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**ABSTRACT**

We study rainmaking as an instrumental religious belief. We present a model in which a religious leader tries to persuade people to believe. Praying for rain can persuade only where the hazard of rainfall during a dry spell is increasing over time, so that prayer is most likely to succeed when people most want rain. We present evidence from prayers for rain in Murcia, Spain, where the hazard rate is increasing, that the church's prayers for rain predict rainfall over two centuries. To generalize this finding, we gather an original data set of whether ethnic groups around the world traditionally prayed for rain. We find that ethnic groups facing an increasing rainfall hazard are 47% more likely to pray for rain, consistent with our model's prediction that societies are more likely to pray for rain where prayer is persuasive.

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# 1 Introduction

> If ye walk in my statutes, and keep my commandments, and do them; Then I will give you rain in due season, and the land shall yield her increase, and the trees of the field shall yield their fruit.
>
> Leviticus, 26:3-4

> If we sacrifice and it rains, what does it mean? I say: it does not mean anything. It is the same as not sacrificing and having it rain.
>
> Xunzi, 3rd century BCE

Religious belief is often directed at worldly goals. Belief reaches beyond human experience, but people also call on the divine to bring fertility, health or good weather. That religious belief has worldly goals makes it hard to reconcile belief with rationality. Once a belief has a worldly goal, it becomes subject to evidence and falsification. How, then, can instrumental belief be sustained? This question has animated more than a century of debate between the giants of anthropology, philosophy and sociology.[1]

We study rainmaking, a canonical example of instrumental belief (Frazer, 1890). Good or bad rainfall can bring life or death. Religious leaders, both in magical belief systems and large formal religions, offer to dull this risk by bringing rain to grow crops or water animals. In the excerpt from Leviticus above, God offers rain in exchange for religious practice. The danger in such an offer is that, if God does not deliver, it may provoke skepticism towards religious authorities and their claims to power, as in the excerpt from Xunzi. Why would people believe in rainmaking if it does not work?

This paper provides a new theory of belief in rainmaking and an empirical analysis of rainmaking practice founded on newly-collected data. The theory lays out, using a model of cultural evolution (Henrich, 2015), how the pattern of rainfall in certain places can support belief in the control of nature. In our model, a religious leader tries to persuade a group of potential adherents (the people) that they can bring rainfall. The leader cannot in fact bring rain, but prays, at an arbitrary time, in hope that rain will follow. The people estimate the probability of rain based on how often it rains when the leader is not praying. If the leader

[1] A traditional school, following Frazer (1890), the founding text of the study of religion in anthropology, argues that both traditional belief systems and major world religions developed by offering ways to control nature (see also Hong, Slingerland and Henrich, 2024). This school views believers as both rational and sincere in their goals. A revisionist school, including the philosopher Ludwig Wittgenstein and Émile Durkheim, the founder of modern sociology, argues, at root, that religious belief and rationality cannot be reconciled. Revisionists see religious practice as a kind of social performance (Parsons et al., 1949; Radcliffe, 1963; Wittgenstein, 1967; Durkheim and Swain, 2008).

happens to pray at a good time, such that rain is more likely to fall during prayer, it may persuade the people that it has caused the rain. Such leaders will be more likely to gain support and their rainfall prayers will therefore persist over generations.

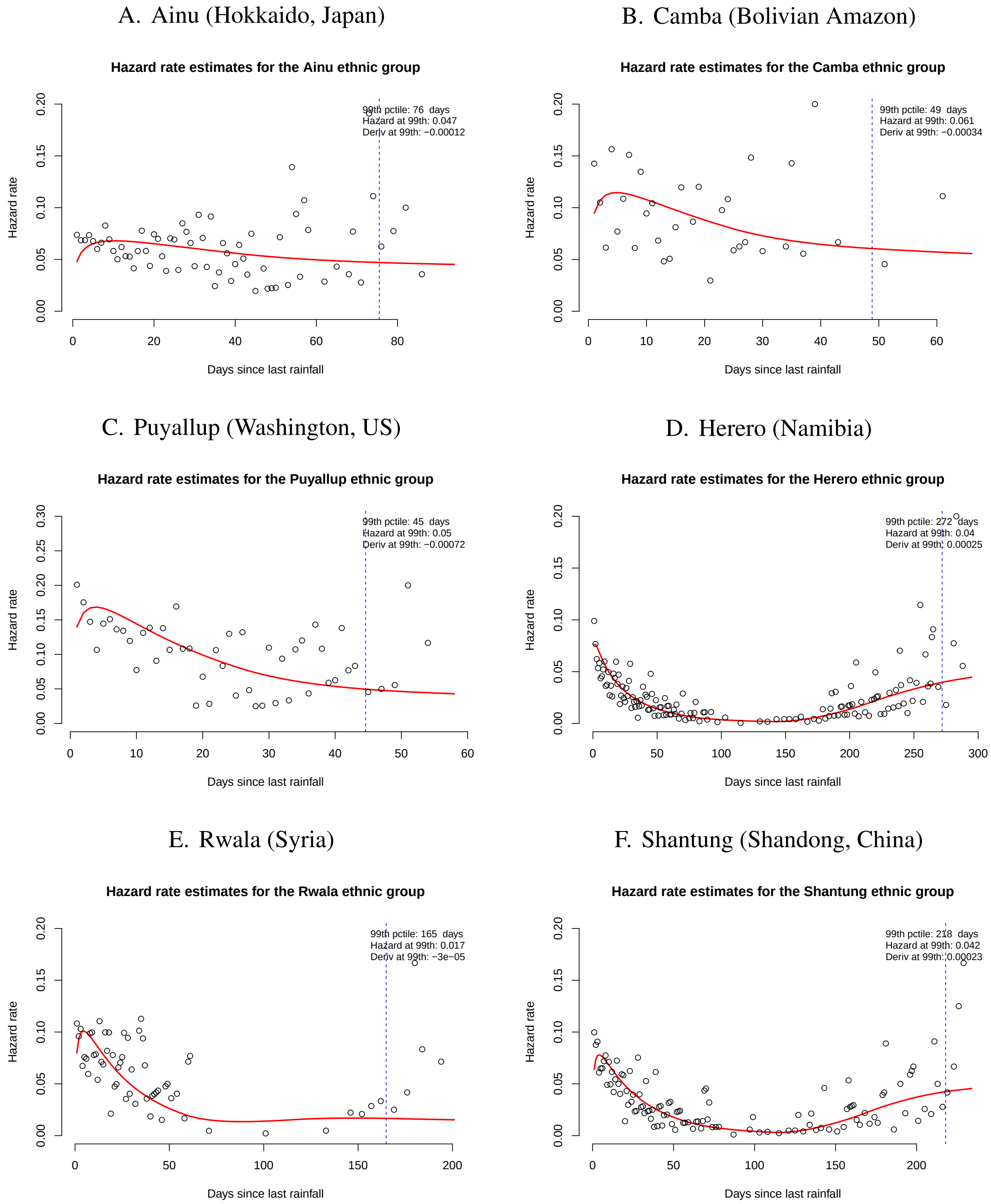
The bridge from our model to the world is that only in some places can praying at the right time be persuasive. Each place is distinguished by a local rainfall hazard function, which gives the probability of rainfall after a spell of days without rain. Figure 1 shows examples. In some places, the rainfall hazard is flat: the probability of rain on a given day is always about the same, regardless of whether it rained recently, as is the case for the Ainu of Japan (panel A). In other places, the rainfall hazard is declining, as for the Puyallup, a Native American tribe from near Seattle (panel C). In still other places, the rainfall hazard is increasing: in a drought, it becomes more and more likely to rain the further one gets from the last rainfall. The Herero of Namibia and the Shantung in China face a ∪-shaped hazard, so that the hazard of rain is increasing in a drought (panels D and F).

In our model, the hazard function matters because only some environments support belief. We prove that only in places with an increasing hazard rate can a leader persuade the people that the leader can bring rainfall. People are rational in forming beliefs but cannot know what the probability of rainfall during times of prayer would have been, if the leader had *not* prayed. When the hazard is increasing, people form a belief, from times without prayer, that the rainfall probability is generally low, and then witness a higher probability of rainfall once prayer begins. The most persuasive prayers begin during a drought, when the demand for rain and the probability of rain are both at their highest. The coincidence of these two factors only happens in environments with an increasing rainfall hazard. Such environments select for traditions of rainfall prayer based on the timing of prayers that have had success in the past. We therefore predict that rainmaking will be more persuasive, and thus more prevalent, when the hazard of rainfall is increasing during a dry spell.

We test this idea empirically with two kinds of evidence. First, we study daily prayers for rain by the Catholic church in the Spanish city of Murcia. We estimate the hazard of rainfall in Murcia and show that it is increasing and thus can support persuasion. The church in Murcia has made *pro pluvia* rogations, prayers for rain, since at least the 14th century (Espín-Sánchez and Gil-Guirado, 2022).[2] These prayers follow a pattern of escalation consistent with our model; prayers are more likely to be undertaken during a drought, and once they are begun, prayers continue until rain falls and the church declares success. We use novel daily data from 1600 to 1836 on the timing of prayers, from church records,

[2] This prior paper, by two of the three authors of the present paper, introduces data on prayer for rain in Murcia and uses the data to prescribe its practice. It does not found prayer for rain in a model of belief nor test for the predictive power of prayer for rainfall, as we do here.

Figure 1: Rainfall Hazard Functions from Around the World




*Notes*: The figure shows estimates of the hazard of rainfall after a dry spell for selected ethnic groups from the *Ethnographic Atlas*. The rainfall data are from the World Meteorological Association for the nearest station to each ethnic group's coordinates. On each panel the circles provide non-parametric Kaplan-Meier estimates of the hazard rate. The fitted curve gives a cubic spline fit to the hazard rate by maximum likelihood as described in Section 3.3. On each panel, we report: the 99th percentile of dry spell length in days; the daily hazard rate of rainfall evaluated at the 99th percentile of spell length; and, the derivative of the daily hazard evaluated at the 99th percentile of spell length.

and on notable rainfall events, from the records of the town council, kept independently of the church, to test whether prayers for rain predict rainfall.

The main finding from Murcia is that prayer is highly predictive of future rainfall, as our model predicts for an environment with an increasing hazard. We find that a prayer for rain in the last month predicts a 71% increase in the probability of a notable rainfall on a given day. The predictive power of rainfall is based in part on the seasonality of prayer matching that of rainfall, but the prayer strategy is not a rote function of the calendar: prayer is predictive of rainfall even within a given month of the year, and prayer Granger-causes rain conditional on lags of recent rainfall. We conclude from the case study of Murcia that, in an environment with an increasing hazard, religious leaders can practice rainfall prayer in a way that predicts rainfall and will thereby tend to promote instrumental belief.

The Murcia case allows exceptional visibility into the timing of rainfall prayer but may show the singular practice of one sophisticated church. It does not give evidence on the origin of belief in general. The revolutionary aspect of Frazer's (1890) study is its attempt to generalize on the causes of belief from a wide body of idiosyncratic practices.

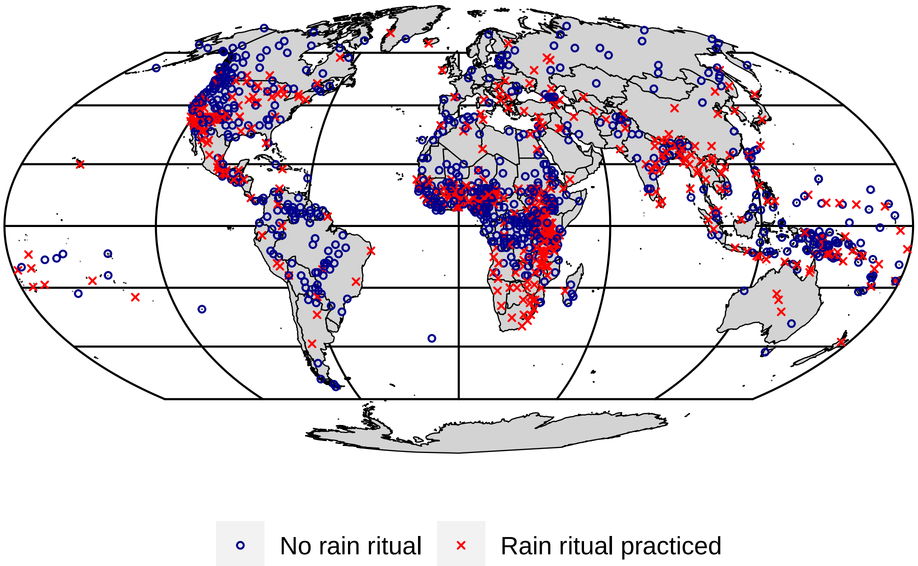
To allow such generalization, we assemble a new data set on the practice of rain rituals around the world. We use as a template the *Ethnographic Atlas* (Murdock, 1967), which measures the traditional economic, political and social practices for 1,290 ethnic groups.[3] We combed through an extensive anthropological literature, drawing on 370 sources, to record rainmaking practice for 1,208 ethnic groups. A typical source is a group-specific anthropological monograph on the customs of a single ethnic group or a handful of related groups; we include our full bibliography as a supplementary appendix. For many groups, we find rich narrative accounts of rainmaking practice. The Cherokee dance for rain and chant a song to the Great Spirit; the Herero sprinkle a calf with water, allow it to wander about, and then sacrifice the animal; Iranian women wage a mock battle and capture their neighbors' animals, to release them only when it rains; the people of Shandong, China beseech the rain dragon for rain, and, if it refuses, abuse the dragon and desecrate its temple (Heimbach Jr, 2001; Schmidt, 1979; Başgöz, 2007; Cohen, 1978).

Our data create worldwide coverage of a traditional practice that has played a central role in accounts of the development of religion (Frazer, 1890). We find that rainmaking is indeed widespread, practiced by 39% of the ethnic groups in the *Atlas* and on every settled continent (Figure 2, panel A). We view this number as a lower bound, since we only mark a group as praying for rain if we find clear evidence of the practice of a rain ritual.

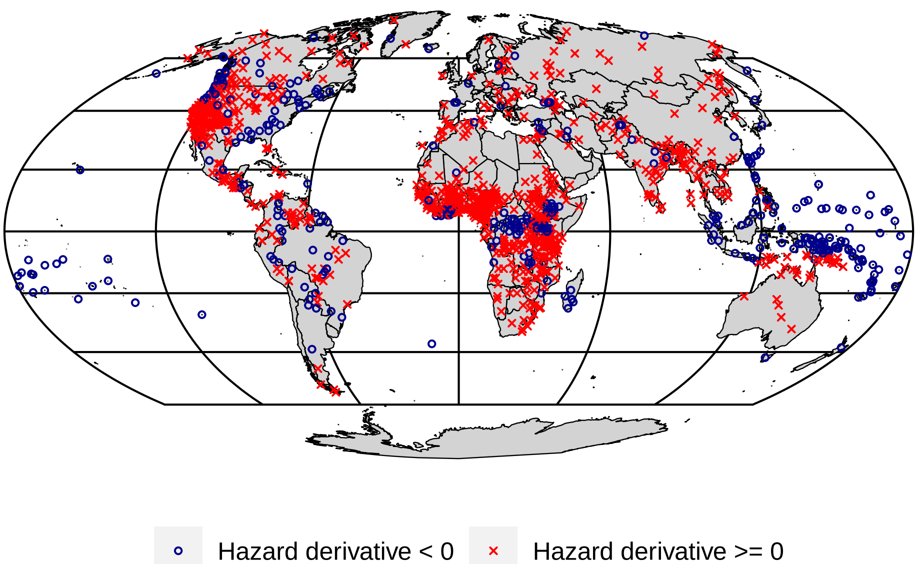
[3]The *Atlas* has been used extensively in economic history (Gennaioli and Rainer, 2007; Nunn, 2008; Alesina, Giuliano and Nunn, 2013; Fenske, 2013; Michalopoulos and Papaioannou, 2013; Alsan, 2015). We use the version of the *Atlas* extended by Giuliano and Nunn (2021) to include additional ethnic groups.

Figure 2: Global Prevalence of Rain Rituals

A. Rain ritual




B. Hazard rate increasing




*Notes*: Panel A shows whether ethnic groups practice a rain ritual or not, based on our original data collection for groups in the *Ethnographic Atlas*. Panel B indicates whether groups face an increasing hazard of rainfall.

The new global data on rainmaking yield two main findings. First, in support of our model of instrumental belief, ethnic groups facing an increasing hazard of rainfall are more likely to pray for rain. We match each ethnic group to its nearest weather station and use modern rainfall data to estimate the hazard function that each group would face in its ancestral location (as in Figure 1). We then use the rainmaking data to test the idea that environments with an increasing rainfall hazard support instrumental belief. We estimate that 30% of groups facing a non-increasing hazard pray for rain and that this increases by 14 pp (standard error 3.7 pp) for groups facing an increasing hazard of rainfall (hence a 47% increase). This result is robust to a battery of geographic and climatic controls. A naïve theory of rainmaking would be that people pray for rain when they do not get much, or perhaps when rainfall is unreliable. We use modern weather data to form weather and climate norms for each group and adopt the climatic variability measure of Giuliano and Nunn (2021) to measure longer-term changes in climate. It is not a dry, or a variable, climate per se that induces prayer—lower average rainfall, longer droughts and climatic variability are not associated with more rainfall prayer, conditional on the shape of the hazard rate—but specifically whether the hazard function is increasing during a drought that matters.

Second, ethnic groups with higher demand for rainfall, for settled agriculture, are more likely to pray for rain. Rainmaking may depend not only on persuasion but also the costs and benefits of rain ritual practice. To test this idea, we use the *Atlas* categorization of a group's traditional means of subsistence to see how demand for rainfall affects rain ritual practice. Groups that are dependent on agriculture are 11 percentage points more likely to practice rainmaking, and ethnic groups dependent on intensive or intensive irrigated agriculture are, respectively, 21 and 32 percentage points more likely (on a base of 32%). The econometric evidence and narratives of rainfall prayer suggest an interpretation that settled agriculture, relative to subsistence from roving or casual agriculture, animal husbandry or fishing, increases demand for the control of nature. Groups that have made fixed, location-specific investments in agriculture are more likely to pray for rain because their sustenance depends on the weather in that one place.

Our interpretation of the findings from both Murcia and the global data is that rainmaking is adopted when it is persuasive. In Murcia, we find that rainfall prayer, as practiced for hundreds of years, is highly predictive of rainfall, which in our model is possible when the hazard of rainfall is increasing. In the global data we validate that ethnic groups are more likely to adopt rainmaking in places where it is demanded and likely to be persuasive. Rainmaking can therefore be understood as an instrumental religious practice, even though it does not work, because it responds to variation in *perceived* efficacy.

This paper contributes to literatures in economic history, economic development, the economics of religion and anthropology. Our paper is part of a literature in economic history that traces the effects of geography on the development of economic and political institutions[4] as well as cultural traits.[5] This literature shows the functional benefits of institutions: institutions and cultural traits emerge at places and times where they benefit society. This basic thesis is drawn from an older, anthropological literature on functionalism, which economics has enriched with new empirical evidence (Malinowski, 1944; Radcliffe-Brown, 1952; Besley, 2021; Nunn, 2022).

Our contribution, relative to this literature, is to show that the environment shapes belief. This mechanism is absent from a pure functional model, in which culture evolves based only on tangible costs and benefits. While we find, as in prior research, that religious practice responds to demand, rainmaking is not simply greatest where it has the highest benefits. Belief also requires persuasion, which depends on the environment. In our model, it may be that households in dry areas suffer from bad rainfall, and would want more rain, but they nonetheless will not find it worthwhile to pray unless they believe that prayer will work. The environment acts on peoples' choices through their information, not only through the payoffs for their actions.

Our paper also contributes to the literature on the origins of religiosity. Religious belief has been argued to be both socially and individually adaptive.[6] People use religion as a means of insurance against natural and economic shocks.[7] Religion has been argued, at a societal level, to play an important role in forming social norms and in legitimizing political rulers (Norenzayan, 2013; Rubin, 2017). An over-arching theme in this literature

[4]For example: Nunn and Qian (2011) show that European cities near areas suitable for potatoes grew faster after the potato arrived; Nunn and Puga (2012) argue that rugged geography raised the cost of enslaving people and so encouraged later economic development; Chaney (2013) documents that in Islamic Egypt the highest religious authority became more powerful when the Nile had an abnormally extreme flood; Fenske (2013) argues that land abundance predicts land rights and population density in Africa; Alsan (2015) shows that a climate suitable for the Tsetse fly reduces the domestication of animals and political centralization.

[5]Alesina, Giuliano and Nunn (2011) and Alesina, Giuliano and Nunn (2013) link traditional plough use to modern fertility and gender norms. Giuliano and Nunn (2021) set out a model in which traditions are more valuable, and therefore more widely followed, in a stable environment. They find empirically that a climate that is more variable across generations reduces the importance of tradition.

[6]Clingingsmith, Khwaja and Kremer (2009) find that completing the Hajj increases beliefs in Muslim unity. Nunn and Sanchez de la Sierra (2017) argue that false beliefs on the efficacy of magic persist because, while dangerous to individuals, they encourage behavior that is socially adaptive for a group. Le Rossignol, Nunn and Lowes (2022) show how people in the Democratic Republic of Congo that hold traditional beliefs are treated differently by others. Bryan, Choi and Karlan (2021) study belief in a randomized experiment and find that proselytizing for evangelical Protestantism increases the income of converts, at least temporarily. Butinda et al. (2023) find that believers update their expectations and invest more in inventory in response to a protective religious ritual.

[7]Globally, the most vulnerable populations tend to be the most religious (Norris and Inglehart, 2004). Chen (2010) and Ager and Ciccone (2018) find that larger financial and rainfall shocks, respectively, are associated with higher participation in organized religion, as a means of insurance. Religiosity and church power increase after natural disasters (Belloc, Drago and Galbiati, 2016; Sinding Bentzen, 2019). Auriol et al. (2020) conduct an experiment in Ghana offering formal insurance to churchgoers. They find that formal insurance causes people to donate less to their church, as well as to secular recipients, in dictator games.

has been to document instrumental benefits: how religion is useful to adherents and how that usefulness drives religiosity and undergirds social and political institutions.

Our contribution is to provide and validate a new theory of why instrumental belief arises in the first place. The literature provides evidence on the benefits of religious practice, but circles the question of why people do or do not find instrumental beliefs to be credible. Landmark reviews on the economics of religion point to a gap in the field precisely here—that we lack theories of belief formation (Iannaccone, 1998; Iyer, 2016). We argue that religious practice is greater where ritual *seems* to be more effective. Rainmaking is a useful practice to study because for rainmaking, unlike for other instrumental practices, we can define and measure the conditions for seeming efficacy precisely.

Finally, our findings on the persuasive nature of rainmaking bring new evidence to an important debate in anthropology. For more than a century, anthropologists have differed on whether to interpret traditional religious practices, including rainmaking as a key example, as sincere attempts to control nature or as simply performative or symbolic (Tambiah, 1990). The traditional school says that belief is instrumental: people engage in rainmaking to make rain (Frazer, 1890; Hong, Slingerland and Henrich, 2024). A revisionist school argues that beliefs about human affairs and the supernatural are fundamentally distinct, and so religious belief should not be expected to respond to empirical evidence.[8] We find that rainmaking is more prevalent where it is more persuasive, supporting the traditional interpretation that belief is instrumental.

The structure of the paper departs slightly from the norm. Section 2 lays out our model of religious persuasion. Section 3 then shows that rainmaking prayers in Murcia, Spain are practiced in a way consistent with our model. Section 4 introduces our global data and describes the variety of rainmaking practices. Both of these sections are self-contained in that they cover the description of the context, data and empirical methods for Murcia and the augmented *Ethnographic Atlas*, respectively. Section 5 then tests whether our model predicts rainmaking globally. Section 6 concludes.

[8]The revisionists separate human beliefs and conduct into the worldly and the sacred. This degree of freedom allows explanations for religious behavior that do not require rationality but explain religious practice as symbolic (Levy-Bruhl, 1926; Parsons et al., 1949; Radcliffe, 1963; Staal, 1979; Durkheim and Swain, 2008). For Wittgenstein (1967), for example, rainmaking is not sincere, but an emotional performance. Recent work on ritual has tried to synthesize rational and performative motivations by arguing that rituals must be opaque to sustain uncertainty over whether they work (Legare and Souza, 2012; Whitehouse, 2023).

# 2 Model

This section models when prayer for rain is likely to be persuasive. Nature determines the pattern of rainfall. A religious leader prays for rain. For some rainfall patterns, a well-timed prayer is more likely to be followed by rain, persuading people to support the leader. Leaders whose prayers happen to be better timed induce higher support and are more likely to survive across generations. The model therefore describes a process of cultural evolution, in which leaders act as cultural entrepreneurs, and those with the most persuasive ideas are more likely to persist (Mokyr, 2012; Hong, Slingerland and Henrich, 2024).

## 2.1 Set-up

**Players and timing.—** Generations are discrete and indexed by $g = \{1, 2, \ldots\}$. A religious leader indexed $j = \{1, 2, \ldots\}$ enters in each generation. There are people of unit mass indexed by $i$ who want rain. Within each generation $g$, there are many rainfall spells. The rainfall process repeats again and again in different spells with a new start each time it rains. Within a spell, time is indexed by $t \in [0, \infty)$, the number of days that have passed since it last rained.

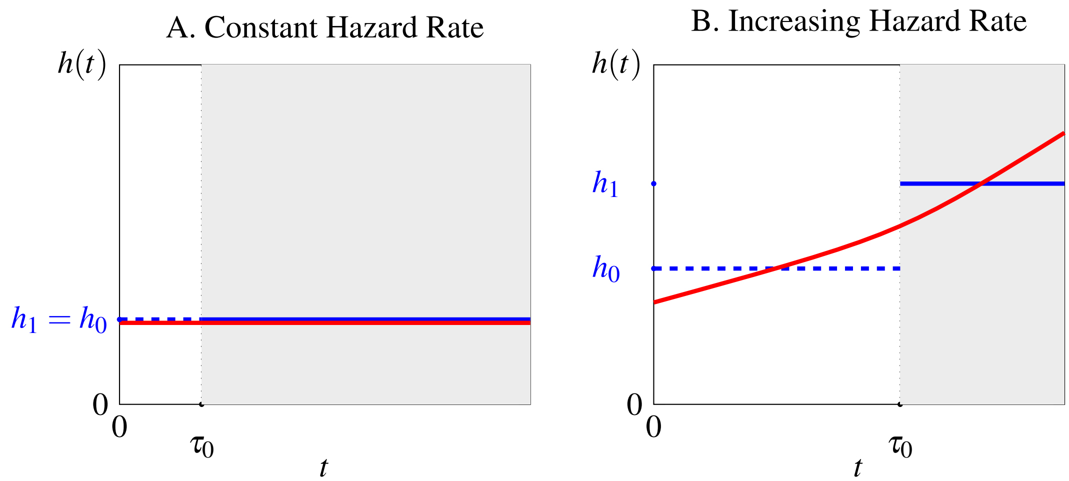
**Rainfall.—** Nature determines the rainfall process. We characterize the process of rainfall with the hazard rate $h(t) = f(t)/(1 - F(t))$, where $f(t)$ is the probability density function (pdf) and $F(t)$ is the cumulative distribution function (cdf). The hazard rate gives the instantaneous probability of rainfall at time $t$ (see Figure 1 for some examples of rainfall hazards). We define two useful parameters of the rainfall process:

$$\alpha \equiv \lim_{\tau \to 0} \frac{1}{1 - e^{-\tau}} \int_0^\tau h(t) e^{-t} dt = h(0) \qquad \eta \equiv \lim_{\tau \to \infty} \frac{1}{1 - e^{-\tau}} \int_0^\tau h(t) e^{-t} dt. \quad (1)$$

Here $\alpha$ is the instantaneous hazard rate at $t = 0$ and $\eta$ is the average unconditional hazard rate. We define the unconditional hazard rate subject to exponential discounting so that this average will exist even when the hazard rate increases for $t \to \infty$.

**Prayer and conditional hazard rates.—** A leader starts praying for rain at some time $\tau_0$ and continues until it rains, which ends one spell and begins the next. The time $\tau_0^j$ of leader $j$ is endowed at entry in generation $j = g$. While we call the prayer start time $\tau_0^j$ a "policy," it is strictly exogenous here, as an endowment of each leader. We can obtain similar results in an alternative formulation of the model in which the leader instead strategically chooses the timing of prayer.

Figure 3: Examples of Religious Experiments created by Rainfall and Prayer Timing




*Notes*: The figure shows examples of the experiments created by different hazard functions for rainfall and prayer policies. The two panels plot the rainfall hazard rate against time on the horizontal axis. The hazard rate is shown by the solid red line or curve and prayer is indicated by the shaded gray intervals. In panel A, the hazard is flat. The hazard rates conditional on no prayer ($h_0$, in solid blue) and with prayer ($h_1$, dashed blue) are the same. In panel B, the hazard is increasing (panel B). We give an example where prayer starts at some $\tau_0 > 0$ and then continues thereafter. The hazard rate during prayer ($h_1$, in solid blue) is higher than the hazard rate without prayer ($h_0$, in dashed blue).

Prayer partitions time into two segments: without prayer and with prayer. Figure 3 illustrates how the timing of prayer interacts with the hazard function. Each panel plots the hazard of rainfall (red solid curve) against the time since the last rainfall. Panel A shows a constant hazard and Panel B shows an increasing hazard.[9] In each panel, the periods during prayer are shaded in grey. The timing of prayer defines the conditional hazard rates

$$h_0(\tau_0) \equiv \frac{1}{1-e^{-\tau_0}} \int_0^{\tau_0} h(t) e^{-t} dt \tag{2}$$

$$h_1(\tau_0) \equiv \lim_{\tau \to \infty} \frac{1}{e^{-\tau_0} - e^{-\tau}} \int_{\tau_0}^{\tau} h(t) e^{-t} dt. \tag{3}$$

In Figure 3, the blue dashed horizontal line in the figure illustrates $h_0(\tau_0)$, the hazard of rainfall without prayer. The blue solid horizontal line indicates $h_1(\tau_0)$, the hazard of rainfall during prayer.

**People's beliefs and actions.—**A person will choose to support the leader when they believe it is more likely than not that prayer works, that is, God hears the leader's prayer

[9] See Figure A1 in the appendix for a decreasing and a ∪-shaped hazard.

and delivers rainfall. A person chooses a binary action $a_i \in A = \{a_0, a_1\}$ when it rains at the end of each spell. Action $a_0$ is *not to support* the leader and $a_1$ is to *support* the leader. Support for the leader may mean offering a donation, giving a religious name to a child or defending their political power.

A person, at the start of every spell, has a prior belief $p < 0.5$ that prayer works. (If $p > 0.5$, the person will always support the leader, even if the leader never prays.) Because there are many rainfall spells, people know the conditional hazard rates without prayer (2) and with prayer (3) in their generation. A person believes that, if prayer does not work, the hazard rate always equals the hazard rate $h_0(\tau_0)$ that the person observes when the leader is not praying. We therefore assume that the person, somewhat naïvely, extrapolates the hazard *function* from the mean hazard that they observe without prayer.

The simple form of beliefs we have assumed here is not necessary for our result that an increasing hazard function allows persuasion. What is needed is that people's forecasts about the probability of rainfall in the absence of prayer are less flexible than the true form of the hazard function. We present here the simplest case, where people believe the hazard rate to be constant and the leader can persuade the people if the hazard rate is increasing. In Appendix A.5, we show how this can be generalized, to a case where the people think the hazard rate is increasing and linear and the leader can persuade if the hazard rate is increasing and convex. The logic is the same: people under-predict the out-of-sample probability of rain without prayer and attribute the gap to divine intervention. Such a belief will never be contravened, because the leader always prays after $\tau_0^j$, so people never see rainfall realizations without prayer that might contradict their beliefs.[10]

If the leader prays *and* God listens, a person believes the hazard rate to be $\omega_i$. This scalar is a fundamental parameter of the model and does not depend on the leader's prayer. Beliefs are distributed among people with $\omega_i \sim F_\omega(\omega_i)$ on support $\omega_i \in [\underline{\omega}, \overline{\omega}]$. We define an assumption about the strength of belief.

**Assumption 1** (Meaningful belief)**.** $\Delta_i \equiv \omega_i - \eta > 0$.

The scalar $\Delta_i$ measures the strength of belief, specifically, the increase in hazard rate that

[10]The idea of inference based only on what is observed is a central theme in the psychologist Daniel Kahneman's career-spanning book "Thinking Fast and Slow" (Kahneman, 2011). He describes a core principle of intuitive reasoning as "what you see is all there is," in which people do not reason or extrapolate beyond their immediate experience. Hong, Slingerland and Henrich (2024) argue, with reference to literature in behavioral economics and psychology, that heuristic decision-making of this kind might contribute to sustained belief in rainmaking, despite that rainmaking is ineffective. While we allow that people may make behavioral errors in inference, it is not necessary that they are making mistakes for our model to apply. In game theoretic terms, since the event of a long drought where prayer has *not* begun is "off-path," beliefs over what happens conditional on this event are not defined. In that sense, people's beliefs cannot be wrong. It is not that they do observe, and fail to learn from, contradictory information, but that they have no opportunity to acquire such information in the first place.

the people expect to see if God listens. Assumption A1 means that a person believes that if God listens the chance of rain will increase beyond the unconditional hazard rate $\eta$.

## 2.2 Analysis of belief within a generation

**Beliefs and the people's problem.—**Prayer creates two possible signals in a given spell. If it rained without prayer signal $s_0$ is realized. Given a policy $\tau_0$, this happens with probability $\mathbb{P}[s_0|\tau_0] = F(\tau_0)$. If it rained during prayer signal $s_1$ is realized. This happens with the complementary probability $\mathbb{P}[s_1|\tau_0] = 1 - F(\tau_0)$.

The people believes that God may or may not listen in a given spell. A person estimates the mean hazard of rainfall if God does not listen as $h_0(\tau_0)$. The person expects the hazard of rain during prayer to be

$$\hat{h}(\tau_0|\omega_i) \equiv p\omega_i + (1-p)h_0(\tau_0), \tag{4}$$

where the parameters $p$ and $\omega_i$ measure the probability God listens and the strength of belief. The person believes that God listened when signal $s_1$ is realized and

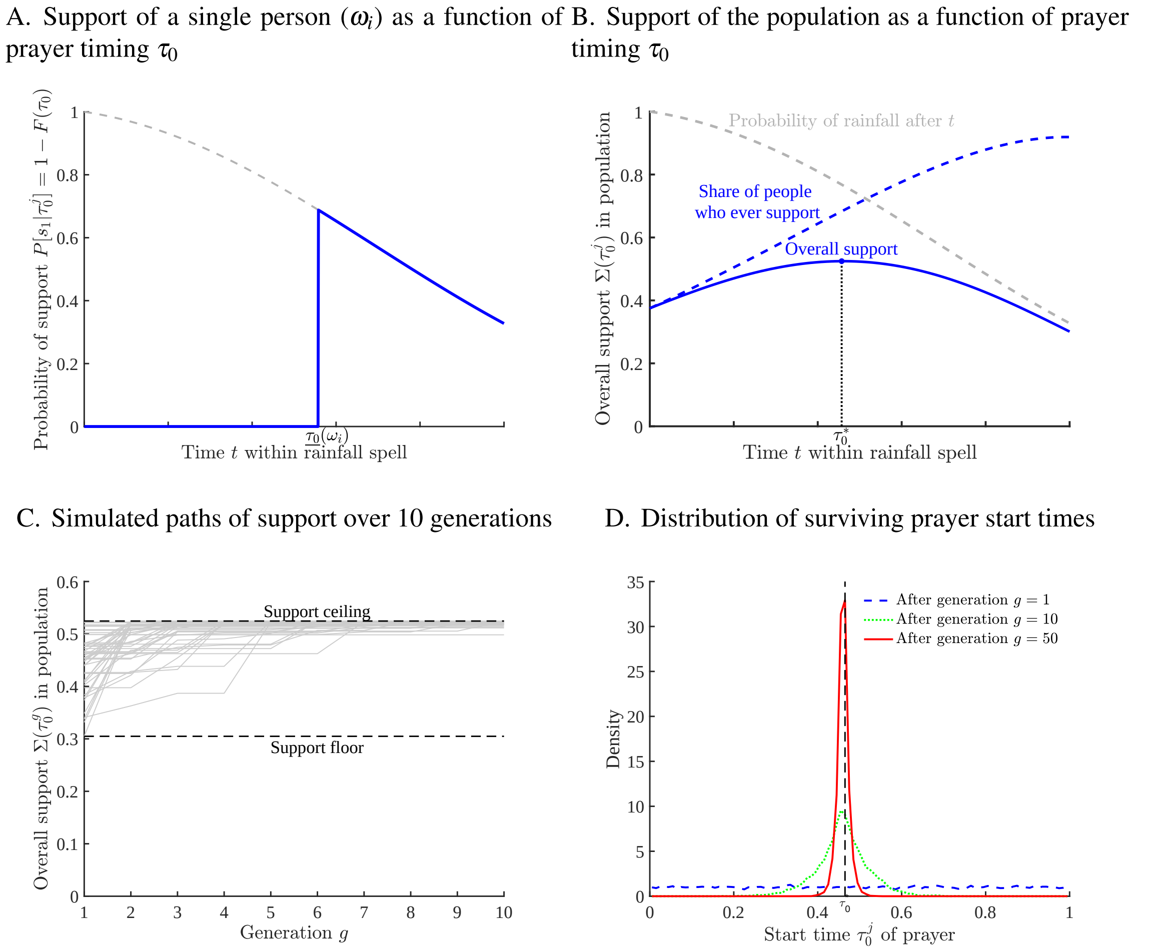
$$h_1(\tau_0) \geq \hat{h}(\tau_0|\omega_i). \tag{5}$$

This key restriction represents the person's skepticism. If signal $s_1$ is realized, but (5) is not satisfied, it means that the hazard of rainfall during prayer is not *generally* as high as the person would expect if God was listening. The person would therefore attribute rainfall during prayer ($s_1$) to the leader getting lucky, during a particular spell, rather than being able reliably to call on God to intervene in the world by bringing rain. A higher probability that God listens $p$ or a stronger belief $\omega_i$ make this threshold more difficult to meet.

Figure 4, panel A illustrates the probability of support as a function of the time $\tau_0$ when prayer starts, for a single person with belief $\omega_i$. We define $\underline{\tau}_0(\omega_i)$ as the lowest value of $\tau_0$ for which (5) is satisfied. Below this threshold, support is zero, because, although rainfall often occurs during prayer, the person does not attribute rainfall to the leader's intervention. Above this threshold, the probability of support is declining as $\mathbb{P}[s_1|\tau_0] = 1 - F(\tau_0)$. In this region, prayer is persuasive, but the later the leader begins praying, the less often rainfall happens during prayer. The probability of support from one person with belief $\omega_i$ is therefore maximized for a prayer starting exactly at $\underline{\tau}_0(\omega_i)$. If prayer starts too late, above some $\overline{\tau}_0(\omega_i)$ (not shown in panel A), the gap between the hazard of rain with and without prayer will again not be large enough to satisfy (5). Proposition 1 summarizes when prayer will be persuasive.

**Proposition 1.** *With an increasing hazard rate, for each $\omega_i$ there is a unique interval $T(\omega_i) = (\underline{\tau}_0(\omega_i), \overline{\tau}_0(\omega_i))$ such that a person will support if and only if $\tau_0^j \in T(\omega_i)$.*

Figure 4: Evolution of People's Support in an Environment with an Increasing Hazard




*Notes*: Panel A shows the support of a person with $\omega_i$. Panel B: dashed grey line is the survival rain function $1 - F(\tau_0)$; red line is the fraction of people that are persuaded by the ritual; blue line is the expected support $\Sigma(\tau_0)$. Panel C shows twenty paths of simulated support with $F_\tau(\tau_0)$ follows $U[0,1]$. Panel D shows the PDF of surviving prayer start times after 1, 10 and 50 generations.

*Proof.* See Appendix A.3. □

A person may remain skeptical. Depending on the hazard function and the strength of the person's belief $\omega_i$, there may not exist any $\tau_0$ that satisfies the constraint (5). Appendix A.3 extends Proposition 1 to describe three tiers of belief $\omega_i$. People with weak beliefs are always convinced by rainfall during prayer, even if the leader *always* prays ($\underline{\tau}_0(\omega_i) = 0$). People with moderate beliefs need a larger gap between the hazard rate with and without prayer to be convinced, and so only support if prayer starts later ($\underline{\tau}_0(\omega_i) > 0$). People with infeasible (i.e., very high) beliefs are never convinced (i.e., $T(\omega_i)$ is empty).

**Dependence of persuasion on hazard function.—**Whether prayer can be convincing depends not only on the strength of belief but also on the shape of the hazard rate. A constant hazard rate, in particular, does not allow persuasion.

**Proposition 2** (Constant hazard rate)**.** *If the hazard rate is constant,* $p < 0.5$*, and a person has meaningful belief* $\omega_i$ *(A1), then the person will not support for any* $\tau_0^j$*.*

*Proof.* A constant hazard rate $h(t) = \alpha$ implies $h_0(\tau_0) = h_1(\tau_0) = \eta = \alpha$. The hazard of rainfall is the same whether the leader is praying or not. Substituting into equation (5) using (4) yields $\eta \geq p(\eta + \Delta_i) + (1-p)\eta$ which implies $\Delta_i \leq 0$, contradicting A1. □

In a location with high rainfall, it will rain a lot when the leader prays, but also when the leader does not pray (as in the epigraph, at the start of the article, from Xunzi). Similarly if rainfall is low. Therefore, our model predicts that, with a constant hazard, prayer will not be persuasive, regardless of the timing of prayer or the average level of rainfall. The person needs to see an increase in the hazard rate during prayer to validate meaningful belief.

The scope for convincing people depends on the environment, i.e., the shape of the rainfall hazard. Consider the case of an increasing hazard rate.

**Proposition 3** (Increasing hazard rate)**.** *If the hazard rate is increasing and* $p < 0.5$*, then there exists a meaningful belief* $\omega_i$ *for which a person will support for all* $\tau_0^j \geq 0$*.*

*Proof.* The constraint (5) binds for belief $\widehat{\omega}_i(\tau_0) = (1/p)(h_1(\tau_0) - h_0(\tau_0)) + h_0(\tau_0)$, meaning a person with at most this strong a belief can be persuaded by prayer $\tau_0$. Suppose $\widehat{\omega}_i$ is not meaningful so that $\widehat{\omega}_i < \eta$. Then $(h_1(\tau_0) - h_0(\tau_0)) < p(\eta - h_0(\tau_0)) < (\eta - h_0(\tau_0))$, implying $h_1(\tau_0) < \eta$, which for $\tau_0 > 0$ contradicts that the hazard rate is increasing. □

This statement distinguishes increasing hazard rates, for which persuasion is possible, from constant hazard rates, for which it is not. Nonetheless, the statement is weak in that it is consistent with prayer for rain gaining very little support, depending on the distribution of people's beliefs. In the next part we consider the support that will be gained by different prayers $\tau_0^j$ given an increasing hazard rate and some distribution of beliefs.

**Prayer timing and overall support.—**The overall support a leader earns depends on the timing of prayer and the distribution of beliefs among the people. Define $\widehat{\omega}_i(\tau_0^j) = (1/p)(h_1(\tau_0^j) - h_0(\tau_0^j)) + h_0(\tau_0^j)$ as the highest value of $\omega_i$ such that (5) is satisfied for $\tau_0^j$. In Appendix A we show that support is monotonic, in the sense that if a person with $\omega_i$ supports during a spell, a person with the weaker belief $\omega_k < \omega_i$ will also support (Lemma 1).

So a leader who begins praying at $\tau_0^j$ will earn support from all $i$ with $\omega_i \in [\underline{\omega}, \widehat{\omega}_i(\tau_0^j)]$, when it rains during prayer. The leader's *overall support* is therefore

$$\Sigma(\tau_0^j) = \int_{\underline{\omega}}^{\widehat{\omega}_i(\tau_0^j)} (1 - F(\tau_0^j))\, dF_\omega \tag{6}$$

where the integrand is *how often* a person will support the leader, across spells, and the range of integration spans the set of people who are convinced by the leader's prayer, when successful. This *following* is fixed by the leader's policy.

Figure 4, panel B illustrates the trade-off in prayer timing. The later a leader prays, in this example, the higher the $\omega_i$ for which (5) will be satisfied, and so the more people support the leader when it rains during prayer (dashed blue line, share of people who ever support). A leader who begins praying later can create a greater gap in the hazard rate between the periods without and with prayer, and therefore convince people with stronger beliefs (higher $\omega_i$), gaining a large following. The cost is that, due to reserving prayer for long droughts, such a leader will gain support less often, because their high standards allow fewer opportunities to convince the people. Therefore the level of overall support is ∩-shaped (solid blue line, overall support), with an internal maximand at $\tau_0^* = \arg\max_{\tau_0} \Sigma(\tau_0)$. This optimal policy balances the credibility of the leader—the need to persuade skeptics—against how often they will be persuaded.

## 2.3 Evolution of belief across generations

With this description of belief within a generation, we can now describe how traditions evolve across generations. Each generation, a new potential leader appears, endowed with $\tau_0^j \sim F_\tau(\tau_0^j)$ where $\tau_0^j \in \mathbb{R}^+$. That is, potential leaders pray at *random* times. Because leaders are not optimizing the timing of their prayer, they do not require or use any information not available to the people. In particular, leaders do not need to know the hazard function.

Each generation $g$ but the first has an incumbent leader who prays beginning at $\tau_0^{g-1}$. We assume a simple transition rule: the challenger will depose the incumbent leader if the challenger gains strictly more support, $\Sigma(\tau_0^j) > \Sigma(\tau_0^{g-1})$. If both candidates gain equal support, then the incumbent will survive with probability $q \in [0.5, 1]$. If the challenger succeeds, the prayer of the challenger $\tau_0^j$ becomes practiced in that generation $\tau_0^g = \tau_0^j$. Otherwise, the prior generation's leader and prayer remain. Proposition 4 summarizes the main prediction on cultural evolution under this transition process.

**Proposition 4** (Cultural evolution)**.** *Let $g(\tau_0^j)$ be the number of generations that ritual $\tau_0^j$ will continue to be practiced. If the hazard rate is increasing, and $T(\omega_i)$ is not empty for all $\omega_i$, then $\mathbb{E}[g(\tau_0^j)] \geq \mathbb{E}[g(\tau_0^k)]$ if and only if $\Sigma(\tau_0^j) \geq \Sigma(\tau_0^k)$.*

*Proof.* See Appendix A.3. □

Rituals with high support are more likely to persist over time. The implication of Propositions 2, 3, and 4 are that in environments with an increasing hazard rate, it is possible for prayer to be persuasive. In these environments, random prayers that gain higher support are more likely to persist. Because each generation adopts a policy weakly more persuasive than the prior generation, the level of support will rise over time as policies move closer to the optimum $\tau_0^*$. Conversely, societies with a long tradition of rain ritual practice will have higher support for (i.e., be more likely to practice) rainfall prayers.

Figure 4, panel C shows draws of simulated paths of cultural evolution. People with weak beliefs support from the start. Over time, the level of support rises weakly monotonically on each path. Each jump in support represents the leader from generation $g-1$ being deposed and a new policy being adopted. The overall level of support therefore converges towards the maximal level of support, which is determined by the share of people who have weak or moderate (therefore not infeasibly high) beliefs. Panel D shows how this process narrows the prayers that are offered. Each solid line on the panel shows the density of the distribution of $\tau_0^g$ at generation $g \in \{1, 10, 50\}$. The density of surviving prayers clusters more closely around the optimum in later generations. Successful ritual practice has a longer expected lifetime because as prayers become more persuasive the probability of a leader being replaced diminishes.

## 2.4 Extension: Tangible Benefits and Costs of Prayers

We now extend the baseline model to allow for tangible benefits of rainfall and costs of prayer. Benefits depend on the demand for rainfall due, for example, to rainfall increasing crop yields. Costs could variously be an offering to a church, the inputs to a ceremony, like sacrificial livestock, or the opportunity costs of time.

Let the benefit of rainfall be $\mu$ and the cost of support be $\kappa$. We call $\hat{\mu} \equiv \mu/\kappa$ net benefits. A person will support if

$$\left(h_1(\tau_0) - \hat{h}(\tau_0|\omega_i)\right)\mu \geq \kappa \tag{7}$$

The constraint (7) for support, which depends on beliefs, benefits and costs, replaces the prior constraint (5), which depends only on beliefs. We define belief net-of-benefits as

$$\widetilde{\omega}_i = \omega_i + \frac{1}{p}\hat{\mu}^{-1} = \omega_i + \frac{1}{p}\frac{\kappa}{\mu} \tag{8}$$

People with belief $\omega_i$, when there are benefits and costs of prayer, act as if they have belief $\widetilde{\omega}_i$ in our baseline model. This belief net-of-benefits is decreasing in net benefits. Intuitively, for a given belief $\omega_i$, people will set a lower belief net-of-benefits threshold to support in places where rainfall has high benefits, or the costs to perform the ritual are low. With this change of variables, we characterize support in the extended model.

**Proposition 5.** *With an increasing hazard rate, with benefits $\mu$ and cost $\kappa$, for each $\omega_i$ there is a unique interval $T(\widetilde{\omega}_i) = \left(\underline{\tau_0}(\widetilde{\omega}_i), \overline{\tau_0}(\widetilde{\omega}_i)\right)$ such that a person will support if and only if $\tau_0^j \in T(\widetilde{\omega}_i)$.*

*Proof.* See Appendix A.4. □

Proposition 5 is analogous to Proposition 1 but now allows tangible benefits and costs of support. The interval of beliefs for which people support is altered by the net benefits of prayer. An increase in net benefits, by increasing the expected value of support, mimics a decrease in the strength of belief $\omega_i$, which makes it easier for the leader to earn support. We interpret this trade-off between belief and benefits as motivated reasoning: people are willing to support either if they believe prayer increases the probability of rainfall a lot, or if the benefits they receive from an increase in rainfall are great (or some combination of the two). We now describe comparative statics of how support, and therefore rain ritual traditions, will co-move with tangible benefits and costs.

**Proposition 6.** *The following relationships hold for support:*

*a. Support always increases with an increasing hazard rate;*

*b. Support always increases with net benefits;*

*c. The increase in support due to an increasing hazard rate may increase or decrease with net benefits.*

*Proof.* See Appendix A.4. □

An increasing hazard rate still increases support in the extended model, as in the base model. Support also increases with net benefits because net benefits act, through $\widetilde{\omega}_i$, just like a change in belief: higher net benefits lower the threshold of belief required for support, and therefore extend the interval for support defined in Proposition 5. Perhaps the most surprising part of the proposition is that the sign of the effect of the *interaction* of an increasing hazard rate with net benefits is ambiguous.

The economic logic for the ambiguous sign of this interaction is straightforward. There is a distribution in the population of $\omega_i$, each person's belief in how much a successful prayer should increase the probability of rainfall. The marginal effect of an increasing hazard on support, in an environment with higher net benefits, will depend on this distribution. It may be that higher net benefits convince most of the people who are "persuadable" (i.e., have moderate $\omega_i$) to support already, such that the *marginal* effect of an increasing hazard on support, while still positive, is *less positive* than it would have been in a population with a lower distribution of net benefits. You can only convince someone once. If people have a lot to gain from rainfall, and therefore support the leader at high rates by default, then there may be fewer people left for the environment to persuade. We formalize this intuition in Appendix A.4. We also provide numerical examples of the model in which the interaction between an increasing hazard and higher net benefits can increase or decrease support, depending on the initial distribution of beliefs.

**Discussion.—** The model provides five empirical predictions: First, societies' rain ritual traditions will select for prayers that are correlated with rainfall. Second, the level of rainfall does not determine whether prayer is persuasive. Third, societies facing a constant hazard rate may have some people who would support the ritual in any case, but will not have persuasive prayer. Fourth, therefore, societies facing an increasing hazard rate, with its persuasive natural experiment, are more likely to pray for rain (i.e., to have a tradition of rain ritual practice). Fifth, when there are tangible benefits of prayer and costs of support, societies with higher net benefits of rainfall are also more likely to practice a rain ritual.

We put forward one model of persuasion but acknowledge that it does not exclude other, closely related alternatives. In our model, we have assumed that policies are randomly endowed, and evolve to become more persuasive over time (Chudek, Muthukrishna and Henrich, 2015; Galor and Özak, 2016; Giuliano and Nunn, 2021). An alternative model would instead have leaders strategically choose the timing of prayer to maximize their support.[11] These models are observationally equivalent, because we observe the long-term relationship between the environment and rain ritual practice, not the path of evolution towards this steady state. The key commonality, for our purposes, is that both the exogenous prayer and strategic prayer cases share the key prediction that persuasion is only possible in an environment with an increasing hazard rate.

# 3 Prayer for rain in Murcia, Spain

This section documents that the pattern of prayers for rain in Murcia, Spain is consistent with our model. Murcia allows us to test the prediction of our model on the correlation of prayer and rainfall because in this case, unlike for the data in the *Atlas*, we observe the details of rain ritual practice, from over 200 years of daily church records of prayer. Prior research has described the tradition of rainfall prayer in Murcia (Espín-Sánchez and Gil-

[11] A line of prior research has argued that the Catholic church, at least, does indeed act strategically to raise participation and belief (Parigi, 2012; Leeson, 2013; Barro and McCleary, 2016; Leeson and Russ, 2018).

Guirado, 2022). We show here that the hazard of rainfall is increasing and that the church's prayers for rain predict rainfall.

## 3.1 Context

The Catholic church has practiced *pro pluvia* rogations—prayers for rain—since at least 511 AD (Martín-Vide and Vallvé, 1995). In Murcia, a city in the south of Spain near the Mediterranean Sea, the church has offered rogations since at least the 14th century (Espín-Sánchez and Gil-Guirado, 2022). The rogations are a series of prayers to induce rainfall. The more severe a drought, the greater the number and intensity of prayers (Gil Guirado, 2013).[12] Governance in Murcia historically has been divided between the Catholic church, led by an ecclesiastical chapter (*Cabildo*), and a secular municipal council (*Concejo*). The church decides the rogation cycle. The municipal council may appeal to the church to begin rogations, on behalf of the people, but the church decides when to begin praying and what prayers to use.

The prayers within a cycle typically escalate, sometimes to great length, until they succeed and it rains. Consider the cycle beginning in January of 1782. On January 8th, the municipal council asked the church to pray, both because drought was harming agriculture and because the scarcity of water degraded water quality and hence public health. On January 12th the church assented and took a collection to offer a rainfall prayer. Rain did not come. On January 25th, the ecclesiastical chapter proposed a prayer, with the municipal council assenting the next day. The prayer started January 28th, with three days of masses dedicated to *Benditas Ánimas del Purgatorio*, the blessed souls in purgatory. Rain did not come. In early February, the church again prayed for rain, with a public procession through the streets, on February 3rd, and *seven* masses dedicated to the *Virgen de Fuensanta*, an image of the Virgin Mary. On February 13th, the prayers were answered and a notable rainfall is recorded in the records of the municipal council. On February 22nd, the church offered a mass of Thanksgiving and a public procession, both dedicated to the *Virgen de Fuensanta*, the object of the successful prayer. It rained again later that week.

The church has several choices through which it may persuade, including the timing of prayer, the intensity of prayer, the choice of objects of prayer and holding prayers of thanks. The church trained priests to use natural disasters, including droughts, for persuasion.[13]

[12] A basic rogation may consist of a dedicated mass to call for rain, the solicitation of collections or prayer to figures representing particular saints or virgins. The next level of rogation would add a public procession and the exhibition of relics such as the *lignum crucis* (wood of the cross). If this prayer fails, or the need is desperate, the church may further elevate prayers by hosting multiple public processions or praying to multiple figures simultaneously. For larger or more elaborate ceremonies the church may require payment, either through the collection of alms or from the municipal or ecclesiastical chapters.

[13] A 19th century manual instructed priests-in-training: "In times of drought, hail, epidemic, earthquake,

The church sometimes offered to intervene in nature in an explicit quid pro quo.[14] While all of these aspects may contribute to persuasion, we focus on the timing of prayer as this is the object of our theory and consistently observed in our data. We also expect good timing is necessary for the church to be persuasive, regardless of its other actions.

## 3.2 Data

Our data come from ecclesiastical and municipal records of Murcia. While we collected data on rogations from 1600 into the 20th century, we restrict our sample to end on December 31st, 1836. In 1837 the abolition of the tithes reduced the church's ability to collect taxes and thereby its funding and influence. This diminution of power was driven by reasons apart from the efficacy of rainmaking.[15] The rogation cycle changed at this time and prayers grow more infrequent afterwards (Espín-Sánchez and Gil-Guirado, 2022).[16]

**Sources.—**The data from the ecclesiastical chapters contain the timing of prayers and characteristics of the prayers offered. We observe the day a prayer was requested by the ecclesiastical chapter or municipal council and the day the prayer was made. We observe the purpose of the prayer: *pro pluvia* rogations to pray for rain, prayers of Thanksgiving to give thanks when it has rained, and, rarely, *pro sereninate* rogations to stop severe rain or floods. The main explanatory variable we will use in our analysis is *Prayer last month* $(= 100)$, a daily indicator equal to 100 if there has been a prayer for rain in the last 30 days. We will use an indicator for *Prayer of thanksgiving* $(= 100)$ on a given day as one measure of rainfall. The advantage of this measure is that the church can only offer a prayer for thanksgiving for rainfall when it has rained. The disadvantage is that the church's thanksgiving prayers could be selected, if the church differentially offers a prayer for thanksgiving for rainfall that comes after the church itself has prayed for rain.

etc. What a bounty you can make with the prayers for God! ... Yes, it is God who sends these ills: He sends them for our own good: What should we do to placate his wrath and make him as auspicious as before?" (Mach, 1864).

[14]On January 3rd, 1651, priests asked the city council to donate two golden crowns in order to return images to their places in the church. Without this donation, the priests suggested, they could not perform their prayers. When certain images or saints did not bring rain, in response to prayer, they would often be displaced in favor of new ones (Lombardi, 1989).

[15]The *ancien régime* of Catholic church power in Spain was abolished in the 1830s when the Spanish crown expropriated church property (the Ecclesiastical Confiscation of Mendizábal, 1835) and banned church taxation (the abolition of the tithes, 1837).

[16]Rogations survive to this day, though they are reserved for more severe droughts. On March 10, 2022, after a long drought, a once-in-a-century prayer took place. Four different sacred images, the *Virgen de la Fuensanta*, *Cristo de la Salud*, *Cristo del Rescate* and *Jesus of Nazareth*, were taken to the streets in a pilgrimage in different parts of the city. Days after Murcia entered a spell of two weeks of heavy rain. On Twitter, on March 22, 2022, @carmenceldran remarked "[Rain] was to be expected, after they took the Virgin of Fuensanta on procession."

The data from the municipal council include the date the municipal council asked for a prayer and records of notable rainfall events. Our rainfall series consists of notable rainfall events recorded in the minutes of the municipal council. The municipal council keeps records independently of the church and had no strategic interest in over-reporting rain. In fact, the council minutes were not even publicly released, lessening concerns about biased reporting of when rain occurred.[17] The shortcoming of this measure is that it records only notable rainfall events so we do not expect it is complete. However, the climate in Murcia is such that a large share of rain corresponds to such notable events (Martín-Vide, 2004). Modern, daily records of rainfall do not exist during our sample period; rainfall records become available in Murcia in the mid-19th century.

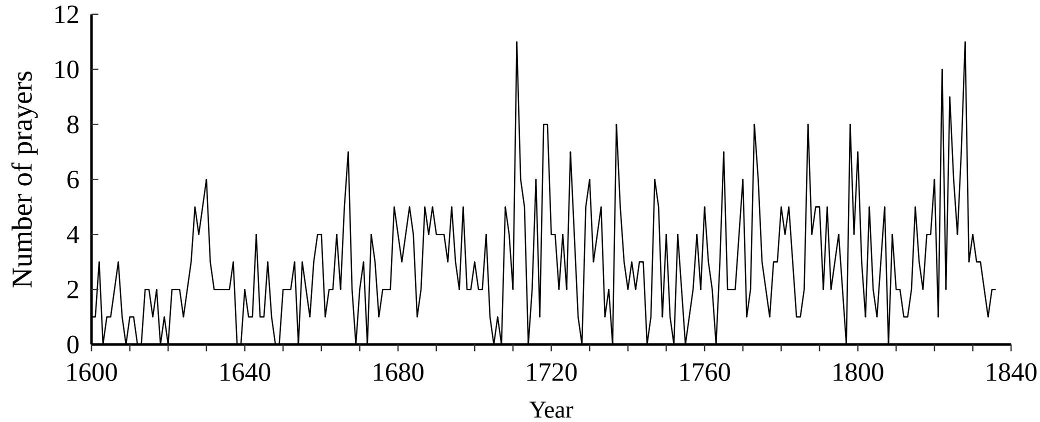
We gather modern rainfall records for the Murcia region from *Agencia Estatal de Metereologia* (AEMET) records for stations in and around the city. These records contain daily measures of the amount of rain. We use rainfall data from stations with daily time series ranging from 63 to 97 years, allowing flexible and precise estimation of the daily rainfall hazard.

**Pattern of rainfall and prayer.—**Figure 5 illustrates the basic features of the data on prayer and recorded rainfall from Murcia. Panel A shows a time series of the number of prayers for rain by year. Panel B shows a spider chart of the seasonality of recorded rainfall and prayer. The distance from the axis on the spider chart indicates the mean number of recorded rainfall or prayer events in a given month of the year over our sample period.

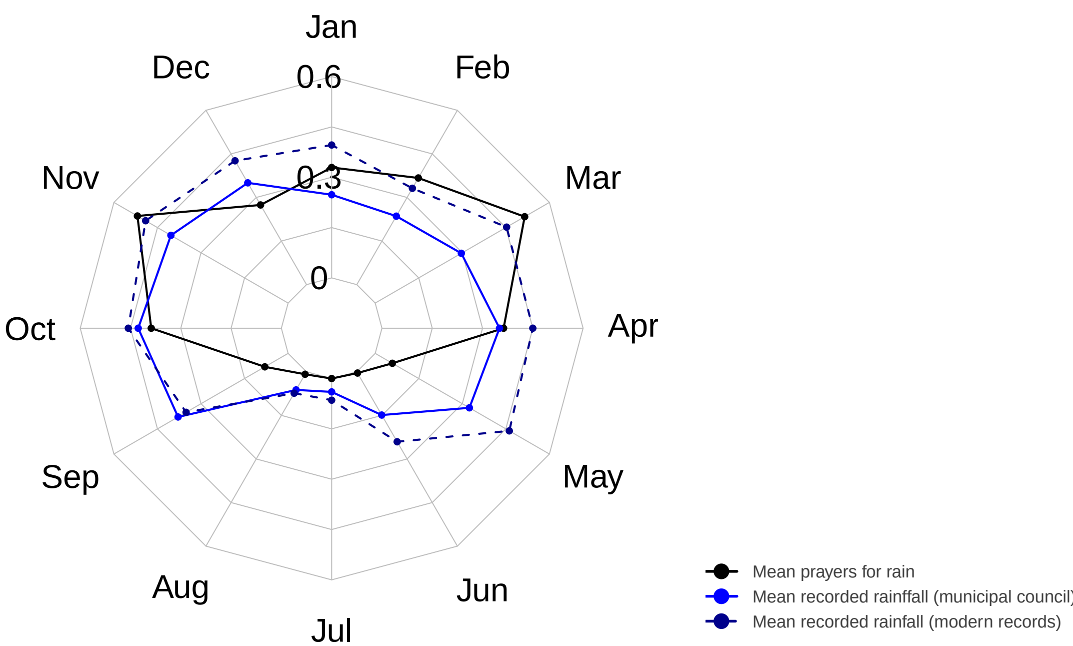
There are three points of interest in the raw data of Figure 5. First, in panel A, while the policy embodied in the rogation cycle may be stable, the resulting number of prayers in any given year varies widely and somewhat erratically. In some years there are no prayers, in others ten. The same prayer policy can result in different prayer outcomes depending on the realizations of recorded rainfall in a given year. If it rains early and often, there is no cause for prayer. Second, in panel B, the seasonality of rainfall events recorded by the municipal council closely matches the seasonality of rainfall events constructed with modern rainfall data. This match gives reassurance that the municipal council's recorded rainfall events, while selected, do reflect important rainfall events accurately. Third, also in panel B, the seasonality of prayers closely mimics or slightly leads the seasonality of recorded rainfall events, as seen by the slight clockwise rotation of the pattern of recorded rainfall (solid blue) with respect to the pattern of prayer (dashed black). The peak months for recorded rainfall prayer are October and November, in which there are prayers roughly

[17] As evidence against reporting bias, we show in Appendix C that the municipal council's reporting of rainfall was unchanged despite a dramatic fall in the frequency of rainfall prayer from 1837 onwards, following the abolition of the tithes.

Figure 5: Prayer and Recorded Rainfall in Murcia, Spain




A. Prayers for rain in Murcia, Spain 1600 - 1836




B. Seasonality of recorded rainfall and rainmaking prayers

*Notes*: Panel A shows the total annual prayers for rain in Murcia, Spain from 1600 to 1836. Prayers for rain are recorded in the minutes of the ecclesiastical chapter (the Ecclesiastical Actas Capitulares (EAC)). Our rainfall series is constructed from notable rainfall events mentioned in the minutes of the municipal council (from the Civil Actas Capitulares (CAC)). The municipal council minutes are kept independently of the church. Panel B shows the average number of recorded rainfall days in a month from the municipal council records and the average prayers for rain in the period 1600-1836 in solid blue and black lines. We use modern rainfall records between 1836 and 1939 to define a rainfall event as precipitation $> 5cm$. Then, we plot a scaled down version of this modern measure (scaled by $1/10$) against the municipal council records in dark blue dashed lines.

every other year (0.5 events per year), with another increase in March. The peak months for recorded rainfall are in October through January, with another increase in March. The seasonality of recorded rainfall and prayer is therefore very tightly linked. We will argue below that prayer is predictive of rainfall above and beyond the correlation implied by this seasonal pattern.

### 3.3 Rainfall hazard estimation

We show in this part that the hazard of rainfall in Murcia is increasing after a dry spell. In our model, this implies that the church can raise support through prayer, depending on its timing, since the hazard of rainfall will rise after prayer begins.

**Estimation of flexible hazard functions.—**The experiment posed by nature is the pattern of rainfall in a place over time. Since this pattern, and specifically whether the hazard of rainfall increases or decreases as time passes without rain, is the key to our predictions, we wish to estimate it as flexibly as possible. Let $t$ be the number of days from one rainfall to the next. For example, if it rains on Monday and again on Thursday, then $t = 3$.[18] The hazard function $h(t)$ gives the probability of rainfall as a function of the time that has passed since the last rain.

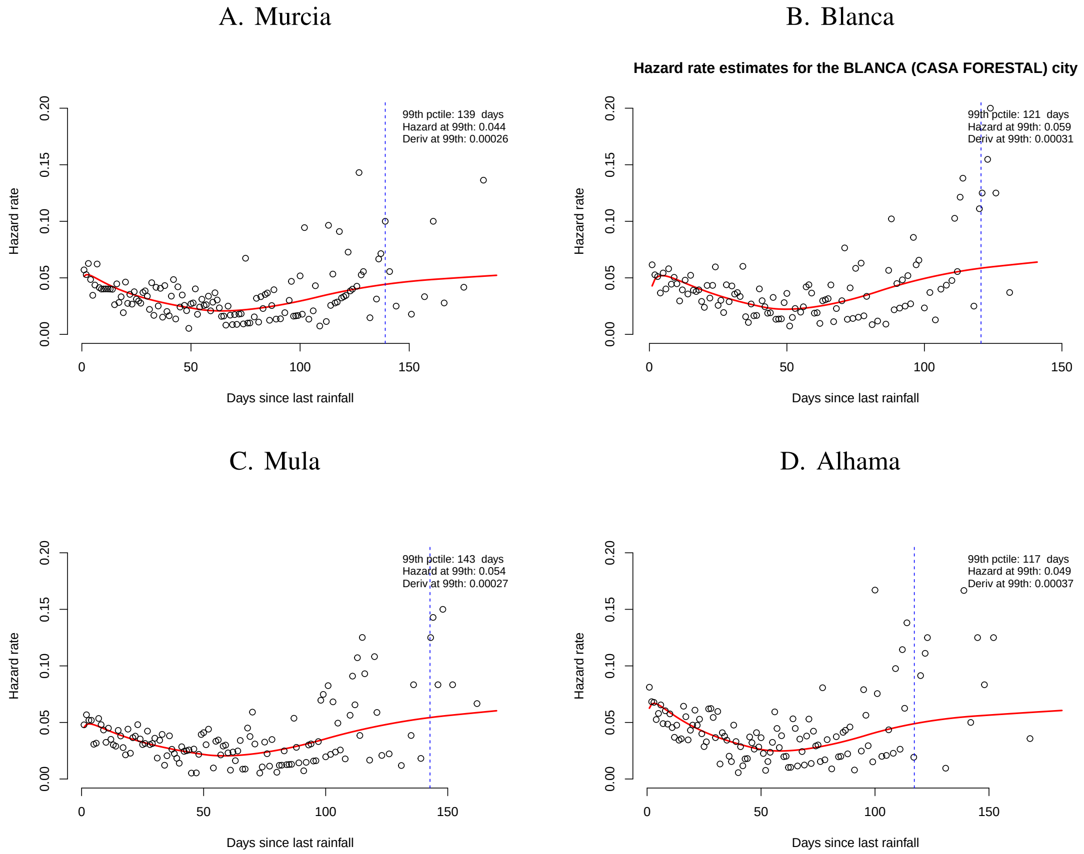
We favor a semi-parametric estimator that allows the shape of the hazard to depend flexibly on the data. Specifically, we use a cubic spline to fit the log cumulative hazard by maximum likelihood, following Royston and Parmar (2002), and then calculate the associated hazard function. Appendix B.5 details the specification and estimation likelihood. The hazard estimation is done separately for multiple weather stations in Murcia and, in Section 4 below, for the weather station nearest to each ethnic group in our global data. This semi-parametric representation of the hazard function allows the hazard estimates to take on a variety of different shapes corresponding to the different rainfall patterns around the world (as seen in Figure 1).

**Hazard function estimates for Murcia.—**We find that the hazard rate in Murcia is increasing, which is the condition, in our model, for the church to be persuasive. The results of the hazard estimation for Murcia are shown in Figure 6. The four panels plot hazard estimates using rainfall data from the city of Murcia and three surrounding towns in the same region, each about 15 miles distant. The hollow circles show non-parametric Nelson-Aalen estimates of the hazard rate (Aalen, 1978).[19] The fitted red curve gives our

[18] To fit a hazard model it is necessary to define how much rainfall constitutes a failure. A light rain is not sufficient to end a drought. We define a failure event as equal to one if daily rainfall exceeds 0.5 centimeters.

[19] These fully non-parametric estimates tend to be volatile, since the estimator is only consistent as the number of observations at each given spell length grows large. For this reason, we favor the semi-parametric

Figure 6: The Hazard of Rainfall in and around Murcia, Spain



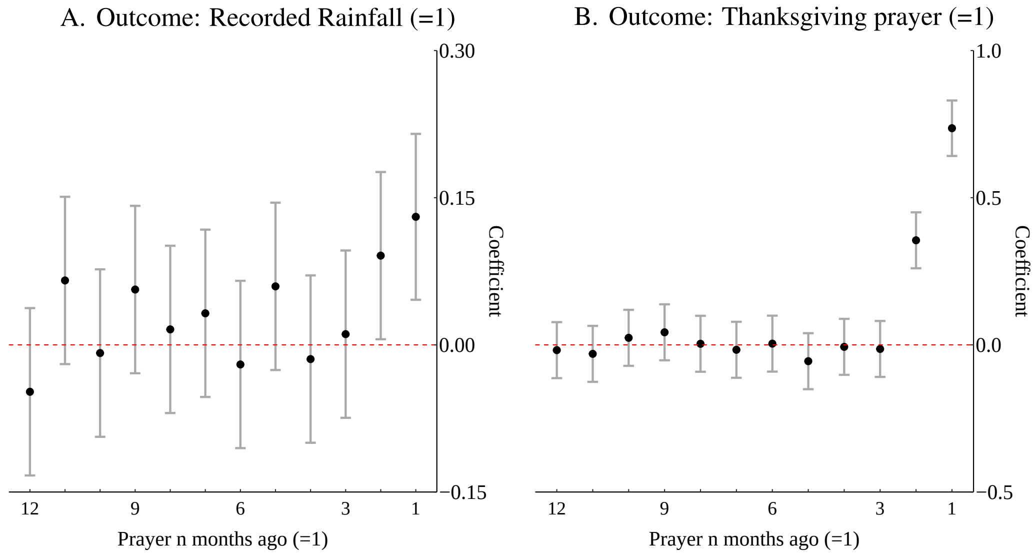

*Notes*: The figure shows estimates of the hazard of rainfall after a dry spell for Murcia, Spain and some surrounding towns. The rainfall data are available for 92 years (panel A), 63 years (panel B), 77 years (panel C) and 97 years (panel D). On each panel the circles provide non-parametric Nelson-Aalen estimates of the hazard rate. The fitted curve gives a cubic spline fit to the hazard rate by maximum likelihood as described in Appendix B.5. On each panel, we report: the 99th percentile of dry spell length in days and the daily hazard rate of rainfall and its derivative evaluated at the 99th percentile dry spell.

preferred cubic spline fit to the hazard rate by maximum likelihood.

The main result from Figure 6 is that the hazard rate in Murcia is increasing after a long dry spell. The hazard of rainfall is initially high after a recent rain, but declines to a minimum roughly two months after it last rained. From that point, the hazard rate increases significantly, until it equals or exceeds the higher hazard just after it rained. The fluctuations in the hazard function over time are large: the hazard rate after a long dry spell is roughly double the hazard rate two months after rainfall. We therefore find that the hazard function of rainfall in Murcia presents the church with the opportunity to persuade. The flexible shape of the hazard function we specify is essential to fit the data. The hazard function is non-monotonic, whereas the most common parametric hazard forms, such as the Weibull

estimates that smooth the hazard function over spells of different lengths.

Figure 7: Coefficients from Regressions of Recorded Rainfall on Recent Prayers




*Notes*: These figures show the coefficients from regressions of recorded rainfall (figure A) and prayers of thanksgiving (figure B) on monthly lags of prayer. The standard error bars have a 95% confidence interval.

distribution of failure times, impose that the hazard must be monotonic.

## 3.4 Prayer and rainfall

The hazard rate presents an opportunity for the church to be persuasive, but whether prayer is actually persuasive depends on the timing of prayers. This part shows that the church prays in a manner such that prayer is highly predictive of subsequent recorded rainfall.

Let $Rainfall_t$ indicate a significant rainfall on a date $t$ as recorded by Murcia's municipal council. Because the probability of rainfall on a given day is small, we scale this variable so that it takes on the value of 100 if rainfall occurs and zero otherwise. We estimate the distributed lag regression

$$Rainfall_t = \beta_1 PrayerLastMonth_t + \sum_{\tau=1}^{T_\tau} \beta_\tau PrayerLagMonth_{t-\tau} + \delta_m + \varepsilon_t \tag{9}$$

where $PrayerLastMonth_t$ equals 1 if there was any rainmaking prayer in the period $(t-30, t-1)$, $PrayerLagMonth_{t-\tau}$ has the same definition, lagged by $\tau$ months, and $\delta_m$ are month-of-year fixed effects. The regression is at the daily level with data from 1600 to 1837. We estimate Newey-West autocorrelation consistent standard errors to account for autocorrelation in the error terms $\varepsilon_t$, which may be present due both to (i) auto-correlation in the rainfall process itself and (ii) the construction of the prayer last month variable using

Table 1: Regressions of Recorded Rainfall and Prayers of Thanks on Recent Prayers for Rain

| | *Recorded rainfall (=100)* | | | *Prayer for thanksgiving (=100)* | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Prayer last month | 0.189*** | 0.144** | 0.131** | 0.861*** | 0.787*** | 0.736*** |
| | (0.053) | (0.057) | (0.057) | (0.071) | (0.072) | (0.073) |
| Month effects | | *Yes* | *Yes* | | *Yes* | *Yes* |
| Month lags | | | *Yes* | | | *Yes* |
| Mean dep. var | 0.203 | 0.203 | 0.203 | 0.254 | 0.254 | 0.254 |
| Years of data | 237 | 237 | 237 | 237 | 237 | 237 |
| *N* | 86,535 | 86,535 | 86,175 | 86,535 | 86,535 | 86,175 |

This table reports coefficients from regressions of rainfall from municipal council records and prayers for thanksgiving on rain on recent prayer for rain in Murcia. Newey-West standard errors are in parentheses with a lag parameter of 30 days. Statistical significance is indicated by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

a rolling 30-day window.[20]

Figure 7 reports coefficients from regressions that include lagged prayers up to 12 months ago as explanatory variables. The two panels use $Rainfall_t$ (panel A) and $Prayer\ of\ thanksgiving_t$ (panel B) as the dependent variables. The figure shows that prayer last month and prayer between one and two months ago both predict future rainfall, for either rainfall outcome measure. Prayer more than two months ago has no significant relationship with future rainfall; the coefficients on lagged prayer for lags between 3 and 12 months ago are all close to zero and statistically not significantly different from zero at the 5% level.

Table 1 reports estimates of equation (9). Column 1 has no controls, column 2 adds month fixed effects, and column 3 adds controls for prior lagged prayers (from 2 to 12 months ago). The coefficient on a prayer last month is estimated to be large and statistically significant (column 1). In the column 2 specification, with month fixed effects, a prayer last month is associated with a 0.144 pp (standard error 0.057 pp) higher probability of rainfall on a given day, relative to a mean daily rainfall probability of 0.203 pp. The predicted probability of rainfall is 71% higher—nearly double—if there has been a prayer in the last month.

The fact that recent prayers predict rainfall even conditional on month fixed effects shows that the predictive power of rainmaking is subtle, and does not arise only from prayer tracing the seasonal pattern of rainfall (as seen in Figure 5, panel B). Both the variable

[20] In our baseline specifications we use a lag parameter $l = 30$ days to construct the standard errors. Appendix Tables Table C9 and Table C10 show the robustness of our estimates to alternative values of this parameter.

number of prayers each year (as seen in Figure 5, panel A) and their predictive power conditional on month-of-year suggest that the church is following an *adaptive* rule. These patterns are consistent with, in particular, the adaptive rule in our model, that the policy that maximizes support will begin to pray only after a long dry spell. With an increasing hazard, the length of a dry spell contains information about the probability of rainfall above and beyond conditioning prayer only on the time of year.

The predictive power of prayer for future rainfall is even stronger if we use later prayers of thanksgiving as our measure of rainfall. Columns 4 through 6 replicate the specifications from column 1 through 3 with *Prayer of thanksgiving* $(= 100)$ as the dependent variable. We find, in column 4, that a prayer last month predicts a 0.799 pp (standard error 0.073 pp) higher probability of a thanksgiving prayer on a given day, relative to a mean daily thanksgiving prayer probability of 0.257 pp. The predicted probability of rainfall (proxied by thanksgiving) is therefore roughly four times higher if there has been a prayer in the last month. We expect the estimates for $\textit{Prayer of thanksgiving}_t$ as the dependent variable to be larger because this variable is more commonly recorded by the church than $Rainfall_t$ is by the municipal council, suggesting church records of rainfall events are more complete.

We therefore find that prayer predicts future rainfall. We conduct further tests in Appendix C to demonstrate that prayer Granger-causes rain. These tests establish that recent prayer has predictive power for rainfall above and beyond recent rainfall.[21] We interpret these results as evidence for the mechanism in the model. Where rain ritual practice has evolved, with an increasing hazard rate, as observed in Murcia, the probability of rainfall will increase after prayer. The fact that prayers predict rainfall creates a separation between the hazard rates observed without prayer and with prayer, which enables a religious leader to maintain support. The increasing hazard creates the appearance of a causal effect of prayer on rainfall.

**Discussion.—**The practice of rainmaking prayers in Murcia, Spain is found to be consistent with our model in several respects. The hazard function of rainfall is increasing after a long dry spell in Murcia (Figure 6). This provides an opportunity for rainfall prayer to be persuasive, and indeed the local church has a tradition of praying for rain that dates back to at least the 14th century (Proposition 4). The timing of prayer over the seasons

[21] A possible interpretation of the above regressions is that, if rainfall is autocorrelated, then prayer may only predict rainfall because prayers are conducted after recent rainfalls. To investigate this idea, we test for Granger causality at different time horizons in Appendix Table C3. The tests consist of regressing rain on distributed lagged models that include (i) lags of rainfall itself up to the given horizon (ii) additionally, lags of prayer. Prayer is said to Granger-cause rain if the joint model (ii) including both lagged rainfall and lagged prayer cannot be rejected in favor of the model with only lagged rainfall. We find that prayer Granger-causes rain at all horizons tested from one week's worth of daily lags up to 13 weeks' worth of daily lags.

corresponds with the timing of rainfall (Figure 5). This correspondence is not mechanical, as the church does not pray the same amount or at the same times every year. The prayers chosen by the church are found to be highly predictive of rainfall over a period of more than two centuries (Figure 7, Table 1).

The data from Murcia support the mechanism of our model but describe only a single case. In order to test whether this mechanism is predictive of religiosity more generally we next turn to describing the global practice of rainmaking.

# 4 The global prevalence of prayers for rain

This section describes global rainmaking practice using the new data on rain rituals we have added to the *Ethnographic Atlas*. Section 4.1 gives examples of rainmaking and draws out several commonalities we observe in the diverse practices of different ethnic groups. Section 4.2 describes our data collection for whether a group practices rainmaking. Section 4.3 applies our rainfall hazard estimation to ethnic groups worldwide.

## 4.1 Context

Rainmaking is arguably the leading example used in anthropology to illustrate the evolution of human belief systems. Frazer (1890) created the modern, systematic study of human belief. Frazer argues that magical, religious and rational belief systems have in common that worldly events follow a set of laws. Rainmakers presume a natural law in which supernatural forces respond to human appeals and try to use that law to control nature. While there is a vast anthropology literature on rainmaking, some of which has noticed the seeming efficacy of rainmaking, our theory of the causes of rainmaking is novel.[22] We also believe this paper is the first comparative statistical study of the determinants of rainmaking across ethnic groups.

**Examples of rainmaking practice.—**Because of the importance of rainmaking in describing the evolution of human belief, anthropologists have produced many rich ac-

[22] There are innumerable monographs on particular groups that attempt to infer the underlying cause of rain ritual practice. Common hypotheses include that rainmaking is caused by dependence on rainfed agriculture (Abu-Zahra, 1988), a lack of rainfall (Akong'a, 1987; van Beek, 2015), the variability of rainfall (Shaffer, 2017), or the seasonality of rainfall (Boudon, 2012; Durkheim, 1912). Our theory is closest to, but more precise than, this last explanation. Durkheim (1912) argued "Though the expectation of a future and contingent event is not without a certain uncertainty, still it is normal that the rain fall when the season for it comes . . . Oft-repeated experiences have shown that the rites generally do produce the effects which are expected of them and which are the reason for their existence." We have not found any prior empirical study that validates that ritual is predictive within a society or tests any of the above hypotheses comparing across societies.

counts describing the practice and motives of rainmaking. We present here a very small sampling of these accounts, selected to show the diversity of global rainmaking practice.

*Cherokee, southeastern United States*. The Cherokee practiced rainmaking with a rain dance (Heimbach Jr, 2001). A direct prayer for rain to the Great Spirit was not always appropriate. Only some spirits could bring rain, and medicine men and women determined which deity to call on. For the rain dance, twelve stones are laid in a circle around a central *oolsati* ("it shines through") stone, preferably of quartz, representing the eye of a dragon. The dancers weave in and out of the stones symmetrically, generating energy that is focused through the *oolsati* stone. A shaman leads the ritual by beating a drum and shaking shells, while the dancers chant a song that depends on the season and the desired amount of rain.[23] Any small deviation in the ceremony will render it ineffective and possibly dangerous. For example, the chant has no power if translated into English.

*Herero, Namibia*. The Herero are a Bantu ethnic group that resides primarily in modern Namibia. They practice rainmaking with a ritual that is the same as the neighboring Tswana (Schmidt, 1979). A subordinate chief initiates the ritual by bringing a black ox to the paramount chief at sunrise and saying "I have come to beg rain, Chief, with this calf." The paramount chief assents by replying "May the rain fall" and sprinkling the ox with water. The ox is then set free to wander, so that the rain may similarly "wander about in the country." The physical parallels between the sprinking of water, the wandering of the calf, and the desired rainfall are an example of what Frazer (1890) calls homeopathic magic, wherein a like cause produces a like effect. The ceremony may be repeated for several days in a row, after which the ox is slaughtered, cooked and eaten.

*Iranians, Iran*. The Iranians are the ancestors of people in modern Iran. The Iranians practice rainmaking ceremonies similar to those in neighboring countries such as Iraq, Turkey and parts of central Asia (Başgöz, 2007). Rainmaking can take the form of a simple prayer for rain with the sacrifice of an animal. Prayers for rain are sanctioned and regulated in Islamic jurisprudence, but originate not in the Koran but in the *hadith*, or holy tradition. Islam formalized that God was the power to be petitioned for rain but otherwise did not alter many traditional rainmaking practices. Başgöz (2007) describes a rich typology including not only prayer but also a public procession, a dramatic musical, homeopathic magic,[24] a bonfire, a special meal for the poor and a mock battle. On the last: when it has not rained

[23] An example of a chant runs: "Redbird! Redbird! Redbird! Redbird! / Hear me, Maker of Rain! / You, up there in the Sunland! / Now, then— / Come down, O Nimbus / and touch the Earth! / It is done!"

[24] In the winter, when no rain falls for a long time, the people assemble and take a long thread. Each person pronounces the names of a *kachal* (bald-headed person) and ties a knot in the thread to mark the name. When forty names (hence forty knots) have been completed, they steal a jar from a stingy neighbor, burn the thread, and put its ashes in the jar with water. They then ascend to the roof of a house and pour the ashen water down through the gutter.

for a long time, the women of a village gather and wage a mock battle with a neighboring village to capture their animals. The animals are taken back to the raiders' village and hidden until it rains, when they will be returned to their owners.

*Shantung, Shandong province, China*. The people of Shantung, now commonly transliterated Shandong, practiced a ritual to bring rain via the rain dragon. Cohen (1978) describes a county magistrate's rainmaking circa 951: "During a drought he made a clay dragon and beseeched rain, but there was no response. Magistrate Li then caned the dragon and rebuked it. On that very day there was sufficient rain." The historical record of rainmaking in China is exceptionally long and rich. Common practices included prayers for rain, prayers to the rain dragon and rain dances. Hong, Slingerland and Henrich (2024) give a host of examples. The governor of Fuzhou, in the drought year of 1078, tried a sequence of rainmaking methods over a period of 20 days. In 1004, the Emperor Zhenzong asked a monk to make rain during a drought. The monk used a dragon image to summon rain, successfully. Zhenzong then remarked "[the method] is unconventional, yet for saving people from drought, it is not to be avoided." The culmination of the rainmaking sequence was to not ask but rather punish the dragon, "where the coercive force increases in magnitude" as time passes without rain (Cohen, 1978). If a deity failed to produce rain, the emperor or the people would ultimately destroy their shrine as a rebuke.

**Examples of the absence of rainmaking.—**For many groups we find no evidence of rainmaking practice. We give only two examples here.

*Camba, Bolivia*. Camba is the name used for ethnic groups indigenous to the subtropical region of eastern Bolivia. We find no record of rainmaking in fairly exhaustive texts on Camba social and agricultural practices, although we can find no fieldwork on the Camba prior to the mid-20th century (Heath, 1959). Descriptions of the Camba's subsistence give some evidence as to why rainmaking might not be practiced. The Camba subsist mainly on agriculture watered with natural flood irrigation. They make no attempt to divert the water or control seasonal flooding. The streams the Camba live near ensure a good harvest even during an exceptionally dry season (Heath, 1959).

*Puyallup, Washington state, United States*. The Puyallup lived along their namesake river, near modern Seattle, Washington. We could find no reference to rainmaking in texts on Puyallup culture, subsistence and religious practices (Ballantine, 2016). The absence of a rain ritual does not imply the absence of all ritual for the Puyallup. The Puyallup belong to the *Salish* language group of Native Americans in the Pacific Northwest. Shamans of the *Salish* group, for example, practiced elaborate soul recovery rituals for those near death, ostensibly to cure them but generally to prepare the soul for death (Caster, 2005).

The Puyallup subsisted mainly on abundant fish from the Puyallup river for many generations. The reliability of this food source may have reduced their need to control the weather. Ethnographies of other Native American groups near the lower Columbia river, who similarly subsisted on fishing, remark on their lack of ceremonial traditions in general (Drucker, 1939).

**Discussion of reasons for rainmaking.—** The above examples and wider reading lead us to draw out some commonalities in rainmaking practice.

**Commonality 1** (Persistence)**.** *For many groups, rain rituals are an archetypal spiritual practice that has persisted for a long time.*

The *recorded* histories of rainmaking in China and in Spain, two cases with exceptionally good record-keeping, span 22 and 14 centuries, respectively (Hong, Slingerland and Henrich, 2024; Espín-Sánchez and Gil-Guirado, 2022). This persistence was not for lack of skepticism towards the value of rainmaking. The Confucian scholar Xunzi was an early skeptic (see the epigraph, as quoted in Hong, Slingerland and Henrich (2024)).

**Commonality 2** (Initiation)**.** *Rainmaking is often started in response to a drought.*

The people appeal to a religious authority who can choose whether to start the rain ritual. This decision is often made with reference to the severity of the drought. For example, a rainmaking text from the Chinese Sui dynasty of the 6th century instructs: "If there is a drought after the fourth month of the year, then [one shall] pray for rain . . . if it does not rain after seven days, one needs to pray all over again. If it still does not rain after the three procedures [here omitted], then pray to the local deities that often bring cloud and rain" (Hong, Slingerland and Henrich, 2024). Durkheim (1912) describes a life-giving ceremony in Australia, with rainmaking as one component. He writes "There are two sharply separated seasons in Australia: one is dry and lasts for a long time; the other is rainy and is, on the contrary, very short and frequently irregular." The ceremony begins "just at the moment when the good [rainy] season seems to be close at hand."

**Commonality 3** (Escalation within a rainmaking cycle)**.** *Rainmaking rituals have a built-in manner of escalation that often continues until it rains.*

The escalation could be purely by repetition, as for the Herero. Among the groups with the best records, however, this escalation is often more sophisticated. The Shantung and the Spanish, in the case of Murcia, both provide examples where an initial, failed ritual will be repeated and escalated until rainfall is realized. The Iranians would release their neighbors' animals only when it rained (Başgöz, 2007).

**Commonality 4** (Demand for control of the weather)**.** *Rainmaking appears more common when subsistence is more sensitive to rainfall.*

Groups like the Camba and Puyallup that have a reliable subsistence even in the absence of rainfall, and that therefore face little seasonal environmental risk, often do not practice a rain ritual. The relationship between the environment and rainmaking is subtle. It is not necessarily that a low level of rainfall, on its own, encourages rainmaking, but rather the residual risk in a form of subsistence after it has been adapted to the local environment. Murcia had an elaborate system of canal irrigation developed over centuries (Donna and Espín-Sánchez, forthcoming). Yet the canals were fed by rain. These specific investments raised productivity but arguably also increased risk by leveraging agricultural dependence on rainfall (see also the case of Islamic Egypt discussed in Chaney, 2013).

Our model can explain these four commonalities. Persistence: in the model, rainmaking is a persistent feature of an ethnic group because the environment of that group, depending on the hazard of rainfall, either would or would not pose a persuasive natural experiment for prayer. Initiation: cultural evolution selects for rainmaking initiated in a drought, after time has passed without rain, to increase the chance of success. Escalation: rainmaking should allow for escalation or continuation in order to raise the conditional hazard during prayer prayer in an environment with an increasing hazard. Demand: in the extension of Appendix A.4, we show that when rainmaking has tangible costs and benefits, it will be more prevalent in areas where the benefits of rainfall are high.

## 4.2 Data

While rainmaking has long been a subject of study there is no prior dataset recording its practice on a large scale. We assemble a global data set on the practice of rainmaking from a multitude of anthropological accounts.

**Sources.—**We use as a template for our data collection the *Ethnographic Atlas* (Murdock, 1967). The *Atlas* records political, social and economic practices for 1,290 ethnic groups around the world as recorded by anthropologists in field studies between 1850 and 1950. While the field studies themselves postdate European contact, the *Ethnographic Atlas* was constructed with the intention of recording practices for different ethnic groups prior to colonization. We include in the *Atlas* the extensions of Giuliano and Nunn (2018).

We add to this data set new records on whether ethnic groups in the *Atlas* practiced rainmaking. We hired research assistants to read anthropological texts for each ethnic group in the *Atlas*. The search protocol found the top ten cited texts for each ethnic group and "rain ritual" and "praying for rain" in Google Scholar and looked through these texts both automatically and manually for any reference to whether an ethnic group practiced a rain ritual, defined as a petition for rainfall, usually but not necessarily through a religious authority. The coding refers to some 370 different texts, many of which describe the practice of a single group or region. We provide a complete bibliography as a supplementary appendix.

The variable for rainmaking was coded as $RainRitual_i$ equal to one if any record was found that a given group $i$ practiced a ritual to make rain. As seen above, accounts of rain ritual practice are typically rich with detail, leaving little risk of false positives. If no evidence was found of a rain ritual, or the evidence was not clear, the variable was coded as zero. It is, of course, harder to provide evidence for the absence of rainmaking than for its practice. However, many texts give clear descriptions of religious practice that does not include rain rituals, as in the case of the Puyallup above.

We supplement the main *Atlas* data set with additional data sources on climate, geography and cropping patterns. The most important of these variables are on rainfall. We get daily, station-level rainfall data from the Royal Netherlands Meteorological Institute, KNMI (WMO, 2021). The availability of daily data is crucial, for our estimation, because we need to estimate not just climate normals but the detailed pattern of time dependence in rain. We match ethnic groups to the nearest modern weather station using their coordinates. Appendix B discusses the details of the data construction and this station matching.

We also use modern data, on rainfed agricultural area, to measure the seasonality of demand for rain. The source data reports rainfed agricultural area by crop and month of year gridded over the whole globe (Kebede et al., 2025). We aggregate this data to calculate the share of area within a 100 km radius of each ethnic group's location that is under rainfed crops in each month of the year. We then classify the growing season as the six continguous months with the highest mean rainfed crop area for each group. The non-growing season is the complementary six months of the year. The use of these modern data assumes some continuity between historical and modern cropping patterns. We show in Appendix Figure B3 that the *Ethnographic Atlas* classification of agricultural dependence for an ethnic group is highly positively correlated with the modern mean share of rainfed crop area near that group over the course of the year.

Table 2: Summary statistics on Atlas and KNMI variables

| | Obs. (1) | Mean (2) | Std. dev (3) | Min (4) | p50 (5) | Max (6) |
|---|---|---|---|---|---|---|
| *Panel A: Atlas variables* | | | | | | |
| Rain ritual (=1) | 1208 | 0.392 | 0.488 | 0.0 | 0 | 1.0 |
| High gods (=1) | 774 | 0.643 | 0.479 | 0.0 | 1 | 1.0 |
| Agriculture dependent (=1) | 1289 | 0.634 | 0.482 | 0.0 | 1 | 1.0 |
| Agriculture: dependence (cont) | 1289 | 45.453 | 26.736 | 2.5 | 50.5 | 92.5 |
| Ag.: intensive irrigated (=1) | 1291 | 0.097 | 0.296 | 0.0 | 0 | 1.0 |
| Ag.: intensive (=1) | 1291 | 0.160 | 0.367 | 0.0 | 0 | 1.0 |
| Ag.: extensive or shifting (=1) | 1291 | 0.365 | 0.482 | 0.0 | 0 | 1.0 |
| Ag.: casual (=1) | 1291 | 0.033 | 0.180 | 0.0 | 0 | 1.0 |
| Ag.: horticulture (=1) | 1291 | 0.077 | 0.267 | 0.0 | 0 | 1.0 |
| Ag.: none (=1) | 1291 | 0.187 | 0.390 | 0.0 | 0 | 1.0 |
| Jurisd. hierarchy (cont) | 629 | 0.728 | 0.938 | 0.0 | 0 | 3.0 |
| Jurisd. hierarchy: 3 levels (=1) | 629 | 0.070 | 0.255 | 0.0 | 0 | 1.0 |
| Jurisd. hierarchy: 2 levels (=1) | 629 | 0.130 | 0.337 | 0.0 | 0 | 1.0 |
| Jurisd. hierarchy: 1 level (=1) | 629 | 0.258 | 0.438 | 0.0 | 0 | 1.0 |
| Jurisd. hierarchy: 0 levels (=1) | 629 | 0.542 | 0.499 | 0.0 | 1 | 1.0 |
| *Panel B: Geographic variables* | | | | | | |
| Elevation (m) | 1291 | 675.067 | 716.937 | -35.0 | 428.00 | 5412.00 |
| Ruggedness (m) | 1291 | 92.919 | 160.567 | 0.0 | 34.22 | 2192.18 |
| Latitude | 1291 | 15.368 | 22.690 | -55.0 | 11.00 | 78.00 |
| Longitude | 1291 | 2.779 | 84.626 | -179.3 | 13.00 | 178.68 |
| Distance from river (km) | 1291 | 289.116 | 932.068 | 0.0 | 69.30 | 9029.52 |
| Distance from lake (km) | 1291 | 520.744 | 971.812 | 0.0 | 286.75 | 9223.54 |
| Distance from ocean (km) | 1291 | 485.886 | 486.673 | 0.0 | 322.46 | 2575.23 |
| Rainfall mean (annual, m) | 1291 | 1.216 | 1.121 | 0.0 | 1.03 | 8.52 |
| Mean temperature (daily, Celsius) | 1291 | 20.363 | 9.017 | -13.9 | 23.73 | 31.11 |
| Hazard of rainfall after a dry spell | 1278 | 0.048 | 0.033 | 0.0 | 0.04 | 0.44 |
| Hazard derivative of rainfall after a dry spell | 1278 | 0.000 | 0.002 | -0.0 | 0.00 | 0.01 |
| Hazard rate increasing (=1) | 1278 | 0.705 | 0.456 | 0.0 | 1.00 | 1.00 |
| Haz rate inc. (growing season) (=1) | 1149 | 0.513 | 0.500 | 0.0 | 1.00 | 1.00 |
| Haz rate inc. (non-growing season) (=1) | 1107 | 0.444 | 0.497 | 0.0 | 0.00 | 1.00 |

*Notes*: This table provides summary statistics on variables from the ethnographic atlas and variables from the KNMI rainfall and weather data. Panel A includes categorical and continuous versions of variables from the original ethnographic atlas, such as agriculture intensity. Panel B includes geographic variables such as latitude and longitude coordinates, as well as average rainfall and temperature from the scraped KNMI data. Additionally, panel B includes variables from the hazard estimation, such as the indicator variable for increasing hazard rate, average hazard rate at the 99th percentile, and the derivative of the hazard at the 99th percentile. These hazard estimates are produced from rainfall spell data, which was created using the KNMI rainfall data.

**Summary statistics.—**Table 2 summarizes the variables in our augmented *Ethnographic Atlas*. Panel A shows variables from the *Atlas* along with the rain ritual variable. We are able to code the practice of rain rituals for 1,208 of the 1,290 groups in the augmented version of the *Ethnographic Atlas*. Globally, 39% of ethnic groups are found to practice a rain ritual. This confirms, systematically, the perception of anthropologists that rainmaking is widespread. Most groups practice agriculture, to some extent, and 26% of groups practice intensive or intensive irrigated agriculture.

Table 2, Panel B shows geographic variables on topography, climate and the like that we calculate from contemporary global data sets. We find that the mean hazard of rainfall after a dry spell, defined as the hazard evaluated at the 99th percentile of the local spell distribution, is 4.8% per day, similar to the probability that we estimated for Murcia (Figure 6). Around the world, 71% of ethnic groups have hazard functions that are estimated to be increasing after a dry spell, as is the case for Murcia. Appendix Table D11 reports summary statistics for *Atlas* and geographic variables separately for ethnic groups based on whether they face an increasing or a non-increasing hazard rate.

Figure 2, panel A maps the prevalence of rainmaking around the world. Rainmaking is practiced on every settled continent. We note several patterns: (i) rainmaking is most common in Africa, Europe and Asia and least common in South America; (ii) rainmaking is more common in Mediterranean Europe than in central or northern Europe; (iii) rainmaking appears less common in areas with very abundant rain, such as Amazonia and the Pacific Northwest of the United States; (iv) rainmaking practice varies within fairly narrow regions including, for example, in the Southwestern United States, East Africa and the Western Pacific.

## 4.3 Rainfall hazard estimation

We now describe our estimates of the rainfall hazard function for ethnic groups around the world. The estimation method is the same as described for Murcia in Section 3.3. We treat the hazard function as a fixed characteristic of each group's ancestral location and pool between 30 and 200 years of daily rainfall data to estimate the hazard for each group. (See Appendix B.3 on the rainfall data and Appendix B.5 on the estimation procedure).

Figure 1 shows the estimated hazard functions for six different ethnic groups from around the world, which have been deliberately selected to show some of the heterogeneity in hazard functions that we estimate. Panel A shows the hazard function for the Ainu group indigenous to the island of Hokkaido, Japan. It is roughly flat, and most dry spells are short (median 11 days). Panel B shows the hazard function for the Camba group of eastern Bolivia. The Camba are an Amazonian people in the rain shadow of the Andes.

The probability of rainfall is high, the hazard rate is decreasing and the 99th percentile dry spell is only 49 days. Panel C shows the hazard function for the Puyallup, who lived near Seattle, Washington in the United States. The probability of rainfall is high and the hazard function is more clearly decreasing. Panel D shows the hazard rate for the Herero, a Bantu group inhabiting Namibia and parts of nearby countries. Namibia has arid, semi-arid and sub-humid areas with two distinct rainy seasons, the short rains from September to November and the long rains, much heavier, from February to April. The resulting hazard function is high after a recent rain, falling to practically zero three months out but rising steeply again after six months. Dry spells of over eight months occur in our data. Panel E shows the hazard rate for the Rwala, a nomadic group that ranged between parts of Saudi Arabia, Jordan and Syria (the coordinates in the data place them in Syria). The Rwala receive an average of 21 inches of rain per year, about half of the average ethnic group in our sample. Their hazard function is estimated to be decreasing after a recent rainfall and then basically flat once two months has passed without rain. Finally, Panel F shows the hazard rate for the Shantung (Shandong) of northeastern China. The shape of the hazard is very similar to that for the Herero though the length of dry spells is generally shorter.

The hazard estimates taken as a group show some of the heterogeneity in rainfall patterns in different parts of the world. Not all hazard functions look like those in Murcia (Figure 6). The level of rainfall and the shape of the hazard are distinct features of the local climate. Both the Herero and the Rwala face a semi-arid climate, but only for the Herero does the rainfall hazard distinctly increase after a long dry spell. The hazard rate for the Herero after a long dry spell is about 4% per day, somewhat lower than in Murcia, though in both cases the hazard at this point increases at a similar rate.

Figure 2, panel B maps an indicator variables for whether the derivative of the hazard function for each ethnic group is estimated to be increasing. There are some areas of the world where the hazard function is nearly always decreasing (e.g., on Pacific Islands). However, in most other areas there is variation in whether the hazard rate is increasing at a smaller geographic scale, within Africa and North America, for example. The prevalence of increasing hazard rates (in panel B) appears to be correlated with the practice of rain rituals (in panel A). For example, within South America, Andean peoples are more likely to have increasing hazards and to practice rainmaking, as compared to Amazonian peoples. Within Africa, increasing hazard rates are common, but especially so in southern Africa, for groups like the Herero, where the practice of rainmaking is nearly universal. Appendix Table D11 compares means of group characteristics for groups with and without an increasing hazard rate. Groups with an increasing hazard, on average, are more likely to practice a rainmaking ritual, are less distant from lakes and rivers, and have lower and less variable rainfall.

Below, we will test the hypothesis that increasing hazard functions predict rainmaking, controlling for a rich set of geographic covariates.

# 5 The Climate as a Determinant of Religious Belief

This section tests whether the rainfall process predicts rainfall prayers in a manner consistent with our model. We relate rainmaking to two main factors. First, whether a group's environment is conducive to persuasion, as measured by whether a group faces an increasing hazard of rainfall. Second, the demand for rainfall, as measured by a group is traditionally dependent on agriculture. We find that both factors strongly predict rainmaking practice.

## 5.1 Regression specification

The main regression specification, at the level of the ethnic group $i$, is

$$RainRitual_i = \beta_1 HazardIncreasing_i\ [+\beta_2 AgricIntensity_i] + \mathbf{X}_i'\alpha + \delta_c + \varepsilon_i. \tag{10}$$

The variables $RainRitual_i$ and $HazardIncreasing_i$ are binary variables and are displayed in Figure 2 and discussed above. We use only information on whether the hazard rate is increasing, but not on its slope.[25] Our baseline specifications include continent fixed effects $\delta_c$ and geographic controls $\mathbf{X}_i$ that are clearly exogenous. In some specifications, we also include $AgricIntensity_i$, which measures the agricultural intensity of a group. Ethnic groups in the *Atlas* vary in how much they rely on agriculture for subsistence and what type of agriculture they practice. We use both continuous and categorical measures of intensity. These variables are omitted from our baseline specification because it is possible that an increasing hazard itself influences agricultural practice, in which case including agricultural intensity as a control may bias our estimates of $\beta_1$.

We draw a battery of control variables from related literature on the geographic antecedents of modern economic outcomes (Alesina, Giuliano and Nunn, 2013; Fenske, 2013; Alsan, 2015). We classify controls into several broad groups: *climate controls* include a quadratic polynomial in mean temperature, the standard deviation of temperature, a quadratic polynomial in mean rainfall, and the standard deviation of rainfall; *geography* controls include latitude north of the equator, latitude south of the equator, longitude, and the distance of a group to the coast, to a major river, and to a major lake; *topography controls* include elevation and ruggedness (Nunn and Puga, 2012). The climate controls are

[25] The prediction of our model is that praying is persuasive only if the slope is increasing, regardless of its magnitude. Our model would additionally predict the timing of prayer as a function of the hazard rate's slope; however, we cannot test this prediction, since we observe the timing of prayer only for Murcia.

particularly important since our model predicts a link between a particular feature of the climate and rainmaking practice. We therefore investigate the robustness of our specification to varying these controls and including other climate norms such as the length of droughts or the standard deviation of rainfall within a year (rather than only across years). Our main control sets consist only of geographic or climatological variables that are clearly exogenous to religious practice. In some specifications, we will also include variables recorded in the *Ethnographic Atlas*, such as agricultural intensity, as explanatory variables of interest.

An econometric concern with the literature on the geographic determinants of culture and development is that spatial autocorrelation can induce spurious correlation between many geographic variables (Conley and Kelly, 2025). We follow the recommendations for the best practices in this literature. All of our specifications include continent fixed effects and detailed controls for geography as discussed above. We report Conley standard errors to account for spatial correlation in $\varepsilon_i$ and discuss the robustness of our inference to alternate choices of the spatial bandwidth and to clustering along with the estimates.

## 5.2 Estimates of the determinants of rainmaking

**Whether the environment allows persuasion.—**The main distinguishing prediction of our model is that rainmaking should be more prevalent where it is more persuasive. In our model, the key to the perceived efficacy of rainmaking is the shape of the hazard function and particularly whether it is increasing after a dry spell. We test this hypothesis by estimating (10) including $HazardIncreasing_i$ as the main variable of interest.

Table 3 reports the results. The specifications from left to right cumulatively add the control variables indicated in the footer: only continent fixed effects (column 1), climate controls without the increasing hazard indicator (column 2), climate controls with the increasing hazard indicator (column 3), climate and geography and topography controls (column 4), separate indicators for an increasing hazard during the dry and rainy seasons (column 5), and an additional control for the length of droughts (column 6). All specifications report Conley standard errors with a spatial bandwidth of 1000 km. Appendix Table D12 considers alternate spatial bandwidths between 100 and 4000 km and also standard errors clustered at the level of the weather station, since some ethnic groups have hazard estimates based on data from common nearby stations (Appendix B shows there are 687 unique stations matched to 1,290 ethnic groups).

The main result is that ethnic groups facing an increasing hazard of rainfall have a markedly higher probability of practicing rainmaking. For ethnic groups facing a decreasing hazard, the probability of rainmaking is 0.30. Facing an increasing hazard rate is estimated to increase the probability of rainmaking by 0.14 (standard error 0.038) (column 1),

Table 3: Rainmaking by Whether the Environment Allows Persuasion

| | *Dependent variable: Rain ritual practiced (=1)* | | | | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Hazard rate increasing (=1) | 0.14*** | | 0.13*** | 0.14*** | | 0.13*** |
| | (0.038) | | (0.038) | (0.037) | | (0.037) |
| Haz rate inc. (growing season) (=1) | | | | | 0.13*** | |
| | | | | | (0.035) | |
| Haz rate inc. (non-growing season) (=1) | | | | | −0.00058 | |
| | | | | | (0.034) | |
| Dry spell duration (months, at p99) | | | | | | 0.0065 |
| | | | | | | (0.0050) |
| Rainfall mean (annual, m) | | −0.074** | −0.036 | −0.024 | −0.012 | −0.0029 |
| | | (0.038) | (0.039) | (0.039) | (0.038) | (0.041) |
| Rainfall std. dev (across years) | | −0.021 | 0.013 | −0.019 | −0.046 | −0.0065 |
| | | (0.089) | (0.086) | (0.086) | (0.087) | (0.085) |
| Continent effects | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Climate controls | | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Geography controls | | | | *Yes* | *Yes* | *Yes* |
| Topography controls | | | | *Yes* | *Yes* | *Yes* |
| Missing seasonal haz. | | | | | *Yes* | |
| *p-value for a test of the joint significance of:* | | | | | | |
| Continent effects | 0.001 | 0.000 | 0.000 | 0.011 | 0.005 | 0.010 |
| Climate controls | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Geography controls | | | | 0.008 | 0.006 | 0.007 |
| Topography controls | | | | 0.080 | 0.128 | 0.091 |
| *p-value for a test of the equality of:* | | | | | | |
| Seasonal hazards | | | | | 0.0057 | |
| Mean dep. var | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| Mean dep. var (dec. haz) | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| $R^2$ | 0.036 | 0.056 | 0.067 | 0.086 | 0.088 | 0.087 |
| Observations | 1195 | 1195 | 1195 | 1195 | 1195 | 1195 |

*Notes*: This table reports coefficients from regressions at the ethnic group level of whether a rain ritual is practiced on an indicator for that group facing an increasing hazard rate. Climate controls include: a quadratic in mean temperature, the standard deviation of temperature, a quadratic in mean rainfall and the standard deviation of rainfall; only the coefficients on mean rainfall and the standard deviation of rainfal are reported. Topography controls include elevation and ruggedness; geography controls include latitude north of the equator, latitude south of the equator, longitude, the distance of a group to the coast, to a major river, and to a major lake. Spatial (HAC-consistent) standard errors are calculated using Bartlett's kernel with truncation at a distance of 1000 km. Statistical significance at certain thresholds is indicated by $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$.

or 47%. This estimate conditions only on continent fixed effects. The estimated effect of an increasing hazard rate on rain ritual practice is practically invariant to the set of controls used (looking across the same coefficient in columns 1, 3, 4, and 6 for example).

We include a range of different climate controls and find evidence that it is an increasing hazard of rainfall specifically that predicts rainmaking and not other, possibly correlated, features of the climate. In column 2, we replace the increasing hazard indicator with climate controls, and report in the table the coefficients on mean rainfall and the standard deviation of rainfall, as the most salient climate controls. We find, in this sparse specification, that a one standard deviation increase in rainfall (1.1 meters, see Table 2, panel B) is associated with a 7.4 pp (standard error 3.8 pp) decrease in the probability of rainfall prayer and that the standard deviation of rainfall itself has a small, null effect of $-2.1$ pp (standard error 8.9 pp). The estimated effect of mean rainfall, however, is not robust to also including the rainfall hazard. In column 3, when we add back the indicator for an increasing hazard, the coefficient on mean rainfall is greatly attenuated and no longer statistically significant. The estimated effect of an increasing hazard rate, by contrast, is invariant to the set of controls used (looking across columns 1, 3 and 4, for example). The controls themselves are strongly predictive of rainmaking. The $p$-value for an F-test of the joint significance of the climate controls is $p < 0.001$, of the geography controls $p < 0.008$ and of the topography controls $p < 0.077$. We therefore find strong evidence that an increasing hazard rate is associated with a higher probability of rainmaking.

Our theory is specific that an increasing hazard rate is the feature of the climate that matters for persuasion. It may be important for persuasion that the increasing hazard is increasing at a time when rainfall is in high demand. In Table 3, column 5, we separate the measure of increasing hazard by the season in which a dry spell began. We classify the growing season as the contiguous six months of the year with the greatest area planted under rainfed agriculture within a 100 km radius of each ethnic group. We find that an increasing hazard rate for spells that began in the growing season predicts a 0.13 (standard error 0.035) higher probability of practicing a rain ritual, the same as in our main estimates. An increasing hazard rate outside the growing season predicts a $-0.00058$ (standard error 0.034) higher probability of practicing a rain ritual. The non-growing season estimate is therefore very small and statistically indistinguishable from zero. We reject that the coefficient on the growing-season increasing hazard is the same as on the non-growing-season hazard ($p$-value $= 0.0058$). We therefore conclude that the predictive power of the increasing hazard is entirely due to whether the hazard is increasing during the growing season, when people most want rain. Appendix Table D13 conducts robustness checks with alternative measures of the seasonality of demand that generally support this finding (see Appendix D.3).

An alternative, less specific theory of rainmaking is that rainmaking will be prevalent where rain is scarce or uncertain. We already find evidence against this, in columns 3 to 5, in that the mean and standard deviation of rainfall are not predictive of rain ritual practice conditional on the hazard rate increasing. In column 6, we add an additional test by including a control for the length of drought, specifically, the 99th percentile of the distribution of the length of dry spells for each ethnic group. We find, again, that the length of drought does not predict rain ritual practice and that the effect of an increasing hazard rate on rain ritual practice is the same after including this control. The regression evidence is extremely specific in that the feature of the climate that predicts rainmaking is exactly whether the hazard rate is increasing, as in our theory, and not alternative measures of an arid or variable climate that might be suggested by lay intuition.

**The demand for rainmaking.—** The second hypothesis we test is whether rainmaking practice depends on an ethnic group's demand for rainmaking. The examples in Section 4.1 suggest that rainmaking may be less prevalent in groups with a more reliable or less rainfall-dependent food supply. For example, tribes of the Pacific northwest in the United States, such as the Puyallup, which do not practice rainmaking and are noted for a general lack of ceremonial traditions (Drucker, 1939), subsist on an abundant, reliable supply of fish. Conversely, if a group needs regular rainfall to sustain its economy, it may have a greater demand for divine intervention. Chaney (2013) illustrates such a case in Islamic Egypt, a highly complex, hierarchical society with large-scale irrigation investments, which nonetheless saw increased religiosity and social unrest during deviant Nile floods.

We use the mode of subsistence of an ethnic group as our proxy for rainfall demand. The *Ethnographic Atlas* has two measures of dependence on agriculture. A continuous measure estimates how much of each group's subsistence came from agriculture. The scale of this measure ranges from 0 to 100%. A categorical measure classifies the main mode of subsistence of a group, among several kinds of agriculture (casual, horticulture, extensive or shifting, intensive, and intensive irrigated). The omitted categories of subsistence include animal husbandry, fishing, and hunting and gathering.

Table 4 estimates equation (10) adding agricultural intensity measures as additional explanatory variables of interest. We find that ethnic groups more dependent on agriculture are much more likely to practice rainmaking. In columns 1 and 2 the dependent variable is an indicator for whether more than 45% of subsistence comes from agriculture (the coding in the *Atlas* measures agricultural dependence in bins of 10 pp that end in 5, like 35-45%). An agriculture-dependent ethnic group is 9.7 pp (standard error 4.9 pp) more likely to practice a rain ritual than a group that is not agriculture dependent (column 2). This ef-

Table 4: Agriculture as a Determinant of Rainmaking Demand

| | *Dependent variable: Rain ritual practiced (=1)* | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Hazard rate increasing (=1) | 0.14*** | 0.14*** | 0.14*** | 0.16*** |
| | (0.038) | (0.037) | (0.037) | (0.038) |
| Agriculture dependent (=1) | 0.12** | 0.097** | | |
| | (0.049) | (0.049) | | |
| Agriculture: dependence (cont) | | | 0.0028*** | |
| | | | (0.00090) | |
| Ag.: intensive irrigated (=1) | | | | 0.37*** |
| | | | | (0.072) |
| Ag.: intensive (=1) | | | | 0.22*** |
| | | | | (0.071) |
| Ag.: extensive or shifting (=1) | | | | 0.14** |
| | | | | (0.065) |
| Ag.: horticulture (=1) | | | | 0.084 |
| | | | | (0.090) |
| Ag.: casual (=1) | | | | −0.014 |
| | | | | (0.089) |
| Agriculture: missing (=1) | | | | 0.042 |
| | | | | (0.072) |
| Continent effects | *Yes* | *Yes* | *Yes* | *Yes* |
| Climate controls | | *Yes* | *Yes* | *Yes* |
| Geography controls | | *Yes* | *Yes* | *Yes* |
| Topography controls | | *Yes* | *Yes* | *Yes* |
| Mean dep. var | 0.39 | 0.39 | 0.39 | 0.39 |
| Mean dep. var(agric = 0) | 0.32 | 0.32 | 0.32 | 0.32 |
| $R^2$ | 0.046 | 0.092 | 0.099 | 0.12 |
| Observations | 1194 | 1194 | 1194 | 1195 |

*Notes*: This table reports coefficients from regressions at the ethnic group level of whether a rain ritual is practiced on measures of agricultural intensity, as well as an indicator for whether a group faces an increasing hazard rate. See Table 3 notes for a description of the controls. Spatial (HAC-consistent) standard errors are calculated using Bartlett's kernel with truncation at a distance of 1000 km. Statistical significance is indicated by $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$.

fect is about one-third of the mean level of rainmaking practice among groups that are not agriculture dependent (0.32). There is a similarly large and positive effect of agricultural dependence on rainmaking when dependence is measured with a continuous variable (column 3). The coefficient of 0.28 pp (standard error 0.09 pp) per 1 pp of dependence implies that increasing dependence from 0 to 50% is estimated to increase rainmaking by 14 pp.

The relationship between agricultural intensity and rainmaking suggest that rainmaking responds to the risk created by agricultural investments. The *Atlas* allows more specificity in this test since it encodes not only the degree of agricultural dependence but also its type. In column 4 we use categorical measures for the type of agriculture practiced by each group as explanatory variables. The most intensive agricultural methods are associated with far higher probabilities of practicing a rain ritual, relative to the omitted category of non-agricultural subsistence. The coefficient on a dummy variable for intensive irrigated agriculture is 0.37 (standard error 0.072), and on intensive agriculture 0.22 (standard error 0.071). By the first estimate, intensive irrigated agriculture, as practiced in Murcia and in Islamic Egypt, more than doubles the baseline probability that a non-agriculture-dependent group practices a rain ritual. By contrast, shifting agriculture has a lesser effect (12 pp) and casual agriculture has a small and statistically insignificant effect on rain ritual practice.

We interpret these estimates as showing that agricultural intensity, because it magnifies dependence on rainfall, is a cause of higher demand for control of the weather. In our model, when rainmaking is costly, a greater benefit of rainfall will increase the prevalence of rainmaking. The Neolithic Revolution is associated with groups becoming stationary. A stationary group is more dependent on the weather in one specific place than a group that subsists on hunting or fishing and, also, than a group that can move to cultivate in different areas in response to bad weather or insufficient rain. Within those that practice agriculture, correspondingly, we find a weaker effect of extensive or shifting agricultural practice on rainmaking.

It may be surprising that the groups with the greatest and most specific agricultural investments, particularly in irrigation, are more likely to practice a rain ritual, since irrigation may be seen as insurance against rainfall shocks. We would argue that two factors explain this finding. First, most plainly, irrigation systems are themselves rainfed. For example, the irrigated water markets in Murcia studied by Donna and Espín-Sánchez (forthcoming) have no storage to smooth inter-annual shocks and prices are therefore highly dependent on rainfall, which dictates water supply. Second, complex societies are not insulated from unpredictable rainfall, as their scale and sophistication may be seen as specific investments that increase agricultural output, but do not insulate the economy from weather shocks. The Chaney (2013) example is relevant here. The caloric productivity gains from settled agriculture may be offset by a Malthusian expansion of population. Scott (2017) argues that post-Neolithic-revolution populations had lower living standards in many respects than their mobile ancestors and contemporaries. Groups that make specific agricultural investments in cropping or irrigation in one place are more dependent on rainfall for subsistence, even if those groups may have higher productivity on average.

**Robustness.—**We interpret that an increasing hazard causes groups to practice rainmaking because it creates an environment that allows persuasion and that intensive agriculture causes groups to practice rainmaking because it increases the demand for rainfall. This part investigates the interpretation and robustness of these results, supported by additional analysis in Appendix D.

The effect of the environment on rainmaking is subtle. A naïve model may predict that people in dry climates, or perhaps in unpredictable climates, pray for rain. Our baseline estimates in Table 3 control for functions of temperature, rainfall and the length of dry spells and find that, while these controls have predictive power, they do not alter the estimated effect of an increasing hazard on rain ritual practice. In Appendix D.4, Table D15 we control for additional moments of rainfall including the variability of rainfall within the year. We continue to find no effect of mean rainfall or the standard deviation of rainfall, either within a year or across years, on rainmaking. Prior research has found that longer-term variability in climate, between generations, predicts lesser persistence in cultural practices (Giuliano and Nunn, 2021). Appendix Table D16 finds that climate variability across generations does not predict rain ritual practice, nor alter the estimated effect of the hazard.

We test in Appendix D.5 for the specificity of our finding on an increasing hazard affecting rain rituals to the point at which we classify the hazard as increasing or decreasing. The model argues that a hazard accommodates persuasion so long as it is increasing eventually. For example, in Appendix Figure A1, panel B, a ∪-shaped hazard allows persuasion because it is increasing after a long dry spell, as is the case empirically for the Herero, for example (Figure 1, panel D). Hence, our baseline specification classifies whether the hazard for a group is increasing by evaluating the hazard derivative at the 99th percentile of the distribution of dry spells for each ethnic group.

The evidence in Appendix D.5 shows that an increasing hazard predicts rain ritual practice *if and only if* measured after a long dry spell. The hazard measured after a short dry spell does not predict rain ritual practice. The reason for the specificity of this empirical result is that classifying the hazard at much lower percentiles of the dry spell distribution results in wholesale *mis*classification of whether a group faces an increasing hazard or not, with many groups that do face an increasing hazard falsely classified as facing a decreasing hazard. For example, Appendix Figure D11 shows hazard functions for some ethnic groups that have a decreasing hazard at the 95th percentile of the dry spell distribution but an increasing hazard at the 99th percentile. Such groups comprise fully 34% of the sample, because the median 95th-percentile spell is only one-third as long as the median 99th-percentile spell (Figure D9) and many groups have ∪-shaped hazards that are still decreasing after short dry spells.

We therefore conclude, with the additional evidence from the tables in Appendixes D.4 and D.5, that the empirical results on the relation of climate to rain ritual practice are extraordinarily precise in their concordance with the model: it is whether the hazard is increasing after a long dry spell that matters. None of the level of rainfall, the variability of rainfall, the length of drought, or even whether the hazard function is increasing at some point predict rain rituals, but only whether the hazard function is increasing during a drought.

**High gods belief as an alternative measure of religiosity.—**We explore whether our model predicts only the practice of rain rituals or also other religious belief. Our model is meant to describe only rain ritual practice and so this analysis is, in a sense, for a placebo outcome. However, rain rituals could spill over to other religious practice, in which case we may find that an increasing hazard predicts belief generally.

The *Ethnographic Atlas*, without our additional data collection, includes only one measure of religious belief, a categorical variable for whether or not an ethnic group believes in "high gods." This variable is available for only 774 ethnic groups, or 60 percent of the total *Atlas*. There are two related definitions of high gods. The *Atlas* codebook, citing Swanson (1960), states: "A high god is defined, following Swanson, as a spiritual being who is believed to have created all reality and/or to be its ultimate governor, even if his sole act was to create other spirits who, in turn, created or control the natural world." Norenzayan et al. (2016) refines this definition by defining a "big god" as also prescribing a moral code, in addition to the above traits. We code an indicator variable *High Gods (*$= 1$*)*, corresponding to the Swanson (1960) definition of high gods, and another indicator *High Gods Moral (*$= 1$*)*, corresponding to the Norenzayan et al. (2016) definition.

We find no relationship between an increasing hazard rate and belief in high gods, by either measure of high gods belief. Appendix Tables D21 and D22 reproduce the specifications of Table 3 using *High Gods (*$= 1$*)* and *High Gods Moral (*$= 1$*)*, respectively, as the dependent variables, in place of belief in a rain ritual. In no specification is an increasing hazard predictive of belief in high gods. The increasing hazard maintains the same strong relationship with rain ritual practice in this restricted sample (Appendix Table D23). We additionally find that the effect of an increasing hazard rate on rain ritual practice is present and about equally strong both for ethnic groups that believe in high gods and those that do not (Appendix Table D24). The finding that an increasing hazard is not correlated with high gods belief suggests that the mechanism connecting an increasing hazard rate to rain ritual practice is specific to belief in rainmaking and not a spillover from belief in high gods.

# 6 Conclusion

We study the determinants of religious belief using a new theory of persuasion and empirical evidence based on new data from Murcia, Spain and a global cross-section of ethnic groups. In the model, people believe in rainmaking if a religious leader can credibly intervene in nature. Whether intervention is credible, in turn, depends on the pattern of rainfall. The leader is able to persuade the people in an environment with an increasing hazard rate. With an increasing hazard, prayers that start during drought will both have a higher probability of rain during prayer and deliver rain when the demand for rain is at its highest.

We find evidence consistent with our model in several respects. First, in Murcia, the church's prayers for rain, which follow a strategy consistent with our model, are highly predictive of subsequent rainfall. Prayer Granger-causes rain. Second, in the global ethnographic data, we find that ethnic groups are 47% more likely to practice rainmaking when they live in an environment that allows persuasion. Third, global rainmaking responds strongly to the demand for rainfall created by intensive agriculture, with rainmaking practice more than twice as likely among groups practicing intensive irrigated agriculture. Rainmaking traditions are therefore consistent with cultural evolution: rainmaking practices endure where they are found to be successful, which selects for environments with an increasing hazard during a drought.

Rainmaking is a useful practice through which to study whether religious belief generically is instrumental. Rainmaking, as we document systematically, is a feature of religions of all kinds, in all major traditions, all over the world. The practice of rainmaking varies while maintaining a common object: to make rain. This specificity makes rainmaking a useful practice for studying whether belief is instrumental, because for rainmaking we can link ritual practice to the environment that determines its *seeming* efficacy. The connection between an increasing hazard and rainmaking practice establishes that this efficacy is important for rainfall prayer to be sustained.

Our empirical analysis follows the plan laid out by Frazer (1890), who argued that "if we can show that a [custom] . . . has existed elsewhere; if we can detect the motives which led to its institution; if we can prove that these motives have operated widely, perhaps universally, in human society, producing in varied circumstances a variety of institutions specifically different but generically alike" only then may we infer the cause of any particular custom. Frazer advocates for inductive reasoning: there is no hope to infer the motive for a particular custom, regardless of how thoroughly we study any one case, without generalization from a wide body of examples. We follow this advice to infer that rainmaking around the world is commonly motivated by instrumental belief.

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# Online Appendix

# Praying for Rain:
# The Climate and Instrumental Religious Belief

José-Antonio Espín-Sánchez, Salvador Gil-Guirado and Nicholas Ryan

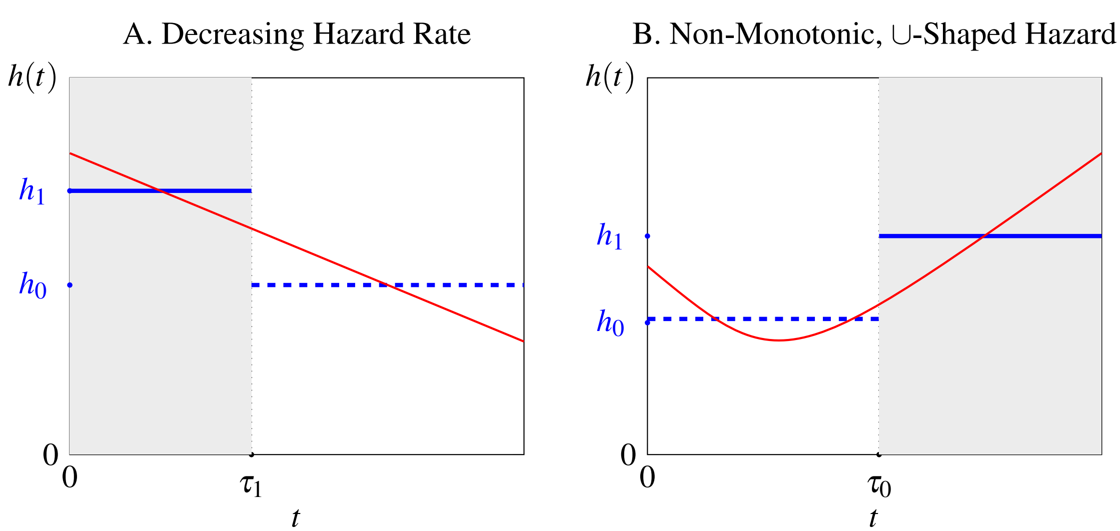
# A Appendix: Model

## A.1 Decreasing and Non-Monotonic Hazards

Figure A1 shows examples of hazard rates that are decreasing or non-monotonic (∪-shaped). Panel A shows the case of a decreasing hazard rate (DHR). Under a decreasing hazard the religious leader (RL) could persuade people. The optimal policy would be to pray immediately after the last rain ($\tau_0 = 0$) and stop praying at $t = \tau_1$. Although this policy works in theory it is unlikely to be useful in practice. The people's demand for rain is increasing over time since the last rain. The optimal policy with a decreasing hazard is to pray for rain when rain is not useful and then to stop praying precisely when rain would be most beneficial to the people. Empirically, we also observe that areas with decreasing hazard rates: (i) have close to constant hazards, rather than decreasing sharply (ii) tend to have very frequent rainfalls, again making the value of prayer for rain practically low.

Panel B shows a case where the hazard rate first declines after rainfall and then increases after a sufficiently long spell as passed. This case is common in the data (see Figure 1 for some examples). In this case the policy of beginning to pray at $\tau_0$ and praying continually thereafter can create separation between the hazard rate without prayer $h_0$ and with prayer $h_1$. This case therefore behaves, in our model, the same as the case with a monotonically increasing hazard rate.

Figure A1: Alternative Hazard Function Shapes




*Notes*: The figure shows examples of the experiments created by different hazard functions for rainfall and prayer policies. The two panels plot the rainfall hazard rate against time on the horizontal axis. The hazard rate is shown by the solid red line or curve and prayer is indicated by the shaded gray intervals. In panel A, the hazard is decreasing. We give an example where prayer starts at $t = 0$ and continues up to $t = \tau_1$. In panel B, the hazard is first decreasing and then increasing.

## A.2 Definitions for the strength of beliefs

This subsection defines parameter values that mark the strength of beliefs. Two specific parameter thresholds separate beliefs into three tiers: weak, moderate and infeasible.

**Assumption 2** (Moderate belief)**.** $p\omega_i > \eta - (1-p)\alpha > 0$.

Assumption 2 (A2) requires that the hazard rate increase if God listens is sufficiently large, relative to the gap between the average hazard rate $\eta$ and the initial hazard rate $\alpha$.

**Assumption 3** (Feasible belief)**.** $p\omega_i \leq h_1(\tau^M) - (1-p)h_0(\tau^M)$,
*where* $\tau^M = \underset{t}{argmax}[h_1(t,\infty) - (1-p)h_0(t,\infty) - p\omega_i]$.

Assumption 3 (A3) requires $\omega_i$ not to be too large, relative to the difference the hazard function allows in conditional hazards with and without prayer. To this point, we have not restricted $\omega_i$ by requiring people's beliefs on the hazard during prayer to be generated from the hazard function or consistent with past experience. It is possible that a person's belief $\omega_i$ is so large that convincing the person becomes infeasible.

We call beliefs *weak* if they do not satisfy A2. We call beliefs *moderate* if they satisfy A2 but not A3. We call beliefs *infeasible* if they do not satisfy A3.

## A.3 Proofs omitted from the main text

**Proof of proposition 1.—**

*Proof.* Proposition 7 below restates and extends Proposition 1 from the main text, characterizing when a given person will support the leader as a function of their belief. We show that the set of values of $\tau_0^j$ that would make a person support the RL is always an (potentially empty) interval and it decreases monotononically on both ends as $\omega_i$ increases. People with *weak* beliefs (small $\omega_i$) would support the RL even if they always pray ($\tau_0^j = 0$). People with *moderate* beliefs would support RL that wait long enough, but not too long, to pray. People with *infeasible* beliefs will not support the RL for any value of $\tau_0^j = 0$. □

**Proposition 7.** *With an increasing hazard rate, for each $\omega_i$ there is a unique interval $T(\omega_i) = (\underline{\tau_0}(\omega_i), \overline{\tau_0}(\omega_i))$ such that a person will support if and only if $\tau_0^j \in T(\omega_i)$.*

a ***Weak belief.*** *If A2 does not hold for $\omega_i$, then $\underline{\tau_0}(\omega_i) = 0$ and and $\underline{\tau_0}(\omega_i)$ is finite. A person supports the RL for $\tau_0^j \in T^*(\omega_i)$.*

b ***Moderate belief.*** *If A2 and A3 hold for $\omega_i$, then $\underline{\tau_0}(\omega_i) > 0$ and $\underline{\tau_0}(\omega_i)$ is finite. A person supports the RL for $\tau_0^j \in T^*(\omega_i)$.*

c ***Infeasible belief.*** *If A3 does not hold for $\omega_i$, then $T^*(\omega_i)$ is empty and a person does not support the RL for any value of $\tau_0^j$.*

*Proof.* We can write $\eta$ as a weighted average of $h_0(\tau_0)$ and $h_1(\tau_0)$ as

$$\eta \equiv (1-e^{-\tau_0})h_0(\tau_0) + e^{-\tau_0}h_1(\tau_0) \tag{11}$$

Thus, we can write $h_1(\tau_0)$ as a function of $h_0(\tau_0)$,

$$h_1(\tau_0) = \eta e^{\tau_0} - \frac{1-e^{-\tau_0}}{e^{-\tau_0}}h_0(\tau_0) \tag{12}$$

Using equations (4) and (5) we can define both terms as a function of $h_0(\tau_0)$. Moreover, the way we have defined $h_0(\tau_0)$, it is just a hazard rate as a function of $\tau_0$

$$\eta e^{\tau_0} - \frac{1-e^{-\tau_0}}{e^{-\tau_0}}h_0(\tau_0) \geq p\omega_i + (1-p)h_0(\tau_0) \tag{13}$$

Simplifying the second term, we now define the function

$$G(\tau_0) \equiv h_1(\tau_0) - \hat{h}(\tau_0|\omega_i) = \eta e^{\tau_0} - p\omega_i + h_0(\tau_0)(p - e^{\tau_0}) \tag{14}$$

The function $G(\tau_0)$ defines when the ritual is sufficiently persuasive based on the key constraint (5). A person will be persuaded to support whenever $G(\tau_0) \geq 0$. The belief $\omega_i$ enters linearly and with a negative sign on $G(\tau_0)$. This means that for sufficiently high values of $\omega_i$ we have $G(\tau_0) < 0$ (no persuasion) and for very low values of $\omega_i$ we may have $G(\tau_0) > 0$ (persuasion).

Below, we show that this function is hill-shaped and that the right tail always becomes negative for sufficiently high values of $\tau_0$. This means we can have three cases regarding existence. First, if the left tail of $G(\tau_0)$ is positive, i.e., $G(0) > 0$, then with $\tau_0 = 0$ we maximize support and persuade a person. Second, if the left tail is negative, but $G(\tau_0) > 0$ for some $\tau_0$, then we would not persuade a person with $\tau_0 = 0$, but there exists some $\tau_0 > 0$ that would persuade them. Third, if $G(\tau_0) < 0$, for all $\tau_0$, then the person cannot be persuaded. We now provide the technical details behind this reasoning.

First, regarding existence, we show that there exist a solution to $G(\tau_0^*) = 0$. If Assumption A2 is satisfied, we have $\overline{\tau_0^*}(\omega_i) > 0$. If Assumption A2 is not satisfied, we have $\overline{\tau_0^*}(\omega_i) = 0$.

Second, regarding uniqueness, we show that there are exactly two solutions to $G(\tau_0) = 0$ if Assumption A2 is satisfied: i) $G(\tau_0)$ is single-peaked; ii) $G(0) < 0$; iii) when $\tau_0$ goes to infinity, we have that $h_0(\tau_0)$ converges to $\eta$ and $G(\tau_0)$ converges to $p(\eta - \omega_i) < 0$. Thus, $G(\tau_0)$ crosses zero twice, first from below at $\underline{\tau_0}(\omega_i)$ and then from above at $\overline{\tau_0}(\omega_i)$. Thus, we have $G(\tau_0) \geq 0$ for all $\tau_0^j \in [\underline{\tau_0}(\omega_i), \overline{\tau_0}(\omega_i)]$. If Assumption A2 is not satisfied, then $G(0) > 0$. In this case $\underline{\tau_0}(\omega_i) = 0$, and $G(\tau_0)$ crosses zero once at $\overline{\tau_0}(\omega_i)$.

*Existence*. To show existence we need to show that there exists a $\tau_0^*$ such that $G(\tau_0^*) = 0$. At

$\tau_0 = 0$, with Assumption A2 we get

$$G(0) = \eta - p\omega_i + \alpha(p-1) < 0. \tag{15}$$

Therefore, if a solution exists, it should be at $\tau_0 > 0$. Under Assumption A3 a solution will exist. Otherwise, the $G(\cdot)$ function will not have a zero.

*Uniqueness*. We argue for the uniqueness of the interval $T(\omega_i)$ by showing that the function $G(\cdot)$ crosses the x-axis at most twice. Taking the first and second derivatives of $G(\cdot)$, we obtain

$$G'(\tau_0) = \eta e^{\tau_0} + h_0(\tau_0)(p - 2e^{\tau_0}) + h(\tau_0)(p - e^{\tau_0}) \tag{16}$$

$$G''(\tau_0) = \eta e^{\tau_0} + (h_0(\tau_0) + h(\tau_0))(p - 2e^{\tau_0}) + h_0(\tau_0)(-2e^{\tau_0}) + h'(\tau_0)(p - e^{\tau_0}) + h(\tau_0)(-e^{\tau_0}). \tag{17}$$

At a critical point $t_1$, where $G'(t_1) = 0$, we have $\eta e^{t_1} + h_0(t_1)(p - 2e^{t_1}) + h(t_1)(p - e^{t_1}) = 0$. We can solve for $\eta e^{t_1}$ as $\eta e^{t_1} = -h_0(t_1)(p - 2e^{t_1}) - h(t_1)(p - e^{t_1})$. Substituting this into $G''(t_1)$ we get

$$\begin{aligned} G''(t_1) = (h_0(t_1) + h(t_1))(p - 2e^{t_1}) - h_0(t_1)(p - 2e^{t_1}) - h(t_1)(p - e^{t_1}) + \\ + h_0(t_1)(-2e^{t_1}) + h'(t_1)(p - e^{t_1}) + h(t_1)(-e^{t_1}) \end{aligned} \tag{18}$$

We know at $t_1$:

1. $h_0(t_1) > 0$
2. $h(t_1) > 0$
3. $h'(t_1) > 0$ (since $h(t)$ is increasing)
4. $e^{t_1} > p$ (since $t_1 > ln(p)$). At any critical point $t_1$ we must have $e^{t_1} \leq p$. Otherwise, we cannot have $G'(t_1) = 0$. All terms in $G'(t_1) = 0$ are either positive or bounded below, and at least one is strictly positive.

Therefore at $t_1$:

- $p - e^{t_1} < 0$
- $p - 2e^{t_1} < p - e^{t_1} < 0$
- All terms become negative except possibly $h'(t_1)(p - e^{t_1})$, but this term is also negative, since $p - e^{t_1} < 0$ and $h'(t_1) > 0$.

Therefore $G''(t_1) < 0$ at any critical point. This implies that the function $G(\cdot)$ has only one critical point and that point is a maximum. Hence $G(\cdot)$ either has two zeroes, has one zero, or does not have any zeroes.

Finally, we can compute the limit of $G'(\tau_0)$ when $\tau_0 \to \infty$. Rearranging we get

$$G'(\tau_0) = e^{\tau_0}[\eta - 2h_0(\tau_0) - h(\tau_0)] + p[h_0(\tau_0) + h(\tau_0)] \tag{19}$$

$h_0(\tau_0) \to \eta$ as $t \to \infty$ (by definition) and $h(\tau_0)$ grows but slower than $e^{\tau_0}$. The term in the first bracket becomes $[-\eta - h(\tau_0)]$, so the first term goes to $-\infty$ exponentially whereas the second term goes to $\infty$ at a rate $ph(\tau_0)$. Therefore, at the limit we have $G'(\infty) = -\infty$. This limit implies that, if $G(\cdot)$ has a zero, there is some maximal $\overline{\tau_0}$ at which it crosses the x-axis for the last time. Therefore the function $G(\cdot)$ diverges for large $\tau$. It is still possible that $G(\cdot)$ has only one zero, but this can only occur via a maximum value at zero exactly, in which case the interval $T(\omega_i)$ is degenerate. These considerations establish the first claim in the proof, that there is a unique interval $T(\omega_i) = (\underline{\tau_0}(\omega_i), \overline{\tau_0}(\omega_i))$ such that the person will support if and only if $\tau_0^j \in T(\omega_i)$.

We now consider how the strength of belief dictates whether this interval has a positive lower bound and is non-empty. Notice that $\omega_i$ appears in $G(\tau_0)$ as a vertical shifter. This means that low values of $\omega_i$ would make $G(\tau_0)$ bigger and high values of $\omega_i$ would make $G(\tau_0)$ smaller and, eventually, negative. We consider the three cases in turn.

a. **Weak belief ($G(0) > 0$).** The RL would like $P[s_1|\tau_0]$ to be as high as possible and therefore to pray as long as possible. Suppose the RL prays all the time $\tau_0 = 0$ so that the person believes $h_0(0) = \alpha$ in the absence of prayer and $h_1(0) = \eta$ when the church prays. Then $G(0) > 0$ can be satisfied if $\eta \leq p(\omega_i) + (1-p)\alpha$, precisely the negation of A2. In this case, then, $\tau_0^* = 0$, because this maximizes the probability of rain during prayer, i.e., $P[s_1|\tau_0] = 1$.

b. **Moderate belief ($G(0) < 0$).** If A2 holds, it is not possible to satisfy (5) and pray all the time. In this case, the objective function is highest when (5) is satisfied with equality, i.e., $G(\tau_0) = 0$. If A3 holds, a solution to this equation exists. By A2 we have $G(0) < 0$. A3 implies that there exists some $\tau^M$, the maximand of $G(t)$, such that $G(\tau^M) > 0$. Therefore by continuity of $G(t)$ there exists at least one value of $\tau_0^*$ with $0 < \tau_0^* < \tau_0^M$ such that $G(\tau_0^*) = 0$. If there exist multiple $\tau_0^*$ such that $G(\tau_0^*) = 0$ then the lowest one is the optimal $\tau_0^*$ since this maximizes the probability of rain during prayer.

c. **Infeasible belief, ($G(t) < 0$).** In this case, $G(\tau^M) < 0 \Rightarrow G(\tau_0) < 0$ for all $\tau_0$. There is therefore no choice of $\tau_0$ that will satisfy (5). The RL cannot convince the person and is indifferent between all prayer strategies.

This covers all possible values of the $\omega_i$ parameter for belief. □

Lemma 1 below shows that support for the RL is monotonic on $\omega_i$. This means that if a person with belief $\overline{\omega}$ supports the RL with a given $\tau_j$, then all people would support the RL.

**Lemma 1.** *If person i with $\omega_i$ supports the RL with $\tau_0^j$. Then, person j with $\omega_j < \omega_i$ also supports the RL.*

*Proof.* The proof relies on the comparative statics of the solutions to $G(\tau_0) = 0$: $\underline{\tau_0}(\omega_i)$ and $\overline{\tau_0}(\omega_i)$. For lower values of $\omega_i$, the lower bound is lower and the upper bound in greater. That means that if a person with a given belief $\omega_i$ supports the leader, then any person with a lower belief $\omega_j$ would also support. The belief $\omega_i$ appears as vertical shifter in $G(\tau_0)$. Lower values of $\omega_i$ make $G(\tau_0)$ greater. Because $G(\tau_0)$ is single-peaked, if it takes positive values for $\omega_i$, then it must also take positive values for $\omega_j$. In other words, if $G(\tau_0(\omega_i)) > 0$, and $\omega_j < \omega_i$, then $G(\tau_0(\omega_j)) > 0$. □

**Proof of proposition 4.—**

*Proof.* For a given incumbent with $\tau_0^i$, we can write the persistence as a function of $\tau_0^i$:

$$\zeta(\tau_0^i) \equiv \mathbb{P}_\tau[\Sigma(\tau_0^j) \leq \Sigma(\tau_0^i)] \tag{20}$$

Let $g(\tau_0^i)$ be the expected number of generations that ritual $\tau_0^i$ will continue to practiced. Showing that the three statements below are equivalent suffices for the proof of Proposition 4.

1. $g(\tau_0^i) > g(\tau_0^j)$
2. $\zeta(\tau_0^i) > \zeta(\tau_0^j)$
3. $\Sigma(\tau_0^i) > \Sigma(\tau_0^j)$.

We now show that these statements are equivalent. First, given the definition of $\zeta(\tau_0^j)$, the second and third statements are equivalent. To show that they are equivalent to the first statement, notice that the probability of survival to the next period is $\zeta(\tau_0^j)$. $g(\tau_0^j)$ follows a geometric distribution as we're counting the number of periods until the first "failure" (non-survival). This probability is

$$\mathbb{P}[g(\tau_0^j) = n] = \zeta(\tau_0^j)^{n-1}(1 - \zeta(\tau_0^j)) \tag{21}$$

where $n$ is the number of generations that RL $\tau_0^j$ would survive. Using the formula for a geometric distribution we know

$$\mathbb{E}[g(\tau_0^j)] = \frac{1}{1 - \zeta(\tau_0^j)} \tag{22}$$

Hence, $\mathbb{E}[g(\tau_0^j)]$ is increasing in $\zeta(\tau_0^j)$, and the first and third statements are equivalent. □

## A.4 Tangible benefits and costs of prayer

The baseline model presented above is intentionally simple. A person supports the RL if the prayers are convincing enough. There is an implicit assumption here that the expected benefit that the person receives from the extra rain is greater than the cost of supporting the church. We now extend the model to allow for a benefit and cost of persuasion for the people. As we show below, if the benefit (relative to the cost) of the extra rain is not high, then a person will not be persuaded, even when the hazard rate is increasing. An implication is that higher benefits, such as higher returns to rainfall, will be associated with greater support and practice of rain rituals. The benefit of rainfall is $\mu$ and the cost of support $\kappa$. The constraint for the person is now equation (7), which depends on beliefs, cost and benefits, instead of (5), which depends only on beliefs. Expanding this equation, we define

$$\tilde{G}(\tau_0) \equiv h_1(\tau_0) - \hat{h}(\tau_0|\omega_i) - \frac{\kappa}{\mu} = \eta e^{\tau_0} - p\omega_i - \frac{\kappa}{\mu} + h_0(\tau_0)(p - e^{\tau_0}) \tag{23}$$

It is useful to define other parameter values that mark the strength of beliefs.

**Assumption 4** (Low Cost). $\frac{\kappa}{\mu} \leq \eta - (1-p)\alpha - p\omega_i$.

Assumption 4 (A4) additionally requires that the hazard rate increase if God listens is not very large, compared to the cost of performing the ritual. If the hazard rate increase is large, and the ritual is cheap, then the person will be convinced even if $\tau_0 = 0$.

**Assumption 5** (Costly Ritual). $p\omega_i + \frac{\kappa}{\mu} \leq h_1(\tau^\kappa, \infty) - (1-p)h_0(\tau^\kappa, \infty)$,
*where* $\tau^\kappa = \underset{t}{argmax}\left[h_1(t,\infty) - (1-p)h_0(t,\infty) - p\omega_i - \frac{\kappa}{\mu}\right]$.

Assumption 5 (A5) is more restrictive than A3. The left hand side of the equation also has the positive term $\frac{\kappa}{\mu}$. This means that praying needs to be sufficiently persuasive not only to satisfy a person's belief threshold, but also that the ritual not be too costly, relative to its benefits. If $\frac{\kappa}{\mu}$ is large enough, then A5 is violated and the person would not accept the *quid pro quo* proposal offered by the leader. Proposition 8 below formalizes this intuition.

**Proof of proposition 5.—**

*Proof.* Proposition 8 below restates and extends Proposition 5 from the main text, characterizing when a given person will support the leader as a function of their benefits, costs and belief. We show that the set of values of $\tau_0^j$ that would make a person support the RL is always a (potentially empty) interval and it decreases monotononically on both ends as $\omega_i$ increases. People with *low* cost (small $\frac{\kappa}{\mu}$) would support the RL even if they always pray ($\tau_0^j = 0$). People with *moderate* cost would support RL that wait long enough to pray. People with *high* cost will not support the RL for any value of $\tau_0^j$. □

**Proposition 8.** *With an increasing hazard rate, with benefits $\mu$ and cost $\kappa$, for each $\omega_i$ there is a unique interval $T(\widetilde{\omega}_i) = \left(\underline{\tau_0}(\widetilde{\omega}_i), \overline{\tau_0}(\widetilde{\omega}_i)\right)$ such that a person will support if and only if $\tau_0^j \in T(\widetilde{\omega}_i)$.*

a. ***Low cost*** $\frac{\kappa}{\mu}$. *If A4 does not hold for* $(\widetilde{\omega}_i)$, *then* $\underline{\tau_0}(\widetilde{\omega}_i) = 0$ *and and* $\underline{\tau_0}(\widetilde{\omega}_i)$ *is finite. The person supports the RL for* $\tau_0^j \in T^*(\widetilde{\omega}_i)$.

b. ***Moderate cost*** $\frac{\kappa}{\mu}$. *If A4 and A5 holds for* $(\widetilde{\omega}_i)$, *then* $\underline{\tau_0}(\widetilde{\omega}_i) > 0$ *and* $\underline{\tau_0}(\widetilde{\omega}_i)$ *is finite. The person supports the RL for* $\tau_0^j \in T^*(\widetilde{\omega}_i)$.

c. ***High cost*** $\frac{\kappa}{\mu}$. *If A4 does not for* $(\widetilde{\omega}_i)$, *then* $T^*(\widetilde{\omega}_i)$ *is empty and the person does not support the RL for any value of* $\tau_0^j$.

*Proof.* The analysis here is analogous to Proposition 7 but with a more stringent constraint. If we replace $p\omega_i$ by $p\omega_i + \frac{\kappa}{\mu}$, Assumptions A1 and A2, become Assumptions A4 and A5, and the proof is analogous. □

The intuition for Proposition 8 is straightforward. When the cost is low and the benefit is high, the participation constraint (equation 7) will hold. A high benefit $\mu$ raises the belief $\omega_i$ for which a person's skepticism constraint is satisfied. The ritual's benefits are so high that always praying will persuade the person. When the cost is high and the benefits are low, for a given distribution of rain, there is no timing of prayers that would persuade the person to support the church. The person may believe in the effectiveness of prayer, but the costs associated with supporting are too high compared with the benefits.

**Proof of proposition 6.—**

*Proof.* First, as in the proof of Proposition 8, we should notice that the parameters $\omega_i$ (belief), $\kappa$ (cost) and $\mu$ (benefit) they all enter the equilibrium conditions, and assumptions A4 and A5, monotonically, and as linear shifters. Thus, the comparative statics of all of them are the same, with $\omega_i$ and $\kappa$ having the same sign and $\mu$ having a different sign. For simplicity, we will show the case for changes in $\omega_i$, but the other two are analogous.

Let $q_j$ be the fraction of people in each of the three categories of beliefs, where $q_0 + q_1 + q_2 = 1$.

- $q_0$ is the fraction of people who always support
- $q_1$ is the fraction of people who support when IHR and if $\tau_0$ is high enough
- $q_2$ is the fraction of people that never support, even with IHR and $\tau_0 = 0$

Let $q^C$ be the fraction of people that support when CHR and $q^I$ the fraction of people that support when IHR. Then:

$$q^C = q_0 \leq q^I \leq q_0 + q_1 \tag{24}$$

In particular, if $\tau_0 \to \infty$, then $q^I = q_0 + q_1$, i.e., when $\tau_0 \to \infty$, everyone in $q_1$ will support. If $\tau_0 = 0$, then $q^I = q_0$, i.e., when $\tau_0 = 0$, no one in $q_1$ will support.

An increase in $\mu$ (or decrease in $\kappa$; or decrease in $\omega_i$) implies:

- $q_0$ goes up
- $q_2$ goes down ($q_0 + q_1$ goes up)
- $q_1$ could go up or down

If $q_1$ goes up, then $q^I$ goes up further than $q^C$. Alternatively, if $q_1$ goes down, then $q^I$ goes up less than $q^C$. In summary, the effect of changing costs/benefits/beliefs is monotonic in $q_0$ and $q_2$, but ambiguous in $q_1$.

We prove each part of the proposition in turn.

**Part 1:** Support always increases with net benefits.

An increase in net benefits $\hat{\mu}$ is equivalent to a decrease in $\omega_i$ across the board, which moves up the $G(\cdot)$ function. This shift has the following effects on the belief categories:

- $q_0$ increases (more people move to weak beliefs)
- $q_2$ decreases (fewer people have unfeasible beliefs)
- $q_0 + q_1$ increases (the total fraction of people who could potentially believe increases)

Since $q^C = q_0$ and $q^I \leq q_0 + q_1$, both $q^C$ and $q^I$ increase with higher net benefits.

**Part 2:** Support always increases with IHR.

By definition, we have $q^C = q_0$ and $q_0 < q^I < q_0 + q_1$. The moderate belief group ($q_1$) believes when IHR if $\tau_0$ is high enough, but never believes under CHR. Therefore, $q^I \geq q^C$.

**Part 3:** The differential increase in support from CHR to IHR may increase or decrease when increasing net benefits.

The differential increase in support is $q^I - q^C = q^I - q_0$. When net benefits increase, we established that $q_0$ increases. However, the effect on $q^I$ depends on how $q_1$ responds:

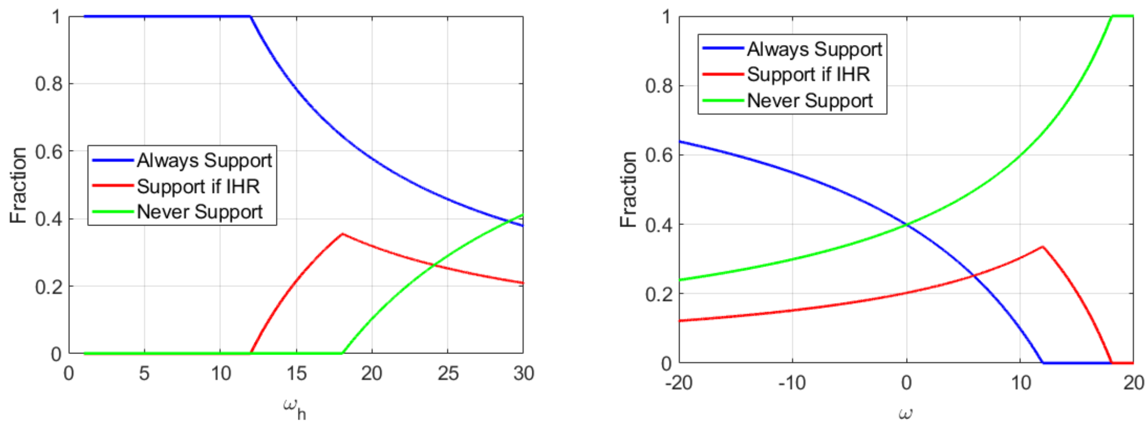
*Case a:* If $q_1$ increases when net benefits rise, then $q^I$ increases more than $q^C$, so the differential $q^I - q^C$ increases.

*Case b:* If $q_1$ decreases when net benefits rise (because some moderate believers become weak believers), then $q^I$ increases less than $q^C$, so the differential $q^I - q^C$ decreases.

Since both cases are possible depending on the specific form of the $G(\cdot)$ function and the distribution of beliefs, the differential increase in support from CHR to IHR may either increase or decrease when net benefits increase. Figure A2 below illustrates this point, when we set $\tau_0 = 0$. Notice that, in both panels, $q_0$ is decreasing and $q_2$ is increasing, as shown above. Notice however,

Figure A2: Evolution of People's Support in an Environment with an Increasing Hazard

A. Support of the population as a function of beliefs    B. Support of the population as a function of net benefits




*Notes*: Values of $q_0$, $q_1$, and $q_2$ for a fix set of parameters when we change $F_\omega$, or net benefits. Panel A: $F_\omega$ follows $U[1,\omega_h]$, we vary $\omega_h$ from 1 to 30. Panel B: $F_\omega$ follows $U[1+\omega, 30+\omega]$, and we vary $\omega$ from -20 to 20.

that $q_1$ is non monotonic in both cases. In this example, we use a uniform distribution for beliefs $F_\omega$ to show that it is not the shape of the distribution of beliefs that creates the non-monotonicity.

In Panel A, we fix all parameters, fixed the lower bound of the distribution of beliefs, but vary the upper bound of the distribution of beliefs. In Panel B, we fix the width of the support of the belief distribution $F_\omega$ but we vary the mean value of the support.

There are two key values for $\omega_i$ here. First, there is the value of $\omega_i$ that makes $G(0) = 0$. This is the lowest value of $\omega_i$ that would make a person support if $\tau_0 = 0$. In this example, it is $\omega_i = 11.97$. Higher values of $\omega_h$ means more people who would not support if $\tau_0 = 0$, i.e., lower $q_0$ and higher $q_1$. Second, there is a value of $\omega_i$ that makes $G(\cdot) \leq 0$, for all $\tau_0$. In this example, it is $\omega_i = 18.07$. People with a higher value of $\omega_i$ would not support. Higher values of $\omega_h$ means more people that would never support, i.e., lower $q_1$ and higher $q_2$.

In Panel A, when the lower bound is very low, we have $q_0 = 1$, i.e., everyone supports. However, when the upper bound is very high, the fraction of people that will always support drops to 0.4. The fraction of people that never support $q_2$ is zero for low values of $w_h$. However, for people in the distribution of $F_\omega$ with a high $\omega_i$ they will never support. Thus, the higher $\omega_h$ a higher fraction of people that never support. Finally, we can see the dynamics for $q_1$. For very low values of $\omega_i$ everyone is in $q_0$. For values of $\omega_h$ greater than 11.97, some people only support if $\tau_0$ is sufficiently high. However, for even higher values of $\omega_h$, some people do not support for any value of $\tau_0$, i.e., some people are in $q_2$. Therefore, even if people are leaving $q_0$ to enter $q_1$, there are even more people leaving $q_1$ to enter $q_2$. The intuition for Panel B is similar.

□

## A.5 Sophisticated Beliefs

In Section 2, we assume that people extrapolate the hazard rate that would be observed, if prayer was not practiced, based on the conditional hazard without prayer. They do not attempt to estimate the shape of the hazard function, to form, for example, a non-constant forecast of the hazard rate. Our framework can also allow for persuasion under more sophisticated specifications for people's beliefs, so long as people cannot estimate the complete hazard function out-of-sample.

We now present a simple example where people believe the hazard rates to be linear, but in practice they are quadratic. Figure A3, panel A shows, for naïve people with constant forecasts, the change in hazard rate during prayer (green solid line) versus the forecast formed during the time without prayer (red solid line). Figure A3, panel B shows for sophisticated people, with linear forecasts, the change in hazard rates during prayer (green solid line) versus without prayer (red dashed line). Even for sophisticated people, because they do not have a forecast fully as flexible as the true hazard function, the out-of-sample hazard is above their forecast, which creates scope for persuasion.

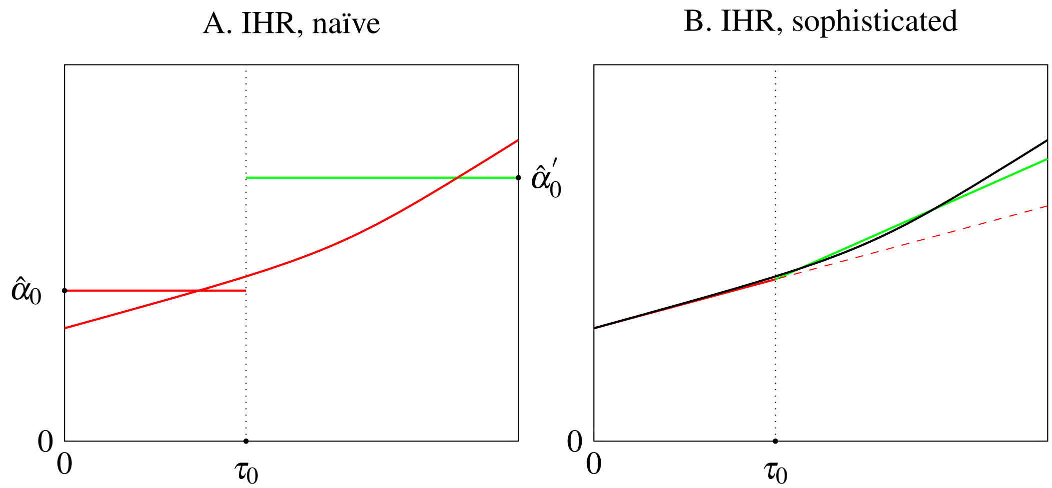
Let the distribution of rain follow a quadratic hazard function: $h(t) = \alpha + \beta t + \gamma t^2$, with cdf $F(t) = 1 - e^{-\left(\alpha t + \frac{\beta}{2}t^2 + \frac{\gamma}{3}t^3\right)}$ and $\alpha, \beta\, \gamma > 0$. In this case, the condition for persuasion is not that the hazard rate is increasing, i.e., $\beta > 0$, but that it is increasing faster than the people think it should increase, i.e., $\gamma > 0$.

We now assume people have the same information as before and will also use that information to estimate the hazard function when the RL prays, based on the information available when the RL does not pray. The people will estimate the slope of the hazard function $\hat{\beta}$ instead of its level. In the example here, the real hazard function is not linear but quadratic. Thus, we have $\hat{\beta} \neq \beta$. People look at the realizations of rain and compute the best fit to the data, based on their (restricted) model. Moreover, since $\beta, \gamma > 0$ (the hazard rate is convex), we have $\hat{\beta} > \beta$. In other words, based on a fixed praying policy for the church, people impute to $\beta$ the extra probability of rain due to $\gamma > 0$.

The policy for the church is to pray starting at $\tau_0$. For a given policy, we can define the beliefs that such policy would generate, the people's cognitive model, i.e., their prediction of rain under prayers, based on the observation of rain without prayers. There are three elements

- $\beta_0(\tau_0) \equiv \frac{1}{1-e^{-\tau_0}} \int_0^{\tau_0} \frac{h(t)}{t} e^{-t} dt$ is the average slope of the hazard rate while the church does not pray.
- $\beta_1(\tau_0) \equiv \lim_{\tau_1 \to \infty} \frac{1}{e^{-\tau_0} - e^{-\tau_1}} \int_{\tau_0}^{\tau_1} \frac{h(t)}{t} e^{-t} dt$ is the average slope when the church does pray.
- $\eta_\beta \equiv \lim_{\tau \to \infty} \frac{1}{1-e^{-\tau}} \int_0^{\tau} \frac{h(t)}{t} e^{-t} dt$ is the average unconditional slope of the hazard rate.

Figure A3: Beliefs of a Sophisticated Person




*Notes*: Panel A shows the optimal praying policy for naive people, who believe the hazard rate is constant. This is our main specification in the paper. Panel B shows the optimal praying policy for sophisticated people, who believe the hazard rate is linear but still extrapolate from experience prior to prayer.

- $\alpha_\beta \equiv h'(0)$ is the slope of the hazard rate at $t = 0$.
- $\omega_\beta$ is the change in slope for the hazard rate that the people believe happens when god exists and the church prays, and $\Delta_\beta \equiv \omega_\beta - \eta_\beta$.

The terms in the integral are now divided by $t$. When the hazard rate is linear in this case, i.e., $h(t) = \beta t$, the term inside the integral would be a constant multiplying $e^{-t}$. The same intuition applies here as in the case in the main body of the paper. We make a stronger assumption A6, about the people's beliefs

**Assumption 6.** $\Delta_\beta > \frac{(1-p)}{p}(\eta_\beta - \alpha_\beta) > 0$.

The people will believe that God exists, and take action $a_1$, if

$$\beta_1(\tau_0, \tau_1) \geq \hat{\beta}(\tau_0, \tau_1) \equiv p\omega_\beta + (1-p)\beta_0(\tau_0, \tau_1). \tag{25}$$

We now present Proposition 9, which in our extended model with linear beliefs corresponds to Proposition 1, in the main text.

**Proposition 9** (Increasing and convex hazard rate)**.** *If $h(t)$ is strictly increasing and convex, and people believe the hazard rates are linear, for each $\omega_\beta$ there is a unique interval $T(\omega_\beta) = (\underline{\tau_0}(\omega_\beta), \overline{\tau_0}(\omega_\beta))$ such that people will support if and only if $\tau_0^j \in T(\omega_\beta)$.*

*Proof.* The proof follows that of Proposition 1, with $\underline{\tau_0}(\omega_\beta)$ such that $\beta_1(\underline{\tau_0}(\omega_\beta)) = p\omega_\beta + (1-p)\beta_0(\underline{\tau_0}(\omega_\beta))$. The objective of the church is to maximize the probability of rain during prayer among all experiments that are sufficient to induce support. In this case, to persuade the people, we need the hazard rate when praying to be greater what the people would predict it would be, based on her information during the period without praying. If the hazard rate is convex, the projected slope of the hazard rate after $\tau_0$ (represented by the dashed red line in Figure A3.D) will be lower than the estimated hazard rate using only information after $\tau_0$ (represented by the solid green line in Figure A3.D). If this condition hold (increasing and concave hazard rate), the analysis is the same as in Proposition 7, changing the corresponding terms, e.g., $\omega_\beta$ instead of $\omega_i$. □

In summary, the simple form of beliefs that we assume in the baseline model is not a necessary condition for persuasion. People can still be persuaded if they have more sophisticated beliefs about the hazard rate during prayer. If people think that the hazard rate is linear, then the hazard rate needs to be increasing and convex to allow persuasion.

# B Appendix: Data

## B.1 Murcia rogations

The sources for data on Murcia are the Civil *Actas Capitulares* (CAC) and Ecclesiastical *Actas Capitulares* (EAC), as described at greater length in Espín-Sánchez and Gil-Guirado (2022). The CAC was an official document of Christian Spain. In Murcia, they date back to the late 13th century. The CAC contain records of decisions and discussions from Municipal Council meetings, which were led by the mayor and held at least once a week. Our rainfall series is constructed from notable rainfall events recorded in the minutes of the municipal council. The EAC is a Catholic church document that records the Ecclesiastical Chapter meetings. These Ecclesiastical Chapter meetings can be thought of as the meeting of a Cathedral's board (*Cabildo*). The meeting notes record whether prayer ceremonies for rain were held, when they were held, and details such as the images involved in the prayer.

## B.2 Ethnographic Atlas

This dataset comes from the *Ethnographic Atlas* (Murdock, 1967). Section 4.2 describes how we augment this data with newly gathered information on the global practice of rainmaking rituals, from anthropology texts on ethnic group practices.

How does our classification of a rain ritual based on these texts agree with other data sources? The Human Relations Area Files (eHRAF) is a database that contains information on cultural and social life for a worldwide sample of societies, many of which overlap with the ethnic groups in the *Ethnographic Atlas*. In Table B1 we cross-tabulate the classification of whether a group practices a rain ritual in our data with a similar classification from the eHRAF. We sample 60 groups selecting 10 at random from each settled continent for the comparison. There are two main findings from the comparison. First, the eHRAF often does not have information on religious practice that would allow us to classify whether a group practices a rain ritual. For 35 out of 60 groups, we classify rain ritual status as missing in eHRAF. Second, for cases where we can make a classification, there is a strong concordance between the classifications in the eHRAF and in our data. In the 25 cases where we code the rain ritual variable in the eHRAF, 22 of the codings are in agreement with the coding in our data set. We therefore conclude that there is a high degree of agreement in the coding of this variable between the two data sets.

## B.3 Rainfall data

We obtain rainfall data to estimate hazard functions from the Global Historical Climatology Network daily (GHCNd). GHCNd is an integrated database of daily climate summaries from land surface stations across the globe, and contains records from more than 100,000 stations in

Table B1: Comparison of Rain Ritual Classification in Our Data with the Human Relations Area Files (HRAF)

| | | Rain ritual status in Human Relations Area Files | | | |
|---|---|---|---|---|---|
| | | Missing (1) | No (2) | Yes (3) | Sum (4) |
| Rain ritual in Our data | Missing | 0 | 0 | 0 | 0 |
| | No | 28 | 16 | 2 | 46 |
| | Yes | 7 | 1 | 6 | 14 |
| | Sum | 35 | 17 | 8 | 60 |

*Notes*: The eHRAF (Human Relations Area Files) is a World Cultures database that contains information on present and past aspects of cultural and social life for a worldwide sample of societies. We select a random stratified sample of 60 ethnic groups, 10 from each continent, from the ethnographic atlas and search the eHRAF database for evidence (or lack thereof) of rain ritual practices for each group. We find that the eHRAF has no data on 35 of these ethnic groups. For 22 groups, the eHRAF records on rain rituals is in accordance with our data. Only 3 groups have conflicting results between our data and the eHRAF.

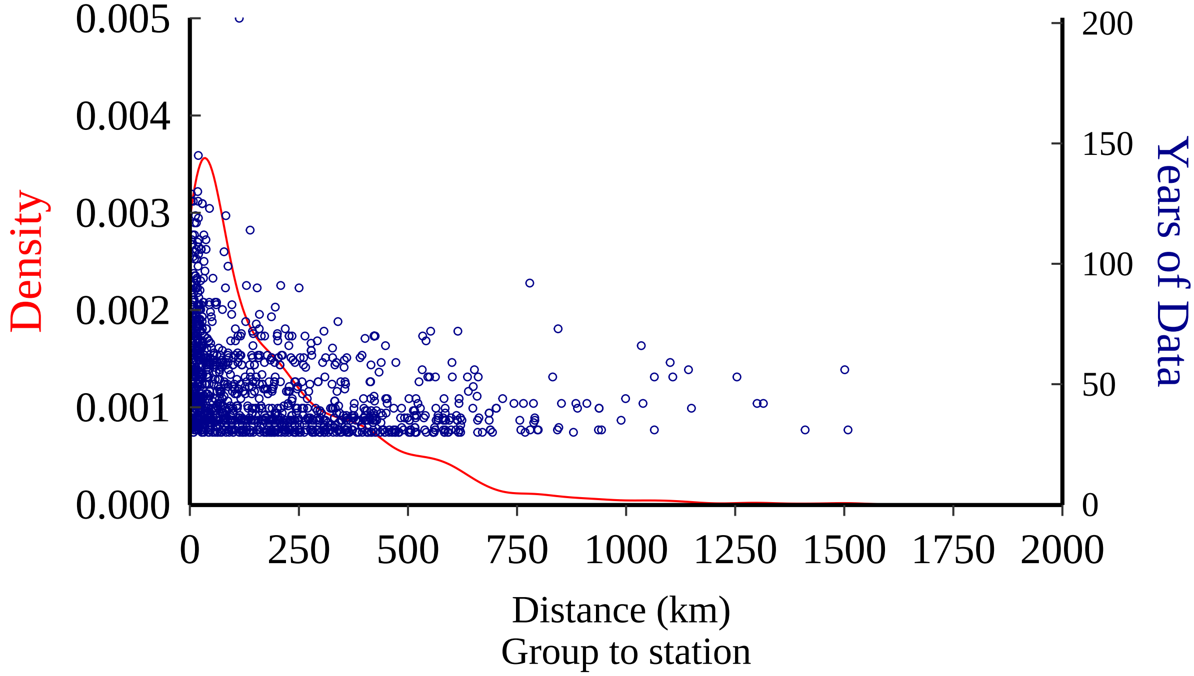
180 countries and territories (WMO, 2021). Using the latitude and longitude coordinates of each ethnic group in the *Ethnographic Atlas*, we match groups to the nearest GHCNd weather station with sufficient data, which we define as at least 30 years of daily rainfall measures.

Figure B1 and Table B2 summarize the weather station matching and rainfall data. Figure B1 shows a scatter plot of the number of years of rainfall data at a station against the distance from a station to the ethnic group to which it is matched. We require stations to have at least 30 years of data and many have 50 years or more. The left axis shows the density of the distribution of distance from ethnic groups to their nearest station. Most groups are less than 200 km from the nearest station, but there is a long tail of groups that are further away (the furthest groups are all from islands, mainly in the Pacific, where there are few stations).

In Table B2, we break out weather station data by continent. Overall, there are 687 stations for 1,291 ethnic group observations. The accuracy of weather station matching is higher in the Americas and Europe than in Africa or Oceania, because of the much higher density of modern weather stations. In the Americas, the median distance from an ethnic group to the nearest station is only 21 km, while in the African continent it is 200 km.

We collect temperature and rainfall data for that station at the daily level. The data are used in two ways. The daily rainfall data is used to construct rainfall spells and estimate the hazard function, as described in the text. The rainfall and temperature data are also aggregated to the annual level to construct climate norms, which we use as controls. Table B2, panel C shows summary statistics on rainfall by continent.

Figure B1: Distance from station and years of data




*Notes*: The figure shows a scatterplot and kernel density plot of years of data collected for each ethnic group and the distance between the group and the weather station where their data was collected. A large majority of groups are less than 500km away from their assigned weather station. Two outlier groups that are over 2000km from their weather station are truncated from the plot.

## B.4 MIRCA-OS Data

We make use of a global spatial dataset of rainfed cropped areas to classify the hazard rate based on whether it increases or decreases in growing versus non-growing seasons. Kebede et al. (2025) construct this dataset for 23 crop classes at 5 year intervals between 2000 and 2015. They construct the maps at 0.001°, 0.01°, 0.05° and 0.1° resolution, at the month level. We base our analysis off of the 2000 map (1997-2003 data) at 0.1° resolution.

We construct a circle of radius 100km around each longitude-latitude pair that represent the location of an ethnic group in the *Ethnographic Atlas* (Murdock, 1967). For each of the 23 MIRCA-OS crops, we extract the values for harvested area (ha) that overlap with the "ethnographic circle"; we include weights for portions of gridded cells that only overlap with our area of interest. We then sum up across crops, the total area of rainfed crops within the proximity of an ethnic group for each month of a calendar year. Figure B2 provides a visualization of these crop area patterns for all six region classifications of the Ethnographic Atlas. At this point, the data has dimension "number of ethnic groups x number of months in a calendar year."

Similar to how we determine the rainy and dry seasons of each ethnic group, we calculate the rolling average crop areas for each calendar month. Then, we mark the months with the highest

Table B2: Weather station matching and rainfall summary statistics

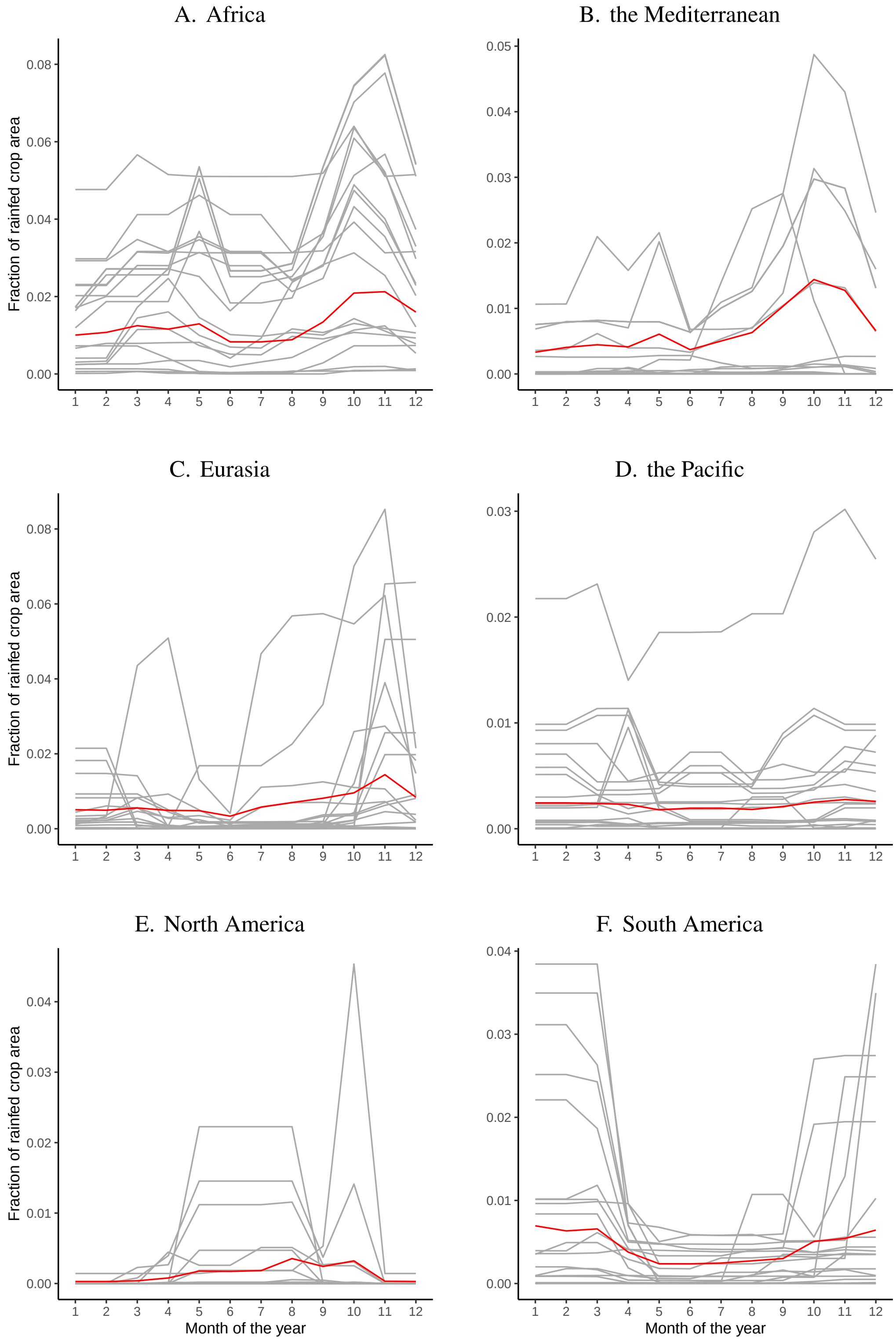
| | Africa (1) | Americas (2) | Asia (3) | Europe (4) | Oceania (5) | Total (6) |
|---|---|---|---|---|---|---|
| *Panel A. Availability of station data* | | | | | | |
| N groups | 529 | 392 | 170 | 69 | 131 | 1291 |
| N unique stations | 155 | 297 | 117 | 64 | 54 | 687 |
| Min years | 30 | 30 | 30 | 30 | 30 | 30 |
| Max years | 91 | 145 | 92 | 202 | 116 | 202 |
| *Panel B. Distance from ethnic group to nearest weather station* | | | | | | |
| Min dist. station (km) | 3.8 | 1.1 | 3.1 | 4.7 | 1.1 | 1.1 |
| Med dist. station (km) | 200.70 | 21.35 | 129.15 | 44.50 | 272.50 | 133.64 |
| Mean dist. station (km) | 243.00 | 112.70 | 226.60 | 56.20 | 412.20 | 210.14 |
| Max dist. station (km) | 790.6 | 2611.4 | 1101.0 | 181.6 | 2248.6 | 2611.4 |
| *Panel C. Rainfall summary statistics* | | | | | | |
| Mean rainfall (cm) | 109.00 | 92.40 | 139.60 | 66.10 | 276.60 | 136.74 |
| Min rainfall (cm) | 0 | 0 | 0 | 0 | 0 | 0 |
| Max rainfall (cm) | 579.41 | 607.87 | 736.18 | 544.20 | 1506.00 | 1506.00 |
| Std. dev rain | 30.30 | 28.60 | 40.20 | 16.70 | 100.00 | 43.16 |

*Notes*: The rainfall data are from the World Meteorological Association for the nearest station to the latitude and longitude coordinates of each ethnic group.

and lowest rolling averages as the end of the growing and non-growing seasons respectively. Other months are classified as growing/non-growing based on these end points. For example, a month is classified as part of the growing season if it falls after the end of the non-growing season but before the end of the growing season. At this point, the dimension of the data remains the same with the added characteristic that a month is either in the growing or non-growing season.

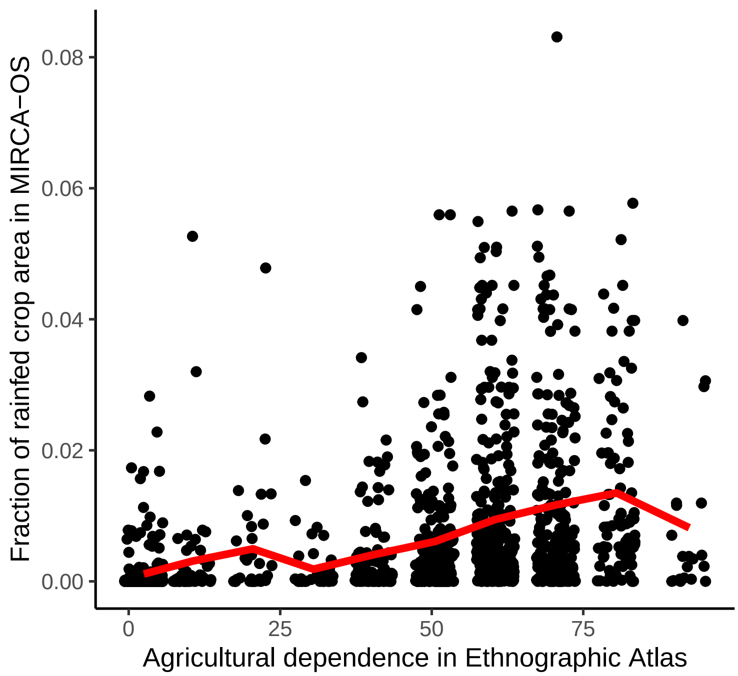
With this dataset, we are able to calculate the hazard rate (99th percentile) for each season. Merging the spell data with the growing/non-growing season data, we calculate the hazard rate when dry spells begin in the growing or non-growing season. As an alternate specification, we also calculate the hazard when the dry spell ends in a particular season. For each ethnic group therefore, we generate a hazard rate for the growing season (when the spell begins here), non-growing season (when the spell begins here), growing season (when spell ends here) and non-growing season (when the spell ends here).

Figure B2: Rainfed Cropping Patterns of Ethnic Groups over Time




*Notes*: This figure shows the patterns of rainfed crop area from MIRCA-OS, as a fraction of the total land area within a 100km radius of each ethnic group, on the y axis. Each panel shows patterns, in grey, for a sample of 20 ethnic groups within the region. We follow the regional classification of the Ethnographic Atlas which categorizes ethnic groups into one of six regions. The red line represents the average rainfed crop pattern for all ethnic groups within a region. The x axis are the months of the calendar year indexed by 1 to 12.

Figure B3: Validation that Modern Rainfed Crop Area is Related to Agricultural Dependence in the *Ethnographic Atlas*




*Notes*: This figure shows the correlation across ethnic groups between agricultural dependence, in the *Ethnographic Atlas*, and modern rainfed crop area. The *Ethnographic Atlas* categorizes agricultural dependence into bins between 0 and 100, as plotted on the x-axis (we add dither to space horizontally the points within a bin). A fraction of rainfed crop area is calculated for a 100 km radius circle around each ethnic group, as described in Section B.4.

## B.5 Flexible hazard estimation

This part describes the estimation of the hazard function. This estimation is run separately for each ethnic group and for each weather station in Murcia.

Let $t$ be the discrete number of days from one rainfall to the next. For example, if it rains on Monday and again on Thursday, then $t = 3$. There is no censoring in the data, as all spells end in rainfall. To fit a hazard model it is necessary to define how much rainfall constitutes a failure. A light rain is not sufficient to end a drought. We define a failure event as equal to one if daily rainfall exceeds 0.5 centimeters.

We are interested to estimate the hazard function $h(t) = f(t)/(1-F(t))$ for probability density function $f(\cdot)$ and cumulative distribution function $F(\cdot)$. The hazard gives the instantaneous probability of rainfall as a function of the time that has passed since the last rain. The cumulative hazard of rainfall by any point in time $x$ is given by $H(x) = \sum_{t=1}^{x} h(t)$. The cumulative hazard is not a probability; it is related to the survival function by $H(t) = -\log S(t)$ for $S(t) = 1 - F(t)$.

The semi-parametric approach specifies the hazard rate as a function of a parameter vector. We use a cubic spline to fit the log cumulative hazard (Royston and Parmar, 2002). Let $H(t|\gamma)$ be the cumulative hazard function. We specify the log cumulative hazard

$$\log(H(t|\gamma)) = \gamma_0 + \gamma_1 t + \gamma_2 v_1(t) + \dots \gamma_{m+1} v_m(t) \tag{26}$$

where $v_j(t)$ is a cubic spline basis function with $m$ knots.[26] We set the knots separately for each weather station based on the distribution of dry spells at that station.[27] The function is constrained to be linear beyond the boundary knots.

We estimate the hazard model by maximum likelihood. The log-likelihood function is

$$log\mathscr{L}(\gamma|t) = \sum_i \left(\log(h(t_i|\gamma)) - H(t_i|\gamma)\right).$$

The arguments of the log likelihood for each spell observation are calculated from the log cumulative hazard (26). This semi-parametric representation of the hazard function allows us to estimate a smooth but flexible hazard across the full range of observed spells. As we will show below, this approach allows the hazard estimates to take on a variety of different shapes corresponding to the

[26]The elements $j = 1, \dots, m$ of the basis are

$$v_j(t) = (t-k_j)_+^3 - \lambda_j (t-k_{min})_+^3 - (1-\lambda_j)(t-k_{max})_+^3, \lambda_j = \frac{k_{max}-k_j}{k_{max}-k_{min}}$$

with knots $k_1, \dots, k_m$. If $m = 0$ there are no internal knots and the function is linear, corresponding to a Weibull distribution of failure times. For $m > 0$ the specification allows that the log cumulative hazard is a cubic function at any point with the cubic coefficient allowed to change at each knot.

[27]We set the maximal knot $k_{max}$ for a weather station at the maximum of the 99th percentile of spell duration and the 5th-longest spell at that station. We set the number of internal knots as a function $m = \min(\text{ceiling}(k_{max}/90), 3)$ of the maximal knot and evenly space the internal knots between the boundary knots 1 and $k_{max}$.

different rainfall patterns around the world.

# C Appendix: Supplementary Results for Murcia

## C.1 Rationale for sample selection and test for manipulation of rainfall records

Figure C4 shows the time series of number of rainfall prayers per year, from 1600 to 2000, and number of notable recorded rainfall events per year, from 1600 to 1860. To test for a structural break coincident with the Abolition of the Tithes in 1837, we restrict the sample to the ten years before and after this event and run a linear regression for each series of an indicator for that event on a dummy variable for years after the Abolition of the Tithes. We find that prayers sharply decrease, with a coefficient on post-Abolition of -2.7 ($p$-value of 0.029), whereas reported rainfall events modestly increase by 0.7 ($p$-value 0.136). Looking over a longer time horizon, the number of recorded rainfall events per year is basically constant before and after the event, as plotted by the dashed blue line. We therefore conclude that there was a large structural break in prayer at the Abolition of the Tithes. We end our sample in 1837 on account of this break. We also conclude that the reporting of notable rainfall events was not altered by the change in the prayer policy of the church. This finding suggests that rainfall events are not being recorded in order to fulfill the prayers of the church.

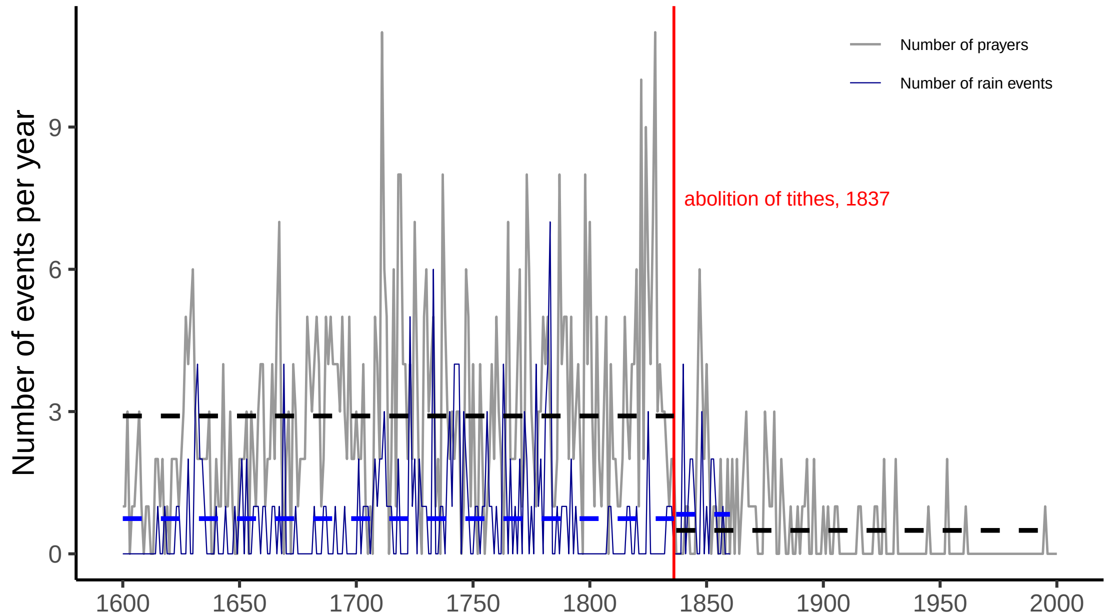
## C.2 Additional specifications and placebo tests

In Section 3 we argue that prayer is predictive of rainfall. Here in Table C3 we present an additional statistical test of whether prayer Granger-causes rain. Table C4 shows the individual coefficients on a Granger regressions lagged by up to 7 days.

Granger causality is defined with respect to a linear distributed lag model with some time horizon. The tests consist of regressing recorded rainfall on distributed lagged models that include (i) lags of recorded rainfall itself up to the given horizon (ii) additionally, lags of prayer. Prayer is said to Granger-cause rain if the joint model (ii) including both lagged recorded rainfall and lagged prayer cannot be rejected in favor of the model with only lagged recorded rainfall. We find that prayer Granger-causes rain at all horizons tested from one week's worth of daily lags up to 13 weeks' worth of daily lags. The $p$-value for the test at each horizon from one week to 13 weeks is reported in the column at right. These tests establish that recent prayer has predictive power for rainfall above and beyond recent rainfall.

Appendix Table C5 reports the results of an alternate specification to Table 1 (and Figure 7) in the main text. Instead of regressing recorded rainfall on indicators for prayers having occurred last month, or up to $n$ months ago, we regress recorded rainfall on a series of indicators for prayer having occurred $d$ *days* ago, and then sum up the coefficients from this distributed lag regression.

Figure C4: Test for Structural Break in Prayer and Recorded Rainfall Series




*Notes*: This figure shows the number of prayers for rain and recorded rainfall events between 1600-2000. The grey and blue solid lines show the number of prayers and rainfall events within the time period. The red vertical line marks the year the church tithes were abolished. The black and blue dashed lines show the average number of events pre- and post- the abolition of the tithes in 1837. Recorded rainfall events are available to 1860.

Appendix Table C5 reports the sums of these coefficients up to a lag of 4 weeks, 8 weeks, and 12 weeks ago. The sum of the coefficients on lagged prayers is significant for all three time horizons considered. We find, for example, that an additional prayer for rain in the last 4 weeks is associated with an increase of 0.00489 in the probability of rainfall on a given day.

Appendix Table C6 regresses a variable equal to 100 if there was a prayer of Thanksgiving for rainfall, on a given *day*, on rainfall recorded in the last month (rolling 30-day period). There is a highly significant relationship between these two rainfall proxies. Rainfall recorded in the last month increases the likelihood of a prayer for Thanksgiving by about 1 percentage point each day, so about 30 percentage points over the course of a month. A magnitude of less than 100 percent is expected as not every recorded rainfall warrants a prayer of Thanksgiving.

Appendix Table C7 regresses a variable equal to 100 if rainfall was recorded on a given day on whether there were rainfall prayers in the last month. This table is a decomposition of Table 1, from the main text, in which prayers for rainfall in the last month are split into two types: prayers for rainfall that were preceded by a request for prayer by the municipal council, which we call solicited, and prayers for rainfall that were *not* preceded by such a request, which we call unsolicited. The coefficient on a prayer for rainfall in the last month is about twice as large for solicited prayers and only statistically significant for solicited prayers. Nonetheless, we cannot reject the hypothesis that

Table C3: Test for Granger-causality of rain

| Res.Df | Df | F | Pr(>F) |
|---|---|---|---|
| 86,542 | -7 | 3.155 | 0.002 |
| 86,521 | -14 | 4.320 | 0.00000 |
| 86,500 | -21 | 3.974 | 0 |
| 86,479 | -28 | 3.271 | 0 |
| 86,458 | -35 | 3.760 | 0 |
| 86,437 | -42 | 3.354 | 0 |
| 86,416 | -49 | 3.078 | 0 |
| 86,395 | -56 | 2.814 | 0 |
| 86,374 | -63 | 2.564 | 0 |
| 86,353 | -70 | 2.496 | 0 |
| 86,332 | -77 | 2.376 | 0 |
| 86,311 | -84 | 2.258 | 0 |
| 86,290 | -91 | 2.241 | 0 |

*Notes*: This table reports the residual degrees of freedom, the difference in degrees of freedom, the F statistic, and corresponding p-value from the granger test of recorded rainfall on prayer. i.e, a test of whether prayer predicts rain. The test is a Wald test comparing the unrestricted model including lags of different orders (1 to 13 weeks) of both prayer and recorded rainfall and the restricted model including only lags of rain.

the coefficients on solicited and unsolicited prayers are the same.

If, despite this failure to reject, we interpret the raw difference in the coefficients, there are at least two hypotheses as to why solicited prayers may have greater predictive power for rainfall. First, a solicited prayer means that both the municipal council and the church in a sense agreed on prayer. For the two parties to request and agree probably implies that the prayer is called in a longer, more extreme drought, when the hazard rate will be highest (given the increasing hazard in Murcia). Second, the municipal council may be more likely to record rainfall events following prayers that it solicited. We do not favor this explanation, as we test above for manipulation of the rainfall records and do not find evidence to this effect.

Table C8 runs placebo regressions of recorded rainfall on recent prayers in the last month (rolling 30-day period) that were meant not to elicit rainfall, but for other purposes. The church organized formal prayers for several other purposes. Two common types of prayer are prayers against pests, such as locusts, and prayers against disease or plague. We encode these prayers in the same way as prayers for rainfall and test as to whether they predict recorded rainfall. We fail to reject the null that prayers against pests and prayers against disease do not predict rainfall, in

Table C4: Regression underlying the Granger Causality Test

| | *Prayer for rain* |
|---|---|
| 1 day lag of prayers | $-0.009^{**}$ |
| | (0.003) |
| 2 day lag of prayers | $-0.001$ |
| | (0.003) |
| 3 day lag of prayers | 0.001 |
| | (0.003) |
| 4 day lag of prayers | $0.007^{**}$ |
| | (0.003) |
| 5 day lag of prayers | $0.011^{***}$ |
| | (0.003) |
| 6 day lag of prayers | $0.025^{***}$ |
| | (0.003) |
| 7 day lag of prayers | $0.013^{***}$ |
| | (0.003) |
| 1 day lag of recorded rain | 0.009 |
| | (0.007) |
| 2 day lag of recorded rain | 0.009 |
| | (0.007) |
| 3 day lag of recorded rain | $-0.003$ |
| | (0.007) |
| 4 day lag of recorded rain | $-0.009$ |
| | (0.007) |
| 5 day lag of recorded rain | $-0.003$ |
| | (0.007) |
| 6 day lag of recorded rain | $-0.003$ |
| | (0.007) |
| 7 day lag of recorded rain | 0.009 |
| | (0.007) |
| p-value for test of joint significance | 0.003 |
| $N$ | 86,584 |

*Notes*: This table reports the regression of prayers for rain on prayers for rain and recorded rainfall, lagged by up to 7 days.

Table C5: Regression of Recorded Rainfall on Lagged Prayers Last Week

| | *Recorded rainfall (=100)* | | |
|---|---|---|---|
| *Sum of lags up to...* | (4 weeks) | (8 weeks) | (12 weeks) |
| Sum of lags | 0.489 | 0.662 | 0.621 |
| | (0.194) | (0.228) | (0.177) |
| *N* | 86,564 | 86,536 | 86,508 |

*Notes*: This table reports the coefficients from regressions of recorded rainfall on recent prayers for rain.The table records the sum of coefficients of the prayers within the preceding 12 weeks. Newey-West standard errors are in parentheses with a lag parameter of 30 days. Statistical significance at certain thresholds is indicated by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table C6: Regressions of Prayers of Thanks on Recent Recorded Rainfall

| | *Prayer for thanksgiving (=100)* | | |
|---|---|---|---|
| | (1) | (2) | (3) |
| Rainfall recorded last month | 0.985*** | 0.916*** | 0.935*** |
| | (0.163) | (0.162) | (0.162) |
| Month effects | | *Yes* | *Yes* |
| Month lags | | | *Yes* |
| | | | |
| Mean dep. var | 0.255 | 0.255 | 0.255 |
| Years of data | 237 | 237 | 237 |
| *N* | 86,562 | 86,562 | 86,202 |

*Notes*: This table reports coefficients from regressions of prayers of thanksgiving on recent recorded rainfall in contrast to Columns(4) to (6) of Table 1. Newey-West standard errors are in parentheses with a lag parameter of 30 days. Statistical significance at certain thresholds is indicated by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

contrast with the predictive power of prayers for rain.

Table C7: Regression of Rainfall on Prayer Requests

| | *Recorded rainfall (=100)* | |
|---|---|---|
| | (1) | (2) |
| Prayers last month (solicited) | 0.204*** | 0.164** |
| | (0.065) | (0.066) |
| Prayers last month (unsolicited) | 0.102 | 0.074 |
| | (0.076) | (0.079) |
| p-value for a test of equality | 0.34 | 0.41 |
| Month effects | | *Yes* |
| Years of data | 237 | 237 |
| *N* | 86,562 | 86,562 |

*Notes*: This table reports the coefficients from regressions of recorded rainfall on recent prayers for rain and the municipal council request that may have preceded them. The table mirrors Table 1 but controlling for the prayers that are solicited by the municipal council. Newey-West standard errors are in parentheses with a lag parameter of 30 days. Statistical significance at certain thresholds is indicated by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table C8: Placebo Regressions of Recorded Rainfall on Prayers Not Meant for Rain

| | *Recorded rainfall (=100)* | | *Prayer for thanksgiving (=100)* | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Prayer against pests last month | −0.118 | | 0.254 | |
| | (0.082) | | (0.213) | |
| Prayer against diseases last month | | −0.128 | | 0.352 |
| | | (0.097) | | (0.256) |
| Month effects | *Yes* | *Yes* | *Yes* | *Yes* |
| Mean dep. var | 0.203 | 0.203 | 0.255 | 0.255 |
| Years of data | 237 | 237 | 237 | 237 |
| *N* | 86,591 | 86,591 | 86,591 | 86,591 |

*Notes*: This table reports coefficients from the regression of recorded rainfall on recent prayer requests made for other environmental concerns. Prayers against pests are any prayers against locusts and insects. The table acts as a placebo for the regression in column (2) of Table 1 but with month fixed effects. Newey-West standard errors are in parentheses with a lag parameter of 30 days. Statistical significance at certain thresholds is indicated by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

## C.3 Robustness to alternative methods of inference

Appendix Table C9 and Appendix Table C10 reproduce the results of Table 1, from the main text, with different values of the lag parameter in the calculation of the Newey-West standard errors. We observe that the standard errors are insensitive to changing the lag parameter from our baseline value of $l = 30$ to $l = 60$ or $l = 90$, respectively. Notice that the standard errors are identical for $l = 60$ and $l = 90$, and virtually identical for $l = 30$.

Table C9: Regressions of Recorded Rainfall and Prayer for Thanksgiving on Rain and Recent Prayer for Rain

| | *Recorded rainfall (=100)* | | | *Prayer for thanksgiving (=100)* | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Prayer last month | 0.189*** | 0.144** | 0.131** | 0.861*** | 0.787*** | 0.736*** |
| | (0.055) | (0.058) | (0.058) | (0.068) | (0.070) | (0.072) |
| Month effects | | *Yes* | *Yes* | | *Yes* | *Yes* |
| Month lags | | | *Yes* | | | *Yes* |
| Mean dep. var | 0.203 | 0.203 | 0.203 | 0.254 | 0.254 | 0.254 |
| Years of data | 237 | 237 | 237 | 237 | 237 | 237 |
| *N* | 86,535 | 86,535 | 86,175 | 86,535 | 86,535 | 86,175 |

*Notes*: This table reports coefficients from regressions of rainfall from municipal council records and prayers for thanksgiving on rain and recent prayer for rain in Murcia. Newey-West standard errors are in parentheses with a lag parameter of 60 days. Statistical significance at certain thresholds is indicated by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

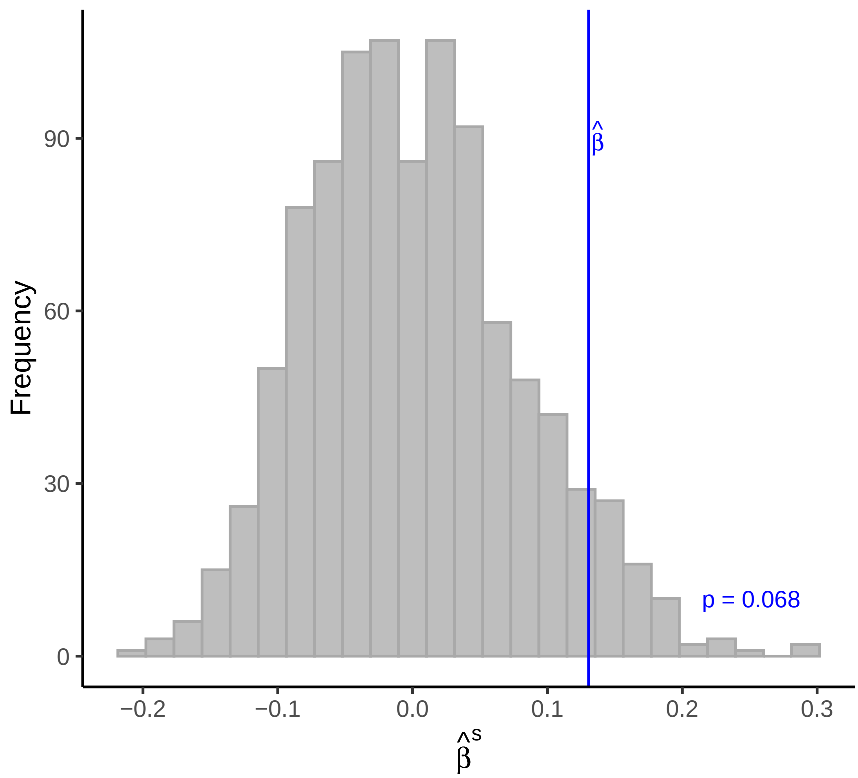
Appendix Figure C5 reports the results of randomization inference for the regression in Table 1, column 3. We conduct randomization inference by first calculating the unconditional probability $p$ of rainfall on each day in our 237-year sample. Then, on each simulation draw, we assign a notable rainfall event to each day with probability $p$ and run the same regression as in Table 1, column 3. Appendix Figure C5 shows the distribution of estimates of the coefficient on Prayer last month across each of these simulation draws, with the estimate in our sample as a benchmark. We calculate a $p$-value of 0.068 via randomization inference, suggesting that a coefficient as large as that observed in our sample is unlikely to have arisen by chance.

Table C10: Regressions of Recorded Rainfall and Prayer for Thanksgiving on Rain and Recent Prayer for Rain

| | *Recorded rainfall (=100)* | | | *Prayer for thanksgiving (=100)* | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Prayer last month | 0.189*** | 0.144** | 0.131** | 0.861*** | 0.787*** | 0.736*** |
| | (0.055) | (0.058) | (0.059) | (0.068) | (0.070) | (0.072) |
| Month effects | | *Yes* | *Yes* | | *Yes* | *Yes* |
| Month lags | | | *Yes* | | | *Yes* |
| Mean dep. var | 0.203 | 0.203 | 0.203 | 0.254 | 0.254 | 0.254 |
| Years of data | 237 | 237 | 237 | 237 | 237 | 237 |
| *N* | 86,535 | 86,535 | 86,175 | 86,535 | 86,535 | 86,175 |

*Notes*: This table reports coefficients from regressions of rainfall from municipal council records and prayers for thanksgiving on rain and recent prayer for rain in Murcia. Newey-West standard errors are in parentheses with a lag parameter of 90 days. Statistical significance at certain thresholds is indicated by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Figure C5: Distribution of coefficients on Prayer last month in placebo regressions using simulated data




*Notes*: The figure shows the distribution of estimates of the coefficient on *Prayer last month*, from the specification of Table 1, column 3, across simulation draws. In each simulation draw we construct a placebo rainfall series by drawing recorded rainfall events at random using the unconditional daily probability of rainfall. The vertical blue line shows the estimate in our sample as a benchmark.

# D Appendix: Supplementary Results for Global Analysis

This appendix describes several alternative specifications and robustness checks for our main results in the global data.

## D.1 Summary statistics by increasing hazard classification

Table D11 gives summary statistics for a set of *Ethnographic Atlas* and geographic variables for ethnic groups, differentiated by whether the group faces an increasing hazard rate (column 1) or a non-increasing hazard rate (column 2). The third column reports the coefficient from a regression of each row variable on an indicator variable for the group facing an increasing hazard and continent fixed effects.

Table D11: Climate, Geographic and Ethnic Group Means by Hazard Slope

| | Increasing Hazard<br>(1) | Non-increasing<br>(2) | Difference<br>(3) |
|---|---|---|---|
| Rain ritual (=1) | 0.44 | 0.30 | 0.16 |
| | [0.50] | [0.46] | (0.036) |
| High gods (=1) | 0.68 | 0.54 | -0.0029 |
| | [0.47] | [0.50] | (0.041) |
| Agriculture dependent (=1) | 0.63 | 0.66 | -0.057 |
| | [0.48] | [0.47] | (0.039) |
| Agriculture: dependence (cont) | 44.5 | 47.9 | -5.31 |
| | [28.0] | [23.6] | (2.33) |
| Ag.: intensive irrigated (=1) | 0.094 | 0.085 | 0.0099 |
| | [0.29] | [0.28] | (0.025) |
| Ag.: intensive (=1) | 0.18 | 0.12 | 0.0034 |
| | [0.38] | [0.33] | (0.039) |
| Ag.: extensive or shifting (=1) | 0.38 | 0.34 | -0.059 |
| | [0.49] | [0.47] | (0.046) |
| Ag.: casual (=1) | 0.038 | 0.019 | 0.017 |
| | [0.19] | [0.14] | (0.013) |
| Ag.: horticulture (=1) | 0.020 | 0.22 | -0.066 |
| | [0.14] | [0.41] | (0.019) |
| Elevation (m) | 727.9 | 554.8 | 119.5 |
| | [739.6] | [646.9] | (88.8) |
| Ruggedness (m) | 85.5 | 113.0 | -12.0 |
| | [143.2] | [196.6] | (14.5) |
| Distance from river (km) | 118.5 | 686.1 | -232.7 |
| | [219.1] | [1621.1] | (72.6) |
| Distance from lake (km) | 332.2 | 962.8 | -275.3 |
| | [312.7] | [1647.3] | (81.4) |
| Distance from ocean (km) | 527.8 | 376.6 | 25.1 |
| | [481.1] | [479.4] | (60.6) |
| Rainfall mean (annual, m) | 0.91 | 1.99 | -0.78 |
| | [0.69] | [1.52] | (0.12) |
| Rainfall std. dev (across years) | 0.24 | 0.57 | -0.22 |
| | [0.17] | [0.56] | (0.039) |
| Mean temperature (daily, Celsius) | 19.9 | 21.2 | -0.43 |
| | [9.39] | [8.07] | (0.80) |
| Temperature standard deviation | 4.98 | 3.36 | 1.31 |
| | [3.89] | [3.33] | (0.28) |

*Notes*: This table reports compares the mean characteristics of groups that face an increasing hazard (column 1) and those that face a non-increasing hazard (column 2). The first two columns report means with standard deviations in brackets underneath. The third column reports the coefficient from a regression of the row variable on an indicator variable for the group facing an increasing hazard and continent fixed effects. The standard error in parentheses beneath is a spatial (HAC-consistent) standard errors calculated using Bartlett's kernel with truncation at a distance of 1000 km.

## D.2 Spatial standard errors

Table D12 repeats the specification of Table 3, column 3 with different bandwidths for the calculation of spatial standard errors. We find very little change in the standard errors for spatial bandwidths up to 4000 km, the greatest level we examined.

Table D12: Rainmaking by Whether the Environment Allows Persuasion, Alternative Standard Errors (Using radii from 100 to 4000 km radius for spatial clustering, or Station-level clusters)

| | *Dependent variable: Rain ritual practiced (=1)* | | | | | |
|---|---|---|---|---|---|---|
| Bandwidth: | (100km) | (500km) | (1000km) | (2000km) | (4000km) | (Clustered) |
| Hazard rate increasing (=1) | 0.14*** | 0.14*** | 0.14*** | 0.14*** | 0.14*** | 0.14*** |
| | (0.037) | (0.037) | (0.037) | (0.036) | (0.040) | (0.037) |
| Continent effects | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Climate controls | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Geography controls | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Topography controls | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Mean dep. var | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| $R^2$ | 0.086 | 0.086 | 0.086 | 0.086 | 0.086 | 0.086 |
| Observations | 1195 | 1195 | 1195 | 1195 | 1195 | 1195 |

*Notes*: This table reports coefficients from regressions at the ethnic group level of whether a rain ritual is practiced on an indicator for an increasing hazard rate. Climate controls include a quadratic in mean temperature, the standard deviation of temperature, a quadratic in mean rainfall, the standard deviation of rainfall; topography controls include elevation and ruggedness; geography controls include latitude north of the equator, latitude south of the equator, longitude, the distance of a group to the coast, to a major river, and to a major lake. Standard errors use a spatial bandwidth, from left to right, of: 100, 500, 1000, 2000 and 4000 km. The right most column clusters standard errors at the weather station level using the modern weather station closest to each ethnic group. Spatial (HAC-consistent) standard errors are calculated using Bartlett's kernel with truncation at a distance determined by the radius. Statistical significance at certain thresholds is indicated by $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$.

## D.3 Seasonality

Demand for rainfall may increase rain ritual practice. We have two ways to test this idea. First, by comparing groups that have greater or lesser demand for rainfall because of their dependence on agriculture. Second, by comparing groups that have greater or lesser demand for rainfall during different seasons of the year.

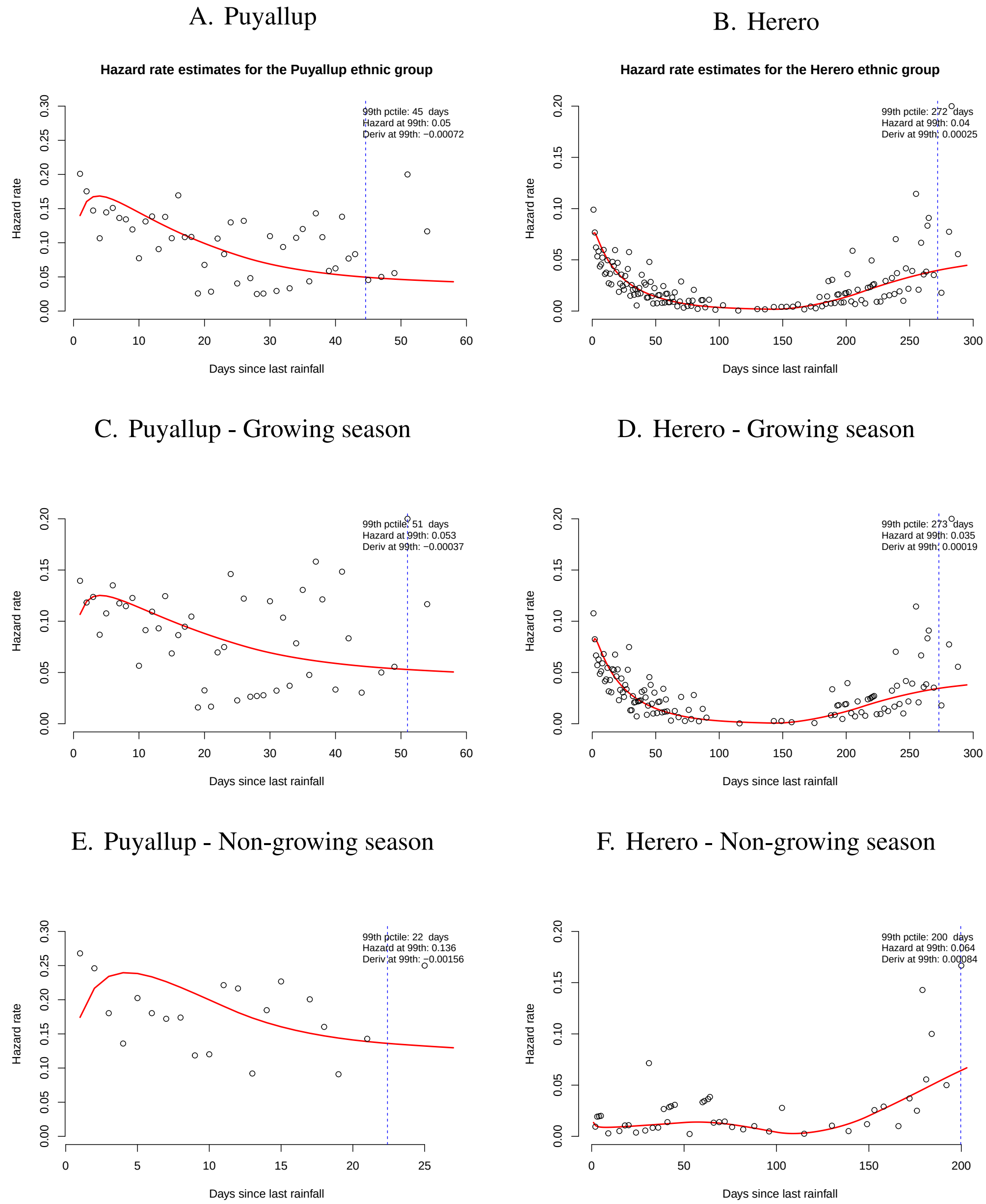
The first test is straightforward to interpret because the link between agriculture and rainfall is obvious and the *Atlas* measures agricultural dependence. Table 4 shows that groups more dependent on agriculture are more likely to practice rain rituals. The increase in the probability of rain ritual practice is greatest for the groups that practice intensive or intensive irrigated agriculture.

The second test proxies for demand for rainfall using the timing of when it rains during the year. Groups may have higher demand for rainfall in seasons when rain is in high demand. An increasing hazard may allow for stronger persuasion if it increases at a time when demand for rainfall is greater. To implement this test, we form proxies for when rainfall demand is greater for each ethnic group. We then estimate the hazard function separately for high-demand and low-demand seasons and regress rain ritual practice on whether these separate hazard functions are increasing in each season.

We use two alternative variables to classify seasons. First, we use the growing and non-growing seasons from modern agronomic data (see Appendix B.4). The idea is that rainfall demand should be higher in the growing season. Second, we use the dry and rainy seasons from modern rainfall data (see Appendix B.3). The idea is that rainfall demand may be higher in the dry season. Both of these proxies are plausible, but their reliability as measures of rainfall demand is unknown. For example, in many climates there is predictable seasonal variation in rainfall, and so people would not expect or demand rainfall during the dry season because they are not cropping at that time. Or, they would demand rainfall only at the end of the dry season, when the transition to the rainy season is expected and crops are planted in anticipation of this transition. For each of these proxies, we re-run our analysis using a seasonal classification of the hazard rate. For example, we define the growing season as the six contiguous months with the greatest rainfed cropped area. We then estimate seasonal hazard functions and classify their slopes in the same manner as for the overall hazard.

Appendix Figure D6 gives some examples of seasonal hazard functions, for the Puyallup and the Herero. Panel A shows the overall hazard function for the Puyallup, panel B the hazard for spells beginning during the growing season and panel C for spells beginning during the non-growing season. For the Puyallup, the hazard function is decreasing overall and for both seasons separately. For the Herero, in the right three panels, both seasonal hazard functions are increasing. The hazard is initially flat in the non-growing season, but increases for long dry spells as the onset of the growing season approaches. This pattern is typical of groups with two distinct seasons of

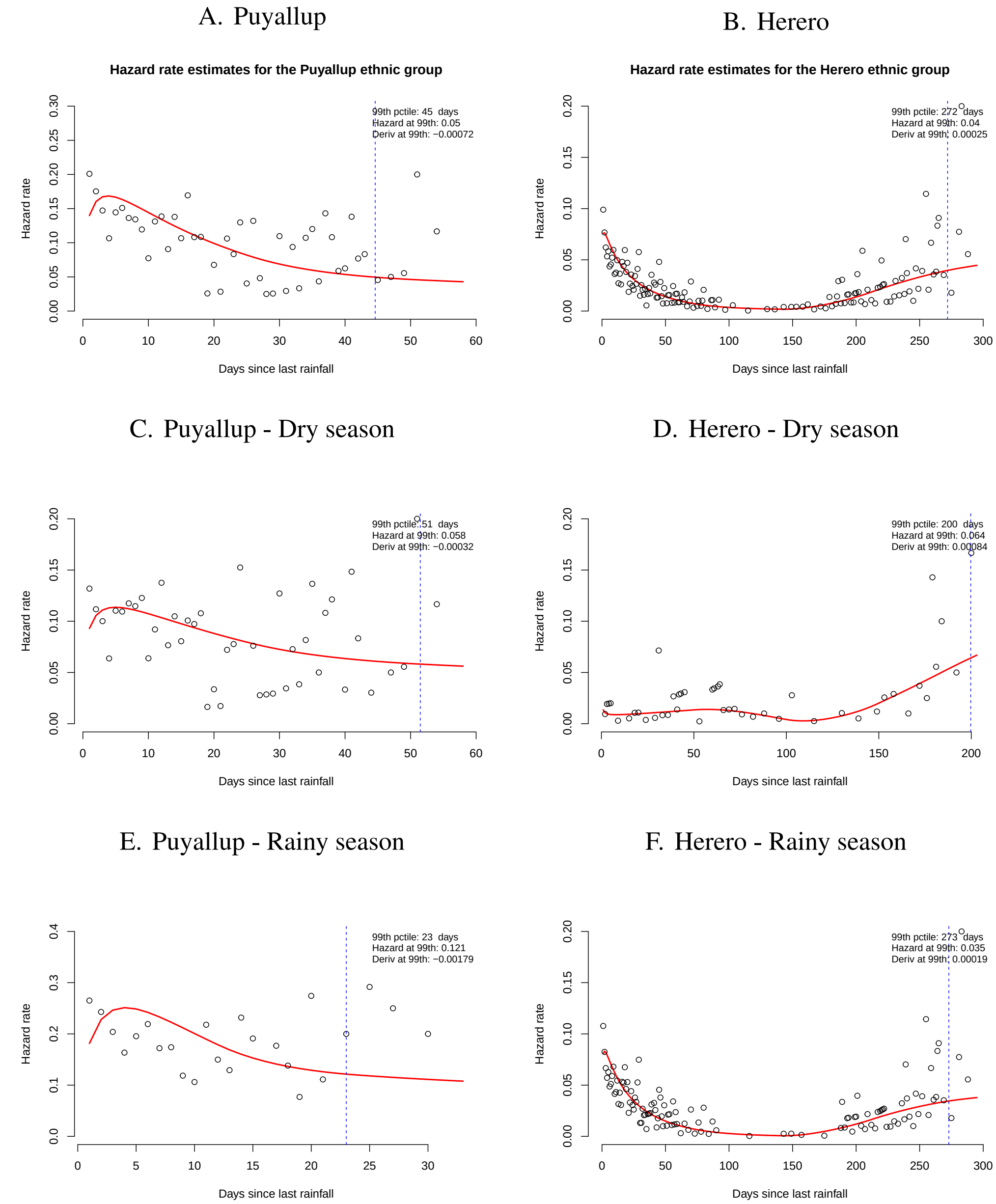
Figure D6: Hazard Functions Differentiated by Growing Season




*Notes*: The figure shows estimates of the hazard of rainfall after a dry spell. The estimates are separated by when in the year a spell begins (growing season vs. non-growing season). Seasons for other ethnic groups in our data are determined using a 6 month rolling mean of the MIRCA-OS rainfed crop area data. The month with the highest rolling mean is assumed to be the last month of the growing season, and the 5 months preceding it are assumed to be the other months of the growing season. Similarly, the month with the lowest rolling mean is assumed to be the end of the non-growing season.

rainfall per year separated by long dry seasons in between. Appendix Figure D7 repeats the hazard functions by season but classifies seasonality based on the dry and rainy seasons rather than the growing and non-growing seasons. Again, the hazard functions look similar in both seasons,

Figure D7: Hazard Functions Differentiated by Season




*Notes*: The figure shows estimates of the hazard of rainfall after a dry spell. The estimates are separated by when in the year a spell begins (dry season vs. rainy season). Seasons for ethnic groups in our data are determined using a 6 month rolling mean of rainfall data. The month with the highest rolling mean is assumed to be the last month of the rainy season, and the 5 months preceding it are assumed to be the other months of the rainy season. Similarly, the month with the lowest rolling mean is assumed to be the end of the dry season.

though for the Herero the hazard increases more steeply at the end of the dry season.

Appendix Table D13 conducts robustness checks for Table 3, column 5, where we differentiate the effect of an increasing hazard rate for rainfall spells during the high demand and low demand seasons. In that table, we classified rainfall spells as belonging to the growing season if they began during the growing season. In Appendix Table D13, we vary the definition of when rainfall spells are in demand: column 1 is the base case, where demand is based on the growing season and spells are in the growing season if they begin in the growing season; in column 2 demand is based on the growing season and spells are in the growing season if they start or end in the growing season; in column 3 demand is based on the growing season and spells are in the growing season if they end in the growing season. In columns 4 through 6, we cycle through the same classifications but use the dry season as our proxy for demand. In column 4 spells are in the dry season if they begin in the dry season; in column 5 demand is based on the dry season and spells are in the dry season if they start or end in the dry season; in column 6 demand is based on the dry season and spells are in the dry season if they end in the dry season.

We find that an increasing hazard rate in the growing season is highly predictive of rain ritual practice. In our preferred specification (column 1), an increasing hazard during the growing season predicts a 0.13 (standard error 0.035) higher probability of practicing a rain ritual. An increasing hazard rate in the non-growing season is not predictive of rain ritual practice. Using the dry season / rainy season classification of demand for rainfall, we find that an increasing hazard rate for spells that began in the dry season predicts a 0.17 (standard error 0.039) higher probability of practicing a rain ritual, somewhat larger than our main estimates (column 4). An increasing hazard rate during the wet season predicts a 0.084 (standard error 0.039) higher probability of practicing a rain ritual, which is statistically different from zero though not from the dry season estimate ($p$-value 0.13) (column 4).

The finding that an increasing hazard during high-demand seasons is predictive of rain ritual practice is broadly robust across alternative definitions of what makes a season high-demand. One apparent exception is in column (3), where we find that a hazard rate increasing during the *non*-growing season, when demand is presumably low, is predictive of rain ritual practice. This result arises only when we classify rainfall spells into seasons on the basis of when a spell *ends*, rather than when it starts. On investigation, this result appears due to selection bias that arises from estimating the hazard based on spell end dates.

Table D13: Rainmaking by Whether the Environment Allows Persuasion, Alternative Methods of Measuring Seasonality

| | *Dependent variable: Rain ritual practiced (=1)* | | | | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Haz rate inc. (growing season) (=1) | 0.13*** | | | | | |
| | (0.035) | | | | | |
| Haz rate inc. (non-growing season) (=1) | −0.00058 | | | | | |
| | (0.034) | | | | | |
| Haz rate inc. (growing season (start or end)) (=1) | | 0.097*** | | | | |
| | | (0.038) | | | | |
| Haz rate inc. (non-growing season(start & end)) (=1) | | 0.076 | | | | |
| | | (0.048) | | | | |
| Haz rate inc. (growing season by spell end) (=1) | | | 0.019 | | | |
| | | | (0.034) | | | |
| Haz rate inc. (non-growing season by spell end) (=1) | | | 0.15*** | | | |
| | | | (0.043) | | | |
| Haz rate inc. dry season (=1) | | | | 0.17*** | | |
| | | | | (0.039) | | |
| Haz rate inc. rainy season (=1) | | | | 0.084** | | |
| | | | | (0.039) | | |
| Haz rate inc. (dry season (start or end)) (=1) | | | | | 0.18*** | |
| | | | | | (0.045) | |
| Haz rate inc. (rainy season (start & end)) (=1) | | | | | 0.052 | |
| | | | | | (0.043) | |
| Haz rate inc. (dry season by spell end) (=1) | | | | | | 0.13** |
| | | | | | | (0.062) |
| Haz rate inc. (rainy season by spell end) (=1) | | | | | | 0.018 |
| | | | | | | (0.041) |
| Continent effects | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Climate controls | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Geography controls | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Topography controls | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Missing seasonal haz. | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| p-value (test of equality of coefficients) | 0.0057 | 0.72 | 0.023 | 0.13 | 0.061 | 0.14 |
| Mean dep. var | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| $R^2$ | 0.088 | 0.086 | 0.089 | 0.098 | 0.089 | 0.084 |
| Observations | 1195 | 1195 | 1195 | 1195 | 1195 | 1195 |

This table reports coefficients from regressions at the ethnic group level of whether a rain ritual is practiced on an indicator for that group facing an increasing hazard rate. For a description of the control variables, see the notes to Table 3. The rainy/dry season are the 6 months of the year with the highest/lowest measured rainfall for each ethnic group. Hazard increasing (at p99) in columns (1) and (4) is defined by a dry spell beginning in the referenced season. Columns (2) and (5) define a growing or dry season by spells beginning or ending in the season, and non-growing or rainy seasons by spells that start and end within the season. Columns (3) and (6) report coefficients where the dry spell ends in the referenced season. Spatial (HAC-consistent) standard errors are calculated using Bartlett's kernel with truncation at a distance of 1000 km. Statistical significance at certain thresholds is indicated by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

The selection bias arises because classifying by spell end date pushes long spells that begin in the growing season into the non-growing season. The classification of the hazard in the non-growing season therefore inherits the increasing hazard at long spell durations from the growing season spells. Appendix Figure D8 illustrates how selection affects estimates of the hazard function. Panel A shows the ∪-shaped hazard for the Kunda ethnic group, panel C shows the hazard for spells that begin in the growing season, and panel E shows the hazard for spells that end in the growing season. The hazard is increasing overall (panel A) and for spells that start in the growing season (panel C). When spells are classified by when they end (panel E), this pushes long spells from the growing season into the non-growing season (not shown). The resulting hazard function for spells beginning in the growing season is truncated (panel E). We no longer classify the growing season hazard as increasing. However, since long dry spells will now appear in the non-growing season sample, we will classify the non-growing season hazard as increasing.[28]

This re-classification is enough to cause the non-growing season hazard to appear increasing even when the true non-growing season hazard is flat or decreasing. Appendix Table D14 shows a cross-tabulation of what fraction of hazard functions are classified as increasing, when dry spells are allocated to seasons based on the start of the spell (row classification) or the end of the spell (column classification). About two-fifths of the ethnic groups with increasing growing season hazards based on the start date of spells are classified as having a non-increasing growing season hazard based on the end date of spells. This tabulation shows the potential importance of selection bias from spells that span seasons for the classification of the hazard function.

Table D14: Classification of Increasing Hazard Rate by Growing Season Definition

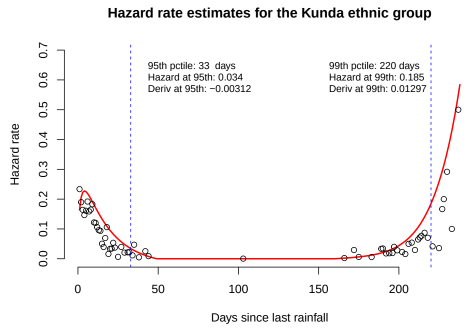
| *Hazard increasing when seasonality based on start of spells* | *Hazard increasing when seasonality based on end of spells* | | | | | |
|---|---|---|---|---|---|---|
| | (0) | (%) | (1) | (%) | Total | (%) |
| 0 | 463 | 40.3 | 96 | 8.4 | 559 | 48.7 |
| 1 | 245 | 21.3 | 344 | 30.0 | 589 | 51.3 |
| Total | 708 | 61.7 | 440 | 38.3 | 1148 | 100.0 |
| Observations | 1148 | | | | | |

We conclude that there is strong evidence that an increasing hazard specifically where and when rainfall is in demand matters more for rain ritual practice. Groups with the greatest dependence on agriculture are the most likely to practice a rain ritual (Table 4). Groups are more likely to practice

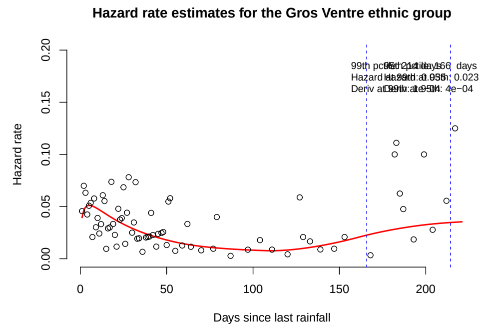
[28] Panels B, D and F refer to the Gros Ventre ethnic group. In this case the slope is negative at spell start and positive at spell end.

Figure D8: Hazard Functions Differentiated by Growing Season

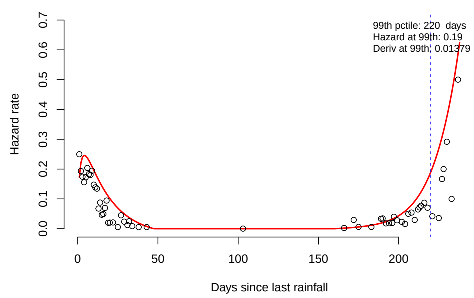
A. Kunda



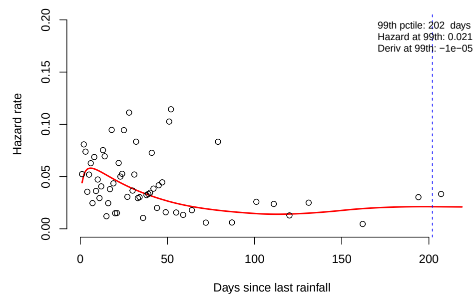

B. Gros Ventre



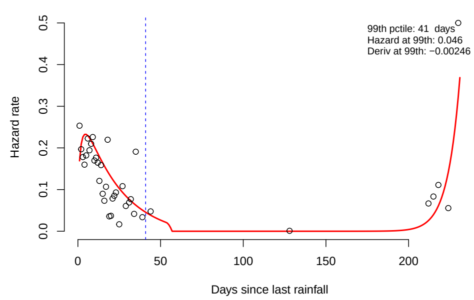

C. Kunda - Growing season by spell start



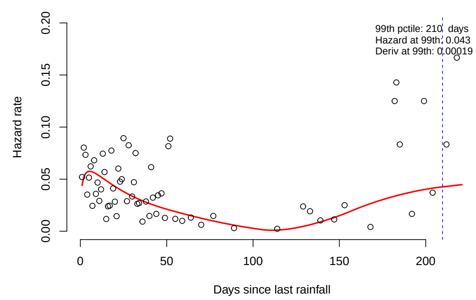

D. Gros Ventre - Growing season by spell start




E. Kunda - Growing season by spell end




F. Gros Ventre - Growing season by spell end




*Notes*: The figure shows estimates of the hazard of rainfall after a dry spell. The estimates are separated by when in the year a spell begins (growing season vs. non-growing season) or when it ends.

a rain ritual if the hazard function is increasing during the growing season, when rainfall is most valuable for agriculture (Table 3, column 5). This result is fairly robust to alternative proxies for the season of high rainfall demand (Appendix Table D13).

## D.4 Robustness to controls for additional climate statistics

We argue that it is specifically an increasing hazard that allows persuasion and not other features of the climate or environment. To probe this idea further, we here investigate how different moments of the rainfall distribution predict the practice of a rain ritual. Table D15 repeats certain specifications from Table 3 with controls for other moments of rainfall, in particular separating the standard deviation of rainfall across years and within years.

The main findings of Table D15 are that: (i) there is a small, negative coefficient of mean rainfall on rain ritual practice, when not controlling for the hazard rate (columns 1 to 3), (ii) there is no effect of mean rainfall on rain ritual practice, controlling for the hazard rate (columns 4 to 6), (iii) there is no effect of the standard deviation of rainfall, either across years or within a year, in any specification (columns 2, 3, 5 and 6). We conclude that it is not the level or even the variability of rainfall, but rather the shape of the hazard function, that best predicts rain ritual practice. In particular, a dry climate (low mean rainfall) in and of itself does not have *any* predictive power for the practice of a rain ritual.

## D.5 Classifying an increasing hazard at different dry spell durations

In our model what matters for the ability to persuade is whether the hazard of rainfall is increasing eventually, after a long dry spell without rain has passed. Our main results classify an increasing hazard empirically based on whether the derivative of the hazard is positive when evaluated at the 99th percentile of the distribution of dry spells, that is, gaps between days with significant rainfall. We chose this value because what matters for persuasion is what happens in the right tail of the distribution of dry spells. However, the choice is somewhat arbitrary since it is not clear a priori how long a spell needs to be to accurately capture the shape of the hazard function.

This section therefore presents a sensitivity analysis for the results using alternative classification rules based on whether the hazard is increasing after shorter dry spells. We find that using a much lower percentile of the dry spell distribution would misclassify many groups that truly face increasing hazard rates for long dry spells as having decreasing hazard rates.

Most dry spells are fairly short. Because a spell is defined as the gap between two days with significant rainfall ($\geq 0.5$ cm), most spells, by construction, occur during periods of the year when it is raining more often. Figure D9 shows the distribution of different quantiles of the length of dry spells across ethnic groups. The left panel shows the distribution across ethnic groups of the 95th percentile of the distribution of dry spells for that group and the right panel the distribution of the 99th percentile dry spell. There are two key points. First, most dry spells are quite short. Evaluated at the 95th percentile, for example, the modal dry spell is three weeks (each bar has width 7 days), and most dry spells are less than a month. Second, the distribution of dry spells stretches out considerably when evaluated at the 99th percentile. Comparing panel B to panel A, there is less

Table D15: Rain ritual and mean rainfall

| | *Dependent variable: Rain ritual practiced (=1)* | | | | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Hazard rate increasing (=1) | | | | 0.13*** | 0.14*** | 0.13*** |
| | | | | (0.040) | (0.037) | (0.037) |
| Rainfall mean (annual, m) | −0.031** | −0.063* | −0.060 | −0.014 | −0.024 | −0.023 |
| | (0.015) | (0.037) | (0.039) | (0.015) | (0.039) | (0.041) |
| Rainfall mean squared | | 0.0051 | 0.0062 | | 0.00031 | 0.00078 |
| | | (0.0050) | (0.0075) | | (0.0052) | (0.0075) |
| Rainfall std. dev (across years) | | −0.051 | −0.038 | | −0.019 | −0.014 |
| | | (0.088) | (0.10) | | (0.086) | (0.10) |
| Rainfall std. dev (within a year) | | | −1.88 | | | −0.79 |
| | | | (9.06) | | | (8.88) |
| Continent effects | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Climate controls | | *Yes* | *Yes* | | *Yes* | *Yes* |
| Geography controls | | *Yes* | *Yes* | | *Yes* | *Yes* |
| Topography controls | | *Yes* | *Yes* | | *Yes* | *Yes* |
| *p-value for a test of the joint significance of:* | | | | | | |
| Continent effects | 0.001 | 0.001 | 0.002 | 0.001 | 0.011 | 0.017 |
| Climate controls | | 0.000 | 0.000 | | 0.000 | 0.000 |
| Geography controls | | 0.012 | 0.012 | | 0.008 | 0.008 |
| Topography controls | | 0.085 | 0.089 | | 0.080 | 0.081 |
| Mean dep. var | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| Mean dep. var (dec. haz) | | | | 0.30 | 0.30 | 0.30 |
| $R^2$ | 0.027 | 0.075 | 0.076 | 0.037 | 0.086 | 0.086 |
| Observations | 1195 | 1195 | 1195 | 1195 | 1195 | 1195 |

*Notes*: This table reports coefficients from regressions at the ethnic group level of whether a rain ritual is practiced on the rainfall level.Climate controls include mean temperature, a quadratic in mean temperature, the standard deviation of temperature, mean rainfall, a quadratic in mean rainfall, the standard deviation of rainfall within a year, the standard deviation of rainfall across years; topography controls include elevation and ruggedness; geography controls include latitude north of the equator, latitude south of the equator, longitude, the distance of a group to the coast, to a major river, and to a major lake. Spatial (HAC-consistent) standard errors are calculated using Bartlett's kernel with truncation at a distance of 1000 km. Statistical significance at certain thresholds is indicated by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

mass at durations of less than a month and more mass above three or even six months. At the 99th percentile, dry spell duration is capturing long gaps between rainfall in areas with seasonal rainfall patterns, rather than common, shorter gaps between rainfall at rainy times of the year.

The considerable lengthening of dry spells in the right tail of the distribution has a significant effect on whether the hazard rate is increasing or decreasing, the key object in our model. Figure D11 shows the hazard functions for select ethnic groups that have decreasing hazard rates

Table D16: Rain ritual and mean rainfall

| | *Dependent variable: Rain ritual practiced (=1)* | | | | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Hazard rate increasing (=1) | | | | 0.13*** | 0.14*** | 0.14*** |
| | | | | (0.040) | (0.037) | (0.037) |
| Rainfall mean (annual, m) | −0.031** | −0.068* | −0.068* | −0.014 | −0.027 | −0.027 |
| | (0.015) | (0.036) | (0.037) | (0.015) | (0.039) | (0.039) |
| Rainfall mean squared | | 0.0039 | 0.0039 | | −0.000088 | −0.000060 |
| | | (0.0043) | (0.0043) | | (0.0045) | (0.0045) |
| Climate variation (across gen.) | | 0.19 | 0.24 | | 0.19 | 0.22 |
| | | (0.16) | (0.22) | | (0.15) | (0.21) |
| Climate variation (within gen.) | | | −0.20 | | | −0.11 |
| | | | (0.68) | | | (0.65) |
| Continent effects | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Climate controls | | *Yes* | *Yes* | | *Yes* | *Yes* |
| Geography controls | | *Yes* | *Yes* | | *Yes* | *Yes* |
| Topography controls | | *Yes* | *Yes* | | *Yes* | *Yes* |
| *p-value for a test of the joint significance of:* | | | | | | |
| Continent effects | 0.001 | 0.001 | 0.001 | 0.001 | 0.010 | 0.009 |
| Climate controls | | 0.000 | 0.000 | | 0.000 | 0.000 |
| Geography controls | | 0.009 | 0.012 | | 0.006 | 0.008 |
| Topography controls | | 0.058 | 0.056 | | 0.057 | 0.056 |
| Mean dep. var | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| Mean dep. var (dec. haz) | | | | 0.30 | 0.30 | 0.30 |
| $R^2$ | 0.027 | 0.077 | 0.077 | 0.037 | 0.087 | 0.087 |
| Observations | 1195 | 1195 | 1195 | 1195 | 1195 | 1195 |

*Notes*: This table reports coefficients from regressions at the ethnic group level of whether a rain ritual is practiced on the rainfall level.Climate controls include mean temperature, a quadratic in mean temperature, the standard deviation of temperature, mean rainfall, a quadratic in mean rainfall, variations in climate abnormalities across generations, variations in climate abnormalities across generations; topography controls include elevation and ruggedness; geography controls include latitude north of the equator, latitude south of the equator, longitude, the distance of a group to the coast, to a major river, and to a major lake. Spatial (HAC-consistent) standard errors are calculated using Bartlett's kernel with truncation at a distance of 1000 km. Statistical significance at certain thresholds is indicated by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

when evaluated at the 95th percentile of their respective dry spell distributions but increasing hazards when evaluated at the 99th percentile. Each panel of the figure, for one group, shows our semi-parametric fit of the hazard function and the evaluation of the hazard at the 95th and the 99th percentiles of the dry spell distribution. All of these groups have ∪-shaped hazards, in which the hazard of rainfall is high after a recent rain, decreases—in some cases nearly to zero—and then has an increasing region after a long dry spell has passed. The 95th percentile dry spell is not

Table D17: Rainmaking by Whether the Environment Allows Persuasion when Societies are more Complex

| | *Dependent variable: Rain ritual practiced (=1)* | | | | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Hazard rate increasing (=1) | 0.13*** | | 0.13*** | 0.13*** | | 0.12*** |
| | (0.038) | | (0.038) | (0.036) | | (0.037) |
| Haz rate inc. (growing season) (=1) | | | | | 0.14*** | |
| | | | | | (0.035) | |
| Haz rate inc. (non-growing season) (=1) | | | | | −0.0041 | |
| | | | | | (0.034) | |
| Jurisd. hierarchy $\geq$ 2 levels (=1) | 0.21*** | 0.19*** | 0.19*** | 0.20*** | 0.21*** | 0.20*** |
| | (0.052) | (0.051) | (0.050) | (0.049) | (0.048) | (0.048) |
| Dry spell duration (months, at p99) | | | | | | 0.0073 |
| | | | | | | (0.0049) |
| Rainfall mean (annual, m) | | −0.072* | −0.035 | −0.021 | −0.0045 | 0.0040 |
| | | (0.038) | (0.039) | (0.039) | (0.039) | (0.042) |
| Rainfall std. dev (across years) | | −0.034 | −0.0013 | −0.034 | −0.060 | −0.020 |
| | | (0.087) | (0.084) | (0.082) | (0.083) | (0.082) |
| Continent effects | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Climate controls | | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Geography controls | | | | *Yes* | *Yes* | *Yes* |
| Topography controls | | | | *Yes* | *Yes* | *Yes* |
| Missing seasonal haz. | | | | | *Yes* | |
| Mean dep. var | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| Mean dep. var (dec. haz) | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| $R^2$ | 0.051 | 0.068 | 0.078 | 0.097 | 0.10 | 0.099 |
| Observations | 1195 | 1195 | 1195 | 1195 | 1195 | 1195 |

*Notes*: This table reports coefficients from regressions at the ethnic group level of whether a rain ritual is practiced on an indicator for that group facing an increasing hazard rate. For a description of the control variables, see the notes to Table 3. Spatial (HAC-consistent) standard errors are calculated using Bartlett's kernel with truncation at a distance of 1000 km. Statistical significance at certain thresholds is indicated by $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$.

long enough to fall in this increasing region, but falls instead in the decreasing region of the hazard before truly long dry spells occur. For this reason, the hazard functions of these groups are misclassified as decreasing if evaluated at the 95th percentile of the dry spell distribution.

This type of misclassification is extremely common, if using the 95th percentile, because many ethnic groups face similar, seasonal patterns of rainfall. Figure D12 plots the derivative of the hazard rate for each group evaluated at the 95th percentile of the dry spell distribution against the derivative of the hazard rate for each group evaluated at the 99th percentile of the dry spell distribution. Each panel is a continent and each point is an ethnic group. For points in the upper-

Table D18: Rainmaking by Whether the Environment Allows Persuasion, Measured at Different Quartiles

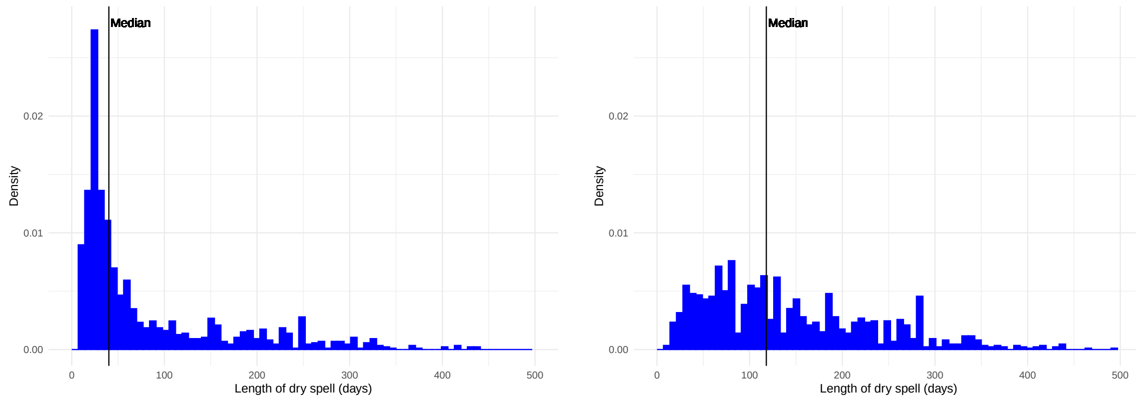
| | *Dependent variable: Rain ritual practiced (=1)* | | | | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Quartiles of increasing hazard=1 | 0.16*** | | 0.16*** | 0.18*** | | 0.16*** |
| | (0.052) | | (0.053) | (0.051) | | (0.055) |
| Quartiles of increasing hazard=2 | 0.10* | | 0.11** | 0.11** | | 0.10** |
| | (0.055) | | (0.051) | (0.049) | | (0.049) |
| Quartiles of increasing hazard=3 | 0.15*** | | 0.14*** | 0.15*** | | 0.14*** |
| | (0.045) | | (0.048) | (0.046) | | (0.047) |
| Quartiles of increasing hazard=4 | 0.13** | | 0.13** | 0.13** | | 0.12** |
| | (0.052) | | (0.052) | (0.050) | | (0.049) |
| Haz rate inc. (growing season) (=1) | | | | | 0.13*** | |
| | | | | | (0.035) | |
| Haz rate inc. (non-growing season) (=1) | | | | | −0.00058 | |
| | | | | | (0.034) | |
| Dry spell duration (months, at p99) | | | | | | 0.0050 |
| | | | | | | (0.0053) |
| Rainfall mean (annual, m) | | −0.074** | −0.028 | −0.015 | −0.012 | −0.000028 |
| | | (0.038) | (0.039) | (0.039) | (0.038) | (0.041) |
| Rainfall std. dev (across years) | | −0.021 | 0.016 | −0.016 | −0.046 | −0.0069 |
| | | (0.089) | (0.086) | (0.085) | (0.087) | (0.085) |
| Constant | 0.34*** | 0.30** | 0.17 | 0.085 | 0.17 | 0.057 |
| | (0.064) | (0.14) | (0.15) | (0.18) | (0.17) | (0.18) |
| Continent effects | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Climate controls | | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Geography controls | | | | *Yes* | *Yes* | *Yes* |
| Topography controls | | | | *Yes* | *Yes* | *Yes* |
| Missing seasonal haz. | | | | | *Yes* | |
| Mean dep. var | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| Mean dep. var (dec. haz) | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| p-value (test of equality of quartiles) | 0.74 | | 0.78 | 0.57 | | 0.75 |
| $R^2$ | 0.038 | 0.056 | 0.068 | 0.087 | 0.088 | 0.088 |
| Observations | 1195 | 1195 | 1195 | 1195 | 1195 | 1195 |

*Notes*: This table reports coefficients from regressions at the ethnic group level of whether a rain ritual is practiced on an indicators for that group facing an increasing hazard rate in the first, second, third and fourth quartiles of the group distribution. For a description of the control variables, see the notes to Table 3. Spatial (HAC-consistent) standard errors are calculated using Bartlett's kernel with truncation at a distance of 1000 km. Statistical significance at certain thresholds is indicated by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

right or lower-left quadrants, the classification of the hazard rate as increasing or decreasing is the same at both percentiles of the dry spell distribution. However, there are many groups that fall

Figure D9: Distribution of Dry Spell Duration Across Ethnic Groups

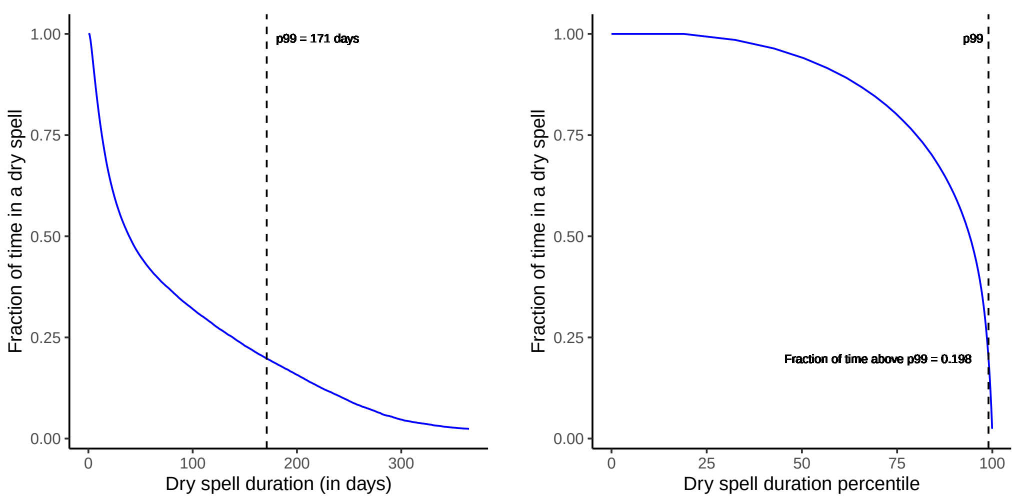
A. Evaluated at the 95th percentile B. Evaluated at the 99th percentile




*Notes*: The figure shows the distribution across ethnic groups of the 95th percentile of the distribution of dry spells (panel A) and the 99th percentile of the distribution of dry spells (panel B). The distributions of dry spells are measured as the length in days between rainfall events of at least half a centimeter at the weather station nearest each group. The horizontal axis is truncated at a duration of 500 days. The medians in the two panels, marked by vertical lines, are 40 and 118 days, respectively.

Figure D10: Fraction of Time Spent in a Dry Spell Across Ethnic Groups

A. Dry spell duration (in days) B. Dry spell duration (in percentile)

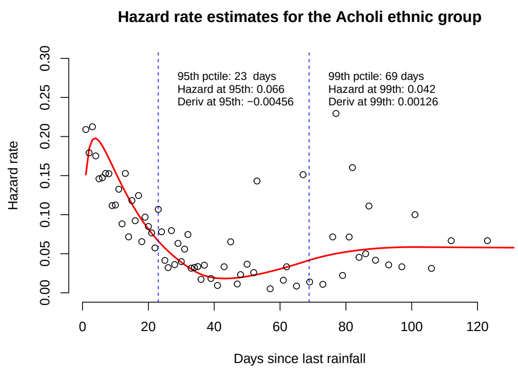



*Notes*: This figure shows the fraction of time a group spends in a dry spell as a function of the length in days (panel A) or percentile (panel B) of that dry spell in the distribution of spells. We take the entire sample of spells, and using the frequency of occurrence and length of the spell, we determine the cumulative fraction of time is spent in a spell of at most length i. In Panel A, we plot this against the spell duration. In Panel B, we take the same y axis but instead plot this against the percentile distribution of spells.

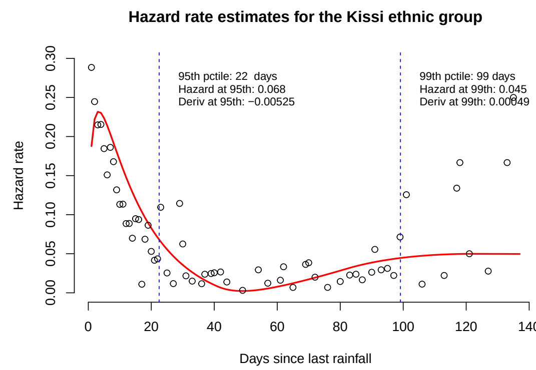
in the lower-right quadrant, like the examples in Figure D11, with decreasing hazards at the 95th percentile but increasing hazards at the 99th percentile. These groups are found on all continents but especially in Africa, Asia and South America. Overall, 71% of ethnic groups have an increasing

Figure D11: Comparison of Hazard Rates at 95th and 99th percentiles of the Distribution of Dry Spells for Select Ethnic Groups

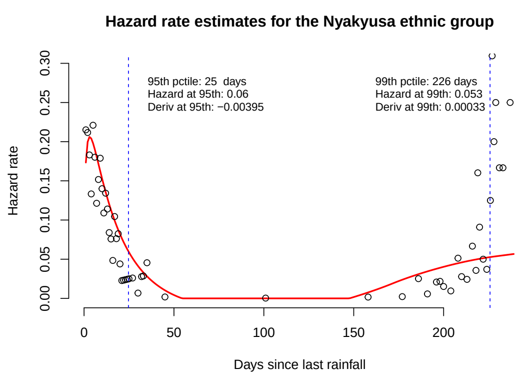
A. Acholi



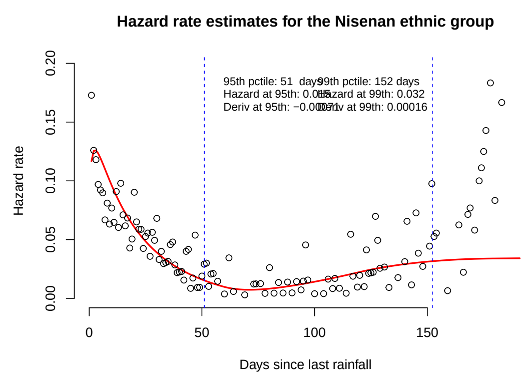

B. Kissi



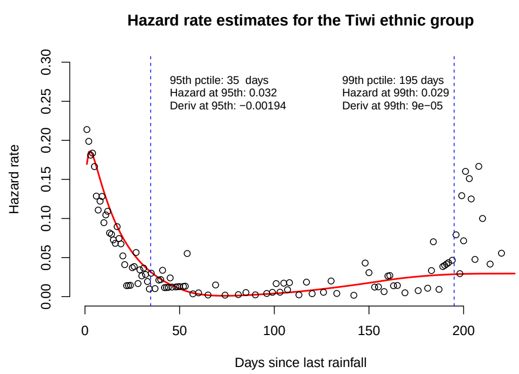

C. Nyakyusa



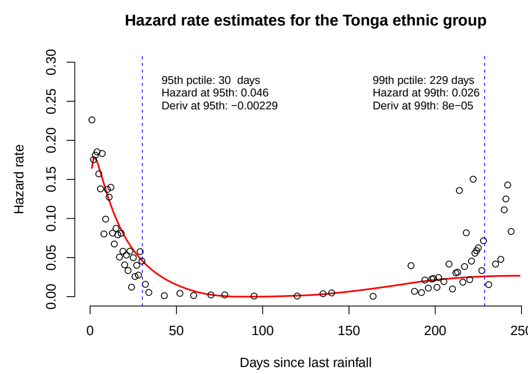

D. Nisenan




E. Tiwi



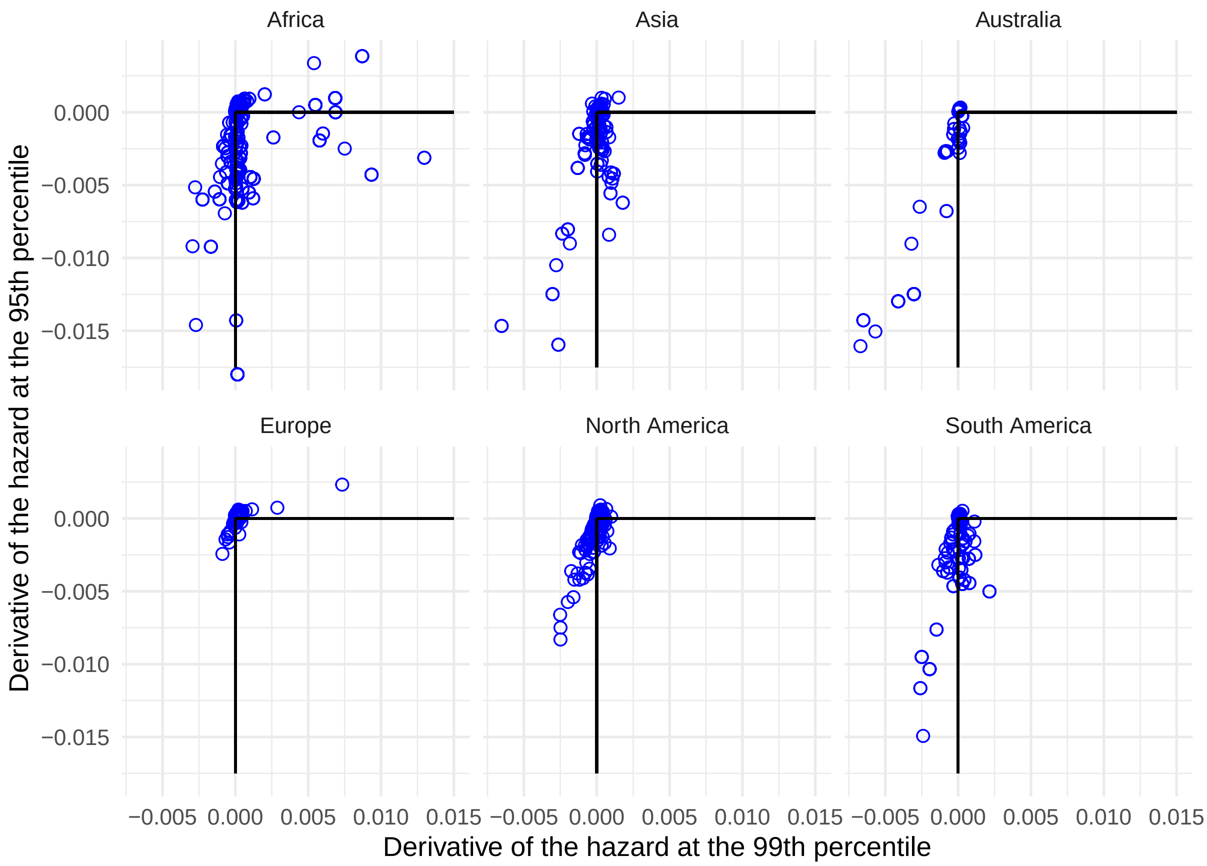

F. Tonga




hazard evaluated at the 99th percentile, but only 37% do at the 95th percentile, meaning fully 34% of all groups have a hazard that changes sign across this range. Thus the cases in Figure D11 in fact represent one-third of all groups and nearly half of all groups with an increasing hazard rate.

Table D19 reproduces our Table 3 results, from the main text, using the column 4 specifica-

Figure D12: Comparison of Hazard Slopes at Different Points in the Dry Spell Distribution




*Notes*: The figure shows a scatterplot, at the ethnic group level, of the derivative of the rainfall hazard for that group evaluated at the 95th percentile of the dry spell distribution against the derivative evaluated at the 99th percentile of the dry spell distribution.

tion, but evaluating whether the hazard rate is decreasing at different percentiles of the dry spell distribution for each group, from the 90th to the 99th percentile (our baseline case). We find that when the hazard is evaluated at high percentiles of the rainfall distribution the effect of an increasing hazard on the practice of a rain ritual is large and positive, and close to our baseline estimate, regardless of the exact percentile chosen. When the hazard is evaluated at lower percentiles of the rainfall distribution, below the 96th percentile, we estimate no effect of an increasing hazard on rain ritual practice. We attribute these null effects to the wholesale misclassification of the independent variable, the increasing hazard rate dummy, that occurs when evaluating the hazard after relatively short durations. For the many, many groups like the Acholi, Kissi, Nyakyusa, and Tonga in Figure D11, the 95th percentile represents a dry spell of just a few weeks, and is too short to capture whether the hazard rate is increasing. In our model, the religious authority would not pray after such a short time but would wait until a period when the hazard was increasing. This result is therefore affirmation that our model captures the correct feature of climate for rain ritual practice, which is whether the hazard rate increases after a *long* dry spell.

Table D19: Rainmaking by Whether the Environment Allows Persuasion, Measured at Different Percentiles of the Distribution of Dry Spells

| | *Dependent variable: Rain ritual practiced (=1)* | | | | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Hazard increasing (at p90) (=1) | −0.052 | | | | | |
| | (0.052) | | | | | |
| Hazard increasing (at p95) (=1) | | −0.026 | | | | |
| | | (0.040) | | | | |
| Hazard increasing (at p96) (=1) | | | 0.043 | | | |
| | | | (0.040) | | | |
| Hazard increasing (at p97) (=1) | | | | 0.14*** | | |
| | | | | (0.043) | | |
| Hazard increasing (at p98) (=1) | | | | | 0.16*** | |
| | | | | | (0.040) | |
| Hazard increasing (at p99) (=1) | | | | | | 0.14*** |
| | | | | | | (0.037) |
| Continent effects | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Climate controls | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Geography controls | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Topography controls | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| *p-value for a test of the joint significance of:* | | | | | | |
| Continent effects | 0.002 | 0.001 | 0.001 | 0.005 | 0.008 | 0.011 |
| Climate controls | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Geography controls | 0.010 | 0.010 | 0.014 | 0.017 | 0.007 | 0.008 |
| Topography controls | 0.069 | 0.087 | 0.086 | 0.084 | 0.063 | 0.080 |
| Mean dep. var | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| Mean dep. var (dec. haz) | 0.40 | 0.39 | 0.36 | 0.32 | 0.29 | 0.30 |
| Mean hazard dummy | 0.16 | 0.37 | 0.44 | 0.54 | 0.71 | 0.71 |
| Mean dry spell at ptile (in days) | 1.78 | 2.83 | 3.20 | 3.66 | 4.23 | 4.89 |
| $R^2$ | 0.076 | 0.076 | 0.076 | 0.086 | 0.089 | 0.086 |
| Observations | 1195 | 1195 | 1195 | 1195 | 1195 | 1195 |

*Notes*: This table reports coefficients from regressions at the ethnic group level of whether a rain ritual is practiced on whether the hazard rate is increasing at different percentiles of the distribution of dry spells, ranging from p90 up to p99. Controls for climate, geography, topography and continent fixed effects are included in all specifications. Climate controls include a quadratic in mean temperature, the standard deviation of temperature, a quadratic in mean rainfall, the standard deviation of rainfall; topography controls include elevation and ruggedness; geography controls include latitude north of the equator, latitude south of the equator, longitude, the distance of a group to the coast, to a major river, and to a major lake. Spatial (HAC-consistent) standard errors are calculated using Bartlett's kernel with truncation at a distance of 1000 km. Statistical significance at certain thresholds is indicated by $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$.

## D.6 High gods belief as an alternate measure of religiosity

Our analysis relates specific climate norms to rainfall prayer. While the prediction from the model of *what* climate norms matter is extremely sharp, it is reasonable to ask whether the measured relationship is due to mechanisms specific to belief in rainmaking, or due to general changes in religiosity due to a certain climate. Even accepting that the empirical analysis does identify the effects of an environment that allows persuasion on rainfall prayer, specifically, it may be that the climate causes a change in general religiosity which then manifests itself in rain ritual practice but also other practices that we may not observe.

The *Ethnographic Atlas*, without our additional data collection, includes only one measure of religious belief, a categorical variable for whether or not an ethnic group believes in "high gods." There are two related definitions of high gods. The *Atlas* codebook, citing Swanson (1960), states:

> A high god is defined, following Swanson, as a spiritual being who is believed to have created all reality and/or to be its ultimate governor, even if his sole act was to create other spirits who, in turn, created or control the natural world.

The related definition of Norenzayan et al. (2016) is:

> Belief in, and commitment to, powerful, all-knowing, and morally concerned supernatural agents who are believed to monitor social interactions and to reward and sanction behaviors in ways that contribute to the cultural success of the group, including practices that effectively transmit the faith. Rhetorically, we call these "Big Gods."

The Norenzayan et al. (2016) definition is stricter than Swanson (1960) in that it also prescribes moral behavior. Prior research has hypothesized that more complex societies are more likely to believe in "high gods," which prescribe a code of moral behavior and intervene in human affairs to enforce it (Swanson, 1960).[29]

In the *Atlas* the belief variable takes on categorical values for whether an ethnic group believes in "high gods" that prescribe a moral code and whether those Gods are believed to be active in human affairs. Table D20 gives a frequency tabulation of the categories of the high gods variable. This variable is available for only 774 ethnic groups, or 60 percent of the total *Atlas*.

[29] Prior research has found that greater levels of social or political complexity are associated with a higher probability of worshipping high gods (Roes and Raymond, 2003; Peoples and Marlowe, 2012). A prominent line of research has argued that the worship of "big gods" *causes* greater levels of cooperation and reduces conflict within a group, aiding the development of complex societies (Norenzayan, 2013). The thesis has been controversial because a correlation between the worship of moralizing gods and social or political complexity does not imply that big gods cause complexity (Geertz, 2014; Atkinson, Latham and Watts, 2015).

Table D20: Categorization of Belief in *Atlas* High Gods Variable

| | freq | pct |
|---|---|---|
| absent or not reported | 276 | 21 |
| not active in human affairs | 258 | 20 |
| active in human affairs, not supportive of human morality | 42 | 3 |
| supportive of human morality | 198 | 15 |
| . | 517 | 40 |
| Total | 1291 | 100 |

For the purposes of comparison to the practice of a rain ritual as a measure of belief, we code an indicator variable *High Gods ($=1$)*, corresponding to the Swanson definition of high gods, if a group's belief in high gods is "not active in human affairs," "active in human affairs, not supportive of human morality" or "supportive of human morality." We code an indicator *High Gods Moral ($=1$)*, corresponding to the Norenzayan definition of big gods, if a group's belief in high gods is "supportive of human morality" and not otherwise. We then investigate whether climatic variables are predictive of high gods belief, measured in these two ways.

Table D21 and Table D22 reproduce the specifications of Table 3 using *High Gods ($=1$)* and *High Gods Moral ($=1$)*, respectively, as the dependent variables, in place of belief in a rain ritual. We find no statistically significant relationship between an increasing hazard rate and belief in high gods, by either measure. For example, in the Table D21, column 4 specification with a rich set of geographic and climatic controls, the coefficient on hazard rate increasing is $-0.051$ (0.044), by contrast with the large, positive and statistically significant coefficient in Table 3, column 4. The high gods variable is available for far fewer ethnic groups than is the rain ritual practice measure, which we collected by hand. To check whether this difference in sample contributes to the difference between the estimated effect of an increasing hazard on rain ritual practice and on high gods belief, respectively, Table D23 repeats our specifications from Table 3, with rain ritual as the dependent variable, restricting the sample to observations where high gods belief is non-missing. We find virtually identical results to those of the full sample in Table 3 despite a sample of 722 ethnic group observations, as opposed to 1195 observations in the original Table 3. Therefore, the lack of a significant relationship between an increasing hazard and high gods belief in Tables D21 and D22 is not due to group selection or sample size concerns.

The finding that an increasing hazard is not correlated with high gods belief suggests that the mechanism connecting an increasing hazard rate to rain ritual practice is specific to belief in rainmaking and not a generalized spillover from belief in high gods. There is no relationship between the climatic norms that dictate persuasion in our model and belief in high gods. Rainmaking, though widely considered a traditional practice, cuts across levels of religious evolution. Rainmaking is common to both traditional (e.g., Cherokee or Herero) and highly organized (e.g., Catholic or Islamic) religious practice. As a final investigation, we also test whether the effect of an increasing hazard on rain ritual practice differs among ethnic groups that believe in high gods (here using only the broader definition to conserve on space). Table D24 reports the results of regressions with rain ritual practice as the dependent variable and the interaction of an increasing hazard rate with different beliefs in high gods as independent variables. We find that an increasing hazard has a large, positive and significant effect on rain ritual practice both among groups that believe in high gods and among groups that do not. The coefficient on the increasing hazard rate is smaller and statistically insignificant among the ethnic groups for which the high gods classification is missing.

On balance, the evidence in this subsection finds no relationship between an increasing hazard and belief in high gods across ethnic groups and no evidence for a mediating effect of high gods belief on the effect of an increasing hazard on rainmaking. The findings support the idea that the increasing hazard mechanism we identify is specific to rainmaking and also operates across a wide range of heterogenous belief systems.

Table D21: High Gods Belief by Whether the Environment Allows Persuasion

| | *Dependent variable: High gods belief (=1)* | | | | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Hazard rate increasing (=1) | −0.0082 | | −0.052 | −0.051 | | −0.034 |
| | (0.043) | | (0.044) | (0.044) | | (0.043) |
| Haz rate inc. dry season (=1) | | | | | −0.048 | |
| | | | | | (0.044) | |
| Haz rate inc. rainy season (=1) | | | | | 0.021 | |
| | | | | | (0.045) | |
| Dry spell duration (months, at p99) | | | | | | $-0.010^{**}$ |
| | | | | | | (0.0046) |
| Rainfall mean (annual, m) | | −0.011 | −0.028 | −0.060 | −0.023 | $-0.098^{**}$ |
| | | (0.039) | (0.040) | (0.042) | (0.052) | (0.045) |
| Rainfall std. dev (across years) | | 0.027 | 0.014 | 0.037 | 0.056 | 0.016 |
| | | (0.098) | (0.099) | (0.10) | (0.11) | (0.10) |
| Continent effects | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Climate controls | | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Geography controls | | | | *Yes* | *Yes* | *Yes* |
| Topography controls | | | | *Yes* | *Yes* | *Yes* |
| Missing seasonal haz. | | | | | *Yes* | |
| *p-value for a test of the joint significance of:* | | | | | | |
| Continent effects | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Climate controls | | 0.009 | 0.007 | 0.042 | 0.059 | 0.010 |
| Geography controls | | | | 0.436 | 0.219 | 0.379 |
| Topography controls | | | | 0.315 | 0.304 | 0.262 |
| *p-value for a test of the equality of:* | | | | | | |
| Seasonal hazards | | | | | 0.28 | |
| Mean dep. var | 0.64 | 0.64 | 0.64 | 0.64 | 0.64 | 0.64 |
| Mean dep. var (dec. haz) | 0.54 | 0.54 | 0.54 | 0.54 | 0.54 | 0.54 |
| $R^2$ | 0.29 | 0.30 | 0.31 | 0.32 | 0.32 | 0.32 |
| Observations | 762 | 762 | 762 | 762 | 762 | 762 |

*Notes*: This table reports coefficients from regressions at the ethnic group level of whether a group believes in high gods on an indicator for that group facing an increasing hazard rate. Climate controls include: a quadratic in mean temperature, the standard deviation of temperature, a quadratic in mean rainfall and the standard deviation of rainfall; only the coefficients on mean rainfall and the standard deviation of rainfal are reported. Topography controls include elevation and ruggedness; geography controls include latitude north of the equator, latitude south of the equator, longitude, the distance of a group to the coast, to a major river, and to a major lake. Spatial (HAC-consistent) standard errors are calculated using Bartlett's kernel with truncation at a distance of 1000 km. Statistical significance at certain thresholds is indicated by $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$.

Table D22: Moralizing High Gods Belief by Whether the Environment Allows Persuasion

| | *Dependent variable: High gods moral (=1)* | | | | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Hazard rate increasing (=1) | 0.063 | | −0.0022 | −0.033 | | −0.036 |
| | (0.058) | | (0.051) | (0.038) | | (0.038) |
| Haz rate inc. dry season (=1) | | | | | −0.10*** | |
| | | | | | (0.036) | |
| Haz rate inc. rainy season (=1) | | | | | −0.016 | |
| | | | | | (0.033) | |
| Dry spell duration (months, at p99) | | | | | | 0.0021 |
| | | | | | | (0.0032) |
| Rainfall mean (annual, m) | | −0.12*** | −0.12*** | −0.15*** | −0.15*** | −0.14*** |
| | | (0.040) | (0.040) | (0.045) | (0.048) | (0.046) |
| Rainfall std. dev (across years) | | 0.10 | 0.10 | 0.11 | 0.12 | 0.12 |
| | | (0.082) | (0.088) | (0.086) | (0.080) | (0.086) |
| Continent effects | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Climate controls | | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Geography controls | | | | *Yes* | *Yes* | *Yes* |
| Topography controls | | | | *Yes* | *Yes* | *Yes* |
| Missing seasonal haz. | | | | | *Yes* | |
| *p-value for a test of the joint significance of:* | | | | | | |
| Continent effects | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Climate controls | | 0.048 | 0.026 | 0.004 | 0.002 | 0.005 |
| Geography controls | | | | 0.122 | 0.080 | 0.122 |
| Topography controls | | | | 0.069 | 0.059 | 0.077 |
| *p-value for a test of the equality of:* | | | | | | |
| Seasonal hazards | | | | | 0.084 | |
| Mean dep. var | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 |
| Mean dep. var (dec. haz) | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 |
| $R^2$ | 0.44 | 0.48 | 0.48 | 0.51 | 0.52 | 0.51 |
| Observations | 762 | 762 | 762 | 762 | 762 | 762 |

*Notes*: This table reports coefficients from regressions at the ethnic group level of whether a group believes in Moral high gods on an indicator for that group facing an increasing hazard rate. Climate controls include: a quadratic in mean temperature, the standard deviation of temperature, a quadratic in mean rainfall and the standard deviation of rainfall; only the coefficients on mean rainfall and the standard deviation of rainfal are reported. Topography controls include elevation and ruggedness; geography controls include latitude north of the equator, latitude south of the equator, longitude, the distance of a group to the coast, to a major river, and to a major lake. Spatial (HAC-consistent) standard errors are calculated using Bartlett's kernel with truncation at a distance of 1000 km. Statistical significance at certain thresholds is indicated by $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$.

Table D23: Rainmaking by Whether the Environment Allows Persuasion, Sample Restricted to Observations with Non-missing High Gods Variable

| | *Dependent variable: Rain ritual practiced (=1)* | | | | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Hazard rate increasing (=1) | 0.13*** | | 0.14*** | 0.16*** | | 0.16*** |
| | (0.046) | | (0.048) | (0.049) | | (0.049) |
| Haz rate inc. dry season (=1) | | | | | 0.17*** | |
| | | | | | (0.053) | |
| Haz rate inc. rainy season (=1) | | | | | 0.089* | |
| | | | | | (0.047) | |
| Dry spell duration (months, at p99) | | | | | | −0.00023 |
| | | | | | | (0.0056) |
| Rainfall mean (annual, m) | | −0.075 | −0.028 | −0.0080 | 0.037 | −0.0088 |
| | | (0.048) | (0.049) | (0.047) | (0.055) | (0.052) |
| Rainfall std. dev (across years) | | 0.027 | 0.065 | 0.060 | 0.062 | 0.059 |
| | | (0.12) | (0.12) | (0.13) | (0.13) | (0.13) |
| Continent effects | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Climate controls | | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Geography controls | | | | *Yes* | *Yes* | *Yes* |
| Topography controls | | | | *Yes* | *Yes* | *Yes* |
| Missing seasonal haz. | | | | | *Yes* | |
| *p-value for a test of the joint significance of:* | | | | | | |
| Continent effects | 0.000 | 0.000 | 0.000 | 0.007 | 0.000 | 0.007 |
| Climate controls | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Geography controls | | | | 0.082 | 0.122 | 0.082 |
| Topography controls | | | | 0.335 | 0.434 | 0.333 |
| *p-value for a test of the equality of:* | | | | | | |
| Seasonal hazards | | | | | 0.28 | |
| Mean dep. var | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 | 0.44 |
| Mean dep. var (dec. haz) | 0.34 | 0.34 | 0.34 | 0.34 | 0.34 | 0.34 |
| $R^2$ | 0.057 | 0.081 | 0.093 | 0.12 | 0.13 | 0.12 |
| Observations | 722 | 722 | 722 | 722 | 722 | 722 |

*Notes*: This table reports coefficients from regressions at the ethnic group level of whether a group practices a rain ritual on an indicator for that group facing an increasing hazard rate. The sample is restricted to observations that have a non-missing classification of whether an ethnic group believes in high gods. Climate controls include: a quadratic in mean temperature, the standard deviation of temperature, a quadratic in mean rainfall and the standard deviation of rainfall; only the coefficients on mean rainfall and the standard deviation of rainfal are reported. Topography controls include elevation and ruggedness; geography controls include latitude north of the equator, latitude south of the equator, longitude, the distance of a group to the coast, to a major river, and to a major lake. Spatial (HAC-consistent) standard errors are calculated using Bartlett's kernel with truncation at a distance of 1000 km. Statistical significance at certain thresholds is indicated by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table D24: Rainmaking by Whether the Environment Allows Persuasion, Interacted with Belief in High Gods

| | *Dependent variable: Rain ritual practiced (=1)* | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Hazard rate increasing (=1) × high gods (=1) | 0.16*** | 0.17*** | 0.17*** | 0.16*** |
| | (0.043) | (0.044) | (0.043) | (0.043) |
| Hazard rate increasing (=1) × high gods (=0) | 0.23*** | 0.21*** | 0.22*** | 0.21*** |
| | (0.054) | (0.054) | (0.052) | (0.053) |
| Hazard rate increasing (=1) × high gods missing | 0.060 | 0.052 | 0.058 | 0.050 |
| | (0.044) | (0.042) | (0.041) | (0.042) |
| Dry spell duration (months, at p99) | | | | 0.0060 |
| | | | | (0.0051) |
| Rainfall mean (annual, m) | | −0.036 | −0.026 | −0.0062 |
| | | (0.038) | (0.038) | (0.041) |
| Rainfall std. dev (across years) | | 0.017 | −0.016 | −0.0041 |
| | | (0.086) | (0.085) | (0.085) |
| Continent effects | *Yes* | *Yes* | *Yes* | *Yes* |
| Climate controls | | *Yes* | *Yes* | *Yes* |
| Geography controls | | | *Yes* | *Yes* |
| Topography controls | | | *Yes* | *Yes* |
| *p-value for a test of the joint significance of:* | | | | |
| Continent effects | 0.001 | 0.000 | 0.004 | 0.003 |
| Climate controls | | 0.000 | 0.000 | 0.000 |
| Geography controls | | | 0.010 | 0.009 |
| Topography controls | | | 0.090 | 0.099 |
| Mean dep. var | 0.40 | 0.40 | 0.40 | 0.40 |
| Mean dep. var (dec. haz) | 0.30 | 0.30 | 0.30 | 0.30 |
| $R^2$ | 0.048 | 0.078 | 0.097 | 0.098 |
| Observations | 1195 | 1195 | 1195 | 1195 |

*Notes*: This table reports coefficients from regressions at the ethnic group level of whether a group practices a rain ritual on an indicator for that group facing an increasing hazard rate. Climate controls include: a quadratic in mean temperature, the standard deviation of temperature, a quadratic in mean rainfall and the standard deviation of rainfall; only the coefficients on mean rainfall and the standard deviation of rainfal are reported. Topography controls include elevation and ruggedness; geography controls include latitude north of the equator, latitude south of the equator, longitude, the distance of a group to the coast, to a major river, and to a major lake. Spatial (HAC-consistent) standard errors are calculated using Bartlett's kernel with truncation at a distance of 1000 km. Statistical significance at certain thresholds is indicated by $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$.

Table D25: Agriculture and the Environment as Determinants of Rainmaking Demand

| | *Dependent variable: Rain ritual practiced (=1)* | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Hazard rate increasing (=1) | 0.11** | 0.096* | 0.094 | 0.16*** |
| | (0.055) | (0.052) | (0.066) | (0.041) |
| Agriculture dependent (=1) | 0.087 | 0.053 | | |
| | (0.062) | (0.063) | | |
| Ag.: dependent (=1) × HRI | 0.043 | 0.064 | | |
| | (0.064) | (0.060) | | |
| Agriculture: dependence (cont) | | | 0.0020* | |
| | | | (0.0012) | |
| Ag.: dependent (cont) × HRI | | | 0.0010 | |
| | | | (0.0012) | |
| Ag.: intensive irrigated (=1) | | | | 0.34*** |
| | | | | (0.11) |
| Ag.: Irrigated × HRI | | | | 0.045 |
| | | | | (0.11) |
| Ag.: intensive (=1) | | | | 0.23** |
| | | | | (0.096) |
| Ag.: Intensive × HRI | | | | −0.014 |
| | | | | (0.079) |
| Ag.: extensive or shifting (=1) | | | | 0.14** |
| | | | | (0.065) |
| Ag.: horticulture (=1) | | | | 0.079 |
| | | | | (0.090) |
| Ag.: casual (=1) | | | | −0.014 |
| | | | | (0.089) |
| Agriculture: missing (=1) | | | | 0.041 |
| | | | | (0.072) |
| Continent effects | *Yes* | *Yes* | *Yes* | *Yes* |
| Climate controls | | *Yes* | *Yes* | *Yes* |
| Geography controls | | *Yes* | *Yes* | *Yes* |
| Topography controls | | *Yes* | *Yes* | *Yes* |
| Mean dep. var | 0.39 | 0.39 | 0.39 | 0.39 |
| Mean dep. var(agric = 0) | 0.32 | 0.32 | 0.32 | 0.32 |
| $R^2$ | 0.046 | 0.093 | 0.100 | 0.12 |
| Observations | 1194 | 1194 | 1194 | 1195 |

*Notes*: This table reports coefficients from regressions at the ethnic group level of whether a rain ritual is practiced on measures of agricultural intensity, as well as an indicator for whether a group faces an increasing hazard rate. Additionally, we report coefficients on the interaction of agriculural intensity measures with an increasing hazard rate. For a description of the control variables, see the notes to Table 4. Spatial (HAC-consistent) standard errors are calculated using Bartlett's kernel with truncation at a distance of 1000 km. Statistical significance at certain thresholds is indicated by $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$.

Table D26: Agriculture and the Environment as Determinants of Rainmaking Demand

| | *Dependent variable: Rain ritual practiced (=1)* | | |
|---|---|---|---|
| | (1) | (2) | (3) |
| Hazard rate increasing (=1) | 0.13*** | 0.13*** | 0.11 |
| | (0.038) | (0.037) | (0.080) |
| Rainfall mean × Inc. Hazard | | 0.031 | |
| | | (0.043) | |
| Temperature mean × Inc. Hazard | | | 0.0012 |
| | | | (0.0035) |
| Continent effects | *Yes* | *Yes* | *Yes* |
| Climate controls | *Yes* | *Yes* | *Yes* |
| Geography controls | | *Yes* | *Yes* |
| Topography controls | | *Yes* | *Yes* |
| Mean dep. var | 0.39 | 0.39 | 0.39 |
| Mean dep. var(agric = 0) | | | |
| $R^2$ | 0.067 | 0.086 | 0.086 |
| Observations | 1195 | 1195 | 1195 |

*Notes*: This table reports coefficients from Table 3 column (4) with interactions of the hazard with climate controls Climate controls include: a quadratic in mean temperature, the standard deviation of temperature, a quadratic in mean rainfall and the standard deviation of rainfall; only the coefficients on mean rainfall and the standard deviation of rainfal are reported. Topography controls include elevation and ruggedness; geography controls include latitude north of the equator, latitude south of the equator, longitude, the distance of a group to the coast, to a major river, and to a major lake. Spatial (HAC-consistent) standard errors are calculated using Bartlett's kernel with truncation at a distance of 1000 km. Statistical significance at certain thresholds is indicated by $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$.

Table D27: Rainmaking by Whether the Environment Allows Persuasion with Bootstrapped Standard Errors

| | *Dependent variable: Rain ritual practiced (=1)* | | | | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Hazard increasing (at p99) (=1) | 0.14*** | | 0.13*** | 0.14*** | | 0.13*** |
| | (0.034) | | (0.038) | (0.037) | | (0.038) |
| Haz rate inc. (growing season) (=1) | | | | | 0.13*** | |
| | | | | | (0.037) | |
| Haz rate inc. (non-growing season) (=1) | | | | | −0.00058 | |
| | | | | | (0.035) | |
| Dry spell duration (months, at p99) | | | | | | 0.0065 |
| | | | | | | (0.0056) |
| Rainfall mean (annual, m) | | −0.074** | −0.036 | −0.024 | −0.012 | −0.0029 |
| | | (0.035) | (0.036) | (0.038) | (0.041) | (0.043) |
| Rainfall std. dev (across years) | | −0.021 | 0.013 | −0.019 | −0.046 | −0.0065 |
| | | (0.095) | (0.095) | (0.097) | (0.098) | (0.098) |
| Continent effects | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Climate controls | | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Geography controls | | | | *Yes* | *Yes* | *Yes* |
| Topography controls | | | | *Yes* | *Yes* | *Yes* |
| Missing seasonal haz. | | | | | *Yes* | |
| Mean dep. var | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| Mean dep. var (dec. haz) | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| $R^2$ | 0.036 | 0.056 | 0.067 | 0.086 | 0.088 | 0.087 |
| Observations | 1195 | 1195 | 1195 | 1195 | 1195 | 1195 |

*Notes*: This table reports coefficients from regressions at the ethnic group level of whether a rain ritual is practiced on an indicator for that group facing an increasing hazard rate. For a description of the control variables, see the notes to Table 3. Standard errors are bootstrapped over 500 iterations in contrast to the Spatial (HAC-consistent) standard errors used in Table 3. Statistical significance at certain thresholds is indicated by $^{*}$ $p<0.10$, $^{**}$ $p<0.05$, $^{***}$ $p<0.01$.

Table D28: Rainmaking by Whether the Environment Allows Persuasion with Augmented Climate Controls

| | *Dependent variable: Rain ritual practiced (=1)* | | | | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Hazard increasing (at p99) (=1) | 0.14*** | | 0.12*** | 0.12*** | | 0.11*** |
| | (0.038) | | (0.040) | (0.039) | | (0.038) |
| Haz rate inc. (growing season) (=1) | | | | | 0.11*** | |
| | | | | | (0.036) | |
| Haz rate inc. (non-growing season) (=1) | | | | | 0.0031 | |
| | | | | | (0.035) | |
| Dry spell duration (months, at p99) | | | | | | 0.0061 |
| | | | | | | (0.0054) |
| Rainfall mean (annual, m) | | −0.020 | 0.0080 | −0.0031 | 0.0052 | 0.013 |
| | | (0.040) | (0.040) | (0.039) | (0.039) | (0.040) |
| Rainfall std. dev (across years) | | 0.025 | 0.051 | 0.022 | 0.0013 | 0.033 |
| | | (0.086) | (0.086) | (0.085) | (0.085) | (0.085) |
| Continent effects | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Climate controls | | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Seasonality controls | | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Geography controls | | | | *Yes* | *Yes* | *Yes* |
| Topography controls | | | | *Yes* | *Yes* | *Yes* |
| Missing seasonal haz. | | | | | *Yes* | |
| Mean dep. var | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| Mean dep. var (dec. haz) | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| $R^2$ | 0.036 | 0.10 | 0.11 | 0.12 | 0.12 | 0.13 |
| Observations | 1195 | 1195 | 1195 | 1195 | 1195 | 1195 |

*Notes*: This table reports coefficients from regressions at the ethnic group level of whether a rain ritual is practiced on an indicator for that group facing an increasing hazard rate. Climate controls include: a quadratic in mean temperature, the standard deviation of temperature, a quadratic in mean rainfall and the standard deviation of rainfall; only the coefficients on mean rainfall and the standard deviation of rainfal are reported. Seasonality controls include controls for subclasses of tropical, temperate, arid, cold and polar seasons. Topography controls include elevation and ruggedness; geography controls include latitude north of the equator, latitude south of the equator, longitude, the distance of a group to the coast, to a major river, and to a major lake. Spatial (HAC-consistent) standard errors are calculated using Bartlett's kernel with truncation at a distance of 1000 km. Statistical significance at certain thresholds is indicated by $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$.

Table D29: Rainmaking by Whether the Environment Allows Persuasion with Group Size Controls

| | *Dependent variable: Rain ritual practiced (=1)* | | | | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Hazard rate increasing (=1) | 0.19*** | | 0.17*** | 0.18*** | | 0.18*** |
| | (0.052) | | (0.052) | (0.052) | | (0.052) |
| Haz rate inc. (growing season) (=1) | | | | | 0.090* | |
| | | | | | (0.049) | |
| Haz rate inc. (non-growing season) (=1) | | | | | 0.0055 | |
| | | | | | (0.053) | |
| Dry spell duration (months, at p99) | | | | | | 0.0055 |
| | | | | | | (0.0057) |
| Mean size of local communities | 0.052*** | 0.040*** | 0.041*** | 0.047*** | 0.048*** | 0.047*** |
| | (0.010) | (0.010) | (0.010) | (0.0100) | (0.010) | (0.0099) |
| Rainfall mean (annual, m) | | −0.12** | −0.066 | −0.023 | −0.047 | −0.0053 |
| | | (0.059) | (0.057) | (0.059) | (0.066) | (0.063) |
| Rainfall std. dev (across years) | | −0.11 | −0.047 | −0.041 | −0.084 | −0.030 |
| | | (0.16) | (0.15) | (0.15) | (0.16) | (0.15) |
| Continent effects | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Climate controls | | *Yes* | *Yes* | *Yes* | *Yes* | *Yes* |
| Geography controls | | | | *Yes* | *Yes* | *Yes* |
| Topography controls | | | | *Yes* | *Yes* | *Yes* |
| Missing seasonal haz. | | | | | *Yes* | |
| Mean dep. var | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| Mean dep. var (dec. haz) | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| $R^2$ | 0.094 | 0.13 | 0.15 | 0.19 | 0.17 | 0.19 |
| Observations | 556 | 556 | 556 | 556 | 556 | 556 |

*Notes*: This table reports coefficients from regressions equivalent to Table 3 with group size controls. For a description of the control variables, see the notes to Table 3. Spatial (HAC-consistent) standard errors are calculated using Bartlett's kernel with truncation at a distance of 1000 km. Statistical significance at certain thresholds is indicated by $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$.