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Moisture variability over the South American Altiplano during the South American Low Level Jet Experiment (SALLJEX) observing season

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[1] During the austral summer, precipitation over the high-altitude plateau of the South American Altiplano exhibits a marked intraseasonal variability which has been associated with alternating moist and dry conditions observed at surface stations near the Altiplano western cordillera. In this study the characteristics of humid (wet) and dry (dry) episodes observed at a station on the western rim of the Altiplano during the summer of 2002–2003 are examined using observational data from the South American Low Level Jet Experiment (SALLJEX) and satellite-based estimates of precipitable water (PW) from Global Positioning System, Moderate Resolution Imaging Spectrometer, and Passive Microwave Radiometer instruments. We find that on wet days, mean moist conditions (PW greater than 10 mm) prevail across the entire plateau. This moisture is apparently brought to the Altiplano by sustained westward advection of air at similar altitude above the continental basin and propagates across the Altiplano to moisten the atmosphere over the Pacific Ocean a considerable distance (>1000 km) west of the plateau. In contrast, during dry events, significant drying of the boundary layer is observed mainly along the western mountain range and over the southern Altiplano. There is no evidence of strong midlevel advection of dry air across the northern Altiplano, and moisture remains constant and high over the northern basin and along the Altiplano eastern ridge. Consequently, precipitation and convective cloudiness show the strongest relation to moisture along the western cordillera of the Altiplano. Significant diurnal variability of moisture is found to occur most strongly on the outer slopes of the Altiplano. There is little indication that daytime upslope flow on the eastern slope of the Altiplano plays a major role in the transport of moisture to the Altiplano during wet episodes.

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1. Introduction

[2] Between 14°S and 22°S the South American Andean ridge divides into an eastern and a western part, forming a high-altitude (~4000 m asl) basin known as the Altiplano. Climatologically, the Altiplano is situated between the hyperarid Pacific coastal desert to the west and the moist continental lowlands to the east. Its semiarid climate is punctuated by a distinctive summertime rainy period between December and March, when 60%–90% of the annual rainfall occurs during intense afternoon thunderstorms [*Garreaud et al.*, 2003]. The annual rainfall is between 200 mm and 1000 mm, decreasing both from north to south and from east to west [*Vuille and Keimig*, 2004]. Precipitation shows great irregularity over intraseasonal to interannual timescales [e.g., *Vuille et al.*, 2000; *Garreaud and Aceituno*, 2001], which has important socioeconomic impacts on the agriculturally based societies of the region [*United Nations Educational, Scientific and Cultural Organization*, 2003]. The Altiplano is also of great interest in paleoclimataology, as archives drawn from its lakes and glaciers provide some of South America's most valuable records of climate change [e.g., *Baker et al.*, 2001; *Vuille et al.*, 1998; *Thompson et al.*, 2003].

[3] During summer, precipitation and convective cloudiness show a marked intraseasonal variability, characterized by alternating "wet" and "dry" episodes each lasting 5–15 days. Several studies have examined the local and synoptic forcing that control this summertime variability. It has been concluded that the moisture content of the Altiplano's boundary layer (ABL) is the key factor that determines the occurrence of widespread convection. For instance, *Garreaud* [1999] noted that the near surface q_v must surpass a certain level (~5 g/kg) for moist convection to be realized in the presence of mechanical lifting over the western Altiplano. Moisture variability is in turn associated with variations in the midlevel and upper level (500–200 hPa) circulation patterns, which alternately act to favor the transport of moist or dry air from the lowlands to the

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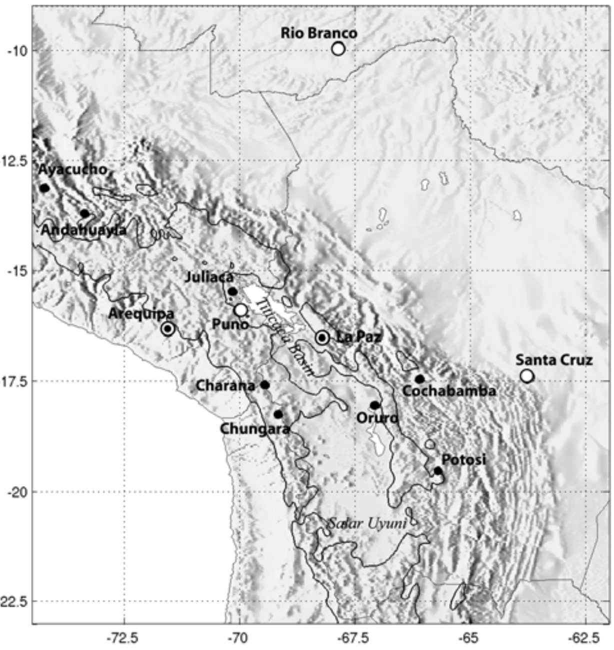


Figure 1. Topography of the central Andes. Thin black lines are coastal and political boundaries and the 4000 m topographic contour. Small solid circles indicate the locations where surface observations were available. Large open circles indicate the locations of PIBAL and radiosonde instruments.

west or east of the Altiplano [*Garreaud*, 1999; *Vuille et al.*, 1998]. The circulation anomalies in this subtropical region are ultimately forced by transient extratropical perturbations in the Southern Hemisphere [*Lenters and Cook*, 1999].

[4] The conceptual model linking the large-scale circulation, ABL moisture and convective activity, has been largely defined on the basis of observations near the western rim of the Altiplano and coarse resolution gridded data (e.g., reanalysis), and assumed to be applicable to the entire plateau. However, recent climatological studies indicate that, at least over interannual timescales, the Altiplano exhibits distinct zones of largely uncorrelated variability [*Vuille*, 1999; *Vuille and Keimig*, 2004], implying that precipitation processes may differ considerably throughout the Altiplano. Examination of the spatial structure of moisture and precipitation over the Altiplano and surrounding areas has been hampered by the lack of station data in this region. *Garreaud* [2000] examined intraseasonal surface moisture variability at 5 stations on the basin. It was shown that variations in water vapor on the western Altiplano are significantly correlated with those at other locations on the plateau. However, also notable in Garreaud's results was a considerable decrease in intraseasonal moisture variability at stations away from the western cordillera, particularly toward the north and west of the Altiplano.

[5] The purpose of this study is to enhance our knowledge of the spatiotemporal variation of boundary layer water vapor over the Altiplano at intraseasonal and shorter timescales, its relation to convection, and the associated moisture transport mechanisms. This is to be accomplished through the analysis of a comprehensive set of in situ and satellite observations for a three month period during the austral summer of 2002–2003. We make use of surface and upper air observations, collected and archived as part of the South American Low Level Jet Experiment (SALLJEX), that are not normally available over the data sparse Altiplano. The unique SALLJEX data sets are supplemented by satellite precipitable water (PW) products from a Global Positioning System (GPS) receiver, the Moderate Resolution Imaging Spectrometer (MODIS), and passive microwave radiometer instruments (PMR). Although we consider the entire Altiplano (22°S and 14°S) in our analysis, we concentrate most strongly on the region between 18°S and 14°S (i.e., the Titicaca basin and surrounding mountains), the rainiest part of the plateau and that where there was the greatest availability of in situ data.

[6] The structure of this article is as follows. Section 2 contains a short overview of each of the observational data sets to be used. Section 3, divided into four parts, contains our observational results. We first (section 3.1) examine the characteristics of moisture variability at reference locations on the western Altiplano and use these observations to define moist and dry periods that occurred during the SALLJEX season. We then examine satellite water vapor observations over the entire Altiplano, and the surrounding lowlands and ocean, using high-resolution MODIS and PMR imagery. In section 3.2 the relation to the occurrence of convection and precipitation over the entire Altiplano is examined using precipitation and T_{bb} observations. In section 3.3 upper air wind observations are examined in order to shed light on the transport mechanisms that control moisture variability. Some of our data includes several samples per day, which allows for a description of the diurnal cycle as presented in 3.4. Finally, in section 4, our key results and their implications are summarized and discussed.

2. Study Area and Observational Data

[7] Figure 1 shows the topography of the Altiplano and the locations of in situ instrumental data. We define the Altiplano as all regions above 3500 m in altitude between 14°S and 22°S. The plateau of the Altiplano is bounded on either side by its eastern and western cordilleras (mountain ranges). In this text we distinguish between the northern and southern Altiplano, which we define as those areas north or south of 18°S, respectively. The region of the northern Altiplano between the surrounding cordilleras will be referred to as the Titicaca Basin. Salar (salt lake) Uyuni occupies the southernmost part of the Altiplano, between 20°S and 21°S.

[8] Observational data span a 93 day period from 15 November 2002 until 15 February 2003. Details regarding the observational data are provided in the following subsections.

2.1. Surface

[9] Surface observations include daily precipitation totals from operational synoptic reports obtained from the global transmission system (GTS), the accumulation period ending at 1200 UTC (0800 local time). At Chungara, on the western Altiplano, a research quality meteorological station was deployed for the duration of SALLJEX, which mea-

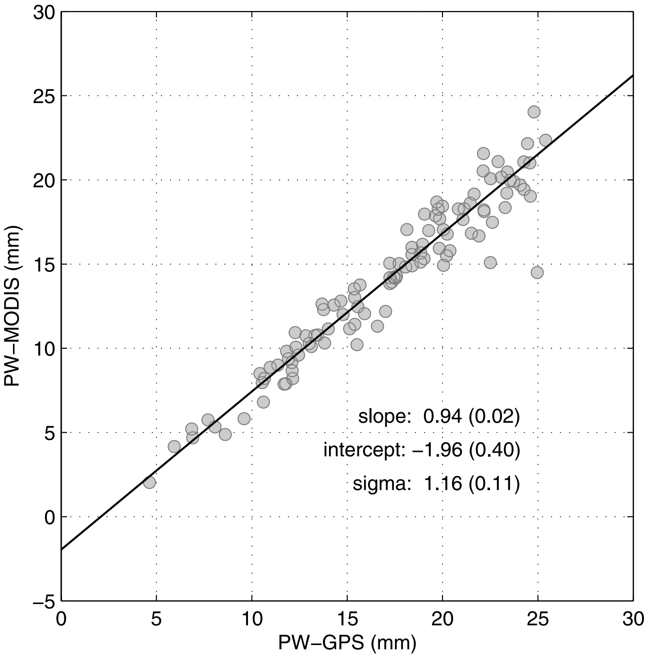


Figure 2. Comparison of estimated precipitable water from GPS and MODIS at Arequipa. The solid black line shows the result of a robust (iteratively reweighted) linear regression. The regression parameters are also shown. Values in parentheses are the estimated standard errors of these parameters. There are 150 paired values in total.

sured temperature, humidity and winds at 15 min intervals, along with daily precipitation.

2.2. Upper Air

[10] Except for sporadic wind soundings at La Paz, the Altiplano and its immediate surroundings are usually devoid of conventional upper air observations. During SALLJEX temporary PIBAL (pilot balloon) and rawinsonde observing systems were deployed at several locations on or near to the Altiplano. The PIBALs are uninstrumented balloons tracked manually by theodolite, whose positions may be used to determine wind velocity in cloud free areas [*Douglas et al.*, 1999]. They were typically released in the early morning (1200 UTC) and in the midafternoon (2100 UTC). We do not consider afternoon PIBALs because, owing to increased afternoon cloudiness, observations frequently stopped below 2000 m asl. Rawinsonde observations were made between 2 and 4 times daily, but only during special interest periods. We use rawinsonde data from two locations, Santa Cruz and Rio Branco, both located in the continental basin about 300 km from the eastern cordillera. All PIBAL and rawinsonde data were obtained from the SALLJEX data management website (http://www.joss.ucar.edu/salljex/dm/data_access_frame.html).

2.3. GPS-PW

[11] Data from a permanent GPS instrument at Arequipa, situated on the western slopes of the Altiplano (2500 m), were used to provide estimates of total precipitable water (PW). GPS-PW is based on the estimation of propagation delays in microwave signals as they pass through the refractive troposphere from GPS satellites to the receiver. The technique is relatively new, but is already well validated, and comprehensive reviews may be found in *Bevis et al.* [1992] and *Businger et al.* [1996].

[12] The Arequipa instrument (geodetic code name AREQ) is operated by the Jet Propulsion Laboratory (JPL) and is part of the IGS (International GPS Service) global monitoring network. To obtain estimates of PW we used the ''final'' tropospheric delay product produced by the IGS [*Beutler et al.*, 1999]. This is a weighted combination of total atmospheric delay estimates from several analysis centers, each using distinct data processing strategies [*Gendt*, 1998]. Delay estimates are provided at 2 hour intervals, and were converted to PW using surface pressure measurements at nearby synoptic station and moisture weighted mean temperature derived from NCEP-NCAR reanalysis, following the methodology outlined by *Bevis et al.* [1994]. On the basis of many past validation studies of GPS-PW [e.g., *Bevis et al.*, 1992; *Tregoning et al.*, 1998], the PW so derived are expected to be accurate to within 1–1.5 mm (RMS). That this level of quality was probably achieved in this study is confirmed by independent comparison with MODIS PW observations, as described in section 2.4.

2.4. MODIS-PW

[13] Observations from the Moderate Resolution Imaging Spectrometer (MODIS) instruments aboard NASA's TERRA and AQUA satellite platforms were available during the observing period. The MODIS instrument is a 36 channel spectrometer operating between visible and long-wave infrared (0.4 to 14.4 μm) wavelengths. The satellites pass over the Altiplano twice per day at approximately 0330 and 1530 UTC (TERRA) and 0630 and 1830 (UTC AQUA). Images are made along a swath of 2330 km width. Raw data (level 1) are processed using standard algorithms to yield a suite of atmospheric data products on the orbital swath (level 2).

[14] Here we make use of the MODIS-05 level 2 near-infrared (NIR) precipitable water product, made available through the NASA Earth Observing System (EOS) data gateway. The NIR solar retrieval algorithm relies on observations of water vapor attenuation in reflected solar radiation in the near-infrared channels [*Gao and Kaufman*, 2003]. The product is thus only produced over areas where there is a reflective surface in this spectral band, that is, over land areas, cloud tops and bodies of water where solar reflection (''sun glint'') is high. Atmospheric water vapor transmittances are estimated using ratios of three water vapor absorbing channels with two atmospheric ''window'' channels. The ratios partially remove the effects of variation of surface reflectance with wavelength. PW images at 1 km resolution are then derived from the transmittances on the basis of theoretical radiative transfer calculations.

[15] To provide an indication of the accuracy of the MODIS and GPS PW data sets, a spot comparison was performed at Arequipa using observations over an extended validation period from 5 November 2002 until 15 April 2003. The comparison of the GPS and MODIS PW estimates is shown in Figure 2. A good linear relation (regression parameters shown in Figure 2) is seen between the GPS NIR PW retrievals. The sigma value of 1.16 mm is equivalent to a relative error of about 5%, in agreement

with the expectations of the NIR algorithm developers [*Gao and Kaufman*, 1998] and with the results of other validations of this MODIS product [e.g., *Li et al.*, 2003]. This level of comparison is typical of what has been achieved in other studies where GPS PW has been compared with radiosonde of water vapor radiometers. While the result is strictly valid only at Arequipa, it nonetheless lends some confidence to the application of MOD05 NIR data product to the examination of the spatial variation of PW in the Altiplano region. We note that the offset and slope parameters of the linear regression are significantly different to 0 and 1 respectively, indicative of significant biases in the MODIS or GPS (or both) estimation procedures. Given that large biases are not usually present in GPS PW estimates, we have opted to use the regression parameters to correct the MODIS-PW imagery. Thus all MODIS-PW observations presented in this study have been adjusted by the equation $PW_{final} = 2.08 + 1.06\ PW_{raw}$. *Li et al.* [2005] demonstrated that GPS-based corrections to MODIS PW imagery of this type are accurate over large areas even when derived from a GPS single station.

2.5. GOES 8 T_{bb}

[16] GOES 8 channel 4 infrared imagery covering central South America at 3 hour intervals, were collected and archived as part of SALLJEX operations. The original 4 × 4 km resolution data, again obtained from the SALLJEX website (section 2.2) were processed to yield gridded fields of equivalent black body temperature (T_{bb}) with 12 km spacing. These data are used in this study as a means of detecting the occurrence of high convective clouds, as indicated by low values of T_{bb}, and thus function as a simple proxy for precipitation [*Garreaud*, 1999; *Vuille and Keimig*, 2004].

2.6. Microwave Radiometer

[17] Microwave radiometer retrievals of PW are used in this study to observe water vapor variation over the Pacific Ocean to the west of the Altiplano. An overview of water vapor retrieval with spaceborne radiometers may be found in work by *Wentz* [1997]. Data from five radiometers have been used to form a combined data set. These include three Special Sensor Microwave Imager (SSM/I) instruments aboard the Defense Meteorological Satellite Program (DMSP) F13, F14 and F15 satellites, the TRMM Microwave Imager (TMI) instrument flown as part of the TRMM mission, and the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) instrument aboard NASA's AQUA satellite. PW data from all five instruments and at all times were combined to form daily gridded fields of PW over the ocean at 0.25° × 0.25° resolution.

3. Results

3.1. Moisture Variation Over the Altiplano

[18] We begin by examining surface-based water vapor observations on the western rim of the Altiplano. Figures 3a and 3b show the surface specific humidity measured at Chungara and GPS-PW at Arequipa, respectively. The Chungara instrument is situated at an altitude of 5000 m at the high point of the western cordillera, near to those of the surface data presented in the prior studies of *Aceituno* [1997], *Hardy et al.* [1998], and *Garreaud* [2000]. As was also found in these studies for other seasons, the near surface specific humidity exhibits marked variations (Figure 3a) throughout the 2002–2003 season. These are particularly evident between 15 November and 7 January, during which time there were four readily identifiable moist periods ($q_v \sim 7$ g/kg) each separated by dry intervals when the q_v dropped below 3 g/kg. Also shown on Figure 3a are those days in which precipitation was recorded at Chungara or nearby Charaña (Figure 1). There is a clear tendency for rainfall in the vicinity of Chungara to occur during moist episodes, with nonzero precipitation recorded at least once during each of the four wet periods prior to 7 January, and on nearly half the days of the consistently moist period that followed. Conversely, there was no precipitation recorded on any of the days during which the mean q_v was less than 4 g/kg.

[19] The time series of surface moisture is remarkably well matched by that of the total PW above Arequipa (Figure 3b). The intraseasonal variation in q_v clearly reflects a variation in total PW of between 10 and 22 mm. The close correspondence between the two stations demonstrates that the Chungara observations have considerable spatial extent both horizontally, as Arequipa is nearly 300 km distant from Chungara, and in the vertical. For example, if the ±5 g/kg variation in q_v occurs within a well mixed layer of depth dz, the corresponding PW variation of ±12 mm requires that dz be approximately 240 hPa (3000 m). It is important to note that the Arequipa instrument is located 50 km west of the cordillera, 2500 m below the height of Chungara. The region of moisture variation thus extends out over the western flanks of the Andes, and may also extend below the height of the plateau.

[20] In this and the following sections, compositing analysis will be used to help elucidate the characteristics the moist of dry episodes identified in Figure 3. Composites are formed on the basis of the three terciles of daily mean GPS-PW for the 93 day study period. The upper and lower terciles, which are defined by those days having a mean PW greater than 22.5 mm or less than 17.5 mm, are hereafter named wet and dry respectively, and are indicated on Figure 3. In the period 15 November to 10 January, dry days fall into five clearly separated episodes encompassing 25 days in total. After January 7, only 6 days are identified as dry. In contrast, the majority (21) of wet days occur in the period after January 7. The other wet days occur on the four peaks in PW between November 20 and January 2. Composites formed from dry and wet days are thus slightly weighted toward to conditions during the first or second half of the SALLJEX season, respectively.

[21] We now make use of satellite estimates of PW are used to examine water vapor variation across the entire Altiplano. We rely primarily on a reduced resolution daily MODIS-PW data set, produced from the original ensemble of high-resolution MOD05 imagery, by binning the raw 1 km resolution data into a 15 × 15 km grid that covers the Altiplano and its surrounds. The PW within each grid box is the mean of all cloud free NIR-PW image pixels from both the TERRA and AQUA instruments.

[22] Figures 4a and 4b show composites of mean daily MODIS-PW for wet and dry episodes, respectively. Data are only plotted for those grid boxes that contain data for at

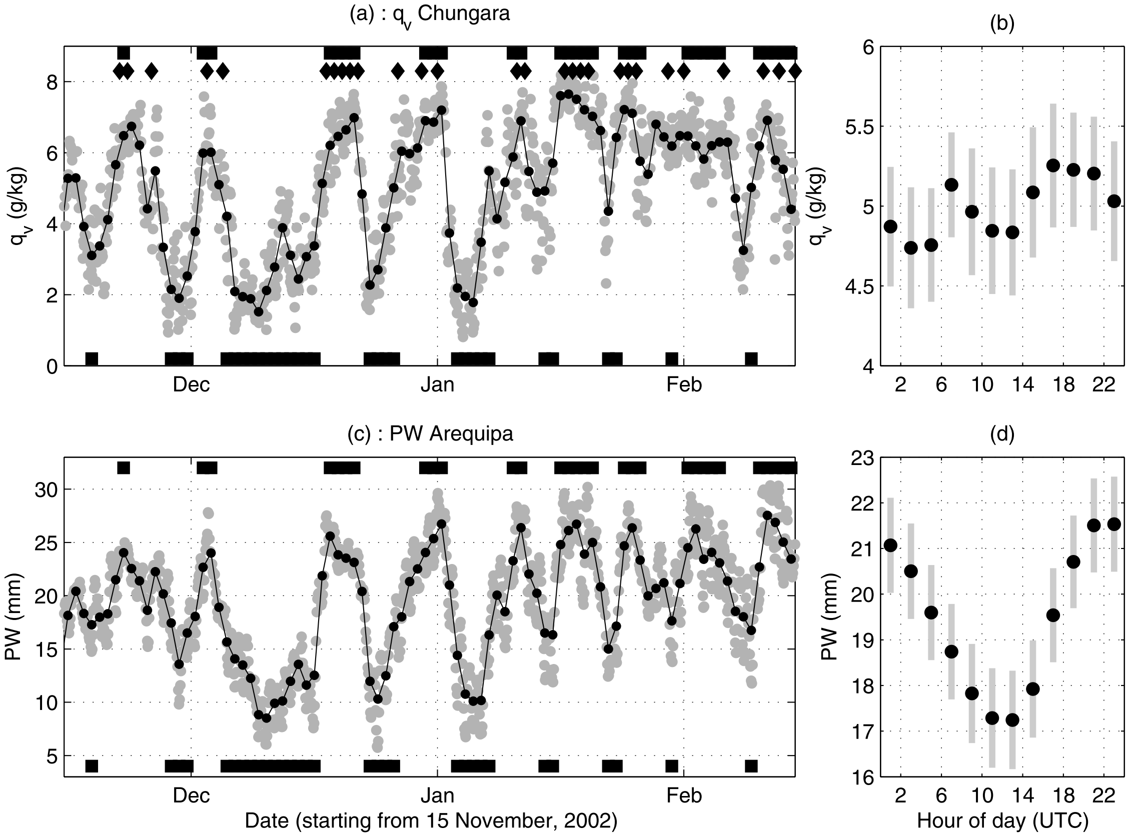


Figure 3. Moisture observations on the western Altiplano. (a, c) Surface specific humidity (q_v) at Chungara and the precipitable water (PW) at Arequipa, respectively. Light gray circles are individual measurements, and black circles connected by lines are UTC daily mean values. Black rectangles along the top (bottom) of the axes indicate days identified as wet (dry) on the basis of the upper (lower) terciles of the daily mean PW at Arequipa. The black diamonds in Figure 3a indicate days on which precipitation was recorded at Chungara or Charaña. (b, d) Daily cycle of mean q_v and PW, respectively. Gray bars show the 95% confidence region for these means.

least 75% of all days. Therefore no data is shown over the continental basin and the eastern slopes of the northern Altiplano, where clouds prevailed almost continuously at the TERRA and AQUA pass times. It is worth noting that the mean PW may be slightly underestimated it does not include contributions from cloudy (and likely, moister) regions. Any such bias is expected to be larger for the WET composite, where clouds were generally more common.

[23] During wet periods (Figure 4a), the PW is approximately uniformly distributed across the plateau, with a mean value of approximately 12 mm. PW is lower over the western and eastern cordilleras, because of the higher altitude of the terrain surface, and increases rapidly down the western slopes of the Altiplano to values of up to 30 mm over the Pacific coastal desert. In the dry composite, the PW is generally lower throughout the plateau, with a mean value of roughly 8 mm. However, unlike the wet composite there is clear spatial gradient in PW, which in this case decreases across the plateau both north to south and west to east, from values close to 12 mm north of Titicaca to as little as 4 mm over Salar Uyuni.

[24] Figure 4c shows the difference in mean PW between the wet and dry composites (ΔPW). ΔPW is largest over the coastal desert west of the Altiplano, particularly near to Arequipa, as is to be expected given the definition of the composites. At points near the Pacific coast, ΔPW is as high as 14 mm, a value greater than that of the mean PW over the plateau. Figure 4d shows ΔPW over the Pacific Ocean derived from PMR retrievals (section 2.6). The region of moisture variability actually extends a large distance, over 1000 km, to the west of the Altiplano. Examination of q_v from surface synoptic reports at stations on the Pacific coast and western slopes of the cordillera show that the surface q_v is more or less constant at stations below heights of about 2000 m (not shown). At higher stations, the q_v time series begin to show variations approaching those observed at Chungara. Thus the region of ΔPW to the west of the Altiplano may be interpreted as a midlevel and upper level "tongue" of moisture capping a temporally stable dry air mass that sits above the eastern Pacific marine boundary layer. Notably, a similar feature has also been identified in NCEP-NCAR reanalysis moisture fields over interannual timescales in the analysis of *Vuille and Keimig* [2004, Figure 8].

[25] Over the Altiplano itself ΔPW shows considerable spatial variation, particularly between the northern and southern basins (Figure 4c). In the northern Altiplano, a region of high ΔPW extends along the western cordillera. However, the PW content of the Titicaca Basin and its eastern cordillera is only slightly smaller (ΔPW ~ 0–3 mm)

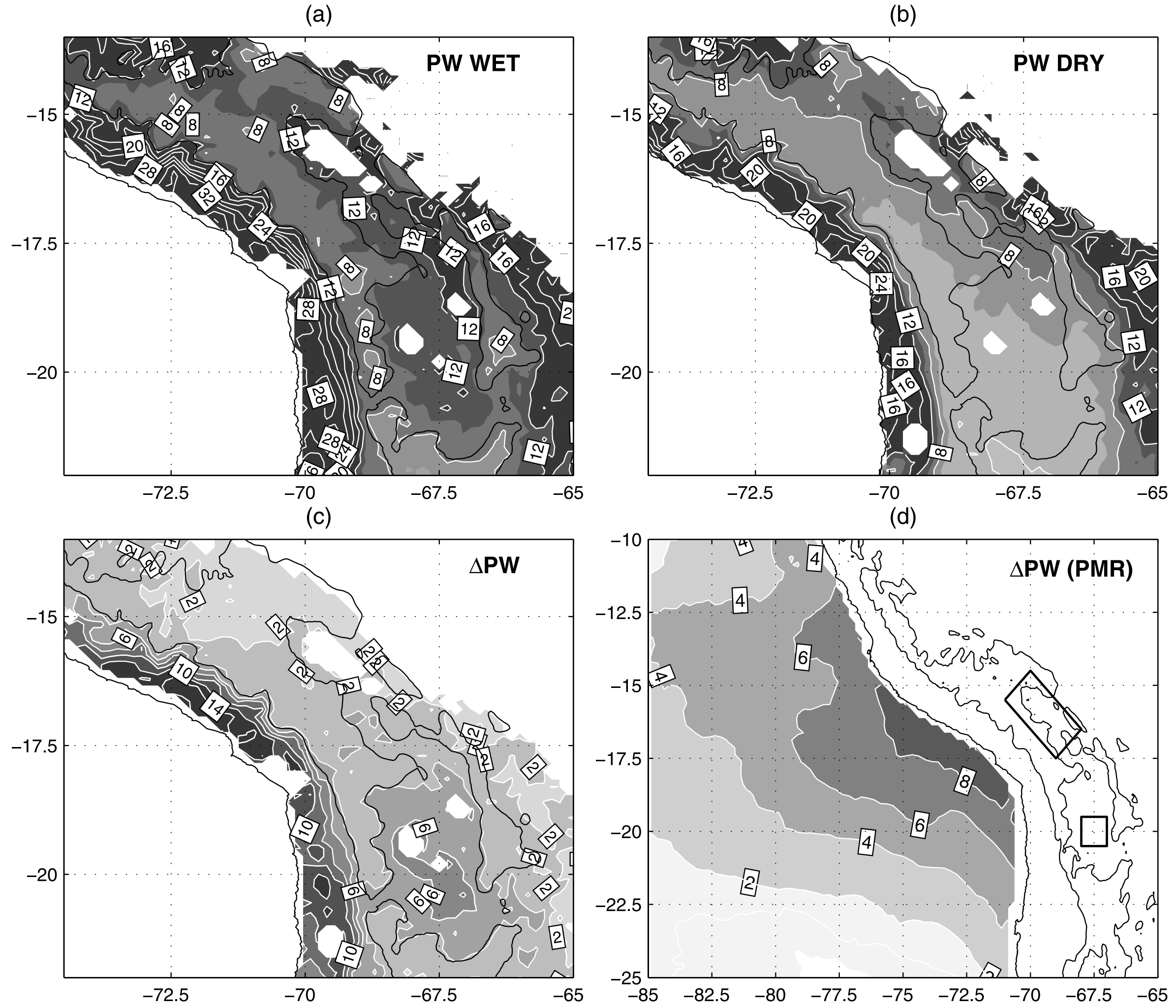


Figure 4. Mean MODIS NIR-PW (AQUA and TERRA observations combined) for (a) wet and (b) dry periods. White lines are contours at 4 mm intervals. The gray filled contours emphasize PW variation in the 0–12 mm range. Contours are plotted only at points where MODIS PW estimates were available on more than 80% of the days in each category. (c) Contours (here at 2 mm intervals) of the difference between PW on wet and dry days (ΔPW). (d) ΔPW determined from combined TMI, AMSR-E, and SSM/I passive microwave radiometer data over the ocean. In all plots, the black lines indicate the Pacific coastline and 4000 m topographic contour.

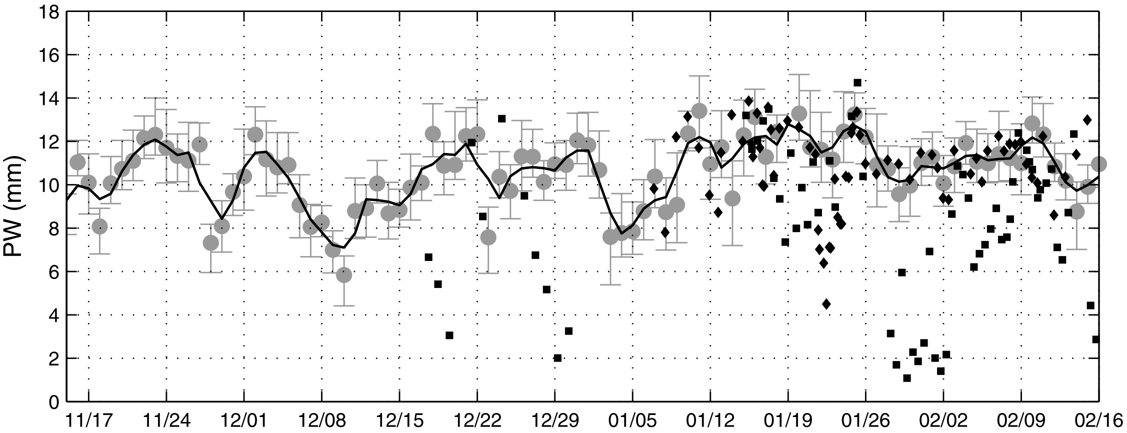
during the dry episodes. In contrast over the southern basin, ΔPW increases to more than 6 mm. The contrasting temporal variability of PW over the two regions is further highlighted in Figure 5, which shows the mean daily PW averaged within the Titicaca Basin (north) and Salar Uyuni (south) (the averaging domains are depicted in Figure 4d). The mean PW over the Titicaca basin remains rather constant, varying between 8 and 13 mm. In the southern region, large fluctuations are observed, between 4 and 14 mm, which bear a strong resemblance to those seen in the GPS-PW time series at Arequipa (Figure 3b).

3.2. Precipitation Patterns Associated With Wet and Dry Events

[26] The association between moisture over the Altiplano and the occurrence of precipitation is now examined. Surface precipitation observations (Table 1) show a clear tendency for higher precipitation across the northern basin during wet events. The number of days recording precipitation was significantly greater during wet periods at all stations except at Ayachuco and Potosi, which are located in the extreme north and southeast of the Altiplano respectively. This is in line with the results of *Garreaud* [2000], who suggested that precipitation events are typically widespread over the Altiplano. Nonetheless, the largest differences in precipitation frequency between wet and dry episodes are observed at stations near to the western cordillera (Charaña, Chungara, Arequipa).

[27] Information regarding the spatial extent of precipitation associated with wet and dry events may be obtained from the T_{bb} data described in section 2.5. Figure 6 shows contour maps of a measure of evening convective cloudiness (CC), which we define as the percentage of days during which the minimum T_{bb} between 1800 and 2400 UTC was lower than 240 K. This temperature threshold has been determined by *Vuille and Keimig* [2004] as that having the optimal relation

(a) : Titicaca (Northern Altiplano)



(b) : Uyuni (Southern Altiplano)

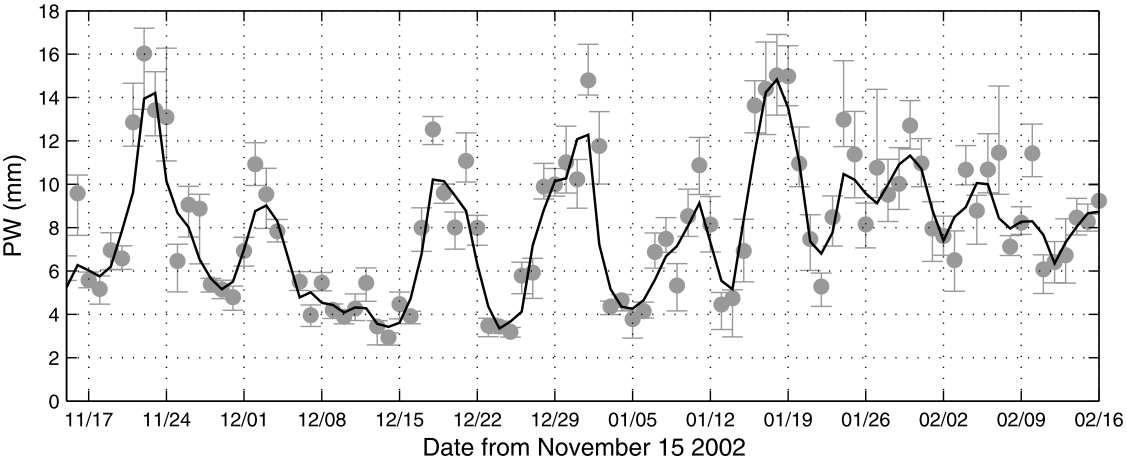


Figure 5. Time series of the daily MODIS NIR-PW over (a) the Titicaca basin and (b) Salar Uyuni. Gray dots show the median PW on each day, and their error bars indicate the interquartile range. The black lines are the weighted 3-day running mean. In Figure 5a, the PW above 4000 m altitude measured by radiosonde at Santa Cruz (diamonds) and Rio Branco (squares) are also plotted. The averaging domains are shown in Figure 4d.

with rainfall over the Altiplano. During dry periods the evening convection is mainly confined to a small region northwest of the Titicaca basin. In contrast, there is considerable evening CC associated with wet events, distributed in a long band stretching from 14°S–19°S. CC is highest (>40%) in the northern Altiplano, where it is concentrated over the western cordillera. To the south, a zone of wet CC between 20% and 40% extends across the central Altiplano and its eastern slopes. The southernmost parts of the plateau (e.g., Salar Uyuni) showed relatively low CC even on wet days (10–20%). The wet CC pattern bears a notable resemblance to the spatial loading patterns of annual precipitation and convective cloudiness revealed in the principal component analyses of *Vuille et al.* [2000] and *Vuille and Keimig* [2004].

[28] The wet and dry CC patterns both show relatively low CC over the north eastern Altiplano and Titicaca basin, somewhat contrary to the rain gauge observations, which show relatively high overall rainfall frequencies at the La Paz, Juliaca and Ororu stations (Table 1). It is likely that rainfall budget of these regions includes contributions not related to afternoon CC. For example CC between 0000 and 0600 UTC (not shown) is also high over and near to Lake Titicaca, a result of convection triggered by nighttime thermal contrasts between the relatively warm lake surface and cold land. On wet evenings, the CC pattern may also be influenced by the generally westward (see section 3.3) advection of the high convective anvil clouds by the upper level winds.

3.3. Winds

[29] In this section, the upper level winds over the northern Altiplano associated with wet and dry episodes are examined. Composite reanalysis fields of upper level winds (not shown) showed that the mean circulation patterns of the wet and dry periods identified in this study conformed those of past studies [e.g., *Garreaud*, 1999; *Vuille and Keimig*, 2004] composed over longer timescales. That is, the mean winds at upper levels (300 hPa) were westerly over the Altiplano during dry periods and easterly during wet episodes.

Table 1. Surface Precipitation Statistics for the Period 15 November 2002 to 15 February 2003[a]

Station	Height, m	R_{tot}, mm	N_{rain}	Percent of Rain Events: Wet	Unclassified	Dry
Ayacucho	2749	164	31	41.9[b]	35.5	22.6[b]
Andahuayla	3444	328	27	44.4	33.3	22.2
Juliaca	3827	167	24	45.8	33.3	20.8
Arequipa	2520	1	1	100	0	0
La Paz	4014	315	44	45.5	36.4	18.2
Charana	4057	123	22	77.3	18.2	4.5
Chungara	4200	46	8	62.5	37.5	0
Oruro	3702	167	29	44.8	34.5	20.7
Cochabamba	2531	157	37	40.5	37.8	21.6
Potosi	3934	135	29	34.5	41.4	24.1
All	N/A	1603	252	46.4[b]	34.5	19.1[b]

[a] R_{tot} is the total rainfall recorded. N_{rain} is the number of days when rainfall was recorded (days span the period 1200–1200 UTC). Wet, unclassified, and dry are the percentage of rainy days in each of the days classified as wet, unclassified, or dry, respectively. The row labeled "All" shows the combined statistics computed across all 10 rain gauges.

[b] Corresponding values of percent wet and percent dry are not significantly different at the 99% level. No significance test was made for the Arequipa data, as the sample size is only 1.

[30] Composite profiles of zonal (*u*) and meridional (*v*) wind components from morning PIBALs were formed from simultaneous observations over the western cordillera (Arequipa) and the Titicaca Basin (combined data from Puno and La Paz). The combination of data from these two latter stations was necessary as there were large gaps in the daily observation series at both sites. Comparison of the occasional soundings made simultaneously at Puno and La Paz showed similar winds above about 500 m asl, indicating that above this height both sites are equally representative of the Titicaca Basin. As many PIBAL soundings terminate early in their ascent, the number of observations used in the composites decreases with height, from about 85% of the possible total near the surface, to about 40% at 9000 m above mean sea level (amsl).

[31] The composite wind profiles are shown in Figures 7a–7d. A significant mean easterly flow (*u* negative) is seen for wet profiles at both sites. Over the Titicaca Basin there is significant easterly flow at all levels above about 4500 m (500 m above the surface), with a maximum mean easterly velocity of 6 m/s at about 6500 m. At Arequipa the profile of *u* is similar, but the easterlies extend down to 3500 m amsl, well below the height of the western cordillera, suggestive of downslope flow on its western side. The dry zonal wind profiles are similar at both sites. Neither shows a significant cross-plateau flow at levels below about 6000 m. Above, westerlies increase slowly with height, to mean values of 4–6 m/s above 8000 m (400 hPa). None of the composite profiles of meridional velocity (*v*) show significant vertical structure, nor is there any significant difference between wet and dry profiles.

[32] The presence of midlevel easterly flow during wet periods is suggests that horizontal moisture transport may occur at these levels. It is thus of interest to see how the Altiplano PW compares with that above the continent to the east. Figure 6a compares the northern Altiplano PW with the total PW above 4000 m derived from SALLJEX radiosonde observations at the lowland stations Santa Cruz and Rio Branco (Figure 1). Observations were collected at these sites mainly during the extended moist period from January 10 until February 10 2003. Not considering occasional spells of very dry air at Santa Cruz, the mean PW at Altiplano altitude above the radiosonde sites is generally comparable to that over the northern Altiplano. Comparison (not shown) of q_v at Chungara and other surface stations on the Altiplano with the radiosonde measurements show that the near surface moisture in the ABL during wet episodes is also similar to that observed at the same altitude over the continental atmosphere. The dry period observed at Santa Cruz between 28 January and 3 February 2003 was caused by a synoptic-scale, upper level south easterly surge of cold air over Paraguay and Argentina. It was not related to, nor

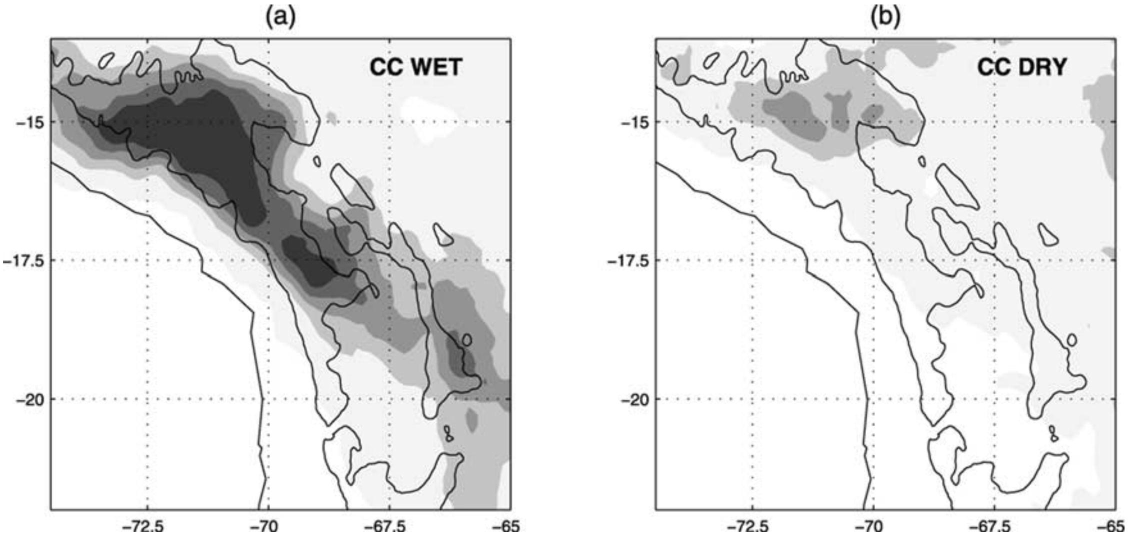


Figure 6. Convective cloudiness (CC) for (a) wet and (b) dry periods between 1800 and 0000 UTC. The gray filled contours show the percentage of days in which the equivalent blackbody brightness temperature measured by GOES 8 was below 240 K at least one time within the time interval. The gray scale ranges from 10% (lightest) to 50% (darkest) at intervals of 10%. Black lines indicate the Pacific coastline and 4000 m topographic contour.

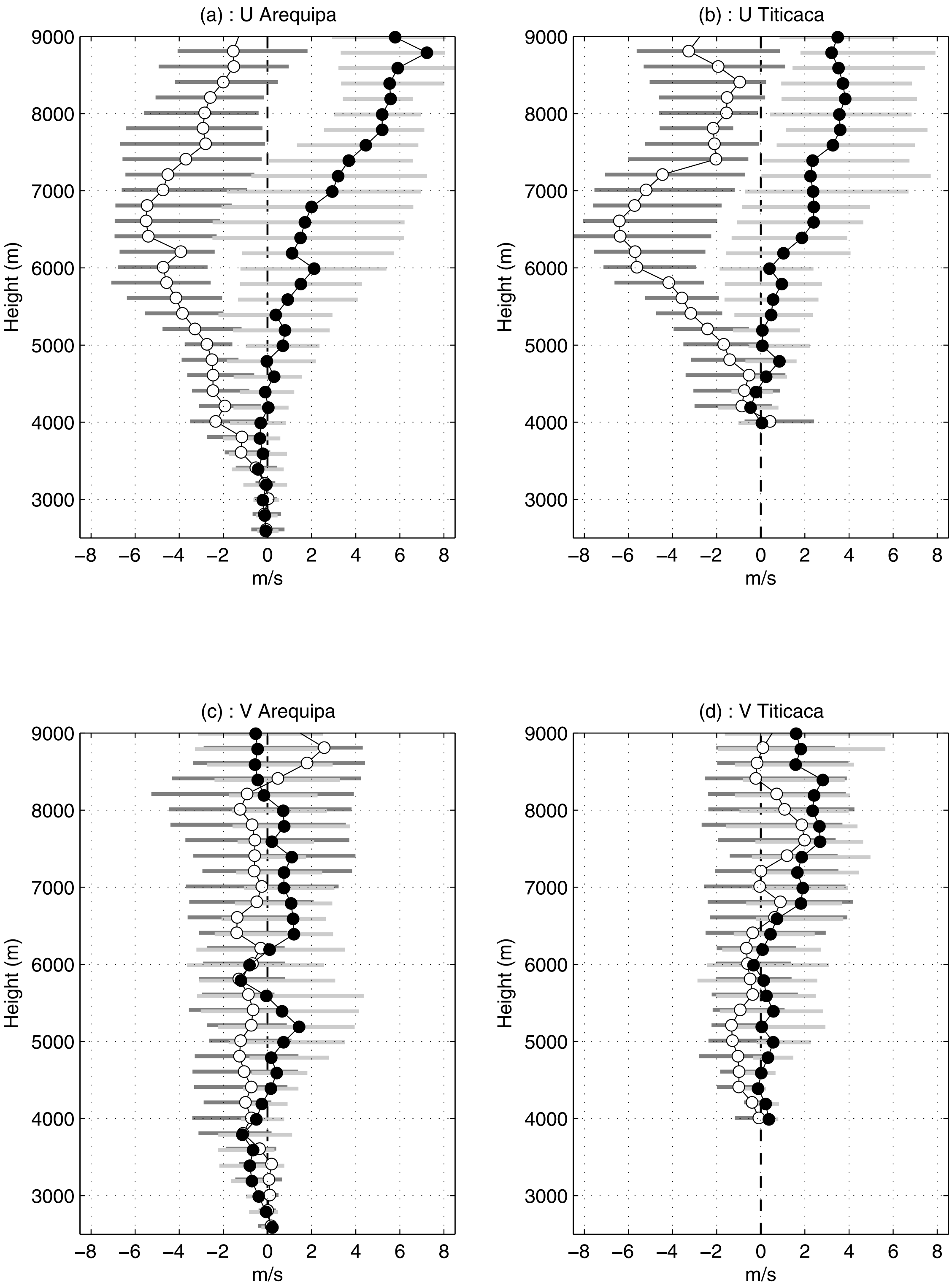


Figure 7. Mean profiles of (top) zonal (u) and (bottom) meridional (v) wind components over (left) Arequipa and (right) Titicaca Basin (i.e., Puno and La Paz combined) for wet (open circles) and dry (solid circles) days. The gray bars represent the interquartile range.

had any noticeable effect on, meteorological processes over the Altiplano.

[33] The wind observations considered thus far are only valid for northern part of the Altiplano. Direct investigation of the character of wet and dry periods over the southern Altiplano is made difficult by the near total lack of conventional observations in the region. The only upper air data from SALLJEX were PIBAL observations at Salar Uyuni, released discontinuously in three intensive observing periods, each lasting about 2 weeks. As such, analyses of these

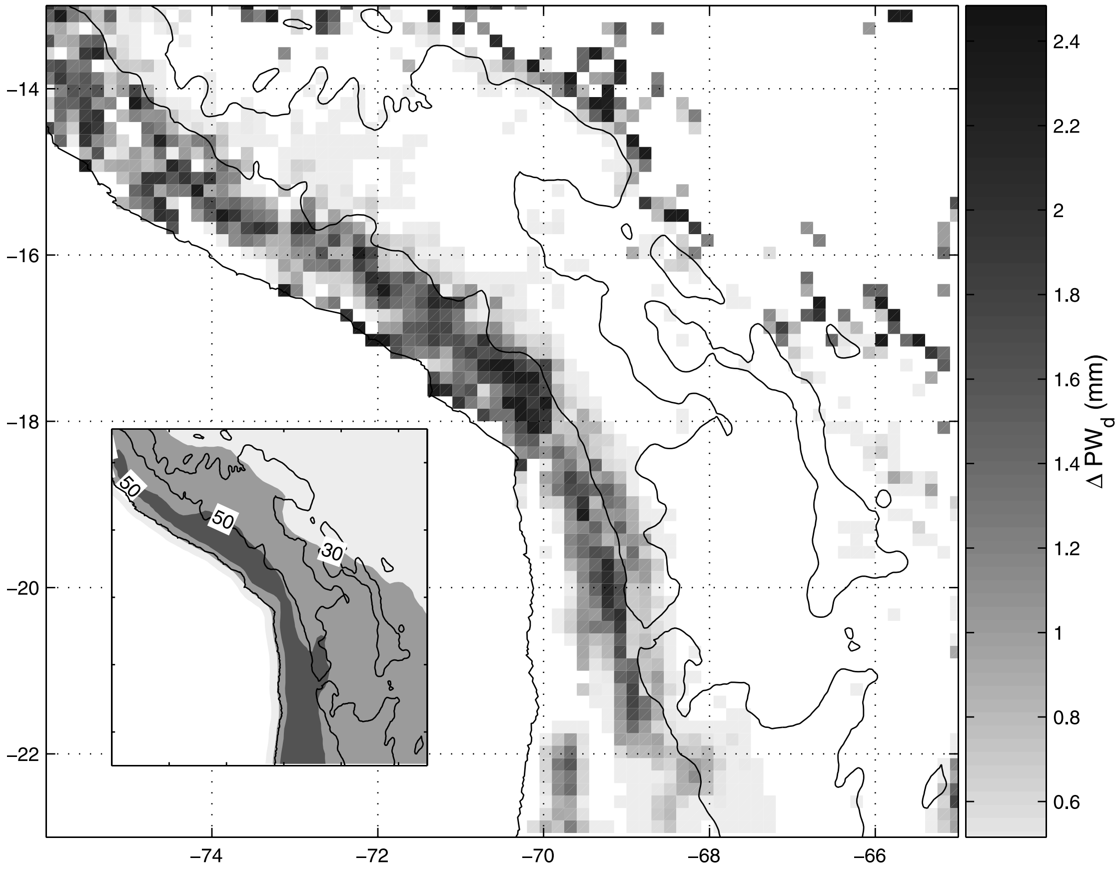


Figure 8. ΔPW_{TA} derived from MODIS 1530 UTC (TERRA) and 1630 UTC (AQUA) satellite passes. Only ΔPW_{TA} values significant at the 95% level are plotted. White areas thus point where either there really is no mean variation or there is insufficient data to establish the significance of the mean. The inset plot shows the percentage of days where ΔPW_{TA} observations were available.

data have not been included in this study. However, a cursory inspection of the available observations (not shown) reveal that westerly winds prevailed throughout the ABL at most observation times, even on days when high PW (>8 mm) was observed by MODIS. It appears possible that recirculation of water vapor previously advected across the northern Altiplano may have occurred in these cases.

3.4. Diurnal Variations

[34] In this section we briefly comment on diurnal variations of moisture observable in the PW data sets. From Figure 3d, it is clear that there is a substantial daily variation in PW at Arequipa, with magnitude of about 4 mm (over 20% of the mean PW) and peak at around 2200 UTC (1800 local time). The daily cycle is related to thermally driven flows on the western slopes of the Andes, which, near to the surface, act to transport moister air from the lower atmosphere upward during the day, and downward at night [e.g., *Chen et al.*, 1996]. Daily cycles of PW of similar magnitude have been observed by GPS instruments on other tropical mountain ranges [e.g., *Wu et al.*, 2003].

[35] The spatial characteristics of the diurnal variations in PW can to some extent be inferred using the MODIS PW data set, by calculating the difference in PW between same day AQUA (1830 UTC) and TERRA (1530 UTC) passes. The PW at Arequipa generally increases by about 2 mm between these times. We define a quantity ΔPW_{TA}, which is the mean difference in PW between same day TERRA and AQUA observations. Figure 8 shows the ΔPW_{TA} at all points where a statistically significant mean value could be obtained. Zones of significant afternoon variation are seen on both the eastern and western slopes of the Altiplano. The values of ΔPW_{TA} at points near to Arequipa (~2 mm) compare well with those inferred from the GPS data (see Figure 3). There is no indication of a significant diurnal variation in PW over the Altiplano itself. Inspection of time series of surface q_v at sites on the Altiplano plateau (not shown), including Chungara, also show no evidence of a significant diurnal cycle. Separation of the ΔPW_{TA} data into dry and wet cases show no significant differences between the composites (not shown). Thus it appears that moisture transportation by diurnal circulations is a process confined to the western and eastern slopes of the Altiplano under most conditions, and does not play a major role in the determination of wet and dry periods over the plateau itself.

4. Summary and Discussion

[36] In this study, surface, upper air and satellite observations have been used to characterize the variation of water vapor, and associated winds, precipitation and convective cloudiness, over the Altiplano during a 93 day period in the austral summer of 2002–2003. The discussion has been largely based on analysis of composites formed for days

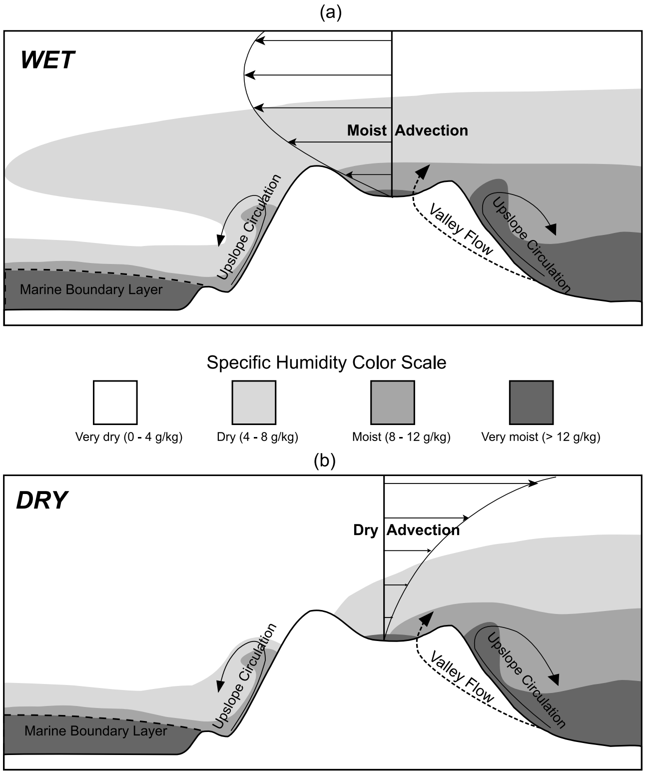


Figure 9. Schematic profile of the northern Altiplano showing the conditions associated with (a) wet and (b) dry episodes, as inferred from the observations presented in this study. The shaded regions represent atmospheric water vapor. Arrows represent prevailing zonal winds above the northern Altiplano and the anticipated afternoon circulation patterns on its eastern and western slopes. The arrows representing up-valley winds are based on the schematic presented by *Egger et al.* [2005, Figure 1].

when humid (wet) or dry (dry) conditions were observed on the western rim of the Altiplano (Arequipa).

[37] We find that during wet episodes:

[38] 1. The mean PW is uniformly distributed across the plateau, with an average value of 12 mm at the altitude of the plateau.

[39] 2. The PW and surface moisture over the Altiplano have values roughly equivalent those observed at the same height over the continent to the east and north of the Altiplano.

[40] 3. The region of high (compared to dry episodes) PW extends over the Pacific Ocean more than 1000 km west of the Altiplano.

[41] 4. In the northern Altiplano, mean easterly flow, of between 2–6 m/s is observed throughout most of the ABL.

[42] 5. The frequency of precipitation and convective cloudiness (CC) is considerably higher than in dry episodes. CC is most concentrated along the western cordillera of the northern Altiplano.

[43] In contrast, during dry episodes:

[44] 1. The PW content over most of the Altiplano is significantly lower compared to wet episodes, particularly over the southern Altiplano and along the western cordillera of the entire plateau.

[45] 2. Values of PW remain relatively high and stable over the Lake Titicaca basin and the north eastern cordillera.

[46] 3. There is no indication of any significant drying of the atmosphere to the east of the Altiplano.

[47] 4. In the northern Altiplano, mean westerly winds are observed at upper levels. However, significant mean westerlies were not observed below 6000 m.

[48] 5. The frequency of convective cloudiness is low (<20%) over all the Altiplano except in its most northern parts. Precipitation frequency is significantly lower at the majority of sites.

[49] In addition, MODIS PW estimates were used to observe the daily cycle of moisture variation over the Altiplano. Diurnal variations in moisture are strong on the eastern and western flanks of the Altiplano. Significant diurnal moisture variation cannot be identified over the plateau.

[50] The results of this study shed light of the probable manner by which moisture reaches the Altiplano during wet episodes. Earlier work by *Garreaud* [1999], based on numerical simulation, indicated that during wet events, downward flux of easterly momentum by the winds aloft tends to accelerate the day time upslope flows on the eastern flanks of the Altiplano, resulting in the transport of moisture rich air from the continental lowlands to the plateau. The midlevel and upper level flow was considered too dry to account for the surface moisture variability on the Altiplano by moisture advection alone. However, the results of this study show that during wet periods, the moisture content above the Altiplano is in fact comparable to that at the same altitude over the continent, and that furthermore a mean easterly flow exists in the ABL that can transport the moist air to the plateau. Thus simple horizontal advection appears sufficient as a moisture transport mechanism for the Altiplano. This conclusion is further supported by the fact that the easterly winds were observed in the early morning, when upslope flows are expected to be weakest, and that diurnal variability in PW over the plateau is significant only on the outer slopes of the Altiplano. The long tongue of moist air out over the Pacific is also evidence of sustained advection occurring during wet episodes.

[51] Our results also show that during dry episodes, the entire Altiplano is not uniformly immersed in dry air from the west. In the northern Altiplano over the Titicaca basin, the integrated water vapor remains consistently high despite the occurrence of periodic dry spells in its western cordillera. The lack of moisture variability in this region is consistent with a general lack of variability seen in fields of surface precipitation and convective cloudiness over interannual timescales [*Vuille et al.*, 2000; *Vuille and Keimig*, 2004], and is also consistent with the surface data on the eastern Altiplano that were presented by *Garreaud* [2000] for the summers 1993 and 1994. From our SALLJEX observations the temporal stability of moisture is most readily explained by the lack of near surface westerly flow over the northern Altiplano during dry days, indicative of minimal westerly advection of dry air to the Titicaca basin and the eastern cordillera. In addition, geographical factors may help to sustain the high levels of moisture in the region. For example the lake Titicaca, which covers a substantial proportion of the northern basin, may moisten the atmosphere by evaporation, as mean evaporation rates of roughly

4 mm/day are expected over the lake surface [*Blodgett et al.*, 1997]. The eastern cordillera of the northern Altiplano is also broken in several places by large mountain passes that may allow inflow of moist air even in opposing synoptic conditions. *Egger et al.* [2005] have shown during winter, when strong synoptic-scale westerlies prevail aloft, strong upslope flows can still occur within these valleys, and may play a significant role in supplying moisture to the northern basin in the absence of midlevel advection.

[52] In Figures 9a and 9b we present two concluding diagrams that summarize the key characteristics of wet and dry episodes in the northern Altiplano that have been observed or implied by the results presented in this study. These schematics strictly apply only to the 93 day observational period that was studied, and some elements of the diagrams are speculative. It is hoped that our one-season sample is at least to some degree representative of the general characteristics of summer time variability, as the observed surface and upper air conditions during wet and dry periods were qualitatively similar to those presented in prior studies. However, confirmation of the general applicability of this conceptual picture will require further investigation in which multiple seasons are considered. In this regard, it is worth mentioning that all of the satellite observations used in the present study could potentially be applied to other seasons (the "youngest" satellite-based instrument is the MODIS (AQUA), which has been operational since May 2002). Obtaining a similar record of the circulation over the Altiplano, as was achieved in this study by the use of the SALLJEX PIBAL measurements, is likely to be more problematic, and their investigation in a multiseason context may perhaps be best achieved through mesoscale modeling. In this case, comparison of the spatiotemporal variation of simulated moisture fields against the water vapor observations now available by satellite instruments such as MODIS may provide an indirect means of confirming the plausibility of model predicted circulation patterns.

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