Praying for Rain[*]

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Abstract

We study rainmaking as an instrumental religious belief. We present a model in which a religious authority 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 the probability of a successful prayer is highest when people most want rain. We test this prediction in 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.

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> 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 commonly 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 criticism, evidence and falsification. How then can instrumental belief be sustained?

We study rainmaking, a canonical example of instrumental religious belief. Frazer (1890), the founding text of the study of religion in anthropology, argues that both traditional, magical belief systems and major world religions developed by offering ways to control nature. Many belief systems offer to bring rain to grow crops and 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?

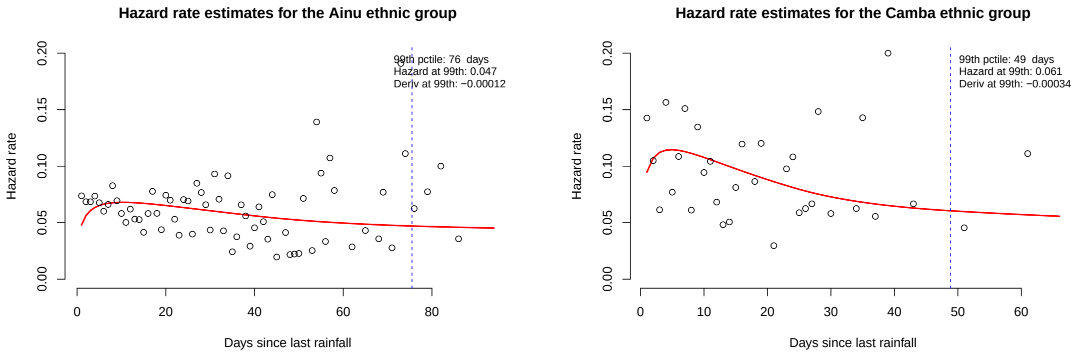
This paper provides a new theory of belief in rainmaking and an empirical analysis of rainmaking practice drawing on newly-collected data. The theory lays out how the pattern of rainfall in certain places can support belief in the control of nature. In our model, a religious authority, the church, tries to persuade an adherent, the peasant, that the church can bring rainfall. The church is free to choose when to pray but cannot in fact bring rain; nor does the church itself know when it will rain. The peasant estimates the probability of rain based on how often it rains when the church is not praying. If the church prays at the right times, such that rain is more likely to fall during prayer, it may persuade the peasant that it has caused the rain.

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

Figure 1: Rainfall Hazard Functions from Around the World

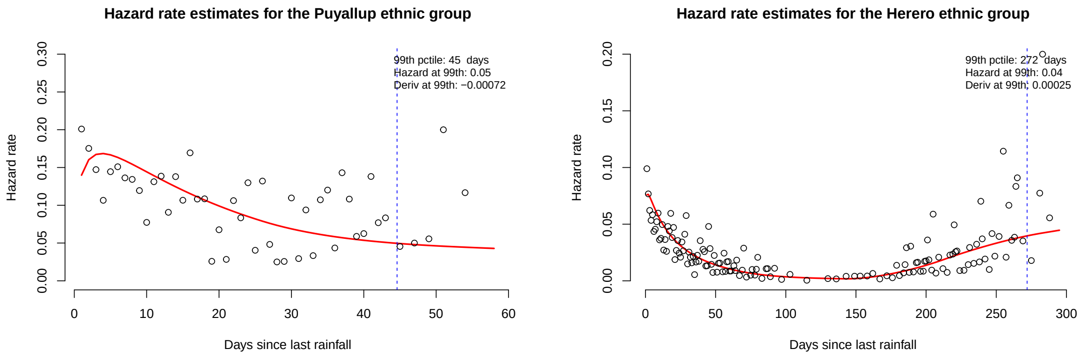
A. Ainu (Hokkaido, Japan)

B. Camba (Bolivian Amazon)



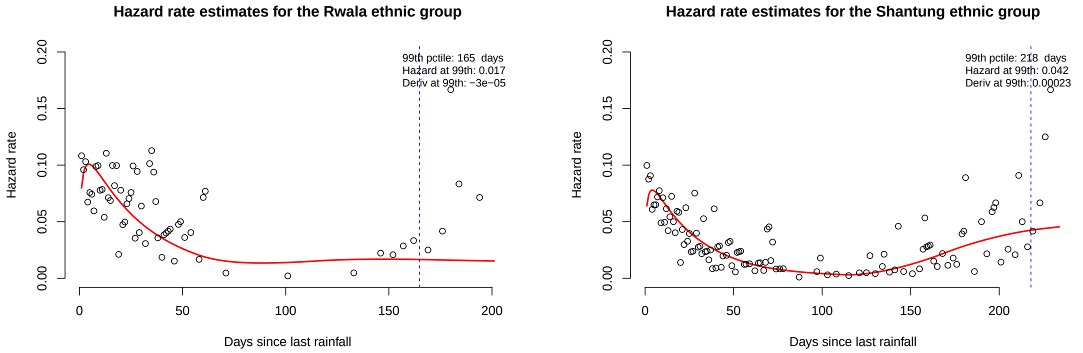
C. Puyallup (Washington, US)

D. Herero (Namibia)



E. Rwala (Syria)

F. Shantung (Shandong, China)



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 2.3. 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.

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 show that only in places with an increasing hazard rate can the church persuade the peasant. The church does so by *late praying*: waiting to start to pray until there is a drought and then praying continuously thereafter until it rains. When the hazard is increasing, the peasant forms a belief, from times without prayer, that the rainfall probability is generally low or moderate, and then witnesses a higher probability of rainfall once prayer begins. Late praying reserves prayer for 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. We therefore predict that rainmaking will be more persuasive, and thus more prevalent, when the hazard function 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, which we show has an increasing hazard rate. The church in Murcia has made *pro pluvia* rogations, prayers for rain, since at least the 14th century (Gil Guirado and Espín-Sánchez, 2022).[1] These prayers follow a pattern of escalation consistent with *late praying*; 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, 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 distributed lags for recent rainfall. We conclude from the case study of Murcia that, in an environment with an increasing hazard, a church can practice rainfall prayer in a way that predicts rainfall and will thereby tend to support instrumental belief.

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[1] 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, particularly how prayer mediated between factions within the church and the decline in prayer after the 1830s (on which see footnote 12). 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.

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 precisely his emphasis on generalizing the causes of belief from a wide body of idiosyncratic practices.

To allow such generalization, we assemble new data on the practice of rain rituals around the world. We use as the basis of our search the *Ethnographic Atlas* (Murdock, 1967), which measures the traditional economic, political and social practices for 1,290 ethnic groups.[2] We combed through an extensive anthropological literature, drawing on 370 sources covering 1,208 ethnic groups, to measure rainmaking for the groups in the *Atlas*. 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 religious practice which has played a central role in accounts of the development of religion (Frazer, 1890). We augment the *Atlas* by adding a variable that indicates whether the group practiced a ritual to make rain. We find that rainfall prayer is widespread. Rainmaking is practiced by 39% of the ethnic groups in the *Atlas* and widely observed on every settled continent (Figure 2, panel A). We view this number as a lower bound, since our coding is conservative and we only mark a group as praying for rain if we find clear evidence of the practice of a rain ritual.

The new global data on rainmaking yields two main findings in support of our model of instrumental belief. First, 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 augmented *Atlas* 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). Our results are robust to a battery of geographic and climatic controls. It is not a dry climate per se that induces prayer—lower average rainfall and longer droughts are not associated with more rainfall prayer—but specifically whether the hazard function

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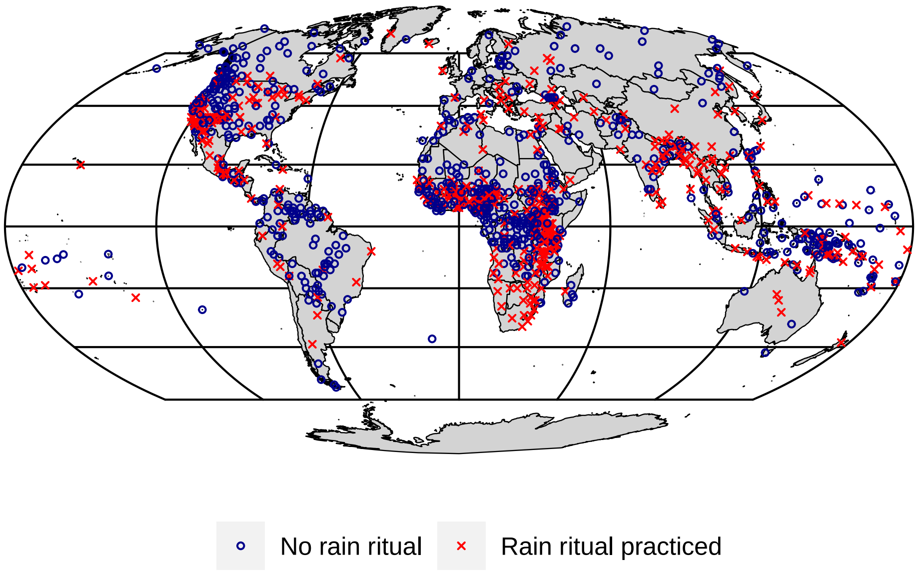
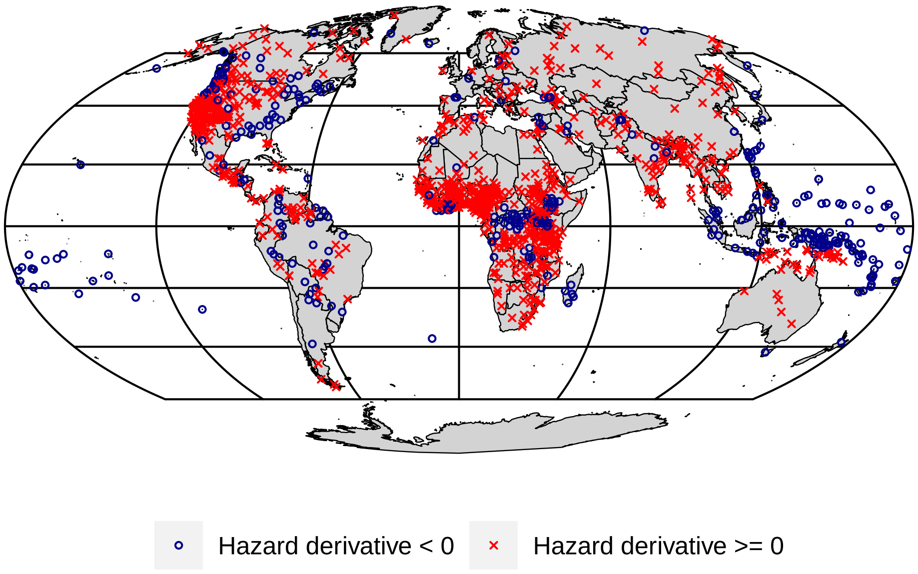
[2] The *Atlas* has been used extensively in economic history (Gennaioli and Rainer, 2007; Nunn, 2008; Alesina, Giuliano and Nunn, 2013; Fenske, 2013; Michalopoulos and Papaioannou, 2013; Alsan, 2015). We use the version of the *Atlas* extended by Giuliano and Nunn (2021) to include additional ethnic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

Figure 2: Global Prevalence of Rain Rituals

A. Rain ritual



B. Hazard rate increasing



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.

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. An extension of our model allows that 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 is dependent on the climate 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 is ineffective, 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 geographic or climatic forces on the development of economic and political institutions.[3] Our work is closest to two papers. Chaney (2013) documents that in ancient Egypt the highest religious authority became more powerful when the Nile had an abnormally extreme flood. 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. Our contribution, relative to this literature, is to show that the climate is a determinant of religious belief and to provide evidence for a specific mechanism for how certain environments support belief.

Our paper also contributes to the literature on the origins of religiosity. Religious belief has been argued to be both socially and individually adaptive.[4] People use religion as

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[3] 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; 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.

[4] 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. Rossignol, Nunn and Lowes (2022) show how individuals who kept traditional in Africa that hold traditional beliefs are treated differently by others. Bryan, Choi and Karlan (2021) study belief in a randomized experiment

a means of insurance against natural and economic shocks.[5] 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 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 above 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. The landmark reviews of 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. While we find, as in prior research, that religious practice responds to demand, we emphasize how belief also relies on persuasion. 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 that prayer is believed to work.

Finally, our findings on the persuasive nature of rainmaking bring new evidence to an important debate in anthropology. Over a century or more of study, anthropologists have differed on whether to interpret traditional religious practices, including rainmaking as a leading example, as sincere attempts to control nature or as simply performative or symbolic. An older school says that belief is instrumental: people engage in rainmaking to make rain (Frazer, 1890; Hong, Slingerland and Henrich, 2021). 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[6] We find that rainmaking is more prevalent where it is more persuasive, supporting the interpretation that

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and find that proseltizing 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.

[5] 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.

[6] The revisionists categorize human beliefs and conduct into the worldly ("profane") and the sacred. This degree of freedom allows explanations for religious behavior that do not require rationality but explain religious practice as performative or symbolic (Parsons et al., 1949; Radcliffe, 1963; Durkheim and Swain, 2008). For Wittgenstein (1967), for example, rainmaking is not sincere, but rather an emotional performance. At times, this characterization has contributed to a view that certain societies were primitive or non-rational.

belief is instrumental.

The structure of the paper departs slightly from the norm. Section 1 lays out our model of religious persuasion. Section 2 then shows that rainmaking prayers in Murcia, Spain are practiced in a way consistent with our model. Section 3 introduces our global data and describes different 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 4 then tests whether our model predicts rainmaking globally. Section 5 concludes.

1 Model

This section models when prayer for rain is likely to be persuasive. Nature determines the process of rainfall. The church, constrained by this process, then chooses when to pray in order to convince the peasant that it has caused the rain.

1.1 Set-up

We consider a game between the church and the peasant in an environment set by nature. 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 after $t \in [0,\infty)$ days have passed since it last rained (see Figure 1 for some examples). We think of the game as repeating again and again in different spells with a new start each time it rains.

We define two useful parameters of the rainfall process

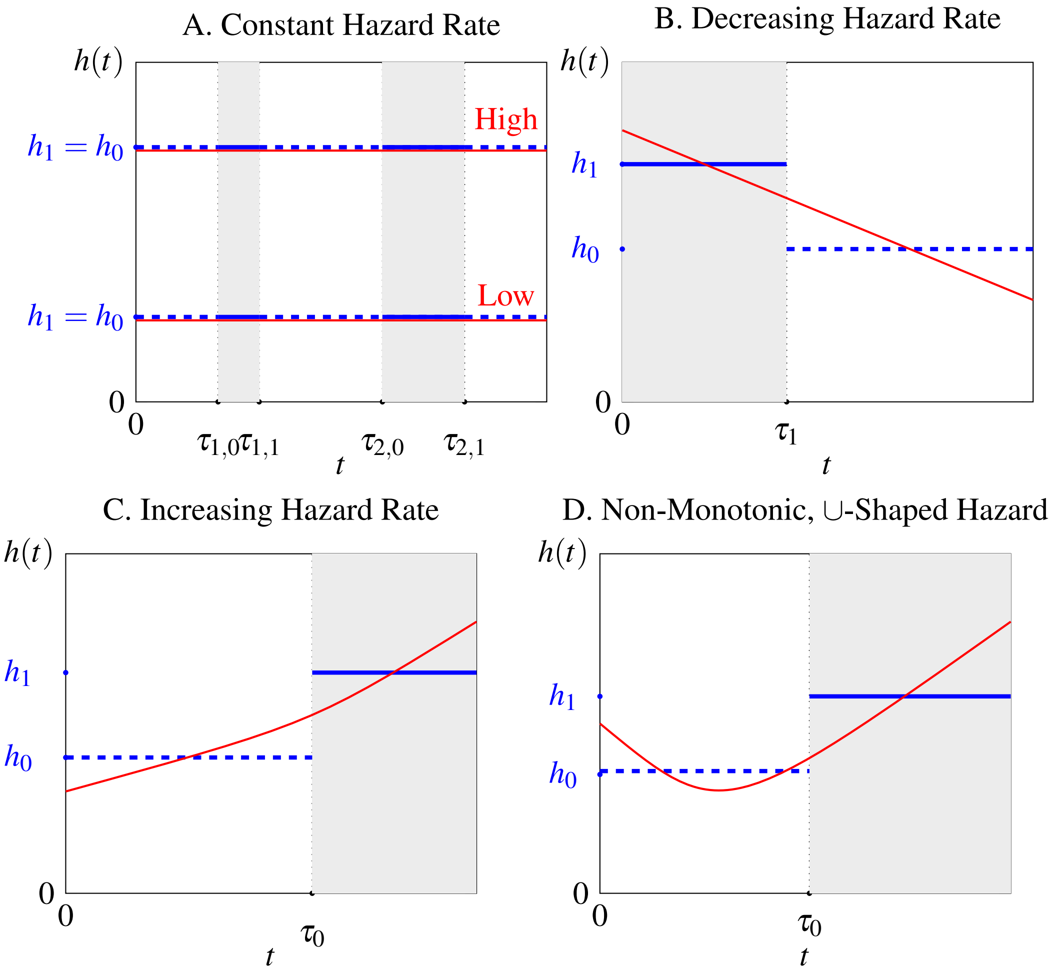
$$\eta \equiv \lim_{\tau\to\infty} \frac{1}{1-e^{-\tau}} \int_0^{\tau} h(t)e^{-t}dt \qquad\qquad \alpha \equiv h(0). \tag{1}$$

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

The strategy of the church.—The church chooses a prayer strategy T that consists of when it will pray for rain. The church can choose to pray at any time: it could always pray, it could pray on some interval, it could pray on some series of intervals. The combination of the rainfall process and the prayer strategy of the church creates an experiment.

Figure 3 illustrates how what experiments are feasible depends on the hazard function. Each panel plots the hazard of rainfall (red solid curve) against the time since the last

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



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, at either a low or a high level. We give an example where prayer happens in two disconnected intervals, the first one shorter and the second one longer. 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 decreasing. We give an example where prayer starts at $t = 0$ and continues up to $t = \tau_1$. In panel C, 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). In panel D, the hazard is first decreasing and then increasing.

rainfall. The four panels show a constant hazard (panel A), decreasing hazard (panel B), increasing hazard (panel C) and ∪-shaped hazard (panel D). In each panel, the periods during prayer, for some illustrative choices of prayer timing, are shaded in grey. The blue solid horizontal line indicates h_1, the hazard of rainfall during prayer, induced by the prayer policy. The blue dashed horizontal line illustrates h_0, the hazard of rainfall without prayer.

The church's strategy T could be complicated. We restrict the environment in order for the optimal strategy to take a simpler form. Specifically, we consider only hazard functions $h(t)$ that are monotonic: increasing, decreasing or constant. We view this restriction as innocuous since what matters for belief is whether the church is able to elicit rain during a drought—after a long dry spell. We will therefore, empirically, classify hazard functions based on their slope after a long period without rain, when all hazard functions will fall into one of these groups. Hence the ∪-shaped hazard of panel D is classified as increasing because it is increasing monotonically during a drought.

For this class of hazard functions, the optimal prayer strategy must take the form of a tuple $T = (\tau_0, \tau_1)$, with $\tau_0 \leq \tau_1$, where prayer begins at τ_0 and stops at $\tau_1 \in [\tau_0, \infty)$ (see Appendix A for an explanation why). The church's choice of when to pray defines the conditional hazard rates

$$h_0(\tau_0, \tau_1) \equiv \frac{1}{1 - e^{-\tau_0}} \int_{T_0} h(t) e^{-t} dt \tag{2}$$

$$h_1(\tau_0, \tau_1) \equiv \frac{1}{e^{-\tau_0} - e^{-\tau_1}} \int_{T_1} h(t) e^{-t} dt, \tag{3}$$

where $T_0 = [0, \tau_0] \cup [\tau_1, \infty)$ denotes the measures of time where the church is not praying and $T_1 = [\tau_0, \tau_1]$ the measure when it is praying. Here (2) is the average hazard rate while the church does not pray and (3) is the average hazard rate when the church prays.

Peasant actions and beliefs.—The peasant chooses a binary action $a \in A = \{a_0, a_1\}$ when it rains at the end of each spell. Action a_0 is *not to support* the church and a_1 is to *support* the church. Support for the church may mean offering a donation, giving a religious name to a child or backing a political leader. The peasant will choose to support the church when the peasant believes it is more likely than not that God listens, that is, exists and intervenes in the world.

The peasant, at the start of every spell, has a prior belief $p < 0.5$ that God is listening.[7] Because the game has been played for a long time, the peasant knows the conditional hazard rates with prayer (3) and without prayer (2). The peasant believes that, if God does not listen, the hazard rate always equals the hazard rate $h_0(\tau_0, \tau_1)$ that the peasant observes when the church is not praying. We therefore assume that the peasant, somewhat naïvely, extrapolates the hazard *function* from the mean hazard that the peasant observes without prayer. We extend the model in Appendix A to show that this assumption is not necessary in order for the church's prayer strategy to persuade the peasant.

If God listens *and* the church prays, the peasant believes the hazard rate to be ω. This

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[7] If $p > 0.5$, the peasant will always support the church, even if the church never prays.

scalar is a fundamental parameter of the model and does not depend on the church's strategy. We maintain throughout one assumption about the parameters of the model.

Assumption 1 (Meaningful belief)**.** $\Delta \equiv \omega - \eta > 0$.

The scalar Δ measures the strength of belief, specifically, the increase in hazard rate that the peasant expects to see if God listens. Assumption 1 (A1) means that belief has some meaning: the peasant believes that if God listens praying will increase the chance of rain, beyond the unconditional hazard rate η.

1.2 Analysis

Beliefs and the peasant's problem.—The prayer strategy may induce changes in the peasant's beliefs. The church's prayer creates two possible signals in a given spell. If the church was not praying when it rained signal s_0 is realized. Given a strategy (τ_0, τ_1), this happens with probability $\mathbb{P}[s_0|\tau_0, \tau_1] = F(\tau_0) + (1 - F(\tau_1))$. If the church was praying when it rained then signal s_1 is realized. This happens with the complementary probability $\mathbb{P}[s_1|\tau_0, \tau_1] = F(\tau_1) - F(\tau_0)$.

The peasant believes that God may or may not listen in a given spell. The peasant estimates the mean hazard of rainfall if God does not listen as $h_0(\tau_0, \tau_1)$. The peasant expects the hazard of rain during prayer to be

$$\hat{h}(\tau_0, \tau_1) \equiv p\omega + (1-p)h_0(\tau_0, \tau_1), \tag{4}$$

where the parameters p and ω measure the probability God listens and the strength of belief. The peasant believes that God listened when signal s_1 is realized and

$$h_1(\tau_0, \tau_1) \geq \hat{h}(\tau_0, \tau_1). \tag{5}$$

We assume that the peasant supports the church with action a_1 in this case. The threshold (5) means that the *observed* hazard of rainfall during prayer is as great as the peasant *expects* to see, given a prior p and belief ω. A higher probability that God listens p or a stronger belief ω make this threshold more difficult to meet.

The strategy of the church.—The church wants to pray so as to induce the peasant to support it as often as possible. The objective of the church can be written as

$$\max_{\tau_0, \tau_1} \mathbb{P}[s_1|\tau_0, \tau_1] \qquad \text{such that} \qquad h_1(\tau_0, \tau_1) \geq \hat{h}(\tau_0, \tau_1). \tag{6}$$

The church wants to maximize the realizations of the signal s_1 subject to the constraint that a realization of s_1 must be convincing enough for the peasant to support the church.

The constrant (5), intuitively, means that the prayer policy must create a large enough gap between the hazard rates with and without prayer to sustain belief.

The value of the objective and whether the peasant is induced to believe depend on the shape of the underlying hazard function. We describe this dependence formally in Appendix A and present the main arguments and intuition here. Consider first the constant hazard case in Figure 3, panel A. In the panel we draw two possible hazard rates, constant at either a high or a low level. The church may pray on a single interval (τ_0, τ_1) or multiple intervals, as illustrated in the panel. For any prayer timing, it will be impossible to induce a hazard h_1 during prayer (solid blue line) that is greater than (indeed, different from) the baseline hazard h_0 without prayer (dashed blue line).

Proposition 1 (Constant hazard rate)**.** *When the hazard rate is constant,* $p < 0.5$ *and A1 holds, the peasant can never be convinced to support the church.*

Proof. A constant hazard rate $h(t) = \alpha$ implies $h_0(\tau_0, \tau_1) = h_1(\tau_{0,} \tau_1) = \eta = \alpha$. The hazard of rainfall is the same whether the church is praying or not. Substituting into equation (5) using (4) yields $\eta \geq p(\eta + \Delta) + (1 - p)\eta$ which implies $\Delta \leq 0$, contradicting A1. $\square$

In a location with high rainfall it will rain a lot when the church prays, but also when the Church 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 when the hazard rate is constant prayer will not be persuasive, regardless of the average level of rainfall (higher or lower constant hazard rate, in panel A). The peasant needs to see an increase in the hazard rate during prayer to validate meaningful belief.

Now consider the decreasing hazard case in panel B. In this case the church can persuade the peasant that it has caused the rain by *Early praying*, starting just after it has rained and then stopping, to induce a higher hazard rate h_1 during prayer (solid blue line) than without h_0 (dashed blue line). However, the church will only convince the peasant it has caused the rain when rain is not needed. Our model omits this dimension of when a rainfall realization is valuable to the peasant. We therefore assert that the decreasing hazard, as with a constant hazard, does not allow persuasion, on the basis that realizations soon after rainfall are not valuable. Appendix A.5, discussed below, considers an extension where the peasant has tangible costs and benefits of support that are constant over time.

Figure 3, panels C and D illustrates cases where the hazard is increasing after a long dry spell. In panel C, the hazard rate is increasing monotonically. In panel D, the hazard rate is non-monotonic, but is eventually increasing after a long enough drought. In both of these cases, the church can induce a higher hazard during prayer by *Late praying*, starting to pray at some time τ_0^* and continuing thereafter. This higher hazard rate may be sufficient to persuade the peasant to support the church, depending on the strength of the peasant's beliefs. Our next results characterize when *Late praying* is optimal, for what range of beliefs the peasant will support in this case, and when the church optimally starts praying.

The optimal prayer policy for an increasing hazard.—We now characterize the optimal strategy of the church in the increasing hazard case. We maintain A1 as before. Appendix A.1 defines a hierarchy of weak, moderate and infeasibly strong beliefs based on the relative values of the parameters Δ, η and α. Our main result then characterizes how the strength of belief affects optimal prayer.

Proposition 2 (Optimal strategy for increasing hazard rate)**.** *If A1 holds and $h(t)$ is strictly increasing, then the optimal policy for the church is* late praying *with $T^* \equiv (\tau_0^*, \infty)$. The choice of τ_0^* is determined by the strength of belief Δ as follows:*

i ***Weak belief*** Δ***.*** *If A2 does not hold, then $\tau_0^* = 0$ and the church always prays.*

ii ***Moderate belief*** Δ***.*** *If A2 and A3 hold, then $\tau_0^* > 0$ and the church prays late.*

iii ***Infeasible belief*** Δ***.*** *If A2 holds but A3 does not, then no choice of τ_0 can convince the peasant. The church is indifferent between all strategies T.*

The proof is in Appendix A. An increasing hazard rate allows persuasive prayer, unless belief is infeasibly strong. The church's optimal strategy is *Late praying* as shown in Figure 3, panel C. The timing for this late prayer to start depends on the strength of the peasant's belief. If the peasant has a weak belief, the church prays all the time, since it is trivial to convince the peasant. If the peasant has a moderate belief, the optimal strategy is for the church not to pray at first, but then to start praying and keep going until it rains.

The church faces an interesting trade-off in deciding *when* to start praying (see Appendix A for the solution for the optimal τ_0^*). If the church starts to pray too early, at a point $\tau_0 < \tau_0^*$, then the peasant will not be convinced enough to support, even when it does rain during prayer, because $h_1(\tau_0, \infty)$ is not sufficiently greater than $h_0(\tau_0, \infty)$. The peasant, seeing that the probability of rain during prayer was not especially high, would attribute rain that did fall during prayer to luck. If the church starts to pray too late, $\tau_0 > \tau_0^*$, then the probability of rain when the church prays will be far higher than when it does not. It will surely convince the peasant when rain does fall during prayer. However, the church is in a sense over-convincing the peasant; if it had begun praying a bit earlier, the peasant would still support when it rained during prayer, and yet it would rain during prayer more often. The optimal policy at τ_0^* balances the credibility of the church—the need to persuade—against how often the peasant can be persuaded. The choice of when to start praying therefore responds to the strength of belief.[8]

Extension with costs and benefits of rain ritual.—The model to this point has assumed, for simplicity, that peasants will support the church if prayers are convincing enough, without accounting for any tangible costs or benefits of support. There is an implicit assumption that the expected benefit that the peasant receives from the extra rain is much greater than the cost of supporting the church. Appendix A.5 relaxes this assumption by allowing that the peasant could have tangible costs and benefits of support.

We find, in this case, that the peasant will support the church if they are sufficiently persuaded *and* the benefits of support are high enough relative to the costs. The costs of support act as an additional constraint in the model which raises the threshold of belief at which the peasant will support the church. Empirically we will measure the benefits of support with the dependence of the peasant on agriculture for subsistence. A peasant highly dependent on agriculture for subsistence will have a high benefit of rainfall and therefore support when they are persuaded, whereas a peasant not so dependent on rainfall may not support, when support is costly, even if they are convinced that the church caused the rain. The model therefore predicts that rainmaking is more likely for ethnic groups more dependent on agriculture.

Extension to more sophisticated peasants.—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 peasant 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 the peasant believes the hazard rate to be constant and the church can persuade the peasant if the hazard rate is increasing. In Appendix A.7, we show how this can be generalized, to a case where the peasant thinks the hazard rate is increasing and linear and the church can persuade if the hazard rate is increasing and convex. The logic is the same: the peasant under-predicts the out-of-sample probability of rain without prayer and attributes the gap to divine intervention. Under the optimal strategy of *Late praying*, such beliefs may be durable. The church always prays after τ_0^*, so the peasant never sees rainfall realizations without prayer that might contradict their beliefs.

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[8] Appendix Figure A1 plots the optimal time to start praying as a function of the strength of belief Δ for linear and quadratic hazard functional forms. The church waits longer to pray, in order to create greater separation between the hazard rates with and without prayer, when Δ is high and so it needs to convince the peasant that God is more powerful.

Discussion.—The model provides four empirical predictions. First, the level of rainfall does not determine whether prayer is persuasive. Second, when the hazard rate is increasing the optimal policy is to start praying and never stop. Third, societies facing a persuasive natural experiment, with an increasing hazard rate, are more likely to pray for rain. Fourth, societies with a high benefit of rainfall are more likely to practice rain rituals.

We put forward one model of persuasion but acknowledge that it does not exclude other, closely related alternatives. In particular, in our model we presume the church is acting strategically to optimally time prayer. A line of prior research has argued that the Catholic church does indeed act strategically to raise participation and belief (Parigi, 2012; Leeson, 2013; Barro and McCleary, 2016; Leeson and Russ, 2018), though other religious authorities may not. However, the environment could shape religious practice through a similar mechanism without strategic behavior, if religious practice were selected through an process of cultural evolution (Chudek, Muthukrishna and Henrich, 2015; Galor and Özak, 2016; Giuliano and Nunn, 2021). Under this view, praying for rain would not gather support in an environment with a flat hazard rate, but would be more likely to survive in an area with an increasing hazard, for example if an authority initially prayed after a long drought and persisted when prayers were successful.

2 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 is an ideal test case because we have over 200 years of daily church records from Murcia on prayers for rain. We show that the church prays such that its prayers are highly predictive of subsequent rainfall.

2.1 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 (Gil Guirado and Espín-Sánchez, 2022). The rogations form a series of prayers to induce rainfall. The more severe a drought, the greater the number and intensity of prayers (Gil Guirado, 2013).[9] Governance in Murcia historically has been divided between the

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[9] 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,

Catholic church, led by an ecclesiastical council, and a secular municipal council. 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 council 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 specifically to use supernatural events to persuade[10] and was sometimes blunt in the quid pro quo that it offered for its intervention.[11] 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.

2.2 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

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either through the collection of alms or from the municipal or ecclesiastical councils.

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

[11] 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).

collect taxes and thereby its funding and influence. This diminution of power was driven by reasons apart from the efficacy of rainmaking.[12] The rogation cycle changed at this time and prayers grow more infrequent afterwards (Gil Guirado and Espín-Sánchez, 2022).[13]

Sources.—The data from the ecclesiastical councils contain the timing of prayers and characteristics of the prayers offered. We observe the day a prayer was requested by the ecclesiastical council or municipal council and the day the prayer was made. We observe the purpose of the prayer: *pro pluvia* rogations to ask for rain, prayers of Thanksgiving after rain, and *pro serinate* 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 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 mentioned 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, removing concerns about biased reporting of when rain occurred. 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 Murcia 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 4 illustrates the basic features of the data on prayer and rain 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 rainfall and prayer. The

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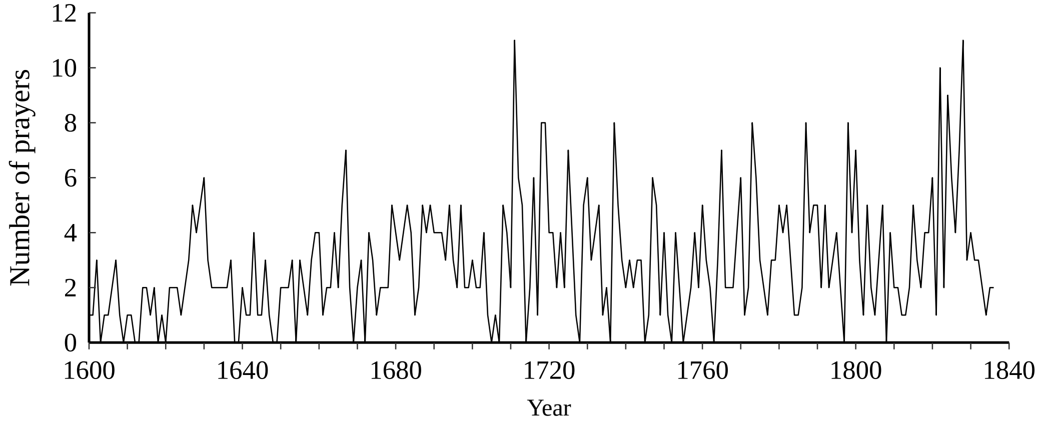
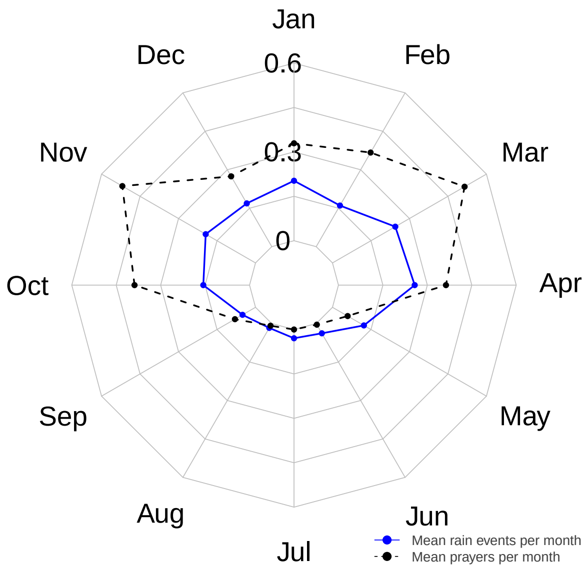
[12] The *ancien régime* of Catholic church power in Spain was abolished in the 1830s when the Spanish crown expropriated church property (the Ecclesiastical Confiscation of Mendizábal, 1835) and banned church taxation (the abolition of the tithes, 1837).

[13] 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."

Figure 4: Prayer and Rainfall in Murcia, Spain



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



B. Seasonality of rainfall and rainmaking prayers

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 church council (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.

distance from the axis on the spider chart indicates the mean number of rainfall or prayer events in a given month of the year over our sample period.

There are two points of interest in the raw data of Figure 4. First, in panel A, while the strategy 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 strategy can result in different prayer outcomes depending on the realizations of rainfall in a given year. If it rains early and often, there is no cause for prayer. Second, in panel B, the seasonality of prayers closely mimics or slightly leads the seasonality of rain events. The peak months for rainfall prayer are October and November, in which there are prayers roughly every other year (0.5 events per year), with another increase in March. The peak months for rainfall are in October through January, with another increase in March. The seasonality of 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.

2.3 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 induce belief through the strategic delay of prayer, since the hazard of rainfall will continually 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 $t = 3$.[14] The hazard function is $h(t)$ 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.4 details the specification and estimation likelihood. The hazard estimation is done separately for multiple weather stations in Murcia and, in Section 3 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 Appendix Figure 5. The four panels plot hazard estimates using rainfall data from the city of Murcia and three surrounding towns

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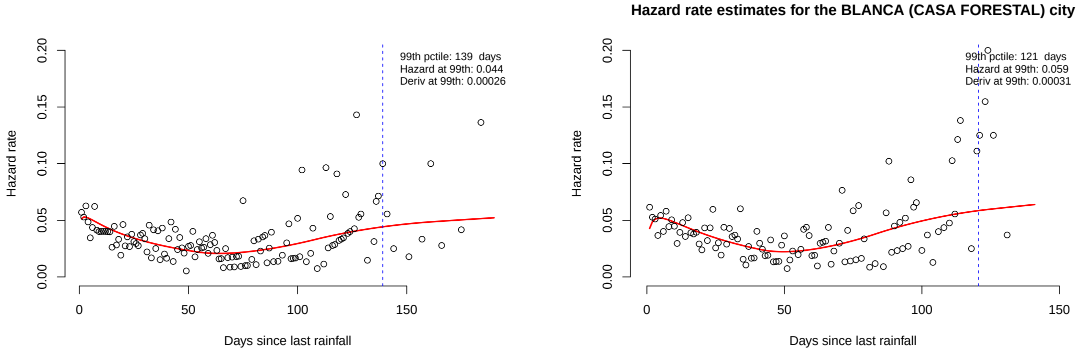
[14] To fit a hazard model it is necessary to define how much rainfall constitutes a failure. A light rain is not sufficient to end a drought. We define a failure event as equal to one if daily rainfall exceeds 0.5 centimeters.

Figure 5: The Hazard of Rainfall in and around Murcia, Spain

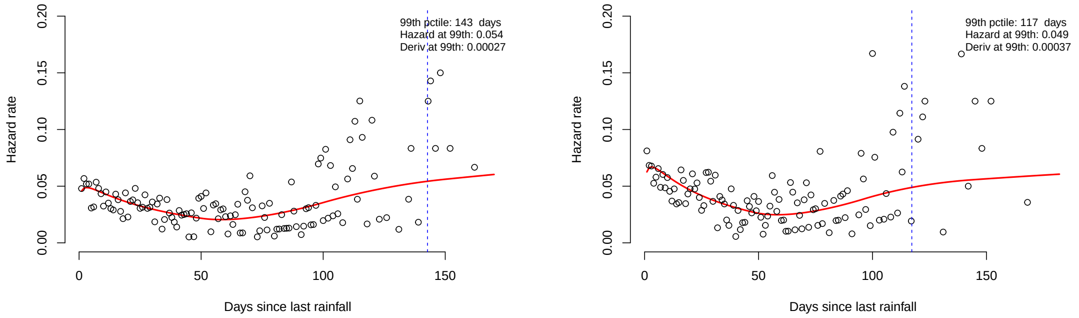
A. Murcia

B. Blanca



C. Mula

D. Alhama



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.4. 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.

in the same region, each about 15 miles distant. The hollow circles show non-parametric Nelson-Aalen estimates of the hazard rate (Aalen, 1978).[15] The fitted red curve gives our preferred cubic spline fit to the hazard rate by maximum likelihood.

The main result from Appendix Figure 5 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

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

is roughly double the hazard rate two months after rainfall. We therefore find clear evidence that the hazard function of rainfall in Murcia presents the church with the opportunity to conduct a persuasive experiment. The flexible shape of the hazard function we specify turns out to be essential to fit the data. The hazard function is non-monotonic, whereas the most common parametric hazard forms, such as the Weibull distribution of failure times, impose that the hazard must be monotonic.

2.4 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 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

$$Rainfall_t = \beta_1 PrayerLastMonth_t + \sum_{\tau=1}^{T_\tau} \beta_\tau PrayerLagMonth_{t-\tau} + \delta_m + \varepsilon_t \tag{7}$$

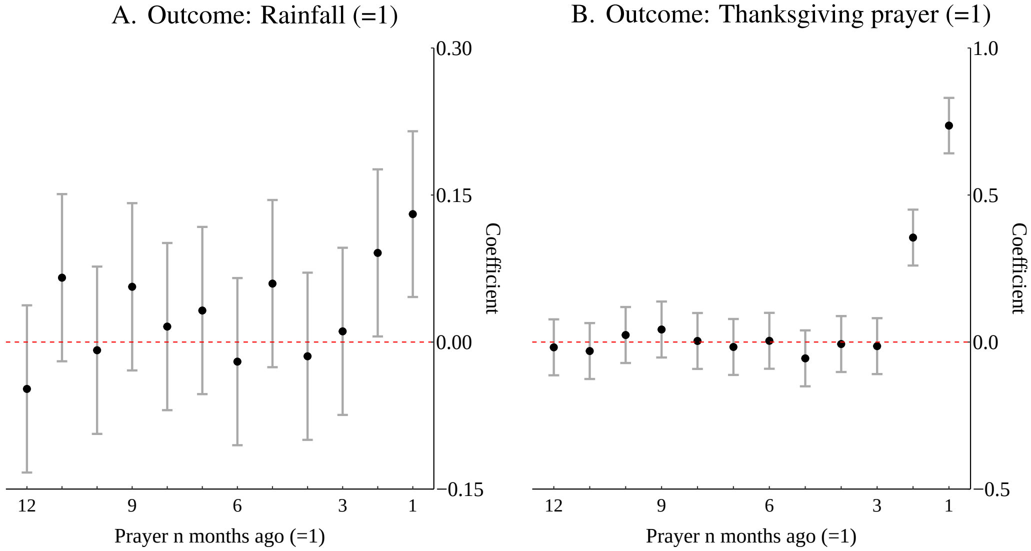
where $PrayerLastMonth_t$ equals 1 if there was any rainmaking prayer in the period $(t-30, t-1)$, $PrayerLagMonth_{t-\tau}$ has the same definition, lagged by τ months, and δ_m are month-of-year fixed effects. The regression is at the daily level with data from 1600 to 1837. We estimate Newey-West autocorrelation consistent standard errors using a lag parameter of 30 days.

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

	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 * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Figure 6: Coefficients from Regressions of Rainfall on Recent Prayers



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

Table 1 shows the results. 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 0.145% (standard error 0.057%) higher probability of rainfall on a given day, relative to a mean daily rainfall probability of 0.203%. Hence the predicted probability of rainfall is 71% higher if there has been a prayer in the last month.

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% (standard error 0.073%) higher probability of a thanksgiving prayer on a given day, relative to a mean daily thanksgiving prayer probability of 0.257%. 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.

Figure 6 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 $\textit{Prayer of thanksgiving}_t$ (panel B) as the dependent variables. The figure shows that prayer last month is most strongly associated with rainfall but that prayer between one and two months ago also predicts future rainfall, for either rainfall 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.

We conduct further tests in Appendix C to demonstrate that prayer Granger-causes rain. 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 C. 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. These tests establish that recent prayer has predictive power for rainfall above and beyond recent rainfall.

Discussion.—The practice of rainmaking prayers in Murcia, Spain is found to be consistent with our model in several respects. The timing of prayer over the seasons corresponds with the timing of rainfall (Figure 4), but this is not mechanical, as the church does not pray at the same time or the same amount every year. The hazard function of rainfall is increasing after a long dry spell in Murcia (Figure 5). This provides an opportunity for the church to create a persuasive prayer strategy. Documentary evidence suggests that the prayer strategy by the church approximates *Late praying*, in that the church begins to pray after a dry spell and does not stop until rain is realized. The timing of prayers actually chosen by the church are found to be highly predictive of rainfall over a period of more than two centuries (Table 1, Figure 6).

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.

3 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 3.1 gives examples of rainmaking and draws out several commonalities we observe in the diverse practices of different ethnic groups. Section 3.2 describes our data collection for whether a group practices rainmaking. Section 3.3 applies our rainfall hazard estimation to ethnic groups worldwide.

3.1 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.[16] 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 accounts 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.[17] Any small deviation in the ceremony will render it ineffective and possibly dangerous. For example, the chant has no power if translated into English.

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[16] 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.

[17] 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!"

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[18], a bonfire, a special meal for the poor and a mock battle. On the last: when it has not rained 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 (2021) 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, suc-

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[18] 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.

cessfully. 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, 2021; Gil Guirado and Espín-Sánchez, 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 (2021)).

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, 2021). 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, 2021). 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 ancient Egypt discussed in Chaney, 2013).

Our model can explain all four of these 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: the initiation of rainmaking should be reserved for a severe drought, after time has passed without rain, to increase the chance of success. Escalation: rainmaking should allow for escalation or continuation in order to follow the church's optimal policy of *Late praying* in an environment with an increasing hazard. Demand: when rainmaking has tangible costs and benefits, it will be more prevalent in areas where the benefits of rainfall are high.

3.2 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.—The basic data set for our analysis is the *Ethnographic Atlas* (Murdock, 1967). It records political, social and economic practices for 1,267 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 $Rain\,ritual_i$ equal to one if any record was found that a given group i practiced a ritual to make rain. 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.

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. 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 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 5). 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.

Figure 2, panel A maps the prevalence of rainmaking around the world. Rainmaking is practiced on every settled continent. We note several suggestive 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.

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)	1290	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 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. rainy season (=1)	1274	0.409	0.492	0.0	0.00	1.00
Haz rate inc. dry season (=1)	1089	0.611	0.488	0.0	1.00	1.00

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.

3.3 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 2.3.

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 5). 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. We will test the hypothesis that increasing hazard functions predict rainmaking below.

4 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.

4.1 Regression specification

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

$$RainRitual_i = \beta_1 HazardIncreasing_i + \beta_2 AgricIntensity_i + \mathbf{X}_i'\alpha + \delta_c + \varepsilon_i. \tag{8}$$

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. 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 only observe the timing of prayer in the case of Murcia. The variable $AgricIntensity_i$ measures the agricultural intensity of a group. We use both continuous and categorical measures of intensity. All specifications include continent fixed effects δ_c and exogenous geographic controls $\mathbf{X}_i$.

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 in mean temperature, the standard deviation of temperature, a quadratic 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 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 (Kelly, 2020). 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 ε_i and discuss the robustness of our inference to alternate choices of the spatial bandwidth and to clustering along with the estimates.

4.2 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 (8) 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 D4 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 1,291 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 esti-

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. dry season (=1)					0.17^{***}	
					(0.039)	
Haz rate inc. rainy season (=1)					0.084^{**}	
					(0.039)	
Dry spell duration (months)						0.0065
						(0.0050)
Rainfall mean (annual, m)		-0.074^{**}	-0.036	-0.024	0.055	-0.0029
		(0.038)	(0.039)	(0.039)	(0.042)	(0.041)
Rainfall std. dev (annual)		-0.021	0.013	-0.019	0.0016	-0.0065
		(0.089)	(0.086)	(0.086)	(0.086)	(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	0.001	0.010
Climate controls		0.000	0.000	0.000	0.000	0.000
Geography controls				0.008	0.010	0.007
Topography controls				0.080	0.136	0.091
p-value for a test of the equality of:						
Seasonal hazards					0.13	
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	0.098	0.087
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. 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 * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

mated to increase the probability of rainmaking by 0.14 (standard error 0.038) (column 1), 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 column 5, we separate the measure of increasing hazard by the season in which a dry spell began. We classify the dry season as the contiguous six months of the year with the lowest mean rainfall (see Appendix Figure D2 for examples of seasonal hazard functions). 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. 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). An increasing hazard rate during the dry season appears more strongly predictive of rainfall prayer. Our model does not sharply distinguish between these cases because it may well be that rainfall demand is high enough, and so prayer worthwhile, even in the relatively wet season.

An alternative, less specific theory of rainmaking is that rainmaking is 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 3.1 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 ancient 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 (8) 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 effect 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 (col-

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

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 * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

umn 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 ancient 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 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 (2021) 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 intensive agriculture causes groups to practice rainmaking because it increases the demand for rainfall and that an increasing hazard causes groups to practice rainmaking because it creates an environment that allows persuasion. 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 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.3, Table D5 we control for additional moments of rainfall including statistics on 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.

We test in Appendix D.4 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 Figure 3, panel C, a $\cup$-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.4 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 D4 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 D3) and many groups have $\cup$-shaped hazards that are still decreasing after short dry spells.

We therefore conclude, with the additional evidence from Appendix Tables D.3 and D.4, 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 a finding that an increasing hazard predicts belief generally would not falsify our model.

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 D8 and D9 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 D10). 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 D11). 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.

5 Conclusion

We study the determinants of religious belief using a theoretical model and empirical evidence from a case study of Murcia, Spain and a global cross-section of ethnic groups. In the model, people believe in rainmaking if the church can credibly intervene in nature. Whether such intervention is credible, in turn, depends on the pattern of rainfall. The church is able to persuade the people in an environment with an increasing hazard rate. With an increasing hazard, the church waits to pray until a drought and then prays continuously, which both raises the probability of rain during prayer and delivers rain when the demand for rain is at its highest. When prayer has tangible benefits and costs, rainmaking will be more likely in areas where rainfall has high benefits, such as through a dependence on settled agriculture.

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. While the evidence aligns with our model, it would also admit a similar model founded in cultural evolution: rainmaking practices endure where they are found to be successful, which would select exactly 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.

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 Definitions for the strength of beliefs

This part defines parameter values that mark the strength of beliefs.

Assumption 2 (Moderate belief)**.** $\Delta > \frac{(1-p)}{p}(\eta - \alpha) > 0$.

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

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

Assumption 3 (A3) requires Δ 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 Δ by requiring peasant beliefs on the hazard during prayer to be generated from the hazard function or consistent with past experience. It is possible that the peasant belief Δ is so large that convincing the peasant 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.2 Characterization of optimal strategy for increasing hazard

Consider the case when the hazard rate is increasing (Figure 3, panel C). In this case the church's prayer can induce a variety of different experiments and therefore beliefs. Here we describe several distinct prayer policies and the conditional probabilities they induce.

- *Early praying* ($\tau_0 = 0$ and $\tau_1 < \infty$). If the hazard rate is increasing, this strategy induces hazard rates $h_0(\tau_0, \tau_1) > \eta > h_1(\tau_0, \tau_1)$. This means that the hazard rate would be lower when praying than when not praying. Under A1 the peasant will not support the church.

- *Intermediate praying* ($0 < \tau_0 < \tau_1 < \infty$). This strategy could induce a higher hazard when praying than when not, for example $h_1(\tau_0, \tau_1) > \eta > h_0(\tau_0, \tau_1)$, depending on the choices of (τ_0, τ_1), but it does not necessarily. If the church stops praying in finite time ($\tau_1 < \infty$), this means that for $t > \tau_1$ the hazard rate is high, greater than $h_1(\tau_0, \tau_1)$, for a period when the church is done praying. This could create $h_0(\tau_0, \tau_1) > \eta > h_1(\tau_0, \tau_1)$.

- *Late praying* ($0 < \tau_0 < \tau_1 = \infty$). This strategy will surely induce a higher hazard when praying than when not, $h_1(\tau_0, \tau_1) > \eta > h_0(\tau_0, \tau_1)$, as in Figure 3, panel C.

The distinction between intermediate and late praying is only whether to stop in finite time, or to continue praying forever until it rains. The church can achieve the highest value of (6) by *late praying*: starting to pray and never stopping. Suppose that the church stops at a finite time τ_1 that satisfies (5), so the peasant does support when it rains during prayer. We can then pick any $\tau_1' > \tau_1$ to achieve a higher value of (6). For a higher $\tau_1' > \tau_1$, the constraint (5) will still be satisfied, as $h_1(\tau_0, \tau_1)$ is increasing and $h_0(\tau_0, \tau_1)$ decreasing in τ_1. Moreover, the probability of s_1 being realized will increase because the time spent praying will be longer. By the same reasoning, when the hazard rate is increasing, the praying policy T will always consist of a single interval of prayer and a single interval of non-prayer. Therefore, in this case, the optimal policy can be represented by a tuple $T = (\tau_0, \tau_1)$.

A.3 Proofs omitted from the main text

Proof of Proposition 2. As argued in the main text, the optimal prayer policy for the church when the hazard is increasing involves late praying ($\tau_0 < \infty, \tau_1 = \infty$). The probability $\mathbb{P}[s_1|\tau_0, \tau_1] = F(\tau_1) - F(\tau_0)$ is decreasing in τ_0 implying that τ_0^* must induce (5) to bind, else the church could further decrease τ_0 to raise $\mathbb{P}[s_1|\tau_0, \tau_1]$. We consider the three cases in turn.

i. **Weak belief Δ.** The church would like $P[s_1|\tau_0, \tau_1]$ to be as high as possible and therefore to pray as long as possible. Suppose the church prays all the time $\tau_0 = 0$ so that the peasant believes $h_0(0, \infty) = \alpha$ in the absence of prayer and $h_1(0, \infty) = \eta$. Then (5) can be satisfied if $\eta \leq p(\eta + \Delta) + (1-p)\alpha$ or $\Delta \leq (1-p)/p(\eta - \alpha)$, precisely the negation of A2. In this case, then, $\tau_0^* = 0$, because this maximizes the probability of rain during prayer, i.e., $P[s_1|\tau_0, \tau_1] = 1$.

ii. **Moderate belief Δ.** 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, which under late praying defines τ_0^* as the solution to

$$d(\tau_0^*) \equiv h_1(\tau_0^*, \infty) - (1-p)h_0(\tau_0^*, \infty) - p(\eta + \Delta) = 0. \tag{9}$$

If A3 holds, a solution to this equation exists. By A2 we have $d(0) < 0$. A3 implies that there exists some τ^M, the maximand of $d(t)$, such that $d(\tau^M) > 0$. Therefore by continuity of $d(t)$ there exists at least one value of τ_0^* with $0 < \tau_0^* < \tau_0^M$ such that $d(\tau_0^*) = 0$. If there exist multiple τ_0^* such that $d(\tau_0^*) = 0$ then the lowest one is the optimal τ_0^* since this maximizes the probability of rain during prayer.

iii. **Infeasible belief Δ.** In this case $d(\tau^M) < 0 \Rightarrow d(\tau_0) < 0$ for all τ_0. There is therefore no choice of τ_0 that will satisfy (5). The church cannot convince the peasant and is indifferent between all prayer strategies.

This covers all possible values of the Δ parameter for belief. □

A.4 Choice of when to start praying

When to start praying for a general hazard function.—In the case of moderate belief there is an interior solution for the optimal value of τ_0^*, when to start praying. The following corollary characterizes that optimal value.

Corollary 1 (When to start praying)**.** *In the increasing hazard case under A2 and A3, τ_0^* is determined by*

$$\frac{1}{1-e^{-\tau_0^*}} \int_0^{\tau_0^*} h(t)e^{-t}dt = \eta - \frac{p\Delta}{e^{\tau_0^*} - p}. \tag{10}$$

Proof of corollary 1. By the definition ofs η, h_0 and h_1, we have

$$\eta = (1-e^{-\tau_0^*})h_0(\tau_0^*, \infty) + e^{-\tau_0^*}h_1(\tau_0^*, \infty) \tag{11}$$

We solve for h_1

$$h_1(\tau_0^*, \infty) = \frac{\eta - (1-e^{-\tau_0^*})h_0(\tau_0^*, \infty)}{e^{-\tau_0^*}}$$

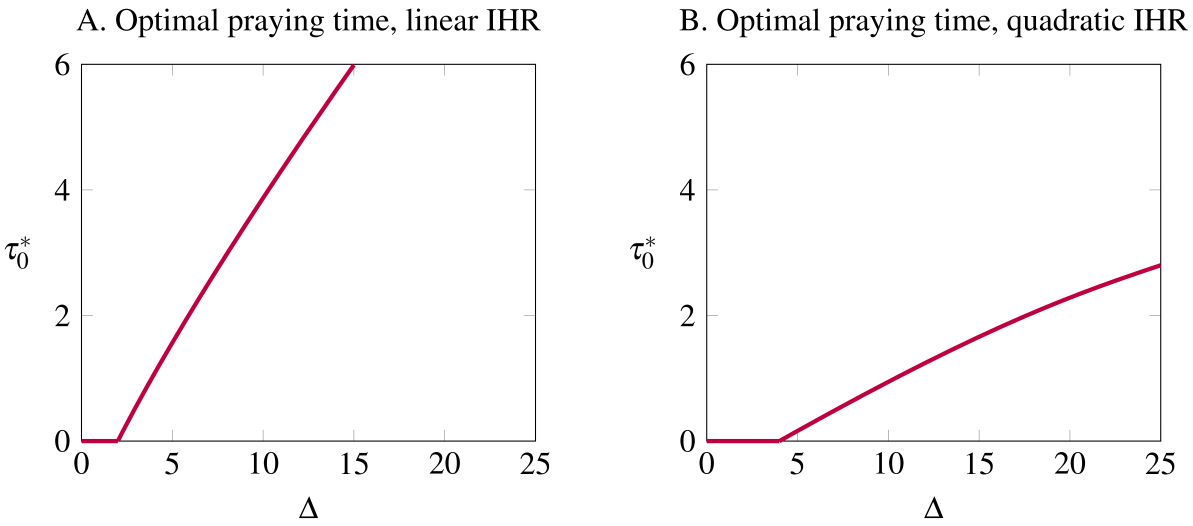
We can substitute this expression into the threshold level of belief, equation (5), to reduce this to an equation in $h_0\left(\tau_0^*, \infty\right)$ alone

$$\begin{aligned}
\frac{\eta - (1-e^{-\tau_0^*})h_0(\tau_0^*, \infty)}{e^{-\tau_0^*}} &= (1-p)h_0(\tau_0^*, \infty) + p(\eta + \Delta) && (12)\\
\eta - h_0(\tau_0^*, \infty) + e^{-\tau_0^*}h_0(\tau_0^*, \infty) &= (1-p)e^{-\tau_0^*}h_0(\tau_0^*, \infty) + p\eta e^{-\tau_0^*} + p\Delta e^{-\tau_0^*}. && (13)
\end{aligned}$$

Grouping terms and simplifying, we can write an implicit solution for τ_0^* as a function of $h_0\left(\tau_0^*, \infty\right)$

$$h_0(\tau_0^*, \infty) = \eta - \frac{p\Delta}{e^{\tau_0^*} - p}. \tag{14}$$

Figure A1: Optimal Prayer Timing for Linear and Quadratic Hazards



The figure shows examples of the optimal time to start praying as a function of belief. In panels A and B we show examples for $p = 0.2$, $\alpha = 1/4$ and $\beta = 0.5$. Panel A shows the solution for the linear case, with $\eta = 3/4$ and the corner solutions for $\tau_0^* = 0$ implying $\Delta = 2$. Panel B shows the solution for the quadratic case, with $\eta = 5/4$ and the corner solutions for $\tau_0^* = 0$ implying $\Delta = 4$.

This expression is as stated in the corollary. Alternatively, had we substituted for h_0, we would obtain an implicit solution for τ_0^* as a function of $h_1\left(\tau_0^*, \infty\right)$

$$h_1(\tau_0^*, \infty) = \eta + p\Delta \frac{(1 - e^{-\tau_0^*})}{1 - pe^{-\tau_0^*}}. \tag{15}$$

Both equations 14 and 15, define an implicit solution for τ_0^*. We can use either equation to solve for τ_0^*. □

Examples of when to start praying for linear and quadratic hazard.— To give some intuition for how the optimal prayer strategy responds to changes in the model parameters, it is useful to go through some examples. Figure A1, panels A and B show the optimal starting time for late prayer as a function of peasant belief for two types of hazard function, linear and quadratic. This part derives the functions plotted in those panels as an example of how to work with the model to characterize the optimal prayer strategy.

The definitions of the average hazard and conditional hazards are

$$\eta \equiv \lim_{\tau\to\infty}\frac{1}{1-e^{-\tau}}\int_0^{\tau} h(t)e^{-t}dt = \int_0^{\infty} h(t)e^{-t}dt \tag{16}$$

$$h_0(\tau_0,\tau_1) \equiv \frac{1}{1-e^{-\tau_0}}\int_0^{\tau_0} h(t)e^{-t}dt \tag{17}$$

$$h_1(\tau_0,\tau_1) \equiv \frac{1}{e^{-\tau_0}-e^{-\tau_1}}\int_{\tau_0}^{\tau_1} h(t)e^{-t}dt \tag{18}$$

Now consider several cases.[19]

Constant hazard rate. For a constant hazard rate all these expressions will yield a constant value equal to the constant hazard. Let $h(t)=\alpha$, then

$$\eta \equiv \lim_{\tau\to\infty}\frac{1}{1-e^{-\tau}}\int_0^{\tau}\alpha e^{-t}dt = \frac{1}{1-e^{-\tau}}\alpha\left[1-e^{-\tau}\right]=\alpha. \tag{19}$$

$$h_0(\tau_0,\tau_1) \equiv \frac{1}{1-e^{-\tau_0}}\int_0^{\tau_0}\alpha e^{-t}dt = \frac{1}{1-e^{-\tau_0}}\alpha\left[1-e^{-\tau_0}\right]=\alpha \tag{20}$$

$$h_1(\tau_0,\tau_1) \equiv \frac{1}{e^{-\tau_0}-e^{-\tau_1}}\int_{\tau_0}^{\tau_1}\alpha e^{-t}dt = \frac{1}{e^{-\tau_0}-e^{-\tau_1}}\alpha\left[e^{-\tau_0}-e^{-\tau_1}\right]=\alpha \tag{21}$$

As discussed in the main text, in this case the church can never convince the peasant and so there is no optimal strategy as such.

Linear hazard rates. Consider a linear hazard function $h(t)=\alpha+\beta t$. This function yields

$$\eta = \alpha+\beta \tag{22}$$

$$h_0(\tau_{0,}\infty) = \alpha+\beta+\frac{\beta\tau_0}{1-e^{\tau_0}} \tag{23}$$

$$h_1(\tau_{0,}\infty) = \alpha+\beta+\beta\tau_0. \tag{24}$$

Where η is the weighted average of $h_0(\tau_{0,}\infty)$ and $h_1(\tau_{0,}\infty)$

$$\eta = \left(1-e^{-\tau_0}\right)h_0(\tau_{0,}\infty)+e^{-\tau_0}h_1(\tau_{0,}\infty).$$

We substitute these expressions into equation (5) to find the solution for τ_0^* in relation to Δ

$$\frac{(p-e^{\tau_0^*})\beta\tau_0^*}{p-pe^{\tau_0^*}}=\Delta \tag{25}$$

This equation gives an implicit solution for τ_0^* as a function of Δ. We plot this function in Figure 3, panel C.

Quadratic hazard rate. Consider a quadratic hazard function $h(t)=(\sqrt{\alpha}+\beta t)^2$. This function

---

[19] When the hazard rate is of the form $h(t)=t^{\theta}$, the definition of η coincides with the Gamma function, i.e., $\Gamma(\theta+1)\equiv\int_0^{\infty}t^{\theta}e^{-t}dt$. When θ is a natural number we can just write $\eta=\Gamma(\theta+1)=(\theta)!$. Likewise, the integral in $h_0(\tau_{0,}\tau_1)$ coincides with the lower incomplete gamma function, i.e., $\gamma(\theta+1,\tau_0)\equiv\int_0^{\tau_0}t^{\theta}e^{-t}dt$; and the integral in $h_1(\tau_{0,}\tau_1)$ coincides with the upper incomplete gamma function, i.e., $\Gamma(\theta+1,\tau_0)\equiv\int_{\tau_0}^{\infty}t^{\theta}e^{-t}dt$. We can use the property $\gamma(\theta,\tau_0)\equiv\Gamma(\theta,\tau_0)-\Gamma(\theta)$.

yields

$$
\begin{aligned}
\eta &= (\sqrt{\alpha}+\beta)^2+\beta^2 && (26)\\
h_0(\tau_{0,}\infty) &= (\sqrt{\alpha}+\beta)^2+\beta^2+\frac{\beta\tau_0\left[2\sqrt{\alpha}+2\beta+\beta\tau_0\right]}{1-e^{\tau_0}} && (27)\\
h_1(\tau_{0,}\infty) &= (\sqrt{\alpha}+\beta+\beta\tau_0)^2+\beta^2. && (28)
\end{aligned}
$$

We substitute these expressions into equation (5) to find the solution for τ_0^* in relation to Δ

$$\frac{(p-e^{\tau_0^*})(2\sqrt{\alpha}+2\beta+\beta\tau_0^*)\beta\tau_0^*}{p-pe^{\tau_0^*}}=\Delta. \tag{29}$$

We use (29) to plot the optimal time to start praying in in Figure 3, panel D.

A.5 Tangible benefit and cost of prayer

The problem for the peasant presented above is intentionally simple. The peasant supports the church if the prayers are convincing enough. There is an implicit assumption here that the expected benefit that the peasant receives from the extra rain are much greater than the cost of supporting the church. We now extend the model to allow for a benefit and cost of persuasion for the peasant. As we show below, if the benefit (relative to the cost) of the extra rain is not high, then the church would not be able to persuade the peasant to support the church even when the hazard rate is increasing.

The benefit of rainfall is μ and the cost of support κ. The peasant will agree to support the church if

$$\left(h_1(\tau_0,\tau_1)-\hat{h}(\tau_0,\tau_1)\right)\mu\geq\kappa \tag{30}$$

The problem for the church is now defined by equation 6, with equation 30 as an added restriction. Notice that the restriction now is similar as before, but with a higher threshold to clear. It is useful to define other parameter values that mark the strength of beliefs.

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

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 church would always pray.

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

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 beliefs need to be sufficiently persuasive not only to satisfy the peasant requirement in terms of increase hazard (Δ). It also requires the ritual not to be too costly. If $\frac{\kappa}{\mu}$ is large enough, then A5 is violated and the peasant would not accept the *quid pro quo* proposal. Proposition 3 below formalizes this intuition.

Proposition 3 (Optimal strategy for increasing hazard rate)**.** *If A1 holds and $h(t)$ is strictly increasing, then the optimal policy for the church is* late praying *with $T^* \equiv (\tau_0^*, \infty)$. The choice of τ_0^* is determined by the ritual cost to benefit ratio $\frac{\kappa}{\mu}$ as follows:*

i ***Low cost** $\frac{\kappa}{\mu}$. If A4 does not hold, then $\tau_0^* = 0$ and the church always prays.*

ii ***Moderate cost** $\frac{\kappa}{\mu}$. If A4 and A5 hold, then $\tau_0^* > 0$ and the church prays late.*

iii ***High cost** $\frac{\kappa}{\mu}$. If A4 holds but A5 does not, then no choice of τ_0 can convince the peasant. The church is indifferent between all strategies T.*

Proof of proposition 3. The analysis here is analogous to Proposition 2 but with a more stringent constraint. If we replace $p\omega$ by $p\omega + \frac{\kappa}{\mu}$, Assumptions A1 and A2, become Assumptions A4 and A5, and the proof is analogous.

$\square$

The intuition for Proposition 3 is straightforward. When the cost is low and the benefit is high, the church does not have to worry about the participation constraint of the peasant (equation 30). The ritual is so cheap that the church will always pray. When the cost is high and the benefits is low, for a given distribution of rain, there is nothing the church can do to convince the peasant to support it. The peasant may believe in the effectiveness of prayer, but the cost associated with supporting the church is too high compared with the benefit. When the the ritual cost to benefit ratio $\frac{\kappa}{\mu}$ is moderate, the church will pray only when the perceived efficacy of the ritual is sufficiently high that it would be worth for the peasant to support the church. Notice that for a low cost, the peasant captures some of the rents, but for a moderate cost the church policy extracts all the rents from the peasant, to the point of making him indifferent between supporting or not.

A.6 Decreasing and Non-Monotonic Hazards

Figures A2.A and A2.B show optimal policies when the hazard rate is not monotonically increasing. Panel A shows a case where the hazard rate is first decreasing and then increasing over time. In this case, the optimal policy may consist of beginning to pray right after the last rain ($\tau_0 = 0$), stop praying at $t = \tau_1$, and then begin praying again at some $t = \tau_2$ without stopping after that. This creates two praying spells, a short one right after the last rain, and a longer one much later. Since the hazard rate is monotonically increasing after $t = \tau_2$, it is optimal to never stop praying during the second spell. This policy creates a high hazard h_1 during praying times, and a low hazard h_0 during non-praying times (the hazard rates in the first and second praying spells need not be the same).

We think such policies are unlikely to be used in practice. Demand for rain would be zero or very low in the time immediately following the last rain. As the example for Murcia indicates, prayers are usually originated when farmers demand the city council to take action during a drought. Our model omits the dimension of when a rainfall realization is valuable to the peasant. If we included such a dimension, or simply restrict attention to prayer strategies that pray when demand is high, then the optimal policy in Figure A2.A is the same as in the case with increasing hazard rates.

Figure A2.B shows the case of a decreasing hazard rate (DHR). Under a decreasing hazard the church can persuade the peasant. The optimal strategy would be to pray immediately after the last rain ($\tau_0 = 0$) and stop praying at $t = \tau_1$. Although this strategy works in theory it is again unlikely to be useful in practice. The peasants' 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 peasant. 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. Thus, it is unlikely that areas with DHR would practice a rain ritual.

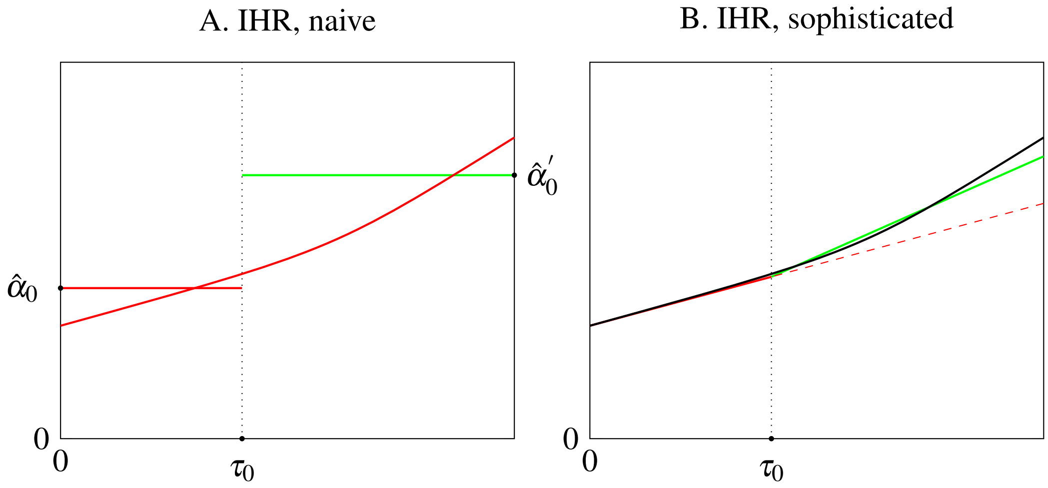
Under the hypothesis that praying for rain needs to be instrumental, and therefore to yield rain that is useful to the peasants, we do not expect to see prayers for rain soon after recent rain. Therefore the optimal strategy in the ∪-shaped hazard case would look like the strategy in the increasing hazard case. The optimal strategy in the decreasing hazard case will not yield any useful rain and is unlikely to be practiced.

A.7 Sophisticated Peasant Beliefs

In Section 1, there is an implicit assumption that farmers do not see time or do not condition their beliefs on time. One way to interpret this is to think that farmers are not very sophisticated, or that they believe that hazard rates are flat. More generally, the assumption is that farmers make a prediction about the hazard rate when the church does not pray, and extrapolate that prediction to the periods when the church is praying. With this interpretation, we could generalize the persuasion problem to allow for more sophisticated peasant beliefs. In practice, for persuasion to work, we do not require peasants to be completely unsophisticated or oblivious to time, i.e., to believe that hazard rates are constant. We only need peasants not to be completely sophisticated. Although the full characterization of such model is beyond the scope of this paper, we now present a simple example where peasants believe the hazard rates to be linear, but in practice they are quadratic.

Figure A2.C shows peasants estimates of the hazard rate when they believe hazard rates are

Figure A2: Beliefs of a Sophisticated Peasant



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

constant and Figure A2.D shows peasant estimates of the hazard rate when they believe hazard rates are linear.

For example, 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 ($\beta > 0$), but that it is increasing faster than what the peasant think it should increase, i.e., $\gamma > 0$. The intuition in our main model was that for long spells the probability of rain was greater than for short spells. This was based on the implicit assumption that peasants believed the hazard function to be constant. Figure A2.C shows that the peasant computed a hazard function when the church did not pray $\hat{h}_0 = \hat{\alpha}_0$, and a different hazard function when the church prayed $\hat{h}_1 = \hat{\alpha}_0'$.

We now assume the peasant has the same information as before and will also use that information to estimate the hazard function when the church prays, based on the information available when the church does not pray. The difference now, is that the peasant believes the hazard function to be linear. The peasant 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 $\hat{\beta} \neq \beta$. The peasant looks at the realizations of rain and compute the best fit of 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, the peasant is imputing to β the extra probability of rain due to $\gamma > 0$.

The strategy for the church is a tuple $T \equiv (\tau_0, \tau_1)$, with $\tau_0 \leq \tau_1$, where τ_0 is the time when prayer begins and $\tau_1 \in [\tau_0, \infty]$ is the time when prayer stops. For a given strategy, we can define the beliefs that such strategy would generate, the peasants' cognitive model, i.e., their prediction of rain under prayers, based on the observation of rain without prayers. There are three elements

- $\beta_0(\tau_{0,}\tau_1) \equiv \frac{1}{1-e^{-\tau_0}}\int_0^{\tau_0}\frac{h(t)}{t}e^{-t}dt$ is the average slope of the hazard rate while the church does not pray.

- $\beta_1(\tau_{0,}\tau_1) \equiv \frac{1}{e^{-\tau_0}-e^{-\tau_1}}\int_{\tau_0}^{\tau_1}\frac{h(t)}{t}e^{-t}dt$ is the average slope of the hazard rate while the church prays. When $\tau_1 \to \infty$, we abuse notation and write $\beta_1(\tau_{0,}\infty) \equiv \underset{\tau_1\to\infty}{lim}\frac{1}{e^{-\tau_0}-e^{-\tau_1}}\int_{\tau_0}^{\tau_1}\frac{h(t)}{t}e^{-t}dt$.

- $\eta_\beta \equiv \underset{\tau\to\infty}{lim}\frac{1}{1-e^{-\tau}}\int_0^{\tau}\frac{h(t)}{t}e^{-t}dt$ is the average unconditional slope of the hazard rate.

- $\alpha_\beta \equiv h^{'}(0)$ is the slope of the hazard rate at $t=0$.

- ω_β is the change in slope for the hazard rate that the peasant believe happens when god exists and the church prays, and $\Delta_\beta \equiv \omega_\beta - \eta_\beta$.

The terms in the integral is 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, A4 in equation 31, about the peasants beliefs

$$A4 : \Delta_\beta > \frac{(1-p)}{p}(\eta_\beta - \alpha_\beta) > 0. \tag{31}$$

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

$$\beta_1(\tau_0,\tau_1) \geq \hat{\beta}(\tau_0,\tau_1) \equiv p\omega_\beta + (1-p)\beta_0(\tau_0,\tau_1). \tag{32}$$

Formally, we now present the extended result.

Proposition 4 (Increasing and convex hazard rate)**.** *If $h(t)$ is strictly increasing and convex, and the peasant beliefs the hazard rates are linear, then the optimal policy for the church is* ***late praying*** *with $T^* \equiv (\tau_0^*,\infty)$ such that $\beta_1(\tau_0^*,\infty) = p\omega_\beta + (1-p)\beta_0(\tau_0^*,\infty)$.*

Proof. The proof is similar to that of Proposition 2. 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 peasant, we need the hazard rate when praying to be greater what the peasant 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 τ_0 (represented by the dashed red line in Figure A2.D) will be lower than the estimated hazard rate using only information after τ_0 (represented by the solid green line in Figure A2.D). If this condition hold (increasing and concave hazard rate), the analysis is the same as in Proposition 2, changing the corresponding terms, e.g., Δ_β instead of Δ. $\square$

In summary, the computation of the equilibrium in this case is analogous to the case when the peasant believes the hazard is constant. The condition for persuasion, however, is different. If the peasant thinks that the hazard rate is constant, an increasing hazard rate is needed for persuasion. If peasants 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 Gil Guirado and Espín-Sánchez (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 mentioned 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. 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 3.2 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

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.

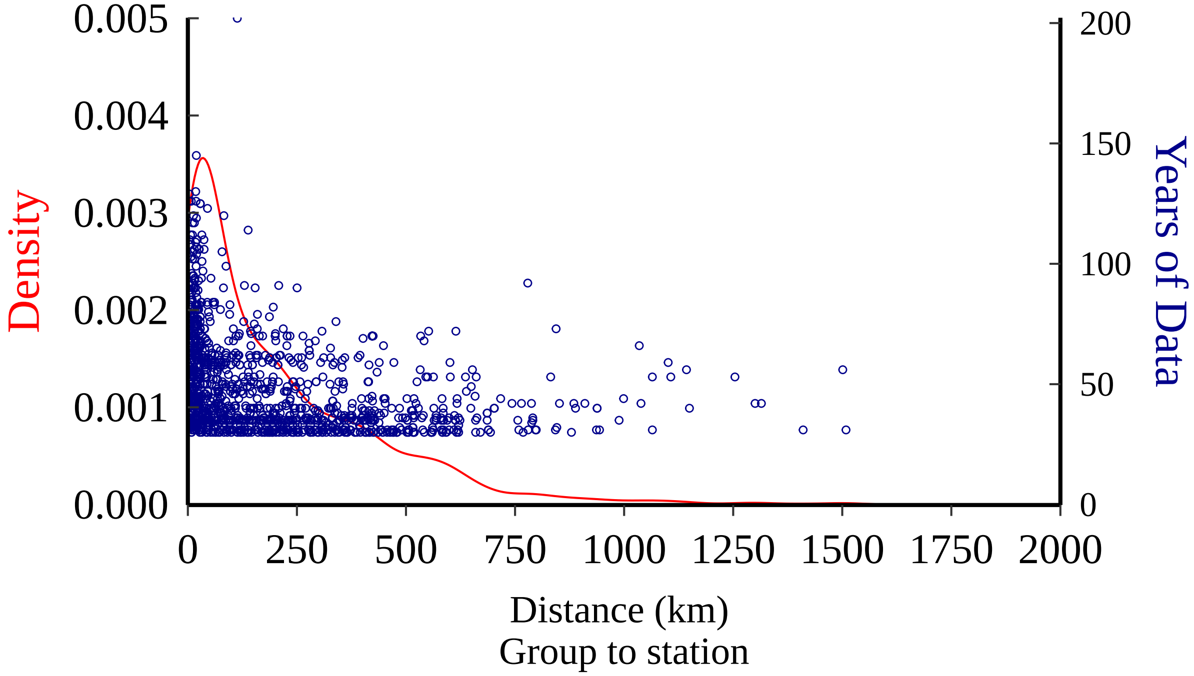
180 countries and territories (WMO, 2021). Using the latitude and longitude coordinates of each ethnic group in the *Ethnographic Atlas*, we match groups to the nearest GHCNd weather station with sufficient data, which we define as at least 30 years of daily rainfall measures.

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



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 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

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

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

cumulative hazard function. We specify the log cumulative hazard

$$\log(H(t|\gamma)) = \gamma_0 + \gamma_1 t + \gamma_2 v_1(t) + \ldots \gamma_{m+1} v_m(t) \tag{33}$$

where $v_j(t)$ is a cubic spline basis function with m knots.[20] We set the knots separately for each weather station based on the distribution of dry spells at that station.[21] The function is constrained to be linear beyond the boundary knots.

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

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

The arguments of the log likelihood for each spell observation are calculated from the log cumula-

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[20] The elements $j = 1, \ldots, m$ 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 $k_1, \ldots, k_m$. 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.

[21] 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}.

tive hazard (33). 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 different rainfall patterns around the world.

C Appendix: Supplementary Results for Murcia

In Section 2 we argue that prayer is predictive of rainfall. Here in Table C we present an additional statistical test of whether prayer Granger-causes rain.

Granger causality is defined with respect to a linear distributed lag model with some time horizon. 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. 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.

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

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 rain 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 rain and the restricted model including only lags of rain.

D Appendix: Supplementary Results for Global Analysis

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

D.1 Spatial standard errors

Table D4 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 D4: 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

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.2 Hazard functions by season

Our baseline measure of whether the hazard function is increasing is estimated from data on all dry spells in all seasons. An increasing hazard may allow for stronger persuasion if it increases at a time when demand for rainfall is greater. As an extension, therefore, we estimate separate hazard functions by season: wet and dry. We define the dry season as the six contiguous months with the lowest average rainfall (neglecting, for simplicity, that some areas have alternating wet and dry seasons in a year). We then estimate seasonal hazard functions and classify their slopes in the same manner as for the overall hazard.

Appendix Figure D2 gives some examples of seasonal hazard functions, for Murcia and the Herero. When the overall hazard function is increasing after a dry spell, this tends to be driven by a dry season hazard that is increasing especially steeply. Panel A shows the overall hazard function for Murcia, panel B the hazard for spells beginning during the dry season and panel C for spells beginning during the wet season. The dry season hazard function is steeply increasing whereas the rainy season hazard is flat or declining. For the Herero, in the right three panels, both hazard functions are increasing but the dry season hazard more steeply. These examples show that an increasing overall hazard function after a dry spell tends mainly to be driven by an increasing hazard for spells beginning in the dry season. This explains why the dry season hazard has a stronger effect on the practice of a rain ritual than does the rainy season hazard (Table 3, column 4), which accords with intuition that rain is most valuable to the peasant during the dry season.

D.3 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 D5 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.

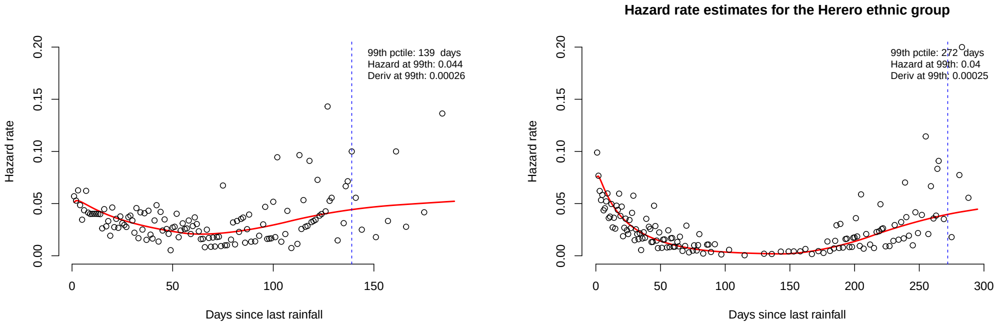
The main findings of Table D5 are that: (i) there is a small, negative coefficient of mean rainfall on rain ritual practice, when not controlling for the hazard rate (columns 1 to 3), (ii) there is no effect of mean rainfall on rain ritual practice, controlling for the hazard rate (columns 4 to 6), (iii) 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.4 Classifying an increasing hazard at different dry spell durations

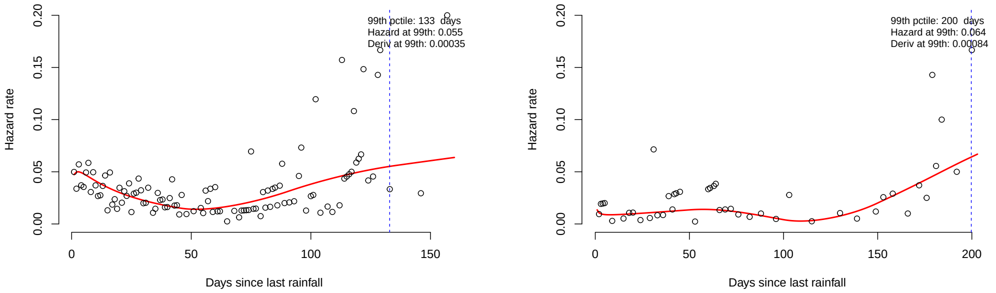
In our model what matters for the ability to persuade is whether the hazard of rainfall is increasing eventually, after a long dry spell without rain has passed. Our main results classify an increasing hazard empirically based on whether the derivative of the hazard is positive when evaluated at the 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

Figure D2: Hazard Functions Differentiated by Season

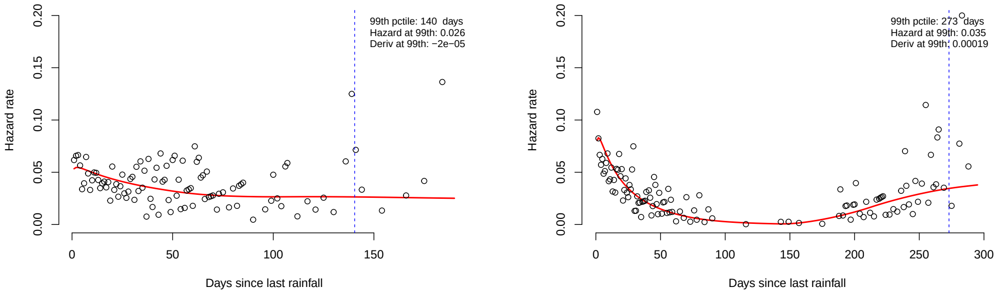
A. Murcia B. Herero



C. Murcia - Dry season D. Herero - Dry season



E. Murcia - Rainy season F. Herero - Rainy season



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 Murcia are determined by the true dates of the beginning/end of the rainy/dry seasons in Murcia, Spain. Seasons for other ethnic groups in our data are determined using a 6 month rolling mean of the 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.

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 classifica-

Table D5: Rainmaking on Rainfall Norms and Whether the Environment Allows Persuasion

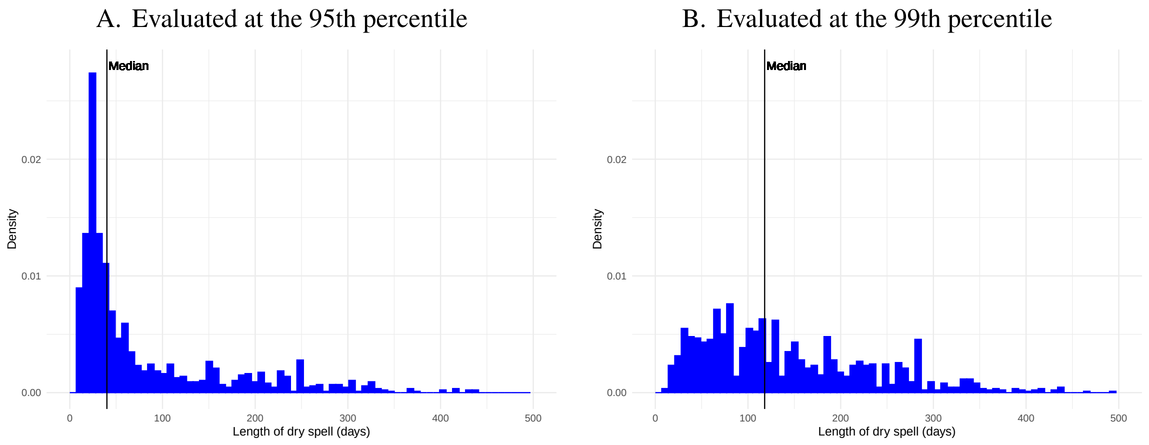
	Dependent variable: Rain ritual practiced (=1)					
	(1)	(2)	(3)	(4)	(5)	(6)
Hazard rate increasing (=1)				0.13^{***}	0.14^{***}	0.13^{***}
				(0.040)	(0.037)	(0.037)
Rainfall mean (annual, m)	-0.031^{**}	-0.063^{*}	−0.060	−0.014	−0.024	−0.023
	(0.015)	(0.037)	(0.039)	(0.015)	(0.039)	(0.041)
Rainfall 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

This table reports coefficients from regressions at the ethnic group level of whether a rain ritual is practiced on mean rainfall and other climate norms. Climate controls include a quadratic in mean temperature, the standard deviation of temperature, 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 * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

tion 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 (≥ 0.5 cm), most spells, by construction, occur during periods of the year when it is raining more often. Figure D3 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 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.

Figure D3: Distribution of Dry Spell Duration Across Ethnic Groups


A. Evaluated at the 95th percentile

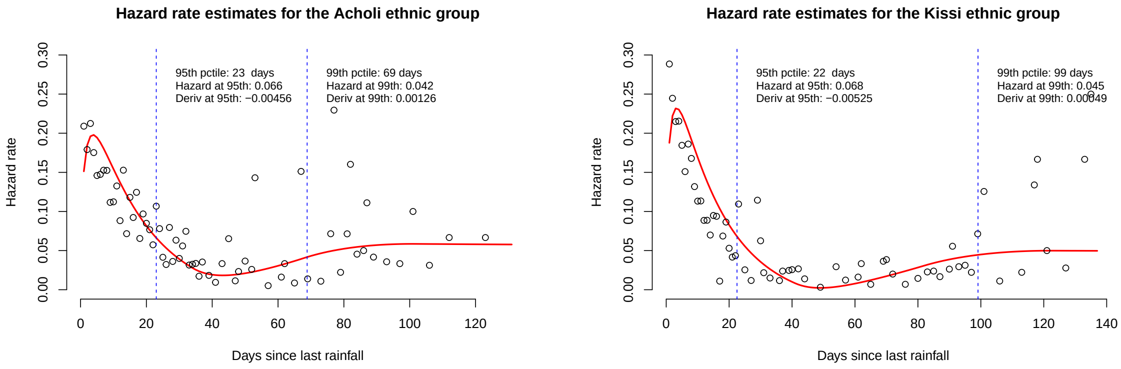
B. Evaluated at the 99th percentile

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.

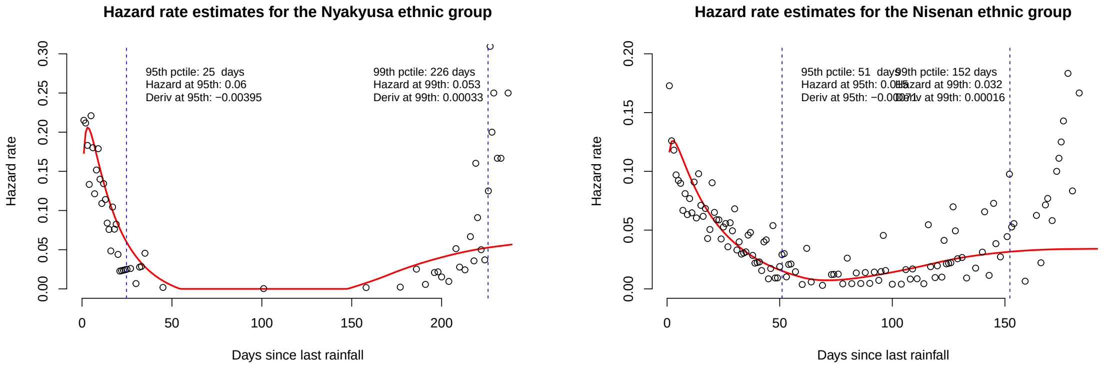
The considerable lengthening of dry spells in the right tail of the distribution has a significant effect on whether the hazard rate is increasing or decreasing, the key object in our model. Figure D4 shows the hazard functions for select ethnic groups that have decreasing hazard rates when evaluated 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 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.

Figure D4: Comparison of Hazard Rates at 95th and 99th percentiles of the Distribution of Dry Spells for Select Ethnic Groups

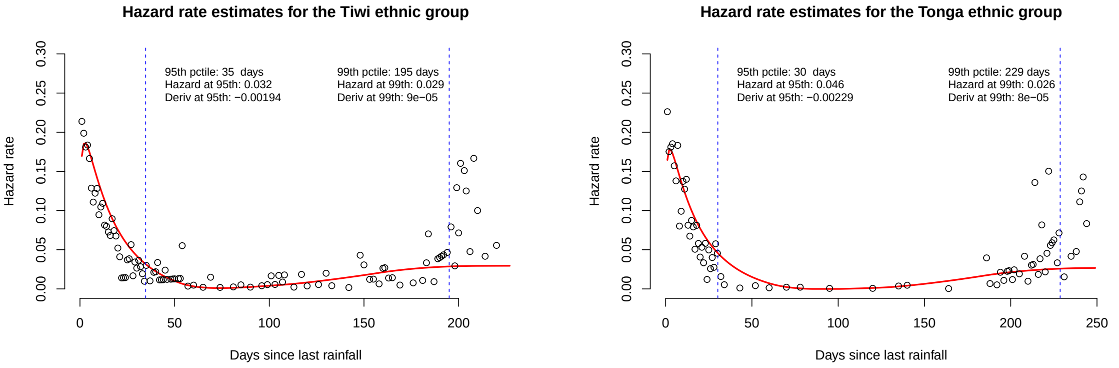
A. Acholi B. Kissi



C. Nyakyusa D. Nisenan

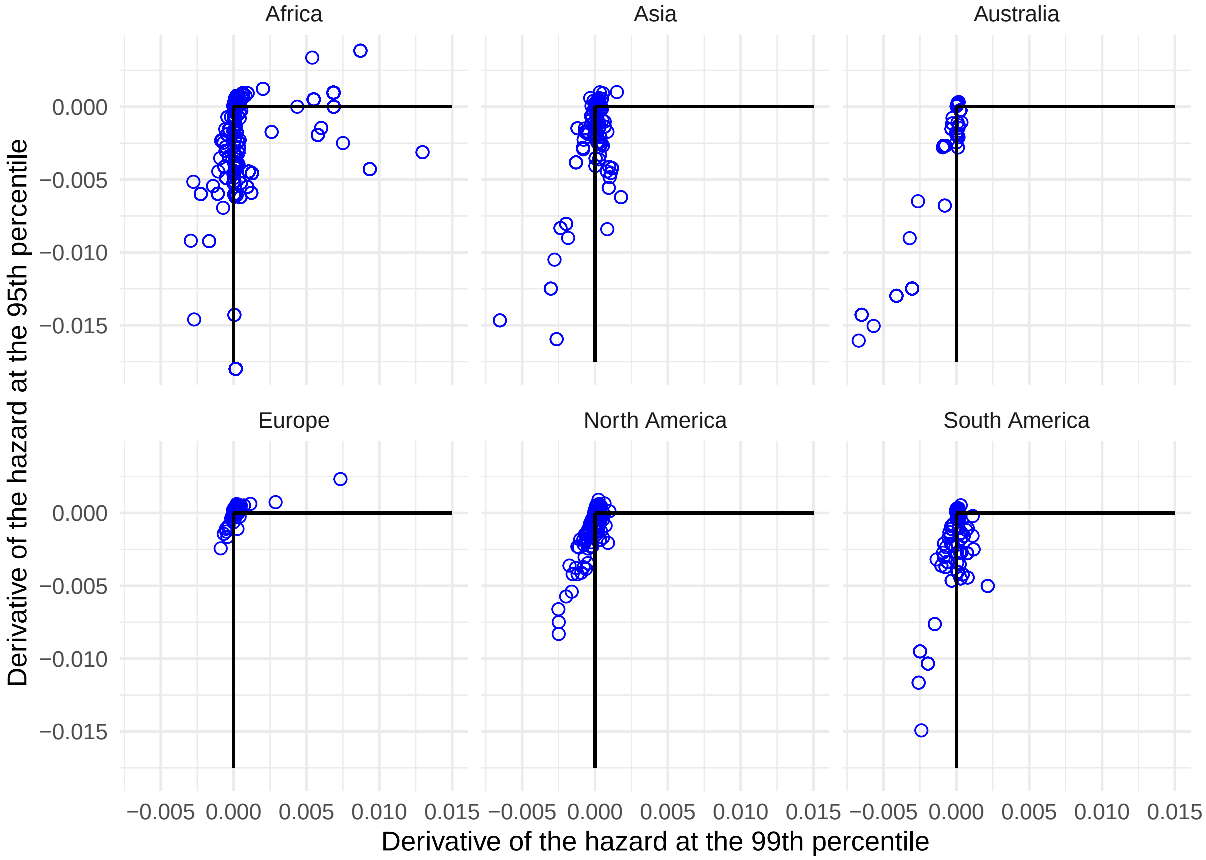


E. Tiwi F. Tonga



This type of misclassification is extremely common, if using the 95th percentile, because many ethnic groups face similar, seasonal patterns of rainfall. Figure D5 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-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 in the lower-right quadrant, like the examples in Figure D4, 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 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 D4 in fact represent one-third of all groups and nearly half of all groups with an increasing hazard rate.

Figure D5: Comparison of Hazard Slopes at Different Points in the Dry Spell Distribution



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.

Table D6 reproduces our Table 3 results, from the main text, using the column 4 specification, 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 D4, 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 D6: 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

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.5 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).[22]

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 D7 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*.

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[22] 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 D7: 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 D8 and Table D9 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 D8, 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 D10 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 D8 and D9 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 D11 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 D8: 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

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 D9: 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

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 D10: 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

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 D11: 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

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 * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.