AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2015GL063428

Key Points:
- Warm ENSO summers limit the occurrence of very large wildfires
- Increased summer precipitation during warm ENSO over interior northwest US
- Summer ENSO-precipitation relationships strengthened in recent decades

Correspondence to:
R. Barbero,
renaudb@uidaho.edu

Citation:
Barbero, R., J. T. Abatzoglou, and T. J. Brown (2015), Seasonal reversal of the influence of El Niño–Southern Oscillation on very large wildfire occurrence in the interior northwestern United States, *Geophys. Res. Lett.*, *42*, doi:10.1002/2015GL063428.

Received 10 FEB 2015
Accepted 18 APR 2015
Accepted article online 22 APR 2015

Seasonal reversal of the influence of El Niño–Southern Oscillation on very large wildfire occurrence in the interior northwestern United States

Renaud Barbero[1], John T. Abatzoglou[1], and Timothy J. Brown[2]

[1]Department of Geography, University of Idaho, Moscow, Idaho, USA, [2]Desert Research Institute, University of Nevada, Reno, Nevada, USA

Abstract Satellite-mapped fire perimeters and the multivariate El Niño–Southern Oscillation index were used to examine the impact of concurrent El Niño–Southern Oscillation (ENSO) phase on very large fire (VLF) occurrences over the intermountain northwestern United States (U.S.) from 1984 to 2012. While the warm phase of ENSO promotes drier and warmer than normal conditions across the region during winter and spring that favor widespread fire activity the following summer, a reduction in VLFs was found during the warm phase of ENSO during summer concurrent with the fire season. This paradox is primarily tied to an anomalous upper level trough over the western U.S. and positive anomalies in integrated water vapor that extend over the northwestern U.S. during summers when the warm phase of ENSO is present. Collectively, these features result in widespread increases in precipitation amount during the summer and a curtailment of periods of critically low-fuel moistures that can carry wildfire.

1. Introduction

Very large fires (VLFs) have widespread ecological and societal impacts and garner large suppression resources and associated costs. The occurrence of VLFs has increased over the western United States (U.S.) in the past three decades [*Dennison et al.*, 2014], contributing to significant societal and ecological impacts [*Keane et al.*, 2008]. VLFs commandeer significant fire suppression resources that have consequent impacts for complementary land management programs [*Thompson et al.*, 2013], contribute to the atmospheric carbon burden and constitute a feedback to climate system [*Liu et al.*, 2010], and have widespread impacts on air and water quality [e.g., *Clinton et al.*, 2006]. Consequently, there has been continued interest in understanding the biophysical and societal factors that contribute to these fires [*Stavros et al.*, 2014; *Barbero et al.*, 2014a; *Lannom et al.*, 2014] to develop effective strategies for fire suppression and proactive land management.

Fire activity in the western U.S. has established links to climate variability antecedent to the fire season and atmospheric conditions during the fire season [e.g., *Westerling et al.*, 2003; *Littell et al.*, 2009; *Abatzoglou and Kolden*, 2013]. Collectively, these factors have been linked to the occurrence of VLFs [*Stavros et al.*, 2014; *Barbero et al.*, 2014b]. Interannual variability in fuel accumulation and desiccation can be modulated by large-scale ocean-atmosphere modes of variability such as El Niño–Southern Oscillation (ENSO). Given the potential predictability of ENSO, efforts have been made to utilize ENSO phase in seasonal wildfire outlooks [e.g., *van der Werf et al.*, 2004; *Barbero et al.*, 2011]. ENSO has well-resolved hydroclimatic impacts on western United States during the cool season with a latitudinal dipole straddling the 40°N parallel with predominantly warmer and drier conditions in the northwest U.S. during the warm phase of ENSO and consequently reduced mountain snowpack [*Redmond and Koch*, 1991; *Cayan*, 1996; *Dettinger et al.*, 1998]. Dendrochronology-based fire histories have demonstrated links between the phase of ENSO during winter and spring and fire activity during the subsequent summer in the interior northwestern U.S., suggesting that the warm phase of ENSO, often in combination with the positive phase of the Pacific Decadal Oscillation, enhances fire activity in the mesic parts of region through antecedent drought stress [e.g., *Heyerdahl et al.*, 2008; *Westerling and Swetnam*, 2003; *Kitzberger et al.*, 2007]. However, fire atlases and more recent fire records from the interior northwest U.S. have not replicated such relationships [*Morgan et al.*, 2008; *Lannom et al.*, 2014].

Because the ENSO phenomenon reaches its highest amplitude and has stronger teleconnections to North American climate during winter, previous efforts placed emphasis on winter ENSO and subsequent

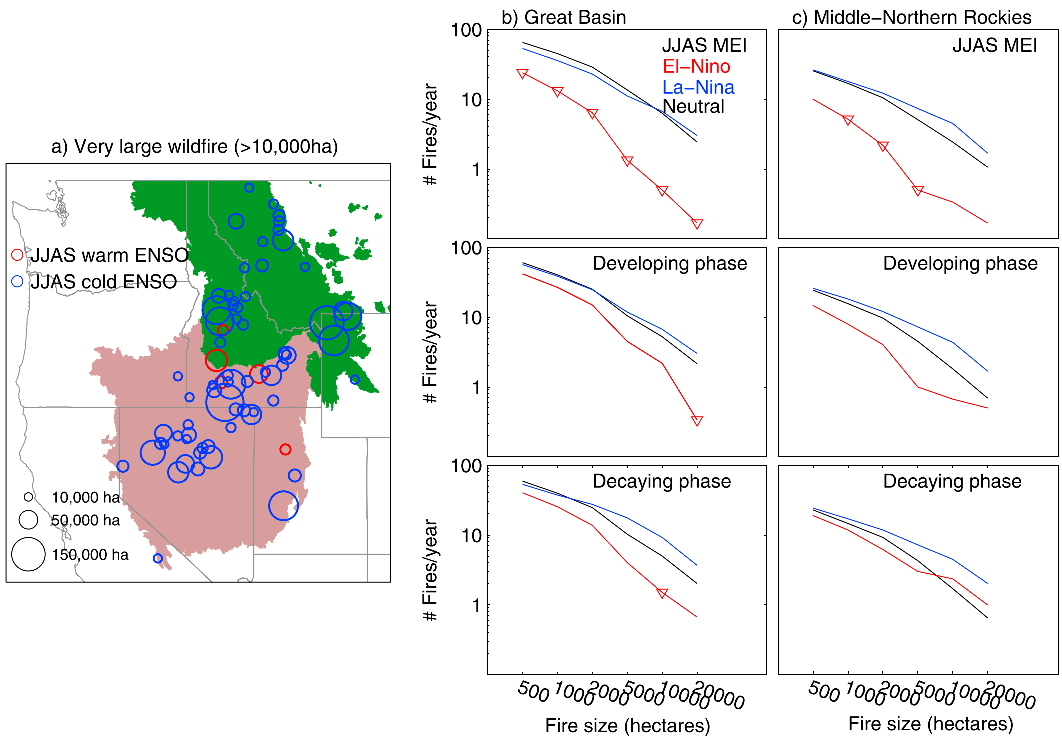

Figure 1. (a) Very large wildfire occurrences (>10,000 ha) associated with warm summer ENSO and cold summer ENSO events (June–September). The circle size indicates fire size. The Middle-to-Northern Rockies (Great Basin) region is indicated by the green (beige) polygon. (b) Mean number of very large wildfire occurrences per year during warm phase ENSO (red), cold phase ENSO (blue), and neutral (black) summers as a function of different thresholds (from 500 ha to 20,000 ha) on a logarithmic scale. The top panel shows ENSO summers defined from June–September MEI, while the middle (bottom) panel shows summers associated with the developing (decaying) phase of ENSO events. (c) Same as Figure 1b for the Middle-to-Northern Rockies ecoregion. The triangles indicate results that were both statistically significant (see text).

climate-fire relationships realized through antecedent relationships [e.g., *Westerling and Swetnam*, 2003; *Trouet et al.*, 2010]. Relationships using summer ENSO phase have not been thoroughly examined, despite the relatively stronger relationships between fire activity and atmospheric conditions during the fire season than antecedent to the fire season [*Abatzoglou and Kolden*, 2013]. Moreover, there is evidence that the influence of ENSO on summer U.S. climate contrasts with the canonical wintertime ENSO influence [*Wang et al.*, 2007, 2012; *Hu and Feng*, 2012]. The confounding antecedent winter and concurrent summer climatic signals associated with ENSO may modulate conditions for wildfire activity including VLFs and have implications for seasonal fire outlooks.

2. Data and Methods

The Monitoring Trends in Burn Severity (MTBS) database was used to acquire fire location, fire discovery date, and burned area for large fires (>404 ha) over the intermountain western U.S. during the primary fire season (June–September) from 1984 to 2012. We excluded area within fire perimeters classified as "unburned to low" by MTBS to more accurately portray the true area burned [*Kolden et al.*, 2012], and given the subjective nature of defining VLF, we considered fire size classes ranging from 500 ha to 20,000 ha. We limited the spatial extent of our analysis to two disparate ecoregion types (Figure 1a) in the interior northwestern U.S. defined using Omernik's level III ecoregions [*Omernik*, 1987] that comprise the most active regions of VLF activity over the western U.S. [*Stavros et al.*, 2014] and recorded nearly two thirds of all fires >20,000 ha in the western U.S. from 1984 to 2012. These two regions were the flammability-limited forested systems of the Northern and Central Rocky Mountains (Northern Rockies, Canadian Rockies, Middle Rockies, and Idaho Batholith level III ecoregions) and primarily fuel-limited nonforested systems of the Great Basin (Northern Basin and Range, Central Basin and Range, and Snake River Plain level III ecoregions).

Monthly temperature and precipitation were acquired from Parameter-elevation Regressions on Independent Slopes Model [*Daly et al.*, 1994] and used to compute the Palmer Drought Severity Index (PDSI) following *Kangas and Brown* [2007]. We explicitly examined April PDSI (i.e., PDSI at the end of April) as a proxy of long-term moisture anomalies prior to the start of fire season. Daily high-resolution surface meteorological data from *Abatzoglou* [2013] were used to compute the energy release component (ERC), a cumulative, hybrid weather-climate metric that indicates potential heat energy released at the flaming front, which has been linked to the occurrence of VLFs [e.g., *Stavros et al.*, 2014; *Barbero et al.*, 2014b]. Days with ERC above the historical 90th percentile value for the entire period of record were hereafter referred to as high ERC days. Finally, we used summer (June–September) 200 hPa winds, total column water (TCW), as well as surface relative humidity from ERA-Interim to examine larger-scale teleconnections to circulation and moisture.

We defined ENSO using the multivariate ENSO index (MEI) [*Wolter and Timlin*, 2011]. We focused on summer (June–September) MEI concurrent with the fire season and qualify warm and cold phases as the upper (80th) and lower (20th) quintiles, respectively, yielding six warm ENSO summers (1987, 1991, 1992, 1993, 1997, and 2009) and six cold ENSO summers (1988, 1989, 1999, 2007, 2010, and 2011). However, ENSO amplitude typically peaks in December. Consequently, if summer MEI reflects warm ENSO conditions, it is likely that this situation either corresponds to a developing phase of El Niño (leading to the peak phase in the following winter) or to a decaying phase following El Niño winter. We thus repeated our analysis considering October–March MEI for both decaying ENSO conditions (peaking during previous winter) and developing ENSO conditions (peaking during subsequent winter), irrespective of summer MEI. These results are shown to contrast from our main focus on summer ENSO phase.

We used composite analysis to establish relationships between the number of VLFs for different size classes and ENSO phase. Composites of the number of high ERC days and ERA-Interim reanalysis fields were also examined by ENSO phase from 1979 to 2013, although results were unchanged for 1984–2012. Anomalies are all presented relative to the baseline climatology. A paired sample Student's t test at the 95% confidence level was applied to assess the statistical significance of the difference between the sample mean (e.g., warm phase ENSO summers) and all other years in the record (e.g., all other summers). Given the relatively small sample size of our record, we only considered results to be statistically significant when the t test held using a leave 1 year out resampling that iteratively excluded 1 year from the composite, making the t test resistant to outliers and potential influential cases. An alternative statistical test using chi-square analysis with Monte Carlo resampling and an alternative t test following *Brown and Hall* [1999] yielded similar results, albeit were less restrictive than the aforementioned statistical tests that we hereafter utilized.

Finally, we provided context for ENSO-wildfire relationships over the past three decades relative to the longer record from 1900 to 2012 by examining differences in teleconnections between MEI and both summer precipitation and spring PDSI from 1900 to 2012. Although precipitation by itself is not the main driver of ERC variations, it has the advantage of being available from the beginning of the century unlike fire danger metrics and may serve as a proxy for interannual variations in fire danger. The extended MEI from 1900 to 2005 was blended with the operational MEI from 2006 to 2012 using linear regression following *Abatzoglou et al*. [2014]. Correlations between June–September MEI and precipitation, and likewise October–March MEI and April PDSI, were calculated for three nonoverlapping periods (1900–1939, 1940–1979, and 1980–2012). Only correlations significant at the 95% confidence level were mapped.

3. Results and Discussion

A significant reduction in VLF frequency for a range of size classes was found in the Great Basin (Figures 1a and 1b) and for VLF size classes above 1000, 2000, and 5000 ha in the Middle-to-Northern Rockies (Figures 1a and 1c) during warm phase ENSO summers. By contrast, VLFs were slightly more frequent during cool phase ENSO summers than neutral summers, but this result was not significant. Results based on cool-season ENSO phase defined using the previous and subsequent winter were directionally similar but were weaker and generally not significant. Unlike most dendrochronologies that suggest increased fire activity in the forested ecoregions of inland northwest U.S. following warm phase ENSO winters, this relationship has not been evident over the past three decades. Rather, we found opposing results as VLF activity declined during warm phase ENSO summers, in agreement with the relationship between annual burned

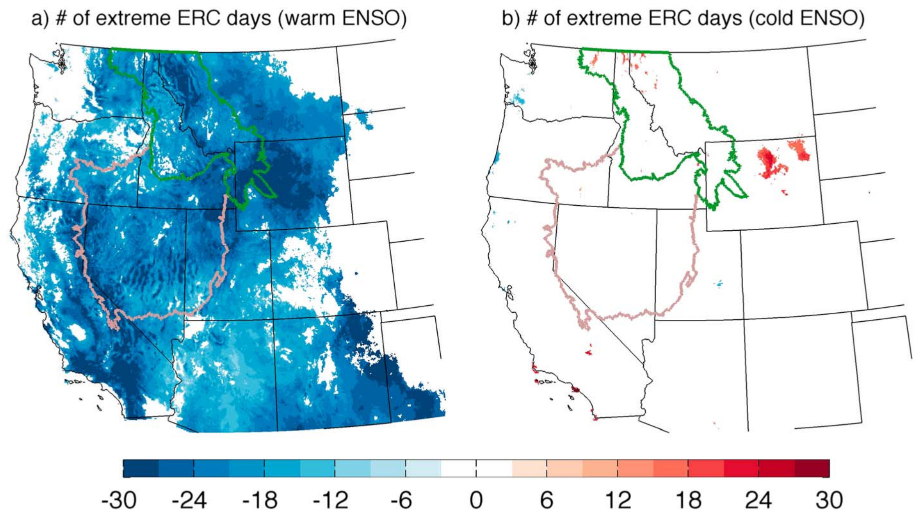

Figure 2. Anomalies in the number of days during June–September, during which the energy release component exceeded the historical local 90th percentile for (a) warm phase ENSO summers and (b) cold phase ENSO summers over the 1979–2012 period. Only significant values according to a *t* test at the 95% confidence level are shown. The Middle-to-Northern Rockies (Great Basin) region is indicated by the green (beige) polygon.

area and summer MEI phase across the inland northwestern U.S. in recent decades as noted by *Lannom et al*. [2014]. As the relationships between VLFs and MEI were strongest for MEI coincident to the fire season, subsequent analyses strictly use June–September MEI.

The occurrence of high ERC days was substantially reduced during warm phase ENSO summers across much of the western U.S. including the study area (Figure 2a), whereas no significant differences were found during cool phase ENSO summers (Figure 2b). Similar patterns were seen when ERC was replaced by precipitation or by the number of days with precipitation >1 mm/d, suggesting that precipitation amount and frequency during warm ENSO summers is crucial for curtailing very high fire danger days and conditions conducive to VLFs. By contrast, no significant relationship was found with summer temperature (not shown). Upper tropospheric circulation for warm phase ENSO summers shows a cyclonic anomaly over the western U.S. and above normal TCW and positive relative humidity anomalies across the northern half of the western U.S. (Figure 3a), in agreement with modeling results by *Wang et al.* [2007] and *Wang et al.* [2012] who showed anomalous upper tropospheric troughing over North America during the summers following warm ENSO events. By contrast, a lack of field significance was seen for cool phase ENSO summers (Figure 3b), despite modeling studies showing a stronger signal of anticyclonic anomalies over North America for cool phase ENSO summers [*Wang et al*., 2007]. While ENSO teleconnections to midlatitudes are weaker in summer, our results suggest a contrast to the canonical wintertime ENSO response across the study area.

Multidecadal variability in relationships between MEI and both summer precipitation and spring PDSI was present over the period of record. Relationships between summer precipitation and summer MEI were ambiguous across the western U.S. in the early twentieth century (Figure 4a), with some negative relationships between MEI and precipitation in the Northern Rockies. However, these relationships became more pronounced featuring widespread positive relationships during the more recent epochs covering much of the Great Basin and the Middle-to-Northern Rockies ecoregions in recent decades (Figure 4c). By contrast, the correlation between April PDSI and winter MEI illustrates the latitudinal dipole of previous studies (Figures 4d–4f) that would impose antecedent climate impacts on wildfire activity in both the northwestern and southwestern U.S. While correlations remained relatively stable in the southwestern U.S., a weakening in the relationship was observed in the northwestern U.S. for the most recent epoch (Figure 4f). Nonstationarity in ENSO-climate impacts across the U.S. has been noted in prior studies [*McCabe and Dettinger*, 1999; *Rajagopalan et al*., 2000]. We suggest that such nonstationarity may also have contributed to the recent strong relationships between summer ENSO phase, precipitation, and VLF activity and, respectively, weaker influence between winter ENSO phase and spring PDSI. This might explain why most previous studies that used dendrochronologies ending in the 1970s found increased fire activity following

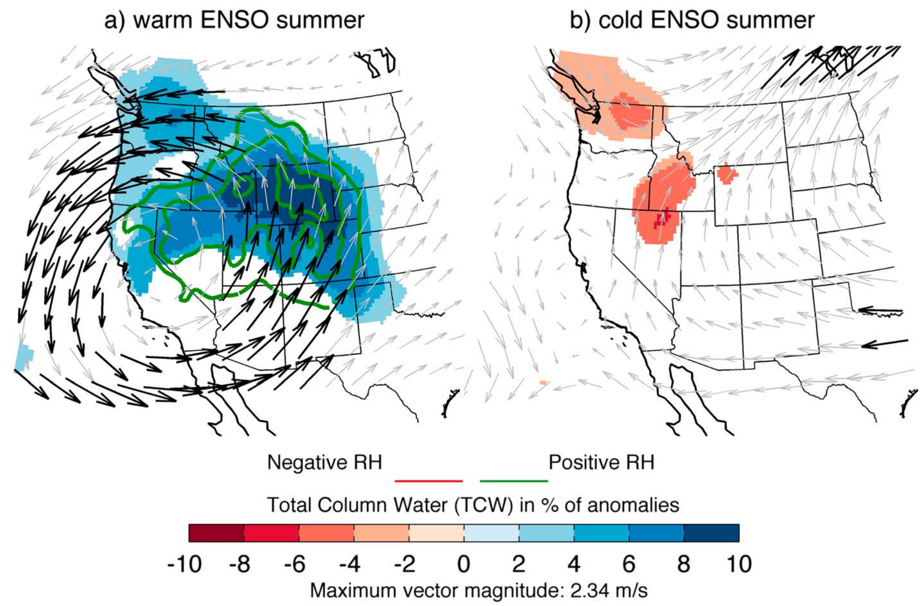

Figure 3. Anomalies of June–September 200 mb wind (vectors), surface relative humidity (contours), and seasonal total column water (shadings) in percentage of anomalies for (a) warm phase ENSO summers and (b) cold phase ENSO summers over the 1979–2012 period. The contours indicate surface relative humidity in steps of 5% from 10% for positive values and from −10% for negative values. Only values significant according to a *t* test at the 95% confidence level are shown. Vectors whose zonal or meridional component was significant according to a *t* test at the 95% confidence level are shown in black.

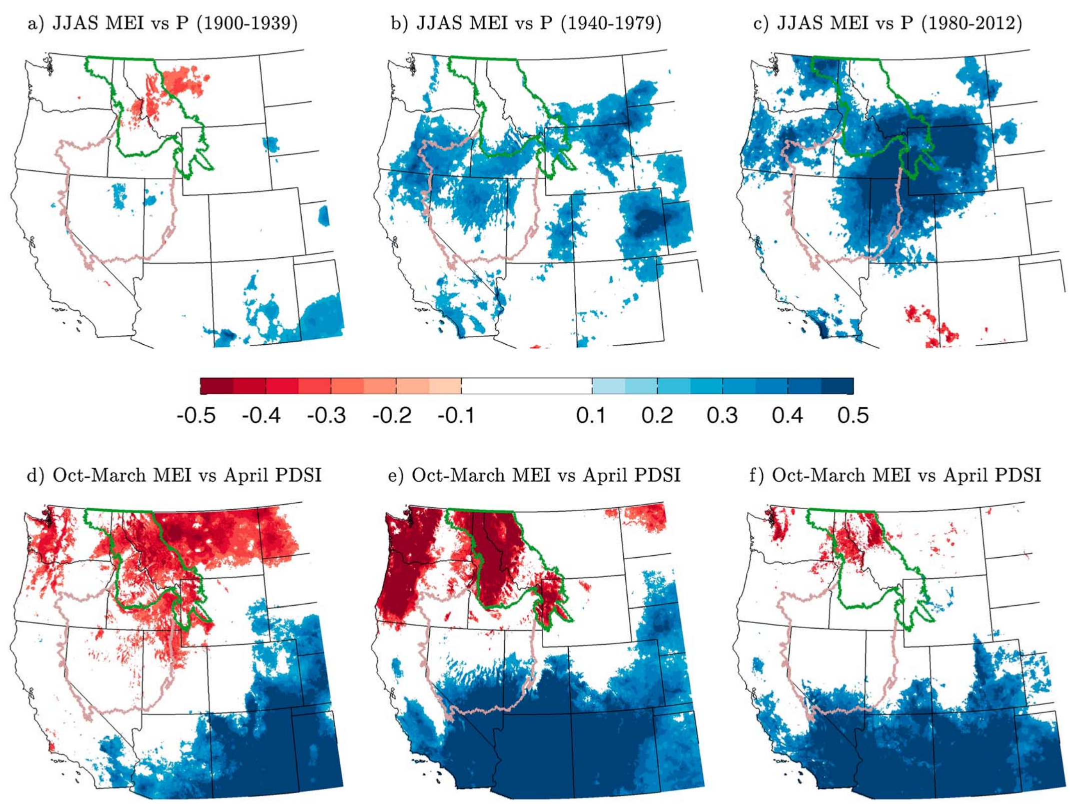

Figure 4. (a–c) Correlations between June–September multivariate ENSO index (MEI) and June–September precipitation for three nonoverlapping time periods. (d–f) Same as Figures 4a–4c for correlations between October–March MEI and the subsequent April Palmer Drought Severity Index (PDSI). Only significant correlations at the 95% confidence level are shown. The Middle-to-Northern Rockies (Great Basin) region is indicated by the green (beige) polygon.

winter El Niño conditions in some regions of the northwest U.S. [e.g., *Westerling and Swetnam*, 2003; *Kitzberger et al*., 2007]. Additional studies might help better elucidate whether these epochal variations in the ENSO-precipitation connection are consistent with observed variations in multidecadal climate variability or are stochastic in nature. For instance, the weakened interannual variability of ENSO since 2000 [*Hu et al*., 2013] as well as the emergence of central Pacific ENSO in recent decades that have been more frequent than eastern ENSO [*Yeh et al*., 2009] have lead to different patterns of extratropical teleconnections and have recently affected U.S. winter precipitation responses to ENSO [*Yu and Zou*, 2013]. Although the examination of the impact of different ENSO flavors is beyond the scope of this study, the changing nature of ENSO might contribute to the epochal variations in the teleconnections and the subsequent variations in fire occurrences.

4. Conclusion

While the warm phase of ENSO typically promotes warmer and drier conditions in the northwestern U.S. during winter and spring promoting favorable conditions for wildfire activity leading into the summer fire season, we provide evidence of a strong reduction in VLF occurrences in the Great Basin and in the Middle-to-Northern Rockies ecoregions during warm phase ENSO summers. The relative absence of VLF during warm phase ENSO summers is related to an increase in summer precipitation amount and frequency that promote a reduction in the occurrence of high fire danger days that are conducive to fire spread. These results are consistent with the strong links between VLF occurrence and prolonged periods of high fire danger [e.g., *Stavros et al*., 2014].

An inherent limitation of this study is the 29 year length of the MTBS time series. Whereas our results were robust over the recent epoch, modulations in midlatitude ENSO teleconnections have been shown to occur on multidecadal time scales [*Gershunov and Barnett*, 1998] and may be responsible for these observed relationships. Additional research on multidecadal variability of midlatitude ENSO teleconnections during June-September may help elucidate dynamic factors. Likewise, reconstructions of ENSO, fire records, and PDSI [e.g., *Heyerdahl et al*., 2008] could be examined for nonstationarity or multidecadal variability in ENSO teleconnections to provide context for the most recent epoch. Nonstationarity in ENSO teleconnections, namely, the strengthening between summer precipitation and summer ENSO phase and weakening between spring PDSI and winter ENSO phase in the recent epoch, may contribute to our findings relative to longer-term fire reconstructions.

Another contributing factor for interannual variability in VLFs is the number of lightning occurrences responsible for fire ignitions. However, we did not find any significant annual relationships between summer MEI and the number of lightning strikes (derived from the National Lightning Detection Network) within each ecoregion over the 1990–2009 period. However, subseasonal variability in lightning activity [e.g., *Abatzoglou and Brown*, 2009] and lightning busts responsible for widespread fire activity and VLF may be overlooked using seasonal averages. Changes in fire suppression practices [*Marlon et al*., 2012] and invasive annual grasses [*Balch et al*., 2013] have also likely modified the potential for VLF and their sensitivity to climate factors over multidecadal time periods. For example, *Miller et al*. [2012] found that summer precipitation has become a stronger predictor of fire season activity in recent decades over longer-term drought stress due to initial attack success in forested parts of northwestern California. Further studies are needed to better elucidate the recent relative influence of summer ENSO phase on conditions during the fire season to that of winter ENSO phase on climate antecedent to the fire season.

Additional studies are required to better understand the subtropical and midlatitude dynamics that facilitate moisture advection into the interior northwestern U.S. during warm phase ENSO summers. Northward propagating surges of monsoonal moisture can deliver significant precipitation to the Great Basin and parts of the Middle-to-Northern Rockies during middle to late summer, although linkages between ENSO phase and moisture surges are not well resolved [*Higgins and Shi*, 2005]. Regardless, given the increasing fire activity across the region over the past several decades, incorporating summer ENSO phase in seasonal outlooks may improve allocation and efficacy of seasonal fire suppression resources.

Acknowledgments

We are appreciative of the constructive feedback of two anonymous reviewers that improve the quality of this manuscript. This research was funded by NOAA Regional Integrated Science Assessment program grant NA10OAR4310218 (J.A.) and the Joint Fire Science Program award 11-1-7-4 (R.B. and J.A.). The wildfire database for this paper is available at http://www.mtbs.gov/, and the climate databases are available at http://apps.ecmwf.int/datasets/data/interim_full_moda/ and http://metdata.northwestknowledge.net.

The Editor thanks two anonymous reviewers for assistance evaluating this manuscript.

References

Abatzoglou, J. T. (2013), Development of gridded surface meteorological data for ecological applications and modeling, *Int. J. Climatol.*, *33*, 121–131, doi:10.1002/joc.3413.

Abatzoglou, J. T., and T. J. Brown (2009), Influence of the madden-julian oscillation on summertime cloud-to-ground lightning activity over the continental United States, *Mon. Weather Rev.*, *137*, 3596–3601, doi:10.1175/2009MWR3019.1.

Abatzoglou, J. T., and C. A. Kolden (2013), Relationships between climate and macroscale area burned in the western United States, *Int. J. Wildland Fire*, *22*, 1003–1020, doi:10.1071/WF13019.

Abatzoglou, J. T., D. E. Rupp, and P. W. Mote (2014), Seasonal climate variability and change in the Pacific Northwest of the United States, *J. Clim.*, *27*, 2125–2142.

Balch, J. K., B. A. Bradley, C. M. D'Antonio, and J. Gomez-Dans (2013), Introduced annual grass increases regional fire activity across the arid western USA (1980–2009), *Global Change Biol.*, *19*, 173–183, doi:10.1111/gcb.12046.

Barbero, R., V. Moron, M. Mangeas, M. Despinoy, and C. Hély (2011), Relationships between MODIS and ATSR fires and atmospheric variability in New Caledonia (SW Pacific), *J. Geophys. Res.*, *116*, D21110, doi:10.1029/2011JD015915.

Barbero, R., J. T. Abatzoglou, C. A. Kolden, K. Hegewisch, N. K. Larkin, and H. Podschwit (2014a), Multi-scalar influence of weather and climate on very large-fires in the eastern United States, *Int. J. Climatol.*, doi:10.1002/joc.4090.

Barbero, R., J. T. Abatzoglou, E. A. Steel, and N. K. Larkin (2014b), Modeling very large-fire occurrences over the continental United States from weather and climate forcing, *Environ. Res. Lett.*, *9*, 124009, doi:10.1088/1748-9326/9/12/124009.

Brown, T. J., and B. L. Hall (1999), The use of *t*-values in climatological composite analyses, *J. Clim.*, *12*, 2941–2944.

Cayan, D. R. (1996), Interannual climate variability and snowpack in the western United States, *J. Clim.*, *9*(5), 928–948.

Clinton, N. E., P. Gong, and K. Scott (2006), Quantification of pollutants emitted from very large wildland fires in Southern California, USA, *Atmos. Environ.*, *40*, 3686–3695.

Daly, C., R. P. Neilson, and D. L. Phillips (1994), A statistical-topographic model for mapping climatological precipitation over mountainous terrain, *J. Appl. Meteorol.*, *33*, 140–158.

Dennison, P. E., S. C. Brewer, J. D. Arnold, and M. A. Moritz (2014), Large wildfire trends in the western United States, 1984–2011, *Geophys. Res. Lett.*, *41*, 2928–2933, doi:10.1002/2014GL059576.

Dettinger, M., D. Cayan, H. Diaz, and D. Meko (1998), North–south precipitation in western North America on interannual-to-decadal timescales, *J. Clim.*, *11*, 3095–3111.

Gershunov, A., and T. P. Barnett (1998), Interdecadal modulation of ENSO teleconnections, *Bull. Am. Meteorol. Soc.*, *79*(12), 2715–2725.

Heyerdahl, E. K., D. McKenzie, L. D. Daniels, A. E. Hessl, J. S. Littell, and N. J. Mantua (2008), Climate drivers of regionally synchronous fires in the inland Northwest (1651–1900), *Int. J. Wildland Fire*, *17*, 40–49.

Higgins, R. W., and W. Shi (2005), Relationships between Gulf of California moisture surges and tropical cyclones in the eastern Pacific Basin, *J. Clim.*, *18*, 4601–4620.

Hu, Q., and S. Feng (2012), AMO- and ENSO-driven summertime circulation and precipitation variations in North America, *J. Clim.*, *25*, 6477–6495.

Hu, Z.-Z., A. Kumar, H.-Li Ren, H. Wang, M. L'Heureux, and F.-Fei Jin (2013), Weakened interannual variability in the tropical Pacific Ocean since 2000, *J. Clim.*, *26*, 2601–2613, doi:10.1175/JCLI-D-12-00265.1.

Kangas, R. S., and T. J. Brown (2007), Characteristics of U.S. drought and pluvial from a high-resolution spatial dataset, *Int. J. Climatol.*, *27*, 1303–1325.

Keane, R. E., J. K. Agee, P. Fulé, J. E. Keeley, C. Key, S. G. Kitchen, R. Miller, and L. A. Schulte (2008), Ecological effects of large fires on U.S. landscapes: Benefit or catastrophe?, *Int. J. Wildland Fire*, *17*, 696–712, doi:10.1071/WF07148.

Kitzberger, T., P. M. Brown, E. K. Heyerdahl, T. W. Swetnam, and T. T. Veblen (2007), Contingent Pacific–Atlantic Ocean influence on multi-century wildfire synchrony over western North America, *Proc. Natl. Acad. Sci., U.S.A.*, *104*, 543–548, doi:10.1073/PNAS.0606078104.

Kolden, C. A., J. A. Lutz, C. H. Key, J. T. Kane, and J. W. van Wagtendonk (2012), Mapped versus actual burned area within wildfire perimeters: Characterizing the unburned, *For. Ecol. Manage.*, *286*, 38–47.

Lannom, K. O., et al. (2014), Defining extreme wildland fires using geospatial and ancillary metrics, *Int. J. Wildland Fire*, *23*, 322–337.

Littell, J. S., D. McKenzie, D. L. Peterson, and A. L. Westerling (2009), Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003, *Ecol. Appl.*, *19*, 1003–1021.

Liu, Y. Q., J. Stanturf, and S. Goodrick (2010), Trends in global wildfire potential in a changing climate, *For. Ecol. Manage.*, *259*, 685–697, doi:10.1016/j.foreco.2009.09.002.

Marlon, J. R., et al. (2012), Long-term perspective on wildfires in the western USA, *Proc. Natl. Acad. Sci., U.S.A.*, *109*, E535–E543.

McCabe, G. J., and M. D. Dettinger (1999), Decadal variations in the strength of ENSO teleconnections with precipitation in the western United States, *Int. J. Climatol.*, *19*, 1399–1410, doi:10.1002/(SICI)1097-0088(19991115)19:13<1399::AID-JOC457>3.0.CO;2-A.

Miller, J., C. Skinner, H. Safford, E. E. Knapp, and C. Ramirez (2012), Trends and causes of severity, size, and number of fires in northwestern California, USA, *Ecol. Appl.*, *22*, 184–203.

Morgan, P., E. K. Heyerdahl, and C. E. Gibson (2008), Multi-season climate synchronized forest fires throughout the 20th century, Northern Rockies, USA, *Ecology*, *89*, 717–728.

Omernik, J. M. (1987), Ecoregions of the conterminous United States (map supplement), scale 1:7,500,000, *Ann. Assoc. Am. Geogr.*, *77*, 118–125.

Rajagopalan, B., E. R. Cook, U. Lall, and K. R. Bonnie (2000), Spatiotemporal variability of ENSO and SST teleconnections to summer drought over the United States during the twentieth century, *J. Clim.*, *13*, 4244–4255.

Redmond, K. T., and R. W. Koch (1991), Surface climate and streamflow variability in the western United States and their relationship to large scale circulation indices, *Water Resour. Res.*, *27*, 2381–2399, doi:10.1029/91WR00690.

Stavros, E. N., J. T. Abatzoglou, N. K. Larkin, D. McKenzie, and E. A. Steel (2014), Climate and very large wildland fires in the contiguous western USA, *Int. J. Wildland Fire*, doi:10.1071/WF13169.

Thompson, M. P., N. M. Vaillant, J. R. Haas, K. M. Gebert, and K. D. Stockmann (2013), Quantifying the potential impacts of fuel treatments on wildfire suppression costs, *J. For.*, *111*(1), 49–58.

Trouet, V., A. H. Taylor, E. R. Wahl, C. N. Skinner, and S. L. Stephens (2010), Fire-climate interactions in the American West since 1400 CE, *Geophys. Res. Lett.*, *37*, L04702, doi:10.1029/2009GL041695.

van der Werf, G. R., J. T. Randerson, G. J. Collatz, L. Giglio, P. S. Kasibhatla, A. F. Arellano, S. C. Olsen, and E. S. Kasischke (2004), Continental-scale partitioning of fire emissions during the 1997 to 2001 El Niño/La Niña period, *Science*, *303*, 73–76.

Wang, H., A. Kumar, W. Wang, and B. Jha (2012), U.S. summer precipitation and temperature patterns following the peak phase of El Niño, *J. Clim.*, *25*, 7204–7215.

Wang, Z., C. P. Chang, and B. Wang (2007), Impacts of El Niño and La Niña on the U.S. climate during northern summer, *J. Clim.*, *20*, 2165–2177.

Westerling, A. L., and T. W. Swetnam (2003), Interannual to decadal drought and wildfire in the western United States, *Eos Trans. AGU*, *84*(49), 545–555, doi:10.1029/2003EO490001.

Westerling, A. L., T. J. Brown, A. Gershunov, D. R. Cayan, and D. R. Dettinger (2003), Climate and wildfire in the western United States, *Bull. Am. Meteorol. Soc.*, *84*, 595–604.

Wolter, K., and M. S. Timlin (2011), El Niño/Southern Oscillation behaviour since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext), *Int. J. Climatol.*, *31*, 1074–1087.

Yeh, S.-W., J.-S. Kug, B. Dewitte, M.-H. Kwon, B. Kirtman, and F.-F Jin (2009), El Niño in a changing climate, *Nature*, *461*, 511–514, doi:10.1038/nature08316.

Yu, J. Y., and Y. Zou (2013), The enhanced drying effect of Central-Pacific El Niño on U.S. winter, *Environ. Res. Lett.*, *8*, 014019, doi:10.1088/1748-9326/8/1/014019.