Tracking COVID-19 urban activity changes in the Middle East from nighttime lights

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Tracking COVID-19 urban activity changes in the Middle East from nighttime lights

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Abstract

In response to the COVID-19 pandemic, governments around the world have enacted widespread physical distancing measures to prevent and control virus transmission. Quantitative, spatially-disaggregated information about the population-scale shifts in activity that have resulted from these measures is extremely scarce, particularly for regions outside of Europe and the US. Public health institutions often must make decisions about control measures with limited region-specific data about how they will affect societal behavior, patterns of exposure, and infection outcomes. The Visible Infrared Imaging Radiometer Suite Day/Night Band (VIIRS DNB), a new-generation spaceborne low-light imager, has the potential to track short-term changes in human activity, but the capability has not yet been applied to a cross-country analysis of COVID-19 responses. Here, we show initial evidence of VIIRS-DNB-detected changes to societal behavior patterns from COVID-19 control measures. We examine multi-year (2015–2020) daily time-series data derived from NASA's Black Marble VIIRS nighttime lights product (VNP46A2) covering 584 urban areas, in 17 countries in the Middle East. Our analysis specifically focuses on the first stage of the pandemic and the Ramadan period, to understand how communities have adhered to COVID-19 measures when they were contrary to long-standing socio-cultural practices. Nighttime lights capture the onset of national curfews and lockdowns well, but also expose the inconsistent response to control measures both across and within countries. In conflict-afflicted countries, lockdowns and curfews resulted in less change in activity, highlighting the compound health and security threats that fragile states face. Our findings show how satellite measurements can aid in assessing the public response to COVID-19 physical distancing policies and the socio-cultural factors that shape their success, especially in data-sparse regions.

Introduction

The Middle East faced unique challenges when responding to the COVID-19 pandemic in the first half of 2020. Several countries in the region entered the pandemic embroiled in political turmoil and conflict, with fractured governance, lack of transparency, and under-resourced public health systems, which complicated the response [71, 4]. Furthermore, Ramadan, which began in April, posed the risk of becoming a multi-national COVID-19 "super-spreader" event [64, 61]. Traditional religious practices and communal gatherings, rooted in solidarity and sharing, were at odds with public health guidance to privatize activity, close markets and public spaces, and cancel iftars, a traditional nighttime shared meal. In some countries, this tension resulted in governments loosening restrictions, caving to economic and religious pressure [58, 91], while in other countries strict curfews and physical distancing directives were bolstered [17].

Physical distancing measures enacted to control COVID-19 transmission were varied across the region —both in their timing and their stringency —as were public responses to these measures. While there are now many databases that track the timing and details of COVID-19 control measures (e.g. the Coronanet government measures database [8], HIT-COVID [90], Oxford-19 Government Response Tracker [33], etc.), there is not commiserate data on societal adherence to these measures. Data that indicates how societal behavior changed in response to control measures (i.e. adherence) is critical for forecasting the spread of viruses and for informing context-specific management for this and future epidemics.

Adherence to physical distancing measures have been captured through surveys [3, 34, 1], news reports [86], and through social media sentiment analysis [69]. While useful for understanding local factors that influence transmission behaviors, these data sources are not systematically collected, have limited geographic coverage, and are thus difficult to scale across space and time. They also most often measure public opinion towards physical distancing measures, which is important for understanding the socio-cultural motivations that influence activity patterns, but is different than capturing activity itself.

The primary source for tracking activity is cell phone location data collected by private companies [6, 39]. When the COVID-19 pandemic began, Google and Apple began releasing mobility data derived from their mapping products (Google and Apple Maps)[51, 50]. The mobility data tracks cumulative daily trips, by geography, using different modes of transportation to reach destinations like retail and recreation, groceries and pharmacies, parks, transit stations, workplaces, and residential areas. Google and Apple mobility data are available for thousands of cities, but coverage is biased towards North American and European regions (80% for Apple; 53% for Google), and there are substantial data gaps over parts of Africa, Asia, and the Middle East. Regions with poor or opaque statistical collection systems and little testing of virus transmission are also most often not covered by Google and Apple. In fact, 12 out of the 19 countries in the Middle East have no sub-national mobility data available for tracking changes in activity (Figure 1). When sub-national mobility data does exist for the region, it is usually aggregated to the province level, so activity patterns at town or city scales can not be differentiated.

Figure 1: Map of countries in the study area, highlighted to indicate data availability. Striped countries have sparse sub-national Google mobility data available, whereas non-striped countries have no sub-national Google mobility data. Countries in purple have urban-level COVID-19 case counts, ones in blue have provincial level case counts, while countries in dark grey only have national level COVID-19 case counts. Of our studied countries 6 had no sub-national data and only one had local level case count and mobility data.

Because of this data gap, understanding about societal adherence to COVID-19 physical distancing measures in developing regions remains limited. Earth-orbiting satellites, capable of global surveys at fine spatial scales, show potential for providing systematic measurements over data sparse regions. In particular, the Visible Infrared Imaging Radiometer Suite's (VIIRS) day/night band (DNB), a new-generation space-borne nocturnal low-light sensor, is uniquely able to capture human activity from space [47]. The VIIRS-DNB measures nighttime lighting (NTL) from street lights, building windows, business districts, and vehicle headlights on a daily basis, characterizing the rhythms of human civilization, associated with holidays [66, 49], conflict [46, 76], and population movements [73, 19].

Recently, studies using simple differencing of monthly VIIRS-DNB composites observed that nightlights decreased in the first month of the pandemic across twenty global megacities [88], and over China [48, 18] and India [27]. These studies indicate that the VIIRS-DNB may be capable of tracking the societal response to COVID-19 and associated physical distancing measures, despite having an overpass around 1:30am, after most human activity has waned [75]. However, NTL time-series are not stationary, so more robust time-series analyses are needed. Furthermore, no studies have used NTL to explore the variation in responses to COVID-19 measures within and across countries, nor assessed their promise as a substitute or supplement for mobility over data-sparse regions.

Here, we assess the ability of NTL to track activity changes from COVID-19 physical distancing measures across 584 urban areas in 19 countries in the Middle East. Using time-series decomposition techniques applied to daily nocturnal satellite imagery (NASA's Black Marble VNP46A2, derived from the VIIRS-DNB on Suomi-NPP), we explore NTL changes from before the start of the pandemic through June 25,2020, a month after the end of Ramadan. Data processing techniques used to aggregate NTL data within urban areas, construct each urban NTL time series, and control for quality observations are described in Methods 0.1. Using these time-series, we measure how well NTL signatures synchronize with mobility data, and explore the population-scale variation in activity change both across and within countries in the region. In addition, we compare Ramadan NTL patterns from 2015-2019 with those from 2020 to assess whether adherence to physical distancing directives changed when these directives were in conflict with traditional socio-cultural practices.

Results

Comparison with Google Mobility data

We performed a time-series cross correlation analysis between Black Marble NTL and Google mobility time-series on the 24 urban areas where there was an overlap in data coverage. We also ran a cross-correlation analysis at the national level in 8 countries that did not have urban-level Google data (see Methods 0.2).

Mobility and NTL had similar temporal signatures in a large majority of urban areas and countries tested (Figure 2). Both NTL and mobility data captured the initial decline in activity from COVID-19 control measures, which went in effect in late March. The time lagged cross correlation analysis confirmed a high degree of synchronicity in NTL and mobility records, with neither series leading or following (average offset=0, $R^2 > .5$ in 21 out of the 24 urban areas, and 7 out of the 8 countries). We also found that NTL time-series have a nearly equal correlation to both Google trips to workplaces and to retail.

While for the majority of cities and countries mobility and NTL proxy each other well, there was wide variation in the strength of the relationship across and within different countries. Within Turkey, there was $>.9$ correlation for the cities of Iskenderun and Nizip, but a negative correlation in Tarsus. Similarly, in Haifa, Israel the two datasets were strong proxies, while in Tel Aviv they were not. At the national scale, we find no relationship between mobility data and NTL data for Iraq, an outlier when compared with the 7 other countries.

If NTL is to be used as a proxy for mobility data, future research must investigate

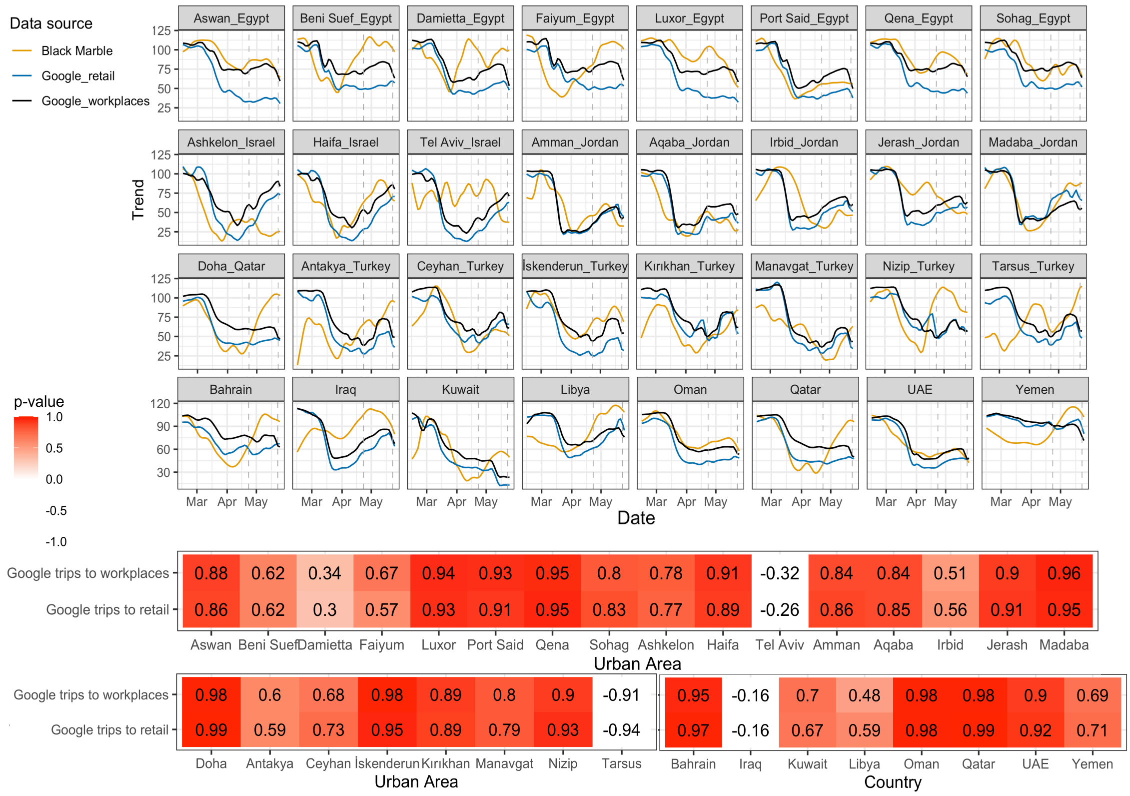

Figure 2: (top) Relative time-series of Google mobility compared against Black Marble data (scaled to overlap) for urban areas in the Middle East. Peaks occurring during Ramadan are captured more by NTL than Google mobility because most Ramadan activity occurs at night (when fasting has been broken). Ramadan period is framed by dashed grey lines). (bottom) P-values from a cross correlation analysis between the Black Marble time series and Google mobility time series show high correlation in most urban areas and countries.

the characteristics of a place that make this relationship reliably strong. Both trips and lights are affected by the physical distancing measures enacted during the pandemic, but they capture different, though related, kinds of behavior change. Within our sample of urban areas, one factor that seems to affect the degree of correlation is the strength of a country's Ramadan NTL signal. During Ramadan, daily fasting pushes meals and family gatherings later into the night, which disproportionately increases NTL. Black Marble and Google mobility time-series diverge during Ramadan(April 23-May 23 in 2020) for several of the Egyptian cities, for Ashkelon, Israel and for countries like Bahrain, Qatar, Kuwait, and Yemen. Ramadan activities were largely disrupted by the pandemic, but Black Marble data still captured an increase for many cities and countries that traditionally celebrate the holiday.

Comparison with policy data

Given the positive results from the cross-correlation analysis, we examined how well the timing of decreases in Black Marble NTL corresponded to the enactment of COVID-19 restrictions. We iteratively identified the largest 15 sustained increases or decreases in radiance in the November

2018-June 2020 Black Marble time-series for each urban area, and the corresponding dates of change, magnitudes of change, and directions of change (Methods 0.3). We compared the dates of changes detected from NTL to dates of national curfews and lockdowns recorded in the Coronanet government measures database [8] for the countries in our study.

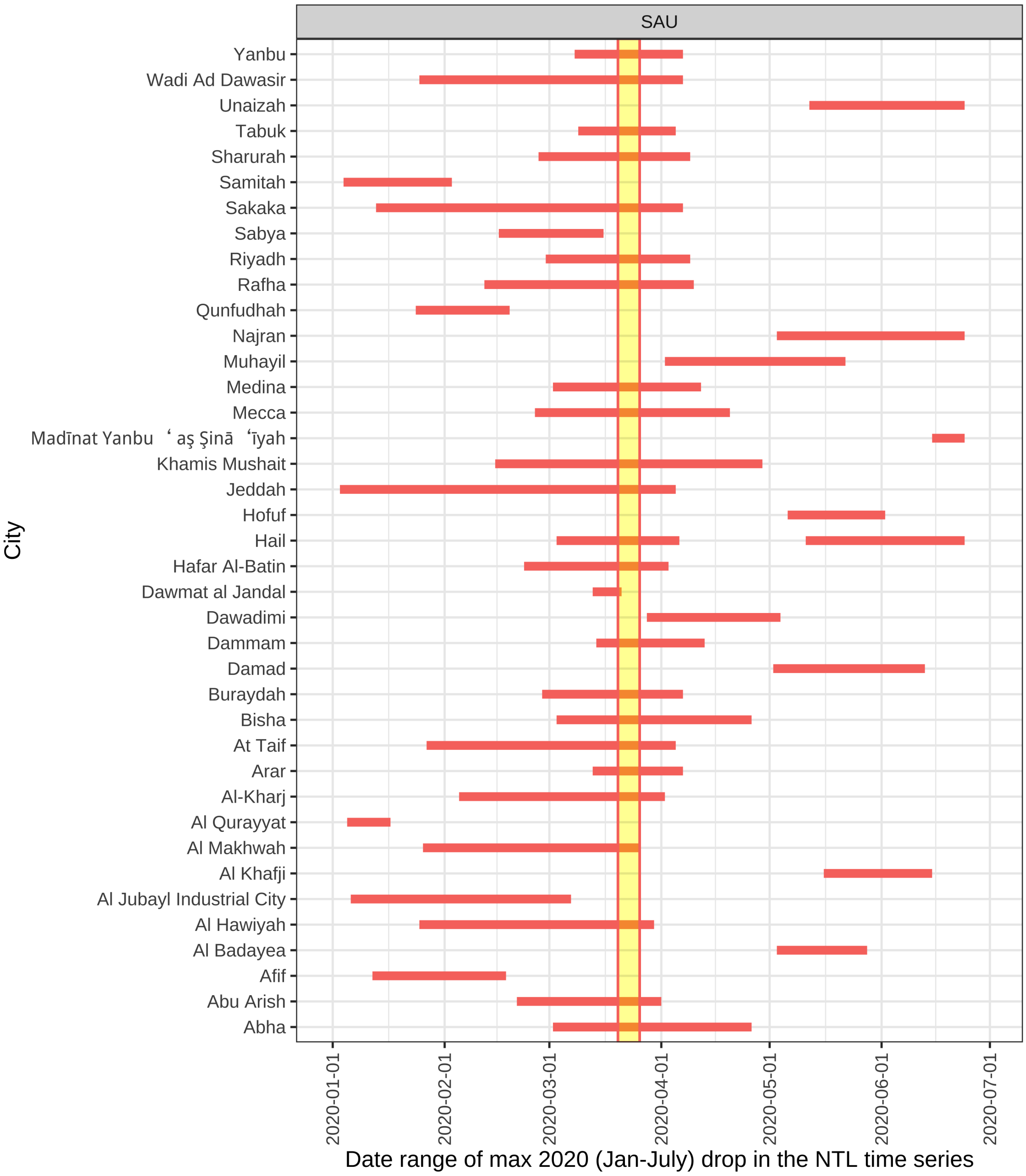

Figure 3: The date range of initialization of a national curfew in Saudi Arabia is depicted as a yellow rectangle, spanning a week, with the center falling on the day the lockdown began (3/23/20) for each urban areas in Saudi Arabia. The curfew initiation date is compared to the date range of the largest continuous decrease identified in the Black marble NTL time series, represented as a horizontal pink line. For 24 of the 39 sampled Saudi Arabian urban areas (62%), the largest continuous decrease overlapped with the date range of curfew initialization.

In most urban areas, physical distancing policies caused a significant abrupt reduction in NTL and associated urban activities. For instance, across urban areas in Saudi Arabia, the largest decreases in nighttime radiance consistently corresponded to the timing of the lockdown in late March (Figure 3). The figure also shows a second group of Saudi Arabian urban areas that had their largest reduction in NTL at the end of Ramadan (May 23-May 27), corresponding with the Eid al-Fitr. During this time, the Saudi government strengthened the curfew, expanding it from 5pm-9am to a full 24 hours, to curtail any potential gatherings or celebrations that could have exacerbated the outbreak [70]. Of the 584 urban areas sampled, nearly 70% had a significant (i.e. top 15) decreases in radiance coinciding with the onset of physical distancing policies (Table 1).

Table 1: Prevalence of Urban Areas in each country with drops in NTL corresponding to physical distancing policies

Country	# of UAs	% UAs w/ NTL drop >1%	% UAs w/ NTL drop >5%	% of UAs w/ max NTL drop in 2020
Afghanistan	13	54	38	15
Bahrain	1	100	100	100
Egypt	77	83	73	53
Iran	157	76	73	50
Iraq	63	59	40	13
Israel	9	89	67	56
Jordan	8	88	75	75
Kuwait	1	100	100	100
Libya	6	0	0	0
Oman	8	88	75	13
Pakistan	43	79	79	56
Palestine	6	N/A	N/A	N/A
Qatar	2	100	100	100
Turkey	116	47	37	25
Saudi Arabia	39	90	82	62
United Arab Emirates	6	83	83	50
Yemen	21	38	38	24

*Table statistics are based on the percentage of urban areas that had a disruption in the nightlights time series within 1 week of the onset of a COVID-19 national lockdown or curfew.

However, the effect of national curfews and lockdowns on urban activity was not uniform across countries. Turkey, had uneven NTL decreases after COVID-19 policies were put in place, with only 37% of its urban areas registering a drop bigger than 5% 1). Countries in on-going conflicts (e.g. Iraq, Afghanistan, Libya, Yemen)—all of which are in the top 20 fragile states according to the Fragile States Index [57]—also had weak or inconsistent nightlight decreases in response to national lockdown or curfews. Less than half of the urban areas sampled in these countries had a NTL decrease of greater than 5%.

COVID-19 changes in Ramadan activity in the Middle East

Ramadan began almost two months after the first cases of COVID-19 in the Middle East, ushering in a new wave of COVID-19 control measures. Past work using Black Marble has shown that NTL radiance spikes for cities across the Muslim world during Ramadan, reflecting a shift in shopping, iftars, and community gatherings to later in the night [66, 9]. To date there is little quantitative, trans-national information about how and where Ramadan activity changed in 2020, as compared to previous years, as a result of public health guidance to avoid these communal activities.

To measure changes during Ramadan, we calculated the "baseline" Ramadan increase as a percentage of the total NTL radiance for each year between 2015-2020, and quantified the change between this baseline and 2020 (Methods 0.4). We found that in some countries COVID-19 eliminated the Ramadan increase traditionally seen in NTL records, while in other countries, Ramadan remained nearly unchanged. Saudi Arabia's average Ramadan NTL radiance fell by almost a third in 2020, from comprising 11.5% of the NTL radiance signal to comprising only 3.7%. Ramadan NTL radiance also shrunk significantly in cities in Egypt (Figure 5), Jordan, Afghanistan, the United Arab Emirates, Palestine, and for Kuwait City, the only sampled urban area in Kuwait. In contrast, there was no significant change for most other countries in the Middle East (Figure 4), and in Qatar,Yemen, and Iraq, Ramadan NTL radiance even increased, on average, in 2020.

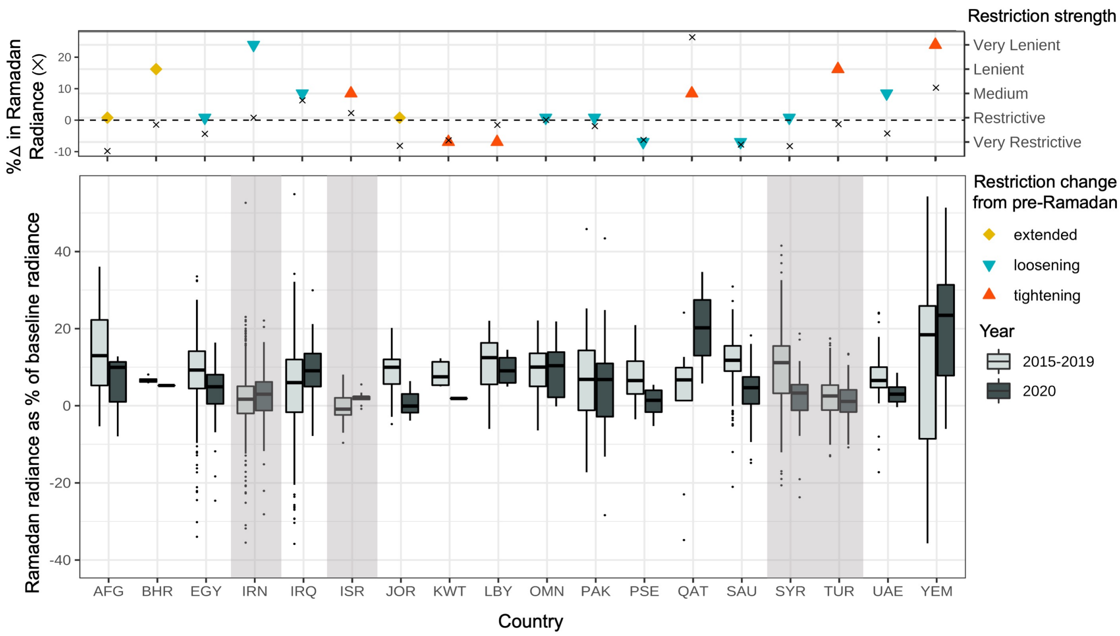

Figure 4: (top) Restriction markers indicate the strength and direction of change of national COVID-19 policies put into place during Ramadan. These markers are compared with the x's which indicate the change between 2015-2019 Ramadan NTL radiance and 2020 Ramadan NTL radiance. (bottom) Boxplot showing the 2015-2019 average Ramadan radiance vs 2020 average Ramadan NTL radiance for urban areas in Middle Eastern countries. Shaded countries indicate that country has few or no urban areas with a Ramadan nightlights increase, even in baseline years.

How well do these differences in the Ramadan change between countries correspond with differences in the strength of COVID-19 policies and regulations? We classified the government measures implemented in each country during Ramadan according to (1) whether they reflected a tightening, loosening, or merely an extension of pre-Ramadan COVID-19 measures and (2) how restrictive the new measures were during Ramadan according to the COVID-19 Government Response Stringency Index [33]. Restriction strength was defined by the average of the stringency index on April 23 and May 23, the beginning and end of Ramadan.

Not surprisingly, we found that countries that enacted stringent control measures during Ramadan often had the largest decreases in Ramadan NTL radiance. Afghanistan, Egypt, Jordan, Kuwait, Palestine, Saudi Arabia, and Syria were all classified as "restrictive" —with daily curfews, cancellation of mass gatherings, and business closures. Conversely, in the countries with the weakest Ramadan restrictions —Iran, Turkey, Bahrain, and Yemen —we observed stable or increased Ramadan NTL radiance in 2020.

Countries with low societal adherence to control measures would theoretically show up as outliers or deviations in the relationship between policy stringency and NTL decrease. Pakistan and Oman are two such outliers, both of which had "restrictive" control measures but showed no significant difference in Ramadan NTL radiance. In Iraq and Qatar, which are classified as "medium", we observed an average increase in Ramadan NTL radiance (6.3% and 26%). Similarly in Libya, one of the most restrictive countries, Ramadan NTL radiance only declined 1.5% in 2020, much less than would be expected by looking at peer countries with "very restrictive" policies.

However, interpreting COVID-19 responses based on simple historical and 2020 Ramadan season comparisons is difficult because of the longer term, simultaneous non-COVID related changes occurring in the region. For example, the increase in Ramadan radiance for Qatar shown in Figure 4 is driven by the small sample size (2 cities) and the longer term trend of urbanization within those two cities. From 2015-2018, the population of Doha grew at an average 2.5% annual growth rate, resulting in a 14% increase in NTL radiance. Conversely, Iraq and Libya were both sites of significant conflict in previous years. The War in Iraq (2013-2017) and the Second Libyan Civil War (2014-2020) dampened Ramadan signals in the baseline years, muddling the 2020 COVID-19 impact (theoretically a decrease) with the post-war recovery (theoretically an increase). Changes in Ramadan activity are intermixed with general (non-Ramadan) COVID-19 related behavioral changes and other long term trends like conflict, which can dampen the NTL baseline, or urbanization and electrification.

National and urban variations in response to COVID-19 restrictions

To disentangle COVID-19 and longer term effects, we use an additive time-series decomposition, to detrend the urban NTL time-series and separate seasonality. Pre- and post- COVID-19 trend and seasonal radiance levels are compared, and the percent change for each urban area is computed (Methods 0.5).

Our results highlight where and how much urban activity levels decreased during Ramadan and generally during the sampled pandemic period. Four different typologies of COVID-19 responses emerged: (1) *full responders*: urban areas that had consistent decreases in activity, both during Ramadan and generally during the pandemic (e.g. Ibri, Oman and Dammam, Saudi Arabia in Figure 5), (2) *general responders*: urban areas where activity levels decreased in response to the pandemic generally, but without a commiserate flattening in Ramadan seasonal activity (e.g. Al-Minya, Egypt in Figure 5), (3) *Ramadan responders*: urban areas with a decrease in Ramadan activity, but little activity change in the post-COVID-19 era generally (e.g. Amman, Jordan in Figure 5), (4) *full non-responders*: urban areas that showed little COVID-19 activity decrease during Ramadan and generally during the pandemic (e.g. Khuzdar, Pakistan and Dhamar, Yemen in Figure 5). There are also urban areas that do not have a pronounced Ramadan signal pre-2020 (non-seasonal urban areas), which are classified solely according to their general change in activity.

These four typologies are represented as the four quadrants in figure 6. *Non-responders* (full and non-seasonal) occupy quadrant 1, with the post-COVID era having equal or increased trend and seasonal radiance as the pre-COVID era. Quadrant 2 and 4 host *Ramadan responders* and *general responders* respectively, with directionally opposite changes in seasonal and trend radiance. *Full responders* occupy quadrant 3, with both seasonal and trend decreases in radiance during the pandemic. The country plots in figure 6 are colored according to the predominant typology of the constituent urban areas.

Countries where a large majority of sampled urban areas were *full responders* included Afghanistan, Egypt, Jordan, and Saudi Arabia. Each of these countries had widespread consistent responses to the pandemic, with a large majority (85% or more) of urban areas having both decreased Ramadan and general activity during the pandemic (Table 2). Predictably, all of these countries, imposed and enforced strict nationwide curfews, business closures, and limitations on mass gatherings–both during Ramadan and throughout the early stages of the pandemic. Qatar was also labelled a *full responder*, though its sample only included two urban areas, and Doha's general decrease was quite mild (-2%).

A second group of countries had consistent activity decreases (in 75% or more of the constituent urban areas) during Ramadan or generally, but not both. Three-quarters of Oman's urban areas sustained decreased activity during the pandemic period (Table 2), but the decrease during Ramadan was less consistent, especially in the capital area of Muscat/Seeb. In Palestine, both Hebron and Jenin, the two sampled seasonal urban areas, showed strong reductions in Ramadan activity, but there was with little commiserate change generally in the post-pandemic era, across urban areas (figure 6). Similarly, the UAE showed more consistent Ramadan decreases (67% of

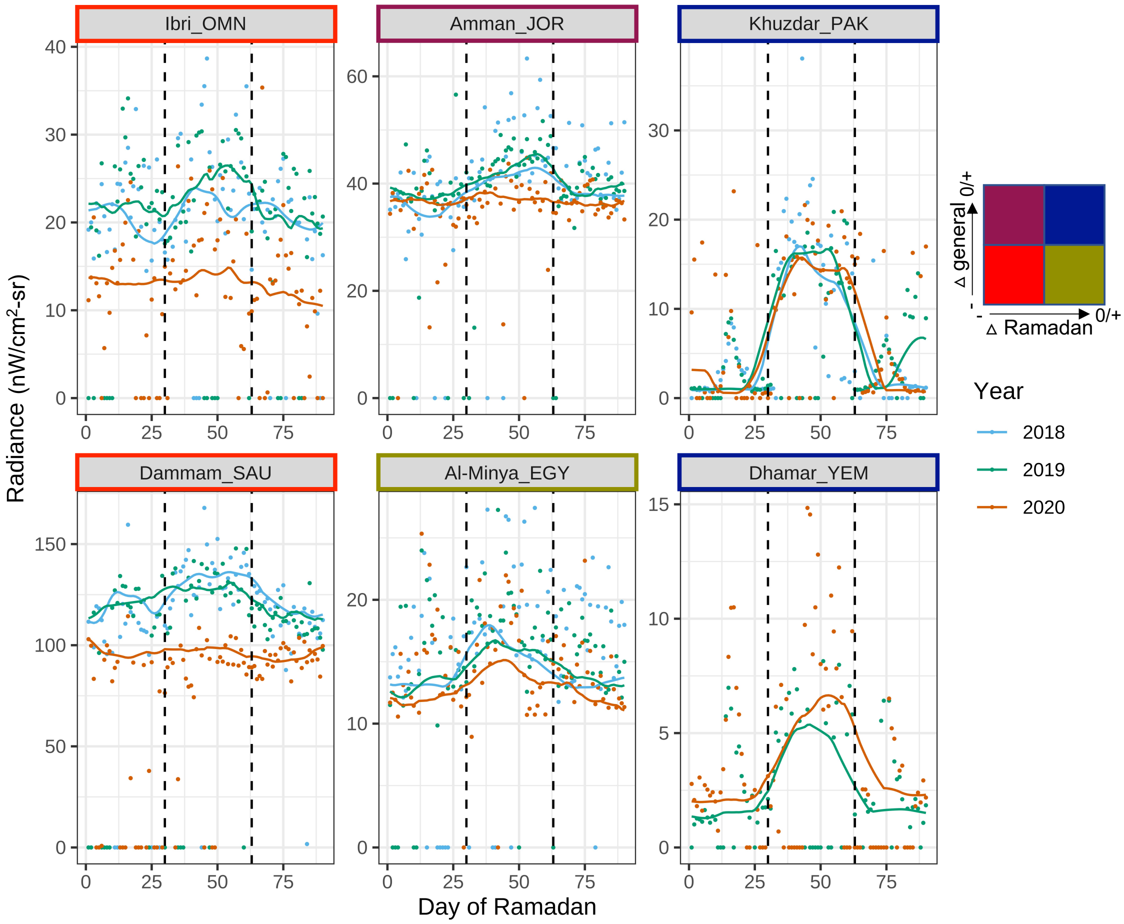

Figure 5: Historical and 2020 radiance for a sample of urban areas: (column 1), Ibri, Oman and Damman, Saudi Arabia are full responders, (column 2, top) Amman, Jordan is a Ramadan responder, (column 2, bottom) Al-Minya, Egypt exemplifies a seasonal city that is a general responder, (column 3) Khuzdar, Pakistan in the Balochistan province and Dhamar, Yeman are examples of full non-responders. The name boxes of urban areas are colored based on where they would fall on a two dimensional grid showing change in activity during Ramadan and generally during the pandemic.

seasonal urban areas) than general decreases in activity (50% of urban areas).

Non-responder dominant countries were those with inconsistent changes amongst their urban areas, which resulted from province-based approaches (e.g. Pakistan, Turkey, Iran) 6. Turkey's results (46% of urban areas with a general decrease) match its control measures, which were not national in extent, but limited to 31 selected cities [26, 14]. In Pakistan, the urban areas of Karachi, Hyderabad, Kandhkot, and Mehar —all of which lie in the Sindh province —had large decreases in their Ramadan signal (-71% on average). Conversely, in Khuzdar and Quetta, in the Balochistan province, NTL radiance levels stayed level or increased (+49% on average), as compared with pre-pandemic Ramadan activity. Our results show only 1/3 of Iran's seasonal urban areas showed decreased Ramadan activity in 2020. On average, radiance in Iran decreased very little during the pandemic (by 1.5%), and only in less than half of the sampled urban areas.

States in conflict were most often *non-responder* countries. Iraq, Libya, Syria, and Yemen

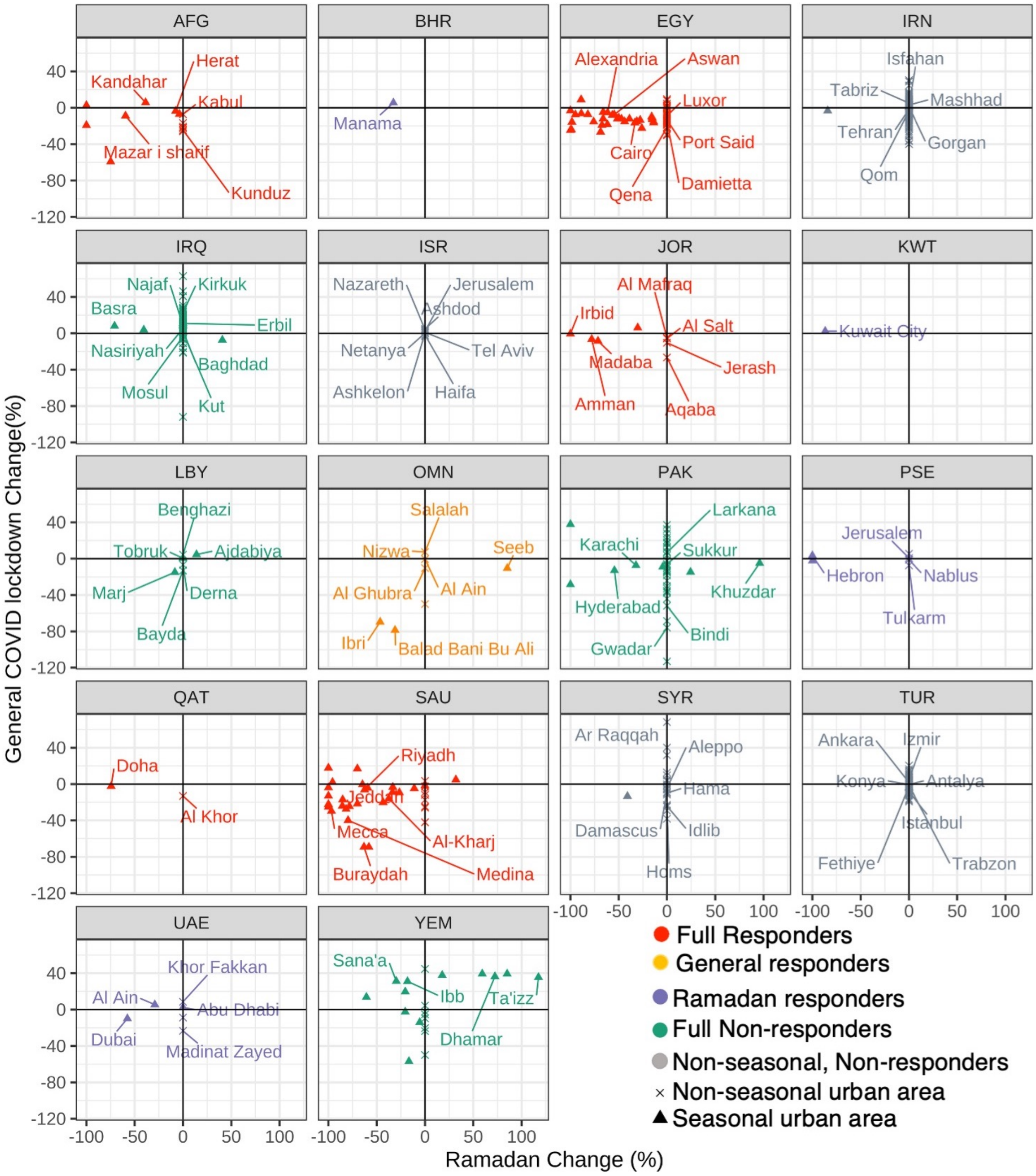

Figure 6: Percent change in Ramadan (seasonal) radiance is shown on the x-axis, while percent change in radiance generally during the remaining COVID-19 period (trend) is shown on the y axis. Country-plots are colored by the dominant typology of constituent urban areas. Seasonal urban areas (those with a consistent Ramadan increase, are represented as triangles, while non-seasonal urban areas are represented as an x.

all had wide variation in their general and Ramadan responses. Yemen, in particular, was the only Middle Eastern country to celebrate Ramadan more in 2020 than in 2019, with an average increase in both general (6%) and Ramadan (9%) radiance (Table 3). In Libya and Iraq, only 1/3 of urban areas had reduced Ramadan activity in 2020, and less than half had decreased radiance generally during the the study period.

Table 2: Consistency of general and Ramadan decreases amongst sampled urban areas (UAs) within Middle Eastern countries

Country	% UAs w/ sustained general decrease	% UAs w/ Ramadan decrease	# of UAs sampled	# of Seasonal UAs sampled
Afghanistan	85	100	13	7
Bahrain	0	100	1	1
Egypt	92	85	77	31
Iran	46	33	157	3
Iraq	24	33	63	6
Israel	22	NA	9	0
Jordan	87	100	8	4
Kuwait	0	1	1	1
Libya	50	33	6	3
Oman	75	67	8	3
Pakistan	67	71	43	7
Palestine	50	100	6	2
Qatar	100	100	2	1
Saudi Arabia	87	96	39	28
Syria	65	100	15	1
Turkey	46	0	116	3
United Arab Emirates	50	67	6	3
Yemen	48	58	21	12

Table 3: Ramadan and general percent change in NTL in urban areas

Country	# of UAs	trend $\delta\%$	stdev	seas. $\delta\%$	stdev
Afghanistan	13	-16	17	-22	35
Bahrain	1	5	NA	0	NA
Egypt	77	-12	8	-19	30
Iran	157	-1.5	12	0	0
Iraq	63	8	20	-1	9
Israel	9	1	3	0	0
Jordan	8	-7	9	-31	44
Kuwait	1	2.4	NA	0	NA
Libya	6	-4	9	0	0 *
Oman	8	-26	35	-4	11
Pakistan	43	-11	30	-4	18
Palestine	6	0	5	-33	52
Qatar	2	-7	7	-37	53
Saudi Arabia	39	-16	19	-41	41
Syria	23	-1	23	-2	9
Turkey	116	0	7	0	0
United Arab Emirates	6	-4	12	-14	24
Yemen	21	6	30	9	42

Discussion

For directly transmitted infectious diseases, human to human contact shaped by daily activity patterns, plays a major role in shaping the dynamics of transmission in an epidemic. Increasingly, public health studies have pointed to the lack of social epidemiological data describing population dynamics as one of the biggest challenges to accurately characterizing the spread of pathogens [6, 22, 24]. In the case of COVID-19, physical distancing (e.g., avoiding travel and crowded public spaces, and limiting physical contact with others) has been an important strategy for containing transmission, though it is often not practiced uniformly across and within countries. There is little existing data that can capture the heterogeneous adherence to control measures across time, which are needed to forecast the effectiveness of these measures [39, 6].

Cell phone mobility data is increasingly being used to evaluate societal adherence to physical distancing measures [39, 45], but publicly-available data is patchy in coverage and nonexistent in many of the poorest, most fragile regions or in lower-resource settings, where use of smartphones is less common. It also often comes pre-aggregated so differences in local mobility patterns (towns or even neighborhoods) can not be examined. Currently when mobility data is not available, models are trained to predict activity patterns based on government policies alone [87], a critical shortcoming in their applicability in regions where the divide between control measures and adherence to those measures is large.

Our results highlight the possibilities and limitations of NTL for providing context-specific information about how physical distancing control measures have changed human behavior on a societal scale. Unlike mobility data, global nightlights data is openly-available, collected continuously at 500m resolution, and can be easily aggregated to describe changes in neighborhoods, cities, provinces, or countries, matching the spatial units of reported policy data, case and death count data. We find that NTL time-series during the first four months of the pandemic had high synchronicity with Google mobility data during the same time period ($R^2 > .5$ in 88% of the cities and countries sampled). This indicates that NTL can act as complement for mobility data when there is sparse coverage or a substitute when there is no availability. NTL also corresponded well with the timing and severity of governmental measures. Drops in radiance in the NTL time-series matched the onset of national control measures in 70% of the sampled cities, and stronger measures were associated with larger decreases in radiance. This confirms that the activities captured in NTL dynamics (e.g. business operations, traffic) indirectly capture the transmission causes that control measures target (e.g. mixing, human to human contact).

Equally important are differences between NTL time-series and mobility data. First, while NTL has global spatial coverage and higher spatial resolution, it is more limited temporally. Cell phones track activity throughout the day, but existing Lower Earth Orbiting (LEO) satellites, like those that collect NTL data, overpass only once per night. Second, unlike trip destinations, the different activities that contribute to nightlights can not be easily differentiated. NTL is primarily associated with downtown centers, commercial areas, manufacturing, public service areas, and transportation [43, 32, 53]. As such, communal gatherings in residential areas are largely invisible to nightlights data, even though they may drive increased transmission. Furthermore, how much each sector contributes to nightlight radiance differs across cities and between countries, making it difficult to identify or compare the causes of decreased urban activity. Third, as with mobility, NTL dynamics are impacted by several socio-cultural and technical processes that are not related to COVID-19 transmission —e.g. conflict, urbanization, electricity insecurity and electrification. To measure adherence reliably, care must be taken to control for these processes and to establish a reliable baseline.

In parts of the Middle East, there is little understanding of numbers of cases, or even deaths, since such statistics are dependent on testing capacity and reporting policies. Recent studies estimate that only 1.25% of COVID-19 deaths in Damascus [87] and 7.7% of deaths in Egypt have been reported [42], spotlighting the Middle East as a region where COVID-19 transmission rates, and the activities that impact them, have been largely untracked. Activity patterns derived from nightlights provide insights into how the Middle East responded to control measures meant to slow the transmission of COVID-19, during Ramadan, and more generally across the first four months of the pandemic.

Our results show, on average, NTL decreases tracked restriction stringency for most countries during Ramadan in the Middle East. Not surprisingly, in countries with lenient restrictions (e.g. Yemen), we found little change in activity between pre-pandemic years and 2020. The inverse was true for countries with "restrictive" or "very restrictive" policies (e.g. Kuwait, Palestine, Saudi Arabia). Outliers included Iraq, which saw an average increase in Ramadan activity over 2020 despite a national curfew, and Libya, Oman, and Pakistan which all had "restrictive" or "very restrictive" control measures, but little Ramadan change. Within countries, we identified a highly heterogeneous response to COVID-19 restrictions, apparent in the degree of dispersion in the scatterplots in Figure 6 and the standard deviations in Table 2, calling into question whether nationally-aggregated data on mobility or activity is even meaningful for local disease transmission forecasts.

Changes in nightlights are the result of behavioral changes influenced by both top-down policy, but also the values and decision-making apparatus of civil society. In some cases, like in Turkey, Pakistan, and Iran, the heterogeneity in responses reflects the balkanized application of top-down control measures across provinces. Turkey stood out from the rest of the region by not ordering a full national lockdown or curfew until April 2021 [82]. The national government in Pakistan, under pressure both economically and from religious leaders, is widely considered to have had an inconsistent response early in the pandemic, sending mixed messaging and misinformation, backtracking on Ramadan restrictions, and downplaying the pandemic's health risks [30, 86]. This left many of the provinces to enact their own measures. Sindh province, which is run by the national government's opposition party, took an early position on the pandemic in mid-March, ordering all public transport, markets, offices, shopping malls, restaurants, and public areas to be shut down [37]. These restrictions were consistently extended through the Ramadan holiday [13]. We observed significantly larger reductions in activity in Sindh urban areas during Ramadan than in non-Sindh urban areas. Similarly, Iran's national government reversed proposed restrictions during Ramadan to appease conservative religious clerics [52]. The information apparatus in Iran was been widely regarded as unreliable [5], which may have stifled activity decreases that otherwise would have been initiated by individuals or civil society.

In other cases, highly heterogeneous responses may reflect differences in the reaction of civil society to control measures. Our results expose a significant divide between control measures and activity changes in conflict countries. Fragile and conflict-afflicted countries, such as Syria, Iraq, Libya, and Yemen, had weak responses to COVID-19 restrictions and the lowest, least consistent decreases in nightlights for both Ramadan and generally. Yemen was the most lenient country in the Middle East, with few control measures in place. In contrast, Syria, Iraq, and Libya closed borders and suspended flights, shut down schools, imposed curfews, banned public gatherings, implemented a mandatory lockdowns, and imposed strict social distancing, however NTL records indicate that little changed in the way of urban activity.

There is little available ground-truth data about changes in activity patterns in fragile states, however the data that exists validates the NTL records. Crowd-sourced photo submissions from Yemen, have also indicated that markets in larger cities (e.g. Sana'a and Ibb) appear to be as busy as they were before COVID-19 restrictions were put in place [31]. Journalistic accounts describe Yemen as one of the only Muslim countries to celebrate Ramadan as usual in 2020 [89]. In phone surveys conducted by the International Organization for Migration in Iraq in April and June, a majority of respondents said half or less of the population stays at home during curfews [23].

Three hypotheses exist for why countries in conflict had smaller or inconsistent changes in activity, despite strict curfews. First, conflict zones often already have existing curfews in place and limits on freedom of movement and assembly, making COVID-19-specific behavior change less significant from baseline activity levels [62, 38]. Second, residents living in fragile states must often prioritize safety, security, and economic concerns over complying with public health restrictions. In Iraq, a considerable percentage of the population resisted COVID-19 restrictions on movement, because of the need to protect livelihoods [36]. In Syria, restrictions were reversed out of fear of economic collapse [55]. Across the Middle East, armed conflict increased during governmental COVID-19 lockdowns, presenting residents with a security-public health compound threat [56]. Third, given the fractured governance and public distrust of policing in conflict zones, there may be fewer resources available for education and enforcement of public health measures [2, 29]. In

Iraq and Libya, strict national restrictions were in place, but some studies document that the government and police forces had trouble convincing citizens to comply [12, 7].

Though the use of nighttime lights (NTL) to study activity changes requires some background understanding of the specific social contexts where it is applied, these preliminary results, along with the global coverage and open availability, make NTL data a promising resource for public health applications. Like many developing countries, most of the Middle East currently has vaccination rates below 30%, [15] making physical distancing measures one of the few available strategies for controlling virus spread. We suggest that the approach operationalized here may be used to adapt epidemiological models to a local context, sharpening COVID-19 transmission forecasts in developing countries, fragile-states, and regions with sparse mobility data. If successful, the approach may be expanded to other infectious diseases, where dynamic measures of human populations are needed to understand outbreaks.

While the VIIRS-DNB was designed for weather and environmental monitoring, the demonstrated value of satellite NTL data for the benefit of public health management opens up new discussions about the role Earth Observation could play to address pressing social challenges traditionally outside of the purview of Earth Science. More frequent NTL observations, captured across the night, is one investment that would have immediate public health benefits. Apart from transforming control strategies for transmissible diseases, dynamic measures of human movement are also essential for immunization campaigns, disease surveillance, and improved response to disasters and outbreaks [63, 79, 74]. Providing actionable information to decision-makers about the nature and variety of shifts in human activities would allow for better understanding of their impact on disease and health.

Methods

0.1 nightlights dataset

We used the 500m daily Black Marble nighttime lights product (VNP46A2, https://ladsweb.modaps.eosdis.na and-measurements/products/VNP46A2/) to create a five year time series of nocturnal radiance observations over 7 tiles covering the Middle East. The Black Marble retrieval algorithm utilizes all high-quality cloud-free and snow-free radiances captured from the VIIRS-VIIRS-DNB sensor on-board the Suomi-NPP satellite, and corrects for atmospheric-, terrain-, vegetation-, lunar-, and stray light effects [67]. Image dates included the six months around Ramadan for 2015-2018 (3/18/15-9/15/15; 3/9/16-9/3/16; 2/26/17-8/24/17; 2/15/18-8/13/18) and 11/7/18-6/25/20.

We used three layers of quality control to create reliable urban nightlight time-series. First, we filtered only high-quality pixel-level observations (QA flag 0 or 1) within each urban area to be averaged each day, for each year. Urban boundaries were defined by the Global Human Settlement Functional Urban Areas (GHS-FUA) dataset [72], which delineates the commuting areas of urban centers globally in 2015, based on objective characteristics like travel time to central business districts, population and population density, and country GDP.

Second, we filtered out low-quality daily urban radiance averages using a majority quality flag. The majority quality flag was based on the percentage of pixels in the urban area that are high quality (QA flag 0 or 1), low quality (QA flag 2), or no data (QA flag 255). If the majority pixels in the urban area were low quality or no data, that date's urban average was excluded and the radiance value was interpolated. A 14 day rolling window was then used to smooth each of the urban time series and remove spurious measurements.

Finally, we filtered for reliable *urban time-series* based on the number and distribution of high quality observations. We created quality assessment summary statistics E and ε for each time-series, where E is the proportion of high quality observations over the entire assessment period, and ε is the proportion of rolling 7 day weeks with at least one high quality estimate. E and ε are calculated as: $E = \frac{\sum_{i=0}^{n} w_i}{n}$ $\varepsilon = \frac{\sum_{j=0}^{n} w_j}{j}$ where $j = n/7$

Urban areas with $E < .08$ or $\varepsilon < .7$ were excluded. These thresholds were tuned to balance the trade-off between keeping a high proportion of urban areas in the sample (65%) while ensuring the the time-series is stable, complete, and without multiple week gaps. 582 urban areas in 19 countries were included in the final sample.

0.2 cross-correlation analysis

To compare the similarity between nightlights signal and mobility signals, we first identified the overlapping subset of cities and countries included in both the Black Marble sample and he Google mobility dataset release. Metropolitan area data was only available for Egypt, Israel, Jordan, and Turkey, and Qatar, and 24 shared urban areas were identified in these countries. We also ran a cross correlation analysis for 8 other countries that had Google mobility data available at the national level.

Google's mobility data is provided originally as % change from baseline, with baseline represented as 0. We add 100 to all google mobility time series so that baseline is represented as 100. Black marble time series, from 1/01/2020-6/25/20, is rescaled to match the range of the Google mobility data, with the baseline, defined as the average of January 2020. We use a 7 day moving average to smooth out weekday/weekend perturbations in both series. Using a time-lagged time-series cross correlation, the mobility and Black Marble variables were determined to neither lead nor lag one another, with the best correlations occurring without a time shift in nearly all urban areas. We report out the cross correlation coefficient as a measure of similarity between the two datasets in each city/country in Figure 2.

0.3 time series disturbance analysis

To identify major breaks and decreases in NTL, we first apply a 30 day moving average to the 11/7/18-6/25/20 Black Marble time-series to smooth out all minor perturbations and identify the most prominent features. Using run length encoding, we divide each time-series into segments that continuously rise or fall, and require that the segments are at minimum 5 days in length, to rule out short-term anomalies like power outages. The largest 15 sustained changes are recorded, along with the corresponding dates of change, magnitudes of change, and directions of change for each urban area. Sustained increases are discarded, to leave a dataset with the largest decreases for each urban area.

This dataset is merged with information about the date range of national lockdowns and curfews for each country included in the Coronanet government measures database [8]. Yemen, Palestine, Pakistan, Bahrain, Iran, and Qatar had no data, so information about measures in these countries were sourced from news articles. In Pakistan, provinces were primarily responsible for early lockdown, which varied, so the authors chose lockdown dates for the Sindh province, matching the location of the majority of urban areas in our sample. Yemen and Bahrain avoided a curfews, so the implementation of restrictions were used as a policy dates. Iraq and Lebanon both started with partial lockdowns and escalated to full lockdowns, so both dates were included–the date range of initialization and date range of intensification.

We identify the overlap between COVID-19 measures in each country and identified sustained COVID-19 decreases in each urban area. Table 1 is reports the the percent of overlap: urban areas that had a 1%, 5% and maximum NTL decrease while COVID-19 measures were implemented.

0.4 Ramadan signal as a percentage of the NTL baseline

For figure 4, we calculated the Ramadan increase as a percentage of the baseline NTL radiance for each year between 2015-2020. Radiances were averaged for days during Ramadan and days not during Ramadan (considered baseline) separately. We then calculated the percentage of the Ramadan mean that was an increase over baseline:

$$R\% = 100 * \frac{\overline{Ramadan} - \overline{baseline}}{\overline{Ramadan}}$$

The figure compares the distribution of $R\%$ for all urban areas in each country for the years 2015-2019 (pre-pandemic) with the distribution in 2020.

0.5 seasonal decomposition

We use an additive time-series decomposition to disaggregate changes in radiance from COVID-19 during Ramadan and generally throughout the pandemic period. The decomposition splits the time series into trend, seasonal, and remainder components. We create a discontinuous time series to input into the decomposition created from the 90 days before during and after Ramadan each year from 2015-2019 (540 days total, 6 periods). The trend is computed as a step function from the average of the data for each year. After detrending, the seasonal component is extracted by taking the median radiance value of each of the 90 days across the first 5 years. The remainder is the leftover when the trend and seasonal component (repeated each year) is subtracted from the original time-series.

The time-series decomposition separates seasonal changes (COVID-19's impact on Ramadan), from 2019-2020 trend changes (COVID-19's impact on activity patterns generally). We only use 2019 and 2020 trend means when calculating the percent change in trend radiance from COVID-19, in order to diminish the impact of longer term trends like electrification and urbanization. For the seasonal change in radiance, we subtract the seasonal component (derived from 2015-2019 medians) from the detrended 2020 data. For this analysis, any urban area where the seasonal component is not at least two times greater than the remainder component is designated "non-seasonal", and seasonal change is recorded as zero.

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Author contributions statement

E.C.S. and M.O.R. conceived the research question and design. M.O.R. conducted the nightlights processing. E.C.S. analyzed the results and wrote the manuscript. All authors reviewed the manuscript.

Additional information

Competing interests The authors declare no competing interests.

1 Supplementary information

1.1 Description of data availability

Satellite data supporting this research (VNP46A2) are available from the NASA LAADS DAAC (https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/VNP46A2/).

Processed data used to produce the results in this study are included as file attachments. Time series data for each FUA for each year are included in the FUA file, with headings as described below:

- SITE: Site ID based on the FUA indexing used in the GHS-FUA dataset [72].
- MONTH, DATE, YEAR: The month, day, and year of NTL observation
- TOA: Top of atmosphere radiance
- L3 DAILY: Lunar BRDF-Adjusted Nighttime Lights Daily Level 3 radiance
- L3 DAILY EXTRAPOLATED: Lunar BRDF-Adjusted Nighttime Lights Daily Level 3 radiance extrapolated so that no data values are ignored
- L3 DAILY 7DAY WINDOW: Level 3 radiance extrapolated and smoothed over a 7 day window
- L3 DAILY 14DAY WINDOW: Level 3 radiance extrapolated and smoothed over a 14 day window

- L3 DAILY 30DAY WINDOW:Level 3 radiance extrapolated and smoothed over a 30 day window
- MOONFRAC: Moon phase fraction (new moon to full moon)
- PERC URB: percent urban pixels within the FUA
- COUNT: number of pixels within the FUA
- %QA LE 1: Percent of pixels within the FUA with a quality flag less than or equal to 1 (high or good quality)
- %QA EQ 2:Percent of pixels within the FUA with a quality flag equal to 2 (poor quality)
- %QA EQ 255:Percent of pixels within the FUA with a quality flag equal to 255 (no retrieval)
- MAJORITY QA FLAG: Quality flag of majority of pixels within the FUA (255, 1 or 0; 2 is considered 255)
- E(X): E as defined in Methods.01
- EPSILON(X): ε as defined in Methods.01
- BM AOD: Black Marble aerosol optical depth
- STAT LABEL: High

We provide the analyzed results used to create Figure 6 in the csv file named "urban areas season general change". Headings in this csv are as follows:

- Cntry ISO: Country 3 letter ISO abbreviation
- SITE: Site ID based on the FUA indexing used in the GHS-FUA dataset [72].
- trendperchange: trend (general) percent change
- seasonperchange: season (Ramadan) percent change
- trendchange: NTL radiance trend change
- seasonchange: NTL radiance season change
- trendmean: NTL radiance trend mean
- seasonmean: NTL radiance season mean
- remaindermean: NTL radiance remainder mean
- eFUA name: FUA name

- Cntry name: Country name
- FUA area: FUA land area
- Lon: longitude
- Lat: latitude
- numcits: number of urban areas in specified country

1.2 R Code for drops and falls identification

The following R code was used to identify rises and falls in the NTL time series for Figure 3 and Table 1, and was derived from Stack Overflow: https://stackoverflow.com/questions/63226725/find-the-biggest-drops-rises-in-a-time-series-without-a-loop-preferably-using-t

```
rise_and_falls <- function(value, time, gap_width = 5, top = 15, type = "fall") {
  type <- match.arg(type, c("fall", "rise"))
  if (type == "fall") {
    rle <- rle(sign(diff(value)) == -1)
  } else {
    rle <- rle(sign(diff(value)) == 1)
  }
  rle$values <- !rle$values & rle$lengths <= gap_width | rle$values
  rle <- rle(inverse.rle(rle)) # Clean up changed runs
  df <- data.frame(
    start = cumsum(rle$lengths) - rle$lengths + 1,
    end = cumsum(rle$lengths),
    len = rle$lengths,
    drop = rle$values
  )
  df <- transform(
    df,
    start_value = value[start],
    end_value = value[end],
    start_time = time[start],
    end_time = time[end]
  )
  df$diff <- df$start_value - df$end_value
```

```
df <- df[order(df$diff),]
if (type == "fall") {
  tail(df, top)
} else {
  head(df, top)
}
}
```

1.3 Table of Country level policy measure strength

Table 4: COVID-19 Policy Measure Strength

country	direction	strength	index	curfew	hours	businesses	Eid	source
Afghanistan	extended	Restrictive	4	yes	24	closed	eased	[68]
Bahrain	extended	Lenient	2	no	0	closed	same	[81]
Egypt	loosening	Restrictive	4	yes	9	closed	tightened	[44], [10]
Iran	loosening	Very Lenient	1	no	0	open	same	[40]
Iraq	loosening	Medium	3	yes	11, 24 (S/S), 24 (Eid)	closed	tightened	[65]
Israel	tightening	Medium	3	no	9 (muslim towns)	closed	tightened	[11]
Jordan	extended	Restrictive	4	yes	16, 24 (Eid)	closed	tightened	[54]
Kuwait	tightening	Very Restrictive	5	yes	16, 24 (Eid)	closed	tightened	[59]
Libya	tightening	Very Restrictive	5	yes	24 (1 wk), 12 (3 wks)	closed	eased	[16]
Oman	loosening	Restrictive	4	partial	0	in Muscat	tightened	[60]
Pakistan	loosening	Restrictive	4	partial	varies by province	closed	eased	[20], [78], [28]
Palestine	loosening	Very Restrictive	5	yes	14.5	partial	eased	[80]
Qatar	tightening	Medium	3	no	0	partial	tightened	[25]
Saudi Arabia	loosening	Very Restrictive	5	yes	16	closed	tightened	[35]
Syria	loosening	Restrictive	4	yes	12	closed	tightened	[77]
Turkey	tightening	Lenient	2	partial	24 (S/S), 24 (Eid)	partial	tightened	[21]
UAE	loosening	Medium	3	yes	8	partial	tightened	[83], [85], [84]
Yemen	tightening	Very Lenient	1	no	0	open	same	[41]