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Supplementary Information

Climate modes

Since most of SA resides in the tropics and some indices are phase-locked to the seasonal cycle (e.g. Niño 3.4), the correlation/regression of climate modes with temperature and precipitation was carried out based on the tropical hydrologic year (July-June) rather than calendar years (Jan.-Dec.), which would have also cut the SASM season in half. The time period of analysis is 50 years, from July 1958- June 2008, allowing the use of data with better spatiotemporal coverage over SA than would have been available for the early half of the 20th century. A similar analysis was carried out previously by Garreaud et al. (2009), but here we extend their analysis to include additional indices that describe Atlantic modes of variability.

Gridded precipitation and temperature data were derived from the UDelaware data set V2.01 (Legates & Wilmott, 1990). Over a dozen different indices of climate variability on interannual to decadal timescales were trialed, but only the six most relevant ones (see Table 1) are discussed and shown in Figs. 2-5. Since this is a linear analysis, it is important to keep in mind that the negative phase of any of these oscillatory modes would lead to a similar influence, but of the opposite sign, over SA. Similarly a perturbation of twice the magnitude would lead to a temperature or precipitation response, which is also twice as large. This assumption of linearity is not equally valid for all modes and all locations, but justified overall, as shown by Garreaud et al. (2009). Another caveat to keep in mind in this type of analysis is that it assumes stationarity in the teleconnections, i.e. that the relationship between local precipitation or temperature and the climate mode has remained constant at least during the last 2k.

Venezuelan Guayana highlands and uplands

The Gran Sabana (GS) lies on the Guayana Shield, which is characterized by an Archaean to Proterozoic igneous-metamorphic basement (Mendoza, 1977; Gibbs & Barron, 1993). The whole GS region is covered by a thick sedimentary layer of Precambrian sandstone and quartzite (the Precambrian Roraima Group), spiked with Paleozoic to Mesozoic intrusive diabbases (Briceño et al., 1990). The GS is an undulated erosion surface developed on the Roraima sediments that forms an *altiplano* slightly inclined to the south, ranging from approximately 750 to 1450 masl (Briceño & Schubert, 1990). This peneplain constitutes the basal level from which the

emblematic tepuis emerge, with characteristic flat summits and vertical cliffs. These table mountains developed on the Roraima Group by differential erosion during the Cretaceous (Briceño & Schubert, 1990). In the uplands, soils are mostly savanna oxisols and shallow inceptisols in floodplains. Histosols are common on top of the tepuis, where they develop peat bogs and extensive peat mats (Huber, 1995a; Zink & García, 2011).

Submesothermic ombrophilous climate occurs in the GS uplands (between 500 and 1200 m elev.) and is characterized by average temperatures between 18 and 24 °C and 2000-3000 mm of total annual precipitation with a weak dry season (<60 mm/month) from December to March (Huber 1995a). In the southern GS, the climate becomes submesothermic tropophilous, which is less humid (1600-200 mm/year) and more seasonal. The GS highlands between 1500 and 2400 masl are under a mesothermic ombrophilous climate, with average temperatures between 12 and 18 °C and 2500-3500 mm of annual precipitation, without a true dry season. Additional moisture is supplied by the frequent occurrence of dense mists. Winds and thunderstorms are frequent. Submicrothermic ombrophilous climates are typical on the highest tepuian summits, above 2400 masl. There, the precipitation and mist regime are similar to the former, but the annual average temperature is lower, approximately 10 °C or less. Freezing temperatures have not yet been measured there and it has been proposed that the constantly high air moisture (Huber & García, 2011) may act as a buffer preventing the air from reaching freezing point. It has been reported that the general lapse rate for the whole region is -0.6 °C/100 masl (Galán, 1992).

The GS uplands are mostly covered by treeless savannas dominated by grasses of the genera *Axonopus* and *Trachypogon*, accompanied by sedges such as *Bulbostylis* and *Rhynchospora*. Woody elements are rare in the GS savannas, and they are restricted to stunted plants that do not emerge above the herb layer (Huber, 1995c). Most GS forests are considered to fall within the category of lower montane forests because of their intermediate position between lowland and highland forests (Hernández, 1999). The GS forests are highly diverse and their composition varies with elevation; common genera include *Virola* (Myristicaceae), *Protium* (Burseraceae), *Tabebuia* (Bignoniaceae), *Ruizterania* (Vochysiaceae), *Licania* (Chrysobalanaceae), *Clathrotropis* (Fabaceae), *Aspidosperma* (Apocynaceae), *Caraipa* (Clusiaceae), *Dimorphandra* (Caesalpinaceae) and *Byrsonima* (Malpighiaceae) (Huber, 1986). Gallery forests are also common along rivers and on lake shores. The GS shrublands usually occur between 800 and 1500 m elevation and are more frequent at the northern area than at the

southern part (Huber, 1995b). They are also highly diverse, and their composition varies according to soil type (rocky, sandy or ferruginous). The common elements are *Clusia* (Clusiaceae), *Humiria* and *Sacoglottis* (Humiriaceae), *Pera* (Euphorbiaceae), *Emmotum* (Icacinaceae), *Matayba* (Sapindaceae), *Bonnetia* (Bonnetiaceae), *Phyllanthus* (Euphorbiaceae), and *Cyrillopsis* (Ixonanthaceae) (Huber, 1995c). A special vegetation type called *morichales*, dominated by the palm *Mauritia flexuosa* L., develops on wide alluvial plains associated with flooded areas such as lake shores and water courses. The upper elevational boundary of the *morichales* is approximately 1000 masl (Rull, 1998); hence, they are restricted to the southernmost part of the GS. Another peculiar vegetation type that grows on peaty soils and is interspersed with treeless savannas is the broad-leaved meadows dominated by *Stegolepis* (Rapateaceae), with *Xyris* and *Abolboda* (Xyridaceae), several Cyperaceae, *Nietneria* (Nartheciaceae) and conspicuous tubular rosettes of *Brocchinia* (Bromeliaceae). The GS highlands are part of the so-called Pantepui phytogeographical province, which is characterized by unique biodiversity and endemism patterns, encompassing all the tepui summits above 1500 masl (Huber, 1994; Berry et al., 1995). The vegetation is characterized by a mosaic of bare rock, pioneer vegetation, tepuian forests, herbaceous formations and shrublands (Huber, 1995c). Pioneer communities are composed mainly of algae (*Stigonema*) and lichens (*Cladonia*, *Cladina*, *Siphula*) growing directly on rocks. The forests are mostly situated along rivers and are dominated by *Bonnetia roraimae*, accompanied by *Schefflera* (Araliaceae), *Spathelia* (Rutaceae), *Stenopadus* (Asteraceae) and *Malanea* (Rubiaceae). The forests on the diabase intrusions are similar, but they are dominated by *Stenopadus* and *Spathelia* instead of *Bonnetia*. Among the herbaceous communities, grasslands and meadows are more important. Grasslands are restricted to flooded plains on the center of the massif and are characterized by grasses (*Cortaderia*, *Aulonemia*), and sedges (*Cladium*, *Rhynchospora*). The meadows are broad-leaved communities dominated by *Stegolepis ligulata* (Rapateaceae), which is endemic to the Chimantá, accompanied by *Xyris*, *Everardia* and *Lagenocarpus* (Cyperaceae), *Lindmania* and *Brocchinia* (Bromeliaceae), *Heliophora* (Sarraceniaceae), and *Syngonanthus* (Eriocaulaceae). Shrubs occur as small clusters or as isolated individuals. Shrublands are the more developed and diverse communities of the Chimantá. The paramoid shrublands are exclusive to this massif and are dominated by species of *Chimantaea* (Asteraceae), a genus endemic to the Chimantá and other neighboring tepuis. The herbaceous stratum is dominated by the bambusoid *Myriocladus*

(Poaceae) and several Xyridaceae, Cyperaceae and Eriocaulaceae, as well as *Lindmannia*, *Everardia* and *Heliophora*.

The GS region is presently the homeland of the Pemón indigenous group, of the Carib-speaking family. Today, they are sedentary, living in small villages, usually in open savannas. Fire is a key component of the Pemón culture and they use it every day to burn savannas and the adjacent forests (Kingsbury, 2001). In addition to the slow and continuous savanna expansion due to the edge effect of fires on the forest-savanna ecotone, accidental uncontrolled fires burning huge forest areas have also been observed on occasion (Fölster, 1986). The reasons for the extent and frequency of these fires include activities such as cooking, hunting, fire prevention, communication and magic, among others (Rodríguez, 2007). Surprisingly, land-use practices such as extensive agriculture or cattle raising, typical of other cultures strongly linked to fire, are not characteristic of the Pemón culture (Rodríguez, 2004). The large number of fires today in the GS uplands (~10,000 each year; Huber, 1995d) are essentially human-made. It is estimated that most of the GS areas are burned every 1-3 years (Hernández & Fölster, 1994). In contrast, the GS highlands remain virtually pristine (Rull, 2007; 2010). The Pemón people do not visit the tepui summits, as they consider the tepuis the home of gods or the remains of their tree of life, and are thus sacred lands forbidden to humans (Gorzula & Huber, 1992). In addition, the tepui summits are remote and nearly inaccessible, as only a few can be reached by foot after several days of walking and climbing. Since the first known expedition in 1884, most visits have been for scientific reasons, as attempts to find any economic profit have failed. No exploitable mineral resources have been found, the soils are unsuitable for agriculture, and there are no grasslands suitable for cattle raising (Gorzula & Huber, 1992). Scientific expeditions ceased in recent decades due to official protection, but tourism increased. However, tourism is restricted to sporadic activities, and there is no permanent establishment or structure on top of the tepuis. Since 1962, several conservation measures have been implemented to protect the tepuis, including the creation of national parks, natural monuments, and biosphere reserves (Huber, 1995d).

Southeastern and Southern Brazil

The Atlantic rainforest occurs in S-SE Brazil as a 100 to 200 km narrow zone in the coastal lowlands along the Atlantic Ocean, and on the coastal eastern slopes of the mountain ranges. The

tropical semi-deciduous forest occurs further inland in SE Brazil. The Cerrado is found primarily in C Brazil, but also in the N part of SE Brazil. The subtropical grasslands are found in highland S Brazil and lowlands of the southernmost region of S Brazil.

Subtropical *Araucaria* forest is found on the S Brazilian highlands between 24 and 30° S (1000-1400 m.a.s.l.), and in SE Brazil in small isolated areas between 18 and 24° S (1400-1800 masl.) (Hueck, 1953). Frost-sensitive tropical Atlantic rainforests reach their limit in the southern region of Santa Catarina state (Klein, 1978; Por, 1992). The climate is warm and humid without any or only a short dry period of less than 2 months. The annual precipitation ranges from 1250 to 2000 mm and up to 4000 mm in the higher coastal mountains. The average annual temperature is between 17 and 24 °C (Nimer, 1989). On the highland in southern Brazil where frosts (in rare cases up to -8/-10 °C) occur during austral winter tropical plants have their limitations, subtropical *Araucaria* forest occurs. In particular *Araucaria angustifolia* require a minimum precipitation of 1400 mm per year with no marked dry seasons. If the rainfall is low often a mosaic of Campos (grassland) and *Araucaria* forest occur. The climate in the subtropical *Araucaria* forest is temperate and humid without pronounced dry periods. The annual precipitation is between 1400 and 2200 mm. The average annual temperature ranges mainly between 12 and 18 °C. Nights in cold winters may have temperatures of -4 to 8 °C in the upper region of the Serra Geral (Nimer, 1989). The tropical semi-deciduous forest occurs in regions in SE Brazil, with an annual dry season between 3 and 5 months and an annual rainfall between 1000 and 1500 mm. The average annual temperature is between 20 and 26 °C. A few isolated patches of Cerrado occur in the area of semi-deciduous forest in SE Brazil (Hueck, 1956). The annual precipitation in most of the Cerrado region is between 1000 and 1750 mm, the annual temperature is between 20 and 26 °C, and the length of the dry season is between 5 and 6 months (Nimer, 1989).

The subtropical grassland, which is called in Brazil Campos, is found on the highland in southern Brazil and in the lowlands of the southernmost region of southern Brazil. The latter is similar to the pampa grassland, which occurs mainly in Uruguay and Argentina. Campos on the S Brazilian highlands often form a mosaic with *Araucaria* forests (Klein, 1978). Campos de Altitude occurs on mountains, at elevations above 1600 m in S Brazil and above 1800 m mainly in SE Brazil (Safford, 1999a,b).

Southern Andes and Extra-Andean Patagonia

There are three main climatic features that interact in this region: (1) the Southern Westerly Wind Belt (SWWB) which majorly influence the southernmost tip of South America up to 38°S; (2) the Subtropical Pacific Anticyclone located around (20-40°S) that interacts with the SWWB modulating the climate of Central Chile; and (3) the South America Summer Monsoon (SASM) that combined with the Bolivian Altiplano, the surface easterly winds and local topography determines the climate of the Altiplano and the Atacama Desert (Garreaud, 2009). The Andes are an important topographic barrier humid air masses coming from Pacific, causing a strong WE precipitation gradient. Precipitation and westerlies flow at 850 hPa (SWWB) present high correlations on the western side of the Andes, less significant on the leeward side, and negative eastwards to Atlantic Ocean (Garreaud et al., 2013). Eventually, wet air masses from the Atlantic Ocean generate extreme precipitation events in dry regions of extra-Andean Patagonia. The other strong climatic gradient varies from the very wet extratropical environments in the southern tip to the hyperarid Atacama Desert, the driest of the world (Miller 1976). Three main climatic regions could be defined: (1) an temperate region (38-56°S) characterized by rainfall year-round in the Andean region and more seasonally precipitation in extra-Andean Patagonia; (2) a central region (38-27°S) characterized by a strong precipitation seasonality (winter rainfalls) in the core area and shows increasing precipitation towards the south up to 40°S and a decreasing to the N (27°S); and (3) a northern region (north of 27°S) which presents scarce precipitation concentrated in high Andes, related to the eastern moisture source (SASM) and absence of precipitation in the core of Atacama Desert.

Pampa plains

Climatic features over Pampa plain are mainly influenced by (1) the SE trade wind circulation associated with the subtropical South Atlantic anticyclone bringing moisture into the subtropics located east of the Andes, and (2) the meridional transport of water vapour (low level jet) from humid lowlands of Brazil to subtropics (Piovano et al, 2009). Mean annual rainfall varies between 600 and 1200 mm, depending on latitude and distance from the sea, and the precipitation regimen experience a pronounced seasonal cycle. The rainy season with maximums on December and March (austral summer) is related to an intense convective activity in continental and oceanic unstable masses and the development of a monsoon-like system (Vera et al., 2006) that could influence south far 35°S. Whereas, during dry season (austral winter) prevails convective activity related to frontal systems, being the subtropical South Atlantic anticyclone the main moisture source. Frequently, atmospheric circulation pattern is modified by episodic incursions of polar air outbreaks that originate pre- and frontal precipitation.

Other important components of the vegetation are Asteraceae, Cyperaceae, Solanaceae, Apiaceae and Chenopodiaceae, that accompanied Poaceae at regional scale and define different edaphic communities locally (Tonello & Prieto, 2008).