Praying for Rain: On the Instrumentality of Religious Belief*

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Abstract

We study the climate as a determinant of religious belief. People believe when religious authorities (the "church") can credibly intervene in nature on their behalf. We present a theoretical model in which nature determines the process of rainfall over time and the church chooses when optimally to pray in order to persuade people that it has caused the rain. We present evidence from prayers for rain in Murcia, Spain that the church follows such an optimal policy and that its prayers therefore predict rainfall. In our model, praying for rain can only persuade people to believe if the hazard of rainfall after a dry spell is increasing over time. We test this prediction in a newly-gathered data set of whether ethnic groups around the world traditionally prayed for rain. We find that (i) prayer for rain is widespread; (ii) prayer for rain is more likely among ethnic groups dependent on intensive agriculture for subsistence; (iii) ethnic groups facing an increasing rainfall hazard are 43% more likely to pray for rain, consistent with our model. We interpret these findings as evidence for the instrumentality of religious belief.

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1 Introduction

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

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

Religious belief and practice are often instrumental: they concern the benefits god might deliver or withhold. People believe that supernatural forces intervene in the world and see human motives in natural phenomena from illness to bad weather. Societies elevate shamans, priests and kings to call on the gods to intervene in the world on their behalf.

Rainfall is a particularly valuable target for supernatural intervention. Agrarian societies depend on rainfall to grow crops. Pastoral societies depend on rainfall to grow fodder and to water animals. Because rainfall is vital, soliciting rain has often been a central object of religious practice. Frazer (1890), the book that created the modern, systematic study of magic and religion, uses rainmaking as a signal example of instrumental belief. His accounts, among many others, give examples of rainmaking from traditional practice and major religions all over the world.[1]

The commonality of belief in rainmaking raises a puzzle: why would people believe in rainmaking if it does not work? Rainfall, historically, has been be beyond human appeals. Yet societies have long practiced rituals to bring rainfall and venerated leaders who succeed in doing so. The fact that such a plainly ineffective practice is so common and persistent

[1] 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 beseech the rain dragon for rain, or, if it refuses, abuse the dragon and desecrate its temple; the Catholic church in Spain organizes an elaborate procession carrying an idol through the streets (Heimbach Jr, 2001; Schmidt, 1979; Başgöz, 2007; Cohen, 1978; Guirado and Espín-Sánchez, 2021).

suggests that its value must *not* be instrumental (Wittgenstein, 1967).

This paper investigates the instrumentality of religious belief through the practice of rainmaking. Our central idea is that rainmaking is more likely to occur in places where a religious authority (hereafter, the "church") is more likely to be persuasive in claiming to make rain. We build a theoretical model in which rainmaking is perceived to be effective even when rainfall is exogenous. We then test this model with new data on the practice of rainmaking around the world.

We formalize when rainmaking is likely to be persuasive. In our model, the church chooses when to pray in order to persuade the people to believe that she causes rain. The general set-up is familiar from the literature on Bayesian persuasion, in which a sender chooses an experiment to run on the basis of which a receiver will take some action (Kamenica and Gentzkow, 2011). The critical difference in our model is that nature decides the rainfall process and therefore constrains the space of possible experiments (Ball and Espín-Sánchez, 2022). We show that the church can run a persuasive experiment only if the hazard rate of rainfall is increasing over time. In this case, the church optimally chooses to begin praying at some point in time and does not stop until rain occurs. This optimal policy will induce a correlation between prayer and subsequent rainfall that makes people infer that prayer works. We therefore predict that rainmaking will be more persuasive, and thus more prevalent, when the hazard function of rainfall is increasing after a dry spell.

We test the model's predictions for the efficacy of rainmaking using newly collected data of two disparate kinds. First, we use detailed data on the practice of rainmaking prayers by the Catholic church in Murcia, Spain, for a period of more than 200 years. This data represents only one historical case but, uniquely, allows us to observe detailed records on prayers for rain and hence the mechanism for persuasive rainmaking. Second, we gather new data on the traditional practice of rain rituals by ethnic groups around the world. This data allows us to extrapolate our prediction for the adoption of rainmaking to a global scale.

The Catholic church in Murcia established a formal system of religious appeals for rain, known as *pro pluvia* rogations, that endured for hundreds of years. Under the rogation system, the town could appeal to the church to pray for rain. The church would then decide when and how to pray. We observe these rainmaking prayers for the period from 1600 to 1833. We additionally collect data from historical records of the municipal council of Murcia on notable rainfall events.

The main finding from the Murcia case is that rainmaking is highly predictive of future rainfall. We find that a prayer in the last month increases the probability of a notable rainfall on a given day by 80%. This relationship is statistically significant and it is not driven merely by seasonality. Prayer leads rainfall events even conditional on recent rainfall: we find that prayer Granger-causes rainfall for a wide range of time horizons. In our model, prayer will be successful only when the hazard of rainfall is increasing. Using contemporary data on daily rainfall, we estimate the hazard of rainfall in Murcia and show it to be increasing in the time without rain. This suggests that Murcia's *pro pluvia* rogations were predictive because of the rainfall hazard in Mediterranean Spain and endured because people there would see evidence for their success.

To extrapolate beyond the Murcia case, we combed through an extensive anthropological literature to measure rainmaking around the world. We use as the basis of our search the ethnographic atlas (Murdock, 1967), which 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; Giuliano and Nunn, 2020). The level of observation in the ethnographic atlas is an ethnic group and the variables are meant to measure the type of production, political and social practices for each group prior to colonial contact. We augment the atlas by adding, for each group, a variable that is equal to one if we could find a record that this group practiced a ritual to make rain.

This data on rainmaking gives a global view of the ubiquity of this religious practice (Figure 1). We find that 39% of the ethnic groups in the atlas practice a rainmaking ritual of some kind. Rainmaking is most prevalent in Africa, where it is practiced by 44% of ethnic groups, but it is observed on every continent to some extent. We find that the adoption of rainmaking is higher when a society's mode of subsistence is less flexible in response to rainfall shocks. The prevalence of rainmaking among groups without agriculture is 30%. Ethnic groups that are dependent on agriculture are 11 pp more likely to practice rainmaking. Ethnic groups that are dependent on intensive irrigated agriculture, which are arguably the most dependent on rainfall, are 37 pp more likely to practice rainmaking.

We interpret these findings as evidence that rainmaking responds to the dependence of a society on rainfall in a given place. Ironically, then, the traditional practice of rainmaking is more prevalent for ethnic groups with more advanced forms of subsistence, which require specific investments, namely intensive agriculture and irrigated agriculture. Our data quantifies for the first time the prevalence and correlates of rainmaking, which has played a central role in anthropological accounts of the development of religion (Frazer, 1890).

To test the main prediction of our model we need also to characterize the heterogeneity in the hazard function for rainfall around the world. To do so, we assemble modern data on daily rainfall from the weather station nearest to the historical location of each ethnic group. We use this data to estimate a flexible, semi-parametric hazard function for the probability of rainfall. We then evaluate whether this hazard function is increasing or decreasing after a long dry spell. In places with an increasing hazard, such as Murcia or Namibia (see Figure 3 and Figure 5, Panel D), rainfall becomes more likely each day as more time passes without rain.

We find, in the global data on rainmaking, that ethnic groups facing an increasing hazard of rain are more likely to practice rainmaking. Our preferred estimate is that an increasing hazard of rain increases the prevalence of rainmaking by 15 pp (standard error 3.9 pp), on a base of 30 pp for groups with a decreasing hazard. These estimates control for an appropriate battery of exogenous geographic controls drawn from the literature on the geographic determinants of economic development.

Our interpretation of these results is that rainmaking is adopted when it is persuasive.

In Murcia we see 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, on the extensive margin of prayer adoption, that ethnic groups are more likely to adopt rainmaking in places where it is likely to be persuasive. Rainmaking can therefore be understood as an instrumental religious practice, even though it is ineffective, because it respond to variation in *perceived* efficacy.

The paper contributes to several literatures in economic development, economic history and anthropology. Our paper is part of a literature that traces the effects of geographic or climatological factors on the development of economic and political institutions.[2] Our work is perhaps closest to Chaney (2013), who documents that in ancient Egypt the highest religious authority became more powerful when the Nile had an abnormally extreme flood. This example shows that more 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. Our contribution, relative to this literature, is to show that climate is a determinant not only of economic or political outcomes directly but also of religious practice.

Our paper also contributes to a related literature on the origins of religiosity and specifically the instrumentality of religious belief. Religious belief is thought to be socially and individually adaptive.[3] On instrumentality, a rich body of work has found that people use religion as a means of insurance against natural and economic shocks.[4] Our work is distinct

[2]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.

[3]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. Clingingsmith, Khwaja and Kremer (2009) find that completing the Hajj increases beliefs in Muslim unity. Bryan, Choi and Karlan (2021) study belief in a randomized experiment and find that proseltizing for evangelical Protestantism increases income, at least temporarily. The authors argue that the mechanism is an increase in subjects' persistence.

[4]Chen (2010) and Ager and Ciccone (2018) find that larger common financial and rainfall shocks, respectively, are associated with higher participation in organized religion, as a means of insurance. Auriol et al. (2020) conduct an experiment in Ghana offering formal insurance to churchgoers. They find that for-

in that we study a persistent difference in beliefs about the efficacy of religion, rather than shocks to the demand for religious "insurance." 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 be effective. Our data also create worldwide coverage of a traditional religious practice.

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 signal example, as sincere attempts to control nature or as simply performative or symbolic (Hong, Slingerland and Henrich, 2021). An older school says that people engage in rainmaking to make rain (Frazer, 1890). A revisionist school argues, in broad terms, that beliefs about human affairs and the supernatural are governed by separate processes, and so religious belief should not be expected to respond to empirical evidence.[5] Our findings contravene this view by showing that rainmaking is more prevalent where it is more persuasive. This suggests that religious beliefs are formed in a rational way and do not require their own separate epistemology.

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

mal insurance causes people to donate less to their church, as well as potential secular recipients, in dictator games.

[5]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.

2 Model

This section models when prayer for rain is likely to be persuasive. The model is in the tradition of the Bayesian persuasion literature. A key difference is that the church, as sender, cannot choose any experiment to conduct, but is constrained in what experiments it can present to the peasant, as receiver, by the rainfall process set by nature.

2.1 Set-up

We consider the problem of the church and the peasant. The church claims to represent God and the peasant makes a quid pro quo arrangement with God in giving his support to the church (Parigi, 2012). To do so, the peasant must be convinced that God works in the world. The state of the world belongs to a state space $\Omega = \{\omega_0, \omega_1\}$ with two elements. In state ω_1 God listens to prayers and intervenes in the world; for brevity, we sometimes call this "God exists." In state ω_0 God does not listen. The peasant chooses a binary action $a \in A = \{a_0, a_1\}$. Action a_1 is to *support* the church and a_0 is *not to support*. Support for the church may mean offering a donation or giving a religious name to a child. In some historical cases, support may more literally mean to support or depose a religious or political leader.

Nature poses a *natural experiment* by determining the process of rainfall. We characterize the process of rainfall with the hazard rate $h(t) = f(t)/(1 - F(t))$, which gives the instantaneous probability of rainfall after t days have passed since it last rained. Time t is continuous. It always rains eventually, which ends the game.

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 at some disconnected series of intervals. The combination of the *natural experiment* posed by nature and the endogenous prayer stratgey of the church creates a *religious experiment*, or simply an experiment.

2.2 Analysis

Beliefs and the peasant's problem.—The prayer strategy may induce changes in the peasant's beliefs. The peasant has a prior belief p that God exists. The prayer of the church creates two possible signals. If the church was praying and it rained then signal s_1 is realized. If it rained and the church was not praying signal s_0 is realized.

What do these signals teach the peasant about God? For a given policy T, we define an experiment $\pi \equiv (\pi_0, \pi_1)$. Let $\pi_1 = \mathbb{P}(s_1|\omega_1)$ be the probability of signal realization s_1 in state ω_1 and analogously for $\pi_0 = \mathbb{P}(s_1|\omega_0)$. We assume without loss that $\pi_1 \geq \pi_0$ so that when God exists it is more likely to rain during prayer. Peasants are Bayesian. They have beliefs $q \in \{q_0, q_1\}$ with $q_d = \mathbb{P}(\omega_d|s_d)$ after observing signal s_d. These probabilities are

$$\begin{aligned} q_0(\pi) &= \mathbb{P}(\omega_0|s_1) = \frac{p\pi_1}{p\pi_1 + (1-p)\pi_0} \\ q_1(\pi) &= \mathbb{P}(\omega_1|s_1) = \frac{(1-p)\pi_0}{p\pi_1 + (1-p)\pi_0}. \end{aligned}$$

The updating of beliefs can be expressed in terms of the likelihood ratio of the probability of state ω_1 over the probability of state ω_0 after a given signal. The likelihood ratio after signals s_1 and s_0, respectively, are

$$l_1 = \frac{p}{1-p} \cdot \frac{\pi_1}{\pi_0} \qquad\qquad l_0 = \frac{p}{1-p} \cdot \frac{1-\pi_1}{1-\pi_0}.$$

The assumption $\pi_1 \geq \pi_0$ implies that $l_1 \geq p/(1-p) \geq l_0$. It will be useful to define the unconditional probability of signal s_1 as $\bar{q}_1(\pi) \equiv p\pi_1 + (1-p)\pi_0$.

The peasant will donate to the church if he believes the evidence in favor of ω_1 is strong. One way to describe this belief is by the movement of the peasant's prior. Suppose that $p < 0.5$ and the peasant will support the church if $l_1 \geq 1$; that is, he believes it more likely than not that God exists. Then the peasant will then support if and only if $\pi_1/\pi_0 > (1-p)/p$.

The strategy of the church.—The church wants to pray so as to induce the peasant to support it as often as possible. We think of the game as repeating again and again with a new start each time it rains. We normalize the payoff of the church for each instance of support to one.

What matters for belief is whether the church is able to elicit rain during a drought. We will therefore restrict attention to hazard functions $h(t)$ that are monotonic: increasing, decreasing or constant. Empirically, we will classify functions based on their slope after a long period without rain. After such a period hazard functions will fall into one of these groups. For this class of hazard functions, we can restrict attention to the following class of prayer strategies without loss. A strategy 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.

Figure 2 illustrates how the hazard function constrains the beliefs that the church is able to induce. The top two panels plot the rainfall hazard rate against time on the horizontal axis. In the first case, the hazard is increasing (panel A). In the second case, it is flat, at either a low or a high level (panel B). The bottom two panels plot the posterior belief $\pi_1(\omega_1|s_1)$ that God exists against the posterior belief $\pi_0(\omega_0|s_1)$ that God does not exist, conditional on observing rain during prayer. The different points on the lower two panels describe the posterior beliefs induced by different prayer strategies of the church. In these panels, on the 45-degree line, the posterior beliefs of the two states after s_1 are equally likely. The peasant has a likelihood ratio of one that God exists (state ω_1). The dashed line represents $(1-p)/p$, which is the threshold of posterior beliefs needed to convince the peasant to support. At points on or above the dashed line, the peasant believes ω_1 is sufficiently likely that he will support after seeing s_1. At any point in the gray area, the peasant does not believe strongly enough and so does not support even when s_1 occurs.

Start by considering the case where the hazard rate is constant (panel B). The probability of rain may be high (shown by the blue line) or low (brown line). Because the hazard rate does not change, the conditional probability that it rains whether you pray or do not pray will be the same. Hence in panel B, the ratio of posterior beliefs π_1/π_0 always equals one as prayer is uninformative.

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

This property holds regardless of whether a place has high or low average rainfall. 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). Therefore our model predicts that groups that face constant hazard rates will not have persuasive prayers regardless of the average level of rainfall.

Now consider the case when the hazard rate is increasing (panel A). In this case the church's prayer can induce a variety of beliefs. Here we describe some distinct prayer policies and the posterior beliefs they induce. The policies are labeled on panel C.

N **Never praying** ($\tau_0 = \tau_1 = +\infty$). This strategy induces beliefs $\pi = (p, p)$. This case would be completely uninformative, as with a constant hazard rate. If the Church never prays, the peasant never learns.

A **Always praying** ($\tau_0 = 0$ and $\tau_1 = +\infty$). This strategy induces beliefs $\pi = (0, 1)$. The church fully reveals whether the distribution of rain with prayer is identical to the Peasant's prior belief about the distribution of prayer without rain.

E **Early praying** ($\tau_0 = 0$ and $\tau_1 < \infty$). This strategy induces beliefs $\pi = (0, \pi_1)$ with π_1 increasing in τ_1 and $\pi_1 \to 1$ as $\tau_1 \to \infty$. If God does not answer prayers, the peasant will learn this with certainty, when the church stops praying before rain occurs.

L **Late praying** ($\tau_0 < \infty$ and $\tau_1 = \infty$). This strategy induces beliefs that lie on the top horizontal line $(\pi_0, 1)$, with π_0 increasing in τ_0 and $\pi_0 \to 0$ as $\tau_0 \to 0$. If God does answer prayers, the peasant will learn this with certainty, since it will eventually rain.

I **Intermediate praying** ($\tau_0 < \infty$ and $\tau_1 < \infty$). This strategy induces beliefs in the triangle above the 45-degree line with $0 < \pi_0 < 1$ and $0 < \pi_1 < 1$. As before, π_1 is increasing in τ_1 and π_0 is increasing in τ_0. This policy is never fully revealing in either state.

The optimal prayer policy.—We are now prepared to state the main result.

Proposition 2 (Increasing hazard rate)**.** *If $h(t)$ is strictly increasing, then the optimal policy for the church is **late praying** with $T^* = \left(F^{-1}(1-2p), \infty\right)$.*

Proof. The objective of the church is to maximize the probability of rain during prayer among all experiments that are sufficient to induce support. The church's objective is the unconditional probability of signal s_1 (rain during prayer) subject to the peasant supporting after this signal occurs. The probability of s_1 is $\bar{q}_1(\pi) \equiv p\pi_1 + (1-p)\pi_0$. The peasant will support if and only if $l_1 \geq 1$, which is satisfied with equality at $\pi_0 = \pi_1 p/(1-p)$. Substituting this constraint in the church's objective yields $\bar{q}_1(\pi) = p\pi_1 + (1-p)\pi_0 = p\pi_1 + p\pi_1 = 2p\pi_1$ which is maximized for $\pi_1 = 1$ and in turn implies $\pi_0 = p/(1-p)$. This optimal policy corresponds to the point $\pi^* \equiv (p/1-p, 1)$, labeled L in panel C. For this experiment, the ex ante probability of observing s_1 is $2\pi_1 p = 2p$. Since it always rains, signal s_0 must be observed with the complementary probability $1-2p$. The optimal policy is then $T^* = \left(\tau_0^*, \infty\right)$ with $\tau_0^* = F^{-1}(1-2p)$ so that it rains prior to prayer with probability $1-2p$. □

Under the optimal policy the church will start praying and keep going until it rains. The church wants the peasant to support as often as possible, but there is a trade-off involved in doing so. If the church starts to pray early, at a point such as $L2$ in panel C, then the peasant will not be convinced enough to support. If the church starts to pray late, as at a point such as $L1$ in panel C, then the probability of rain when it prays will be far higher than when it does not. However, the church is in a sense over-convincing the peasant; if it prayed 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 L balances the credibility of the church—the need to persuade—against how often the peasant can be persuaded.

We solve for the optimal policy when facing the hazard in Figure 2, panel A as a numerical example. The distribution of rain is assumed to follow a quadratic hazard function:

$h(t) = \alpha_0 + \alpha_1 t + \alpha_2 t^2 = 0.3 + 0.2t + 0.3t^2$, with cdf $F(t) = 1 - e^{-\left(\alpha_0 t + \frac{\alpha_1}{2} t^2 + \frac{\alpha_2}{3} t^3\right)}$. The hazard rate is increasing for $t \geq 0$ so it is optimal to start praying at τ_0^* and never stop. Let $p = 0.3$. Using $p = 0.3$ and inverting the cdf we get $\tau_0^* = F^{-1}(0.4) = 1.01$. With this strategy, it will rain while the church is praying 60% of the time. The strategy creates a high hazard rate conditional on praying h_1, shown by the green line, and a low hazard rate conditional on not praying h_0, shown by the red line.

The model therefore provides several 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, people facing a persuasive natural experiment, with an increasing hazard rate, are more likely to pray for rain.

3 Prayer for rain in Murcia, Spain

This section documents that the pattern of prayers for rain in Murcia, Spain is consistent with our model. Murcia is an ideal test case because we have over 200 years of church records on prayers for rain. We show that the church prays such that its prayers are highly predictive of subsequent rainfall.

3.1 Context

Murcia is a city in the south of Spain near the Mediterranean sea. Governance in Murcia historically has been divided between the Catholic church, led by an ecclesiastical council, and a secular municipal council.

The Catholic church has practiced *pro pluvia* rogations—prayers for rain—since at least 511 (Guirado and Espín-Sánchez, 2021). In this respect it is not unusual; other branches of the Catholic church near the Mediterranean also have such ceremonies (Martín-Vide and Vallvé, 1995). The rogations are an escalating series of prayers offered to induce rainfall: the more severe a drought, the greater the intensity of prayer (Gil Guirado, 2013). A basic rogation may consist of a dedicated mass to call for rain, the solicitation of collections or prayer to figures representing particular saints or virgins. The next level of rogation would add a public procession and the exhibition of relics such as the *lignum crucis* (wood of the cross). If this prayer fails, or the need is desperate, the church may further elevate prayers by hosting multiple public processions or praying to multiple figures simultaneously. For larger or more elaborate ceremonies the church may require payment, either through the collection of alms or from the municipal or ecclesiastical councils.

The rogation cycle is always decided on by the church. The municipal council may appeal to the church to begin rogations, on behalf of the people, but the church decides when to begin prayers and what prayers to use. Typically the prayers within a cycle escalate until the rogations succeed in eliciting rain or, on occasion, are deemed hopeless.

Cycles can be simple. Consider the cycle beginning on November 13th of 1739. The ecclesiastical council requested a prayer. The church prayed the next day, taking a collection for rainfall. While the municipal council does not record rainfall immediately, the church proposed a prayer of Thanksgiving on November 27th, to which the municipal council assented; we therefore infer it must have rained in the meantime, or else there would be nothing for which to give thanks. The municipal council records then show multiple notable rainfalls from early December of 1739 into January of 1740.

Cycles can be complex. Consider the cycle beginning in January of 1782. On January 8th, the municipal council requested the church to pray, both because drought was harming agriculture and because the scarcity of water degraded water quality and thereby harmed public health. On January 12th the church assented and took a collection for rain without any particular dedication. Rain did not come. On January 25th, the ecclesiastical council itself proposed a prayer, with the municipal council assenting the next day. The prayer was done starting on 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 initiated a prayer itself, with a public procession through the streets, on February 3rd, and seven masses dedicated to the Virgin of Fuensanta. 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 Virgin of Fuensanta, the object of the successful prayer. It rained again later that week.

Cycles can, of course, fail. In January and February of 1709, at the request of the municipal council and amidst discontent in the population, the church offered four separate prayers for rain, of varying intensity, dedicated to the Virgin of Fuensanta, the Virgin of Los Remedios (a title of the Virgin Mary), and ultimately Jesus of Nazareth. Rain did not come. On March 19th the church acknowledged its failure with a mass closing the rogation cycle (this event is explicitly recorded, in our data, as a mass "without the benefit of rain").

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. A manual in the 19th century 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). The church was sometimes blunt in the quid pro quo that it offered for its intervention. On January 3rd, 1651, for example, priests asked the city council to pay two golden crowns in order to return images to their places in the church. Without these images, 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). We focus on the timing of prayer as this is the object of our theory and we expect timing is the most important dimension of the church's signaling actions.

3.2 Data

Our data come from ecclesiastical and municipal records of Murcia. While we collected data on rogations from 1600 into the 20th century, we restrict our sample to end on

December 31st, 1832. In 1833 the abolition of the tithes sharply reduced the church's ability to collect taxes, and thereby its funding and influence.[6] While rogations continued the cycle appears to have changed and prayers grow more infrequent after this time (Guirado and Espín-Sánchez, 2021).

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 are *Prayer last month* $(= 1)$, a daily indicator for whether 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. We exclude, from this measure, prayers of thanksgiving that were offered without the benefit of rain.

The data from the municipal council include the date the municipal council asked for a prayer and records of notable rainfall events. The rainfall records indicate the intensity of rain, whether it was weak, moderate or heavy. The great advantage of this measure is that the municipal council records are independent of the church, and so there is no potential for 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. 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 rainfall series of from 63 to 97 years, allowing accurate estimation of the daily rainfall hazard.

[6]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). These events were driven by reasons aside from the efficacy of rainmaking.

3.3 Rainfall hazard estimation

We show in this part that the hazard of rainfall in Murcia is increasing after a dry spell. As described 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. We therefore present hazard estimates both with a non-parametric, Nelson-Aalen estimator and a semi-parametric cubic spline estimator. The estimation procedure described here for Murcia will be followed exactly in Section 4 below for our global data on rainfall, so we lay it out in some detail.

Let t be the number of days between rainfalls. For example, if it rains on Monday and again on Thursday, then $t = 3$. 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 at any given time, conditional on a certain spell having passed without 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 $S(t) = 1 - F(t)$.) In the data we use i to index a spell of length t_i in ascending order $i = 1, \ldots, m$ for m distinct spell lengths. Let d_i be the number of rainfall events (failures) at time t_i and n_i the number of spells at risk just before t_i. The Nelson-Aalen estimator of the hazard is made in two steps. First define the cumulative hazard:

$$H(t_j) = \sum_{t_i \le t_j} \frac{d_i}{n_i}.$$

Then calculate the hazard estimate per unit time at any time t_j as

$$h(t_j) = \frac{H(t_{j+1}) - H(t_j)}{t_{j+1} - t_j}.$$

This estimator has the advantage of being completely non-parametric with respect to the distribution of periods without rain and therefore the hazard function. The main disadvantage of this estimator is that is consistent only as the number of observations at each unique failure duration becomes large (Aalen, 1978). In any finite sample there are likely to be few observations, and hence very imprecise estimates, near the maximum spell length. We are especially interested in the probability of rainfall after a long dry spell. For this reason, while we display Nelson-Aalen estimates as a basis for comparison, we use a semi-parametric approach for our main estimates of the hazard function.

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

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

where $v_j(t)$ is the basis function

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

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. We set the knots separately for each weather station based on the distribution of dry spells at that station.[7] The function is constrained to be linear beyond the boundary knots.

[7] 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}.

There is no censoring in the data as all spells end in rainfall. To fit hazard model estimates 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 for the purpose of hazard estimation.

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

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

The arguments of the log likelihood for each spell observation are calculated from the log cumulative hazard (1). 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 "natural experiments" around the world.

Hazard function estimates for Murcia.—This part shows that the hazard rate in Murcia is increasing, which is the condition, in our model, for the church to be persuasive. The results of the hazard estimation for Murcia are shown in Figure 3. The four panels plot hazard estimates using rainfall data from the city of Murcia and three surrounding towns in the same region, each about 15 miles distant. On each panel, the hollow circles show non-parametric Nelson-Aalen estimates of the hazard rate. The fitted red curve gives a cubic spline fit to the hazard rate by maximum likelihood as described in Section 3.3.

The main result from the figure is that the hazard rate in Murcia is increasing after a 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 is estimated to increase significantly, until it equals or exceeds the higher hazard just after it rained. 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.[8]

[8]The most common parametric hazard forms, such as the Weibull distribution of failure times, impose

The fluctuations in the hazard function over time are large enough to be meaningful. The hazard rate after a long dry spell is roughly double the hazard rate two months after rainfall. A long dry spell, at the 99th percentile, is around 120 to 140 days for these different towns. At this interval, the hazard rate of rain in a day is about 0.05. Suppose that rainfall across days were independent (which is not quite true, given that the hazard is not flat). Then a hazard rate of 0.05 implies that the probability of rain in a given week is 30%. With the hazard derivative as measured, the probability of rain in a week at this point in the distribution is increasing by about 1 percentage point (3.6%) per week.

3.4 Prayer and rainfall

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

Let $Rainfall_t$ indicate a significant rainfall on a given day 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 regressions like

$$Rainfall_t = \beta_1 PrayerLastMonth_t + \delta_m + \varepsilon_t$$

where $PrayerLastMonth_t$ equals one if there was any rainmaking prayer in the period $t \in (-30, -1)$ and δ_m are month-of-year fixed effects. The regression is at the daily level with data from 1600 to 1833. We estimate Newey-West autocorrelation consistent standard errors using a lag parameter of 30 days.

Table 8 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

that the hazard must be monotonic.

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 $Prayer\ of\ thanksgiving_t$ as the dependent variable are larger because this variable is more commonly recorded by the church than $Rainfall_t$ is by the municipal council, suggesting church records of significant rainfall events are more complete.

Figure 4 reports coefficients from regressions that include lagged prayers up to 12 months ago as explanatory variables. The two panels use $Rainfall_t$ (panel A) and $Prayer\ of\ thanksgiving_t$ (panel B) as the dependent variables. The figure shows that prayer last month 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 **??** to demonstrate that prayer Granger-causes rain. A possible objection to 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 Table **??**. 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 hazard function of rainfall is increasing after a long dry spell in Murcia (Figure 3). 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 8, Figure 4). The data from Murcia support the mechanism of our model but ultimately describe only a single case. In order to test whether this mechanism is predictive of religiosity more generally we next turn to describing the global practice of rainmaking.

4 The global prevalence of prayers for rain

This section describes rainmaking practice and documents the global prevalence of prayers for rain.

4.1 Context

Rainmaking is arguably the leading example used in anthropology to illustrate the evolution of human belief systems. Frazer (1890) created the modern, systematic study of human belief in anthropology. Frazer argues that beliefs evolve, from the magical to the religious and ultimately the rational, but that *all* of these systems are characterized by a common belief that worldly events follow a set of laws. Each belief system also shares the common goal of applying these laws to explain and control nature. The difference between stages is just in the nature of the laws that nature is thought to obey. Rainmaking is a signal example, common in both magical belief systems and organized religion, of human attempts to control nature. Rainmakers presume a natural law in which supernatural forces respond to human appeals.

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 women and women (called day keepers) could determine which deity. 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.[9] Any small deviation in the ceremony will render it ineffective and possibly dangerous. For example, the chant has no power if translated into English.

Herero, Namibia. The Herero are a Bantu ethnic group that resides primarily in modern Namibia. They practice rainmaking with a ritual that is the same as the neighboring Tswana (Schmidt, 1979). A subordinate chief initiates the ritual by bringing a black ox to the paramount chief at sunrise and saying "I have come to beg rain, Chief, with this calf."

[9] 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!"

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[10], 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

[10]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.

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 five rainmaking methods over a period of 20 days. The Emperor Zhenzong asked a monk to make rain; the monk used a dragon image to summon rain, with success; Zhenzong then remarked "[the method] is unconventional, yet for saving people from drought, it is not to be avoided." In this context, punishing the dragon is the extreme culmination of a rainmaking sequence "where the coercive force increases in magnitude" as time passes without rain (Cohen, 1978). As part of this escalation, 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 at least 600 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 14 and 22 centuries, respectively (Guirado and Espín-Sánchez, 2021; Hong, Slingerland and Henrich, 2021). 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)). Failures of rainmaking are often met by an alternation or adaptation of the practice, rather than its abandonment. For example, when rainmaking in Spain faltered, the church would often select different virgins or saints to which to pray next time. The very specificity of rainmaking rituals provides many candidate explanations for their failure.

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

The people appeal to a religious authority who can choose to ignore their appeal or to grant it and start the rain ritual. This decision is often made with explicit 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) Another extant

Chinese rainmaking text specifies a complete rainmaking strategy contingent on the date of the year and the prior results.

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 much 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.

Our model provides an explanation for several of these commonalities. 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. The initiation of rainmaking should be reserved for a severe drought, after time has passed without rain, to increase the chance of success. And rainmaking should allow for escalation in order to follow the church's optimal policy, in an environment with an increasing hazard, of continuing to pray after it has started to do so.

4.2 Data

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

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 (2020).

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 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 covering different ethnic groups, 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 $Rain\,ritual_g$ equal to one if any record was found that a given group g 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.

Table 8 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 1209 of the 1290 groups in the augmented version of the ethnographic atlas. Globally, 39% of ethnic groups are found to practice a rain ritual. This confirms the perception of anthropologists that rainmaking is widespread. A large fraction (32%) of ethnic groups in the atlas are in Africa though there are groups around the world.

Table 8, 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 A discusses the details of the data construction. 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 3). Around the world, 71% of ethnic groups have hazard functions that are estimated to be increasing after a dry spell, as we estimated was the case for Murcia.

Figure 1 maps the prevalence of rainmaking around the world (panel A). Rainmaking is practiced on every continent to differing extents. 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 (Murcia being an example) than in central or northern Europe; (iii) rainmaking appears less common in areas with very abundant rain, such as Amazonia and the Pacific Northwest of the United States; (iv) rainmaking practice varies within fairly narrow regions including, for example, in the Southwestern United States, East Africa and the Western Pacific.

4.3 Rainfall hazard estimation

This part describes our estimates of the rainfall hazard function for ethnic groups around the world. The estimation method is the same as described for Murcia in Section 3.3.

Figure 5 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. 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 inhabited land 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 nearly a year 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 Heroro 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 3). 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 (Figure 3), though in both cases the hazard at this point increases at a similar rate.

Figure 1, 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.

5 The climate as a determinant of religious belief

This section tests whether the rainfall process predicts rainfall prayers in a manner consistent with our model. We relate rainmaking to the climate of each ethnic group as well as their traditional mode of subsistence.

5.1 Regression specification

The main regression specification is of the form

$$Rain\ ritual_g = \beta_1 HazardIncreasing_g + \beta_2 AgricIntensity_g + \mathbf{X}_g' \alpha + \delta_c + \varepsilon_g. \tag{2}$$

The variables $Rain\ ritual_g$ and $HazardIncreasing_g$ are displayed in Figure 1 and discussed above. The variable $AgricIntensity_g$ measures the agricultural intensity of a group. We use both continuous and categorical measures of intensity. All specifications include continent fixed effects δ_c.

The vector $\mathbf{X}_g$ contains geographic controls for each ethnic group. We draw our control sets 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). 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 correlation in geography can induce spurious correlation between historic practices and modern outcomes (Kelly, 2020). We follow the recommendations for the best practices in this literature. All of our specifications include continent fixed effects and the detailed controls for geography as discussed above. We report Conley standard errors to account for spatial correlation in ε_g and discuss the robustness of our inference to alternate choices of the spatial bandwidth with the estimates.

5.2 Estimates of the determinants of rainmaking

The mode of subsistence.—The first hypothesis we test is whether rainmaking depends on an ethnic group's mode of subsistence. The examples in Section 4.1 suggest that rainmaking may be less prevalent in groups with a more reliable or less rainfall-dependent food supply. The ethnographic atlas allots ethnic groups into a measure of agricultural dependence that estimates how much of that group's subsistence came from agriculture. The scale of this measure ranges from 0 to 100%. The omitted categories of subsistence include animal husbandry, fishing, and hunting and gathering.

Table 3 estimates (2) with agricultural intensity measures as the main explanatory variables. 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 a binary measure of whether more than 45% of subsistence comes from agriculture. An agriculture-dependent ethnic group is 0.095 (standard error 0.050) 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). The column 3 estimates show a similarly large and positive effect of agricultural dependence on rainmaking when dependence is measured with a continuous variable. Increasing dependence from 0 to 50% is estimated to increase rainmaking by 14 percentage points.

The relationship between specific investments in agriculture and rainmaking suggest that rainmaking responds to the risk created by agricultural investments. 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. The coefficient on a dummy varible for intensive irrigated agriculture is 0.33 (0.075), and on intensive agriculture 0.22 (0.072). By the first estimate, intensive irrigated agriculture doubles the baseline probability that a non-agriculture-dependent group practices a rain ritual. By contrast, shifting agriculture has a lesser effect (0.12 pp) and "casual" agriculture has a small and statistically insignificant effect on the practice of rain rituals.

We interpret these estimates as showing that agricultural intensity is a cause of higher demand for control of the weather. 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 dependent on hunting or fishing. Within those that practice agriculture, correspondingly, we find a weaker effect of extensive or shifting agricultural practice on rainmaking. The caloric productivity gains in agriculture may be offset by a Malthusian expansion of population. Therefore groups that make specific agricultural investments in cropping or irrigation for one place are more dependent on rainfall for subsistence, even if those groups may have higher productivity on average.

The depth of political organization.— The second hypothesis we test is whether rainmaking is correlated with the complexity of an ethnic group's governance. Swanson (1960) coded ethnographic data on religion and argued that more complex societies were more likely to believe in high gods. A "high god" or "big god" is one that prescribes a code of moral behavior and intervenes in human affairs to enforce it. 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 3, columns 5 and 6 present regressions of whether an ethnic group practices a rain ritual on the number of levels of jurisdictional hierarchy in the group's political organization. The rain ritual variable, being newly collected, has not been used in the literature on the relation between religion and complexity. The column 5 measure is continuous and column 6 categorical. We find that higher levels of jurisdictional hierarchy–vertical layers of political organization–are associated with a much greater tendency to practice rainmaking. For example, in the column 6 estimates, having 3 levels of hierarchy is associated with a 24 pp (standard error 11 pp) increase in the tendency to practice a rain ritual, relative to the omitted category of groups with no levels of hierarchy. The effect size is comparable to that of practicing intensive agriculture.

While this result, like those in the prior literature, is a correlation, it provides some color to the relationship between religion and complexity. Rainmaking is common to both traditional (e.g., Cherokee or Herero) and highly organized (e.g., Catholic or Islamic) religious practice. The fact that greater complexity is associated with a greater practice of rainmaking suggests that it is not the "high" nature of "high gods" that induces a correlation between complexity and religious practice. This correlation is observed even for a traditional religious practice that cuts across levels of religious evolution. Our finding in this way is consistent with studies that suggest the distinction between traditional and moralistic religious practice is not sharp. For example, case studies show that so-called small, animistic gods were also viewed as imposing a moral code, so this property should not be reserved for the "high gods" (Singh, Kaptchuk and Henrich, 2021). To the extent this distinction is not clear, it becomes harder to causally attribute growth in social or political complexity to the worship of high gods.

Whether the environment allows persuasion.—The analysis has shown that rainmaking is associated with a group's mode of subsistence and political organization. If we take the mode of subsistence as exogenous to religious practice, we may interpret that intensive agriculture increases the demand for rainmaking because it leverages a group's dependence on rainfall.

The main prediction of our model is not that rainmaking should respond to demand, but 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 now augment the regressions above by adding an indicator for whether an ethnic group faces as increasing hazard rate as an explanatory variable.

Table 4 reports the results. The specifications from left to right cumulatively add the control variables indicated in the footer: only continent fixed effects (column 1), and then climate and geography and topography controls (columns 2 and 3). In columns 4 through 6 we additionally add categorical controls for mode of subsistence, jurisdictional hierarchy, and both of these sets, drawn from Table 3. All specifications report Conley standard errors with a spatial bandwidth of 1000 km.

The main result is that ethnic groups facing an increasing hazard of rainfall have a markedly higher probability of practicing rainmaking. For ethnic groups facing a decreasing hazard, the probability of rainmaking is 0.30. Facing an increasing hazard rate is estimated to increase the probability of rainmaking by 0.13 (standard error 0.039) (column 1), or 43%. This estimate conditions only on continent fixed effects. The estimated effect of an increasing hazard rate is invariant to the set of controls used (looking across columns 1 to 3). 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.

The effect of the increasing hazard rate on rainmaking practice is very similar when adding as explanatory variables the mode of subsistence or jurisdictional hierarchy from Table 3. We find that an increasing hazard rate increases the probability of rainmaking by 0.15 (standard error 0.039) with both of these controls, slightly larger than but not distinguishable from the prior point estimate. The effects of agricultural intensity are similar, or slightly stronger, than estimated in the prior table when including all of the explanatory variables simultaneously (column 6). The correlation of jurisdictional hierarchy with the practice of a rain ritual is still present but somewhat attenuated relative to the Table 3, column 6 estimates.

Robustness checks and discussion.—An increasing hazard rate is highly predictive of the practice of rainmaking. A naïve model may predict that people in dry climates pray for rain. In the estimates of Table 4, we control for the mean and standard deviation of rainfall but find that the coefficients on these controls are uniformly small (not reported).

Appendix Table **??** shows that higher levels of rainfall are associated with a lower probability of rainmaking when the increasing hazard rate indicator is not included as a control. However, when both variables are included, the effect of mean rainfall on rain ritual practice is attenuated and no longer significantly different from zero. It is not the level of rain that matters, but whether the pattern of rainfall poses a natural experiment that allows rainmaking to be persuasive. This result supports a view that groups adapt to permanent differences in their average climates.

Appendix Table **??** shows that the precision of our estimates is robust to changes in the spatial bandwidth used to calculate the standard errors. We report bandwidths between 100 and 4000 km and find that even over this large range there is little change in the spatial standard error on our main variable of interest.

The estimates show that rainmaking is not only a matter of need but also of when persuasion can be effective. We interpret this main result as showing that climatological norms that favor persuasion cause a greater level of religious belief. We are confident in giving this result a causal interpretation for two reasons. First, the climate facing an ethnic group in their traditional homeland is exogenous. The only exception to this rule would be for selective migration of a group; we show, correspondingly, that groups that practice mobile or rotating forms of subsistence are less likely to practice rainmaking (Table 4). Second, our model gives a clear mechanism for why an increasing hazard rate should induce greater belief. Under an increasing hazard rate, the optimal strategy of the church induces belief because prayer is associated with a higher probability of rainfall after a drought, when it is most needed. The documentary evidence from Murcia and from select other groups supports the idea that the church may follow such a strategy in practice.

6 Conclusion

We study the determinants of religious belief using a theoretical model and empirical evidence from both a case study of Murcia, Spain and a global cross-section of ethnic groups. In the model, the people will believe in a religion to the extent that the church can credibly intervene in nature. Whether such intervention is credible, in turn, depends on the natural experiment posed by rainfall, which constrains the experiments the church may construct.

We find evidence consistent with our model in several respects. First, in Murcia, the church's strategy of praying for rain appears consistent with our optimal strategy, when the rainfall hazard is increasing, of praying late and never stopping. Second, the prayers that result are found to be highly predictive of subsequent rainfall. Prayer Granger-causes rain. Third, in the global ethnographic data, we find that ethnic groups are 43% more likely to practice rainmaking when they live in an environment that allows persuasion.

One advantage of studying rainmaking as a form of religious belief is the simultaneous breadth and specificity of rainmaking practice. Breadth, because rainmaking is a feature of religions of all kinds, and all over the world: we show that 39% of ethnic groups traditionally practiced rainmaking, and this estimate is likely a lower bound. Rainmaking is observed in all major religious traditions. Specificity, because rainmaking has a clear object: to make rain. We show that this specificity means that features of the environment ought to dictate when rainmaking is able to persuade. That rainmaking has such a specific object makes it a useful practice for studying more generically whether religious belief is instrumental, because we can connect rainmaking to exogenous features of the environment.

Our empirical work follows the plan laid out by Frazer (1890). Frazer systematized the study of belief. He 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" then we may infer the motives underlying any particular custom. He 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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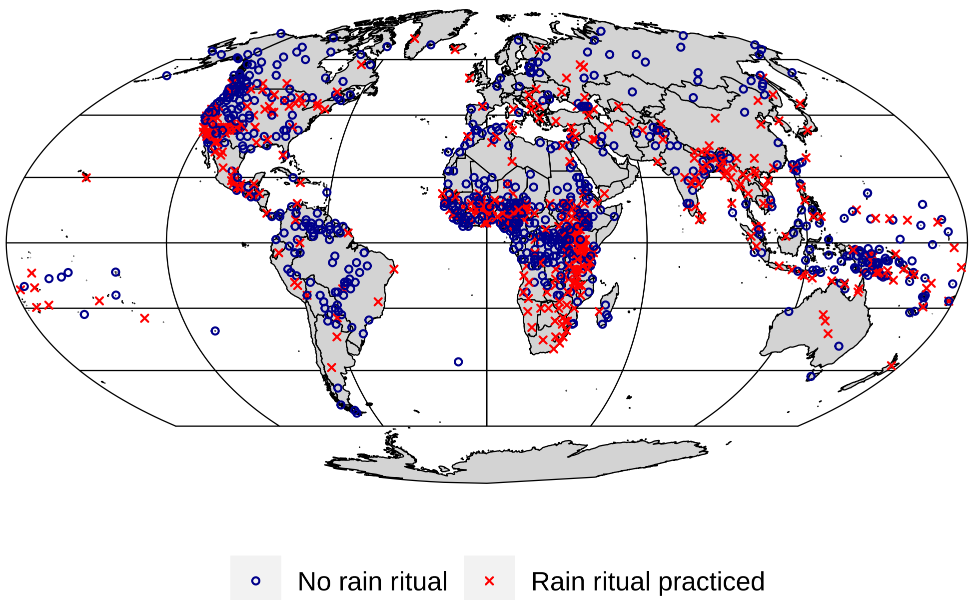
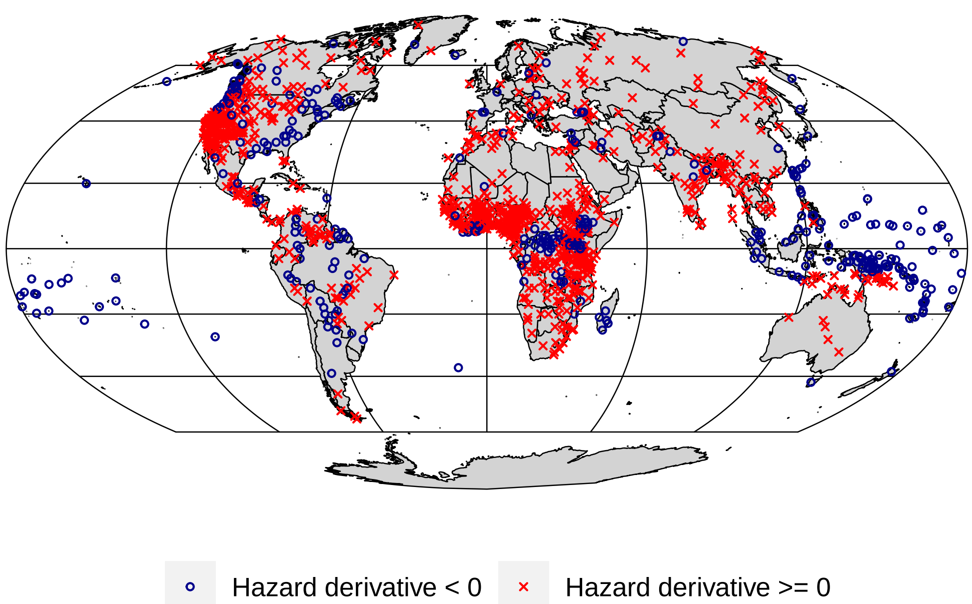
7 Figures

Figure 1: Global prevalence of rain rituals

A. Rain ritual

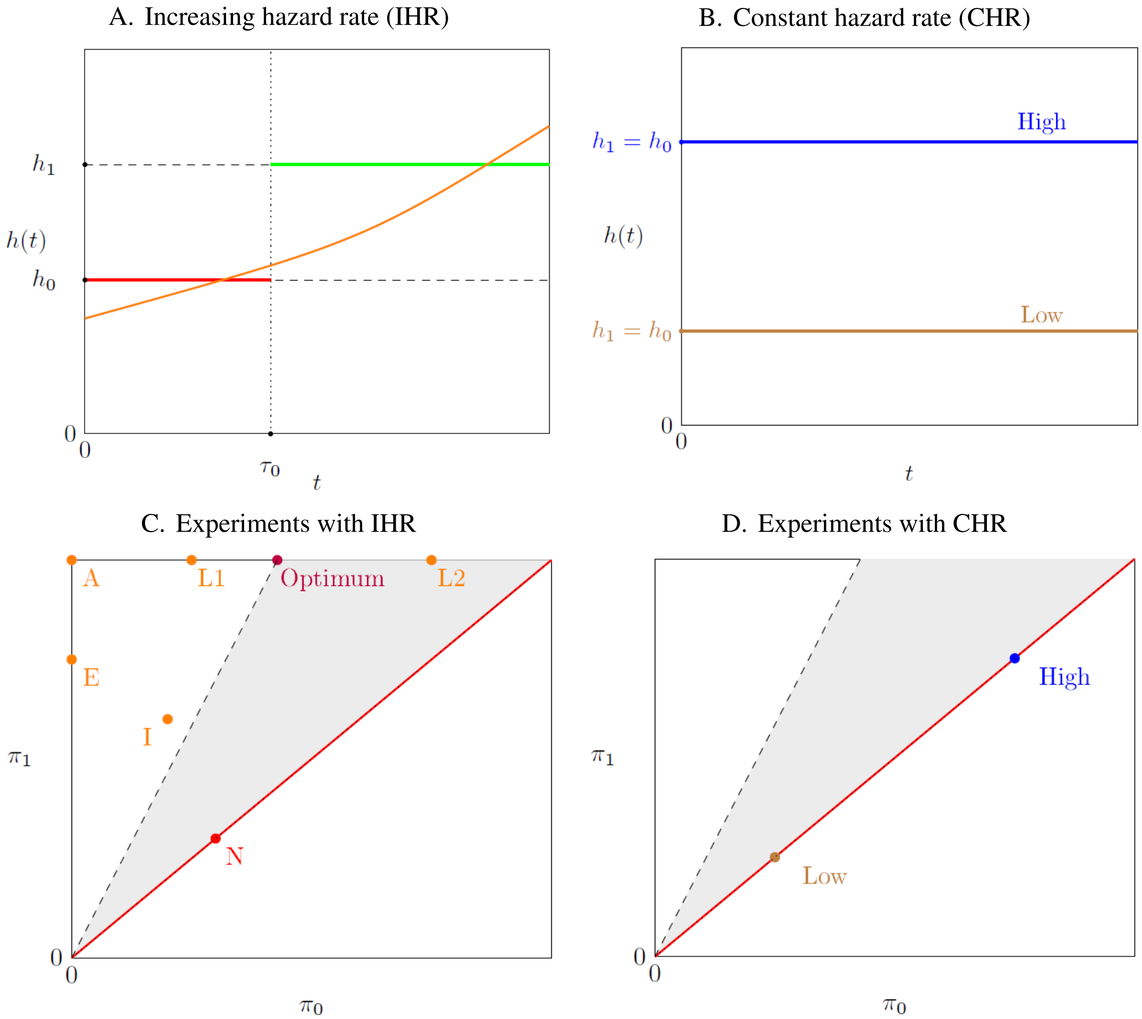


B. Hazard rate increasing



This figure shows the geographic location of ethnic groups for which we have rain ritual data. The blue circles represent groups with no rain ritual, whereas those with red stars represent those with a rain ritual reported. These data come from the ethnographic atlas, with rainfall dummies, dataset.

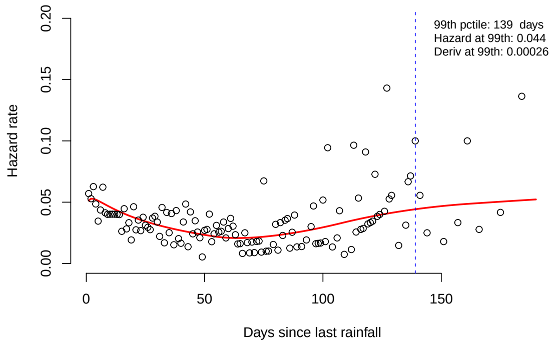
Figure 2: The hazard of rainfall as a constraint on persuasive experiments



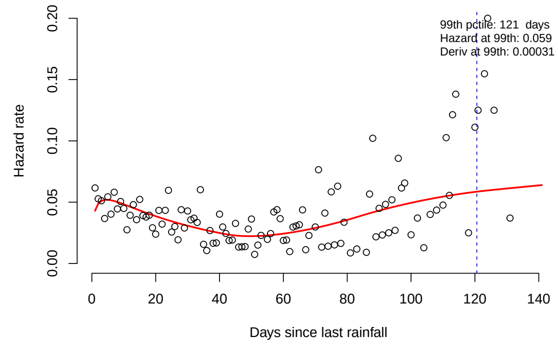
The figure shows examples of the experiments created by different rainfall patterns and prayer policies. The top two panels plot the rainfall hazard rate against time on the horizontal axis. In the first case, the hazard is increasing (panel A). In the second case, it is flat, at either a low or a high level (panel B). The bottom two panels plot the posterior belief $\pi_1(\omega_1|s_1)$ that God exists against the posterior belief $\pi_0(\omega_0|s_1)$ that God does not exist, after observing rain during prayer. The different points on the lower two panels describe the posterior beliefs induced by different prayer strategies of the church.

Figure 3: The hazard of rainfall in and around Murcia, Spain

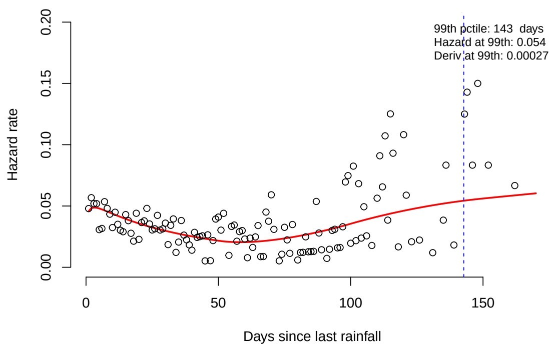
A. Murcia



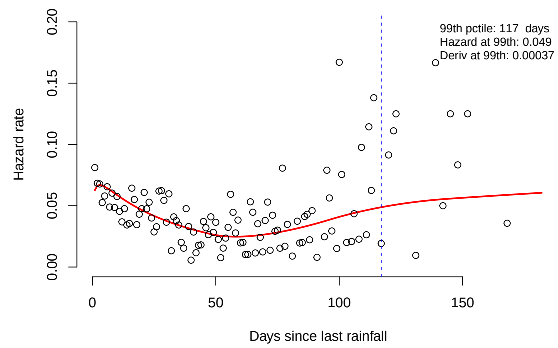
B. Blanca



C. Mula

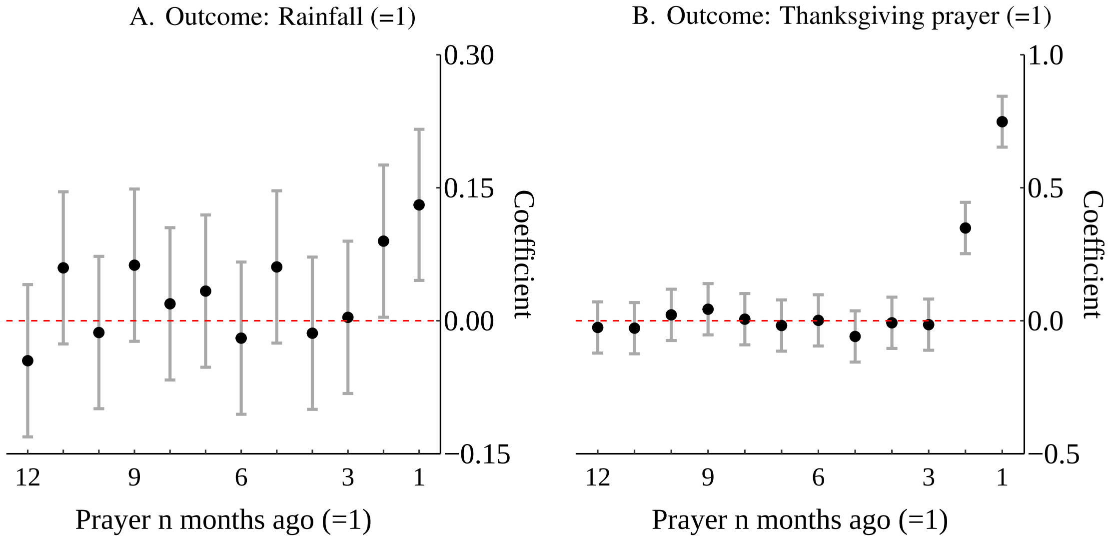


D. Alhama



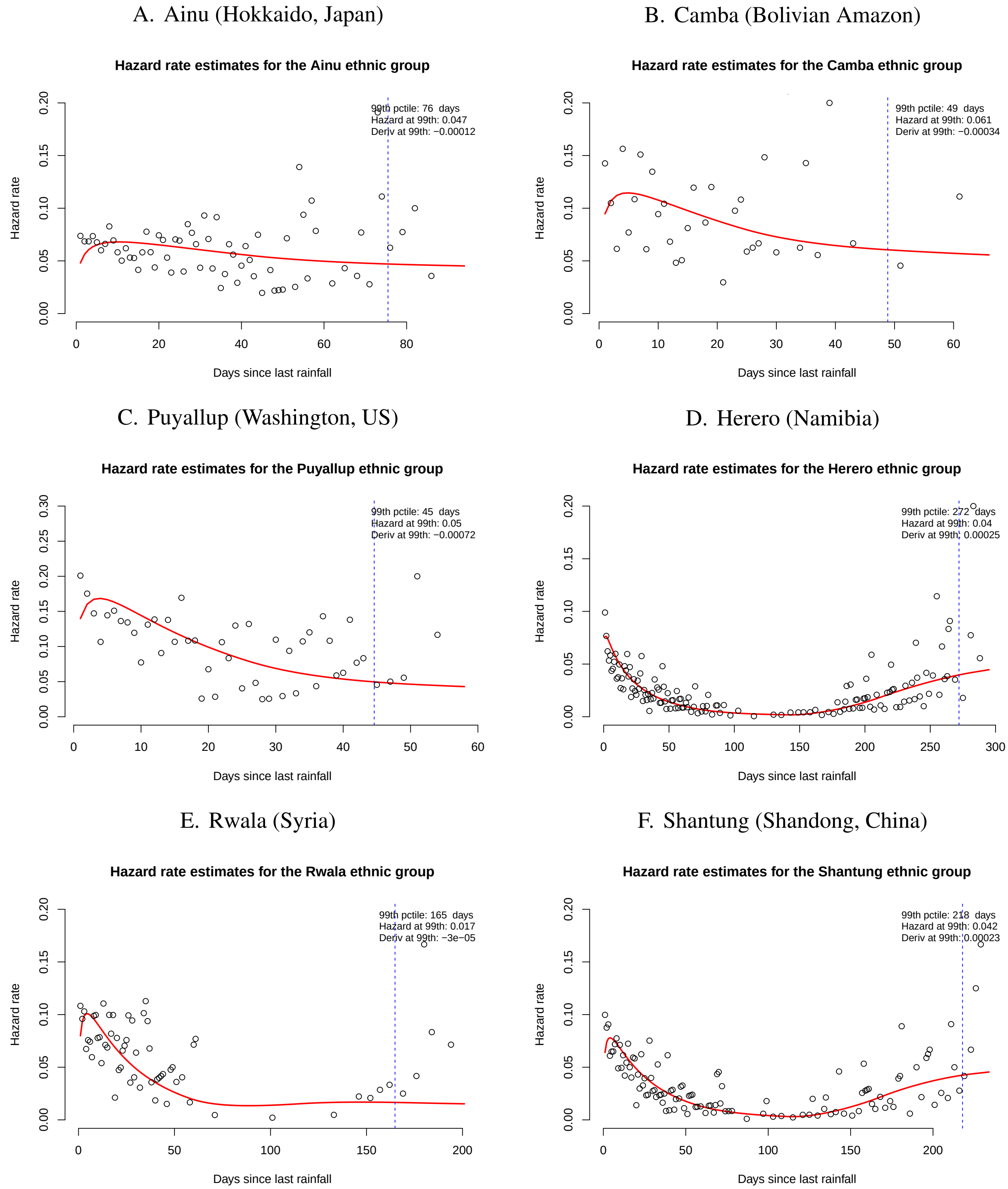
The figure shows estimates of the hazard of rainfall after a dry spell for Murcia, Spain and some surrounding towns. The rainfall data are available for 92 years (panel A), 63 years (panel B), 77 years (panel C) and 97 years (panel D). On each panel the circles provide non-parametric Kaplan-Meier estimates of the hazard rate. The fitted curve gives a cubic spline fit to the hazard rate by maximum likelihood as described in Section 3 3.3. 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.

Figure 4: Regressions of rainfall and prayer for rain on monthly lags



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.

Figure 5: Examples of the rainfall hazard around the world



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

8 Tables

Table 1: Regressions of rainfall and prayer for thanksgiving on rain and recent prayer for rain

	Rainfall (=100)			*Prayer for thanksgiving (=100)*		
	(1)	(2)	(3)	(4)	(5)	(6)
Prayer last month	0.187***	0.145**	0.131**	0.873***	0.799***	0.748***
	(0.054)	(0.057)	(0.058)	(0.072)	(0.073)	(0.074)
Month effects		*Yes*	*Yes*		*Yes*	*Yes*
Month lags			*Yes*			*Yes*
Mean dep. var	0.203	0.203	0.203	0.257	0.257	0.257
Years of data	233.15	233.15	233.15	233.15	233.15	233.15
N	85,074	85,074	84,714	85,074	85,074	84,714

This table reports coefficients from regressions of rainfall from municipal council records and prayers for thanksgiving on rain and recent prayer for rain in Murcia. The dependent variables take on two values, either 100 for a rainfall event or prayer or 0 otherwise. Therefore the coefficient on "Prayer last month" is in units of percentage points. Newey-West standard errors are in parentheses with a lag parameter of 30 days. Statistical significance at certain thresholds is indicated by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 2: Summary statistics on Atlas and KNMI variables

	Obs. (1)	Mean (2)	Std. dev (3)	Min (4)	Pct50 (5)	Max (6)
Panel A: Atlas variables						
Rain ritual (=1)	1208	0.392	0.488	0.0	0	1.0
High gods(dummy)	1290	0.786	0.410	0.0	1	1.0
Africa (=1)	1290	0.336	0.473	0.0	0	1.0
Eurasia (=1)	1290	0.105	0.306	0.0	0	1.0
Mediterranean (=1)	1290	0.124	0.330	0.0	0	1.0
North America (=1)	1290	0.221	0.415	0.0	0	1.0
Pacific (=1)	1290	0.129	0.336	0.0	0	1.0
South America (=1)	1290	0.084	0.278	0.0	0	1.0
Agriculture dependent (=1)	1290	0.634	0.482	0.0	1	1.0
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: 3 levels (=1)	1291	0.034	0.182	0.0	0	1.0
Jurisd. hierarchy: 2 levels (=1)	1291	0.064	0.244	0.0	0	1.0
Jurisd. hierarchy: 1 level (=1)	1291	0.125	0.331	0.0	0	1.0
Jurisd. hierarchy: 0 levels (=1)	1291	0.264	0.441	0.0	0	1.0
Panel B: Geographic variables						
Elevation	1290	675.590	716.969	-35.0	428.50	5412.00
Ruggedness	1290	92.991	160.609	0.0	34.27	2192.18
Latitude	1290	15.370	22.699	-55.0	10.60	78.00
Longitude	1290	2.701	84.612	-179.3	13.00	178.68
Distance from river (km)	1290	289.337	932.395	0.0	69.32	9029.52
Distance from lake (km)	1290	521.148	972.081	0.0	287.19	9223.54
Distance from ocean (km)	1290	486.125	486.786	0.0	323.07	2575.23
Mean rainfall (annual, m)	1290	1.216	1.122	0.0	1.02	8.52
Mean temperature (daily, Celsius)	1290	20.356	9.018	-13.9	23.72	31.11
Hazard of rainfall after a dry spell	1277	0.048	0.033	0.0	0.04	0.44
Hazard derivative of rainfall after a dry spell	1277	0.000	0.002	-0.0	0.00	0.01
Hazard rate increasing (=1)	1291	0.708	0.455	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.

Table 3: Economic and political predictors of global rainmaking

	Dependent variable: Rain ritual practiced (=1)					
	(1)	(2)	(3)	(4)	(5)	(6)
Agriculture dependent (=1)	0.11**	0.095*				
	(0.049)	(0.050)				
Agriculture: dependence (cont)			0.0028***			
			(0.00093)			
Ag.: intensive irrigated (=1)				0.33***		
				(0.075)		
Ag.: intensive (=1)				0.22***		
				(0.072)		
Ag.: extensive or shifting (=1)				0.12*		
				(0.068)		
Ag.: horticulture (=1)				0.077		
				(0.092)		
Ag.: casual (=1)				−0.013		
				(0.086)		
Agriculture: missing (=1)				0.027		
				(0.076)		
Jurisd. hierarchy (cont)					0.095***	
					(0.022)	
Jurisd. hierarchy: 3 levels (=1)						0.24**
						(0.11)
Jurisd. hierarchy: 2 levels (=1)						0.20***
						(0.063)
Jurisd. hierarchy: 1 level (=1)						0.066
						(0.055)
Jurisd. hierarchy: missing (=1)						−0.035
						(0.039)
Continent effects	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Climate controls		*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Geography controls		*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Topography controls		*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Mean dep. var	0.39	0.39	0.39	0.39	0.39	0.39
Mean dep. var(agric = 0)	0.32	0.32	0.32	0.32	0.32	0.32
R^2	0.035	0.085	0.093	0.11	0.096	0.097
Observations	1209	1209	1208	1209	1209	1209

This table reports coefficients from regressions at the ethnic group level of whether a rain ritual is practiced on measures of agricultural intensity and jurisdictional hierarchy. Climate controls include mean temperature, a quadratic in mean temperature, the standard deviation of temperature, mean rainfall, a quadratic in mean rainfall, the standard deviation of rainfall; 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 4: Rainmaking by whether the environment allows persuasion

	Dependent variable: Rain ritual practiced (=1)					
	(1)	(2)	(3)	(4)	(5)	(6)
Hazard rate increasing (=1)	0.13***	0.13***	0.13***	0.15***	0.13***	0.15***
	(0.039)	(0.039)	(0.038)	(0.039)	(0.038)	(0.039)
Ag.: intensive irrigated (=1)				0.36***		0.31***
				(0.072)		(0.079)
Ag.: intensive (=1)				0.25***		0.20***
				(0.070)		(0.073)
Ag.: extensive or shifting (=1)				0.14**		0.11*
				(0.066)		(0.067)
Ag.: horticulture (=1)				0.088		0.070
				(0.090)		(0.091)
Ag.: casual (=1)				0.0064		−0.019
				(0.086)		(0.087)
Agriculture: missing (=1)				0.046		0.046
				(0.073)		(0.075)
Jurisd. hierarchy: 3 levels (=1)					0.23**	0.13
					(0.11)	(0.11)
Jurisd. hierarchy: 2 levels (=1)					0.20***	0.15**
					(0.062)	(0.061)
Jurisd. hierarchy: 1 level (=1)					0.068	0.041
					(0.055)	(0.054)
Jurisd. hierarchy: missing (=1)					−0.041	−0.016
					(0.039)	(0.042)
Continent effects	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Climate controls		*Yes*	*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	0.000	0.000	0.001	0.000	0.000	0.000
Climate controls		0.000	0.000	0.002	0.000	0.005
Geography controls			0.008	0.001	0.009	0.002
Topography controls			0.077	0.113	0.040	0.085
Mean dep. var	0.39	0.39	0.39	0.39	0.39	0.39
Mean dep. var (dec. haz)	0.30	0.30	0.30	0.30	0.30	0.30
R^2	0.039	0.070	0.089	0.12	0.11	0.13
Observations	1209	1209	1209	1209	1209	1209

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

A Appendix: Data

1.1 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 Guirado and Espín-Sánchez (2021). The CAC was an official document of Christian Spain dating 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.

1.2 Ethnographic Atlas

This dataset comes from the Ethnographic Atlas (Murdock, 1967), augmented with global practice of rainmaking rituals data collected by research assistants. For the collection of rain ritual data, a rain ritual is defined as a petition for rainfall, usually done through a religious authority.

This dataset covers characteristics of 1291 ethnic groups. In addition to the rain ritual practice indicator variable, the main variables used are those which describe agricultural practice and jurisdictional hierarchy. The Atlas contains the latitude and longitude of each ethnic group's traditional homeland.

1.3 Rainfall data

This data is obtained 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 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. We then collect the temperature and timeseries 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. The rainfall and temperature data are also aggregated to the annual level to construct climate norms, which we use as controls.

B Appendix: Supplementary results

Table B1: Rain ritual and mean rainfall

	Dependent variable: Rain ritual practiced (=1)					
	(1)	(2)	(3)	(4)	(5)	(6)
Hazard rate increasing (=1)				0.12^{***}	0.13^{***}	0.13^{***}
				(0.041)	(0.039)	(0.038)
Mean rainfall (annual, m)	-0.031^{**}	-0.074^{**}	-0.064^{*}	-0.014	-0.035	-0.026
	(0.015)	(0.037)	(0.035)	(0.015)	(0.038)	(0.037)
Mean rainfall squared		0.0064	0.0046		0.0018	-0.000029
		(0.0049)	(0.0049)		(0.0050)	(0.0051)
Continent effects	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Climate controls		*Yes*	*Yes*		*Yes*	*Yes*
Geography controls			*Yes*			*Yes*
Topography controls			*Yes*			*Yes*
p-value for a test of the joint significance of:						
Continent effects	0.000	0.000	0.000	0.000	0.000	0.001
Climate controls		0.000	0.000		0.000	0.000
Geography controls			0.010			0.008
Topography controls			0.082			0.077
Mean dep. var	0.39	0.39	0.39	0.39	0.39	0.39
Mean dep. var (dec. haz)				0.30	0.30	0.30
R^2	0.031	0.061	0.080	0.040	0.070	0.089
Observations	1209	1209	1209	1209	1209	1209

This table reports coefficients from regressions at the ethnic group level of whether a rain ritual is practiced on the rainfalll level.Climate controls include mean temperature, a quadratic in mean temperature, the standard deviation of temperature, mean rainfall, a quadratic in mean rainfall, the standard deviation of rainfall; 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 B2: Rain ritual and increasing hazard rate (Using radii from 100 to 4000 km radius for SE)

	Dependent variable: Rain ritual practiced (=1)					
Bandwidth:	(100km)	(250km)	(500km)	(1000km)	(2000km)	(4000km)
Hazard rate increasing (=1)	0.13***	0.13***	0.13***	0.13***	0.13***	0.13***
	(0.037)	(0.038)	(0.038)	(0.038)	(0.038)	(0.041)
Continent effects	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Climate controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Geography controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Topography controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Mean dep. var	0.39	0.39	0.39	0.39	0.39	0.39
R^2	0.089	0.089	0.089	0.089	0.089	0.089
Observations	1209	1209	1209	1209	1209	1209

This table reports coefficients from regressions at the ethnic group level of whether a rain ritual is practiced on the derivative of the hazard rate.Climate controls include mean temperature, a quadratic in mean temperature, the standard deviation of temperature, mean rainfall, a quadratic in mean rainfall, the standard deviation of rainfall; 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, 250, 500, 1000, 2000 and 4000 km. 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 * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table B3: Granger test: Rain on lag prayer

Res.Df	Df	F	Pr(>F)
85,081			
85,088	-7	3.200	0.002
85,060			
85,074	-14	4.381	0.00000
85,039			
85,060	-21	4.026	0
85,018			
85,046	-28	3.392	0
84,997			
85,032	-35	3.879	0
84,976			
85,018	-42	3.450	0
84,955			
85,004	-49	3.171	0
84,934			
84,990	-56	2.894	0
84,913			
84,976	-63	2.638	0
84,892			
84,962	-70	2.504	0
84,871			
84,948	-77	2.380	0
84,850			
84,934	-84	2.261	0
84,829			
84,920	-91	2.246	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 - in which rain is explained by lags of different orders (1 to 13 weeks) of prayer and rain - and the restricted model - in which rain is only explained by lags of rain.