Journal of Hydrology 562 (2018) 346–357

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

The bridge between precipitation and temperature – Pressure Change Events: Modeling future non-stationary precipitation

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ARTICLE INFO

This manuscript was handled by Marco Borga, Editor-in-Chief, with the assistance of Francesco Marra, Associate Editor

Keywords:
Precipitation analysis
Weather type categorization
GCM temperature
Hourly precipitation
Average monthly temperature
Pressure change event
Probability of precipitation
Extreme event

ABSTRACT

Anthropogenic warming may change precipitation patterns, impacting infrastructure performance and reliability. Future precipitation statistics generated using General Circulation Models (GCM) are, however, often biased and not easily applied to problems such as runoff estimation. Stochastic weather generation is hence used as an alternative to GCMs in hydrology and hydraulic modelling. This paper explores the dependence of fine temporal precipitation characteristics on air pressure and air temperature using historic observations. The goal is to develop, based on the key causes of precipitation, a climatological basis for a stochastic precipitation generator for non-stationary precipitation under climate change conditions. The analysis focuses on precipitation in the urban Northeast United States and utilizes pooled observations from meteorological stations in New York City, Philadelphia, and Boston over 60 years. A negative correlation between hourly Probability of Precipitation (POP) and air pressure is observed. When the historical records are discretized using air Pressure Change Events (PCE), Decreasing Pressure Change Events (DePCEs) had a higher POP and a higher Precipitation Depth (PD) than Increasing Pressure Change Events (InPCEs). Temperature was more strongly associated with PD during DePCEs than InPCEs; this association was more pronounced during high magnitude PCEs and extreme events. The potential for simulating future hourly precipitation by associating historic hourly precipitation patterns with PCE's and monthly temperature is assessed.

1. Introduction

Global climate variability and change is largely caused by modifications to the global energy and water cycles. To improve our ability to adapt to precipitation changes under global warming (Trenberth et al., 2003), research is necessary to characterize the relationship between precipitation and temperature (Trenberth, 1998; Trenberth et al., 2003; Allan and Soden, 2007; Neiman et al., 2008; Lenderink and van Meijgaard, 2010). This relationship is complex, as it varies over space and time. Although General Circulation Models (GCMs) can generally investigate coarser temporal scales (e.g. annual or decadal) in larger geographic areas (e.g. Northeast US, global), more uncertainties are observed at smaller temporal and spatial scales, since local climate is also influenced by local geography, land cover, and related circulation patterns (Mitchell et al., 1999; Räisänen, 2001; Zveryaev and Allan, 2005; Sorteberg and KvamstØ, 2006).

Researchers have tried to link these two factors using physical and atmospheric explanations. For example, Trenberth et al. (2003) suggested that through convection, the moisture required for precipitation is drawn from an area of atmosphere that is about four times the rainy area. A 7% increase in air moisture holding per degree of warming at the local level has been used to imply a similar rate of global precipitation change, based on the Clausius–Clapeyron relation (Trenberth and Shea, 2005; Sun et al., 2007). Other studies investigate this relationship at different time scales, from monthly (Trenberth and Shea, 2005; King et al., 2014) to daily (Sun et al., 2007; Westra et al., 2013) and sub-daily (Lenderink and van Meijgaard, 2008, 2010); still others explore this relationship based on differences in precipitation patterns, looking at means (Allen and Ingram, 2002; Trenberth, 2011), extremes (Groisman et al., 2005; Meehl et al., 2005; Shaw et al., 2011; Meehl et al., 2012; Kunkel et al., 2013), and events of varying durations (Panthou et al., 2014; Wasko et al., 2015b).

For example, Madden and Williams (1978) found a frequent negative correlation between precipitation and summer air temperature at time scales ranging from inter-annual to multi-decadal in the contiguous United States and Europe. Zhao and Khalil (1993) confirmed a similar negative correlation in the summer, after exploring monthly data of the contiguous United States from 1905 to 1984. However, on

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https://doi.org/10.1016/j.jhydrol.2018.05.014
Received 28 February 2018; Received in revised form 4 May 2018; Accepted 5 May 2018
Available online 08 May 2018
0022-1694/

days with mean daily temperatures in excess of 12 °C, Lenderink and van Meijgaard (2008) found that the probability of one-hour precipitation extremes in De Bilt, Netherlands increased much faster than the Clausius–Clapeyron relation suggests, extending this finding to larger European simulations.

In general, projections from GCMs are used to interpret the relationship between precipitation and temperature at coarser temporal scales (e.g. annual or decadal) under climate change scenarios when considering larger geographic areas (e.g. Northeast US, global). Yet, precipitation datasets at fine time scales (e.g. hourly or sub-hourly) are required to study the potential impacts of climate change on water resource management, urban hydrology, and agriculture. For example, one of the two primary causes of runoff is Hortonian excess precipitation, whereby runoff is generated instantaneously whenever the intensity of precipitation exceeds the infiltration capacity of the land surface. To assess whether precipitation will be more intense under climate change, and possibly increase runoff generation, precipitation sequences downscaled from GCM projections are needed at fine temporal scales. Despite the dynamic methods used by Regional Climate Models (RCMs), stochastic precipitation generators, based on downscaled GCM projections, have been developed as an alternative (Fowler et al., 2007; Wilks, 2010) and used extensively for flood risk management (Haberlandt et al., 2008), sizing reliable rainwater harvesting systems (Basinger et al., 2010), and other water resource management tasks (Shamir et al., 2015). Stochastic precipitation generators create long continuous Markovian sequences of precipitation through a variety of methods (Wilks and Wilby, 1999). One technique for sequence generation uses samples from parameterized statistical distributions of wet-day rain volume (Stern and Coe, 1984; Wilks, 1998), arrival and cell conditions intensity and duration (Rodriguez-Iturbe et al., 1987, 1988; Wasko et al., 2015a; Wasko and Sharma, 2017), and event characteristics (Heneker et al., 2001); another relies on non-parametrically sampling historical observations (Lall et al., 1996; Lall and Sharma, 1996; Sharma and Lall, 1999; Basinger et al., 2010) with a moving window to preserve seasonality (Rajagopalan et al., 1996).

The quality of downscaled GCM precipitation datasets is contingent upon accurate temperature predictions and a strategy for minimizing prediction bias (Johnson and Sharma, 2009; Johnson and Sharma, 2012). Researchers found that pressure and temperature have the most agreement across the GCMs (Johnson and Sharma, 2009), while precipitation has the least consensus(Kendon et al., 2008; Johnson and Sharma, 2009). A better understanding of the relationship between precipitation and temperature is necessary to increase confidence in precipitation projections derived from other GCM projections, such as monthly temperature.

This paper explores how fine temporal scale (e.g. hourly) precipitation patterns are related to coarser temporal scale (e.g. average monthly) temperature. The physical causes of precipitation in a free atmosphere system are discussed first. Next, an investigation into the relationship of air pressure and precipitation is explored both at hourly time steps, and on an event basis. This analysis is then extended to examine how event based precipitation characteristics are impacted by Average Monthly Temperature (AMT). The results are used to discuss the potential development of a new stochastic precipitation generator that produces synthetic hourly precipitation time series by non-parametrically resampling historical observations, informed by GCM projections of AMT, among other variables.

2. Mechanisms of precipitation

One of the key causes of precipitation is the condensation of air that ascends as it moves laterally over irregular terrain (orographic lifting) or is physically displaced by atmospheric phenomena (e.g. via frontal lifting) (Bjerknes and Kristiania, 1922). Condensed moisture then falls to the ground as precipitation after drops coalesce enough to overcome the forces of drag (Ahrens et al., 2012).

In a free atmosphere, the primary cause of condensation is the displacement of air masses (Bjerknes and Kristiania, 1922). The earliest researcher describing precipitation generated from the frontal movement of air masses was Bjerknes and Kristiania (1923), who studied atmospheric circulation patterns. There are three main categories of frontal precipitation (Bjerknes and Kristiania, 1922; Bjerknes and Kristiania, 1923): (1) A cold front forms when cold, dry stable air masses lift and replace relatively unstable, warm, moist air masses previously found near the land surface. Typically, the cold air moves from the northwest to southeast direction in the northern hemisphere. The cold air forces its way under the warm air, which is then convected upward, where it cools, condenses, and coalesces, often causing short-duration, high-intensity precipitation. (2) By contrast, a warm front is formed by the advance of a warm moist air mass and the simultaneous slow retreat of cold dry air. Most commonly, warm air moves from the southeast to the northwest in the northern hemisphere. Since warm air has a lower density, it rolls up and over the cold air and can cause light to moderate precipitation over a large geographic area. (3) Occludal fronts occur when cold and warm fronts collide, causing a cyclone with low pressure in the joint area. Occludal fronts typically move to the northeast, and cause synoptic (because both warm and cold fronts are present) precipitation over large land areas. Fig. 1 graphically illustrates the three types of fronts.

Ahrens et al. (2012) summarized general relationships between precipitation, temperature, and pressure for each of the three types of fronts (Table 1). Note that the trends in temperature changes are not consistent for all front types, especially for the Occludal front, which makes it difficult to develop a direct relationship between temperature and precipitation. However, when air is lifted by any of the three different frontal mechanisms, air pressure at the ground surface is

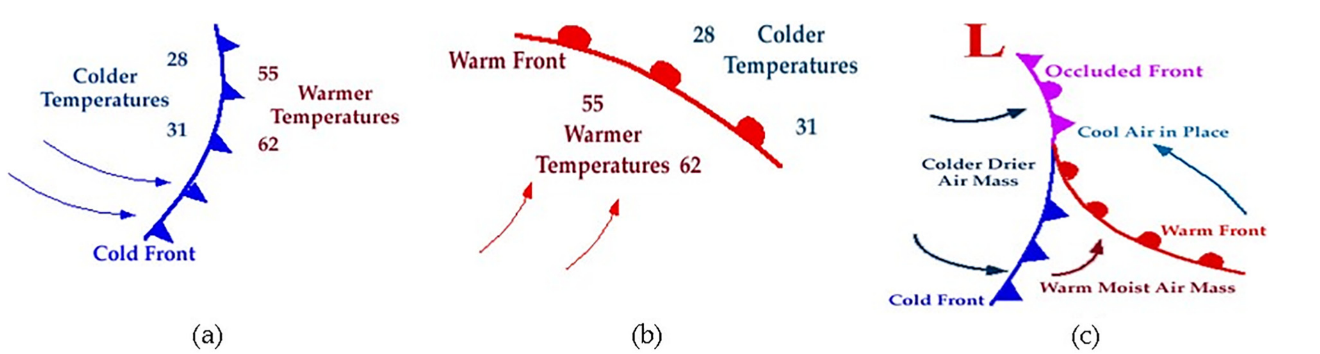

Fig. 1. Air mass front types (the numbers in plot indicate temperature in Fahrenheit) (a) Cold front, blue arrows indicate the direction of movement, (b) Warm front, red semi-cycles indicate the direction of movement, (c) Occludal front, purple arrows and semi-cycles show the direction of move, both cold front and warm front move counter-clockwise and produce low pressure region in the joint area. (Urbana-Champaign, 2010). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)