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CAN RELIGIOSITY BE SENSED WITH SATELLITE DATA?

AN ASSESSMENT OF LUMINOSITY DURING RAMADAN IN TURKEY

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Abstract Social scientists have long been interested in how religious beliefs and practices impact and are impacted by socio-political and economic processes. Most recently, scholarly attention has focused on the interplay between religiosity and local actors, events, and institutions. Until now, measures of religiosity have relied heavily on self-reports in surveys, but these cannot always be safely collected and tend to be costly. Even where available, survey-based measures may be too obtrusive and are rarely representative of sub-national units. Here, I propose an inexpensive method that uses satellite imagery to unobtrusively estimate religiosity across small geographic units. I hypothesize that night-lights are affected by the behavior of fasting Muslims during Ramadan, especially in places where daytime activities are otherwise unchanged (i.e., where there is no "day-night inversion"). I explore and confirm the validity of this measurement strategy in the Turkish case, using a series of high-quality surveys and electoral results, representing 973 administrative districts. I conclude with a discussion of the external validity of this method and an overview of the ethical concerns raised by the use of remote sensing to estimate religiosity, in the Muslim world and elsewhere.

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Across the social sciences, religious beliefs and practices are commonplace as both inputs and outputs. In political science, religiosity—the strength of these beliefs and/or regularity of these practices—predicts policy preferences and vote choice (e.g., De La O and Rodden 2008), political participation and turnout (e.g., Jones-Correa and Leal 2001), and even violence (e.g., Neuberg et al. 2014). In economics, religiosity impacts investment, growth, and tax morale (e.g., Guiso, Sapienza, and Zingales 2003; Torgler 2006). As an output, religiosity is influenced by a number of socio-economic and political processes: from education (e.g., Glaeser and Sacerdote 2008) and inequality (e.g., Solt, Habel, and Grant 2011), to government policies, in both the short and the long term (e.g., Grzymała-Busse 2012; Margolis 2017).

In evaluating how religiosity impacts and is impacted by these different variables, existing models rely on estimates of religious belief and practice from self-reports in surveys (Finke and Bader 2017). As the number and quality of surveys has increased (Heath, Fisher, and Smith 2005; Lupu and Michelitch 2018), theoretical and empirical work has increasingly considered cross-national and sub-national models in religiosity (e.g., Barro and McCleary 2003; Gelman 2010; Campante and Yanagizawa-Drott 2015). Similarly, with a growing commitment to causal identification, new studies explore how religiosity is shaped by unexpected events, from financial and ecological crises (e.g., Immerzeel and van Tubergen 2013; Bentzen 2019), to civil and international conflicts (e.g., Carmil and Breznitz 1991; Zussman 2014).

Both of these advancements highlight some limitations of survey-based religiosity metrics. There are obvious sampling constraints, as political calculations and safety concerns make it difficult to survey certain populations at certain times. Even where surveys can safely and easily be conducted, cost considerations keep samples too small to be representative of smaller sub-national units. And direct questions about beliefs and practices fail to offer an "unobtrusive" measure, which experts recommend (Finke and Bader 2017).

Following the growing use of satellite imagery in the social sciences, I propose a new method for estimating religiosity that is unobtrusive, cost-effective, and able to capture local dynamics without sampling constraints. Specifically, I hypothesize that changes in night-light luminosity during Ramadan will reflect religiosity in some Muslim-majority areas. As practicing Muslims abstain from food and water during the daylight hours, they tend to stay up later than they would otherwise, in order to eat and drink (Roky et al. 2001). As long as regular daytime activity continues during the holy month, non-fasting Muslims continue to go to sleep as usual, increasing night-lights only where more residents fast. Meanwhile, in some less religious areas, night-lights may even dim during Ramadan, if "unholy" (*haram*) activity at bars and nightclubs is curtailed and displaced during the holy month.

If valid, this remotely sensed method offers a low-cost, unobtrusive measure of religiosity: either the share of fasting Muslims and/or the extent of displaced *haram* nightlife. Validating the method requires identifying a Muslim community (e.g., city, country) where daytime activity is largely unaffected by Ramadan and where there is sufficient variation in religiosity across sub-units (e.g., neighborhoods, districts). Existing and reliable measures of religiosity across these units are also needed to establish convergent validity. In this initial study, I offer Turkey as an ideal test case.

Background

MODELS AND MEASURES OF RELIGIOSITY

Since Marx and Durkheim, social scientists have considered the role of religiosity in politics and economics. As briefly mentioned in the introduction, religious beliefs and practices have entered into models of political preferences, both in the American context (e.g., Wald, Owen, and Hill 1988; Glaeser, Ponzetto, and Shapiro 2005; Barreto and Bozonelos 2009) and in comparative perspective (e.g., Esmer and Pettersson 2007; De La O and Rodden 2008), and predict which citizens vote (e.g., Olsen 1972; Jones-Correa and Leal 2001; Djupe and Grant 2002) and protest (e.g., Verba, Schlozman, and Brady 1995; Hoffman and Jamal 2014; Arikan and Bloom 2018). Some studies also highlight the link between religiosity, on the one hand, and radicalization and violence, on the other (e.g., Fair, Malhotra, and Shapiro 2012; Neuberg et al. 2014; Lyons-Padilla et al. 2015; Kiendrebeogo and Ianchovichina 2016; Pedersen, Vestel, and Bakken 2018). In economics, religiosity covaries with productivity, risk aversion, thriftiness, and tax morale (e.g., Guiso, Sapienza, and Zingales 2003; McCleary and Barro 2006; Torgler 2006; Dohmen et al. 2011; Renneboog and Spaenjers 2012).

Focusing on variation across individuals, many early empirical models of religiosity relied on survey-based self-reports, about the importance of religion in respondents' lives, whether they define themselves as religious, and how regularly they pray or attend religious service (e.g., McAndrew and Voas 2011; Bader and Finke 2014). As the temporal and geographic coverage of surveys increased, scholars aggregated these responses and considered how religiosity might impact, and be impacted by, local and national conditions. For example, economists identified a link between religiosity and economic development at the national level (e.g., Barro and McCleary 2003; Campante and Yanagizawa-Drott 2015). Meanwhile, political scientists estimated multi-level models of religiosity, political preferences, and participation (e.g., Scheve and Stasavage 2006; Gaskins, Golder, and Siegel 2013; Arikan and Bloom 2018). A new line of inquiry in political economics assessed how religious beliefs and practices are impacted by exogenous shocks, from financial crises (e.g., Immerzeel and van Tubergen 2013; Storm

2017), to natural disasters (e.g., Sibley and Bulbulia 2012; Bentzen 2019) and violence (e.g., Zussman 2014; Zic 2017).

These new models seek to explain patterns across communities (e.g., regions, countries) and/or changes over time, and survey-based measures struggle with these kinds of comparisons. First and foremost, surveys have critical sampling constraints. Although the number of cross-national surveys has increased (e.g., Heath, Fisher, and Smith 2005; Lupu and Michelitch 2018), coverage is far from universal.[1] Importantly, data are often missing from places considered too expensive or unsafe to survey, and these considerations likely correlate with other variables of interest. Even where surveys are conducted, modules about religious beliefs and practices may be deemed politically sensitive by local officials, so that data availability reflects the local salience of religion, missing where it is arguably most important.[2] Given the high cost of surveys, they are usually administered in "waves," many years apart, making annual estimates scarce.[3] Beyond concerns about data availability are those about representativeness, especially at the sub-national level. Given cost considerations, samples are kept as small as possible given the population of interest, representative only of large geographic units (e.g., regions and states rather than districts or counties) or a limited number of smaller ones.

In the introduction to their edited volume, *Faithful Measures*, Finke and Bader (2017) encourage scholars of religion to look beyond traditional survey-based measures, noting that multi-item indices of religious beliefs and practices are incomplete and expensive to administer. They specifically argue in favor of "unobtrusive measures" of religiosity, which "can often be collected on low budgets and require minimal interference in the lives of those being studied" (p. 8). Unobtrusive measures would also control for response biases that sometimes affect self-reported religiosity.[4] The alternative measurement strategies that Finke

1. Across the World Values Survey and region-specific surveys (i.e., Afrobarometer, AsiaBarometer, Caucasus Barometer, East Asian Barometer, Eurobarometer, European Values Survey, Latin American Political Opinion Project, Latinobarometer), questions about religiosity have been asked of over 800,000 people from 145+ countries. Still, in addition to small and island nations, Angola, Central African Republic, Chad, Democratic Republic of Congo, Cuba, Eritrea, North Korea, Mauritania, Oman, Republic of Congo, Somalia, Syria, and the United Arab Emirates have never been surveyed.

2. Questions about religious service attendance were absent from the WVS in China (1995), Israel (2001), Jordan (2007), Kuwait (2014), Morocco (2011), and Qatar (2010), ostensibly because they were not approved by domestic research councils.

3. Among the cross-national surveys that include a consistent measure of religiosity, only the Latinobarometer is administered annually.

4. Social desirability influences self-reported religiosity in some contexts (e.g., Hadaway, Marler, and Chaves 1993; Sedikides and Gebauer 2010). Further, self-reports are sometimes influenced by recent events (e.g., Zussman 2014), by how questions are framed (e.g., Burge and Lewis 2018), and by who does the asking (e.g., Blaydes and Gillum 2013; Benstead 2014).

and Bader discuss in their volume—archival documents, internet sources, social media—qualify as less obtrusive, but they do not offer a spatially disaggregated view of religiosity across sub-national units, and many come with additional costs (e.g., time, data procurement).

REMOTE SENSING IN THE SOCIAL SCIENCES

Based on Finke and Bader's (2017) framework, I seek a measure of religiosity that is unobtrusive and low-cost, immune from sampling constraints and representative of local dynamics. One approach consistent with these criteria is remote sensing, i.e., observations of local characteristics from a substantial distance, usually via satellites.

Use of remote sensing to estimate social and economic variables is now more than two decades old (e.g., Elvidge et al. 1994; Imhoff et al. 1997), with important applications in economics (e.g., Chen and Nordhaus 2011; Henderson, Storeygard, and Weil 2012), geography (e.g., Witmer 2015; Levin, Ali, and Crandall 2018), and political science (e.g., Kroth, Larcinese, and Wehner 2016; Weidmann and Schutte 2017; Billing 2019). Early applications relied on lower-quality images from the Defense Meteorological Program (DMSP) Operational Line-Scan System (OLS), but since the launch of the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument on the Suomi NPP satellite mission in 2011, image quality is vastly improved. VIIRS's Day/Night Band is better able to capture low light and has on-board sensors that identify and correct for sources of stray light. Images are of high enough quality (375 meters per pixel) to allow for analysis of small sub-national units.

That said, the images produced by VIIRS are hardly error-free and require some post-processing. Cloud coverage interferes with the ability of the sensors to pick up illumination from below, and lunar radiance can easily overwhelm human-made light from the ground. Annual and monthly composites of the satellite imagery have been compiled to control and correct for all these concerns. The composites use images from moonless nights only—to control for the influence of lunar radiance—and employ additional filters and algorithms, beyond VIIRS's on-board calibration system, to identify and remove stray light, and to control for cloud coverage (Elvidge et al. 2017). Most existing applications of remote sensing in the social sciences rely on one or both of these composites.

Beyond image correctives, there are additional issues about remote sensing that social scientists should consider. Although able to discern variation across small sub-national units, unlike surveys, satellite images cannot say anything about individuals, so it is possible to draw false conclusions (i.e., ecological fallacies) about individual behavior from aggregate images (King 1997). In terms of measurement validity, the distance between observer and those being observed increases the interpretative leap from concept to indicator. This distance also introduces important questions about research ethics: unlike surveys, satellites do not require informed consent or even IRB review. Scholars using satellites to study human behavior must keep these issues in mind, especially when the variable of interest could be considered sensitive.

SENSING RELIGIOSITY REMOTELY

In thinking about remotely sensing variation in religious beliefs and practices, I build on existing work by Greif, Román, and Zhan (2012) and Román and Stokes (2015) that considers how religious holidays impact nighttime activity, captured by satellites overhead. Although the heavy use of Christmas lights on or around December 25 arguably does not reflect levels of religiosity on the ground, changes in nighttime activity during the holy month of Ramadan may do so more effectively.

During the thirty-day holiday, practicing Muslims refrain from eating and drinking during daylight hours. As a result, they tend to stay up later than they would normally, to break their fast and celebrate with friends and family (Roky et al. 2001; BaHammam 2003). In areas where fasting is more prevalent, this behavior should produce an observable increase in nighttime luminosity during the holy month, as compared to a similar, but "secular" period. This pattern should hold except in those Muslim-majority societies where regular daytime activity shuts down during Ramadan. Here, where there is "day-night inversion" during the holy month, the entire community—whether or not they are fasting—sleeps during the day and stays up at night, the only time when shops and restaurants are open for business. Where day-night inversion occurs, night-lights will be considerably brighter during the holy month than at other times, but the rate of increase will not reflect the extent of fasting, rather the extent of local economic activity.[5]

Where day-night inversion is not the common practice, brighter night-lights during Ramadan in a given location should indicate that practicing Muslims live there: they fasted during the day and are therefore awake later than they would otherwise be. In areas populated by non-observant Muslims, there may also be a visible *reduction* in night-lights: if they typically engage in *haram* nightlife that involves drinking alcohol, official and unofficial sanctions against these activities during Ramadan would lead to earlier-than-normal bedtimes (Afifi 1997; Çelen 2015). In Muslim communities where drinking is allowed outside of Ramadan, the reduction in night-lights during the holiday will reflect how widespread this activity typically is.[6]

5. To the best of my knowledge, there has been no study of day-night inversion during Ramadan in the Muslim world, although variation in this practice is noted by some (e.g., Chamari et al. 2016). Before applying the proposed measure, scholars should confirm—ideally, through fieldwork—whether inversion occurs in their community of interest.

6. Some Muslims both fast during Ramadan and drink alcohol in other months. For them, overall night-light use may remain largely unchanged during the holy month, even if the source differs—

Based on this logic, remote sensing of religiosity during Ramadan should be valid if at least one of two conditions holds—that, were it not Ramadan, (1) religious people would be asleep and (2) secular ones awake. In capturing the first effect, the matter of timing is important. First, one should avoid capturing publicly sponsored events around the time of fast-breaking (*iftar*) (Karaosmanoğlu 2010) so as not to misinterpret the provision of these public services as an indicator of local observance. Similarly, in communities where drummers wake all residents before the pre-dawn (*sahūr*) meal, it is better to ignore the hour or two before sunrise.

To test the validity of the proposed measure, I require at least one case, i.e., a region of some kind, without day-night inversion, ideally where *haram* activity is not fully regulated outside of Ramadan. Since a key benefit of the proposed method is its ability to capture sub-national variation, it is useful to have some within-case variation in religiosity. And, of course, at least one reliable existing estimate of religiosity, independent of remotely sensing data, across sub-national units is needed. For this exploratory study, I suggest a test case that ticks all of these boxes: Turkey.

THE TURKISH CASE

For many reasons, Turkey is an ideal candidate for this exercise. This Muslim-supra-majority country spent centuries at the center of the largest Muslim empire, but after the Ottoman collapse, it underwent a process of secularization, led by Mustafa Kemal Atatürk. And since 2002, it has been single-handedly ruled by the Islamic-based Justice and Development Party (*Adalet ve Kalkınma Partisi*, AKP) and its leader, Recep Tayyip Erdoğan. So both secular and Islamic threads run deep throughout Turkish society (Hale and Özbudun 2009), and both are on display during Ramadan: daytime activity is largely unchanged during the holiday, and there is plenty of *haram* nightlife that is displaced during the holy month by implicit social pressures and explicit government policies (Toprak et al. 2009; Çelen 2015).

To validate the proposed measurement strategy, I look for evidence of convergent validity by comparing changes in Ramadan luminosity to two existing estimates of religiosity in Turkey. First, since 2010, KONDA Research and Consultancy has run a monthly, nationally representative

i.e.,, from *haram* activities before the holiday, to break-fasting during. As opposed to fully non-practicing, non-religious Muslims—who drink and do not fast, and whose night-light activity will be strictly reduced during Ramadan—and fully practicing, religious Muslims—who do not drink and do fast, and whose night-light activity will strictly increase during the holiday—those who drink *and fast* can be viewed as somewhat religious. The overall correlation should remain the same—areas populated with non-practicing Muslims see a reduction in night-lights during Ramadan, while areas populated with practicing Muslims see an increase in luminosity, and those populations with somewhat religious Muslims see no overall change.

"Barometer" survey that includes questions about religious beliefs and practice.[7] Across the full series, more than 115,000 respondents have been surveyed, from over 500 (of 973) districts (*ilçeler*), nested in 67 (of 81) provinces. Some questions about religiosity—e.g., whether respondents self-identify as devout, and whether women cover their heads—are asked consistently, while others—e.g., about fasting during Ramadan—are available for a more limited subsample. And unlike in some contexts, where religion is a sensitive subject, in Turkey, where both secular and religious communities are acknowledged and accepted, these direct questions yield unbiased responses (Brenner 2014).

Along with self-reported measures, support for the AKP is a reasonable (though noisier) behavioral proxy for religiosity (Güneş-Ayata and Ayata 2002; Çarkoğlu 2008). Average AKP vote share across general elections (2002–2018) is positively correlated with each survey-based measure across districts ($r = 0.418$ for fasting, 0.402 for head-covering, and 0.376 for percent devout, all $p < 0.01$). Using either measure, one sees considerable subnational variation across Turkish districts (figure 1). The next question is whether changes in Ramadan night-lights follow similar patterns.

Methods

Most existing applications of satellite imagery in the social sciences rely on annual or monthly composites. To control for lunar radiance, composites restrict data to moonless nights, and they apply filters and algorithms to correct for cloud coverage and any remaining sources of stray light. Because Ramadan follows the lunar calendar, rather than the Gregorian one, neither annual nor monthly composites are useful in this application. Thus, I collected raw images from NASA satellites and corrected for lunar radiance, cloud coverage, and stray light. Here, my goal was to develop a straightforward method that social scientists with quantitative skills could employ. This introduces more noise into my estimates than more complex algorithms would, providing a lower-bound estimate of validity.

I use images from each passing satellite since January 2012 through the Distributed Active Archive Center (DAAC) hosted by NASA'S Level-1 and Atmosphere Archive and Distribution System (LAADS) (National Aeronautics and Space Administration 2018).[8] These cover 97 lunar months,

7. I have access to data from 55 surveys, conducted between March 2010 and September 2015. In each, sampling is stratified on population, education, and recent election results, so that responses are representative at the national and province levels, with age and gender quotas applied in every sampled unit.

8. At the time of writing, images were available from 19 January 2012 to 25 January 2020.

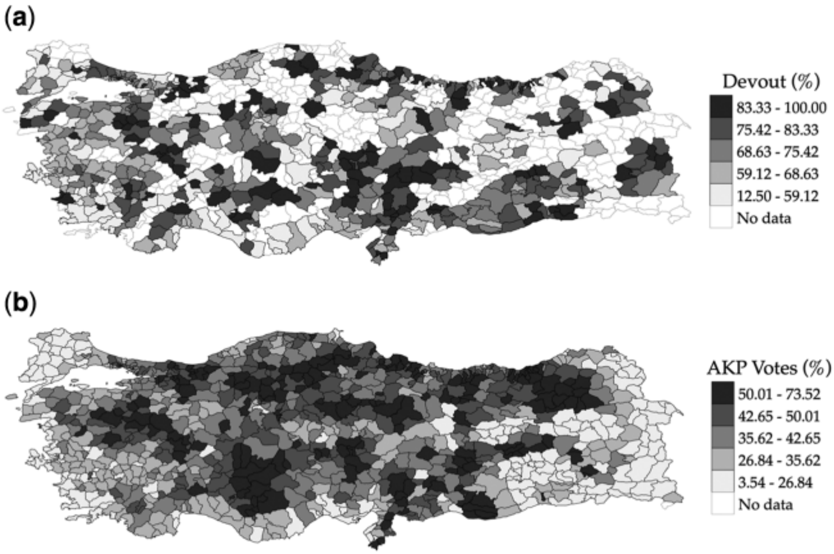

Figure 1. Variation in religiosity, across Turkish districts (*İlçeler*). Figure 1a illustrates variation in the percentage of survey respondents who say they are devout, calculated from 146,973 respondents across 55 KONDA Barometer surveys (March 2010–September 2015). Figure 1b illustrates district-level variation in average support for the AKP across all general elections in which it has competed (2002–2018).

including eight Ramadans (2012–2019).[9] Images are formatted as HDF4 files and contain multiple layers of data, including latitude, longitude, lunar angle, and light radiance per pixel. I convert each into smaller GeoTIFF files, using Python's GDAL package (GDAL/OGR Contributors 2019), and overlay a shapefile of Turkish districts.[10] Another set of packages—EarthPy (Wasser et al. 2019), GeoPandas (GeoPandas Developers 2019), Rasterio (Gillies 2019)—are used to calculate nighttime radiance within districts by taking the sum of lights across all pixels within each unit.

To control for lunar radiance, I take advantage of the fact that Ramadan always aligns with the moon's cycle: the holiday begins with a new moon. Although I cannot restrict the analysis to moonless nights only, I can use

9. In Turkey in 2012, Ramadan fell between 20 July and 18 August; in 2013, 9 July–7 August; 28 June–27 July 2014; 18 June–16 July 2015; 6 June–4 July 2016; 26 May–24 June 2017; 16 May–14 June 2018; and 6 May–3 June 2019.

10. Although luminosity can be calculated within any geographic unit, including entirely arbitrary shapes, I use administrative divisions because they correspond to the units in the surveys and electoral returns.

relatively moonless ones—i.e., the first and last 5 nights of Ramadan, the first/last 5 of the previous lunar month, each with less than 12 percent lunar disk illumination (Cao and Bai 2014). This limits the influence of lunar radiance and keeps its impact before and during Ramadan roughly balanced.

Within these ±5 nights, I focus on the relevant time period. Night-light captures of Turkey begin at 9:30 PM and end around 2:30 AM, with the bulk collected between 10:15 and 1:30 AM (see Appendix figure A1). To avoid capturing government-sponsored fast-breaking events, I drop images taken 2–3 hours after sunset; and to control for neighborhood drummers who may wake everyone up before the pre-dawn meal, I disregard the 1–2 hours before sunrise. The remaining images are taken during the "dead-of-night," between 11:00 PM and 2:00 AM.[11]

Within this timeframe, I calculate average luminosity in each night, across all passes. Before doing so, I use a relative neighborhood dissimilarity algorithm (Vu, Gopalkrishnan, and Namburi 2008) to identify outliers, caused by stray light or local flashes.[12] After these are removed, I am able to impute most missing observations using spline interpolation (de Boor 2001). At the end of this process, the average number of passes is 1.15 per district each night (down from 1.91 in the raw data).

The final challenge is cloud coverage. Most existing solutions use VIIRS's own cloud mask product (Kopp et al. 2014), but I hoped to identify cloud-affected estimates from within the data, eliminating the need to process a second set of images. Readings affected by cloud coverage indicate very little luminosity, since both natural and artificial lights are obscured. The distribution of low-end luminosity readings indicates an irregular cluster of observations just below 1.00, suggesting that readings at or below this "threshold" are likely due to cloud coverage. I confirm this by leveraging the correlation between night-lights and economic development across districts, finding that the correlation is significantly strengthened when readings below 1.00 are dropped.[13]

11. Because Ramadan 2012–2019 fell during the summer, sunset was relatively late, and sunrise early, generating a narrower timeframe than in other seasons.

12. Identifying and removing outliers—at the district level—is far easier than existing methods, identifying outliers on the *pixel* level (Elvidge et al. 2017).

13. Across districts in each year, I estimate local economic development using the first principal component of three proxies—rates of urbanization, literacy, and university completion—which I compare to average luminosity in the ±5 nights of all non-Ramadan months in each year, varying whether the average reflects all luminosity readings or only those above a certain threshold: 0.75–1.15, at 0.05 increments. Compared to averages including all readings ($r = 0.176$), those without extreme low-light readings are more strongly correlated with local economic development, with the strongest correlation achieved when using the 1.00 threshold ($r = 0.343$). After correcting for cloud coverage, these averages closely resemble existing studies of night-lights in Turkey using pre-processed monthly and annual composites (Basihos 2016; Stathakis, Tselios, and Faraslis 2015).

After processing the images, I calculate the percent change in log nighttime luminosity during Ramadan in every district for each year (2012–2019), comparing the first and last 5 nights of the holiday to the ±5 nights of the previous lunar month. Using just the previous lunar month (as opposed to all non-Ramadan months) maximizes similarity between the two lunar cycles being compared; and using the previous month (rather than the following one) avoids picking up lingering holiday-related behavior after Ramadan ends, including post-holiday travels and yet-abnormal sleep patterns.[14]

Results

CHANGES IN LUMINOSITY DURING RAMADAN

Averaging annual changes in each district across all years reveals a net increase in nighttime activity during Ramadan: $\mu = 12.7$ percent ($\sigma = 23.8$). This increase is considerably larger than in any other pair of months, which range from 0.49 to 2.74 percent. This seems to indicate that, across the entire country, there is more nighttime activity during Ramadan than in the previous month. Still, a sizable number of districts—roughly a third (29.9 percent)—exhibit a decline in luminosity during the holy month, possibly due to the displacement of *haram* activity.

Assessing geographic variation in Ramadan luminosity across Turkey's 12 statistical regions (*İstatistiki Bölge Birimleri Sınıflandırması*, İBBS), I find that Northeastern, Central Eastern, and Eastern Anatolia experience the largest increases, on average, while Istanbul, Eastern Marmara, the Mediterranean, and the Aegean regions see the smallest (see Appendix figure A2). This pattern matches existing work on religious conservatism in Turkey, which emphasizes a divide between the eastern, peripheral provinces (more religiously conservative) and those in the west, closer to the so-called "center" (less conservative) (Kalaycıoğlu 1999; Mardin 1973).

VALIDITY ACROSS INDIVIDUALS, DISTRICTS, AND PROVINCES

To test the validity of the satellite-based measure using data from individuals, I rely on self-reported religiosity from the KONDA Barometer surveys. In a few of these, after Ramadan each year (2010–2015), respondents are asked to estimate on how many days (0–30) they fasted. In a larger subset of the surveys, they are asked to self-identify as irreligious, somewhat religious, or devout. And across all 55 surveys, they report whether they (if they are female) or their wives (if they are married males) cover their heads. In

14. In Turkey, the first three days after Ramadan are a public holiday, and many individuals go to visit their families, likely changing the distribution of night-lights.

Table 1. Predicting individual religiosity with Ramadan luminosity in home districts

	Dependent variable							
	Fast		Devout		Cover		AKP	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Δ Luminosity *β*	0.101	0.078	0.116	0.095	0.102	0.075	0.053	0.060
p-value	0.082	0.168	0.000	0.000	0.000	0.000	0.030	0.004
Survey FEs	✓	✓	✓	✓	✓	✓	✓	✓
Clustered SEs	✓	✓	✓	✓	✓	✓	✓	✓
Urbanization	✓	✓	✓	✓	✓	✓	✓	✓
Demographics		✓		✓		✓		✓
R^2	0.004	0.100	0.012	0.097	0.048	0.275	0.008	0.090
Districts	198	198	439	439	602	602	598	598
N	7,073	6,608	98,578	92,327	126,002	118,575	132,000	124,593

NOTE.—Standardized coefficients and p-values from OLS models, two for each measure of religiosity: (i) days fasted (*Fast*) during Ramadan; (ii) binary indicator of self-identification as devout (*Devout*); (iii) binary indicator of head-covering (*Cover*); and (iv) binary indicator of self-reported support for the AKP in most recent election (*AKP*). Check marks indicate inclusion of demographic controls: binary indicators of respondent gender, age category (under 28, 29–43, over 44), levels of educational attainment (less than high school, completed high school, university or higher), income quintiles, Sunni Islam, and Turkish ethnicity. All models include survey fixed effects, have standard errors clustered at the district level, and control for the district's level of urbanization, as indicated by check marks.

addition, they are asked to self-report which party—including the Islamic-based AKP—they supported in the most recent election.[15]

For each measure, I assess how respondents' self-reported religiosity relates to the change in luminosity during Ramadan in their home district. In every model, I include survey fixed effects, cluster standard errors at the district level, and control for whether the survey classifies the district as a "city," "town," or "village." In a second set of models, I also include individual-level covariates: respondents' age, gender, education, income, sect, and ethnicity.[16] Across the eight models (see table 1), I find consistent evidence that Ramadan luminosity is related to self-reported religiosity. In each case, a likelihood ratio test confirms that the model is significantly improved by the inclusion of the night-light metric (see Appendix table A1).

15. Each survey asks about the most recent local and/or general election. Where both are available, I focus on the choice in the general election. See the Supplementary Material for more information about the methodology of these surveys.
16. The small number of non-Muslims are excluded from the analysis.

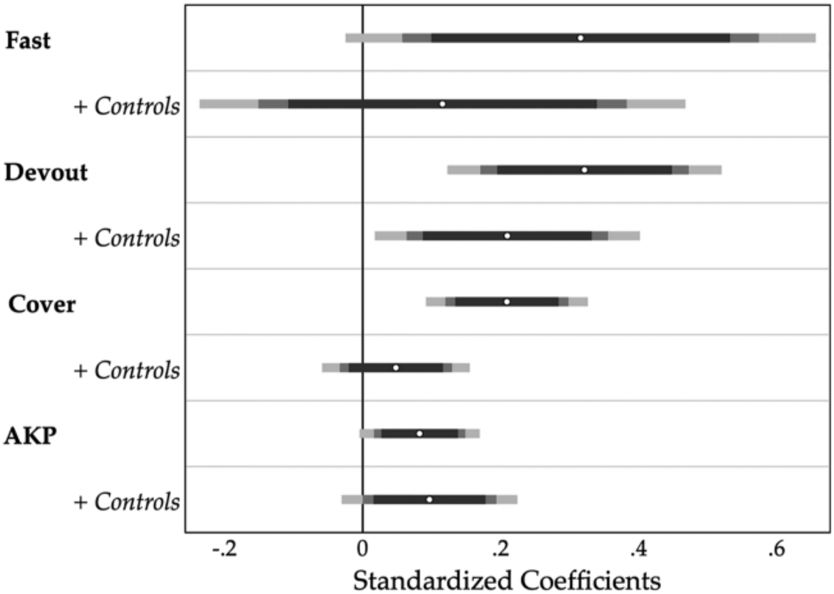

Figure 2. Ramadan luminosity and religiosity, across districts. Standardized coefficients of percent change in Ramadan luminosity (2012–2019) on average religiosity. All measures of religiosity same as in previous analysis (table 1) except for AKP support, which is the vote share across all general elections (2002–2018). Controls include average urbanization, literacy, and university completion rates across district-years (2012–2018). All models include standard errors clustered at the district level. Bars display 90%, 95%, and 99% confidence intervals.

In a second set of analyses, I look for evidence of convergent validity at the district level, as opposed to across individual survey respondents. Here, I use aggregated survey responses as well as the average performance of the AKP across general elections (2002–2018) in place of individuals' support for the AKP in the most recent local or general election. Figure 2 displays standardized coefficients from a set of OLS models, each estimated at the district level with clustered standard errors, some with district-level controls for development, i.e., average urbanization, literacy, and university completion rates (2012–2018) (Turkish Institute of Statistics (Türkiye İstatistik Kurumu TÜİK) 2018a, 2018b).[17]

17. At the time of writing, results of the 2019 Address-Based Population Registration System (*Adrese Dayalı Nüfus Kayıt Sistemi*, ADKNS) had not been released.

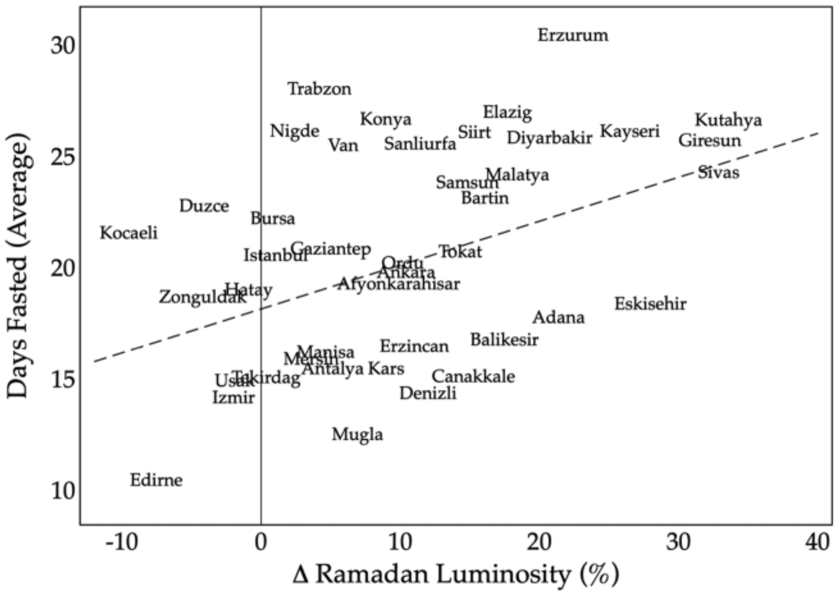

Figure 3. Changes in Ramadan night-lights and self-reported fasting. Percent change in night-lights during Ramadan (2012–2019), compared to average number of days fasted during Ramadan, within provinces (*iller*).

Similar to the individual-level analysis, I find consistent associations between religiosity and luminosity at the district level. Of the eight models, all coefficients are positive, and six are statistically significant at conventional levels, even with the inclusion of controls. As above, models of self-reported fasting suffer from a smaller sample size ($N = 198$), although the bivariate coefficient is statistically significant. And I am able confirm the relationship between luminosity and AKP support when replacing self-reported preferences with actual vote tallies.

Because KONDA's samples are not designed to be representative within districts, I also confirm these results at the province level. Figure 3 displays the bivariate relationship between self-reported fasting and Ramadan luminosity across 42 provinces Even across a small number of units, the correlation is relatively strong ($r = 0.444$) and highly significant ($p < 0.01$). Bivariate correlations between change in luminosity and other measures of religiosity are all positive, although only fasting achieves statistical significance at conventional levels.[18]

18. For *Devout*: $r = 0.220$, $p = 0.121$; for *Cover*: $r = 0.163$, $p = 0.192$; and for AKP vote shares: $r = 0.067$, $p = 0.550$.

PLACEBO TESTS

Three sets of tests—across individuals, districts, and provinces—indicate the convergent validity of the luminosity measure, but some further consideration is warranted. The results may be an artifact of comparing luminosity across two particular lunar months, with little to do with Ramadan. To examine this, I calculate the percent change in luminosity between every pair of months in the lunar calendar, comparing the ± 5 nights of any given month with the ± 5 nights of the preceding one.[19]

Using self-reported religiosity across individuals, I find some evidence that changes between some non-Ramadan months are related to religiosity (the first and second, and the third and fourth), but not consistently across all measures.[20] Otherwise, all other relationships are null, indicating the importance of Ramadan in the patterns reported above. When I move the placebo tests up to the district level, changes between none of the non-Ramadan month pairs are significantly positively related to any measure of religiosity. And similarly, at the province level, there is no statistically significant correlation between any of the existing measures of religiosity and change in luminosity across pairs of months outside of Ramadan. Thus, the observed increase in luminosity during Ramadan does seem to be related to the holiday.

ASSESSING VALIDITY OVER TIME

Average change in Ramadan luminosity from all years (2012–2019) covaries with other measures of religiosity across sub-national units. But there are additional questions about whether each annual estimate is valid, on its own, and whether trends in Ramadan luminosity reflect changes in religiosity within units.

To answer the first of these questions, I calculate the bivariate correlation between the change in Ramadan luminosity in each year and the four district-level measures of religiosity—average days fasted, percent self-reported as devout, rate of female head-covering, and actual AKP vote shares. Of the 32 correlations, all but 5 are positive, and none of the negative correlations is statistically significant. Moreover, 12 of the positive correlations are significant at conventional levels (see Appendix table A2).

19. I exclude the month following Ramadan because night-time activity in the first few of days of this month may yet reflect some holiday-related behaviors

20. These two placebo comparisons were the only ones significantly positively correlated with all four measures of religiosity in bivariate comparisons. But only two of these eight relationships held in a fully specified regression model: rates of head-coverings are associated with average luminosity changes between the first and second months, while the share of devout respondents is related to changes between the third and fourth months.

Table 2. Changes in Ramadan luminosity and religiosity, panel data

	Dependent variable								
	Devout			Cover			AKP		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
ΔLuminosity β	0.163	0.153	0.100	0.039	0.045	−0.010	0.050	0.012	0.044
p-value	0.000	0.000	0.027	0.272	0.204	0.797	0.000	0.137	0.000
Controls		✓			✓			✓	
District FEs			✓			✓			✓
Districts	242	242	242	242	242	242	896	896	896
District-years	762	754	762	762	754	762	2007	2007	2007

NOTE.—Standardized coefficients and p-values from OLS models, two for each measure of religiosity: (i) share who self-identify as devout in the district in a given year (2012–2015); (ii) share of women (or wives) who cover their heads in a district-year (2012–2015); and (iii) AKP vote share in each general election (2011, 2015, 2018). Check marks indicate inclusion of controls—urbanization, literacy, and university completion rates of districts each year—and district fixed effects. All standard errors clustered at the district level.

A better test of cross-temporal validity compares the annual changes in Ramadan luminosity within districts to a measure of local religiosity in that same year. Using panel data of the 242 districts surveyed at least twice by the KONDA Barometer (2012–2015), as well as a panel of all district-level general election results (2011, 2015, 2018), I find that the change in Ramadan luminosity in each year tends to covary with annual estimates of religiosity (see table 2).[21] Results are most robust for the share of respondents who self-identify as devout in a district in a given year, which survives the inclusion of district-level controls and district fixed effects; but, across all three measures, the coefficients are almost always positive and often statistically significant.

ROBUSTNESS CHECKS AND SCOPE CONDITIONS

Having provided converging evidence for the validity of the satellite-based measure of religiosity, I am able to dig a little deeper into the conditions under which the metric works best. More specifically, I have put forward two hypotheses: first, that increases in night-lights during Ramadan indicate that practicing Muslims, who fasted during the day, are awake later than they

21. Because the survey-based measure of Ramadan fasting is available in only a handful of surveys, it is not possible to include it in the panel analysis.

would otherwise be; and second, that decreases in night-time luminosity during the holy month are the result of displaced *haram* activity involving alcohol. Splitting the sample into two groups—districts where there was an observed average increase in night-lights and those where luminosity declined—I am able to test the two hypotheses.

At both the individual and district level, I find that the relationships between Ramadan night-lights and other measures of religiosity are far less consistent in places where luminosity decreased. Meanwhile, all of the relationships hold (and are even strengthened) when looking only at districts where an increase in night-lights is observed. For example, the correlation between days fasted and Ramadan luminosity is 0.181 ($p = 0.040$) across the 129 districts where luminosity increased but only 0.018 ($p = 0.881$) in the 69 districts where it decreased. And the correlation between AKP vote share and luminosity is significant and positive ($r = 0.107$, $p < 0.01$) in districts where luminosity increased ($N = 673$), while it is negative and null where luminosity decreased ($N = 286$). This seems to indicate weaker support for the second of the two hypotheses.

This pattern raises some important questions about observed decreases in luminosity. What can explain these changes, if not displaced *haram* nightlife? Comparing results from urban and rural districts, I find significantly smaller increases in luminosity (and more decreases) in cities compared to towns and villages. Since *haram* activity tends to occur (and is then displaced) in urban centers, it seems reasonable that cities would see a (larger) reduction in their night-lights during Ramadan.[22] At the same time, if nightlight tends to occur in more commercial, less residential areas, then it may be displaced in places other than where survey respondents live, answer surveys, and vote. This should serve to weaken the correlation between Ramadan luminosity and measures of religiosity from urban areas, as is observed.

Conclusion

My initial assessments indicate that change in nighttime luminosity during Ramadan, compared to the previous lunar month, is a valid proxy for religiosity across sub-national units in Turkey. A simple average of relatively noisy annual data produces an estimate of religiosity that performs consistently well when compared to a number of different measures—both self-reported (e.g., fasting, religiosity, party preferences) and behavioral (e.g., vote shares)—across different levels of analysis: individuals, districts, and

22. Of course, urban areas also tend to be more secular, so it is important to take this into account when interpreting this result.

provinces. In addition, annual estimates are noisier but still tend to covary with measures of religiosity, including changes over time within units.

For this initial assessment, the remotely sensed measure of religiosity was achieved with relatively basic image corrections. Further work can and should be done to assess whether more complex correctives are able to improve validity across units and over time. The Black Marble suite of products, promising to correct for lunar radiance, as well as cloud coverage and stray light, in each overhead pass (Román et al. 2018), has the potential to transform how changes in luminosity during Ramadan are assessed. The ability to fully control and remove lunar radiance opens up the possibility of additional validity checks, including assessing variation within the holy month, for example, based on the day of the week. For example, if declines in luminosity during Ramadan reflect displaced *haram* activities, then these effects should be largest on weekend evenings.

While the current method has produced a valid indicator of religiosity in the Turkish case, its validity in other contexts has yet to be established. When expanding the analysis to other locations, it is important to focus only on places where daily activities are largely unchanged by Ramadan, so that sleep patterns are only disrupted for those who are observing the fast. But if a broader cross-national comparison is possible, it may be useful to note that survey-based estimates of religiosity are available for a number of Muslim-majority countries.[23] Another valuable extension would be to Muslim-majority areas of non-Muslim countries, for example, German cities with large Turkish populations, areas around Detroit, Michigan, with a large number of Arab Americans, and so on.

Once the images from VIIRS (2012–present) have been analyzed, scholars will need to generate funds to acquire daily DMSP-OLS images from earlier periods, which are not freely available, so that the validity of the measure can be confirmed over a longer stretch of time and across different satellite technologies. Once the timeframe has been expanded, questions about the role of seasonality in the results presented here can be addressed. Because the summer months limit the number of satellite passes that fall in the dead of night, these results arguably constitute a lower-bound estimate of validity. But it is also possible that the behavior of fasting and non-fasting Muslims operates differently during other seasons, and the current set of available images cannot address these questions.

Before concluding, it is imperative to discuss appropriate applications of satellite images, beyond a consideration of whether they produce valid measures. As mentioned above, unlike the case with surveys, there is no IRB application for remotely sensed measurement, and there is no expectation of

23. Currently, survey-based measures of religiosity from the cross-national survey projects are available for the following Muslim-majority countries: Albania, Algeria, Azerbaijan, Bahrain, Bangladesh, Brunei, Burkina Faso, Egypt, Guinea, Indonesia, Iran, Iraq, Jordan, Kazakhstan, Kuwait, Kyrgyzstan, Lebanon, Libya, Malaysia, Mali, Morocco, Niger, Nigeria, Northern Cyprus, Pakistan, Palestine, Qatar, Saudi Arabia, Senegal, Sierra Leone, Suda, Tunisia, Turkey, Uzbekistan, and Yemen.

informed consent from those whose behavior is being captured. Therefore, it is essential that great care is taken with these data, to preserve the anonymity of the people and places being observed. At the very least, the geographic units being analyzed should be sufficiently large to maintain the privacy of the individuals living there. And Muslim communities targeted by their governments should be considered off-limits to this type of inquiry.

With these considerations in mind, new uses of remote sensing in the social sciences can be developed, leveraging changes in human behavior that produce a visible difference in nighttime luminosity. To remotely sense religiosity elsewhere, scholars should identify religious practices that impact when, where, and/or how much light is produced. For example, observant Jews often stay up the night before Shavuot to study Torah, generating more light than would normally be produced. And during Día de los Muertos in Mexico, lights may appear where they otherwise would not: in and around cemeteries. Applications to other cultural phenomena, beyond religion, could leverage the timing of international sporting events to estimate national fervor by measuring who is staying up late to watch their national team play. So long as the data are handled with care and the research designed responsibly, creative applications are warmly welcomed.

Appendix

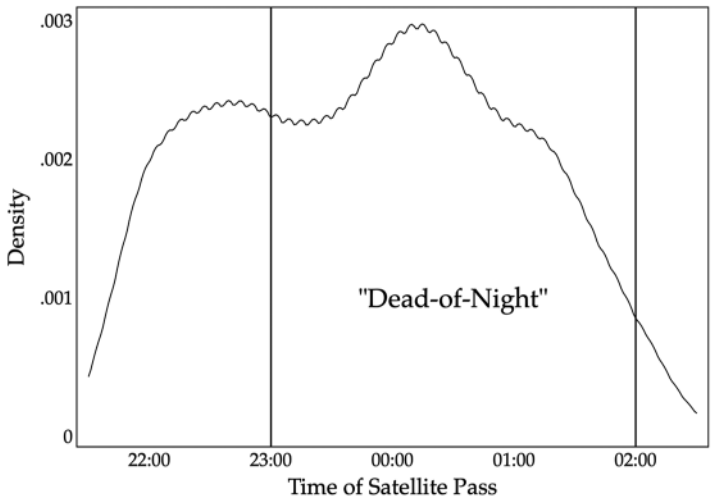

Figure A1. Distribution of VIIRS passes over time, 2012–2019. Kernel density plot of all available passes of VIIRS over Turkey between 2012 and 2019. Passes in the "dead of night" (11:00 PM–02:00 AM) indicated by solid black lines.

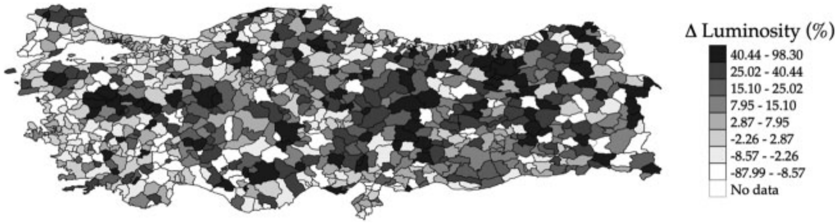

Figure A2. Average change in luminosity during Ramadan (%) (2012–2019). Percent change in nighttime luminosity during Ramadan across districts, averaged across years (2012–2019).

Table A1. Improvements in model fit: Predictions of individual religiosity

		Dependent variable							
		Fast		Devout		Cover		AKP	
Predictor		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ΔLuminosity	β	0.078		0.095		0.075		0.060	
	p-value	0.168		0.000		0.000		0.004	
Female	β	0.076	0.074	0.041	0.040	−0.221	−0.222	0.053	0.052
	p-value	0.005	0.006	0.000	0.000	0.000	0.000	0.000	0.000
Age:									
29-43	β	0.114	0.113	0.049	0.049	0.194	0.194	0.150	0.150
	p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
44+	β	0.066	0.065	0.137	0.136	0.254	0.254	0.081	0.081
	p-value	0.092	0.098	0.000	0.000	0.000	0.000	0.000	0.000
Education:									
High school	β	−0.048	−0.049	−0.375	−0.376	−0.541	−0.541	−0.314	−0.315
	p-value	0.154	0.150	0.000	0.000	0.000	0.000	0.000	0.000
University	β	−0.066	−0.065	−0.433	−0.432	−0.822	−0.821	−0.459	−0.458
	p-value	0.132	0.141	0.000	0.000	0.000	0.000	0.000	0.000
Income (TL):									
301-700	β	−0.049	−0.050	−0.069	−0.072	0.005	0.002	0.027	0.025
	p-value	0.551	0.550	0.015	0.011	0.711	0.870	0.267	0.303
701-1200	β	−0.040	−0.044	−0.149	−0.156	−0.057	−0.065	0.030	0.024
	p-value	0.624	0.599	0.000	0.000	0.000	0.000	0.244	0.346
1201-2000	β	0.019	0.011	−0.211	−0.221	−0.159	−0.169	0.021	0.013
	p-value	0.813	0.888	0.000	0.000	0.000	0.000	0.444	0.634
2001-3000	β	−0.018	−0.024	−0.247	−0.258	−0.282	−0.293	−0.004	−0.013
	p-value	0.835	0.775	0.000	0.000	0.000	0.000	0.878	0.655
3000+	β	−0.152	−0.162	−0.260	−0.273	−0.426	−0.439	−0.054	−0.063
	p-value	0.108	0.086	0.000	0.000	0.000	0.000	0.085	0.042

(*continued*)

Table A1. (*continued*)

		Dependent variable							
		Fast		Devout		Cover		AKP	
Predictor		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Sunni	β	1.232	1.236	0.485	0.482	0.881	0.878	0.742	0.740
	p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Turkish	β	−0.196	−0.206	−0.215	−0.225	−0.193	−0.201	0.131	0.125
	p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Urbanization:									
Town	β	0.006	0.003	−0.041	−0.049	−0.181	−0.186	−0.005	−0.009
	p-value	0.941	0.976	0.157	0.122	0.000	0.000	0.833	0.709
City	β	−0.008	−0.019	−0.041	−0.059	−0.274	−0.289	−0.021	−0.032
	p-value	0.914	0.797	0.223	0.066	0.000	0.000	0.474	0.249
Survey FEs		✓	✓	✓	✓	✓	✓	✓	✓
Clustered SEs		✓	✓	✓	✓	✓	✓	✓	✓
	R^2	0.100	0.098	0.097	0.094	0.275	0.273	0.090	0.089
	Districts	198	198	439	439	602	602	598	598
	N	6608	6608	92327	92327	118575	118575	124593	124593
	χ^2	12.9		278.9		312.6		168.6	
	p-value	0.002		0.000		0.000		0.000	

Note.—Standardized coefficients and p-values from OLS models, two for each measure of religiosity: (i) days fasted during Ramadan; (ii) binary indicator of self-identification as devout; (iii) binary indicator of head-covering; and (iv) binary indicator of self-reported support for the AKP in most recent election. Controls include binary indicators of respondent gender, age (excluded category: under 28), educational attainment (excluded category: less than high school), income quintiles (excluded category: less than 300 TL), Sunni Islam, Turkish ethnicity, and level of urbanization of district (excluded category: rural). All models include survey fixed effects and have standard errors clustered at the district level, as indicated by check marks. $\chi2$ and p-value from two-tailed likelihood ratio test of each pair of models.

Table A2. Annual changes in Ramadan luminosity, validity tests

	ΔLuminosity							
Variable	(2012)	(2013)	(2014)	(2015)	(2016)	(2017)	(2018)	(2019)
Fast								
r	0.077	0.083	0.086	−0.050	−0.069	0.347	0.028	0.007
p-value	0.295	0.287	0.281	0.503	0.358	0.000	0.706	0.924
Devout								
r	0.107	0.114	0.210	0.080	0.004	0.295	0.052	0.051
p-value	0.035	0.033	0.000	0.137	0.931	0.000	0.306	0.322
Cover								
r	0.109	0.147	0.092	0.115	−0.013	0.139	0.053	0.067
p-value	0.013	0.001	0.050	0.017	0.762	0.002	0.224	0.135
AKP								
r	0.139	0.057	0.054	0.031	−0.012	0.089	0.057	−0.066
p-value	0.000	0.140	0.157	0.465	0.727	0.019	0.115	0.075

Note.—Bivariate correlations between the percent change in luminosity during Ramadan compared to the previous month, in each year (2012–2019), and four measures of religiosity at the district level: (i) average number of days fasted during Ramadan [0,30]; (ii) share of those who self-identify as devout; (iii) share of women (or wives) who cover their heads; and (iv) average vote share of AKP across general elections. P-values reported in parentheses.

Data Availability Statement

REPLICATION DATA AND DOCUMENTATION are available at https://doi.org/10.7910/DVN/0P7DZC and http://www.alivny.com

Supplementary Material

SUPPLEMENTARY MATERIAL ma y be found in the online version of this article: https://doi.org/10.1093/poq/nfab013.

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