Diagnoses and Prediction of Anomalous River Discharge in Northern South America

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ABSTRACT

The annual cycles of rainfall and river discharge in northern South America are dominated by the seasonal latitude migration of the intertropical convergence zone. The catchments in the west (Madden, Magdalena and Orinoco) have their high stands between August and December, while those of the Guyanas (Cuyuni, Essequibo, Suriname, Maroni and Oyapock) peak between May and July. Anomalously abundant discharge is in almost all catchments (except Orinoco) associated with the high SO phase (defined by anomalously high/low pressure at Tahiti/Darwin), weakened Caribbean tradewinds, and accelerated cross-equatorial southerly flow over the eastern Pacific.

In a series of experiments a sharp distinction was kept between a "dependent" dataset (1940–70, or the part available in the river series) used as training period and an "independent" portion of the record (1971–87) reserved for prediction. Stepwise multiple regression models for bimonthly "seasons" used as input river discharge as regressand, and as regressors, index series of Tahiti minus Darwin pressure difference, equatorial Pacific sea surface temperature PWT, zonal wind component over the Caribbean and meridional wind component over the eastern equatorial Pacific, all two seasons earlier. The resulting equations were then used to predict the discharge anomalies in the independent dataset 1971–87. There is considerable predictive skill for various rivers/seasons, with the overall best predictability for the low discharge time of year. In particular, for Magdalena 55% and for Essequibo 74% of the interannual variance of January–February discharge during 1971–87 is predictable by this method, in which for Essequibo PWT serves as sole predictor.

1. Introduction

A series of empirical investigations in the course of the past two decades (review in Hastenrath 1988a) has demonstrated close associations between the interannual variability of the large-scale circulation and rainfall anomalies in a few tropical regions, while climate anomaly mechanisms are apparently less distinct in other extensive areas of the low latitudes. In particular, effects of the Southern Oscillation (SO) are pervasive, but strong responses are found only in limited portions of the tropics. The early works of Walker and Bliss (1932) as well as the recent papers by Estoque et al. (1985), Ropelewski and Halpert (1987, 1989), Acetuno (1988, 1989) and Rogers (1988) indicate that northern South America is among the domains with a conspicuous SO signal in rainfall.

Accordingly, this region appears to be a prime "target of opportunity" for studying the general circulation functioning of extreme climatic events. Various large river systems drain this part of the continent towards the Caribbean Sea and the tropical North Atlantic (Fig. 1). Their year-to-year variations have a critical bearing on water resources management. Moreover, discharge measurements from climatically homogeneous river basins may provide indices for the interannual variability of hydrometeorological conditions over large catchments. This is an attractive option given the widespread decay of the scarce climatological station networks in the tropics over the past two decades. Hydrological series are used here as primary evidence of interannual climatic variability, although several long-term gauging series have been discontinued since the 1970s (Table 1). The objectives of the present study are to elucidate the general circulation diagnostics of anomalous river discharge in northern South America, to explore the possibility of predicting such events and to draw attention to the importance of long-term hydrological monitoring for the purposes of climate dynamics.

2. Observations

The hydrological series of selected catchments distributed from the Panama Canal Zone across northern South America to the Guyanas is most important for this study. (Fig. 1, Table 1). All of these are records of discharge, except for the water level gaugings for the Orinoco; the periods of record vary and various gauging stations have ceased to function (Table 1). Water level and discharge measuring practices are described in hydrological textbooks (Meinzer 1943; King and Brater...
For present purposes, river runoff provides an integral measure of the hydrometeorological conditions in a catchment as a whole. This is useful because existing raingauge networks are difficult to maintain and do not resolve the large spatial and temporal variability of tropical rainfall well. Over a long time span, runoff is the excess of rainfall over evaporation for the catchment. Typically, rainfall varies more strongly than does evaporation from land surfaces, both in the annual cycle and from year to year. Accordingly, river discharge is primarily a proxy for rainfall, although caution should be exercised regarding the possible consequences of human activities. The discharge lagging behind rainfall (Fig. 4) reflects a buffering effect resulting from the temporary storage in plant canopy and soil.

The pressure difference, Tahiti (18°S, 150°W) minus Darwin (12°S, 131°W), was used as an index SOI (10⁻¹ mb) of the Southern Oscillation (SO). A high SO phase is defined by anomalously high/low pressure at Tahiti/Darwin.

An index PWT (10⁻² °C) of the SST anomaly in the equatorial central Pacific (domain 2°–6°N, 90°–170°W; 2°–6°S, 90°–180°W; 6°–10°S and 110°–150°W), as described by Wright (1984), was used as another measure of the SO.

Surface ship observations in the tropical Atlantic between 30°N and 30°S (Hastenrath and Lamb 1977) for the period 1948–83 were compiled into five degree square areas, as shown in Fig. 1. Elements used here are sea level pressure (SLP), zonal (u) and meridional (v) wind components, sea surface temperature (SST) and total cloudiness (CLOUD). The COADS tapes (Oort et al. 1987), which have more recently become available, draw largely on the same source data. These were used for the compilation of indices of the zonal wind component in the domain 10°–20°N, 70°–80°W (ZON) and of the meridional wind component in the block 0°–6°N, 80°–90°W (MER) for the years 1940–87, as indicated in Fig. 1. Spurious upward trends in ship observations of wind speed, due to changing mea-
<table>
<thead>
<tr>
<th>River</th>
<th>Code (Fig. 1)</th>
<th>Gauging Site</th>
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<th>m³ s⁻¹</th>
<th>cm</th>
<th>Years</th>
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<td>X</td>
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<tr>
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<td>Pokigron</td>
<td>224</td>
<td>X</td>
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<td>1952-73</td>
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<tr>
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<td>Grand Santi</td>
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<td>OY</td>
<td>Maripa</td>
<td>850</td>
<td>X</td>
<td></td>
<td>1953-81</td>
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</tr>
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</table>

Measurement practices, have been discussed in Wolter and Hastenrath (1989). These were most pronounced in the first half of the century and may not seriously affect the analyses presented in sections 7 and 8.

The annual cycle of large-scale organized convection is documented by a novel data bank (Garcia 1985) of satellite-derived, highly reflective clouds (HRC), compiled with a one degree latitude-longitude grid resolution. Data for the years 1971–87 were obtained on magnetic tape from the Cooperative Institute for Research in Environmental Sciences (CIRES) in Boulder, Colorado. For details, refer to Garcia (1985) and Hastenrath (1990a). From this data bank, indices were compiled of the latitude position LAT (°N) and the amount AMT (days of HRC per month) of the band of maximum HRC at the longitudes of the various hydrological catchments. The longitudes for which HRC data were evaluated are as follows: Madden 81°–79°W, Magdalena 76°–74°W, Orinoco 71°–69°W, Cuyuni 61°–59°W, Essequibo 59°–57°W, Suriname 56°–54°W, Maroni 55°–53°W and Oyapock 53°–51°W.

Individual monthly means of the zonal and meridional wind components at the 850, 500, and 200 mb levels were extracted from U.S. Weather Bureau, ESSA and NOAA (1957–88) for the following five radiosonde stations in northern South America and the Southern Caribbean: Cayenne, Raizet, Maracay, Bogotá and Plesman. However, only the last station proved to possess a record long and continuous enough for purposes of the present study. The 850 mb zonal and meridional wind components over Plesman, u85 PL and v85 PL (m³ s⁻¹), are of interest here.

Monthly values of the various aforementioned elements were combined into time series of bimonthly seasons (January–February JF, March–April MA, May–June MJ, July–August JA, September–October SO and November–December ND).

3. Methods

The statistical techniques applied in this study include correlation and stepwise multiple regression (Statware Inc. 1986). Linear correlation is used to ascertain the associations of river discharge with the large-scale circulation and in particular with indicative atmospheric and oceanic fields in the tropical Atlantic and eastern Pacific (ref. section 2). The significance testing of correlation patterns is described in section 4.

The application of stepwise multiple regression to climate prediction has been described in Hastenrath (1988b, 1990b), on which the following account is based. The general regression equations are

\[ RIV = b_0 + b_1X_1 + b_2X_2 + \cdots + b_nX_n \]  (1)

where RIV is the predictand, the \( b_i \) the coefficients of the regression model, the \( X_i \) the regressors (variables in Table 2), and \( n \) the number of regressors employed in the regression model. A significance level \( \alpha \) is specified where the retained regression coefficients are accepted as different from zero.

A regression model is constructed on a “dependent” dataset, and the formula in the form of Eq. (1) thus obtained is then used in a predictive mode on an “independent” dataset. That is, the coefficients \( b_i \) are determined from a subset of the record, and these coef-
coefficients along with the observed values of $x_i$ are then entered in Eq. (1) to calculate the values of RIV for a portion of the record not used in determining the coefficients $b_i$. In an operational setting, the early portions of the record must be used to develop predictions of later years. In particular, an early time span will be used to determine the regression coefficients, while a later portion of the record is to be predicted. These portions of the record will be referred to here as the “dependent” and “independent” datasets.

Four measures are used to appraise the forecast potential: the correlation coefficient CORR between the forecast RIV' and observed RIV, the root-mean-square error RMSE, the absolute error ABSE and the bias BIAS. The aforementioned statistics are compiled as follows:

\[
\begin{align*}
\text{RMSE} & = \left[ \sum \frac{(RIV' - RIV)}{n} \right]^{0.5} \\
\text{ABSE} & = \sum \left| RIV' - RIV \right| / n \\
\text{BIAS} & = \sum (RIV' - RIV) / n,
\end{align*}
\]

where the summation extends over the forecast years.

Regarding the significance testing of correlation coefficients, it should be noted that geophysical time series are not, as a rule, serially independent. Therefore, Quenouille's (1952) method was used to account for the reduction of the effective number of degrees of freedom due to persistence. This is based on the lag autocorrelation of the time series.

4. Significance testing of correlations patterns

In the testing of the patterns of correlation with the various RIV series two steps are distinguished as described in Hastenrath et al. (1987). At a first level of testing, the local significance of individual correlation coefficients was ascertained using the Fisher $z$ transformation, choosing the conventional 5% significance level and using Quenouille’s (1952) method to account for the reduction of effective degrees of freedom in the time domain due to persistence.

At a second level of testing, the field significance of correlation patterns was determined through Monte Carlo simulations following a procedure similar to that explained in Livezey and Chen (1983). Of the total number $N_F$ of individual correlations, $N$ reach the local significance at the 5% level. The field significance at the 5% level is exceeded when $N$ surpasses $N^*$, where $N^*$ is 95 percentile of the number of locally significant correlations in a field correlated with random series with statistical characteristics as the original RIV series.

The procedure for field significance testing consists of two steps. In the first step, assume no spatial interdependence. The $N^*$ is equal to the 95 percentile of binomial distribution with $N$ trials and success probability $p = 0.05$ (Livezey and Chen 1983). If $N$ does not exceed $N^*$ the pattern does not possess field significance at the 5% level, and the procedure is terminated. Otherwise proceed to the second step in which the spatial interdependence within the field is accounted for. Except for the altered sequence of elements, the original RIV series is randomly scrambled so as to produce random series with statistical properties identical to the original RIV series. In 500 Monte Carlo experiments, such randomly scrambled RIV series are correlated with the particular field.

This yields 500 values of the numbers $N_{mc}$ of locally significant correlations. When $N$ exceeds the 95 percentile $N^*_{mc}$ of empirically determined $N_{mc}$'s, the pattern is considered to possess field significance at the 5% level. Field significance at the 5% level, determined as described above, will in section 7 be referred to in short as “field significance.”

5. Annual cycle of circulation, rainfall, and river discharge

The large-scale circulation setting of the tropical Americas is described in various earlier publications (e.g., Hastenrath 1966, 1967; Snow 1976; Hastenrath...
and Lamb 1977), and a brief summary must suffice here.

Throughout the year (Fig. 2), the northeast trades emanating from the North Atlantic high sweep over the Caribbean Sea into northern South America and across the Central American land bridge into the eastern Pacific to meet the cross-equatorial flow from the Southern Hemisphere along a confluence line embedded within a trough of low pressure located year round to the north of the equator. Further contained in this near-equatorial low pressure trough is a band of maximum convergence, convection, cloudiness and rainfall (intertropical convergence zone, ITCZ) located to the south of the wind confluence. At the height of the boreal winter (Fig. 2a and 2c) the axis of the North Atlantic subtropical anticyclone is located relatively far south, the trade inversion is well developed, and the trade winds blow vigorously across the Central American Isthmus. Along with the extreme southerly position of the near-equatorial wind confluence (Fig. 2a), the band of maximum convection is found relatively far south (Figs. 2c and 3). This is the dry season in much of the Caribbean and northern South America (Figs. 3 and 4). Proceeding toward the height of the boreal summer (Fig. 2b and d), the North Atlantic anticyclone migrates northward, the trade inversion weakens, and the trade wind airstream deepens. The ITCZ over the eastern Pacific attains its northernmost position around June and September–October, with some southward shift in July–August, but this double latitude variation is not found in the Atlantic sector. The latitude range of the ITCZ in the course of the year broadly increases eastward, and its southward retreat after September tends to be rapid over the eastern part of the continent (Fig. 3).

The seasonal latitude migration of the ITCZ (Figs. 2 and 3) is of particular interest in relation to the annual cycles of rainfall (Fig. 3) and hence river discharge (Fig. 4) in northern South America. In the following, the various hydrological catchments shall be considered proceeding from west to east (Table 1, Figs. 1, 3, 4).

The Madden Reservoir (Fig. 3a) is, throughout the year, located well to the north of the zone of maximum convective cloudiness, but receives its most copious rainfall from May to November when the maximum convection belt hovers around its northermmost position and when it is most intense. At the longitudes of the seven other river catchments (Fig. 3b–h) the intensity of the HRC maximum varies much less throughout the year. Apart from a secondary August
maximum related to a bimodal precipitation march, discharge from the Madden Reservoir is largest in November (Fig. 4a), broadly concordant with the main rainfall maximum. The Magdalena River basin experiences a double passage of the maximum convection belt in the course of the year, and concomitantly rainfall peaks in April–May and October–November (Fig. 3b). With a slight lag, the corresponding discharge maxima occur in June and November–December.

The most important hydrometeorological portion of the Orinoco River catchment extends northward to near the northernmost seasonal excursion of the zone of maximum convective cloudiness (Fig. 3c). The May–July rainy season peak broadly coincides with the northward sweep of the convection zone over the catchment. With some lag commensurate with the size of the catchment, the highest water level is reached in August (Fig. 4c). Proceeding farther eastward into the Guyanas, the latitude range of the seasonal ITCZ migration increases substantially, and the catchments of the Cuyuni, Essequibo, Suriname, Maroni, and Oyapock Rivers (Fig. 3d–h) experience the passage of the maximum convection belt both on its northward and southward sweeps. However, just as for the Orinoco basin, only the northward advance of this convection maximum is associated with a rainfall peak; in May–June for Essequibo and in May for the other catchments. The maximum of river discharge follows with some lag in July at the Cuyuni and Essequibo (Fig. 4d–e), while for the other smaller rivers (Fig. 4) discharge and precipitation maxima broadly coincide in May. In synthesis, the latitudinal migration of the ITCZ throughout the year appears to provide a major control for the annual cycle of rainfall and water discharge in the various hydrological catchments of northern South America.

6. Interannual variability of river discharge

Figure 5 illustrates the interannual variability of hydrometeorological conditions in the various river basins of northern South America. Values are represented for the respective month of maximum discharge/water level in the average annual cycle, normalized with respect to a fixed base period. The correlations between the various hydrological series are further presented in Table 2. Figure 5 and Table 2 show that the river basins

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**Table 2:**

<table>
<thead>
<tr>
<th>River Basin</th>
<th>Correlation with Rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cuyuni</td>
<td>High</td>
</tr>
<tr>
<td>Essequibo</td>
<td>Low</td>
</tr>
<tr>
<td>Suriname</td>
<td>Moderate</td>
</tr>
<tr>
<td>Maroni</td>
<td>Low</td>
</tr>
<tr>
<td>Oyapock</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

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**Fig. 3.** Annual cycles of the maximum of highly reflective clouds (HRC, period 1971–87; source: Garcia, 1985) at longitudes of catchments of (a) Madden MD, (b) Magdalena MG, (c) Orinoco OR, (d) Cuyuni CU, (e) Essequibo ES, (f) Suriname SU, (g) Maroni MR, (h) Oyapock OY, (ref. Fig. 1). Solid line and left-hand scale denote the latitude of the maximum (°N and S), and dotted line and right-hand scale amount (number of days per month). Horizontal broken lines indicate latitudinal extent of catchments. Dot raster in vertical columns (source: Snow 1976) marks the months of rainy season peaks.
from the Orinoco eastward, which reach their high stands in boreal summer, tend to strongly co-vary. Very different interannual variations are indicated for Magdalena and Madden, which stand highest in the early part of the boreal winter semester. Progressing from west to east, the various river basins thus show an overall plausible pattern of spatial coherence. In addition, some differences between basins may be due to "noise" such as deficiencies in observations or effects of human activities.

7. Circulation diagnostics

The purpose of this section is to ascertain the large-scale circulation departures associated with anomalous river discharge in northern South America. Since the average annual march of discharge in this region is to a large extent controlled by the seasonal latitude migration of the ITCZ (ref. section 5), anomalies of ITCZ position are of foremost interest here. These are in part, but not exclusively, related to the SO (Hastenrath 1976; Hastenrath et al. 1987; Aceituno 1988). Based on these considerations, the following circulation indices detailed in section 2 were given particular attention; zonal wind component within the speed maximum (Hastenrath and Lamb 1977, charts 14–25) over the western Caribbean (ZON) representing the strength of the tradewind easterlies; meridional wind component in a strip of the equatorial eastern Pacific (MER) as a measure of the cross-equatorial flow from the Southern Hemisphere; Southern Oscillation pressure index SOI; index of SST anomaly in the equatorial central Pacific (PWT); latitude (LAT) and amount (AMT) of the band of maximum of highly reflective clouds; and upper-air zonal and meridional wind components at radiosonde stations in northern South America. Furthermore, the fields of surface pressure, wind, SST and cloudiness were analyzed in relation to the interannual variations of river discharge.

Table 3 shows the relationship of anomalous river discharge with interannual variations of key circulation parameters. Given the typical time lag of hydrological catchments, the correlations of river series, with the preceding season’s circulation indices, approximately reflect simultaneous associations of rainfall and circulation anomalies.

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Fig. 4. Annual cycles of river hydrology and rainfall for catchments of (a) Madden MD, (b) Magdalena MG, (c) Orinoco OR, (d) Cuyuni CU, (e) Essequibo ES, (h) Suriname SU, (g) Maroni MR, Oyapock OY (ref. Fig. 1). Solid lines join monthly values expressed as percentage departures from the annual mean indicated by horizontal broken line; being discharge (m$^3$ s$^{-1}$) except for water level (m) at Orinoco. For MD, MG, OR, period is 1948–83, but for ES 1950–83, CU 1946–82, SU 1952–73, MR 1953–77 and OY 1953–81. Dot raster in vertical columns (source: Snow 1976) marks the months of rainy season peaks.
With these qualifications, Table 3 indicates for Madden Reservoir abundant water supply in the latter part of the boreal summer semester during the high SO phase with weakened tradewind easterlies over the Caribbean, which is consistent with a northward displaced ITCZ characteristic of the high SO phase (Hastenrath et al. 1987). There is also some indication of an enhanced and northward displaced convection band during years of abundant water supply.

Magdalena, which experiences its maximum around the same time of year as Madden, exhibits particularly strong positive correlations with SOI, ZON, MER, and \( u_{85} \) PL as well as a strong negative correlation with PWT (Table 3). These correlations can be interpreted as bearing out for years of copious discharge a high SO phase with weakened tradewind easterlies over the Caribbean and accelerated cross-equatorial flow over the eastern Pacific. This is indicative of a northward displaced ITCZ, as it is characteristic of the high SO phase in boreal summer (Hastenrath et al. 1987).

Orinoco, which reaches its maximum earlier in the year than Madden and Magdalena, shows little relation to the selected circulation parameters (Table 3). This may be due to the location of the catchment area, noise in the hydrological series, or other factors. Cuyuni and Essequibo, situated to the East of the Orinoco watershed, reach their maximum around the same time of year. Essequibo exhibits significant correlations (Table 3) that can again be interpreted as indicating for summers with abundant river discharge a high SO phase and accelerated cross-equatorial flow over the eastern Pacific, consistent with a northward displaced ITCZ.

The other three rivers of the Guianas, namely Suriname, Maroni, and Oiapock, reach their largest discharge at approximately the same time of year and earlier than the rivers farther west. Correlations are weak, although enhanced discharge is indicated for the years of high SO phase. For Suriname and Maroni, no correlation coefficients are given with LAT and AMT because of the short overlap of the river and HRC series (Ref. Table 1). Also noteworthy are the significant correlations of Oiapock with MER and AMT.

Expanding on the exploration of near-simultaneous associations with selected circulation indices in Table 3, the hydrological series of the calendar months of maximum discharge were correlated with the same or the immediately preceding season's fields of SLP, \( u \), \( v \), SST, and CLOUD in the tropical Atlantic and eastern Pacific. The field significance of correlation patterns was ascertained by Monte Carlo experiments as described in section 4. For only three of these sets, in which field significance was reached for all five aforementioned elements, are correlation patterns reproduced here (Figs. 6–8).

As apparent in Fig. 4a, Madden discharge reaches a first peak in August and the main maximum in No-
TABLE 3. Coefficients of correlation (in hundreths) between river discharge/water levels (ref. Table 1 and Fig. 1) at indicated season of maximum and various circulation patterns in preceding season. Period is 1940–87 except as indicated. One and two asterisks denote significance at the five and one percent levels, respectively. SOI Southern Oscillation pressure index; PWT index of sea surface temperature in equatorial central Pacific (domain 2–6°N, 90–170°W); 2°N–2°S, 90–180°W; 6–10°S, 110–150°W). ZON surface zonal wind component in domain 10–20°N, 70–80°W; MER surface meridional wind component in domain 0–6°N, 80–90°W; LAT latitude of maximum of highly reflective clouds (1971–87); AMT amount of maximum of highly reflective clouds (1971–87); u85 PL 850 mb zonal wind component over Plesman (1957–87); v85 PL 850 mb meridional wind component over Plesman (1957–87).

<table>
<thead>
<tr>
<th>River</th>
<th>Season</th>
<th>SOI</th>
<th>PWT</th>
<th>ZON</th>
<th>MER</th>
<th>LAT</th>
<th>AMT</th>
<th>u85 PL</th>
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November. Correlation patterns for November are similar but overall weaker than those for August, and only the latter are displayed here in Fig. 6. This maps the patterns of correlation between Madden August discharge and indicative atmospheric and oceanic fields in July–August. The SLP correlation map (Fig. 6a) shows significant negative values over much of the tropical North Atlantic and the adjacent Caribbean, contrasting with strong positive correlations over the eastern Pacific. Positive \( u \) correlations (Fig. 6b) dominate the Caribbean and the eastern Pacific where positive \( v \) correlations (Fig. 6c) also prevail. With reference to the climatic mean patterns (Hastenrath and Lamb 1977, charts 8, 9, 21, 22), these maps indicate for abundant Madden discharge weakened pressure gradients across the Central American Isthmus, weakened tradewind easterlies over the Caribbean, and accelerated southwesterly wind component over the equatorial eastern Pacific. All features are characteristic of the high SO phase in boreal summer (Hastenrath et al. 1987). Likewise, typical of both abundant Madden discharge and the high SO phase (Hastenrath et al. 1987) are the anomalously cold eastern Pacific waters indicated in Fig. 6d. Note that Madden discharge is positively correlated with the SO (Table 3). Finally, the cloud correlation map (Fig. 6e) shows significant positive correlations over the Gulf of Panama that are consistent with increased cloudiness accompanying enhanced Madden discharge.

Figure 7 presents the correlation maps between Magdalena November discharge and atmospheric and oceanic fields in September–October. Given the significant positive correlation of Magdalena discharge with the SO, it is not surprising that the panels of Fig. 7 resemble the major features of the SO correlation patterns of boreal summer (Hastenrath et al. 1987). Likewise, the pattern characteristics of Fig. 7 for Magdalena are similar to those of Fig. 6 for Madden. Thus, the SLP correlation map (Fig. 7a) shows significant positive values over the eastern Pacific that contrast with negative correlations over the low-latitude Atlantic and the Caribbean, or a modification of the pressure gradient pattern over the southwestern Caribbean similar to Fig. 6a. Figures 7b and c show significant positive \( u \) and \( v \) correlations over the southwestern Caribbean and the neighboring eastern equatorial Pacific, indicating that abundant Magdalena discharge weakened Caribbean tradewinds and enhanced southwesterlies over the Gulf of Panama. Figure 7d bears out for abundant Magdalena discharge anomalously cold waters in the eastern Pacific, which are also typical of the high SO phase and consistent with the positive correlation between Magdalena discharge and SOI (Table 3). The cloud correlation map (Fig. 7e) indicates for abundant Magdalena discharge enhanced cloudiness over the southwestern Caribbean and eastern Pacific, or a domain surrounding the Magdalena watershed.

Figure 8 shows the patterns of correlation between Essequibo July discharge and atmospheric and oceanic fields in May–June. While Essequibo has a significant positive correlation with the SO (Table 3), it should be noted that May–June falls into the transition between the contrastingly different SO correlation patterns of boreal winter and summer. The SLP correlation map (Fig. 8a) shows significant positive correlations extending from the eastern Pacific across the Caribbean into the North Atlantic, similar to the SO correlation pattern of boreal winter (Hastenrath et al. 1987). The \( u \) and \( v \) correlations maps (Fig. 8b,c), while overall field significant, show locally significant correlations in areas distant from the Essequibo watershed. Negative SST correlations (Fig. 8d) prevail in the Eastern Pacific and the North Atlantic, similar to the correlations with the SO (Hastenrath et al. 1987). The field significant panel of cloudiness correlations (Fig. 8e) exhibits no details of obvious relevance to the Essequibo catchment.

From this diagnostic exploration for the eight hydrological basins it is apparent that Madden and Magdalena, which reach their high stand in November—
December, are most conspicuously associated with anomalies in the large-scale circulation. Discharge from these catchments tends to be most abundant in the high SO phase with weakened Caribbean trade winds and accelerated cross-equatorial flow over the eastern Pacific. Proceeding eastward, the annual cycles of rainfall and river level reach their maxima in May–July and August–September, respectively, for the Orinoco. In the river catchments of the Guayanas, yet farther East, rainfall and discharge maxima occur even earlier in boreal summer. Associations of discharge anomalies with the large-scale circulation are most distinct for the Essequibo, which also shows the most copious discharge during the high SO phase.

8. Prediction

In this study the record 1940–70, or the part thereof available for the river series, was used as “dependent” dataset or “training period” to develop regression models. In particular, the training period consisted of 1940–70 for Madden, Magdalena, and Orinoco, but of 1946–70 for Cuyuni, 1950–70 for Essequibo, and 1953–70 for Oyapock (ref. Tables 1 and 4). Suriname and Maroni, whose records extend little beyond 1970 (ref. Table 1), were not considered for the development of regression and prediction models. The record from 1971 onward was reserved as “independent” dataset for prediction experiments. Thus, the independent dataset encompassed 1971–87 for Madden, Magdalena, Orinoco and Essequibo but was limited to 1971–82 for Cuyuni and to 1971–81 for Oyapock (ref. Tables 1 and 4).

Regarding phase relationships, it is interesting to note that some rivers/seasons reach their highest correlation with SOI of the same or even following seasons, as was also reported by Aceituno (1988) for Magdalena. Likewise, Indian monsoon rainfall anomalies are correlated more strongly with the subsequent rather than the preceding phase of the SO (Wu and Hastingrath 1986). Thus, rainfall may actually presage subsequent atmospheric developments more effectively than being determined by the antecedent circulation conditions itself. However, this is not helpful for the present objectives of predicting anomalous river discharge.

With a view toward practical usefulness, the effort was directed towards the prediction of discharge anomalies from information two seasons ahead. It seemed most relevant to explore the predictability of discharge at the extrema of the average annual cycle, but in addition the forecasting potential was also ex-
Fig. 7. Patterns of correlation between Magdalena November discharge and September–October values of indicated elements during 1948–83. Catchment area (ref. Fig. 1) is indicated by thin solid line. Other symbols are as for Figs. 6–8.

Fig. 8. Patterns of correlation between Essequibo July discharge and May–June values of indicated elements during 1950–83. Catchment area (ref. Fig. 1) is indicated by thin solid line. Other symbols are as for Figs. 6–8.
The regression models to which this element was not offered as input (pure climate prediction).

Table 4 shows the entrance levels \( \alpha \) at which the various regressors were admitted into the model. These are given in the steps 5%, 10%, and 15%, and in greater detail beyond that. As a rule, no regressor was admitted at \( \alpha \) larger than 20%. An apparent exception is PWT in model 4, which entered first at the 5% level, was then removed, and subsequently entered again at 25%.

The variance explained by the resulting regression models ranges from 14% to 64%. Only for Magdalena and to a lesser extent for Essequibo, with their strong annual cycle persistence of water discharge, is the inclusion of RIV found helpful. The coefficients of the 16 regression models [ref. Eq. (1)] are listed in Table 5. The sign of the coefficients is interesting in context with the diagnostic relationships discussed in section 7. Not surprisingly, coefficients are all positive for RIV, reflecting the seasonal persistence of water discharge. Coefficients of SOI are positive and those of PWT are negative (with one exception), consistent with enhanced discharge during the high SO phase. It is interesting to note that the one positive PWT coefficient in model 4 (Table 5) is related to a rather large entrance level \( \alpha \) (Table 4), and in fact resulted in an exceedingly large dropoff of the percentage of explained variance from the dependent to the independent record (Table...
TABLE 5. Coefficients a and b, of regression models Eq. (1). Shown in bold print are models 4, 13, 14, and 16, for which scatter diagrams are displayed in Figs. 9–11. Regressors are: river discharge RIV (m$^3$ s$^{-1}$); pressure difference Tahiti minus Darwin SOI (10$^{-4}$ mb); equatorial Pacific sea surface temperature anomaly PWT (10$^{-3}$ °C); zonal wind component over western Caribbean ZON (m s$^{-1}$); meridional wind component over equatorial eastern Pacific MER (m s$^{-1}$).

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TABLE 6. Forecast performance. Shown in bold print are models 4, 13, 14, and 16, for which scatter diagrams are displayed in Figs. 9–12. Predictors are: river discharge/water level RIV (m$^3$ s$^{-1}$); pressure difference Tahiti minus Darwin SOI (10$^{-4}$ mb); equatorial Pacific sea surface temperature anomaly PWT (10$^{-3}$ °C); zonal wind component over western Caribbean ZON (m s$^{-1}$); meridional wind component over equatorial eastern Pacific MER (m s$^{-1}$); CORR = correlation coefficient between predicted and observed river discharge, in hundredths; RMSE = root-mean-square error; ABSE = absolute error; BIAS = bias. For CORR and BIAS, one and two asterisks indicate significance at the 5% and 1% levels, respectively.

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4). Coefficients of ZON and MER are positive throughout (Table 5) reflecting the reduced Caribbean tradewinds and accelerated cross-equatorial flow over the eastern Pacific characteristic of enhanced river discharge.

Turning to prediction, the regression models (Table 5) developed from the training period were then used to calculate discharge for the independent part of the record (1971–87 or portion thereof). The percentage variance explained by the forecast is listed in Table 4 and the forecast performance is further detailed in Table 5. All 16 models show skill, but the forecast performance varies over a considerable range. Overall, apart from Orinoco, the predictability is least for Maden and Cuyuni but remarkably large for Magdalena, Essequibo, and Oyapock.

For Magdalena, the January–February season of low discharge is found most predictable, especially when use is made of the antecedent river conditions (climate plus hydrological forecasting; model 4). The forecast performance of model 4 is illustrated in the scatter diagram Fig. 9. More than half of the interannual variability of January–February discharge can be predicted from antecedent atmospheric–oceanic and river conditions, and RMSE, ABSE, and BIAS, are moderate (Fig. 9, Table 6).

For Essequibo, it is again the January–February season of low water stand which is most predictable, although the potential is also considerable for other seasons. Strong forecast performance is achieved with models (13) and (14), as is illustrated in the scatter diagrams Figs. 10 and 11. Model (13) benefits from

---

**Figure 9.** Scatter diagram of forecast versus observed Magdalena January–February discharge ($m^3/s$). Numbers indicate the years and dotted line 45 degree angle; model 4 (ref. Tables 4–6). Regression base period 1940–70 (mean 5,459 $m^3/s$), forecast period 1971–87. RMSE = 1,314; ABSE = 1,059; BIAS = +108, all in $m^3/s$; CORR = +0.74, significant at the 1% level.

**Figure 10.** Scatter diagram of forecast versus observed Essequibo January–February discharge ($m^3/s$). Numbers indicate the years and dotted line 45 degree angle; model 13 (ref. Tables 4–6). Regression base period 1950–70 (mean 1,153 $m^3/s$), forecast period 1971–87. RMSE = 471, ABSE = 396, BIAS = +334, all in $m^3/s$; CORR = +0.84, significant at the 1% level.

**Figure 11.** Scatter diagram of forecast versus observed Essequibo January–February discharge ($m^3/s$). Numbers indicate the years and dotted line 45 degree angle; model 14 (ref. Tables 4–6). Regression base period 1950–70 (mean 1,153 $m^3/s$), forecast period 1971–87. RMSE = 256, ABSE = 206, BIAS = +72, all in $m^3/s$; CORR = +0.86, significant at the 1% level.
the hydrological persistence (RIV) in addition to the atmospheric predictors SOI and MER. This model is able to predict 71% of the interannual variance of January–February discharge (Tables 4 and 6) but suffers from a significant positive bias (Table 4 and Fig. 10). Model (14), using PWT as sole predictor, performs even better by predicting 74% of the variance (Tables 4 and 6) without significant bias. The relative merits of models (13) and (14) should be weighed further with reference to Tables 4 and 6. While model (13) has the drawback of producing a significant positive bias (Table 6), it appears relatively stable in that the explained variance is similar for the training period 1950–70 and for the forecast period 1971–87 (Table 4). By comparison model (14), which produces a larger explained variance without significant bias (Table 6), appears less stable in that the explained variance is much smaller for the training period 1950–70 than for the forecast period 1971–87 (Table 4). A type (14) model would presumably perform less well prior to 1971. It is suggested that the recent portion of the record may be more predictable because of better observations and intrinsically closer climate-circulation relationships.

For Oyapock January–February proves particularly predictable as for Magdalena and Essequibo, although the minimum in the annual cycle of discharge occurs somewhat earlier here, namely around November (Fig. 4). The forecast performance of model 16 is illustrated in the scatter diagram Fig. 12. Without information on antecedent river conditions, approximately half of the interannual variance of January–February discharge can be predicted well in advance, and RMSE, ABSE, and BIAS are small. As for models (4) and (14), high discharge cases tend to be somewhat underpredicted (Figs. 9, 10, and 12).

It is interesting to compare the forecast performance summarized in Table 6 with that of mere hydrological persistence. The performance of forecasts for January–February discharge from the September–October discharge values is shown in Table 7, part a, for the four rivers listing January–February predictions in Table 6. For Magdalena, Table 7 indicates a somewhat larger explained variance but a much larger positive bias than model (4) in Table 6. For Cuyuni, the performance is similar to model (11) in Table 6. For Essequibo, Table 7 gives a smaller explained variance and a much larger bias than model (14) in Table 6. For Oyapock, the explained variance is much lower and the bias little less than for model (16) in Table 6. Correlations of January–February discharge with the preceding November–December values are somewhat larger than with September–October, except for Magdalena and Essequibo (Table 7, parts c and a). Finally, correlations with the discharge anomalies in the preceding year’s January–February (Table 7, part c) are very small and for the very short Oyapock series even negative.

In synthesis, there is considerable prospect for the prediction of anomalous discharge of certain rivers/seasons from information available over the entire 1940–87 record. In particular, PWT can be produced in near real time (Hastenrath 1990b), which by itself

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Table 7. Performance of forecasts of January–February discharge. (a) as sole predictor the September–October discharge; CORR = correlation coefficient between predicted and observed river discharge, in hundredths; RMSE = root-mean-square error; ABSE = absolute error; BIAS = bias. (b) CORR with preceding November–December discharge. (c) CORR with preceding January–February discharge. For CORR and BIAS, one and two asterisks indicate significance at the 5% and 1% levels, respectively.
opens the prospect of predicting Essequibo January–February discharge on an operational basis.

9. On the potential of further predictors

An attempt was made to estimate the possible predictive usefulness of LAT, AMT, u85 PL, and v85 PL (ref. section 2) in addition to the elements SOI, PWT, ZON, and MER, available over the entire 1940–87 record and used as predictors in section 8. To that end, regression experiments were conducted over the period 1971–87 using as input all eight of the aforementioned elements, as well as RIV. Based on these experiments, it is suggested that HRC and Plesman upper-air winds may provide additional information useful for predictive purposes, when these records expand.

10. Conclusions

The World Climate Program (World Meteorological Organization 1980) identified climate prediction as a central objective. For the tropics, essential progress has been made in the course of the 1980s with empirically-based methods which combine extensive investigations of general circulation diagnostics with statistical analysis (Hastenrath 1986, 1990c). A sound empirical understanding also appears basic for the possible future application of atmosphere-ocean numerical models to climate prediction. An immediate challenge in tropical climate prediction are now “targets of opportunity” where interannual rainfall variability is prevailing controlled by anomalous behavior of well-defined quasi-permanent components of the large-scale circulation. Northern South America is such a region because it receives much of its precipitation from the convective activity in the ITCZ and its interannual variability exhibits a strong association with the Southern Oscillation. Moreover, river discharge series available for this region provide a useful measure of the hydrometeorological conditions over large catchment areas.

The diagnostic analyses in the present study confirm for the catchments in the western portion of the region, which receives much of its rainfall between May and November, that abundant water discharge is accompanied by weakened Caribbean tradewinds and accelerated cross-equatorial flow over the eastern Pacific. These circulation features reflect a northward displaced ITCZ, which is characteristic of the high SO phase in boreal summer (Hastenrath et al. 1987) and which is furthermore consistent with the positive correlations between the SO and river discharge. In the river catchments of the Guyanas, where most of the precipitation falls from April to July, variations of discharge are less conspicuously associated with those of the surface wind field over the Caribbean and the eastern Pacific. However, even here abundant discharge occurs in the high SO phase.

Regression equations developed from observations up to 1970 bear out the aforementioned diagnostic circulation-discharge relationships and were used in a predictive mode to predict discharge anomalies for the years from 1971 onward. With a view towards practical usefulness, river discharge was predicted from information two (bi-monthly) seasons ahead. Prospects were examined for both pure climate prediction (no antecedent river information) and combined climate and hydrological prediction. For most river/seasons there is considerable predictive skill, and overall, this is best for the time of year with low discharge. More than a third of the interannual variance of January–February discharge of the Magdalena can be predicted from the antecedent atmospheric–oceanic conditions and more than half can be predicted if antecedent river information is used as well. Similarly, for Oyapock, approximately half of the variance is predictable without use of river information. Essequibo discharge was found to be highly predictable; in particular, 74% of the interannual variance of January–February discharge can be predicted from the antecedent SST anomalies in the equatorial central Pacific alone. As this information is now available in near real-time, operational prediction of Essequibo discharge appears feasible. Viewed in perspective, the prospects for seasonal prediction in northern South America compare favorably with other “targets of opportunity” throughout the tropics.

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REFERENCES


Statware Inc., 1986: STAT 80 TM for Apple Macintosh, professional version, release 2.10., version 1.0. Salt Lake City, Utah, 521 pp. [Available from Statware Inc., P.O. Box 510881, Salt Lake City, Utah 84151]


