Rain, Rain, Go away: 137 potential exclusion-restriction violations for studies using weather as an instrumental variable

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Abstract

Instrumental variable (IV) analysis assumes that 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 make the instrument invalid. Weather has been widely used as an instrumental variable 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 studies using weather as an IV. A review of 185 social science studies reveals 137 variables which have been linked to weather, all of which represent potential exclusion violations. I conclude with practical steps for systematically reviewing existing literature to identify possible exclusion violations when using IV designs.

Note: This is a working paper. Comments and corrections are very welcome at

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Endogeneity is one of the most pervasive challenges faced by social scientists. Naively, we might assume that the causal relationship between two social science variables X and Y can be estimated simply by their observed relationship (showed in the left directed acyclic graph (DAG) in figure 1). However, social scientists are usually skeptical of this simple picture and believe that most sets of variables inevitably share some unmeasured confounders U (middle DAG). One strategy for conducting causal research even in the presence of endogeneity is instrumental variable (IV) regression where a third variable W, thought to be uncorrelated with the error term, is used to predict X and this prediction $\hat{X}$ is then used to predict Y, on the assumption that W is uncorrelated with the error term, and is associated with Y only through its relationship with X (referred to as the exclusion restriction). W's ability to causally manipulate X independently of U allows the unbiased causal estimation of the relationship between X and Y using two stage least squares (2SLS). The DAG for the IV model is shown in the right panel of figure 1).

One widely used instrument is the weather. The weather is intuitively appealing as a source of exogenous variation because it seems instantly plausible that the weather is essentially random, uninfluenced by human

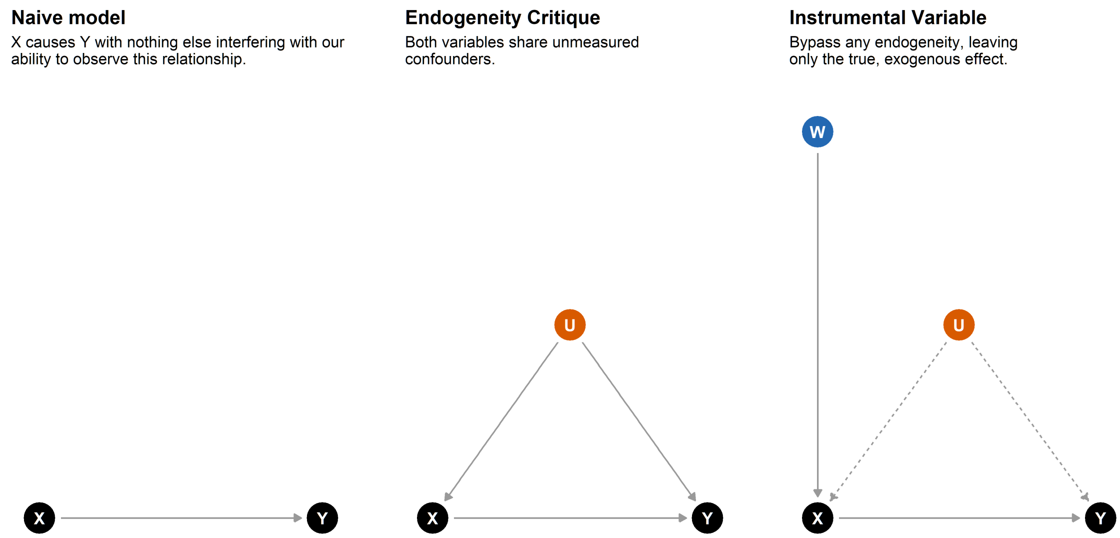

Figure 1: Instrumental variables as a fix for endogeneity

behavior, and presumably only related to human outcomes through specific narrow causal paths. In this paper, I examine whether the IV DAG really represents a plausible account of IV weather studies. In particular, I ask whether the vital exclusion restriction assumption of IV models is plausible in the case of weather as an IV.[1 2]

Rather than independently validating possible confounding routes from weather to outcomes, I use the IV literature itself to identify alternative causal pathways (similar arguments have been made against the use of population size as an instrument by Bazzi and Clemens (2013)). I review 111 papers using weather as an instrumental variable and an additional 74 papers looking at the direct effect of weather on other outcomes. In total, I conservatively identify 137 variables which social science has linked to weather, through many different causal pathways. As Bartels (1991) shows, even small violations of the IV assumptions can lead IV regression to be highly biased (even to the point of underperforming simple OLS). Consequently, this review calls into question many findings based on weather IVs.

Using weather as an IV has not been without its critics. Kubitza and Krishna (2020) mentions the overuse of

[1]Thanks to Jack Bailey, Chris Prosser, and the University of Manchester Democracy and Elections Group for feedback on drafts of this paper. This paper started as a Twitter discussion with Alex Coppock https://twitter.com/jon_mellon/status/990968700542095361?s=20.

[2]After the initial upload of this working paper, it was brought to my attention that Gallen and Raymond (2019) made similar points to this research note in a 2019 working paper. That paper looks at a broader array of instrumental variables, but does identify a substantial number of endogenous covariates of weather within the economics literature. This paper can therefore be considered a replication of the economics results and an expansion of the findings to other fields in social science, particularly political science.

rainfall as an instrument in impact evaluations even where the theoretical plausibility is questionable. Sarsons (2015) points out a likely exclusion restriction violation in IV models of rainfall on economic growth, as she finds that rain predicts conflict in India even where incomes were not affected.[3] Betz, Cook, and Hollenbach (2019) and Cooperman (2017) point out that rainfall and many other instruments suffer from spatial interdependence which is rarely adequately accounted for in practice. Auffhammer et al. (2013) note several practical problems with weather variables including coverage bias, spatial autocorrelation, the use of interpolated data, and country heterogeneity. These issues are also taken up by Dell, Jones, and Olken (2014) who carefully dissect many other measurement and analysis issues when studying weather effects in social science. Finally, Schultz and Mankin (2019) point out that conflict (usually considered an outcome in the weather→income→conflict causal chain) actually predicts poorer weather measurement.[4]

While the plausibility of the exclusion restriction is not directly testable, future work can at least try to avoid using instruments which have well documented alternate paths to the outcome of interest in the existing literature. In other words, our *minimum* standard for accepting the exclusion restriction assumption should be that it is not disproven within the existing literature. To help with this I set out a systematic process for searching the existing literature for relationships which could represent possible exclusion restrictions for a particular IV. If the instrument you are considering has been linked to a vast series of important variables, it is probably not exogenous and IV is not an appropriate identification strategy.

This paper proceeds as follows. First, I describe the exclusion criterion in more detail. Second, I outline my review strategy. Third, I show the results of the review, and the scale of the exclusion violations for weather as an IV. Next, I explain specific threats to particular IV inferences and describe a strategy for finding possible exclusion restriction violations in the existing literature. Finally, I conclude by discussing what these results might indicate about the use of IVs in social science more generally.

[3]This finding could potentially have been enough to stop people using weather as an instrument. However, my review contains 50 IV-weather papers from 2016-2020, so more evidence appears to be needed.

[4]I do not assess violations of the other IV assumptions in this paper but there are reasons to think these may sometimes be violated in practice. For instance, monotonicity is likely violated when areas with different industries or crops have opposite responses to increased rainfall. Similarly, W. C. Kang (2019) found the opposite pattern of turnout and rainfall in South Korea because (they argue) rainfall led young people to cancel their other plans and vote instead.

1 Throwing caution to the wind? Weather and the Exclusion restriction

We assume the true data generating model (DGM) for Y is: $Y = \alpha + \delta X + \psi U + \epsilon$. However, because we do not observe U (the unobserved variables which makes X and Y endogenous), the OLS estimator $\hat{\delta}$ for the effect of X in our model is: $Y = \hat{\alpha} + \hat{\delta} X + \eta$, where η is the combined error term that includes the true random error ϵ and the non-random error attributable to not including U in the model (Cunningham 2018). This means our estimate of $\hat{\delta}$ of δ is biased as follows:

$$\hat{\delta} = \delta + \psi \frac{Cov(UX)}{Var(X)}$$

However, if weather is correlated with X, we can estimate the local average treatment effect (LATE) of X on Y, δ, consistently and without bias as follows:

$$\hat{\delta} = \frac{Cov(Y, weather)}{Cov(X, weather)}$$

provided that $Cov(U, weather) = 0$ and $Cov(\epsilon, weather) = 0$. These two requirements are collectively referred to as the exclusion restriction and mean that the instrument cannot be correlated with either part of the combined error term η.

In summary, weather is exogenous and causally affects X, while not affecting Y in any way, except through weather's relationship to X. Importantly, this DAG assumes no other routes from weather to Y exist. If other routes existed, this would be an exclusion violation and IV regression would no longer provide a valid identification strategy.

2 Getting wind of exclusion restriction violations statistically

While most sources agree that the exclusion restriction is fundamentally theory-based and cannot be tested with statistical methods alone (Cunningham 2018; Kippersluis and Rietveld 2018), there are statistical techniques which are relevant to the exclusion restriction. I briefly review these to explain why they do not address the concerns raised in the rest of this paper.

The first of these tests is the Sargan-Hansen test for over-identifying restrictions. The Sargan-Hansen test is applicable to the specific situation where more instruments are included than instrumented variables. In this case, it is possible to test whether the residuals for the second stage model (not including instrument I) are correlated with the instruments, which could indicate an exclusion violation. Weather-IV studies rarely use multiple instruments, so this test is not that relevant in most of the studies reviewed in this paper. Additionally, the Sargan Hansen test does not test the validity of the instruments but merely that they do the same thing as each other. The test itself assumes that at least enough instruments to "just-identify" the model are valid (Kiviet 2020). In other words, the Sargan Hansen test directly tests the assumption $Cov(\epsilon, weather) = 0$ but not the assumption $Cov(U, weather) = 0$.

The zero-first-stage test looks at the effect of the treatment in a sub-sample where the effect of the instrument on X should be zero and verifies that there is no relationship between the instrument and outcome in that subset. While this will pick up on *some* exclusion violations, it cannot affirmatively prove there are no violations. Weather effects seem like plausible cases where this could be the case. It is plausible that the same factors reduce the influence of weather on multiple potential instrumented variables. A dammed river probably reduces the effect of rainfall on income, migration, and conflict, but does nothing to distinguish the causal ordering of income, migration, and conflict. Most of the plausible zero-first-stage subsets for weather are simply going to be situations where weather is generally less important. In other words, if the subset of cases where $Cov(X, weather) = 0$ are also cases where $Cov(U, weather) = 0$, then the test does not exclude the possibility that $Cov(U, weather) \neq 0$ across the whole sample.

Both of these tools are valuable, but they do not remove the need for researchers to think through the theoretical plausibility of their instruments.

3 Approach for reviewing the flood of weather IV papers

The goal of this paper is not to give an exhaustive or representative review of studies using weather as an IV. Exclusion violations are threats to the validity of studies using weather as an IV, whether the set of exclusion violations is exhaustive or representative of all known violations. For the same reason, I included studies regardless of whether they are published studies, working papers or theses.

I reviewed the first 500 results for the search term 'weather "instrumental variable" ' in Google Scholar (the search returned 12,700 results in total). Additionally, I added in the first 100 results from 'rain "instrumental variable" ', a handful of studies I had previously identified, and any other relevant studies cited within the initial searches. This produced 111 studies which used weather as an IV, and an additional 74 studies which used weather directly. These studies were most commonly in economics, political science, and international development, but almost all social science disciplines have used weather as an IV to some extent.

All studies were entered into a table tracking the instrumental variable, instrumented variable and outcome variable. If more than one combination of these was present, I included a row for each combination. I also included a measure of the time-period over which the weather was measured and spatial resolution of the weather measurement.

For the purposes of this analysis, I treat studies which do not explicitly use IV designs but follow the same logic as IVs as IV studies. This includes some studies on rainfall and turnout, which explicitly see weather as affecting other outcomes via turnout, but do not always use 2SLS models for their analysis (e.g. Gomez, Hansford, and Krause 2007; W. C. Kang 2019), although others do explicitly use IV models (e.g. Artés 2014; Arnold and Freier 2016; Lind 2019; Lo Prete and Revelli 2014)). However, these studies still generally refer to the importance of weather's exogeneity and random assignment as reasons to believe the conclusions reached about the mechanisms linking rainfall to the outcome of interest.

For analysis, I recoded the variables into coarser theoretical categories. For instance, the following variables were recoded as "income": 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. Less coarse categories would better distinguish concepts but would inflate the count of potential exclusion violations. The number of exclusion concerns in this paper is therefore a relatively conservative count. Similarly, I recoded all weather-related variables into a single category of weather.

The existence of other causal pathways into the social world for weather does not necessarily prove that a particular use of an instrument is invalid. However, it is worth recalling why we use IV regression in the first place. Most variables of interest in social science are embedded in complex endogenous causal networks that we cannot hope to fully disentangle. Simple OLS estimators are therefore presumptively biased in social science. The appeal of IV regression is that we have an exogenous variable that enters this network only in one specific place analogous to an experimenter manipulating a variable directly. However, if weather enters the causal network in many places, it becomes unclear whether arguing for the validity of weather as an instrument is different to arguing that a particular independent variable of interest is not confounded by some unspecified set of other variables.

4 Does it matter whether we measure rain or shine?

Not all weather IVs are interchangeable. There are two main ways in which weather IVs might be differentiated: temporally and by weather phenomena.

Temporally, the situation is clearer for studies using long-period weather IVs. If a weather phenomenon has an effect at the daily level, it is at least plausible that this effect will aggregate to confound relationships over longer periods. Long-period weather IV studies (long term climate differences or differences on the order of years) are therefore vulnerable to exclusion violations identified in all other weather IV studies. However, the inverse is not necessarily true. Many studies which use weather IVs over short time periods (e.g. the rain on election day) control for the long-term trend in weather in that area. While controlling for other time periods will inevitably be imperfect, it is at least conceivable that variation in weather in other time periods could be accounted for (although this is done haphazardly in practice).

However, even short-term studies will be vulnerable to other mechanisms acting at time periods not controlled for. For instance, many turnout IV studies, control for the average weather on that day of the year over the previous decade. However, this does not account for the fact that the weather on election day will be correlated with the weather over the past week or month in that area. This means that medium-term weather effects will still potentially confound short-term studies.

To show the different mechanisms that might confound different studies, I show both the overall causal network related to weather and the causal network from studies using weather variation at the monthly level or more frequently.

In terms of variation by weather phenomena, there are certainly cases where specific weather phenomena (e.g. strength of monsoon seasons) are not relevant to another setting (e.g. turnout in British elections). However, this is the exception, as it is generally the case that all weather variables are part of a complex causal network and are therefore non-independent. This complexity means that the nature of confounding relationships across weather phenomena may be hard to predict in advance but still represent confounding relationships (remember that the lines in DAGs do not represent simple linear relationships but causal connections). At the simplest level, precipitation, temperature, and wind speed are all correlated (Auffhammer et al. 2013). A relationship between one weather variable and an outcome of interest therefore implies the existence of some relationship to all other weather variables.

5 Results of the rain check

Figure 2 shows the causal web derived from the 185 social science studies that use weather as a variable. It is useful to contrast this figure with the assumed DAG in figure 1. In that figure, weather entered the causal network only through the single X variable of interest. In reality, weather enters the causal network of interest to social science in 71 places, and indirectly reaches a total of 132 variables of interest to social scientists. These all represent exclusion violations for the DAG in figure 1.

As mentioned above, shorter term weather variation IVs may not be confounded by long term variables. I therefore also plot the causal network for studies with a weather frequency of a month or less. It should be noted that the outcome variables in these studies often take place over longer periods of time (e.g. government spending via the outcome of an election), so not all variables represent plausible exclusion

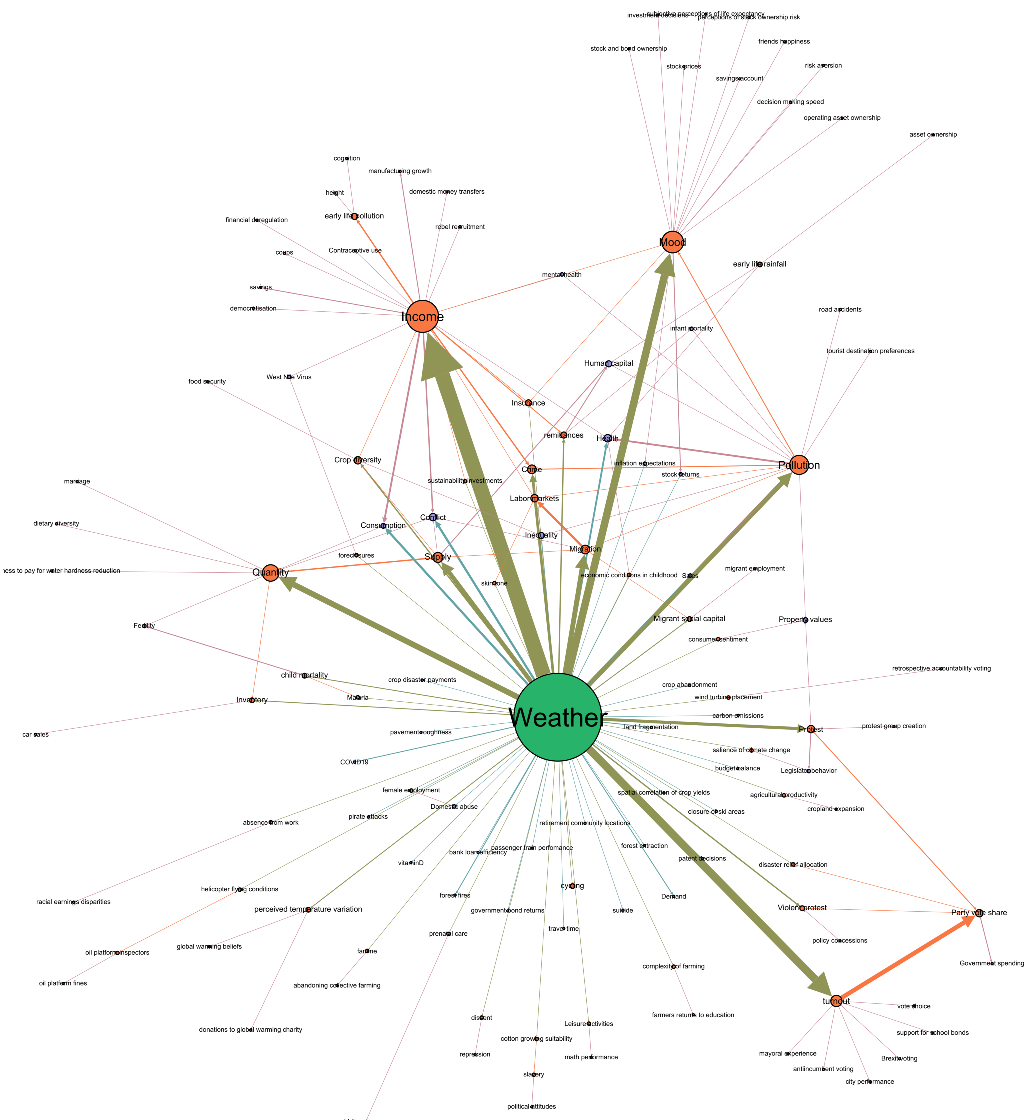

Figure 2: The causal web of weather as derived from 185 social science papers. Size of nodes and ties are proportional to the number of instances appearing in the literature. Color key: weather (green), instrumented variable (orange), and outcome (purple)

violations for all other variables. Even this reduced set of studies have 28 instrumented variables and 57 variables in total on the causal graph.

These variables include several important variables that represent plausible routes to many social science outcomes including: pollution, crime, economic activity, mood, leisure activities, consumer sentiment, stock market performance, health, and skin tone.

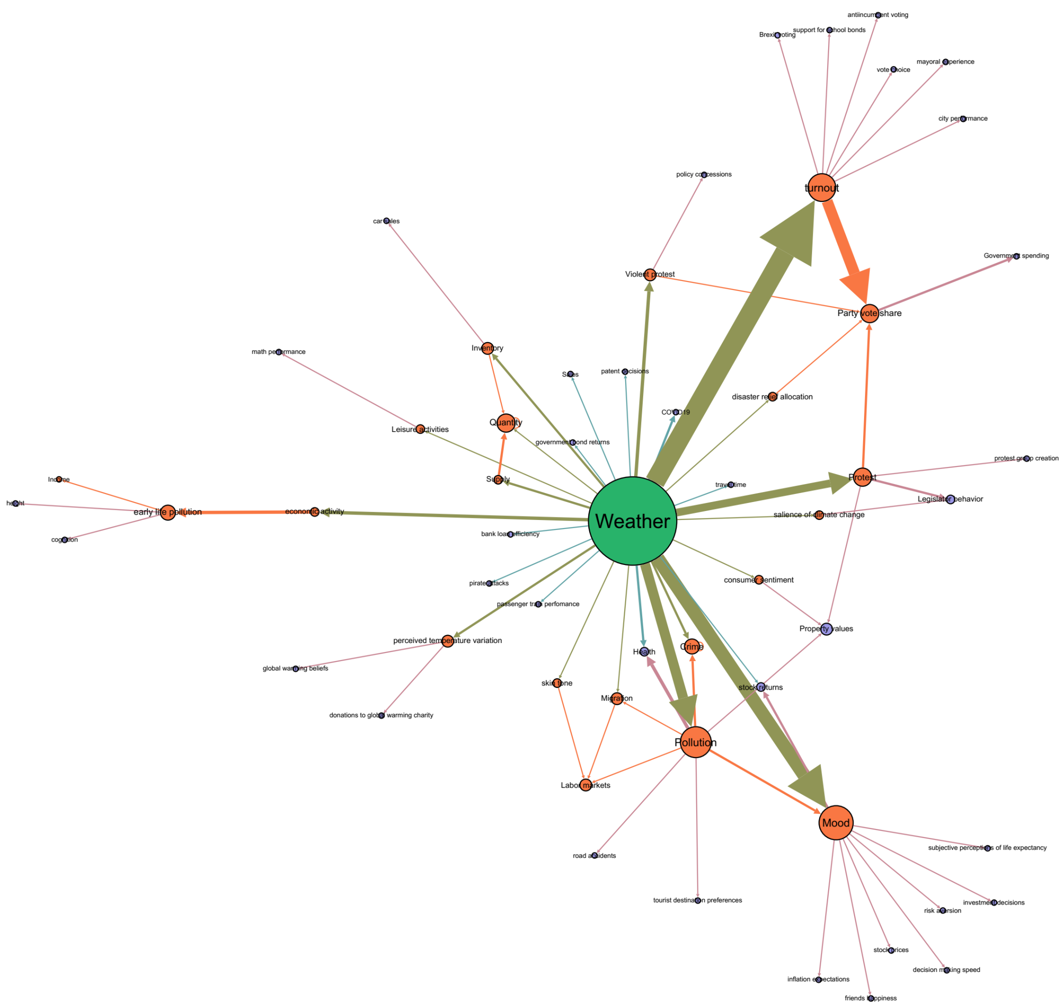

Figure 3: The causal web of weather as derived from 64 social science papers using weather varying monthly or more frequently. Size of nodes and ties are proportional to the number of instances appearing in the literature. Color key: weather (green), instrumented variable (orange), and outcome (purple).

For both causal graphs, some of these relationships are more directly relevant to some studies than others. Most researchers are probably justified in assuming that “helicopter flying conditions” and “pirate attacks” are not exclusion violations for their research. However, some causal routes have wide relevance to almost all research outcomes.

The first of these causal routes is mood. Several studies establish a link between weather conditions and mood. These studies then claim a large number of links between mood and other variables including: decision making speed, investment decisions, inflation expectations, risk aversion, financial decisions, and perceived life expectancy. It is hard to think of a social science variable which could not be plausibly causally influenced by at least one of these variables or directly by mood itself. Mood is a threat to both long-term and short-term weather IV studies.

The next major causal route is pollution. Pollution levels have been instrumented by many aspects of weather including wind speed (Peet 2014; Zheng et al. 2019; Xinye and Wei 2019; Bondy, Roth, and Sager 2020), wind direction (Luechinger 2014; Fan and Wang 2020), atmospheric inversions (Bondy, Roth, and Sager 2020; Cui et al. 2019; Sager 2019), rainfall (Peet 2014; Fontenla, Ben Goodwin, and Gonzalez 2019) and many others. Perhaps most surprisingly, warmer weather is strongly correlated with lead exposure (Levin et al. 2020) (blood lead levels rise 10%-60% in warm weather). Pollution in turn has been linked to crime (Bondy, Roth, and Sager 2020), mental health (Gu et al. 2020), mortality (Fan and Wang 2020), road accidents (Sager 2019), retail sales (H. Kang, Suh, and Yu 2019), house prices (Fontenla, Ben Goodwin, and Gonzalez 2019), mobility (Cui et al. 2019), cognition (Peet 2014), and mood (Zheng et al. 2019; Xinye and Wei 2019). Once again, it is difficult to argue that any variable in social science is not affected by some of these factors. Importantly, pollution can be a threat to both long-term and short-term weather IV studies.

The next major causal route is a recently discovered link: skin tone. Katz et al. (2020) observe that some workers become darker skinned when exposed to sunlight while others do not tan. They use an IV approach to claim that the gap in labor market outcomes, between those who tan and those who do not, widens during sunny periods. Given the pervasiveness of colorism in societies around the world, the confounding effect of skin tone with weather is another major point of entry into the messy causal web of the social world. The upshot of this is that weather instruments are now plausibly proxying for racial prejudice. Skin tone could potentially be a confounding variable for long-term or short-term IV studies.

The last major causal entry I consider is crime. Studies have claimed that crime is affected directly by weather (Chia et al. 2016; Ranson 2014; Reichhoff 2017; Horrocks and Menclova 2011; Jacob, Lefgren, and Moretti 2007; Bruederle, Peters, and Roberts 2017), or indirectly through income (Mehlum, Miguel, and Torvik 2004; Blakeslee and Fishman 2018; Pereira and Menezes 2020) or pollution (Bondy, Roth, and Sager 2020). Indirect or direct exposure to crime is associated with psychological distress (Heinze et al. 2017; Burdette and Hill 2008) and substantial behavioral changes (Burdick-Will, Stein, and Grigg 2019; Berens and Dallendörfer 2019).

There are also major causal routes that are particularly relevant to studies using longer term weather and climate as instruments (although these can certainly affect inferences using short-term weather as an instrument if long-term climate is not accounted for).

The most widely instrumented variable in economics and political economy studies is income, both in terms of individual or household incomes and aggregate incomes. The mechanism for this link is most often described in terms of the success or failure of crops, but many papers acknowledge that the mechanisms could be more varied. Income is a hugely important variable, so it represents a large exclusion violation for other studies using weather as an IV.

Conflict has usually been modeled as resulting from changes in income instrumented by weather. However, recent studies cast doubt on this interpretation, with Sarsons (2015) finding that conflict increases in response to weather shocks regardless of income changes. As (Sarsons 2015) indicates, this is concerning for claims that weather's relationship to income fulfills the exclusion restriction. Similar concerns are raised by (Landis et al. 2017) who find that distance from rivers only slightly mediates the effect of rainfall on conflict. Overall, these results suggest that there can be some form of relationship between weather and conflict that does not flow through income. This means that conflict represents a potential exclusion violation for weather-IV studies in general.

Migration follows a similar pattern. These studies generally justify the use of weather as an IV by weather's effect on income (lower incomes provide a push factor for emigrants and higher incomes are a pull factor for immigrants) (Strobl and Valfort 2015; Nawrotzki, Riosmena, and Hunter 2013; Pajaron and Vasquez 2020). However, these studies also offer (usually qualitatively) other possible links between weather and migration including direct displacement by disaster (Nandi, Mazumdar, and Behrman 2018), violence, political unrest, and health (Pajaron and Vasquez 2020). However, these studies usually do not explicitly model the income to migration step of the process and often do not consider the other possible causal routes from income to their dependent variable of interest. In fact, one study which did examine the income-migration link (Marchiori, Maystadt, and Schumacher 2017), dismissed the role of income variability as "negligible". Even outside of low income countries, there is evidence for non-economic links between migration patterns and weather, with Moretti (1998) finding that good weather predicts the location of retirement communities within the US, and Rappaport (2007) finding the same pattern for internal US migration more generally. Taken together, the existing literature suggests that migration is a potential exclusion violation for weather-IV studies including those instrumenting income using the weather.

The next major causal route is via the legacy of slavery. Acharya, Blackwell, and Sen (2016) use cotton growing suitability as an instrument for slavery in the southern United States. That measure, in turn, contains climate as an input. For studies in the US, the use of weather as an IV potentially introduces a confound with legacies of slavery. The legacy of slavery is primarily a threat to inferences in studies using long-term weather IVs or not otherwise accounting for long-term weather.

5.1 Winds of Change? Multiple routes from weather to incumbent support

The exclusion restriction becomes particularly questionable when we look at the multiple routes that the literature has identified from weather to particular dependent variables. A good example of this is incumbent vote share, which has been studied using weather as an instrument or explanatory variable in multiple ways.

Achen and Bartels (2016) interpret the relationship between weather and incumbent vote share as supporting their theory of blind retrospection (Rubb (2008) makes a similar argument for monsoons in India). Droughts and wet spells have negative effects on citizens which they erroneously attribute to the incumbent president's performance.

Other studies have instead linked weather to incumbent voting because lower rainfall is related to higher turnout on election day and more anti-incumbent voting (Hansford and Gomez 2010). A state that is in drought might therefore be expected to have higher turnout and more anti-incumbent voting.

Alternatively Bassi (2013) argues that rainy weather reduces voters' risk tolerance (through effects on mood) which in turns reduces voters' willingness to support incumbents. This theory means that weather would have unexpected effects on democratic outcomes, but not via the narrower mechanism of blind retrospection. More generally, Cohen (2011) finds very large effects of sunlight on Presidential approval, with models predicting a 15 percentage point increase in the probability of independents approving of President George W. Bush in the sunniest versus least sunny areas. This fits with a sizable literature linking weather to mental health (Magnusson 2000; Bauer et al. 2012) and mood (Coviello et al. 2014; Guven and Hoxha 2015; Baylis et al. 2018), and the large literature on the effect of emotions on political attitudes and voting behavior (Brader and Marcus 2013; Wagner and Morisi 2019).

It is not hard to see how other linkages in the literature could affect incumbent vote share either. Another possible pathway is via perceived skin tone. If an area is sunny, people who tan may be perceived as being darker skinned and subjected to colorist discrimination (in line with the findings of Katz et al. (2020)). This could affect outcomes either by affecting the people who become darker skinned or through the reactions of people to seeing more dark-skinned people around them. Being the subject of discrimination is associated with anti-incumbent voting (Sanders et al. 2014).

Another possible explanation is that areas with poor weather patterns are much more likely to experience outmigration (Strobl and Valfort 2015; Giulietti, Wahba, and Zenou 2018; Viswanathan and Kumar 2015; Corbi and Ferraz 2018; Pajaron and Vasquez 2020; Marchiori, Maystadt, and Schumacher 2012), so apparent links between weather and voting could reflect climate-driven changes in the composition of the electorate across areas.

Another pathway would be via exposure to crime. Many studies have found that lower rainfall is associated with rises in crime (Horrocks and Menclova 2011; Jacob, Lefgren, and Moretti 2007; Bruederle, Peters, and Roberts 2017; Moretti 1998). It is therefore likely that people in areas with sunnier weather will have had more direct or indirect exposure to crimes in their area recently. While weather-induced crime might not be the fault of an incumbent, the voters will not know that in any individual case, so incumbent punishment would not be evidence for blind retrospection.

There is also the possibility that the effects of weather on income, economic security, home ownership and various other variables might affect voting through changing voters' objective interests (for instance, poorer voters tend to vote for left wing parties) rather than through a misplaced accountability mechanism or a different propensity to vote at all.

Even though many of these studies look at weather on different timescales, the relationships are still relevant to each other. An unusually wet year in a state is composed of a series of unusually wet days, so election day weather is likely correlated with yearly weather deviations (although not necessarily in a straightforward way) and with long term climate.

5.2 Do any results weather the storm?

Based on the papers reviewed, the studies on the safest ground are economic studies of crop and livestock supply and demand. These generally examine short-term weather fluctuations' effects on the supply curve to identify price-elasticity of demand. However, even here there are very plausible exclusion violations. Multiple studies show the effects of weather on consumption and sales. The supply-constrained farmers are also often buyers in the same or adjacent markets, so a supply-side shock which reduces their income (or anticipated income) will also represent a demand side shock on the rest of the market. In other cases, extreme weather shocks simply limit the ability of consumers to engage in marketplace transactions by reducing their mobility. On the other hand, if weather shocks damage consumers' existing holdings of a good, this may increase demand. In the case of severe weather shocks, governments may also intervene in markets, which will have a variety of effects. We can also consult the large causal web for other potential exclusion violations for even this simple case. Since weather can cause social unrest, crime, migration, and mortality, it is not hard to see how even the simplest of IV studies could suffer from exclusion violations.

This is not to say a weather IV can never work. The most plausible case would be a paper looking at supply shocks from very localized weather events over short time periods, where the demand for that good was located somewhere with uncorrelated weather patterns where the consumers and producers do not overlap.

To summarize, unless a researcher can make the case that each of the 132 variables identified here are either 1) irrelevant to the context they are studying, 2) come later in the causal chain than all their variables of interest, or 3) are orthogonal to all of their variables of interest, then they should not use weather as an IV.

One line of research which is not affected by these problems, are papers using reduced-form equations to look at the total causal effect of weather on particular outcomes (Dell, Jones, and Olken 2014). This paper merely suggests that interpreting the mechanisms behind these total effects will be challenging. However, for studies hoping to predict the effects of climate change and extreme weather on the social and economic world, this may be less important. Indeed the plethora of variables studied, suggests that weather effects are very numerous.

6 The tip of the iceberg?

While this paper focuses on weather as an IV, the message is more general: a good instrument is hard to find. This paper could just as easily have been written about other widely used instruments (population density, historical splits in countries, lead exposure, colonialism, distance from the equator and distance from anything else are possible examples). Indeed, many of these instruments have been criticized for similar reasons (Morck and Yeung 2011).

Weather is also a confounder for many instruments. Distance from the equator is associated with weather for obvious reasons, which has a knock-on effect of confounding colonialism and population density as instruments. Countries tend to split in contiguous parts which rarely have the same weather. Weather is correlated with month of birth. Lead poisoning is highly seasonal and seems to be increased by warm weather in a variety of ways (Levin et al. 2020).

These concerns also apply to the inevitable papers that will be written using the COVID-19 pandemic as an instrument. COVID-19 has affected everything, so it is not plausibly a natural experiment or a random assignment for anything but itself. COVID-19 may also be affected by the weather (Shen, Cai, and Li 2020a), causally attaching it to the messy web of relationships described in the rest of this paper.

7 A ray of hope? Practical advice for IVs

The problem with the exclusion-restriction is that its plausibility is fundamentally theory-based. Whether or not you can reasonably use an instrument depends on whether you offer convincing arguments for the specific case of interest.

Is it possible to offer any practical guidance on finding or excluding instruments? The following approach does not guarantee the theoretical plausibility of an instrument but would at least exclude most cases where the exclusion restriction is already disproven in the literature. Compared to current practice, this would be a marked improvement. This approach can also be used by reviewers when assessing IV studies.

Once you have a plausible instrument, I, instrumented variable, X, and dependent variable, Y, you should aim to build a possible network of causal connections from the literature.

First, you should search for articles which already link I and Y. If you find any such articles, do they posit or prove plausible pathways that for the I-to-Y link that do not run through X. If so, you should probably discard the instrument. However, if you choose to continue (if, for instance, you can show that the confounding variable comes after Y in the causal ordering), you should clearly document your reasons for believing that the mechanism that the paper posits does not represent an exclusion violation in your study (this applies to all of the following steps as well).

Second, review the literature on Y for all other variables that have been found to be associated with it. For each associated variable, Q, search the literature for "I + Q" to find any existing research which links the associated variable to your instrument. If these searches find plausible links, then you have discovered a plausible exclusion violation in the literature. This probably means that you should discard the instrument.

Third, review the literature on I and closely related concepts to I. For each associated variable R, search the literature for "Y + R" to find existing research which links your associated variable R to the dependent variable. Once again, any plausible links mean that you have discovered an exclusion violation and should probably discard the instrument.

Finally, review the two lists of associated variables Q and R for any possible links between them. Follow up on any links you find even slightly plausible. If you discover causal pathways, you should probably abandon the instrument.

It should be noted that the literature review should include studies with observational or causal links between variables and accept studies from any discipline. Even if two variables are associated non-causally, it still indicates that there is some pathway between them in a DAG, even if indirectly. This is sufficient to undermine the exclusion restriction, except in very specific circumstances.

This approach is not a substitute for other theoretical consideration of the instrument and its relationships and should always be used in addition to existing validation procedures. However, if this approach had been followed for weather IV studies, the many exclusion restriction violations would have been immediately apparent.

Perhaps the most valuable part of this approach would be requiring scholars to make their standards for accepting the exclusion restriction assumption explicit. This approach provides a systematic way of generating potential exclusion violations rather than leaving the reader to guess what possible violations were considered too minor to worry about.

8 Are IVs on thin ice?

This paper shows that a very commonly used instrumental variable (IV) is flawed because it systematically fails the exclusion restriction for most plausible uses.

More importantly these results suggest our standards for accepting instruments are too generous and atheoretical. The causal revolution in social science has exposed the wishful thinking that underlies much of naïve regression modeling. However, the same rigor that is used to critique the implicit assumptions of exogeneity for selection on observables also needs to be applied to all the assumptions of IV regression.

Nothing in this paper disproves the empirical claims of any particular paper. Many of the papers using weather IVs provide other independent sources of evidence, and additional robustness checks such as placebo tests. However, these results do suggest that the underlying assumptions (as embodied in the IV DAG) are not strictly true.

A reader might wonder whether these results are such a problem. In any particular case, surely the confounding routes to the dependent variable are not so great as to overturn a result. This could be true in some cases, but the identification strategy is starting to sound less like the clean logic of the IV model and more like selection on observables with extra steps.

The evidence for poor exclusion-restriction practices adds to a body of evidence that IV regression studies are often not well conducted. Brodeur, Cook, and Heyes (2018) found that IV studies showed more evidence of p-hacking than DID, RCT or RDD studies, with nearly a quarter of marginally significant claims in IV papers being misleading. Similarly, Lee et al. (2020) finds that the standard first stage F-test used in IV regression is underpowered, and that more than half of IV papers in the American Economic Review were no longer significant after accounting for this.

This paper does offers a way forwards for improving IV inference by proposing a method for systematically reviewing the literature for exclusion restriction violations. We cannot hope to systematically prove the exclusion restriction, but we can aspire to at least recognize exclusion violations which are already well documented in the scientific literature.

Cunningham (2018) argues that a good instrument should have a "certain ridiculousness". Until the secret endogenous route to causation is explained, the linkage between the instrument and the outcome seem absurd. In a world where Australians and Californians cannot leave their houses for months at a time due to forest fires, and 1-3 billion people are projected to be left outside of temperature ranges that humans have historically inhabited (Xu et al. 2020), linkages between weather and the social world are just not ridiculous enough.

9 Appendix: Literature review table

Table 1: 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.

x	y	source	temporal	spatial	context
absence from work	racial earnings disparities	Lahiri (2018)	yearly	states	US
Weather	Supply	Di Falco and Chavas (2008)	0-10 years	regions	Italy
Crop diversity	Supply	Di Falco and Chavas (2008)	0-10 years	regions	Italy
Weather	turnout	Persson, Sundell, and Öhrvall (2014)	one day	municipalities	Sweden
Leisure activities	math performance	Laidley and Conley (2018)	daily	individual	US
Quantity	Fertility	Schultz (2011)	yearly	parishes	England
Quantity	marriage	Schultz (2011)	yearly	parishes	England
Weather	Conflict	Theisen (2012)	yearly	country	Kenya
salience of climate change	Legislator behavior	Herrnstadt and Muehlegger (2014)	weekly	congressional voting aggregated to state	US
Crime	Inequality	Chia et al. (2016)	yearly	commuting zones	US

x	y	source	temporal	spatial	context
complexity of farming	farmers returns to education	Gurgand (2003)	yearly	regions	Taiwan
Weather	Migration	Kim, Sesmero, and Waldorf (2018)	monthly	villages	India
Malaria	child mortality	Leimdörfer and Hauge (2020)	one year	households	Niger
Weather	Crime	Ranson (2014)	monthly	counties	US
Pollution	Migration	Cui et al. (2019)	daily	cities	China
Weather	Consumption	Davies (2010)	two years	villages	Malawi
Weather	travel time	Chen and Mahmassani (2015)	one day	indvidual	San Francisco
Weather	Mood	Chen and Mahmassani (2015)	one day	indvidual	San Francisco
turnout	Party vote share	Arnold and Freier (2016)	one day	municipalities	Germany
Migration	Labor markets	Strobl and Valfort (2015)	monthly	regions	Uganda
Quantity	Quantity	Graddy (2006)	daily	market as a whole	Fulton Fish Market (New York)

x	y	source	temporal	spatial	context
Weather	Demand	Flyr et al. (2019)	billing period	business premises	Fort Collins municipal utility
Pollution	Mood	Zheng et al. (2019)	daily	cities	China
Weather	Supply	Seo (2019)	yearly	whole country	Thailand
consumer sentiment	Property values	Hu and Lee (2020)	daily	house sales	Sydney
Inventory	car sales	Cachon, Gallino, and Olivares (2019)	weekly	dealerships	US
Weather	forest fires	Gillett et al. (2004)	yearly	grid cells	Canada
Weather	Inequality	Bayani-Arias and Palanca-Tan (2017)	aggregated over multiple years	regions	Philippines
expected losses from extreme weather events	firm cash holding	Huang, Kerstein, and Wang (2018)	cross-sectional	firms	worldwide
Migrant social capital	Migration	Giulietti, Wahba, and Zenou (2018)	yearly	households	China
Weather	Crime	Reichhoff (2017)	yearly	counties	California

x	y	source	temporal	spatial	context
dissent	repression	Ritter and Conrad (2012)	yearly	countries	Africa
Weather	Health	Han and Foltz (2015)	two months previous	households	Mali
Supply	Migration	Viswanathan and Kumar (2015)	yearly	districts	India
Pollution	Health	Bae, Lim, and Hong (2020)	hourly	Seoul	Seoul
Weather	Supply	Pipitpukdee, Attavanich, and Bejranonda (2020)	yearly	province	Thailand
Pollution	Human capital	Vahedi (2015)	cross-sectional	individual	US
Supply	Human capital	Groppo and Kraehnert (2017)	yearly	districts	Mongolia
Pollution	Mood	Xinye and Wei (2019)	hourly	municipalities	China
Supply	Human capital	Schachner (2014)	yearly	regions	Mongolia
Weather	Demand	Atalla, Bigerna, and Bollino (2018)	yearly	countries	worldwide

x	y	source	temporal	spatial	context
Quantity	willingness to pay for water hardness reduction	Farah and Torell (2018)	monthly	counties	US
Supply	Quantity	Hendricks, Janzen, and Smith (2015)	yearly	countries	worldwide
Crop diversity	Income	Asfaw, Palma, and Lipper (2016)	long run weather	enumerator areas	Niger
Crop diversity	food security	Asfaw, Palma, and Lipper (2016)	long run weather	enumerator areas	Niger
Crop diversity	Inequality	Asfaw, Palma, and Lipper (2016)	long run weather	enumerator areas	Niger
Weather	spatial correlation of crop yields	Tack and Holt (2016)	yearly	continuous	Iowa and Illinois
Weather	land fragmentation	Hoang (2018)	long run weather	commune	Vietnam
Income	financial deregulation	He (2011)	6 year averages	provinces	China
Mood	friends happiness	Coviello et al. (2014)	daily	cities	US

x	y	source	temporal	spatial	context
turnout	Party vote share	Hansford and Gomez (2010)	one day	counties	non-Southern US
turnout	antiincumbent voting	Hansford and Gomez (2010)	one day	counties	non-Southern US
turnout	Party vote share	Hansford and Gomez (2010)	one day	counties	non-Southern US
Weather	bank loan efficiency	Apergis, Artikis, and Mamatzakis (2012)	daily	banks	US
Pollution	Crime	Bondy, Roth, and Sager (2020)	daily	wards	London
Pollution	Crime	Bondy, Roth, and Sager (2020)	daily	wards	London
foreclosures	West Nile Virus	Tevie, Bohara, and Valdez (2014)	yearly	counties	California and Colorado
Income	West Nile Virus	Tevie, Bohara, and Valdez (2014)	yearly	counties	California and Colorado

x	y	source	temporal	spatial	context
Pollution	infant mortality	Luechinger (2014)	yearly	counties	Germany
Income	Crime	Pereira and Menezes (2020)	monthly	municipalities	Brazil
Mood	stock prices	Khanthavit (2019b)	daily	stock market	Thailand
Weather	retirement community locations	Moretti (1998)	long run weather	cities	US
Supply	Quantity	Mulder and Scholtens (2013)	daily	countries	Netherlands and Germany
Pollution	mental health	Gu et al. (2020)	one year	cities	China
Weather	Consumption	Vo (2020)	quarterly	households	Australia
Income	manufacturing growth	Shifa (2015)	yearly	countries	worldwide
Weather	Income	Bui et al. (2014)	households	districts	Vietnam
Weather	Consumption	Bui et al. (2014)	households	districts	Vietnam
Pollution	Health	Fan and Wang (2020)	monthly	counties	US
Weather	Pollution	Fan and Wang (2020)	monthly	counties	US

x	y	source	temporal	spatial	context
Weather	Income	Lagerlöf and Basher (2006)	long run weather	provinces	North America
Income	Insurance	Elum, Nhamo, and Antwi (2018)	long run weather	farms	South Africa
Income	coups	Kim (2016)	yearly	countries	worldwide
Mood	risk aversion	Guven and Hoxha (2015)	one day	individuals	Netherlands and Germany
Mood	subjective perceptions of life expectancy	Guven and Hoxha (2015)	one day	individuals	Netherlands and Germany
Mood	investment decisions	Guven and Hoxha (2015)	one day	individuals	Netherlands and Germany
Mood	inflation expectations	Guven and Hoxha (2015)	one day	individuals	Netherlands and Germany
Mood	decision making speed	Guven and Hoxha (2015)	one day	individuals	Netherlands and Germany
Mood	savings account	Guven and Hoxha (2015)	previous year	individuals	Netherlands and Germany

x	y	source	temporal	spatial	context
Mood	stock and bond ownership	Guven and Hoxha (2015)	previous year	individuals	Netherlands and Germany
Mood	operating asset ownership	Guven and Hoxha (2015)	previous year	individuals	Netherlands and Germany
Mood	Insurance	Guven and Hoxha (2015)	previous year	individuals	Netherlands and Germany
Mood	perceptions of stock ownership risk	Guven and Hoxha (2015)	previous year	individuals	Netherlands and Germany
perceived temperature variation	global warming beliefs	Li, Johnson, and Zaval (2011)	one day	individual	US and Australia
perceived temperature variation	donations to global warming charity	Li, Johnson, and Zaval (2011)	one day	individual	US and Australia
female employment	Domestic abuse	Chin (2011)	one year	states	India
Income	rebel recruitment	Nillesen and Verwimp (2011)	one year	villages	Burundi
Weather	Income	Barrios, Bertinelli, and Strobl (2010)	yearly	countries	Africa

x	y	source	temporal	spatial	context
agricultural productivity	cropland expansion	Zaveri, Russ, and Damania (2020)	yearly	grid cells	worldwide
Income	Consumption	Akobeng (2017)	yearly	regions	Ghana
Weather	government bond returns	Khanthavit (2019a)	daily	market as a whole	Thailand
Pollution	road accidents	Sager (2019)	daily	grid cells	UK
Weather	Crime	Horrocks and Menclova (2011)	daily	districts	New Zealand
turnout	support for school bonds	Gong and Rogers (2014)	one day	municipalities	US
economic conditions in childhood	Health	Lee and Li (2019)	yearly	country	China
Quantity	Quantity	Berry and Schlenker (2011)	previous year	states	US
Pollution	tourist destination preferences	Wang et al. (2020)	daily	tourist sites	Beijin
Income	Consumption	Wolpin (1982)	10 years previously	districts	India
Violent protest	Party vote share	Wasow (2020)	daily	counties	US
Weather	crop disaster payments	Nadolnyak and Hartarska (2012)	yearly	counties	US

x	y	source	temporal	spatial	context
Income	remittances	Yang and Choi (2007)	one year	weather station	Philippines
Income	Consumption	Yang and Choi (2007)	one year	weather station	Philippines
Weather	Domestic abuse	Cools, Flatø, and Kotsadam (2020)	one year	grid cells	Africa
Migration	Labor markets	Pugatch and Yang (2011)	lagged year	mexican states	US/Mexico
Migration	Labor markets	Corbi and Ferraz (2018)	yearly	towns	Brazil
turnout	Party vote share	Horiuchi and Kang (2018)	one day	counties	US
wind turbine placement	retrospective accountability voting	Stokes (2016)	long run weather	districts	Ontario
Weather	Mood	Baylis et al. (2018)	daily	cities	worldwide
Income	mental health	Hanandita and Tampubolon (2014)	previous year	districts	Indonesia
sustainability investments	Income	Henderson and Ryabova (2020)	yearly	farms	California

x	y	source	temporal	spatial	context
Inventory	Quantity	Graddy and Kennedy (2010)	daily	whole market	Fulton Fish Market (New York)
Weather	Health	Burgess et al. (2014)	yearly	districts	India
turnout	Brexit voting	Rudolph (2020)	one day	local authority	UK
Weather	carbon emissions	Considine (2000)	yearly	sectors	US
Weather	Consumption	Considine (2000)	yearly	sectors	US
Weather	Consumption	Considine (2000)	yearly	sectors	US
disaster relief allocation	Party vote share	Fukumoto, Kikuta, and Yanagi (2019)	one day	districts	Japan
Income	Mood	Falco and Doku (2019)	previous year	continuous	Nile Basin Region of Ethiopia
Weather	Migration	Pajaron and Vasquez (2020)	yearly	provinces	Philippines
Migration	Labor markets	Badaoui, Strobl, and Walsh (2013)	weekly	regions	Thailand

x	y	source	temporal	spatial	context
child mortality	Fertility	Bertelli (2015)	three years earlier	arcdegrees	Nigeria
Weather	crop abandonment	Cui (2020)	yearly	county	US
Pollution	Sales	H. Kang, Suh, and Yu (2019)	monthly	regions	South Korea
Crime	Crime	Jacob, Lefgren, and Moretti (2007)	weekly	jurisdictions	US
Weather	patent decisions	Kovács (2017)	daily	whole country	US
Weather	closure of ski areas	Beaudin and Huang (2014)	yearly	ski areas	New England
turnout	Party vote share	W. C. Kang (2019)	one day	districts	South Korea
Protest	Party vote share	Pinckney (2019)	one day	counties	US
Protest	Legislator behavior	Pinckney (2019)	one day	counties	US
Protest	protest group creation	Pinckney (2019)	one day	counties	US
Mood	stock returns	Khanthavit (2017b)	daily	whole market	Thailand
Income	Contraceptive use	Abiona (2017)	yearly	villages	Uganda
famine	abandoning collective farming	Bai and Kung (2014)	yearly	provinces	China

x	y	source	temporal	spatial	context
Labor markets	Income	Swamy and Fikkert (2002)	yearly	countries	worldwide
Income	Conflict	Hodler and Raschky (2014)	yearly	countries	Africa
Weather	pirate attacks	Cook and Garrett (2013)	daily	whole country	Somalia
Pollution	Labor markets	Fontenla, Ben Goodwin, and Gonzalez (2019)	30 day average	postcodes	Mexico City
Pollution	Property values	Fontenla, Ben Goodwin, and Gonzalez (2019)	30 day average	postcodes	Mexico City
Weather	suicide	Deisenhammer (2003)	various	various	various
Weather	Health	Hales et al. (2000)	daily	whole city	Christchurch, New Zealand
Pollution	Health	Hales et al. (2000)	daily	whole city	Christchurch, New Zealand
prenatal care	birth outcomes	Gajate-Garrido (2013)	during mother's pregnancy	whole city	Philippines
Income	remittances	Pajaron (2017)	yearly	municipalities	Philippines

x	y	source	temporal	spatial	context
Income	domestic money transfers	Pajaron (2017)	yearly	municipalities	Philippines
turnout	Party vote share	Keele and Morgan (2013)	one day	counties	US
Weather	passenger train perfomance	Xia et al. (2013)	daily	whole country	Netherlands
Weather	budget balance	Lis and Nickel (2010)	yearly	countries	worldwide
Weather	Migration	Marchiori, Maystadt, and Schumacher (2012)	yearly	countries	Africa
Weather	Migration	Marchiori, Maystadt, and Schumacher (2012)	yearly	countries	Africa
Weather	Quantity	Cashin, Mohaddes, and Raissi (2017)	yearly	countries	21 Countries
Weather	Income	Cashin, Mohaddes, and Raissi (2017)	yearly	countries	21 Countries
Weather	inflation expectations	Cashin, Mohaddes, and Raissi (2017)	yearly	countries	21 Countries

x	y	source	temporal	spatial	context
Weather	Quantity	Cashin, Mohaddes, and Raissi (2017)	yearly	countries	21 Countries
Quantity	dietary diversity	Kubik and May (2018)	previous year	grid cells	South Africa
Migration	Labor markets	Kleemans and Magruder (2018)	yearly	districts	Indonesia
Migration	Conflict	Bhavnani and Lacina (2015)	yearly	states	India
Pollution	Health	Moretti and Neidell (2011)	daily	zip code	Los Angeles
Income	Crime	Blakeslee and Fishman (2018)	yearly	districts	India
Supply	Conflict	Caruso, Petrarca, and Ricciuti (2016)	yearly	provinces	Indonesia
child mortality	Fertility	Pitt and Sigle (1997)	monthly	weather station	Senegal
Weather	COVID19	Shen, Cai, and Li (2020a)	daily	regions	worldwide

x	y	source	temporal	spatial	context
Weather	forest extraction	Völker and Waibel (2010)	yearly	households (self-reported weather shocks)	Vietnam
Income	Health	Fichera and Savage (2015)	previous year	weather station	Tanzania
Income	Conflict	Miguel and Satyanath (2011)	previous year	countries	worldwide
Weather	Health	Frijters, Lalji, and Pakrashi (2020)	daily	counties	US
Weather	Mood	Frijters, Lalji, and Pakrashi (2020)	daily	counties	US
Weather	COVID19	Shen, Cai, and Li (2020b)	daily	regions	worldwide
Weather	Quantity	Veljanoska (2018)	yearly	districts	Uganda
Quantity	Conflict	Maystadt and Ecker (2014)	yearly	regions	Somalia
Income	savings	Aklilu (2007)	previous year	regions	Peru

x	y	source	temporal	spatial	context
Weather	turnout	Cooperman (2017)	one day	counties	US
turnout	Party vote share	Gomez, Hansford, and Krause (2007)	one day	counties	US
Weather	vitaminD	Sayers et al. (2009)	98 days pre-birth	full study	UK
Income	Conflict	Miguel, Satyanath, and Sergenti (2004)	yearly	countries	Africa
Weather	Protest	Zhang (2016)	daily	cities	DC and NY
Weather	Violent protest	Zhang (2016)	daily	cities	DC and NY
Quantity	Consumption	Lee and Chiu (2011)	yearly	countries	OECD countries
Weather	Migration	Nawrotzki, Riosmena, and Hunter (2013)	yearly	states	Mexico
Weather	Conflict	Sarsons (2015)	yearly	districts	India
Insurance	Income	Falco et al. (2014)	previous few years	municipalities	Italy
Weather	Crime	Bruederle, Peters, and Roberts (2017)	monthly	wards	South Africa
Weather	stock returns	Khanthavit (2017a)	daily	whole market	Bangkok, Thailand

x	y	source	temporal	spatial	context
Income	manufacturing growth	Shifa (2015)	yearly	countries	whole world
Quantity	Supply	Santeramo and Searle (2019)	yearly	countries	whole world
cycling	cycling	Goetzke and Rave (2011)	self-reported	municipalities	Germany
Income	Crime	Mehlum, Miguel, and Torvik (2004)	yearly	districts	Germany
Weather	land fragmentation	Bui et al. (2020)	yearly	communes	Vietnam
Mood	stock returns	Khanthavit (2019c)	daily	whole market	Thailand
skin tone	Labor markets	Katz et al. (2020)	weekly	metropolitan areas	US
Income	Consumption	Dacuycuy (2016)	previous year	provinces	Philippines
Weather	Inequality	Bayani-Arias and Palanca-Tan (2017)	3 years	provinces	Philippines
Weather	pavement roughness	Aguiar-Moya, Prozzi, and de Fortier Smit (2011)	yearly	pavement sections	US

x	y	source	temporal	spatial	context
turnout	vote choice	Artés (2014)	one day	municipalities	Spain
turnout	city performance	Lo Prete and Revelli (2014)	one day	municipalities	Italy
turnout	mayoral experience	Lo Prete and Revelli (2014)	one day	municipalities	Italy
Protest	Party vote share	Madestam et al. (2013)	one day	counties	US
Protest	Legislator behavior	Madestam et al. (2013)	one day	counties	US
Weather	Conflict	Hsiang, Burke, and Miguel (2013)	yearly	countries	worldwide
Protest	Property values	Collins and Margo (2007)	one day	census tracts	US cities
turnout	Party vote share	Knack (1994)	one day	counties	US
Violent protest	policy concessions	Huet-Vaughn (2013)	one day	weather station	France
Weather	Quantity	Wright (1929)	monthly	whole market	US
early life rainfall	Health	Maccini and Yang (2009)	previous year	districts	Indonesia
early life rainfall	Human capital	Maccini and Yang (2009)	previous year	districts	Indonesia
early life rainfall	asset ownership	Maccini and Yang (2009)	previous year	districts	Indonesia

x	y	source	temporal	spatial	context
Weather	Conflict	Hsiang, Meng, and Cane (2011)	yearly	countries	worldwide
Income	democratisation	Bruckner and Ciccone (2011)	yearly	countries	Africa
Supply	Quantity	Angrist, Graddy, and Imbens (2000)	daily	whole market	Fulton Fish Market (New York)
remittances	infant mortality	López-córdova (2006)	yearly	municipalities	Mexico
remittances	Human capital	López-córdova (2006)	yearly	municipalities	Mexico
remittances	Human capital	López-córdova (2006)	yearly	municipalities	Mexico
Income	savings	Paxson (1992)	previous year	regions	Thailand
Migrant social capital	migrant employment	Munshi (2003)	three or six years earlier	communities	Mexico/US
Weather	Conflict	Landis et al. (2017)	monthly	grid cells	Niger River Basin
Weather	Sales	Maunder (1973)	weekly	whole country	US

x	y	source	temporal	spatial	context
Income	Migration	Marchiori, Maystadt, and Schumacher (2017)	yearly	countries	Africa
Weather	Migration	Rappaport (2007)	long run weather	counties	US
Weather	lead exposure	Levin et al. (2020)	monthly	various	various
Weather	Mood	Bauer et al. (2012)	long run weather	cities	24 countries
Weather	Mood	Magnusson (2000)	various	various	worldwide
Weather	antiincumbent voting	Achen and Bartels (2016)	yearly	states	US
Weather	presidential approval	Cohen (2011)	daily	weather station	US
Income	incumbent voting	Healy and Malhotra (2010)	yearly	counties	US

Table 2: IVRelationships identified in the literature for IV studies where there are multiple intermediate variables. All studies have weather as an initial IV.

IV2	x	y	source	temporal	spatial	context
turnout	Party vote share	Government spending	Lind (2019)	one day	municipalities	Norway

IV2	x	y	source	temporal	spatial	context
turnout	Party vote share	Government spending	Tamada (2009)	one day	prefectures	Japan
helicopter flying conditions	oil platform inspectors	oil platform fines	Muehlenbachs and Cohen (2014)	quarterly	oil platforms	Gulf of Mexico
cotton growing suitability	slavery	political attitudes	Acharya, Blackwell, and Sen (2016)	long run weather	counties	US
economic activity	early life pollution	cognition	Peet (2014)	daily	Barangays	Philippines
economic activity	early life pollution	Income	Peet (2014)	daily	Barangays	Philippines
economic activity	early life pollution	height	Peet (2014)	daily	Barangays	Philippines

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