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Abstract

The ability to reliably project National wildland fire activity and related suppression costs for a year or longer in advance might be beneficial for the long-term strategic planning of fire-management resources and budgets. This study attempts to develop a two-year fire-activity & suppression-cost projection employing an empirical approach based on statistical analysis of reported data. Central to this approach is the hypothesis that the internal kinetic energy of the lower troposphere is a major driver of wildland fire activity in terms of total acreage burned annually. Since temperature is proportional to the atmospheric kinetic energy, for the above hypothesis to be true, there should be a statistically significant relationship between spatially averaged seasonal temperatures over USA and annual wildfire acreages. Using satellite-based temperature measurements and official fire statistics, it is shown that such a relationship does indeed exist and can be used to predict future fire activity if coupled with an appropriate temperature forecast.

A new technique for forecasting long-term temperature anomalies over USA is proposed based on a close match of patterns discovered between USA and Australian temperature series and the fact that the USA seasonal temperature lags the Australian seasonal temperature by 27 months. A regression analysis of USA fire activity data against 27-month forward shifted Australian temperature anomalies for the March - September time period employing information from the last 5 years (2011 – 2015) produced an accurate model of the annual acres burned as a function of the fire-season average temperature anomaly. This model was applied with predicted temperature anomalies for the USA (based on the time-shifted Australian temperatures) to project wildland fire activity at the National level for 2016, 2017 and 2018. Using financial data from 2008 to 2015, two exponential relationships were found between total acres burned annually on one hand and the yearly fire-suppression costs incurred by USFS and USFS-DOI combined on the other. Applying these cost-area relationships with predicted wildfire acreages for the period 2016 – 2018 resulted in projections of likely annual fire-suppression expenditures for the next two years.

The above forecasting method yielded the following main results: a) Due to a transient cooling episode, which began in the late 2014 and will continue well into the next year, the fire activity in 2017 will likely be below the 2005-2015 annual average with expected 7.0 ± 1.4 million acres burned and fire-suppression costs of $0.801B ± $0.2B to USFS and $0.283B ± $0.05B to DOI Agencies; b) In 2018, USA will experience the lagged effect of a mega El Niño currently unfolding in the equatorial Pacific. This will most likely result in a sharp increase in wildland fire activity to a new record high level of 12.6 ± 1.1 million acres burned or ≈76% above the 10-year average. Thus, 2018 might see one of the busiest fire seasons in the US history! The fire-suppression costs incurred by both USFS and DOI in 2018 would be at least twice as high as the 2005-2015 annual average, and quite likely more than 4 times that average. The combined USFS-DOI suppression costs could reach $5.2B ± $2.4B in 2018, thus requiring a special Congressional appropriation of Disaster Funds to meet the heightened demand for firefighting resources by land-management agencies.
1. Introduction

Weather conditions are known to strongly impact ignition probabilities as well as the growth and spread of wildfires. Meteorological parameters such as dew point, relative humidity, wind speed, atmospheric stability, and precipitation amount oftentimes control fire behavior. These parameters are manifestations of the internal kinetic energy of the lower-troposphere system. According to the [Gas Law](https://en.wikipedia.org/wiki/Gas_law), temperature is proportional (linearly related) to the atmospheric internal energy. Thus, one can view changes in the seasonal average temperature over a region as variations in the amount of tropospheric kinetic energy controlling wildfires. This physics-based reasoning leads to the hypothesis that, on a National level, there should be a relationship between inter-annual variations of near-surface seasonal temperature and cycles of wildfire activity measured in terms of total area burned per year. If such a relationship does exist, it would allow the prediction of future wildfire activity from forecast changes in seasonal mean temperature. Furthermore, if the yearly fire-suppression costs at the National level depend on the wildfire acreage burned, one could develop useful projections for the monetary resources required to support future firefighting operations as a function of forecasted changes in the seasonal average temperature. Heretofore, these types of long-term projections have been the purview of the National Weather Service and the National Predictive Services. The novel aspect of this study is the usage of satellite-based temperature measurements along with reported wildfire acreage and data on incurred annual suppression costs to develop predictive models for wildland fire activity and related firefighting expenditures applicable on a multi-year basis.

2. Method

In order to investigate the feasibility of an empirical approach to predicting annual fire activity and related suppression costs at the National level, I analyzed information from two independent datasets: a) the lower-troposphere (LT) monthly temperature anomalies provided by the University of Alabama at Huntsville (UAH) based on measurements from the Advanced Microwave Sounding Unit (AMSU) onboard of several meteorological satellites; and b) the national wildfire statistics published by the National Interagency Fire Center (NIFC) in Boise ID. The UAH dataset is one of two global temperature records going back to 1979 that utilizes satellite measurements of oxygen microwave emissions at various wavelengths. The other such dataset is maintained by Remote Sensing Systems Inc. The UAH and RSS records show almost identical LT global temperature trends and monthly anomalies in terms of timing and magnitude. Hence, this analysis only uses UAH data. Generally speaking satellite-derived temperature anomalies are preferable over similar products based on surface measurements since the latter oftentimes contain biases due to the urban heat-island effect and/or an incomplete spatial coverage of measurements.

Figure 1 portrays monthly and annual variations of the UAH LT temperature anomaly for the Globe from Jan 1996 through July 2016. There have been 4 major El Niño events during this 20-year period with the latest mega El Niño (which began in the fall of 2014) still unfolding at
the present time. The overall temperature trend during the 20-year period is slightly positive at +0.11 °C per decade. However, excluding the latest incomplete El Niño from the record produces a zero trend between Jan 1996 and Jan 2014. This suggests that temperature trends ought to be evaluated over time periods encapsulating complete ENSO cycles in order to be unbiased.

Figure 1 Dynamics of the mean global monthly and annual (13-month running average) temperature anomaly of the lower troposphere (LT) according to the UAH satellite dataset retrieved from satellite-based AMSU measurements of oxygen microwave emissions.

Figure 2 depicts the spatially averaged dynamics of monthly and annual LT temperature anomalies over the Contiguous USA between 1996 and 2016. The 20-year trend of this regional time series is +0.08 °C per decade, which is similar to the global trend illustrated in Fig. 1. Note that the USA temperature exhibits a significantly larger interannual amplitude of variation compared to the global temperature. This is due to the damping effect of an increased area on the averages of monthly and annual temperature amplitudes.

Upon examination of the US temperature series in Fig. 2 and comparing it to the global series in Fig. 1 one notices that the 13-month running means in both records follow similar temporal patterns with the USA temperature effectively lagging the global temperature by 18 – 25 months. Thus, the 2008 La Niña, which caused a perceptible drop in the mean global temperature, manifested over the USA some 2 years later in 2010. Similarly, the strong El Niño event of 2010, which evolved from the 2008 La Niña, showed up in the USA temperature record in 2012 causing an unusually active fire season across the lower 48 states during that year. The lag of USA temperatures behind global temperatures appears to be a retarding phenomenon.
possibly caused by persistent seasonal patterns in the Rossby waves of the Northern and Southern tropospheric jet streams.

![Mean monthly and annual (13-month running average) temperature anomalies in the lower troposphere of the Contiguous USA according to the UAH satellite dataset.](image)

**Figure 2** Mean monthly and annual (13-month running average) temperature anomalies in the lower troposphere of the Contiguous USA according to the UAH satellite dataset.

However, what is the relationship of wildland fire activity to temperature? Figure 3 compares annual data on wildfire acreage in USA with the 13-month running average of observed temperature anomalies over the lower 48 States from 2000 to the present. It is evident that the wildland-fire activity exhibits a periodicity (i.e. a cyclic pattern of variation), which is generally in sync with seasonal temperature fluctuations. The overall trend of fire activity during the past 16 years is +29,640 acre/year. Although small, this trend is significantly different from zero and parallels the slightly positive trend of temperatures (+0.068 C/decade) observed over the USA during the same period. Fire activity at the National level only appears to diverge from the trajectory set by the seasonal temperature anomalies during three out of the last 16 years, i.e. in 2004, 2005, 2006 and 2007. Even though the exact reasons are not currently known, it is worth noting that this deviation is found in a period preceding the implementation of robust fire reporting applications such as the Wildland Fire Decision Support System (WFDSS) and the Integrated Reporting of Wildland-Fire Information (IRWIN) system. The relationship between the total annual acreage burned and average seasonal temperature anomalies substantially improves (as measured by the coefficient of determination $R^2$ and the standard error of estimate $\sigma_e$) after 2009 ($R^2 = 0.816; \sigma_e = 8.953$) compared to the 2000 - 2015 background period ($R^2 = 0.546; \sigma_e = 41.764$) and becomes especially strong past 2010 ($R^2 = 0.862; \sigma_e = 1.587$). The pattern of a progressive improvement in this relationship appears to tracks IT advancements...
made in the US wildland fire reporting since 2008. Based on these findings, the analyses presented here only utilize data after 2008. The above results lend support to the hypothesis formulated in the Introduction section that the internal kinetic energy of the lower troposphere is a major driver of wildland fire activity at the National level.

**Figure 3** National wildland fire activity expressed in terms of annual acreage burned compared with fluctuations of the lower-troposphere annual temperature over the conterminous USA (temperature shown is the dark red curve from Fig 2). Note the remarkable synchronicity in phase between the two time series. Fire activity correlates particularly well with average seasonal temperature anomalies after the operational implementation of WFDSS and IRWIN in 2009 likely due to an improved fire reporting.

In order to predict future fire activity using the empirical relationship between LT temperatures and total burned area illustrated in Fig. 3 one needs to have a technique for forecasting changes in the mean seasonal temperature over the USA at least 18 months in advance. Forecasting regional temperatures over such a time period are typically done via climate models. However, in view of the significant biases reported for these models by recent studies (e.g. Wahl et al. 2011; Wang et al 2014; Davy and Esau 2014; Richter 2015), I decided to look for an alternative approach based on statistical matching of observed temperature patterns among different regions and cross-correlation of temperature time series.

The lag of USA temperatures with respect to global temperature cycles noticed earlier gave me the idea that one might be able to predict long-term changes in the USA seasonal and annual temperatures using an observed temperature time series from another region, which has a similar oscillation pattern but leads in phase. After analyzing data from several regions, I discovered that the oscillation pattern of the LT temperatures over Australia (AUST) matches remarkably well the temperature pattern over USA since 2010 while showing a substantial phase lead. A cross-correlation analysis between temperature series from USA and AUST employing a
varying time lag revealed that the AUST series has a phase lead of 27 months (as indicated by a peak of the cross-correlation coefficient at 0.764). Figure 4 illustrates the close phase match (overlap) between USA seasonal temperature anomalies and the AUST series after the latter has been shifted 27 months forward. Note that AUST temperatures have somewhat smaller amplitude of oscillation compared to USA temperatures as evident by the slight difference in scales between the left and right vertical axis in Fig. 4. However, the most important feature for a successful prediction of future fire activity in the USA is the synchronicity of variation between the two temperature series, not the similarity of amplitudes.

![Figure 4](image.png)

**Figure 4** Comparison of lower-troposphere annual temperature anomalies over the Contiguous USA with a similar temperature series from Australia after shifting the latter 27-month forward. The nearly perfect phase match between the two series from Jan 2010 to July 2016 indicates that one might reasonably employ the Australian temperature series as a *predictor* of expected changes in the US seasonal temperature through October 2018.

The pattern shown in Fig. 4 suggests that one could employ the time-shifted AUST temperature series as a *predictor* of changes likely to occur in the USA seasonal temperature during the next 27 months, i.e. through October 2018. Of course, this rests on the expectation that the excellent phase match observed between these time series for a period of 6 years (i.e. from July 2010 to July 2016) will continue for another 2.25 years. How realistic is such an expectation, however? To answer this question, I compared the temperature series of USA and AUST throughout the full length of the UAH satellite record beginning in 1980. The lead/lag analysis based on a cross-correlations of the data series at different time lags revealed the following: a) the USA seasonal temperature follows a very similar pattern of interannual variation as the AUST temperature; b) the USA temperature lags the AUST temperature throughout the entire record, but the length of the lag varies through time; thus, between 1980
and the end of 1993, the lag was only 2-3 months; between 1994 and 1999/2000, the lag transitioned (increased) to 17-18 months remaining stable thereafter for 10 - 11 years until 2009/2010; in the early 2010, the lag rapidly shifted to 27 months, where it has remained for the past 6 years. This pattern suggests that, once the lag is stabilized, it tends to persist for 11-14 years at a time. Therefore, there is a good chance that the current 2.25-year lead of AUST temperatures with respect to USA temperatures will continue for at least another 5 years. This boosts one’s conference in the 2-year projections described in Section 3.

The next step in my analysis was to look for a relationship between the annual acreage burned in USA and the time-shifted AUST seasonal temperature series. Figure 5 displays this relationship based on data from the last 5 years (i.e. from 2011 to 2015). It is important to note that the period 2011 – 2015 probably has the most accurate fire-activity data, since it was fully covered by WFDSS and other fire-reporting applications. As evident from the graph, the total annual area burned in the USA shows a close correspondence to the March-September average anomaly of time-shifted AUST temperatures. The resulting regression model $A_b = f(\Delta T)$ shown at the top of Fig. 5 has a coefficient of determination $R^2 = 0.986$ and a standard error $\sigma_e = 0.501$.

![Figure 5 Relationship between annual acreage burned in the USA ($A_b$, Million acres) and the March-September average anomaly ($\Delta T$, °C) of the time-shifted Australian temperature series (i.e. the red curve in Fig. 4) over the past 5 years. $R^2$ is a coefficient of determination of the empirical model, and $\sigma_e$ is a standard error of the regression.](image)

Finally, in order to successfully project fire-suppression costs for 2016 - 2018, one needs to have a statistical model that relates yearly acreages burned to annual fire-suppression expenditures. I used yearly data on wildland fire acres and suppression costs from 2008 to 2015 published by NIFC to investigate the relationship between these two variables. Figure 6 displays
results from this analysis. For five out of the 8 years studied, the fire-suppression expenditures increased exponentially with the annual acreage burned. Three years (i.e. 2008, 2013 and 2014) had anomalously high suppression costs for the amount of area scorched by wildfires. It is reasonable to assume that funds expended in some years might be more affected by subjective human factors than in other years, and may not be fully explainable by wildfire acreage. Hence, these years were excluded from the regression analysis that produced the final equations $C_{FS} = f(A_b)$ and $C_{tot} = f(A_b)$ shown in Fig. 6 describing the USFS and total fire-suppression costs (in Billion Dollars) as functions of the annual area burned ($A_b$, Million acres).

Figure 6 Empirical relationships between annual wildland fire acreage and yearly fire-suppression costs during the period 2008 – 2015. Due to anomalously high expenditures in 2008, 2013 and 2014, these years were excluded from the regression analysis leading to the models $C_{FS} = f(A_b)$ and $C_{tot} = f(A_b)$ predicting the USFS and total fire-suppression costs, respectively. Also shown for each regression model are the coefficient of determination ($R^2$) and the standard error of regression ($\sigma_e$).

3. Results and Discussion

Combining empirical relationships shown in Figs. 5 and 6 with the time-shifted AUST temperature series from Fig. 4 resulted in the following projections of wildland fire activity and suppression costs for the period 2016 – 2018.

Figure 7 depicts past and future dynamics of seasonal temperatures and wildland fire activity in the USA. In 2016, it is projected that $8.65 \pm 1.3$ M acres will likely burn, which is about midway between the 10-year (2005-2015) average of 7.146 M acres per year and the record of 10.125 M acres set in 2015. In 2017, the fire activity will likely drop below the 10-year average to $7.051 \pm 1.378$ M acres burned due to a transient cooling period, which began in the spring of
2016 and will continue until the fall of 2017. In 2018, the continental portion of USA will experience the lagged effect of a mega El Niño currently unfolding in the equatorial Pacific (see Fig. 1). This will likely result in a sharp increase of wildland fire activity during that year to a new record high level of $12.614 \pm 1.131$ M acres burned or $\approx 76\%$ above the 10-year average. Thus, 2018 might see one of the busiest fire seasons in the US history!

![Graph](image)

**Figure 7** Past (observed) and future (projected) dynamics of seasonal temperature anomalies and annual wildland fire activity in the USA from 2010 to 2018. Due to a lag in the atmospheric circulation over USA compared to that over Australia (a result of long-lived Rossby-wave pattern in tropospheric jet streams), USA will experience the effect of the 2015-2016 mega El Niño in about two years from now (i.e. in 2018). This will likely cause a record high wildland fire activity and one of the busiest fire seasons in the US history.

Figure 8 portrays the projected annual fire-suppression costs that USFS and DOI are likely to incur between 2016 and 2018. Total expenditures in 2016 are expected to be close to the 10-year average of $1.466B/year. In 2017, suppression costs will likely fall below the 2005-2015 annual mean as a result of a reduced national fire activity driven by cooling weather conditions. However, in 2018, we will likely witness a new historical record in fire-suppression expenditures. The USFS and DOI costs are projected to be at least twice as high as the 10-year annual average, and quite likely more than 4 times that average! The combined USFS-DOI suppression costs could skyrocket to $5.212B \pm 2.4B$ in 2018, thus requiring a special Congressional appropriation of Disaster Funds to meet the heightened demand for firefighting resources by land-management agencies. The projected sharp increase of fire-suppression costs in 2018 is a result of a predicted record-high wildland-fire activity during that year (Fig. 7) and the observed exponential rise of expenditures with the total acreage burned (Fig. 6).
Figure 8 Projected fire-suppression costs for the period 2016 – 2018 based on predicted wildland fire activity (Fig. 7) and the observed exponential rise of expenditures with wildfire acreage (Fig. 6).
A word of caution is required in regard to the above cost projections, however. Unlike wildfire acreage, which mostly depends on natural forcing controlled by the kinetic energy content of the lower troposphere, fire-suppression costs are subject to political (human) decision-making and as such may not be as reliably predictable as wildland fire activity. The data presented in Fig. 6 indicate that federal land-management agencies can significantly overspend on fire-management operations during certain years.

One should keep in mind that the above fire-activity & suppression-cost projections are contingent upon the assumption that future changes in the average seasonal temperature over the USA will follow a pattern closely matching variations of the seasonal temperature over Australia during the past 27 months (see discussion in the Method section above). Although the probability for substantial departure of the USA seasonal temperature from the trajectory outlined by the AUST temperatures is quite small, it is certainly not zero. The results from this analysis also depend on the tropospheric jet streams maintaining their current seasonal behavior over the next 27 months.

4. References


