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Merging gauge and satellite rainfall with specification of associated uncertainty across Australia

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ABSTRACT

Accurate estimation of spatial rainfall is crucial for modelling hydrological systems and planning and management of water resources. While spatial rainfall can be estimated either using rain gauge-based measurements or using satellite-based measurements, such estimates are subject to uncertainties due to various sources of errors in either case, including interpolation and retrieval errors. The purpose of the present study is twofold: (1) to investigate the benefit of merging rain gauge measurements and satellite rainfall data for Australian conditions and (2) to produce a database of retrospective rainfall along with a new uncertainty metric for each grid location at any timestep. The analysis involves four steps: First, a comparison of rain gauge measurements and the Tropical Rainfall Measuring Mission (TRMM) 3B42 data at such rain gauge locations is carried out. Second, gridded monthly rain gauge rainfall is determined using thin plate smoothing splines (TPSS) and modified inverse distance weight (MIDW) method. Third, the gridded rain gauge rainfall is merged with the monthly accumulated TRMM 3B42 using a linearised weighting procedure, the weights at each grid being calculated based on the error variances of each dataset. Finally, cross validation (CV) errors at rain gauge locations and standard errors at gridded locations for each timestep are estimated. The CV error statistics indicate that merging of the two datasets improves the estimation of spatial rainfall, and more so where the rain gauge network is sparse. The provision of spatio-temporal standard errors with the retrospective dataset is particularly useful for subsequent modelling applications where input error knowledge can help reduce the uncertainty associated with modelling outcomes.

1. Introduction

Accurate estimation of spatial rainfall at fine scales is crucial for many practical hydrological and environmental modelling purposes, such as rainfall–runoff modelling, hydraulic structure design, and pollutant transport. There are two common methods for measuring rainfall: (1) using direct measurements (e.g. rain gauges) and (2) using remote sensing techniques (e.g. weather radar or satellite-based techniques). The conventional way of obtaining spatial rainfall is through conversion (e.g. averaging or interpolation) of point rainfall measured at rain gauge locations. While the point rainfall itself is only a representation of average over an area, the approach is somewhat reliable if there is a dense network of rain gauges. However, in areas where there is only a sparse network of rain gauges, this approach to obtain spatial rainfall (as well as rainfall at other temporal scales) is subject to a large degree of uncertainty. Furthermore, rainfall measured using rain gauges is uncertain due to the effects of wind, flaws in rain gauge installation, wetting losses, and other random and systematic errors (e.g. Sevruk, 1996; Ren and Li, 2007).

Some of the above problems may be mitigated with the use of satellite-based techniques for rainfall measurements. Satellite-based techniques provide continuous rainfall at much finer temporal and spatial resolutions than ground-based rain gauges do. However, they are also uncertain due to temporal sampling and retrieval of rainfall rate from satellite signals (e.g. Gebremichael et al., 2010). There exist several satellite-based global rainfall products; however, the products from the Tropical Rainfall Measuring Mission (TRMM) rainfall estimates (e.g. Kummerow et al., 2000) are arguably the most extensive and most widely used for rainfall studies in tropical regions.

The TRMM was launched in November 1997 with an aim to measure tropical rainfall from space with combined passive and active microwave instruments (Kummerow et al., 2000). Several studies have favourably assessed the utility of TRMM rainfall data by comparing them with rain gauge observations (e.g. Chiu et al., 2006; Hughes, 2006; Chokngamwong and Chiu, 2008) as well as by using TRMM rainfall data for streamflow simulation (e.g.

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Collischon et al., 2008; Su et al., 2008; Bitew and Gebremichael, 2011). Some efforts have also been made to merge TRMM rainfall data with rain gauge observations (Huffman et al., 1995; Grimes et al., 1999; Oke et al., 2009; Li and Shao, 2010), including for Australia. For instance, Li and Shao (2010) showed that a nonparametric kernel merging of gauge and TRMM rainfall data improves Australian rainfall estimation in terms of biases when compared with other approaches. Oke et al. (2009) used TRMM data as a predictor in geostatistical estimation methods to estimate daily rainfall in Australia. It was demonstrated that incorporating TRMM data in rainfall estimation did not increase the overall accuracy, although some improvement was obtained in areas with sparse rain gauge network. They argued that the reason for the moderate performance of the merging is due to the poor correlation of TRMM data with gauge observations as well as to the existence of large bias in TRMM daily rainfall data, especially in coastal and high altitude regions.

The outcomes of these studies are encouraging as to the usefulness of merging satellite and rain gauge measurements, and there is certainly a great potential for further advances. This provides the motivation for the present study towards improving spatial rainfall estimation in Australia. More specifically, the study attempts to merge the high-quality monthly rainfall data measured using rain gauges and the accumulated monthly TRMM 3B42 data. Unlike the previous studies on merging such data for Australia (e.g. Oke et al., 2009; Li and Shao, 2010), which have used relatively dense rain gauge network, we analyse three sparse rain gauge networks to specifically investigate the benefit of incorporating TRMM rainfall in data-limited areas. We also develop a new basis to assess uncertainty of the estimated gridded rainfall data at a monthly timestep for each grid. The analysis involves the following steps: First, a comparison of rain gauge rainfall and TRMM 3B42 data is carried out. Second, a methodology is described to estimate gridded monthly rain gauge rainfall using thin plate smoothing splines (TPSS) and modified inverse distance weight (MIDW) method. Third, the gridded rain gauge rainfall is merged with the monthly accumulated TRMM 3B42. Finally, cross validation (CV) errors at sampling locations as well as standard errors at grid points are estimated. We analyse a network of 230 rain gauges across Australia, which have high-quality rainfall data (Lavery et al., 1997).

2. Study area and data

2.1. Study area

The Australian climate varies from tropical in the north to arid in the middle to temperate in the south. The oceans surrounding Australia have a large impact on its climate. For instance, the El-Niño Southern Oscillation (ENSO), the western Pacific and the Indian Ocean sea surface temperatures (SST), and the Southern Ocean atmospheric variability influence the climates of different regions of Australia by varying degrees (Taschetto and England, 2009). The country is largely dry, especially the middle and the west, with the rainfall highly variable in space and time. More than 80% of the country gets an annual rainfall of less than about 600 mm. However, the tropical region of the far north gets an annual rainfall as high as about 4000 mm. Rainfall is mainly monitored using the thousands of rain gauges installed at different parts of the country. However, the majority of these rain gauges have been installed only near the coasts of east, south east and south west of Australia, where much of the population is concentrated and in big cities. In the interior of the country, which is largely desert and very sparsely populated, the number of rain gauges is very few.

2.2. Data

The rainfall data used in this study are high-quality monthly rain gauge rainfall as well as TRMM 3B42 products across Australia. The sources and features of these data are presented next.

2.2.1. Rain gauge data

Rainfall data observed over a period of 10 years (January 1998–December 2007) at 230 rain gauges across Australia are considered (Fig. 1). These 230 stations are selected from high-quality monthly rainfall measuring rain gauges, identified by Lavery et al. (1997) through detailed statistical tests of homogeneity as well as other quality-testing criteria (such as observational practice, site relocations and exposure of instruments). Where there are missing data (on average, just 1% of the gauges have missing values in a given month during 1998–2007), they are filled by the long-term rainfall mean of the respective month.

2.2.2. TRMM data

The TRMM rainfall products are downloaded from the Goddard Distributed Active Archive Center (GDAAC). The Version 6 products of TRMM 3B42 for the period 1998–2007 are considered in this study, and the available daily TRMM 3B42 data are used to calculate the accumulated monthly rainfall for analysis.

2.2.3. Latitude, longitude and elevation

Latitude, longitude and elevation at each rain gauge station are obtained from the Australian Bureau of Meteorology (BOM). Latitude and longitude at grid locations are determined by successively adding the grid size (0.05°) to the starting values of latitude and longitude. Elevation data at 0.05° × 0.05° latitude/longitude grid (about 5 km × 5 km) are obtained by aggregating 90 m Digital Elevation Model (DEM) of the Shuttle Radar Topography Mission (SRTM), which is extracted from the Consortium for Spatial Information (http://www.cgiar-csi.org/).

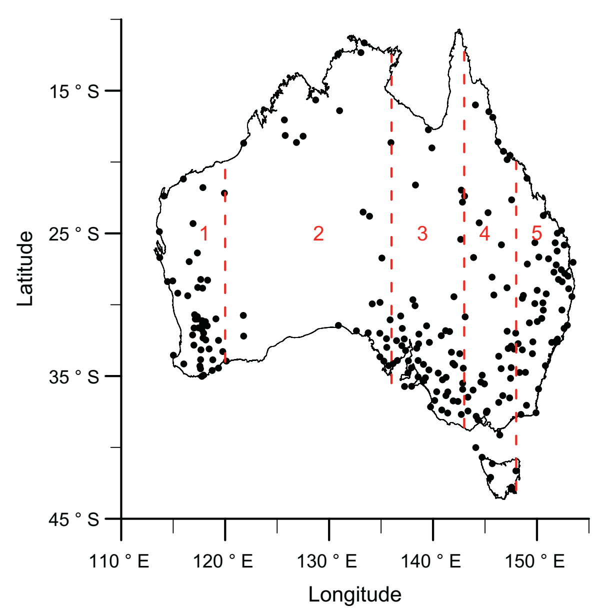

Fig. 1. Location map of 230 rain gauge stations in Australia. The figure also shows five regions considered for leave-region-out cross validation (L-R-OCV) (numbers 1–5).