OBSERVED DIURNAL CIRCULATIONS AND RAINFALL OVER THE ALTIPLANO DURING THE SALLJEX

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OBSERVED DIURNAL CIRCULATIONS AND RAINFALL OVER THE ALTIPLANO DURING THE SALLJEX

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ABSTRACT

The South American Altiplano has been exposed to prolonged (>1000-year) dry and wet periods in the past according to paleoclimate records. The transitions between these climatic states, however, seem to have occurred rapidly. This study provides a background for understanding the role of mesoscale processes in dry-to-wet transitions by describing lake- and salar-induced circulations and rainfall over the present altiplano from special observations. These include special networks of pilot balloon and daily rainfall observations collected in the vicinity of Lake Titicaca and the Salar de Uyuni during the rainy season of 2002-3, as part of the South American Low Level Jet Experiment (SALLJEX). Rainfall observations indicate that nocturnal convection over Lake Titicaca is nearly double the rainfall amounts over the surrounding altiplano with values that exceed 200 mm mo^{-1}. Over the Salar de Uyuni, however, convective clouds are largely absent according to satellite observations. Daytime onshore flow and associated low-level divergence were observed over both Lake Titicaca and the Salar de Uyuni, with comparable magnitudes but larger values over the latter. Nocturnal offshore flow and associated low-level convergence were present over the lake but not over the salar, where the divergence values neared zero by sunrise. The arrival of flow from gaps in the surrounding mountain ranges, present near both features, produces rainfall only over the lake. The lack salar-induced nocturnal convergence and high boundary layer moisture content seem to be the factors that suppress the generation of rainfall over the salar.

1. INTRODUCTION

The South American altiplano is an elevated plateau located in the Central Andes between 14°S and 22°S (Figure 1). It is also a closed basin with a surface area of 196,000 km^2. The orography is characterized by a flat corridor that slopes gently downward from ~3850 meters above sea level (mASL) at 15°S to 3653 mASL at 20°S. The plateau is surrounded by mountain ranges whose peaks exceed 6000 mASL, and it shelters numerous lakes and dry salt flats (known locally as “salars”), the largest of which are Lake Titicaca (16°S) and the Salar de Uyuni (20°S). The climate is semi-arid with annual rainfall totals that near 200 mm yr^{-1} in the southwestern sectors and exceed 800 mm yr^{-1} over Lake Titicaca. Most of the rainfall occurs during the austral summer, with 90% concentrated between November and March (Garreaud and Aceituno, 2000).

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The altiplano has been exposed to prolonged (<1000 year-long) dry and wet periods as revealed by high-resolution paleoclimate records. Some of the wet periods were sufficiently long and intense to lead to the formation of paleolakes, which at some point covered most of the southern altiplano and the plains adjacent to Lake Titicaca. During recent history, flooding due to prolonged wet conditions has also been observed. Persistent rainy conditions in the upper altiplano cause the levels of Lake Titicaca to rise and the lake to overflow, which produces (1) flooding in the populated Lake Titicaca sector (Bourges et al, 1992) and (2) a southward migration of the overflowing waters, which sometimes fill the Salar de Uyuni with several centimeters of water (Sylvestre et al., 2001).

The transitions between dry and wet climate regimes have been investigated by different authors in term of changes in the planetary circulation and insolation over the altiplano. Baker et al. (2001) noted that the main wet and dry phases occurred, respectively, in phase with summertime (January) insolation maxima and minima. Abbott et al. (2003)

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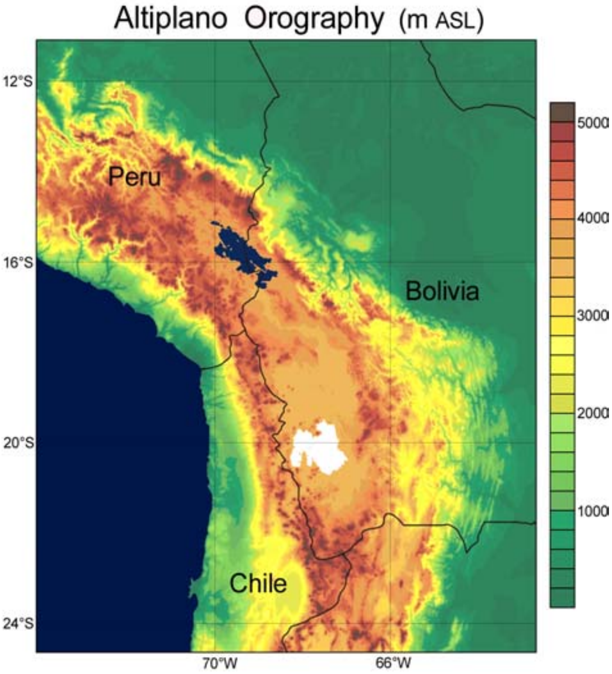


Fig. 1. Altiplano 30-second USGS terrain elevation in mASL. Lake Titicaca (16°S/69.5°W) and Salar de Uyuni (20°S/67.5°W) are indicated with dark blue and white respectively. The Pacific Ocean to the west is in dark blue. Country names and boundaries are indicated in black.

suggested that the insolation changes should influence the location and strength of the Bolivian High, an upper troposphere anticyclone that forms over the altiplano during the rainy season, and strongly affect the precipitation regime over the region. Remote climate fluctuations also seem to play a role. Baker et al. (2001) argued that periods of enhanced trade winds over the north Atlantic lead to increased advection of moisture into the Amazon and altiplano and consequently lead to rainy conditions. Although the role of planetary-scale changes on dry-to-wet altiplano climate transitions has been explored, the role of local processes such as lake- and salar- induced mesoscale circulations has not been documented in the literature.

The precipitation falling over Lake Titicaca, which accounts for ~55% of the lake's water input (Ronteltap, 2004), appears to be mostly produced by nocturnal convective storms (Figure 2). These storms are triggered by the convergence of offshore flow over the lake. If the development of nocturnal convection were mainly a function of the strength of the convergence over a lake, a salar flooded with a sufficiently deep layer of water should trigger the nocturnal convection mechanism by modifying the strength of the nighttime land breezes and by changing the low-level stability. Persistent convection over the salar would preserve and enlarge the depth of the water layer eventually turning the salar into a lake and possibly shifting the overall altiplano climate towards wetter conditions. The importance of the above hypothesis, which is very speculative, is that it involves mesoscale meteorological processes in the change from a dry climatic state to a wet one over the altiplano. Such a mesoscale-induced climatic state transition, if it exists, would be very difficult to incorporate into climate models attempting to model paleoclimate states of the altiplano, since their spatial resolution is far too coarse to model the mesoscale processes producing the rainfall associated with the altiplano lakes.

The present study, based on Galvez (2005), uses observations to describe the mesoscale circulations and rainfall induced by Lake Titicaca and Salar de Uyuni. This approach provides (i) a background to start understanding the role of mesoscale processes on the salar-lake transitions, (ii) helps to provide a context for interpreting weather and climate on fine spatial scales over the altiplano region and (iii) provides a description of the atmospheric conditions that lead to large rainfall amounts for regional and climate forecasting improvements.

Fig. 2. Nocturnal convective storm that developed over the western shore of Lake Titicaca during the PACS-SONET December 2000 Field Experiment. The picture was taken from the the town of Copacabana, on the south-central side of the lake, looking west. Note stars in the sky. The picture was taken using a digital camera with long time exposure.

2. METHODOLOGY

The present study is merely observational. The analysis is based upon hourly pilot balloon wind profiles and surface observations collected in the vicinity of Lake Titicaca and Salar de Uyuni, daily rainfall observations collected on the Peruvian side of the altiplano, and GOES-8 infrared satellite imagery. The period of study is the rainy season (Nov-Feb) of 2002-3. The observations were made as part of the South American Low Level Jet Experiment (SALLJEX), which involved an increased number of atmospheric measurements over a broad region.

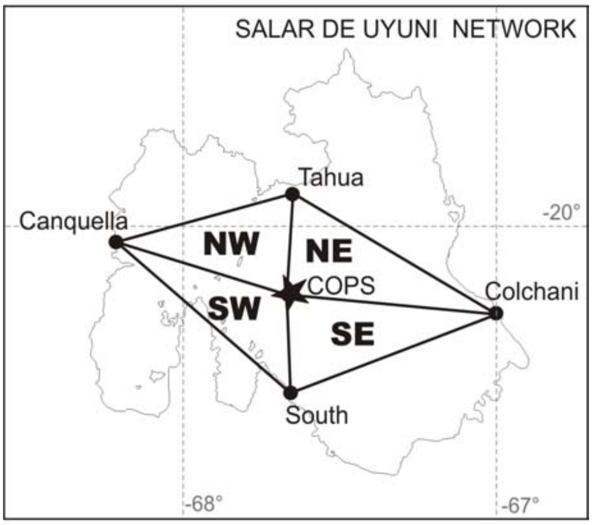
Wind data

The pilot balloon wind data were collected during two short (5-7 consecutive days each) independent field campaigns carried out in the vicinity of the Salar de Uyuni and Lake Titicaca. Both experiments consisted on networks of 5 to 7 pilot balloon stations (Figure 3). The sites were located to minimize, as much as possible, very local topographic effects, yet still form reasonable polygons for areal divergence calculations to infer vertical motions (Figure 3).

The Salar de Uyuni experiment, carried out during 25-30 November 2002, consisted of 5 pilot balloon stations with one located near the center of the salar. The Lake Titicaca experiment, carried out during the period 3-9 January 2003, consisted of 7 pilot balloon stations distributed along the edges of the lake. All of the stations were operated by volunteer observers from different South American institutions, principally the Universidad Mayor de San Andrés (UMSA), the Administración de Aeropuertos y Servicios Auxiliares para la Navegación Aérea (AASANA), the Bolivian Weather Service (SENAMHI-Bolivia), the Instituto Geofísico del Perú (IGP) and the Peruvian Weather Service (SENAMHI).

Diurnal soundings were collected on an hourly basis and nocturnal soundings at 3-hour intervals. The data were quality controlled, sounding by sounding, and then exposed to a linear interpolation in time whenever 1 or 2 hourly observations were missing. Fortunately, at lower levels where the effects of the salar and the lake are expected to be the largest, not much interpolation was needed. For breeze analyses onshore and offshore components of the flow were considered. Over Lake Titicaca, a 40° counterclockwise rotation was applied to obtain the along-lake and across-lake components of the flow. A 3-hourly centered mean was finally applied to reduce the amplitude of high frequency variations (“meteorological noise”) associated with the flow.

Divergence was computed from the pilot balloon data using one of the methods described by Davies-Jones (1993). A linear windfield was assumed between stations and the divergence calculated for each of the triangles presented in Figure 3, solving for systems of 2x2 equations.



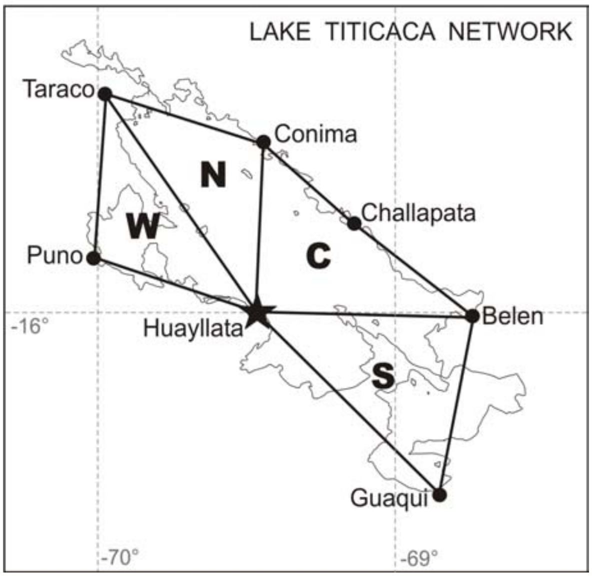


Fig. 3. Salar de Uyuni (top) and Lake Titicaca (bottom) pilot balloon networks and polygons used for the divergence estimations. Four triangular regions were analyzed over Lake Titicaca (West, North, Central, and South) and 4 over Salar de Uyuni (NE, SE, SW, E).

Rainfall data

The rainfall data were collected on a daily basis using simple plastic raingauges (hereafter, SALLJEX raingauges) during Nov-May 2002-3. The network design considered placing the highest densities on the islands and along the shores of Lake Titicaca, since the purpose was to describe the gradients associated with the lake-induced nocturnal storms. The Peruvian side of the network provided data for ~200 sites. Data from the Bolivian side of the network, unfortunately, could not be recovered. The gauges were operated by volunteer observers trained during the installation campaign. To assure data quality, simple forms and a manual describing the process to measure rainfall were handed out and explained to the observers at every site. Quality control procedures applied to the rainfall datasets included (1) comparison of rainfall from SENAMHI sites in which SALLJEX raingauges were operated simultaneously and (2) station-to-station correlations to filter the low-correlated sites.

Satellite data

Satellite composites were constructed using GOES-8 infrared satellite data provided by the UCAR Joint Office of Science Support (JOSS). The data have a horizontal resolution of 4 km and a temporal resolution of 30 minutes, providing 48 frames to describe the diurnal cycle of convection. Even though the direct relationship between rainfall and cloud top temperature is quite complex, this tool was found useful to describe the basin-wide distribution and evolution of the cold clouds, and in particular the diurnal cycle, since the raingauge network provided only daily rainfall data.

GOES-8 IR4 brightness data were converted into temperature using table 5-1a provided by Weinreb et al. (2001). The frequency of convective clouds was evaluated at different levels by analyzing the cloud top temperatures colder than different temperature thresholds. Time series of daily averages obtained from these calculations were correlated with the lake station rainfall observations measured at the corresponding pixels. The largest correlations occur at a temperature threshold of ~ –13°C which suggest that this temperature threshold is preferred for the generation of the satellite composites. The diurnal cycle of convection was constructed by calculating half-hourly composites of cold cloud frequencies over the entire Altiplano. Then the diurnal cycles of cold cloudiness for LESDs and NLESDs were constructed. The seasonal diurnal cycle was subtracted to obtain the departure of the cold cloud temperature frequencies from the seasonal average to compare convection anomalies from both categories.

3. RESULTS

Rainfall and convection

The diurnal cycle of convection from satellite composites is summarized in Figure 4 where two extremes of the cycle are presented. The left panel illustrates the afternoon convection peak and the right panel the nocturnal convection counterpart in terms of 4-hour averaged frequencies of clouds with temperatures colder than –15°C. Although rainfall cannot be related directly to these composites, they do provide information about where and when convection with tops above ~450 mb occur in the altiplano.

The afternoon analysis suggests the presence of convection during more than 35% of the days near the edges of the basin except over the southern altiplano. The westward displacement of the maxima from the mountain ranges in the northern altiplano and the dry southwestern altiplano range reflect the large scale circulation with easterly/westerly flow in the northern/southern altiplano. Frequency minima can be observed over Lake Titicaca and over Salar de Uyuni. The orders of magnitude of these minima are of 12% and 3% respectively, and they are contaminated by cirrus clouds from the storms that develop over land. The frequency of surface-based convection over these features during the afternoon may actually be considerably lower than what the composite indicates.

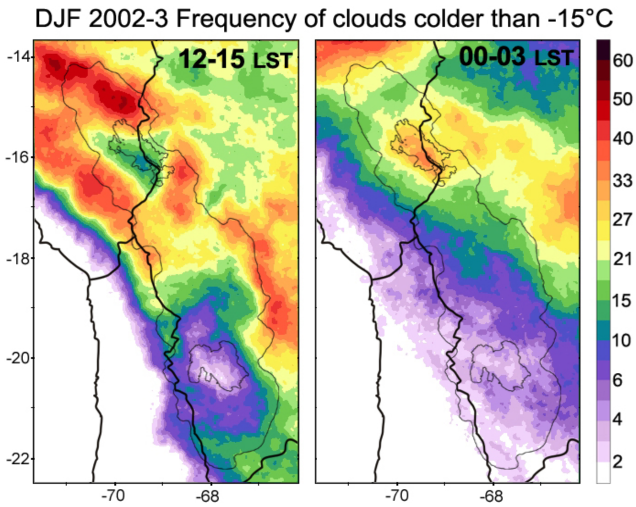


Fig. 4. Diurnal cycle of convection from the seasonal (Dec-Feb 2002-3) frequency of clouds colder than –15°C calculated for 12-15 LST (left) and 00-03 LST (right). Country borders are indicated with a thick black line. Thin lines are used to delimit the altiplano, Lake Titicaca and Salar de Uyuni.

The diurnal convection, which peaks towards the end of the afternoon, weakens after sunset and propagates towards the east, approaching the center of the basin before midnight. The cold cloud frequency maximum over Lake Titicaca occurs between 22 and 01 LST and although the frequency decreases towards the morning, it yet remains larger than the cold cloud frequency over the surrounding terrain. The nocturnal analysis displayed in Figure 4 indicates a frequency maximum on the order of 30% over Lake Titicaca and a minimum on the order of 3% over the Salar de Uyuni between 00 and 03 LST. This not only suggests that the convection over Lake Titicaca occurs primarily during the night but also highlights the absence of convection over the salar during the same period.

An analysis of the rainfall accumulated during the December-February 2002-3 period is presented in Figure 5. According to this analysis, the nocturnal convective storms that form over Lake Titicaca represent the largest source of rainfall over the northern

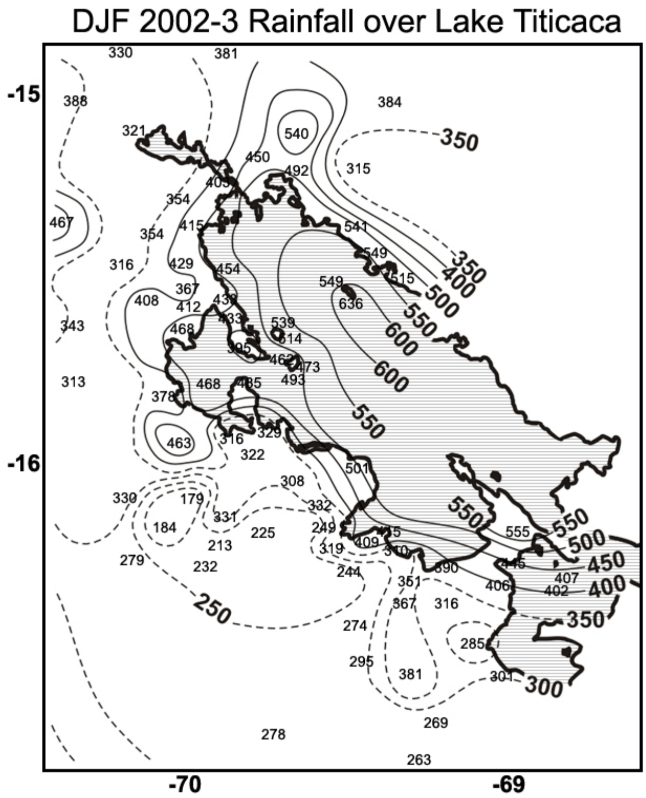


Fig. 5. Rainfall totals in the vicinity of Lake Titicaca collected during December-February 2002-3. The lake is outlined with thick black line and shaded with gray horizontal lines. Rainfall isophlets larger than 350 mm are indicated with solid lines and the rest using dashed lines.

altiplano. During the December-February 2002-3 period the observed values were as high as 200 mm month^{-1} over the lake, almost twice the 110 mm month^{-1} collected along a ~50km-wide strip that extended inland from the lakeshore. The analysis incomplete since the eastern part of the domain belongs to Bolivia, where the observations could not be recovered.

Lake- and Salar-induced circulations

Figure 6 summarizes the morning (07 LST), afternoon (13 LST) and evening (19 LST) mean winds for the 100-200 mAGL layer during the Lake Titicaca and Salar de Uyuni experiments. For Lake Titicaca the observations show flow towards the lake during the morning, and flow towards the land during the afternoon. During the evening northeasterly winds extend across sites on the eastern side of the lake. The Salar de Uyuni shows a less coherent pattern of winds, with weak morning winds becoming uniformly outward-flowing from the salar during the afternoon. By the evening there are much stronger winds from a southwesterly direction extending across the salar. This afternoon increase in the westerly winds was noted vividly at each site, and some of the sites had their tents blown down by the strong winds. These winds were not the product of convective downdrafts, as there were few if any clouds to the west. The depth of the onshore breezes was also calculated and found to range between 700 and 1400 mAGL for both the lake and the salar.

The diurnal cycle of divergence calculated over the polygons illustrated in Figure 3 is presented in Figure 7. Ignoring the large values of convergence during the evening and early night associated with the strong flows over the lake and salar, the divergence values oscillate between –50 x $10^{-6}s^{-1}$ and +100 x 10^{-6} s^{-1}. The largest values of late-night / early-morning (05-08 LST) convergence occur over Lake Titicaca and range between –50 x 10^{-6} s^{-1} and -10 x 10^{-6} s^{-1}. Over the Salar de Uyuni the flow remains divergent during the same period with low values of convergence around 07 LST

During the day both features induce divergence with larger values over the salar. Over Lake Titicaca the divergence ranges from +10 x 10^{6} s^{-1} to +60 x 10^{6} s^{-1} between 12 and 04 LST, whereas over the salar it ranges from +30 x 10^{6} s^{-1} to +120 x 10^{6} s^{-1} during the same period. A clear change between convergent flow towards divergent flow over the Lake occurs at about 8:30 LST over all the polygons.

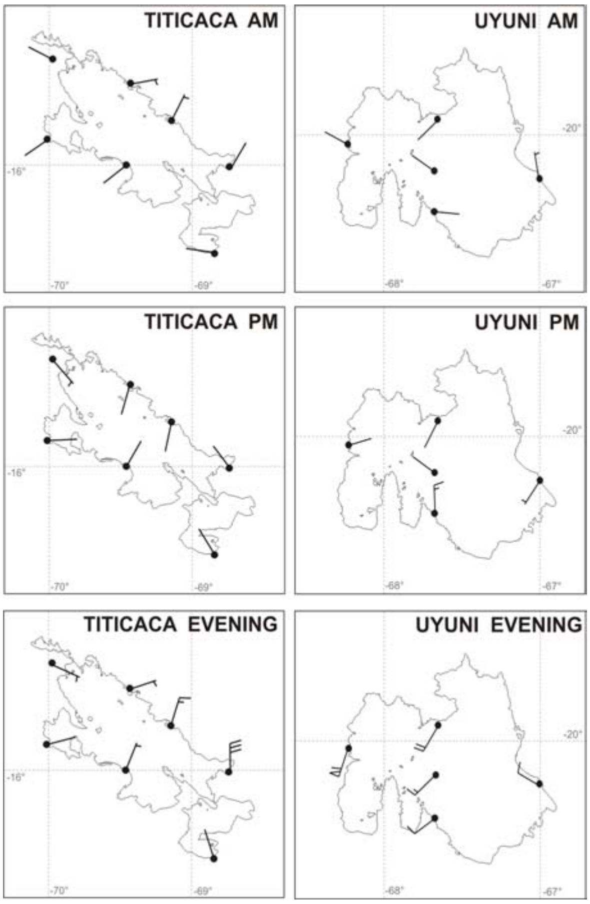


Fig. 6. Winds for the 100-200 mAGL layer, averaged for the Lake Titicaca (left) and the Salar de Uyuni (right) experiments and plotted for different times of the day. The top panels represent the early morning winds corresponding to the hour of maximum convergence (07 LST). The central panel illustrates the winds corresponding to the hour of maximum divergence (13 LST). The bottom panels correspond to the periods with the strongest winds (19 LST). The wind barbs are in knots.

in the southern tier. The values range from $-10 \times 10^{-6} s^{-1}$ to $+40 \times 10^{-6} s^{-1}$. According to these findings we can infer that, as expected, the nocturnal convergence induced by the lake is larger than that induced by the salar, if any.

Strong evening convergence occurs over the lake and the salar in response to the strong northeasterly and southwesterly winds that develop respectively. The largest values occur over the salar and reach $-200 \times 10^{-6} s^{-1}$ in two of the sectors analyzed. Although the weaker flow over Lake Titicaca produces weaker convergence that peaks at $-100 \times 10^{-6} s^{-1}$ in the northern end of the lake at 21 LST, convection develops only over the lake whereas the salar remains dry. Furthermore, the period of most frequent convection over Lake Titicaca is in phase with the period of maximized convergence, which suggests that low-level convergence is an important forcing in the generation of convective storms over Lake Titicaca when additional atmospheric conditions are prone for their development. This conditions seem to be absent over the Salar de Uyuni, which implies that convergence alone is not sufficient for the development of convection over the salar. There are other factors that must be present for its development and are not.

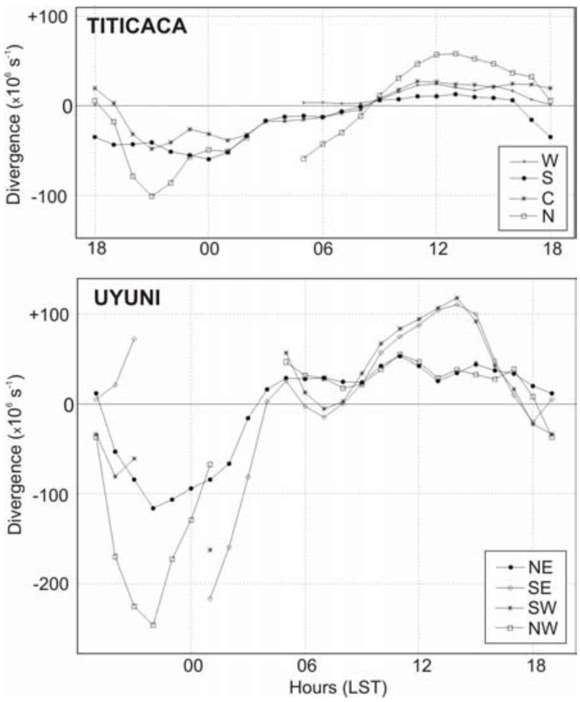


Fig. 7. Average diurnal cycle of divergence at 100-200 mAGL, for Lake Titicaca (top) and for the Salar de Uyuni (bottom). Each panel shows four curves; these give the time-evolution of divergence over each of the triangles shown in Figure 3. Strong nighttime winds prevented many nighttime observations for the Uyuni experiment.

4. CONCLUDING REMARKS

Lake Titicaca produces rainfall totals (~200 mm mo^{-1}) that nearly double those that occur over the surrounding altiplano. The most frequent convective development occurs during the night with a maximum between 22 and 01 LST. In contrast, convection is absent over the Salar de Uyuni according to satellite data, with cold cloud frequencies lower than 5% throughout the entire diurnal cycle. Although the frequency of cold clouds seems to be larger during the afternoon that during the night except over Lake Titicaca, the rainfall rates that the nocturnal clouds produce appear to be larger than the ones produced by the afternoon ones. This suggests that non-explored factors such as dry air entrainment and microphysical processes could be playing a role on the production of lower rainfall rates over land than over the lake, and should be explored with detail in a future study.

The diurnal onshore breezes induced by both Lake Titicaca and the Salar de Uyuni are of comparable magnitude (1-3 m s^{-1}) and depth (700-1400 m AGL), whereas nocturnal offshore breezes are observed only over Lake Titicaca with speeds in the order of 1-2 m s^{-1}. The salar's "onshore" breezes are slightly stronger (+0.5-1.5 m s^{-1}) and more organized than those induced by the lake in response to larger diurnal temperature contrasts in the drier and less complex surrounding terrain of the southern altiplano. Calculations at 150 mAGL showed divergent flow during the afternoon over both features. During early morning, however, convergence is present over the lake but not over the salar, which suggests that the nocturnal surface temperature contrasts in the salar region may not be sufficient to develop offshore circulations. The inability of the salar to induce low-level convergence does hinder the development of nocturnal convection over it. Non-dynamical forcing factors, however, seem to play a role as well in the suppression of the development of convection over the salar. This was revealed by the absence of surface-based moist convection over the Salar de Uyuni during periods of strong low-level convergence (~ 200 x $10^{-6}s^{-1}$). These periods were produced by strong late afternoon southwesterly flow that develops on a daily basis. This suggests the lack of high boundary layer moisture contents as a suppressing factor for surface-based convection over the Salar de Uyuni.

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