Proceedings of 8 ICSHMO, Foz do Iguaçu, Brazil, April 24-28, 2006, INPE, p. 745-752.

MODULATION OF RAINFALL BY LAKE TITICACA USING THE WRF MODEL

José M. Gálvez[1] and Michael W. Douglas[2]

[1] CIMMS/University of Oklahoma, Norman, OK 73069
[2] NSSL/NOAA, Norman, OK 73069

ABSTRACT

Rainfall over Lake Titicaca occurs in the form of nocturnal lake-induced convective storms. They represent ~55% of the lake's water input and therefore have implications in climate and paleoclimate scales. This study uses the Weather Research and Forecasting (WRF) model to investigate the role of the lake in the modulation of these storms. The goals are to improve regional weather and climate forecasts and to provide information about the role of lakes on dry-to-wet transitions in the altiplano. The results point to low-level convergence and moisture as essential for the development and maintenance of the storms. The mid-tropospheric flow also seems to play an important role in their enhancement or suppression based on the interaction with local circulations induced by orography. Weak southeasterly flow favors storm development. Strong flow, especially from the northeast, suppresses storm development by shifting the region of low-level convergence away from the source of heat and moisture.

1. INTRODUCTION

Rainfall over Lake Titicaca has an important role on the hydrology of the South American Altiplano. Prolonged rainy conditions over the Titicaca basin cause the lake levels to rise and overflow. This produces (1) flooding in the highly 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). Given that precipitation represents the 55% of the water input for the lake (Ronteltap, 2004), forecasting rainfall over Lake Titicaca turns out to be important to diagnose changes in the levels of the lake.

On the other hand, paleoclimate studies have revealed that the altiplano has been exposed to several prolonged dry and wet periods in the past, some of which lead to the formation and dissipation of large paleolakes. The mechanism of formation is similar to that described in the above paragraph: through increased rainfall and flooding of the lowest portions of the basin. Although 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, the role of the mesoscale circulations induced by the lakes and dry salt flats has not been explored yet. This study does so using numerical Weather Research and Forecasting (WRF) model simulations to complement observational and numerical modeling findings described by Galvez (2005). Understanding the role of the lake-induced circulations and rainfall will provide general information about the role of the altiplano lakes in dry-to-wet climate transititions that have been observed over the region in millennial timescales.

The main goal of this study is therefore to describe the circulations and rainfall induced by Lake Titicaca using WRF model numerical simulations, with the ultimate purpose of improving the local and regional weather and climate forecasts.

Figure 1. 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 Isla del Sol, near the center of the lake, looking west. It was taken during the night (note stars in the sky) using a digital camera with long time exposure.

2. METHODOLOGY

The study was carried out using the results from 2 sets of numerical experiments made with the WRF model (Skamarock et al., 2005). The first set was produced using NCEP Global Tropospheric Analyses as initial and boundary conditions for 10 cases within the SALLJEX period, herein referred as 'SALLJEX simulations'. The second set are idealized simulations constructed using ideal thermodynamic and momentum profiles and will be referred as 'Idealized simulations'. The domains covered by these set of experiments are summarized in Figure 2. The experiments were carried out on a Dual-Core Intel Xeon Processor computer. For both sets of simulations, the bottom boundary conditions were the standard data sets available for the WRF model. Lake Titicaca's surface temperature, however, had to be modified to a climatological annual mean value of 13°C (Carmouze, 1991) since it was originally set to 0°C. The convective parameterization was shut off given the horizontal resolution, assuming that rainfall could be simulated explicitly.

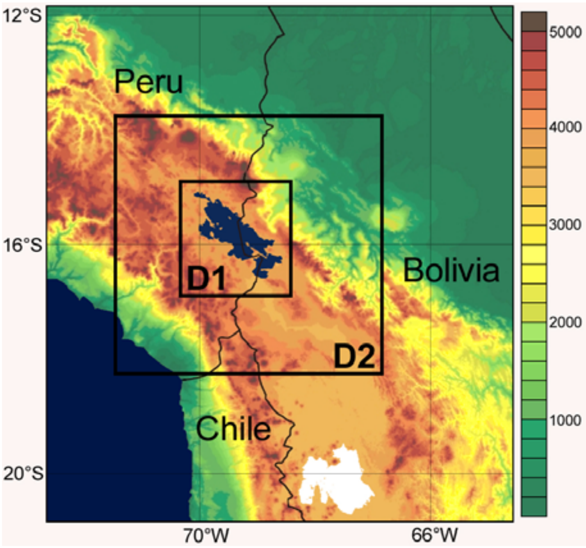

Figure 2. Altiplano orography in mASL and domains employed in the numerical study. D1 corresponds to the SALLJEX simulations and D2 to the idealized simulations. Lake Titicaca (16°S) is indicated with dark blue and Salar de Uyuni (20°S), the largest dry salt flat in the world, with white.

The model physical options employed are also described in Skamarock et al. (2005). The microphysical scheme (Lin et al. 1983; Rutledge and Hobbs, 1984) includes six classes of hydrometeors: water vapor, cloud water, rainwater, cloud ice, snow and graupel. This is a relatively sophisticated scheme in WRF and was chosen because ice microphysics may be important in the altiplano convective processes, given the altitudes where the convection occurs. The land surface model used in the WRF simulations was the Noah LSM (Skamarock et al, 2005), which has the purpose of providing sensible and latent fluxes to the boundary layer scheme. Based on the MM5 OSU land surface model, the Noah LSM uses a 4-layer soil temperature and moisture model with canopy moisture and snow cover prediction included. The surface layer processes are treated with the Monin-Obukhov similarity theory to compute surface exchange coefficients for heat, moisture and momentum. The Yonsei University (YSU) boundary layer scheme, the next generation of the MRF boundary layer scheme, was selected. It uses counter-gradient terms to represent fluxes due to non-local gradients, which adds an explicit treatment of the entrainment layer at the PBL top, and the vertical mixing is determined by the vertical stability. The RRTM longwave radiation parameterization by Mlawer et al. (1997) was employed. It is a one-dimensional (vertical) spectral band scheme that uses pre-set tables to accurately represent longwave processes due to water vapor, ozone, CO_2, and trace gases (if present), as well as accounting for cloud optical depth. For short-wave radiation the Dudhia (1989) scheme, extracted from MM5, was utilized. It is based on a simple downward integration of solar flux, accounting for clear-air scattering, water vapor absorption (Lacis and Hansen, 1974), and cloud albedo and absorption. It uses look-up tables for clouds from Stephens (1978).

i. SALLJEX simulations

The SALLJEX set of simulations consists on 10 numerical 24-hour long experiments carried out over the Lake Titicaca region with a horizontal resolution of 1.3 km. A box of 150x160x31 gridpoints was established as the simulation domain. The vertical resolution consists on 31 sigma levels with higher resolution in the lower troposphere. Each simulation is initialized at 12 UTC (07 LST) and extends 24 hours into DAY+1 at 12 UTC (07LST), capturing an entire diurnal cycle. The simulation is initialized in the morning to let the period of interest (00-12 UTC) be simulated at least 12 hours after the initialization. Another reason is to allow the diurnal circulations to moisten the altiplano boundary layer and produce a realistic distribution of moisture. The distribution of the nocturnal boundary layer moisture in the region is a function of the distribution of the convection during the previous afternoon and of the nocturnal convection that occurs simultaneously. Nocturnal boundary layer moisture in the altiplano exhibits therefore large spatial variability that the homogeneous-atmosphere initial conditions are unable to describe.

The initial and boundary conditions chosen are NCEP Global Tropospheric Analyses for the January-February 2003 period, which coincided with the peak of the northern altiplano rainy season. These are gridded analyses that cover the world every 6 hours and are prepared by the NCEP Final Global Assimilation System (FNL). The data in the analyses are organized in grids with a horizontal resolution of 1 degree and 26 pressure levels in the vertical. The FNL system collects observations from at least 6 hours past synoptic time ingesting a larger number of observations and producing more realistic analyses. From the 10, 6 simulations produced convection and are those initialized at 12 UTC on 12 Jan, 18 Jan, 20 Jan, 22 Jan, 25 Jan and 26 Jan. The ones that did not produce rainfall were the 05 Jan, 11 Jan, 30 Jan and 1 Feb simulations.

ii. Idealized simulations

Two additional simulations were carried out as part of an ongoing modeling experiment that has the aim to test the effects of the synoptic flow on the development of nocturnal storms over Lake Titicaca. The domain covered a region of approximately 500 x 500 km centered over the lake using a horizontal resolution of 2.5 km and 31 sigma levels in the vertical. The initial and boundary conditions were those of a horizontally-homogeneous atmosphere constructed using an average sounding. The vertical temperature and moisture profiles were obtained by averaging the NCEP Global Tropospheric Analyses over a box centered between 12°S-24°S and 61°W-73°W during the SALLJEX period. The moistest 10% of the soundings were selected to assure the generation of rainfall since the thermodynamic large-scale conditions seem to be key for the development of nocturnal rainfall over the lake (Galvez, 2005). Calm winds were used to initialize the control simulation (hereafter, CR) and weak southeasterly winds (~4 m s-1) to initialize the second simulation (hereafter, SE).

The simulation period extended 48 hours to (i) compare the results from the two simulated nights and to (ii) allow the diurnal circulations to moisten the altiplano boundary layer, consideration taken into account in the SALLJEX simulations design as well.

3. RESULTS

The WRF model was able to reproduce the circulations and rainfall induced by Lake Titicaca at resolutions of 1.3 and 2.5 km. The advantage of using a horizontal resolution of 1.3 km is that the grid captured the effects of Lake Titicaca reasonably well since the lake was resolved with at least 50 points in the across-direction. Conversely, the 2.5 km domain used about 30 grid points to represent it. The 1.3 km simulations also produced finer structures such as well-defined lines of convection and convective cells. As expected, the rainfall rates simulated were larger than those simulated by the 2.5 km simulations. An example is the nocturnal rainfall simulated using the 20-21 January 2003 initial and boundary conditions (Figure 3). The model was able to produce rainfall totals larger than 30 mm day^{-1}, which were actually present in the observations described by Galvez (2005) during the strongest lake-induced nocturnal convective events. On the other hand, the advantage of using a coarser domain was the feasibility of placing the boundaries away from the altiplano in order to capture the effects of flows generated from the eastern and western slopes of the Andes, as well as to simulate the entire Titicaca basin circulations.

i. Simulated diurnal cycle

The diurnal cycle of the circulations and rainfall over Lake Titicaca is here discussed in terms of the results from the CR simulation and complemented with results obtained by the SE and SALLJEX simulations. Comparisons with the observations presented by Galvez (2005) are considered for validation. Two features that should be considered before the analysis are the Consata canyon and nearby gap in the eastern mountain range. The Consata canyon is a valley located immediately to the northeast of Lake Titicaca and is part of the Amazon basin. This canyon is separated from the altiplano by a relatively low (~200 – 700 m above the altiplano level) mountain range that represents a gap in the eastern mountain range, which otherwise raises to 700 – 2000 m above the altiplano level. Furthermore, the distance between this narrow mountain range and the lake is in the order of 15-20 km. These characteristics together make the gap important in the transport of air from the eastern slopes of the Andes into the Lake Titicaca region. The wind analysis will be focused on the winds simulated at 10 mAGL since they reflect the component of atmospheric momentum forced by differential surface heating.

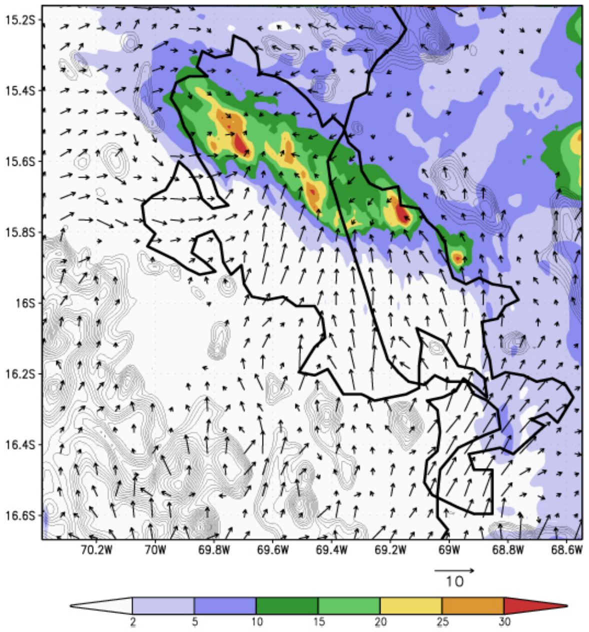

Figure 3. Nocturnal rainfall in mm simulated using the initial and boundary conditions of 20-21 January, 2003 by the 1.3 km-resolution WRF model.

As expected, the simulations produced low-level offshore flows that develop during the morning and peak right after local noon with speeds that range between 2 and 4 m s^{-1}, slightly stronger than the 1 - 3 m s^{-1} described by Galvez (2005). The onshore breezes penetrate about 10 to 20 km inland and are more evident in the northwestern shore of the lake, where they can be separated from the orography-driven circulations since the terrain is flat. The deepest penetration occurs between 14 and 15 LST. Parallel to the development of the lake breezes, strong (5-7 m s^{-1}) upslope winds build up over the Consata canyon. These winds reach the eastern mountain range gap at 13 LST and accelerate exceeding 7 m s^{-1} after 14 LST, when they enter the altiplano. The strong winds reach the lake after 15 LST. At this time northeasterly winds are present over the entire lake region partly due to downward momentum transport from the gap flow and part due to the diurnal lake-induced circulations. The core of the gap flow arrives between 15 and 16 LST and peaks between 18 and 19 LST with wind speeds that range from 7 to 10 m s^{-1}. The largest wind speeds are simulated over the northeastern side of the lake and over the southeastern end. After 19 LST the wind speeds start decreasing. Also by this time of the day nocturnal valley circulations start to develop over land directed towards Lake Titicaca, the lowest part in this sector of the basin. Enhanced convergence develops in the southwestern side of the lake where the direction of the valley flows opposes to that of the lake flows.

The hours that follow are crucial for the understanding of the distribution of rainfall around and over the lake, since the strongest convection in the region occurs between 20 and 02 LST according to satellite imagery (Galvez, 2005). As the night progresses and the valley flows arrive in the lake, 4 regions of low-level convergence develop. These regions vary overnight in response to changes in the strength of these circulations. From these regions, the most persistent is the one located over the Gulf of Juli (hereafter, Juli Bay), in the central portion of the southwest shore. This region develops in the lee of the eastern mountain range gap and is produced by the blocking effects of the shallow mountains located in the gap-region. It is remarkable that relative large rainfall rates with respect to nearby observations were observed in the stations located in the vicinity of the Juli Bay (Figure 4). Figure 4 also highlights the regions of preferred low-level convergence between 20 and 23 LST during days in which the synoptic forcing is low. The results were similar when the synoptic flow was weak SE, with a 5-20 km northwestward displacement and intensification of the regions of preferred low-level convergence.

According to the simulations, the flows induced by orography (valley flows) are the dominant circulations in the placement of the regions of convergence instead of the lake-induced circulations. Lake Titicaca favors the strength of the low-level convergence by allowing an acceleration of the flows due to low surface friction values. Towards sunrise, the stronger flows develop in the northern tier of the lake in response to larger low-level temperature contrasts and to the arriving valley flows channeled by the geometry of the northern altiplano. According to the simulations, the remnants of this flow prevails until 12 LST, even when the onshore circulations are already established. This favors the development of the largest region of low-level divergence over the northern third of Lake Titicaca with southerly flow south of this region by 13 LST.

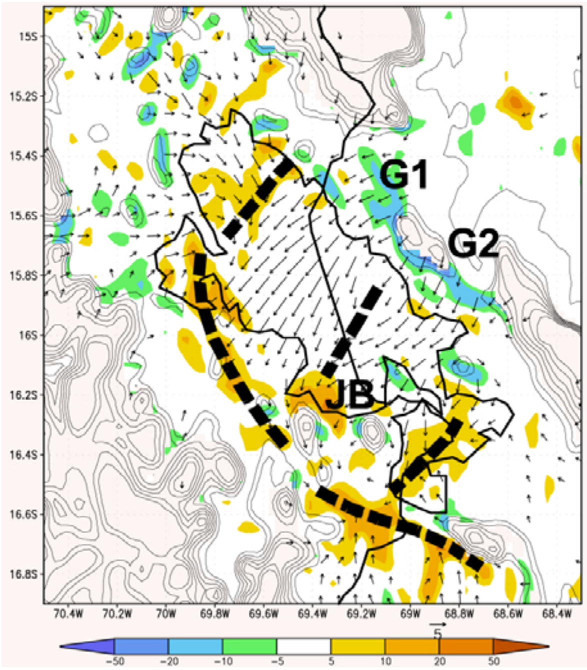

Figure 4. Scheme that illustrates the regions of preferred convergence and vertical motion between 20 and 23 LST. The 10 mAGL winds are indicated in m s^{-1} (arrows), the vertical velocities at 600 mb in cm s^{-1} and the topography above 4000 mASL is contoured every 200 m. Lake Titicaca and the Peruvian-Bolivian border are indicated with a thick black line. The regions of preferred low-level convergence are indicated using thick dashed lines. The gaps in the eastern mountain range are indicated with the acronyms 'G1' and 'G2', and the Juli Bay with the acronym 'JB'. The figure is constructed using information from two nights from the CR simulation.

Figure 5 shows an east-west cross-section centered at 16.1°S. It provides an example of the diurnal cycle of the vertical structure of the across-lake circulations, cloudiness and rainfall during wet events. The across-lake (i.e. rotated 30°) component of the wind is shaded in colors. The figure shows a very shallow boundary layer over Lake Titicaca near noon (11-15 LST) associated with lake-induced subsidence, important part of the lake onshore breeze diurnal cell. The depth of the boundary layer oscillates between 10 and 30 mb over the lake and between 30 and 100 mb over land. During the evening the boundary layer over Lake Titicaca deepens to ~30 mb and to 40 mb late in the evening, during the period of most frequent and intense convective activity. Onshore circulations can be evidenced in Figure 4, especially between 05 and 07 LST, right after sunrise.

Relative humidity is generally the lowest around noon due to an increase in temperature and also to a decrease in water vapor due to the effects of subsidence over the region. Moisture contents peak in the evening due to (i) moisture provided by the afternoon convection, (ii) the arrival of moist flow from the eastern slopes of the Andes and (iii) the enhancement of low-level convergence over the lake. The increase of moisture coupled with the increase in evening low-level convergence leads to the highest rainfall rates early in the night as described with satellite data by Galvez (2005). This increase in moisture can also be visualized in Figure 6, which displays the diurnal cycle of equivalent potential temperature, which accounts for the combined effects of moisture and potential temperature.

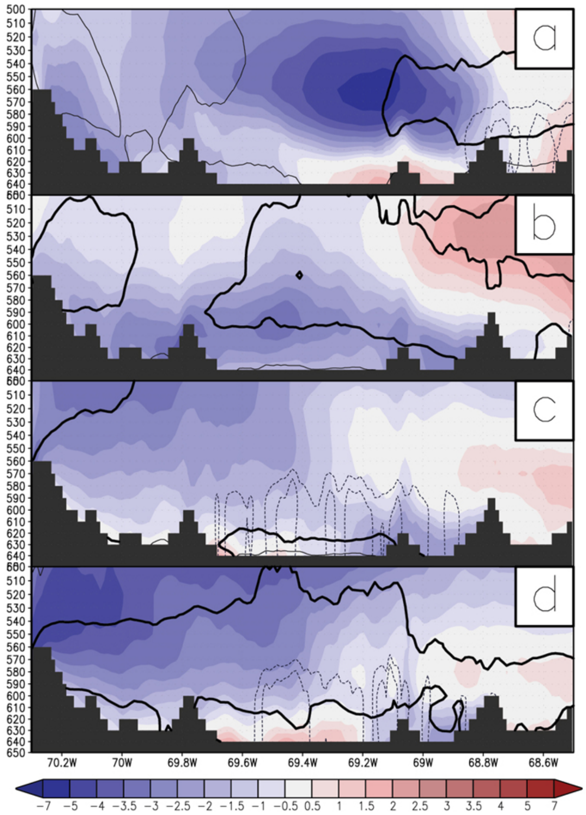

Figure 5. Cross-section at 16.1°S showing the diurnal cycle of the across-lake rotated component of the wind in m s^{-1} (shaded), the 80% relative humidity contour (thin black line), the 95% relative humidity contour (thick black line) and the 5, 10, 15, 20, 25, 30, 35 and 40 10^4 g kg^{-1} rainwater contours for (a) 11-15 LST, (b) 17-21 LST, (c) 23-03 LST, and (d) 05-07 LST averaged over the SALLJEX simulations.

Figure 6 indicates low equivalent potential temperatures (θ_e) over the Lake around noon (panel a) associated with a dry and cool atmosphere with respect to the surroundings. The highest θ_e values occur over the eastern altiplano, where not only temperatures are higher but the moisture contents due to the proximity to the

Amazon basin. By the late afternoon (panel b) higher θ_e values develop, as mentioned before due to an increase in low-level and mid-tropospheric moisture due to convection and advection from the eastern slopes, as previously described. The highest θ_e values occur in the eastern shore of the Lake and propagate towards the center as the night progresses. Mid troposphere moisture content decreases since the basin-wide convective activity decreases after sunset. By the end of the night, the only focus on convection is constrained to the center of the lake, and the θ_e values have decreased even more.

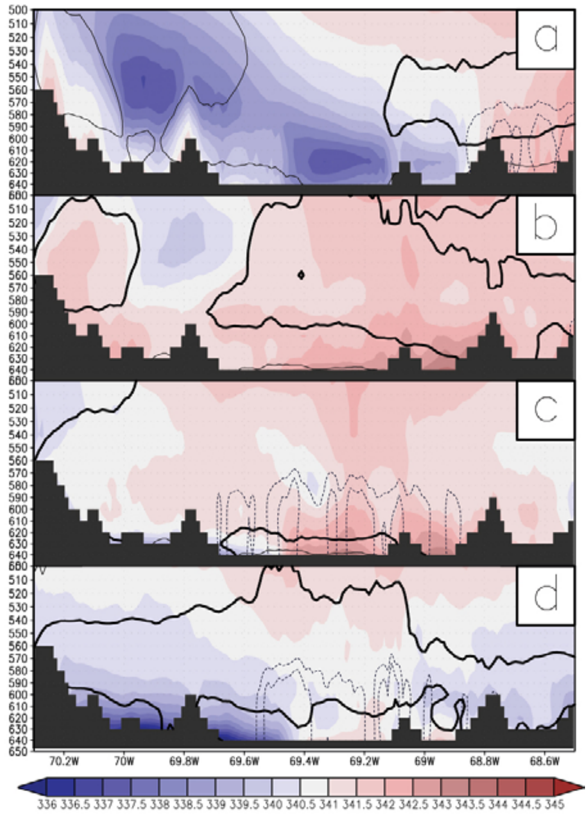

Figure 6. Cross-section at 16.1°S showing the diurnal cycle of equivalent potential temperature in °K (shaded), the 80% relative humidity contour (thin black line), the 95% relative humidity contour (thick black line) and the 5, 10, 15, 20, 25, 30, 35 and 40 10^4 g kg^{-1} rainwater contours for (a) 11-15 LST, (b) 17-21 LST, (c) 23-03 LST, and (d) 05-07 LST averaged over the WET SALLJEX simulations.

A strong temperature inversion develops over the altiplano to the west of Lake Titicaca, which propagates into the western side of the lake advecting drier and colder air. Although these inland-generated flows stimulate the development of convection by enhancing the low-level convergence when they arrive in the lake region, they also suppress it by mixing cooler and drier air into the region. The convective activity is generally annulled behind the leading edge of these offshore breezes. The suppression of nocturnal convection by the arrival of cold-dry breezes is particularly common in the northwestern sector of the Lake as found by the numerical simulations and previously described in this section. This is one of the reason why synoptic weak south and southeasterly flow favor the development of convection, particularly in the northern part of the lake. The simulation initialized using 4 m s^{-1} southeasterly winds produced larger rainfall totals than those produced by the CR, which was forced with quiescent initial and boundary conditions. This is consistent with the SALLJEX simulations, in which the largest rainfall totals occurred when the flow was from the southeast.

ii. Conditions that favor nocturnal convection

The conditions that favor nocturnal convection were explored using the SALLJEX simulations results by comparing those simulations that produced nocturnal rainfall totals of ~ 10 mm day^{-1} with those that produced nearly zero rainfall (Figure 7). A difference in the low-level wind speeds is noticeable with lower wind speeds over the lake present during rainy events. During the dry events, the regions of low-level convergence were decoupled from the local moisture source, Lake Titicaca, since they were displaced inland to the southwest of the lake by the prevailing northwesterly flow. On the other hand, the region of low-level convergence was placed just west of the lake SE-NW axis during weak southeasterly flow events. This region coincided with the region of the largest rainfall with values as high as 7 mm day^{-1} that resulted after averaging the 24-hour rainfall over the 6 wet simulations. The largest control on rainfall, however, seems to be exerted by the moisture content near and just over the altiplano boundary layer as evidenced by the lower-right panel in Figure 7. Moisture changes in the order of 1 g kg^{-1} in the 550-600 mb layer seem to have a large effect in the development of nocturnal convection over Lake Titicaca.

iii. Location of the low-level convergence

According to the simulations, the location of the region of nocturnal lake-induced low-level convergence (hereafter, RLC) is a function of the speed and direction of the mid-tropospheric flow over the northern altiplano. Near calm mid-tropospheric conditions favor the development of the RLC right over Lake Titicaca, whereas windy conditions displace the location of the RLC downstream from the lake axis. This seems to be crucial for the development of nocturnal convection. The simulations suggest that nocturnal convective storms are favored by the maintenance of the RLC over the lake. The reason is that the low-level air placed over the lake is warmer and moister than the air located over the surrounding altiplano. When the RLC is shifted away from the lake by the mid-tropospheric flow, it encounters cooler and drier air, which in term suppresses the storm development and maintenance.

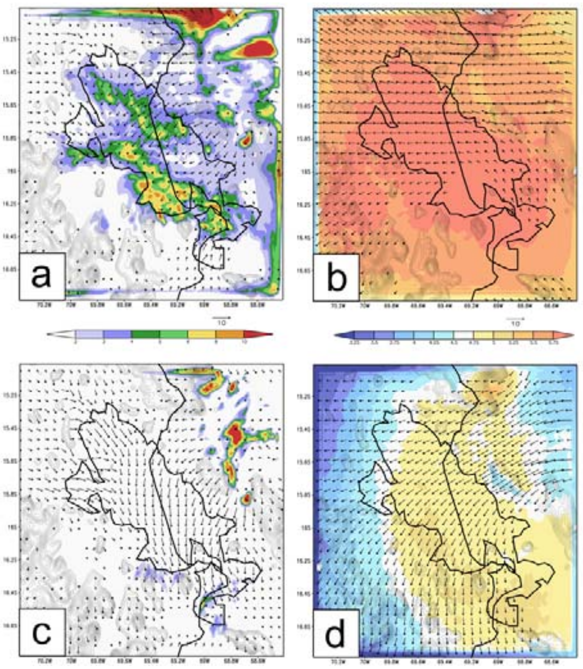

Figure 7. Convective storm that developed over the western shore of Lake Titicaca during the PACS-SONET December 2000 Field Experiment. The picture was taken from the Isla del Sol, near the center of the lake, looking west. It was taken during the night (note stars in the sky) using a digital camera with long time exposure.

4. CONCLUSIONS

The simulated diurnal cycle of the circulations and rainfall resembles that described by Galvez (2005) using SALLJEX pilot balloon observations. Low-level offshore flows developed during the mornings and weaker onshore flows during the night. The circulations induced by the altiplano orography seem to prevail over those induced by the lake, which was particularly evidenced by the no-wind simulation results. In this simulation the regions of low-level convergence were not aligned with the lake axis but with the boundaries between flows induced by orography. The lake favored the increase on the convergence mainly by promoting the flow acceleration due to the low surface friction, instead than by the generation of nocturnal offshore breezes. Moisture in the vicinity of lake Titicaca reaches a minimum during the late morning hours when the lake-induced subsidence is maximized and before the afternoon convection moistens the atmosphere, and reaches a maximum during the late afternoons and evenings due to the combined effects of (i) convection moistening, (ii) arrival of moist air from the eastern slopes of the Andes and (iii) low-level convergence over the lake region.

Regarding the development of nocturnal convection, the results point to low-level convergence and high boundary layer moisture as essential for the development and maintenance of nocturnal storms. The magnitude convergence provided by the lake and nocturnal circulations that collide over it seems to be weak and produces vertical motions in the order of ~.5 m s^{-1}. This is consistent with satellite observations that indicate that most of the storms develop below 450 mb. High moisture contents immediately over the boundary layer also seem to be important, since dry air entrainment quickly dries the boundary layer suppressing moist convection.

The mid-tropospheric flow also seems to play an important role in their enhancement or suppression based on the interaction with local circulations induced by orography. Weak southerly/southeasterly flow favors storm development. It enhances the low-level convergence over the lake since the the northwest altiplano – Lake Titicaca nocturnal temperature gradient added to the effects of nocturnal drainage produces a mean northwesterly flow that propagates into the lake. It also exerts the same effect with respect to the northeasterly flow produced by the gaps in the eastern mountain range. Furthermore, favors the alignment of traveling air parcels along the axis of the lake promoting the coupling between the region of low-level convergence and the region with the highest moisture contents.

On the other hand, strong flow, especially from the northeast, suppresses storm development by decoupling the region of low-level convergence from the source of heat and moisture. Counter-intuitively, periods of synoptic northeasterly flow tend to suppress nocturnal storms through these mechanisms.

REFERENCES

Bourges, J., J. Cortes and E. Salas, 1992: Hydrological Potential. In "Lake Titicaca a synthesis of limnological knowledge" (C. Dejoux and A. Iltis, eds), pp. 523-538. Kluwer Academic Publishers, Dordrecht, Boston, London.

Carmouze, J.P., 1991: El Balance Energético, El Lago Titicaca, *ORSTROM pub*, pp. 149-160.

Dudhia, J., 1989: Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model, *J. Atmos. Sci*, Vol. 46, 3077-3107.

Galvez, J. M., 2005: Modulation of Rainfall by the South American Altiplano Lakes. M.S. Thesis, Department of Meteorology, University of Oklahoma, 101 pp.

Lacis, A. A., and J. E. Hansen, 1974: A parameterization for the absorption of solar radiation in the earth's atmosphere. *J. Atmos. Sci*, Vol. 31, 118-133.

Lin, Y., R. D. Farley and H. D. Orville. 1983: Bulk Parameterization of the Snow Field in a Cloud Model. *Journal of Applied Meteorology*: Vol. 22, No. 6, pp. 1065–1092.

Mlawer, E. J., S. J. Taubman, P. D. Brown, M. J. Iacono, and S. A. Clough, 1997: Radiative transfer for inhomogeneous atmosphere: RTTM, a validated correlated-k model for the long-wave. *J. Geophys. Res.,* Vol. 102 (D14), pp. 16663–16682.

Rutledge, S. A. and P. V. Hobbs. 1984: The Mesoscale and Microscale Structure and Organization of Clouds and Precipitation in Midlatitude Cyclones. XII: A Diagnostic Modeling Study of Precipitation Development in Narrow Cold-Frontal Rainbands. *Journal of the Atmospheric Sciences*: Vol. 41, No. 20, pp. 2949–2972.

Ronteltap M., J. Rieckermann, and H. Daebel, 2004: Managements Efforts at Lake Titicaca. The Science and Politics of International Freshwater Management. Swiss Federal Institute of Technology Zurich.

Skamarock, W.C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barber, W. Wang, and J. G. Powers, 2005: A description of the Advanced Research WRF Versión 2. *NCAR technical note*. 88 pp.

Stephens, G. L., 1978: Radiation profiles in extended water clouds. Part II: Parameterization schemes. *J. Atmos. Sci*., Vol. 35, 2123-2132.

Sylvestre, F., S. Servant-Vildary, and M. Roux 2001: Diatom-based ionic concentration and salinity models from the south Bolivian Altiplano (15-23°S). *Journal of Paleolimnology*. Volume 25, 279-295 pp.