Journal of Hydrology 519 (2014) 792–802

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Seasonal precipitation forecasts over China using monthly large-scale oceanic-atmospheric indices

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ARTICLE INFO

Article history:
Received 19 September 2012
Received in revised form 23 July 2014
Accepted 4 August 2014
Available online 11 August 2014
This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Harald Kunstmann, Associate Editor

Keywords:
Seasonal precipitation forecasts
China
Climate indices
Bayesian joint probability modelling
Bayesian model averaging

SUMMARY

Forecasting precipitation at the seasonal time scale remains a formidable challenge. In this study, we evaluate a statistical method for forecasting seasonal precipitation across China for 12 overlapping seasons. We use the Bayesian joint probability modelling approach to establish multiple probabilistic forecast models using eight large-scale oceanic-atmospheric indices at lag times of 1–3 months as predictors. We then merge forecasts from the multiple models with Bayesian model averaging to combine the strengths of the individual models. Forecast skill and reliability are assessed through leave-one-year-out cross validation. The merged forecasts exhibit considerable seasonal and spatial variability in forecast skill. The merged forecasts are most skillful over west China in spring periods and over central-south China in autumn periods. In contrast, forecast skill in most wet summer and dry winter periods is generally low. Positive forecast skill is mostly retained when forecast lead time is increased from 0 to 2 months. Forecast distributions are found to reliably represent forecast uncertainty. Climate indices derived from sea surface temperature in the western Pacific and Indian Ocean tend to contribute more to forecast skill than indices of the El Niño-Southern Oscillation. Large-scale atmospheric circulation patterns, represented by the Arctic Oscillation and North Atlantic Oscillation, appear to contribute little to forecast skill.

1. Introduction

In China, seasonal precipitation forecasts can be highly valuable for rain-fed agriculture, flood and drought disaster reduction, the energy sector, water resources management, human settlements, the environment and many other purposes. However, it remains an enormous challenge to produce forecasts of precipitation at the seasonal time scale that are of sufficient accuracy to meet public demands (Hwang et al., 2001; Kim and Kim, 2010).

China's large geographical size and sharp topographic relief give rise to a variety of climatic conditions: arid desert in the north-west; the semi-arid Loess Plateau and grassland areas in the north; the semi-humid Sichuan Basin in the center; and the humid coastal area in the southeast. Precipitation over China is influenced by complex interactions of ocean, atmosphere and land surface processes. It is therefore not surprising that seasonal precipitation forecasting for China is particularly difficult.

Seasonal forecasting is founded on the principle that large-scale processes evolve slowly, providing some predictability of climate at the seasonal time scale (Villarini and Serinaldi, 2011). Seasonal forecasts can be generated from statistical models or from physically derived dynamical models. Statistical models are based on a time-lag relationship between predictor and predictand. Dynamical models use physically-based equations to describe the motion of the general atmospheric and oceanic circulation, such as the coupled ocean–atmosphere general circulation models (CGCMs) used in United States (US) National Centers for Environmental Prediction (NCEP) Climate Forecast System version 2 (CFSv2, Saha et al., 2010) and the European Centre for Medium-Range Weather Forecasts (ECMWF) seasonal forecast System 4 (SYS4, Molteni et al., 2011).

While some recent results have suggested marked progression of coupled dynamical models for forecasting large-scale climate variables with lead times of six months and beyond (Wang et al., 2009a; Sohn et al., 2012), there is still only very limited skill in forecasting regional precipitation even at a lead time of one month, and particularly for mid-high latitudinal regions like China

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http://dx.doi.org/10.1016/j.jhydrol.2014.08.012
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(Karamouz et al., 2008; Lang and Wang, 2010; Lee et al., 2010; Villarini and Serinaldi, 2011). This may be partly because most of the dynamical model forecast skill can be attributed to El Niño-Southern Oscillation (ENSO) variability (Kumar et al., 2007; Cohen and Jones, 2011). However, ENSO variability can only account for a limited amount of precipitation variability in the mid-high latitudinal regions (Yoo et al., 2004; Gao et al., 2006). Statistical models that directly link precipitation with multiple large scale oceanic-atmospheric conditions can play a useful role in forecasting seasonal precipitation. At the very least, they provide a benchmark for further development of dynamical models.

Several studies have investigated statistical precipitation forecasting for select regions and seasons in China. Fan et al. (2008) developed a year-to-year increment approach to forecast summer rainfall over the middle-lower reaches of the Yangtze River Valley. The predictors used were six large-scale atmospheric indices including the Antarctic Oscillation, the Ural circulation, the East Asian circulation, the Southern Pacific sea level pressure, the meridional wind shear and the Yangtze River vorticity. Hartmann et al. (2008) employed a neural network technique to forecast summer rainfall over the Yangtze River basin, using a large number of predictors including the Southern Oscillation Index, the East Atlantic and Western Russia pattern, the Scandinavia pattern, the Polar and Eurasia pattern and 11 indices derived from sea surface temperatures (SSTs), sea level pressures and snow data. Wu et al. (2009) proposed a regression model to forecast an East Asian summer monsoon (EASM) index using a North Atlantic Oscillation index, an ENSO developing index and an ENSO decaying index as predictors. Yasuda et al. (2009) used an artificial neural network model to forecast summer rainfall over the Loess Plateau region; the predictors used were spring SST over the Pacific Ocean. Nearly all these studies focused on the EASM season, and they characterised only deterministic relationships between predictors and seasonal precipitation.

In this study, we evaluate probabilistic seasonal precipitation forecasts for all 12 overlapping seasons, across the whole of China and at a number of lead times. Forecasts for dry seasons are just as valuable as forecasts for wet seasons. For example, a strong autumn drought occurred over southwestern China in 2009. It seriously affected more than 80% of the vegetation in Yunnan, Guangxi, and Guizhou provinces, and more than 60 million residents suffered drinking water shortages (Zhang et al., 2013). If this hazard were forecast well in advance, its adverse effect might have been alleviated.

We employ a Bayesian method to produce forecasts. The method was introduced by Wang et al. (2012a) for forecasting seasonal precipitation for Australia and has also been applied to post-processing dynamical climate model forecasts (Hawthorne et al., 2013; Peng et al., 2014), combining statistical and dynamical models (Schepen et al., 2012a), combining multiple international dynamical models (Schepen and Wang, 2013) and forecasting streamflow extremes (Bennett et al., 2014). In the context of statistical seasonal precipitation forecasting, the method first establishes multiple statistical models using a Bayesian joint probability (BJP) approach. In each model, the predictand is seasonal rainfall total and the predictor is one of the observed climate indices. Forecasts from the multiple models are then merged through Bayesian model averaging (BMA) to obtain combined forecasts.

The BJP approach, used in this study for establishing individual forecast models, was first introduced by Wang et al. (2009b) and Wang and Robertson (2011) for forecasting seasonal streamflows and has been adopted by the Australian Bureau of Meteorology to produce operational forecasts. A key advantage of the approach over many other approaches is that it produces probabilistic forecasts that have statistically reliable forecast probability distributions. This is achieved by using a joint normal distribution for the predictor and predictand after suitable transformations and by accounting for parameter uncertainty. Transformations are critical for normalizing data and stabilizing variances. Parameter uncertainty can be important when dealing with few data, as is usually the case with seasonal variables (compared to daily variables for example; see Pokhrel et al., 2013).

The use of BMA to merge forecasts from multiple models is to combine the unique strengths of the individual models to achieve the best possible forecast skill (Raftery et al., 2005; Wang et al., 2012a). In addition, the multiple model combination approach is more robust in dealing with highly correlated predictors than approaches that include all predictors in a single model (such as in a multiple regression setting). This will be further discussed in Section 3.3.

In this paper, we use eight large-scale oceanic-atmospheric indices as predictors based on our review of literature. Forecast performance, in terms of forecast accuracy and statistical reliability, is evaluated through leave-one-year-out cross validation. We use our evaluation results to highlight the climate indices that are important for forecasting precipitation in different seasons and regions over China, to guide further development of statistical models for China in the future.

The remainder of this paper is structured as follows. Section 2 describes the data and the climate indices used in this study. Section 3 provides an overview of the BJP and BMA modelling approaches and of measures used to evaluate forecast performance. Section 4 presents and discusses forecast evaluation results. Section 5 summarizes and concludes the paper.

2. Data and climate indices

2.1. Gridded precipitation data

The observed precipitation data used in this study is extracted from the Precipitation REConstruction over Land (PREC/L) dataset developed by the US National Ocean and Atmospheric Administration (NOAA) (Chen et al., 2002). This dataset is based on gauge observations from over 17,000 stations around the globe, including about 700 stations in China. The spatial distribution of these stations is presented in Chen et al. (2002). This dataset has been used for various studies, and the mean distribution and annual cycle of precipitation shows good agreement with those in several published gauge-based datasets, especially for the northern hemisphere (Chen et al., 2002). This dataset consists of monthly values from 1948 to the present, and is updated in near real-time. It has a resolution of 2.5° in latitude and longitude, with a total of 184 grid cells cover China. We downloaded this dataset from the website of the Physical Sciences Division of the NOAA Earth System Research Laboratory, at http://www.esrl.noaa.gov/psd/.

Fig. 1 shows mean seasonal precipitation over China derived from the PREC/L dataset for the period 1950–2011. Seasonal precipitation over China exhibits great temporal and spatial variability. In general, precipitation increases from northwest to southeast. The largest seasonal precipitation occurs in June–July–August (JJA), when most of the Chinese territory receives more than 200 mm, but some regions in the west receive less than 20 mm. In DJF, precipitation is less than 50 mm across most of China.

2.2. Climate indices

A number of large-scale oceanic-atmospheric indices (hereafter *climate indices*) have been identified to have teleconnections with the inter-annual variability of seasonal precipitation over China, and may be useful for forecasting seasonal precipitation.