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Monthly streamflow forecasts for the State of Ceará, Brazil

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Abstract This paper presents the methodologies employed to generate monthly and seasonal streamflow forecasts for the State of Ceará, Brazil. The procedure uses a variety of linked models. Seasonal climate forecasts provided by the General Circulation Model ECHAM 4.5 are used to feed two regional atmospheric models, the Regional Spectral Model (RSM) and the Regional Atmospheric Modeling System (RAMS), that provide monthly and seasonal regional precipitation forecasts for the State. These precipitation forecasts are then interpolated into a finer resolution grid to estimate the monthly-averaged basin precipitation. A bias-correction procedure is applied to these forecasts so they can be used by a conceptual lumped hydrological model to generate monthly and seasonal streamflow forecasts for several sites within the State. The paper also discusses the bias-correction procedures applied for the precipitation forecast, the estimation of the hydrological model parameters for ungauged sites, and the use of ensemble forecasts.

Key words climate forecast; seasonal forecast; streamflow forecast; ensemble forecast

INTRODUCTION

Spatial-temporal variability of water availability is a key issue in water management, especially in semi-arid regions where annual streamflow is often highly variable. For instance, the coefficient of variation of annual flow of many rivers in the State of Ceará, located in the semi-arid region of Brazil, is greater than one, a large value when compared to rivers in other regions of the world.

Despite the existence of large reservoirs within the State, which reduces the vulnerability of the water resources system, the water allocation process in the State is still highly dependent on the amount of water that flows into these reservoirs annually during the rainy season. More than 80% of the annual rainfall occurs in the February–June wet season, while it is common to have zero flow during the dry season (July–December). The uncertainty associated with the reservoirs' inflows in the following season is one of the most important risk factors that are taken into account in the negotiable water allocation process, which happens every August.

The highly uncertain hydrological scenario forces risk-averse water managers to make conservative decisions, such as assuming zero flow for the following wet season. This policy certainly minimizes the risk of water supply failures or agricultural economic losses, but some stakeholders and other water professionals argue that the zero-flow scenario is too restrictive, causing a slow-pace development of the region, especially in the agriculture sector.

There is consensus in the scientific community, and perhaps to a lesser degree among water professionals, about the potential benefits of climate information in water resources management. Important advances in the understanding and modelling of atmospheric phenomena in the last decade provided an improvement in the quality of climate forecasts. Obviously, forecast uncertainties may be large and they depend on factors such as the forecast horizon, quality of available data, and atmospheric processes that drive the local climate.

There are different techniques to provide seasonal and monthly forecasts. One approach consists of deriving an empirical relationship between streamflow and climate indicators, as in Souza & Lall (2003). Their semi-parametric statistical approach has been used since 2004 to provide seasonal forecasts for many reservoirs within the State. An alternative, denoted here dynamic forecast, employs atmospheric models in conjunction with a hydrological model to provide seasonal and monthly streamflow forecasts (Tucci *et al*., 2003; Gamble *et al*., 2003; Hartman *et al*., 2003; Wang *et al*., 2004; Grantz *et al*., 2005).

This paper describes the methodologies employed to generate monthly and seasonal streamflow forecasts for the State of Ceará based upon climate and hydrological models. These procedures were used in experimental mode during the wet season of 2006.

DYNAMIC FORECAST

The streamflow dynamic forecast methodology employed in the State of Ceará uses a series of linked models. Global and regional atmospheric models are used to provide monthly and seasonal precipitation forecasts. These forecasts are then used as input data to a lumped hydrological model to generate monthly and seasonal streamflow forecasts for many sites of interest within the state.

An important issue, due to scale differences, is how to transfer the precipitation information provided by climate models to a hydrological model. Climate models often have a coarse spatial resolution compared to hydrological models. As a lumped hydrological model is used, the concern was mainly related to the definition of a drainage area threshold above which a streamflow forecast would make sense. Based on the spatial resolution of the climate models, the streamflow forecast for the State is limited to sites whose drainage area is larger than 3600 km^2.

This section presents briefly the climate and hydrological components of the forecast methodology, including a description of the models, the use of ensembles, the bias-correction procedure of the precipitation forecast, and the hydrological parameter estimation at ungauged sites.

Climate component

Climate models The monthly and seasonal precipitation forecast is obtained by the use of global and regional atmospheric models. Climate forecasts obtained by ECHAM4.5, developed by the Max Plank Institute, are used to feed two regional atmospheric models, the Regional Spectral Model (RSM), developed by the National Centers for Environmental Prediction (NCEP), and the Regional Atmospheric

Modeling System (RAMS) developed by Colorado State University. Given the limited space, details of the configuration of both models are omitted here; the reader should refer to Sun *et al.* (2005) and Costa *et al.* (2005).

The RSM spatial resolution over the Brazilian semi-arid region is 60 × 60 km, covering the area limited by 100°W–10°E and 20°N–30°S, with a grid of 109 by 72 points. Results show that RSM is capable of representing seasonal and interannual precipitation variability. RAMS spatial resolution is finer, 40 × 40 km with 41 vertical levels in the atmosphere, and 11 levels to represent the soil.

Ensemble forecast results provided by numerical atmospheric models are highly dependent on the initial conditions because of the very nonlinear physical processes that occur in the atmosphere. The climate forecast employed here tries to assess this uncertainty through the use of an ensemble formed by equally-likely precipitation series, each based on different initial conditions.

Each set of initial conditions, which is used to generate the ensemble members, is derived by applying a perturbation procedure, based on a random seed technique, to the global climate forecast. So, instead of having four precipitation time series forecasts, one for each model (RSM and RAMS) and one for each sea-surface temperature (SST) scenario (persisted anomaly and predicted SSTs), the procedure provides an ensemble with 40 members, 20 members obtained by the RAMS models, and the other 20 generated by the RSM model, each model simulating the two SST scenarios.

Bias-correction procedures and the quality of climate information in previous evaluations show that the climate models employed here have good skill in predicting precipitation anomalies around the mean value. However, these models present large bias which must be appropriately removed in order to be used for streamflow forecasts (Wang *et al*., 2004; Wood *et al*., 2002; Leung *et al.*, 1999; Chen *et al*., 1996). Two bias-correction methods have been studied, but they will not be discussed here due to the lack of space. The method currently used preserves the mean and variance observed during the climatology period (1971–2000). The correction is made on a monthly basis.

Figure 1 shows box plots of seasonal-corrected precipitation ensemble forecasts (RSM) for one of the streamflow gauges in the State for years 2002–2005 along with observed precipitation values. Box plots of climatology (1971–2000) are also included, providing an interesting comparison. It can be seen that the climate forecast can bring relevant information to the decision-making process beyond that contained in the systematic record. At least for this basin, the climate forecast probability distribution is tighter than the climatology's. Moreover, one can easily observe that the observed value is closer to the forecast probability distribution than to the climatology probability distribution. This proximity can be quantitatively evaluated by using the Ranking Probability Score System (RPSS) (Franz *et al.*, 2003), which evaluates the benefit of the forecast relative to the climatology. Its value ranges from – ∞ to 100%. The greater the RPSS value, the greater the relative value of the forecast. In this case, the RPSS value was 70%.

Hydrological component

Hydrological model The streamflow forecast procedure employs the lumped conceptual model SMAP (Soil Moisture Accounting Procedure) developed by Lopes *et*

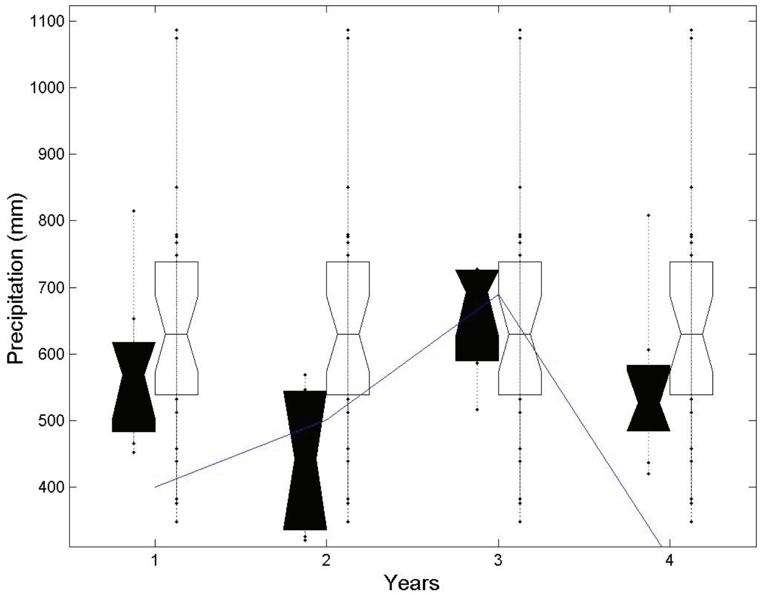

Fig. 1 Box plots comparing seasonal basin-average precipitation forecast (black) and climatology (white) for 2002–2005 (RSM w/ predicted SST). Solid line represents observed values. RPSS = 70%. Forecast made in December of previous year.

al. (1981). SMAP is a rainfall–runoff model based upon the ESMA (Explicit Soil Moisture Accounting) developed by Dawdy & O'Donnell (1965). This study employs the monthly time step version of SMAP.

The reasons for selecting a lumped conceptual rainfall–runoff model rather than a distributed model were the ease of implementation, simplicity of the model structure, which helped in the calibration process, and its popularity in the Brazilian hydrological community. Distributed models have some potential advantages over lumped conceptual models since they allow a more adequate representation of the spatial variability of basin characteristics. However, distributed models can be very expensive to implement because they need a considerable amount of data, which are not always available, especially in developing countries. Moreover, the calibration process of distributed models is often complex with a large number of parameters, whose estimated values maybe highly uncertain given the poor spatial distribution of the often scarce hydrological data available in regions such as semi-arid Brazil.

Considering that the goal of this paper is to provide monthly and seasonal streamflow forecasts, the authors considered that all the effort and data needed for the use of a distributed model would not necessarily pay off given the forecast time scale of interest, i.e. climate scale (months to seasonal). In this sense, the relevance of the rainfall temporal distribution being taken into account is reduced since the time of concentration for the basins considered here is much lower than one month. A monthly conceptual lumped model seems to be more appropriate for the application at hand.

Like other conceptual models, SMAP represents water storages and fluxes within the basin by employing linear reservoirs. The model has a quite simple structure. It consists of two reservoirs that represent the storage and flux in the top layer of the soil and in the aquifer, and it uses an exponential function that depends on the precipitation and soil moisture to estimate the surface runoff (Fig. 2).

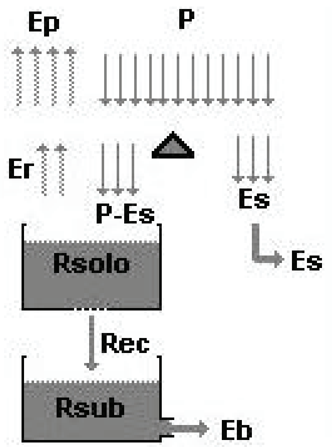

Fig. 2 Representation of SMAP model (Lopes *et al.*, 1981).

For each precipitation record (P), a mass balance is performed. A proportion of the precipitation contributes to surface storage (ES) as a function of P, soil moisture (SM), and an exponent Kes, given by ES = P x SM^{Kes}.

The portion P-ES is subject to evaporation (P-ES-EP). The resulting amount of water contributes to a second linear reservoir (Rsolo), which represents the top soil layer. At this reservoir, soil moisture is updated over time according to actual evapotranspiration losses (ER), which depend on reservoir storage level and top soil storage capacity. Another Rsolo output is the recharge (REC) of the groundwater reservoir (Rsub), computed using the field capacity concept (CAPC). The corresponding reservoir level (Rsub) is depleted at a constant rate (K), resulting in the baseflow (EB). The total streamflow at the outlet of the basin is computed as the summation of surface runoff and baseflow. The input monthly data needed to run the model are the basin-average rainfall in mm (P), the potential evapotranspiration in mm (EP), and the drainage area in km^2.

Parameter estimation The model has six parameters that need to be calibrated. However, there are no streamflow data available at many sites of interest, mainly reservoirs; therefore model calibration is not possible, which leads to the derivation of regional regression models of the SMAP parameters. Alexandre *et al*. (2005) showed that only two out of the six SMAP parameters exhibited spatial variability within Ceará State. The regional equations for both parameters are:

$$E(Kes) = -0.888 + 0.003P + 0.041CAD \quad E(SAT) = 3213.4 - 22.9Cr$$

where P is the mean annual rainfall (mm), CAD is the water soil capacity (mm), and Cr is the percentage of drainage area located over crystalline geological formation.

Streamflow forecast

The dynamic streamflow forecast procedure has been used in experimental mode since January 2006. The forecast is made for 13 streamflow gauge stations and 8 reservoirs located in the State of Ceará (Fig. 3) with drainage area varying from 3000 to 26 000 km^2.

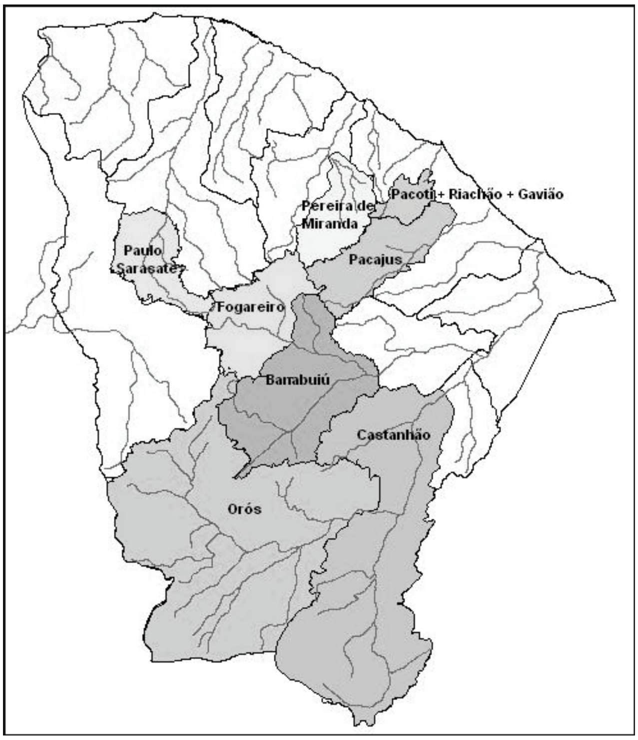

Fig. 3 State of Ceará with the reservoirs' incremental basins.

Due to the presence of reservoirs located upstream of the sites of interest, the streamflow forecast is made for the incremental basin.

The forecasts are issued once a month during the December–April period, covering the wet season that spans from January to June. Each forecast is formed by an ensemble of 20 members, 10 based on forecast precipitation obtained by the RAMS model, and the other 10 based on the RSM model (only predicted SSTs).

The streamflow forecast is highly sensitive to the initial soil moisture condition in the basin, especially the one-month-ahead streamflow value. This can be a problem because these basins have no real-time soil moisture monitoring network at this point. Even if site-specific soil moisture measurements were available, defining a soil moisture parameter value that is representative of the whole basin is not a trivial task because of heterogeneity issues.

In order to reduce the effects of the soil moisture initial condition at the beginning of each month, the hydrological model runs from December to June. This procedure takes advantage of the fact that the soil moisture at the end of November is always zero, or nearly so. Actual observed rainfall is used to run the model in the months previous to the forecast date.

Figures 4 and 5 show how the dynamic streamflow forecast is presented to the public. Figure 4 illustrates the differences between a deterministic forecast and a probabilistic forecast based on an ensemble forecast. It shows a statistical summary of the 10-member ensemble streamflow and precipitation forecasts for Boa Esperança gauge station employing RSM results with predicted SST, providing an idea of the uncertainties involved. It should be noted that the ensemble describes only the uncertainties related to the initial conditions used in the climate models, but there are

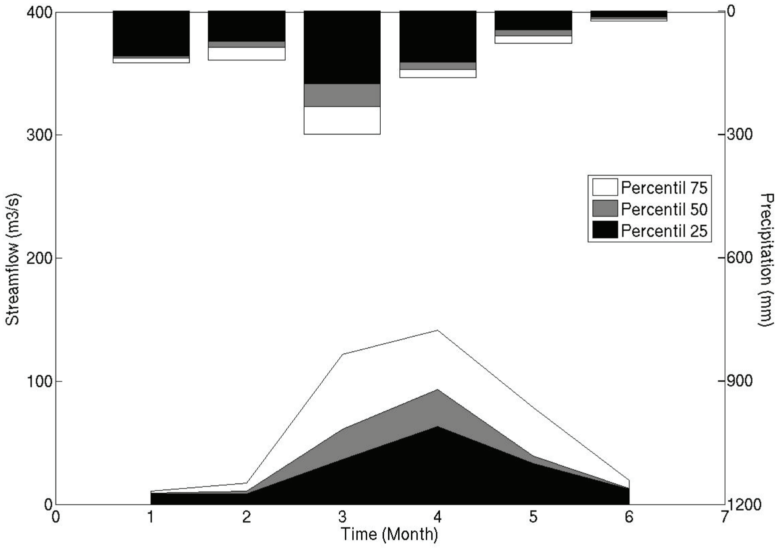

Fig. 4 Summary statistics of the precipitation and streamflow forecasts for Boa Esperança streamflow gauge station (ensemble with 10 members obtained by RSM model w/predicted SST).

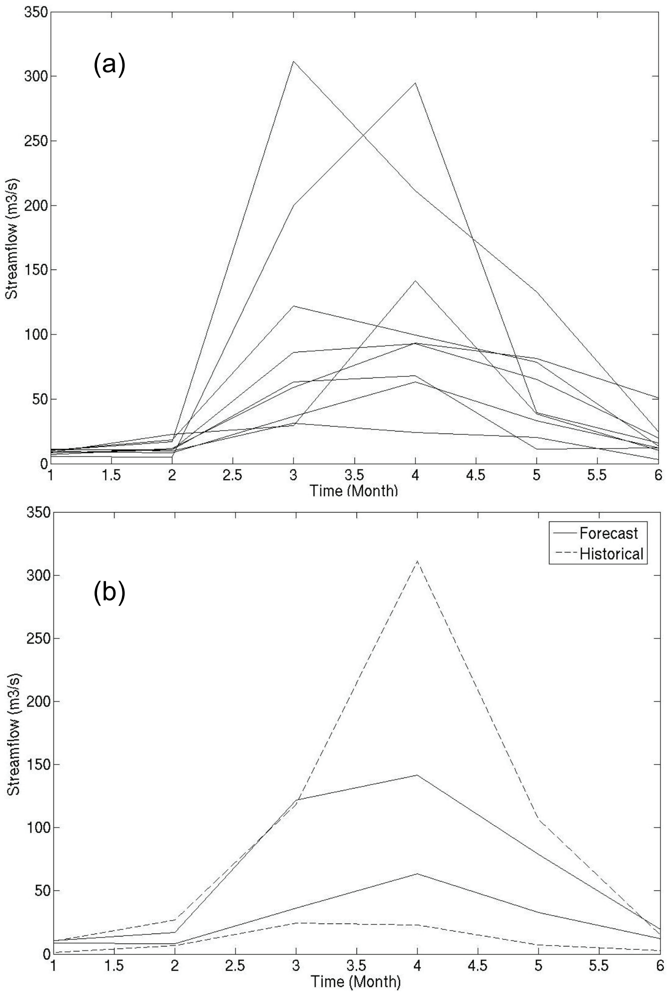

Fig. 5 (a) 10 members of the RSM ensemble forecast for Boa Esperança gauge station. (b) interquantile range of both historical record and ensemble forecast.

other sources of uncertainties not taken into account, such as model structure and parameter estimation.

Figure 5(a) presents the 10 members of the RSM ensemble streamflow forecast for Boa Esperança streamflow gauge, that were issued in January 2006. The January value is the same to all members because the model uses actual observed rainfall for the previous months. A comparison between historical streamflow records and the ensemble forecast provides an idea of the potential benefits of the latter. If the forecast range is as large as the range observed in the past, the forecast provides no relevant information to the decision-making process. Figure 5(b) shows exactly the opposite. The interquantile range of the ensemble forecast is tighter than that of the historical record, showing that the streamflow forecast may bring relevant information to the water management decision-making process. However, only after a comprehensive evaluation study, based on observed streamflows, will it be possible to assess the quality of the current methodology.

CONCLUSIONS

This paper describes the methodologies employed to generate monthly and seasonal streamflow forecasts for the State of Ceará, Brazil, which can be used to improve the water allocation process within the State.

The streamflow forecast procedure is currently running in experimental mode. The first time the forecast was issued was in January 2006. The forecast is issued once a month from December to April, covering the whole wet season that spans from January to May.

The paper presents the atmospheric models employed to generate the climate precipitation forecast, as well as the bias-correction procedure used to correct the basin-average precipitation, so that it can be employed as input to the lumped hydrological model. Results based on precipitation forecasts during the 2002–2005 wet seasons show that these forecasts can be very useful for streamflow forecasts, at least for some regions of the State. Future investigations are still necessary to understand the quality of these forecasts, which should vary according to forecast date, lead time of the forecast, and geographic location.

The paper also discusses the hydrological component of the streamflow forecast procedure, including a description of the SMAP model as well as the regional regression model that was derived for the State to estimate the SMAP parameters at ungauged sites.

Some streamflow forecast results for 2006 are presented along with a discussion regarding the limitations and potential benefits of the ensemble streamflow forecasts for the State. A more comprehensive evaluation study of the quality of the forecast, based on observed streamflow at gauged sites, is necessary and is under way.

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REFERENCES

Alexandre, A. M. B., Martins, E. S., Clarke, R. T. & Reis, D. S. Jr (2005) Regionalização de parâmetros de modelos hidrológicos. In: *Anais do XVI Simpósio Brasileiro de Recursos Hídricos*. ABRH, João Pessoa – PB, Brasil.

Chen, M., Dickinson, R. E., Zeng, X. & Hahmann, A. N. (1996) Comparison of precipitation observed over the continental United States to that simulated by climate model. *J. Climate* **9**, 2233–2249.

Costa, A. A. (2005) Modelagem numérica de mesoescala aplicada à previsão de clima no Nordeste Brasileiro (MONUMENT) – *Relatório Técnico*.

Dawdy, D. R. & O'Donnell, T. (1965) Mathematical models of catchment behaviour. *J. Hydraul. Div. Trans. ASCE* **91**(HY4), 123–127.

Franz, K. J., Hartmann, H. C., Sorooshian, S. & Bales, R. (2003) Verification of National Weather Service ensemble streamflow predictions for water supply forecasting in the Colorado River Basin. *J. Hydromet.* **4**, 1105–1118.

Gamble, J. L., Furlow, J., Snover, A. K., Hamlet, A. F., Morehouse, B. J., Hartmann H. & Pagano, T. (2003) Assessing the impact of climate variability and change on regional water resources: the implications for stakeholders. In: *Water: Science, Policy, and Management: Challenges and Opportunities* (ed. by R. Lawford & S. Eden), 341–368. American Geophysical Union, Washington DC, USA.

Grantz, K., Rajagopalan, B., Clark, M. & Zagona, E. (2005) A technique for incorporating large-scale climate information in basin-scale ensemble streamflow forecasts. *Water Resour. Res.* **41**, W10410, doi:10.1029/2004WR003467.

Hartman, H. C., Bradley, A. & Hamlet, A. (2003) Advanced hydrologic predictions for improving water management. In: *Water: Science, Policy, and Management: Challenges and Opportunities* (ed. by R. Lawford & S. Eden), 285–307. American Geophysical Union, Washington DC, USA.

Leung, L. R., Hamlet, A. F., Lettenmaier, D. P. & Kumar, A. (1999) Simulations of the ENSO hydroclimate signals in the Pacific Northwest Columbia River Basin. *Bull. Am. Soc.* **80**(11), 2313–2329.

Lopes, J. E. G., Braga, B. P. F. & Conejo, J. G. L. (1981) Simulação hidrológica: aplicações de um modelo simplificado, In: *Anais do III Simpósio Brasileiro de Recursos Hídricos*, v.2, 42–62, Fortaleza, CE, Brasil.

Souza Filho, F. A. & Lall, U. (2003) Seasonal to interannual streamflow forecasts for Ceara, Brazil: applications of a multivariate, semi-parametric algorithm. *Water Resour. Res*. **39**(11), doi:10.1029/2002WR001373.

Sun, L., Moncunill, D. F., Li, H., Moura, A. D. & Souza Filho, F. A. (2005) Climate downscaling over Nordeste, Brazil, using the NCEP RSM97. *J. Climate* **18**, 551–567.

Tucci, C. E. M., Clarke, R. T. & Collischonn, W. (2003) Long-term flow forecast based on climate and hydrologic modeling Uruguay River Basin. *Water Resour. Res.* **8**(7), 1181, doi:10.1029/2003WR002074.

Wang, Y., Leung, L. R., McGregor, J. L., Lee, D.-K., Wang, W.-C., Ding, Y. & Kimura, F. (2004) Regional climate modeling: progress, challenges, and prospects. *J. Met. Soc. Japan* **82**(6), 1599–1628.

Wood, A., Mauerer, E. P., Kumar, A. & Lettenmaier, D. (2002) Long-range experimental hydrologic forecasting for the Eastern United States. *J. Geophys. Res.* **107**(D20), 4429, doi:10.1029/2001JD000659.