Rain, Rain, Go Away: 195 Potential Exclusion-Restriction Violations for Studies Using Weather as an Instrumental Variable

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Abstract

Instrumental variable (IV) analysis assumes the instrument only affects the dependent variable via its relationship with the independent variable. Other possible causal routes from the IV to the dependent variable are exclusion-restriction violations and invalidate the instrument. Weather has been widely used as an instrument in social science to predict many different variables. The use of weather to instrument different independent variables represents strong *prima facie* evidence of exclusion violations for all weather-IV studies. A review of 289 studies reveals 195 variables previously linked to weather: all representing potential exclusion violations. Using sensitivity analysis, I show that the magnitude of many of these violations is sufficient to overturn numerous existing IV results. I conclude with practical steps to systematically review existing literature to identify and quantify possible exclusion violations when using IV designs.

1 Introduction¹

Endogeneity is a pervasive challenge for social scientists. The causal relationship between

X_1 and Y cannot be estimated simply by observing their relationship (first DAG in table

1) as most variables share unmeasured confounders U (second row). One strategy is to

use an instrumental variable (IV) W that causally affects X_1 but is uncorrelated with the

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error term. W 's ability to manipulate X_1 independently of U allows for consistent causal estimation of the relationship between X_1 and Y using techniques like two-stage least squares (2SLS) subject to identifying assumptions.

IV estimation assumes that W affects Y only through X_1 (the exclusion restriction) as shown in table 1's third row.²³ However, this assumption is violated if another pathway between W and Y exists such via X_j in the fourth row of table 1. If we assume that any alternative pathway between W and Y is mediated by at least one variable, the exclusion restriction can be restated as the claim that no variable X_j exists that is both caused by W and which causes Y (and that X_1 does not fully mediate either link). The untestability⁴ of the exclusion restriction comes from the fact that there is no guarantee that we have enumerated all X_j variables. If we had a definitive list of X_j variables, the assumption would be testable provided we could establish the presence or absence of $X \rightarrow X_j$ and $X_j \rightarrow Y$ in each case.

Although we lack a complete list of X_j variables, we can search for social science variables claimed to be caused by W . These variables are strong candidates for exclusion-restriction violations, as they usually only additionally require the existence of the $X_j \rightarrow Y$ relationship

²In practice, most IV studies also include a set of exogenous covariates K . While I describe unconditional IV estimation here, the same logic applies except that the various independence assumptions are conditional on K .

³I follow Angrist, Imbens, and Rubin (1996) in treating the exogeneity assumption separately to the exclusion restriction.

⁴Statistical techniques can detect exclusion-restriction violations but not confirm their absence. The Sargan-Hansen test applies when there are more instruments than instrumented variables by testing whether the residuals for the second-stage estimate (dropping one instrument at a time) correlate with the instruments (Kiviet 2020). The zero-first-stage test verifies that the treatment's reduced-form effect is zero in a sub-sample where the instrument should not affect X_1 (Kippersluis and Rietveld 2018).

Scenario	Description	DAG
Naive model	X_1 causes Y with nothing else interfering with our ability to observe this relationship	$X_1 \longrightarrow Y$
Endogeneity critique	X_1 and Y share unmeasured confounders (U)	<pre> graph TD U((U)) -.-> X1[X1] U((U)) -.-> Y((Y)) X1[X1] --> Y((Y)) </pre>
Instrumental variable	Bypass any endogeneity, leaving only the true exogenous effect	<pre> graph LR W((W)) --> X1[X1] X1[X1] --> Y((Y)) U((U)) -.-> X1[X1] U((U)) -.-> Y((Y)) </pre>
Exclusion-restriction violation	Relationship between X_1 and Y is no longer identified	<pre> graph LR W((W)) --> X1[X1] W((W)) --> Xj[Xj] X1[X1] --> Y((Y)) Xj[Xj] --> Y((Y)) U((U)) -.-> X1[X1] U((U)) -.-> Y((Y)) </pre>

Table 1: DAGs illustrating Instrumental variables and endogeneity

(exceptions are described in table 2). Systematically searching for $W \rightarrow X_j$ links is an efficient approach to identify potential exclusion-restriction violations.

This approach turns the exclusion restriction from an untestable claim to a set of substantive claims about social science variables. It also includes a weaker, untestable claim that there are no undocumented X_j variables violating the exclusion restriction.

I present a process to: 1) search for exclusion-restriction variables in existing literature, 2) assess and document exclusion-restriction violations, and 3) conduct sensitivity analysis to assess the impact of violations on results.

I apply this approach to a widely used instrument: the weather. The weather is appealing as a source of exogenous variation because it seems obvious that the weather is essentially random

and only related to human outcomes through narrow causal paths. I examine whether the exclusion-restriction assumption is plausible for weather IVs.

Weather instruments are not without critics. Sarsons (2015) identifies likely exclusion-restriction violations in IV estimates of rainfall on economic growth, as rain predicts conflict even where incomes are unaffected and Horiuchi and Kang (2018) express concern that rainfall's effect on vote share is larger than can be explained by turnout alone. Gallen and Raymond (2019) raise exclusion-restriction concerns for rainfall and other overused IVs in economics. This paper goes beyond their analysis by examining studies in other social science fields, and quantifying the strength of exclusion-restriction violations using sensitivity analysis. Cooperman (2017) argue that rainfall suffers from spatial interdependence. Weather also has measurement problems (Dell, Jones, and Olken 2014; Schultz and Mankin 2019).

Rather than independently discovering violating routes from weather to outcomes, I use the IV literature itself to identify alternative causal pathways. I review 159 weather-IV studies and an additional 130 studies of the direct effect of weather. In total, I identify 195 variables that social scientists have linked to weather through many causal pathways. Consequently, this review challenges many weather-IV findings.

Any exclusion-restriction violation will bias an IV estimate, but small violations may be

acceptable. I assess the severity of these violations by using the first-stage of IV estimates of weather on X_j variables to conduct sensitivity analysis (Cinelli and Hazlett 2020a) on other weather IVs. This allows me to show how large a relationship would have to exist between an X_j variable and a dependent variable to make an IV estimate insignificant. For some IV studies, X_j would have to explain as little as 0.01% of variance in Y to make the IV estimate of X_1 on Y insignificant. However, in other cases, X_j variables could not make the IV estimate insignificant, even if X_j were perfectly correlated with Y . While both scenarios have exclusion-restriction violations, the sensitivity of the IV estimate in the former case should concern us more.

I demonstrate the process of assessing potential exclusion-restriction violations by examining which X_j variables represent an exclusion-restriction violation for a weather-IV estimate of the effect of economic activity on civil conflict.

The paper proceeds as follows. First, I discuss the implications of one IV study using the same instrument as another. Second, I outline my approach to reviewing literature on an instrument, conducting sensitivity analysis, and assessing and documenting potential exclusion-restriction violations. Third, I show the review's results, the extent of exclusion violations for weather as an IV, and the sensitivity of IV results to these violations, including applying the full assessment method to a study examining the effect of economic activity on

civil conflict. I conclude by discussing the implications of these results for social science IVs.

2 What does another study using the instrument imply?

What does another study using the same instrument for a different variable indicate? For example, study 1 argues W is an instrument for X_1 to predict an outcome (Y) to avoid unobserved confounders (U). Study j proposes that W serves as an instrument for another variable X_j .

The simplest answer is that study j represents an exclusion-restriction violation where X_j represents an alternate pathway from W to Y that does not include X_1 (shown in the fourth row of table 1). Other possibilities are presented in table 2, with each row displaying a DAG compatible with study 1 and study j 's IV estimate, the new result and study 1's IV estimate. The DAG uses wavy red arrows to show causal links that must be absent for causal identification of study 1's IV estimate.

First, we can reject the claim that W causes X_j if the original claim was flawed or found in an inapplicable context (exception 1). For example, using prevailing winds (W) to estimate the effect of grain shipments (X_j) on 15th century urbanization (Y) is irrelevant to a study using W to predict 21st century pollution levels (X_1).

If X_j is part of X_1 (exception 2), it does not generally violate the exclusion restriction.

Study 1 may use natural gas deposits (W) to instrument pollution exposure's (X_1) effect on mortality (Y), while study j uses natural gas deposits to instrument sulfur dioxide exposure (X_j). Sulfur dioxide exposure is part of pollution exposure, so this is not an exclusion-restriction violation for study 1.

If X_1 is part of X_j , X_j may not be an exclusion-restriction violation if no other part of X_j (Q) is caused by W and causes Y (exception 3). For example, using elevation (W) as an instrument for heart attacks (X_1) would not necessarily be undermined by a claim that elevation causes health (X_j), if the effect of elevation on health is solely due to its effect on heart attacks. If elevation affects another component of health (Q) such as diabetes, X_j would be an exclusion-restriction violation.

If X_j is part of Y (exception 4), it is not an exclusion-restriction violation unless W directly affects X_j . Study 1 may use proximity to college (W) as an instrument for education's (X_1) effect on income (Y), while study j uses proximity to college as an instrument for self-employment income (X_j). In this scenario, X_j is not an exclusion-restriction violation for study 1.

If Y is part of X_j , it may not be an exclusion-restriction violation (exception 5). The key assumption is either that W does not affect any part of X_j apart from Y , or Q does not affect

Y . Reworking the previous example, study 1 uses proximity to college (W) to instrument education's (X_1) effect on self-employment income (Y), and study j uses W to instrument income (X_j). Study j does not violate study 1's exclusion restriction provided that proximity to college does not influence self-employment income through income components unrelated to education. For instance, if self-employment income is crowded out by salary income earned from working at local colleges, it may constitute an exclusion-restriction violation.

Next, X_j may mediate the effect of X_1 on Y (exception 6). For example, drought (W) may cause agricultural incomes (X_1) to fall, leading to competition for resources (X_j), ultimately resulting in violence (Y). The existence of study j which uses droughts as an instrument for competition for resources does not necessarily invalidate study 1 which uses droughts as an instrument for agricultural income. However, study 1 must make a strong assumption: that there is no other causal pathway between droughts (W) and competition for resources (X_j) other than via agricultural income (indicated by the wavy red arrow on the DAG).

Another possibility is that X_j does not cause Y (exception 7). Suppose that study 1 uses military draft lottery number (W) as an instrument for education's (X_1) effect on income (Y), while study j uses draft lottery number as an instrument for military service (X_j). If military service does not affect earnings, then study j does not violate study 1's exclusion restriction.

Finally, X_j may mediate the effect of W on X_1 (exception 8). For example, droughts (W) may cause lower crop yield (X_j), reducing agricultural income (X_1), leading to violence (Y). Study j's use of droughts as an instrument for crop yield does not automatically invalidate study 1's use of droughts as an instrument for agricultural income's effect on violence. However, it requires an additional assumption: there are no other routes from crop yield (X_j) to violence (Y) other than through agricultural income (represented by the red wavy line). If an alternate pathway exists, such as via starvation or migration, this represents an exclusion-restriction violation and invalidates study 1's use of W as an instrument for X_1 .⁵

⁵If a route from W to X_1 that does not go via X_j exists, W can be a valid instrument by conditioning on X_j and all confounders between X_j and Y . Though technically valid, the assumptions stretch credulity.

If none of these exceptions apply, then X_j is an exclusion-restriction violation with the DAG shown in the fourth row of table 1.

In this scenario, Gallen and Raymond (2019) recommend conditioning on X_j to recover the causal effect of X_1 on Y . However, this approach necessitates measuring all X_j variables in the same dataset. Additionally, it requires that the DAG has the structure in figure 1: that the unobserved confounders of X_1 and Y (U_1) have no covariance with the unmeasured confounders of X_j and Y (U_j). In complex causal settings where IV is an attractive approach, making strong assumptions about unmeasured and even unknown variables is difficult to justify. If these assumptions are not met, X_j is a collider for U_1 and Y is an invalid control (Cinelli, Forney, and Pearl 2022). Conditioning on X_j creates a backdoor path between U_1 and W meaning the effect of X_1 on Y is not causally identified (because it is confounded by U_1) and can be highly biased (Deuchert and Huber 2017). Since X_j is an exclusion-restriction violation but cannot be conditioned on, there is no remaining way to identify study 1's IV estimate.

Figure 1: DAG showing a situation where conditioning on X_j allows W to be used as an instrument to estimate the causal effect of X_1 on Y . $\rightsquigarrow$ indicates causal links that must be absent.

Exception	Claim	DAG
1	W does not cause X_j in this context	
2	X_j is part of X_1	
3	X_1 is the only part of X_j caused by W	
4	X_j is part of Y	
5	Y is part of X_j	
6	W only causes X_j via X_1	
7	X_j does not cause Y	
8	X_j only causes Y via X_1	

Table 2: Situations where X_j is not an exclusion-restriction violation for an IV estimate of X_1 on Y despite another study finding an effect of W on X_j . $\rightsquigarrow$ indicates causal links that must be absent. Where there are multiple such links, at least one must be absent. A boxed variable inside a larger box indicates that the variable is a component of the variable represented by the larger box.

This discussion has focused on identifying whether the estimate is strictly causally identified. In practice, exclusion-restriction violations vary in magnitude, with corresponding levels of bias in the causal estimate. When the effect of X_j on Y is small, the overall bias may be minimal. Similarly, conditioning on X_j may not dramatically bias the estimates when the effect of U_j on X_j and Y is small enough, (Gallen and Raymond 2019). I address the magnitude of biases from exclusion-restriction violations using sensitivity analysis.

3 Exclusion-Restriction Violation Assessment Methodology

This section outlines a methodology for evaluating exclusion-restriction violations for an instrument based on existing literature. I explain the general methodology at each step and also provide detail on how I apply this methodology to the weather-IV example in this paper. This approach can be applied retrospectively to an existing IV claim or prospectively as part of new IV studies.

The methodology involves four steps. First, the literature is used to identify X_j variables linked to study 1's instrument W . Second, potential exclusion-restriction variables are filtered for relevance using broad filters, such as country income level. Third, each X_j variable is assessed using theory and literature to determine whether it falls under any of the exceptions in table 2. Any remaining X_j variables are likely to indicate an exclusion-restriction

violation for study 1.

However, the violation’s importance depends on the strength of the $W \rightarrow X_j$ and $X_j \rightarrow Y$ causal links. Thus, the fourth step examines the bias in study 1’s estimate through sensitivity analysis, using estimates of relationship strength from applicable literature.

3.1 Weather example

Weather IVs are widely used by social scientists, so provide a rich example for the exclusion-restriction methodology. I test the methodology in two ways in this paper. I test most of the stages of the process on as many weather-IV estimates as possible. This helps to understand how vulnerable a typical weather-IV estimate is to exclusion-restriction violations.

The exception-search stage is too intensive to perform on every IV estimate. I therefore, also show the full process on a single IV estimate of the effect of economic activity on civil conflict (using rainfall as an instrument). This relationship has been repeatedly studied using weather instruments (Miguel and Satyanath 2011; Jensen and Gleditsch 2009; Miguel, Satyanath, and Sergenti 2004), with various criticisms (Sarsons 2015; Ciccone 2011) leveled at those studies. I examine a study using subnational data for African countries (Hodler and Raschky 2014) with information available for sensitivity analysis. Hodler and Raschky (2014) find an effect of -0.303 (SE = 0.111) on conflict probability for a 1-unit increase in

the log of economic activity (measured using light intensity).

3.2 Enumerate potential exclusion-restriction violations

The method aims to identify as many potential exclusion-restriction violations (documented causal links $W \rightarrow X_j$) for an IV study (study 1) as possible. The researcher enumerates possible linkages between an instrument W and variables that could affect humans (X_j) by searching the literature about W and examining what variables W has been used to predict. IV studies which also use W as an instrument are a particularly valuable source of X_j variables because they make explicitly causal claims and often provide estimates that can be used in sensitivity analysis. Researchers should also search the literature for X_j variables that are causally affected by closely related variables to W . For example, a researcher using elevation as an instrument should search for studies using variables such as air pressure or mountainous terrain as instruments or predictors. The researcher should also include any plausible X_j variables they can think of that are not covered in the existing literature. Since a single exclusion restriction violation can undermine the IV strategy, researchers may choose to examine an initial batch of X_j variables for their effect on study 1's estimate rather than attempting to fully enumerate all X_j variables. If this initial batch does not reveal exclusion-restriction violations that cause unacceptable levels of bias, researchers should extend the literature search until they either find an unacceptable exclusion-restriction violation or have

exhausted the literature.

3.2.1 Application to weather IVs

I apply the same method for enumerating potential exclusion-restriction variables to both the broad analysis of weather-IV studies and the narrow economic activity $\rightarrow$ civil conflict case. This literature review serves the dual purpose of identifying 1) the weather-IV studies under examination for the broad analysis and 2) the potential exclusion-restriction variables (X_j) for those studies.

Although these studies use various weather phenomena as instruments, different weather types are part of a complex causal network and are generally substantially correlated⁶ both spatially⁷ and longitudinally (Nicholls, Drosowsky, and Lavery 1997). This means the causal relationship $rain \rightarrow X_j$ implies some form of causal relationship between temperature and X_j , and wind speed and X_j , although the strength of that relationship may be attenuated.

To generate potential exclusion-restriction variables for weather-IV studies, I reviewed the first 500 results for the search term ‘weather “instrumental variable”’ on Google Scholar (while the search returned 12,700 results in total, the results after 500 seemed largely off topic). I also included the first 100 results from ‘rain “instrumental variable”’, a few previ-

⁶These correlations do not account for measurement error. Correlations between different weather phenomena are not much lower than the correlations between different measurements of the same phenomenon (Auffhammer et al. 2013).

⁷Annual precipitation (2014 World Development Indicators) correlates with 2014 yearly-average temperature (World Bank Climate Knowledge Portal) at the country level at $r=0.28$.

ously identified studies, and relevant studies cited in other papers. This yielded 159 weather-IV studies, and 130 studies using weather as the independent variable of interest. These studies were primarily in economics, political science, and international development.

All studies were entered into a table (table B1) tracking the instrument, instrumented variable, and outcome variable. If a study contains more than one combination of these, I include a row for each combination. I also record the frequency of weather measurement, and IV, reduced-form, and first-stage estimates where available.

For analysis, I recoded the variables into coarser theoretical categories. For example, I coded GDP, household income, average income, economic growth, permanent income, income, agricultural income, growth, per-capita income, crop revenue per hectare, poverty, transitory income, agricultural growth, and farm financial performance as “income”. Less coarse categories would better distinguish concepts but would increase the count of potential exclusion-restriction violations (since I enumerate $W \rightarrow X_j$ relationships but not $X_j \rightarrow Y$ relationships).

3.3 Filter potential exclusion-restriction violations for relevance

While the literature is a useful source of information about potential exclusion-restriction violations, not all existing $W \rightarrow X_j$ claims will be relevant to study 1’s estimate. Because I

only focus on whether the link exists at this stage, I do not need to worry about factors that change the strength of the $W \rightarrow X_j$ link across contexts, but only factors that could make the link exist in the context of study j but not study 1. If the enumeration step produced a large number of potential exclusion-restriction variables, it may be useful to apply heuristics to limit variables to those most likely to affect study 1. The exact filters will depend on the study: political regime might be relevant for a voting behavior study, whereas economic development could be more relevant for a study of economic growth.

3.3.1 Application to weather IVs

I consider two factors that could lead a causal relationship between weather and X_j to exist in one context but not another: 1) the temporal frequency of the weather variable and 2) the economic context of each study.

3.3.1.1 Temporal frequency Weather can be measured at different levels of temporal aggregation e.g. daily versus yearly rainfall variation. Shorter periods are generally relevant to longer periods but not the inverse. An effect of daily sunlight levels on happiness might generalize to an effect of yearly sunlight effects. However, it is less likely that an effect of yearly rainfall on income would generalize to daily variation in rainfall. Long-period weather-IV studies (differences on the order of years) are therefore vulnerable to exclusion-restriction

violations from all other weather-IV studies. However, if short-term studies control for long-term weather, it should be possible to remove exclusion-restriction violations working via longer-term weather. For example, turnout weather-IV studies often control for the average weather on that date but this does not account for the correlation between election-day weather and weather patterns in the area over the past week or month, so fully controlling for other time periods is challenging.

I split the studies into short-term (weather measured monthly or more frequently) and long-term (weather measured less than monthly).

3.3.1.2 Economic development The relevance of exclusion-restriction variables may vary because the societies studied are different. Although societies vary along many dimensions, the most relevant factor for weather appears to be economic development. Poorer countries tend to have economies based on agriculture and raw-material extraction, while richer countries have more diversified economies. Consequently, the effects of weather may differ across these settings.

To mitigate this problem, I categorize the countries in each study based on the World Bank's current development levels. High and higher-middle income countries are grouped as high income, while lower-middle and lower income countries are grouped as low income. This

compromises between only considering exclusion-restriction violations from identical contexts and allowing estimates from poor agricultural contexts to be relevant to high-income countries.

3.4 Search for exceptions where X_j is not a potential exclusion-restriction violation

Each X_j variable is assessed using the steps in table 2 to assess 8 possible exceptions for why it may not be an exclusion-restriction violation. The subsequent step is only taken if the previous step fails to identify an exception. Literature searches and theoretical consideration should inform the decision at each stage. If an exception is found for X_j , the evidence and/or theory should be documented so readers can assess its validity.

If no exceptions apply, X_j violates study 1's exclusion restriction.

3.4.1 Application to weather IVs

I do not attempt to search for exceptions for the broad set of weather IVs as this would require investigating 13,356 possible causal relationships (159 Y variables and 84 X_j variables). However, an individual study would only need to assess 84 X_j variables for causal links to the Y variable for that study.

To demonstrate this step, I apply the exception-search method to the IV estimate of economic activity's effect on civil conflict (Hodler and Raschky 2014).

3.5 Sensitivity Analysis

The methodology so far aims to gather examples of exclusion-restriction violations for an IV study (study 1). However, the presence of exclusion-restriction violations does not necessarily imply large biases in study 1’s IV estimates. Instead, we must examine whether X_j is a large enough violation of the exclusion-restriction assumption to alter the study 1’s conclusions. I assess the IV estimate’s sensitivity by looking at the reduced-form (Cinelli and Hazlett 2020a), with an estimate being sensitive if the bias would make it non-significant or change the sign of the effect. While I focus on exclusion-restriction violations reducing an effect’s magnitude, they could also arbitrarily increase its magnitude, depending on the sign of the $W \rightarrow X_j$ and $X_j \rightarrow Y$ relationships. I treat the X_j variables as confounders, although this means the sensitivity analysis could be affected by post-treatment bias if X_j and Y share unmeasured confounders. Therefore, the sensitivity estimates indicate the likely level of bias but should not be considered the final substantive answer. The sensitivity analysis currently only applies to the IV regression reduced form in the case of a single instrument. However, multiple-instrument studies are not systematically less susceptible to exclusion-restriction violations.

The impact of an exclusion-restriction violation on an IV study’s conclusions depends on two quantities: the partial R^2 of the relationship between the instrument W and an exclusion-

restriction variable X_j ($R_{X_j \sim W|K}^2$), and the partial R^2 of the relationship between X_j and the dependent variable Y ($R_{Y \sim X_j|W,K}^2$), where K is the set of exogenous predictors in the original study.

Based on a pair of partial- R^2 values for a particular X_j , I compute the bias of the coefficient (Cinelli and Hazlett 2020a) using the *sensemkr* package (Cinelli, Ferwerda, and Hazlett 2020) (where n is the sample size and p is the number of predictors):

$$bias = SE \sqrt{\frac{R_{Y \sim X_j|W,K}^2 R_{X_j \sim W|K}^2}{1 - R_{X_j \sim W|K}^2} (n - p - 1)} \quad (1)$$

and the corrected standard error:

$$SE_{corrected} = SE \sqrt{\frac{1 - R_{Y \sim X_j|W,K}^2}{1 - R_{X_j \sim W|K}^2} \cdot \frac{n - p - 1}{n - p - 2}} \quad (2)$$

These are used to calculate a new central estimate and confidence interval which can be used to assess whether the revised estimate is unacceptably different from the original. In this paper, I consider an unacceptable change to be one that makes the result no longer significant with the same sign (or a change of equivalent magnitude in the same direction as the original effect).

But how large are the relevant partial- R^2 values? These can be derived in various ways including with new data analysis or from studies which provide the estimates in this format.

The IV literature provides useful estimates of $R^2_{X_j \sim W|K}$ through its first-stage estimates of the relationship between W and various X_j variables measured via F-statistics ($F_{X_j, W|K}$).⁸

For study 1, estimates of relationships between W and the X_j in other studies' (j) indicate the strength of possible exclusion-restriction violations.

If both partial- R^2 values are available, the revised estimate can be directly calculated. However, often one or both will be unavailable. If one partial- R^2 value is missing, it is possible to ask how large the other partial- R^2 value would need to be in order to change the original result unacceptably. If the second partial- R^2 would have to be huge to overturn a result, then the exclusion-restriction violation is unlikely to greatly change study 1's substantive conclusion. If the second partial- R^2 value could be minuscule yet still overturn the result, we should be wary of trusting study 1's conclusions.

If partial- R^2 values are unavailable, researchers can calculate pairs of values that needed to invalidate study 1's result and consider whether they can confidently rule out all of those

⁸The $R^2_{Y \sim X_j|K}$ for a model predicting Y using a set of q instruments (X_j) and p exogenous predictors (K) is derived from the F-statistic $F_{Y, X_j|K}$: $R^2_{Y \sim X_j|K} = \frac{F_{Y, X_j|K} q}{(n-p-q) + q F_{Y, X_j|K}}$, where n is the number of observations. The degrees of freedom for the F-statistic are estimated from the available information about the number of observations, predictors, and instruments. Some studies likely accounted for clustering in their first-stage F-statistic but this information is rarely available, so I conservatively calculate degrees of freedom as $n - p - q$. Since the more robust approaches will return a smaller F-statistic, this assumption means I will tend to underestimate $R^2_{W \sim X_j|K}$ values and—consequently—the impact of exclusion-restriction violations. When researchers apply this technique they may want to consider calculating $R^2_{Y \sim X_j|K}$ from replication data for crucial X_j variables to avoid these approximations.

combinations.

3.5.1 Filter fit statistics for transportability

For a $R^2_{X_j \sim W|K}$ estimate from study j to be relevant to study 1, three requirements must be met: 1) study 1 and j must use the same instrument,⁹ 2) study 1 and j must model the same variance type (e.g. within-person),¹⁰ and 3) study 1 must not control for X_j .¹¹

3.5.2 Application to weather IVs

For the broad analysis of weather IVs, I am only able to examine reduced-form estimates that use single weather instruments and provide sufficient information to derive the reduced-form equation.

While all the studies I consider use some form of weather as an instrument, the exact variable used varies across studies (see table D1). Rainfall is the most common followed by temperature. Different weather types will not have the same strength of relationship to a particular X_j . A study that demonstrates a strong link between rainfall and X_j does not imply that X_j is as strongly related to sunlight intensity or snowfall. I therefore only consider study j 's

$R^2_{X_j \sim W|K}$ estimate if it makes use of the same weather variable as study 1.

⁹This is a stricter standard than at the enumeration stage where only the presence of a causal link is required.

¹⁰Different variance types make it difficult to compare goodness-of-fit due to different DGMS, uneven sizes of geographical units, and different amounts of variance.

¹¹Controlling for X_j is inadvisable since it involves conditioning on a collider but would make the sensitivity analysis mischaracterize the bias. I therefore exclude first-stage estimates for X_j variables controlled for in study 1. Other exogenous controls (K) may affect partial- R^2 transferability but additional controls (beyond fixed effects) typically have a small effect on variance left to explain.

The variance being modeled differs across weather studies (see table E1). For instance, some weather-IV studies use individual-level data at a single time point (between-person) while others use district-level data over time (within-subnational). The most common variance modeled is within-subnational . For instance, a yearly panel of US states with year and state fixed-effects. Within-person (or household) variation is the next most modeled form of variance: using person fixed-effects, lagged-dependent-variable, or first-differencing strategies. Studies that use within-unit variation often refer to the strategy as modeling the effect of weather shocks (because the effect of average weather is removed by unit fixed effects)

Few weather-IV estimates are excluded for controlling for other causal pathways. Of the 120 X_j variables with a $R^2_{X_j \sim W|K}$, only 39 are used as a control variable in one of the 63 reduced-form estimates. Income is the most commonly controlled exclusion-restriction variable, controlled for in 14% of IV estimates.

4 Results

4.1 Enumerating potential exclusion-restriction violations for weather IVs

In the assumed DAG in the third row of table 1, weather only affects the causal network through X_1 . In reality, the literature review of 289 studies finds that weather enters the social science causal network through 124 different variables, and indirectly reaches 194 variables of

interest to social scientists. Each of these variables represents a potential exclusion-restriction violation for the IV DAG (including the economic activity $\rightarrow$ civil conflict DAG). This is illustrated in figure 2 which shows the causal web for the most common weather type: rainfall. This is derived from 192 studies using rainfall and shows the wide variety of causal pathways the literature claims are linked to rain.

4.2 Filter potential weather exclusion-restriction variables for relevance

The overall weather DAG lists all potential exclusion-restriction violations from the literature, but scholars may prefer a narrower selection of relevant studies. Figure 3 displays causal links asserted in weather studies (of all weather types) by country income and temporal frequency. Few studies examine short-term weather variation in low-income countries, so only 11 variables are linked to weather including pirate attacks (Cook and Garrett 2013), COVID-19 (Shen, Cai, and Li 2020), exercise (Aral and Nicolaides 2017), and protest (Ritter and Conrad 2016).

The other time/income combinations show a large network of potential exclusion-restriction violations to consider. Short-term weather variation in high-income countries has 71 variables, long-term weather variation in low-income countries has 83 variables (this is the relevant set of X_j variables for the economic activity $\rightarrow$ civil conflict example), and long-term variation in high-income countries has 122 variables. Most weather-IV studies have many

relevant potential exclusion-restriction violations.

If all of these $W \rightarrow X_j$ relationships exist, the typical weather-IV study requires hundreds of additional identifying assumptions, which quickly becomes implausible.

4.3 Which variables have been linked to weather?

The DAGs reveal myriad potential exclusion-restriction violations, encompassing crucial social science variables.

Income is the most widely-instrumented variable in weather-IV studies of high-income and low-income countries. The link between weather and income is usually attributed to crop yield. But crop yield has also been proposed as a mechanism for weather effects on other X_j variables such as food prices and food production for personal consumption (e.g. Kubik and May 2018). This means IV studies may attribute the effects of price levels, hunger, or malnutrition to income, thereby overestimating its effect.

Weather causally affects many variables unrelated to agriculture, but the relevance of these variables will vary. Most researchers can assume “helicopter flying conditions” and “pirate attacks” are not possible exclusion-restriction violations. However, many causal pathways are widely relevant to social science outcomes.

The first causal pathway is mood. Several studies claim weather influences mood (e.g. Meier,

High income countries/short-term

High income countries/long-term

Low income countries/short-term

Low income countries/long-term

Figure 3: The causal webs of weather derived from 289 papers. Broken down by country income classification and temporal frequency. Size of nodes and ties are proportional to the number of appearances in the literature. Color key: weather (green), instrumented variable (orange), and outcome (purple)

Schmid, and Stutzer 2019; Bassi 2019). In one weather-IV study, mood was linked to decision-making speed, investment decisions, inflation expectations, risk aversion, financial decisions, and perceived life expectancy (Guven and Hoxha 2015). Almost any social science variable could be causally influenced by at least one of these variables. Mood threatens both long-term and short-term weather-IV studies.

Another major causal route is pollution. Pollution has been instrumented by weather variables including wind speed (e.g. Peet 2020; Bondy, Roth, and Sager 2020), wind direction (e.g. Fan and Wang 2020), atmospheric inversions (Bondy, Roth, and Sager 2020; Sager 2019), and rainfall (e.g. Peet 2020). Pollution—in turn—has been linked to variables including crime (Bondy, Roth, and Sager 2020), mental health (Gu et al. 2020), mortality (Fan and Wang 2020), road accidents (Sager 2019), house prices (Fontenla, Goodwin, and Gonzalez 2019), cognition (Peet 2020), and mood (Zheng et al. 2019). Pollution threatens both long-term and short-term weather-IV studies.

Skin tone is another important variable. Katz et al. (2020) find that some people tan when exposed to sunlight while others do not. Using a weather-IV approach, they argue the gap in labor-market outcomes between those who do and do not tan widens during sunny periods. This suggests that weather may impact social science outcomes through racial prejudice. Skin tone could be an exclusion-restriction violation for long-term or short-term weather-IV

studies.

Migration follows a similar pattern. Migration studies generally justify the use of weather as an IV by weather's effect on income, as lower incomes provide a push factor for emigrants and higher incomes are a pull factor for immigrants (e.g. Strobl and Valfort 2015). Even outside of low-income countries, there is evidence for non-economic links between migration patterns and weather, with Moretti (1998) finding good weather predicts the location of US retirement communities, and Rappaport (2007) finding the same pattern for US internal-migration more generally.

The next causal route is via the legacy of US slavery. Acharya, Blackwell, and Sen (2016) use cotton-growing climate (which includes weather variables) as an instrument for slavery. Slavery's legacy is therefore a potential exclusion-restriction violation for US IV studies using long-term weather.

There are hundreds of other variables including autism, government spending, drone strikes, UFO sightings, global warming beliefs, alcohol consumption, electricity demand, recycling, malaria, sex ratios, education, insurance, lead exposure, female labor force participation, witch trials, cinema attendance, child labor, birth month, cattle theft, democracy, urbanization, and bicycle usage.

4.4 Searching for exceptions where X_j is not an exclusion-restriction violation

I demonstrate how to identify potential exceptions for X_j being an exclusion-restriction violation using an IV estimate of the causal effect of economic activity on civil conflict (Hodler and Raschky 2014).

Table 3 shows the 50 relevant X_j variables other studies claim are caused by weather. The assumption column shows the outcome for the variables in the X_j column. The justification and evidence for each categorization is shown in greater detail in table A1. My goal is not to advocate for these specific classifications, but to illustrate how the substantive assumptions behind the exclusion restriction can be shown explicitly to readers (who can decide whether they are convinced by the reasoning in table A1).

I categorize six variables as not being violations because the proposed $W \rightarrow X_j$ relationship does not apply to the current context (exception 1). For example, the claim that rainfall causes female labor force participation is based on studies of India (Chin 2012) and Vietnam (Thai and Myrskylä 2012), where rice-farming is considered women’s work. Rice is a smaller part of African agriculture. I also reject X_j variables where the claim is based on flawed work. For instance, the human capital and urbanization links to rainfall are based on a single cross-sectional working paper (Lagerlöf and Basher 2006) that used rainfall to instrument

Table 3: IV identification assumptions for the causal effect of economic activity (X_1) on civil conflict (Y) for potential exclusion-restriction variables (X_j) discovered to be related to a weather instrument (W) in relevant literature. Remaining exclusion-restriction violations shown in bottom row.

Exception	Assumption	X_j
1	W does not cause X_j in this context	Female employment Early life pollution Individual Responsibility Human capital Urbanization Month of birth
2	X_j is part of X_1	Agricultural productivity Income Agricultural production Labor force Wealth Crop prices Sectoral employment Agricultural wages Price Consumption Hydroelectric power Unemployment Energy demand
3	X_1 is the only part of X_j caused by W	
4	X_j is part of Y	Rebel recruitment Crime
5	Y is part of X_j	
6	W only causes X_j via X_1	Forest extraction Access to rented land Expenditure inequality Child Labor Budget balance Firm cash holding Inflation expectations Inequality Livestock prices
7	X_j does not cause Y	Farming practices Child mortality Crop diversity Child health Fertility Health Dust Exposure Mortality
8	X_j only causes Y via X_1	Energy prices
None	X_j is an exclusion-restriction violation	Immigration Emigration Health access Mental health Malaria Lead exposure Transport infrastructure Hunger Alcohol consumption Mood Land fragmentation

multiple different X_j variables. The published version of that paper omits this analysis.

Next, 13 X_j variables are not considered exclusion-restriction violations because they are part of X_1 (exception 2). “Economic activity” is broad, so many other variables such as “crop production” and “income” can be considered components of it. Weather-IV studies with a narrower X_1 variable (such as crop income) would not be able to exclude as many X_j variables at this stage.

Two variables are eliminated because X_j is part of Y (exception 4). Rebel recruitment can be reasonably treated as an inherent part of civil conflict rather than a separate process. Similarly, some scholars argue there is no strict boundary between crime and civil conflict (Collier 2000).

I eliminate nine cases where X_1 mediates the relationship between W and X_j and, crucially, where there is no reason to believe that W has causal pathways to X_j that do not run via X_1 (exception 6). I used the original studies linking W and X_j to establish whether multiple mechanisms were posited or only an economic activity mechanism. For instance, Ajefu and Abiona (2019) link weather shocks to child labor, but explicitly treat weather as a purely income-based shock meaning child labor falls under exception 6. Conversely, although weather’s effect on emigration is often described as a response to income shocks

(Kleemans and Magruder 2018; Pugatch and Yang 2011), others describe it as working via direct displacement such as Hurricane Maria’s effect on Puerto Rican emigration (DeWaard, Johnson, and Whitaker 2020). This means emigration does not fall into this exception.

There are also situations where I assert that the $X_j \rightarrow Y$ relationship does not exist (exception 7). In each case, I search the literature for evidence of the relationship and consider plausible links not discussed in the literature. For example, no studies claim child mortality causes civil conflict in the near term, and it is difficult to imagine why this relationship would exist. Out of 20 X_j variables examined for causal links to civil conflict, 12 appear to cause civil conflict and 8 do not. This highlights that most endogenous social science variables are causally connected.

Finally, there were one cases where the causal effect of economic activity on civil conflict is fully mediated by economic activity (exception 8). For instance, Natalini, Bravo, and Newman (2020) only posit economic mechanisms for the link between energy prices and civil conflict.

No cases were found where X_1 is the only relevant part of X_j (exception 3); or Y is part of X_j (exception 5).

This leaves 11 X_j variables which are likely exclusion-restriction violations for the effect

of economic activity on civil conflict. These include malaria (which prolongs civil wars according to Bagozzi (2016)), emigration (which provides an exit option for participants and victims of conflict according to Peters and Miller (2022)), and hunger (which drives civil conflict independently of economic effects according to Koren and Bagozzi (2017)).

These exclusion-restriction violations imply the economic activity $\rightarrow$ civil conflict IV model is not causally identified. However, the extent of bias in the estimate depends on the strength of the $W \rightarrow X_j$ and $X_j \rightarrow Y$ causal links.

4.4.1 Multiple pathways to the same dependent variable

While I do not apply the full exception-search methodology to the broad set of weather-IV estimates, the literature review uncovered some sets of studies implying multiple pathways between weather and the same dependent variable.

10 weather-IV studies have crime as a dependent variable. However, the X_j variables that crime is claimed to be causally influenced by include income (e.g. Mehlum, Miguel, and Torvik 2006), crop production (Papaioannou 2017), air quality (Bondy, Roth, and Sager 2020), church attendance (Moreno-Medina 2021), and immigration (Chalfin 2014), as well as directly through heat-induced aggression (Jacob, Lefgren, and Moretti 2007; Ranson 2014; Blakeslee and Fishman 2018).

Party vote share is the dependent variable in 17 studies, with X_j most commonly being turnout (Knack 1994; Kang 2019; Horiuchi and Kang 2018; Hansford and Gomez 2010; Gomez, Hansford, and Krause 2007; Artés 2014; Arnold and Freier 2016) (rain makes people less willing to go to the polls). However, other studies argue that election-day weather affects voters' mood (Duhaime and Moulton 2018; Bassi 2019) or risk tolerance (Bassi 2019), or that previous weather discouraged protest attendance (Wasow 2020; Madestam et al. 2013). Finally, 15 studies have conflict as a dependent variable, with income being the most common X_j variable (Miguel and Satyanath 2011; Miguel, Satyanath, and Sergenti 2004; Jensen and Gleditsch 2009; Hsiang, Meng, and Cane 2011; Hodler and Raschky 2014). However, other conflict studies use weather to instrument agricultural production (Caruso, Petrarca, and Ricciuti 2016), water scarcity (Landis et al. 2017), livestock prices (Maystadt and Ecker 2014), and immigration (Bhavnani and Lacina 2015).

These examples demonstrate that some weather-IV studies have directly contradictory identifying assumptions. But even without directly observing $X_j \rightarrow Y$, the existence of $W \rightarrow X_j$ changes the IV strategy from only requiring claims about the narrow domain of weather, to making causal claims about the complex social world.

4.5 Sensitivity analysis of weather IVs

The literature review contained 57 weather-IV estimates with reduced-form estimates or sufficient information to reverse-engineer the reduced-form. The literature also produced 120 first-stage estimates that I converted into $R^2_{X_j \sim W|K}$ values.

On average, I identified 35 potential exclusion-restriction violations per reduced-form equation (98 if dependent variables are included). However, on average, I only found a suitable $R^2_{X_j \sim W|K}$ estimate for four X_j variables for each reduced-form equation and in 14 cases I found none. Importantly, the broad analysis of weather IVs has not searched for exclusion-restriction exceptions, so some of these apparent violations will fall into one of those exceptions. When applying this method to a particular IV claim, it would be important to include this step.

This means the sensitivity analysis covers only a small fraction of the potential exclusion-restriction violations documented in the literature, which is an unknown fraction of the true number of potential exclusion-restriction violations.

Figure 4 shows each reduced-form estimate's sensitivity (y-axis) to the X_j variables with relevant $R^2_{X_j \sim W|K}$ estimates. The shading and number indicate the strength of the $R^2_{Y \sim X_j|W,K}$ relationship required to make the $X_1 \rightarrow Y$ IV estimate insignificant. Smaller values indicate

that a weak $X_j \rightarrow Y$ relationship could make a study result insignificant.

Figure 4: The minimum relationship between an exclusion-restriction violation variable, X_j , and dependent variable Y ($R^2_{Y \sim X_j|W,K}$) required to make the IV relationship between X_1 and Y ($\hat{\delta}$) insignificant. Strength of required relationship indicated using shading on log-10 scale. Dark green shading indicates X_j cannot make the relationship insignificant. Lowest $R^2_{Y \sim X_j|W,K}$ tested was 0.0001.14 reduced-form equations without relevant $R^2_{X_j \sim W|K}$ estimates omitted. Fit statistics are filtered using the broad criteria and fit statistic criteria.

Despite exclusion-restriction violations, some studies are likely robust to large relationships between X_j and Y . For instance, Collins and Margo (2007) estimate the effect of violent protests on property prices using a rainfall instrument. In total, eight variables with relevant first-stage estimates could affect this estimate including property crime, violent crime, mood, and traffic. But none of these could make the result insignificant even if they were perfectly correlated with property prices. While many additional potential exclusion-restriction violations do not have first-stage estimates, the result appears relatively robust to exclusion-restriction violations.

Other studies require only small $X_j \rightarrow Y$ relationships. Moreno-Medina (2021) examines the effect of church attendance on various types of crime by using the number of weeks where it rained between 9am and 1pm on Sunday in a year as an instrument for church attendance. There are five relevant potential exclusion-restriction violations with first-stage fit statistics available: emigration, erosion, income, crop production, and agricultural productivity. For the weakest result (alcohol arrests), any of these variables would only need to explain 0.07% of variance in alcohol arrests to make the result insignificant. None of the paper's findings would require one of the exclusion-restriction variables to explain more than 0.14% of variance in a type of crime. While these variables are major drivers of crime, it is plausible that they could explain tiny fractions of a percent of variation in crime. Even though the instrumented

variable in the paper is rain on Sundays, the tiny proportion of variance needed to make the results insignificant imply almost anything could overturn them.

A high proportion of studies have at least one potential exclusion-restriction variable that could easily make the result insignificant. Of the 43 reduced-form estimates with at least one exclusion-restriction estimate to test, 22 had at least one X_j variable that would need to explain less than 1% of variance in Y to make the result insignificant, and 19 have at least one X_j variable that would need to explain less than 0.1% of variance in Y to make the result insignificant. Only 8 were sufficiently robust that no relationship between X_j and Y could make the estimate insignificant.

Since most X_j variables were not tested due to data limitations, these results represent a lower bound of weather-IV estimate sensitivity.

Figure 5 shows the strength of relationships required to make the IV estimate of economic activity on civil conflict insignificant. In order to believe the results are acceptably biased (defined as the coefficient and standard error not changing enough to make the result insignificant or increasing in magnitude by an equivalent amount), we must assume that each pair of partial- R^2 values is below the curve in figure 5. If a reader finds this plausible for the 11 exclusion-restriction variables, then it is reasonable to believe the effect of economic

activity on civil conflict. If both $R^2_{X_j \sim W|K}$ and $R^2_{Y \sim X_j|W,K}$ were around 0.0045, the results would no longer be significant. A higher variance explained for one would reduce the size needed for the other.

I would personally be skeptical of basing an important empirical claim about the world on the assumption that none of the 11 exclusion-restriction variables lie above this curve. However, the important point is that readers can assess what they are required to believe to accept the result.¹²

As discussed in the earlier sensitivity analysis, transferring partial- R^2 values across contexts requires meeting several criteria. Of the 11 exclusion-restriction variables, only emigration has an $R^2_{X_j \sim W|K}$ value that meets these requirements: two relevant studies report a mean $R^2_{X_j \sim W|K}$ of 0.011 between rainfall and emigration (Corbi and Ferraz 2018; Badaoui, Strobl, and Walsh 2017). If this value applies to the economic activity $\rightarrow$ civil conflict estimate, emigration and conflict would only need an $R^2_{Y \sim X_j|W,K}$ of 0.001 to render the effect of economic activity on civil conflict insignificant. Even this figure should be treated carefully. While some studies link rainfall to emigration through mechanisms other than income, many studies argue income is a relevant pathway. Consequently, emigration may need to explain more variance to overturn the result.

¹²Since there are multiple exclusion-restriction violations that create unacceptable bias, I do not continue the exclusion-restriction variable search. However, if a researcher was willing to accept this level of bias, they would need to continue to enumerate X_j variables from the literature to ensure that they had not missed important exclusion-restriction variables.

No applicable $R^2_{X_j \sim W|K}$ values exist for rainfall’s effect on malaria. However, the literature provides three first-stage estimates based on other variance types: between-person (Chang et al. 2014), within-country (McCord, Conley, and Sachs 2017), and between-subnational (Cutler et al. 2010), ranging from 0.0084 to 0.031. Even the smallest of these implies an $R^2_{Y \sim X_j|W,K}$ of 0.0021 would render the IV estimate insignificant.

Explicit sensitivity conditions allow readers to see what substantive claims required for an IV result to hold. Here, the effect of economic activity on civil conflict is sensitive to small effects of variables that the literature demonstrates are exclusion-restriction violations. However, studies with stronger estimates or less problematic instruments may require weaker assumptions to accept the IV results. By explicating and quantifying the conditions for strict identification and sensitivity readers can better assess the plausibility of IV claims.

5 Conclusions

Cunningham (2018) argues that a good instrument should have a “certain ridiculousness”. Until the causal pathway is explained, the link between the instrument and outcome seems absurd. In a world where forest fires prevent Australians and Californians from leaving their homes for months, and 1-3 billion people are projected to be left outside of historically-habitable temperature ranges (Xu et al. 2020), the link between weather and the social

Figure 5: Combinations of $R^2_{Y \sim X_j | W, K}$ and $R^2_{X_j \sim W | K}$ that would make the effect of economic activity on conflict no longer significant. Pairs of values below the curve are insufficient to make the result insignificant. Pairs above the curve would make the result insignificant.

world is not absurd enough.

This paper shows that a widely used instrument is flawed because it systematically violates the exclusion-restriction assumption for most plausible applications. These findings suggest our standards for accepting instruments are overly lenient and atheoretical. The causal revolution in social science has revealed the wishful thinking underlying selection-on-observables. The same rigor must be applied to IV assumptions.

Nothing in this paper disproves particular empirical claims. Many weather-IV papers provide independent sources of evidence, and robustness checks (e.g. placebo tests) and some results will be true by chance. Nevertheless, my results suggest the underlying assumptions of weather-IVs are not strictly true, and many results are likely wrong.

Evidence for widespread exclusion-restriction violations adds to growing evidence that IV regression studies are often poorly conducted. Brodeur, Cook, and Heyes (2020) found IV studies showed substantial evidence of p-hacking. Similarly, Lee et al. (2021) find the standard first-stage F-test used in IV regression is underpowered, and that over half of IV papers in the American Economic Review were no longer significant after accounting for this. Lal et al. (2021) find that most top political science IV articles make statistical errors, including inappropriate standard error and F-statistic calculations.

It is tempting to interpret instruments as being “used up” by multiple uses. However, it is important to distinguish the fact of whether an exclusion-restriction violation exists from our knowledge of that fact (which new research can change). This may seem unfair to authors who used the best available information, but the goal of this method is to assess empirical claims not to cast judgment on researchers.

While a scholar cannot know whether a new instrument will turn out to have exclusion-restriction violations, there are some classes of instruments where W does not seem as likely to have multiple X_j pathways. Random assignment to a treatment with partial compliance is unlikely to suffer from exclusion-restriction violations (e.g. winning a charter school lottery as an instrument for attending charter school (Angrist et al. 2017)). Narrow policy changes also seem less susceptible. For instance, Porzio, Rossi, and Santangelo (2022) instrument a

cohort’s average years of education with the school-leaving age when they were young.

By contrast, other widely used instruments (e.g. population density, historical splits in countries, lead exposure, colonialism, distance from anything) likely suffer from the problems described in this paper. Indeed, many of these instruments have faced criticism for similar reasons (Morck and Yeung 2011; Gallen and Raymond 2019).

This paper offers a way forwards for IV inference through a method for systematically finding and assessing exclusion-restriction violations from existing literature. This process unpacks the exclusion restriction into a series of substantive (and potentially testable) claims about the world. While we cannot prove the exclusion restriction, we can use the literature to identify and assess variables that have been linked to our instrument. This paper also demonstrates how sensitivity analysis (Cinelli and Hazlett 2020a, 2020b) can be used to quantify the strength of an exclusion-restriction violation required to overturn a result. This approach allows researchers to acknowledge violations of their identifying assumptions without having to abandon analysis that is not perfectly identified.

Avoiding contradictions in the literature is important beyond weather IVs. Typical non-experimental social science models implicitly assume a sparse causal graph which is unrealistic given the volume of papers making causal claims.¹³ Unfortunately, this volume means

¹³Over 60,000 social science articles are published annually (see appendix C).

constructing a realistic causal graph is likely beyond the means of individual social scientists.

Infrastructure to systematically record, dispute, and qualify the literature's causal claims could allow scientists to appropriately specify models with non-experimental data.

Causal knowledge in social science has few easy shortcuts. Apparently simple solutions such as IVs still rely on strong substantive claims about the world. To build cumulative knowledge, we must engage directly with the messy causal web of the social world.

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Supplementary Information for Rain, Rain, Go Away: 195 Potential Exclusion-Restriction Violations for Studies Using Weather as an Instrumental Variable

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Appendix A: Evidence for assumptions in Income and Conflict Example

Table A1: Assumptions for the effect of economic activity (X_1) on civil conflict (Y) to be strictly causally identified related to potential exclusion restriction variables (X_j) discovered to be related to weather in relevant literature.

X_j	Exception	Assumption	Evidence
Female employment	1	W does not cause X_j	Chin (2012) and Thai and Myrskylä (2012) both focus on women harvesting rice which is less relevant to Africa.
Early life pollution	1	W does not cause X_j	Doesn't happen on correct time frame.
Individual Responsibility	1	W does not cause X_j	Davis (2016) uses n=89 country cross-section (weak evidence) and mechanism is a long-run values one rather than year to year variation (not relevant).
Human capital	1	W does not cause X_j	Lagerlöf and Basher (2006) simultaneously instrument population density, sex ratios, urbanization, and education using rainfall. 2007 published version omitted these claims.
Urbanization	1	W does not cause X_j	Lagerlöf and Basher (2006) simultaneously instrument population density, sex ratios, urbanization, and education using rainfall. 2007 published version omitted these claims.
Month of birth	1	W does not cause X_j	Less relevant in equatorial areas.

Agricultural productivity	2	X_j is part of X_1	Agricultural productivity is a core part of economic activity in this context.
Income	2	X_j is part of X_1	Income is an indicator of economic activity.
Agricultural production	2	X_j is part of X_1	Crop production is a core part of economic activity in this context.
Labor force	2	X_j is part of X_1	The labor force is a central part of economic activity.
Wealth	2	X_j is part of X_1	Wealth is closely tied to economic activity.
Crop prices	2	X_j is part of X_1	Crop prices are an indicator of economic activity.
Sectoral employment	2	X_j is part of X_1	Labor markets are a central part of economic activity.
Agricultural wages	2	X_j is part of X_1	Agricultural wages are a strong indicator of economic activity in this context.
Price	2	X_j is part of X_1	Prices are closely tied to economic activity.
Consumption	2	X_j is part of X_1	Consumption is a component of GDP.
Hydroelectric power	2	X_j is part of X_1	Hydroelectric power is a contributor to economic activity.
Unemployment	2	X_j is part of X_1	Labor markets are a central part of economic activity.
Energy demand	2	X_j is part of X_1	Energy demand could reasonably be defined as part of economic activity. Given its importance to the economy it seems like an important component and it does represent actual activity rather than just prices.
Rebel recruitment	4	X_j is part of Y	Rebel recruitment is a component of civil conflict.
Crime	4	X_j is part of Y	Collier (2000) argues that rebellions are an extension of organized crime.
Forest extraction	6	W only causes X_j via X_1	Völker & Waibel (2010) consider forest extraction to be a response to weather-induced income shocks.
Access to rented land	6	W only causes X_j via X_1	Tione & Holden (2020) imply income pathway only.
Expenditure inequality	6	W only causes X_j via X_1	Bayani-Arias & Palanca-Tan (2017) make a differential income effect argument.
Child Labor	6	W only causes X_j via X_1	Ajefu & Abiona (2019) only reference income mechanism.
Budget balance	6	W only causes X_j via X_1	Income effects are the primary mechanism proposed by Lis2010.

Firm cash holding	6	W only causes X_j via X_1	An economic activity effect of climate disasters does seem to be the primary mechanism, although there's a case for interpreting it as a capital/wealth shock rather than an income shock.
Inflation expectations	6	W only causes X_j via X_1	Inflation is driven by differences in production (which is part of economic activity).
Inequality	6	W only causes X_j via X_1	Inequality does seem to being generated by economic factors here although we could quibble about wealth/capital versus income.
Livestock prices	6	W only causes X_j via X_1	Original paper argues that the livestock prices are affected by the productivity of the cattle grazing process (just in the same way as crop failure would be included).
Farming practices	7	X_j does not cause Y	No literature claims or plausible pathways for $X_j \rightarrow Y$.
Child mortality	7	X_j does not cause Y	No literature claims or plausible pathways for $X_j \rightarrow Y$.
Crop diversity	7	X_j does not cause Y	No literature claims or plausible pathways for $X_j \rightarrow Y$.
Child health	7	X_j does not cause Y	No literature claims or plausible pathways for $X_j \rightarrow Y$.
Fertility	7	X_j does not cause Y	No literature claims or plausible pathways for $X_j \rightarrow Y$.
Health	7	X_j does not cause Y	No literature claims or plausible pathways for $X_j \rightarrow Y$.
Dust Exposure	7	X_j does not cause Y	No literature claims or plausible pathways for $X_j \rightarrow Y$.
Mortality	7	X_j does not cause Y	No literature claims or plausible pathways for $X_j \rightarrow Y$.
Energy prices	8	X_j only causes Y via X_1	Energy prices affect civil conflict primarily because of the economic hardship it creates. A wrinkle is that the conflict happens because of the attribution to energy prices specifically rather than just by manipulating economic activity.

Appendix B: Literature review table

Table B1: Relationships identified in the literature. IV studies have an X and Y variable listed, while studies looking at the relationship between weather and another variable have weather listed as the X variable.

Source of IV estimate/observed			
correlation	X	Y	Context
Zimmermann (2020)	Rainfall	Human capital	India
Zheng et al. (2019)	Pollution	Mood	China
X. Zhang, Lu, and Xue (2022)	Carbon trading	Energy efficiency	China
T. Zhang (2016)	Rainfall	Protest	DC and NY
T. Zhang (2016)	Rainfall	Violent protest	DC and NY
T. Zhang (2016)	Temperature	Protest	DC and NY
T. Zhang (2016)	Temperature	Violent protest	DC and NY

Source of IV estimate/observed			
correlation	X	Y	Context
Zaveri, Russ, and Damania (2020)	Agricultural productivity	Crop area	worldwide
Yang and Choi (2007)	Income	Remittances	Philippines
Yang and Choi (2007)	Income	Immigration	Philippines
Yang and Choi (2007)	Income	Consumption	Philippines
Xinye and Wei (2019)	Pollution	Health	China
Xinye and Wei (2019)	Pollution	Mood	China
Xia et al. (2013)	Rainfall	Passenger train performance	Netherlands
Xi et al. (2022)	Temperature	Cinema attendance	49 Chinese cities

Source of IV estimate/observed			
correlation	X	Y	Context
Xi et al. (2022)	Rainfall	Cinema attendance	49 Chinese cities
Wolpin (1982)	Income	Consumption	India
Wiwanitkit (2006)	Rainfall	Dengue infection	Thailand
Wasow (2020)	Violent protest	Party vote share	United States
Wang et al. (2020)	Haze	Tourist destination preferences	Beijing
Waldman, Nicholson, and Adilov (2006)	TV watching	Autism	California, Oregon, Washington

Source of IV estimate/observed			
correlation	X	Y	Context
Völker and Waibel (2010)	Rainfall	Forest extraction	Vietnam
Vo (2020)	Temperature	Consumption	Australia
Viswanathan and Kumar (2015)	Agricultural production	Emigration	India
Viswanathan and Kumar (2015)	Agricultural production	Immigration	India
Ventura-Cots et al. (2019)	Alcohol consumption	Liver cirrhosis	worldwide
Veljanoska (2018)	Rainfall	Agricultural production	Uganda
Vahedi (2015)	Pollution	Human capital	United States
Trinh, Feeny, and Posso (2021)	Rainfall	Mental health	Vietnam

Source of IV estimate/observed			
correlation	X	Y	Context
Trinh, Feeny, and Posso (2021)	Rainfall	Child health	Vietnam
Tiwari, Jacoby, and Skoufias (2017)	Income	Hunger	Nepal
Tione and Holden (2020)	Rainfall	Access to rented land	Malawi
Theisen (2012)	Rainfall	Conflict	Kenya
Thai and Myrskylä (2012)	Female employment	Breastfeeding	Vietnam
Tevie, Bohara, and Valdez (2014)	Foreclosures	West Nile Virus	California and Colorado
Tevie, Bohara, and Valdez (2014)	Income	West Nile Virus	California and Colorado

Source of IV estimate/observed			
correlation	X	Y	Context
Tamada (2009)	Party vote share	Government spending	Japan
Tack and Holt (2016)	Temperature	Spatial correlation of crop yields	Iowa and Illinois
Tack and Holt (2016)	Rainfall	Spatial correlation of crop yields	Iowa and Illinois
Swamy and Fikkert (2002)	Labor force	Income	worldwide
Swamy and Fikkert (2002)	Wealth	Income	worldwide
Strobl and Valfort (2015)	Immigration	Unemployment	Uganda

Source of IV estimate/observed			
correlation	X	Y	Context
Stokes (2016)	Wind turbine placement	Incumbent voting	Ontario
Spencer and Strobl (2019)	Weather disaster	Crime	Jamaica
Skoufias and Vinha (2012)	Rainfall	Child health	Mexico
Skoufias and Vinha (2012)	Temperature	Child health	Mexico
Siyi, Ruoyu, and Daoguang (2017)	Weather disaster	Tax avoidance	China
Shifa (2015)	Income	Manufacturing growth	worldwide
Shen, Cai, and Li (2020)	Sunlight	COVID19	worldwide
Shen, Cai, and Li (2020)	Temperature	COVID19	worldwide
Shen, Cai, and Li (2020)	Humidity	COVID19	worldwide

Source of IV estimate/observed			
correlation	X	Y	Context
Seo (2019)	Weather disaster	Agricultural production	Thailand
T. Schultz (2011)	Food prices	Fertility	England
T. Schultz (2011)	Food prices	Marriage	England
Schachner (2014)	Agricultural production	Human capital	Mongolia
Sayers et al. (2009)	Clouds	VitaminD	United Kingdom
Sayers et al. (2009)	Sunlight	VitaminD	United Kingdom
Sarsons (2015)	Rainfall	Conflict	India
Santeramo and Searle (2019)	Crop prices	Quantity	worldwide

Source of IV estimate/observed			
correlation	X	Y	Context
Saldaña-Zorrilla and Sandberg (2009)	Weather disaster	Emigration	Mexico
Sager (2019)	Pollution	Road accidents	United Kingdom
Rudolph (2020)	Turnout	Referendum voting	United Kingdom
M. R. Rosenzweig and Binswanger (1993)	Rainfall	Income	India
M. Rosenzweig and Wolpin (1993)	Rainfall	Livestock prices	India
Mark Rosenzweig and Stark (1989)	Income	Immigration	India

Source of IV estimate/observed			
correlation	X	Y	Context
Mark Rosenzweig and Stark (1989)	Income	Employing servants	India
Mark Rosenzweig and Stark (1989)	Income	Distance travelled for marriage	India
Mark Rosenzweig and Stark (1989)	Income	Property values	India
Roenneberg and Aschoff (1990)	Temperature	Month of birth	worldwide
Ritter and Conrad (2016)	Protest	Repression	United States
Ritter and Conrad (2016)	Protest	Repression	Africa

Source of IV estimate/observed			
correlation	X	Y	Context
Reuveny and Moore (2009)	Weather disaster	Emigration	developed countries
Reichhoff (2017)	Temperature	Crime	California
Reichhoff (2017)	Rainfall	Crime	California
Rappaport (2007)	Humidity	Immigration	United States
Rappaport (2007)	Temperature	Immigration	United States
Rappaport (2007)	Rainfall	Immigration	United States
Ranson (2014)	Temperature	Crime	United States

Source of IV estimate/observed			
correlation	X	Y	Context
Ranson (2014)	Rainfall	Crime	United States
Rana (2013)	Sectoral employment	Terrorism	Pakistan
Qiu, Chen, and Shi (2020)	COVID19	New COVID19 infections	China
Pugatch and Yang (2011)	Emigration	Wages	Mexico/US
Pitt and Sigle (1997)	Rainfall	Child mortality	Senegal
Pitt and Sigle (1997)	Rainfall	Fertility	Senegal
Pipitpukdee, Attavanich, and Bejranonda (2020)	Temperature	Agricultural production	Thailand

Source of IV estimate/observed			
correlation	X	Y	Context
Pipitpukdee, Attavanich, and Bejranonda (2020)	Rainfall	Agricultural production	Thailand
Pinckney (2019)	Protest	Party vote share	United States
Pinckney (2019)	Protest	Legislator behavior	United States
Pinckney (2019)	Protest	Protest	United States
Persson, Sundell, and Öhrvall (2014)	Rainfall	Turnout	Sweden
Pereira and Menezes (2020)	Income	Crime	Brazil
Peet (2020)	Early life pollution	Human capital	Philippines

Source of IV estimate/observed			
correlation	X	Y	Context
Peet (2020)	Early life pollution	Income	Philippines
Peet (2020)	Early life pollution	Health	Philippines
Paxson (1992)	Income	Savings	Thailand
Paul (2005)	Weather disaster	Emigration	Bangladesh
Parham and Michael (2010)	Rainfall	Malaria	Tanzania
Parham and Michael (2010)	Temperature	Malaria	Tanzania
Papaioannou (2017)	Agricultural production	Property	British
		crime	colonies
Papaioannou (2017)	Agricultural production	Theft	British
			colonies
Papaioannou (2017)	Agricultural production	Cattle	British
		raiding	colonies

Source of IV estimate/observed			
correlation	X	Y	Context
Papaioannou (2017)	Agricultural production	NA	British colonies
Papaioannou (2017)	Agricultural production	Violent crime	British colonies
Pajaron and Vasquez (2020)	Income	Immigration	Philippines
Pajaron (2017)	Income	Consumption	Philippines
Pajaron (2017)	Income	Debt	Philippines
Pajaron (2017)	Income	Remittances	Philippines
Pajaron (2017)	Income	Net assets	Philippines
Pajaron (2017)	Income	Domestic money transfers	Philippines

Source of IV estimate/observed			
correlation	X	Y	Context
Oster (2004)	Income	Witch trials	Renaissance Europe
Nübler et al. (2020)	Rainfall	Human capital	Kenya
Nillesen and Verwimp (2011)	Rainfall	Rebel recruitment	Burundi
Nawrotzki, Riosmena, and Hunter (2013)	Rainfall	Immigration	Mexico
Naudé (2010)	Weather disaster	Net migration	45 Sub-Saharan African Countries

Source of IV estimate/observed			
correlation	X	Y	Context
Nadolnyak and Hartarska (2012)	Rainfall	Crop	United
		disaster	States
		payments	
Nadolnyak and Hartarska (2012)	Temperature	Crop	United
		disaster	States
		payments	
Munshi (2003)	Migrant social capital	Migrant	Mexico/US
		employment	
Mulder and Scholtens (2013)	Energy production	Energy	Netherlands
		prices	and
			Germany
V. Mueller, Gray, and Kosec	Rainfall	Emigration	Pakistan
(2014)			

Source of IV estimate/observed			
correlation	X	Y	Context
V. Mueller, Gray, and Kosec (2014)	Temperature	Emigration	Pakistan
Valerie Mueller and Quisumbing (2011)	Weather disaster	Wages	Bangladesh
Valerie Mueller and Osgood (2009)	Rainfall	Wages	Brazil
Muehlenbachs and Cohen (2014)	Oil platform inspectors	Oil platform fines	Gulf of Mexico
Moretti and Neidell (2011)	Pollution	Health	Los Angeles
Moretti (1998)	Rainfall	Retirement community locations	United States

Source of IV estimate/observed			
correlation	X	Y	Context
Moretti (1998)	Temperature	Retirement	United
		community	States
		locations	
Moreno-Medina (2021)	Church attendance	Drug arrests	United
			States
Moreno-Medina (2021)	Church attendance	Alcohol	United
		arrests	States
Moreno-Medina (2021)	Church attendance	White collar	United
		arrests	States
Moreno-Medina (2021)	Church attendance	Violent	United
		crime	States
Moreno-Medina (2021)	Church attendance	Property	United
		crime	States

Source of IV estimate/observed			
correlation	X	Y	Context
Miguel and Satyanath (2011)	Income	Conflict	worldwide
Miguel, Satyanath, and Sergenti (2004)	Income	Conflict	Africa
Meier, Schmid, and Stutzer (2019)	Mood	Referendum voting	Switzerland
Mehlum, Miguel, and Torvik (2006)	Income	Violent crime	Germany
Mehlum, Miguel, and Torvik (2006)	Income	Property crime	Germany
Maystadt and Ecker (2014)	Livestock prices	Conflict	Somalia
Maunder (1973)	Temperature	Sales	United States

Source of IV estimate/observed			
correlation	X	Y	Context
Maunder (1973)	Rainfall	Sales	United States
Martin et al. (2021)	Farming practices	Carbon emissions	emerging markets
Martin et al. (2021)	Farming practices	Pollution	emerging markets
Marchiori, Maystadt, and Schumacher (2017)	Rainfall	Urbanization	Africa
Marchiori, Maystadt, and Schumacher (2017)	Rainfall	Income	Africa
Marchiori, Maystadt, and Schumacher (2017)	Temperature	Urbanization	Africa

Source of IV estimate/observed			
correlation	X	Y	Context
Marchiori, Maystadt, and Schumacher (2017)	Temperature	Income	Africa
Marchiori, Maystadt, and Schumacher (2012)	Rainfall	Immigration	Africa
Marchiori, Maystadt, and Schumacher (2012)	Temperature	Immigration	Africa
Magnusson (2000)	Sunlight	Mood	worldwide
Madestam et al. (2013)	Protest	Legislator	United
		behavior	States
Madestam et al. (2013)	Protest	Party vote	United
		share	States
Maccini and Yang (2009)	Rainfall	Health	Indonesia

Source of IV estimate/observed			
correlation	X	Y	Context
Maccini and Yang (2009)	Rainfall	Human capital	Indonesia
Maccini and Yang (2009)	Rainfall	Wealth	Indonesia
Luechinger (2014)	Pollution	Child mortality	Germany
Lo Prete and Revelli (2020)	Turnout	Life quality	Italy
Lo Prete and Revelli (2020)	Turnout	Speed of revenue collection	Italy
Lo Prete and Revelli (2020)	Turnout	Environmental quality	Italy

Source of IV estimate/observed			
correlation	X	Y	Context
Lo Prete and Revelli (2020)	Turnout	Speed of public good provision	Italy
Lo Prete and Revelli (2020)	Turnout	Mayoral quality	Italy
Lo Prete and Revelli (2020)	Turnout	Number of mayoral candidates	Italy
Lo Prete and Revelli (2020)	Turnout	Waste recycling	Italy
López-córdova (2006)	Remittances	Human capital	Mexico

Source of IV estimate/observed			
correlation	X	Y	Context
López-córdova (2006)	Remittances	Child mortality	Mexico
López-córdova (2006)	Remittances	Marginalization	Mexico
López-córdova (2006)	Remittances	Poverty	Mexico
Liu, Thomadsen, and Yao (2020)	Social distancing	COVID19	United States
Lis and Nickel (2010)	Weather disaster	Budget balance	worldwide
Lind (2019)	Party vote share	Government spending	Norway
Li, Johnson, and Zaval (2011)	Perceived Temperature variation	Global warming beliefs	US and Australia

Source of IV estimate/observed			
correlation	X	Y	Context
Lewin, Fisher, and Weber (2012)	Rainfall	Agricultural production	Malawi
Lewin, Fisher, and Weber (2012)	Rainfall	Emigration	Malawi
Levin et al. (2020)	Rainfall	Lead exposure	various
Levin et al. (2020)	Humidity	Lead exposure	various
Levin et al. (2020)	Temperature	Lead exposure	various
Levin et al. (2020)	Sunlight	Lead exposure	various
Leimdörfer and Hauge (2020)	Child mortality	Fertility	Niger

Source of IV estimate/observed			
correlation	X	Y	Context
W.-S. Lee and Li (2020)	Economic conditions in childhood	Health	China
C. Lee and Chiu (2011)	Energy prices	Consumption	OECD countries
Ledlie et al. (2018)	Rainfall	Child health	Ethiopia
Larreboure and Gonz (2021)	Protest	Female candidate votes	United States
Larreboure and Gonz (2021)	Protest	Minority candidate votes	United States
Landis et al. (2017)	Rainfall	Conflict	Niger River Basin

Source of IV estimate/observed			
correlation	X	Y	Context
Laidley and Conley (2018)	Exercise	Human capital	United States
Lahiri (2018)	Unemployment	Racial earnings disparities	United States
Lagerlöf and Basher (2006)	Urbanization	Income	North America
Lagerlöf and Basher (2006)	Sex ratio	Income	North America
Lagerlöf and Basher (2006)	Human capital	Income	North America
Kumar and Viswanathan (2012)	Agricultural production	Emigration	India
Kubik and May (2018)	Food prices	Hunger	South Africa

Source of IV estimate/observed			
correlation	X	Y	Context
Kovács (2017)	Clouds	Patents	United States
Kovács (2017)	Temperature	Patents	United States
Koks et al. (2019)	Rainfall	Transport infrastructure	worldwide
Kochar (1999)	Income	Consumption	India
Knack (1994)	Turnout	Party vote share	United States
Kleemans and Magruder (2018)	Emigration	Unemployment	Indonesia
Kleemans and Magruder (2018)	Emigration	Wages	Indonesia
Y. Kim, Sesmero, and Waldorf (2018)	Rainfall	Immigration	India

Source of IV estimate/observed			
correlation	X	Y	Context
N. Kim (2016)	Income	Coup	worldwide
Khanthavit (2019c)	Mood	Stock returns	Thailand
Khanthavit (2019a)	Air pressure	Government bond returns	Thailand
Khanthavit (2019a)	Clouds	Government bond returns	Thailand
Khanthavit (2019a)	Rainfall	Government bond returns	Thailand
Khanthavit (2019a)	Humidity	Government bond returns	Thailand
Khanthavit (2019a)	Haze	Government bond returns	Thailand

Source of IV estimate/observed			
correlation	X	Y	Context
Khanthavit (2019a)	Temperature	Government bond returns	Thailand
Khanthavit (2019b)	Mood	Stock returns	Thailand
Khanthavit (2017a)	Air pressure	Stock returns	Bangkok, Thailand
Khanthavit (2017a)	Rainfall	Stock returns	Bangkok, Thailand
Khanthavit (2017b)	Mood	Stock returns	Thailand
Keele and Morgan (2016)	Turnout	Party vote share	United States

Source of IV estimate/observed			
correlation	X	Y	Context
Kazianga and Udry (2006)	Income	Consumption	Burkina Faso
Katz et al. (2020)	Skin Tone	Unemployment	United States
Kapoor et al. (2020)	Social distancing	COVID19	United States
W. Kang (2019)	Turnout	Party vote share	South Korea
H. Kang, Suh, and Yu (2019)	Pollution	Sales	South Korea
P. Jensen and Gleditsch (2009)	Income	Conflict	african countries
R. Jensen (2000)	Income	Human capital	Cote D'Ivoire

Source of IV estimate/observed			
correlation	X	Y	Context
R. Jensen (2000)	Income	Hunger	Cote D'Ivoire
Jayachandran (2006)	Agricultural production	Agricultural wages	India
Jacoby and Skoufias (1997)	Income	Human capital	India
Jacobsen and Marquering (2008)	Mood	Stock returns	worldwide
Jacob, Lefgren, and Moretti (2007)	Traffic	Future traffic	United States
Jacob, Lefgren, and Moretti (2007)	Property crime	Future property crime	United States

Source of IV estimate/observed			
correlation	X	Y	Context
Jacob, Lefgren, and Moretti (2007)	Violent crime	Future violent crime	United States
Ito and Reguant (2016)	Energy production	Energy prices	Spain/Portugal
Huet-Vaughn (2013)	Violent protest	Policy concessions	France
H. Huang, Kerstein, and Wang (2018)	Weather disaster	Firm cash holding	worldwide
F. Huang et al. (2011)	Rainfall	Malaria	Tibet
Hu and Lee (2020)	Consumer sentiment	Property values	Sydney
Hsiang, Burke, and Miguel (2013)	Temperature	Conflict	worldwide

Source of IV estimate/observed			
correlation	X	Y	Context
Hsiang, Burke, and Miguel (2013)	Rainfall	Conflict	worldwide
Hsiang, Meng, and Cane (2011)	Temperature	Conflict	worldwide
Horrocks and Menclova (2011)	Temperature	Crime	New Zealand
Horrocks and Menclova (2011)	Rainfall	Crime	New Zealand
Hornbeck et al. (2012)	Erosion	Property values	United States
Horiuchi and Kang (2018)	Turnout	Party vote share	United States
Horiuchi and Kang (2015)	Rainfall	Party vote share	United States
Hoogeveen, Van Der Klaauw, and Van Lomwel (2011)	Wealth	Marriage	Zimbabwe

Source of IV estimate/observed			
correlation	X	Y	Context
Hodler and Raschky (2014)	Income	Conflict	Africa
Herrnstadt and Muehlegger (2014)	Issue salience	Legislator behavior	United States
Henry, Spencer, and Strobl (2020)	Weather disaster	Consumption	Jamaica
Hendricks, Janzen, and Smith (2015)	Agricultural production	Crop prices	worldwide
S. Henderson and Ryabova (2020)	Sustainability investments	Income	California
J. Henderson and Brooks (2016)	Party vote share	Representative voting behavior	United States

Source of IV estimate/observed			
correlation	X	Y	Context
Heinen, Khadan, and Strobl (2019)	Rainfall;Wind speed	Price	15 Caribbean Islands
Healy and Malhotra (2010)	Weather disaster	Incumbent voting	United States
Hansford and Gomez (2010)	Turnout	Incumbent voting	non- Southern US
Hansford and Gomez (2010)	Turnout	Party vote share	non- Southern US
Hanandita and Tampubolon (2014)	Income	Mental health	Indonesia
Hales et al. (2000)	Temperature	Mortality	Christchurch, New Zealand

Source of IV estimate/observed			
correlation	X	Y	Context
Hales et al. (2000)	Pollution	Mortality	Christchurch, New Zealand
Guven and Hoxha (2015)	Mood	Unemployment	Netherlands
Guven and Hoxha (2015)	Mood	Risk tolerance	Netherlands
Guven and Hoxha (2015)	Mood	Inflation expectations	Netherlands
Guven and Hoxha (2015)	Mood	Decision making speed	Netherlands

Source of IV estimate/observed			
correlation	X	Y	Context
Guven and Hoxha (2015)	Mood	Subjective perceptions of life expectancy	Netherlands
Guven and Hoxha (2015)	Mood	Holding investments	Germany
Guven and Hoxha (2015)	Mood	Savings	Germany
Guven and Hoxha (2015)	Mood	Insurance	Germany
Guven and Hoxha (2015)	Mood	Operating asset ownership	Germany

Source of IV estimate/observed			
correlation	X	Y	Context
Gurgand (2003)	Rainfall	Farmers	Taiwan
		returns to	
		education	
Gu et al. (2020)	Pollution	Mental	China
		health	
Grosso and Kraehnert (2017)	Agricultural production	Human	Mongolia
		capital	
Graddy and Kennedy (2010)	Food prices	Quantity	Fulton Fish
			Market (New
			York)
Graddy (2006)	Food prices	Quantity	Fulton Fish
			Market (New
			York)

Source of IV estimate/observed			
correlation	X	Y	Context
Gong and Rogers (2014)	Turnout	Support for	United
		school bonds	States
Gomez, Hansford, and Krause	Turnout	Party vote	United
(2007)		share	States
Goetzke and Rave (2011)	Cycling	Cycling	Germany
Giulietti, Wahba, and Zenou	Migrant social capital	Migration	China
(2018)			
Gillett et al. (2004)	Temperature	Forest fires	Canada
Gajate-Garrido (2013)	Health access	Child health	Philippines
Fujiwara, Meng, and Vogl (2016)	Turnout	Future	United
		turnout	States
Frijters, Lalji, and Pakrashi	Temperature	Health	United
(2020)			States

Source of IV estimate/observed			
correlation	X	Y	Context
Frijters, Lalji, and Pakrashi (2020)	Temperature	Mood	United States
Frijters, Lalji, and Pakrashi (2020)	Rainfall	Health	United States
Frijters, Lalji, and Pakrashi (2020)	Rainfall	Mood	United States
Fraga and Hersh (2011)	Rainfall	Turnout	United States
Fontenla, Goodwin, and Gonzalez (2019)	Pollution	Property values	Mexico City
Fontenla, Goodwin, and Gonzalez (2019)	Pollution	Wages	Mexico City

Source of IV estimate/observed			
correlation	X	Y	Context
Flyr et al. (2019)	Temperature	Water	Fort Collins
		consumption	municipal
			utility
Fisher-Vanden, Mansur, and	Energy consumption	Production	China
Wang (2015)			
Fisher-Vanden, Mansur, and	Energy consumption	Factor	China
Wang (2015)		substitution	
Fichera and Savage (2015)	Income	Vaccination	Tanzania
Fichera and Savage (2015)	Income	NA	Tanzania
Fichera and Savage (2015)	Income	BMI	Tanzania
Fichera and Savage (2015)	Income	Health	Tanzania
Feng, Oppenheimer, and	Agricultural production	Immigration	US Corn
Schlenker (2012)			Belt

Source of IV estimate/observed			
correlation	X	Y	Context
Feng, Krueger, and Oppenheimer (2010)	Agricultural production	Immigration	Mexico
Farah and Torell (2018)	Snow	Water prices	United States
Farah and Torell (2018)	Snow	willingness to pay for water hardness reduction	United States
Faradiba (2021)	Rainfall	Malaria	Indonesia
Fan and Wang (2020)	Pollution	Mortality	United States

Source of IV estimate/observed			
correlation	X	Y	Context
Fan and Wang (2020)	Wind direction	Pollution	United States
Di Falco and Doku (2019)	Income	Mood	Nile Basin Region of Ethiopia
Di Falco et al. (2014)	Insurance	Income	Italy
Di Falco et al. (2014)	Crop diversity	Income	Italy
Elum, Nhamo, and Antwi (2018)	Insurance	Income	South Africa
Elsner and Wozny (2019)	Radiation exposure	Human capital	Germany
Elliott et al. (2019)	Weather disaster	Manufacturing revenue	China
Elliott, Strobl, and Sun (2015)	Weather disaster	Income	China

Source of IV estimate/observed			
correlation	X	Y	Context
Dustmann, Fasani, and Speciale (2017)	Migration legal status	Consumption	Italy
Duhaime and Moulton (2018)	Mood	Party vote share	United States
Douglas, Lena, and Mårten (2009)	Radiation exposure	Human capital	Sweden
Di Falco et al. (2019)	Income	Discount rates	Ethiopia
Di Falco and Chavas (2008)	Rainfall	Agricultural production	Italy
Di Falco and Chavas (2008)	Crop diversity	Agricultural production	Italy

Source of IV estimate/observed			
correlation	X	Y	Context
Deschênes and Greenstone (2012)	Temperature	Agricultural production	United States
Dercon (2004)	Rainfall	Consumption	Ethiopia
Del Valle et al. (2018)	Weather disaster	Income	Guandong, China
Dell, Jones, and Olken (2009)	Temperature	Income	worldwide
Davis (2016)	Individual responsibility	Income	worldwide
Davies (2010)	Rainfall	Consumption	Malawi
Dacuycuy (2016)	Income	Consumption	Philippines
X. Cui (2020)	Temperature	Crop aban- donment	United States
C. Cui et al. (2019)	Pollution	Emigration	China

Source of IV estimate/observed			
correlation	X	Y	Context
Coviello et al. (2014)	Mood	Friends	United
		mood	States
Courtemanche, Pinkston, and Stewart (2020)	Exercise	BMI	United
			States
Courtemanche, Pinkston, and Stewart (2020)	Cycling	BMI	United
			States
Corbi and Ferraz (2018)	Emigration	Unemployment	Brazil
Cooperman (2017)	Rainfall	Turnout	United
			States
Cools, Flatø, and Kotsadam (2020)	Rainfall	Domestic	Africa
		abuse	
Cook and Garrett (2013)	Wind speed	Pirate	Somalia
		attacks	

Source of IV estimate/observed			
correlation	X	Y	Context
Considine (2000)	Temperature	Carbon	United
		emissions	States
Considine (2000)	Temperature	Consumption	United
			States
Collins and Margo (2007)	Violent protest	Property	US cities
		values	
Cohen (2011)	Clouds	Presidential	United
		approval	States
Chin (2012)	Female employment	Domestic	India
		abuse	
Chia et al. (2016)	Violent crime	Inequality	United
			States

Source of IV estimate/observed			
correlation	X	Y	Context
Chia et al. (2016)	Property crime	Inequality	United States
Chhaochharia et al. (2019)	Perceived economic outlook	Capital expenditure	United States
Chhaochharia et al. (2019)	Perceived economic outlook	Labor markets	United States
Chen and Mahmassani (2015)	Rainfall	Travel time	San Francisco
Chen and Mahmassani (2015)	Rainfall	Mood	San Francisco
Chavas et al. (2019)	Rainfall	Agricultural production	Italy

Source of IV estimate/observed			
correlation	X	Y	Context
Chavas et al. (2019)	Temperature	Agricultural production	Italy
Chavas et al. (2019)	Weather disaster	Disaster payments	Taiwan
Chalfin (2014)	Emigration	Crime	Mexico/US
Cashin, Mohaddes, and Raissi (2017)	Air pressure	Energy prices	21 Countries
Cashin, Mohaddes, and Raissi (2017)	Air pressure	Income	21 Countries
Cashin, Mohaddes, and Raissi (2017)	Air pressure	Inflation expectations	21 Countries
Cashin, Mohaddes, and Raissi (2017)	Air pressure	Price	21 Countries

Source of IV estimate/observed			
correlation	X	Y	Context
Caruso, Petrarca, and Ricciuti (2016)	Agricultural production	Conflict	Indonesia
Cachon, Gallino, and Olivares (2019)	Inventory	Sales	United States
Burgess et al. (2014)	Temperature	Mortality	India
Burgess and Donaldson (2010)	Rainfall	Hunger	India
Q. Bui et al. (2020)	Weather disaster	Land fragmentation	Vietnam
A. Bui et al. (2014)	Weather disaster	Income	Vietnam
A. Bui et al. (2014)	Weather disaster	Consumption	Vietnam
Bruederle, Peters, and Roberts (2017)	Temperature	Crime	South Africa
Bruckner and Ciccone (2011)	Income	Democracy	Africa

Source of IV estimate/observed			
correlation	X	Y	Context
Branco and Feres (2020)	Rainfall	Unemployment	Brazil
Branco and Feres (2020)	Rainfall	Sectoral employment	Brazil
Boustan, Fishback, and Kantor (2010)	Net migration	Income	United States
Boustan, Fishback, and Kantor (2010)	Net migration	Wages	United States
Boustan, Fishback, and Kantor (2010)	Net migration	Unemployment	United States
Bondy, Roth, and Sager (2020)	Pollution	Crime	London
Blumberg (2015)	Rainfall	Female employment	South East Asia and Africa

Source of IV estimate/observed			
correlation	X	Y	Context
Blanc and Strobl (2016)	Weather disaster	Agricultural production	Philippines
Blanc (2012)	Temperature	Agricultural production	37 sub saharan african countries
Blanc (2012)	Rainfall	Agricultural production	37 sub saharan african countries
Blakeslee and Fishman (2018)	Rainfall	Crime	India
Blakeslee and Fishman (2018)	Temperature	Crime	India
Bhavnani and Lacina (2015)	Immigration	Conflict	India

Source of IV estimate/observed			
correlation	X	Y	Context
Bertelli (2015)	Child mortality	Fertility	Nigeria
Berry and Schlenker (2011)	Crop prices	Crop area	worldwide
Berry and Schlenker (2011)	Crop prices	Crop area	United States
Berry and Schlenker (2011)	Crop prices	Agricultural production	United States
Bensassi, Mohan, and Strobl (2017)	Weather disaster	Crop prices	Britain
Ben Lakhdar and Dubois (2006)	Rainfall;Sunlight;Temperature	Turnout	France
Beltrán, Maddison, and Elliott (2019)	Weather disaster	Property values	England
Beltrán, Maddison, and Elliott (2018)	Weather disaster	Property values	various

Source of IV estimate/observed			
correlation	X	Y	Context
Bellet, De Neve, and Ward (2019)	Mood	Sales	United Kingdom
Beine and Parsons (2015)	Rainfall;Temperature	Immigration	worldwide
Beaudin and Huang (2014)	Snow	Closure of ski areas	New England
Baylis et al. (2018)	Humidity	Mood	worldwide
Baylis et al. (2018)	Clouds	Mood	worldwide
Baylis et al. (2018)	Rainfall	Mood	worldwide
Baylis et al. (2018)	Temperature	Mood	worldwide
Bayani-Arias and Palanca-Tan (2017)	Rainfall	Expenditure inequality	Philippines
Bayani-Arias and Palanca-Tan (2017)	Weather disaster	Inequality	Philippines

Source of IV estimate/observed			
correlation	X	Y	Context
Bauer et al. (2012)	Sunlight	Mood	24 sites in 13 middle and high income countries
Batkeyev and Deremer (2022)	Pollution	Crime	Kazakhstan
Bassi, Colacito, and Fulghieri (2013)	Clouds	Risk tolerance	United States
Bassi (2019)	Mood	Party vote share	United States
Barrios, Bertinelli, and Strobl (2010)	Rainfall	Income	Developing countries
Barnhart (1925)	Rainfall	Party vote share	United States

Source of IV estimate/observed			
correlation	X	Y	Context
Bai and Kung (2014)	Hunger	Farming practices	China
Bae, Lim, and Hong (2020)	Pollution	Mortality	Seoul
Badaoui, Strobl, and Walsh (2017)	Emigration	Wages	Thailand
Badaoui, Strobl, and Walsh (2017)	Immigration	Wages	Thailand
Atalla, Bigerna, and Bollino (2018)	Temperature	Energy demand	worldwide
Asfaw, Pallante, and Palma (2018)	Crop diversity	Inequality	Niger
Asfaw, Pallante, and Palma (2018)	Crop diversity	Hunger	Niger

Source of IV estimate/observed			
correlation	X	Y	Context
Asfaw, Pallante, and Palma (2018)	Crop diversity	Income	Niger
Artés (2014)	Turnout	Party vote share	Spain
Arnold and Freier (2016)	Turnout	Party vote share	Germany
Arezki and Brückner (2012)	Income	Remittances	41 Sub-saharan African countries
Aral and Nicolaides (2017)	Exercise	Friends exercise	worldwide

Source of IV estimate/observed			
correlation	X	Y	Context
Apergis, Artikis, and Mamatzakis (2012)	Rainfall;Temperature;Snow;Clouds	Bank loan efficiency	United States
Angrist, Graddy, and Imbens (2000)	Food prices	Quantity	Fulton Fish Market (New York)
Allcott, Collard-Wexler, and O'Connell (2016)	Rainfall	Hydroelectric power	India
Allcott, Collard-Wexler, and O'Connell (2016)	Hydroelectric power	Production	India
Akobeng (2017)	Agricultural wages	Consumption	Ghana
Aklilu (2007)	Income	Savings	Peru
Ajefu and Abiona (2019)	Rainfall	Unemployment	India
Ajefu and Abiona (2019)	Rainfall	Child labor	India

Source of IV estimate/observed			
correlation	X	Y	Context
Ahmed et al. (2011)	Rainfall	Agricultural production	Tanzania
Aguiar-Moya, Prozzi, and de Fortier Smit (2011)	Rainfall	Pavement roughness	United States
Adhvaryu et al. (2019)	Dust Exposure	Health	West Africa
Adhvaryu et al. (2015)	Temperature	Mood	19 African countries
Achen and Bartels (2016)	Rainfall	Incumbent voting	United States
Acharya, Blackwell, and Sen (2016)	Slavery	Racism	United States
Acharya, Blackwell, and Sen (2016)	Slavery	Racial policy preferences	United States

Source of IV estimate/observed			
correlation	X	Y	Context
Acharya, Blackwell, and Sen	Slavery	Party vote	United
(2016)		share	States
Abiona (2017)	Agricultural wages	Contraceptive	Uganda
		use	
Theisen and Holtermann (2010)	Rainfall	Conflict	Africa
Burke et al. (2009)	Temperature;Rainfall	Conflict	Africa
Burke et al. (2009)	Temperature	Conflict	Africa
Saeed and Spagat (2021)	Drone strikes	Terrorism	Pakistan
Belasen and Polachek (2009)	Weather disaster	Wages	Florida
Currie and Rossin-Slater (2013)	Weather disaster	Child health	United
			States
Persico and Marcotte (2022)	Pollution	Suicide	United
			States

Source of IV estimate/observed			
correlation	X	Y	Context
Cutler et al. (2010)	Malaria	Consumption	India
Chang et al. (2014)	Malaria	Health	Taiwan
McCord, Conley, and Sachs (2017)	Malaria	Fertility	worldwide
K. Schultz and Mankin (2019)	Temperature	Conflict	Africa
Kitamura (2022)	UFO sightings	Party vote share	United States

Appendix C: Number of social science articles published annually

Between 2010 and 2020, Scopus lists an average of 58,544 journal articles published in “Sociology and Political Science” and “Economics and Econometrics” each year (Thelwall and Sud 2022).

Table D1: Number of existing IV studies in this paper’s review that uses each weather type as an instrument for an x-variable.

Weather	Number of studies
Rainfall	219
Temperature	50
Wind speed	14
Sunlight	11
Clouds	8
Wind direction	8
Snow	6
Atmospheric inversion	5
Humidity	4
Weather disaster	4
Air pressure	3
Wave height	3
Haze	1
Storms	1
Terrain	1
Weather-related absences	1

^a Counts are of uses of an instrument, so studies using multiple weather variables as an instrument appear multiple times.

Appendix D: Weather types used

Table D1 shows the number of studies using each weather variable (some studies use multiple types of weather).

Table E1: Count of weather-IV reduced forms and $R^2_{X_j \sim W|K}$ modeling different variance types. IV studies refers to the count of estimates modeling that variance type. Reduced-form count refers to the count of IV estimates with available information to use the reduced-form in sensitivity analysis. $R^2_{X_j \sim W|K}$ refers to the count of estimates of the strength of the $W \rightarrow X_j$ relationships available in the literature.

Variance modelled	Reduced-form count	$R^2_{X_j \sim W K}$ count
within-subnational	27	47
within-person	12	19
between-subnational	8	20
between-person	8	18
within-country	3	6
time-series	0	5
between-organization	2	1
within-organization	0	3
between-country	1	1
between-event	2	0

Appendix E: Variance type modelled

Table E1 shows the level of variance the weather-IV reduced-forms and $R^2_{X_j \sim W|K}$ estimates are based on.

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