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When the election rains out and how bad weather excludes marginal voters from turning out

Søren Damsbo-Svendsen, Kasper M. Hansen *

Department of Political Science, University of Copenhagen, Denmark

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ABSTRACT

Ostensibly random and trivial experiences of everyday life, e.g., local weather, can have significant political consequences. First, we present a comprehensive meta-analysis of 34 studies of electoral turnout and rainfall – the vast majority demonstrating a negative association. Secondly, we present a new analysis of a voter panel with validated turnout for a complete electorate merged with fine-grained meteorological observations to show that Election Day rainfall reduces turnout by 0.95 percentage points per centimeter, while more sunshine increases turnout. Marginal voters (young voters) are up to six times more susceptible to bad weather and respond more positively to pleasant weather. Thus, bad weather exacerbates unequal democratic participation by pushing low-propensity voters to abstain. Efforts to include marginal voters therefore ought to be intensified during poor weather, and elections could even be moved to seasons with more pleasant weather to improve participatory equality.

Bad weather can depress voter turnout in democratic elections and with more intense and frequent bad weather expected in the future due to global warming, local Election Day weather will become increasingly consequential. Extreme weather at elections is thus one important way through which global climate change directly and tangibly interferes in politics. The basic mechanism behind the negative effect of bad weather on electoral turnout is simple and well-known: it increases the cost of voting and decreases the net utility of voting (Downs, 1957; Riker and Ordeshook, 1968). As weather largely is exogenous to human actions, when measured objectively, experiences with poor Election Day weather have provided a very concrete way of testing the causal effect of increasing voting costs. Multiple studies have showed that bad weather, particularly rainfall, depresses turnout in many different electoral contexts and climates around the globe. However, notable exceptions exist, e.g., a null effect in Sweden (Persson et al., 2014) and miniscule *positive* effects of bad weather in Norway (Lind, 2020) and South Korea (Kang, 2019).

We have located 34 studies of the rainfall-turnout effect conducted across high and low salience elections, at different points in time, and with different types of data and research designs.[1] In Table 1, we present an overview of the studies, key design characteristics, context, and data, and provide a meta-analysis of weighted and unweighted average effects in Fig. 1. Most of the identified studies take highly comparable approaches, typically employing linear models of turnout on a continuous measure of rainfall at an aggregate level, such as polling districts. Most of the studies also demonstrate a negative association between turnout and rainfall, which reflects in a simple, unweighted average effect of −0.816 percentage points per centimeter of rainfall (2.073 per inch). A more appropriate inverse variance-weighting results in a *positive* weighted average of 0.003 per centimeter (0.008 per inch), which is brought about by two recent outlier studies that exhibit very small positive effects with extremely low standard errors (Gavazza et al., 2019; Lind, 2020). This reveals the limitation of a generic inverse variance-weighting approach to meta-analysis; inevitably, it is very

* Corresponding author.
E-mail addresses: sdas@ifs.ku.dk (S. Damsbo-Svendsen), kmh@ifs.ku.dk, kmh@kaspermhansen.eu (K.M. Hansen).
URL: https://www.kaspermhansen.eu (K.M. Hansen).

[1] This includes the present study. We have primarily searched *Web of Science core collection, Google Scholar, and Google* (completed September 2022). The searches have both been on keywords (e.g. AB=(turnout AND (rain OR rainfall OR precipitation)) and among references within the identified studies. We include peer reviewed academic articles (31), conference papers (1) and working papers (3) to be as inclusive as possible and increase the likelihood of incorporating, e.g., unpublished null results. In the meta-analysis below, we have included one estimate per paper, except for studies that analyze multiple data sets (Knack, 1994; Persson et al., 2014). We also include studies that revisit previously published data, e.g., the frequently used Gomez et al. (2007) panel dataset, but apply a new research design or estimation approach.

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Table 1
Overview of 34 studies on the effect of rainfall on voter turnout.

Source	Country	Election(s)	Study level	Details
Merrifield (1993)	US	General (1982)	Aggregate (state)	AA,–,I
Knack (1994), I	US	Presidential (1984–1988)	Individual (survey, validated turnout)	AA,0,I
Knack (1994), II	US	House (1986)	Individual (survey, validated turnout)	AA,0,I
Shachar and Nalebuff (1999)	US	Presidential (1948–1988)	Aggregate (state)	AA,–,I
Gatrell and Bierly (2002)	US (Kentucky)	Presidential, state, gubernatorial (1990–2000)	Aggregate (county)	AA,–,T
Lakhdar and Dubois (2006)	France	Parliamentary (1986–2002)	Aggregate (départements)	AA,–,I
Gomez et al. (2007)	US	Presidential (1948–2000)	Aggregate (county)	AA,–,I
Horiuchi and Saito (2009)	Japan	Parliamentary (1990–2000)	Aggregate (municipality)	WP,–, D
Fraga and Hersch (2010)	US	Presidential (1948–2000)	Aggregate (county)	AA,–,I
Hansford and Gomez (2010)	US	Presidential (1948–2000)	Aggregate (county)	AA,–,I
Eisinga et al. (2012)	The Netherlands	Parliamentary (1971–2010)	Aggregate (municipality)	AA,–,I
Steinbrecher (2013)	Germany	Parliamentary (1994–2009)	Individual (survey)	CP,0,L
Artés (2014)	Spain	Parliamentary (1986–2011)	Aggregate (municipality)	AA,–,I
Lo Prete and Revelli (2014)	Italy	Multiple (2001–2010)	Aggregate (city)	WP,–, D
Persson et al. (2014), I	Sweden	Parliamentary (1976–2010)	Aggregate (municipality)	AA,0,I
Persson et al. (2014), II	Sweden	Parliamentary (1991–2006)	Individual (survey, validated turnout)	AA,0,I
Persson et al. (2014), III	Sweden	Parliamentary (2002–2010)	Individual (survey, validated turnout)	AA,0,I
Sforza (2014)	Italy	Parliamentary (2008–2013)	Aggregate (municipality)	WP,–, D
Arnold and Freier (2016)	Germany (North-Rhine Westphalia)	Municipal and state (1975–2010)	Aggregate (municipality)	AA,–,I
Fujiwara et al. (2016)	US	Presidential (1952–2012)	Aggregate (county)	AA,–,I
Chen (2020)	Taiwan	Parliamentary (1998–2012)	Aggregate (county)	AA,–,I
Cooperman (2017)	US	Presidential (1948–2000)	Aggregate (county)	AA,–,T
Lee and Hwang (2017)	South Korea	Parliamentary and municipal (1995–1999)	Aggregate (municipality)	AA,–,I
Arnold (2018)	Germany (Bavaria)	Municipal (1946–2009)	Aggregate (municipality)	AA,–,I
Horiuchi and Kang (2018)	US	Presidential (1948–2000)	Aggregate (county)	AA,+,I
Stockemer and Wigginton (2018)	Canada	Parliamentary (2004–2015)	Aggregate (districts)	AA,–,I
Leslie and Arı (2018)	UK	Referendum (2016)	Aggregate (constituency)	AA,–,I
Gavazza et al. (2019)	UK	Municipal (2006–2010)	Aggregate (districts)	AA,+,I
Kang (2019)	South Korea	Parliamentary (2000–2012)	Aggregate (districts)	AA,–,I
Meier et al. (2019)	Switzerland	Direct democratic votes (1958–2014)	Aggregate (municipality)	AA,–,D
Rudolph (2020)	UK	Brexit referendum (2016)	Aggregate (districts)	AA,–,I
Garcia-Rodriguez and Redmond (2020)	Ireland	Parliamentary (1989–2016)	Aggregate (constituency)	AA,–,I
Lind (2020)	Norway	Municipal (1972–2010)	Aggregate (municipality)	AA,+,I
Our study	Denmark	Municipal (2013–2017)	Individual (registry, validated turnout)	AA,–,I

Notes: Abbreviations include AA = academic article (peer reviewed), CP = conference paper, WP = working paper. + = significant positive rainfall effect, 0 = insignificant effect, – = significant negative rainfall effect, I = included in Fig. 1, D = uses a rainfall dummy variable, L = applies logit regression, T = otherwise incalculable (comparable estimates are incalculable in six studies). The 27 studies used to calculate the average statistics (Fig. 1) adopt comparable linear regression approaches. All estimates from these studies have been recalculated to centimeters of rainfall (from inches, meter, or millimeter), and *t*-statistics have been transformed into standard errors. For IV-studies, we report the linear first-stage effect of rainfall on turnout. Studies are sorted by year of publication (oldest first). See appendix for more details (Table A12).

sensitive to studies that identify effects with extremely high certainty. We therefore present several alternative averages: (a) SE-weighted averages excluding the two outlier studies that are weighted higher than all other studies combined, (b) SE-weighted averages excluding aggregate-level studies, and (c) N-weighted averages. Overall, we believe (a) −0.417 is the best of the meta-estimates, which range from −0.915 to 0.003.

The 34 rainfall-turnout studies are generally quite comparable in their empirical approach with some relevant variations, e.g., in the institutional setup, electoral systems, between high and low salience elections, and between regions with higher or lower normal precipitation. For example, the norm of voting as a citizen's duty should arguably be higher in high salience elections and in proportional electoral systems, where all votes count, thus reducing the expected weather effect in such contexts (Blais, 2000). Moreover, rainfall as a cost of voting should arguably have stronger effects in normally dry regions. But no such patterns are apparent. We encourage other researchers to use the metadata, we have collected, to further pursue these and other questions (see more study details in Table A12). The strongest rainfall effects are clearly found in aggregate-level studies of turnout, e.g., municipalities or constituencies, whereas estimates tend to be non-significant in the few existing individual-level studies.

The most cited study is Gomez et al. (2007) and the follow-up study by Hansford and Gomez (2010). Both analyze the same aggregate-level panel dataset of Election Day weather and turnout at US presidential elections, and they have influenced subsequent work greatly in terms of research design and data. The designs used in weather-turnout studies have evolved tremendously over the past decades from aggregate-level studies, sometimes based on self-reported turnout, to sophisticated individual-level designs based on validated voter records and objective weather observations from nearby weather stations. We take another step in this direction with a first-of-its-kind study of superior high-quality data comprising an electorate-wide panel of validated registry-based voter records. Individual-level panel data allows us to not just revisit the weather-turnout thesis but contribute with much stronger evidence of the causal effects of Election Day weather on turnout as well as the heterogeneity of weather effects.

Electoral turnout is the key health indicator of modern democracy. When poor weather depresses turnout, it therefore indirectly weakens democratic legitimacy (Lijphart, 1997; Beetham, 1991). More importantly, bad weather can exacerbate inequalities in electoral participation because obstacles to voting affect marginal voters more than core voters (Gomez et al., 2007; Bhatti et al., 2020). Whereas core voters with a robust voting habit and a strong sense of civic duty are largely immune to the costs of bad weather, marginal voter groups may be highly susceptible (Knack, 1994).

Our new study of the weather-turnout effect features several novelties and advantages. First, it is the first to use validated turnout data at the individual level with repeated measurements of an (almost) complete electorate.

Secondly, these unique data allow us to estimate individual-level panel models, which rule out certain types of omitted variable bias that previous research had to rule out by assumption. We thus contribute to the turnout literature with more credible results.

Thirdly, we investigate how obstacles to voting affects marginal voters (i.e., young voters) to a higher degree than core voters, which is a question with major democratic implications, but also one that requires a very large number of observations.

Fourthly, previous work has focused almost exclusively on rainfall with the occasional addition of another weather variable, for example temperature (Gatrell and Bierly, 2002; Stockemer and Wigginton, 2018). However, weather – poor or pleasant – is a compound phenomenon determined by precipitation, temperatures, cloud cover, humidity, wind speed, etc. Previous work that only includes rainfall is therefore essentially underspecified. We take a first step toward a more comprehensive approach by analyzing rainfall, solar irradiation (sunshine), and temperature together, thus allowing us to explore if nice Election Day weather also shapes turnout. We also explore nonlinear weather effects.

Finally, the setting is new. Danish media routinely make anecdotal references to the relationship between turnout and weather, but the relationship has yet to be systematically examined in the case of Denmark. So far, researchers have not found evidence of detrimental weather effects in any of the five Nordic countries (Bengtsson et al., 2014; Lind, 2020; Persson et al., 2014). Like the other Nordics, Denmark is a highly cooperative multiparty system with automatic voter registration and a high average local election turnout of around 70% (Hansen, 2020). Unlike the other Nordics, the geography is highly homogeneous, small, and flat with a uniform temperate and predominantly coastal climate.

Our results show that local rainfall does in fact cause a reduction in the probability of voting. On average, the probability of turning out for election decreases by 0.95 percentage point when rainfall increases by 1 cm (2.41 per inch). This estimate is close to the simple, unweighted average effect in the meta-analysis (Fig. 1). The negative effect of rainfall is nonlinear in the sense that small amounts of rainfall are inconsequential, whereas heavy rain makes a substantial difference. We also find positive, mostly linear turnout effects of higher levels of sunshine, i.e., nice Election Day weather. Crucially, young voters (except for first-time voters) are affected up to six times more by rainfall, and are also affected more by sunshine, suggesting that marginal voters are much more susceptible to weather-induced costs of voting and that bad weather can exacerbate inequality in democratic participation.

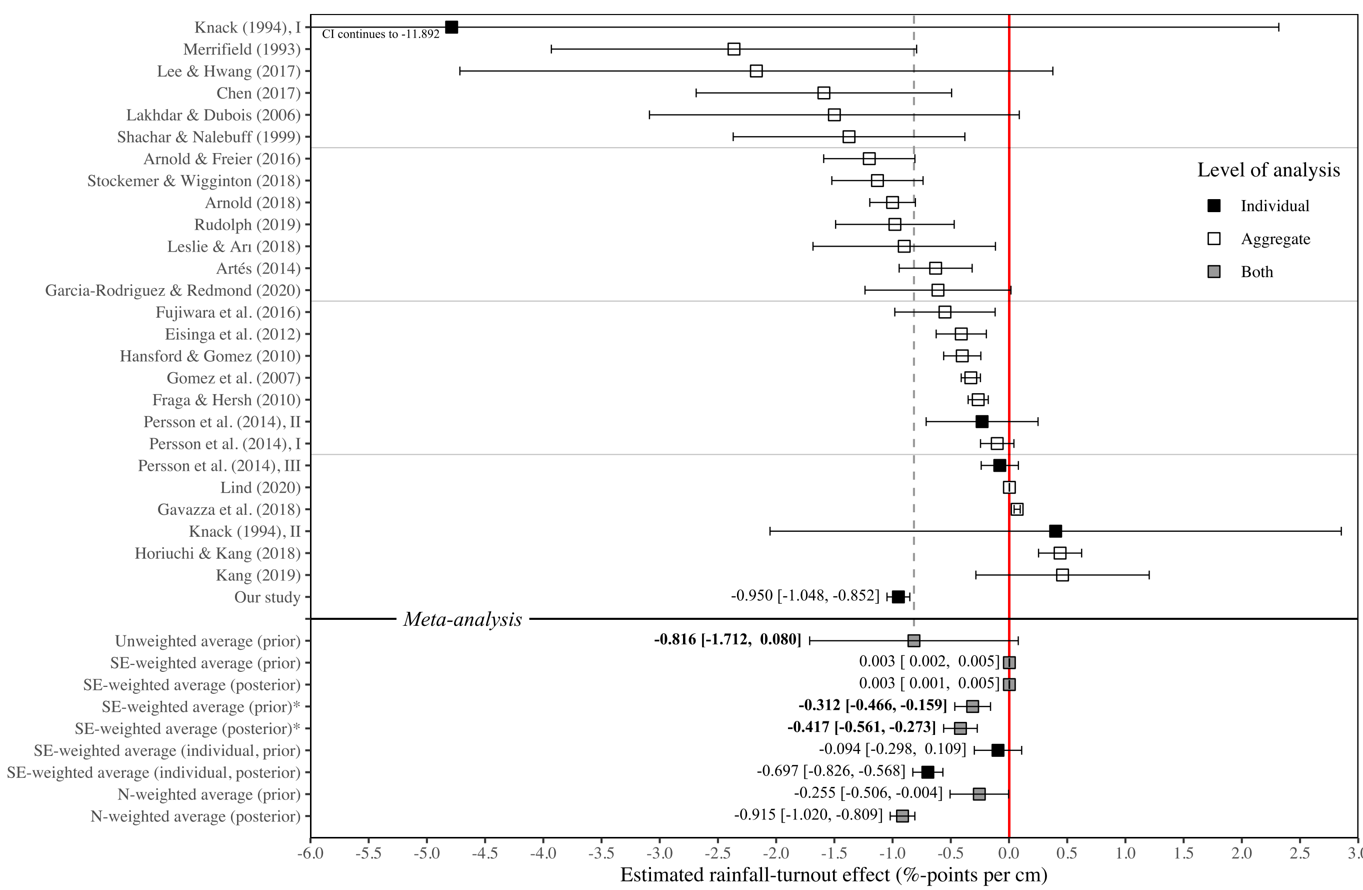

Fig. 1. Meta-analysis of 27 studies on the effect of rainfall on voter turnout. N = 27. The meta-analysis calculates weighted average effects using generic inverse variance-weighting of the unstandardized linear regression coefficients for rainfall (in cm) and turnout (percent) using the formula: *SE–weighted average* = $\frac{\sum_1^N estimate_i \times \frac{1}{standard\ error_i^2}}{\sum_1^N \frac{1}{standard\ error_i^2}}$. *N-weighted averages* substitute the number of observations *N* for the $\frac{1}{standard\ error_i^2}$ weight. *Prior* averages exclude our study, *posteriors* include it.
*Estimates excluding Lind (2020) and Gavazza et al. (2019) with higher inverse variance-weights than all other studies combined. The dashed line marks the unweighted average.

1. Theory: how bad weather on Election Day increases the cost of voting

A growing body of research shows how weather affects political opinions and behavior in a multitude of ways, both through dramatic extreme weather events and more subtle variations in personal weather experiences. For instance, individuals use the seasonality or normality of recent temperatures as a heuristic when expressing their opinions on climate change (Damsbo-Svendsen, 2021; Howe et al., 2019), while flooding experience strengthens perceptions and concern of climate change (Ogunbode et al., 2020; Rüttenauer, 2021). The effect of local weather on turnout is another prime example of how local weather, increasingly because of global climate change, interferes directly in politics.

The mechanism through which bad weather depresses turnout is simple and highly intuitive: it increases the cost of voting in a very tangible sense. In bad weather, getting to and from the polling place and standing in line outside is often unpleasant and involves more logistic consideration and planning. Campaigners also experience a higher cost of canvassing in bad weather, which can dampen their level of activity and reduce mobilization effects (e.g., Eisinga et al., 2012; Gomez et al., 2007). In addition, bad weather can induce a bad mood, or even a state of light depression, which may also help explaining why both voters (Howarth and Hoffman, 1984; Meier et al., 2019) and campaigners are more likely stay at home in bad weather (Lamare, 2013).

The other side to the argument is rarely explored; what if the weather not only presents obstacles to turnout, but pleasant Election Day weather instead is conducive to turnout? The limited research on positive weather effects on turnout suggests that warmer, more pleasant weather could boost turnout rates (e.g., Lakhdar and Dubois, 2006; Eisinga et al., 2012; Van Assche et al., 2017). Some researchers argue that the influence of weather partially reflects its effects on the enjoyability of (outdoor) activities other than voting – on the opportunity costs of voting, in other words (Kang, 2019; Lind, 2020). In theory, poor weather could indeed increase turnout and pleasant weather reduce it. But the bulk of existing literature suggests that the change in the direct costs of voting more than offsets the potential effects on opportunity cost, which seems plausible given that special, symbolic character of the voting act as compared to other types of activities.

Another important question requiring attention is if weather-turnout effects are linear, as often assumed; does a centimeter of rain have the same implications on a mostly dry Election Day as it would in an election soaking in rain? Merrifield (1993) found no evidence of nonlinearity, whereas Meier et al. (2019) more recently did. We provide new evidence to this question as well.

We emphasize the importance of weather effects on turnout among marginal voters and draw on Fowler's understanding of "those whose decisions to turn out are sensitive to exogenous factors" (2015: 205). The term thus refers to eligible voters who, for various reasons, are particularly sensitive to increasing costs of voting. Young people, for example, are typically marginal voters because they have not had the opportunity to establish a robust voting habit (Bhatti and Hansen, 2012a; 2016). We expect weather effects, negative and positive, to exhibit stronger influence on marginal voters such as young voters, but also, for instance, those who live alone and are disinclined to make going to the polls a social activity (Dahlgaard et al., 2021), voters with a low estimated propensity of voting (Enos et al., 2013), and voters with a history of abstaining. This heterogeneity is key to understanding the implications of poor Election Day weather for electoral inequalities and democratic representation.

2. Research design: fixed effects modelling of individual turnout and local weather

We approach the question of how Election Day weather influences turnout through the case of municipal elections in Denmark. Danish local elections take place simultaneously in all 98 municipalities every four years on the third Tuesday of November. The fixed election schedule holds constant various seasonality effects, and the wet and windy November weather makes it a useful case for exploring the effects of bad weather. Danish local elections are proportional elections of municipal councilors, who elect a mayor from among their midst. The municipalities administrate the lion's share of the universal welfare budget including schools, kindergartens, eldercare, local roads, and public transportation. The salience of the local elections is therefore comparatively high with an average turnout of 70% over the last 50 years, yet significant variation remains within individuals and across groups (see Hansen, 2020 for detailed turnout statistics). Voters are automatically registered in voter files, and all eligible citizens receive a polling card by mail before the election. In-person voting on Election Day is a strong norm (94.5% in 2017, the remainder mostly comprises early voting, e.g., in retirement homes), which allows for reliable matches of turnout behavior and individually experienced Election Day weather.

2.1. *Voter turnout*

Validated voter turnout records are collected for virtually all eligible voters in the 2013 and 2017 local elections in Denmark.[2] We exclude early voters (~3% of the data set) to create a binary outcome variable indicating individual-level turnout at the polls on Election Day (1) or abstention (0). Hence, all included voters showed up in person at their local polling station to cast their vote. We further restrict the data to voters of age 80 or younger because of significant selection among the elderly in early voting and health, and because of sharply decreasing observations at older ages. We acknowledge the normative issues with this step and encourage other researchers to focus more on elderly voter groups (see Bhatti and Hansen, 2012b). Out of the 4,459,145 unique eligible voters in our final data set, 3,306,504 (~73%) were eligible at both elections and thus appear twice in our panel.[3]

Voters in their early twenties are a group with relatively low turnout rates in many places, including the Nordic countries and the US (Bhatti et al., 2012). Thus, a distinct turnout-age "rollercoaster" also exists in Denmark (see Figure A1): turnout rates are high for new voters but decrease sharply when the young voters move away from home before growing steadily from the mid-twenties until sometime after age 70 (Bhatti et al., 2012; Bhatti and Hansen, 2012a,b; Hansen, 2020).

[2] Individual turnout is registered at the polling station as part of the electoral procedures. Voting records are thus administrative data administrated by the municipalities and based on the voting system (voter lists). At the 2013 local election, all municipalities took part in the effort to collect voting records, and we thus collected validated records for 98.9% of eligible voters (the negligible data loss is due to system failure and administrative errors). At the 2017 local election, we managed to collect validated records for 91.3% of eligible voters (7 out of 98 municipalities decided not to participate because they found it too time consuming). Crucially, there is no individual selection into the collection of voting records, which means that they are representative of the country on other characteristics (see Bhatti et al., 2014; Hansen, 2018). The records are checked for typos, aggregated to the polling station level, and cross-validated against the official election result. From the voting records, we have access to the following individual-level variables: turnout (voted early, abstained, voted on Election Day), birthday, gender, municipality, and home address geographic coordinates.

[3] The drop in observations in the balanced portion of the panel is explained by (a) our imposed age restriction (18–80), (b) some voters living in, or moving to or from, one of seven non-participating municipalities (in 2017) (c) voters becoming eligible between 2013 and 2017 (e.g., being a first-time voter or a recently enfranchised immigrant in 2017), or passing away, or, to a lesser extent, (d) other voters that make use of early voting in at least one election.

2.2. Election Day weather

The area of Denmark proper is 42,933 km^2 (16,577 square miles) – larger than Switzerland but smaller than Costa Rica, larger than Maryland but smaller than West Virginia. There are no mountains (the highest point is 171 meters above sea level) and the entire country shares a highly homogeneous temperate coastal climate (Danish Ministry of Energy, Utilities and Climate, 2017). Consequentially, annual rainfall exhibits very low geographical variation ranging from 50 cm in the driest regions to 90 cm in the wettest (DMI, 2018). We collect weather observations from the Danish Meteorological Institute (DMI) through the new publicly accessible C*limate Data* API, which provides detailed weather observations validated by meteorologists (DMI, 2021). Weather observations from the elections are available for 95, 27, and 45 weather stations for precipitation, solar irradiance, and temperature, respectively (Fig. 2). Thus, solar irradiation inevitably relies more on interpolation (plausibly a minor issue for the measurement validity of sunshine compared to if it had been, e.g., precipitation).

Rainfall is measured as accumulated precipitation (cm), *sunshine* as average solar irradiation (W/m^2, normalized), and *temperature* as average degrees (Celsius). We refer to solar irradiation as sunshine, although it also captures the sun's radiation though the cloud cover in the absence of visual sunshine. Election Day weather is calculated as the cumulative sum of rainfall and simple average of sunshine and temperature based on hourly observations from midnight until the polling stations close at 8pm.[4]

The average distance between voters and their nearest weather station is 10.2 km for rainfall, 17.0 km for sunshine, and 13.4 km for temperature. For each voter, election date, and weather parameter, we triangulate local weather from the three nearest weather stations and compute an inverse-distance weighted average based on the following formula[5]:

$$Local\ weather_{vt} = \frac{\sum_{i}^{3}\left(\frac{Observation_{it}}{Distance_i^2}\right)}{\sum_{i}^{3}\left(\frac{1}{Distance_i^2}\right)}$$

where i indexes the weather station (from nearest to third nearest), t indicates the election date, and v indicates the voter. Voters are thus assigned unique values based on the geographical coordinates of their home address. For example, a voter who lives 10, 20, and 30 km from weather stations measuring 5, 10, and 0 mm of rain is assigned a weighted average of 5.51. Due to the distance weighting, approximately 73% of this estimate is contributed by the 10 km-station, 18% by the 20 km-station, and only 8% by the 30 km-station. For voters living close to a weather station, the lion's share of the weather estimate will come from that station. This procedure increases measurement validity and variation compared to matching voters to only the nearest station, especially when stations are relatively far away (Wang and Scharling, 2010).

Table 2 describes the variation in Election Day weather and Figure A2 in the appendix shows maps of the weather distribution. Variation is limited, but still sufficient due to the large number of observations. The observed Election Day weather is relative mild and typical (i.e., non-extreme) for November weather in Denmark, and even the maximum observed sunshine is several times lower than on any day in the summer. This arguably makes for a stronger test of the weather-turnout thesis; if we can detect it here, it is likely to be even more substantial in cases with more extreme weather.

3. Estimation strategy and models: OLS and two-way fixed effects

We estimate two types of linear probability models (OLS) with fixed effects: a pooled OLS model and an individual-level two-way fixed effects model. In the *pooled model*, we pool all eligible voters from both elections and regress Election Day turnout (voted in-person or abstained) on local rainfall, sunshine, and temperature with *municipality* fixed effects to account for (time-invariant) municipal-level patterns in local climate and voting behavior and *election* fixed effects to account for general (unit-invariant) differences between elections. We also add controls for age (third degree polynomial), gender, living close to the coast, local population density (natural log), closeness of the election, and municipal population size (natural log) and share of non-Western immigrants.[6] The latter two are especially important determinants of turnout in Danish local elections (Bhatti and Hansen, 2019). Adding the control variables should result in more precise estimates, and it may also reduce confounding, especially in the pooled model, to the extent that the control variables are correlates of local weather patterns. Given that the study spans just four years, climate change *per se,* i.e., changes in normal weather, is effectively held constant, and, similarly, local turnout patterns are also highly invariant across the country within this short time span, thus alleviating concerns about problematic spatio-temporal trends (Lind, 2017). Since weather patterns tend to be spatially dependent, the pooled model uses cluster-robust standard errors at the level of polling districts and election (alternative standard errors are provided in Table A10).

Estimates from the pooled model have a causal interpretation to the extent that weather experiences are allocated as-good-as-random within municipalities (Lind, 2017). This assumption has been invoked frequently in studies of weather effects (e.g., Egan and Mullin, 2012; Persson et al., 2014) and studies that use rainfall as an instrumental variable (Lind, 2020; Miguel et al., 2004; Sforza, 2014). While the assumption of as-if randomness in weather exposure is not self-evident – and has been criticized recently (Mellon, 2021) – we think it is relatively reasonable in small, flat, and temperate Denmark (conditional on municipality and living close to coasts). As the appendix shows, weather exposure is also reasonably, however not perfectly, balanced across age, gender, distance to coast, and local population density (see Figure A3-A8).

The key threat to identification in the pooled model is if where people decide to live is related to the local climate and weather. Naturally, there is substantial sorting in where individuals and families choose to live based on, e.g., income, education, profession, having children, and these factors also shape voting behavior. However, to induce confounding there needs to be significant systematic correlations between residential areas and the local climate within municipalities. While this is possible in theory, the modest variation in local weather in Denmark likely translates into weak correlations between areas and local weather. Still, to effectively eliminate this bias risk, we utilize the panel structure of the data to apply *voter* fixed effects in our second estimation strategy.

The *panel model* substitutes voter fixed effects for municipality fixed effects, thus establishing a classic two-way fixed effects (TWFE)

[4] Polling stations open at 8am. We begin measuring at midnight rather than 8am because weather conditions from before the polling stations open, including in the night, can carry into the morning and day and influence voters' decision-making. Specifically, we assume, first, that voters make and change their plans before going to the polls, especially in the morning right before the polls open, and, secondly, that voters possibly incorporate memories of the weather a couple of hours before into judgements of the current weather.

[5] This resembles DMIs interpolation algorithm (Wang and Scharling, 2010), including the weighting by squared distance to give preference to nearby observations.

[6] Closeness of the election is measured as vote share difference between the largest party and the runner-up (Fraga and Hersch, 2010; Knack, 1994). Living close to the coast is a dummy variable for living less than 5 km from a coast. Non-Western immigrants in the municipality are a proxy for individual-level immigrant status.

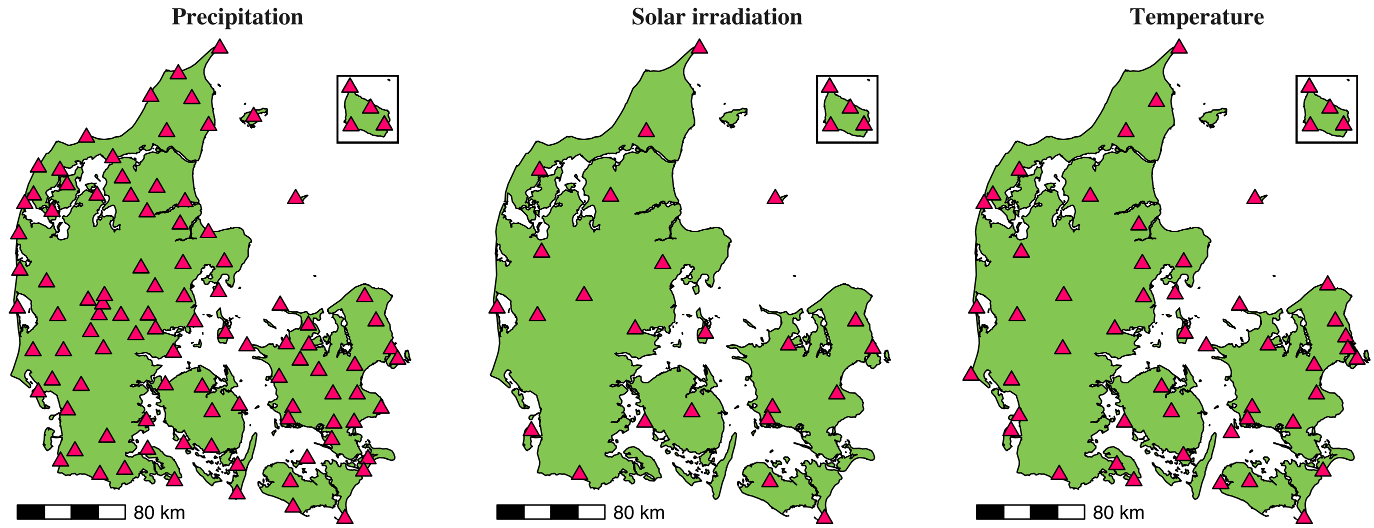

Fig. 2. Locations of 166 DMI weather stations in Denmark.

Table 2
Descriptive weather statistics.

	Full sample		2013 Election		2017 Election	
Weather variable	Mean (SD)	Min – Max	Mean (SD)	Min – Max	Mean (SD)	Min – Max
Acc. rainfall (mm)	1.2 (1.6)	0.0–10.0	2.3 (1.5)	0.1–8.5	0.1 (0.4)	0.0–10.0
Avg. sunshine (W/m^2)	19.7 (6.7)	6.2–42.9	15.2 (5.0)	6.2–35.8	24.5 (4.8)	6.5–42.9
Avg. temperature (°C)	4.3 (2.2)	−0.5–7.8	6.2 (0.4)	5.2–7.8	2.3 (1.4)	−0.5–5.4

Source: DMI (2021). Measured and summarized at the level of 7,855,649 voters.

estimator. This model estimates weather effects *within voters* over time and, like the pooled model, also accounts for general variation between the two elections. Specifically, we estimate the following equation:

$$Turnout_{it} = \alpha_i + \alpha_t + \beta_1 Rainfall_{it} + \beta_2 Sunshine_{it} + \beta_3 Temperature_{it} + Z_{it} + \varepsilon_{it}, \quad (1)$$

where α_i is individual fixed effects, α_t is time fixed effects, and Z_{it} is a vector of time-varying control variables. The panel model is identical to the pooled model, except that it replaces municipality fixed effects with individual fixed effects (and drops the time-invariant gender control). Since the panel model is modelling within-voter variation, we use cluster-robust standard errors that account for address (household) and election (time) dependence (Table A10 provides alternative standard errors).

This individual-level panel design eliminates any omitted variable bias from invariant voter characteristics such as gender, personality traits, and past voting experience. It also implies a strong geographical control, which eliminates selection bias related to geography, but only for voters who did not move (to a different local climate) between the elections. Around 86% lived in the same municipality at both elections. For movers, the individual fixed effects still greatly reduce variation in factors that shape decisions about where to live (income, education, ideology, children, etc.). A drawback of the panel model is that it only effectively models the balanced portion of the panel, i.e., the 73% observed at both elections.[7]

As ours is the first study to use an individual-level panel design, and to use official voting records for a complete electorate, we can provide more credible results on the causal effects of Election Day weather on turnout. Furthermore, our side-by-side presentation of results from a pooled model and a panel model enables us to empirically gauge the possible biases from designs that rely on the assumption of as-good-as-random weather exposure.

4. Results: rainfall reduces turnout, sunshine increases it

This section presents the results of our analysis of the relationship between Election Day weather – rainfall, sunshine, and temperature – and individual turnout. After investigating the weather-turnout thesis at the general level, we provide evidence that the rainfall effect is nonlinear and show how young voters are much more susceptible to weather effects, negative and positive, than more experienced voters.

Table 3 shows the main models' effect estimates. Recall that the panel model is methodologically superior for identifying causal weather effects because it eliminates bias from unit-invariant and time-invariant factors, i.e., voter characteristics that are effectively constant between the two elections. The pooled model, with only election and municipality fixed effects, should yield similar results to the panel model to the extent that individuals are exposed to local weather in an as-if random fashion (within municipalities).

As expected, the effect of rainfall on the probability of voting is negative and statistically significant in both models. Some voters are in fact deterred from voting when it rains. Based on the panel model, each centimeter (0.39 inches) of rainfall reduces the probability of voting by 0.95 percentage points.

Sunshine on Election Day also affects voting propensity, even after controlling for rainfall and temperature, with which it naturally

[7] See footnote 3. Importantly, self-selection into the panel is highly limited. The pooled model does not exclude these groups.

Table 3
Turnout and Election Day weather.

	Pooled model	Panel model
	Election Day turnout	
	(1) OLS	(2) TWFE
Rainfall (cm)	−0.0250*** (0.0005)	−0.0095*** (0.0005)
Sunshine (W/m^2 normalized)	0.0045*** (0.0004)	0.0028*** (0.0000)
Temperature (Celsius)	0.0001 (0.0005)	0.0016*** (0.0001)
Election FEs	+	+
Municipality FEs	+	
Voter FEs		+
Additional controls	+	+
Cluster-robust SEs	Polling district + election	Address + election
N observations	7,855,649	7,855,649
N unique voters	4,549,145	4,549,145

Note: Additional controls include age, age,[2] age,[3] ln(population), close to coast dummy, ln(local population density), non-western immigrant population share, closeness of the election, and gender (only in the pooled model). See all coefficients in the appendix, Table A2. Cluster-robust SEs in parentheses clustered on (1) polling district and election and (2) address/household and election. ***p < 0.001; **p < 0.01; *p < 0.05.

correlates.[8] A change from the lowest to the highest recorded level of sunshine (6.2–42.8 W/m^2) increases the probability of voting by 1.55 percentage points, according to the panel model. By implication, a thick cloud cover also reduces turnout. The fact that sunshine affects voting behavior after adjusting for rainfall supports the notion that weather-turnout effects are not only about rain-induced costs and inconveniences, but also about whether voting is a pleasant activity. What is less clear, however, is if the sunshine effect mostly reflects that voting is more enjoyable and convenient, including transportation to and from the polling place, or rather reflects psychological effects.

For temperature, results are less clear, as the models disagree. In the panel model, an increase from the lowest to the highest observed Election Day temperature (−0.5–7.8 °C) implies an increase of 1.30 percentage points in the probability of voting.

Most existing studies only examine the effect of one weather variable (at a time), and predominantly rainfall. To allow for a more direct comparison, and as a robustness check to alleviate concerns about multicollinearity, Table A5 in the appendix shows effects for rainfall, sunshine, and temperature, estimated separately. Here, the panel model indicates turnout effects of −1.50 percentage points for rainfall, 0.32 for sunshine, and 0.20 for temperature (approximately 14–58% stronger effects).

The panel model greatly reduces any confounding from factors that shape where voters live but are roughly constant over a four-year period. Thus, the difference between estimates from the two models can tell us something about the validity of the as-good-as-random assumption, i.e., that local weather exposure is orthogonal to individual factors. The absolute value of panel model estimates are 2.6 times smaller, 1.6 times smaller, and 16 times larger, respectively. This indicates that relying entirely on the assumption of as-if randomness could lead to severe bias, which echoes recent critiques of treating weather exposure and rainfall as randomly distributed (Cooperman, 2017; Lind, 2017; Mellon, 2021). In fact, individual characteristics may be systematically associated with variations in local weather. We should therefore be cautious with (pooled) cross-sectional analyses of weather and political behavior and place more trust in estimates from panel models. Future studies should aim to employ panel designs, natural experiments, or at least more comprehensive selection-on-observables designs to isolate conditional randomness in weather exposure.

5. Nonlinear effects: the effect of rainfall depends on the baseline

The next millimeter of rain could have very different implications depending on the amount of rain that has already fallen. In other words, weather effects may be nonlinear, but the literature only shows limited, inconclusive evidence about this (Merrifield, 1993; Meier et al., 2019). We test the proposition by adding squared rainfall, sunshine, and temperature terms to the panel model. The marginal effects of rainfall and sunshine depending on the baseline is shown in Fig. 3.

Whereas the sunshine effect is closer to linear, the rainfall effect is strongly nonlinear.[9] In the case of no rainfall, at the outset of the graph (left panel), an additional millimeter of rain does not affect turnout. The rainfall effect kicks in after a baseline of around 2 mm of rain (0.08 in), where it begins to impose real costs on planning and outdoor activities (Figure A9 illustrates the nonlinear relationship between predicted turnout and weather). The strongest rainfall effect, at the maximum observed precipitation of a full centimeter, amounts to almost −4 percentage points per centimeter.[10]

6. Heterogeneous effects: marginal voters are much more sensitive to weather effects

If increased weather-induced costs of voting exacerbate inequalities in turnout, this has implications for electoral outcomes, representation, and, ultimately, the legitimacy of democracy. We hypothesize that marginal voters are more susceptible to adverse weather effects on their voting behavior – and likely also to the positive effects of pleasant weather. Below, we test if weather effects are moderated by voter age or, more specifically, election cohort. Election cohorts reflect the exact number of local elections in which a voter has had the opportunity to vote by the 2013 election.[11] For cohort 1, for example, 2013 was the first election in which they were eligible to vote and 2017 was the second.[12] This approach allows us to compare cohorts of experienced voters to cohorts of new voters who have yet to establish a voting routine and, consequently, might be more readily swayed by the perceived costs and benefits of voting.

We extend the panel model (see Table 3) to include interaction terms between each weather variable and the election cohort, i.e., the number of municipal elections experienced as an eligible voter by the 2013 election. We treat election cohort as a categorical variable to allow flexibility in the relationship between weather, turnout, and cohort.

Fig. 4 shows how the partial effects of rainfall and sunshine are strongly moderated by whether one is an experienced voter (or non-

8 Rainfall, solar irradiation, and temperatures are inherently correlated, which could raise suspicions of collinearity issues. For instance, it rarely rains when the sun is shining. However, this is mostly true at extreme values of the weather variables, i.e., outside the range of weather observed here, and bivariate weather correlations are weak to moderate – ranging from −0.01 (rainfall and sunshine in 2013) to −0.42 (sunshine and temperature in 2013). See appendix for bivariate weather variable correlations (Table A1) and separate models for each weather variable, which yield the same overall conclusions (Table A5).

9 Based on the quadratic terms in Table A3.

10 The same graph based on the pooled model shows the same nonlinear pattern for the rainfall effect, only substantially stronger (Figure A4).

11 This assumes that all voters either were born in or immigrated to Denmark before their eighteenth birthday.

12 Correspondingly, the age of cohort 1 in 2013 ranges from exactly 18 years–22 years (and 1 day), while the age of cohort 2 in 2013 ranges from 22 years (and 2 days) to 26 years (and 3 days). More details in Table A4.

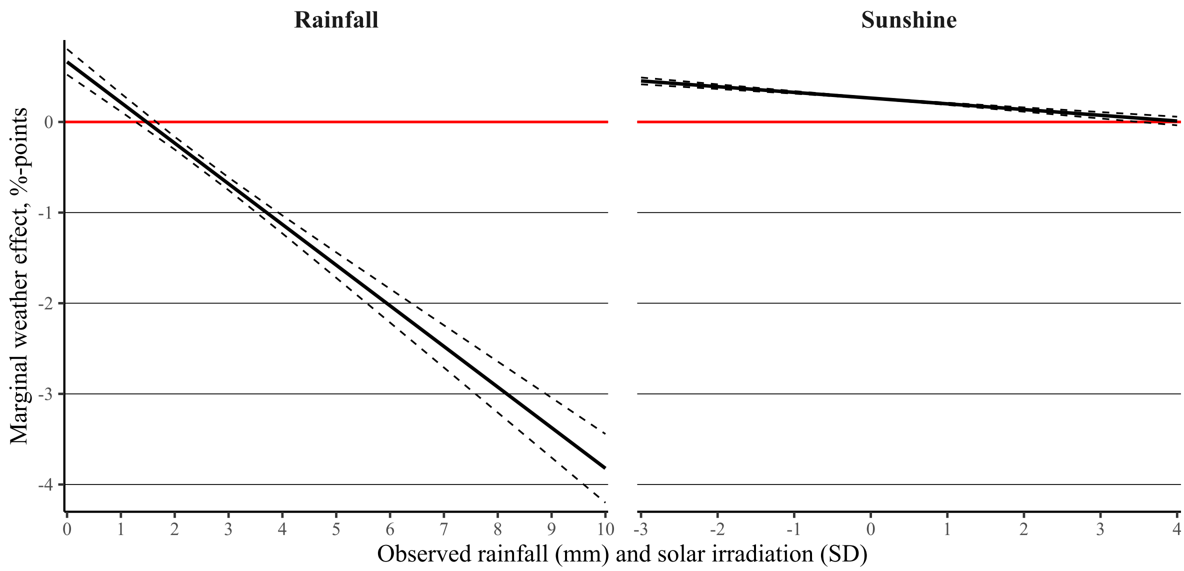

Fig. 3. Evidence of nonlinear weather effects on turnout. The graphs show marginal weather effects computed for different levels of baseline weather intensity. Estimates are based on the panel model (see Table 3) with second-order weather terms added to the equation. See regression table (Table A3), pooled model graphs (Figure A10), and temperature graph (Figure A11) in appendix. 95% CIs (cluster-robust SEs).

voter) or a debutant.[13] The negative rainfall effect is very strong for young voters, especially the cohorts 2 and 3 for whom the 2013 election was the second and third election in their adult life. In cohort 2, the rainfall effect is −5.63 percentage points per centimeter of rainfall – an almost six times stronger effect than the average effect of −0.95. Strikingly, the negative effect is virtually non-existent for the youngest first-time voters. This mirrors absolute turnout rates depicted in Figure A1 and is probably primarily explained by the fact that parents make sure to bring their adult children, who typically still live at home, along to the polls (Bhatti and Hansen, 2012a). For more mature voters, the rainfall effect gradually wanes and disappears until it shows signs of reversing at old ages.[14]

Election Day sunshine shows the same pattern, i.e., a relatively strong effect on voters in their twenties and early thirties, who have experienced two to three elections in their adult life, followed by a gradual tapering off. Turnout in the youngest cohort is unaffected by nice weather as well, whereas slightly more seasoned voters, who have typically left their childhood home, are more susceptible.

In sum, the analysis supports the hypothesis that marginal voters are more susceptible to exogenous changes to the costs and benefits of voting. Except for first-time voters, young and inexperienced voters are deterred from voting by bad weather to a much larger degree than more mature voters. But they are also drawn to the polls by the positive effect of pleasant weather to a higher degree, which shows the weather-voting effect is not merely negative, related to obstacles, costs, and inconvenience, but has a positive counterpart in nice weather, which can make voting a more appealing activity. The implication is that how the weather turns out on Election Day potentially induces representational inequalities into the Election not only due to geography (if it rains in only one region of the country, fewer voters will turn out there), but crucially also because marginal voters are affected much more strongly than core voters.

7. Robustness checks: consistency across model specifications and samples

In the appendix, we report additional evidence and several robustness checks in support of our conclusions. First, as mentioned, we show that effect estimates are similar, generally slightly higher, when only one weather variable is included in the panel model at a time (Table A5). These alternative estimates may be more directly comparable to existing studies and, furthermore, circumvent potential multicollinearity issues.

Secondly, we show that effect estimates are slightly different when no control variables are added, but not to an extent that alters the conclusions (Table A6). This speaks to the discussion about whether individual weather exposure largely is exogenous or if it depends on covariate adjustment and the selection-on-observables assumption.

Thirdly, despite being a minor concern in the geographic case of Denmark, we attempt to account for the fact that some voters move to another municipality, where the local climate may be different. We do this by (a) adding municipality fixed effects to the panel model and (b) estimating the panel model with a sample restricted to the approximately 86% who did not move to another municipality, thus controlling completely for geography by estimating effects within non-movers. Both approaches result in only marginally different estimates (Table A7). Relatedly, we restrict the sample to the approximately 1.8 million voters between age 40 and 59, for whom potential confounders, e.g., education, occupation, children, income, are closer to invariant over time and, thus, more successfully eliminated in the panel model. Despite discarding 64% of the data, these resulting estimates are remarkably consistent with the full-sample estimates (Table A7).

Fourthly, in some rare cases, hundreds of voters share the same home address and, as a result, also share the exact same weather exposure. Specifically, 492 addresses (0.02%) have more than 100 eligible voters registered. These people may live in dorms, retirement homes, or be assigned a generic address such as the town hall because they are, e.g., homeless, expats, or deployed military personnel. This could cause measurement error but restricting the sample to addresses with less than 100, 50, and 10 residents does not substantially change the results

[13] Graphs drawn for the pooled model can be found in the appendix (Figure A12). The pooled model allows for estimation based on the entire sample (e.g., including first-time voters in the 2017 election) and for number of elections to be based on exact age at the elections rather than cohort. The same general pattern emerges, albeit more distinctly and with much higher effect estimates. Most importantly, the starkest contrast in the pooled model is also between first-time and second-time voters.

[14] The reversal at high ages should be interpreted with caution because of possible selection issues at this end of the spectrum. In short, it tends to be more healthy elderly individuals who are included in the analysis (less healthy individuals are more likely to effectively be excluded due to early voting in retirement homes or passing away between the elections).

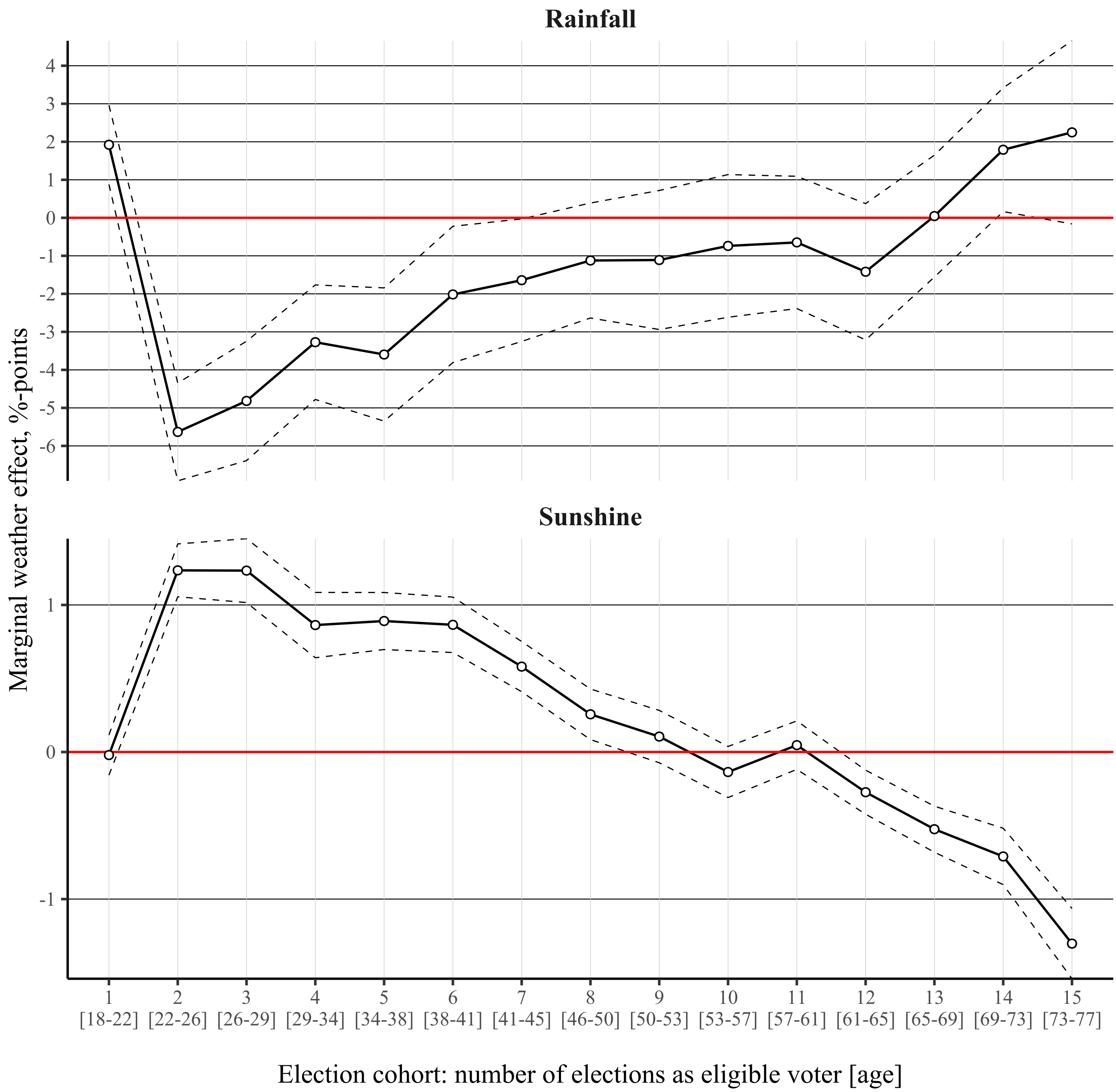

Fig. 4. Marginal turnout effects of rainfall and sunshine conditional on election cohort or the number of elections experienced.
The graphs show estimated marginal weather effects for each cohort of voters that have experienced 1–15 elections as adults (including the 2013 election). Election cohorts largely, but not perfectly, correspond to voter age in 2013 (square brackets). Estimates are based on the panel model (see Table 3) with interaction terms added between each weather variable and election cohort (categorical). The model includes all the control variables as reported in Table 3. Temperature graphs and pooled model graphs are provided in appendix. 95% CIs (cluster-robust SEs).

(Table A8).

Fifthly, observations from only the nearest weather station may intuitively appear more valid than a weighted average of the nearest three, especially for voters living close to one. Although weather estimates tend to be dominated by the nearest station, we nevertheless also empirically examine how sensitive results are to the triangulation procedure compared to just using the nearest observation by estimating the panel model with only the nearest weather observation. At the same time, we apply an increasingly restrictive maximum distance to the nearest weather station – varying from 30 km to 3 km – to exclude faraway voters. Figure A14 shows that estimates are stable and consistent with the main results down to around the 10 km boundary, after which the sample likely become severely biased.

Sixthly, we conducted a placebo test using mock weather from 30 to 60 days before the elections, which clearly show that Election Day weather has an especially high impact on turnout. The placebo coefficients for *rainfall* amount to merely 2.8% and 10.4% of the real coefficient in the pooled model (in absolute terms) and 0.4% and 4.2% in the panel model. The largest rainfall placebo effect in the panel model is thus a 0.04 percentage point turnout reduction per centimeter of rain (compared to the true value of 0.95). The placebo coefficients for *sunshine* amount to 0.2% and 0.4% (pooled model) and 7.1% and 0.7% (panel model) of the real coefficient.

Seventhly, with weather data it is notoriously hard to choose the right standard errors that correctly take into account the various dependencies in the data (Cooperman, 2017; Lind, 2017). We have used (cluster-robust) standard error estimators that we believe sufficiently account for the most important dependencies. But since the reader may hold different views, Table A10 provides an extensive list of alternative standard errors.

Finally, we provide the main models as logistic regressions to show that they produce identical results in terms of direction and statistical significance (Table A11).

8. Conclusion and discussion: weather experience and electoral turnout

The effect of weather exposure on electoral turnout is an appealing illustration of the cost of voting theory. Bad weather on Election Day increases the cost of voting, which means that rainfall should reduce turnout. Numerous studies have investigated this relationship in different contexts and with varying data and research designs. But recent studies challenge the conventional wisdom and important questions remain unanswered. With this article, we bring new empirical evidence to these questions.

First, our meta-analysis of 27 comparable weather-turnout studies shows that a clear majority find a negative effect of rainfall on turnout, which results in a naïve average effect of −0.82 percentage points per centimeter of rainfall. However, two recent studies, which find puzzling (although not necessarily inexplicable) *positive* associations between rainfall and turnout with extremely low uncertainty (Gavazza et al., 2019; Lind, 2020), dominate the inverse variance-weighted average, which normally would be a more appropriate estimate than the simple unweighted average. When we exclude these two outlier studies, we get a weighted average effect of −0.42 percentage points per centimeter of rainfall, and other alternative meta-analytical estimates range between −0.915 and 0.003 (Fig. 1).

To bring improved evidence to the still unsettled question of how Election Day weather shapes turnout, we proceeded with a stand-alone study that has several significant advantages over the existing body of work. Most importantly, it is the first individual-level study based on validated voting records for an entire electorate at two consecutive elections. Our administrative voter records have low measurement error, enable us to improve individual-level causal inference in panel models, and allow us to investigate heterogeneous effects. Using these superior panel data, we show that bad weather does indeed depress turnout at the individual level. Specifically, we estimate that a centimeter of rainfall reduces the probability of voting by 0.95 percentage points. This rainfall effect is substantial and comparable to, for example, the effects of Get-Out-The-Vote campaigns (Hansen, 2020).

Rainfall effects are nonlinear in the sense that the first millimeter of rainfall is largely inconsequential for turnout, whereas turnout decreases more drastically at high levels of baseline precipitation. This arguably suggests that as we expect more extreme weather in the future due to global heating, including more frequent and intense cloudbursts, we should expect to occasionally see participation in elections severely affected by bad weather.

We also find that higher levels of sunshine, i.e., more pleasant Election Day weather, significantly increase the probability of voting net of rainfall and temperature effects. Both the negative rainfall effect and the positive sunshine effect correspond with the logic of the cost of voting; bad weather increases the cost associated with transportation to and from the polling place, standing in line, etc., while pleasant weather reduces these costs and makes voting a more enjoyable activity.

A crucial component in our understanding of weather effects on turnout is their heterogeneous character. Weather effects would not necessarily be important if all citizens were influenced equally. That would simply imply a higher or lower overall turnout depending on the weather with no implications for democratic representation or electoral outcomes. But if marginal voter groups tend to be more susceptible, bad Election Day weather can cause severe electoral inequalities.

We show that young voters, who have typically left their childhood home but not yet established a robust voting habit, are much more susceptible to the weather. The marginal turnout effect of rainfall peaks for voters in their mid-twenties, who are not first-time voters, but rather have experienced two or three elections as eligible voters, and who are unlikely to still live with their parents. Specifically, in this young voter group, each centimeter of rain reduces the probability of voting by −5.6 percentage points – or six times more than the average. A full centimeter of local rainfall on Election Day is a relatively uncommon event and, hence, a quite strong treatment, but a response of more than five percentage points in predicted turnout is nevertheless remarkable. For more seasoned voters, the rainfall effect gradually wanes. We find similar reverse patterns for sunshine. Future research should examine the effects for other marginal voter groups, for instance based on an estimated propensity to vote approach (Enos et al., 2013).

The heterogeneity of weather effects implies that bad weather on Election Day increases the turnout gap between high and low propensity voters, between core and marginal voters, thus increasing inequalities in electoral participation and harming democratic representation. Based on rainfall records from the last 30 years in Denmark, we would expect 1.1 mm less rainfall on any given day in April, the driest month, compared to November, where Danish local elections take place. Simply moving the elections to April would improve electoral equality by increasing expected turnout among young voters, and plausibly other marginal voter groups too, by more than a half percentage point – an impact close to the typical Get-Out-The-Vote campaign (Hansen, 2020).

In sum, we find robust and consistent effects of local weather on turnout in small, flat, and geographically homogenous Denmark, where the electoral system is characterized by extremely effective automatic voter registration, high-salience elections, and strong civic duty and turn-out-to-vote norms (Hansen, 2020). In contexts with more heterogeneous or extreme weather, larger barriers to turnout, weaker civic duty norms, weaker electoral salience, lower historical turnout, and larger marginal voter groups, we might expect decisions to turn out for election to be even more sensitive to Election Day weather conditions. Furthermore, with more extreme weather expected in the future, the weather effects presented in this paper's meta-analysis and new stand-alone study provide conservative estimates of how the weather will influence electoral turnout in the future. Once in a while, we will see elections that rains out with major implications for democratic representation.

Replication data

Data for the meta-analysis, weather data, and R code are available through Harvard Dataverse at hhttps://doi.org/10.7910/DVN/U7HY94. Individual-level turnout records are stored on servers at Statistics Denmark and cannot be made publicly available for legal, security, and privacy reasons. An online appendix with supplementary analysis is published with the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.electstud.2022.102573.

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