Clim Dyn
DOI 10.1007/s00382-009-0637-1

Influence of the Andes Mountains on South American moisture transport, convection, and precipitation

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Received: 31 March 2009 / Accepted: 13 July 2009

Abstract Mountain ranges are known to have a first-order control on mid-latitude climate, but previous studies have shown that the Andes have little effect on the large-scale circulation over South America. We use a limited-domain general circulation model (RegCM3) to evaluate the effect of the Andes on regional-scale atmospheric dynamics and precipitation. We present experiments in which Andean heights are specified at 250 m, and 25, 50, 75, and 100% of their modern values. Our experiments indicate that the Andes have a significant influence on moisture transport between the Amazon Basin and the central Andes, deep convective processes, and precipitation over much of South America through mechanical forcing of the South American low-level jet (LLJ) and topographic blocking of westerly flow from the Pacific Ocean. When the Andes are absent, the LLJ is absent and moisture transport over the central Andes is mainly northeastward. As a result, deep convection is suppressed and precipitation is low along the Andes. Above 50% of the modern elevation, a southward flowing LLJ develops along the eastern Andean flanks and transports moisture from the tropics to the subtropics. Moisture drawn from the Amazon Basin provides the latent energy required to drive convection and precipitation along the Andean front. Large northerly moisture flux and reduced low-level convergence over the Amazon Basin leads to a reduction in precipitation over much of the basin. Our model results are largely consistent with proxy evidence of Andean climate change, and have implications for the timing and rate of Andean surface uplift.

Keywords Climate dynamics · Uplift · South America · Regional modeling · Andes

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1 Introduction

Large, mid-latitude mountain ranges have a first-order control on large-scale atmospheric circulation by modifying stationary wave patterns. For example, the Rocky Mountains and the Tibetan plateau modify the mid-latitude storm tracks and regions of subsidence and drying by influencing upper-tropospheric flow (e.g. Broccoli and Manabe 1992; Kutzbach et al. 1989). The Andes Mountains are the dominant topographic feature in South America, extending over 7,000 km from $\sim$7°N to 45°S, with Andean plateau elevations as high as $\sim$4,000 m over a large portion of the central Andes. Despite its enormity, previous studies have suggested the Andes Mountains have only a minor influence on large-scale atmospheric patterns over South America. The major stationary features, including the Bolivian High and the Nordeste Low, the low-level northerly flow over northern and central South America, and the large-scale precipitation are mainly products of diabatic heating over the Amazon Basin and are only marginally affected by the Andes (e.g. Figueroa et al. 1995; Kleeman 1989; Lenters and Cook 1995, 1997).

However, it has been shown that the Andes affect regional-scale climate by blocking zonal flow and influencing regional wind pattern and precipitation. Mechanical forcing by the Andes is critical to the formation of the

South American low-level jet (LLJ) (Campetella and Vera 2002; Gandu and Geisler 1991). The Andes block and deflect low-level trade winds from the equatorial Atlantic to form a northerly/northwesterly barrier jet that flows along the eastern flanks of the mountains (Virji 1981) and transports moisture from the Amazon Basin to the subtropical regions of the continent (Vera et al. 2006). On a more local scale, the Andes focus precipitation along the eastern flanks of the northern and central Andes due to orographic lifting and the inducement of small-scale convergence and convection (Lenters and Cook 1995). Though linkages between the Andes and regional dynamics and precipitation have been established, the details and significance of these interactions on modern climate are less certain. For example, it is unclear to what extent the Andes, through their impact on the LLJ, affect the heat and moisture transport from the tropics to higher latitudes and how important this moisture transport is to convective processes that drive precipitation. It is also not known whether the Andes significantly influence low-level flow away from the Andean flanks or whether it affects precipitation in remote regions, including the Amazon Basin and the South Atlantic Convergence Zone (SACZ).

Knowledge of these interactions is important for understanding paleoclimate as well as modern climate processes. The modern Andes are a geologically young feature that was uplifted during the Neogene ($\sim$25 Ma to present) due to the subduction of the Nazca Plate below South America (Isacks 1988). Paleoclimate proxies for this time indicate that climate conditions along the eastern margin of the Andean plateau changed from arid to humid (e.g. Kleinert and Strecker 2001; Starck and Anzotegui 2001), while the western flanks of the plateau became hyperarid (e.g. Alpers and Brimhall 1988; Rech et al. 2006). To determine whether Neogene paleoclimate was responding mainly to surface uplift or some other forcing requires an understanding of the evolution of interactions between the Andes and regional climate.

The objective of this study is to investigate the influence of the Andes on regional climate over South America. In particular, we focus on the effect of the Andes on the LLJ, moisture transport, and precipitation processes. The influence of the Andes on South American climate has been previously studied through the use of global and regional climate models (Campetella and Vera 2002; Figueroa et al. 1995; Gandu and Geisler 1991; Lenters and Cook 1995). However, these models are limited in their utility due to their coarse resolution, lack of diurnal and/or seasonal heating, or absence of hydrological processes. As a result of these limitations, moisture transport and seasonal precipitation could not be simulated, or was biased by the unrealistic representation of the Andes as a low, broad topographic feature. This study represents an advance on previous studies by using a regional general circulation model (RegCM3) capable of representing the narrow, steep topography of the Andes (Fig. 1a), and a convection scheme that has been shown to provide a realistic simulation of present-day climatology. To evaluate dynamical and physical atmospheric changes associated with variations in Andean plateau height during the Cenozoic, we present a series of experiments in which Andean heights are specified at 250 m, and 25, 50, 75, and 100% of their modern values. Our results indicate that even though the Andes have little effect on large-scale stationary features they have a fundamental impact on moisture transport and precipitation across South America.

2 Methods

2.1 Model

The RegCM3 (Pal et al. 2007) is a third generation, three-dimensional regional climate model, based on the original model developed by Giorgi et al. (1993a, b), with a dynamical core that is adopted from the hydrostatic version

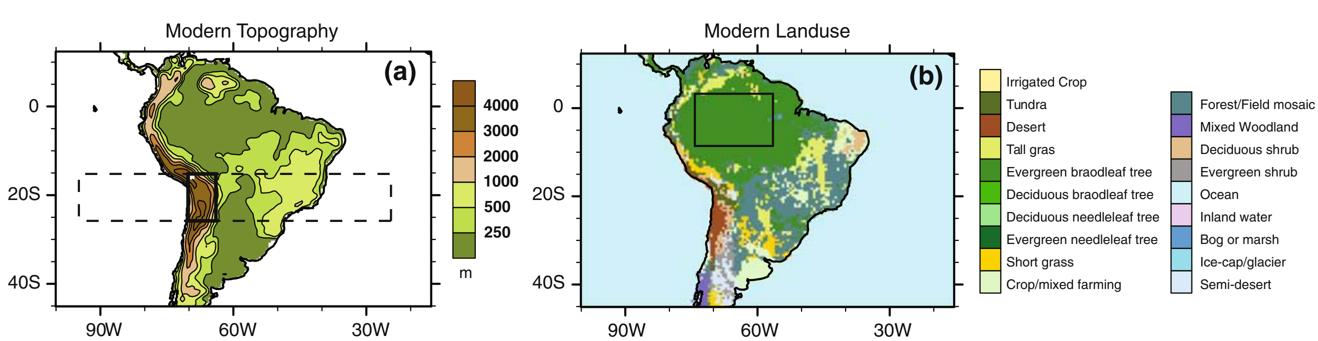

Fig. 1 Model domain with topography and land cover in South America. **a** Present day elevations used in RegCM3 are from the United States Geological Survey (USGS). *Solid box* indicates the domain for the Andean plateau region; *dashed box* shows the profile location for height/pressure-longitude plots. **b** Land surface description used in RegCM3 is based on the Global Land Cover Characterization dataset and defined by BATS (Biosphere Atmosphere Transfer Scheme). *Box* indicates the domain for the Amazon Basin

of the Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model (MM5) (Grell et al. 1994). It is a primitive-equation, hydrostatic, compressible model with sigma-vertical coordinates (Giorgi et al. 1993a). Improvements in the representation of precipitation physics, surface physics, atmospheric chemistry and aerosols in the RegCM allows an enhanced model performance in tropical and subtropical regions (Pal et al. 2007).

RegCM3 experiments were performed for South America using a continental scale domain with 60 km horizontal resolution and 18 levels in the vertical (Fig. 1). The land surface is represented by the Biosphere-Atmosphere Transfer Scheme (BATS, Dickinson et al. 1993) that is designed to describe the role of vegetation and interactive soil moisture in modifying the surface-atmosphere exchanges in momentum, energy, and water vapor (Fig. 1b) (Giorgi and Marinucci 1996). Sea-surface temperatures (SST) were obtained from the NOAA optimum interpolation (OI) SST analysis (Reynolds et al. 2002). Atmospheric lateral boundary conditions from 40 yr reanalysis (ERA-40) data are derived from the European Centre for Medium-Range Weather Forecast (ECMWF). Simulations are 10 years in length (January 1991–December 2000) and results are based on the last 5 years of simulation.

Convective precipitation was computed by two different schemes, the Grell scheme (Grell 1993) and the MIT-Emanuel scheme (Emanuel 1991). In this study, we present results from experiments using the MIT-Emanuel convection scheme, because it provides the best fit to modern precipitation over the tropics and subtropics of South America. This convective scheme assumes that the mixing in clouds is highly episodic and inhomogeneous and considers convective fluxes based on idealized model of sub-cloud-scale updrafts and downdrafts (Pal et al. 2007). In comparison to other convective schemes, the Emanuel scheme includes a formulation for auto conversion of cloud water into precipitation in cumulus clouds (Pal et al. 2007). Our experiments are in good agreement with previous studies that have shown that the use of the RegCM3 version together with the Emanuel convection scheme leads to improved simulations of precipitation, temperature and low-level wind pattern compared to the RegCM3/Grell configuration and other RCMs (Pal et al. 2007; Seth et al. 2006). In particular, previous results have shown a strong dry bias in austral summer over the Amazon region mostly related to deficient parameterization of convection and poor presentation of surface processes over tropical areas (e.g. Berbery and Collini 2000; Chou et al. 2002; DeSales and Xue 2006; Rojas and Seth 2003) that is absent in analogous simulations with the Emanuel scheme (Seth et al. 2006).

2.2 Model setup and free parameters

The goal of this study is to quantify the impact of Andean uplift on South American climate dynamics. Our model domain ranges from 100°W to 15°W and 12°N to 45°S. Previous studies have shown that large domains are necessary to accurately simulate sensitivity to forcings within the domain (Seth and Giorgi 1998; Seth and Rojas 2003). For this reason, a large domain, extending over parts of the Atlantic and Pacific Ocean, was chosen (Fig. 1). To this end, we designed experiments to account for different Andean elevations without changing other parameters. In total, five experiments were completed with discrete Andean elevations (AE). The 100% AE simulation assumes a present-day Andean elevation that is based on a global digital elevation model from the USGS with elevations regularly spaced at 30-arc seconds (USGS 1996). Unlike previous GCM studies of the region, our simulations resolve the high elevations (exceeding 4,000 m) and narrow extent of the Andes (Fig. 1a). The 75, 50, and 25% experiments simulate the climate when the Andes were reduced to three quarters, one half, and one quarter of the modern Andean elevation, respectively. For the no Andes case (0% AE), Andean elevations were specified as 250 m. In other regions of South America, the topography was maintained at modern elevations. In this study, we do not account for global climate change during the Cenozoic. Trace gases (i.e. 355 ppmv CO_2, 1714 ppbv CH_4, 311 ppbv NO_2), SST, vegetation cover, solar luminosity, and orbital parameters were specified to represent modern conditions and remain constant in all experiments. The influence of these factors on the Cenozoic evolution of South American climate will be addressed in a future study.

3 Modern climatology

A comparison between simulated and observed data indicates that RegCM3 performs very well in capturing the general climatology in South America. The model performance for modern precipitation is assessed by using independent precipitation observations from the Global Historical Climatology Network (GHCN) data base (Fig. 2a, b) (NOAA/NESDIS/NCDC 2003). We interpolated the mean seasonal precipitation from climate stations in South America with records of monthly precipitation exceeding 10 years. The model captures the distribution of summer (DJF, December; January; February) precipitation across South America, including regions of maximum precipitation in the central part of the Amazon Basin and along the eastern flanks of the central Andes, as well as arid conditions over northeast Brazil, Venezuela, northern Chile

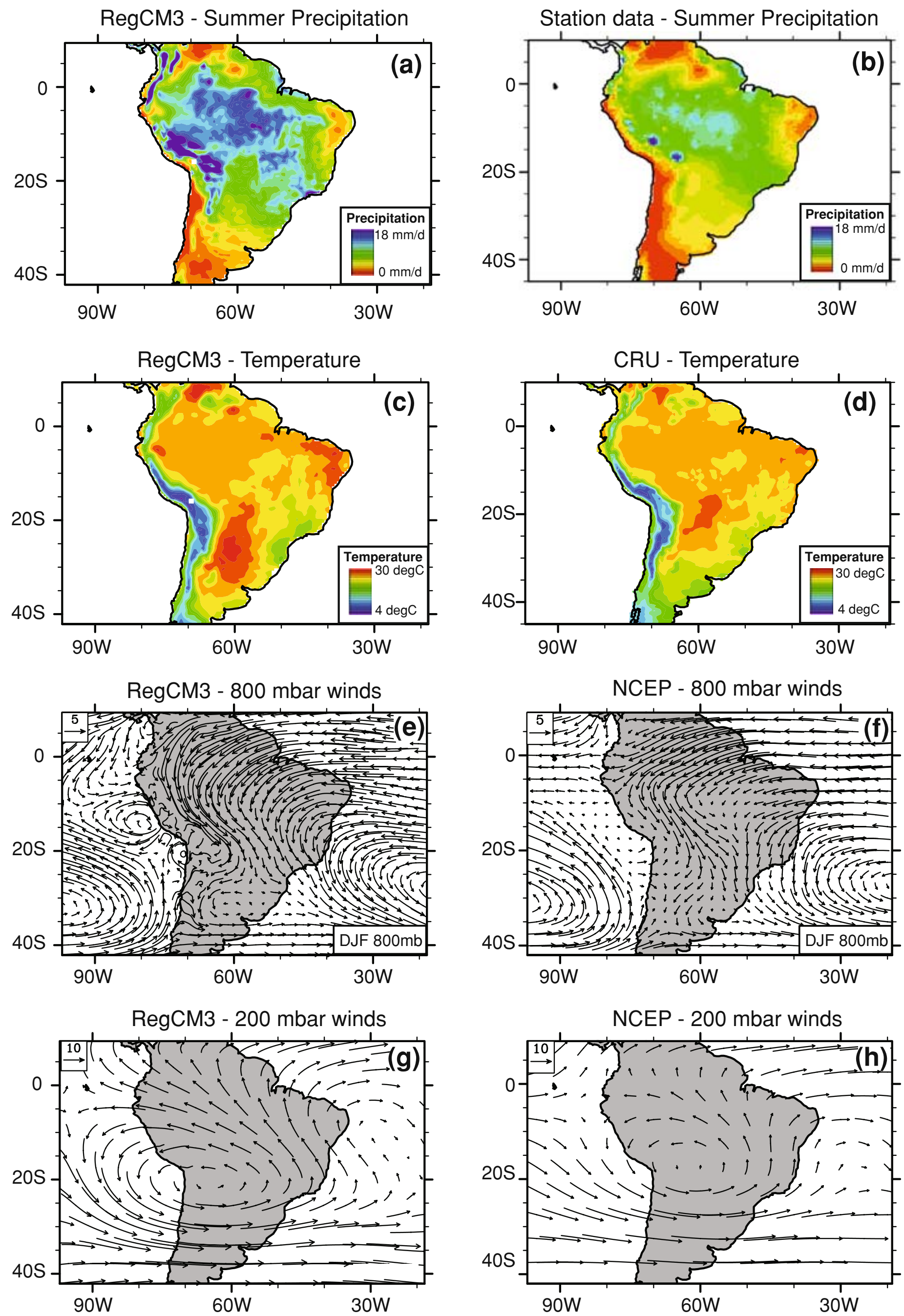

Fig. 2 Comparison of modeled data versus observations for precipitation, temperature, and winds. All plots show summer conditions (December, January, February). **a** RegCM3 modeled modern summer precipitation in South America. **b** Observed summer precipitation, based on precipitation time series from the Global Historical Climatology Network (GHCN) database. Interpolated monthly precipitation data are from climate stations that recorded more than 10 years of precipitation for each month to ensure the relevance of the data. **c** RegCM3 modeled summer temperature. **d** Same as (**c**), but interpolated from CRU data. **e** RegCM3 modeled winds at 800 mbar sigma level. **f** Same as (**e**), but interpolated from NCEP reanalysis data. **g** RegCM3 modeled winds at 200 mbar sigma levels. **h** Same as (**g**), but interpolated from NCEP reanalysis data. Small discrepancies between the climatologic fields from modeled data and reanalysis data are based on the different horizontal resolution of the datasets. Note that the RegCM3 model simulated climate parameters with a horizontal resolution of 60 km, the CRU data are based on a 0.5 × 0.5° grid, while the NCEP data are from a global grid with spatial resolution of 2.5 × 2.5°

and southern Argentina (compare Fig. 2a, b). The modeled summer precipitation over the Amazon Basin is approximately 30% higher than the observed precipitation in this area. We attribute the overestimate of precipitation to the land surface model that likely overestimates the moisture component that is recycled over the Amazon Basin, resulting in high precipitation rates. Preliminary experiments with RegCM coupled to the Community Land Model (CLM), with an improved canopy integration scheme and a better simulation of the hydrological cycle, yield lower precipitation rates in line with observations. In addition to overestimating Amazon precipitation, the modeled summer precipitation along the eastern flanks of the Andes and on the Andean plateau is more pronounced than in the observed pattern with the Andean plateau region receiving several mm/day rainfall that is not observed in the station data. However, seasonal variations in precipitation including the high rainfall associated with seasonal migration of the SACZ (e.g. Horel et al. 1989; Wang and Fu 2002) are well simulated by RegCM3. Therefore, despite small discrepancies in the absolute amounts of precipitation over the Andean plateau region, the relative

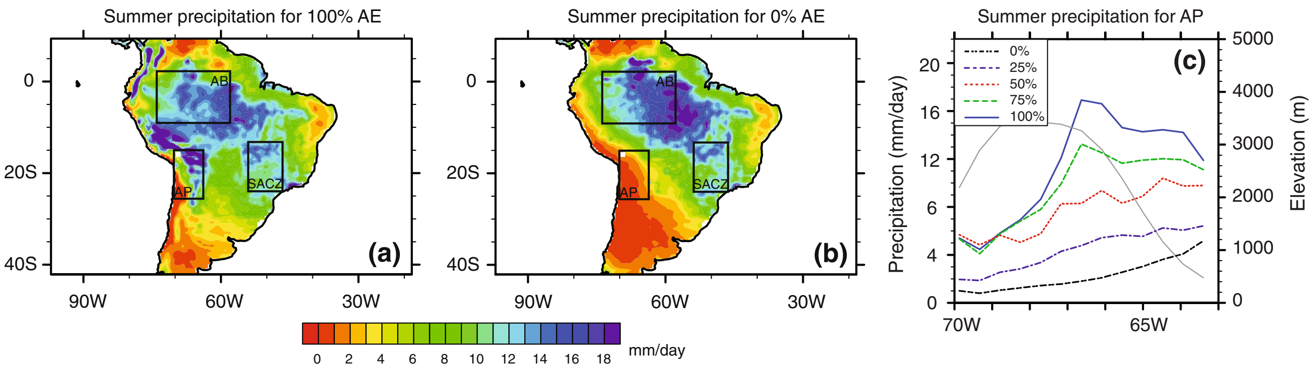

Fig. 3 Precipitation in South America during the summer (averaged over December, January, February). **a** Total precipitation for simulations with modern Andes. *Boxes* represent the Amazon Basin (AB), the Andean plateau (AP), and the South Atlantic Convergence Zone (SACZ), respectively. **b** Same as (**a**), but for simulations with no Andes. **c** Total precipitation over the Andean plateau region (15–26°S) for different Andean heights (in percent from modern elevation). *Solid gray line* represents modern topography

precipitation amounts between different scenarios are most likely realistic.

In addition to the precipitation distribution, RegCM3 also captures other important climatological features over South America. For example, simulated summer surface temperatures agree well in structure and magnitude with the Climatic Research Unit (CRU) derived temperatures, with maximum values in Northern Argentina, northeast Brazil, and Venezuela (Fig. 2c, d). The Chaco Low, a low-pressure system observed in central South America during the summer, is well developed. The modeled low-level (800-mbar) circulation over South America, with strong easterlies in the northern part of South America and an anticlockwise rotation of winds over the central part of the continent, resembles NCEP reanalysis winds at the same level (compare Fig. 2e, f). Moreover, the upper-level (200 mbar) circulation, including the Bolivian High (see "Section 4.3"), an intense quasi-stationary anticyclone (e.g. Horel et al. 1989; Lenters and Cook 1997; Virji 1981) that forms in a region of high precipitation in response to condensational heating (e.g. DeMaria 1985; Lenters and Cook 1997; Silva-Dias et al. 1983), is simulated. Our simulation places the center of the anticyclone at around 20°S and 65°W (Fig. 2g), in good agreement with data obtained from geostationary satellite images that locate the Bolivian High at 17°S and 65°W (Virji 1981) and NCEP reanalysis data (Fig. 2h).

4 Results

4.1 Precipitation and low-level circulation for simulations with modern Andes

Precipitation in South America is highly seasonal with ~50–80% of precipitation falling in austral summer. Summer precipitation in South America is focused in the Amazon Basin, along the eastern flanks of the northern and central Andes, and the SACZ (Fig. 3a). Precipitation maxima are generally ~15 mm/day for all three regions. Most of the precipitation is convective in origin, but the climatological conditions that promote convection differ between regions.

In the Amazon Basin, precipitation is nearly uniform throughout the year. Convection over the Amazon Basin is triggered by convergence of moisture-laden northeasterly trade winds across the basin with the North Atlantic Ocean as the primary moisture source (Fig. 4a). Transport of moist, warm air by zonal winds and strong evapotranspiration (not shown) due to rainforest vegetation and high soil moisture provide additional conditions that favor vigorous convection over the Amazon Basin. Convection in the lower and middle troposphere is indicated by the development of thick clouds to ~400 mbar (not shown).

In the extratropics, simulated precipitation is highly seasonal. The model captures the summer precipitation maxima over east-central South America associated with the SACZ (Fig. 3a). This precipitation is predominantly convective, as indicated by the presence of high clouds (Fig. 5a). The formation of convective precipitation in this region is related largely to the seasonal strengthening of the South Atlantic High, which directs low-level flow from the tropics to the subtropics (Fig. 4a). The convergence of this warm moist air from the Amazon Basin provides the moisture and energy for deep convection and precipitation.

A significant seasonal precipitation cycle exists in the Andean plateau region with strong summer precipitation (Fig. 3a) and very dry conditions during the winter. Seasonality in Andean precipitation is related to the seasonal insolation cycle over South America and the associated migration of the inter-tropical convergence zone. As indicated by a strong southward component of wind directions,

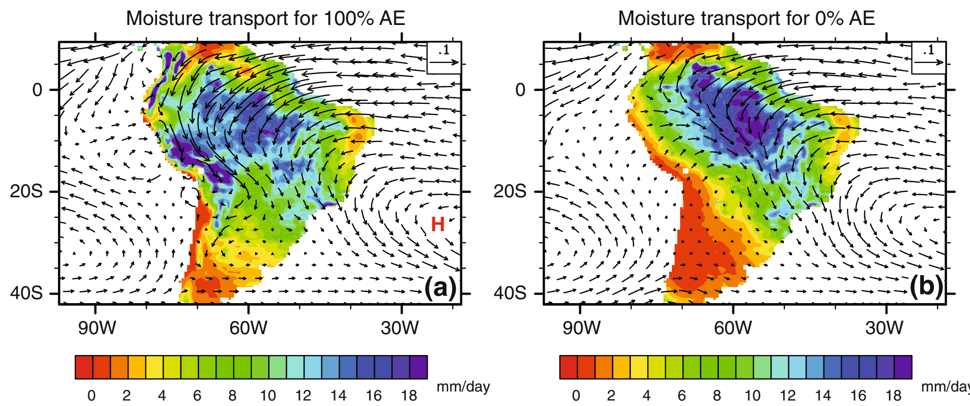

Fig. 4 Low-level (800 mbar) moisture transport/winds in South America. **a** Moisture transport during the summer for simulations with modern Andes. *H* represents the South Atlantic High. **b** Same as (**a**), but for simulation with no Andes

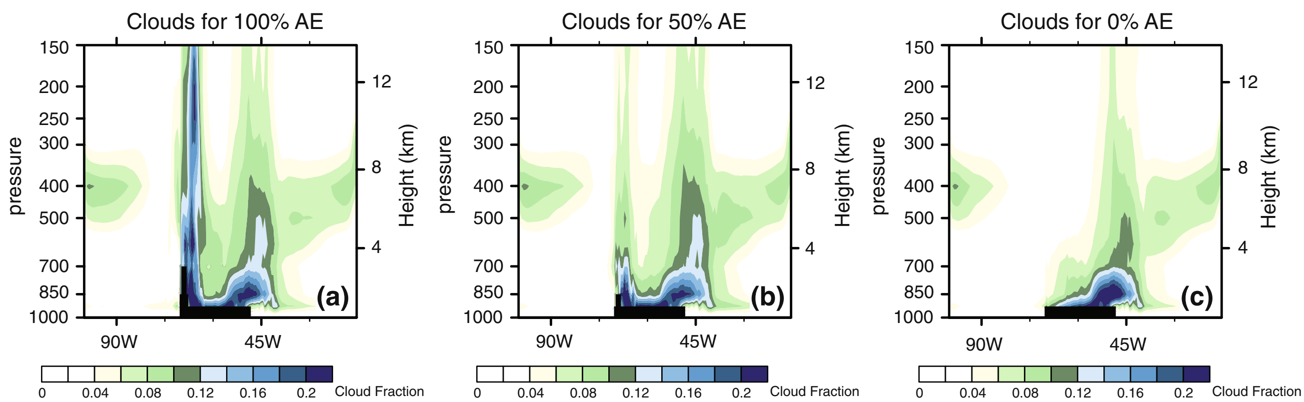

Fig. 5 Clouds over South America between 15 and 26°S latitude during summer. **a** Height/Pressure-longitude profile for clouds over the Andean plateau region and the SACZ for simulations with modern Andes. **b** Same as (**a**), but for simulations with 50% Andean heights. **c** Same as (**a**), but for simulations with no Andes

moisture is supplied by transport of water vapor from the Amazon Basin up the eastern slopes of the Andes (Fig. 4a). Through orographic lifting, the Andes trigger condensation, latent heat release, and strong convective updrafts during the summer. The formation of high clouds that extend into the lower stratosphere up to 150 mbar is symptomatic of these convective updrafts (Fig. 5a). Deep convection provides 65% of the precipitation. A smaller portion of the precipitation results from the passage and orographic lifting of frontal systems, i.e., large-scale precipitation. Orographic and convective lifting along the eastern side of the Andes is evident by the strong negative vertical velocity (omega) (Fig. 6a), indicating upward airflow.

Summertime, low-level flow over the Amazon Basin, the SACZ, and Andes is dominated by northerly winds. Along the eastern flanks of the Andes, this low-level flow organizes into a fast-flowing low-level jet (LLJ). A cross section of meridional wind at 15–26°S, depicted in Fig. 7a, illustrates the well-develop jet, which has maximum northerly velocities of over 8 m s^{-1} and monthly average peak velocities up to $\sim$11 m s^{-1}. The LLJ is also a region of high specific humidity (Fig. 7b) and high relative humidity (Fig. 7c). In fact, it is this large southward transport of water vapor that defines the LLJ's role in South American climate. The southward-transported vapor provides the latent heat and moisture source for precipitation along the Andean flanks. In support of this view, strong convection, cloud formation (Fig. 5a) and upward motion (Fig. 6a) correspond with regions of maximum latent heating and near-surface convergence (Fig. 8a) along the eastern margin of the Andes. In contrast, the subtropical Pacific on the western side of the Andes does not contribute substantial amounts of moisture or latent heat, because the low-level flow is blocked by the steep Andean topography and large-scale subsidence (Figs. 6a, 7a).

In sum, our model results indicate that the role of the Andes in precipitation processes is not only due to orographic lifting. Rather, the Andes influence precipitation through dynamical processes involving the development of

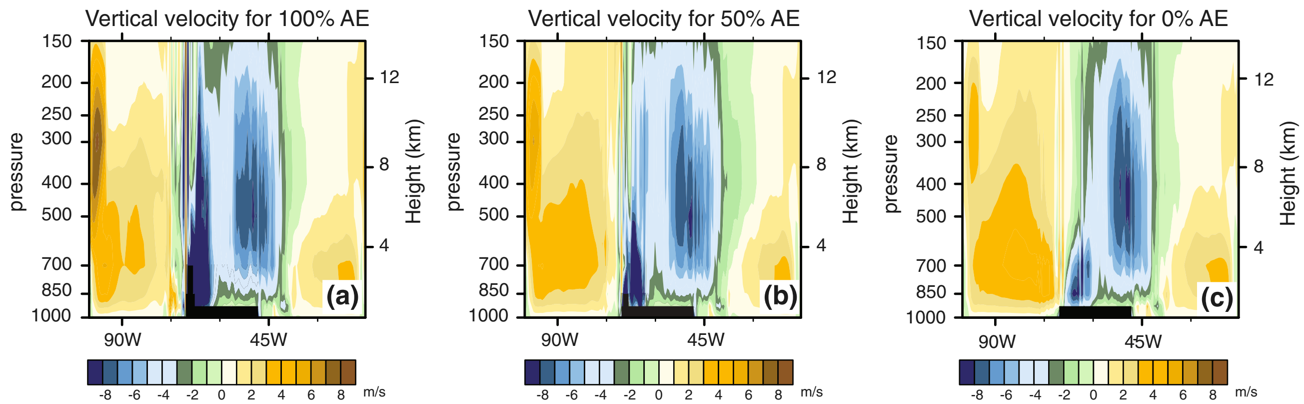

Fig. 6 Vertical velocity (omega) across South America between 15 and 26°S latitude during summer. Height/pressure-longitude profile with negative values indicating a strong upward air component. **a** Simulations with modern Andes. **b** Simulations with 50% Andean heights. **c** Simulations with no Andes

the LLJ, moisture transport, and the development of deep convection.

4.2 Effects of uplifting topography on precipitation and low-level circulation

In the previous section, we describe on the basis of climatological relationships that the modern Andes play an important role in modulating low-level circulation, moisture transport and precipitation. To explicitly demonstrate the interplay between the Andes, convection, and precipitation, and to improve our understanding of how and when Andean topography influences local and regional processes, we explore changes in South American climatology over a range of prescribed Andean elevations.

The Andes have a substantial impact on precipitation across much of western South America. When the Andes are absent, precipitation along the eastern flanks of the central Andes is extremely low with ~2–4 mm/day (Fig. 3b). With increasing Andean plateau height, precipitation increases continuously to ~15 mm/day for the modern Andes (Fig. 3c). The reduction in Andean precipitation is related to a decrease in moisture transport and suppression of convection.

Moisture transport along the central Andes is strongly affected by the removal of topography. Without an orographic barrier, the LLJ and its transport of relatively warm, moist air disappears (Fig. 7g, h) and latent heat along the flanks of the Andes is low (<100 W m^{-2}; Fig. 8b). With a deficit in moisture and latent heat, convective processes are suppressed, evident by a reduction in high clouds over the central Andes (compare Fig. 5a, c). In the absence of the Andes, prevailing winds over the plateau region are sourced from the Pacific Ocean (Fig. 4b). The southwesterly flow is characterized by low water vapor content (<6 g kg^{-1}) and low relative humidity (<0.5) (Fig. 7g–i) due to low surface temperatures associated with the Humboldt Current along the west coast of South America and subtropical atmospheric subsidence (e.g. Rutllant and Ulriksen 1979). Moreover, without a barrier, the lifting mechanism disappears and vertical velocities in the lower atmosphere are strongly reduced (Fig. 6c).

Initial uplift of the Andes to less than 50% of modern elevations leads to an increase in precipitation, specific humidity and relative humidity over the plateau area and along the eastern Andean flanks (Figs. 3c, 9a, b). An increase in water vapor content over these regions during initial uplift of the Andes is related to a strengthening of the Chaco Low over central South America that redirects the moisture flux from lower to higher latitudes (not shown). The increased moisture transport increases surface latent heating from ~60 W m^{-2} to >140 W m^{-2} (Fig. 9c). With increasing moisture and latent heat release, clouds start to form along the eastern flanks of the Andes (Fig. 5b) causing the reflection of incoming solar radiation to space. The reduction in surface heating results in a decrease in sensible heating from ~120 W m^{-2} to less than ~60 W m^{-2} (Fig. 9d).

When the Andes reach 50% of their modern elevation, the LLJ is initiated (Fig. 7d). Atmospheric dynamics similar to modern are established and amplify as the Andes rise to their modern elevation. At 50% of their modern elevation, the Andes block the dry westerly flow and drastically change zonal and meridional moisture transport. The deflection of easterly winds originating over the Amazon Basin results in the establishment of strong northerly airflow along the eastern flanks of the Andes that transport moisture from the tropics to the central Andes, increasing the surface water vapor and the relative humidity (Fig. 7d–f).

Further uplift of the Andes to modern elevations causes a strengthening of the LLJ (compare Fig. 7a, d) and

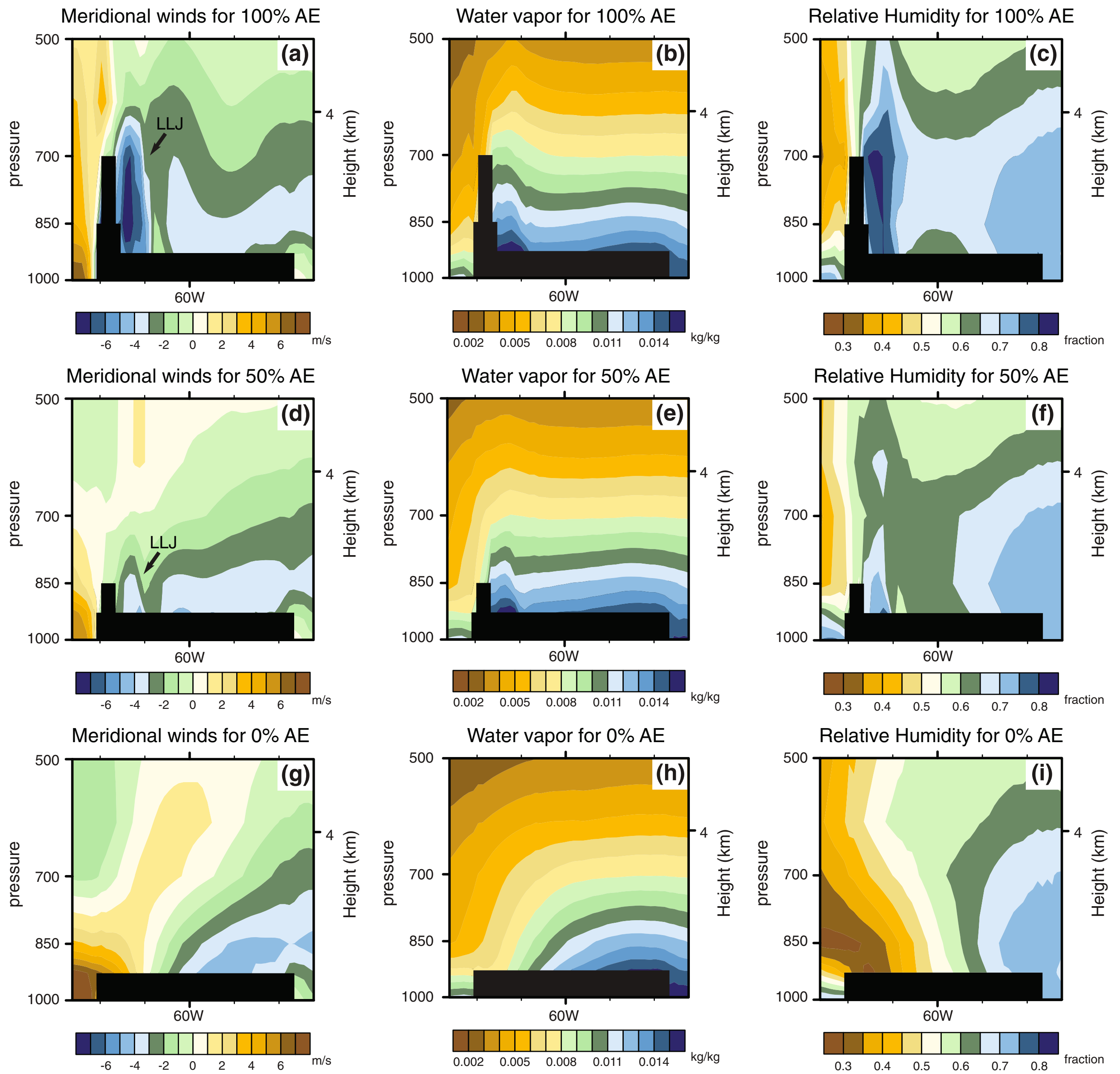

Fig. 7 Meridional winds, water vapor and relative humidity across South America between 15 and 26°S latitude during summer. **a** Simulation with modern Andes indicate the formation of a low-level jet (LLJ) with a strong northerly component along the eastern flanks of the Andes, **b** bringing high water vapor content **c** and results in high relative humidity. **d**, **e** and **f** show meridional wind, water vapor and relative humidity for simulation with 50% Andean heights. **g**, **h**, and **f** same as (**d**), (**e**), (**f**), but for simulation with no Andes

increases the meridional moisture transport to modern values of $\sim$25 g kg^{-1} ms^{-1} at atmospheric pressures of 800 mbar (Fig. 9e). The significant increase in moisture flux due to the LLJ along the eastern flanks of the Andes correlates with a significant increase in relative humidity (Figs. 7c, 9b) and a significant increase in precipitation (Fig. 3c). Due to rainout along the Andean flanks and enhanced subsidence on parts of the plateau, water vapor amounts on the plateau decrease (Fig. 9a). Because most of the moisture is transported to the central Andes at high atmospheric levels, surface latent heat and sensible heat remain almost constant during the final stage of Andean uplift (Fig. 9c, d).

Changes in Andean topography also modify precipitation and moisture transport across the Amazon Basin. In the absence of the Andes, precipitation in the eastern and central part of the basin is $\sim$3–4 mm/day higher than under modern conditions (Fig. 10a). The higher precipitation magnitudes are the result of enhanced low-level convergence over the Amazon Basin due to a reversal of wind

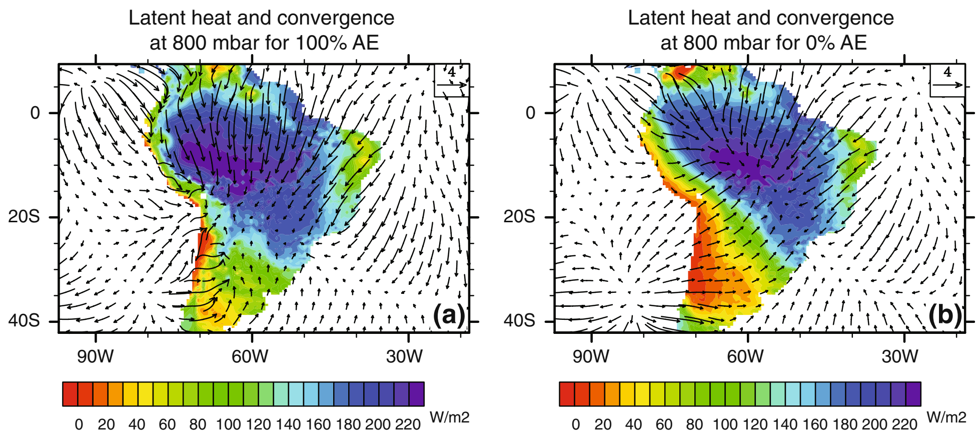

Fig. 8 Surface latent heat (*shown in colors*) and convergence at 800 mbar (*arrows*) during summer. **a** Simulations with modern Andes. **b** Simulations with no Andes

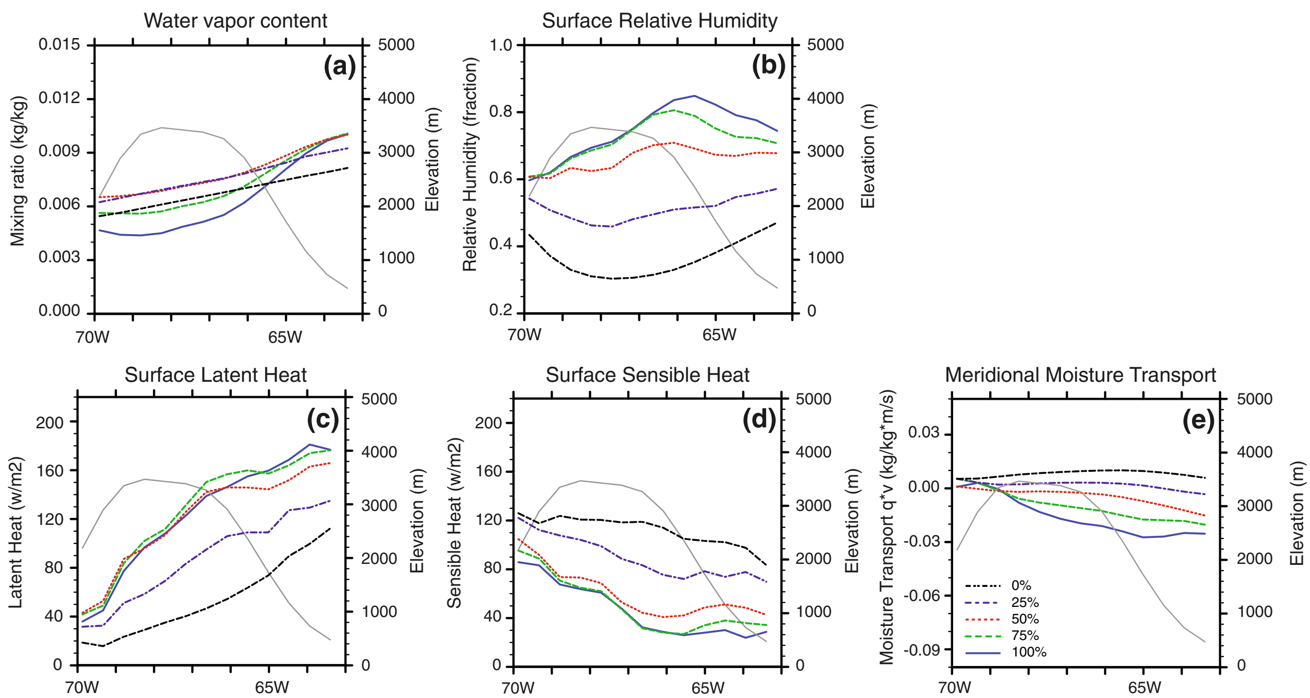

Fig. 9 Moisture and heat over the Andean plateau region (15–26°S) for different Andes heights (in percent from modern elevation) during summer. *Solid gray line* represents modern topography. **a** Water vapor content at 800 mbar. **b** Surface relative humidity. **c** Surface latent heat. **d** Surface sensible heat. **e** Meridional moisture transport (q × v) at 800 mbar. Positive values show moisture transported from the south, negative values indicate northerlies

direction over the western part of the basin (Fig. 4b). Low-level convergence of westerlies and easterlies focuses moisture convergence (Fig. 8b) and deep convection over large parts of the basin. With increasing Andean elevations, the eastern part of the Amazon Basin experiences a significant increase in zonal moisture flux that transports water vapor to the west (Fig. 10b) and causes a decrease in precipitation of up to 25% (Fig. 10a). The western part of the Amazon Basin is characterized by a strong increase in north-south directed transport of moisture from 25 to 90 g kg^{-1} ms^{-1} (Fig. 10c) and a change from predominant westerlies to easterlies between three quarters and modern Andean elevations. The significant increase in meridional moisture transport provides the source for increasing moisture flux into the Andean plateau region, resulting in higher precipitation along the eastern flanks of the Andes.

The SACZ is largely unaffected by changes in Andean topography. Precipitation across the SACZ stays almost the same; differences between modern and no-Andes simulations are smaller than 1 mm/day. Prevailing wind directions, water vapor content, and moisture transport across the SACZ are also unchanged (not shown). The absence of any significant changes is confirmation that this region is largely controlled by the influence of the South Atlantic

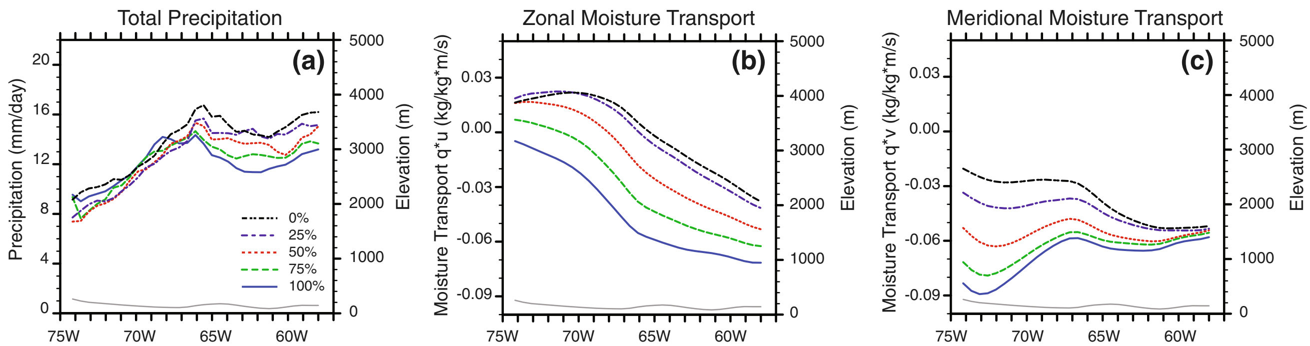

Fig. 10 Moisture over the Amazon Basin (3°N to 9°S) for different plateau heights (in percent from modern elevation) during summer. *Solid gray line* represents modern topography. **a** Total precipitation. **b** Zonal moisture transport (q × u) at 800 mbar. Positive values indicate moisture transported from the west, negative values indicate moisture transport from the east. **c** Meridional moisture transport (q × v) at 800 mbar. Positive values show moisture transported from the south, negative values indicate northerlies

High, which is not substantially affected by changes in Andean elevations.

Our results emphasize the influence of the Andes and their uplift on moisture transport. A direct relationship is observed between the strength of the LLJ, precipitation, and moisture flux in the Amazon Basin and along the Andes. Moisture transport via the LLJ is the dominant factor in triggering modern precipitation along the Andes. Sensible heat is not the primary cause for modern convection over the Andean plateau area.

4.3 Large-scale upper-level circulation

Previous studies have suggested that climate over the Andean plateau is closely related to the upper-level circulation, because mid- and upper-tropospheric winds influence low-level circulations (Garreaud 1999; Garreaud et al. 2003; Lenters and Cook 1999). Figure 11a emphasizes the strong correlation between 200-mbar zonal winds and modern precipitation. Although our modeled maximum zonal flow exceeds observational magnitudes (Garreaud et al. 2003), the relationship with upper-level easterlies favoring high modern precipitation over the Andean plateau region, while westerly flow causes dry conditions, is evident (Fig. 11a). Previous studies have shown that easterly flow in the upper troposphere over the central Andes leads to stronger than average upslope flow over the eastern slopes and easterly low-level winds, increasing the moisture transport from the continental lowlands that feeds the convection over the Andean plateau region (Garreaud 1999). Our simulations reveal that the connection between upper-level flow and precipitation breaks down when the Andes are absent. In the absence of the Andes, the direction and magnitude of upper-level flow changes very little, while precipitation over the Andean plateau area decreases significantly (compare Fig. 11a, b). The dynamical link between the upper-level zonal wind and precipitation is weak, because low-level winds are predominantly from the west.

Different factors have been proposed to influence the upper-air circulation, including the strength and the position of the Bolivian High (e.g. Garreaud et al. 2003; Lenters and Cook 1997). The Bolivian High is the characteristic feature in the modern upper-level circulation of South America (Fig. 12) (e.g. Lenters and Cook 1997; Virji 1981). Although the center of the anticyclone is located close to the Andean plateau (Figs. 1a, 12a), previous studies have shown that direct mechanical effects of Andean topography on the Bolivian High are insignificant (e.g. Silva-Dias et al. 1983; Lenters and Cook 1997; Schwerdtfeger 1961). Our simulations are consistent with these findings and indicate that the Bolivian High also forms in simulations with no Andes (Fig. 12b). The Bolivian High weakens and shifts eastward when the Andes are absent. This shift is related to a shift in the low-level convergence associated with the maximum latent heat release in the southern part of the Amazon Basin for the no Andes case (Fig. 8) and implies that the Bolivian High develops as a direct response to low- to mid-tropospheric heating. This is in good agreement with previous studies that have shown that Amazonian heating is the dominant driving force in generating the upper-level high pressure system over South America, while the dynamic effect of the Andes is relatively unimportant (e.g. Silva-Dias et al. 1983; Lenters and Cook 1997; Schwerdtfeger 1961).

5 Discussion

5.1 Interaction between the Andes and regional climate dynamics

Our results indicate that the Andes play an important role in modulating regional atmospheric conditions. Previous

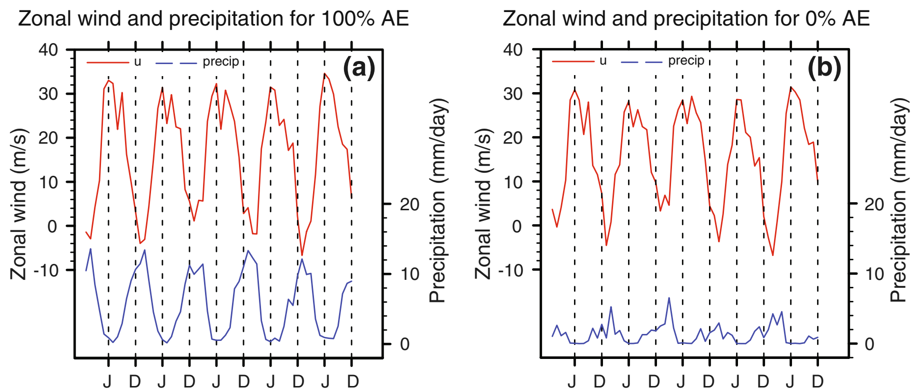

Fig. 11 Inter-annual variations (J = June, D = December) in upper-level (200 mbar) circulation (*red line*) and precipitation (*blue line*) across the Andean plateau area (15°–26°S/71°–62°W). **a** Total precipitation and zonal wind for simulations with modern Andes. **b** Same as (**a**), but for simulations with no Andes. Note that the easterlies exceed observational magnitudes, but the correlation between zonal winds and precipitation can be still observed for modern simulations

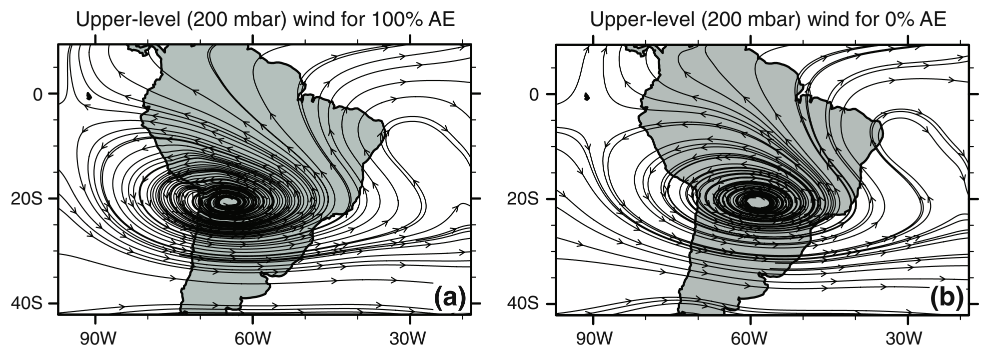

Fig. 12 Upper-level (200 mbar) winds during summer. **a** Winds for simulations with modern Andes. **b** Winds for simulations with no Andes

studies have demonstrated that low-level northerly flow develops due to diabatic heating over the Amazon Basin and the presence of a subtropical high (e.g. Figueroa et al. 1995; Rodwell and Hoskins 2001). Our results support this conclusion; northerly low-level flow over central South America and the South Atlantic High are well developed in our no-Andes experiment. However, in our simulations the establishment of the LLJ, which is a dominant factor in modern South American climatology, is directly related to the elevation of Andean topography. The LLJ represents the geostrophic response to the trade winds converging with the front of the northern eastern Andes. The deflection of easterly trade winds and the initiation of the LLJ occur once Andean elevations are 50% of their modern heights. With further uplift of the Andes, the LLJ strengthens, as indicated by an increase in southward velocities by nearly 100% on the eastern flank of the Andes. Previous studies have indicated that the LLJ is mainly related to mechanical forcing by the Andes (e.g. Campetella and Vera 2002; Figueroa et al. 1995). Our results certainly support the role of mechanical forcing in the development of the LLJ, but also suggest that moist physics may be playing an important role in amplifying the LLJ. Our results support the idea that the uplift of the Andes enhances low and mid-tropospheric latent heating, increasing convergence at low levels and divergence at upper tropospheric levels along the Andes (Fig. 8). In turn, the enhanced low-level (zonal) flow perpendicular to the Andes (Fig. 13) drives a stronger LLJ, and further moisture transport. However, a better understanding of the horizontal and vertical structure of the LLJ and its relationship to convection is critical to quantify the individual mechanisms responsible for the intensification of the LLJ. For example, a strengthening of the modern LLJ has been associated with amplification of the Chaco Low in northern Argentina (e.g. Salio et al. 2002). Yet, in our studies, the Chaco Low is most intense when the Andes are low due to high sensible heating and reduced cloud cover (not shown), whereas the LLJ forms at higher Andean elevation.

The LLJ is the key feature providing moisture and energy for convection and precipitation along the Andes. Therefore, the influence of the Andes on regional climate is not purely mechanical through orographic lifting, but mainly due to modifications of dynamical processes. Through their impact on low-level circulation, the Andes not only influence the climate in immediate vicinity of the mountain range, but also have a direct impact on the climatology of remote areas such as the Amazon Basin. In the

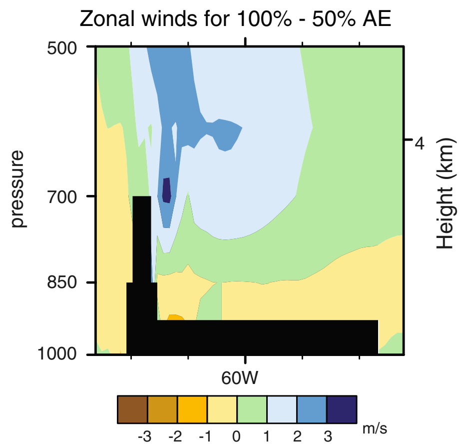

Fig. 13 Difference in zonal wind between simulations with modern Andes and 50% Andean heights. Enhanced low-level zonal flow perpendicular to the Andes in the modern case intensifies the LLJ and increases the moisture transport

absence of the Andes, westerly winds can penetrate into parts of the Amazon Basin resulting in an enhanced convergence of low-level flow, strengthening convection and precipitation over the basin. If the Andes are present, the LLJ draws in moisture from the Amazon region and modifies the moisture flux within the basin.

Overall the formation of the Andes is a key aspect for driving the mechanisms that control the regional wind pattern and precipitation over South America.

5.2 Moisture transport from the tropics to higher latitudes

The transport of water vapor from the Amazon Basin to the central Andes is critically important to Andean precipitation. Previous studies have suggested that the Amazon Basin is an open system and that outflow of atmospheric moisture from the basin may contribute an important input to the hydrological cycle in the surrounding regions (e.g. Eltahir and Bras 1994). However, evidence for potential effects on moisture supply and precipitation in surrounding regions was missing. Moreover, a few studies have suggested that moisture variability over the Andean plateau region cannot be accounted for by moisture fluctuations over the eastern lowlands (e.g. Garreaud et al. 2003; Garreaud 2000). Our results indicate that precipitation in the central Andes region is directly related to the moisture content of the Amazon Basin. The LLJ is the dominant feature transporting moisture from the tropics to higher latitudes. The moisture transported by the LLJ provides the latent heat required to drive convective updrafts and enhances convection and precipitation along the eastern flanks of the Andes. The LLJ draws in water vapor from the Amazon region and modifies the moisture flux within the basin. The strong moisture flux out of the Amazon Basin is balanced by stronger moisture influx from the Atlantic Ocean and slightly reduced convection and precipitation due to less pronounced convergence of low-level winds over the basin. Therefore, the surface water vapor content over the Amazon Basin remains constant and changes in surface latent heat over the region are small (not shown) for different Andean heights.

Uplift of the Andes and associated changes in the moisture transport across the Amazon Basin and along the eastern flanks of the Andes have a very small influence on the convection and precipitation across the SACZ. These results are in contrast to previous studies that have suggested that the generation of the SACZ is the result from the combined action of an Amazonian latent heat source and the steep Andean topography (Figueroa et al. 1995; Nogues-Paegle et al. 1998). An observed dipole structure between the SACZ and the LLJ with a weak SACZ associated with stronger LLJ and vice versa has been associated with intra-seasonal convective anomalies (e.g. Garreaud and Aceituno 2001; Goncalves et al. 2006; Lenters and Cook 1999; Nogues-Paegle and Mo 1997). However, on the longer timescales investigated here, we do not find a direct dynamical effect of the Andes on convective activity across the SACZ or a correlation between the strength of the LLJ and the SACZ. Our results lead us to conclude that convection and precipitation across the SACZ is mainly related to the latent heat over the Amazon Basin and the strength of the South Atlantic High that govern the low-level flux between the Amazon Basin and the SACZ.

5.3 Implications for paleoclimate

Our results have implications for the paleoclimatic evolution of South America, and show that modern climate is not representative of past climates when the Andes were lower. In general, our experiments predict that uplift of the Andes results in (1) a significant increase in precipitation along the eastern flanks of the Andes, (2) more arid conditions along the western flanks, and (3) no significant precipitation change over the Amazon Basin. These changes begin and intensify when the Andes reach approximately one-half of its modern elevation.

Our results are consistent with observations inferred from geological observations (Strecker et al. 2007 and references therein). For example, several studies have proposed a climate shift from arid to humid conditions along the eastern flanks of the Andes in Bolivia and Argentina during the Upper Miocene (between 10 and 7 Ma) based on changes in stratigraphic units, plant fossils and faunal assemblages (e.g. Kleinert and Strecker 2001; Starck and Anzotegui 2001; Uba et al. 2005, 2006). Along the western flanks, a change from semiarid to hyperarid conditions has been proposed for the middle Miocene (e.g. Alpers and Brimhall 1988; Rech et al. 2006). In the Atacama Desert, changes in soil compositions between 19 and 13 Ma (Rech et al. 2006) as well as the termination of supergene alteration and copper-sulfide enrichment between 14 and 8.7 Ma (Alpers and Brimhall 1988) and a strong reduction in sediment transfer from the Andes to the western lowlands between 10 and 6 Ma (Hoke et al. 2004) have been interpreted to reflect a significant shift towards more arid conditions along the western flanks of the Andes. In addition, a decrease in modeled net precipitation (difference between total precipitation and evapotranspiration) across the southern part of the Andean plateau is consistent with observations that commonly link the onset of aridification over the plateau area with the onset of internal drainage and the deposition of salt-bearing units between 24 and 15 Ma (Alonso et al. 1991; Vandervoort et al. 1995).

Although our model results are in good agreement with observations from the Andean flanks and the Amazon Basin, a mismatch between model and observations exists over the northern part of the Andean plateau. Despite an increase in evapotranspiration with increasing Andean heights, our simulations suggest an increase in net precipitation over parts of the Andean plateau. The mismatch may be due to the specific domain used for plateau interpretations, and/or prescription of constant boundary conditions such as vegetation and sea-surface temperature. For example, modeled changes in climate are interpreted for the entire Andean plateau area between 15 and 26°S, while proxy data are often based on interpretations of local observations. In addition, changes in vegetation across the Andes may influence the moisture availability over the plateau area. Prescribing dense vegetation at low Andean elevations in place of the modern desert biome could facilitate moisture retention in the topsoil on the mountain slopes potentially contributing to greater local evapotranspiration and higher precipitation in the no Andes case.

Overall, our findings show how the tectonic evolution of the Andes has influenced South American climate. This knowledge may help constrain the surface uplift history of the Andes by constraining minimum Andean elevations during the Cenozoic. The onset of hyperaridity during the middle Miocene in the Atacama Desert has been related to surface uplift and the creation of a rain shadow along the western flanks of the Andes. Our results suggest that at least half the modern Andean elevation is necessary to block zonal flow and establish easterlies that bring moisture from the Amazon Basin to the central Andes. These findings are in very good agreement with estimated minimum Andean paleoelevations of >2 km prior to 12–15 Ma for the central Andes (e.g. Alpers and Brimhall 1988; Rech et al. 2006), but suggests an earlier uplift history than those based on stable isotope paleoaltimetry (e.g. Garzione et al. 2006; Gosh et al. 2006). However, changes in amount and source of rainfall reported here could have a substantial influence on the $\delta^{18}O$ composition of rainwater on the Andean plateau, significantly complicating paleoaltimetry estimates (Ehlers and Poulsen 2009).

5.4 Caveats

The objective of this study is to understand how the Andes influence regional climate over South America and to analyze climate sensitivity to progressive Andean uplift. The model setup is designed to provide the most straightforward assessment of how climate responses to mechanical uplift of the Andes. We emphasize two important caveats to this work, one related to the modeling methodology and the other related to the paleoclimate implications. First, results presented in this study are from experiments with modern global reanalysis data as atmospheric lateral boundary conditions. The advantage of this method is that boundary conditions are based on assimilated observed data and do not include biases from global models. We have previously run experiments with the regional model nested within a global atmospheric climate model (Genesis.2.3.). The global model was run for different Andean elevations and then predicted atmospheric variables were used as boundary conditions to RegCM3. In this case, the atmospheric boundary conditions included the effects of changing Andean elevations. In general, both methods show a similar sensitivity of regional climate to different Andean elevations, indicating that the boundary conditions at the model domain are not significantly affecting our results.

Second, our experiments are clearly idealized and are not meant to be simulations of specific Cenozoic timeslices. The uplift of the Andes was not uniform, but likely varied across the range (Allmendinger et al. 1997; Barnes et al. 2008; McQuarrie et al. 2008). Moreover, during the Cenozoic uplift of the Andes, additional tectonic and climatic factors were evolving that may have influenced regional and global climate including minor continental drift of South America, the glaciation of Antarctica, changes in large-scale ocean circulation and SST, the decline of atmospheric pCO_2, and evolution of land-surface characteristics. The influences of modern SSTs and land-surface characteristics on South American precipitation have previously been investigated (Cook and Vizy 2008; Enfield 1996; Lenters and Cook 1995; Seth and Rojas 2003). These studies have shown that despite an influence of annual variations in SSTs and precipitation magnitude over the eastern parts of South America (e.g. Northeast Brazil), changes in the SSTs do not have a significant effect on precipitation on the interior and western part of the

Amazon Basin (e.g. Enfield 1996; Lenters and Cook 1995; Seth and Rojas 2003). Precipitation over the Andean plateau has been reported to be influenced by El Niño/La Niña conditions with a tendency towards below average summer precipitation during El Niño events (e.g. Aceituno 1988; Vuille 1999).

Changes in the modern distribution of Amazon rainforest can have a large influence on precipitation in the basin (Cook and Vizy 2008) and past changes may have influenced the Amazon hydrological cycle. With vegetation and soil moisture as important factors driving convection over the Amazon Basin more studies are necessary to evaluate the effect of changing Amazon rainforest on precipitation in the basin itself and its influence on moisture transport towards the Andean plateau region. However, although the Amazon Basin is a dynamic environment, it has been proposed that the Amazon rainforest existed throughout the Cenozoic (e.g. Colinvaux and Oliveira 2001; Hoorn 2006; van der Hammen and Hooghiemstra 2000). Marine incursions from the north have been reported to reach the western Amazon Basin during the Miocene, but the spatial and temporal extent of these incursion is still a matter of debate (Hoorn et al. 1996; Rasanen et al. 1995). The replacement of rainforest land cover by a water body could result in an increase in moisture availability and transport, and requires future investigation.

6 Conclusions

We used a high-resolution (~60 km) limited-domain climate model with a reasonable representation of Andean topography to investigate the effect of the Andes on South American climate. The Andes have a direct mechanical influence on the climatology of South America by forcing orographic precipitation along the eastern flanks of the Andes, and blocking westerly flow from the Pacific. Importantly, the Andes Mountains are critical to the development of the LLJ that draws in and transports moisture from the Amazon Basin to the Andean region. When the Andes are absent the LLJ is absent; southward moisture transport is low; convection is suppressed; and precipitation decreases dramatically along the eastern flanks of the Andes. The Andes also influence convection over the Amazon basin. The absence of the Andes reduces moisture export from the Amazon, and leads to enhanced low-level convergence and increased convection and precipitation in parts of the Amazon Basin.

Our model results indicate that atmospheric flow and processes similar to modern initiated once Andean elevations reached approximately 50% their modern heights. At around 2,000 m elevation the Andes start to block zonal flow, resulting in a reversal of dominant wind direction and a change in water vapor source over the western part of the continent. The LLJ starts to form and intensifies with further Andean uplift due to enhanced latent heat release, increasing low-level convergence and stronger low-level (zonal) flow perpendicular to the Andes. Local processes (local latent heating) drive precipitation for Andean elevation lower than half the modern, while regional-scale processes (transport of moist warm air from the Amazon) initiate precipitation when the Andes are higher than 50% their modern elevation.

Acknowledgment Support for this research was provided by grants to C. Poulsen and T. Ehlers from the University of Michigan's Graham Environmental Sustainability Institute and from the US National Science Foundation (EAR Award 0738822). We thank two anonymous reviewers for constructive comments on the manuscript.

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