Changes and variation in the discharge regime of the Upper Suriname River Basin and its relationship with the tropical Pacific and…

Article *in* Hydrological Processes · May 2008

DOI: 10.1002/hyp.6733

Nurmohamed Riad
Anton de Kom University

HYDROLOGICAL PROCESSES
Hydrol. Process. (2007)
Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/hyp.6733

Changes and variation in the discharge regime of the Upper Suriname River Basin and its relationship with the tropical Pacific and Atlantic SST anomalies

Riad Nurmohamed,[1]* Sieuwnath Naipal[1] and Cor Becker[2]
[1] *Department of Infrastructure, Faculty of Technology, University of Suriname, Leysweg, PO Box 9212, Paramaribo, Suriname*
[2] *Meteorological Service Suriname, Magnesiumstraat 41, Paramaribo, Suriname*

Abstract:

Long-term changes and variability in river flows in the tropical Upper Suriname River Basin in Suriname (2–6 °N, 54–58 °W) are analysed, including the relation to sea surface temperatures (SSTs) in the tropical Atlantic and Pacific Ocean. To analyse variability, lag correlation and statistical properties of the data series are used. Long-term changes are analysed using parametric and non-parametric statistical techniques. The analyses are performed for the period 1952–1985. The results show that both river discharge series at Semoisie and Pokigron are non-stationary and have a negative trend. The negative rainfall trend in the centre of Suriname may be responsible for the negative trend in the annual river discharges in the basin. The highest correlation (Pearson's coefficient c) is obtained when the Tropical North Atlantic (TNA) SSTs lags the monthly discharges at Pokigron by 3–4 months ($c = 0{\cdot}7$) and when the Tropical South Atlantic (TSA) SSTs lags the discharges by 4 months ($c = -0{\cdot}7$). It also follows that the high (low) monthly flows, from April–August (September–March) are associated with increasing (decreasing) SSTs in the TNA and with decreasing (increasing) SSTs in the TSA. The results also reveal that years with low (high) discharges are more related to warmer (colder) SSTs during the year in the TNA region and a southward displacement of the Inter-Tropical Convergence Zone (ITCZ). However, the Pacific El Niño (La Niña) events may also be responsible for low (high) flow years in this basin. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS climate variability; El Niño; La Niña; river discharge; (non)parametric statistical tests; Suriname; tropical Atlantic SST anomalies; tropical Pacific SST anomalies

Received 24 August 2006; Accepted 26 February 2007

INTRODUCTION

Hydrological processes of watersheds such as surface runoff and evapotranspiration are sensitive to changes in land use and climate change (Maidment, 1992). The Intergovernmental Panel on Climate Change (IPCC, 2001) has shown that global climate change in the last century has resulted in an increase in the earth's average surface air and sea temperature by about 0·3–0·6 °C. This change has affected the global hydrological cycle, primarily rainfall and runoff (Solomon *et al*., 1987; Jones *et al*., 1996; McMichael *et al*., 1996; WMO/UNESCO, 1997; Lozan *et al*., 1998; Tamara *et al*., 1999; IPCC, 2001). Extreme climate and weather events have been responsible for about 90% of all disasters such as floods, extreme droughts and hurricanes in the last ten years. Socio-economic sectors and the environment e.g. infrastructure, agriculture, fisheries and health have been affected (Kundzewicz, 2000; Ross and Lott, 2000). Both long- and short-term changes in climate may also affect water resources.

In the north and northeast of South America, rainfall is mainly influenced by the tropical Atlantic sea surface temperature (SST) through the Walker and Hadley circulation (Ambrizzi *et al*., 2005). The Walker circulation consists of air rising in the eastern Pacific, diverging eastwards and sinking in the equatorial Atlantic before returning to the west. During the Hadley circulation, ascending air from South America moves from the Tropical North Atlantic (TNA) region (5·5–23·5 °N, 15–57·5 °W), descends in the equatorial Atlantic and flows southward to South America (Wang, 2001). Rainfall in northern South America is also influenced by the Pacific El Niño Southern Oscillation (ENSO) related SST anomalies (SSTAs), the Atlantic zonal equatorial mode (the 'Atlantic Niño') and the Tropical Atlantic Meridional Gradient (TAMG) (or tropical Atlantic dipole index) (Wang, 2001; Wang, 2005). SSTA is defined as the difference between the observed value and the long term mean of all the observations. The different SST areas are discussed in the sub-section *Data*. Some of these processes are schematically shown in Figure 1.

The Pacific ENSO is one of the well-known phenomena that may cause floods and droughts in different parts of the tropics (10 °S–10 °N). Some significant El Niño events occurred in the periods 1957–1958, 1965–1966, 1982–1983, 1986–1987 and 1997–1998. During these events, the SSTAs in the equatorial Pacific

* Correspondence to: Riad Nurmohamed, Department of Infrastructure, Faculty of Technology, University of Suriname, Leysweg, PO Box 9212, Paramaribo, Suriname. E-mail: r.nurmohamed@uvs.edu

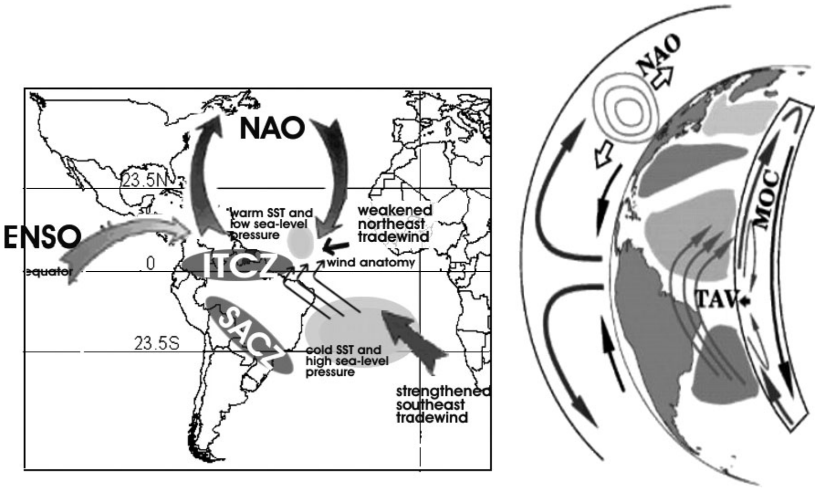

Figure 1. A schematic of the remote influence of the Pacific ENSO (Walker and Hadley circulation) and NAO (Hadley circulation) on the SSTAs north of the equator (tropical Atlantic variability) (after Marshall *et al*., 2001). TAV = Tropical Atlantic Variability and MOC = Atlantic Meridional Overturning Circulation

were positive (warm phase). The Pacific Walker cell and the Atlantic Hadley circulations were stronger and weaker, respectively. This leads to a weakening of the north-easterly trade winds in the TNA and less surface evaporation in the TNA region (Marshall *et al*., 2001). As a result, SST increases in the TNA, with a lag of 4–5 months, reaching its maximum in the periods December–February and March–May. During these periods, rainfall below normal is experienced in northern South America (Ropelewski and Halpert, 1987, 1989, 1996; Rajagopolan *et al*., 1997; Marshall *et al*., 2001; Wang 2001). During La Niña events, SSTAs in the equatorial Pacific are negative (cold phase). La Niña events reach their peak between June–September. Precipitation above normal is experienced in the periods December–February and March–May in northern South America (Acevedo *et al*., 1999; Obasi, 1999; Robertson and Mechoso, 2002; Turner, 2004; Wang, 2005).

The Atlantic Niño is similar but weaker than the Pacific Niño. Most warm events of the Atlantic Niño (e.g. 1963, 1968, 1973, 1981, 1984 and 1987) occurred in August–September and a few in December–February (Wang, 2005). During these events, the Atlantic Walker circulation is weakened and the easterly trade winds in the western Atlantic decrease. The Hadley circulation is strengthened and SSTs increase in the equatorial western Atlantic.

The tropical Atlantic meridional SST gradient is calculated as the tropical North Atlantic SSTs minus the tropical South Atlantic SSTs, and is correlated with the north–south displacement of the Inter-Tropical Convergence Zone (ITCZ) (Ambrizzi *et al*., 2005; Wang, 2005). When the gradient is strongly positive, air rises over the TNA and moves southward and causes less precipitation over northern South America, especially during December–February. When the gradient becomes strongly negative, rainfall increases over this area.

Recent studies by Villwock (1998), Garzoli *et al.* (1999), Giannini *et al*. (2000) and Marshall *et al*. (2001) have shown that the rainfall in northern South America is more related to the SSTAs in the TNA than the Tropical South Atlantic (TSA) and the tropical Pacific ENSO. SSTs warmer than normal in the TNA and colder than normal in the TSA correspond to weaker (stronger) than normal north-easterly (south-easterly) trade winds in the TNA and a northward displacement in the ITCZ during March–May. This causes an increase in rainfall in this region.

In Suriname (2–6 °N, 54–58 °W), the high temporal and spatial variability of rainfall determines the hydrological regime of rivers. Prolonged dry periods, due to the remote influence of ENSO, were experienced in northwest Suriname in 1925/1926, 1939/1940, August–November 1982, December 1982–February 1983 and 1997/1998 (Houben and Molenaar, 1998; Mol *et al*., 2000; Webster and Roebuck, 2001). The drought of 1997/1998 was also experienced in the neighbouring countries Guyana and northeast Brazil. In the last 25 years, the variable rainfall has affected the proper operation of the van Blommenstein reservoir in Suriname that is being used for hydropower generation. This reservoir receives its water from the Upper Suriname River catchments (Figure 2) and has a drainage area of about 7860 km^2. The lake inflows were reduced significantly for at least four periods (18 months over 1987/1988, March 1999, January 2001 and September 2004–January 2005). Although the reasons are still unclear, these periods may be linked to the warm phase of the Atlantic Niño (Webster and Roebuck, 2001; Nurmohamed and Naipal, 2004; Wang, 2005). Because of the importance of this reservoir for the economy of Suriname, a better understanding of the climate–river discharge behaviour in the Upper Suriname River Basin is required. In this study, statistical methods will be used to analyse long-term changes, the variation in the river discharges in the basin and the influence of the Pacific and Atlantic SST on the river discharge.

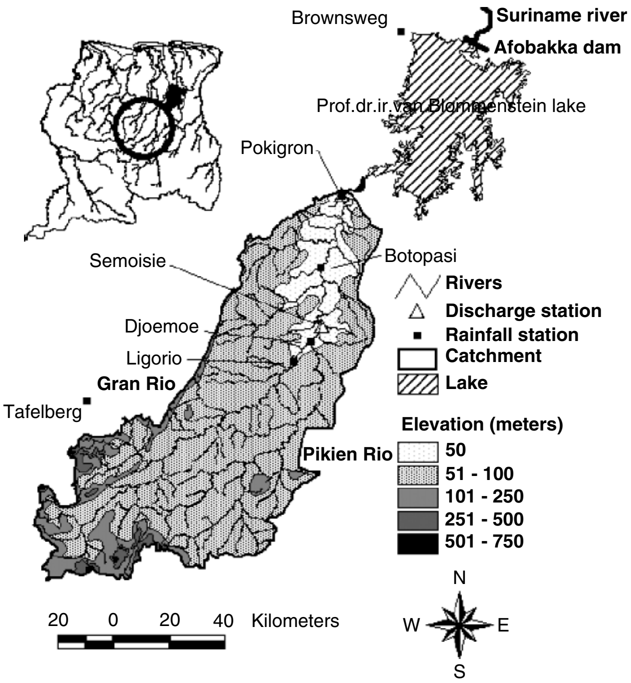

Figure 2. Map showing the Upper Suriname River catchments with the locations of river discharge and rainfall gauge stations

DATA AND METHODOLOGY

Data

The largest available data sets (1952–1985) used in this study are the monthly river discharges of station Semoisie (drainage area of ~5682 km^2) and Pokigron (drainage area of ~7860 km^2). Figure 2 shows the locations of these stations. The river discharge series are provided by the Hydraulic Research Division (WLA), the Bureau for Hydroelectric Power Works (BWKW) and the monthly inflows (1911–2001) in the van Blommenstein reservoir by the Bauxite Institute Suriname/Suriname Aluminum Company LLC. The observed time series of monthly and annual mean river discharges at Semoisie Q_{Sem} and Pokigron Q_{Pok} are shown graphically in Figures 3 and 4.

Within these catchments, a few rainfall gauge stations are available but the observed data are insufficient for climate change and climate variability analysis. The two closest rainfall stations with sufficient data are Brownsweg (490 m Normal Surinamese Level or NSP) and Tafelberg (323 m NSP) (Figure 1). The observed monthly rainfall (1961–1985) of these stations is shown in Figure 5. The meteorological data is issued by the Meteorological Service Suriname (MDS).

A summary of the hydrological characteristics of the Upper Suriname River catchments is presented in Table I. Monthly observed SSTs (1950–2003) are adapted from the National Oceanic and Atmospheric Administration (NOAA-CIRES Climate Diagnostics Center, 2004) for the TNA (5·5–23·5 °N, 15–57·5 °W), the TSA (0–20 °S, 10 °E–30 °W), the Extreme Eastern Tropical Pacific ENSO 1 + 2 (0–10 °S, 90–80 °W) and East Central Pacific ENSO 3 + 4 (5°N–5 °S, 160 °E–150 °W). The monthly Atlantic Niño SSTAs (3 °S–3°N, 20 °W–0°) and SSTAs in the tropical Atlantic (‘dipole index’) were provided by Wang (2006) (NOAA).

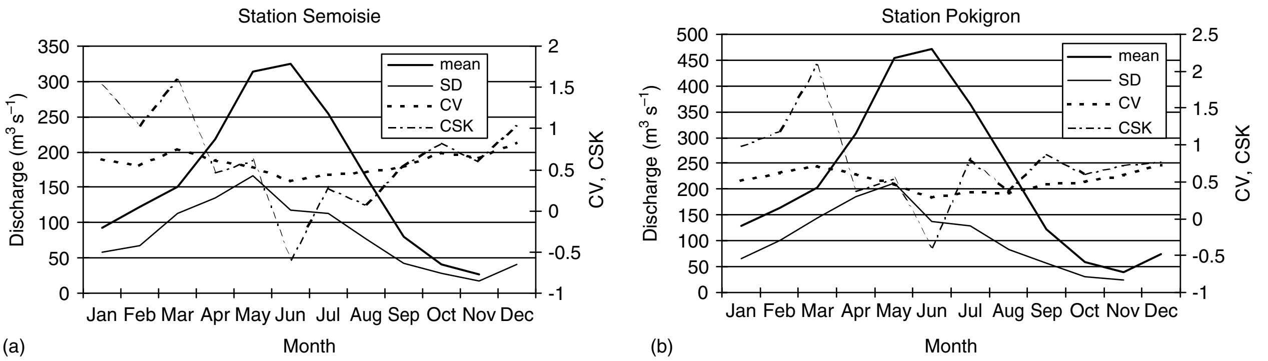

Figure 3. Observed monthly mean river discharges of the Upper Suriname River including standard deviation SD, coefficient of variation CV and coefficient of skewness CSK at (a) Semoisie and (b) Pokigron (1952–1985)

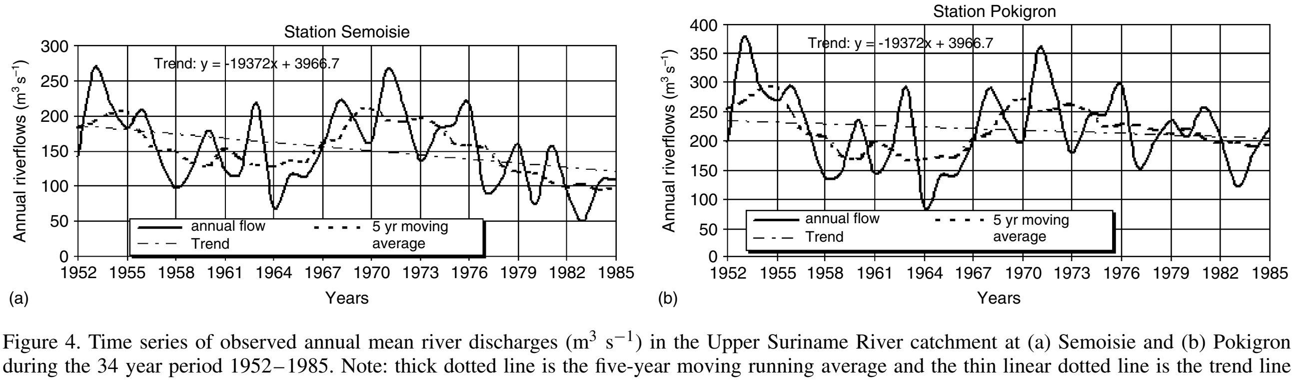

Figure 4. Time series of observed annual mean river discharges (m^3 s^{-1}) in the Upper Suriname River catchment at (a) Semoisie and (b) Pokigron during the 34 year period 1952–1985. Note: thick dotted line is the five-year moving running average and the thin linear dotted line is the trend line

DOI: 10.1002/hyp

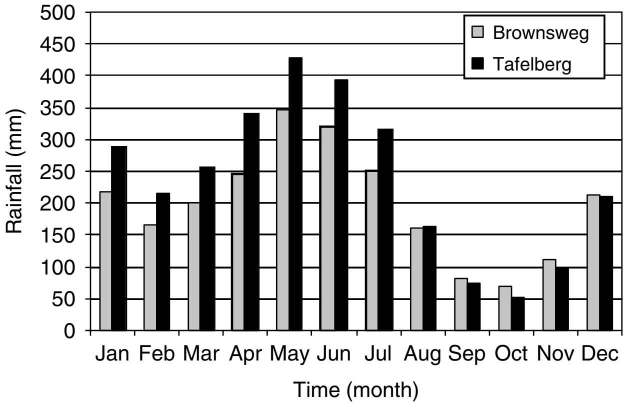

Figure 5. Time series of observed monthly mean rainfall (mm) at station Brownsweg and Tafelberg during the 25 year period 1961–1985

Table I. Hydrological characteristics of the Upper Suriname River Basin

Discharge Station	Semoisie	Pokigron
Catchment area upstream of station (km^2)	5682	7860
Elevation (m NSP)	94	78
River length (km)	160	235
Mean annual discharge (m^3 s^{-1})[a]	153	219
Maximum annual discharge (m^3 s^{-1})[a]	662	923
Minimum annual discharge (m^3 s^{-1})[a]	2	6
Annual flow depth (mm)	850	879
Annual rainfall (mm)[b]	2700	2600
Runoff coefficient (−)	0·31	0·34
Annual evaporation (mm)[b]	1825	1850

[a] Calculations based on annual time series of 34 years (1952–1985) for both stations.
[b] Nurmohamed and Naipal (2004), Lenselink and van der Weert (1970).

The SST anomaly is obtained by subtracting the annual (monthly) climatologies (for 12 months) for each data series for the individual annual (monthly) data. Figure 6 shows the SSTAs for the different regions for the period 1952–1985. Figure 6a shows that the annual SSTAs in the TNA region are prevailingly positive during 1961–1970 and prevailingly negative during 1971–1976. During 1977–1985, the TNA region is mostly warmer than normal and the TSA region mostly colder than normal (Figure 6b). A warm TNA and cold TSA region indicate that trade winds in the TNA region are weakened and in the TSA region are strengthened. The ITCZ is shifted northwards of Suriname, reducing precipitation above Suriname. Figure 6c and 6d shows the SSTAs in the Pacific Ocean. During the 33 year period from 1952, there were four strong warm events (El Niño), specifically: 1957–1958, 1965–1966, 1972–1973 and 1982–1983. During this period, one can also notice

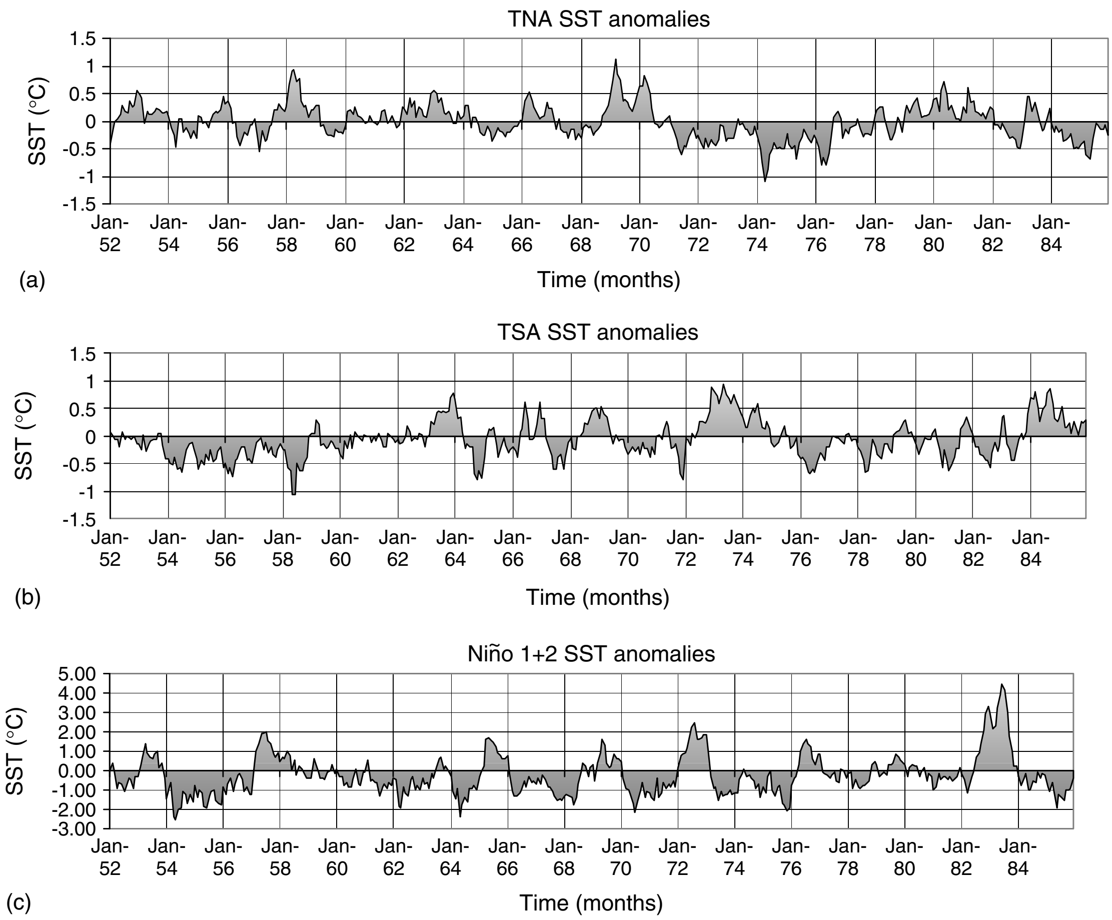

Figure 6. Time series of SSTAs in the (a) TNA region (5·5–23·5 °N, 15–57·5 °W), (b) TSA region (0–20 °S, 10 °E–30 °W), (c) Niño 1 + 2 region (0–10 °S, 90–80 °W), (d) Niño 3 + 4 region (5°N–5 °S, 160 °E–150 °W), (e) Atlantic Niño region (3 °S–3°N, 20 °W–0°), (f) TA region, calculated as TNA–TSA SST (TNA: 5–25°N, 55–15 °W; TSA: 0–20 °S, 30 °W–10 °E)

DOI: 10.1002/hyp

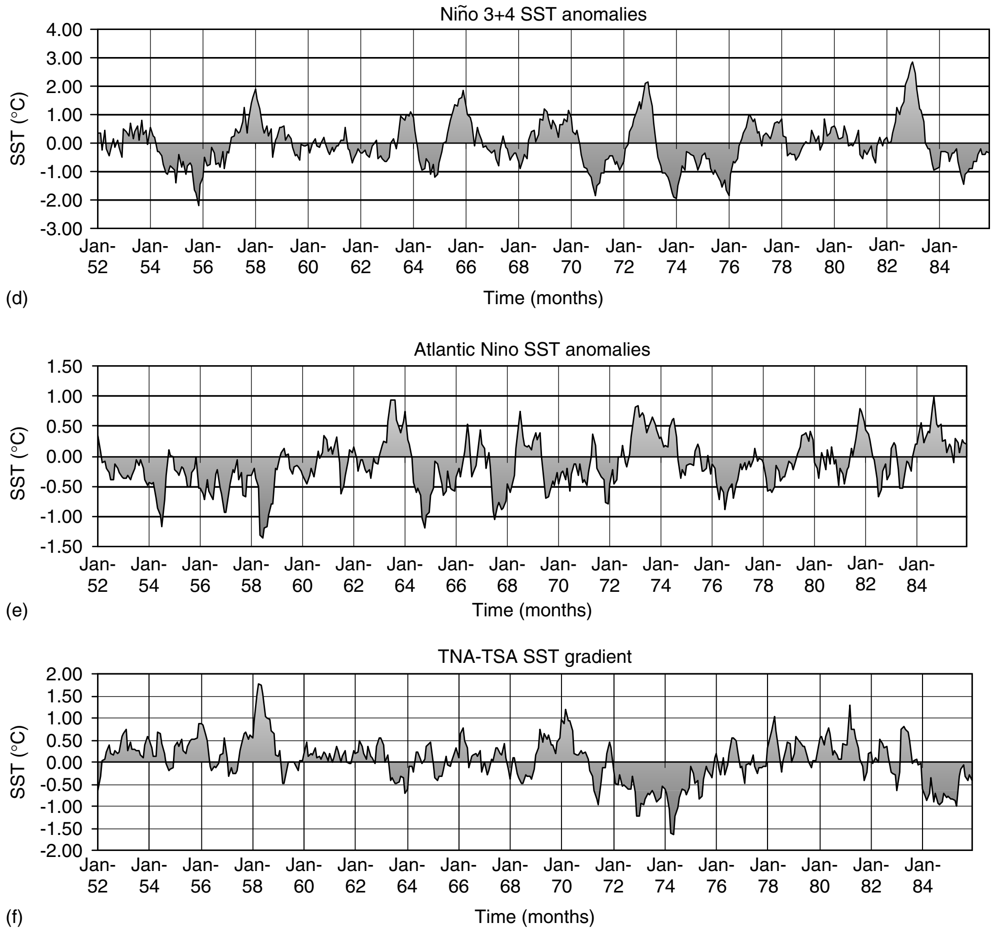

Figure 6. (*Continued*)

a few strong cold events (La Niña), for example in 1955–1956, 1970–1971, 1973–1974 and 1975–1976. Figure 6e shows the SSTAs in the tropical Atlantic Ocean and from this figure we can see that five extreme warm events (SSTA >0·7 °C) occurred during 1952–1985, for example, in July 1963, January 1973 and August 1981. Figure 6f shows that the TNA-TSA SSTA gradient is mainly positive for 1952–1970 and 1976–1983 and prevailing negative during 1971–1975.

Methodology

Most of the methods applied are widely used in similar studies and have been recommended by WMO (1988). The goodness-of-fit test (the Chi-square test and the Kolmogorov-Smirnov test) is applied to test if the monthly and annual river discharges (1952–1985) follow a normal distribution. Temporal variability of the river discharges in the Upper Suriname River Basin is studied using statistical parameters (for example the mean, coefficient of variation, coefficient of skew ness) (WMO, 1988). The formula for the mean $\overline{x}$, the standard deviation s_x, the coefficient of variation CV and the coefficient of skewness CSK are taken from Mamdouh *et al.* (1993). For detecting climate change from hydrological time series (randomness, stationary and homogeneity) different parametric and non-parametric statistical tests from the literature are used (Haan, 1977; WMO, 1988; Helsel and Hirsch, 1992; Mamdouh *et al*., 1993; McCuen, 2003). If the measured data are not influenced by human activities, but natural activities, the data series are random (or inconsistent). In stationary time series (normal variability), the statistical properties (e.g. the mean, variance and standard deviation) do not change in time. Homogeneous time series do not have a trend or cycle effect (Mamdouh *et al*., 1993).

General tests for randomness are carried out using the serial correlation coefficient, the Von Neumann ratio test. The Student's t-test (for shift in the mean) and the F-test (for shift in the variance) are used to test non-stationarity of the annual river discharges. For this purpose, the data series are divided in two equal series: 1952–1968 (17 years) and 1969–1985 (17 years). To determine if a deterministic component (trend or jump) exists in the observed annual river discharges, auto/serial correlation analysis is used. To test randomness against jump (break point year) in the annual river flows, the Standard Normal Homogeneity Test of Alexandersson (single and double shift in the mean) (SNHT), the Craddock's Cumulative Deviations Test (CDT), the Worsley Likelihood Ratio Test (WLRT) and the t-test are used (Salas, 1992; WMO, 1988). To detect monotonic increasing or decreasing trends in the monthly and annual time series, the non-parametric Mann-Kendall, Spearman's and Pearson's tests are used. The river discharges are also evaluated

DOI: 10.1002/hyp

using a filtering technique (the moving average filter). A 5 year wavelength is used as it is less sensitive than a 10 year wavelength.

The interannual relationship between the observed monthly river discharges and the observed monthly Atlantic and Pacific SSTs is studied using lagged correlation analyses. These analyses are carried out on a monthly and seasonal scale using the Anclim model (Stipanek, 2003) and the Royal Netherlands Meteorological Institute (KNMI) Climate Explorer (2005). In addition, high and low river discharges are analysed and compared to the El Niño and La Niña events according to Null (2003), Turner (2004) and the International Research Institute or IRI (2005). In this study, a high river flow year occurs if $x \geq \bar{x} + \text{STDEV}$ (68% confidence limit) and a low river flow year if $x \leq \bar{x} - \text{STDEV}$ where x is the river discharge, $\bar{x}$ is the long-term mean and STDEV is the standard deviation.

To maintain consistency and to enable available statistical tables to be utilized, all tests used are performed at a 5% significance level and calculated using the Modstat (Knodt, 2003), AnClim (Stipanek, 2003) and XLStatistics (Carr, 2000) statistical programs.

RESULTS AND DISCUSSION

Analysis of long-term changes in the river discharges

The annual river discharge series (1952–1985) at Semoisie and Pokigron show a linear Pearson's correlation coefficient $c = 0{\cdot}89$ while the monthly river discharge series show $c = 0{\cdot}94$. A significantly high correlation ($c = 0{\cdot}97$, $p < 0{\cdot}05$) is found between the annual discharge at Pokigron and the van Blommenstein lake inflows for the period 1952–1985.

Both the Chi-square and Kolmogorov–Smirov tests show that the annual river discharge series (1952–1985) at station Semoisie and Pokigron are normally distributed and the F-test and Student's t-test have shown that the annual river discharge series at both stations are non-stationary. The Mann-Kendall, Spearman's and Pearson's tests have shown that the annual discharge series at Semoisie and Pokigron display a negative linear trend. During 1952–1985, a reduction of about 62·7 $m^3\ s^{-1}$ is observed at Semosie (trend value is 1·9 $m^3\ s^{-1}\ yr^{-1}$; $p = 0{\cdot}04$) and at Pokigron a reduction of about 29·7 $m^3\ s^{-1}$ is observed during the same period (trend value is 0·9 $m^3\ s^{-1}\ yr^{-1}$; $p = 0{\cdot}44$). The different statistical test results are presented in Table II. The difference in the river discharge trend value may be caused by the variation in the rainfall distribution over the study area (see Figure 7) and the difference in annual rainfall trends in the centre of Suriname. A recent study by Nurmohamed and Naipal (2004) have shown that the annual rainfall at Tafelberg (southwest of the basin) shows a negative trend of 14·5 mm yr^{-1} ($p = 0{\cdot}10$) and the annual rainfall at Brownsweg (north of the basin) shows a positive trend of 33·2 mm yr^{-1} ($p = 0{\cdot}35$) for the period 1961–1985.

The annual river flows at Semoisie and Pokigron (Figures 4a and b) show periods with an increasing and a decreasing linear trend. Based on the results of the moving average, four periods can be distinguished at Semoisie: a decrease in the period 1953–1958; a levelling off in 1958–1965; an increase between 1964 and 1971; and a decrease after 1971. The same method shows three main periods in the time series at Pokigron (Figure 4b): a steep decrease during 1952–1964; a slow increase in the period 1964–1971; and a slow decrease after 1971. The steepest decrease in annual river flow at Semoisie

Table II. Results of different statistical tests on the river discharges at Semoisie and Pokigron (1952–1985) at a 5% level of significance

Statistical characteristics	Type	River discharge at Semoisie	River discharge at Pokigron	Tests
Normal distributed (goodness-of-fit test)	Monthly, annual	Yes (except March, October/December)	Yes (except March, October/December)	Chi-square test and Kolmogorov-Smirnov tests
Independent (deterministic component)	Annual	No	Yes	Autocorrelation analyses
Random (general test of randomness)	Monthly, annual	No (except December)	Yes (except March)	Serial correlation coefficient and Von Neumann ratio test
Non-stationary (shift in mean/variance)	Annual	No	No	F-test and the Student t-test
Linear trend (significant)	Annual	Yes	No	Mann-Kendall, Spearman's and Pearson's tests
Random (jump/shift)	Annual	Yes (1977)	No	Cumulative Deviation test, Worsley Likelihood ratio test, T test and Standard Normal Homogeneity test of Alexandersson test

DOI: 10.1002/hyp

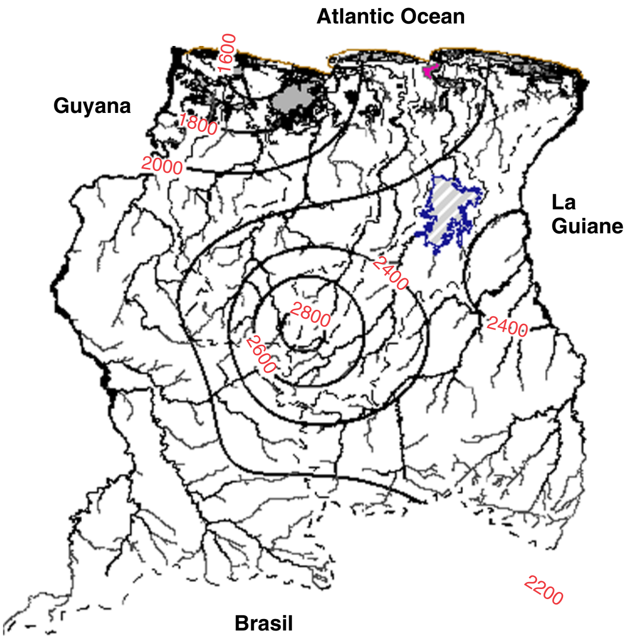

Figure 7. Contour map of annual precipitation totals (mm) in Suriname for the period 1961–1985. Note: the circles show the location of the rainfall station

was noticeable in the period 1975–1983 and was about $-79{\cdot}0\ m^3\ s^{-1}$ (about 52% of the long-term annual mean river discharge). At Pokigron the greatest drop in annual river flow of about $-92{\cdot}7\ m^3\ s^{-1}$ (about 42% of the long-term annual mean river discharge) was seen in the period 1953–1958.

The oscillations in annual time series of period ~15 years may be attributed to the natural oscillation of the global atmospheric–ocean system and/or solar variability (Chiew *et al.*, 2005). In the first period (Semoisie: 1953–1958; Pokigron: 1952–1964), the SSTs in the TSA, Niño 1 + 2, Niño 3 + 4 and Atlantic Niño region (Figure 6) are predominantly negative ($> -0{\cdot}5\ ^\circ C$), while the TNA–TSA gradient is predominantly positive ($\sim 0{\cdot}5\ ^\circ C$). The decrease in discharge during this period may be related to the strong cooling effect of the Pacific SST and the Atlantic Niño SST on the warm waters in the TNA, which cause less air to rise and a decrease in precipitation in the study area. The increase in discharge in the period 1965–1970 may be related to the strong positive SST anomaly in the TNA (higher than $0{\cdot}5\ ^\circ C$), especially during 1969–1970. A warm TNA causes surface air to rise, easterly trade winds in the TNA to weaken and the water vapour to condense, resulting in an increase in precipitation or river discharge in the study area. For the decrease in discharge after 1971 at Pokigron, a possible explanation may be found in the strong negative TNA–TSA gradient ($< -0{\cdot}5\ ^\circ C$), especially during 1971–1976. The statistical analyses (Table II) have shown that only the annual river discharge series at Semoisie show a break point year in 1977. This may have been caused by the change from dry years to wet years (see Figure 4). It may be concluded that there is a strong relation between shifts and climate variability, in particular the SSTAs, in the tropical Atlantic and tropical Pacific. In the following sections, more analyses will be performed to understand the discharge behaviour.

River discharge variability and sea surface temperature relationship

The annual cycle of the discharge at Semoisie and Pokigron (Figure 3) is characterized by a maximum in May–June and a minimum in October–November. The monthly discharge follows almost the same seasonal pattern as the monthly rainfall at the nearby rainfall stations (Figure 5). Figure 3 also shows the high interannual discharge variability as the monthly standard deviation is always greater than 50% of the mean monthly discharge. The highest coefficient of variation at both stations are in March (0·72–0·75) and December (0·72–0·83). This has to do with the sudden increase in rainfall or river discharge in these months. Because of the high consistency of Q_{Pok} with Q_{Sem} and the lake inflows, only the time series at Pokigron will be considered in the further analyses.

Figure 8 shows the monthly observed SST for the four regions, including the monthly discharge at Pokigron Q_{Pok} for the period 1952–1985. This figure shows that the TNA SSTs are higher than the TSA SSTs, except in February–April. SST in the TNA (TSA) is warmest in September (March) and coldest in March (September). The lagged correlation analyses (Pearson's coefficient) show that the maximum (minimum) flows are related to high (low) SSTs in the TNA and TSA region.

The lagged relationship between the seasonal SSTAs in the TNA, TSA, Niño 1 + 2 and Niño 3 + 4 regions and the river discharge anomalies at Pokigron is graphically shown in Figure 9. A positive lag indicates that the SSTA is the leading index and a positive (negative) correlation indicates that large (small) river discharge anomalies are related to large SSTAs. The river discharge anomaly is calculated as a three-monthly average divided by the long-term mean of the time series (1952–1985). From these results, it seems that the discharge in the Upper Suriname River Basin is more strongly correlated with the Pacific SSTAs in December–February (DJF) ($c = -0{\cdot}63$ for Niño 1 + 2 SSTAs, with a lag of 8 months), June–August (JJA) ($c = -0{\cdot}73$ for Niño 3 + 4 SSTAs, with a lag of 5 months) and September–November

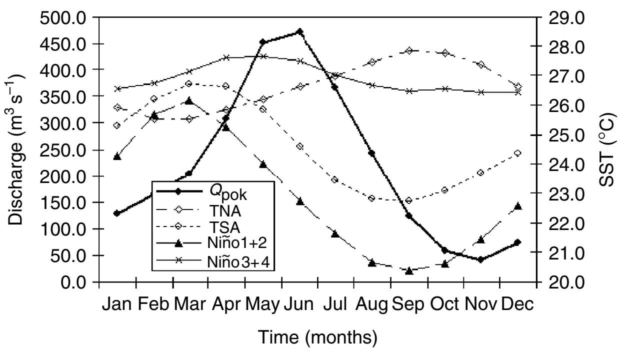

Figure 8. Monthly variation of observed SST in the TNA, TSA, Niño 1 + 2 and Niño 3 + 4 regions, and the monthly observed discharge at Pokigron for the period 1952–1985

DOI: 10.1002/hyp

(SON) ($c = -0{\cdot}65$ for Niño $3 + 4$ SSTAs, with a lag of 4 months). In March–May (MAM), the discharge in the Upper Suriname River Basin has a slightly stronger correlation with the SSTAs in the TSA region ($c = -0{\cdot}46$ with a lag of 2 months) than with the Pacific SSTAs.

Table III shows the highest cross-correlation coefficients between the observed monthly SSTs and between the monthly SSTAs in the different regions. The results show that the Pacific El Niño influences the TA SST. The Niño $3 + 4$ SST shows a stronger correlation with the TNA SST in all the seasons compared to the Niño $1 + 2$ SST. The highest correlation ($c = 0{\cdot}66$–$0{\cdot}68$) is obtained when the Niño $3 + 4$ SST leads the TNA SST by 3–4 months in March–May and June–August (Table IV). In the TSA region, the Niño $1 + 2$ SST shows a slightly stronger correlation with the TSA SST compared to the Niño $3 + 4$ SST. A high correlation is also found between the December–February TSA SST and the Niño $3 + 4$ SST 5–6 months earlier (∼0·37). During DJF, the TSA SSTAs show a much higher correlation ($c = 0{\cdot}39$ with a lag of 7 months) with the discharge anomalies than the TNA SSTAs ($c = -0{\cdot}17$ with a lag of 6 months) (Figures 9a and b).

During December–April, the TNA region becomes cold and the TSA region warm (Figure 6). North-easterly trade winds north of the equator are strengthened, while the south-easterly trade winds south of the equator are weakened (Villwock, 1998; Webster, 2005). The ITCZ is displaced south of Suriname causing a reduction in precipitation including river discharge, mainly during

Table III. The highest lagged cross-correlation coefficient c_k (with 95% confidence interval, $k = 0$–12 months) between the monthly SSTAs

	TNA	TSA	Niño 1 + 2	Niño 3 + 4
TNA	1·00	−0·13 (lag 1)	0·26 (lag −5)	0·46 (lag −5)
TSA		1·00	−0·21 (lag 12)	−0·27 (lag 12)
Niño 1 + 2			1·00	0·68 (lag 1)
Niño 3 + 4				1·00

Note: the SSTAs in the first column are taken as the first time series and the SSTAs in the first row as the second time series.

Table IV. Highest lagged cross-correlation coefficients of monthly SSTAs for the December–February (DJF), March–May (MAM), June–August (JJA) and September–November (SON) periods for the same regions as in Table III

Predictor/Period	DJF	MAM	JJA	SON
c_k (TNA–TSA SSTAs)	−0·34 (lag 12)	−0·29 (lag 9)	−0·15 (lag2–3)	−0·45 (lag 9)
c_k (TNA–Niño 1 + 2 SSTAs)	0·19 (lag 3)	0·50 (lag 5–6)	0·48 (lag 6–7)	0·22 (lag 4)
c_k (TNA–Niño 3 + 4 SSTAs)	0·41 (lag 8)	0·68 (lag 3–4)	0·66 (lag 4)	0·38 (lag 6)
c_k (TSA–Niño 1 + 2 SSTAs)	0·44 (lag 4)	0·19 (lag 7–8)	−0·27 (lag 1)	0·14 (lag 12)
c_k (TSA–Niño 3 + 4 SSTAs)	0·37 (lag 5–6)	−0·14 (lag 4)	−0·30 (lag 1)	0·11 (lag 2)
c_k (Niño 1 + 2—Niño 3 + 4 SSTAs)	0·85 (lag 0)	0·66 (lag 0)	0·70 (lag 1)	0·87 (lag 1)

Note: The first row of SSTAs is taken as the first series and the second row of SSTAs as the second series. A positive lag indicates that the second series is the leading index.

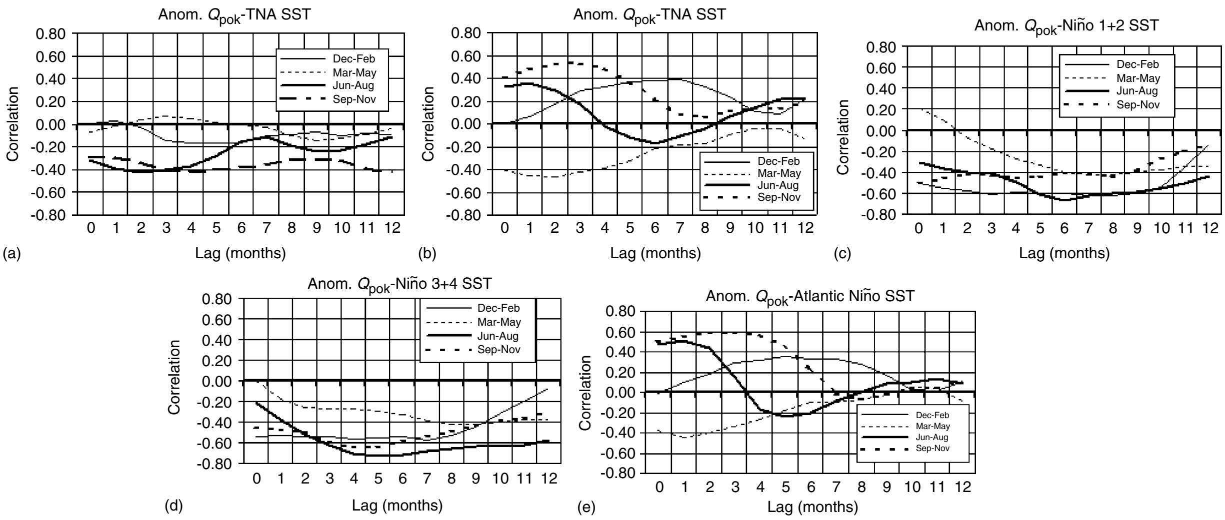

Figure 9. Lag correlation coefficient (Pearson's coefficient) of the river discharge anomalies at station Pokigron for December–February (DJF), March–May (MAM), June–August (JJA) and September–November (SON) with the (a) TNA SSTAs, (b) TSA SSTAs, (c) Niño $1 + 2$ SSTAs, (d) Niño $3 + 4$ SSTAs and (e) Atlantic Niño SSTAs for the period 1952–1985. Note: positive lag implies SSTAs leading index

DOI: 10.1002/hyp

February–April (Figure 3). During MAM, the TSA SSTAs also show a much higher correlation ($c = -0{\cdot}46$ with a lag of 1 month) with the discharge anomalies than the TNA SSTAs ($c = -0{\cdot}07$ with 0 months lag). In this period, oceanic air rises over the TNA warm water region, easterly trade winds from the sea are weakened north of the equator and evaporation increases over the TNA region. Easterly trade winds south of the equator increase and bring the tropical heat sources of the Amazon over Suriname. The ITCZ is displaced northwards of Suriname and precipitation increases over northern South America. During JJA, both north-easterly and south-easterly trade winds are strong and while the ITCZ travels from the south of Suriname to the north, it also collides with the geographical relief of the country (near Tafelberg) as well as with the trade winds. The movement of ITCZ over Suriname becomes slower and the wet season is extended. In this period, the ITCZ is present over almost all of Suriname. Both TNA ($c = -0{\cdot}42$ with a lag of 2 months) and TSA SSTAs ($c = 0{\cdot}35$ with a lag of 1 month) show a high correlation with the discharge anomalies. During SON, the ITCZ has already passed over Suriname and is found to the north above the Atlantic Ocean. The TSA region is cold. In this period, the trades south of the equator increase surface winds and cause evaporative cooling, resulting in less rainfall over Suriname. The TSA SSTA show a stronger correlation ($c = 0{\cdot}53$ with a lag of 3 months) with the discharge anomalies than the TNA SSTAs ($c = -0{\cdot}42$ with a lag of 4 months).

When comparing low flow years (1958, 1959, 1961, 1964, 1965, 1966, 1977 and 1983) and high flow years (1953, 1954, 1956, 1968, 1971 and 1976) at Pokigron with the annual Atlantic and Pacific SSTs and the Atlantic Niño index, no clear relation is found. However, during low flow years, the SSTAs in the TNA region (Figure 8a) are predominantly positive (except in 1959, 1964, 1965 and 1977) while during high flow years, SSTAs in the TNA region are predominantly negative (except in 1953). SSTAs in the TSA region (Figure 8b) for low and high flow years are almost all negative, except in 1966 and 1968. Four of the eight low years (1958, 1965, 1977 and 1983) correspond to El Niño events and three of the six high flow years (1956, 1971 and 1976) correspond to La Niña events. According to Ambrizzi *et al.* (2005), the decrease in rainfall (or discharge) during some of the El Niño events in the north and northeast of South America, especially during DJF and MAM, is related to the strong Walker and Hadley circulation. Figure 9 shows that the Niño $3 + 4$ SSTAs have a much stronger correlation than other SSTs with the Q_{Pok} anomalies during DJF ($c = 0{\cdot}54$–$0{\cdot}57$ with Niño $3 + 4$ SSTAs with a lag of 0–7 months) and JJA ($c = -0{\cdot}63$ to $-0{\cdot}73$ with Niño $3 + 4$ SSTAs with a lag of 3–12 months). It is also found that most of the Q_{Pok} anomalies of the eight low flow years coincide with positive Niño $3 + 4$ SSTAs for DJF, MAM, JJA and SON (for lag -5 months), while only the years 1961 and 1965 show negative Niño $3 + 4$ SSTAs for MMA and JJA. That only positive indexes are found during the whole year may be related to the fact that ENSO events generally begin in March/April, reach their peak between December and February and decline the following March. Most of the Q_{Pok} anomalies of the six high flow years coincide with negative Niño $3 + 4$ SSTAs for all seasons (for lag -9 months). Positive Niño $3 + 4$ SSTAs can be seen in JJA, SON and DJF (1953) and in MAM and JJA (1954). A similar pattern is also found for the Q_{Pok} anomalies in MAM (for lag 7–12 months). This clearly shows that the amount of precipitation or discharge during DJF, MAM and JJA can be reduced due to El Niño events and, therefore, extending the long dry season.

CONCLUSIONS

The relationship between the discharges in the Upper Suriname River Basin and the SSTs in the tropical Atlantic (TNA, TSA and Atlantic Niño) and Pacific Atlantic (Niño $1 + 2$ and Niño $3 + 4$) are analysed for the period 1952–1985. Understanding of short-term changes and the variation in the discharge regime has been gained. The long-term annual discharge in the Upper Suriname River Basin is characterized by a negative trend, which is caused by the negative rainfall trend in the centre of Suriname.

The high monthly variation in the river discharge during the year is caused by the north–south movement of the ITCZ twice a year above Suriname. When the TNA warms up during April–August (or the TSA cools), the discharge increases due to a rise in rainfall which reaches its peak in May–June. The ITCZ is then present over all of Suriname. During September–November, the ITCZ moves to the north of Suriname over the Atlantic Ocean and the rainfall decreases. The lowest discharge is reached in October–November. In December–April, the TNA becomes cold, the TSA warm and the ITCZ is displaced southward of Suriname. The belt of rainfall is, however, much smaller than in April–August.

The annual cycle of maximum and minimum river discharges can be linked to the anomalously warm/cold SSTAs in the tropical north/south Atlantic. The low flow years may be related to a warmer TNA during the year and high flow years to a colder TNA during the year. The deficit in flow may be related to the absence of the ITCZ (southward displacement) during these years. The ITCZ is sensitive to a warm tropical Atlantic. Similar results for rainfall in South America were also reported in Ambrizzi *et al.* (2005). The results in this study also show that the river discharges may also be influenced by the Pacific SSTs through the tropical Atlantic variability, especially in December–February by the Niño $1 + 2$ SSTAs, and in June–August and September–November by the Niño $3 + 4$ SSTAs.

From the obtained results, we may conclude that regional ocean warming in the tropical Atlantic and Pacific, due to global warming, may increase the SSTs and El Niño-like conditions and, therefore, high river flows (floods) and low flows (including prolonged dry periods) in the Upper Suriname River Basin (IPCC, 2001). Further research is required to determine the role

DOI: 10.1002/hyp

of the Atlantic and Pacific SST in the rainfall in Suriname in order to better understand the interannual changes of discharges in the river basin.

ACKNOWLEDGEMENTS

Partial funding for this study was provided by the Research and Development Fund of the University of Suriname (no. Bv/FB/sw-520). We acknowledge the valuable comments of two anonymous reviewers.

REFERENCES

Acevedo M, McGregor K, Andressen R, Ramirez H, Ablan M. 1999. Relations of climate variability in Venezuela to tropical pacific SST anomalies. In *Proceedings of the 10th Symposium on Global Change Studies*, Dallas, Texas, 1999. America Meteorological Society: Annual Meeting, Dallas, TX; 81–84. http://www.ias.unt.edu/~acevedo/research/abstract/AMS99.HTM.

Ambrizzi T, de Souza EB, Pulwarty RS. 2005. The Hadley and Walker regional circulations and associated ENSO impacts on South American seasonal rainfall, In *The Hadley Circulation: present, past and future*. Diaz HF and Bradley RS (eds). Kluwer Academic Publishers: Netherlands; 203–231.

Carr R. 2000. XLStatistics 5·71. XLent Works, Australia. Retrieved August 8, 2004 from http://www.deakin.edu.au/~rodneyc/xlstats.htm.

Chiew FHS, Peel MC, Amrithanathan GE, Pegram GGS. 2005. Identification of oscillation in historical stream flow data using empirical model decomposition. In *Proceedings of Regional hydrological impacts of climate change-hydroclimatic variability*, Special Publication 296. International Association of Hydrological Sciences: Oxfordshire; 53–70.

Garzoli Z, Enfield D, Reverdin G, Mitchum G, Weisberg R, Chang P, Carton J. 1999. COSTA, Climate observing system for the tropical Atlantic, Workshop Miami, May 4–7, 1999. Retrieved July 16, 2004 from http://www.aoml.noaa.gov/phod/COSTA/.

Gianninni A, Kushnir Y, Cane M. 2000.. Interannual variability of Caribbean rainfall, ENSO and the Atlantic Ocean. *Journal of Climate* **13**: 297–311.

Haan C. 1977. *Statistical Methods in Hydrology*. The Iowa State University Press: USA; 128–311.

Helsel D, Hirsch R. 1992. Statistical methods in water resources. *Studies in Environmental Science* **49**: 208–352.

Houben L, Molenaar A. 1998. *Rehabilitation of the East-West Road Connection, causes and repair methods of road cracks in recently rehabilitated road stretch and advice on technical specifications for a planned new road (draft)*. Delft University of Technology: The Netherlands; 1–16.

Intergovernmental Panel on Climate Change IPCC. 2001. *Climate Change 2001: the Scientific Basis*. Albritton DL, Meira Filho LG, Cubasch U, Dai X, Ding Y, Griggs DJ, Hewitson B, Houghton JT, Isaksen I, Karl T, McFarland M, Meleshko VP, Mitchell JFB, Noguer M, Nyenzi BS, Oppenheimer M, Penner JE, Stocker T, Trenberth KE. (eds). WMO/UNEP: Switzerland; 1–98.

International Research Institute (IRI) 2005. ENSO information. Retrieved March 6, 2005 from http://iri.Columbia.edu/Climate/Enso/index.html.

Jones J, Changming L, Ming-Ko W, Hsiang T. 1996. *Regional Hydrological Response to Climate Change.* Kluwer Academic Publishers: Netherlands; 1–423.

Knodt R. 2003. *MODSTAT software and manual*. Bellingham: USA.

KNMI. 2005. Climate Explorer. Retrieved July 6, 2005 from http://climexp.knmi.nl.

Kundzewicz Z. 2000. Coping with hydrological extremes. *Water International* **25**(1): 66–75.

Lenselink K, van der Weert R. 1970. *Estimating free water evaporation in Suriname*. Surinaamse landbouw, Suriname; 70–79.

Lozan JL, Grassl H, Hupfer P. 1998. *Climate of the 21st Century: Changes and Risks*, GEO Publications: Hamburg, Germany; 5–448.

McCuen R. 2003. *Modeling Hydrologic Change*. Lewis Publishers CRC Press LLC: USA; 135–288.

McMichael AJ, Haines A, Epstein PR. 1996. *Climate Change and Human Health*. WMO/WHO/UNEP: London; 123–174.

Maidment DR. 1992. Hydrology. In *Handbook of Hydrology*, Maidment DR (ed). McGrawHill Inc: USA.

Mamdouh S, Oorschot van H, De Lange S. 1993. *Statistical Analysis in Water Resources Engineering*. Ashgate Pub Co.: Rotterdam, Netherlands; 1–390.

Marshall J, Kushnir Y, Battisti D, Change P, Czaja A, Dickson R, Hurrel J, McCartney M, Saravanan R, Visbeck M. 2001. North Atlantic Climate Variability: phenomena, impacts and mechanism, *International Journal of Climatology* **21**: 1863–1898.

Mol J, Resida D, Ramlal J, Becker C. 2000. Effects of El Niño-related drought on freshwater and brackish water fishes in Suriname, South America, *Environmental Biology of Fishes* **59**: 429–440.

NOAA–CIRES Climate Diagnostics Center. 2004. Climate Indices: Monthly Atmospheric and Ocean Time Series. Retrieved August 7, 2004 from http://www.cdc.noaa.gov/ClimateIndices/.

Null J. 2003. El Niño & La Niña Years: A consensus list. Retrieved August 8, 2004 from http://ggweather.com/enso/years/htm.

Nurmohamed R, Naipal S. 2004. Trends and Variation in Monthly Rainfall and Temperature in Suriname. In *Proceedings of BALWOIS Conference on Water Observation and Information System for Decision Support*, 25–29 May 2004, Ohrid, FY Republic of Macedonia.

Obasi G. 1999. *The 1997–1998 EL Niño event: a Scientific and Technical Retrospective*. WMO/UNECSO/UNEP/ICSU: Switzerland; 1–96.

Rajagopolan B, Kushir Y, Tourre Y, Cane M. 1997. *Temporal Variability of North Atlantic Oscillation and Tropical Atlantic SST*. Lamont–Doherty Earth Observatory of Columbia University: New York.

Robertson A, Mechoso C. 2002. Links between the American Ocean and the South American Climate Variability. CLIVAR Exchanges, **7** (3/4), 16–18 (Report).

Ropelewski CF, Halpert MS. 1987. Global and regional precipitation patterns associated with the El Niño/Southern Oscillation. *Monthly Weather Review* **115**: 1606–1626.

Ropelewski CF, Halpert MS. 1989. Precipitation patterns associated with the high index phase of the Southern Oscillation. *Journal of Climate* **2**: 268–284.

Ropelewski CF, Halpert MS. 1996. Quantifying Southern Oscillation—precipitation relationships. *Journal of Climate* **9**: 1043–1059.

Ross T, Lott N. 2000. *A climatology of recent extreme weather and climate events,* Technical Report No 2000-02, National Climatic Data Center, Asheville, USA.

Salas JD. 1992. Analyses and modelling of hydrological time series. In: *Handbook of Hydrology*, Maidment DR (eds). McGrawHill Inc, United States of America; 19.1–19.20.

Solomon S, Beran M, Hogg W. 1987. *The influence of climate change and climate variability on the hydrological regime and water resources,* Publication 168. International Association of Hydrological Sciences: Oxfordshire; 1–619.

Stipanek P. 2003. AnClim v4·6·23 - *Software for time series analysis*. Department of Geography, Masaryk University, Brno, Czech Republic. 1·47MB. Retrieved April 2, 2005 from http://www.klimahom.com/software/index.html.

Tamara SL, Sundquist ET, Schwartz SE, Hall DK, Fellows JD, Killeen TL. 1999. Climate Change and Greenhouse Gases. *America Geophysical Union, Earth Observing System* **80**(39): 453–463.

Turner J. 2004. The El Niño-Southern Oscillation and Antarctica. *Journal of Climate* **24**: 1–31.

Villwock A. 1998. *Clivar Initial Implementation Plan*. Retrieved March 27, 2004 from www.clivar.com/publications/othre_pubs/iplan/iip/pd2.htm.

Wang C. 2001. Atlantic climate variability and its associated atmospheric circulation cells, *Journal of Climate* **15**: 1516–1536.

Wang C. 2005. ENSO, Atlantic climate variability, and the Walker and Hadley circulations, In *The Hadley Circulation: present, past and future*. Diaz HF, Bradley RS (eds). Kluwer Academic Publishers: Netherlands; 173–202.

Webster PJ. 2005. The elementary Hadley circulation. In: *The Hadley Circulation: present, past and future*. Diaz HF, Bradley RS (eds). Kluwer Academic Publishers: Netherlands; 9–60.

Webster T, Roebuck L. 2001. *Water Resources Assessment of Suriname*. US Army Corps of Engineers: USA; 1–50.

World Meteorological Organization (WMO). 1980. *Analyzing long time series of hydrological data with respect to climate variability*, (WCAP-3); 1–12.

World Meteorological Organization. 1988. *Analyzing long time series of hydrological data with respect to climate variability* (WCAP-3) (Report); 1–12.

WMO/UNESCO. 1997. W*ater Resources Assessment—Handbook for Review of National Capabilities*. World Meteorological Organization (WMO) and United Nations Educational Scientific and Cultural Organization (UNESCO) (Report); 1–113.