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The geography of rainfall in Mauritius: Modelling the relationship between annual and monthly rainfall and landscape characteristics on a small volcanic island

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A B S T R A C T

The variability of rainfall has considerable implications on model parameter estimation and calibration, which may lead to a large degree of uncertainty in model output from climate change impact assessments, water resources planning, and management, design of hydraulic works and urban development. Small island developing states (SIDS) are more sensitive, and have a lower capacity to adapt to climate change than mainland countries, yet, estimates of future rainfall over SIDS are subject to large relative uncertainties. Ordinary least squares regression analyses are used to model mean annual and monthly rainfall in Mauritius over the period 2000–2011, and derive a physical basis for understanding spatial patterns in rainfall. The final models incorporate latitude, longitude, slope, distance to coast, elevation and their interactions and account for 68% of the variance in mean annual rainfall and 55–72% of variance in mean monthly rainfall across the island. The variables included in the model and the spatial patterns that they bring about are physically consistent with basic rainfall generating processes. We highlight the value of incorporating the modelled estimates into a hydrological model, and discuss the applicability of our modelling framework in terms of cost, computational efficiency and transferability to other mountainous areas, particularly on small island developing states.

Introduction

The trend in the study of hydrologic systems is to create hydrological simulation models that analyze large volumes of data, link multiple social and environmental factors under current and alternative future scenarios, and provide water managers and decision makers with insight that can facilitate judgments about the best actions to take. Hydrologic models of river basins have significance for a broad range of studies such as quantifying the effect of climate change, water resources planning and management, design of hydraulic works and urban development (Daniel et al., 2011; Singh, Subramanian, & Refsgaard, 1999). Rainfall variability has considerable implications for model parameter estimation and calibration, which may lead to a large degree of uncertainty in model output from climate change impact assessments, water resources planning, and management, design of hydraulic works and urban development (Beven, 2001; Bormann & Diekkrüger, 2003). A large number of factors play a role in the formation of rainfall across various spatial and temporal scales, and knowledge of these factors is necessary to inform hydrologic models. These factors include mesoscale processes, which occur over regions ranging from a few kilometers to approximately one hundred kilometers in diameter (Ahrens, 2007), such as orographic effects, mountain–valley circulations, and seasonal changes in prevailing winds, synoptic scale processes including high and low pressure areas and associated weather fronts, which influence the spatial distribution of rainfall over larger areas (100–1000 km^2) (Nicholson, 1996), and global scale processes such as the El Niño Southern Oscillation and Indian Ocean Dipole, which affect rainfall worldwide. This paper is part of a larger study to model the hydrological impacts of rainfall variability on the small mountainous island of Mauritius under current and alternative future climate, population growth and water demand scenarios. The first step in this task is to map the annual and monthly rainfall regimes across the island, and derive an understanding of regional and local scale processes that shape the spatial patterns

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of rainfall during the course of the year. The research questions for this paper are: 1) How much variation in annual, and monthly rainfall is explained by station location, and associated landscape properties known to drive rainfall on mountainous islands? 2) What are the relationships between mean annual rainfall, and 3) How do these relationships vary across the island on a month to month basis?

Several studies have shown that the determination of the relationship between rainfall and landscape properties such as altitude, aspect, and slope within a linear regression model produces accurate estimates, as well as a physical basis for interpretation of spatial patterns in rainfall in mountainous areas (Basist, Bell, & Meentemeyer, 1994; Brunsdon, McClatchey, & Unwin, 2001; Daly, Neilson, & Phillips, 1994; Hession & Moore, 2011; Marquınez, Lastra, & Garcıa, 2003; Um, Yun, Jeong, & Heo, 2011). However, the derivation of these relationships can be complicated by uneven station distribution (Hulme & New, 1997). Landscape attribute data may also be sparse, and a lack of explanatory variables commonly affects model fit, reducing the ability to fully explain the influence of topography and associated derivatives on rainfall patterns. Model development can still be complex when attribute data are readily available, since justifying the inclusion of multiple explanatory variables can include rationalizing additional effort and/or high cost of data collection, as well as the justification for increasing model complexity (Spackman, 1993). In some cases, efforts to model the relationship between rainfall and topography have also failed to capture the non-stationary nature of the relationship, as evidenced by patterns of spatial autocorrelation in the regression residuals (Fotheringham, Brunsdon, & Charlton, 2003). Attempts to overcome model misspecification, data scarcity problems, and failure to account for spatial non-stationarity in the rainfall/topography relationship may involve complex spatial trend surfaces functions, spatial autoregressive models and spatial error models (Ballantyne, 1983; Hession & Moore, 2011). Daly et al. (1994), Daly, Helmer, & Quiñones (2003) developed a computationally intensive algorithm that divides and groups rainfall stations into individual topographic facets based on slope orientation, weights the station data points to control for the effects of multiple physiographic variables, and uses climate-topography regression functions to produce rainfall estimates. We use a low cost, computationally efficient approach, which is easily transferable to other mountainous areas where reliable historical data is available.

Small Island Developing States (SIDS) are highly dependent on rainfall due to pressure on water resources from high population density, limited freshwater resources and storage capacity (Falkland, 1999; Granger, 2003). These islands are more sensitive, and have a lower adaptive capacity to climate change than mainland countries (Mills & Hancock, 2005; Mimura et al., 2007). On small mountainous islands, small small-scale topographic features are below the typical horizontal and vertical resolution of General Circulation Models (GCMs) (Timm & Diaz, 2009), therefore GCM-derived estimates of future rainfall over small islands are subject to large relative uncertainties, with even the direction of the change being uncertain (Kelman & West, 2009). Of further concern is that most SIDS have neither the resources nor the expertise to effectively evaluate the risk associated with climate change (Mills & Hancock, 2005). Compared to islands in the Pacific Ocean and the Caribbean Sea, SIDS in the Indian and Eastern Atlantic Ocean are among the least studied of the SIDS (Mills & Hancock, 2005). Very few inventories of water resources are available and as a result limited progress has been made in scientific research and long term planning (Mills & Hancock, 2005). However, unlike most SIDS, extensive spatial and temporal hydrometeorological records exist on Mauritius, offering a unique opportunity for applied hydrological and meteorological research.

Materials and methods

Study site

Mauritius (20.2°S, 57.3°E) is a group of small volcanic islands located in the southwest Indian Ocean. The main island (1865 km^2), which is the focus of this study, features a central plateau at 400–500 m elevation representing a former caldera. These uplands slope gently to coastal lowlands. The long term mean (1971–2000) annual temperature and rainfall over Mauritius are 22 °C and 2100 mm respectively. Rainfall is seasonal, with a rainy season from November to April, and a season of lower totals from May to October. Approximately 40% of the annual total falls between January and March, contemporary with the southward migration of the inter-tropical convergence zone towards subtropical latitudes and the occurrence of tropical cyclones. During the drier season anticyclonic conditions prevail, interrupted by the occasional cold front. Mean annual rainfall is subject to pronounced orographic influences, and varies longitudinally from 1400 mm in the eastern coastal lowlands, to 4000 mm on the uplands, and 800 mm along the western coastal lowlands.

Mean annual precipitation (used as a dependent variable) is calculated from the complete monthly rainfall records of 85 stations across the island from 2000 to 2011. The data are derived from Monthly Meteorological Summaries (Mauritius Meteorological Services), which were made available by the Mauritius Sugar Industry Research Institute (MSIRI) archives department. Mean annual precipitation values are standardized using long-term means and variances. Station elevation, slope, aspect, distance from the nearest coast, latitude and longitude (independent variables) are derived using an Aster Digital Elevation Model (30 m cell size) (Meyer et al., 2011; LP DAAC, 2011) and Geographic Information System Arc GIS 10 (ESRI, 2011). The topographic attributes of slope and aspect are processed using Arc GIS Spatial Analyst surface contour tools. We calculate the distance between individual stations (points) to the coast by creating a binary mask of the outline and using the Straight Line tool to create a surface of distance to coast before extracting values from the points of interest (Appendix A).

We estimate an ordinary least squares (OLS) linear model to test the statistical significance of spatial and topographic predictors that are hypothesized to be associated with precipitation in mountainous areas, and to better understand the local-scale drivers of rainfall on Mauritius. The general model takes the form of:

$$\widehat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon$$

where x_1, x_2, x_k represent the independent variables, β_0 is the y-intercept, β_1 to β_k are coefficients determined for each independent variable, and ε is the residual error. Pearson's product moment (r) is used to test independent variables for multicollinearity. High correlation between covariates potentially inflates standard errors and biases the estimates of the coefficients, justifying the removal of the highly correlated variables from the model (Field, 2009). A conservative correlation threshold of 0.8 is selected, above which one of the highly correlated independent variables is removed. The variables latitude, longitude, elevation, distance to coast, and slope are continuous, while aspect is converted into four separate dummy variables. For example, a slope facing East ($\leq$180 and $\geq$0°) was coded as one while all other directions were coded as zero. We refer to the adjusted r-squared values to evaluate the goodness of fit of the model (Field, 2009), as well as the Corrected Akaike's