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The relationships between Pacific and Atlantic Ocean sea surface temperatures and Colombian streamflow variability

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Summary An evaluation of Pacific and Atlantic Ocean sea surface temperatures (SSTs) and Colombian streamflow was performed to identify coupled regions of SST and Colombian streamflow variability. Applying the Singular Value Decomposition (SVD) statistical method, SSTs (and Colombian streamflow for 10 stations) were evaluated for (a) the Pacific Ocean, (b) the Atlantic Ocean, and (c) the combined Pacific and Atlantic Ocean for a 41 year period of record (1960–2000). A lead-time approach was adopted such that spring–summer seasonal (April through September) SSTs were evaluated with streamflow for the following calendar-year (January through December). The El Niño-Southern Oscillation (ENSO) has been acknowledged in previous research efforts as an influence of Colombian streamflow. The ENSO signal identified that warmer (cooler) equatorial SSTs resulted in lesser (greater) streamflow. In general, the use of predefined published indices, such as ENSO, is appealing for water managers and forecasters. However, the utilization of SSTs for entire regions (Pacific and Atlantic Oceans) eliminates any spatial bias as to which oceanic SST region (or regions) impact hydrology. This will assist in the identification of regions that may not be represented in existing indices and could lead to improved forecasting. The SVD 1st temporal expansion series of Pacific (and the combined Pacific and Atlantic) Ocean SSTs and streamflow for several stations resulted in correlation values greater than that of well known climate indices (e.g., ENSO), which could result in improved streamflow predictability.

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Introduction

Atmospheric–oceanic climatic and sea surface temperature (SST) variability can provide important predictive information about hydrologic variability in regions around the world. Significant research has focused on identifying atmospheric–oceanic climatic phenomena such as the El Niño-Southern Oscillation (ENSO) (Philander, 1990), the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997) and the Atlantic Multidecadal Oscillation (AMO) (Enfield et al., 2001) while further research has identified what influence these phenomena have on hydrology (e.g., Cayan and Peterson, 1989; Cayan and Webb, 1992; Kahya and Dracup, 1993, 1994a,b; Enfield et al., 2001; Rogers and Coleman, 2003; Maurer et al., 2004; McCabe et al., 2004). Although each of these oceanic/atmospheric phenomena represents SST variability, the SST variability represented is for a specific, spatially pre-determined region. In general, the use of pre-defined published indices is appealing for water managers and forecasters. However, the utilization of SSTs for entire regions (Pacific and Atlantic Oceans) eliminates any spatial bias as to which oceanic SST region (or regions) impact hydrology. This will assist in the identification of regions that may not be represented in existing indices and could lead to improved forecasting.

Various methods, such as canonical correlation analysis, combined principal component analysis and singular value decomposition (SVD) are available to determine relationships between two, spatial–temporal fields such as SSTs and streamflow. Bretherton et al. (1992) evaluated several statistical methods and concluded SVD was simple to perform and preferable for general use while Wallace et al. (1992) determined that SVD isolates the most important modes of variability.

SVD has also been used to identify relationships between oceanic SST variability and hydrologic variability. Uvo et al. (1998) applied SVD to evaluate Pacific and Atlantic Ocean SSTs (independently) and northeast Brazilian precipitation utilizing both a simultaneous and lagged approach. Wang and Ting (2000) evaluated Pacific Ocean SSTs and continental US precipitation for concurrent (overlapping) time periods and identified simultaneous patterns of SST influence on precipitation. Enfield and Alfaro (2000) and Giannini et al. (2000) also used SVD to analyze SSTs and rainfall variability. Rajagopalan et al. (2000) utilized SVD and applied a lag approach to evaluate global SST impacts on continental US drought (PDSI). Rodriguez-Fonseca and de Castro (2002) utilized a lag approach when applying SVD to evaluate Atlantic Ocean SSTs and Iberian/Northwest African precipitation. Shabbar and Skinner (2004) applied SVD and utilized a lag approach in which winter global SSTs and summer Canadian drought (e.g., Palmer Drought Severity Index (PDSI) values] were evaluated and determined each mode representing a distinct oceanic/atmospheric phenomena (e.g., 1st mode – AMO, 2nd mode – ENSO, 3rd mode – PDO). Tootle and Piechota (2006) evaluated Pacific and Atlantic Ocean SSTs which resulted in the identification of several SST regions associated with streamflow regions in the continental United States.

Colombia's mountainous terrain and large network of rivers has led to the development of a large hydroelectric power network. As of December 2004, 64% of the total energy was generated in hydroelectrical plants, 28% in gas fueled thermoelectrical plants, 5% in coal fueled thermoelectrical plants and the rest, 3% other (not specified) (source: Unidad de Planeacisn Minero Energitica (UPME)]. There are 26 ''large'' reservoirs in Colombia that have volumes greater than 25 hectometers[3].

While ENSO and Colombian hydrology have been examined (Poveda et al., 2001; Gutiérrez and Dracup, 2001), the current research improves on previous studies by identifying regions of Pacific (and Atlantic Ocean SST) and Colombian hydrologic variability, specifically for streamflow. The use of streamflow as the hydrologic variable is important since streamflow acts as an integrator of the various components of the hydrologic cycle (e.g., precipitation, infiltration, evapotranspiration) and is vital for the economy (i.e., hydroelectric power) of Colombia. By utilizing a lead-time approach, the research will provide predictive information about Colombian streamflow which may be utilized in long-range forecasts.

Data

SVD datasets

The major datasets used to develop the relationships between Colombian streamflow and oceanic SST variability were streamflow data for Colombia and oceanic SST data for the Pacific and Atlantic Oceans.

Streamflow stations with records of at least 40 years were selected. The selected stations are located in several Colombian Rivers (Magdalena, Cauca, San Juan de Micay and Sogamoso) were provided by the Instituto de Hidrología, Meteorología y Estudios Ambientales, IDEAM. This resulted in 10 stations having calendar-year flowrate data (kmP[3P]) for the period of 1960–2000 (Fig. 1).

SST data for the Pacific and Atlantic Oceans were obtained from the National Climatic Data Center (http://www.cdc.noaa.gov/cdc/data.noaa.ersst.html). The oceanic SST data consists of average monthly values for a 2° by 2° grid cell (Smith and Reynolds, 2002). The extended reconstructed global SSTs were based on the Comprehensive Ocean–Atmosphere Data Set (COADS) from 1854 to present (Smith and Reynolds, 2002).

The region of Pacific Ocean SST data used for the analysis was longitude 120°E to longitude 60°W and latitude 60°S to latitude 20°N while the region of Atlantic Ocean SST data used for the analysis was longitude 50°W to longitude 10°E and latitude 20°N to latitude 60°S. The region for the combined Pacific and Atlantic Ocean SST data was longitude 120°E to longitude 10°E and latitude 60°S to latitude 20°N. The selection of the regions expands upon the work of Uvo et al. (1998) who only utilized Pacific Ocean SSTs ranging from 24.75°N to 24.75°S for evaluating the influence on Brazilian precipitation. When correlating the PDO index (see 'Climatic indices' section) with the 10 previously defined streamflow stations, the correlation values resulted in no stations exceeding 90% significance with the PDO index. Similarly, when correlating the AMO index (see 'Climatic indices' section) only two of the 10 stations exceeding 90% significance. The correlation of the Niño 3.4 index (see

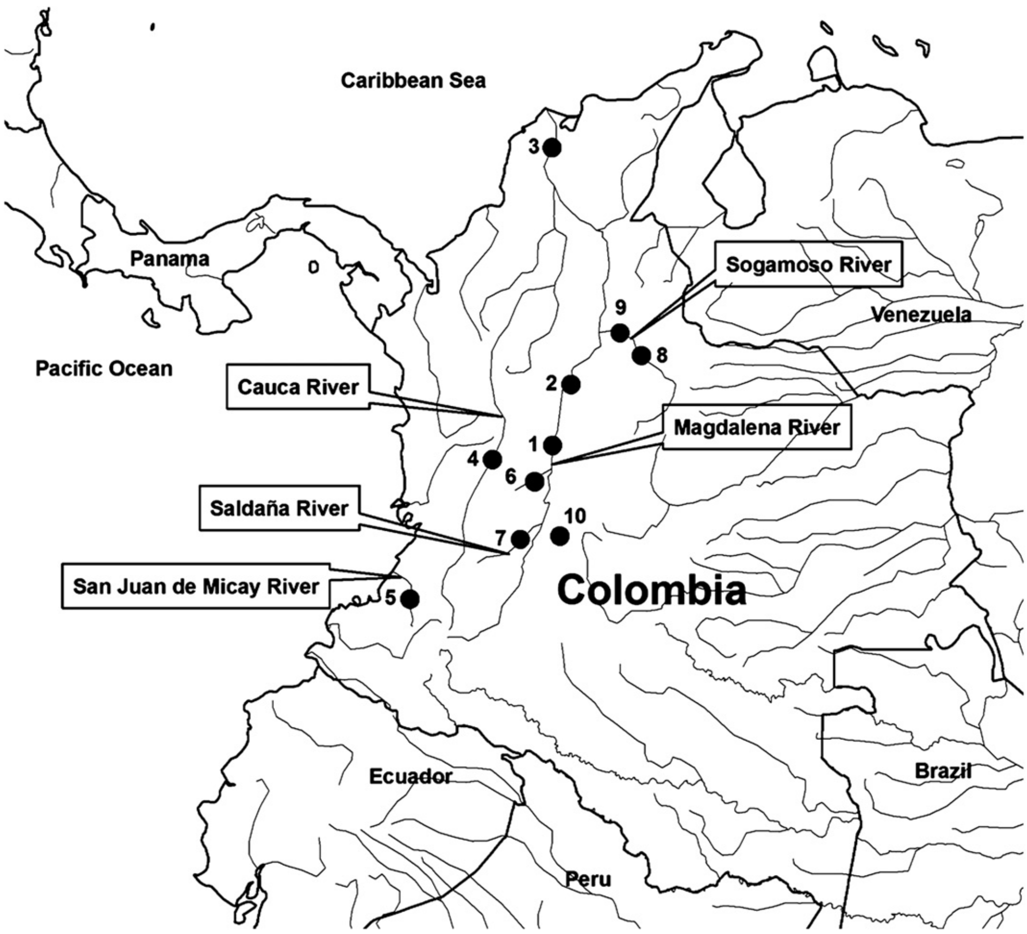

Figure 1 Locations of unimpaired Colombian streamflow stations.

'Climatic indices' section) resulted in six of the 10 stations exceeding 90% significance. The selection of these regions encompasses the major portions of the tropical Pacific and Atlantic oceans which influence the climate of Columbia. The North Pacific and Atlantic (poleward of 20°N) was not included since these regions primarily influence the climate of the northern hemisphere. Isolating the SSTs in the Southern Hemisphere would help with isolating modes of SST variability that most influence Columbia streamflow.

The average monthly SSTs were averaged for the spring–summer season (April to September) covering a period from 1959 to 1999 (41 years). This results in a 3-month lag between the end of the SST season and the beginning of the streamflow year (i.e., lead-time). This is just one of many analyses that could be done to investigate the many lag correlations between SSTs and streamflow. The focus in this study was to make an initial investigation of how Pacific and Atlantic SST influence streamflow in Columbia.

For both the Pacific, Atlantic and Pacific/Atlantic Ocean SSTs and Colombia streamflow data sets, anomalies were calculated in which the anomaly was defined as the deviation of the seasonal (or calendar-year) mean from the long-term average. The anomalies were then standardized by the standard deviation, and the standardized anomalies for both data sets were used in the following analysis.

The authors acknowledge the short time period (41 years) used in this research. While a longer time period would be more appropriate, this is not possible with instrumental records. Similar to Uvo et al. (1998), the authors separated the data into a 20-year (1959–1978) and 21-year (1979–1999) period of record and the results of the SVD analysis were similar to the results reported in the current research. The separation of the analysis into two time periods tests the temporal stability of the relationships between SSTs and streamflow.

Climatic indices

The major datasets representing oceanic–atmospheric climatic phenomena are the Niño 3.4 index, the PDO index and the AMO index.

The Niño 3.4 (Trenberth, 1997) SST region is located along the equatorial Pacific Ocean (5°S–5°N, 170°–120°W) and monthly index data were obtained from the National Weather Service (NWS) Climate Prediction Center (CPC) (http://www.cpc.ncep.noaa.gov/data/indices/). The Niño 3.4 index was used since it is an overall representation of ENSO. More specific regions (e.g., Niño1+2, Niño 3, Niño 4,) provide more specific locations of SST variability and may not capture the overall ENSO cycle. The PDO is a oceanic/atmospheric phenomena associated with persistent, bimodal climate patterns in the northern Pacific Ocean (poleward of 20°N) that oscillate with a characteristic period on the order of 50 years (a particular phase of the PDO will typically persist for about 25 years) (Mantua et al., 1997; Mantua and Hare, 2002). PDO index (Mantua et al., 1997; Hare and Mantua, 2000) values were obtained from the Joint Institute for the Study of the Atmosphere and Ocean, University of Washington (http://tao.atmos.washington.edu/pdo/). The Atlantic Multidecadal Oscillation (AMO) index was introduced by Enfield et al. (2001) as a simple basin average of north Atlantic Ocean (0°–70°) Sea Surface Temperatures (SSTs). The AMO displays a low-frequency periodicity of 65–80 years. The AMO index consists of detrended SST anomalies for the previously defined Atlantic Ocean region. AMO index values are available from the National Oceanic and Atmospheric Administration (NOAA) Climate Diagnostics Center (CDC) (http://www.cdc.noaa.gov/ClimateIndices/).

The average monthly values for the climatic indices (ENSO, PDO and AMO) were averaged for the spring-summer season (April through September) covering a period from 1959 to 1999 (41 years).

Methods

Singular value decomposition (SVD)

SVD is a powerful statistical tool for identifying coupled relationships between two, spatial–temporal fields. While Bretherton et al. (1992) provides a detailed discussion of the theory of SVD, a brief description of SVD, as applied in the current research, is hereby provided.

Initially, a matrix of standardized SST anomalies and a matrix of standardized streamflow anomalies were developed. The time dimension of each matrix (i.e., 41 years) must be equal while the spatial component [i.e., number of Pacific, Atlantic, Pacific/Atlantic Ocean SST cells or Colombian streamflow stations] can vary in dimension. The cross-covariance matrix was then computed for the two spatial, temporal matrices and SVD was applied to the cross-covariance matrix and physical information of the relationship between the two fields can be obtained. The resulting SVD of the cross-covariance matrix created two matrices of singular vectors and one matrix of singular values. The singular values were ordered such that the first singular value (1st mode) was greater than the second singular value and so on. Bretherton et al. (1992) defines the squared covariance fraction (SCF) as a useful measurement for comparing the relative importance of modes in the decomposition. Each singular value was squared and divided by the sum of all the squared singular values to produce a fraction (or percentage) of squared covariance for each mode.

Finally, the two matrices of singular vectors were examined, generally referred to as the left (i.e., SSTs) matrix and the right (i.e., streamflow) matrix. The first column of the left matrix (1st mode) was projected onto the standardized SST anomalies matrix and the first column of the right matrix (1st mode) was projected onto the standardized streamflow anomalies matrix. This resulted in the 1st temporal expansion series of the left and right fields, respectively. The left heterogeneous correlation figure (for the 1st mode) was determined by correlating the SST values of the left matrix with 1st temporal expansion series of the right field and the right heterogeneous correlation figure (for the 1st mode) was determined by correlating the streamflow values of the right matrix with the 1st temporal expansion series of the left field. The temporal expansion series have a physical meaning since they represent SST variability that may not already be included in existing indices and could represent a new index of SST variability. This may then be useful in forecasting streamflow for stations that have high correlations with the temporal expansion series.

Utilizing an approach similar to Rajagopalan et al. (2000) and Uvo et al. (1998), heterogeneous correlation figures displaying significant (90%) correlation values for SST regions and streamflow regions were reported for the Pacific Ocean, Atlantic Ocean and Pacific/Atlantic Ocean. The selection of a 90% significance level balances the need to identify statistically significant correlations, while also recognizing that the relationships between SSTs and streamflow is subtle and may not stand out if a high level of significance (e.g., 99%) was used. Detrended time series by removing autocorrelation was also utilized and did not significantly impact the regions identified in the heterogeneous correlation figures.

While SVD is a powerful tool for the statistical analysis of two spatial, temporal fields, there exist several caveats (or limitations) to its use that should be investigated (Newman and Sardeshmukh, 1995). Generally, if the leading (1st, 2nd or 3rd) modes explain a significant amount of the variance of the two fields, then SVD can be applied to determine the strength of the coupled variability present (Newman and Sardeshmukh, 1995). However, when using SVD to examine two fields, the examiner must exhibit caution when attempting to explain the physical cause of the results (Newman and Sardeshmukh, 1995).

SST and climatic influences on Colombian streamflow

Upon completion of the SVD analysis, the SVD SST temporal expansion series for the Pacific, Atlantic and Pacific/Atlantic Oceans were correlated with the individual streamflow stations. These results were compared to correlation results of the individual streamflow stations with the PDO, ENSO and AMO indices. The results of the correlation analysis will identify if the SVD SST temporal expansion series provide stronger predictors of streamflow when compared to using the oceanic–atmospheric indices. It should be noted that the field significance was not tested here and this would account for dependence between streamflow stations that are close to each other.

Results

The results of the SVD analysis of Pacific, Atlantic and Pacific/Atlantic Ocean SSTs and Colombian streamflow are presented in 'Pacific Ocean SSTs and Colombian streamflow', 'Atlantic Ocean SSTs and Colombian streamflow' and 'Pacific/Atlantic Ocean SSTs and Colombian streamflow' sections. The potential strength of the SVD SST temporal expansion series as a streamflow predictor is presented in 'SVD SST temporal expansion series as a predictor of Colombian streamflow' section.

Pacific Ocean SSTs and Colombian streamflow

Pacific Ocean SSTs and Colombian streamflow resulted in squared covariance fractions (SCF) of 74% – 1st mode, 10% – 2nd mode and 9% – 3rd mode. The 1st mode of variability (only) was reported, based on the significant squared covariance fraction reported for the 1st mode. The total number of Pacific Ocean SST Cells was 3219. For the 1st mode of variability, 1220 Pacific Ocean SST Cells (38%) were identified as significant.

Fig. 2 represents heterogeneous correlation maps (90% significance or $|r| > 0.26$) displaying significant Pacific Ocean SST and Colombian streamflow stations for the 1st mode of SVD. The Pacific Ocean SST heterogeneous correlation Fig. 2a was determined by correlating the Pacific Ocean SST values with the 1st temporal expansion series of Colombian streamflow while the Colombian streamflow heterogeneous correlation Fig. 2b was determined by correlating the Colombian streamflow values with the 1st temporal expansion series of Pacific Ocean SSTs.

Pacific Ocean SSTs (positive ''+'' sign) were identified in the equatorial Pacific Ocean (i.e., ENSO) and in the south-central Pacific Ocean (Fig. 2a) that correlated with Colombian streamflow. Additionally, a Pacific Ocean SST (negative ''–'' sign) region was identified near the eastern coast of Australia (Fig. 2a) that correlated with Colombian streamflow. Eight (of ten) streamflow stations (Fig. 2b) were identified as being correlated (negative ''–'' sign) with Pacific Ocean SSTs (Stations 1, 2, 3, 4, 8, 9 and 10). Since the streamflow stations (negative ''–'' sign) identified have the opposite sign of the equatorial Pacific Ocean (i.e., ENSO) region (positive ''+'' sign) identified, an El Niño (La Niña) will result in decreased (increased) streamflow.

Atlantic Ocean SSTs and Colombian streamflow

Atlantic Ocean SSTs and Colombian streamflow resulted in squared covariance fractions (SCF) of 44% – 1st mode, 25% – 2nd mode and 15% – 3rd mode. The 1st and 2nd modes of variability were reported, based on the significant squared covariance fraction reported for the 1st and 2nd modes. The total number of Atlantic Ocean SST Cells was 1,372. For the 1st mode of variability, 112 Atlantic Ocean SST Cells (8%) were identified as significant while for the 2nd mode of variability, 85 Atlantic Ocean SST Cells (6%) were identified. The authors acknowledge that these small areas may be spurious and not reflect a worthy relationship between Atlantic Ocean SSTs and Colombian streamflow. Fig. 3 represents heterogeneous correlation maps (90% significance or $|r| > 0.26$) displaying significant Atlantic Ocean SST and Colombian streamflow stations for the 1st and 2nd modes of SVD. The Atlantic Ocean SST heterogeneous correlation Fig. 3a and c were determined by correlating the Atlantic Ocean SST values with the 1st (or 2nd) temporal expansion series of Colombian streamflow while the Colombian streamflow heterogeneous correlation Fig. 3b and d was determined by correlating the Colombian streamflow values with the 1st (or 2nd) temporal expansion series of Atlantic Ocean SSTs.

For the 1st mode of Atlantic Ocean SSTs, there were negative correlations between the 1st mode streamflow coefficients with SSTs in the southwestern Atlantic Ocean and the region offshore of the Amazon River (northern Brazil) (Fig. 3a). Two streamflow stations (Stations 4 and 5) (Fig. 3b) were identified as being negatively correlated with Atlantic Ocean SSTs for similar regions in Fig. 3a. Since the streamflow stations (negative ''–'' sign) identified have the same sign as the Atlantic Ocean SSTs (negative ''–'' sign) identified, increased (decreased) SSTs will result in increased (decreased) streamflow. However, there were only two stations and this does not represent a strong regional relationship between Atlantic SSTs and Columbian streamflow.

For the 2nd mode, Atlantic Ocean SSTs (negative ''–'' sign) were identified in the southwestern Atlantic Ocean

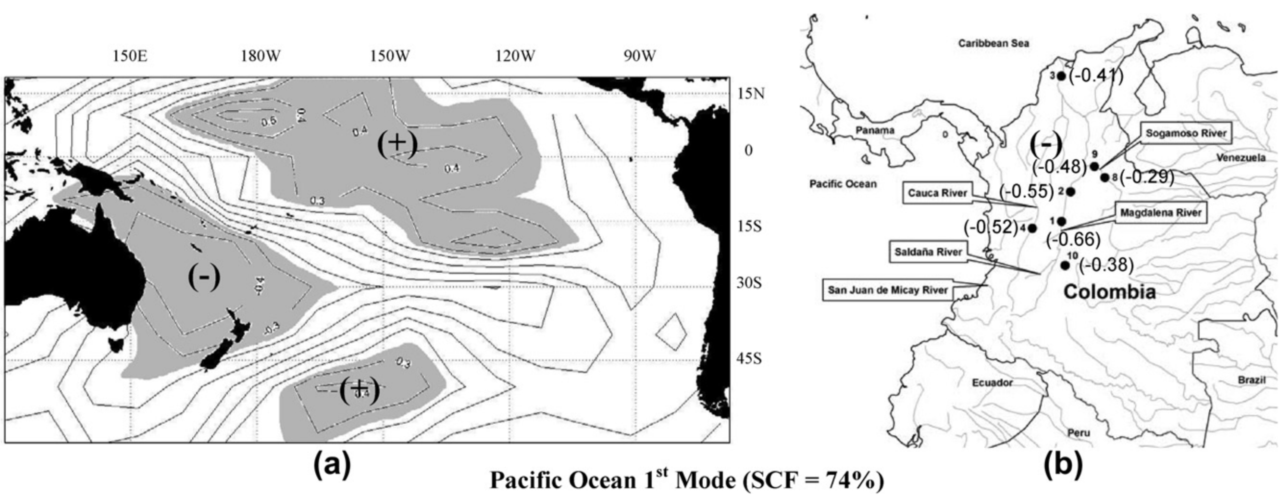

Figure 2 Heterogeneous correlation figures for SVD for previous year spring–summer season Pacific Ocean SSTs and current calendar-year Colombian streamflow (a) Pacific Ocean SSTs (1st mode) and (b) Colombian streamflow stations (1st mode). Significant [>90%] SST regions were indicated with gray shading. Significant [>90%] negative (positive) streamflow stations were represented by black (gray) circles.

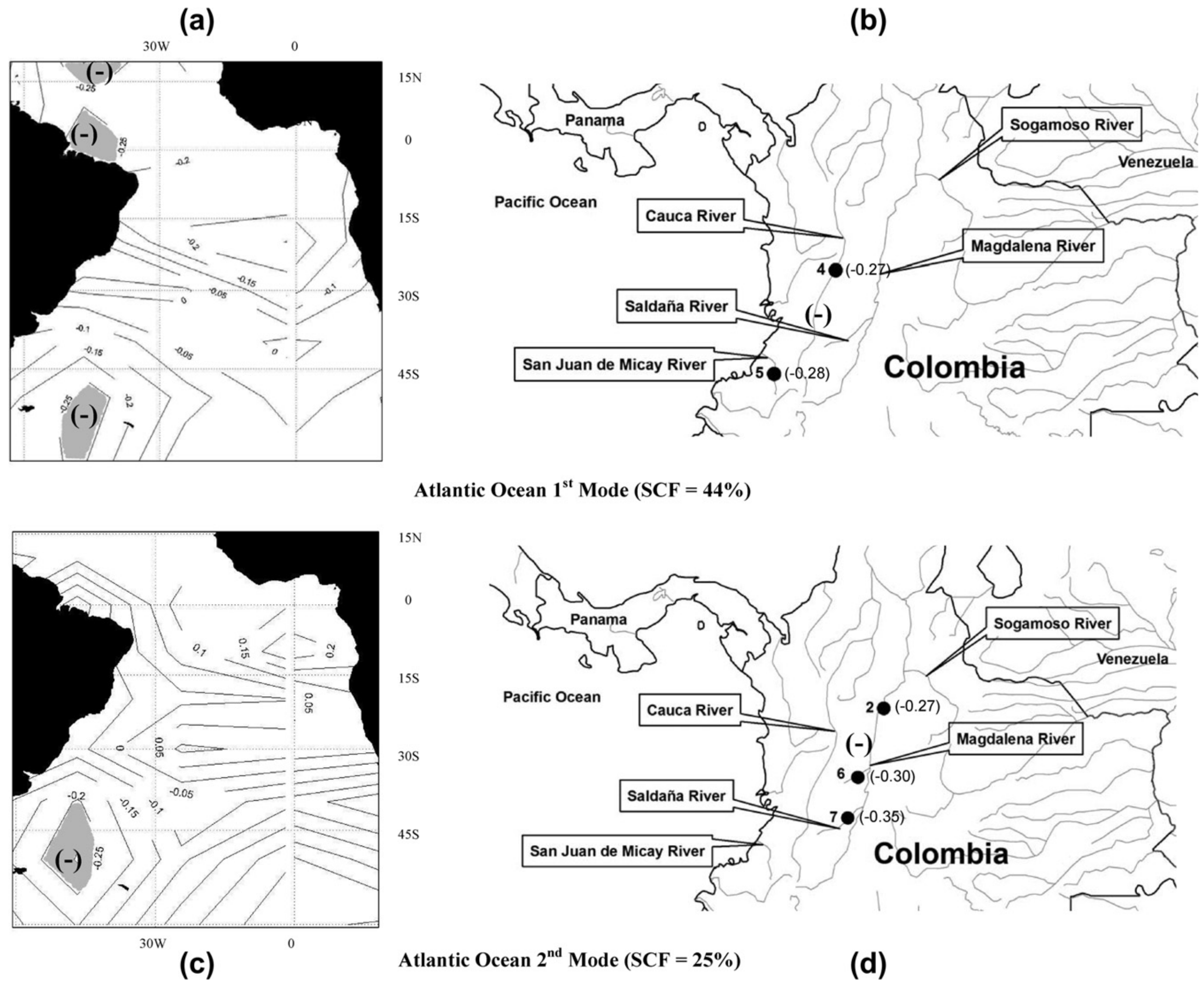

Figure 3 Heterogeneous correlation figures for SVD for previous year spring-summer season Atlantic Ocean SSTs and current calendar-year Colombian streamflow (a) Atlantic Ocean SSTs (1st mode), (b) Colombian streamflow stations (1st mode), (c) Atlantic Ocean SSTs (2nd mode) and (d) Colombian streamflow stations (2nd mode). Significant [>90%] SST regions were indicated with gray shading. Significant [>90%] negative (positive) streamflow stations were represented by black (gray) circles.

(Fig. 3c) that correlated with Colombian streamflow. Three streamflow stations (Stations 2, 6 and 7) (Fig. 3d) were identified as being correlated (negative ''−'' sign) with Atlantic Ocean SSTs. As with the 1st mode, since the streamflow stations (negative ''−'' sign) identified have the same sign as the Atlantic Ocean SSTs (negative ''−'' sign) identified, increased (decreased) SSTs will result in increased (decreased) streamflow. Stations 5, 6 and 7 were identified when using Atlantic Ocean SSTs but were not identified when using Pacific Ocean SSTs. This may result in Atlantic Ocean SSTs being improved predictors of streamflow (for these stations) when compared to Pacific Ocean SSTs, despite the strong ENSO signal present in Colombian streamflow.

Pacific/Atlantic Ocean SSTs and Colombian streamflow

Pacific/Atlantic Ocean SSTs and Colombian streamflow resulted in squared covariance fractions (SCF) of 67% − 1st mode, 13% − 2nd mode and 10% − 3rd mode. The 1st, 2nd and 3rd modes of variability were reported. While the authors acknowledge a decrease in the squared covariance fractions reported for the 1st, 2nd and 3rd modes, each mode resulted in unique streamflow stations being identified and, thus, an interesting result.

The total number of Pacific/Atlantic Ocean SST Cells was 4,591. For the 1st mode of variability, 1191 Pacific/Atlantic Ocean SST Cells (26%) were identified as significant. For the 2nd mode of variability, 1984 Pacific/Atlantic Ocean SST Cells (43%) were identified as significant while for the 3rd mode of variability, 280 Pacific/Atlantic Ocean SST Cells (6%) were identified as significant. Fig. 4 represents heterogeneous correlation maps (90% significance or $|r| > 0.26$) displaying significant Pacific/Atlantic Ocean SST and Colombian streamflow stations for the 1st, 2nd and 3rd modes of SVD. The Pacific/Atlantic Ocean SST heterogeneous correlation Fig. 4a, c and e were determined by correlating the Pacific/Atlantic Ocean SST values with the 1st (or 2nd or 3rd)

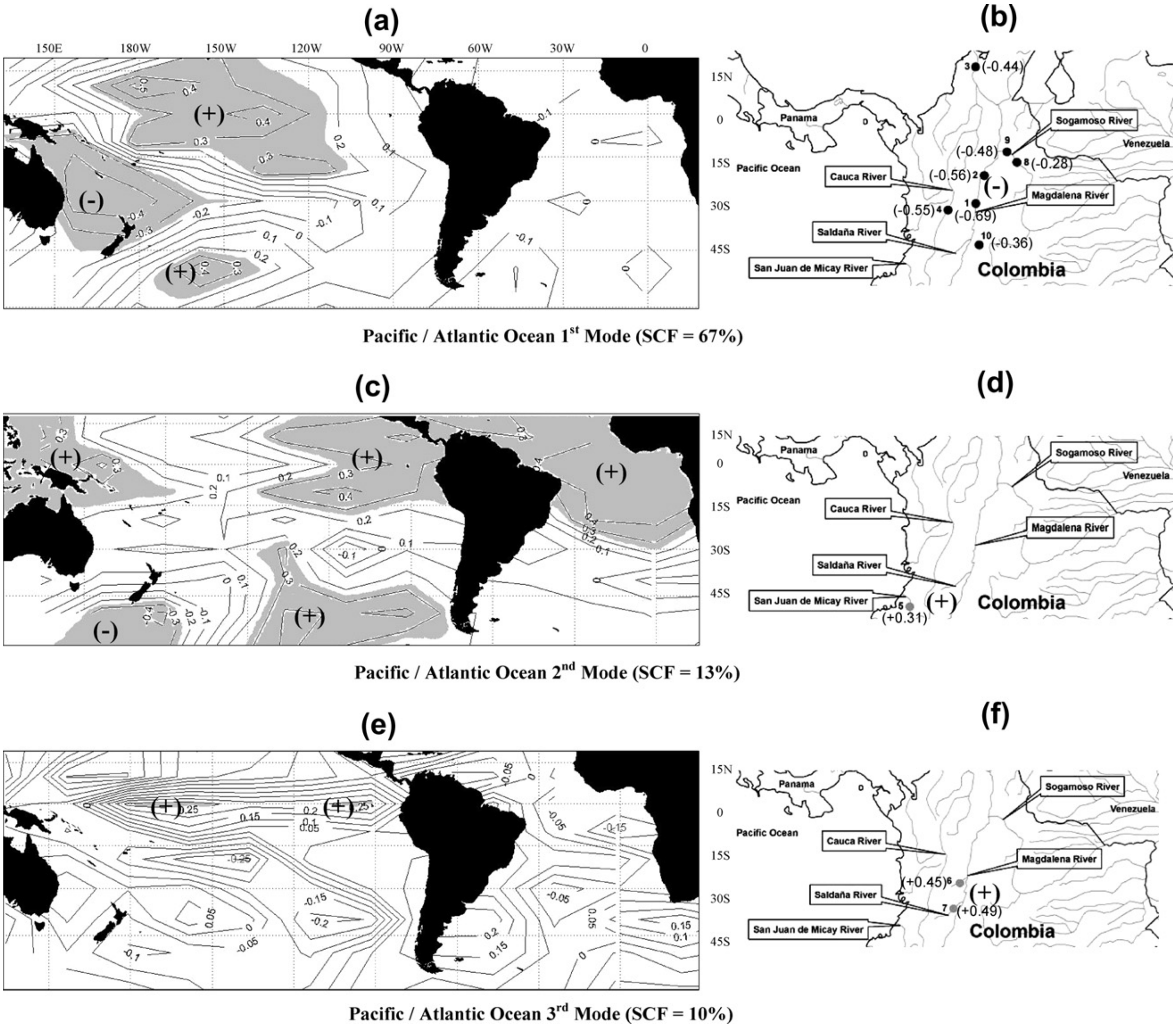

Figure 4 Heterogeneous correlation figures for SVD for previous year spring—summer season Pacific/Atlantic Ocean SSTs and current calendar-year Colombian streamflow (a) Pacific/Atlantic Ocean SSTs (1st mode), (b) Colombian streamflow stations (1st mode), (c) Pacific/Atlantic Ocean SSTs (2nd mode), (d) Colombian streamflow stations (2nd mode), (e) Pacific/Atlantic Ocean SSTs (3rd mode), (f) Colombian streamflow stations (3rd mode). Significant [>90%] SST regions were indicated with gray shading. Significant [>90%] negative (positive) streamflow stations were represented by black (gray) circles.

temporal expansion series of Colombian streamflow while the Colombian streamflow heterogeneous correlation Fig. 4b, d and e were determined by correlating the Colombian streamflow values with the 1st (or 2nd or 3rd) temporal expansion series of Pacific/Atlantic Ocean SSTs.

For the 1st mode, the Pacific/Atlantic Ocean SSTs regions (Fig. 4a) identified that correlated with Colombian streamflow were almost identical to the regions identified by the 1st mode of Pacific Ocean SSTs (Fig. 2a). Also, no significant SST regions were identified in the Atlantic Ocean (Fig. 4a). The results show that, for the 1st mode of Pacific/Atlantic Ocean SSTs, the ENSO signal appears to be the dominant influence on Colombian streamflow. Finally, the streamflow stations identified (Fig. 4b) were identical to the streamflow stations (Stations 1, 2, 3, 4, 8, 9 and 10) by the 1st mode of Pacific Ocean SSTs (Fig. 2b).

For the 2nd mode, spatially large Pacific/Atlantic Ocean SSTs were identified in several regions (Fig. 4c) that correlated with Colombian streamflow. In the Pacific Ocean, SSTs (positive ''+'' sign) were identified in the equatorial Pacific Ocean west of South America, north of Australia in the western Pacific Ocean and in the southeastern Pacific Ocean. A Pacific Ocean SST region (negative ''—'' sign) was also identified south of New Zealand. For the Atlantic Ocean, a spatially large SST region (positive ''+'' sign) was identified along the equator between South America and Africa; however, only one streamflow station (Station 5 — positive ''+'' sign) was identified. This suggests that this Atlantic SST region does not have a strong influence on Columbia streamflow.

For the 3rd mode, the Pacific/Atlantic Ocean SSTs region (Fig. 4e) identified that correlated with Colombian stream-

Table 1 Correlation (*r*) values of previous year spring-summer Niño 3.4 index, PDO index, AMO index, SVD SST temporal expansion series (Pacific Ocean 1st Mode – Pac1, Atlantic Ocean 1st Mode – At1, Atlantic Ocean 2nd Mode – At2, Pacific/Atlantic Ocean 1st Mode – PacAt1, Pacific/Atlantic Ocean 2nd Mode – PacAt2 and Pacific/Atlantic Ocean 3rd Mode – PacAt3) and current calendar-year streamflow

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Niño 3.4 index	−0.45	−0.29	−0.22	−0.30	−0.08	0.39	0.38	−0.06	−0.33	−0.24
PDO index	−0.08	−0.11	0.03	−0.07	0.03	−0.10	−0.07	0.06	−0.11	−0.14
AMO index	0.13	0.04	0.30	0.20	0.38	−0.15	−0.07	0.08	0.16	0.02
Pac1	−0.66	−0.55	−0.41	−0.52	−0.21	0.20	0.19	−0.29	−0.48	−0.38
At1	−0.23	−0.08	−0.25	−0.27	−0.28	0.15	−0.06	0.04	0.03	0.10
At2	−0.18	−0.27	0.00	−0.04	0.11	−0.30	−0.35	−0.04	−0.15	−0.12
PacAt1	−0.69	−0.56	−0.44	−0.55	−0.25	0.20	0.17	−0.28	−0.48	−0.36
PacAt2	0.01	−0.09	0.17	0.13	0.31	−0.16	0.07	−0.15	−0.15	−0.23
PacAt3	−0.08	0.11	0.14	0.04	0.18	0.45	0.49	0.16	−0.11	0.11

flow was a spatially small ''band'' (positive ''+'' sign) along the equatorial Pacific Ocean. No significant SST regions were identified in the Atlantic Ocean (Fig. 4e). The two streamflow stations identified (Stations 6 and 7) were the same sign (positive ''+'' sign) as the SST region. Considering that only two stations were identified, the 3rd mode probably does not have a strong influence on Columbia streamflow. However, the additional skill may assist in long-range forecasting since an increase (decrease) SSTs may lead to increased (decreased) streamflow. As previously identified, this result is opposite of the established ENSO signal in Colombian streamflow that warmer (El Niño) SSTs result in decreased streamflow while cooler (La Niña) results in increased streamflow.

SVD SST temporal expansion series as a predictor of Colombian streamflow

To further verify the strength (or weakness) of the SVD SST temporal expansion series as a possible predictor of Colombian streamflow, each streamflow station (calendar-year volume) was correlated with the SVD SST temporal expansion series (previous spring-summer season) as identified in 'Pacific Ocean SSTs and Colombian streamflow', 'Atlantic Ocean SSTs and Colombian streamflow' and 'Pacific/Atlantic Ocean SSTs and Colombian streamflow' sections. For example, Station 1 was found to be associated with the Pacific Ocean 1st SVD SST temporal expansion series and the Pacific/Atlantic Ocean 1st SVD SST temporal expansion series while Station 5 was found to be associated with the Atlantic Ocean 1st SVD SST temporal expansion series and the Pacific/Atlantic Ocean 1st SVD SST temporal expansion series. These results were compared to the results of correlating each streamflow station (calendar-year volume) with the previous spring–summer seasons Niño 3.4 index, PDO index and AMO index (Table 1). The intent is to evaluate which predictors would be most useful for streamflow forecasting. In practice, the rigorous evaluation of these predictors would be performed where indices and/or modes of SST variability that were not highly correlated with streamflow would not be used in a forecast model.

The results show that the SVD SST temporal expansion series consistently produces higher correlation values (compared to the various indices) when correlated with the streamflow stations. For example, the Pacific Ocean 1st SVD SST temporal expansion series and the Pacific/Atlantic Ocean 1st SVD SST temporal expansion series resulted in correlation values almost twice in magnitude when compared to correlation values for the Niño 3.4 index for Stations 1, 2, 3 and 4. While a strong ENSO signal was acknowledged for Colombian streamflow, the Pacific Ocean 1st SVD SST temporal expansion series and the Pacific/Atlantic Ocean 1st SVD SST temporal expansion series appear to result in a better predictor of streamflow. For Stations 6 and 7, the Pacific/Atlantic Ocean 3rd SVD SST temporal expansion series resulted in the highest correlation values while for Stations 8, 9 and 10, the Pacific Ocean 1st SVD SST temporal expansion series and the Pacific/Atlantic Ocean 1st SVD SST temporal expansion series resulted in the highest correlation values. Station 5 was the only station in which the correlation value of an index (AMO) exceeded the correlation value of the SVD SST temporal expansion series.

Conclusions

An evaluation of Pacific and Atlantic Ocean SST variability and Colombian streamflow variability was performed. The SVD temporal expansion series for Pacific Ocean SSTs (1st P mode) and Pacific / Atlantic Ocean SSTs (1st mode) generally reflect ENSO variability; however, the potential of these SST regions as streamflow predictors is stronger than a general ENSO index such as Niño 3.4. The PDO and AMO are associated with the northern Pacific and northern Atlantic Oceans, respectively, and, through the use of correlation, their signals were not significantly identified in Colombian streamflow. The SST regions covered by PDO and AMO were not included in this study and could be the topic of future research to further investigate PDO and AMO linkages. The focus in this study was to isolate southern hemisphere SST regions.

An additional contribution of this research was the identification of potential streamflow predictors (SVD SST temporal expansion series) that may improve long lead-time forecasts of Colombian streamflow. The SVD SST temporal expansion series considers and integrates the climate signals with other Pacific (Atlantic) Ocean influences. The significant correlations confirm that utilizing the ocean basins, as a whole, could result in improved streamflow predictability. It is noteworthy that the relationship between the indices and SSTs with streamflow may not be a linear relationship as was assumed in this study. Maurer et al. (2004) found a nonlinear relationship between indices and North American streamflow. Thus, the assumption of linearity may underestimate the predictability of streamflow. Future research to forecast streamflow using SST temporal expansion series may utilize nonparametric methods to avoid the assumption of linearity. In addition, the lagged relationship between SSTs would be needed to show the potential of predicting streamflow in advance given some observed SST values for a particular region.

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