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Climate change presents increased potential for very large fires in the contiguous United States

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Abstract. Very large fires (VLFs) have important implications for communities, ecosystems, air quality and fire suppression expenditures. VLFs over the contiguous US have been strongly linked with meteorological and climatological variability. Building on prior modelling of VLFs (>5000 ha), an ensemble of 17 global climate models were statistically downscaled over the US for climate experiments covering the historic and mid-21st-century periods to estimate potential changes in VLF occurrence arising from anthropogenic climate change. Increased VLF potential was projected across most historically fire-prone regions, with the largest absolute increase in the intermountain West and Northern California. Complementary to modelled increases in VLF potential were changes in the seasonality of atmospheric conditions conducive to VLFs, including an earlier onset across the southern US and more symmetric seasonal extension in the northern regions. These projections provide insights into regional and seasonal distribution of VLF potential under a changing climate, and serve as a basis for future strategic and tactical fire management options.

Additional keywords: climate-fire models, climate variability, fire risks, megafires.

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Introduction

Very large fires (VLFs; often defined as the top 5 or 10% of the largest fires) account for a majority of burned area in many regions of the US (e.g. Strauss *et al.* 1989), increasingly threaten and affect homes and communities, have unique ecological effects on ecosystems, contribute to widespread degradation in air quality (e.g. Schultz *et al.* 2008) and lead to numerous indirect effects including those on human health (e.g. Johnston *et al.* 2012) and water quality (e.g. Rhoades *et al.* 2011). An increase in the number of VLFs has been observed in recent decades across the US (Dennison *et al.* 2014). Although difficult to apportion causation, both the legacy of fire suppression allowing for increased fuel accumulation (Marlon *et al.* 2012) and a more favourable climate (Barbero *et al.* 2014*a*) have likely enabled more frequent VLFs. According to the National Interagency Fire Center, direct federal expenditures on fire suppression in the US have more than doubled in recent decades, exceeding US$1 billion per year since the year 2000, the vast majority of which is spent on large incidents. Collectively, such changes have taxed fire suppression resources and prompted the need for fire agencies to reallocate funding from a broader set of land management objectives to specifically fighting fire.

Most VLFs in the US occur coincident with favourable fuel and fire spread conditions facilitated by antecedent climate and current extreme fire weather conditions respectively (e.g. Riley *et al.* 2013; Stavros *et al.* 2014*a*; Barbero *et al.* 2014*b*). These relationships are similar to the broader body of climate–fire studies linking interannual climate variability and spatially aggregated burned area (e.g. Westerling *et al.* 2003; Littell *et al.* 2009). Observed changes in climate may have already influenced wildfire potential over parts of the globe (e.g. Stocks *et al.* 1998; Gillett *et al.* 2004; Westerling *et al.* 2006), and projected changes in climate over the next century are hypothesised to significantly alter global wildfire regimes (e.g. Flannigan *et al.* 2009), including across parts of the US, via changes in fire danger (e.g. Brown *et al.* 2004; Abatzoglou and Kolden 2011; Liu *et al.* 2012), moisture deficits (Westerling *et al.* 2011*a*; Westerling *et al.* 2011*b*) and vegetation composition (Bradley 2009). Prior studies reported increased annual (sometimes monthly) burned area for parts of the US with climate change (e.g. Spracklen *et al.* 2009; Westerling *et al.* 2011*a*, 2011*b*; Yue *et al.* 2013); however, such studies have been limited to the western US and did not provide insights on future VLF occurrence (see Table 1). In the only known study to date on climate change and VLF, Stavros *et al.* (2014*b*) projected substantial increases in VLFs across the western US. However, their projections and modelling efforts focused on very coarse-scale management units that did not discriminate

Table 1. Summary of the differences among the current paper and a sampling of similar studies that projected changes in future fire activity or fire danger indices under climate change across parts of the US

The table shows the temporal resolution (timescale), spatial resolution, period, geographic location, fire metric, vegetation types considered and main conclusion of each study. Only studies using a time-variant fire metric were considered. VLF, very large fire; ERC, energy release component; GACC, Geographic Area Coordination Center; KBDI, Keetch–Byram drought index; FFWI, Fosberg fire weather index

Reference	Timescale	Spatial scale	Period	Location	Fire metric or fire proxy	Vegetation type	Projected changes in fire activity or fire proxy
Brown *et al.* 2004	Daily	~250 km	2010–2089	Western US	ERC	None	Increases in the number of high ERC days
Spracklen *et al.* 2009	Annual	~50 km	2000–2050	Western US	Burned area	Bailey's ecoregions	Increases of 54% in annual burned area by 2050
Liu *et al.* 2010	Monthly	~60 km	2070–2100	Global scale	KBDI	None	Increases in monthly KBDI across parts of the world
Westerling *et al.* 2011*a*	Monthly	~12 km	2020–2085	California	Large fire and burned area	Vegetated *vs.* non-vegetated lands	Increases in burned area in Northern California
Westerling *et al.* 2011*b*	Monthly	~12 km	1991–2100	Greater Yellowstone	Large fire and burned area	Forested lands	Increases in burned area and fire frequency
Abatzoglou and Kolden 2011	Daily	~8 km	2046–2065	Western US	ERC	None	Earlier onset and lengthening of fire season
Liu *et al.* 2012	Daily	~50 km	2041–2070	Conterminous US	KBDI & FFWI	None	Increases in seasonal KBDI and FFWI
Yue *et al.* 2013	Monthly	~50 km	2046–2065	Western US	Burned area	Bailey's ecoregions	Increases in monthly burned area and expansion of fire season
Luo *et al.* 2013	Daily	~50 km	2041–2070	Western US	Haines Index	None	Increases in the consecutive number of high daily Haines index
Stavros *et al.* 2014	Weekly	GACC	2031–2060	Western US	VLF occurrence	None	Increases in VLF occurrence in climate-limited ecosystems
Current study	Weekly	~60 km	2041–2070	Conterminous US	VLF occurrence	Omernik ecoregion	Increases in VLF occurrence across historically VLF prone regions

across ecoregions or include other portions of the US where VLFs have been observed in recent decades (Barbero *et al.* 2014*b*). Our study extends prior work by Stavros *et al.* (2014*b*) by resolving projected changes in VLF that account for varying climate–fire relationships facilitated through common vegetation assemblages at the ecoregion scale (e.g. Littell *et al.* 2009). Additionally, using the modelling framework proposed by Barbero *et al.* (2014*a*), we were able to capture intra-ecoregional variability in VLF at spatial (~60-km grid) and temporal (weekly) scales that may be more relevant for informing management approaches to climate change than coarser scale approaches. Finally, our modelling approach includes projections of VLF encompassing fire-prone regions across the eastern half of the US where smoke from VLF affects large populations.

We examined changing opportunities for VLF (>5000 ha) occurrence under climate change scenarios using empirical relationships between climatic factors and VLF occurrence developed by Barbero *et al.* (2014*a*). This empirical modelling effort cannot account for other factors that influence VLF such as changes in vegetation, land management and ignitions. However, by isolating projected changes in atmospheric drivers of VLFs, we sought to identify geographic hotspots of changing VLF occurrences. This guidance in turn may be useful in devising climate adaptation strategies for ecosystems and communities and help prioritise potential mitigation strategies.

Data and methods

Climate projections were obtained from 17 global climate models (GCMs) using historical forcing experiments from 1971 to 2000 and Representative Concentration Pathways 8.5 (RCP8.5) forcing experiments from 2041 to 2070. The 17 GCMs comprised all CMIP5 models that contained daily output for both historical and RCP8.5 experiments for all variables required to compute fire danger measurements. We chose to focus on a single scenario (RCP8.5) as natural climate variability and inter-model variability are the dominant contributors to uncertainty in climate projections at such lead times and spatial scales (e.g. Hawkins and Sutton 2009). Coarse-scale GCM daily meteorological output was statistically downscaled using the Multivariate Adaptive Constructed Analogs method (Abatzoglou and Brown 2012) and the surface meteorological data of Abatzoglou (2013) to 1 : 24° resolution across the contiguous US. Following Barbero *et al.* (2014*a*), we calculated a set of predictors with established links to VLFs including meteorological variables (i.e. temperature, relative humidity, precipitation), the Palmer Drought Severity Index, annual climatic water deficit and fire danger indices from the National Fire Danger Rating System (Deeming *et al.* 1977), the Canadian Forest Fire Danger Rating System (Van Wagner 1987), and the Fosberg Fire Weather Index (Fosberg 1978). These variables reflect different timescales that are linked to VLF occurrence across ecoregions (table S1 from Barbero *et al.* 2014*a*). Climate–VLF relationships adhere to established interannual climate–fire relationships (e.g. Littell *et al.* 2009) in climate-limited and fuel-limited systems while also incorporating shorter timescales that are more directly linked to fire behaviour. Whereas all surface meteorological data were bias corrected through downscaling, a secondary bias correction was performed on all derived variables (e.g. fire danger indices, drought

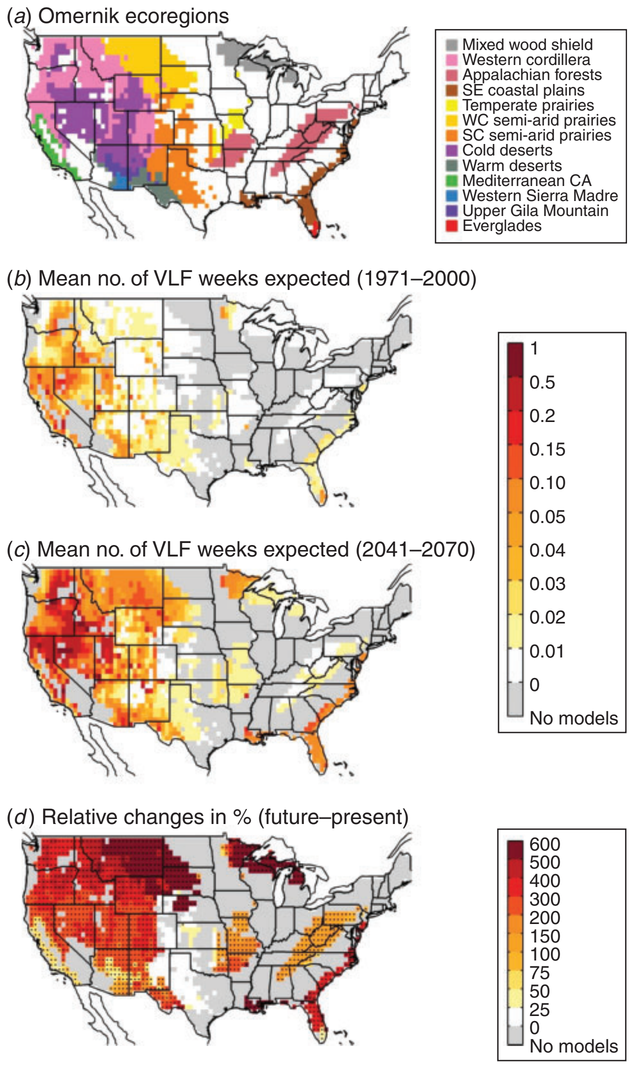

Fig. 1. *a*) Aggregated ecoregions at ~60 km (full names of regions are shown in Table 1; abbreviations are defined in Table 2). Multi-model mean annual number of very large fire (VLF) weeks per surface unit (~60 × 60 km) for historic climate experiment (*b*, 1971–2000) and mid-21st century climate experiment (*c*, 2041–2070). Relative changes are shown in panel *d*). Stippling indicates pixels where the multi-model mean difference exceeded two standard deviations of 20th-century runs (i.e. spread among global climate models) and at least 90% of the models agree on the sign of change. Grey pixels indicate regions with no or insufficient number of VLF to build robust models.

metrics) following Stavros *et al.* (2014*b*). This bias correction forces data for the historical modelled period (1971–2000) to match the statistical moments of the observed distribution, and applies the same transformation to the future modelled period (2041–2070) thereby preserving differences between the two modelled datasets.

Barbero *et al.* (2014*a*) developed robust stepwise generalised linear models (GLMs) linking the occurrence of the top 10% of the largest historical VLFs (>5000 ha) from 1984 to 2010 to atmospheric predictors at sub-ecoregion scales (~60-km grids) and weekly (6 day) timescales for 13 Omernik (Omernik 1987) Level II ecoregions of the US (Fig. 1*a*). Separate models were developed for each ecoregion given that climate–VLF relationships are mediated through vegetation, which when runs at the 60-km scale allowing for spatial heterogeneity in predictors within an ecoregion (Table 2). A full description of model development and assessment is provided in Barbero *et al.* (2014*a*). Briefly, they used a logistic model with a logit link to model the probability of VLF week within each ecoregion at the voxel (defined here as a gridded value in a 3-dimensional space; i.e. time × space) scale (~60 km) using potential predictor variables. Interactive and non-linear terms were not included in the GLM. Predictor variables that did not exhibit significant relationships ($P < 0.05$) were discarded from stepwise model selection procedure. Model stability was examined through resampling approaches using a case–control design (Keating and Cherry 2004) that uses all VLF weeks and resampling with replacement of a subset of non-VLF weeks ($n = 50\,000$) drawn from the distribution of voxels within an ecoregion. They used the most frequent set of predictor variables from 1000 simulations for subsequent modelling. The area under the curve was used to evaluate model skill (reported in Table 2).

We project VLF probability at weekly timescales on ~60-km grids using downscaled GCM data aggregated to the aforementioned spatiotemporal resolution and the GLM equations from Barbero *et al.* (2014*a*). Specifically, we define VLF potential (P) as the expected number of VLF ($10^{-4}\,km^{-2}$) per week. This model is applied assuming that contemporary climate–fire relationships remain unchanged, thereby overlooking potential changes in vegetation. We avoided extrapolating our model outside the observed range of variability (e.g. Wotton *et al.* 2010; Moritz *et al.* 2012) by limiting variables to the range of historical variability for each ecoregion. Projected changes in P were examined across 17 GCMs at weekly and annual timescales between the mid-21st century (2041–2070) and late 20th century (1971–2000) runs. We focus on changes in the multi-model mean response (defined as the simple average of the 17 GCMs) and identify regions where the signal is robust, defined by where the multi-model mean difference between mid-21st-century P and late-20th-century P exceeds two standard deviations of 20th-century runs (i.e. spread among models) and at least 90% of the models agree on the sign of change (IPCC 2013). We also quantify changes in P for ecoregion across the 17 models to demonstrate the range and robustness of projected changes. Finally, we examined the length of the season during which atmospheric conditions are expected to be conducive to VLFs within each ecoregion. Although a universal definition of a VLF season is lacking, we considered the number of weeks during which at least one pixel within an ecoregion had probability above the historical 99th percentile (defined at the ecoregion level).

Results

Projected increases in P were modelled across much of the US, with the largest absolute increase in regions that observed numerous VLFs in recent decades including much of the intermountain West covering the Great Basin and Northern Rockies, as well as the Sierra Nevada and Klamath Mountains in Northern California (Fig. 1*b*, *c*). Increases were also projected across Northern Lakes and Forests, and in the Southern Coastal Plain,

Table 2. Equations describing weekly VLF probabilities at 60 km for each ecoregion

The second column gives $\bar{\beta}$ parameters (see Barbero *et al.* 2014*a* for further information on model development) for predictors that were selected in the stepwise regression. The third column indicates the mean area under the curve between simulated very large fire probabilities and observations from 1000 Monte Carlo simulations. Fourth and fifth columns indicate the multi-model mean of mean annual number of very large fires (VLFs) expected (VLF potential) per surface unit (10^4 km^{-2}) for the historical and future periods respectively. Predictors used in the equations are defined in Barbero *et al.* 2014*a*

Ecoregions	$\exp(\bar{\beta})/1+\exp(\bar{\beta})$	$\overline{AUC}$	VLF P 1971–2000	VLF P 2041–2070
Mixed Wood Shield	$\bar{\beta}=-15.24+BI\times 0.15+CWD\times 0.04$	0.95	0.14	0.80
Western Cordillera	$\bar{\beta}=-9.76+TEMP\times 0.22+ERC\times 0.05+PDSI\times(-0.25)$	0.95	0.81	3.31
Appalachian forest	$\bar{\beta}=4.08+RH\times(-0.17)+PDSI\times(-0.30)$	0.91	0.14	0.29
South-east (SE) Coastal Plains	$\bar{\beta}=-10.65+ERC\times 0.13+ISI\times 0.29$	0.89	0.38	1.03
Temperate prairies	$\bar{\beta}=5.12+RH\times(-0.21)$	0.95	0.24	0.41
West-central (WC) semiarid prairies	$\bar{\beta}=-12.22+ERC\times 0.09+ISI\times 0.20$	0.96	0.21	1.32
South-central (SC) semiarid prairies	$\bar{\beta}=-9.35+FFWI\times 0.23+PDSI_{-1}\times 0.23$	0.84	0.30	0.35
Cold deserts	$\bar{\beta}=-7.90+TEMP\times 0.26+EP\times(-0.47)+PDSI\times 0.0916+ISI\times 0.14+PRCP_{JAS}\times(-0.14)$	0.95	0.96	3.61
Warm deserts	$\bar{\beta}=-9.79+ISI\times 0.22+PDSI\times 0.16$	0.90	0.44	1.22
Mediterranean California (CA)	$\bar{\beta}=-4.20+TEMP\times 0.12+RH\times(-0.10)+FFWI\times 0.12$	0.90	1.87	3.03
Western Sierra Madre	$\bar{\beta}=-10.97+ISI\times 0.25+PDSI_{-1}\times 0.29$	0.95	1.59	3.61
Upper Gila Mountain	$\bar{\beta}=-11.28+ERC\times 0.08$	0.87	0.89	1.25
Everglades	$\bar{\beta}=-10.91+ERC\times 0.19$	0.84	1.44	1.87

including much of Florida. These changes are consistent with an overall warming, more frequent heat waves (Diffenbaugh and Ashfaq 2010), and diminished soil moisture during the dry season (Orlowsky and Seneviratne 2012; IPCC 2013). The largest relative changes in P were found across the northern tier of the US (Fig. 1*d*); however, these changes result in moderate absolute increases in P in regions that had historically low P.

Seasonal changes in P are illustrated for four ecoregions representative of changes modelled for other ecoregions (Fig. 2). Non-significant increases in annual P were projected in some non-forested ecoregions of the central US including the South-central semiarid prairies ecoregion (Fig. 2*a*). Respectively small and ambiguous changes in seasonal P were a function of muted and mixed changes in predictor variables historically important for VLFs in that region. Conversely, large increases in P were noted for the Western Cordillera ecoregion (Fig. 2*b*) due to increased temperature, and decreased relative humidity and precipitation during the summer that collectively lower fuel moisture and increase fire danger indices. Consequently, a significant and nearly symmetric increase in the P on either side of the historic seasonal maximum was modelled for the ecoregion that results in heightened P during the core of the fire season and an extension of the seasonal window conducive to VLFs. An earlier onset of the VLF season is projected across the south-western US including the Warm deserts ecoregion (Fig. 2*c*), corresponding to overall warming and a northward retraction of the winter storm track that results in decreased spring precipitation (e.g. Gao *et al.* 2014) and a resultant increase in the Initial Spread Index (ISI) – one of the leading predictor variables in that ecoregion. Conversely, models do not project any substantial change near the historical end of the VLF season associated with the arrival of monsoonal precipitation. Similarly, models project an earlier onset of the VLF season in the Everglades (Fig. 2*d*) in relation to anticipated warmer winter temperature and a return to normal conditions near the core of the historical VLF season.

Most ecoregions of the US not only experience higher mean annual P (Fig. 3*a*) but also a temporal expansion of extreme probability with climate change (Fig. 3*b*). The largest seasonal expansion of extreme probability is projected for the Western Cordillera, Mixed Wood Shield, Cold Deserts or South-east Coastal Plains ecoregions, where large increases in P are projected on either side of the seasonal maximum. However, most southern ecoregions (i.e. Everglades, Western Sierra Madre or Upper Gila Mountain) are likely to experience asymmetric changes in P, featuring an earlier onset of atmospheric conditions favourable to VLF development but only small changes near the historical end of the VLF season. Substantial inter-model spread in projected changes in mean annual P and weeks of extreme probability are evident; however, nearly all model projections suggest increases above historical levels. One outlier model (GFDL-ESM2G) projects a decrease in VLF for the Mixed Wood Shield arising from a reduction in climatic water deficit and its incorporation in modelling VLF for that region.

Conclusion and discussion

Anthropogenic climate change is projected to increase VLF potential in the US through both an increase in frequency of conditions conducive to VLFs during the historical fire season and an extension of the seasonal window when fuels and weather support the spread of VLFs. The largest absolute changes are projected for regions across the western US where heightened VLF potential is the product of projected increases in fire danger and temperature, and decreased precipitation and relative humidity during the fire season (e.g. Abatzoglou and Kolden 2011; Liu *et al.* 2012; Luo *et al.* 2013; Stavros *et al.* 2014*b*). Projected changes in P by the mid-21st century follow a similar pattern to those modelled using observed changes in climate over the past three decades (Barbero *et al.* 2014*a*), although they are substantially larger in magnitude and suggest a continuation of more frequent VLF occurrences.

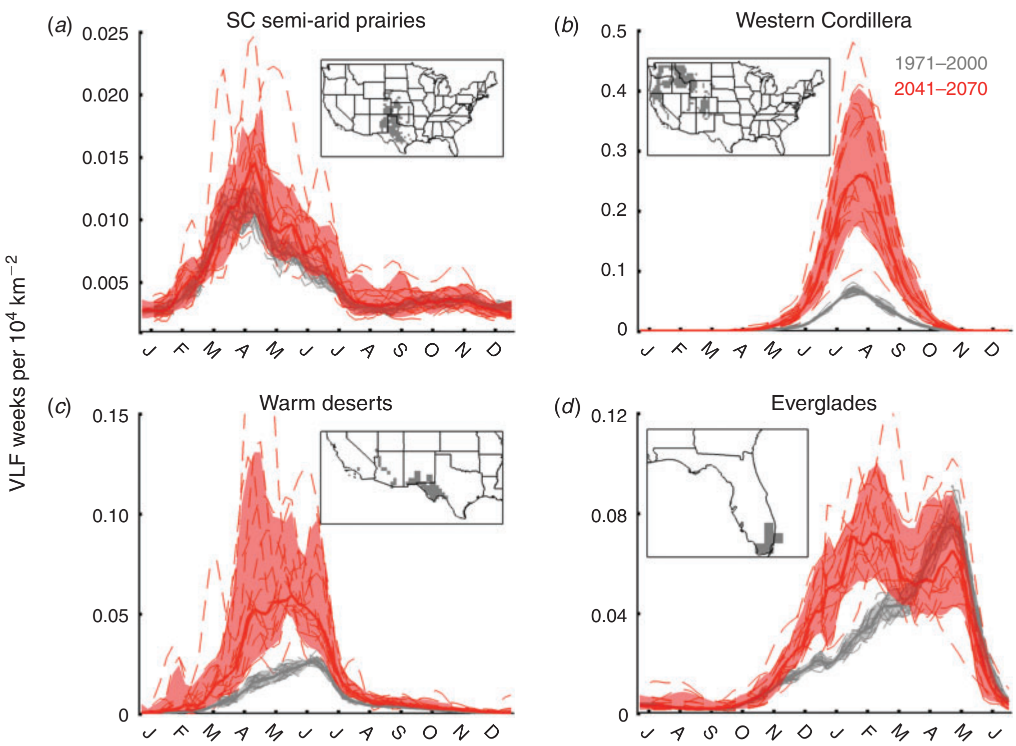

Fig. 2. Mean seasonal cycle of very large fire (VLF) potential (P) aggregated to Level II ecoregions from 1971 to 2000 (grey) and 2041 to 2070 (red). P is expressed as the mean number of VLF expected per surface unit (10^4 km^{-2}) per week. Individual models are shown by dashed curves and the solid bold lines indicate the multi-model mean. Grey and red envelopes indicate the 90% inter-model spread. The insert within each panel indicates the location of ecoregions. Notice that the last panel (*d*) (Everglades) shows VLF P from July to June.

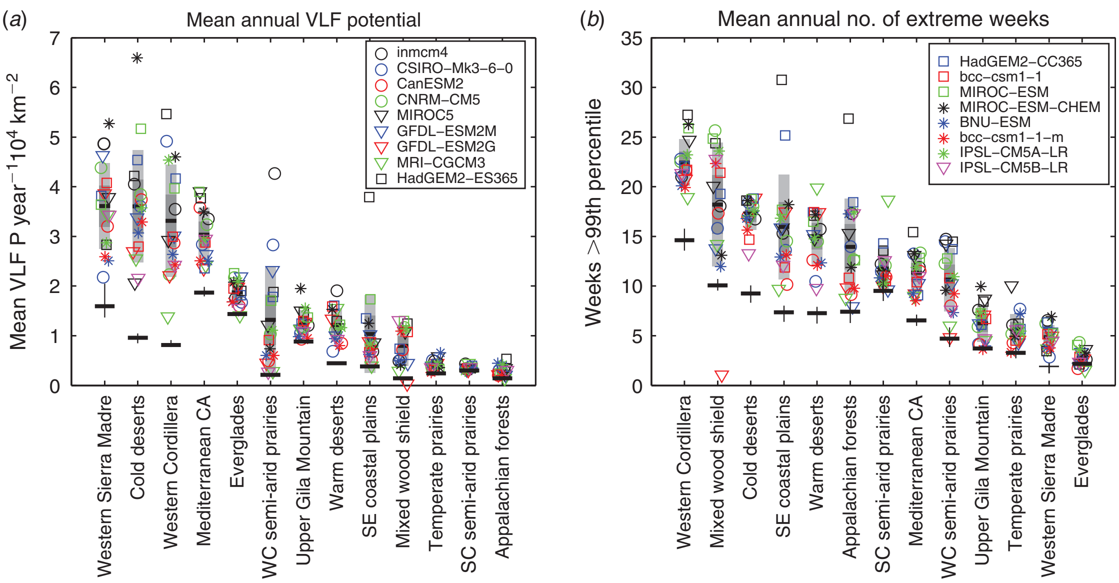

Fig. 3. *a*) Mean annual number of VLF weeks expected per surface unit (10^4 km^{-2}) within each ecoregion and *b*) the number of weeks during which at least one pixel within each ecoregion exceeded the historical 99th percentile. Vertical black lines indicate the historical range (1971–2000) across different global climate models and horizontal lines indicate the multi-model mean. Future projections for the mid-21st century (2041–2070) are depicted by symbols (as denoted by the legend split across the two plots), with the dark and light shading denoting one and two standard deviations from the multi-model mean respectively. The ranking of ecoregions is based on the multi-model mean of future runs (from largest to smallest values).

Previous modelling studies project increased burned area under future climate across parts of the US using large-scale aggregated data on seasonal or monthly timescales (e.g. Spracklen *et al.* 2009; Yue *et al.* 2013). Our results provide an additional basis for such projections by showing that climate change may also enable increased opportunities for VLF occurrence that ultimately strongly contributes to total burned area. Our results also add to the much coarser scale VLF projections of Stavros *et al.* (2014*b*) by elucidating VLF projections at scales more relevant to wildfire and air quality management. Our results were in general agreement with Stavros *et al.* (2014*b*); however whereas they found small changes in VLF probabilities in Northern California and Western Great Basin, we show large increases within these regions in agreement with projected increases in burned area from Westerling *et al.* (2011*a*). Although the projected increases in P were smaller in absolute values in the eastern than in the western US, increased VLF occurrence may have broader effects on private property and air quality in the more densely populated regions of the eastern US than in the more sparsely populated western US.

Several uncertainties in such a modelling exercise may circumvent realised changes in VLFs. First, though models from Barbero *et al.* (2014*a*) exhibited strong skill, alternative models using different combinations of predictors may alter the magnitude of projected change depending on the sensitivity of such predictors to climate change. Second, models were developed using contemporary climate–fire relationships that are mediated through vegetation. Changes in vegetation distribution may alter fire regimes and subsequent climate–fire relationships used in modelling resulting in non-stationary fire–climate relationships (e.g. McKenzie *et al.* 2014; Higuera *et al.* 2015). For example, regions that experience frequent fire under climate change may have insufficient vegetation to carry VLF (e.g. Rocca *et al.* 2014), and shifts in forest composition and productivity in areas including the south-western US (e.g. Hurteau *et al.* 2014) may buffer modelled increases in VLFs. Conversely, changes in the distribution of invasive annual grasses conducive to VLFs may also shift in the future (Bradley 2009), altering model projections. Whereas dynamic global vegetation models designed to simulate vegetation dynamics (e.g. Lenihan *et al.* 2008) may provide a better understanding of the future complex relationships between vegetation, climate and fire, such process-based models provide fire estimates at coarse time steps and often prescribe fire return intervals or limit the spatial extent of fire *a priori* (McKenzie *et al.* 2014). Third, our modelling approach is considered conservative because we limited predictor variables to the historical range of variability and thus may underestimate future P in certain ecoregions where the historic range of variability will be exceeded. Finally, changes in ignition patterns and frequency resulting from changing distributions of lightning (Romps *et al.* 2014) and human factors may contribute to VLFs in ways other than modelled here.

Projected increases in VLF potential have important implications for terrestrial carbon emissions (Schultz *et al.* 2008; Prentice *et al.* 2011) and ecosystems (Keane *et al.* 2008), as well as communities, regional air quality and human health. Irrespective of the aforementioned caveats in modelling, the increased occurrence of VLFs will have significant effects on the effectiveness of traditional fire suppression activities. VLFs often require prolonged fire suppression commitments of resources, resulting in regional or national drawdown of resources that limit the capacity to fight fires in other regions, particularly when VLFs become the top national priority due to proximity to resources at risk or infrastructure. VLFs also tend to require much more complex, multi-agency management teams, fewer of which are available during the fire season. This complexity also can be associated with greater costs per unit area to fight the fire, as city and county agencies are often involved. The seasonal lengthening of conditions conducive to VLF will likely tax suppression-based activities, particularly during years of widespread and chronic VLF potential. Finally, an increase in the number of VLF could ultimately have negative effects on more holistic and science-driven fire management policies, such as reducing the amount of prescribed fire or fire used for resource benefits if managers fear that conditions will always be conducive to the development of VLFs. Recognising that potential for VLFs is likely to increase is key to developing proactive policies to combat these negative effects.

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