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Key Points:

- Weekly cycles in meteorological parameters are largely caused by anthropogenic aerosols
- Weekly cycles in active fires are highly pronounced for many parts of the world
- Cycles strongly influenced by the working week and the day(s) of rest linked to religion

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Weekly cycles of global fires—Associations with religion, wealth and culture, and insights into anthropogenic influences on global climate

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Abstract One approach to quantifying anthropogenic influences on the environment and the consequences of those is to examine weekly cycles (WCs). No long-term natural process occurs on a WC so any such signal can be considered anthropogenic. There is much ongoing scientific debate as to whether regional-scale WCs exist above the statistical noise level, with most significant studies claiming that anthropogenic aerosols and their interaction with solar radiation and clouds (direct/indirect effect) is the controlling factor. A major source of anthropogenic aerosol, underrepresented in the literature, is active fire (AF) from anthropogenic burning for land clearance/management. WCs in AF have not been analyzed heretofore, and these can provide a mechanism for observed regional-scale WCs in several meteorological variables. We show that WCs in AFs are highly pronounced for many parts of the world, strongly influenced by the working week and particularly the day(s) of rest, associated with religious practices.

1. Introduction

The study of weekly cycles (WCs) in meteorological variables goes back to the 1920s [*Ashworth*, 1929] when focus was on WCs near the main anthropogenic sources of heat and air pollution emissions in or near urban and industrial areas [*Arnfield*, 2003; *Sanchez-Lorenzo et al.*, 2012]. Over the decades, statistical tests highlighted the varying nature of WC signals and their causes, with many researchers finding significant WCs in various meteorological variables [*Gordon*, 1994; *Simmonds and Kaval*, 1986; *Simmonds and Keay*, 1997; *Cerveny and Balling*, 1998, 2005; *Forster and Solomon*, 2003; *Gong et al.*, 2006, 2007; *Bell et al.*, 2008, 2009; *Rosenfeld and Bell*, 2011; *Farias et al.*, 2014; *Georgoulias et al.*, 2015], while others have proposed that the observed signals are no stronger than the background variability [*DeLisi et al.*, 2001; *Hendricks Franssen*, 2008; *Hendricks Franssen et al.*, 2009; *Barmet et al.*, 2009; *Stjern*, 2011]. It has been suggested that, apparently, conflicting results are to be expected because the aerosol interaction with solar radiation and clouds vary greatly with time of year, surface land use, city characteristics [*Bell and Rosenfeld*, 2008], and a number of other factors. WC studies concerning the synoptic and global scale have become more common in recent times, with results producing much debate. *Sanchez-Lorenzo et al.* [2012] provide a review of the WC literature and the range of statistical approaches that have been applied to the issue. *Daniel et al.* [2012] have emphasized the importance of applying appropriate statistical analyses to this issue, a viewpoint with which we strongly agree. Anthropogenic activity linked to WCs on city scales are due to human heat generation or the release of atmospheric pollution [*Simmonds and Keay*, 1997]. Most studies producing significant WC signals posit that anthropogenic aerosols and their interaction with solar radiation and clouds are the factor controlling the significant regional-scale WCs [*Bell et al.*, 2008; *Rosenfeld and Bell*, 2011]. One of the key global sources of aerosols is active fires (AFs), quantifying the extent to which these AFs occur on a WC has the potential to explain WCs in meteorological variables at a variety of spatial scales.

Aerosols from AFs can warm the climate directly (the direct effect) by absorbing solar radiation [*Jacobson*, 2001; *Chung et al.*, 2005; *Forster et al.*, 2007] and reducing snow albedo [*Forster et al.*, 2007] but can also reduce the shortwave irradiance at the surface by scattering and reflection [*Schulz et al.*, 2006]. AF aerosols act as cloud condensation nuclei and ice nuclei, altering cloud characteristics and thermodynamics (the indirect effect). This aids the formation of cloud droplets, leading to easier-forming, longer-living clouds, which can act to suppress rainfall [*Rosenfeld*, 2000] and increase albedo [*Lohmann et al.*, 2000; *Chuang et al.*, 2002]. This suppression of early rainout can lead to the invigoration of storms and increased rainfall [*Rosenfeld* *and Bell*, 2011]. Therefore, the net effect of AF aerosol is not entirely clear and still debated. AF heat and aerosols will influence the local meteorology instantly, but aerosols can take days to travel to fire-free areas and thus potentially delay the WC signal in meteorological variables in downstream regions. Examining AFs directly allows us to investigate WCs at the source of a major contributor to anthropogenic pollution, providing a mechanism for regional-scale WCs through subsequent effects on meteorological variables.

Wildfires can be caused naturally (mostly by lightning) and anthropogenically, through arson or "prescribed" burning of forests and savannahs for land clearing/management for agricultural and domestic uses. Lightning occurrence itself can also be influenced by anthropogenic WC activities [*Bell et al.*, 2009; *Farias et al.*, 2014], which may act to enhance the signal by triggering midweek fires, though associated enhanced precipitation may also extinguish fires. These potentially confounding influences are consistent with the results of *Bistinas et al.* [2014] who found little association between burned area and lightning. The fire regimes, both natural and anthropogenic, vary greatly with each country/region's geography, climate, cultural/religious practices, and level of economic development. Detection of the presence or otherwise of a WC in anthropogenic fire is the key aim of this study, due to the debated but undeniable net influence that fire has on meteorological variables.

2. Data and Methods

2.1. Fire Detection

Using satellites is the only way to obtain AF data for analysis at a global scale [*Chuvieco et al.*, 2008]. Significant progress in this field has taken place since the launches of the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on the Terra (launched December 1999) and Aqua (May 2002) satellites. The MODIS Fire Team has developed an "active fire" product giving the location of burning fires [*Justice et al.*, 2002]. Daily (0000 UTC to 0000 UTC) global data (June 2000–the present) are used in this study, consisting of four daily passes at each location, downloaded from the NASA Earth Observations website (http://neo.sci.gsfc.nasa.gov/view.php?datasetId=MOD14A1_M_FIRE). We use all available complete calendar years 2001–2013 so as not to bias to a particular time of year. There are 208 (4.4%) days with no data available, ranging from 28 Mondays to 34 Thursdays, including 8 days removed because of their clearly erroneous values. The data (in units of fire counts per 1000 km^2) have been gridded at 0.1° resolution by the MODIS Land Science Team from the 1 km official MODIS AF product (MOD14A1). For numerical convenience we have normalized the data so that it represents the fire counts in each 0.1° x 0.1° grid box. We are less concerned here with the absolute values of AFs and rather more focused on the variability when examining WCs. The 0000 UTC to 0000 UTC daily data mean that in some parts of the world the days will be misrepresented. For example, a Monday in eastern Australia will represent 1000 h (or 1100 h during daylight saving) on Monday to 1000 h (1100 h) on Tuesday. This is a limitation as the daily values give no indication of time of occurrence.

AF detections use infrared anomalies relative to the adjacent pixels during each of the 10 min satellite overpass time. The algorithm uses brightness temperatures derived from the MODIS middle infrared (4 μm) and thermal infrared (11 μm) channels, testing whether the signals in the identified fire pixels are different from those of surrounding, nonfire pixel [*Justice et al.*, 2002]. The AF product often fails to detect rapidly burning, small and low-intensity fires, but reliably detects larger fires, limited to cloud-free areas.

Figure 1a shows total fire counts for the whole time period from the 0.1° gridded data. The fire count global pattern is similar to earlier global fire maps [*Giglio et al.*, 2006; *Chuvieco et al.*, 2008; *Krawchuk et al.*, 2009; *Oom and Pereira*, 2012]. The counts for Boreal summer (May–August; hereafter BS; Figure 1b) and Austral summer (November–February; hereafter AS; Figure 1c) are also shown to quantify the mean seasonal changes. The results shown here are consistent with those presented by *Chuvieco et al.* [2008].

2.2. Fire Counts

The total fire counts were calculated by summing each daily AF counts data for each 0.1° pixel over 2001–2013. Study areas were selected, split up by country where appropriate (e.g., USA and Mexico are very different economically), by region/geographical land use (e.g., the Amazon) or by clusters of fire-abundant areas (e.g., northern Australia). The total AFs were calculated for each calendar day of the week (Monday–Sunday) for each of the study areas. With many areas of high fire frequency having very strong variations on seasonal and annual timeframes [*Chuvieco et al.*, 2008], we adopted a simple method to filter out interannual and intraannual cycles

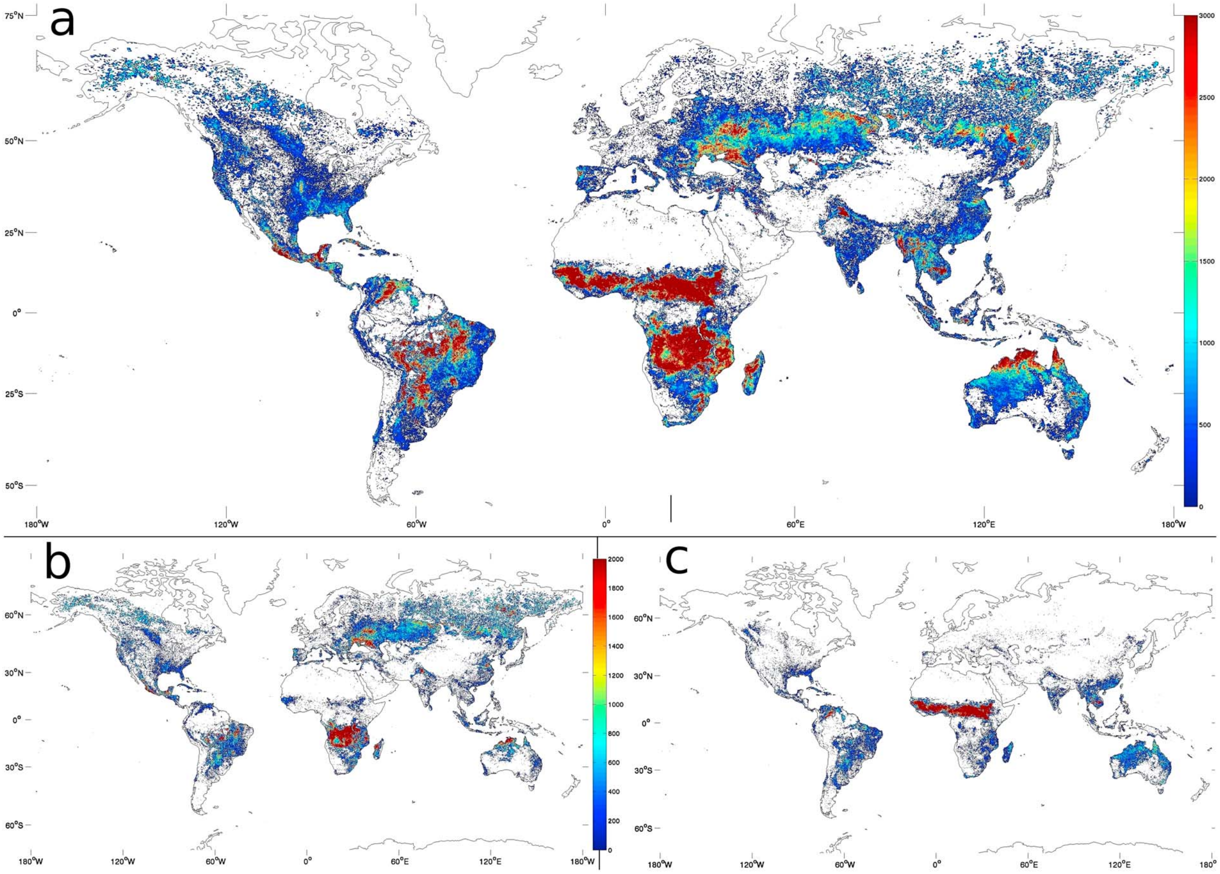

Figure 1. Total counts of active fire 2001–2013 (1000 km^2)$^{-1}$. (a) All year. (b) Boreal summer (May–August). (c) Austral summer (November–February).

in the AF raw data time series by computing the daily deviation from the running mean, a technique used by *Barmet et al.* [2009]. We used a 31 day running mean (and hereafter we denote the daily deviations from this as DD31RM) following *Bäumer and Vogel* [2007]. The total DD31RM AF counts were also made for each day of the week. This allows for statistical testing to be done for each day of the week while reducing the influence of seasonal and annual variability, largely irrelevant when considering WCs. This also greatly reduces the level of autocorrelation in the data.

2.3. Statistical Testing

To test the null hypothesis of no significant WC of AFs, we performed two Monte Carlo tests for each region based on the range between the days of the week with the minimum and maximum AF totals. The first (hereafter MC1) randomly shuffles the original data [see *Hendricks Franssen et al.*, 2009], and a WC is constructed on the adjusted time series. The maximum-to-minimum range is then calculated from this simulated WC, and this is performed 10,000 times providing a probability density function (PDF) of the weekly range of AFs. This PDF is compared to the range of the original WC and gives us an indication of the extent to which the amplitude of the WCs could have occurred randomly. However, this common-applied technique may erroneously inflate the level of significance of our analysis as it eliminates the autocorrelation associated with the data. The second Monte Carlo test (hereafter MC2) is similar to MC1 but addresses this autoregressive issue by randomly removing 5% of the data (run 10,000 times) but retains the order of the remaining elements of the time series rather than shuffling the data. MC2 creates a Monte Carlo-based PDF that preserves most of the temporal autocorrelation due to the order being preserved. We also make use of the nonparametric Kolmogorov-Smirnov test (KS test) to examine whether the maximum and minimum days of fire activity are drawn from the same distribution [*Wilks*, 2011]. A correlation (Spearman rank) is made between these days and degrees of freedom lowered accordingly in the KS test to reduce the effective sample size [*Wilks*, 2011].

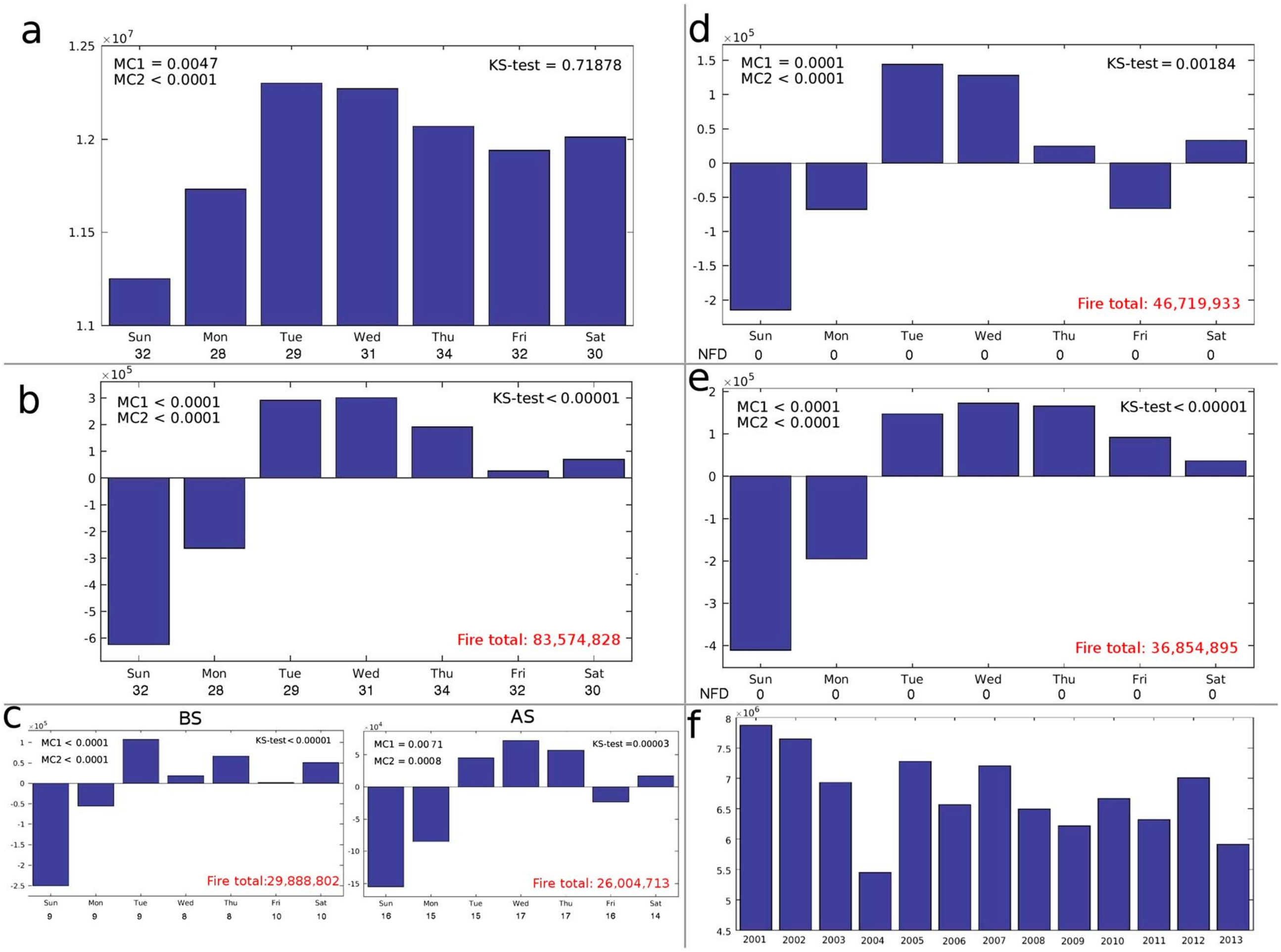

Figure 2. (a) Global active fire counts for each day of the week 2001–2013 and *p* values from Monte Carlo (MC1 and MC2) and KS tests; active fire total and number of missing data days are also included. (b) As with Figure 2a, but for global DD31RM. (c) As with Figure 2b, but for counts for Boreal summer (BS) and Austral summer (AS). (d) As with Figure 2b, but for the Northern Hemisphere. (e) As with Figure 2b, but for the Southern Hemisphere. (f) Annual global active fire totals.

3. Active Fire Weekly Cycles

3.1. Global

A strong WC is displayed in the raw data (Figure 2a), maximizing in the middle of the week and with a Sunday minimum. There were a total of 11.25 million Sunday fires globally over 2001–2013, this being 1.05 million (8.5%) fewer than the Tuesday total. This range is larger than in *any* of the 10,000 simulated WC ranges in MC2, and there were just 47 (0.5%) randomly simulated ranges larger in MC1. This gives a strong indication that there is a global WC of AFs above the random noise level, indicating that the nature of the AF WCs are very strongly influenced by the working week. However, the KS-test comparing Sunday (the minimum) and Tuesday (the maximum) is not significant due to high dependence between populations, this circumstance resulting from the high autocorrelation in the data. Figure 2b shows the DD31RM giving a stronger WC signal as expected. *Gordon* [1994] was the first to apply satellite-derived data to a global WC study, investigating WCs in temperature from the 1000–400 hPa layer. Despite the different variables being investigated in his and our studies, the structure shown in Figures 2a–2e has considerable similarity with Gordon's results. This provides a potential explanation for the widely debated [*Sanchez-Lorenzo et al.*, 2012] presence of regional-scale WCs, with fires providing a source of regional-scale anthropogenic aerosol and heat release.

Both seasons (Figure 2c) show a strong Sunday minimum, with the AS displaying a quasi-sinusoidal WC with a Wednesday peak. The BS has a less coherent WC pattern with a strong Tuesday peak, perhaps related to the relative small spread of fires in the AS compared to the BS (Figure 1a) putting more emphasis on the fire-active Amazon and African regions, both with strong WCs as discussed below.

Figure 2f highlights the annual variability of AF over the 2001–2013 period. The range varies between about 5.4 million AFs in 2004 and 7.9 million AFs in 2001, and there appears to be a declining trend, though is not statistically significant. This decline may be related to changes in the distribution of global precipitation, variations in the phase of climate indices such as El Niño–Southern Oscillation, shifts in anthropogenic land practices [*Jolly et al.*, 2015], or to increasing population density leading to reduced fire frequency [*Knorr et al.*, 2014]; however, no robust conclusions can be drawn from such a short study period.

3.2. Hemispherical

Figures 2d and 2e reveal strongly statistically significant AF WCs in both the Northern (NH) and Southern Hemispheres (SH). Both hemispheres display a strong Sunday minimum and a Tuesday and Wednesday peak for the NH and SH, respectively, both highly significant. The NH includes countries that have varied working weeks. Most European and American countries have a Monday–Friday working week, with the predominant faith being Christianity [*Smart*, 1999], with many Asian and Central American countries having a Monday–Saturday week. Some Muslim-influenced Middle Eastern countries have a Saturday–Wednesday week, e.g., Saudi Arabia and Kuwait, and some such as the Qatar and United Arab Emirates have a Sunday–Thursday working week. This is a possible explanation for the Friday relatively low AF activity. The ocean-dominated SH's more amplified WC is perhaps due to influence from fewer regions and is investigated separately below. The results in Figure 2 indicate that the global WC is produced by a variety of WCs, and because of this diversity, we now focus on specific regions of the globe which, according to Figure 1a, experience large fire numbers.

3.3. USA

In areas with developed economies and regulated labor force, AFs tend to be more regular, have a longer season, and have less variability [*Chuvieco et al.*, 2008]. This is shown in Figure 1, where fires in fire-abundant first world countries like the USA and Australia are present throughout the year. The USA's AF WC is very strong (Figure 3a), with nearly twice as many fires on Wednesday compared to Sunday, with the WC sinusoidal pattern influenced by the Monday–Friday working week. Prescribed burns in the USA are mainly conducted in the higher moisture boreal winter (BW) season, though often fail to achieve fuel reduction goals [*Ryan et al.*, 2013], leading to year round prescribed burns. This is seen in the seasonal WCs for the BS and BW (not shown) as they are very similar. This pattern provides a potential mechanism for WCs in the USA's daily temperature range [*Forster and Solomon*, 2003; *Kim et al.*, 2010] and increased midweek rainfall and storm activity [*Bell et al.*, 2008; *Rosenfeld and Bell*, 2011; *Tuttle and Carbone*, 2011] from the increased mid-week aerosols released from the AFs.

3.4. Australia

The WC AF for Australia is statistically significant, displaying a Saturday minimum (due to timing error–see section 2), with Sunday the second lowest day and a Tuesday peak (Figure 3b). When split into northern (Figure 3c) and southern Australia (Figure 3d), it is clear that the WC is associated with the nontropical areas in the south, whereas the north WC is not statistically significant in the KS test or MC1, though is in MC2 at the 5% level. According to *Chuvieco et al.* [2008], the more fire-abundant north has more seasonality to fires (corresponding with the dry winters and wet summers), whereas the main fire regions in the south burn for more of the year. The seasonal WCs for northern Australia (not shown) do not display a coherent WC pattern, whereas the south does, especially in the austral winter. This indicates a WC in prescribed burning off during the cooler months, whereas, in the natural wildfire season (January and February), the practice is more opportunistic and the signal damped by natural wildfires. The governments of states that include areas in southern Australia (temperate region) encourage autumn/winter/spring burning for land owners (e.g., Government of Western Australia (http://www.dfeswa.gov.au)), although in Victoria it becomes too wet during the winter months.

3.5. Europe and Asia

Europe's WC (Figure 4a) reveals a Sunday minimum and Thursday maximum, and this difference is statistically significant in the KS test though not for the Monte Carlo tests. Here fires burn for a large portion of the year [*Chuvieco et al.*, 2008], but the absolute numbers are low especially in BW. Spain (Figure 4b) also has a statistically significant WC in the KS test though not for the Monte Carlo tests with a Saturday minimum and Tuesday maximum, though the pattern is not coherent with a low Monday and Wednesday. Italy (Figure 4c) has a maximum of AFs on Sunday, though the amplification is low and not statistically significant.

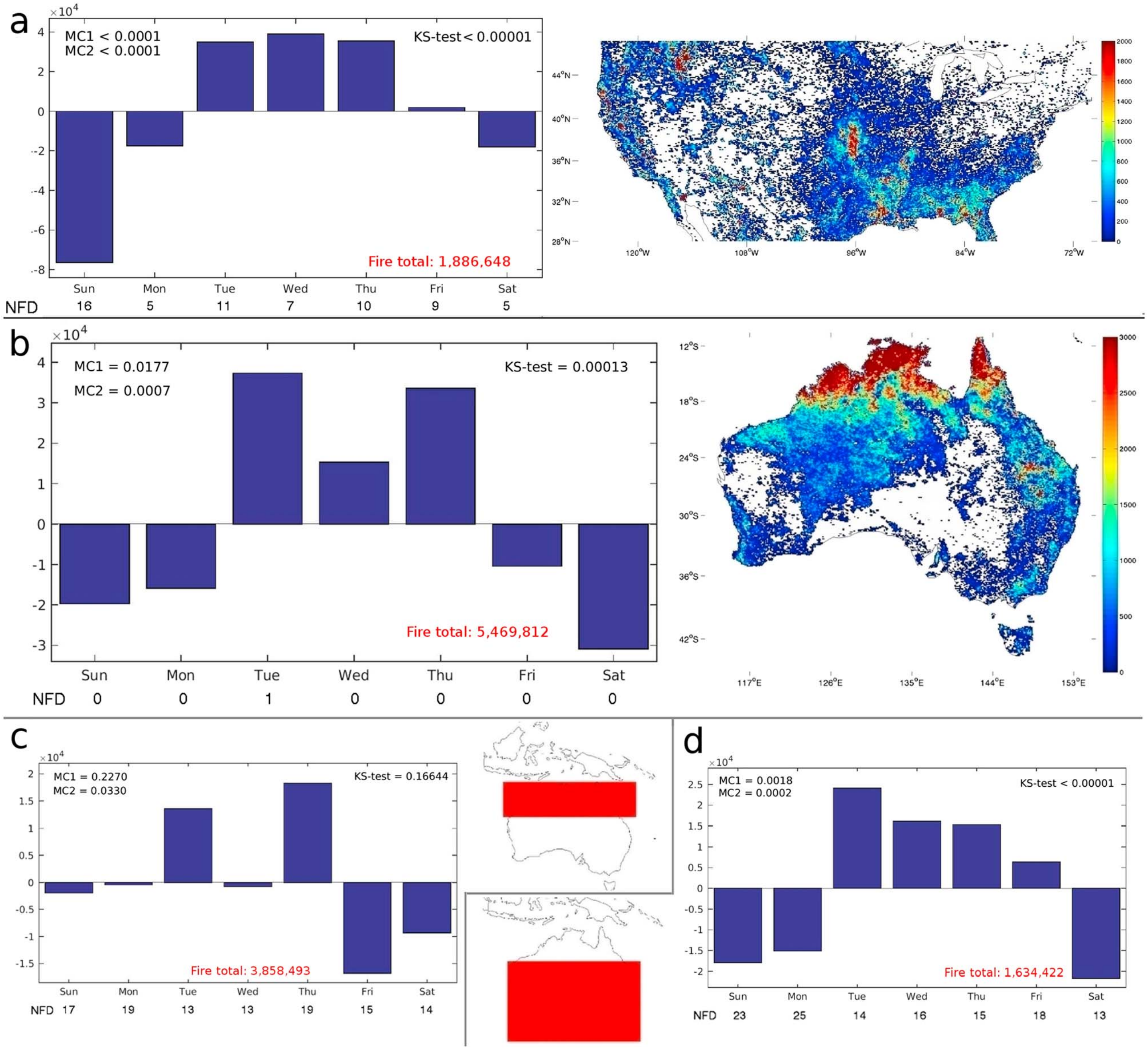

Figure 3. (a) As with Figure 2a, but for the USA. Number of nonfire days (NFDs) also included, along with active fire maps (0.1 × 0.1°). (b) As with Figure 3a, but for Australia. (c) As with Figure 3a, but for northern Australia. (d) As with Figure 3a, but for southern Australia.

The results appear to be at variance with those of *Georgoulias et al.* [2015] who investigated 2000–2009 rainfall for southwest and central Europe, indicating that fires are not responsible for this pattern. However, the temporal ranges of the studies do not correspond, so caution must be taken when speculating on previous results. Southeast Europe (Figure 4d) displays a WC pattern with a Sunday minimum, though is not statistically significant.

The areas just north of the Black and Caspian Seas and eastward to Kazakhstan are fire-abundant areas (Figure 1a). The AF WCs of the region split into eastern Europe/western Russia (Figure 4e) and Kazakhstan (Figure 4f) sections are shown. These areas are overwhelmingly populated by persons of the Muslim faith [*Smart*, 1999], where Friday is "the day of assembly" and prayer. This could be the reason why the AF WCs have minima on Thursday and Friday. The Monte Carlo and KS tests reveal that the signal is not significant. With the high number of nonfire days, high variability, and strong seasonality to the AFs in these areas [*Chuvieco et al.*, 2008], any significant signal may be being masked. Despite this, the WC patterns seen in these

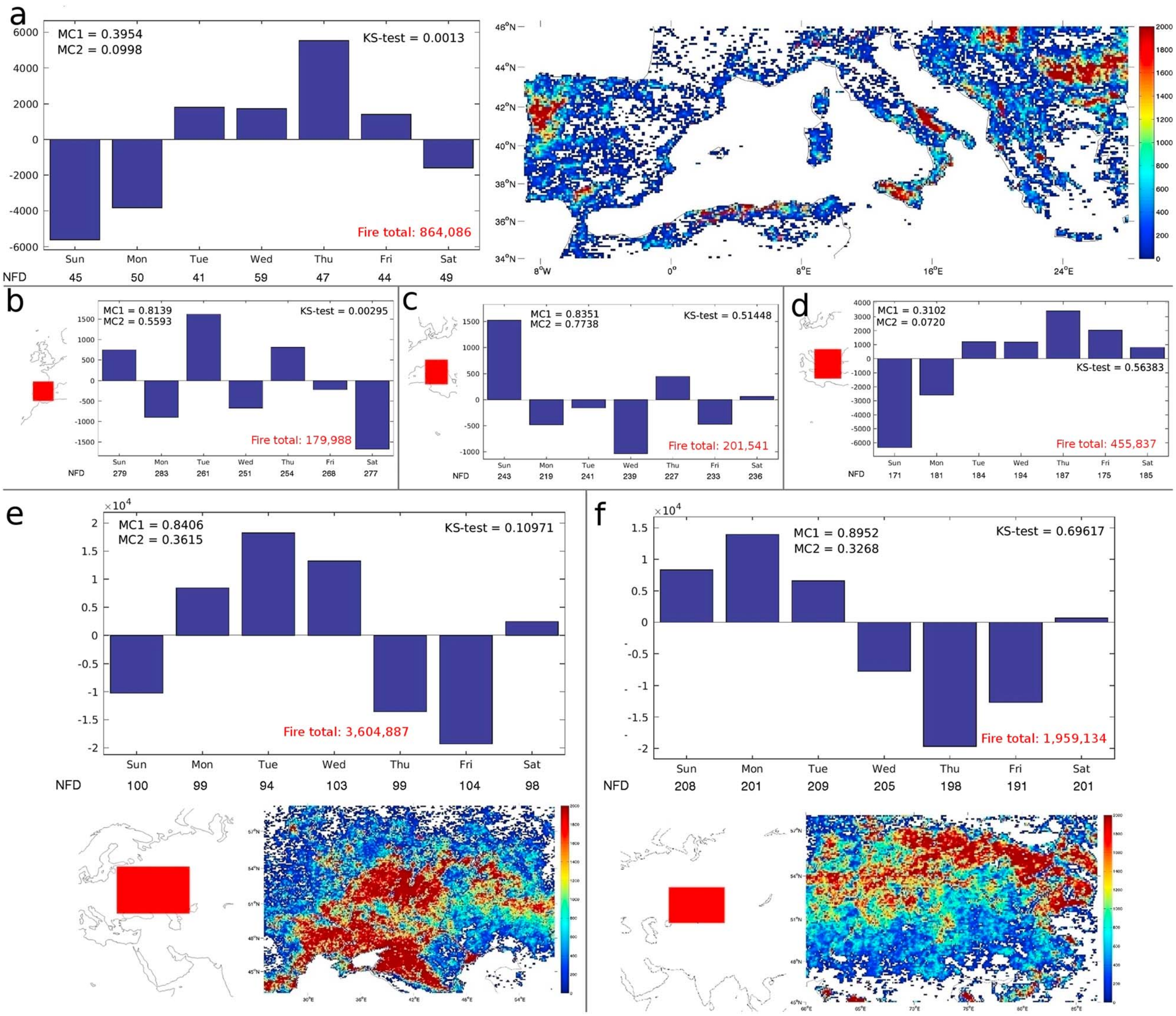

Figure 4. (a) As with Figure 3a, but for southern Europe. (b) As with Figure 4a, but for Spain. (c) As with Figure 4a, but for Italy. (d) As with Figure 4a, but for southeastern Europe. (e) As with Figure 4a, but for eastern Europe and western Russia. (f) As with Figure 4a, but for Kazakhstan.

Muslim-influenced areas indicate how days of rest can affect the regional-scale WCs of AF, with potentially major subsequent effects on meteorological variables.

India has a maximum of fire activity occurring on Sunday (not shown), opposite to the global pattern, statistically significant in MC1 though not in the other tests. India has a 6 day working week, with a Sunday rest day, so it is unclear why Sunday is the peak fire day. In China, most manufacturing activities occur on Monday to Saturday, but this is not reflected in the AF cycle (not shown), which has a Saturday minimum that is not statistically significant. Previous studies of WCs in China have found some significant WCs in daily temperature range and rainfall [*Gong et al.*, 2006, 2007], but this is not seen in the WC of AFs. The Southeast Asian area of Thailand, Myanmar, Laos, Cambodia, and Vietnam generally has Sunday minimum and Wednesday peak (not shown) statistically significant in the Monte Carlo tests but not in the KS. This minimum can be explained by the fact that the working week in Thailand is from Monday–Saturday. Further south, predominantly Muslim Indonesia, as with Kazakhstan, has a Thursday minimum (not shown) that is not statistically significant.

3.6. Amazon and Mexican Regions

The Brazilian Amazon is currently one of the most active regions of deforestation and biomass burning in the world [*Giglio et al.*, 2006]. In large parts of the Amazon prescribed fires are used for agricultural purposes

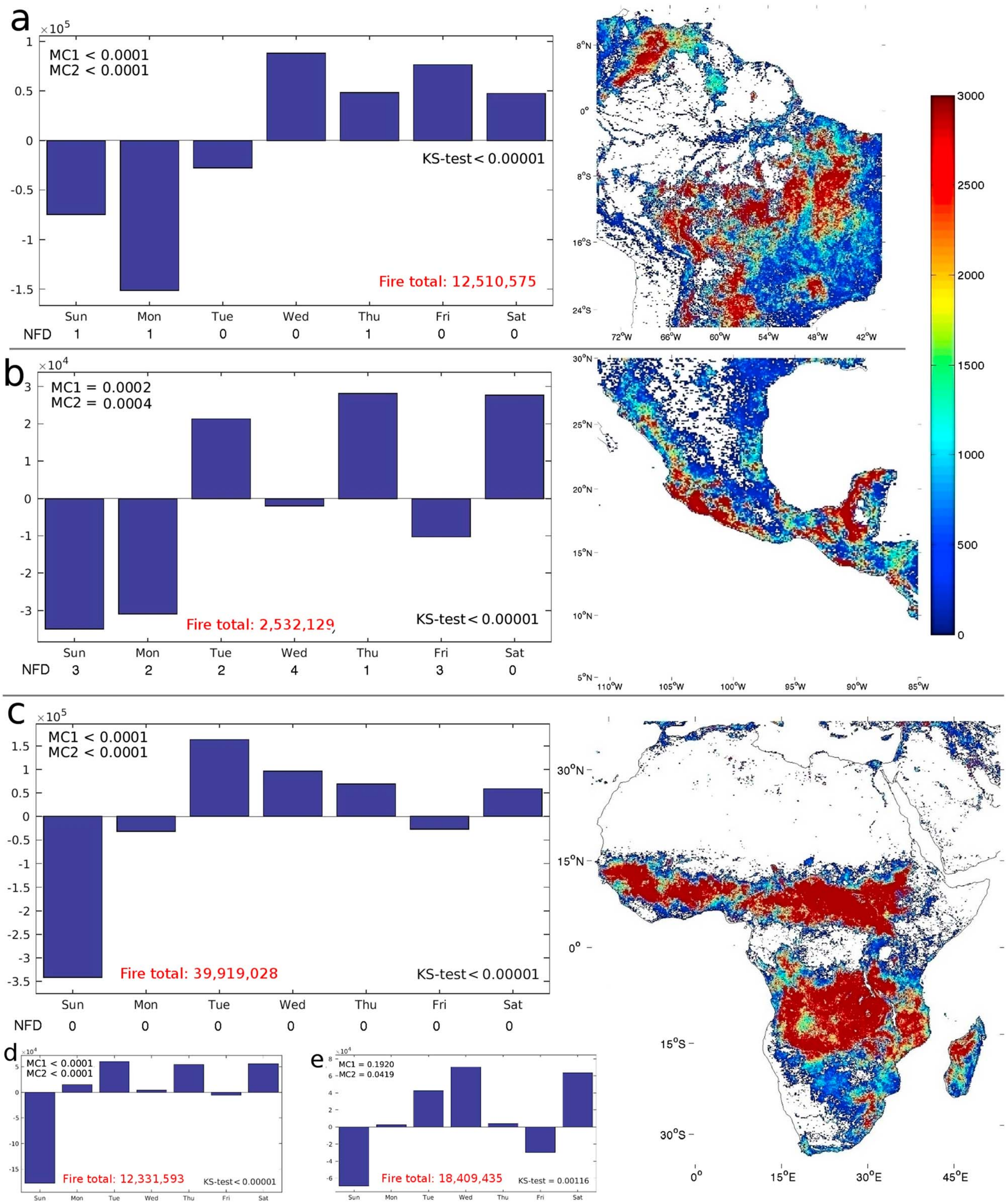

Figure 5. (a) As with Figure 3a, but for the Amazon region. (b) As with Figure 5a, but for Mexico. (c) As with Figure 5a, but for Africa. (d) As with Figure 5a, but for African boreal summer. (e) As with Figure 5a, but for African austral summer.

[*Schroeder et al.*, 2008], and this is reflected in the AF map in Figure 5a. The WC of the Amazon is statistically significant with a Monday minimum, along with a Wednesday peak. Part of the reasons for this low Monday value is probably due to the method of data recording (0000 UTC–0000 UTC) that partly blends the local Sunday and Monday. The low-AF Sunday is almost certainly associated with the fact that the predominant faith throughout is Christianity.

The majority of Mexico's fires are anthropogenic, primarily accidentally started, with some prescribed. The fire season in Mexico intensifies in late March and reaches its maximum in May [*Crounse et al.*, 2009]. Mexico has highly significant AF WC (Figure 5b). The working week runs from Monday–Saturday here, and the AF minimum is on Sunday, closely followed by Monday, again, potentially partly due to the method of data recording. There are 3 days on which there are strong peaks, namely Tuesday, Thursday, and Saturday; the reasons for which are unclear. The seasonal WCs look very different (not shown), with a very strong Sunday minimum for the BW months, which is not so extreme for the BS months. This is perhaps due to the BW being outside the Mexican fire season, so any prescribed burning is more apparent, with far fewer total fires.

3.7. Africa

The African continent is responsible for 43% of the 2001–2013 global AF. AFs are mostly anthropogenic, heavily influenced spatially by precipitation patterns [*Archibald et al.*, 2009]. This is clear in the seasonal fire patterns in Figure 1, with the majority of fires occurring in the dry seasons for the relevant hemisphere, and the map (Figure 5c) displays these two main fire areas, just north and just south of the equator. *Chuvieco et al.* [2008] indicate that the fire-abundant areas in Africa burn for a relatively short portion of the year, other than parts of more developed South Africa. With anthropogenic fires used for recycling nutrients to improve grasslands that support grazing, attract wildlife for hunting, reducing fuel loading, and for agricultural purposes [*Andela and van der Werf*, 2014], Figure 5c shows a very strong AF WC. Most Africans follow the Christian calendar [*Smart*, 1999], so it is not surprising that there is a strong Sunday minimum. However, in the fire region just north of the equator, in countries such as northern Nigeria, Chad, and Sudan, there is a major Muslim population [*Smart*, 1999] that is reflected in the WC, with Friday possessing the second lowest number of AFs, potentially due to Friday prayers. When split into seasons, there are clear differences. In the BS (Figure 5d), the largely Christian region just south of the equator experiences its fire season and the Sunday minimum is very strong, whereas in the AS (Figure 5e), when the Muslim-influenced region just north of the equator experiences its fire season, there is less of a Sunday minimum, with Friday also experiencing low fire activity. This again gives an indication that the prevailing religion of a region can greatly influence the WC of fire on a regional scale, also observed by *Pereira et al.*[2015].

4. Conclusions

Understanding the large-scale weekly cycle of fires provides an insight into the effect that humans have on the atmosphere, highlighting the spatial diversity of subsequent influences on meteorology. Our results show that weekly cycles in active fires are highly pronounced for many parts of the world, and these cycles are strongly influenced by the working week and particularly the day(s) of rest linked to religion. The study potentially provides a previously unconsidered mechanism for the large-scale weekly cycles in meteorological variables and points to how social constructs can affect the climate.

Detection of the presence or otherwise of a WC in anthropogenic fire was the key aim of this study. We have not addressed here the important question as to the extent to which an increase of AFs brings an increase in aerosols. Estimates of aerosol emissions from fires are highly uncertain and have been more commonly linked to burned area rather than AFs [*Knorr et al.*, 2012]. To quantify this, we are planning a number of important extensions of this research. Focus now moves on to the detection of WCs in aerosols directly (and their associated radiative impacts), also using data from the MODIS instruments. Quantifying the links between AFs and large-scale WCs in meteorological variables found in the literature is another important addition.

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Erratum

The originally published version of this article, the fire counts in the data were assumed to be within the relevant 0.1° x 0.1° grid box. However, the units of fire spatial density are actually fire counts per 1000 km^2, which means the fire counts were approximately an order of magnitude too high (by the ratio of these two areas). This error has been corrected and text updated in sections 2.1, 3.1, and 3.7, the legend of Figure 1, and the addition of a reference (*Pereira et al.*, 2015). Additionally, Figures 2, 3, 4, and 5 have been corrected. This version may be considered the version of record.