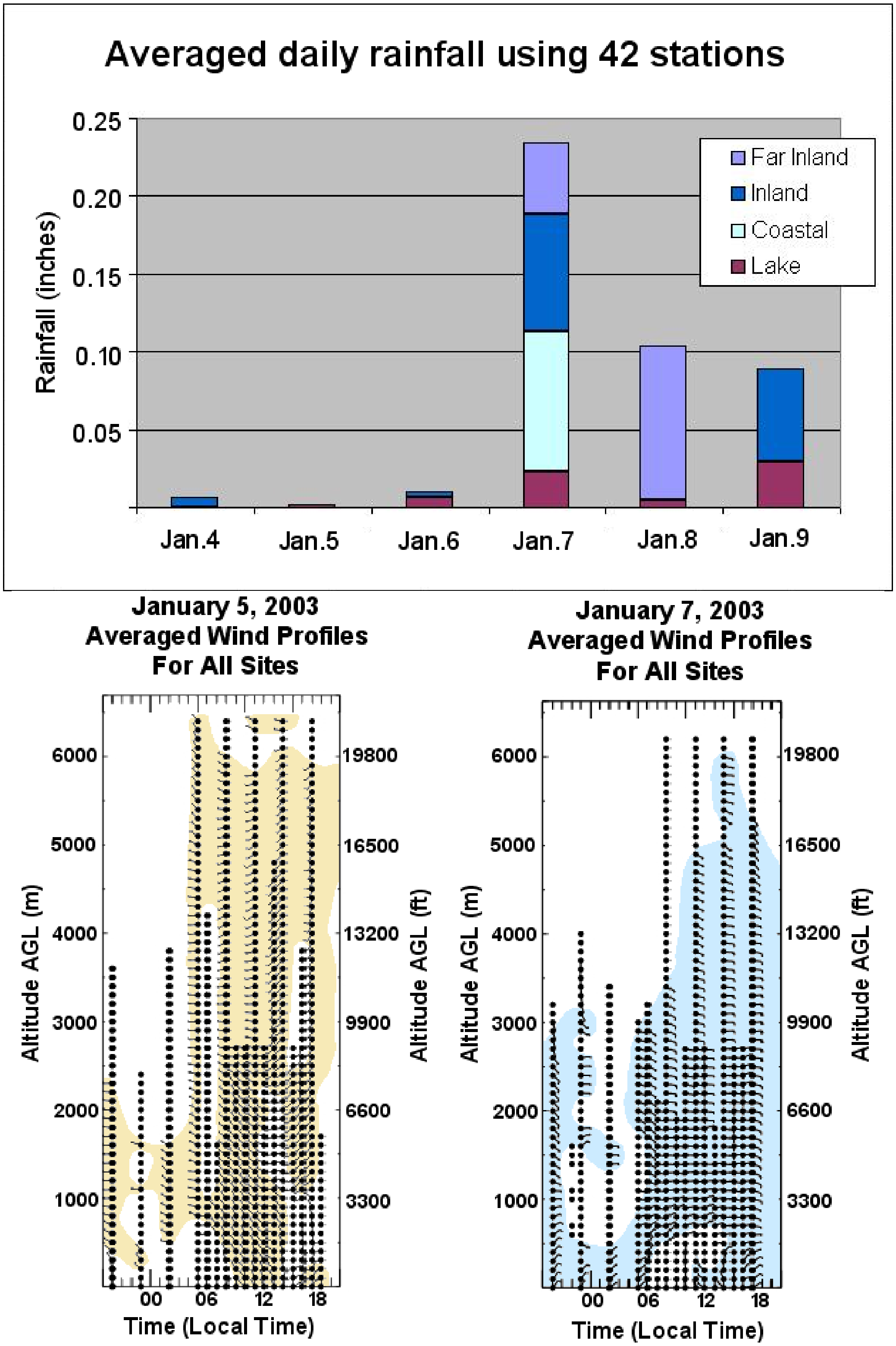


Figure 8: Comparison of dry and wet days of the Lake Titicaca Experiment. Graph of total average rainfall in inches for each of the days of the experiment, with classifications indicated. Hourly Average for all sites, for pibal sounding on driest and wettest days (Jan.5 & Jan.7) with westerly and easterly flow shaded.

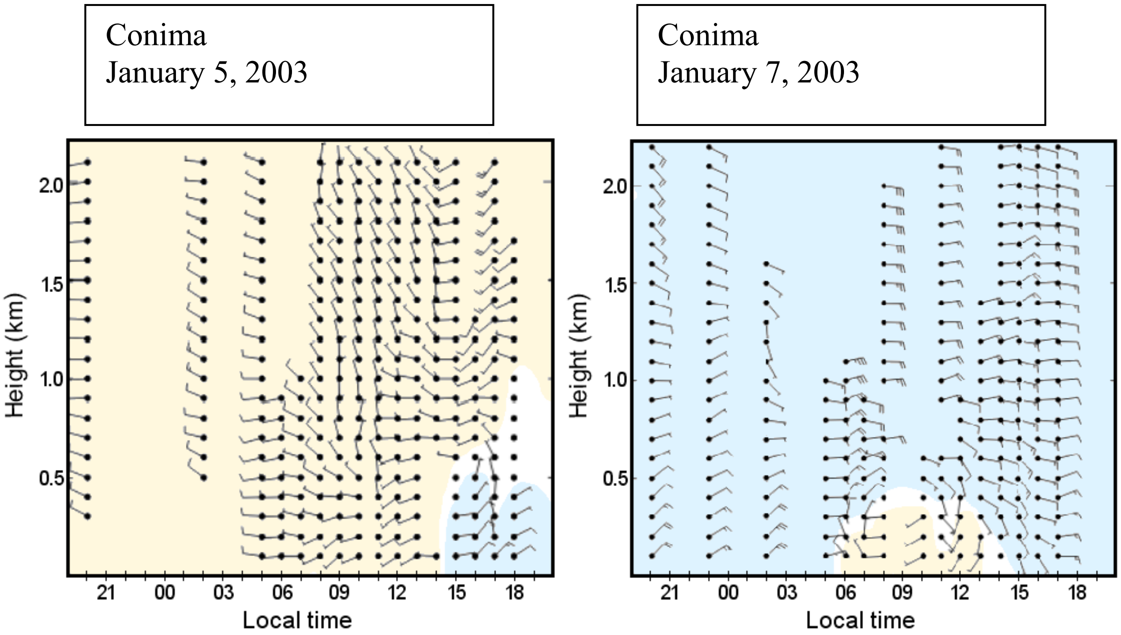
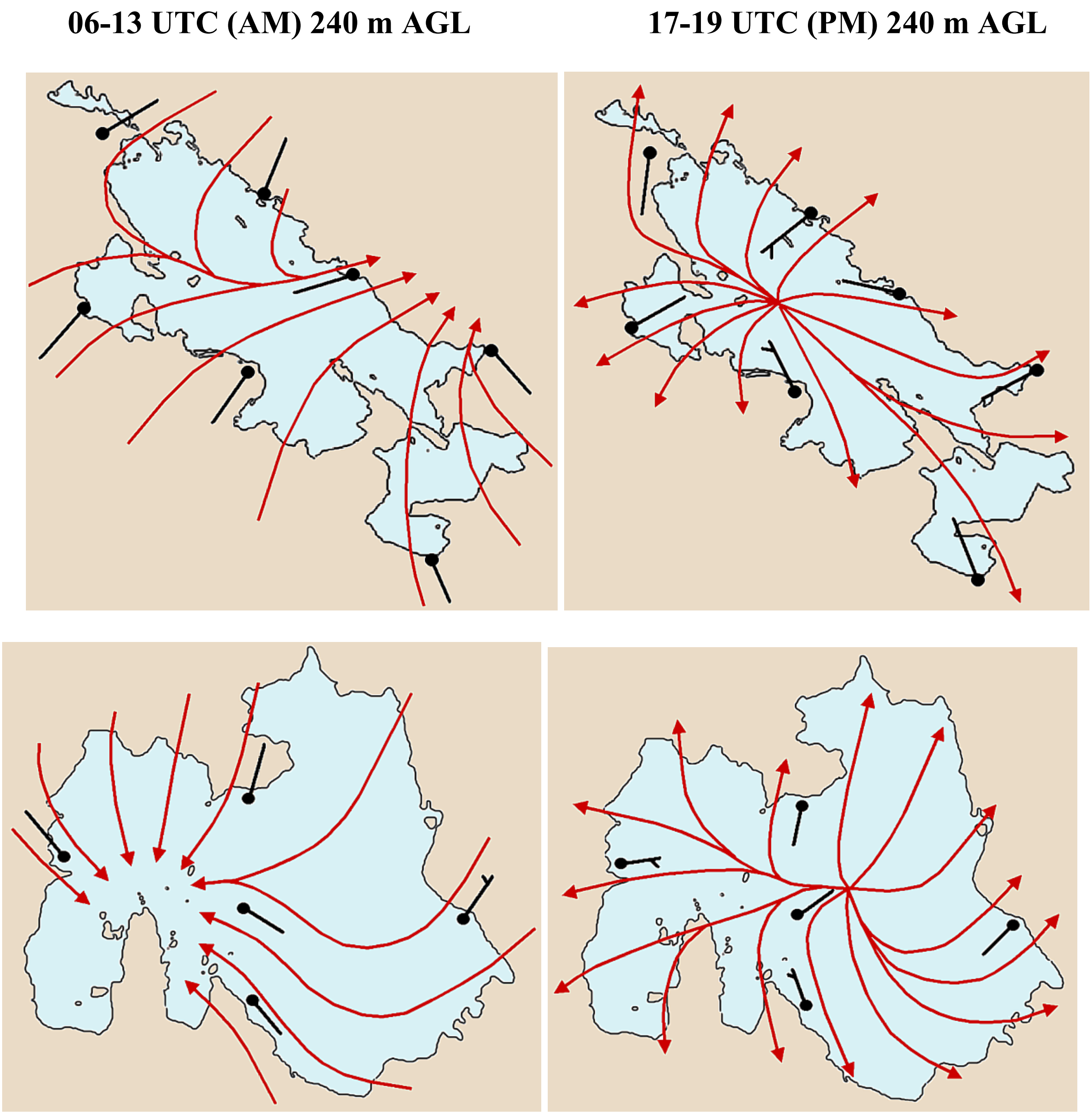


Figure 9: Hourly Pibal soundings up to 2000 m above the surface at Conima for January 5, 2003 and January 7, 2003.



06-13 UTC (AM) 240 m AGL

17-19 UTC (PM) 240 m AGL

Figure 10: Streamlines analysis of anomalous flow over Lake Titicaca and Salar de Uyuni for 06-13 UTC (AM) and 17-19 UTC (PM) at 240 m AGL.