**Hot air or water warm: thermal extremes and fishkills in the north-central US**

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**Abstract**

Mass die-offs of fish, or fishkills, have increased in frequency and intensity concurrent with increased thermal conditions and variability. Fishkills are often caused the direct and indirect effects of extreme thermal conditions, and previous models in neighboring landscapes have suggested that air and water temperature metrics are significant explanatory factors. We compiled fishkill records across the north-central United States (2003-2013) and compared the occurrence of summerkills with local air and waterbody-specific water temperature estimates. We found that mean air temperature was a better predictor than mean surface temperature. We used these predicions to estimate future fishkills, which are expected to increase in frequency under RCP 8.5. This is important because modelled air temperature data are more widely available than water temperature data, furthering the potential to predict these events. Good for basic and applied.

**Introduction 1 (bigger picture, I like 2 better)**

Many 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). Extreme events may substantially affect biological communities (Jentsch et al., 2007; Jentsch and Beierkuhnlein, 2008; Bailey and van de Pol, 2016) and their occurrence be a major factor influencing the persistence of populations (Mangel and Tier 1994). However, the relative infrequency and unpredictability of extreme 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 increasingly used to predict the frequency and intensity of future extreme events (McKechnie and Wolf, 2010; Phelps et al., 2019; Till et al., 2019).

One type of extreme biological event that has been increasing in frequency and intensity concurrent with increases in the mean and variability of thermal conditions is the mass die-off of fish (Fey et al., 2015; Buckley and Huey, 2016; Anderson, 2017), which are often referred to as fishkills (La and Cooke, 2001). Although fishkills may be caused be a suite of environmental conditions, many are caused by the direct and indirect effects of extreme thermal conditions (Fey et al., 2015). Recent studies about fishkills 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 significant explanatory factors for the occurrence of these extreme events. While both studies suggest that regional fishkills may be caused by thermal, 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). In addition, more about lakes and stuff. 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.

We compiled fishkill events (2003-2014) from Minnesota (Phelps et al., 2019) and Wisconsin (Till et al., 2019) with concurrent air (PRISM Climate Group, Oregon State University) and water temperature estimates (Winslow et al., 2017) for waterbodies across both states. We created several sets of models using non-penalized logistic regressions and penalized lasso and ridge regressions, and used these models to predict the occurrence of fishkills in the mid- and late 21st century (2041-2059; 2081-2099) under RCP 85 projections. This will help both basic and applied research.

**Introduction 2 (focus on fishkills)**

Recent increases in the frequency and intensity of heatwaves and other extreme thermal conditions (Mitchell et al., 2006; Rahmstorf and Coumou, 2011; Kirkpatrick and Lewis, 2020) have coincided with heat-induced mass mortality events (Fey et al., 2015). These mass die-offs often occur in in aquatic environments because they may generate compounding, deleterious environmental conditions such as extreme thermal conditions, hypoxia, and harmful algal blooms (Source). These extreme events may profoundly affect **community structure** (Source), and their occurrence be a major factor influencing the persistence of populations (Mangel and Tier 1994).

However, the relative infrequency and unpredictability of extreme biological events, such as mass mortality 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 increasingly used to predict the frequency and intensity of future extreme events (McKechnie and Wolf, 2010; Phelps et al., 2019; Till et al., 2019).

In particular, extreme thermal conditions **may profoundly affect** lentic communities by causing hypoxia, inducing thermal stress, and occasionally resulting in mass mortality events of organisms with relatively low thermal tolerances, such as freshwater fish (Source).

Mass mortality events of fish, or fishkills, often occur in lakes and other waterbodies that experience drastic thermal changes (Source). Importantly, most global freshwater lakes are relatively small (Cael and Seekell, 2016) and occur in northern temperate climates (Verpoorter et al., 2014). Models of northern temperate lakes predict an earlier onset of stratification, increased summer temperatures, and increased intensity and duration of stratification, which might be lethal to fish (De Stasio Jr., et al. 1996). Freshwater fish are predominantly affected by these events, which are often referred to as fishkills (Fey et al., 2015; Buckley and Huey, 2016; Anderson, 2017).

One type of extreme biological event that has been increasing in frequency and intensity concurrent with increased environmental variability are mass die-offs of freshwater fish (Fey et al., 2015; Buckley and Huey, 2016; Anderson, 2017), which are often referred to as fishkills (La and Cooke, 2001). Although fishkills may be caused by a suite of environmental factors (Source), extreme thermal conditions and associated oxygen stress have been major causes of these events over the past century (Fey et al., 2015). **These events often happen in northern temperate lakes due t changing temperatures.** Recent studies have compiled records of fishkills in neighboring regions of the north-central United States and suggested that air (Phelps et al., 2019) and water (Till et al., 2019) thermal extremes have significant explanatory power. However, air and water temperatures do not exhibit a linear relationship (van Vliet et al., 2013; O’Reilly et al., 2015) and 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 accessible than water temperature data in many parts of the world (Source), determining which thermal measurements may provide more reliable explanatory power will benefit basic and applied research about these emerging extreme events.

Previous models about fishkills in northern temperate climates caused by thermal extremes have suggested that air or water thermal extremes are significant explanatory variables for the occurrence of these events (Phelps et al., 2019; Till et al., 2019). However, air and water temperatures do not exhibit a linear relationship (van Vliet et al., 2013; O’Reilly et al., 2015) and 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).

We compiled fishkill events (2003-2014) from Minnesota (Phelps et al., 2019) and Wisconsin (Till et al., 2019), and concurrent air (PRISM Climate Group) and water temperature (Winslow et al., 2017) estimates for waterbodies across both states. We then used future air (Source) and water temperature (Source) estimates to model fishkill events in the mid- and late 21st century (2041-2059; 2081-2099) under RCP 85 projections.

extreme thermal conditions, hypoxia, and (Source).

(Source). In particular, heat-induced mortality events

The coincidence of these extreme climatic and biological events may profoundly affect **community structure** (Source), and the occurrence of such events be a major factor influencing the persistence of populations (Mangel and Tier 1994).

However, the relative infrequency and unpredictability of extreme biological events, such as mass mortality 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 increasingly used to predict the frequency and intensity of future extreme events (McKechnie and Wolf, 2010; Phelps et al., 2019; Till et al., 2019).

Many 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). Extreme events may substantially affect biological communities (Jentsch et al., 2007; Jentsch and Beierkuhnlein, 2008; Bailey and van de Pol, 2016) and their occurrence be a major factor influencing the persistence of populations (Mangel and Tier 1994).

**Materials and Methods**

*Fishkills*

We compiled records of fishkills (2003-2013) that occurred in **X** waterbodies across Minnesota (Phelps et al. 2019) and Wisconsin (Till et al. 2019). Fishkill records for Minnesota (*n* = 164) were obtained from the Minnesota Department of Natural Resources (MNDNR) Pathology Laboratory and staff reports (Phelps et al. 2019). Fishkill records for Wisconsin (*n* = 359) were obtained from the Wisconsin Department of Natural Resources (WDNR) and citizen observations (Till et al. 2019). We used the *rgeos* package (Bivand and Rundel, 2020) to associate each fishkill with the centroid of the nearest waterbody based on coordinates from MNDNR and WDNR, and manually verified these associations with the original locality descriptions. Waterbodies that were represented by multiple sets of coordinates in the MNDNR and WDNR databases were described by the mean coordinates. Although there are recommendations for the number of fish mortalities that constitute a fishkill (>25; La and Cooke 2011), we considered all records to be fishkills because the underlying mortality estimates were primarily derived from brief observations yet fish mortalities from these events may accrue over several weeks (Mhlanda et al., 2006; Hobbs and McDonald, 2010). To account for potential for multiple observations of the same fishkill and to match the temporal resolution of modeled thermal data, we combined all records that occurred in the same waterbody and month into a single fishkill.

Although fishkills may be caused by a variety and combination of environmental stressors (Zscheischler et al. 2018; Gehman et al. 2018), we used the description and diagnosis of each event to assign a major cause: anthropogenic (*n* = 11), infectious (*n* = 245), summerkill (*n* = 82), winterkill (*n* = 97), or unknown (*n* = 88). Because summerkills and winterkills are often caused by similar environmental conditions, such as extreme thermal conditions and hypoxia (**Source**), these events were also distinguished by meteorological season. Specifically, we restricted summerkills to fishkills that occurred between June and September, and winterkills to fishkills that occurred between November and April. We then classified observed fish taxa by family (**Source**) and thermal category (cold-, cool-, or warm-water) based on a regional assessment of native and non-native freshwater fish (Lyons et al., 2009). If a taxonomic family was described by multiple thermal categories, we used the most frequent thermal category. **If multiple observations were combined into a single fishkill, all dead fish taxa that were observed across events were included and the most frequent cause across events was considered the major cause.**

*Air and water temperatures*

We acquired concurrent (2003-2013) monthly air (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 6 Nov 2020) and water temperature estimates (Winslow et al., 2017) across both states. For monthly air temperature, the centroid of each waterbody was associated with the nearest location that had modeled monthly maximum, mean, and minimum air temperature (1/8-degree resolution). Monthly water temperature data were waterbody-specific and based upon an extensive assessment of thermal dynamics across lakes in the north-central United States (Winslow et al. 2017). **To compare thermal conditions of waterbodies that did and did not have recorded fishkills,** we calculated *z*-scores for each waterbody by comparing the mean monthly air and surface water temperature for each summerkill with the mean monthly air and surface water temperature of each waterbody, respectively, across the study period. To reduce collinearity amongst thermal variables, we performed principal component analyses (PCA) for air (maximum, mean, and minimum air temperature) and water temperature (maximum surface, mean surface, and mean bottom temperature). The first principal component for air and water temperature explained 72% and 94% of the thermal variation, respectively. To account for observation bias toward fishkills that occurred in areas with relatively high human population densities, we rounded the centroid coordinates of each waterbody to the nearest 0.1º and associated these coordinates with 2010 US census block data (**Source**).

**We used Levene’s tests to compare variance of thermal metrics for summerkills and summer non-events (i.e., no reported summerkills). We used one-way ANOVAs and Dunnett’s tests if variance was homogenous, and Welch’s adjusted t-test and post-hoc Tukey tests if variance was non-homogenous. All analyses were performed in R (version 3.6.3, R Development Core Team) and considered an alpha value of 0.05.**

*Model selection*

We created two sets of models that explicitly considered 1) the extensive water temperature data available for our study region and 2) the limited availability of water temperature data across many geographic regions. To consider the potential effect of all thermal, geographic, and anthropogenic variables without subjectively removing particular variables or overfitting the models, we performed lasso and ridge penalized regressions using the glmnet package (**Source**). We performed 5-fold cross-validation to determine the appropriate lambda value for each lasso and ridge model. **We compared these penalized regressions to non-penalized logistic regressions to determine the best fit model.** We also performed random effects models to determine whether there were waterbody-specific effects.

and 3) the potential for disproportionate impacts of thermal extremes on cold- and warm-water fish taxa (Lyons et al., 2019).

We partitioned datasets into training (75%) and testing sets (25%) and compared model fits via logloss. The reduced set was better so we used that. List number of non-zero cofficients for each. Lasso models work by this. **We compared all of these by AIC at first or logloss.**

*Forecasting summerkills and thermal extremes*

We used comparisons between fishkills records and concurrent thermal conditions (2003-2013) to create predictive models of future fishkills during the mid- (2041-2059) and late-20th century (2081-2099). Future air temperature data were obtained from the NOAA GFDL CM3 model (**Source**). Future water temperature data were obtained from Winslow et al., (2017), which was built, in part, using the NOAA GFDL CM3 model. Both future air and water temperature estimates are based on Representative Concentration Pathway (RCP) 8.5 projections (**Source**).

**Results**

*Summerkills*

We observed X summerkills across Minnesota and Wisconsin in X unique waterbodies. These summerkills. Median air temperatures were higher at summerkill waterbodies than non-summerkill waterbodies. The median water and air temperature of waterbodies were higher during months that had recorded summerkills compared to summer non-events (Stats).

*Thermal categories*

The proportion of events that affected cold- cool- and warm-water fish taxa were X, Y, and Z, respectively

**Discussion**

*Summary*

Mass die-offs of freshwater fish that were reported as summerkills coincided with increased air and water thermal conditions (Source). Understanding this provides information for basic and applied research.

Small lakes (Downing et al 2006, from MacPhee thesis and all below)

Loss of thermocline (De Stasio et al 1996)

Loss of bottom, cold-water habitat in shallow lakes (Moore et al 1996, Cahill et al 2005)

Zooplankton species richness declines at high temperaturs (Patalas 1990)

*Fish*

There are many mechanisms by which species may die due to thermal extremes or variability (Source). The thermal threshold of several fish species examined (bass, walleye) was breached during the observed thermal extremes (23 from till). Stratificatoin. Cyanobactria and harmful algal blooms can contribute to hypoxia (25 from till). Differentiating between these causes requires more reporting. Do infection too.

*Lakes*

Most of our lakes were shallow, warm-water lakes (21 from Till). Most lakes occur in northern temperature regions (HydroLakes), which are expected to experience increasing mean and variability temperature. However, air and water temperatures do not exhibit a linear relationship (van Vliet et al., 2013; O’Reilly et al., 2015) and 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). Most global lakes are small (Cael and Seekell, 2016) and occur in northern temperate regions (Verpoorter et al., 2014).

Models predict an earlier onset of stratification, increased summer temperatures, and increased intensity and duration of stratification, which might be lethal to fish (De Stasio Jr., et al. 1996).

Increases of events and where (forecasts)

Geomorphology

Differences between states. Great Lakes effect buffered Wisconsin from something. We tried Level III ecoregion and it didn’t benefit.

What else affects these events.

Closing

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Tables and Figures

Table 1. Counts of fishkills by family. # Fishkills by family and cause from RmD 06

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Family | Thermal category | Fishkills | Percentage of fishkills during summer | Most frequent cause |
| Acipenseridae |  |  |  | Anthro / summer |
| Amiidae |  | 0 |  | ? |
| Catostomidae |  |  |  | Summerkill |
| Centrarchidae |  |  |  | Infectious |
| Cottoidae |  | 0 |  | ? |
| Cyprinidae |  |  |  | Winterkill |
| Esocidae |  |  |  | Inf / summer |
| Gasterosteidae |  | 0 |  | ? |
| Gobiidae |  | 0 |  | ? |
| Ictaluridae |  |  |  | Infectious |
| Lepisosteidae |  |  |  | 0 |
| Osmeridae |  |  |  | Unknown |
| Percidae |  |  |  | Infectious |
| Salmonidae |  |  |  | Summerkill |
| Sciaenidae |  |  |  | Unknown |