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Climate teleconnections to Yangtze river seasonal streamflow at the Three Gorges Dam, China

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Abstract:

In this study, we identify climatic influences on summer monsoon inflow to the Three Gorges Dam (TGD) in the Yangtze River Basin and use indices of these influences to predict streamflow one season ahead. Summer monsoon streamflow at Yichang hydrological station (YHS) was analyzed for the period 1882–2003. Statistical analysis was used to develop a predictive model for summer streamflow using preceding climate variables. Linear correlation maps were constructed using 3-month ahead climate fields to identify regions that exhibit teleconnections with streamflow at Yichang. The analysis revealed regions in the eastern Indian and western Pacific Oceans that influence YHS streamflow. These regions and variables are consistent with those identified by previous studies of regional rainfall. In addition, snow cover in the Yangtze upland region provides predictive skill, likely due to snowmelt contributions to streamflow. A regression model for prediction using these indices provides a prediction R^2 greater than 0.5, which is robust under the ‘leave one out’ cross-validation. A skillful prediction can provide guidance for water management in the Yangtze River Basin, e.g. the Three Gorges Dam and future projects for South-to-North water transfer. Copyright © 2006 Royal Meteorological Society

KEY WORDS climate indices; streamflow prediction; regression analysis; Three Gorges Dam; Yangtze (Changjiang) River

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INTRODUCTION

Water is a vital resource for human as well as natural ecosystems. The availability of water is greatly influenced by climate conditions that vary on seasonal, interannual, and decadal time scales. Characterization of hydrological variability on climate timescales and identification of connections to climate forcings provide potential improvement for hydrologic forecasts when the climate forcings are predictable or slowly evolving (Souza and Lall, 2003; Croley, 2003; Hamlet and Lettenmaier, 1999). Climate-based forecasts of hydrologic variables benefit water resources decision-making, such as reservoir release decisions (Hamlet *et al.*, 2002; Westphal *et al.*, 2003; Kim and Palmer, 1997).

A better understanding of the teleconnections between climate anomalies and runoff provides opportunities for improving predictability of runoff in some regions of the world (Hamlet and Lettenmaier, 1999). Many researchers have investigated the statistical relationship between

hydrologic variables and climate signals, finding them useful for hydrologic forecasting (Piechota and Dracup, 1999; Gutierrez and Dracup, 2001; Hidalgo and Dracup, 2003; Schär, *et al.* 2004). Some recent international studies include Chiew *et al.* (1998) for rainfall and streamflow in Australia, Harshburger *et al.* (2002) for rainfall and streamflow in Idaho, Fowler and Kilsby (2002) for northern England, and Karamouz and Zahraie (2004) for the Salt River Basin in Arizona. In addition, snow cover (SNOW) and depth have been found to enhance the forecasting of surface runoff where snow is a significant component of streamflow (Linsley and Ackerman, 1942; Church, 1937; Maurer *et al.*, 2004). The study by Maurer *et al.* (2004) combined climate teleconnections and snow measurements to investigate the predictability of streamflow over North America, and found skill up to one year ahead in some cases. However, in the literature there are no previous analyses that investigate the predictability of water resources in China, or specifically the Yangtze River, which are critical to the development of China.

Various reports on the water resources and management issues in China have emerged recently, highlighting the acute challenges that loom (e.g. McCormack, 2001; Xia

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and Chen, 2001; Zhang and Zhang, 2001; Varis and Vakkilainen, 2001; Lu, 2004; Xu *et al.*, 2004a,b, 2005). Considering the significant water constraints in China, a strategy to more efficiently manage large water projects using seasonal to interannual water supply forecasts is critical. In this paper, we attempt to identify major modes of variability in global climate variables that may be used to produce seasonal forecasts of Yangtze River streamflow. Such forecasts may aid in the management of the flow of the Yangtze River in the current era of new infrastructure development and fast growing demand for water.

The Yangtze river is the third longest river in the world, extending about 6300 km from the Qinghai–Tibet Plateau eastwards to the East China Sea, with a drainage area of $1.8 \times 10^6 \text{ km}^2$, which is nearly 20% of the total area of China (Figure 1). The basin accounts for 35% of the national production, 24% of the national arable land, and 32% of the national gross output of agriculture. The rice harvest in the basin comprises 70 to 75% of the national total. Moreover, the economic benefits from the whole Yangtze River basin amounted to almost half the GNP of China in the 1990s (National Bureau of Statistics, 2002). About 400 million people live in this catchment and many face the risk of floods.

The Yangtze River has experienced severe floods in the course of history, and notable events in the 20th century occurred in 1924, 1926, 1931, 1935, 1948, 1949, 1954, 1983, 1991, 1996, 1998, and 1999. The great

flood of the summer of 1998 was an extremely serious basin-wide disaster and was one of the worst natural disasters recorded (3700 deaths, 223 million people displaced, and up to \$30 billion worth of property damaged) in the Yangtze River basin. There appears to be a link between major floods and warm El Niño–Southern Oscillation (ENSO) events. Major floods were noted in 1924, 1926, 1931, 1954, 1991, and 1998, and each of these has been described as an El Niño year.

There are many studies focused on climate scale dynamics that characterize rainfall in the Yangtze basin. Many of these studies examine the notable relationship between Pacific sea-surface temperature (SST) and summer monsoon rainfall. Chang *et al.* (2000 a,b) provide a summary of this work. Strong summer monsoons appear to follow El Niño conditions in the preceding winter and winter La Nina conditions are followed by weak monsoons. Interdecadal variation has been identified in several studies and several studies document the changes in anomaly patterns in the mid or late 1970s (Yang and Lau, 2004; Gong and Ho, 2002). Since that time, northern China has received less June–July–August (JJA) rainfall while southeast China has received more (Gong and Ho, 2002). This regime change may be linked to SST forcing in the western Pacific and Indian Oceans. Yang and Lau (2004) found a strong link between SSTs in this area and JJA rainfall in central eastern China and posit that the decadal variations in rainfall are driven by similar variations in SSTs. Our analysis of Yangtze streamflow

Figure 1. Location of the Yichang hydrological station in the Yangtze River basin.. This figure is available in colour online at www.interscience.wiley.com/ijoc

revealed similar links with the ocean state as documented in the above studies of rainfall.

DATA SOURCES AND METHODOLOGY

Data sources

The streamflow data for this study were recorded at the Yichang hydrological station (YHS, 111.28°E, 30.70°N, Figure 1). The streamflow data at YHS before 1987 were extracted from the China Hydrological Yearbooks, which summarize measurements from a network of hydrographic stations throughout the Yangtze River catchment. The original records for each station provide information on the station coordinates (latitude and longitude), catchment area, mean monthly and annual streamflow and sediment load, and the magnitude and date of occurrence of the maximum daily streamflow. After 1987, the streamflow data was collected from the Ministry of Water Resources of China. We first performed screening of the data for erroneous values. YHS, which is in western Hubei, the upper-middle reach of the River, and about 1837 km from the estuary, has streamflow records dating back to 1882. Yichang is known as the 'Gateway to the Three Gorges'. The Three Gorges Dam (TGD) is only about 40 km upstream. The drainage area above YHS is about 10^6 km². Yangtze River streamflow ranges from 0.3 to 5.22×10^4 m³/s and features a clear seasonal variation, with maximum flows coinciding with the summer monsoon season (Figure 2). In an ordinary year, the discharge range is from approximately $2.0\text{--}4.0 \times 10^4$ m³/s during the flood season to about 4000 m³/s during the dry season. Although many changes to land and water use have occurred over the 122-year hydrologic record within the basin, no statistically significant trends were detected in the streamflow time series. There have been no major diversions or obstructions of the Yangtze River upstream of YHS and, to the best of our knowledge, the streamflow values are not notably impacted by control structures.

With the completion of the TGD, measurements at YHS will represent a significantly altered hydrologic system. Still, analysis of historical YHS data will continue to serve as a practical estimate of 'historical inflows' to the TGD.

With the advent of satellite-based observations beginning in the 1970s, availability of global environmental data, including climate data, has increased greatly. In this study, we utilized these globally gridded data sets to construct a season-ahead prediction model of inflows to the TGD (YHS streamflow). The use of a relatively short record for development of a climate-based prediction model has to consider the caveats that the skill of the model may decrease if the correlation between the predictors and prediction deteriorates, as has afflicted the attempts to predict the Indian summer monsoon (Krishna Kumar *et al.*, 1999).

Streamflow values were averaged over June–July–August (JJA) during the period 1882–2003 to represent the monsoon season streamflow. Climate index data were accessed from the International Research Institute (IRI) for Climate and Society data library (<http://iridl.ldeo.columbia.edu/>) and included global SST, outgoing longwave radiation (OLR), SNOW, and sea-level pressure (SLP). Data sets for SST, OLR, and SLP were obtained from the anomaly gridded product of Kaplan *et al.* (1998), NOAA-CIRES CDC interpolated OLR, and the Northern Hemisphere Monthly SLP (Trenberth, 1992), respectively. Snow data was collected from NOAA's Climate Prediction Center website (Robinson *et al.*, 1993). The available data for SST, OLR, SLP, and SNOW are from years 1856, 1975, 1899, and 1970, respectively. The 3-month averages for March–April–May were used for prediction-model development.

Methodology

Simple methods of statistical analysis were used in this study to describe the relationship between summer (JJA)

Figure 2. Annual cycle of Yichang Hydrological Station streamflow.. This figure is available in colour online at www.interscience.wiley.com/ijoc

streamflow and climate variables of the preceding season and to evaluate predictive ability. Linear correlation maps were constructed using March–April–May (MAM) values (3 month prior) to identify regions that exhibit teleconnections with streamflow at YHS. Rank correlations were also evaluated to detect evidence of a nonlinear relationship. Data from these regions were extracted and transformed into climate indices. The indices were formed using a spatial average over the areas of interest of the gridded time series. Initial exploratory data analysis revealed mildly nonlinear relationships between the YHS streamflow and some of the predictors. Consequently, we explored both linear and quadratic regression models in a stepwise regression framework. The general model considered is of the form

$$\hat{Y}_{flow} = \alpha_0 + \sum_{i=1}^p (\alpha_i X_i + \beta_i X_i^2) + \varepsilon \quad (1)$$

where $\hat{Y}_{flow}$ is the predicted streamflow, X_i is the i^{th} climate predictor, α_i and β_i are the corresponding regression coefficients, ε is the error term, and p is the number of climate predictors in the selected model.

The best prediction model (variables to be retained, linear and quadratic terms) was identified using stepwise regression.

RESULTS

Characteristics of streamflow at YHS and influence of climate variables

The predictability for the Yangtze was hypothesized on the basis of earlier studies of East Asian rainfall and

its connection to oceanic conditions and ENSO. Several studies of East Asian rainfall have described a teleconnection with ENSO (Huang and Wu, 1989; Dai and Wigley, 2000). Correlations calculated here between the time series of streamflow and several measures of ENSO were not statistically significant. However, this relationship is known to vary over time, and is similar to the relationship between the Indian Monsoon and ENSO (Webster and Yang, 1992; Krishna Kumar *et al.*, 1999; Fasullo and Webster, 2002) and the Thailand summer monsoon (Singhrattana *et al.*, 2005; in press). Running correlations using a 20-year window between YHS streamflow and two ENSO indices, Nino3.4 and SOI, are shown in Figure 3. Each shows a relationship that varies significantly with time, including a sign change, and a strong increase in correlation strength beginning about 1980. Weng *et al.* (1999) also found a notable shift in the structure of the principal components of Pacific SSTs, which occurs in the late 1970s. Singhrattana *et al.* (2005) found a strengthening of the relationship between ENSO and the Thai monsoon post 1980. Most likely, the ENSO teleconnection is modulated by another low frequency determinant of the regional climate perhaps originating in the Indian Ocean.

Linear correlation maps between selected climate variables averaged over MAM and YHS streamflow for JJA for the years 1979 to 2003 are shown in Figure 4. Strong correlations were found with SSTs, OLR, SNOW, and SLP primarily in the western Pacific, and for SST, also in the eastern Indian Ocean. Rank correlations, which are more robust for non-normal data, were similar. The figures imply that the area around 10°S–10°N to 140–230°E influences Yangtze runoff because SST and OLR averaged over MAM are both correlated with

Figure 3. Running correlations using a 20-year window between YHS streamflow and two ENSO indices, Nino3.4 and SOI. The relationship shows pronounced decadal variability and a strengthening after the late 1970s.

Figure 4. Correlation analysis between JJA streamflow and March-April-May (MAM) (a) SST, (b) OLR, (c) SNOW, and (d) SLP. The areas chosen as predictors are indicated by boxes. An index for each was constructed using the spatial average of the variable over the box area.. This figure is available in colour online at www.interscience.wiley.com/ijoc

JJA streamflow at YHS. This area where the correlations are significant is likely related to ENSO dynamics, based on location and the sign of the correlations (which match expected ENSO impacts on rainfall and streamflow). Studies of East Asian rainfall have found the conditions in the western Pacific and Indian Oceans and ENSO modes of variability in the central and eastern Pacific to be closely linked with rainfall in the Yangtze basin (Yang and Lau, 2004; Chang *et al.*, 2000; Wang *et al.*, 2000).

In a study of Indian and Pacific SST and East Asian rainfall modes, Yang and Lau (2004) found that an ENSO-like mode in the Pacific and a secondary mode in the east Indian–western Pacific warm pool dominate the spatial relationship with East Asian rainfall. Our results for Yangtze streamflow are similar to their results in both the location of correlations and sign. The area of negative correlation with SSTs located near the equator, which is designated as SST1, likely corresponds to an ENSO signal, specifically, the horseshoe area of negative SST anomalies that lies to the west of the warm anomalies in the eastern Pacific. During the ENSO warm events, East Asian monsoon circulation is weakened, causing less rainfall in northern China and leading to increased rainfall, streamflow, and flooding in south central China because the subtropical high remains to the south. The area of positive SST correlation in the east Indian–western Pacific warm pool area, which we

designate as SST2, corresponds to increased rainfall (and thus streamflow) during non-ENSO years due to warm SSTs in that area. Our results are consistent with the conclusions of previous studies, which state that the SSTs in the eastern Indian and central and western Pacific influence the strength and location of the western Pacific subtropical high, affecting rainfall and streamflow in East Asia (Yang and Lau, 2004; Wu *et al.*, 2003).

From Figure 4, potential predictors were identified from the SST, OLR, SNOW, and SLP data sets according to regions where the correlations were strong and were consistent with the expectations based on results of precipitation studies (Yang and Lau, 2004; Wu *et al.*, 2003). Rectangular zones that encompassed these regions were specified as follows: SST (SST1: -10 – 10° N to 150 – 180° E; SST2: -20 – 0° N to 75 – 110° E), OLR (OLR1: -10 – 10° N to 140 – 180° E; OLR2: -10 – 0° N to 200 – 230° E); SNOW (30 – 40° N to 85 – 100° E); and SLP (25 – 45° N to 135 – 160° E). The MAM values for each variable were spatially averaged over the selected box. Table I lists the correlation coefficients of the spatially averaged MAM indices with JJA runoff, all of which are significant at the 95% confidence level or higher.

The correlation coefficients of the SST indices with JJA runoff at YHS were -0.40 (SST1 – West Pacific) and 0.545 (SST2 – East Indian) (Table I and Figure 4(a)). The results for OLR, SNOW, and SLP were all very similar for the selected data boxes. In addition to the location

Table I. Predictors based on spatial average of selected zones from the global climate data sources.

Climate predictors	Zone selected		Correlation coefficient with JJA streamflow
SST1	10°N ~ 10°S	150°E ~ 180°E	-0.40 ^a
SST2	20°N ~ 0°N	75°E ~ 110°E	0.55 ^b
OLR1	10°N ~ 10°S	140°E ~ 180°E	0.62 ^b
OLR2	10°N ~ 0°N	200°E ~ 230°E	-0.56 ^b
SNOW	30°N ~ 40°N	85°E ~ 100°E	-0.53 ^b
SLP	25°N ~ 45°N	135°E ~ 160°E	0.40 ^b

^a Significant at 95% confidence.

^b Significant at 99% confidence.

in the western Pacific mentioned above, the indices represent significant correlations in the northern Pacific near the Chinese coast (SLP). The SNOW index (SNOW) is located in the high elevation headwaters of the Yangtze and represents potential snowmelt runoff.

Frequency domain analysis

Decadal variability in East Asian rainfall has been well documented (Chang *et al.*, 2000 a,b; Gong and Ho, 2002; Yang and Lau, 2004). In our analysis of the temporal structure (interannual and decadal variability) of summer streamflow, wavelet power spectrum analyses of monsoon season (JJA) and annual runoff were used. The analyses employed the Morlet wavelet and zero

padding (Torrence and Compo, 1998). The time series of both annual and JJA streamflow at YHS from 1882 to 2003 shows strong periodicity at the 3 to 8, 16, and 32-year periods (Figure 5). This is consistent with an ENSO-like influence on streamflow (3 to 8 years) and lower frequency modulation by another influence. A filtered analysis using a 7-year moving average of annual YHS streamflow revealed a strong decadal variation (not shown).

Wavelet analyses were also performed on the predictors SST1 and SST2. In general, the analyses support the characterization of SST1 as an ENSO-like influence on Yangtze streamflow and the eastern Indian Ocean (SST2) as an increasingly important signal, especially influencing the most recent period of higher flows. SST1 exhibits an ENSO-like signal of 3- to 8-year periodicity with markedly increased activity from 1960 to the present. The time series of SST2 displays more power at 16 years and a fairly steady signal at 3 to 5 years, which also appears to strengthen since 1960. The higher frequency power (3 to 5 years) of SST2 is similar to SST1 and ENSO; however, the low frequency power (16 years) is unique to SST2 and many suggest an Indian Ocean modulation. In previous studies, an upward trend in precipitation has been documented for the Yangtze basin region and this, as well as the increase in summer flooding in the 1990s, has been associated with warming in the western Pacific warm pool (Gong and Ho, 2002; Yang and Lau, 2004). SST2 appears to be associated with this signal.

Figure 5. Wavelet power spectrum for JJA streamflow. SST1 exhibits an ENSO-like signal of 3- to 8-year periodicity with markedly increased activity from 1960 to the present. The time series of SST2 displays more power at 16 years and a fairly steady signal at 3 to 5 years, which also appears to strengthen since 1960. The cone of influence is marked by the dashed line. Wavelet analysis is based on Torrence and Compo (1998) using the Morlet wavelet. This figure is available in colour online at www.interscience.wiley.com/joc

Figure 6. Cross-wavelet analysis between JJA streamflow and MAM SST in (a) western Pacific Ocean (SST1) and (b) eastern Indian Ocean (SST2). Coherence power is high in the 16-year frequency band and is generally between 4 and 8 years. The cross-wavelet analysis between the two time series provides a measure of coherence at each frequency. This indicates that not only do the two time series share peaks in the frequency spectrum but also that the peaks are coincident. This figure is available in colour online at www.interscience.wiley.com/ijoc

Cross-wavelet analyses between SST1, SST2, and the Yangtze streamflow (Figure 6) are used to confirm that the frequency structure in the Yangtze flow is shared by the two predictors. The cross-wavelet analysis between the two time series provides a measure of coherence at each frequency. Coherence power is high in the 16-year frequency band and is generally between 4 and 8 years. This is an indication that the frequency structure in the Yangtze flow sequence is replicated as intermittent oscillations at different times in SST1 and SST2 in the same frequency bands that we found to be statistically significant for the Yangtze flows.

Prediction of JJA runoff with climate indices

The statistically significant correlations of JJA streamflow at YHS with the MAM values of the selected climate indices served as the foundation for a statistical seasonal-streamflow prediction model. Exhaustive (backward and forward stepping) stepwise multivariate linear and quadratic regressions were employed to determine the best model of JJA streamflow using the predictors. In all cases, both linear and quadratic forms of this predictor were checked. Cross-validation (leave one out) was used to derive a robust estimation of model performance. The cross-validation process as implemented here removes a single year from the training set, estimates the regression coefficients with the remaining data, and then predicts the flow for the year that was omitted. This is repeated for each year, providing an assessment of how well the model performs when an observed value is not available for parameter estimation, which would be the case in an operational prediction mode. The best model as determined by the stepwise regression procedure consisted of a quadratic model of the variables SST1, SST2, and SNOW. Statistics of the model are shown in Table II. The model captured 56% of the streamflow variance ($R^2 = 0.56$) using data from 1970 to 1999. The prediction period was shortened to these years to enable the use

of the SNOW data. The model is specified as follows:

$$\hat{Y}_{flow}(m^3/s) = (1.17X_1^2 + 1.31X_3^2 + 0.79X_2 + 2.1) \times 10^4 \quad (2)$$

where $\hat{Y}_{flow}$ is the predicted streamflow for JJA, X_1 and X_2 are SST1 and SST2, respectively, and X_3 is SNOW. The cross-validated R^2 dropped to 0.43. This degree of reduction in R^2 is not unusual under cross-validation.

As noted above, the relationship between ENSO and the Asian summer monsoon seems to have experienced a modal shift in the late 1970s (Singhtrana *et al.*, 2005; Weng *et al.*, 1999; Fasullo and Webster, 2002). We investigated the performance of the model on a smaller data set reflecting the recent relationship between Pacific Ocean dynamics and the Asian monsoon that occurred at this time. The model was constructed with the same variables as identified above for the years 1979–1999. The results were notably improved, with a model R^2 of 0.76 and a cross-validated R^2 of 0.67. These values are likely an overestimate of the skill that would be realized in future predictions; however, they offer a sense of the potential predictability, given the further insight for the dynamic relationship between ENSO and the Asian

Table II. Summary of the regression model for prediction of JJA streamflow at Yichang Hydrologic Station (YHS) for 1970–1999 using SST1, SST2, and SNOW as predictors. The model has an R^2 of 0.56. Under the 'leave one out' cross-validation, the R^2 becomes 0.43.

Period	Prediction model (R^2)	Cross-validation (R^2)
1970–1999	0.56	0.43
1979–1999	0.76	0.67

Figure 7. Time series of model prediction results (open circle) and observed JJA streamflow at Yichang Hydrologic Station (YHS, solid circle), using quadratic regression with March–April–May values of SST1, SST2, and SNOW as predictors for 1970–1999. This figure is available in colour online at www.interscience.wiley.com/ijoc

monsoon and the significance of increased correlation since the late 1970s.

Figure 7 shows the results of the regression models and the time series of observed JJA runoff. As the figure shows, the models show decent skill in predicting high flow events, such as those in the years 1974, 1983, 1991, and 1998. These years are all associated with strong ENSO signals, either warm or cold. Notable omissions by the models occurred in 1981 and 1994, years with no ENSO signal and a weak El Niño, respectively. This is not unusual. Predictive skill in seasonal climate forecasts is often limited to years in which the ENSO signal is strong (Goddard *et al.*, 2001). Since a large number of the most severe floods in the Yangtze basin are associated with ENSO events, the model should still provide useful guidance in many of the years. Figure 8 depicts the cross-validated (leave one out) predictions of the model. Plots of the model residuals (not shown) supported the assumption of mean zero, which are independently and identically normally distributed errors. On the basis of these metrics and the noted caveats, the regression model appears to be suitable as a forecasting tool.

SUMMARY AND DISCUSSION

The results of this analysis demonstrated the existence of strong influences of ocean conditions of the eastern Indian Ocean, the western Pacific, and snow pack in the Yangtze upland region on streamflow at the YHS in the Yangtze River. This evidence of teleconnection between

Yangtze streamflow and conditions in the Indian and Pacific Oceans, as parameterized by our indices of SSTs, OLR, and SLP, are consistent with the conclusions on the studies of East Asian rainfall. In summary, an ENSO-like signal in the western Pacific and a separate low frequency signal in the eastern Indian Ocean explain much of the variability in Yangtze streamflow. Measurement of the spring snow pack is also a significant source of predictive skill, which is likely due to the contributions of snowmelt to flow. A prediction model based on two indices of MAM SSTs in the eastern Indian and western Pacific Oceans and an index of snow pack provide a useful prediction of the JJA streamflow totals. The variance explained under cross-validation is only 43%. However, this is achieved with a relatively short training period for the model. Additional exploration of data and model structure may yet improve these results. It is perhaps significant that the model skill improves after 1979, a time previously noted in the literature as depicting a shift of some kind. If this shift is identified and explained, the prediction skill of the model may be improved for that time. The skill of the model presented suggests that the adjustments in reservoir operation in critical years may be possible one season ahead.

The predictors for the model were selected on the basis of (a) linear correlation and (b) their consistency with the published literature that relate rainfall in the region to climate dynamics. The latter set of analyses reflects both empirical multivariate analysis and identification of patterns from numerical integration of climate models. In all

Figure 8. Time series of model prediction results (open circle) and observed JJA streamflow at Yichang Hydrologic Station (YHS, solid circle), using quadratic regression with March–April–May values of SST1, SST2, and SNOW as predictors for 1979–1999. This figure is available in colour online at www.interscience.wiley.com/ijoc

cases, a linear dependence criterion is used for identifying the association. Considering this, it is interesting that a mildly nonlinear regression model using these predictors outperformed the linear model. In a way, this is not a surprise, as it is well-documented (Chiang *et al.*, 2000) that tropical convection (and hence atmospheric moisture transport from a source region) increases dramatically and quasi-linearly with SST when the local SST exceeds $26\text{--}28^\circ\text{C}$ for a sustained period. A quadratic regression model would be expected to reasonably capture this threshold response, which may be why it performs well here.

Ideally, one would use a metric of nonlinear dependence to identify suitable predictors. However, given the short record used here, we were not keen to add this extra degree of freedom to predictor selection. Work in this direction using longer records is planned. It should lead to improved and better-documented predictability.

The characterization of climate influence on Yangtze streamflow may be useful for water resources management in the short-term and can lead to projections of decadal-scale variations of streamflow for long-term planning. Operation of the TGD, South-to-North water transfer planning, and flood control measures may all benefit from seasonal streamflow forecasting. We are devising an experiment to demonstrate how changes in operating rules using seasonal forecasts could result in higher water and energy output and system efficiency and resilience. In particular, decadal variability should not be overlooked in

large-scale water resources planning. For example, published studies suggest that the current regime of abundant water in south China and scarcity in the North may be a temporary condition and subject to reversal. There is a possibility that aspects of this reversal are predictable on a year-by-year basis under the assumption that the structural relationship between the climate forcing and streamflow response does not change. The results of this research help in further understanding the influence of climatic changes on floods in the Yangtze basin and provide a scientific background for the flood control activities in large catchments in Asia.

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