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TOPICAL REVIEW

How will climate change shape climate opinion?

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Abstract

As climate change intensifies, global publics will experience more unusual weather and extreme weather events. How will individual experiences with these weather trends shape climate change beliefs, attitudes, and behaviors? In this article, we review 73 papers that have studied the relationship between climate change experiences and public opinion. Overall, we find mixed evidence that weather shapes climate opinions. Although there is some support for a weak effect of local temperature and extreme weather events on climate opinion, the heterogeneity of independent variables, dependent variables, study populations, and research designs complicate systematic comparison. To advance research on this critical topic, we suggest that future studies pay careful attention to differences between self-reported and objective weather data, causal identification, and the presence of spatial autocorrelation in weather and climate data. Refining research designs and methods in future studies will help us understand the discrepancies in results, and allow better detection of effects, which have important practical implications for climate communication. As the global population increasingly experiences weather conditions outside the range of historical experience, researchers, communicators, and policymakers need to understand how these experiences shape-and are shaped by-public opinions and behaviors.

1. Introduction

Climate change perceptions shape both individual and societal responses to the climate crisis. For example, an individual who dismisses the existence of climate change may underestimate the risk of extreme weather events and, consequently, may not take appropriate adaptive actions. Likewise, voters who do not recognize the existence of climate change may be less likely to support policies that mitigate climate risks. However, humans are poorly equipped to perceive our changing climate directly. Instead, we perceive shifting local weather conditions and weather-related extreme events like heat waves, floods, and wildfires.

Climate change is currently driving these and other local weather conditions beyond historical ranges. For example, most of the world's population lives in places where local temperatures have increased [1]. Our individual and societal ability to detect and respond to these changes is critical. Can publics accurately perceive shifting temperatures? Do perceptions of local weather trends and weather events shift public climate perceptions, beliefs, attitudes, and behaviors? Do individuals attribute these experiences to climate change? Can these perceptions prompt increased policy action as climate impacts intensify [2–4]? These are all empirical questions that have drawn the attention of social scientists over two decades.

In this article, we review scholarship on how personal experiences with environmental phenomena (including weather and weather-related events) are associated with climate change perceptions, beliefs, attitudes, behaviors, and policy support. We collectively refer to these constructs as public opinion about climate change or *climate opinions*. As we show, despite extensive research efforts, the relationship between weather and climate opinions still remains unclear. Several recent studies point to an association between elevated temperatures [5–19] or extreme weather events [20–27] with greater climate change concern, belief that human-caused climate change is happening, or support for climate policies. Other

studies, however, do not support such a relationship [28–34]. Prior beliefs and personal experience may also condition weather perceptions [35–39]. For example, an individual who is dismissive of climate change may misperceive their own experiences with extreme weather events, be less likely to take appropriate adaptive actions, and be more vulnerable to future climate change impacts [36, 38].

Several previous reviews examine the influence of weather on perceptions and opinions of climate change [40–44]. Most commonly, these reviews have identified an effect of temperature anomalies or trends on public opinion (in this literature, *anomaly* refers to a departure from the long-term average value). However, they note that there are gaps in our understanding of the timescales over which weather influences public opinion [40, 45], questions about whether personal experience shapes climate opinions or whether pre-existing beliefs shape experiences [41, 44], the need to study these phenomena in a wider range of populations beyond North America and Europe [40, 41], the need for more longitudinal analyses [40, 41], and the need for greater consistency in research practices [40, 41].

Here, we undertake a larger and systematic review of the growing literature on the relationship between weather and climate opinion. We review and interpret this literature to identify consistencies and inconsistencies in research findings. We then outline the methodological factors that may explain these contrasting results. We particularly highlight: (1) variation in how climate and weather[4] trends are measured; (2) inconsistencies in survey wording, sample selection and composition, and variable selection; (3) differences in the spatial and temporal scales of survey and weather data; (4) uneven attention to causal identification; (5) statistical complications due to multiple comparisons and spatial autocorrelation; and, (6) limited engagement with theory. Based on these findings, we then propose directions for future research and best practices for researchers seeking to understand the relationship between weather and climate opinions.

2. Methods

We reviewed articles that empirically investigate the relationship between public opinion about climate change and experience with local weather, climate, and extreme events. We used a systematic search strategy on the Google Scholar database using the following keywords: 'climate,' 'warming,' 'perceptions,' 'opinion,' 'weather,' 'experience,' and 'extreme.' We also considered articles citing or cited by relevant identified articles. Our initial search query identified about 16 000 results. To refine our search further, we considered only the first 25 pages of search results, since results are sorted in descending order by search relevance.

We then used the following criteria for inclusion: (1) the article must be published in a peer-reviewed academic journal; (2) the article must describe a primary empirical study (reviews or primarily theoretical papers were excluded); (3) the article must examine at least one of the following constructs related to opinion about climate change or global warming: belief that climate change is happening and/or human caused, worry or concern about climate change, or support for climate change mitigation and/or adaptation policies; and (4) the article must examine at least one of the following in association with climate change opinion: weather conditions, extreme weather events, or climate indicators (e.g. temperature or precipitation anomalies or trends). Our search is inclusive of papers published through 1 February, 2019.

Based on these criteria, we identified 73 articles for inclusion in this review. These articles were published between 2006 and 2019.

3. Results and discussion

3.1. Trends in weather effects on climate opinion

There is modest support for an association between weather experience or extreme events (broadly defined) and climate opinion. Of the 73 articles included in this review, 59 (81%) measure a direct effect on climate opinion from either subjective experience or measured exposure to a variety of weather, climate, or extreme event indicators. However, the magnitude of this effect varies widely. As discussed below, there are substantial differences in measurement across studies that complicate interpretation or meta-analysis of these results.

3.1.1. Subjective experience and climate opinion

Of the articles reviewed, 32 (44%) examine the association between subjective experience with abnormal weather conditions or extreme events and climate opinion. Studies that examine subjective experience ask participants to self-report whether they have personally experienced a specific weather-related phenomenon, trend, or extreme event [13–15, 24, 32, 36, 38, 46–50], whether they have experienced its effects [21, 25, 51–54], or if they have generally experienced unusual weather patterns [55, 56]. Alternatively, some studies ask participants if they have personally experienced the effects of climate change itself [37, 57–59]. In some studies, survey questions about personal experience are also combined with external observational data on weather conditions or trends [15, 20, 32, 36, 38, 39, 46, 50, 60, 61].

Based on this literature, there is a fairly robust relationship between perceived or subjective experience

[4] We define 'weather' broadly as short-term (e.g. daily) conditions or variations in the atmosphere, and 'climate' as longer-term conditions or variations.

and related climate opinion questions. Of 32 papers that address the association between self-reported experiences and climate opinion, 27 (84%) find evidence for such a relationship. For example, a large study of surveys from 119 countries found that perception of rising temperatures at the local level was an important predictor of climate risk perceptions [14]. In general, these studies suggest that people who think they have experienced the effects of global warming (or have experiences of extreme weather) also tend to believe that global warming is happening and to be more concerned about it. However, these studies alone do not establish a causal relationship between experience and opinion. Despite the associations identified in these papers, climate opinions may also shape the weather-related experiences that people self-report, as we discuss in section 3.1.4 below.

3.1.2. The effect of objective temperature experiences on climate opinion

Of the reviewed articles, 51 (70%) examine the association between externally measured weather variables or extreme events and climate opinion. Of these, 46 (90%) used some measurement of temperature or temperature-related extreme events (e.g. heat or cold waves). Temperature is typically operationalized as either the absolute air temperature over a certain time period, or a temperature anomaly: the difference in the absolute temperature from a long-term base period. A small number of studies also examine trends in temperature over a set time period. The prevalent use of temperature as an independent variable likely arises from its conceptual salience with global warming or climate change, as well as the ease with which temperature observations from weather stations or gridded data can be joined with survey responses by location.

Among studies that have tested temperature as an independent variable predicting climate opinion, some provide evidence for a 'local warming' effect (e.g. [5, 6, 10, 11, 15, 18, 62]), showing that elevated temperatures in the short term (daily to monthly) are associated with increased concern about climate change, belief that it is happening and human-caused, or policy support. For example, in one analysis, temperature anomalies in the week prior to a survey predict opinion about whether global warming is happening [9]. These same studies indicate that the magnitude of the effect is relatively low and not persistent as the experience of elevated temperatures recedes over time (e.g. [9, 63]). Other studies that have examined associations between short-term temperature and climate opinions have found no effect [7, 19, 64].

There are mixed findings among studies that have investigated the relationship between longer-term temperatures or temperature trends and public opinion. The largest recent study of US survey data ($N = 348,500$) from 1999 to 2017 finds that higher average annual temperatures at the state level are associated with a small but robust increase in worry about climate change [65]. This finding is reflected in similar studies that have examined seasonal-to-annual temperatures, e.g. [7, 8, 17, 19, 20, 63, 64, 66–68]. For example three studies find that 10 year summer temperature trends are positively related to beliefs about human-caused global warming in the US [19, 64, 66]. In addition, an index representing the ratio of previous record high temperatures to record low temperatures over several years (with more record high temperatures expected under a warming climate) is associated with estimates of county-level climate opinions in the US [12, 69]. However, other studies that have focused on longer-term temperatures or trends have found little to no effect on climate opinions [28, 30, 32, 34, 70, 71].

The few longitudinal studies that have examined how changes in climate opinions may be associated with local temperature observations have generally found little to no effect. For example, monthly US temperature anomalies do not predict changes in opinions over 2.5 years from 2008 to 2011 [31], and there were minimal effects of monthly temperature anomalies in a large panel analysis of Cooperative Congressional Election Study data over a four-year period from 2010 to 2014 [72].

3.1.3. The effect of objective non-temperature experiences on climate opinion

While temperature is the most commonly used observed weather variable, other studies examine precipitation observations (e.g. [10, 64, 65]) or derived climatic variables (such as drought indices) (e.g. [30, 67]). Of studies that use objective weather data, 21 (41%) use data related to precipitation. In contrast to temperature, most studies have identified little to no association between precipitation or related variables alone and climate opinions [10, 31, 32, 64]. For example, a very large study in the US [65] shows no relationship between median annual precipitation and climate opinion. By contrast, an earlier US study [20] does find that the seasonal snowfall anomaly (as compared to the 30 year average) predicts beliefs about whether global warming is happening in the US However, this variable is not independent from temperature, since the occurrence and amount of snow is related to air temperature.

Beyond temperature and precipitation, some studies have also examined a range of impacts and occurrences of various extreme weather events. Of studies using external measures rather than self-reported experiences, 20 (39%) include measures related to extreme weather events. Several of these studies have used published aggregated indices of weather extremes as predictors of climate opinions, such as the US Climate Extremes Index that combines temperature, precipitation, drought severity, and landfalling tropical storms [28, 30, 33, 73]. These studies do not find a relationship between these aggregated extremes indices and climate opinions.

A further set of studies focus explicitly on the relationship between the impacts of weather-related extreme events and climate opinions, with mixed results. Several US studies utilize the National Oceanic and Atmospheric Administration's Storm Events Database [74] (or derived products like the Spatial Hazard Events and Losses Database [75]). This dataset records the impacts of weather-related events that cause loss of life, injuries, or major property damage, or are unusual enough to generate media attention (georeferenced at the county or forecast area level). For example, one study [76] examines weather-related property damage at the county level and does not find a direct effect on climate opinions. Another recent example [46] finds that hurricanes, tornadoes, floods, and droughts are unrelated to climate opinions, in contrast to self-reported experience for certain types of events. This finding is echoed by several other studies [17, 71, 72]. Yet, a few other studies do find that indices of extreme weather events predict climate opinion, such as a study of US Gulf Coast counties [67], a national US study using natural hazard fatalities [70], and a national US study using the number of extreme weather events by region [22, 23].

A final set of papers involve case studies of certain communities affected by extreme weather events, or the effect of a specific event on changes in climate opinion. A set of studies in the UK [21, 24, 53] focus on the experience of floods; these find that flood impacts predict climate opinion. However, an earlier UK study [54] finds that flood experiences does not affect climate opinion, and a recent study suggests that coping capacity moderates the negative emotions from a flood event that would motivate opinion change [52]. A recent study in the US [77] surveyed four communities exposed to tornadoes or wildfires and finds that event proximity does not predict climate opinion, as opposed to subjective harm from the event. Similarly, case studies of particular events like a flood event in Boulder, Colorado [78] or a drought in the US Midwest [29] show no effect on climate opinions. By contrast, a study in New Jersey finds that hurricane exposure predicts support for pro-climate political candidates [27].

3.1.4. The effect of climate opinion on perceptions or subjective experiences of local weather

A subset of studies focuses on how people perceive weather or climate conditions at the local level. Rather than using beliefs about global climate change as a dependent variable, these studies examine whether people perceive the climate in their local area to be getting warmer, whether recent seasons are warmer or colder than normal, or related local climate trends [25, 35, 36, 38, 39, 50, 60, 61, 71, 79–81].

Multiple studies have found that these subjective experiences of local weather or climate conditions are associated with broader climate opinions and political affiliation or ideology. In short, people who are already more concerned about global warming are more likely to think they have experienced its impacts, or have experienced weather conditions consistent with global warming [35, 36, 38, 39, 61, 71]. These trends are typically attributed to motivated reasoning or related phenomena.

Although studies of local climate perceptions show that climate opinions shape such perceptions, they also show that people are often able to detect a signal of local weather or climate despite biases created by motivated reasoning. For example, a study of Oklahoma residents found that they were able to perceive local seasonal temperature and precipitation anomalies despite biases introduced by political ideology [81]. Similarly, a study in Norway found that perceptions of seasonal temperature and precipitation were strongly associated with measured conditions while also exhibiting biases associated with climate opinions [36]. Detection of climate trends at the local level may be limited to larger-magnitude variations across large areas; however, a study in Florida found that five-year trends in temperature were not associated with perceived temperature trends across the state, although trends in precipitation were faintly detected [32]. The types of self-reported weather experiences shaped by climate opinions have not yet been fully explored, but there are suggestions that temperature-related experiences are more sensitive to biases driven by climate opinions than experiences related to precipitation or other extreme events [36, 38, 50].

3.2. Measurement diversity

A major constraint on systematic comparison of this literature stems from measurement diversity. Although the papers we review generally share the aim of identifying how experiences with weather and climate influence climate opinions, both the suite of treatments (i.e. potential explanatory factors) and the specific outcome variables of interest vary considerably. Whether experience is measured through self-reported or objective data, many additional non-trivial discrepancies exist. Survey questions are worded differently, and weather and climate data are integrated from diverse sources with varying spatiotemporal extent and resolution. Furthermore, climate indicators are operationalized in many different ways, and distinct approaches exist for spatially and temporally matching climate indicators to respondents. First, we explore the diversity in measurements of physical climate changes, the treatment of interest. Then, we consider the diversity of dependent variables that scholars have examined.

3.2.1. Heterogeneous measurement and conceptualization of independent variables

Measurements of climate and weather (the treatment variables) vary considerably across the studies we review. As noted previously, a first-order distinction is

between the 32 papers that measure the effect of subjective or reported experiences of weather and climate, versus the 51 papers that examine the influence of objectively measured weather and climate changes. Ten papers examine both subjectively (self-reported) and objectively measured weather or climate changes.

Local temperature measurements used in these studies vary in their use of absolute versus relative values, spatial extents and time intervals, and data sources. Temperature data for many studies are taken from the Global or United States Historical Climatological Network, which is an integrated database of climate summaries from land surface stations subjected to a common suite of quality assurance review. Station data are limited, however, in their ability to represent the continuous range of weather conditions across the Earth's surface. As distance increases from a station, its accuracy in capturing local conditions declines. Thus, it may be difficult to accurately represent weather experiences for populations living distant from a weather station (a challenge that is particularly prevalent in areas of the developing world with sparse station networks). To address this issue, other studies use gridded datasets derived from station and/or satellite data that create a continuous surface of modeled weather or climate variables. One example is the parameter-elevation regressions on independent slopes model (PRISM) dataset [82], which combines data from a variety of US monitoring networks. PRISM employs a range of modeling techniques that incorporate the influences of topography, for example, to derive spatially accurate estimates of climate parameters. Whether the use of these divergent data sources explains divergent findings has not been systematically assessed. In particular, it is not clear whether one type of data source provides climate data closer to what individuals in a particular location actually perceive. As a result, it is impossible to carefully diagnose the source of observed differences in treatment effects between studies employing these different datasets and associated indicators derived from these datasets. Similarly, there are multiple different sources of data and ways of calculating long-term temperature trends and extremes, including a heat stress index [32], climate extremes indices (e.g. [46]) and annual or seasonal trends based on temperature minimums, maximums, or means (e.g. [61, 67]).

Other weather and climate measurements are also characterized by these measurement inconsistencies. For example, heavy precipitation must be measured relative to some 'normal' base period or distribution, whether as deviations or percentiles. Heavy precipitation is also highly localized. In contrast, the extended absence of precipitation (i.e. drought) has a much larger and more homogeneous spatial imprint than heavy precipitation events, temperature anomalies or heat waves; it is also measured very differently. Drought can be measured through the duration of consecutive dry days, but thus far analyses of drought perceptions have relied on readily available indices such as the Palmer Drought Severity Index [28, 73, 79] or the US Drought Monitor [29, 68, 72]. Such indices, however, were not originally designed from the perspective of understanding how people experience weather and climate change but rather were designed for use in climatological, agricultural, and similar purposes. It remains unclear whether drought measurements operationalized in this fashion are consistent with how individuals perceive or experience drought.

Many papers that consider subjective experience focus on experience with extreme events or disasters, especially flooding [24, 47, 48, 52–54], but also tropical cyclones, drought, wildfire, and other changes [47, 49]. Such differences are non-trivial, as each event carries very different risks, is associated with different economic costs, and affects individuals and communities in very different ways. We need to better understand the different interpretations of subjective experiences in these varied contexts. At least one study explores this topic with open-ended responses, which provides insight into the diversity of interpretations of personal experience [59]. Additional studies using open-ended responses would be productive to understand the variety of ways in which climate change is expressed and perceived locally.

3.2.2. Heterogeneous measurement and conceptualization of dependent variables

As with the independent variables, the variety of dependent variables is also substantial (table 1). Studies examine a diverse range of climate experiences and opinions, from whether individuals accurately detect changes in their local area (measured instrumentally) [32, 35, 83], to whether measured (or reported) changes are associated with increased awareness, a change in affect or emotion [48, 52], beliefs (e.g. [25, 76]), belief certainty [13, 37], risk perceptions (e.g. [6]), self efficacy, mitigation or adaptation policy preferences (e.g. [23, 62]), and intended behaviors. We identified no studies that measured actual behavioral changes. However, some studies measured behavioral intentions, including political behaviors, such as support for green politicians [27], media use [83], and intended reductions in energy use [24]. Most studies rely on individual question items but some construct narrow [70] or broad [65] risk perception indices from multiple items.

3.2.3. Variation in geographic coverage

Examining the intersection of weather or climate and perceived experience or climate opinions requires careful attention to spatial considerations. Researchers make decisions about the scale of the study (from local to global), the distribution of individuals within the study domain, the distribution of weather or climate trends and events considered, and how climate data will be matched with individuals in the study. The

Table 1. Examples of survey question wordings used as dependent variables in selected studies.

Concept	Item	Citation
Perceptions of local flooding frequency change	Comparing the past 10 years with 20 or 30 years ago, do you think that number and size of destructive floods in New Hampshire have: [Increased; Stayed the same; Decreased; Don't know/no answer]	[80]
Global warming beliefs	Recently, you may have noticed that global warming has been getting some attention in the news. Global warming refers to the idea that the world's average temperature has been increasing over the past 150 years, may be increasing more in the future, and that the world's climate may change as a result. What do you think? Do you think that global warming is happening? [Yes; No; Don't know]	[31]
Global warming beliefs	Do you think climate change is a serious problem for the whole world? [Not severe at all; Not so severe; Somewhat severe; Very severe; Not clear]	[47]
Global warming beliefs	From what you know about global climate change or global warming, which one of the following statements comes closest to your opinion? [Global climate change has been established as a serious problem and immediate action is necessary; There is enough evidence that climate change is taking place and some action should be taken; We don't know enough about global climate change and more research is necessary before we take any actions; Concern about global climate change is exaggerated and no action is necessary; Global climate change is not occurring and this is not a real issue.]	[72]
Perceived experience with climate change	Have you experienced any extreme weather conditions that you interpret as caused by long-term, global climate change? [Yes, probably; Do not know; Probably not; Definitely not]	[60]
Support for climate policy	I will support a national policy to mitigate climate change. [1 = Strongly disagree; 7 = Strongly agree]	[55]
Global warming risk perceptions	How serious of a threat do you think global warming is to [You and your family; Your local community; People of Florida; People in the United States; People in other countries; Plants and animals] [1 = Very serious; 4 = Not at all serious]	[32]
Weather as evidence for or against climate change	The cold winter which occurred during late 2010 suggests that climate change may not be happening. [5-point scale Strongly agree-Strongly disagree]	[26]
Concern about global warming	How much do you personally worry about global warming? [A great deal; A fair amount; Only a little; Not at all]	[30]

Table 2. Overview of papers by focus country.

Country	Number of papers
United States	52
United Kingdom	8
China	4
Norway	2
New Zealand	1
Taiwan	1
Multiple countries	5

studies reviewed span the full range of local to global analyses, but the vast majority are conducted within the United States, and many are national (table 2). The spatial distribution of people and climate are given varying degrees of attention. Samples may be selected based on particular extreme weather events in order to directly test the effects of those events (e.g. flooding). In other cases, an exploratory approach is taken. In some cases, respondents' locations are known (i.e. household addresses) and so analyses are performed at the individual level (e.g. [31, 32, 38, 66]), whereas in other cases respondents are aggregated by zip code, county, or even state levels (e.g. [8, 12]). The varying degrees of mismatch between respondent locations and weather or climate 'treatments' introduces uncertainties into any assessment of treatment effects.

Based on the geographic scope of studies identified in the review, it is clear that more non-US research is necessary, especially in China, India, and the global South, which represent some of the areas most vulnerable to climate change impacts. In addition, for studies that focus on the effects of climate changes that have relatively well-defined spatial signatures (e.g. wildfires, flooding, hurricanes), careful attention should be paid not only to the location of respondents within the geographic area, but also to how those respondents are matched with their respective weather or climate treatments. Weighting climate indicators according to the spatial distribution of population densities within a county or state, for example, is a relatively straightforward way to account for the uneven distribution of both climate and population in any area (e.g. [1, 84]). Population density grids are publicly available and would improve estimates of treatment effects in places that encompass large rural or sparsely-populated areas in particular.

3.3. Methodological approaches

Although sharing a similar aim, the studies reviewed here vary in their specific objectives and thus employ a range of methods (table 3). They also build on a long

Table 3. List of articles included and brief description of relevant results.

Citation		Brief summary
Akerlof *et al*, 2013	[59]	In one Michigan county, perceived personal experience of global warming was associated with heightened global warming risk perceptions. (Alger County, Michigan, United States)
Bergquist and Warshaw, 2019	[65]	An index of US public opinion polls found that public concern about climate change peaked in 2000 and 2017 and coincided with state temperature anomalies. (United States)
Blennow *et al*, 2012	[55]	Strength of belief in climate change and perception of local effects were found to predict climate adaptation opinions among private forest owners. (Portugal, Germany, Sweden)
Boag *et al*, 2018	[57]	Although forest managers were aware of local environmental change, awareness was not associated with adaptive action to climate change. (Oregon, United States)
Bohr, 2017	[5]	Very cold or warm temperature anomalies from a 5 year baseline predicted perceptions of global warming impacts. Temperature anomalies exacerbated political polarization over the causal attribution of global warming. (United States)
Borick and Rabe, 2014	[20]	Seasonal snowfall and temperature departures from normal predicted beliefs about the existence of global warming; respondents reported that weather was important in shaping their views. (United States)
Brody *et al*, 2008	[70]	No correlation between long-term trend in number of warmer-than-average days per year and climate change risk perception. (United States)
Brooks *et al*, 2014	[6]	Temperature anomalies on the day individuals were surveyed was associated with concern about climate change. (United States)
Broomell *et al*, 2015	[58]	A multi-country survey found that respondents were more likely to support general mitigation efforts than specific actions of mitigation, and support was predicted by personal experiences with global warming. (Australia; Brazil; Canada; Chile; China; Germany; Spain; France; Hong Kong; Israel; India; Italy; Japan; Korea; Netherlands; Poland; Russia; South Africa; Slovakia; Sweden; Turkey; Taiwan; United Kingdom; United States)
Broomell *et al*, 2017	[35]	Results from a randomized experiment found that individuals were generally able to perceive significant temperature anomalies but classified less extreme anomalies based on their global warming beliefs. (United States)
Brulle *et al*, 2012	[28]	National aggregate indices of extreme weather did not have an effect on aggregate public opinion about climate change over nine years. (United States)
Capstick and Pidgeon, 2014	[26]	Individuals interpreted cold weather based on levels of pre-existing skepticism about climate change. However, after a period of abnormally cold temperatures, three times as many people interpreted the anomalies as evidence of the climate change.(United Kingdom)
Carlton *et al*, 2016	[29]	After a period of drought in the US Midwest in 2012, there were no significant changes in climate change beliefs or attitudes toward adaptation among agricultural advisors. (Indiana, Iowa, Michigan, Nebraska, United States)
Carmichael and Brulle, 2017	[30]	Weather events were minimally associated with the level of concern about climate change; only extreme drought conditions were related to climate change concern. (United States)
Carmichael *et al*, 2017	[73]	An analysis of the factors influencing public concern about climate change (between 2002 and 2013) found that extreme weather did not increase concern about climate change among Democrats or Republicans. (United States)
Cutler, 2016	[76]	Household income, political party affiliation, beliefs about climate change, and property damage from severe weather events were found to have an interactive effect to shape perceptions of climate change risk. (United States)
Dai *et al*, 2015	[49]	Perceived experiences of extreme weather events (particularly heatwaves) in five cities in China were strongly correlated with climate change beliefs. Physical or financial damages due to extreme weather events strengthened the relationship. (China)
Demski *et al*, 2017	[21]	Flooding experience in the UK was associated with greater perceived vulnerability and risk perceptions of climate change, and support for mitigation and adaptation policies. (United Kingdom)
Deryugina, 2013	[7]	Short-term temperature fluctuations (1 day–2 weeks) had no effect on global warming beliefs, but longer-term fluctuations (1 month–1 year) were predictors of global warming beliefs according to an analysis of longitudinal survey data. Only respondents with conservative political ideology were affected by temperature anomalies. (United States)
Donner and McDaniels, 2013	[8]	Aggregate climate change belief and concern was correlated to national mean temperature anomalies over the previous 3–12 months. (United States)
Druckman and Shafranek, 2016	[93]	Participants who were primed to think about temperatures over a long period of time were less likely to overestimate the percentage of abnormally warm days over the past year. Temperature on the day of the survey was correlated with global warming belief, worry, and anthropogenic attribution among the control group, but not the primed group. (United States)
Egan and Mullin, 2012	[9]	Local temperatures over the past week were associated with climate change beliefs. However, the effect was not related to long-term attitude change. (United States)

Table 3. (Continued.)

Citation		Brief summary
Fownes and Allred, 2018	[61]	Respondents were more likely to report that they had personally experienced climate change when surveyed on abnormally warm days. Respondents who reported believing in climate change were more likely to report they had experienced climate change and the effect was stronger among those who attributed climate change to anthropogenic causes. (New York State, United States)
Goebbert *et al*, 2012	[50]	Actual weather changes were less predictive of perceived changes in local temperatures, but better predictors of perceived flooding and droughts. Beliefs about local changes in temperature were more politicized than beliefs about changes in precipitation. (United States)
Hamilton and Keim, 2009	[68]	Winter warming was associated with a greater probability of perceiving local climate change, even after adjusting for unexplained regional differences. (19 counties in Alabama, Colorado, Kansas, Kentucky, Maine, Mississippi, New Hampshire, Oregon, Washington, United States)
Hamilton and Stampone, 2013	[10]	Climate change beliefs were predicted by temperature anomalies on the interview day and the previous day. Temperature effects were concentrated among those who identified as political independents. (New Hampshire, United States)
Hamilton *et al*, 2016a	[79]	Older residents were more likely to perceive that summer temperatures had increased. Three subgroups assumed to have greater experience with land including forest owners, year-round residents, and long-term residents were neither more nor less likely than others to perceive warming summer temperatures. (Northeast Oregon, United States)
Hamilton *et al*, 2016b	[80]	Perceptions of flood risk were associated with political ideology rather than physical vulnerability or personal experience with local weather changes. (New Hampshire, United States)
Howe and Leiserowitz, 2013	[38]	Subjective experiences of seasonal average temperature and precipitation during the previous winter and summer were related to recorded weather conditions and beliefs about global warming. (United States)
Howe, 2018	[36]	Respondents were sensitive to changes in temperature and precipitation, but global warming beliefs had a large effect on perceptions of seasonal temperature, and less on seasonal precipitation. (Norway)
Joireman *et al*, 2010	[11]	Respondents' global warming beliefs were correlated with outdoor temperatures during the study. (Northwestern United States)
Kaufmann *et al*, 2017	[12]	Temperature anomalies accounted for spatial variation in the percentage of the population that believes that global warming is happening at the county level (United States)
Konisky *et al*, 2016	[22]	There was a positive relationship between extreme weather experience and concern about climate change. However, the effect of extreme weather on public concern was only significant for recent weather events. (United States)
Krosnick *et al*, 2006	[13]	People who believed they had experienced rising temperatures in recent years were more likely to express belief in global warming. (United States)
Lee *et al*, 2015	[14]	A multi-country survey found country level variation in the predictors of climate change awareness and risk perceptions. Perceived temperature change was a significant predictor across nearly all geographies, but strongest in Africa and Asia. (119 countries)
Lee *et al*, 2018	[62]	Respondents reported temporarily higher levels of support for agricultural adaptation policies after exposure to abnormally warm temperatures. (Michigan, United States)
Li and Zaval, 2011	[15]	Respondents surveyed in the US and Australia that believed the day that they were surveyed was warmer than usual expressed greater concern about climate change (and weremore willing to donate money to a global-warming charity) compared to those who thought the day was cooler than usual. (United States; Australia)
Lo and Jim, 2015	[108]	Residents' concern about climate change was associated with perceptions of changes in local temperatures and cyclone frequency. (Hong Kong, China)
Lujala *et al*, 2015	[51]	Norwegians who reported that they experienced natural hazard damages were more concerned about personal consequences of climate change. (Norway)
Lyons *et al*, 2018	[46]	Subjective experience of extreme weather events was associated with climate change beliefs for less visible events (droughts and polar vortex) as opposed to more overt events like tornadoes, hurricanes, and floods. Objective indicators were unrelated to climate opinion. (United States)
Marlon *et al* 2018	[32]	Respondents were unable to detect 5 year increases in temperature, but some could detect change in precipitation. Climate change risk perceptions were more strongly predicted by subjective experiences of environmental change, climate change beliefs, and political ideology compared to local weather variables. (Florida, United States)
Marquart-Pyatt *et al*, 2014	[33]	Variation in a climate extremes index did not influence perceptions of the timing of climate change and had a negligible effect on perceptions of the seriousness of climate change. (United States)
McCright *et al*, 2014	[39]	Temperature anomalies influenced perceived warming but not attribution of warmer-than-usual winter temperatures (to global warming). Abnormally warm temperatures were influenced more by scientific agreement, anthropogenic attribution of climate change, perceived risk of global warming, and political orientation. (United States)

Table 3. (Continued.)

Citation		Brief summary
Mildenberger and Leiserowitz, 2017	[31]	Neither local temperature nor precipitation anomalies predicted longitudinal changes in public opinion about climate change. (United States)
Myers *et al*, 2013	[37]	Perceived personal experience of global warming was associated with increased global warming belief certainty. Inversely, high belief certainty influenced perceptions of personal experience. (United States)
Niles and Mueller, 2016	[60]	Farmers who expressed belief in anthropogenic climate change were more likely to perceive increased temperatures than farmers who did not express belief in climate change. (New Zealand)
Ogunbode *et al*, 2018	[52]	Respondents with a strong ability to cope with flooding were unlikely to experience negative emotions that might prompt personal action to mitigate climate change; coping ability moderates the link between flood experience and mitigation intentions. (United Kingdom)
Ogunbode *et al*, 2019	[53]	Personal experience of a flooding event predicted perceived threat from climate change, and indirectly predicted mitigation responses among individuals who attributed the floods to climate change. (United Kingdom)
Palm *et al*, 2017	[72]	Recent experience with hot summers, warm winters, droughts, and natural disasters was minimally associated with attitude change related to anthropogenic climate change. (United States)
Potoski *et al*, 2015	[91]	Wealthier respondents were found to be overrepresented in surveys during warmer temperatures. Exposure to unseasonable temperatures was correlated with reduced concern about climate change. (United States)
Ray *et al*, 2017	[23]	Individuals who experienced recent extreme weather events were more likely to support climate change adaptation policy in general, but the effect was variable across specific adaptation policies and diminished with time. (United States)
Ripberger *et al*, 2017	[81]	Survey respondents generally perceived climate anomalies, especially when anomalies were extreme and persistent; this finding was robust to political differences. (Oklahoma, United States)
Risen and Critcher, 2011	[16]	In an experimental study, participants who experienced higher temperatures were more likely to believe in the existence of global warming. (Cornell University and University of Chicago, United States)
Rudman *et al*, 2013	[27]	New Jersey residents who experienced significant hurricane impacts were more likely to support politicians who supported of climate change policies. (New Jersey, United States)
Schuldt and Roh, 2014	[92]	Among climate skeptics, those primed with cold weather exhibited a decrease in belief in global warming, but not climate change. (Upstate New York, United States)
Scruggs and Benegal, 2012	[63]	In a large survey dataset, there was a modest positive relationship between the most recent seven-day temperature anomaly and the likelihood of reporting that global warming is occurring. (United States)
Shao and Goidel, 2016	[67]	Political orientation was found to have a stronger influence on perceptions of local weather conditions compared to objective weather conditions. Local weather perceptions were found to influence climate change attitudes. (United States)
Shao *et al*, 2014	[19]	Individuals who had experienced increasing summer temperatures were more likely to perceive immediate impacts and severity of global warming. (United States)
Shao *et al*, 2016	[64]	Individuals exposed to long-term trends of abnormally warm summer temperatures and cooler spring temperatures were more likely to perceive the existence of anthropogenic global warming. (United States)
Shao, 2016	[71]	Individuals who expressed belief that global warming is happening, and should be a priority were more likely to perceive recent weather anomalies. Perceived weather was much more predictive of global warming beliefs than observed weather. (United States)
Shao, 2017	[66]	Warmer winter temperatures and cooler spring temperatures over the past 10 years was associated with the belief that overall global temperatures have been rising. (United States)
Shepard *et al*, 2018	[78]	Residents connected flooding events to climate change despite contradictory scientific claims about the relationship. Events did not change existing climate change beliefs but did facilitate a greater sense of vulnerability and increased awareness about climate change risk. (Boulder County, Colorado, United States)
Shum, 2012	[34]	The state of the economy had a significant effect on attitudes toward emissions reduction, however, annual temperature deviations did not. (Austria; Belgium; Bulgaria; Croatia; Cyprus; Czech Republic; Denmark; Estonia; Finland; France; Germany; Greece; Hungary; Ireland; Italy; Latvia; Lithuania; Luxembourg; Malta; Netherlands; Poland; Portugal; Romania; Slovakia; Slovenia; Spain; Sweden; United Kingdom)
Spence *et al*, 2011	[24]	Those who had direct experience with flooding expressed greater concern about climate change. Greater concern about climate change was associated with a stronger willingness to mitigate climate change. (United Kingdom)

Table 3. (Continued.)

Citation		Brief summary
Sun and Han, 2018	[47]	Climate-related disaster experience did not have a significant impact on perceptions of global warming severity or perceived personal impact. (Taiwan)
Taylor *et al*, 2014	[25]	Respondents perceived heat waves and hot summer temperatures as less common during their lifetimes. However, periods of heavy rainfall, coastal erosion, and mild winters were perceived to have increased in frequency. Climate change beliefs were predicted by perceived changes in hot and wet-weather related events. (United Kingdom)
van der Linden, 2014	[48]	Personal experience with extreme weather events predicted climate risk perceptions, but risk perceptions were also strongly related to affect. (United Kingdom)
Wang and Lin, 2017	[83]	The occurrence of a typhoon predicted perceived experience of unusual weather among Chinese respondents, while abnormally warm summer temperatures did not. Typhoon occurrence also indirectly predicted global warming belief certainty and attitudes toward mitigation behavior. (China)
Wang, 2017	[56]	Personal experience with climate change impacts positively predicted climate change beliefs. (China)
Whitmarsh, 2008	[54]	Flood victims did not exhibit a significant difference from non-victims in their understanding of and responses to climate change. However, experience of air pollution significantly influenced perceptions of climate change and behavioral responses. (south England, United Kingdom)
Zahran *et al*, 2006	[109]	Local temperature trends predicted climate change policy support, as did sea level rise risk. (United States)
Zanocco *et al*, 2018	[77]	An analysis of selected US communities exposed to extreme weather events found that reported harm aligned with proximity and community damages from the event. However, interpretations of the events and attributions to climate change were guided by political ideology.(Laurel County, Kentucky; Winston County, Mississippi; Yavapai County, Arizona, Lake County, California, United States)
Zaval *et al*, 2014	[18]	Present temperature anomalies were associated with an overestimation of the frequency of similar past events, which was related to an increased belief in and concern for global warming. (United States)

history of exploiting natural weather variations to study social science phenomena. Often, weather is used as an econometric 'instrument': a source of random variation that predicts a variable of interest and thus helps to estimate an endogenous variable's causal effect on an outcome of interest. For example, scholars have used rainfall variation to study the relationship between economic growth and civil conflict [85], the relationship between poverty and crime [86], and the relationship between riots and property value [87]. Scholars in both economics and political science have also examined the direct causal effect of weather variation on economic and political outcomes [88–90].

Scholarship on weather and public opinion can theoretically exploit this same variation. Studies of weather and public opinion can thus benefit from the fact that weather is a direct object of interest (the 'treatment'), and that plausible sources of exogenous variation in this treatment are readily available. Yet, the literature reviewed here is divided by its attention to causal inference.

3.3.1. The limits of model-dependent inference

At one pole, a number of papers describe associations between weather experiences and climate opinions without explicit attention to causal identification. These papers rely on multivariate controls to estimate the the effect of weather on diverse outcomes.

However, these studies face certain limitations. First, weather conditions are spatially autocorrelated; in other words, conditions are likely to be more similar for participants located closer to each other. Spatial dependence is inherent in many human and physical processes. Traditional regression models assume independence between observations. However, when studying the relationship between weather and public opinion, it is particularly important to account for spatial dependence in predictor variables. This will reduce the chance of underestimating standard errors and the likelihood of Type I errors (or incorrectly rejecting a null hypothesis). Multi-level models, clustered standard errors, or geographically weighted regression are several methods to account for geographic structure in predictors. However, most papers focused on the relationship between weather and climate opinions do not attempt to account for possible errors introduced by spatial autocorrelation using these or other methods, nor do they attempt to measure the extent to which spatial autocorrelation is present in their modeled regression residuals (though see [38]).

Second, studies that rely on self-reported measures of weather exposure face an additional inferential threat. In these cases, it can be difficult to tell whether public opinion responds to weather exposure, or perceptions of weather exposure are motivated by underlying opinions (see section 3.1.4 above).

Third, because weather varies geographically, geographic patterns of a particular weather variable may sometimes coincide with the geographic patterns of other unmeasured social, cultural, political, or demographic predictors. This means that meteorological variables may be correlated with other latent phenomena that are also causal drivers of a particular dependent variable. For example, if a period of cold weather strikes the central US while coastal areas are hotter than normal, then this weather pattern will be strongly correlated with underlying patterns of American political geography. This correlation will bias a cross-sectional multivariate analysis that predicts opinion using cold weather experiences. A related complication arises due to the possibility of multiple comparisons. Weather and climate datasets contain a wide range of variables that may be used as predictors of, for example, individual survey responses. These variables can be aggregated over multiple time periods selected by the researchers. Without adjustment, multiple comparisons among predictors can increase the risk of inferential errors.

3.3.2. Causal identification of weather on perceptions

A limited set of papers address these methodological issues head-on. These papers use as-if random variation in weather as the basis for their research design. Of course, most weather patterns are not randomly assigned across a large country or region. Instead, causal identification claims rest on the idea that, conditional on a particular area or geography, variation in weather is as-if random.

These papers thus exploit randomness in short-term or local weather conditions to test how weather extremes shape public opinion [7, 9, 65]. According to the logic of these papers, weather patterns vary more arbitrarily *within* a given county or local area. These differences can be causally identified. By contrast, when everyone in a given area is simultaneously treated with a large event like a hurricane or regional heat wave, then our efforts to understand the causal effect of weather will be compromised by non-random factors that are simultaneously associated with both weather trends and climate opinions.

These threats to inference can be managed through the inclusion of geographic fixed effects, preferably at the local level. Yet, only a handful of papers covered by this review include fixed or random effects at any level, including regional [20, 33, 46, 68], state [7, 9, 39, 91], or geographies below the state level (e.g. county, city, weather station) [9, 22, 36, 49, 65, 76, 77, 79].

Further, these studies would then benefit from demonstrating that, conditional on geographic fixed effects, populations which receive a particular weather treatment are identical to those that do not (but see [9] who do show that observed covariates cannot predict weather fluctuations). Instead, some articles simply assume that 'weather fluctuations are as good as random once geographic controls are included' ([7],

p 406). More work needs to be done by the research community to understand whether or when this assumption is founded.

When pooling data over time, articles should also include time dummies to control for secular shocks [9, 31, 33, 62, 65, 81] or other more sophisticated controls such as linear time trends [65]. Similarly, between-country analyses should utilize country-level fixed or random effects [34, 63].

While the majority of observational studies reviewed relied on cross-sectional statistical analysis, a growing group of papers exploit panel data. These papers provide traction in estimating whether shifts in weather conditions are linked to shifting public opinions [8, 19, 28, 30, 31, 34, 37, 63, 65, 81]. Their results are not always consistent with cross-sectional studies (see above). In part, the drivers of shifts in climate opinions may not be the same as the drivers of absolute climate opinion levels. At the same time, panel analysis controls for a greater number of potential omitted variables, including any factors that are time-invariant in two-way fixed effect specifications.

An even smaller set of papers ($n = 5$) involve researcher-controlled experimental tests. Since researchers cannot control weather itself, these papers tend to test the causal effect of messages about extreme weather or exposure to particular extreme weather prompts. For example [18, 92], use a survey experiment to test whether public opinion in the aftermath of an extreme event changes whether a survey gauges their opinion on 'climate change' or 'global warming'. Another study [93] evaluates how shaping the prompt used to encourage evaluation of weather experiences shapes opinion. Other studies examine the effect of information, heat-related, or problem-severity primes [11, 18]. The lone article reviewed that used lab experiments [16] finds that warmth and thirst both increased subject belief in climate change and desertification risks. Beyond direct experience, climate-related experiences may also occur indirectly through exposure to media coverage or communication with other people such as friends or family. In addition, media coverage may interact with direct experience in influencing climate opinions. Future research should examine how such indirect experiences, and communication about direct experiences, might influence climate opinions. For example, such research could combine techniques to measure exposure to weather-related events with emerging techniques to measure exposure to media content [94] or online activity [95].

More broadly, the vast majority of articles reviewed here are quantitative in their approach. These articles all rely on cross-sectional or panel analysis of survey datasets. Only two articles we reviewed approached the study of opinion through qualitative interview-based or ethnographic lenses [57, 78]. For example [57], draws from 50 interviews with landowners in Oregon. These studies remind us that public attitudes towards climate change should not simply be reduced to survey scales. Instead, there is value in understanding the rich and multidimensional content of climate opinions, and understanding the ways in which weather experiences construct these beliefs. In general, this approach is under-represented in the existing literature. Some excellent work on this topic fell outside this review's sampling strategy, since it has been published in book form. For example [96], presents an ethnographic study on public experiences with an unusually mild winter in a Norwegian town. The book outlines how public engagement with climate change is shaped by social efforts to regulate emotions. In line with works like these, scholars with expertise in interview, focus-group. Focus-group and ethnographic methods could make a major contribution to this literature by expanding the scope of research on weather and public opinion.

3.4. The need for theoretical context and integration

The studies reviewed draw on theoretical frameworks from across many disciplines. Some studies forego theoretical groundings and limit their focus to documenting empirical associations (e.g. [10, 66, 73]), however, many [16, 48, 59, 61, 77, 83] contextualize their work using one of two psychological theories: dual-process theory [97], which emerged from the cognitive-experiential self theory [98], and construal level theory (CLT) [99].

Dual-process theory distinguishes between two parallel and interacting modes of information processing—experiential (also called System 1) and analytical (System 2). Experiential processing is fast, and driven by affect and intuition. It encodes reality through concrete images and emotions [98]. Analytical (System 2) processing is conscious, deliberative, and comparatively slow. It employs abstract symbols, words, and numbers to encode reality. Critically, experiential processing predicts attitudes and behaviors much more strongly than analytical processing because it requires less cognitive effort [100]. However, both systems operate together to support judgments and decision-making. Although their interactions can be highly nuanced depending on context and may relate to other key psychological aspects like emotion [101], we highlight the potential importance of experiential versus analytical processing for individual interpretation of their weather-related experiences (figure 1).

CLT theorizes the nature and importance of psychological distance [99]. CLT argues that we understand and interact with the world according to the perceived 'psychological distance' of different stimuli. Distances are measured along different dimensions including space, time, and hypotheticality. Transcending our here-and-now selves requires different levels of abstraction, or mental construal [99]. Higher levels of construal and abstraction—and thus psychologically distant concepts—are expected to require more analytical processing. Likewise, phenomena that are

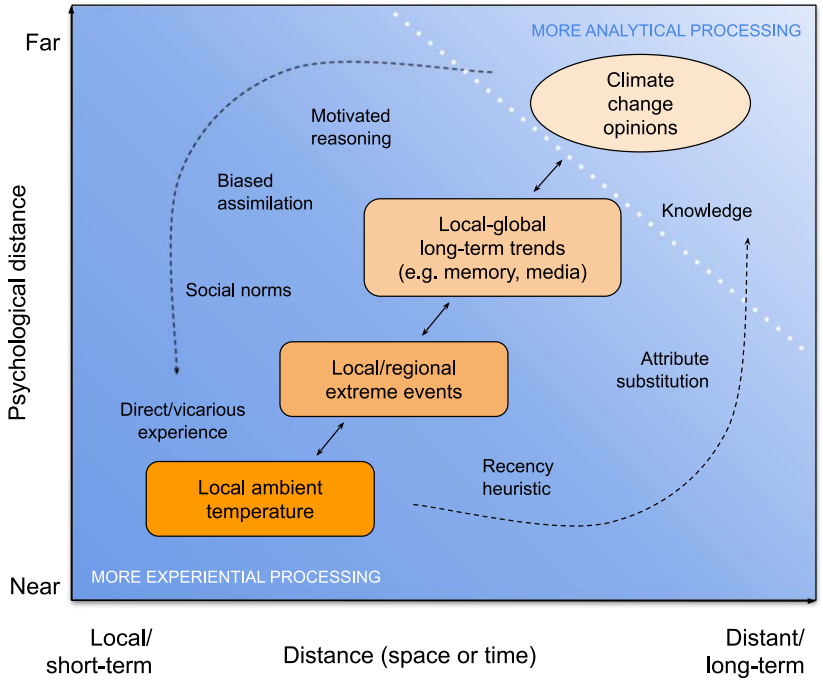

Figure 1. Conceptual diagram of contextual factors that relate to climate change opinions. Concepts range in distance and time from local/short-term to distant/long-term (*x*-axis) as well as in psychological distance (*y*-axis). Climate change opinions may be shaped by local weather experiences. In turn, climate opinions may influence perceptions of local to regional weather or extreme events. Psychologically near concepts, regardless of whether they are near or distant in space or time, are likely to be more compelling in communication.

physically close in both time and space (or hypotheticality) may induce more experiential processing.

Given that experiential processing can be more powerful than analytical processing in driving decision-making and behavior, physically and psychologically close experiences of climate change, such as abnormally hot days, may influence climate opinions more than longer-term, gradual or distant climatic change. And indeed, the effect of short-term weather (e.g. on the day of a survey) on climate opinions has been demonstrated in many studies [10, 11, 16, 61, 93]. However, using recent or available information about the weather or extreme events can also decrease climate risk perceptions [102, 103].

Moreover, the natural variability of weather and seasonal cycles (including winter, even in a much warmer world) make it inherently problematic to emphasize experiential processing and limit analytical reasoning in motivating climate actions. Likewise, gradual trends in climate can be difficult to detect against the backdrop of natural climate variability. Thus, many studies that examine the influence of subtle climate trends or anomalies on climate opinions find essentially no effects at all [28, 31, 32, 72].

While experiential and analytic processing underlie all reasoning about climate change to some extent [100], neither imply a specific result for climate opinions. Individual reactions to weather experiences will thus be influenced by values, worldviews, associations, and emotions. Similarly, changes to the 'psychological distance' of climate change can have diverse effects. A distant frame may invoke analytical reasoning, whereas a more proximate perspective may be more emotionally engaging [104]. While either frame could potentially increase motivation to reduce climate change more than the other, psychologically close frames, regardless of whether they are geographically near or far, are likely to be most engaging.

4. Conclusions

The growing number of articles to study the relationship between climate experiences and climate opinion highlight sustained interest among researchers on this topic. Yet, our review reveals substantial heterogeneity of research setting, variable choice, methodological approach, and theoretical frameworks. In light of these differences, systematic comparisons remain difficult. In general, scholars have found modest evidence that short-term variation in temperature increases climate opinions. However, the size of the temperature-opinion effect—if present—is likely to be small. Efforts to identify the links between shifts in precipitation rates and extreme weather events also remain unsettled.

Practically, if climatic anomalies exhibited a large influence on public opinion (for example, equivalent to the influence of political affiliation on climate opinion in the US) such a large effect would likely have been detected, given the multi-decade research record reviewed here. However, even modest effects may have

important consequences for future public opinion trends as temperatures rise and experiences with unusual weather accumulate; long-term studies may enable better detection of such effects [105]. These cumulative impacts of climate change may yet be sufficient to motivate local to national political action. At the same time, scholars should remind policymakers that retrospective evidence from previous weather conditions or climate trends is limited in its applicability to future conditions. An important consideration for future research is the extent to which local weather conditions or anomalous events become normalized among current and future populations. For example, there are hints that local temperature anomalies quickly become unremarkable in public discourse [106]. Such acclimatization may hinder the ability of populations to perceive the true magnitude of underlying climate trends and limit the generalizability of findings about the effect of past weather on opinion.

We particularly urge researchers in this space to pay careful attention to research design. The combination of georeferenced surveys with georeferenced weather observations allows researchers to reliably estimate the unique local weather conditions for individual survey respondents. This type of research design is common among papers we reviewed. It offers a major advance against research efforts that measure associations between self-reported experiences and opinions, which we suggest have a limited capacity to identify the causal effect of weather on opinion. However, we also suggest researchers pay more attention to the limitations imposed by geography: people living close to each other are more likely to experience the same weather conditions, yet people in close proximity to each other also tend to be more similar in general (in terms of sociodemographics) than to people farther away. This is also the case for climate change opinions, where people in nearby communities tend to have similar opinions [69]. This makes it challenging to statistically identify how weather conditions or a weather event may have influenced people's beliefs and attitudes without careful attention to the distribution of weather events. Indeed, spatial dependence in weather conditions may explain some of the variation in effects shown in the literature. Researchers must be particularly attentive to issues of spatial autocorrelation, omitted variables, and multiple comparisons.

One approach to managing geographic dependencies is to conceptualize weather conditions prior to a survey as a natural experimental stimulus. Natural experiments, if well-designed, can manage problems posed by omitted variables, spatial dependence and multiple comparisons. These approaches pay particular attention to the drivers of spatial variation in climatic events, and often include local-scale fixed effects in their specifications. In doing so, they can isolate individuals who experience a weather event from those who do not but are otherwise similar. Other studies provide strong causal identification by collecting longitudinal data that allow changes in opinion to be documented at the level of the individual.

Future research should also explore how context- and place-dependent experiences with climate change affect climate opinions and behaviors. Widely available weather and climate data, while useful for measuring physical climate trends, may not correspond to ways that people experience climate change in different places with varying cultural or environmental contexts. While our review did not explicitly focus on non-weather-related experiences of climate change, subsequent studies could separately investigate how such experiences, such as sunny-day flooding due to sea-level rise, the impacts of ocean acidification, or glacial retreat shape climate change opinions. Further, previous reviews have called for research in more diverse geographic contexts [40, 41]. We echo this call, and emphasize the particular importance of additional research in the global South where many communities will experience disproportionate impacts from climate change.

We also note the apparent absence of studies that examine the effects of climate-related experiences on realized behavior (though see [107]). Instead, virtually all quantitative literature on this topic uses survey-based measurements of opinions or, at best, behavioral intentions. We suggest that researchers give particular attention to new social and political outcome variables that can increase the external validity of research on this topic. For example, do climate-related experiences increase the propensity of individuals to undertake adaptive planning? Can extreme events increase public uptake of new energy technologies? Do climate-related experiences shape political participation or voting preferences? Behaviors among influential subpopulations are also an important area for future research. For example, media coverage decisions by journalists with respect to extreme weather events may influence how people vicariously experience such events or interpret their own direct experiences. We expect that studies linking weather experiences to realized behavioral outcomes will advance the state of the field.

Viewing the research reviewed through the lens of psychological theory highlights additional avenues for research. Understanding the constructed nature of experience together with the importance of experiential processing in driving judgments and decision making suggests that it may be helpful to improve our understanding of how measured climate changes influence subjective beliefs about those changes. If this pathway can be strengthened, perhaps through a clearer understanding of what changes exactly are interpreted as evidence of global climate change, communication efforts could potentially be targeted to reinforce causal models in the public mind.

In addition, paying more attention to affect and emotion as factors that can influence perceived experience with global warming may yield communication benefits. Overall, grounding future studies within relevant theoretical or conceptual frameworks may also help to focus data collection initiatives and facilitate the identification of gaps in knowledge about how objective and subjective weather drive climate opinions. Helping the public make causal connections between their experiences of climate change and its causes, impacts, and solutions will continue to require active engagement by climate scientists, the media, and others who understand the linkages. The more those linkages can be made in a way that engages experiential processing and minimizes psychological distance, the more meaningful and effective they are likely to be.

In sum, despite the sustained attention that this topic has received, substantial gaps still remain in our understanding of public responsiveness to climate change-related experiences. This systematic review points out some of these gaps. As the global population experiences weather that is increasingly outside the range of historical memory, researchers, communicators, and policymakers must remain attentive to these empirical needs to understand how climate experiences shape public opinions and behaviors.

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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References

[1] Lehner F and Stocker T F 2015 From local perception to global perspective *Nat. Clim. Change* **5** 731–4
[2] Beckage B *et al* 2018 Linking models of human behaviour and climate alters projected climate change *Nat. Clim. Change* **8** 79
[3] Hansen J, Sato M, Glascoe J and Ruedy R 1998 Common-sense climate index: is climate changing noticeably? *Proc. Natl Acad. Sci.* **95** 4113–20
[4] Hansen J, Sato M and Ruedy R 2012 Perception of climate change *Proc. Natl Acad. Sci.* **109** E2415–23
[5] Bohr J 2017 Is it hot in here or is it just me? Temperature anomalies and political polarization over global warming in the American public *Clim. Change* **142** 271–85
[6] Brooks J, Oxley D, Vedlitz A, Zahran S and Lindsey C 2014 Abnormal daily temperature and concern about climate change across the united states *Rev. Policy Res.* **31** 199–217
[7] Deryugina T 2013 How do people update? The effects of local weather fluctuations on beliefs about global warming *Clim. Change* **118** 397–416
[8] Donner S D and McDaniels J 2013 The influence of national temperature fluctuations on opinions about climate change in the US since 1990 *Clim. Change* **118** 537–50
[9] Egan P J and Mullin M 2012 Turning personal experience into political attitudes: the effect of local weather on Americans' perceptions about global warming *J. Politics* **74** 796–809
[10] Hamilton L C and Stampone M D 2013 Blowin' in the wind: short-term weather and belief in anthropogenic climate change *Weather Clim. Soc.* **5** 112–9
[11] Joireman J, Barnes Truelove H and Duell B 2010 Effect of outdoor temperature, heat primes and anchoring on belief in global warming *J. Environ. Psychol.* **30** 358–67
[12] Kaufmann R K *et al* 2017 Spatial heterogeneity of climate change as an experiential basis for skepticism *Proc. Natl Acad. Sci.* **114** 67–71
[13] Krosnick J A, Holbrook A L, Lowe L and Visser P S 2006 The origins and consequences of democratic citizens' policy agendas: a study of popular concern about global warming *Clim. Change* **77** 7–43
[14] Lee T M, Markowitz E M, Howe P D, Ko C-Y and Leiserowitz A A 2015 Predictors of public climate change awareness and risk perception around the world *Nat. Clim. Change* **5** 1014–20
[15] Li Y, Johnson E and Zaval L 2011 Local warming: daily temperature change influences belief in global warming *Psychol. Sci.* **22** 454–9
[16] Risen J and Critcher C 2011 Visceral fit: while in a visceral state, associated states of the world seem more likely *J. Personality Soc. Psychol.* **100** 777–93
[17] Zahran S, Brody S D, Grover H and Vedlitz A 2006 Climate change vulnerability and policy support *Soc. Nat. Resour.* **19** 771–89
[18] Zaval L, Keenan E A, Johnson E J and Weber E U 2014 How warm days increase belief in global warming *Nat. Clim. Change* **4** 143–7
[19] Shao W, Keim B D, Garand J C and Hamilton L C 2014 Weather, climate, and the economy: explaining risk perceptions of global warming, 2001–10 *Weather Clim. Soc.* **6** 119–34
[20] Borick C P and Rabe B G 2014 Weather or not? examining the impact of meteorological conditions on public opinion regarding global warming *Weather Clim. Soc.* **6** 413–24
[21] Demski C, Capstick S, Pidgeon N, Sposato R G and Spence A 2017 Experience of extreme weather affects climate change mitigation and adaptation responses *Clim. Change* **140** 149–64
[22] Konisky D M, Hughes L and Kaylor C H 2016 Extreme weather events and climate change concern *Clim. Change* **134** 533–47
[23] Ray A, Hughes L, Konisky D M and Kaylor C 2017 Extreme weather exposure and support for climate change adaptation *Global Environ. Change* **46** 104–13
[24] Spence A, Poortinga W, Butler C and Pidgeon N F 2011 Perceptions of climate change and willingness to save energy related to flood experience *Nat. Clim. Change* **1** 46–9
[25] Taylor A, de Bruin W B and Dessai S 2014 Climate change beliefs and perceptions of weather-related changes in the united kingdom: climate change beliefs *Risk Anal.* **34** 1995–2004
[26] Capstick S B and Pidgeon N F 2014 Public perception of cold weather events as evidence for and against climate change *Clim. Change* **122** 695–708
[27] Rudman L A, McLean M C and Bunzl M 2013 When truth is personally inconvenient, attitudes change: the impact of extreme weather on implicit support for green politicians and explicit climate-change beliefs *Psychol. Sci.* **24** 2290–6

[28] Brulle R, Carmichael J and Jenkins J 2012 Shifting public opinion on climate change: an empirical assessment of factors influencing concern over climate change in the US, 2002–2010 *Clim. Change* **114** 169–88

[29] Carlton J S *et al* 2016 The effects of extreme drought on climate change beliefs, risk perceptions, and adaptation attitudes *Clim. Change* **135** 211–26

[30] Carmichael J T and Brulle R J 2017 Elite cues, media coverage, and public concern: an integrated path analysis of public opinion on climate change, 2001–2013 *Environ. Politics* **26** 232–52

[31] Mildenberger M and Leiserowitz A 2017 Public opinion on climate change: is there an economy-environment tradeoff? *Environ. Politics* **26** 801–24

[32] Marlon J R *et al* 2019 Detecting local environmental change: the role of experience in shaping risk judgments about global warming *J. Risk Res.* **22** 936–50

[33] Marquart-Pyatt S T, McCright A M, Dietz T and Dunlap R E 2014 Politics eclipses climate extremes for climate change perceptions *Glob. Environ. Change* **29** 246–57

[34] Shum R Y 2012 Effects of economic recession and local weather on climate change attitudes *Clim. Policy* **12** 38–49

[35] Broomell S B, Winkles J-F and Kane P B 2017 The perception of daily temperatures as evidence of global warming *Weather Clim. Soc.* **9** 563–74

[36] Howe P D 2018 Perceptions of seasonal weather are linked to beliefs about global climate change: evidence from norway *Clim. Change* **148** 467–80

[37] Myers T A, Maibach E W, Roser-Renouf C, Akerlof K and Leiserowitz A A 2013 The relationship between personal experience and belief in the reality of global warming *Nat. Clim. Change* **3** 343–7

[38] Howe P D and Leiserowitz A 2013 Who remembers a hot summer or a cold winter? The asymmetric effect of beliefs about global warming on perceptions of local climate conditions in the US *Glob. Environ. Change* **23** 1488–500

[39] McCright A M, Dunlap R E and Xiao C 2014 The impacts of temperature anomalies and political orientation on perceived winter warming *Nat. Clim. Change* **4** 1077–81

[40] Capstick S, Whitmarsh L, Poortinga W, Pidgeon N and Upham P 2015 International trends in public perceptions of climate change over the past quarter century *Wiley Interdiscip. Rev. Clim. Change* **6** 35–61

[41] Borick C P and Rabe B G 2017 Personal experience, extreme weather events, and perceptions of climate change *Oxford Research Encyclopedia of Climate Science* (http://climatescience.oxfordre.com/view/10.1093/acrefore/9780190228620.001.0001/acrefore-9780190228620-e-311)

[42] Weber E U 2010 What shapes perceptions of climate change? *Wiley Interdiscip. Rev. Clim. Change* **1** 332–42

[43] Weber E U 2015 What shapes perceptions of climate change? New research since 2010 *Wiley Interdiscip. Rev. Clim. Change* **7** 125–34

[44] Hornsey M J, Harris E A, Bain P G and Fielding K S 2016 Meta-analyses of the determinants and outcomes of belief in climate change *Nat. Clim. Change* **6** 622–6

[45] Egan P J and Mullin M 2017 Climate change: US public opinion *Annu. Rev. Political Sci.* **20** 209–27

[46] Lyons B A, Hasell A and Stroud N J 2018 Enduring extremes? polar vortex, drought, and climate change beliefs *Environ. Commun.* **12** 876–94

[47] Sun Y and Han Z 2018 Climate change risk perception in taiwan: correlation with individual and societal factors *Int. J. Environ. Res. Public Health* **15** 91

[48] Van Der Linden S 2014 On the relationship between personal experience, affect and risk perception: the case of climate change *Eur. J. Soc. Psychol.* **44** 430–40

[49] Dai J, Kesternich M, Löschel A and Ziegler A 2015 Extreme weather experiences and climate change beliefs in China: an econometric analysis *Ecol. Econ.* **116** 310–21

[50] Goebbert K, Jenkins-Smith H C, Klockow K, Nowlin M C and Silva C L 2012 Weather, climate and worldviews: the sources and consequences of public perceptions of changes in local weather patterns *Weather Clim. Soc.* **4** 132–44

[51] Lujala P, Lein H and Rød J K 2014 Climate change, natural hazards, and risk perception: the role of proximity and personal experience *Local Environ.* **20** 489–509

[52] Ogunbode C A *et al* 2018 The resilience paradox: flooding experience, coping and climate change mitigation intentions *Clim. Policy* **19** 703–15

[53] Ogunbode C A, Demski C, Capstick S B and Sposato R G 2019 Attribution matters: revisiting the link between extreme weather experience and climate change mitigation responses *Glob. Environ. Change* **54** 31–9

[54] Whitmarsh L 2008 Are flood victims more concerned about climate change than other people? The role of direct experience in risk perception and behavioural response *J. Risk Res.* **11** 351–74

[55] Blennow K, Persson J, Tomé M and Hanewinkel M 2012 Climate change: believing and seeing implies adapting *PLoS One* **7** e50182

[56] Wang X 2017 Understanding climate change risk perceptions in china: media use, personal experience, and cultural worldviews *Sci. Commun.* **39** 291–312

[57] Boag A *et al* 2018 Climate change beliefs and forest management in eastern Oregon: implications for individual adaptive capacity *Ecol. Soc.* **23** 1

[58] Broomell S B, Budescu D V and Por H-H 2015 Personal experience with climate change predicts intentions to act *Glob. Environ. Change* **32** 67–73

[59] Akerlof K, Maibach E W, Fitzgerald D, Cedeno A Y and Neuman A 2013 Do people 'personally experience' global warming, and if so how, and does it matter? *Glob. Environ. Change* **21** 81–91

[60] Niles M T and Mueller N D 2016 Farmer perceptions of climate change: associations with observed temperature and precipitation trends, irrigation, and climate beliefs *Glob. Environ. Change* **39** 133–42

[61] Fownes J R and Allred S B 2019 Testing the influence of recent weather on perceptions of personal experience with climate change and extreme weather in New York state *Weather Clim. Soc.* **11** 143–57

[62] Lee G-E, Loveridge S and Winkler J A 2018 The influence of an extreme warm spell on public support for government involvement in climate change adaptation *Ann. Am. Assoc. Geogr.* **108** 718–38

[63] Scruggs L and Benegal S 2012 Declining public concern about climate change: can we blame the great recession? *Glob. Environ. Change* **22** 505–15

[64] Shao W, Garand J C, Keim B D and Hamilton L C 2016 Science, scientists, and local weather: understanding mass perceptions of global warming* *Soc. Sci. Q.* **97** 1023–57

[65] Bergquist P and Warshaw C 2019 Does global warming increase public concern about climate change? *J. Politics* **81** 686–91

[66] Shao W 2017 Weather, climate, politics, or God? Determinants of American public opinions toward global warming *Environ. Politics* **26** 71–96

[67] Shao W and Goidel K 2016 Seeing is believing? an examination of perceptions of local weather conditions and climate change among residents in the US gulf coast *Risk Anal.* **36** 2136–57

[68] Hamilton L C and Keim B D 2009 Regional variation in perceptions about climate change *Int. J. Climatol.* **29** 2348–52

[69] Howe P D, Mildenberger M, Marlon J R and Leiserowitz A 2015 Geographic variation in opinions on climate change at state and local scales in the USA *Nat. Clim. Change* **5** 596–603

[70] Brody S D, Zahran S, Vedlitz A and Grover H 2008 Examining the relationship between physical vulnerability and public perceptions of global climate change in the United States *Environ. Behav.* **40** 72–95

[71] Shao W 2016 Are actual weather and perceived weather the same? Understanding perceptions of local weather and their effects on risk perceptions of global warming *J. Risk Res.* **19** 722–42

[72] Palm R, Lewis G B and Feng B 2017 What causes people to change their opinion about climate change? *Ann. Am. Assoc. Geogr.* **107** 883–96
[73] Carmichael J T, Brulle R J and Huxster J K 2017 The great divide: understanding the role of media and other drivers of the partisan divide in public concern over climate change in the USA, 2001–2014 *Clim. Change* **141** 599–612
[74] NOAA 2019 Storm events database *Technical Report* National Centers for Environmental Information, National Oceanic and Atmospheric Administration, Asheville, NC (https://www.ncdc.noaa.gov/stormevents/)
[75] CEMHS 2018 The spatial hazard events and losses database for the United States, Version 17.0 (Online Database) *Technical Report* Center for Emergency Management and Homeland Security, Arizona State University, Phoenix, AZ (https://cemhs.asu.edu/sheldus)
[76] Cutler M J 2016 Class, ideology, and severe weather: how the interaction of social and physical factors shape climate change threat perceptions among coastal US residents *Environ. Sociol.* **2** 275–85
[77] Zanocco C *et al* 2018 Place, proximity, and perceived harm: extreme weather events and views about climate change *Clim. Change* **149** 349–65
[78] Shepard S, Boudet H, Zanocco C M, Cramer L A and Tilt B 2018 Community climate change beliefs, awareness, and actions in the wake of the september 2013 flooding in boulder county, colorado *J. Environ. Stud. Sci.* **8** 312–25
[79] Hamilton L C *et al* 2016 Wildfire, climate, and perceptions in Northeast Oregon *Reg. Environ. Change* **16** 1819–32
[80] Hamilton L C, Wake C P, Hartter J, Safford T G and Puchlopek A J 2016 Flood realities, perceptions and the depth of divisions on climate *Sociology* **50** 913–33
[81] Ripberger J T *et al* 2017 Bayesian versus politically motivated reasoning in human perception of climate anomalies *Environ. Res. Lett.* **12** 114004
[82] Daly C, Gibson W P, Taylor G H, Johnson G L and Pasteris P 2002 A knowledge-based approach to the statistical mapping of climate *Clim. Res.* **22** 99–113
[83] Wang X and Lin L 2017 The relationships among actual weather events, perceived unusual weather, media use, and global warming belief certainty in china *Weather Clim. Soc.* **10** 137–44
[84] Howe P D, Markowitz E M, Lee T M, Ko C-Y and Leiserowitz A 2013 Global perceptions of local temperature change *Nat. Clim. Change* **3** 352–6
[85] Miguel E, Satyanath S and Sergenti E 2004 Economic shocks and civil conflict: an instrumental variables approach *J. Political Econ.* **112** 725–53
[86] Mehlum H, Miguel E and Torvik R 2006 Poverty and crime in 19th century germany *J. Urban Econ.* **59** 370–88
[87] Collins W J and Margo R A 2007 The economic aftermath of the 1960s riots in american cities: evidence from property values *J. Econ. Hist.* **67** 849–83
[88] Gomez B T, Hansford T G and Krause G A 2007 The republicans should pray for rain: weather, turnout, and voting in us presidential elections *J. Politics* **69** 649–63
[89] Dell M, Jones B F and Olken B A 2014 What do we learn from the weather? the new climate-economy literature *J. Econ. Literature* **52** 740–98
[90] Cooperman A D 2017 Randomization inference with rainfall data: Using historical weather patterns for variance estimation *Political Anal.* **25** 277–88
[91] Potoski M, Urbatsch R and Yu C 2015 Temperature biases in public opinion surveys *Weather Clim. Soc.* **7** 192–6
[92] Schuldt J P and Roh S 2014 Of accessibility and applicability: how heat-related cues affect belief in 'global warming' versus 'climate change *Soc. Cogn.* **32** 217–38
[93] Druckman J N and Shafranek R M 2016 The conditional nature of the local warming effect *Weather Clim. Soc.* **9** 15–26
[94] Slater M D 2016 Combining content analysis and assessment of exposure through self-report, spatial, or temporal variation in media effects research *Commun. Methods Meas.* **10** 173–5
[95] Stier S, Breuer J, Siegers P and Thorson K 2019 Integrating survey data and digital trace data: key issues in developing an emerging field *Soc. Sci. Comput. Rev.* (https://doi.org/10.1177/0894439319843669)
[96] Norgaard K M 2011 *Living in Denial: Climate Change, Emotions, and Everyday Life* (Cambridge, MA: MIT Press)
[97] Kahneman D 2011 *Thinking Fast and Slow* (London: Macmillan)
[98] Epstein S 1994 Integration of the cognitive and the psychodynamic unconscious *Am. Psychol.* **49** 709
[99] Trope Y and Liberman N 2010 Construal-level theory of psychological distance *Psychol. Rev.* **117** 440
[100] Marx S M *et al* 2007 Communication and mental processes: experiential and analytic processing of uncertain climate information *Glob. Environ. Change* **17** 47–58
[101] Evans J S B 2008 Dual-processing accounts of reasoning, judgment, and social cognition *Annu. Rev. Psychol.* **59** 255–78
[102] Brügger A, Dessai S, Devine-Wright P, Morton T A and Pidgeon N F 2015 Psychological responses to the proximity of climate change *Nat. Clim. Change* **5** 1031
[103] Mildenberger M, Lubell M and Hummel M 2019 Personalized risk messaging can reduce climate concerns *Glob. Environ. Change* **55** 15–24
[104] Brügger A, Morton T A and Dessai S 2016 'Proximising' climate change reconsidered: a construal level theory perspective *J. Environ. Psychol.* **46** 125–42
[105] Marlon J R 2019 Hot dry days increase perceived experience with global warming (https://dx.doi.org/10.2139/ssrn.3453287) (in review)
[106] Moore F C, Obradovich N, Lehner F and Baylis P 2019 Rapidly declining remarkability of temperature anomalies may obscure public perception of climate change *Proc. Natl Acad. Sci.* **116** 4905–10
[107] Hazlett C and Mildenberger M Wildfire exposure increases pro-climate political behaviors (https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3452958) (in review)
[108] Lo A Y and Jim C Y 2015 Come rain or shine? Public expectation on local weather change and differential effects on climate change attitude *Public Understand. Sci.* **24** 928–42
[109] Zahran S, Brody S D, Grover H and Vedlitz A 2006 Climate change vulnerability and policy support *Soc. Nat. Resour.* **19** 771–89