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

R. Barbero, J.T. Abatzoglou Department of Geography, University of Idaho, Moscow, Idaho, USA

N.K. Larkin Pacific Wildland Fire Sciences Laboratory, US Forest Service, Seattle, WA, USA

C. Kolden Department of Geography, University of Idaho, Moscow, Idaho, USA

B. Stocks Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, ON, Canada

> Corresponding Author Address: Dr. Renaud Barbero Department of Geography University of Idaho 875 Perimeter Drive MS 3021 Moscow, ID 83844-3021 Email: <u>renaudb@uidaho.edu</u>

Submitted to International Journal of Wildland Fire, short communication January 2015

### Abstract

Very large fires (VLFs) have important implications for communities, ecosystems, air quality and fire suppression expenditures. VLFs over the contiguous United States (US) have been strongly linked with meteorological and climatological variability. Building on prior modeling of VLFs (>5,000ha), an ensemble of 17 global climate models were statistically downscaled over the US for climate experiments covering the historic and mid-21<sup>st</sup> century time 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. Complimentary to modeled 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 on regional and seasonal distribution of VLF potential under a changing climate, and serve as a basis for future strategic and tactical fire management options.

## 1. Introduction

Very large fires (VLFs; often defined as the top 10% or top 5% of the largest fires) account for a majority of burned area in many regions of the United States (e.g., Strauss et al., 1989), increasingly threaten and impact homes and communities, have unique ecological impacts 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 United-States (Dennison et al., 2014). While difficult to apportion causation, both the legacy of fire suppression allowing for increased fuel accumulation (Marlon et al., 2012) and a more favorable climate (Barbero et al., 2014b) have likely enabled more frequent VLFs. According to the National Interagency Fire Center, direct federal expenditures on fire suppression in the United States (US) have more than doubled in recent decades, exceeding 1.5B US dollars per year since 2000, a 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 favorable 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., 2014a; Barbero et al., 2014a). 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., Gillett et al., 2004; Westerling et al., 2006; Flannigan et al., 2008; Flannigan et al., 2009; Wotton et al., 2010), and projected changes in climate over the next century are hypothesized to significantly alter wildfire regimes across parts of the US via changes in fire danger (e.g., Stocks et al., 1998; Liu et al., 2012; Abatzoglou and Kolden, 2011), moisture deficits (Westerling et al., 2011), and vegetation composition (Bradley, 2009). Prior studies found increased in annual (sometimes monthly) burned area for parts of the US with climate change (e.g., Spracklen et al., 2009; Westerling et al., 2011; Yue et al., 2013); however, such studies have been limited to the western US and did not provide insights on the future occurrence of VLF events. To date, the only known study examining changes in VLF occurrence with climate change (Stavros et al. 2014b), projected substantial increases in VLFs at very coarse-scale fire units for the western US. However, projected changes in the timing and magnitude of VLFs in a changing climate at spatial scales relevant to fire managers across the entire contiguous US have not been examined.

We examined changing opportunities for VLF (>5,000ha) occurrence under climate change scenarios using empirical relationships between climatic factors and VLF occurrence developed by Barbero et al. (2014b). This empirical modeling effort cannot account for other factors that influence VLF potential such as changes in vegetation and land management. However, by isolating projected changes in atmospheric drivers of VLFs, we sought to identify geographic hotspots of changing VLF potential. This guidance in turn may be useful in devising climate adaptation strategies for ecosystems and communities and help prioritize potential mitigation strategies.

## 2. Data and methods

Climate projections were obtained from the daily output of 17 Global Climate Models (GCMs) from 1971-2000 using historical forcing, and for the 2041-2070 period using the Representative Concentration Pathways 8.5 (RCP8.5) forcing. The 17 GCMs comprised all CMIP5 models that contained daily output for both historical and RCP8.5 experiments for all variables required as input to compute fire danger measurements. 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 degree resolution across the contiguous US. Following Barbero et al. (2014b), 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 (PDSI), 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). 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 metrics) following Stavros et al. (2014b). This bias correction forces data for the historical modeled period (1971-2000) to match the statistical moments of the observed distribution, and applies the same transformation to the future modeled period (2041-2070) therein preserving differences between the two modeled datasets.

Barbero et al. (2014b) developed robust stepwise Generalized Linear Models

(GLMs) linking the occurrence of the top 10% of the largest historical VLFs (>5,000 hectares) from 1984-2010 to atmospheric predictors at subecoregion scales (~ 60-km grids) and weekly (6-day) timescales for 13 Omernik (Omernick, 1987) level II ecoregions of the US (Figure 1a). Separate models were developed for each ecoregion given that climate-VLF relationships are mediated through vegetation, which when run at 60-km scale allowed for spatial heterogeneity in predictors within an ecoregion (Table 1). We model historical and future VLF probabilities at weekly timescales on 60-km grids using downscaled GCM data aggregated to the aforementioned spatiotemporal resolution and the GLM equations. We apply this model assuming that contemporary climate-fire relationships remain unchanged, thereby overlooking potential changes in vegetation through which climate-VLFs links are mediated. 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 variability for each ecoregion. VLF potential (P) is hereafter expressed in units of VLF weeks per surface unit per unit time.

Projected changes in P were examined across 17 GCMs at weekly and annual timescales between the mid-21<sup>st</sup> century (2041-2070) and late 20<sup>th</sup> century (1971-2000) runs. We focus on changes in the multi-model mean response and regions where the signal is considered robust, defined by where the multi-model mean difference exceeds 2 standard deviations of the internal variability of historical runs and at least 90% of the models agree on the sign of change (IPCC, 2013). We also quantify changes in P at the level II ecoregion scale 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. While 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 P above the historical 99<sup>th</sup> percentile (defined at the ecoregion level).

## 3. Results

Projected increases in P were modeled 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 (Figure 1b,c). Increases were also projected across Northern Lakes and Forests, and in the Southern Coastal Plain, 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 (Figure 1d); however, these changes result in moderate absolute increases in P in regions that had historically low P.

Seasonal changes in P are illustrated for three ecoregions representative of changes modeled for other ecoregions (Figure 2). Non-significant increases in annual P were projected in some non-forested ecoregions of the central US including the South-Central semi-arid prairies ecoregion (Figure 2a). Respectively small and ambiguous changes in seasonal P were a function of muted and mixed changes in predictor variables historically important in VLFs in that region. Conversely, large increases in P were noted for the Western Cordillera ecoregion (Figure 2b) 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 modeled 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 southwestern US including the Warm deserts ecoregion (Figure 2c), 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 (Figure 2d) in relation with anticipated warmer winter temperature and a return to normal conditions near the core of the historical VLF season.

Most ecoregions of the US will not only experience higher mean annual P (Figure 3a) but also a temporal expansion of extreme P under future climate (Figure 3b). The largest seasonal expansion of extreme P is projected for the Western Cordillera, Mixed Wood Shield, Cold Deserts or Southeast 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 favorable 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 P are evident; however, nearly all model projections suggest increases above historical levels.

## 4. 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, increased temperature, and decreased precipitation and relative humidity coincide with fire season (e.g. Liu et al. 2012; Abatzoglou and Kolden, 2011; Stavros et al., 2014b). Projected changes in P by the mid-21<sup>st</sup> century follow a similar pattern to those modeled using observed changes in climate over the past three decades (Barbero et al., 2014b), although are substantially larger in magnitude and suggest a continuation of more frequent VLF occurrences. While previous modeling projected increased burned area under future climate across parts of the US (e.g., Spracklen et al., 2009), we provide an additional basis for such projections by showing that climate change may enable increased opportunities for VLF occurrence. While the projected increases in P were smaller in absolute values in the eastern US than in the western US, increased VLF occurrence may have stronger impacts on private property and air quality in the more densely populated regions of the eastern US than in the relatively uninhabited western US.

Several uncertainties in such a modeling exercise may circumvent realized changes in VLFs. First, while models from Barbero et al., (2014b) 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 modeling resulting in non-stationary fire-climate relationships (e.g., McKenzie et al., 2014). 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 Southwestern US (e.g., Hurteau et al., 2014) may buffer modeled increases in VLFs. Conversely, changes in the distribution of invasive annual grasses conducive to VLFs may also shift in the future (Bradley et al., 2009) altering model projections. While 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 modeling approach is considered conservative since 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 modeled here.

Projected increases in VLF potential have important implications for terrestrial carbon emissions (Prentice et al., 2011; Schultz et al., 2008), ecosystems (Keane et al., 2008), as well as communities, regional air quality and human health. Irrespective of the aforementioned caveats in modeling, the increased occurrence of VLFs will have significant impacts 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, multiagency 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, since city and county agencies are often involved. Finally, an increase in the number of VLF could ultimately have negative impacts to 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. Recognizing that potential for VLFs is likely to increase is key to developing proactive policies to combat these negative effects.

## References

- Abatzoglou, J.T., and Kolden, C.A. 2011. Climate Change in Western US Deserts: Potential for Increased Wildfire and Invasive Annual Grasses. *Rangeland Ecology & Management*, 64: 471-478
- Abatzoglou, J. T., and Brown, T. J. 2012, A comparison of statistical downscaling methods suited for wildfire applications. *International Journal of Climatology* 32: 772–780. doi: 10.1002/joc.2312
- Abatzoglou , J.T. 2013. Development of gridded surface meteorological data for ecological applications and modeling. *International Journal of Climatology* 33: 121– 131. doi: 10.1002/joc.3413.
- Barbero, R., Abatzoglou, J.T., Kolden, C., Hegewisch, K., Larkin, N.K., and Podschwit, H. 2014a. Multi-scalar influence of weather and climate on very large-fires in the Eastern United States. *International Journal of Climatology* doi:10.1002/joc.4090
- Barbero, R., Abatzoglou, J.T., and Steel, E.A. 2014b, Modeling very large-fire occurrences over the continental United-States from weather and climate forcing, *Environmental Research Letters*, 9, doi:10.1088/1748-9326/9/12/124009
- Bradley, B.A. 2009. Regional analysis of the impacts of climate change on cheatgrass invasion shows potential risk and opportunity. *Global Change Biology* 15: 196-208.
- Deeming, J.E., Burgan, R.E., and Cohen, J.D. 1977. The National Fire-Danger Rating System – 1978. USDA Forest Service Intermountain Forest and Range Experiment Station. *Gen. Tech. Rep. INT-39*, Ogden, Utah.
- Dennison, P.E., Brewer, S.C., Arnold, J.D., Moritz, M.A. 2014. Large wildfire trends in the western United States, 1984-2011. *Geophysical Research Letters* 41: 2928-2933. doi:10.1002/2014GL059576.
- Diffenbaugh, N. S., and Ashfaq, M. 2010. Intensification of hot extremes in the United States. *Geophys. Res. Lett.*, 37, L15701, doi:10.1029/2010GL043888.
- Fosberg M A 1978 Weather in wildland fire management: the fire weather index Proc. of the Conf. on Sierra Nevada Meteorology (South Lake Tahoe, NV) pp 1–4
- Flannigan, M.D., Stocks, B.J., Turetsky, M.R. and Wotton, B.M. 2008. Impact of climate change on fire activity and fire management in the circumboreal forest. Global Change Biology, 14(1-12).
- Flannigan, M. D., Krawchuk, M.A., de Groot, W.J., Wotton, B.M., and Gowman, L. M. 2009. Implications of changing climate for global wildland fire. *Int. J. Wildland Fire* 18: 483–507

- Gao, Y., Leung, L.R, Lu, J., Liu, Y., Huang, M., and Qian, Y. 2014. Robust spring drying in the southwestern U.S. and seasonal migration of wet/dry patterns in a warmer climate. *Geophys. Res. Lett.* 41, doi:10.1002/2014GL059562.
- Gillett, N. P., Weaver, A.J., Zwiers, F.W., and Flannigan, M.D. 2004. Detecting the effect of climate change on Canadian forest fires. *Geophys. Res. Lett.* 31, L18211, doi:10.1029/2004GL020876.
- Hurteau, M.D., Bradford, J.B., Fulé, P.Z., Taylor, A.H., and Martin, K.L. 2014. Climate change, fire management, and ecological services in the southwestern US. *For. Ecol. Manage.* 327: 280–289.
- IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CB09781107415324.
- Johnston, F.H., Henderson, S.B., Chen, Y., Randerson, J.T., Marlier, M., Defries, R.S., Kinney, P., Bowman, D.M.J.S., nd Brauer, M. 2012. Estimated global mortality attributable to smoke from landscape fires. *Environ Health Perspect* : 120, 695–701.
- Keane, R.E., Agee, JK, Fulé P, Keeley, J.E., Key, C., Kitchen, S.G., Miller. R., and Schulte, L.A. 2008. Ecological effects of large-fires on US landscapes: benefit or catastrophe? *International Journal of Wildland Fire* 17: 696–712. doi:10.1071/WF07148.
- Lenihan, J.M., Bachelet, D., Neilson, R.P., and Drapek, R. 2008. Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California. *Climatic Change 87(Suppl.)* : 215–230. doi:10.1007/S10584-007-9362-0
- Littell, J.S., McKenzie, D., Peterson, D.L., and Westerling, A.L. 2009. Climate and wildfire area burned in western U. S. ecoprovinces, 1916-2003. *Ecological Applications* 19: 1003-1021.
- Liu, Y.Q., Goodrick, S.L., and Stanturf, J.A. 2012. Future U.S. wildfire potential trends projected using a dynamically downscaled climate change scenario. *Forest Ecol. Manage.* http://dx.doi.org/10.1016/j.foreco.2012.06.049.
- Marlon, J.R., Bartlein, P.J., Gavin, D.G., Long, C.J., Anderson, R.S., Briles, C.E., Brown, K.J., Colombaroli, D., Hallett, D.J., Power, M.J., Scharf, E.A., and Walsh, M.K. 2012. Longterm perspective on wildfires in the western USA. *Proceedings of the National Academy of Sciences of the United States of America* 109 E535–E543.
- Moritz, M.A., Parisien, M-A., Batllori, E., Krawchuk, M.A., Van Dorn, J., Ganz, D.J., and Hayhoe, K. 2012. Climate change and disruptions to global fire activity. *Ecosphere* 3:art49. http://dx.doi.org/10.1890/ES11-00345.1.

- McKenzie, D., Shankar, U., Keane, R.E., Stavros, E.N., Heilman, W.E., Fox, D.G., and Riebau, A.C. 2014. Smoke consequences of new wildfire regimes driven by climate change. *Earth's Future* 2: 35–59. doi:10.1002/2013EF000180.
- Omernik, J.M. 1987 Ecoregions of the conterminous United States (map supplement). Annals of the Association of American Geographers 77: 118-125, scale 1:7,500,000
- Orlowsky, B., and Seneviratne, S. I. 2012. Global changes in extreme events: regional and seasonal dimension. *Climatic Change* 110(3-4): 669-696.
- Prentice, I.C., Kelley, D.I., Foster, P.N., Friedlingstein, P., Harrison, S.P. and Bartlein, P.J. 2011. Modeling fire and the terrestrial carbon balance. *Glob. Biogeochem. Cy.* 25: 1–13.
- Rhoades, C.C., Entwistle, D., and Butler, D. 2011. The influence of wildfire extent and severity on streamwater chemistry, sediment and temperature following the Hayman Fire, Colorado. *International Journal of Wildland Fire* 20(3): 430-442.
- Riley, K.L., Abatzoglou, J.T., Grenfell, I.C., Klene, A.E., and Heinsch, F.A. 2013. The relationship of large-fire occurrence with drought and fire danger indices in the western USA, 1984–2008: the role of temporal scale. *International Journal of Wildland Fire.* doi:10.1071/WF12149.
- Rocca, M.E., et al. 2014. Climate change impacts on fire regimes and key ecosystem services in Rocky Mountain forests. *Forest Ecol. Manage.* http://dx.doi.org/10.1016/j.foreco.2014.04.005.
- Romps, D.M., Seeley, J.T., Vollaro, D., and Molinari, J. 2014. Projected increase in lightning strikes in the United States due to global warming. *Science*: 346 (6211), 851–854; DOI: 10.1126/*science*.1259100.
- Schultz, M. G., Heil, A., Hoelzemann, J. J., Spessa, A., Thonicke, K., Goldammer, J. G., Held, A.
  C., Pereira, J. M. C. and van het Bolscher, M. 2008. Global wildland fire emissions from 1960 to 2000. *Global Biogeochem. Cycles* 22: GB2002.
- Spracklen, D.V., Mickley, L.J., Logan, J.A., Hudman, R.C., Yevich, R., Flannigan, M.D., and Westerling, A.L. 2009. Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. *Journal of Geophysical Research* 114: D20301 doi:10.1029/2008jd010966.
- Stavros, E.N., Abatzoglou, J.T., Larkin, N.K., McKenzie, D., and Steel, E.A. 2014a. Climate and very large wildland fires in the contiguous western USA. *International Journal of Wildland Fire* http://dx.doi.org/10.1071/WF13169.
- Stavros, E.N., Abatzoglou, J.T., McKenzie, D., and Larkin, N.K. 2014b. Regional projections of the likelihood of very large wildland fires under a changing climate in the contiguous Western United States. *Climatic Change* ?

- Stocks, B.J., Fosberg, M.A., Lynham, T.J., Mearns, L., Wotton, B.M., Yang, Q., Jin, J-Z, Lawrence, K., Hartley, G.R., Mason, J.A., and McKenney, D.W. 1998. Climate change and forest fire potential in Russian and Canadian boreal forests. *Climatic Change* 38(1): 1–13. doi:10.1023/A:1005306001055.
- Strauss, D., Bednar, L., and Mees, R. 1989. Do one percent of forest fires cause ninetynine percent of the damage? *Forest Science* 35: 319-328.
- Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Government of Canada, Canadian Forestry Service, Ottawa, Ontario Forestry Technical Report 35. 37 p.
- Westerling, A.L., Brown, T.J., Gershunov, A., Cayan, D.R., and Dettinger, M.D. 2003. Climate and Wildfire in the Western United States. Bulletin of the American Meteorological Society, 84(5): 595-604.
- Westerling, A.L., Hidalgo, H.G., Cayan, D.R., and Swetnam, T.W. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. *Science* 313: 940–943.
- Westerling, A. L., Bryant, B. P., Preisler, H. K., Holmes, T.P., Hidalgo, H., Das, T., and Shrestha, S. 2011. Climatic change and growth scenarios for California wildfire. *Climatic Change* 109(s1): 445–463.
- Wotton, B.M., Nock, C.A., and Flannigan, M.D. 2010. Forest fire occurrence and climate change in Canada. *Int. J. Wildland Fire* 19: 253–271.
- Yue, X., Mickley, L.J., Logan, J.A., and Kaplan, J.O. 2013. Ensemble projections of wildfire activity and carbonaceous aerosol concentrations over the western United States in the mid-21<sup>st</sup> century. *Atmospheric Environment:* 767-780 doi:10.1016/j.atmosenv.2013.06.003.

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

**Table:** Equations describing weekly VLF probabilities at 60-km for each ecoregion. The second column gives  $\beta$  parameters (see Barbero et al. (2014) for further information on model development) for predictors that were selected in the stepwise regression. Third and fourth columns indicate the multi-models mean of mean annual number of VLFs expected (VLF Potential) per surface unit ( $10^4 km^{-2}$ ) for the historical and future periods, respectively.

## a) Omernick Ecoregions



b) Mean # of VLF weeks expected (1971-2000)



**Figure 1:** Multi-model mean annual number of VLF weeks per surface unit  $(10^4 km^{-2})$  for historic climate experiment (top, 1971-2000) and mid-21<sup>st</sup> century climate experiment (middle, 2041-2070). Relative changes are shown in the bottom panel. Stippling indicates pixels where the multi-model mean difference exceeded 2 standard deviations of internal variability of historical runs and at least 90% of the models agree on the sign of change. Gray pixels indicate regions with no or insufficient number of VLF to build robust models.



**Figure 2:** Mean seasonal cycle of VLF potential (P) aggregated to level II ecoregions from 1971-2000 (gray) and 2041-2070 (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 while the solid bold lines indicate the multi-model mean. Gray 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.



a) Historical and future annual VLF potential

**Figure 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 99<sup>th</sup> percentile. Horizontal red lines indicate the historical range (1971-2000) across different GCMs, with the vertical red line indicating the multi-model mean. Future projections for the mid-21<sup>st</sup> century (2041-2070) are indicated for each model by a symbol 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-models mean of future runs (from largest to smallest values).