**Hot air or water warm: thermal extremes and mass die-offs of fish in the north-central US**

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**Abstract**

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**Introduction**

Many types of extreme climatic and biological events have been increasing in frequency and intensity around the world (Mitchell et al., 2006; Rahmstorf and Coumou, 2011; Fey et al., 2015). These extreme events may substantially affect biological communities (Jentsch et al., 2007; Jentsch and Beierkuhnlein, 2008; Bailey and van de Pol, 2016) and may be a major factor affecting the persistence of populations (Mangel and Tier 1994). However, the relative infrequency and unpredictability of these events often impedes the collection of detailed biological and environmental data prior to, during, and immediately after these events (Bailey and van de Pol, 2016; Altwegg et al., 2017). To circumvent these inherent logistical challenges, long-term biological and environmental data have been used to predict the occurrence of extreme events over time (McKechnie and Wolf, 2010; Phelps et al., 2019; Till et al., 2019). Yet, in some instances, studies about the same type of extreme event in adjacent landscapes have suggested different explanatory environmental factors (Phelps et al., 2019; Till et al., 2019). In such cases, understanding which environmental factor is a more accurate predictor of an extreme event may greatly benefit basic and applied fields.

One type of extreme biological event that has been increasing in frequency and intensity concurrent with increased environmental variability is the mass die-off of freshwater fish (Fey et al., 2015; Buckley and Huey, 2016; Anderson, 2017). These mass die-offs are caused be a suite of environmental conditions including extreme thermal conditions and subsequent oxygen stress (Fey et al., 2015). In fact, thermal extremes have been suggested as a major contributor to these die-offs in recent history. Recent studies about these events in the north-central United States have suggested that nighttime land surface temperature (Phelps et al., 2019) and mean water surface temperature (Till et al., 2019) are good explanatory factors. While both of these factors suggest that thermal extremes may be a major cause of regional fish die-offs, air and water temperatures do not exhibit a linear relationship (van Vliet et al., 2013; O’Reilly et al., 2015). For example, recent analyses of global freshwater lake surface temperatures suggested that ice-covered lakes, such as those in the north-central United States, are warming at a faster rate than local air temperatures (O’Reilly et al., 2015). Because air temperature data is more widely available than water temperature data in many parts of the world (Source), determining whether air temperature is a suitable environmental predictor of these may enhance our ability to understand when and where these events may occur on a global scale.

To further our predictive power of these extreme events, we compiled mass die-offs of fish (2003-2014) in Minnesota (Phelps et al., 2019) and Wisconsin (Till et al., 2019), and concurrent air and water temperature estimates for waterbodies across both states. Based on these comparisons, we used future air and water temperature estimates for the mid- and late 21st century (2041-2059; 2081-2099) under RCP 85 projections to predict future trends of mass die-offs of fish across the north-central United States.

**Materials and Methods**

We compiled datasets of mass die-offs of fish (2003-2013) that occurred in waterbodies of Minnesota (Phelps et al. 2019) and Wisconsin (Till et al. 2019). Minnesota data (n = X) were obtained from the Minnesota Department of Natural Resources (MNDNR) Pathology Laboratory, as well as MNDNR staff reports about wildlife mortality events related to waterbodies across the state (Phelps et al. 2019). Wisconsin data (n = X) were obtained from the Wisconsin Department of Natural Resources (WDNR) and citizen observations (Till et al. 2019). Although recommendations about how many fish mortalities constitute a mass die-off of fish, which are often referred to as fishkills (La and Cooke 2011), we included all observations of fish die-offs because the number of reported fish deaths were likely derived from isolated, short-term observations.

We used the *rgeos* package (Source) to associate each fish die-off event with the nearest waterbody centroid according to coordinates provided by MNDNR (Source) and WDNR (Source). If waterbodies were characterized by multiple locations, these waterbodies were described by the mean coordinate values of all locations associated with a waterbody. Affected fish taxa were grouped by taxonomic family and the lowest taxonomic level possible, as well as categorized by warm-, cool-, or cold-water species (Lyons et al. 2009). Although fish die-offs may result from multiple environmental stressors (Zscheischler et al. 2018; Gehman et al. 2018), we cautiously prescribed a major cause type to each fish die-off event. Major causes included direct human perturbation (anthropogenic), infectious agent (infectious), summertime environmental conditions (summerkill), wintertime environmental conditions (winterkills), and unknown conditions. List months for each season? We then grouped fish die-offs by month and condensed multiple events that occurred in the same waterbody and month into a single event. In condensed events, all affected fish taxa were accounted for and the most frequent cause type across duplicate events was considered the cause type.

We then compared the occurrence of fish die-off events for each major cause with monthly air (PRISM Climate Group) and water (Winslow et al., 2017) temperature estimates over the concurrent period (2003-2014). Concurrent water temperature estimates are waterbody-specific and were based on an assessment of lake metrics and atmospheric temperature data from the North American Land Data Assimilation (Winslow et al. 2017). Concurrent air temperature estimates have 1/8-degree (~8 km) resolution and were associated with the nearest waterbody centroid.

We then used comparisons between historical thermal conditions and fish die-offs (2003-2013) to create predictive models for fish die-offs during the mid- (2041-2059) and late-20th century (2081-2099). Future water temperature estimates were obtained from Winslow et al., (2017). Future monthly air temperature estimates were obtained from the NOAA GFDL CM3 model (Source), which was one of the models used to obtain future water temperature estimates (Winslow et al., 2017). Both future air and water temperature estimates are based on Representative Concentration Pathway (RCP) 8.5 projections (Source).

Models and stats. Z-scores, PCA, forecasting?

**Results**

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**Discussion**

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**Acknowledgements**

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