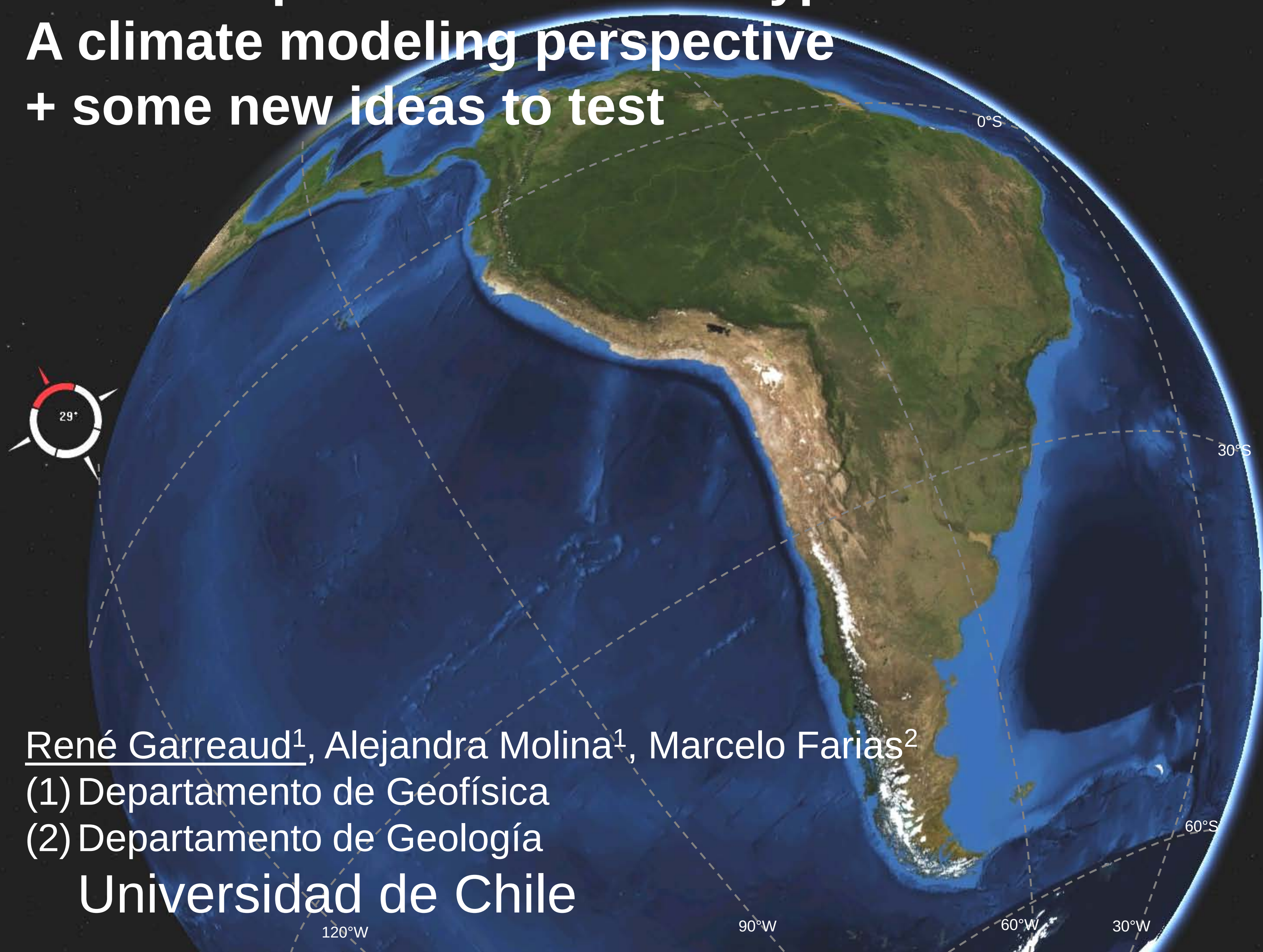
Andean uplift and Atacama hyper-aridification: A climate modeling perspective + some new ideas to test



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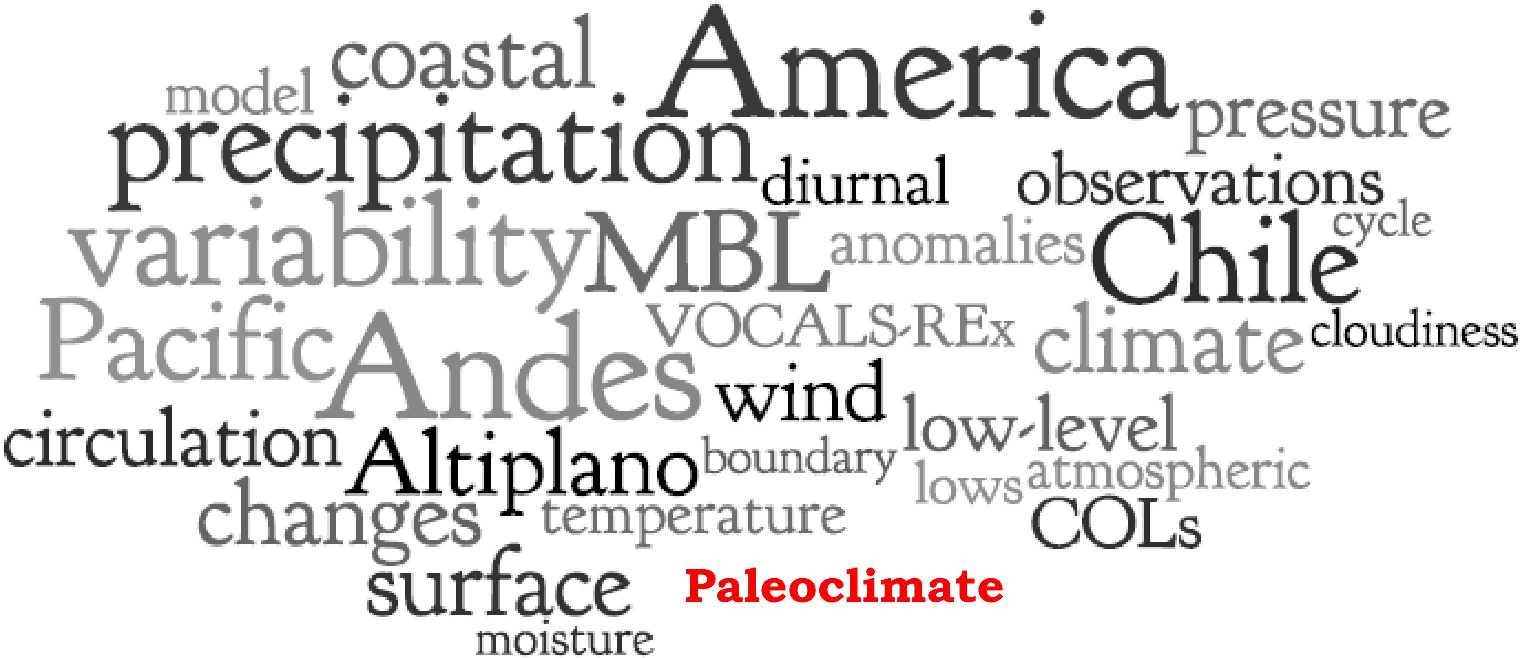
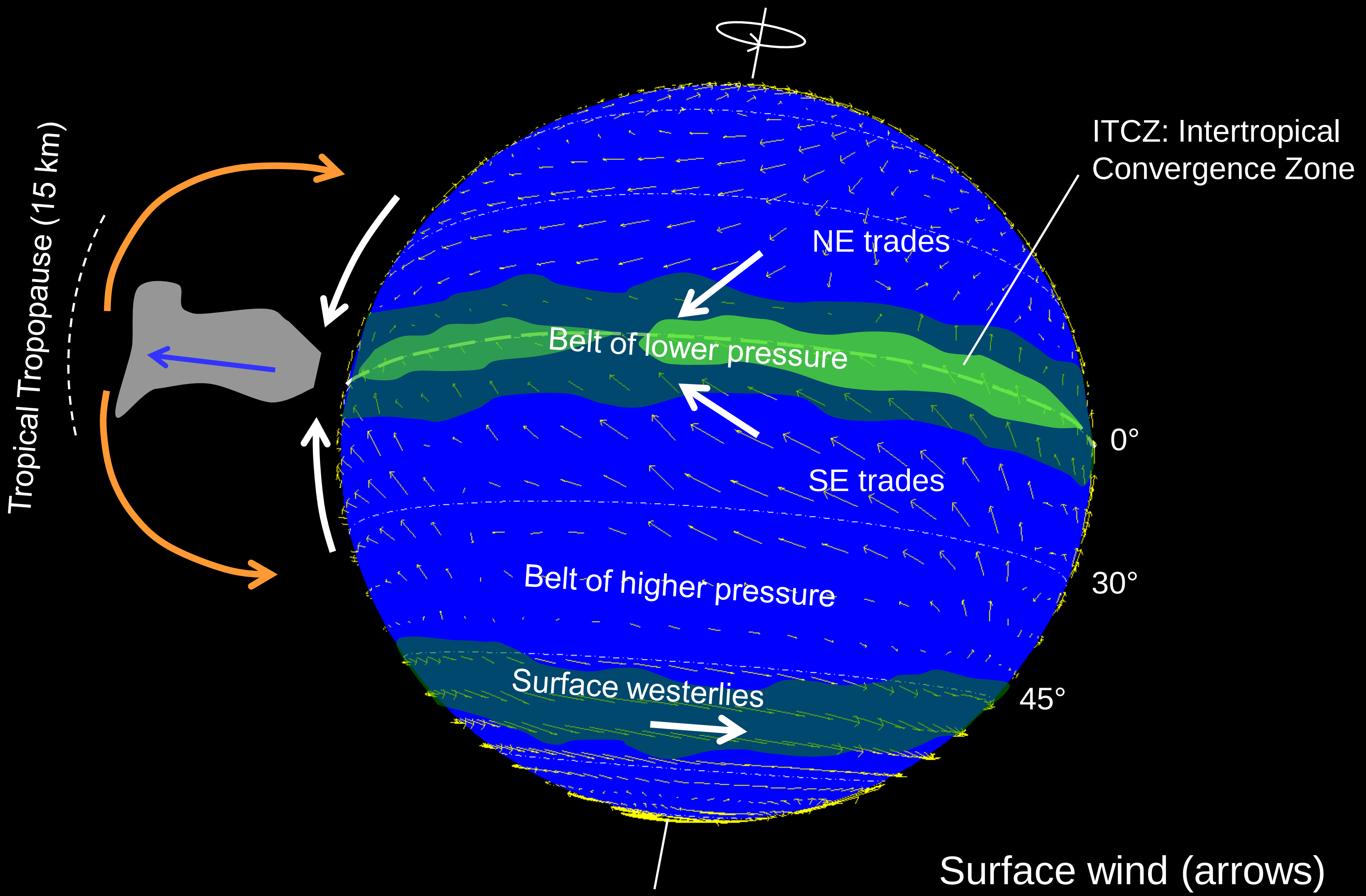
My word-cloud based on paper’s abstract (2000-2010) and constructed using Wordle



In short time scales (days-centuries), climate-geomorphology uncoupled
- Geomorphology is a fixed BC for climate
- Climate doesn’t alter landscape (actually, it does)

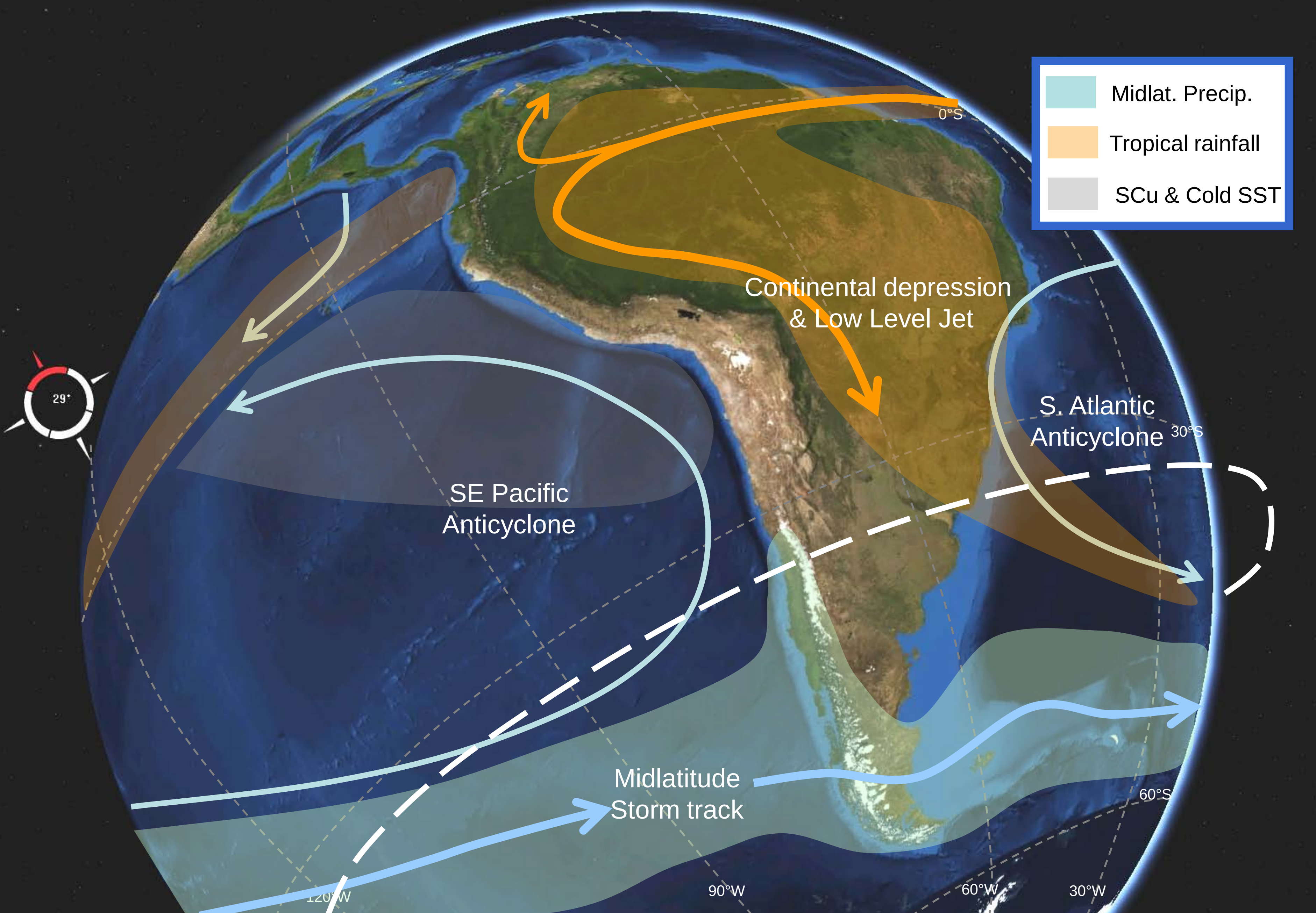
In long time scales (>10000 years), climate-geomorphology coupled
- Geomorphology is not fixed an can alter climate
- Climate changes modifies geomorphology

General circulation in an aqua-planet
Perpetual Equinox

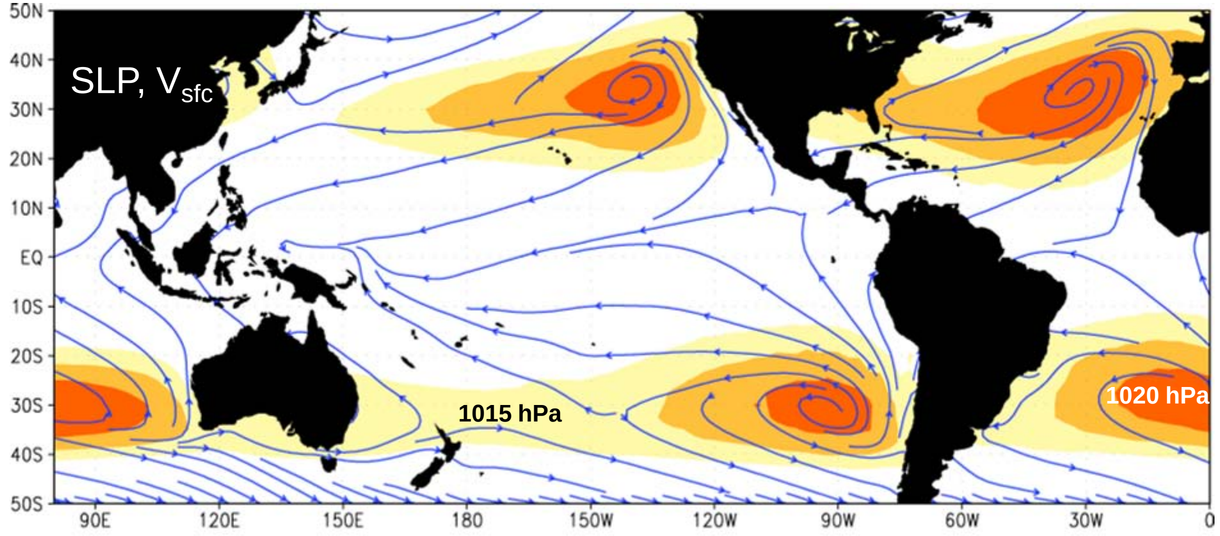


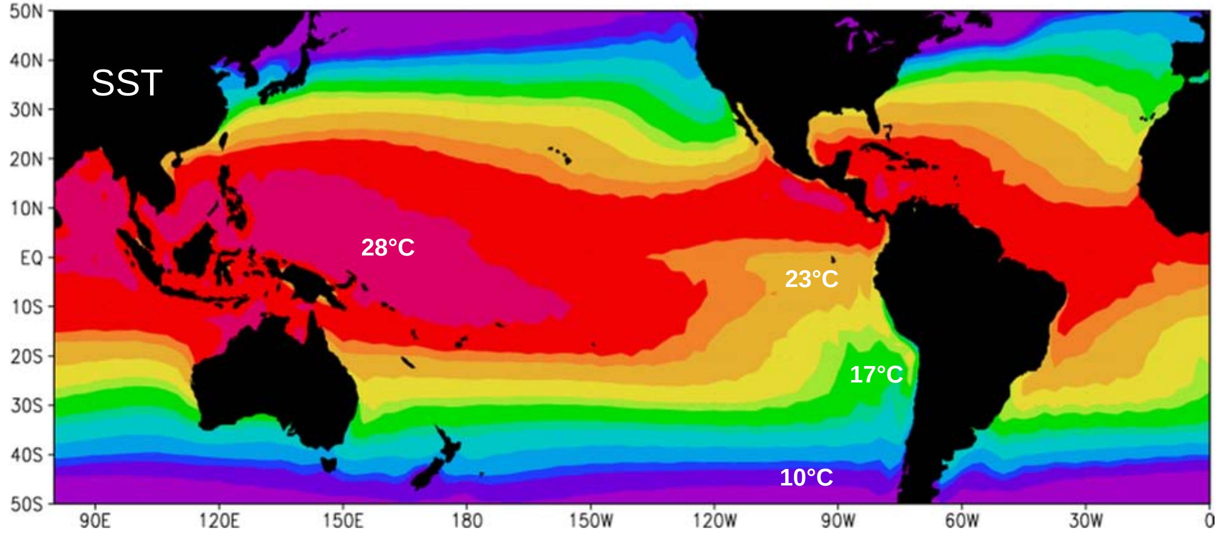
Surface wind (arrows)
Precipitation (green shadow)

Idealized (zonally symetric) circulation disturbed by continents

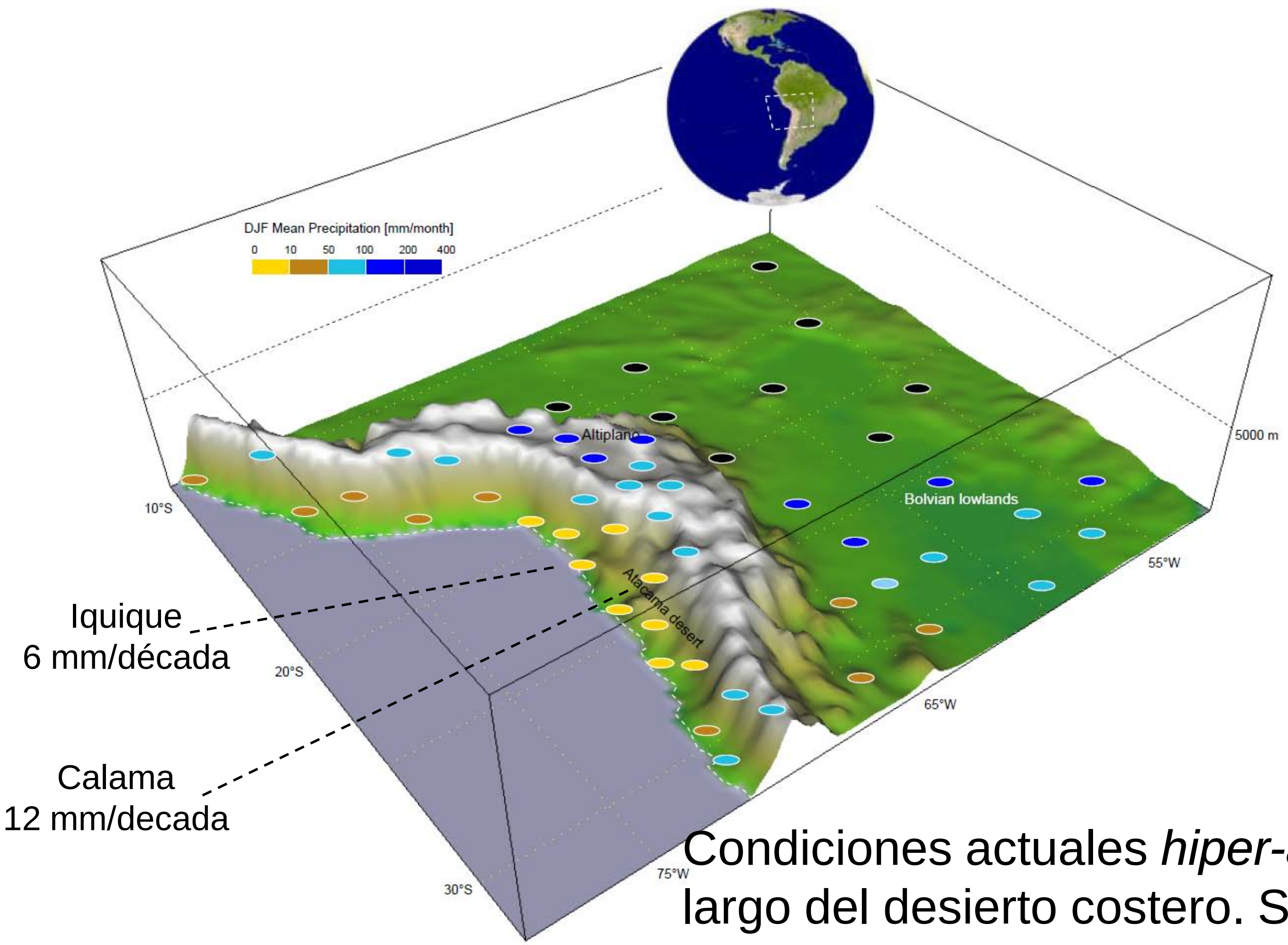


High Andes & dry Atacama
Factor I: Subtropical Location



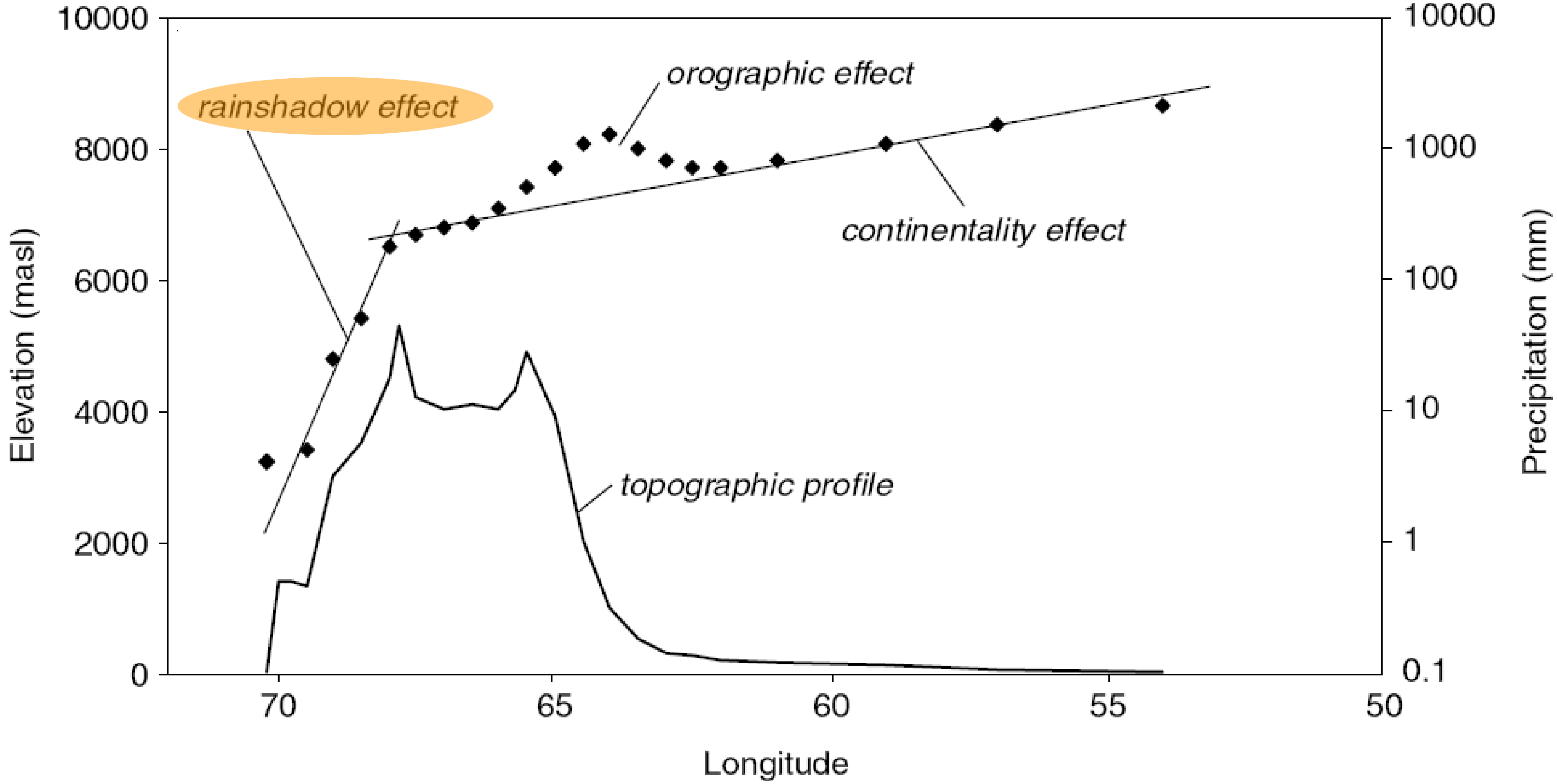


High Andes & dry Atacama



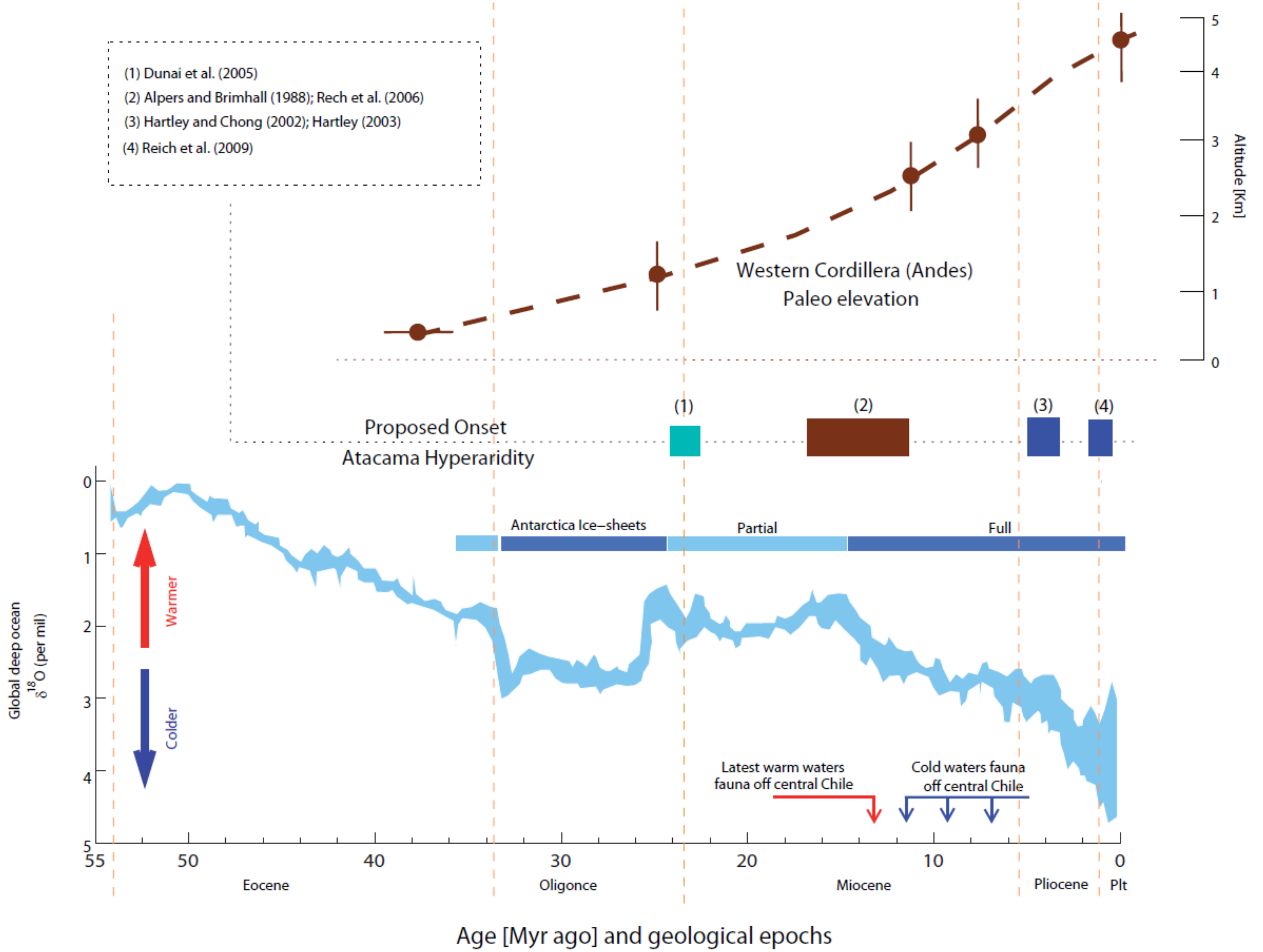
Condiciones actuales *hiper-áridas* a lo largo del desierto costero. Sin embargo, abundante evidencia geológica de un pasado remoto (Ma) menos extremo en cuanto a déficit de precipitación

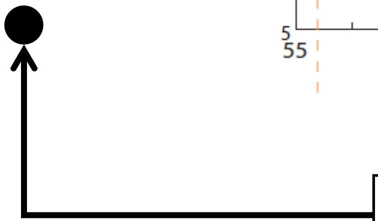
High Andes & dry Atacama
Factor II: Rain shadow effect



Hartley and Houston 2003

High Andes & dry Atacama





Posicionamiento de Sud América en rango actual de latitudes (80-100 Ma)

Andean uplift ► Atacama hyper-aridification

INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **23**: 1453–1464 (2003)
Published online 6 August 2003 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/joc.938

THE CENTRAL ANDEAN WEST-SLOPE RAINSHADOW AND ITS POTENTIAL CONTRIBUTION TO THE ORIGIN OF HYPER-ARIDITY IN THE ATACAMA DESERT

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Received 31 January 2003
Revised 19 May 2003
Accepted 22 May 2003

ABSTRACT

The west slope of the central Andes exhibits a pronounced rainshadow effect. Precipitation between 15° and 27 °S is dominated by summer convective activity from Amazonia, and data analysis shows that the increase in precipitation with elevation due to the rainshadow effect best fits an exponential correlation. Coupling with limited data from high elevations suggests that the correlation is accurate to 4500 m above sea level (m a.s.l.) and perhaps to 5500 m a.s.l., suggesting that increased precipitation goes unrecorded over the peaks of the western Cordillera. South of 27 °S the precipitation is dominated by winter frontal sources and shows no well-defined relationship with elevation. The core zone of hyper-aridity in the Atacama Desert extends from 15 to 30 °S at elevations from sea level to 3500 m a.s.l. Although the Atacama Desert has existed since at least 90 Ma, it is considered that the initial onset of hyper-aridity was most likely to have developed progressively with the uplift of the Andes as they reached elevations between 1000 to 2000 m a.s.l. coupled with the intensification of a cold, upwelling Peruvian Current between 15 and 10 Ma. Also apparent in the palaeogeographic record are subsequent fluctuations between (semi-) arid to hyper-arid conditions that were probably largely controlled by changes in orbital and oceanic forcing. Copyright © 2003 Royal Meteorological Society.

5.3. Elevation forcing

Regional uplifts, such as the Andes, have been shown unequivocally to cause increasing aridity (Manabe and Broccoli, 1990; Ruddiman *et al.*, 1997). At elevations of 1000 m the effects of topographic forcing begin to be felt (Browning, 1980), with increasing effect by the time elevation has reached 2000 m (Hay and Wold, 1998; Otto-Bliesner, 1998), and palaeoclimate modelling of the Himalayas suggests that the impacts on climate may develop progressively and in step with increasing uplift Zhiseng *et al.* (2001).

Andean uplift ► Atacama hyper-aridification

VOLUME 5 JOURNAL OF CLIMATE NOVEMBER 1992

The Effects of Orography on Midlatitude Northern Hemisphere Dry Climates

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(Manuscript received 18 July 1991, in final form 13 February 1992)

ABSTRACT

The role of mountains in maintaining extensive midlatitude arid regions in the Northern Hemisphere was investigated using simulations from the GFDL Global Climate Model with and without orography. In the integration with mountains, dry climates were simulated over central Asia and the interior of North America, in good agreement with the observed climate. In contrast, moist climates were simulated in the same regions in the integration without mountains. During all seasons but summer, large amplitude stationary waves occur in response to the Tibetan Plateau and Rocky Mountains. The midlatitude dry regions are located upstream of the troughs of these waves, where general subsidence and relatively infrequent storm development occur and precipitation is thus inhibited. In summer, this mechanism contributes to the dryness of interior North America

Atacama hyper-aridification Andean uplift

articles

Cenozoic climate change as a possible cause for the rise of the Andes

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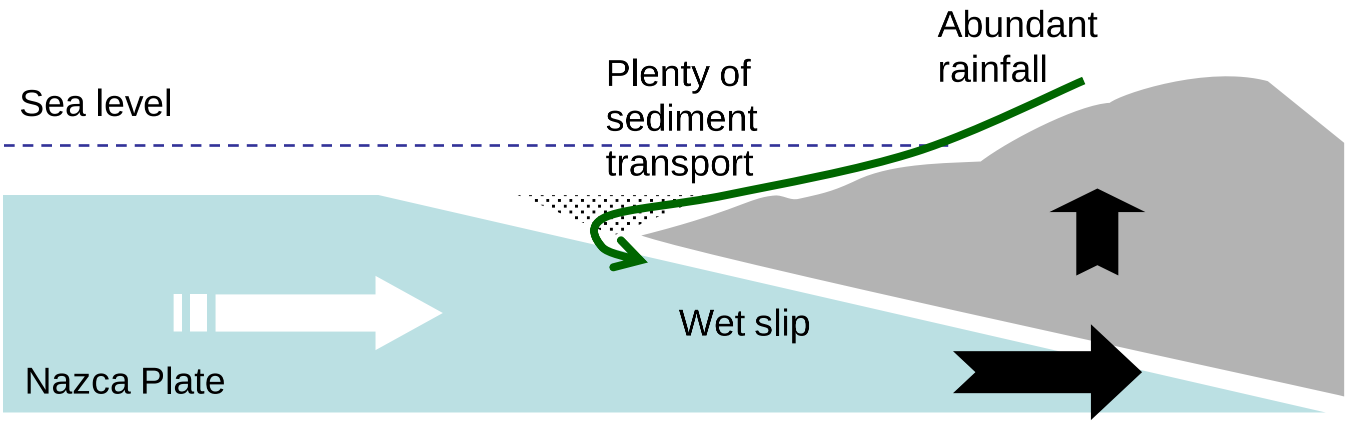
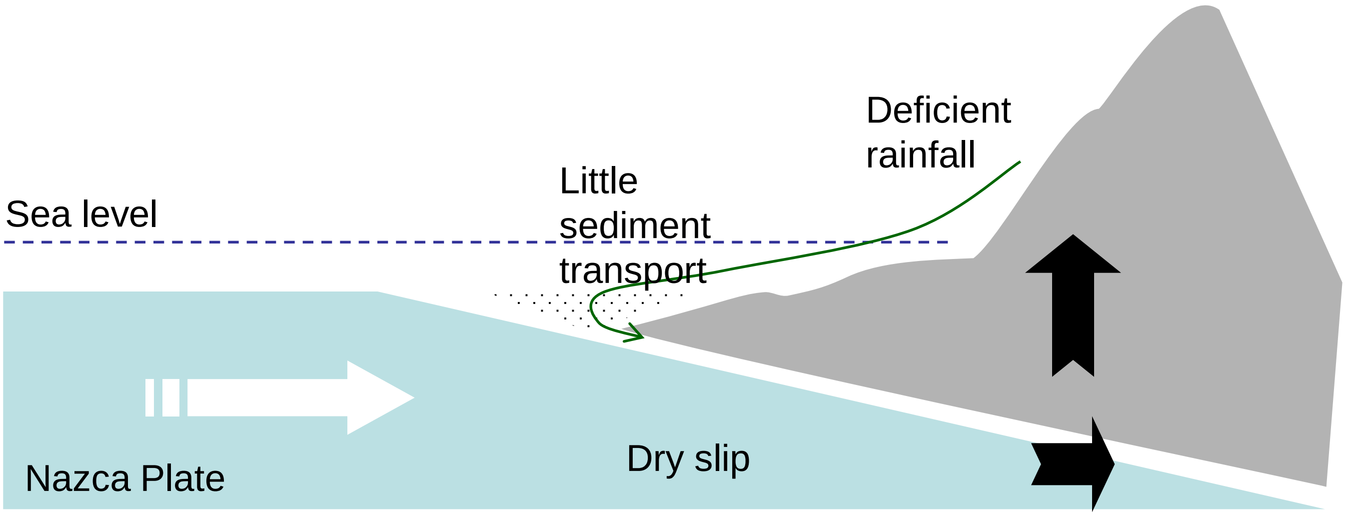
Causal links between the rise of a large mountain range and climate have often been considered to work in one direction, with significant uplift provoking climate change. Here we propose a mechanism by which Cenozoic climate change could have caused the rise of the Andes. Based on considerations of the force balance in the South American lithosphere, we suggest that the height of, and tectonics in, the Andes are strongly controlled both by shear stresses along the plate interface in the subduction zone and by buoyancy stress contrasts between the trench and highlands, and shear stresses in the subduction zone depend on the amount of subducted sediments. We propose that the dynamics of subduction and mountain-building in this region are controlled by the processes of erosion and sediment deposition, and ultimately climate. In central South America, climate-controlled sediment starvation would then cause high shear stress, focusing the plate boundary stresses that support the high Andes.

Lamb and Davis; Nature 2003

Atacama hyper-aridification   Andean uplift





Adapted from Lamb and Davis; Nature 2003

Southeast Pacific Cooling ► Atacama hyper-aridification

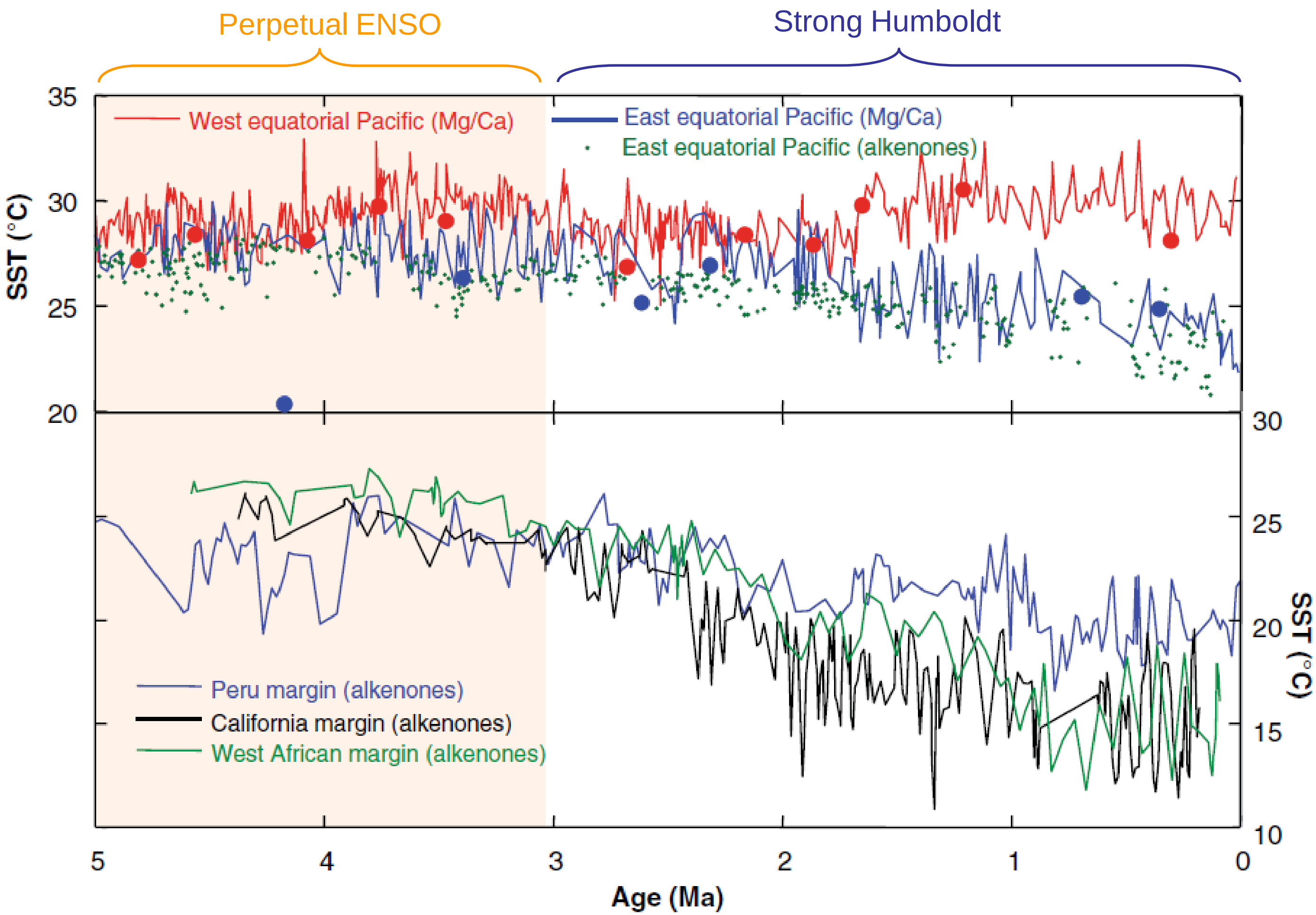


Fig. 3. (**Top**) SST records in the western equatorial Pacific (red line, ODP site 806) and in the eastern equatorial Pacific (blue line, site 847), both based on Mg/Ca and adapted from (*11*), and that for the eastern Pacific based on alkenones (green dots, site 847) and adapted from (*24*). Larger circles are for the data based on Mg/Ca but from (*44*) for ODP sites 806 (red) and 847 (blue). Pink shading denotes the early Pliocene. For discussion, see (*6*). (**Bottom**) Alkenone-based SST records for the California margin (black, ODP site 1014) (*24*), the Peru margin (blue, site 1237) (*24*), and the West African margin (green, site 1084) (*22*). The locations of the ODP sites are shown in Fig. 2; for the exact geographical locations, see (*47*).

Philander et al. 2004

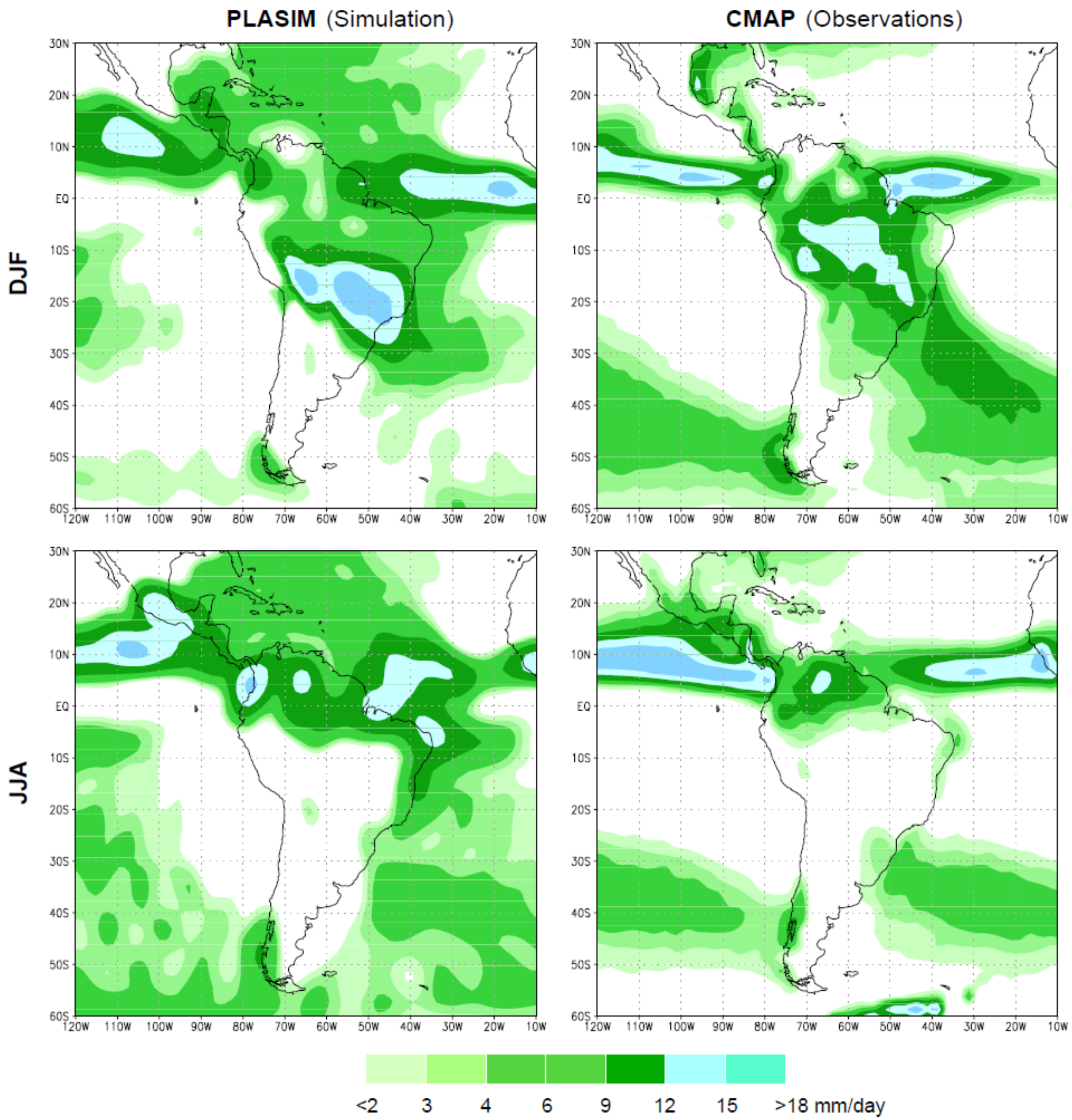
Conceptually, both Andean uplift (enhanced bloking of moist air) and SEP cooling (less evaporation from ocean) may increase dryness of the Atacama desert…it would be nice to use a “simple” climate model to study these two conditions.

We use PLASIM, an Earth System Model of Intermediate Complexity from Hamburg University:

- Atmospheric component: PUMA
- Simple slab model for SST and Sea Ice
- SIMBA for biosphere
- Coarse resolution: 3ºx3º lat-lon

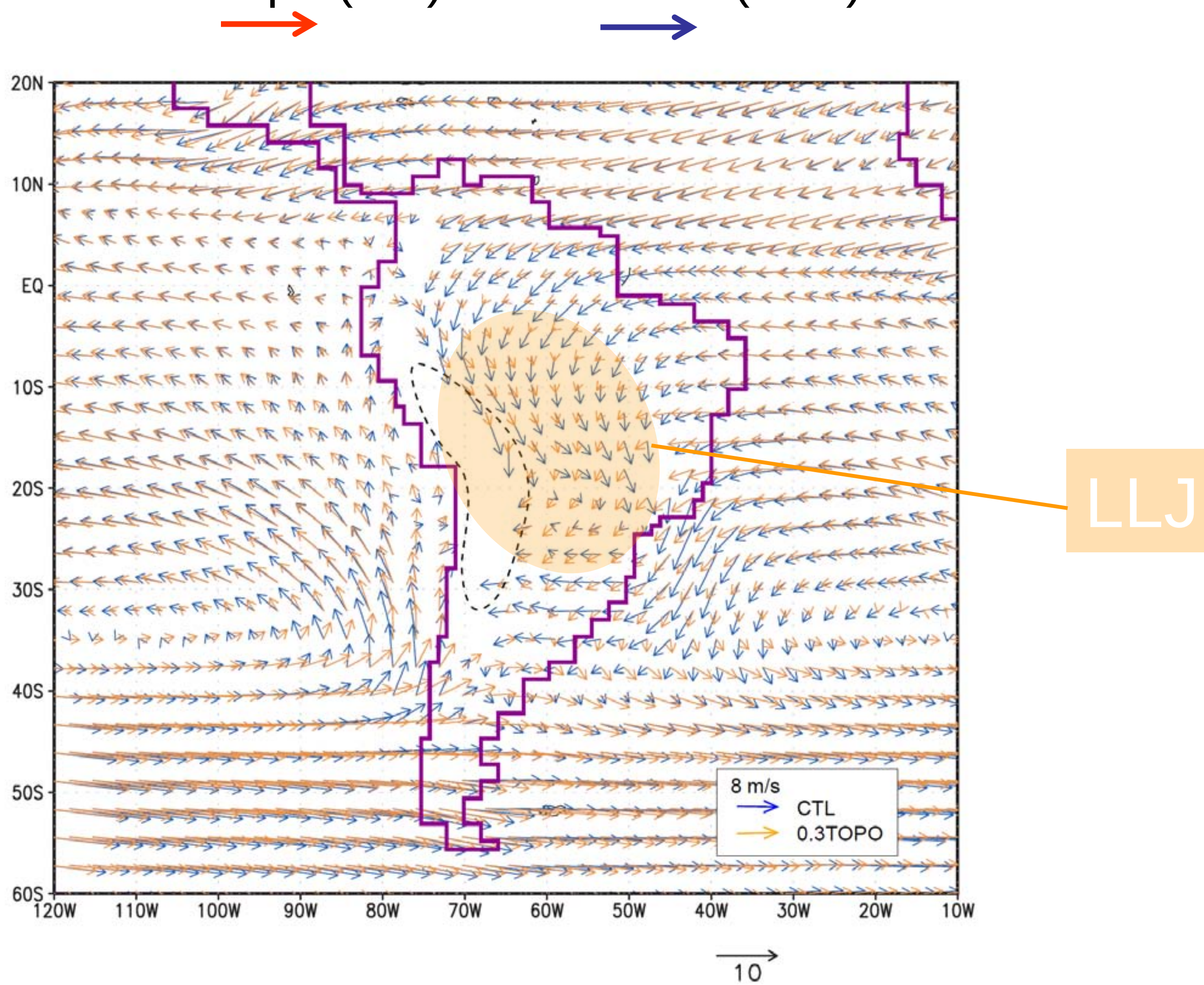
We performed 50 year long simulations altering one Boundary condition at a time

Model Validation



Model Validation

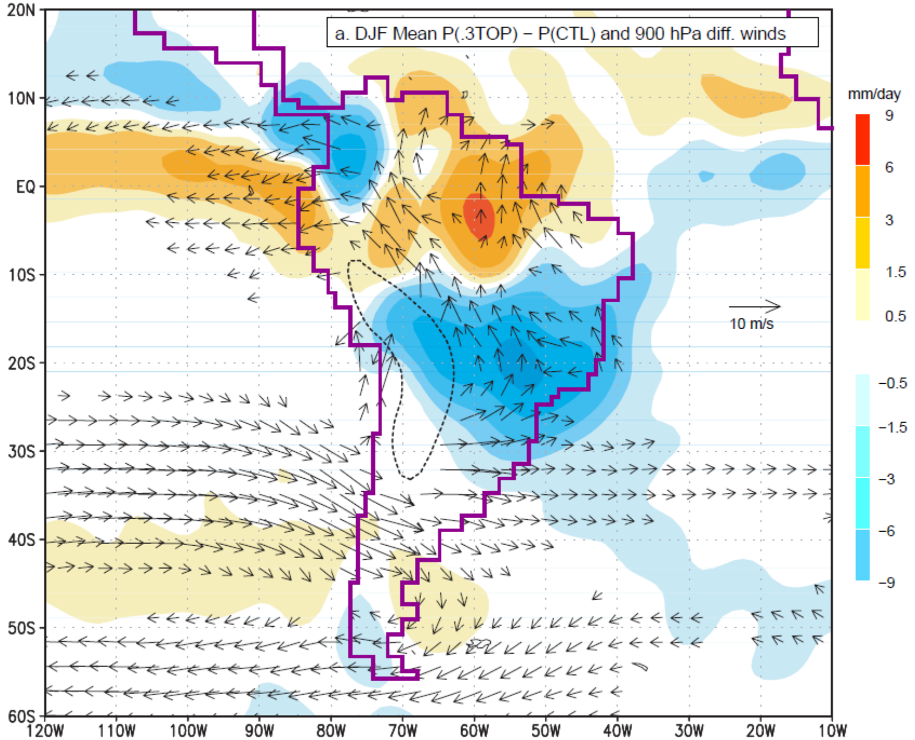
Long-term meanDJF **900 hPa wind**
0.3*Topo (red) and Control (blue)



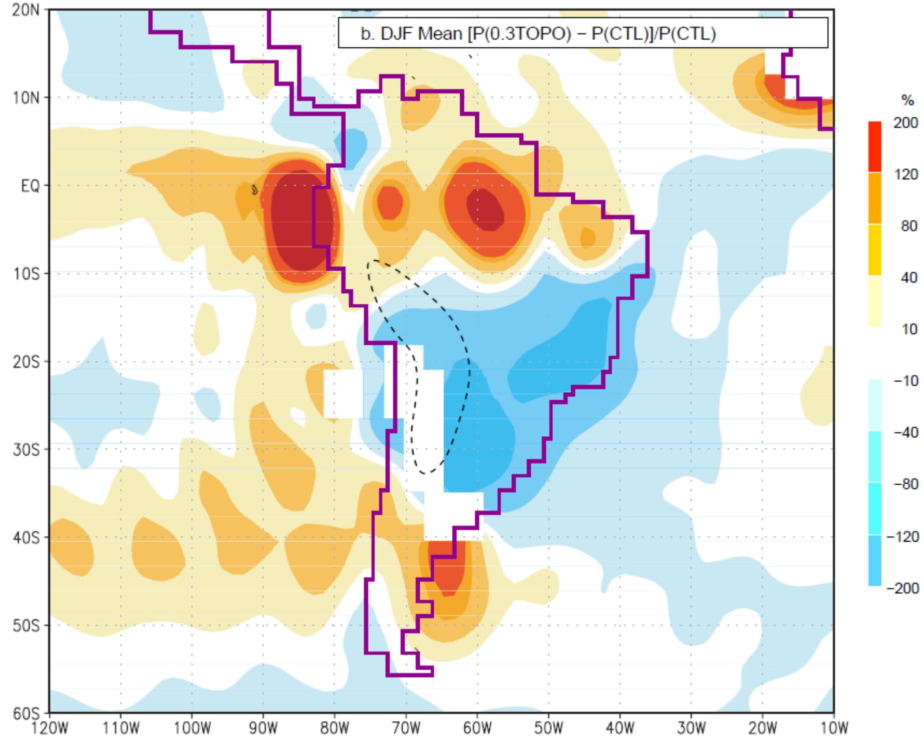
PLASIM Topography Experiments

0.3*Topo minus Control (DJF)

900 hPa winds and Precip



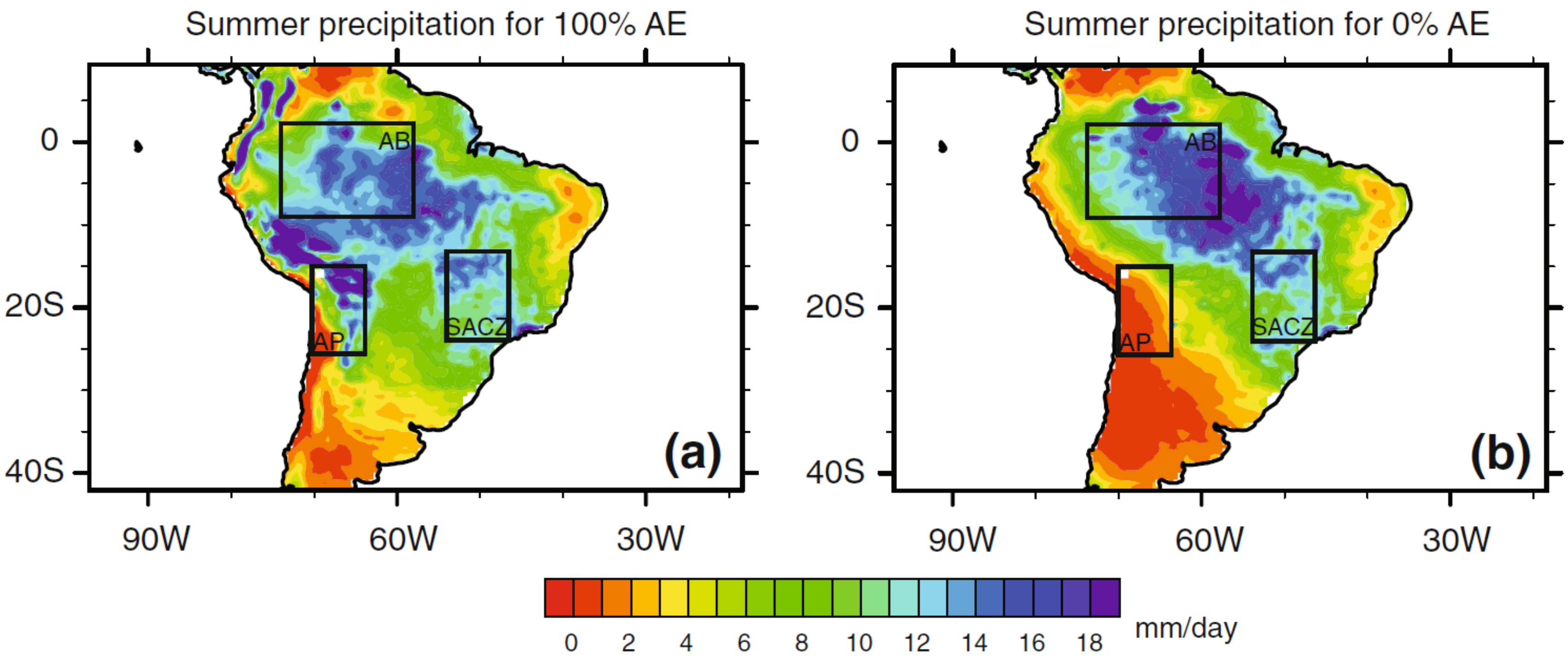
% Precip (ΔP/Pc)



REGCM Topography Experiments

CTL

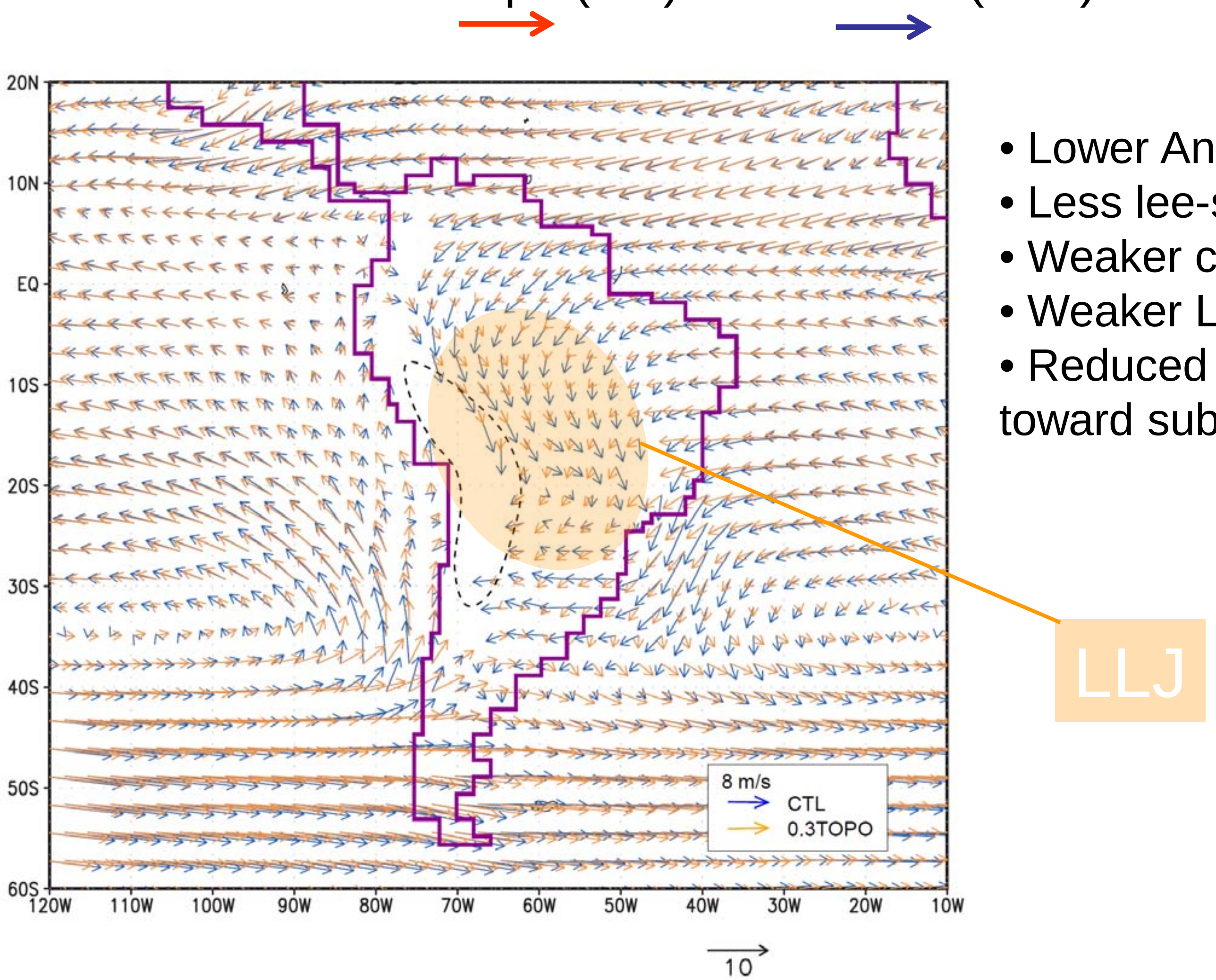
Low Andes



Insel et al. 2009, Climate Dynamics
Ehlers and Poulsen 2009, EPSL

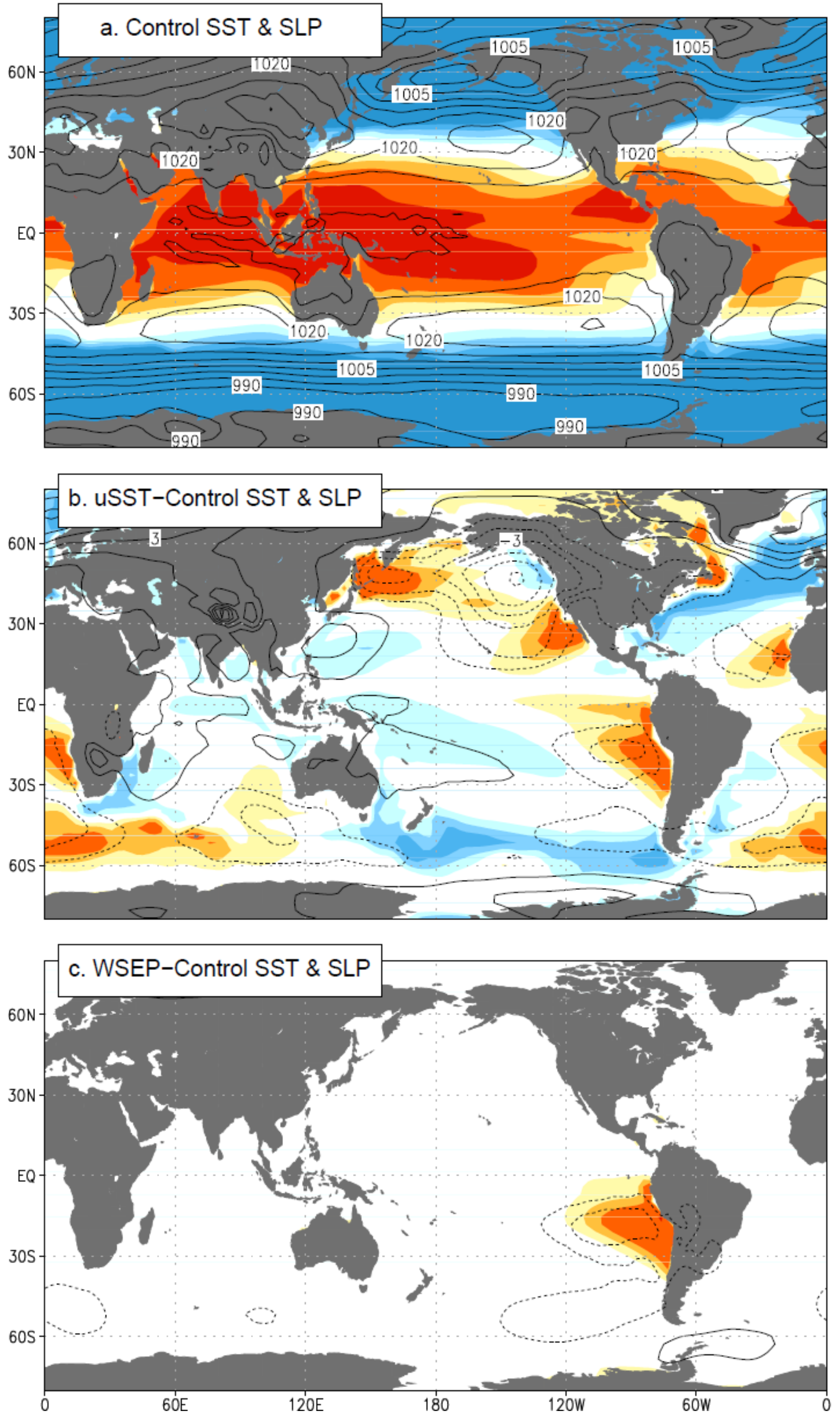
PLASIM Topography Experiments

Long-term meanDJF **900 hPa wind**
0.3*Topo (red) and Control (blue)



- Lower Andes
- Less lee-side subsidence
- Weaker continental low
- Weaker LLJ
- Reduced moist transport toward subtropics

PLASIM “Humboldt” Experiments



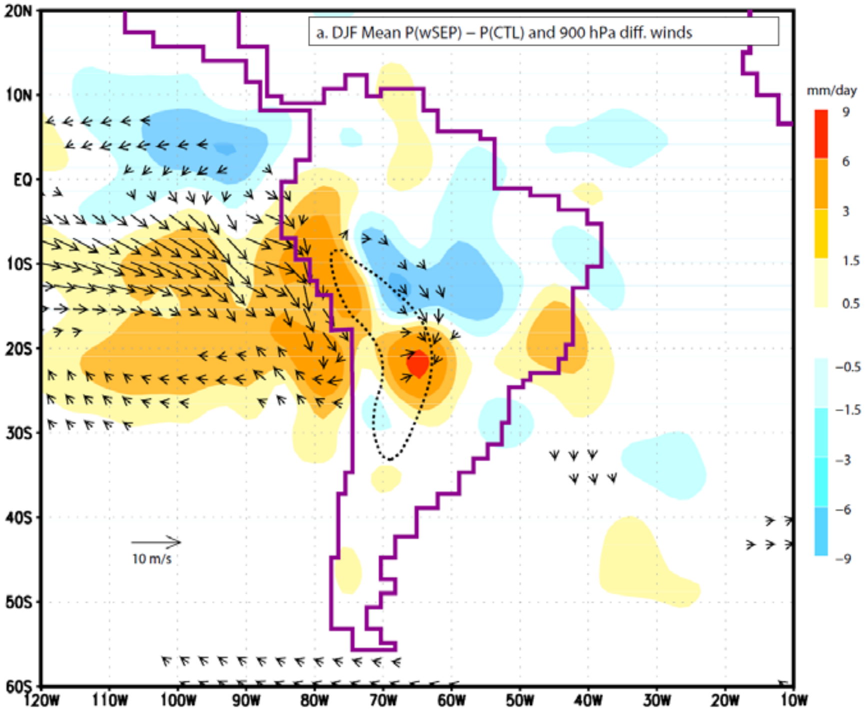
uSST: SST(φ) only

wSEP: warmer Southeast Pacific

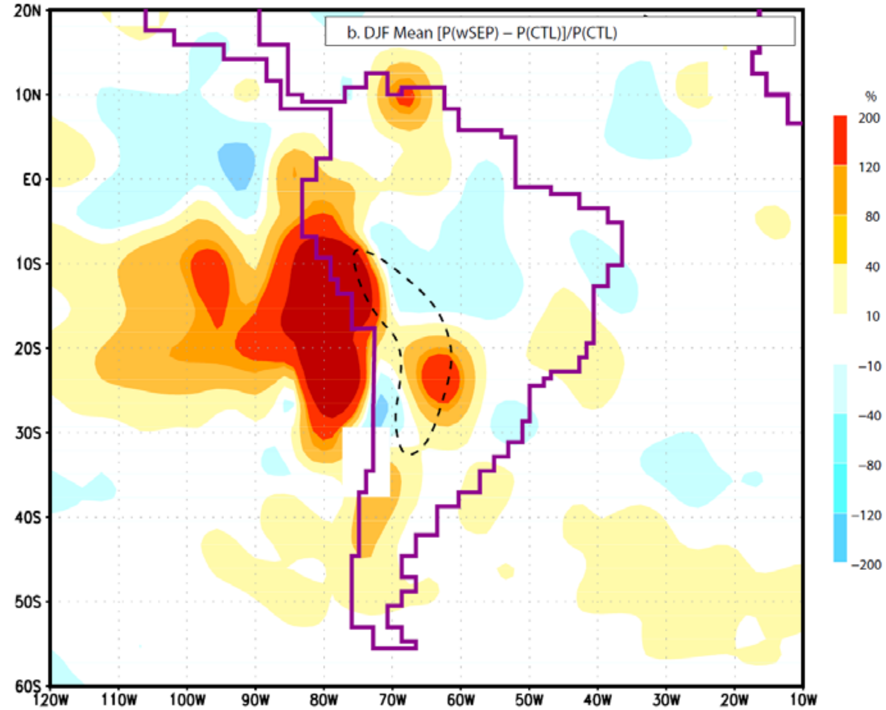
PLASIM “Humboldt” Experiments

wSEP minus Control (DJF)

900 hPa winds and Precip



% Precip (ΔP/Pc)



PLASIM "Humboldt" Experiments

Large scale field allows diagnostic of Precipitation
(Lenters and Cook 1995):

Precip – Evap = Convergence + Advection + Transient

Differences between wSEP minus CTL for a grid box over the SEP:

+2.5 mm   +1.4 mm   +0.7 mm   +0.2 mm

In human terms, shallow, non-precipitating stratus embedded in a cool MBL are replaced by moderate-precipitating, trade wind cumulus in warmer MBL.

SST

GFDL GCM “Humboldt” Experiments

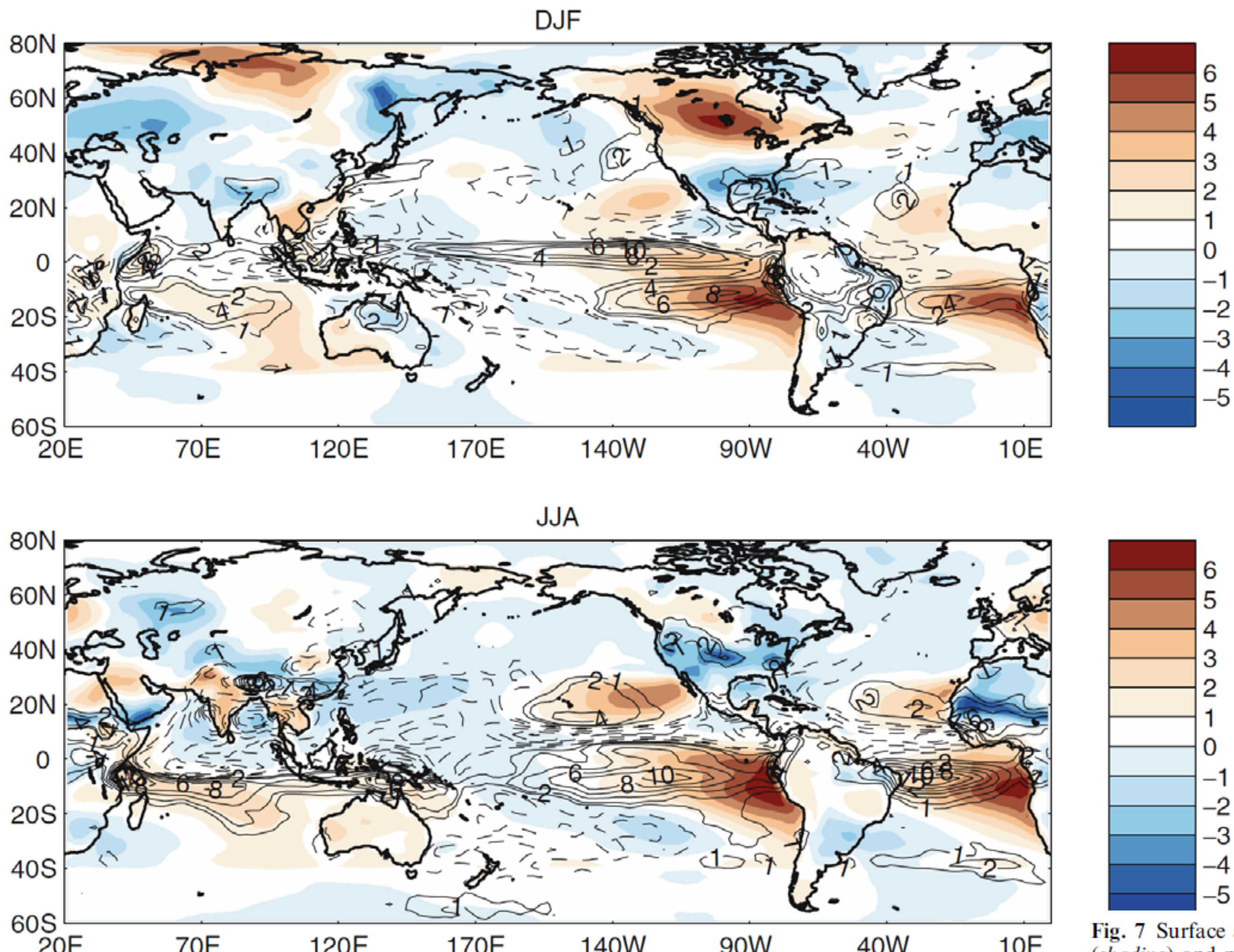


Fig. 7 Surface air temperature (*shading*) and precipitation (*contours*) differences between TPLIO and Control for December–February (*upper panel*) and June–August (*lower panel*). Precipitation in mm/day and temperature in degrees C

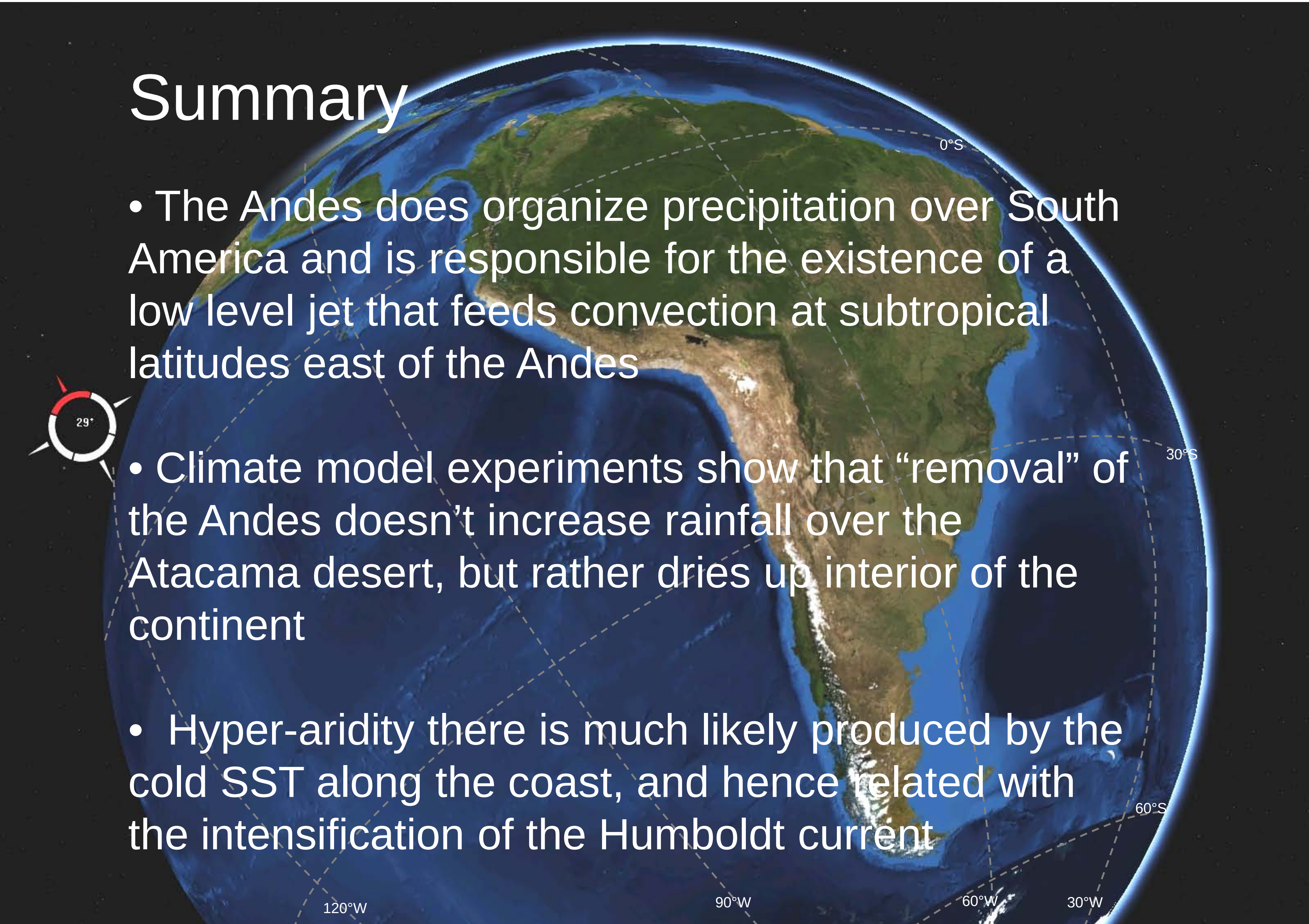
Barreiro et al. 2005, Climate Dynamics

Summary

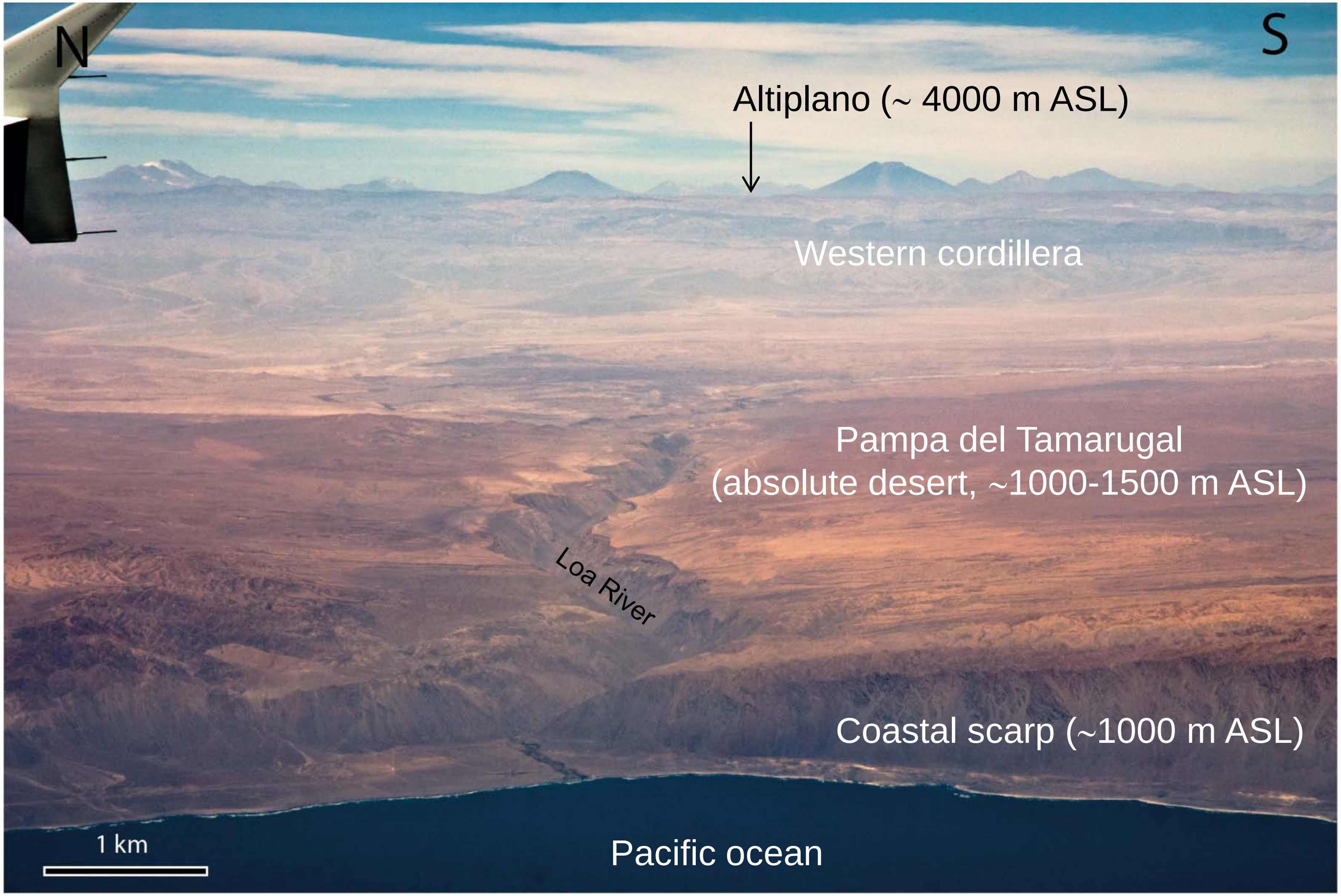
- The Andes does organize precipitation over South America and is responsible for the existence of a low level jet that feeds convection at subtropical latitudes east of the Andes

- Climate model experiments show that “removal” of the Andes doesn’t increase rainfall over the Atacama desert, but rather dries up interior of the continent

- Hyper-aridity there is much likely produced by the cold SST along the coast, and hence related with the intensification of the Humboldt current

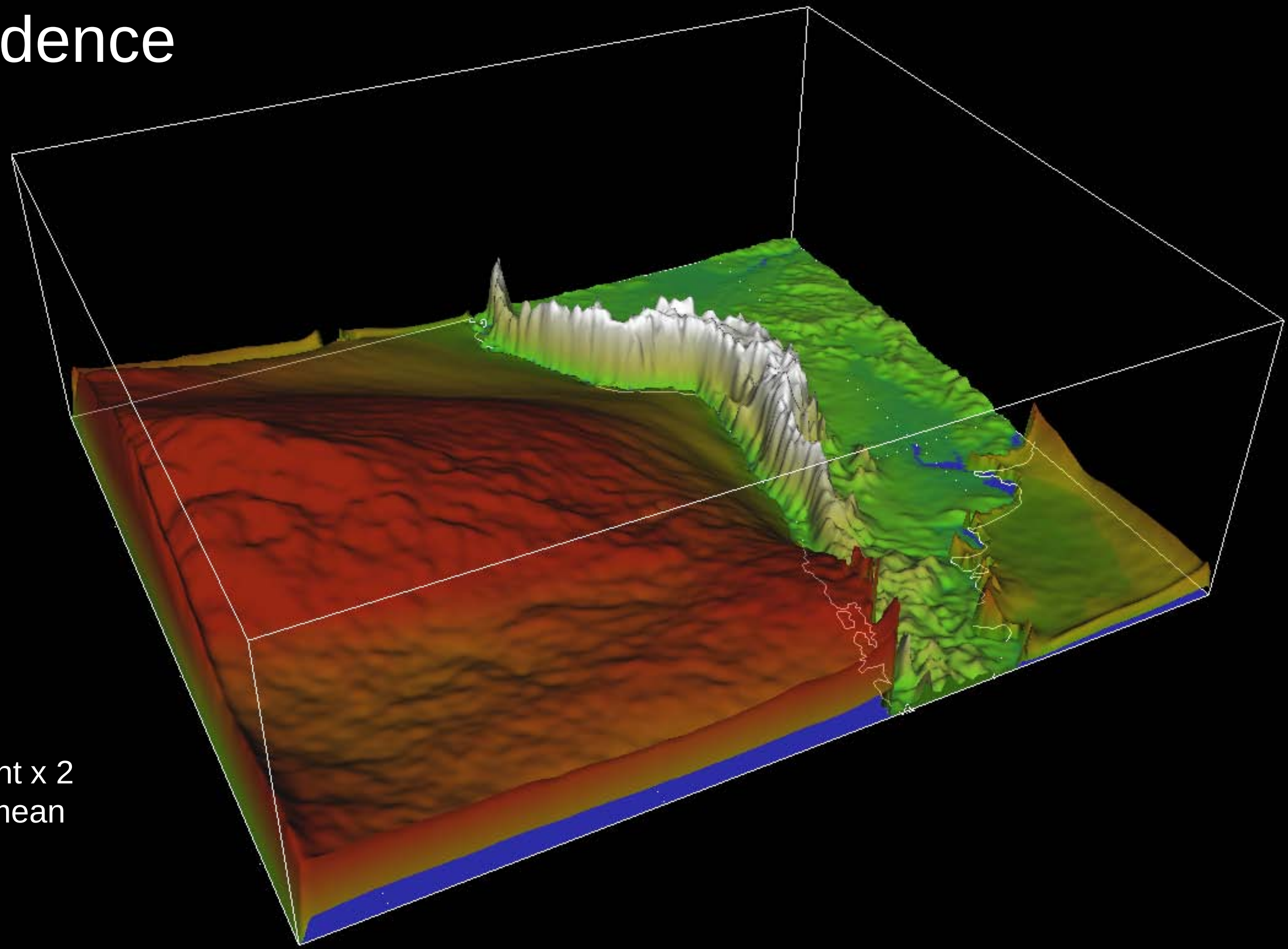


Some new questions: how does remote-past changes in northern Chile relief (specially coastal scarp) affected the Altiplano climate?



Picture courtesy of Aurelie Coudurier

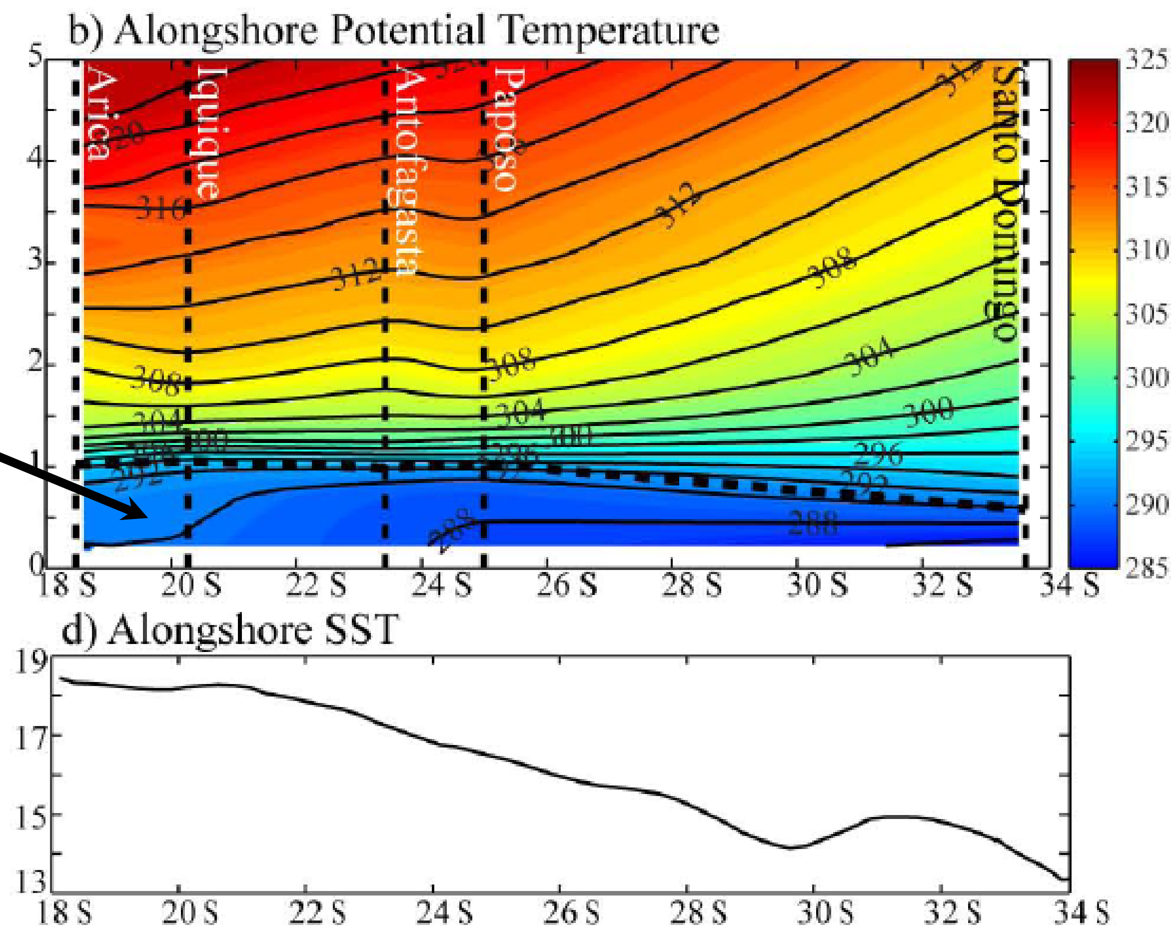
Lower troposphere over the SE Pacific
Cloud topped marine boundary layer (MBL) capped by a strong temperature inversion driven by subsidence



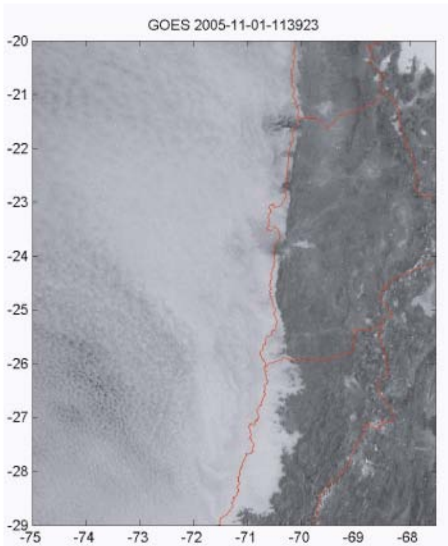
Simulated MBL Height x 2
Oct-Nov mean

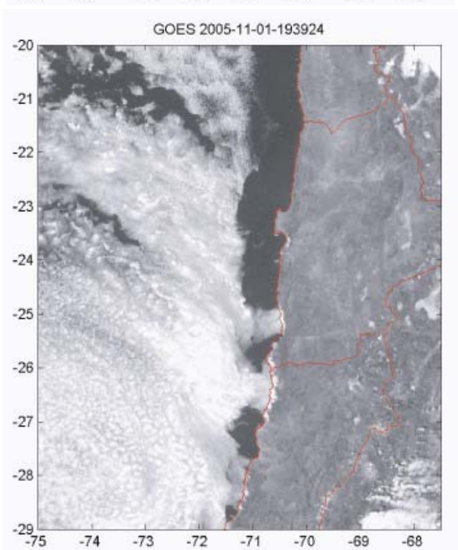
MBL height ~ 1000 m ASL nearly constant along the coast. This value results from a balance between large-scale subsidence and turbulence driven turbulence atop MBL

Low T, high q



High Andes & dry Atacama
Factor III: Diurnal circulations





RUTLLANT ET AL.: 1997–1998 DICLIMA EXPERIMENT ACL

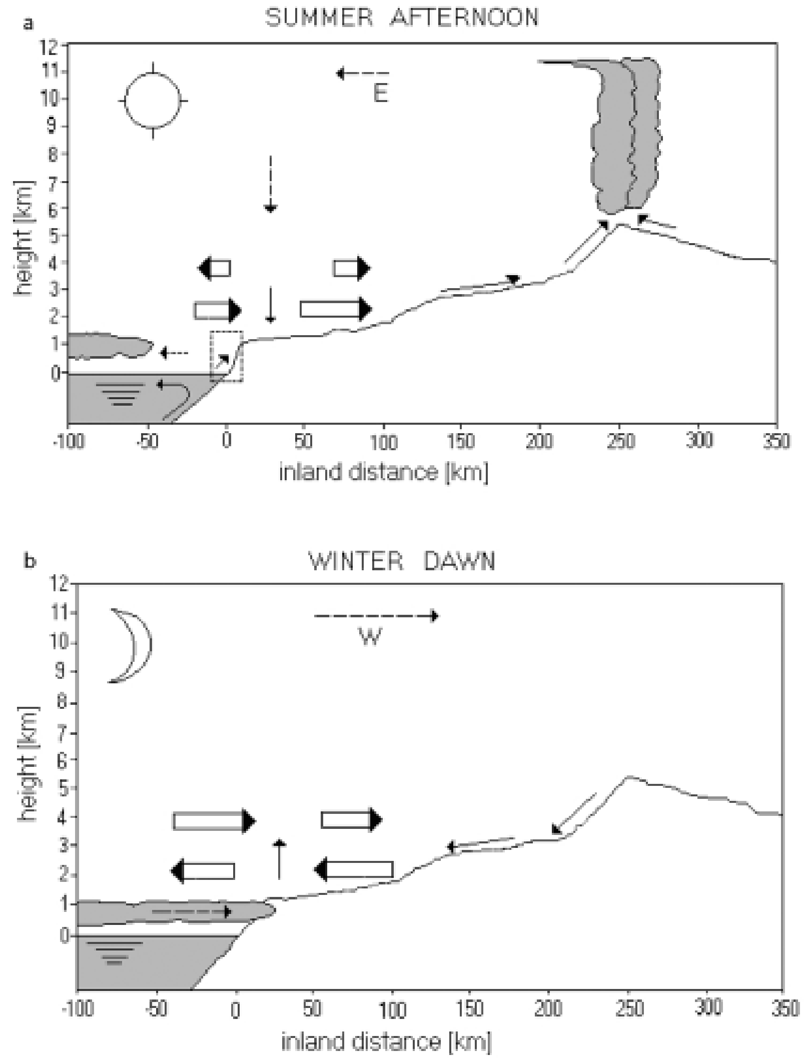
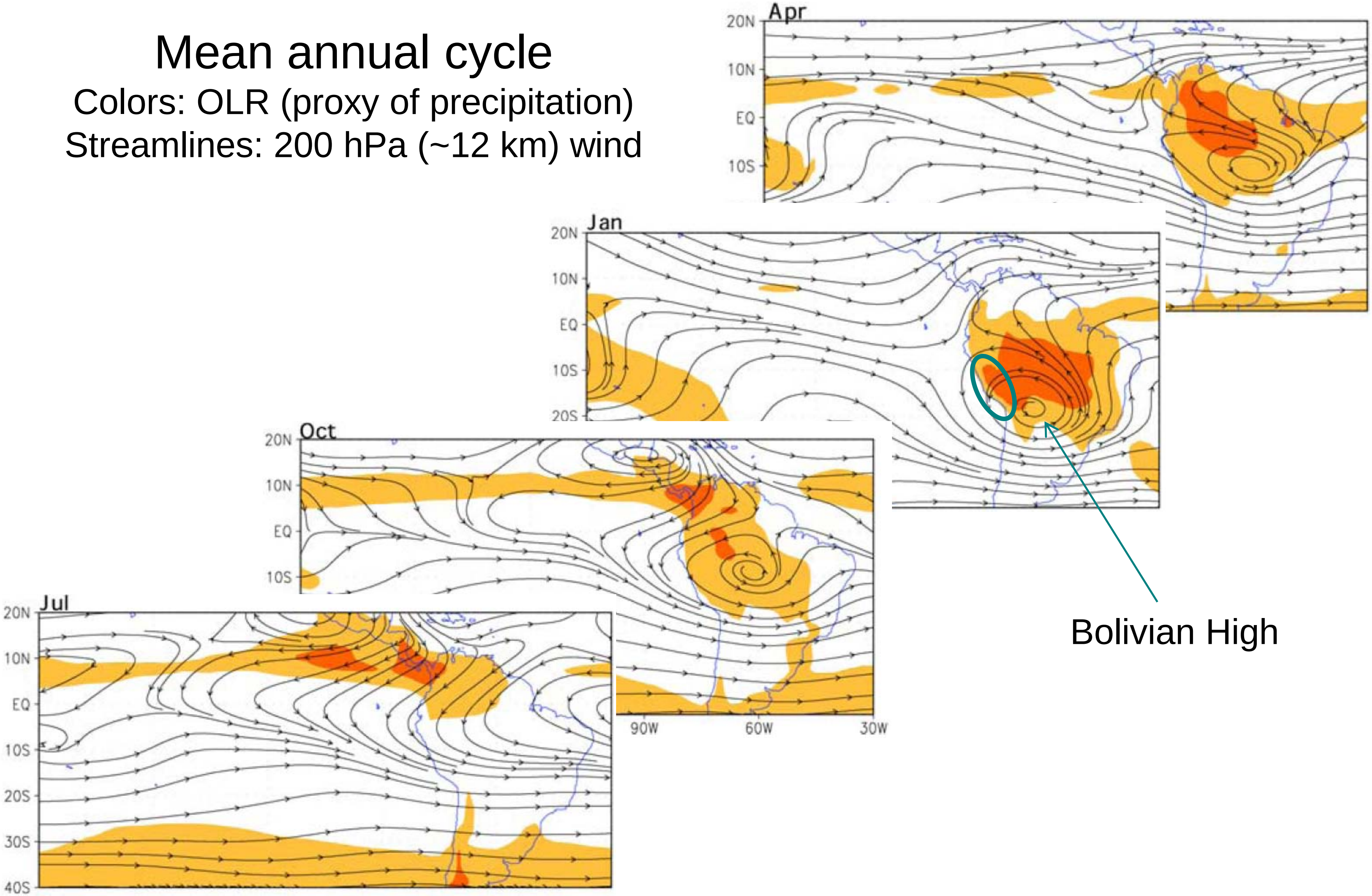


Figure 9. Schematic diagrams of the zonal mass flux (thick arrows) and zonal flow (thin arrows) across the arid northern coast of Chile: (a) austral summer afternoon conditions and (b) austral winter early morning conditions. The dashed rectangle in Figure 9a represents the cross section depicted in Figure 8.

South America monsoonal regime and Altiplano rainfall

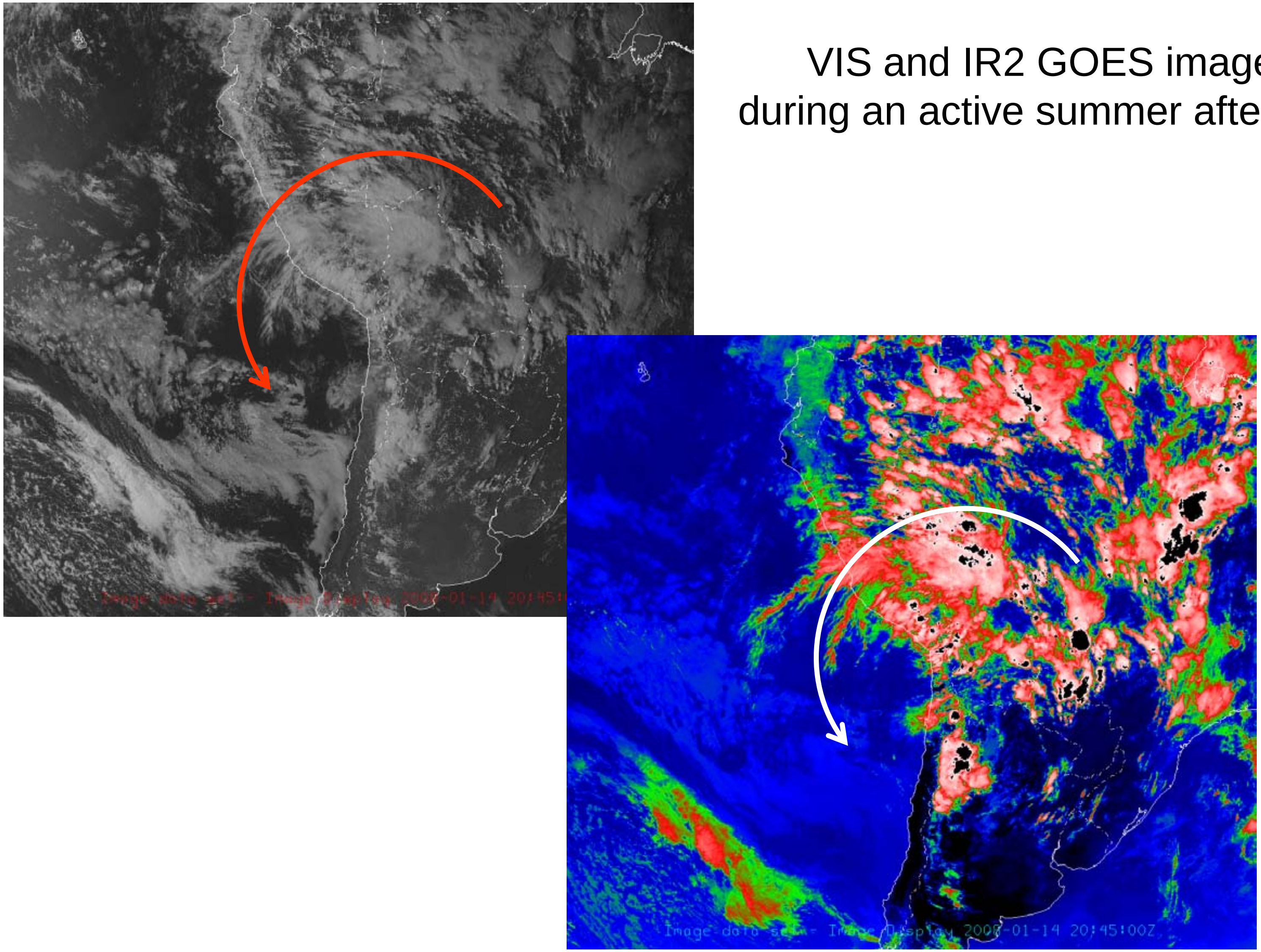
Mean annual cycle

Colors: OLR (proxy of precipitation)
Streamlines: 200 hPa (~12 km) wind

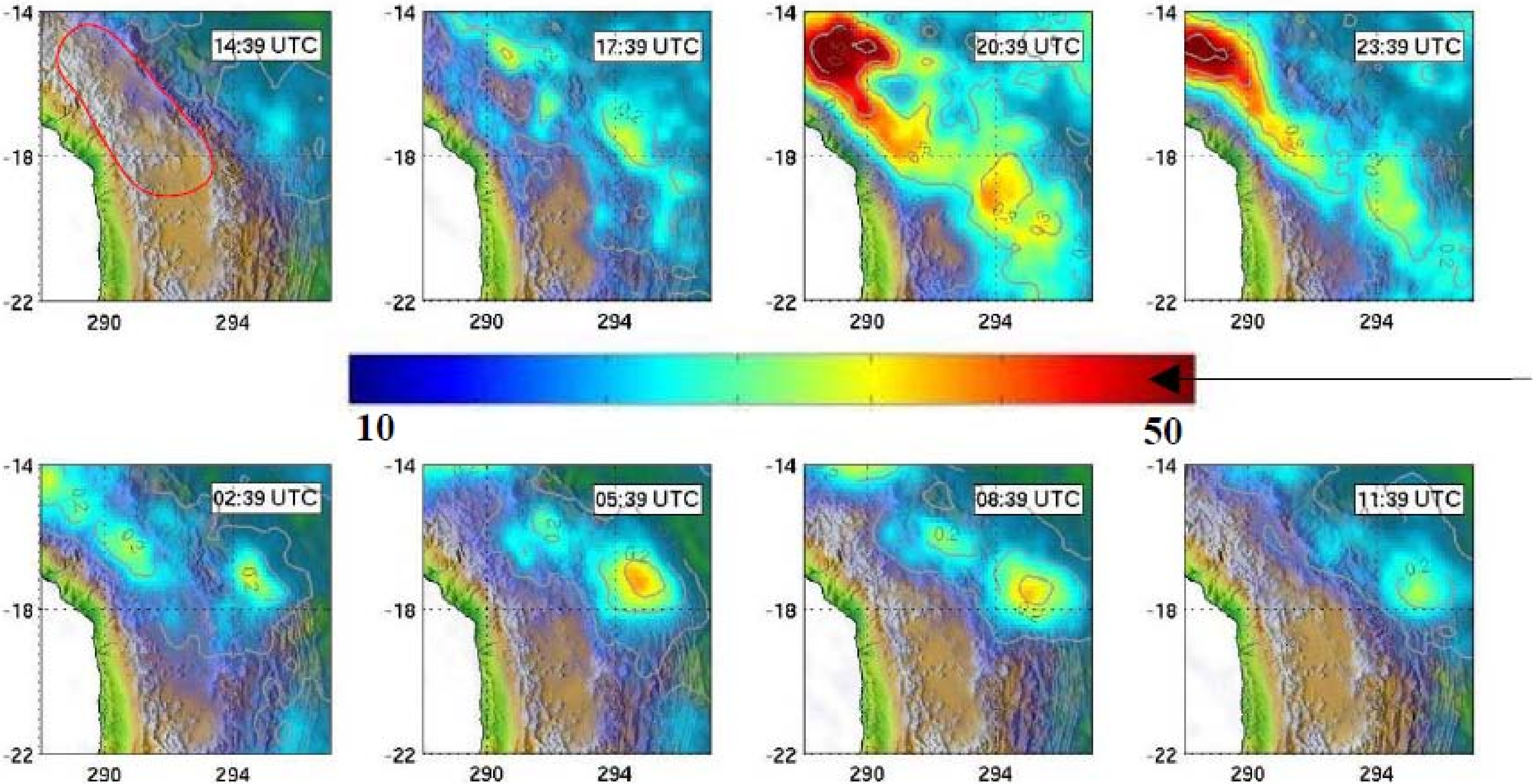


South America monsoonal regime and Altiplano rainfall

VIS and IR2 GOES images
during an active summer afternoon



Geographical distribution and diurnal cycle of the convective clouds over the central Andes



Ciclo anual y distribución espacial de PP

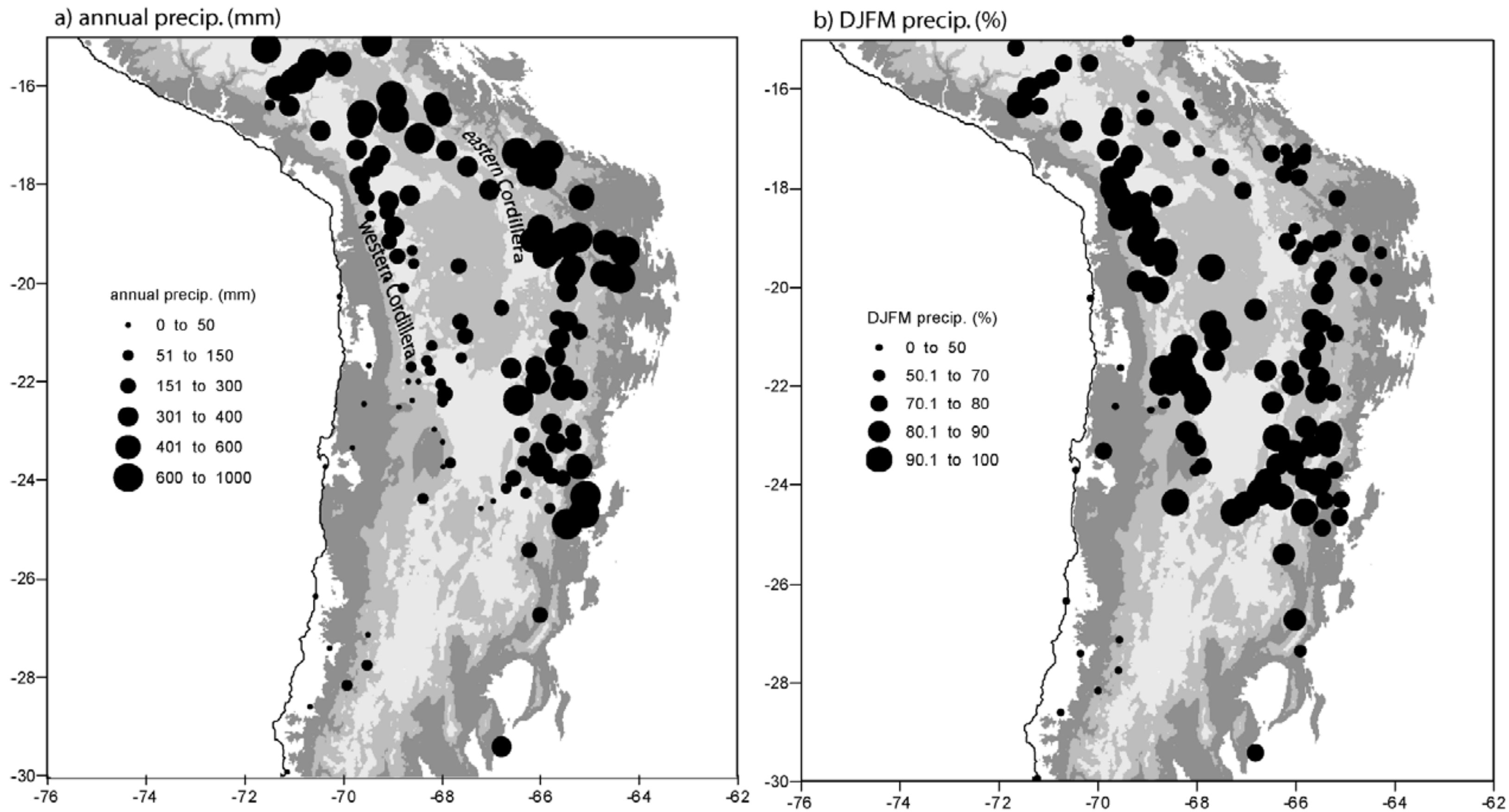
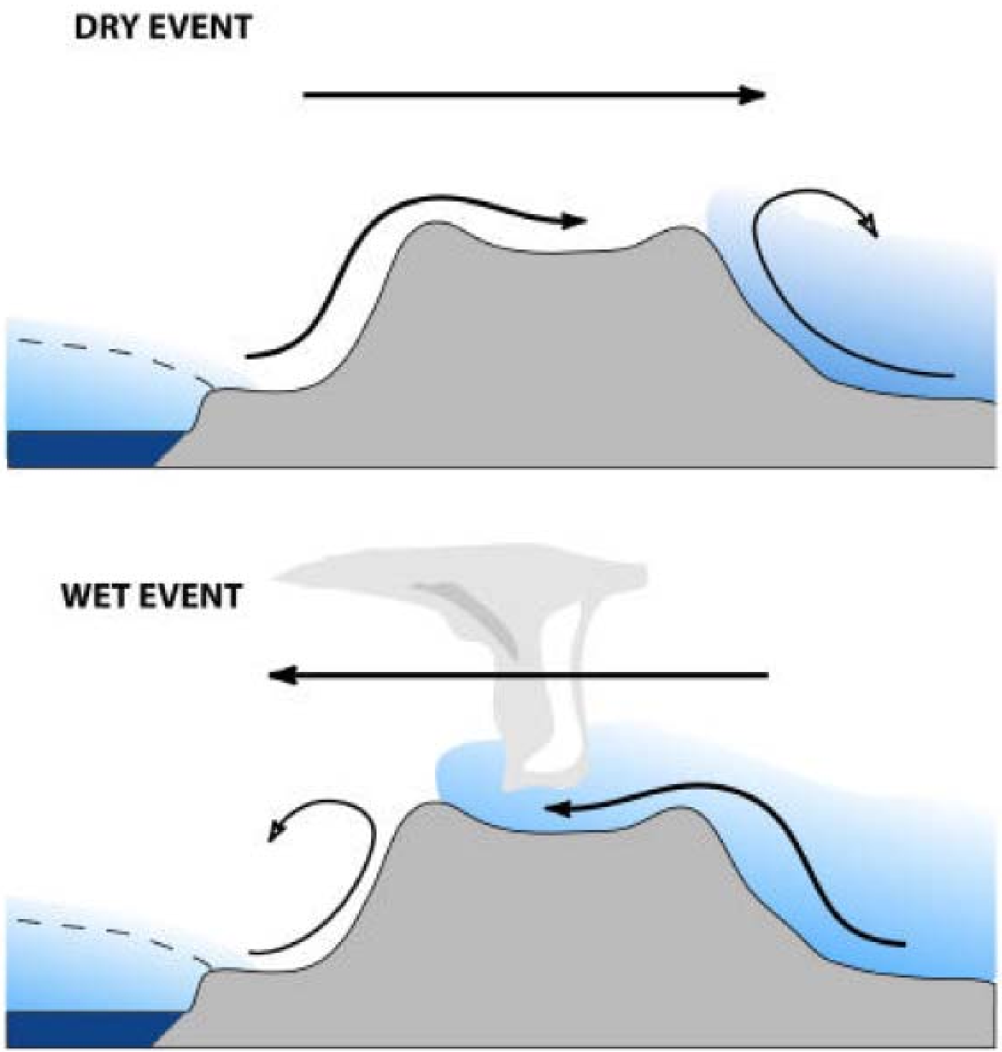


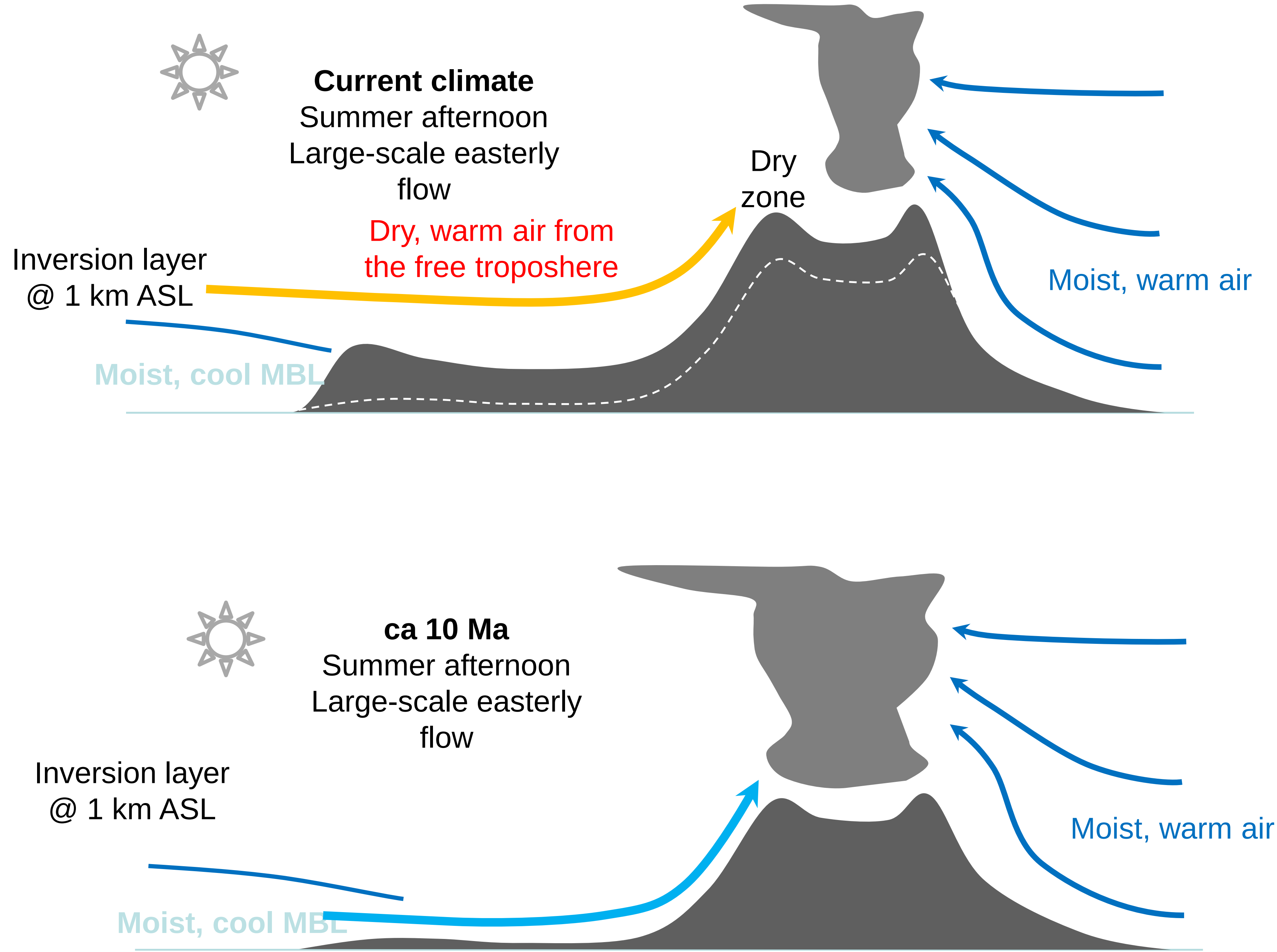
FIG. 1. (a) Long-term annual mean precipitation amount (mm) and (b) percent precipitation in DJFM of the annual total in the central Andes. To the east of the Andes only rain gauge data >1500 m are shown. Shading indicates elevation zones above 1000 m (dark gray), 2500 m (medium gray), and 4000 m (light gray). Record lengths of individual stations vary.

Summer Altiplano rainfall variability

An {Easterly flow (continental advection) – wet conditions} relationship is seen at synoptic, seasonal and interannual scales



Falvey and Garreaud 2005



Current climate
Summer afternoon
Large-scale easterly flow
Dry zone
Dry, warm air from the free troposhere
Inversion layer @ 1 km ASL
Moist, cool MBL
Moist, warm air
ca 10 Ma
Summer afternoon
Large-scale easterly flow
Inversion layer @ 1 km ASL
Moist, cool MBL
Moist, warm air

Reduction of the coastal cordillera height likely produces more humid conditions in the western cordillera (westward expansion of the Altiplano winter regime)…but how much?

Numerical simulations with high horizontal resolution…

Wait about a year to find out….

Merci!