Appendix A: Efforts of tools and organization to adapt to climate variability in Central America

There are several tools and organizations dedicated to the adaptation to climate variability in Central America, but there is still much to be done. Examples of successful experiences are:

1) Since 1997, the Regional Climate Outlook Forums (RCOFs) have been working to produce climate prediction products (IRI 2001). These forums have been financed by different international agencies with the assistance of different local entities such as the Regional Committee of Water Resources (CRRH in Spanish) in Central America (Donoso and Ramírez 2001; García-Solera and Ramírez 2012), a committee that is part of the Central American Integration System (SICA in Spanish).

2) The Central American Flash Flood Guidance (CAFFG; http://www.hrc-lab.org/right_nav_widgets/realtime_caffg/index.php) is a system designed to produce in real-time relevant flash-flood information for all seven countries of Central America with a 200 km^2 spatial resolution. Meteorological offices of the countries of Central America are in charge of interpreting the results of the system and issuing alerts.

3) There are many studies regarding food security issues in Central America (e.g. Benegas et al. 2009; Tyler et al. 2013, Gauster 2014, Marengo et al. 2014), some of them with more focus on climate than others.
Even when considering these and other efforts to mitigate the effects of climate variability in the area, Central America is a region with susceptibility to disasters related to hydroclimatic variability, usually (but not exclusively) during extreme El Niño-Southern Oscillation (ENSO) years and also during years when tropical storms and/or hurricanes have characteristics (intensities or trajectories) that make them particularly damaging (for examples see Amador 2011; Amador et al. 2011; Amador et al. 2013; Amador et al. 2014). These susceptibilities are also associated with societal vulnerabilities (Amador and Alfaro 2014), and therefore better information and tools could improve planning and designing the needed infrastructure. This is particularly true, as three of the seven Central American countries are in the top 15 most exposed countries to natural hazards (earthquakes, storms, floods, droughts and sea level rise) worldwide and four of the region's countries are in the top 15 considered at most risk (see pages 9 and 44 of Welle et al. (2014)). Risk comprises exposure to natural hazards and the vulnerability of a society.

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Appendix B. Sources of variability in Central America

Amador et al. (2006) presented a review of the main controls that affect climate in Central America. For brief alternative descriptions see also Hidalgo and Alfaro (2014), Hidalgo et al. (2015) and the following Section. The most dominant synoptic influence in Central America is the subtropical high of the north Atlantic (Taylor and Alfaro 2005). The main large-scale processes that affect climate in the region at inter-annual time scales are El Niño-Southern Oscillation (ENSO), Caribbean and Atlantic climatic processes such as the Caribbean Low-Level Jet (CLLJ; Amador 1998; 2008) or Tropical North Atlantic (TNA; Enfield et al. 1999) climatic variations, the location of the Inter-tropical Convergence Zone (ITCZ), and other features such as the Mid-Summer Drought (MSD; Magaña et al. 1999, Alfaro 2014). There are many studies on climate variability in the region, but only Hidalgo et al. (2015) was done using high-resolution data for Central America. Also, the vast majority of the studies are focused on P, and few use Tavg data. For example Alfaro (2014) studied various characteristics of the MSD using P from a set of stations. Results showed that warmer (cooler) conditions in ENSO indexes tend to be associated to drier (wetter) MSD events. Hidalgo et al. (2015) studied the relationships between the latitudinal center of ITCZ, CLLJ and precipitation in Central America. A dynamical mechanism connecting Caribbean and Pacific climate was proposed in Hidalgo et al. (2015) study.

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Appendix C. Location of stations and gridded original data

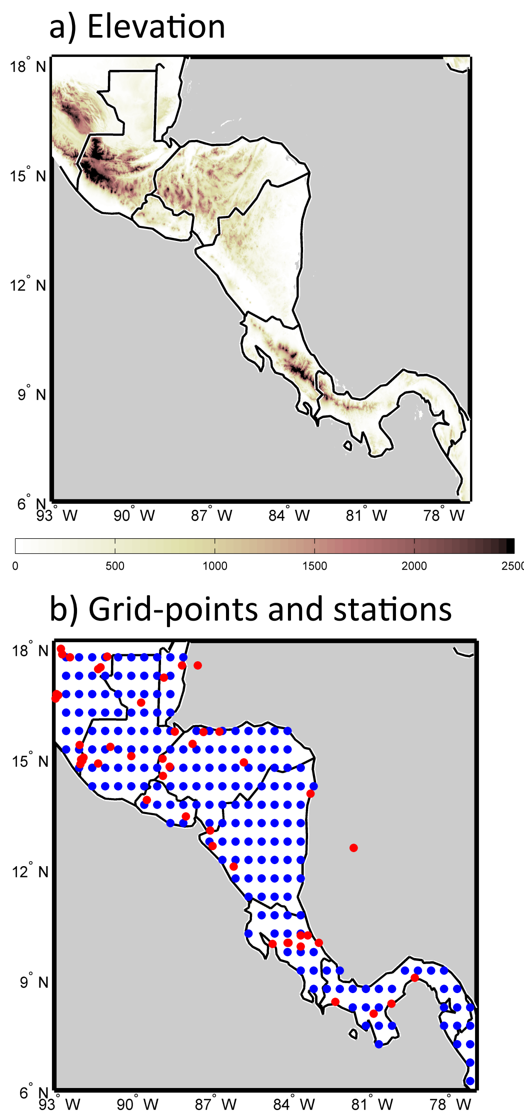

Fig. S1 Terrain elevation (m.a.s.l.) of Central America (top) and locations of gridded (blue dots) and station (red dots) data used to generate a higher-resolution monthly temperature data (bottom).

Appendix D. Profiles of temperature during inversions.

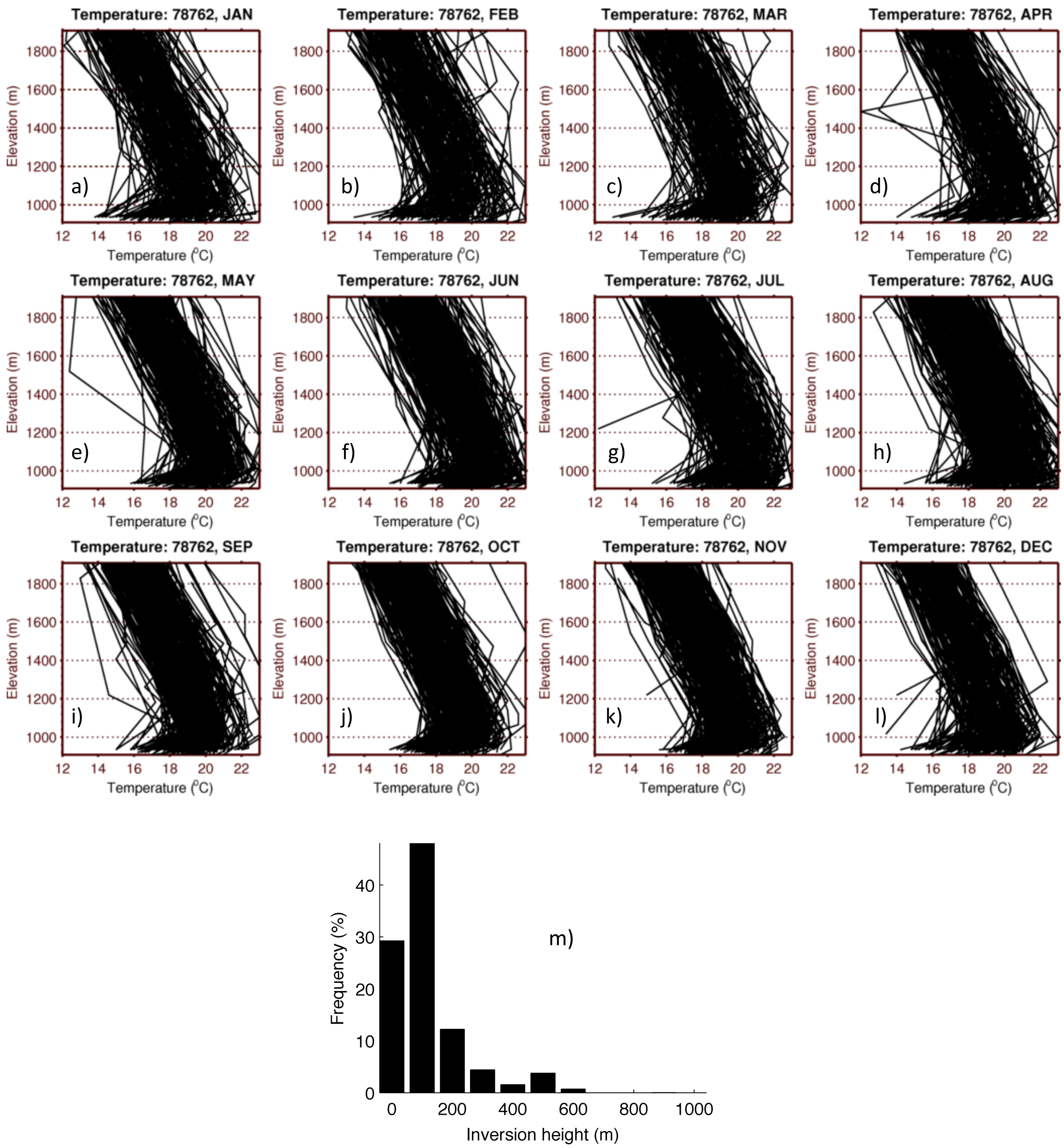

Fig. S2 Temperature profiles of the bottom 1000 meters of the atmosphere at Juan Santamaria Airport (#78762) in Costa Rica (sub-figures a to l). Only those days when inversions occurred in the bottom 1000 meters are shown. The bottom sub-figure (sub-figure m) shows a histogram of the distribution of the inversion height. Inversions occurred in 40% of the records and are evenly distributed across the months. The median inversion height is 118 meters, and the median inversion depth is 1.2 ^{o}C. Data for 1973-2013 period.

Appendix E. Division of Central America into free-atmosphere and boundary-layer regions.

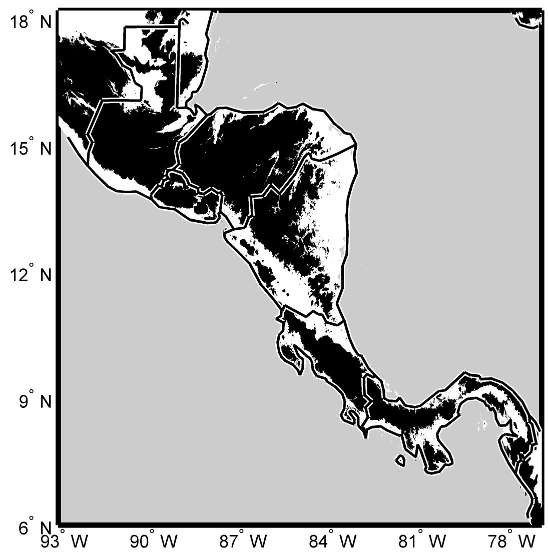

Fig. S3 Regions classified as "boundary-layer" (white) and "free-atmosphere" (black) for the effect of calculating the vertical layer weight (W(l)) in the gridding method employed here.

Appendix F. Prediction of the sign of P and Tavg anomalies based on the contrast or agreement of Sea Surface Temperature anomalies in the Pacific and Caribbean.

In Figure S4, the time-series of the annual anomalies of P and Tavg computed by averaging the grid-points over the regions with significant correlations according to figures 2e and 2f, are shown. In the case of P, those years when the standardized Niño3.4 and TNA indexes presented different sign were highlighted with a '+' or '*' symbol according to the sign of the difference between the indexes. For Tavg, those years when the indexes have the same sign are highlighted with the same symbols, but this time according to the sign of their summation. As can be seen, for 29 out of 30 years (the exception is 1993), knowing whether the Niño3.4 is in-phase or out-of-phase with the TNA and the sign of the difference (in the case of contrasting oceanic conditions) or the summation (in the case of same-phase oceanic conditions), served as an indication of the phase of P or Tavg respectively. For example, if a particular year has a warmer than normal Tropical Pacific (indexed by Niño3.4) and a colder than normal Tropical Atlantic (or vice-versa), we are in a situation where the contrasting oceanic conditions are a good indicator of the sign of the P anomaly for that year. The sign of the difference between the standardized Niño3.4 minus TNA index determines the sign of the P anomaly. Conversely, if a particular year the sign of the SSTa in the Tropical Pacific is of the same as the sign as the anomaly in the TNA region, we are in a situation when we have valuable information that indicates the sign of the Tavg anomaly for that year. In summary, in some years we can have an almost perfect indication of the sign of P and in the other years the sign of Tavg. The amplitudes of P and Tavg are also widely correlated to the difference or summation index, as shown in figures 2e and 2f. The use of the information of the contrast between Pacific and Caribbean SSTa to predict seasonal precipitation has been studied before (e.g. Alfaro 2007b; Maldonado and Alfaro 2010; 2011; Fallas-López and Alfaro 2012a;b; Maldonado et al. 2013), but there are almost no studies linking temperature with this contrast (Alfaro 2000; Alfaro 2007a;. Fallas-López and Alfaro 2014), Future work will study the seasonal predictability of Tavg and derived variables such as evapotranspiration.

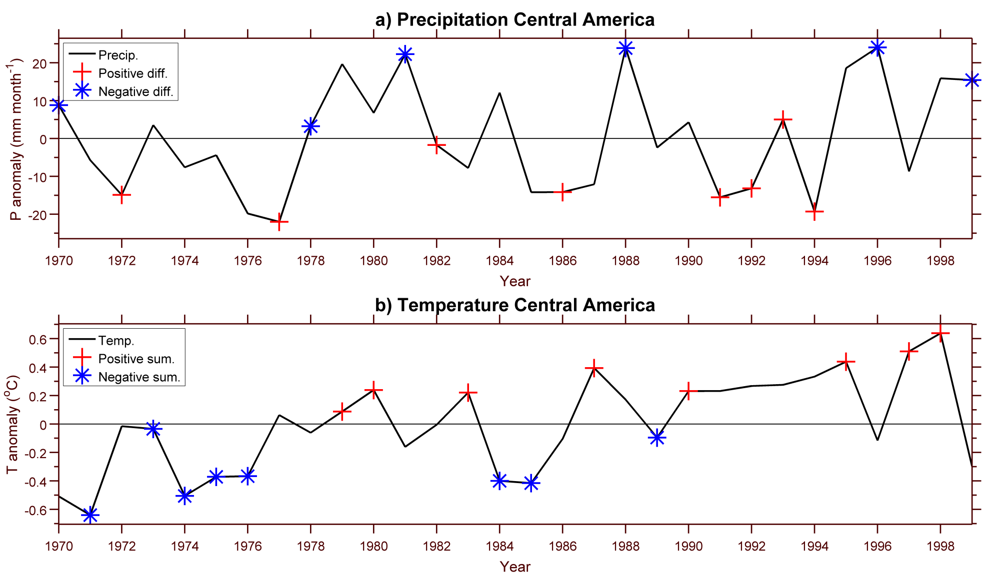

Fig. S4 Time-series of annual precipitation (top) and temperature (bottom) anomalies averaged over the regions that showed significant correlations in Figure 2e and 2f. The '+' and '*' symbols denote whether the difference (top) or the summation (bottom) of the standardized anomalies between Niño3.4 and TNA are positive or negative. Notice that in the top figure the symbols are shown only for those years where the two indexes are out of phase, while in the bottom figure the symbols are shown only for those years that are in phase.

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Appendix G. Rotated Empirical Orthogonal Function (REOF) Analyses.

In order to decompose the variability of the P and Tavg data into eigen-modes, we performed a REOF analysis or Rotated Principal Component Analysis. The type of rotation selected was Varimax, the most common method. Rotation produces more distinction the REOFs and therefore helps in the interpretation of the results (Haan 1977). The REOF analysis produces temporal vectors of Z-scores that are uncorrelated to each other. There are as many Z-scores time series as grid-points of data, but usually a majority of the variance is accumulated in the first few REOFs; and therefore only those few REOFs are interpreted (the unused REOFs represent noise or local effects that contribute very little to the variance). In this way, REOF analysis can be used for data reduction. The Z-scores are correlated back to the original data to obtain "loading" patterns that indicate the locations where there are more or less influence of the scores.

In Figure S5 the Z-scores for the first three REOFs of P and Tavg are presented. The percentage variances captured by those REOFs are indicated in Table S3. In Table S4, the correlation between the Z-scores and several atmospheric and oceanic indexes are shown. The loading patterns are included in Figure S6. The decision on how many components to retain was performed based on North et al. (1982) (not shown). Results indicated that the first three precipitation REOFs are statistically separated to the rest, but they are not independent to each other (and therefore interpretation is still difficult) (not shown). For temperature, the first two REOFs are mixed but they are independent to the rest (not shown).

The loading pattern of P-REOF1 is interesting, as other studies have shown that certain processes have spatial extensions that approximately match this pattern, such as the coverage of the Central America Dry Corridor (Hidalgo et al. 2015), the projected pattern of dryness at the end of the century over the region (Hidalgo et al. 2013), and the correlation between the latitudinal center of mass of the Inter-tropical Convergence Zone and P in Central America during the summer (Hidalgo et al. 2015). In addition, the correlations of Table S4, suggest that the Z-scores of P-REOF1 are strongly correlated with the CLLJ, meaning that the pattern reflects the influence of the trade winds on P in the region, it is also significantly correlated with AMO. This is important, as these results suggest an explanation on why there seems to be different P regime and climatic controls above 10^{o}N approximately. The loading pattern P-REOF2 does not seem to have such strong correlations with the indexes, but is significantly correlated with Niño3.4, the PDO and the summation index (Niño3.4+TNA). P-REOF3 is even more difficult to interpret, as the results suggest some significant correlation with Niño3.4, but it also show the influence of trends.

Tavg-REOF1 is correlated strongly with the summation index (Niño3.4+TNA) and the original indexes (Niño3.4, AMO and TNA). It shows a positive trend. Tavg-REOF2 is essentially the influence of ENSO, but is also mixed with Caribbean processes such as the CLLJ. Tavg-REOF3 is significantly correlated with the PDO, and it is interesting to note the step in the Z-score around 1980. The PDO also presented a climate shift in 1976/77 (Ebbesmeyer et al. 1991, Mantua et al. 1997), with impacts in many environmental variables across the Pacific Basin (see Table 1 of Hidalgo and Dracup 2003). It seems unlikely that the effects of the 1976/77 shift in the PDO could have such lagged effect on Central America's temperature of several years, but since both time-series present shifts with a difference of just three years, the statistical correlation is amplified.

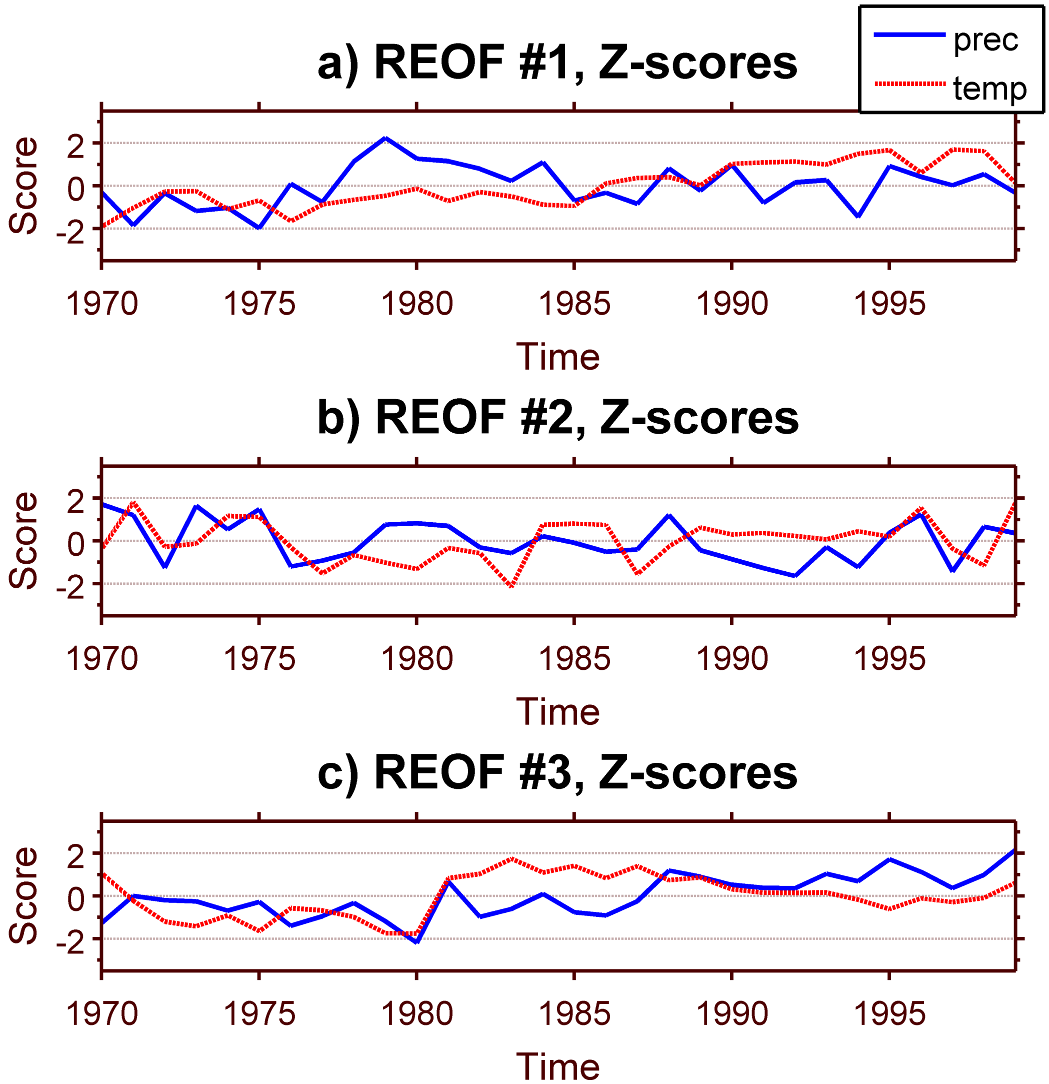

Fig. S5 Time-series of scores of rotated Empirical Orthogonal Functions (REOFs) of annual precipitation and temperature over Central America. The scores for precipitation and temperature are plotted here in the same sub-figures, but there is not necessarily a relationship between the precipitation and temperature REOFs.

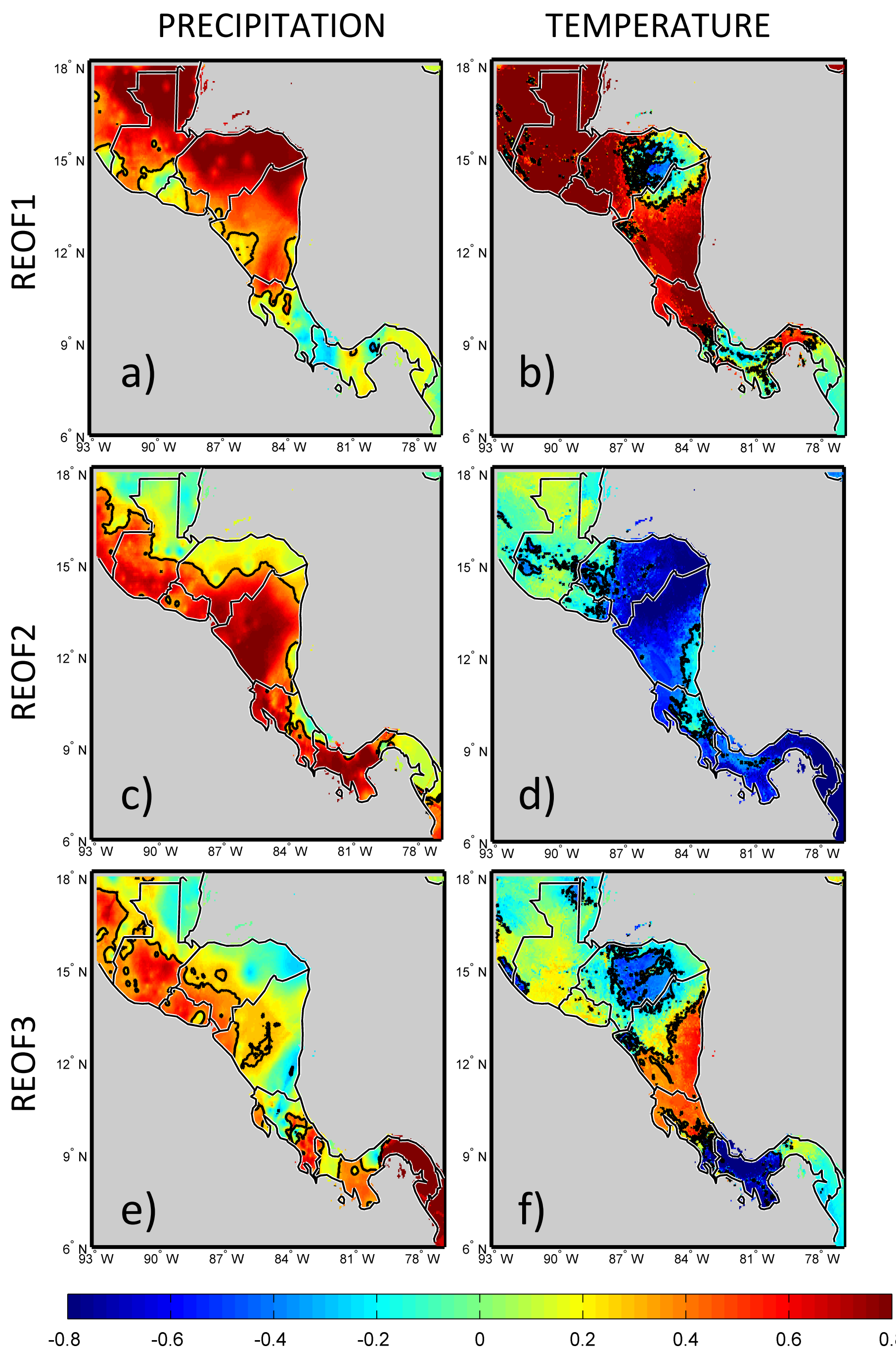

Fig. S6 Loading patterns expressed as correlation between the scores in Figure S5 and the original precipitation and temperature data for the three first REOF modes of precipitation (left) and temperature (right).

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Appendix H. Canonical pairs of P and Tavg.

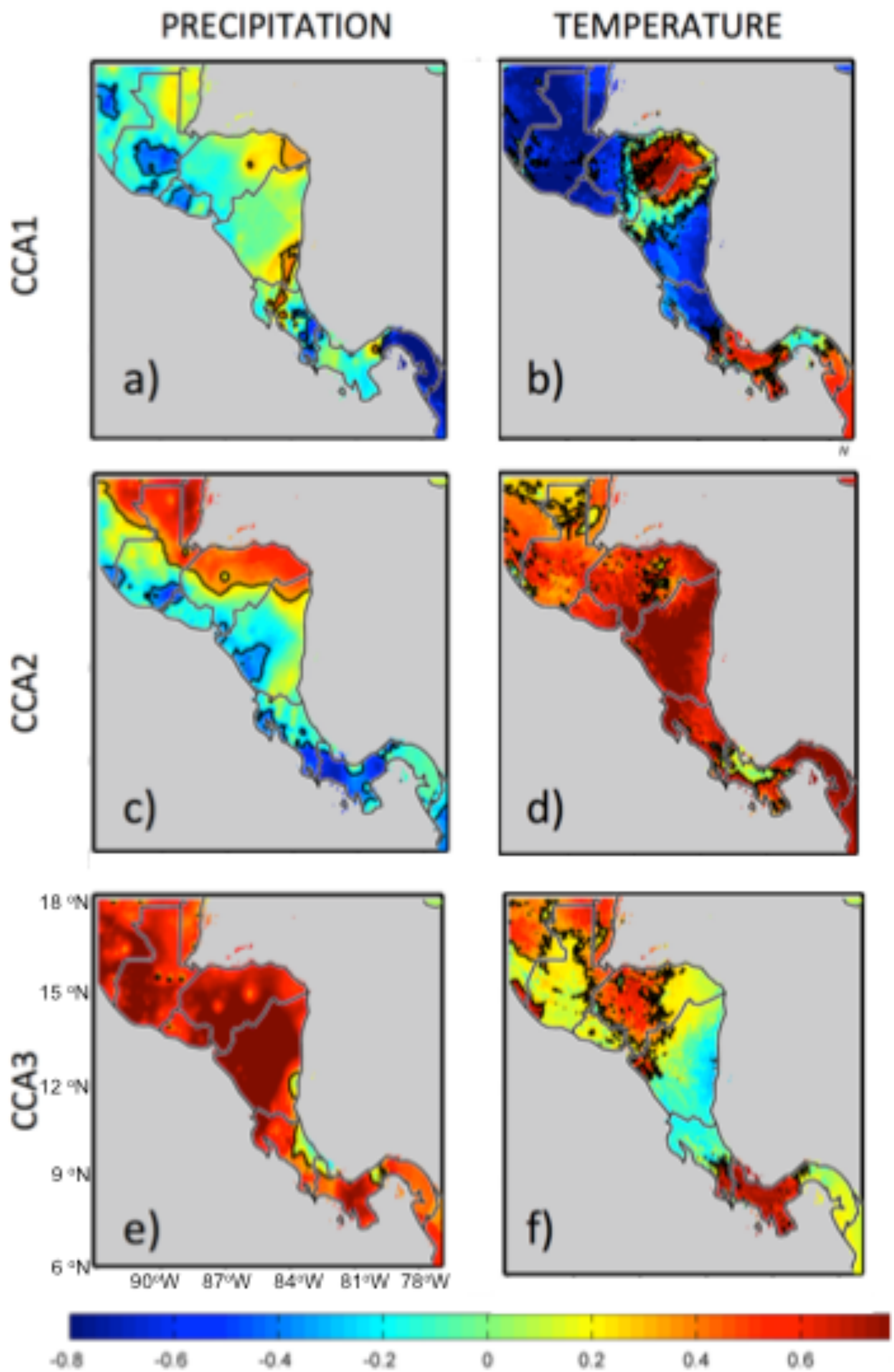

Fig. S7 Loading patterns expressed as correlation between the scores and the original precipitation and temperature data for the three first Canonical Correlation modes between precipitation and temperature.

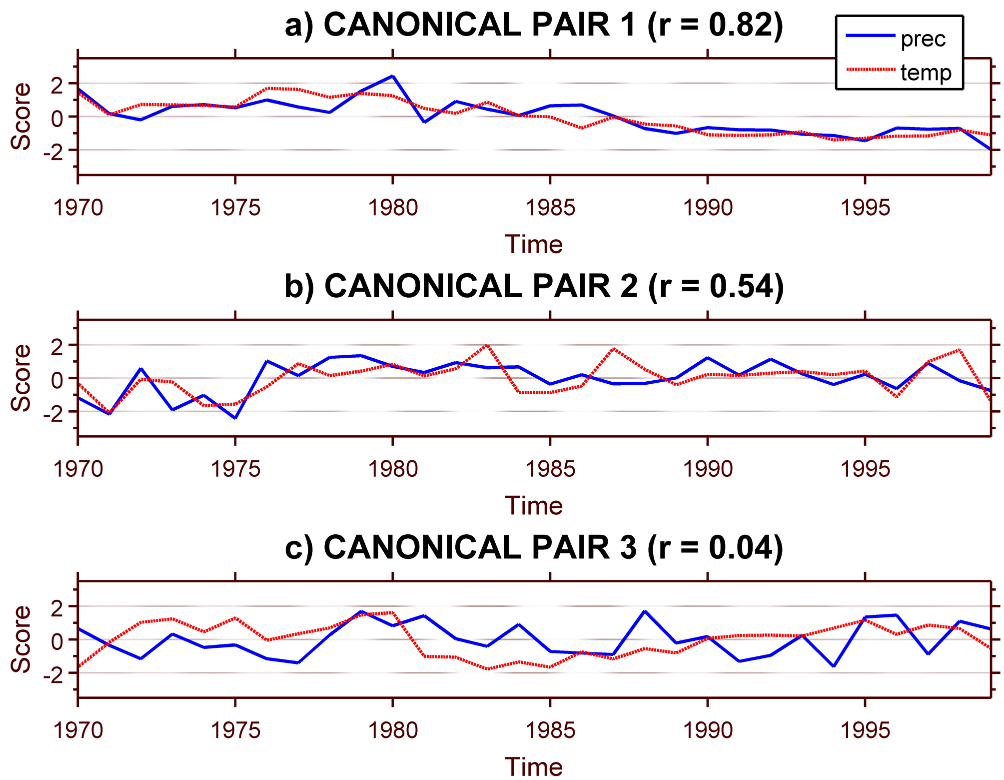

Fig. S8 Time-series of scores of canonical pairs of annual precipitation and temperature over Central America. Contrary to the REOFs' scores of Figure S5, the precipitation and temperature scores for the Canonical Pairs are desired to be as inter-correlated as possible.

Appendix I. Tables

Table S1. Parameters used in gridding method to produce Tavg dataset. Full description of these parameters can be found in Daly et al. (2002).

Parameter name	Description	Value
r	Radius of influence (km^2)	50
s_f	Minimum number of on-facets stations desired on regression	3
s_t	Minimum number of total stations desired on regression	10
β_{1m}	Minimum valid regression slope ($^oC\ km^{-1}$)	Layer 1: -10 Layer 2: -10
β_{1x}	Maximum valid regression slope ($^oC\ km^{-1}$)	Layer 1: 10 Layer 2: 0
β_{1d}	Default valid regression slope ($^oC\ km^{-1}$)	Layer 1: -6 Layer 2: -6
a	Distance weighting exponent	2.0
F_d	Importance factor for distance weighting	0.8
b	Elevation weighting exponent	1.0
F_z	Importance factor for elevation weighting	0.2
Δz_m	Minimum station-grid cell elevation difference (m)	200
Δz_x	Maximum station-grid cell elevation difference above which elevation weight is zero (m)	1500
c	Facet weighting exponent	1.5
g_m	Minimum inter-cell elevation gradient, below which a cell is flat (m/cell)	1
λ_x	Maximum DEM filtering wavelength for topographic facet determination (km)	80
p_x	Maximum coastal proximity difference, above which proximity weight is zero	3
v	Coastal proximity weighting exponent	1.0
y	Vertical layer weighting exponent	1.0

Table S2. Year-to-year inter-correlation between oceanic and atmospheric indexes (1970-1999). Significant correlations at the p=0.05 level are underlined. (See definitions of the indexes in the main text).

INDEX	PDO	TNA	CLLJ	AMO	Niño3.4-TNA	Niño3.4+TNA
Niño3.4	<u>0.51</u>	0.25	<u>-0.41</u>	0.16	<u>0.61</u>	<u>0.79</u>
PDO		<u>0.35</u>	0.06	0.29	0.13	<u>0.55</u>
TNA			<u>0.50</u>	<u>0.87</u>	<u>-0.61</u>	<u>0.79</u>
CLLJ				<u>0.52</u>	<u>-0.74</u>	0.06
AMO					<u>-0.58</u>	<u>0.65</u>
Niño3.4 -TNA						0.00

Table S3. Percentage of the variance explained for the first three modes of rotated Empirical Orthogonal Functions of precipitation and temperature.

Mode #	Precipitation (%)	Temperature (%)
1	25.19	41.22
2	22.62	31.49
3	19.05	10.17
Total	66.86	82.87

Table S4. Correlation of REOF scores of precipitation and temperature with atmospheric and oceanic indexes. Significant correlations at the p=0.05 level are underlined. (See definitions of the indexes in the main text).

INDEX	PRECIPITATION			TEMPERATURE		
	REOF1	REOF2	REOF3	REOF1	REOF2	REOF3
Niño3.4	0.40	0.41	-0.41	0.69	1.00	0.12
PDO	-0.06	0.43	-0.30	0.53	0.51	0.44
TNA	-0.57	0.21	-0.11	0.55	0.25	0.11
CLLJ	-0.84	-0.08	0.05	0.05	-0.41	-0.01
AMO	-0.55	-0.03	-0.31	0.66	0.16	0.13
Niño3.4-TNA	0.80	0.16	-0.25	0.11	0.61	0.01
Niño3.4+TNA	-0.11	0.39	-0.33	0.79	0.79	0.14

Table S5. General Circulation Models used in this study.

#	MODEL	MODELING CENTER OR GROUP	RUNS
1	ccsm4	Canadian Centre for Climate Modelling and Analysis (CCCMA)	3
2	cesm1_cam5	Centro Euro-Mediterraneo per I Cambiamenti Climatici (CMCC)	3
3	cmcc_cms	CMCC	1
4	ec_earth	EC-EARTH consortium	1
5	giss_e2_r	Geophysical Fluid Dynamics Laboratory (GFDL)	1
6	miroc5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology. (MIROC)	2
7	mpi_esm_lr	Max Planck Institute for Meteorology (MPI-M)	3

References

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Appendix J. Description of statistical downscaling procedure.

Bias correction:

The bias correction procedure is based on monthly average temperature data from the National Center of Environmental Prediction and the National Center of Atmospheric Research (NCEP/NCAR) Reanalysis (Kalnay et al. 1996). The dataset was provided by the National Oceanographic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, Earth System Research Laboratory, Physical Sciences Division (NOAA/OAR/ESRL PSD) in Boulder, Colorado, USA, and accessed from their website at http://www.esrl.noaa.gov/psd. Monthly precipitation data from 1979 to 1999 were also obtained from the Global Precipitation Climatology Project (GPCP; Adler et al., 2003), version 2.2, provided by NOAA/OAR/ESRL PSD. The GPCP dataset combines satellite and rain-gauge sources at a spatial resolution of 2.5 × 2.5 degrees.

The General Circulation Model (GCM) and the Reanalysis precipitation and temperature data were converted to the resolution of the GPCP for bias correction. The precipitation and temperature data from the models listed in Table S5 (1979 -1999) was first corrected by quantile mapping the model data against the quantiles defined by the GPCP precipitation and Reanalysis temperature data according to the type of variable that was being analyzed.

Downscaling

Each month of the projected data (2000-2049) was analyzed to find the closest value within the baseline (1979-1999) pool of data without bias correction. A multiplicative factor for precipitation and an additive factor for temperature between the projected and historical data were calculated for each projected value using the data without bias correction. The factor was applied to each bias corrected estimate (of the historical value) to produce each bias-corrected projected estimate at the coarse resolution.

The anomalies of the bias corrected precipitation and temperature data at coarse resolution were obtained. These anomalies were interpolated to the high-resolution grid of the datasets of this study. The seasonal cycles for the high-resolution data were added to the downscale estimates to produce the high-resolution estimates (1979-2049).

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