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Driving rain indices for India at 1°×1° gridded scale

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ABSTRACT

Estimates of driving rain index at finer spatial resolutions facilitate a reliable consideration of potential moisture loads in the design of efficient building envelopes for any given location. In this study, a driving rain index map for India has been developed at 1°×1°(lat./long.) resolution using 60-years' 1951–2010) monthly data for rainfall and wind. The objective has been facilitated by calculating the driving rain indices for each of the 357 grids that cover the entire geographical stretch of India. The results affirm that, large tracts of central, eastern and southern India are shielded from driving rain, while the rest endure moderate to high severity. The higher latitudes of northeastern and west coastal areas are identified as the most severe regions. Furthermore, a non-parametric Mann-Kendall test and Sen's slope estimator have been used to determine the temporal trends of calculated indices at 95% confidence level. The indices have been found to exhibit a statistically significant decreasing trend over several regions of India thereby implying a decline of moisture loads. Estimates of average and most frequent wind directions have also been presented for individual grids to facilitate the design and orientation of building envelopes.

1. Introduction

Materials used in the construction of building facades are often porous and imbibe moisture under the hydric influences of ambient environment. The wetting of material-fabric eventually instigates the deterioration of its quality and performance causing loss of structural integrity and serviceability of the built facilities. The common instances of inflicted damage include, cracking and spalling of surface-layers under freeze-thaw action (Litvan, 1980); disruption of microstructure due to the dissolution and crystallization of salts (Charola, 2000); loss of stiffness and strength due to cyclic swelling and shrinkage induced by wetting-drying conditions (Benavente et al., 2008); and cracking caused due to the formation of expansive compounds within the matrix of the material (Idorn, 1992). The pervasive problem of corrosion in reinforcement concrete elements is also known to be a moisture dependent phenomenon (Lopez and Gonzalez, 1993; Andrade et al., 2002). The accumulation of moisture in building materials also promotes microbial growth leading to the deterioration of envelopes and of the quality of indoor air through the emission of mycotoxins and organic volatiles (Gaylarde et al., 2003; Bornehag et al., 2001). Furthermore, the dampening of building envelope lowers its insulating efficiency with a consequent escalation of indoor heating and cooling loads (Bhattacharjee, 2013). From the foregoing discussion it becomes evident that, an apt consideration of moisture loads is imperative to the design of durable structural components and efficient building facades. The pertinence is especially critical for severe influences such as rains (Abuku et al., 2009).

The joint occurrence of wind and rain creates an oblique rainfall vector called the driving rain. The horizontal and vertical components of driving rain act perpendicular to the vertical and horizontal planes and are hence referred to as the vertical and horizontal rains respectively. The quantity of vertical rain which impinges upon a unit area of a façade in unit time is also termed as the wind-driven rain (WDR) intensity. During a typical rainfall event, the exposed facades of a building come under the influence of vertical rain and eventually get subjected to the risk of moisture induced deterioration. The concomitant necessity to develop efficient building envelopes has over the course of the past century driven continuing research towards empirical, semi-empirical and numerical characterization of driving rain (Blocken and Carmeliet, 2004). Observations ascertained the non-uniform action of WDR on windward building façades with the top corners getting the maximum exposure followed by the top and side edges (Abuku et al., 2009; Blocken et al., 2009). Similar findings were obtained with CFD simulations taking into account the diverse factors of rainfall intensity, rain-drop size distribution and wind flow patterns and were in turn used to constitute catch ratios/local factors essentially describing the distribution of impinging flux on different parts of the facade (Karagiozis et al., 1997; Choi, 1994). Other aspects that have

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remained pertinent to area include, the study of raindrop physics; investigation of spreading, bouncing, evaporation and absorption characteristics of raindrops at exposed surfaces; moisture intrusion and runoff generation (Abuku et al., 2009a, 2009b, 2009c; Blocken et al., 2013). These endeavors are expected to further improve the accuracy of heat-air-moisture (HAM) simulations in years ahead.

Another significant outcome of field observations was in establishing the proportionality of WDR intensity to wind speed and horizontal rainfall intensity (Lacy, 1965; Hoppestad, 1955). The hypothesis subsequently facilitated the development of WDR maps for several countries in Europe, America, Asia and Africa (Boyd, 1963; Lacy, 1964; Grimm, 1982; Sauer, 1987; Chand and Bhargava, 2002; Akingbade, 2004; Sahal, 2006; Giarma and Aravantinos, 2011; Pérez-Bella et al., 2012). Essentially a depiction of the spatial variation of driving rain indices (product of average wind speed and average amount of total rainfall), a driving rain map depicts the relative severity of driving rain exposure across various locations with its accuracy relying heavily on the time resolution of available wind speed and rainfall data. Nevertheless, such a map provides valuable clues to the designer to provide for adequate measures in contriving efficient building envelopes. The aid is particularly imperative for a geographically vast country such as India which experiences a rich variety of weather conditions encompassing a hot and dry western part, cold Himalayas in north, coastal belts with strong variations in annual rainfall and high rainfall areas of north-east.

This study utilizes average monthly and average annual gridded data to determine annual driving rain indices designated hereafter as *maDRI* [Eqs. (2) and (2a)] and aaDRI *[Eq. (3)] respectively. The endeavor is targeted towards the development of maDRI* and aaDRI *maps for India at 1°×1° spatial grid resolution using pertinent rainfall and wind data pertaining to a period 60 of years (1951–2010). The rainfall data were obtained from the archives of India Meteorological Department (IMD), Pune, while those for wind were obtained from the web-repository of National Oceanic & Atmospheric Administration (NOAA) Earth System Research Laboratory, USA. This work is an initial attempt to use gridded data for the calculation of driving rain indices.*

The generated map offers a better representation of driving rain conditions in India as compared to the one reported previously by Chand and Bhargava (2002) owing to the complete spatial coverage provided by grids as against that provided by discrete stations. The reliability of indices calculated using gridded data is exhibited in the close match of *maDRI-aaDRI* relationship determined in the present study to the one reported in (Chand and Bhargava, 2002) based on station data. Furthermore, the spatial distribution of driving rain severity depicted by the constituted map has been found to exhibit a close resemblance to the monsoonal patterns of India. This establishes the plausibility of using gridded data in deriving indices and estimates of station level exposure conditions. Furthermore, a trend analysis of driving rain index for each year based on MK test and Sen's slope estimator have been found to exhibit a statistically significant decreasing trend over several regions of India thereby implying a decline of moisture loads. Plots of average and most frequent wind directions have also been determined for the various grids to facilitate informed decisions on building orientation.

2. Gridded climate data

The meteorological stations generally record climatic variables at fixed spatial points. This inherently limits the availability of climatic information to discrete locations. The interpolation of available data to equidistant grid points provides a complete spatial coverage encompassing even those areas for which direct observations are not available. The process of constituting gridded data involves dividing the geographical stretch of the country into square grids, each containing a certain number meteorological stations, and then implementing spatial interpolation to generate the data. The interpolation techniques can be either deterministic or probabilistic in nature. The nearest neighborhood method (NNM), inverse distance weighting (IDW) and spline fitting are some of the commonly used deterministic techniques. The probabilistic methods, on the other hand, include various kriging techniques (Hartkamp et al., 1999).

The constitution of gridded data also admits the integration of observations made from satellites, ships and other sources in cases where the availability of conventional data is scarce (Kalnay, 1996). The synthesized data therefore provides a more reliable account of the climate for sparsely gauged regions. Furthermore, the implementation of quality checks on raw data obtained from various sources and their integration addresses the issues of missing and outlying values which exist even in regions with dense network of conventional observatories.

2.1. Rainfall data

Daily rainfall records of 1°×1° gridded resolution were obtained from the archives of IMD. The data set comprised of a total of 1120 grids (35×32), each of approximately 100 km×100 km size, located in the rectangular region extending between 6.5°N −37.5°N to 66.5°E −101.5°E. Out of these 1120 grids, only 357 grids pertain to the Indian mainland and are considered in subsequent analysis.

As indicated in (Rajeevan et al., 2005), gridded rainfall data for India was first constituted using observations recorded at 1803 stations over the period of 1951–2003. These stations were selected out of a total of 6329 observatories for which a minimum of 40 years' of rainfall records were available. Fig. 1 shows the distribution of these stations across different grids. An increase in the number of observatories qualifying the 40-year criteria since 2003 has led to subsequent updates of the original data set. This, to an extent, has accounted for the sparsity of stations over the northern parts of the country (Pai et al., 2014). The data adopted in this study covers the period of 1951–2010 and is based on records of 2140 stations. However, information on the spatial distribution of these 2140 stations is not available to the authors.

IMD implements an IDW interpolation technique proposed by Shepard to generate the gridded data (Shepard, 1968). In this method, a circular search area of suitable radii is formed with the mid-point of grid at its centre to encompass a minimum of one and a maximum of four nearest stations. The grid value is subsequently interpolated as the weighted average of station-observations, with the weight diminishing in relation to increasing distance from the centre. More details of the

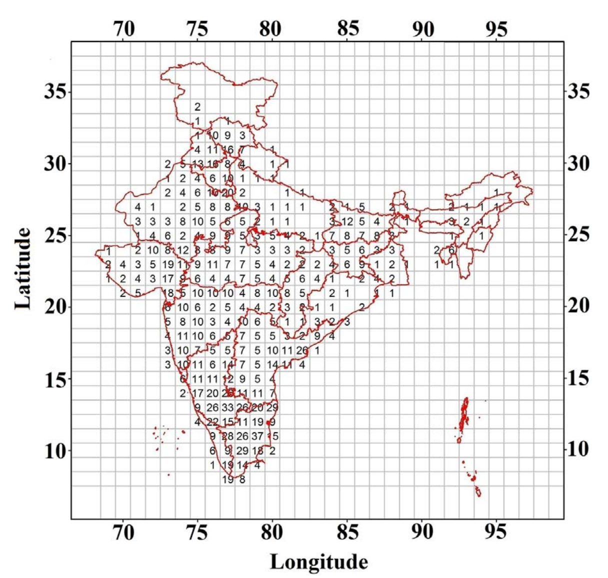

Fig. 1. Distribution of rainfall stations with at least 40 years of data as on 2003.