Response to Anonymous Reviewer #1 to manuscript TC-2020-55-RC1

Title: Giant dust particles at Nevado Illimani: a proxy of summertime deep convection over the Bolivian Altiplano

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We thank the Anonymous Referee #1 for his constructive comments and suggestions. All line numbers correspond to the discussion paper and all added texts to the discussion paper are marked blue.

Specific Comment #1: Lines 44-45: while moist air advection from the east is suppressed.

[Answer]: *We fixed this sentence.*

Specific Comment #2: L 95: explain ice layer formation

[Answer]: *We changed the text to:*

L 95: Ice layers (less than 5 cm thick) occurred frequently along the firn core (Fig. S1), generally in closely spaced groups of 2 or 3 individual layers. In addition, less than 1 cm thick ice layers (or possibly wind crusts, hardly distinguishable from the former at greater depths) commonly occurred along the core. These features indicate few events of meltwater percolation, and ensure the proxies recorded in the firn core are well-preserved.

Specific Comment #3: L 110: Give some more details about the standard protocol: how is settling of giant particles prevented, stirring, the mean standard deviation of what?

General Comment #1: The correlation between giant particles and δD, considered as proxy for convection is based on the relative mass proportion of giant particles. Considering the fact that determining giant particles in a liquid sample is tricky, because they tend to settle, you need to substantiate the robustness of your results better. Specify if the given mean standard deviation between the two measurements with the coulter counter (lower than 3%) applies also to the giant particles alone.

[Answer]: *Lower uncertainties were obtained for number distribuitions. Therefore, we converted (along all the text) the proportions of giant particles in terms of mass (GPPms) to terms of number (GPPnb). In order to explain that, we changed the Section 2.2 to:*

L 105: Samples were melted at room temperature, and a ~10 mL aliquot from each was transferred to an Accuvette Beckman Coulter vial, previously washed with Millipore Q-POD® Element ultra-pure water (in an ISO 5 Class laminar flow bench located inside an ISO 6 Class clean laboratory). Each sample was treated following standardized protocols (Delmonte et al., 2002). A Beckman Coulter Multisizer 4 equipped with a 100 µm orifice was used to measure dust concentration and grain size (400 size channels within the 2–60 µm interval of spherical equivalent diameter). Samples were continuously stirred until the moment of the analysis, as the larger particles tend to settle rapidly. Systematic analysis of ultra-pure water blanks allows estimating a mean signal to noise ratio around 97. Each sample was measured twice, consuming 0.5 mL per measurement. The mean relative standard deviation (RSD) between these two measurements considering both the number and the mass of particles was 7% and 29%, respectively.

The higher deviation for the mass in comparison to the total number of particles was expected due to the presence of heavy giant particles having diameters >20 µm (coarse silt), for which small differences in size estimation lead to higher uncertainties. Indeed, when considering only the giant particles the mean RSDs were 55% and 63% for the number and mass distributions, respectively. Thus, the proportion (%) of giant particles (GPPnb) as well as total particle concentration, were calculated from the number size distribution. Approximately 14% of the samples showed very large uncertainties (RSD >100%) for GPPnb and were discarded. The mean RSD for GPPnb was 45%.

Specific Comment #4: L 137: LOD: concentration in dust or ice sample?

[Answer]: *We changed to:*

L 136: Errors for the elemental concentrations in our samples ranged from 3% for La to 17% for Cs, and the detection limits ranged from 0.1 µg per gram of dust for Sm to 7 µg g^{-1} for Ce (Table S2).

General Comment #2: Show examples of the size distributions for the wet and dry season.

[Answer]: *We added a new Figure to the Supplement (Fig. S2):*

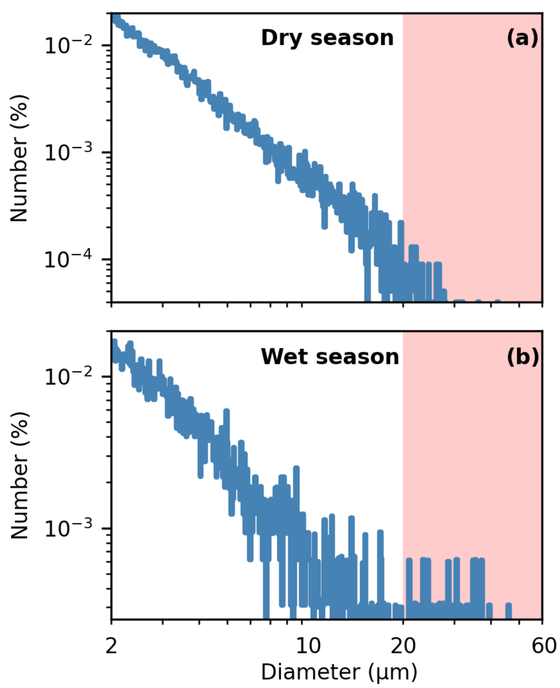

Figure S2: The number size distribution of a typical sample from the (a) dry and (b) wet season. Red areas highlight the giant particles (between 20 and 60 µm).

Specific Comment #5: Fig. 2: Show PC1 separately, in the current figure it is difficult to distinguish δD and GPPms.

General Comment #3: Show in addition the record of mass or number of giant particles for every sample. From the presented data it is unclear if the number or mass of giant particles also has a seasonal or any other variability or not.

Since total particle mass concentrations are low during the wet season (when you observe the correlation), the relative mass proportion is the ratio of two small numbers, probably having a large uncertainty. Add uncertainty bars.

[Answer]: *We changed Fig. 2 by adding the number of giant particles together with the total number of particles. This is described in a new paragraph (L 181). In addition, we transferred PC1 to a new Figure (Fig. 3).*

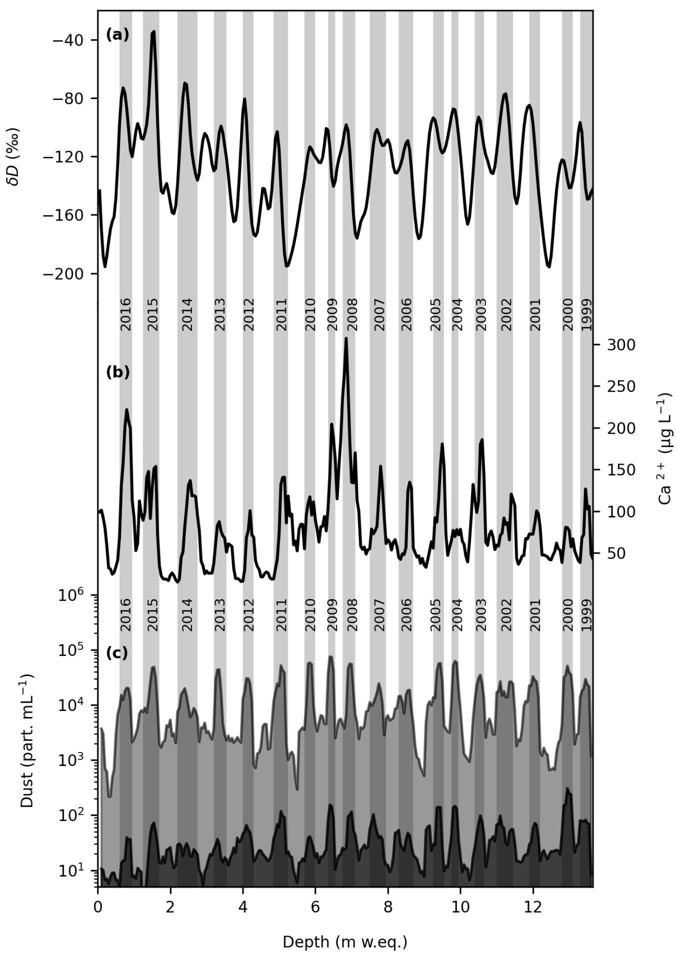

Figure 2: Dating of the Nevado Illimani firn core by annual layer counting (ALC) based on different proxies discussed in the text: (a) δD, (b) ionic Calcium, and (c) total and giant dust particles concentrations (light and dark gray, respectively, both are in logarithmic scale). Gray shaded vertical bands correspond to the dry season for each calendar year. All data are reported as 3-point running average of data re-sampled at 0.05 m w.eq.

L 181: By considering just the giant particles we also observed a seasonal pattern, with median concentrations of 15 part. mL^{-1} during the wet season and 30 part. mL^{-1} during the dry season. The well-defined oscillatory pattern of dust concentration variability reflects the extreme seasonality of precipitation over both local and regional dust sources, and the succession of dry and wet conditions. Therefore, each sample was classified as belonging to the wet or to the dry season according to dust concentration. Sublimation has a limited influence to this seasonality (Ginot et al., 2002).

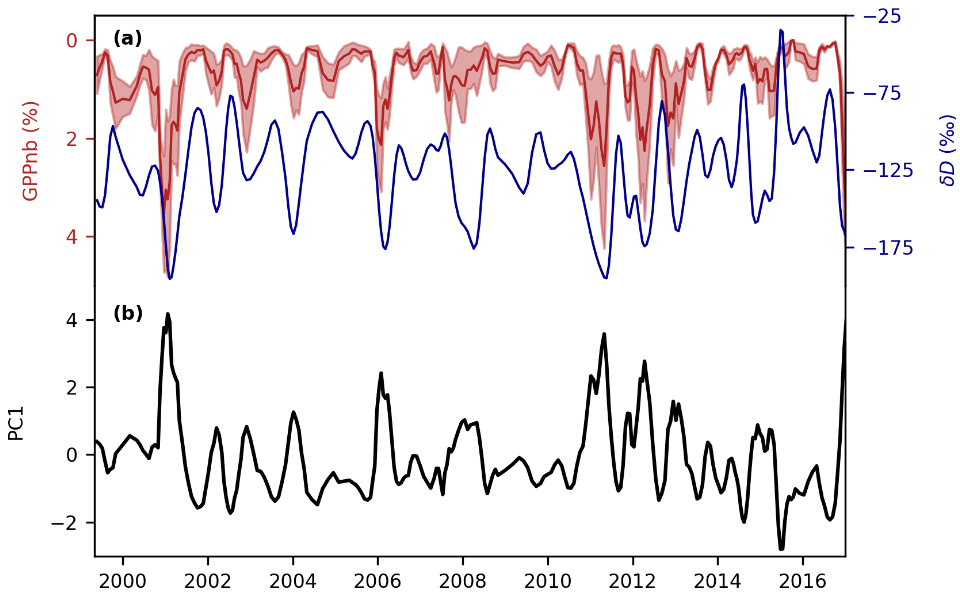

Figure 3: (a) Relationship over the 18-years record between the percentage of giant particles with respect to the total dust particles number (GPPnb, reverse scale) and the δD. Uncertainties for each GPPnb value (expressed by the red shaded area) are relative to the standard deviation between Coulter Counter measurements. (b) The first principal component of these two series (representing 82% of the total variance). All data are reported as 3-point running average of the data previously re-sampled at 0.05 m w.eq.

Specific Comment #6: L 185: Calcium carbonate is also soluble in water (solubility 13 mg/l), and most likely therefore not detected in mineralogical analyses.

[Answer]: *We changed to:*

L 185: Because scarcity of calcium carbonates was revealed by mineralogical analyses (Fig. 4, see below), we argue that most of the ionic calcium observed in firn samples is present as a soluble species, probably $CaSO_4$, and not detectable through Raman spectroscopy on single insoluble particles. However, we consider the possibility of calcium carbonate depletion due to scavenging during dust transport and/or dissolution during the melting of the samples, as discussed by Wu et al. (2016) based on ice core samples from Tibetan Plateau. In addition, we cannot exclude that Ca-bearing aerosols might have been initially a mixture of pure gypsum and calcium carbonates that successively reacted with atmospheric H_2SO_4 (Röthlisberger et al., 2000).

Specific Comment #7: L 199: Massive dust deposition – I think this is exaggerated. Have you compared dust concentrations at Illimani with that in other high-alpine ice cores? Are the dust layers visible in the core?

[Answer]: *We changed the word massive to significant higher. Then, we compared our data to other Andean ice core dust record:*

L 178: Dust concentration varies from ~2,000 particles mL^{-1} (hereafter part. mL^{-1}) during the wetter season, to ~10,000 part. mL^{-1} during the dryer season (median values). The two size distributions shown in Fig. S2 illustrate this variability. When considering extreme values, the variation range exceeds three orders of magnitude, being the lowest concentration during the wet season 150 part. mL^{-1} and the highest one during the dry season 140,000 part. mL^{-1}. Our results are in agreement with average dust concentrations from Quelccaya ice cap during the 20th century, ~10,000 part. mL^{-1} and ~25,000 part. mL^{-1} for the size ranges of 1.6–16 µm and 0.6–20 µm, respectively (Thompson et al., 1986, 2013).

General Comment #4: Before being lifted up by convection, dust particles need to be mobilized from the ground, which requires strong wind (advection). Have you checked wind speeds in the dust source areas? Dust source areas are located SE of Illimani, whereas humidity in the wet season originates in the Amazon Basin, due to stronger easterly winds and eastward upslope flow (especially enhanced during La Niña conditions). The link between local dust sources and easterly upslope flow is not immediately obvious. Your hypothesis would require large-scale convective processes also affecting the Altiplano. Do you have indications for that? Your precipitation data show the opposite. Hurley et al. (2015, 2016) offer a different hypothesis for depleted stable isotope ratios, i.e. the amount effect is associated with South American cold air incursions, linking synoptic-scale disturbances and monsoon dynamics to tropical ice core $\delta^{18}O$. Have you considered that as potential explanation for dust mobilization/uplift? How was the attribution to wet and dry season or even DJF, JJA for the ice core values conducted? This is critical and needs to be explained.

[Answer]: *We considered the hypothesis of Hurley et al. (2015). First we added information to the Introduction (L 37), then we changed Sect. 3.3 (starting on L 290). Furthermore, we made some changes on Table 2, Fig. 6 (former Fig. 5) and Fig. S3 (former Fig S.2), due to the use of GPPnb instead of GPPms:*

L 37: Precipitation on the Bolivian Altiplano is largely concentrated in the summer months (Garreaud et al., 2003), in response to the peak phase of the South American Summer Monsoon (SAMS). During summer (DJF), the intensification and southward displacement of the Bolivian High promotes strong easterly winds and a turbulent entrainment of easterly air masses over the Andean ridge. In addition, the upward motion over western Amazon, which is part of the meridional circulation between the tropical North Atlantic and western tropical South America, lead to increased convection and reduced tropospheric stability over the Central Andes (Segura et al., 2020). Such an atmospheric context favours the establishment of an eastward upslope air-flow and the advection of moisture from the Amazon basin toward the Andes (Zhou and Lau, 1998). Furthermore, there is the occurrence of transient disturbances within the SAMS, such as midlatitude cold air incursions that migrate equatorward from southern South America to the Amazon basin, and are responsible to most of the precipitation in the Quelccaya ice cap (Vera et al., 2006; Hurley et al., 2015).

L 290: In order to test the hypothesis of a relationship between giant particles and convective precipitation, we analyzed monthly precipitation and wind speed records from five meteorological stations located in the central Andes (Fig. 1). Data was provided by SENAMHI, Bolivia (www.senamhi.gob.bo/sismet), whereas monthly outgoing longwave radiation (OLR) data on a 2.5° x 2.5° grid box (Liebmann and Smith, 1996) was obtained from NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (https://www.esrl.noaa.gov/psd/). OLR data centered at 17.5 °S, 70 °W was used as an index of the convective precipitation over the Altiplano, as it presents strong negative correlations with regional rainfall observations (Garreaud and Aceituno, 2001). These datasets were re-sampled into DJF (December to February) and JJA (June to August) time series and compared with our seasonally resolved GPPnb series. For each wet and dry season, defined by dust concentration variability (Sect. 3.1), a mean GPPnb was obtained.

Results reported in Table 2 clearly show that during wet season GPPnb is positively correlated (at 95% level) to DJF precipitation at Patacamaya (17.2 °S, 67.9 °W, 4498 m a.s.l.). No significant correlations were found with wind speeds. Because of the convective nature of precipitation episodes, and high spatial variability in precipitation over the Bolivian Altiplano (Aceituno, 1996), it is expected that only precipitation data from stations in the closest vicinity of the Nevado Illimani show good agreement with glaciological data. Furthermore, Patacamaya was the only station in which precipitation correlated to dust related ions from Nevado Illimani during the 20th century (Knüsel et al., 2005). Thus our results also indicate that the dust record is influenced by the precipitation regime in the area south of Nevado Illimani. In agreement, by analyzing snowpits and meteorological data from 2003 to 2014 at the Quelccaya ice cap, Hurley et al. (2015) concluded that depleted δD and increased snow accumulation were related to convection along the leading edge of cold air incursions advecting from south. Both Nevado Illimani and Quellcaya ice cap show a coherent variability in their stable water isotopes record (Hoffman et al., 2003).

Also, GPPnb is negatively correlated with the DJF OLR centered over the Altiplano (Table 2), indicating that deep convection increases giant particle entrainment and suspension, humidity and precipitation over the region. We conclude that the more intense is summer convection, the higher is the relative mass of giant dust particles suspended in the atmosphere and the more depleted is the δD.

Table 2: Seasonal correlations between Giant Particles Percentage (GPPnb) and δD, rainfall observations and outgoing longwave radiation (OLR). The period between December and February was defined as the wet season, and the period between June and August as the dry season. Significant correlations at 95% level are shown in bold.

GPPnb	δD	El Alto	Calacoto	Patacamaya	Oruro	Potosi	OLR
Wet	**-0.71**	0.47	0.39	**0.76**	0.25	0.41	**-0.69**
Dry	**-0.70**	0.04	-0.21	-0.09	-0.08	-0.23	0.07

During dry seasons, conversely, GPPnb is not significantly correlated with JJA OLR and precipitation (Table 2), although it is still correlated with δD, as shown by seasonal mean values reported in Fig. 6. As observed by Vimeux et al. (2005), this lack of correlation with meteorological data reflects the low and constant level of regional precipitation. However, regional JJA precipitation amounts might represent an underestimation, as considerable precipitation amounts can occur especially when cold air masses move over the Altiplano (Vuille, 1999). Thus our data potentially responds to the sparse and occasional winter convection.

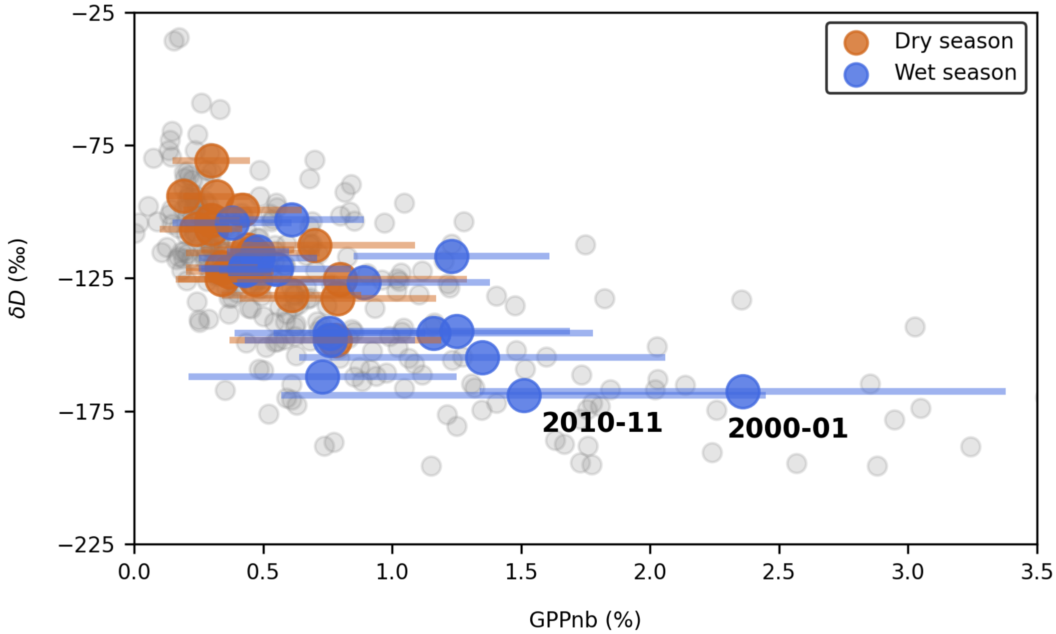

Figure 6: Seasonal mean GPPnb and δD for the dry seasons (orange circle) and the wet season (blue circle). Error bars (horizontal bands) for GPPnb are based on the mean relative standard deviation for the samples integrating each season. Light gray dots on background are raw data. The 2001-01 and 2010-11 La Niña events are reported.

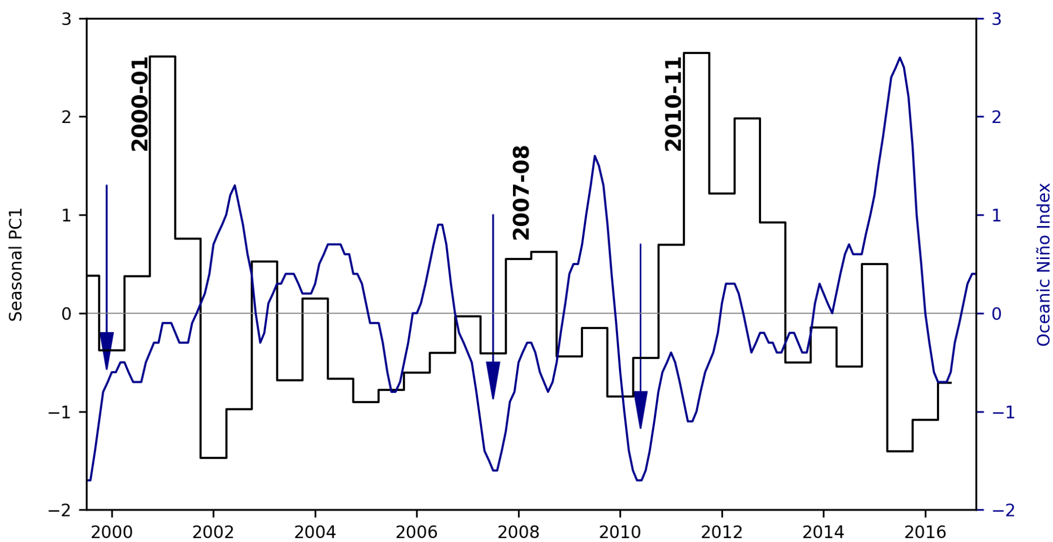

Figure S3: Comparison of the seasonal PC1 of GPPnb and δD (black line) and the Oceanic Niño Index (ONI) (blue line) typically used for identifying El Niño (warm) and La Niña (cool) events in the tropical Pacific. It is possible to note that the highest convection (high PC1) is associated to summer seasons of La Niña years.

Specific Comment #8: L 500: delete percentage

[Answer]: *We fixed it.*

Specific Comment #9: Table S2: Give also ice core concentrations for comparison with other publications.

[Answer]: *We added a comparation in Table S2. The references we included in the text are listed bellow.*

Table S2: Average elemental concentrations measured by Instrumental Neutron Activation Analysis, and the procedural errors and the detection limits (DL). For comparison, we also present mean concentrations of dust particles from high elevation ice cores in the Alps (Thevenon et al., 2009) and in the Tibetan Plateau (Wu et al., 2009).

Element	Ce	Cs	Eu	Hf	La	Sc	Sm	Th	Yb
Concentration (ppm)	89.8	21.1	1.60	13.1	40.8	13.7	8.14	17.6	2.71
Error (%)	7.24	13.8	6.65	9.97	4.05	3.97	7.27	7.16	10.8
DL (ppm)	7	4	0.8	3	0.5	0.3	0.1	4	0.1
Colle Gnifetti ice core, Alps (ppm)	1.76	1.20	1.78	5.24	2.74	18.6	4.63	3.49	6.25
Dunde ice core, Tibetan Plateau (ppm)	65.7		1.09	4.04	32.6		5.51	14.3	2.93

Included references:

Hurley, J. V., Vuille, M., Hardy, D. R., Burns, S. J. and Thompson, L. G.: Cold air incursions, d18O variability, and monsoon dynamics associated with snow days at Quelccaya Ice Cap, Peru, J. Geophys. Res. Atmos., 120, 7467–7487, doi:10.1002/2015JD023323, 2015.

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Thevenon, F., Anselmetti, F. S., Bernasconi, S. M. and Schwikowski, M.: Mineral dust and elemental black carbon records from an Alpine ice core (Colle Gnifetti glacier) over the last millennium, J. Geophys. Res. Atmos., 114(17), 1–11, doi:10.1029/2008JD011490, 2009.

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Vera, C., Higgins, W., Amador, J., Ambrizzi, T., Garreaud, R., Gochis, D., Gutzler, D., Lettenmaier, D., Marengo, J., Mechoso, C. R., Nogues-Paegle, J., Silva Dias, P. L. and Zhang, C.: Toward a unified view of the American monsoon systems, J. Clim., 19(20), 4977–5000, doi:10.1175/JCLI3896.1, 2006.

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Wu, G., Zhang, X., Zhang, C. and Xu, T.: Mineralogical and morphological properties of individual dust particles in ice cores from the Tibetan Plateau, J. Glaciol., 62(231), 46–53, doi:10.1017/jog.2016.8, 2016.