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Climate driven changes to rainfall and streamflow patterns in a model tropical island hydrological system

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SUMMARY

Rising atmospheric CO_2 and resulting warming are expected to impact freshwater resources in the tropics, but few studies have documented how natural stream flow regimes in tropical watersheds will respond to changing rainfall patterns. To address this data gap, we utilized a space-for-time substitution across a naturally occurring and highly constrained (i.e., similar geomorphic, abiotic, and biotic features) model hydrological system encompassing a 3000 mm mean annual rainfall (MAR) gradient on Hawai'i Island. We monitored stream flow at 15 min intervals in 12 streams across these watersheds for two years (one normal and one dry) and calculated flow metrics describing the flow magnitude, flow variability (e.g., flow flashiness, zero flow days), and flow stability (e.g., deviations from Q_{90}, daily flow range). A decrease in watershed MAR was associated with increased relative rainfall intensity, a greater number of days with zero rainfall resulting in more days with zero flow, and a decrease in Q_{90}:Q_{50}. Flow yield metrics increased with increasing MAR and correlations with MAR were generally stronger in the normal rainfall year compared to the dry year, suggesting that stream flow metrics are less predictable in drier conditions. Compared to the normal rainfall year, during the dry year, Q_{50} declined and the number of zero flow days increased, while coefficient of variation increased in most streams despite a decrease in stream flashiness due to fewer high flow events. This suggests that if MAR changes, stream flow regimes in tropical watersheds will also shift, with implications for water supply to downstream users and in stream habitat quality for aquatic organisms.

1. Introduction

Climate change is projected to have large impacts on watershed function, including changes to the magnitude and frequency of rainfall events (Allen and Ingram, 2002; IPCC, 2013; Muller et al., 2011; Oki and Kanae, 2006), to transpiration and water use by vegetation (Kirschbaum, 2004), and to relative humidity (Still et al., 1999), evaporation, and soil moisture (Seneviratne et al., 2010). These climate driven changes will, in turn, alter the timing and availability of freshwater resources for human and natural systems (Chapin III et al., 2010; Dettinger and Diaz, 2000; Milly et al., 2005; Oki and Kanae, 2006). Across the tropics, climate is changing due to rising greenhouse gases (IPCC, 2013), and emission projections suggest this trend will continue, resulting in substantial changes to the climate system. Rainfall in the tropics is driven by the convergence of Hadley cells within the intertropical convergence zone (ITCZ) whose location is largely driven by oceanic currents (Sachs et al., 2009; Wohl et al., 2012). Consequently, small changes in sea surface temperature (SST) anticipated in a warmer climate will alter tropical rainfall patterns (Chiang et al., 2001; Haug et al., 2001). Changing SST and air temperature influences total column water vapor (TCWV) with direct implications for moisture, clouds, and total rainfall, while accentuating seasonal and inter-annual variability in rainfall (Lauer et al., 2013; Mimura et al., 2007). Reductions in cloud cover due to the strengthening of Hadley-cell subsidence in the subtropics has resulted in changes in solar radiation affecting potential evapotranspiration (PET). Declines in insolation due to increased cloud cover over windward mountain slopes may also be affecting PET and available surface water (Nullet and Ekern, 1988). As the climate warms, increases in evaporation rates from ocean surfaces will raise atmospheric water vapor, reducing the temperature lapse rate on mountains in the tropics with subsequent effects on condensation level, surface cloud formation, height of the cloudbank, and cloud forest formation (Foster, 2001). Global climate models generally function at

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coarse scales in relation to watersheds (Lauer et al., 2013). Thus, detailed studies of potential climate impacts on hydrological processes, especially in regions with complex topography such as tropical islands, are important for assessing social, economic, and ecological vulnerabilities. While there are on-going efforts to forecast future rainfall and temperature patterns globally, sparingly little is known about how these effects will alter stream flow regimes in the tropics (Suen, 2010).

On Hawai'i Island, daily rainfall events have become more severe with greater extreme events during La Niña years (Chen and Chu, 2014). Projected increases in air and ocean temperatures for the eastern Pacific Region (Ruosteenoja et al., 2003) are expected to alter the ITCZ, and with it, the frequency and duration of El-Nino southern oscillations (ENSO), the magnitude of precipitation extremes (e.g., storm intensity, drought) as well as a decline in total rainfall (Chu et al., 2010; Palmer and Rälsänen, 2002; Timm et al., 2011). Downscaling climate models predict a southward shift in the ITCZ and potential reductions in leeward rainfall with little change in windward rainfall, although there is much variation among models (Lauer et al., 2013; Timm and Diaz, 2009). The strong relationship between tropical rainfall intensification and warming SST is likely to result in larger heavy rainfall events and a reduction in light to moderate rainfall in some regions (Lau and Wu, 2011), although the number of heavy rainfall events is not expected to increase in Hawai'i in the 21st Century (Timm et al., 2013). These changes will shift rates of infiltration, PET and the onset and duration of surface runoff with consequences for the availability of freshwater (Wohl et al., 2012). In recent decades (1975–2006), Hawai'i has experienced a 0.163 °C decade^{-1} increase in surface air temperatures (Giambelluca et al., 2008) and a 27.5% decline in annual coastal precipitation (Chu et al., 2010; Kruk and Levinson, 2008). These changes are correlated with a 23% reduction in median base flow in Hawaiian streams from 1943–2008 compared to 1913–1943 (Bassiouni and Oki, 2012). The current trend of a diminishing vertical lapse rate could mean a shift towards a more stable atmosphere and may result in steadily drier conditions (Cao et al., 2007; Chu and Chen, 2005; Timm and Diaz, 2009), reducing groundwater recharge and stream discharge (Johnson, 2012; Milleham et al., 2009). Similarly, an increase in trade wind inversion frequency is projected to increase the number of dry days between storms, increasing the frequency and severity of drought and low or no flow conditions (Cao et al., 2007; Easterling et al., 2000). During ENSO periods, shifts in ocean currents and temperatures have already resulted in prolonged periods of drought (McGregor and Nieuwolt, 1998), with reductions in the capacity of streams and underlying aquifers to support community and ecosystem needs (Burns, 2002; Meehl, 1996; Pounds et al., 1999).

Natural fluctuations in stream flow, including the magnitude and frequency of floods and droughts, play an important role in the evolution and life history strategies of freshwater organisms, and in structuring communities and economic systems. Such variation provides natural 'disturbances' that affect the persistence of species and regulate population sizes, as well the physical and biological structure of the habitat (Lytle and Poff, 2004). In contrast to temperate continental systems, tropical island watersheds are spatially compact and tend to be characterized by steep slopes and low stream order. As a result, tropical hydrographs tend to be flashier and highly responsive to rainfall; flow can shift by orders of magnitude within hours (Wu, 1969). Shifts in the distribution of rainfall over time are expected to alter watershed runoff characteristics, with consequences for the transport of sediment or pollutants in runoff (Strauch et al., 2014). These flood events are important to the flux of nutrients within streams (Aalto et al., 2003) or to near shore environments (Mead and Wiegner, 2010; Wiegner et al., 2009), the creation or maintenance of habitat (McIntosh et al., 2002; Wolff, 2000), and the life history traits of native species (Radtke and Kinzie III, 1996; Radtke et al., 1988; Smith et al., 2003).

For example, amphidromous gobies, shrimps, and snails that are the dominant organisms in tropical island streams (Resh and Deszalay, 1995) require flood events so that newly hatched stream larvae can quickly reach the ocean and juveniles developing in the near-shore waters can find streams to recolonize (McDowall, 2007; Radtke and Kinzie III, 1996). Hence evolutionarily rapid deviations from these regimes, or fundamental changes to regime amplitudes, can threaten the survival of species or whole communities (Ha and Kinzie III, 1996; Radtke and Kinzie III, 1996). Changing flow variability can also result in unpredictable erosion–deposition processes affecting channel morphology and habitat availability; reducing macroinvertebrate species richness and biomass, and affecting habitat and substrate stability (Cobb et al., 1992; Layzer and Madison, 1995; Munn and Brusven, 1991). Reductions in dry season (summer) flows will generate more pool-like conditions, resulting in the proliferation of pest species (e.g. mosquitoes) and the growth of generalist non-native fish species that can tolerate a variety of conditions (e.g., low dissolved oxygen; Pusey and Arthington, 2003) with potential negative consequences for Hawaiian stream ecosystems (Holitzki et al., 2013). Further, understanding how flow variability responds to changes in rainfall is critical for the construction and maintenance of climate resilient water supply infrastructure (e.g., water intake, diversions, effective culvert size and design, bridges and stream crossings).

Given the centrality of freshwater to society, enormous efforts in temperate regions have been directed at modeling stream flow and forecasting the effects of climate change on water supply. These models are complex, highly parameterized, and robustly validated (see Clausen and Biggs, 2000). In the tropics however, the availability of basic information required for model parameterizations have greatly limited the ability to forecast possible future changes to flow regimes (Wohl et al., 2012), and yet many regions of the tropics are exactly where the biggest effects of climate change will be expressed (Mora et al., 2013).

To increase our understanding of how changes in rainfall might influence flow regimes and the flashy nature of Pacific Island streams, we used a space-for-time hydrological study system that encompasses watersheds with mean annual rainfall (MAR) values spanning 3000 mm. A space-for-time substitution utilizes a naturally occurring environmental gradient to test hypotheses related to the effects of the gradient variable (independent) on other variables (dependent). In this system, other factors important to watershed function vary minimally across the project area: similar watershed shape and slope, >85% of stand basal area dominated by one canopy species and one mid-story species, upper elevations (above 700 m) are closed-canopy forest, and all soils are similar aged Hydrudands of volcanic origin (Mauna Kea). This level of constraint across such an enormous rainfall gradient is unique (Vitousek, 1995). While little is known about the extent of perched and dike-impounded groundwater supplies in this region (Lau and Mink, 2006), we assumed the influence of subsurface geology was consistent throughout the study area based on trends in other islands (Sherrod et al., 2007). We hypothesized that declines in long-term MAR would: reduce the daily mean rainfall and increase the number of zero rainfall days, resulting in a decline in flow yield (H1); and drive an increase in relative rainfall intensity and a decrease in rainfall stability resulting in greater flow variability and instability (H2). We also hypothesized the number of zero rainfall days will increase in the dry year compared to the normal year resulting in more zero flow days (H3).