Climatology, variability and trends in United States vapor pressure deficit, an important fire-related meteorological quantity

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ABSTRACT

Unlike the commonly used relative humidity, vapor pressure deficit (VPD), is an absolute measure of the difference between the water vapor content of the air and its saturation value and an accurate metric of the ability of the atmosphere to extract moisture from the land surface. VPD has been shown to be closely related to variability in burned forest area in the western United States. Here the climatology, variability and trends in VPD across the U.S. are presented. VPD reaches its climatological maximum in summer in the interior southwest U.S. due to both high temperatures and low vapor pressure under the influence of the northerly, subsiding eastern flank of the Pacific subtropical anticyclone. Maxima of variance of VPD are in the southwest and southern Plains in spring and summer and are to a large extent driven by temperature variance but vapor pressure variance is also important in the southwest. La Niña-induced circulation anomalies cause subsiding, northerly flow that drive down actual vapor pressure and increase saturation vapor pressure in fall through spring. High spring and summer VPD can also be caused by reduced precipitation in preceding months, as measured by Bowen ratio anomalies. A case study of 2002 leading up to the Rodeo-Chediski, AZ, and Hayman, CO. fires shows very high VPD caused by antecedent surface drying and subsidence warming and drying of the atmosphere. VPD has increased in the southwest U.S. since 1961, driven by warming and a drop in actual vapor pressure, but decreased in the northern Plains and midwest, driven by an increase in actual vapor pressure.

1. Introduction

In, for the field of meteorology, an unusually passionate polemic, Anderson (1936) argues for measuring and reporting the water vapor content of the atmosphere relative to saturation in terms of vapor pressure deficit (VPD) rather than relative humidity (RH). VPD is the difference between the saturation vapor content of air at temperature T_a, $e_s(T_a)$, and its actual vapor pressure, e_a, viz:

$$VPD = e_s(T_a) - e_a, \tag{1}$$

whereas RH is given by their ratio expressed in percent form, viz:

$$RH = 100 \times \frac{e_a}{e_s(T_a)}. \tag{2}$$

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Anderson (1936) points out that RH is not an absolute measure but merely a ratio of two known quantities expressed as a percentage. In contrast VPD gives an absolute measure of the atmospheric moisture state independent of temperature. For example, the same VPD above a surface that is not water-limited and for a given wind speed and atmospheric stability, leads to the same rate of evaporation, regardless of temperature. Expressing RH and VPD in terms of each other we get:

$$RH = 100(1 - VPD/e_s(T_a)), \tag{3}$$

$$VPD = e_s(T_a)(1 - RH/100). \tag{4}$$

In these relations we see the basic problem with RH. For any given RH the VPD varies exponentially because of the Clausius-Clapeyron dependency of $e_s(T_a)$ on T_a. That is, at very low temperatures a given RH will correspond to a very small VPD while at high temperatures the same RH will correspond to a very high VPD. Similarly a given VPD will correspond to a much higher RH at high temperatures than at lower temperatures. The point of Anderson (1936) was that the water balance stress placed upon an organism is determined by the VPD and not the RH. Despite his arguments VPD has not exactly caught on. The daily weather forecasts still routinely report RH but never VPD and meteorologists and the public alike are far more familiar with RH reports, often mentally factoring in the temperature dependence when considering the implications.

Despite the lack of popularity of VPD it deserves a new lease on life. In two recent papers Williams et al. (2014b,a) show that VPD is the meteorological variable that best correlates with burned area for forest fires in the U.S. southwest over past decades. Forest fire is an every year concern in the southwest U.S. Though fire is a naturally occurring phenomenon to which forest ecosystems, including fauna and flora, are adjusted and, in some cases, even dependent upon, it poses considerable problems for society. First is of course the protection of life which has become ever more difficult as the population of the southwest has expanded and more and more people are living at the 'urban-forest interface' (Pyne 2009). After this, damage to property is a concern. Further, and quite fundamentally, the lands of western North America are now all, to a greater or lesser extent, managed by people and, very often, even if indirectly, by the Federal government. Dealing with fire is one of the key problems of land management; how to manage a process that is at the same time natural and essential and tremendously damaging? Now that western forests are experiencing drought and heat stress combined with outbreaks of bark beetles and unprecedented areas of burns, stresses that are expected to only get worse as human-induced climate change advances (Allen et al. 2010; Bentz et al. 2010; Williams et al. 2013), fire-management is ever more important (Stephens et al. 2013). Hence it is imperative to better understand the processes that control fire.

Many prior studies have sought relationships between climate and wildfire (e.g. Westerling et al. (2003, 2006); Westerling and Bryant (2008); Littell et al. (2009); Abatzoglou and Kolden (2013); Riley et al. (2013)). In regard to links between climate and forest fire incidence VPD explains more variance than precipitation, various drought indices and temperature individually can (Williams et al. 2014b; Sedano and Randerson 2014)). This is of course a confirmation of Anderson (1936)'s plea for the ecological relevance of VPD. It is not surprising that VPD is more successful in explaining burned forest fire area than other variables are. It is essentially a measure of the ability of the atmosphere to extract moisture from the surface vegetation thus reflecting variations in the moisture content and flammability of forests. It is more explanatory in this regard than RH because it accounts for the fact that it is the combination of low RH and high temperature that creates the most fire-prone conditions. VPD is also more explanatory than temperature (e.g. Westerling et al. (2006)) since it reflects the nonlinear dependence of e_s on temperature and also measures the actual moisture content of the air, with the combination of high e_s and low e_a creating the most fire prone conditions. Of course VPD only indirectly measure the antecedent soil moisture conditions which also influence the current moisture content of vegetation. Hence it might be expected that preceding precipitation, or an index of current drought severity (such as Palmer Drought Severity Index that factors in prior precipitation and estimates of evapotranspiration), would offer additional explanatory power over VPD alone. Consistently, Williams et al. (2014b,a) found a combination of current VPD and prior year precipitation offered the best explanation of burned forest area.

Given the demonstrated importance of VPD to at least one topic of great ecological and social importance, it seems worthwhile to explore better the basic spatial and temporal variations of VPD across North America in terms of seasonal cycle, geographic variation, interannual variability and long term trends. To our knowledge no such study has been conducted. Gaffen and Ross (1999) did conduct a study of climatology and trends of specific and relative humidity across the U.S. Their maps of daytime RH show, in winter, high values along the west coast and in the southeast and low values in the northeast and, in summer, a striking west-east lower-higher contrast. Interesting though these maps are, it is almost automatic to ask what controls these temporal and spatial distributions - temperature, specific humidity or both? - and how do they relate to the difference between actual and saturation water vapor content?

The current study is motivated both by the desire to develop a better understanding of the controls on moisture undersaturation in the atmosphere and also the need to improve understanding of the outbreak and spread of forest fires. As such, after providing a cross-U.S. analysis of the climatology and variability of VPD we will examine the atmosphere-ocean-land causes of VPD variability in the southwest, as well as the long terms trends in VPD. We will also provide a case study of the VPD anomalies, and their causes, leading up to June 2002 when two major southwest fires (the Rodeo-Chedeski and Hayman fires) occurred.

2. Data and Methods

High quality, spatially and temporally extensive humidity data are hard to come by in general. Here we use the PRISM data set developed by the PRISM Climate Group at Oregon State University, details of which can be found at `http://www.prism.oregonstate.edu` and in Daly et al. (2000), and which was obtained from the International Research Institute for Climate and Society as `http://iridl.ldeo.columbia.edu/SOURCES/.OSU/.PRISM/`. Because of data availability we limit ourselves to the 1961 to 2012 period (see Williams et al. (2014b,a) for this rationale). The PRISM data provides monthly means of maximum (T_{max}) and minimum (T_{min}) daily temperature and dew point temperature (T_d). The mean monthly air temperature is approximated as $T_a = (T_{max} + T_{min})/2$ and $e_s(T_a)$ and e_a are calculated from:

$$e_s(T_a) = e_{s0} exp\left[17.67(T_a - T_0)/(T_a - T_0 + 243.5)\right], \tag{5}$$

$$e_a = e_{s0} exp\left[17.67(T_d - T_0)/(T_d - T_0 + 243.5)\right], \tag{6}$$

where T_a and T_d are in Kelvin and $T_0 = 273.15K$. We are aware that because of the nonlinear dependence of e_s on T_a any averaging of temperatures in space and time introduces errors in the sense of underestimating e_s. Williams et al. (2014b,a) in their study of the southwest U.S. did account for this by using some statistical relationships between daily and monthly temperature data. Here we do not do this and instead simply compute e_s from averaged temperature. It is considered, after evaluation, that the approximation introduces an acceptable degree of error. For geopotential heights and vertical velocities we use the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) Renalysis (Kalnay et al. 1996; Kistler et al. 2001). The NCEP-NCAR Reanalysis was chosen as the only Reanalysis that assimilates all available information that extends back before 1979 and hence overlaps the PRISM precipitation data. For surface sensible and latent heat fluxes, used to compute Bowen ratio, we used data from the Global Land Data Assimilation System (GLDAS) 2.0 available at `http://disc.sci.gsfc.nasa.gov/gesNews/gldas_2_data_release`. GLDAS uses a land surface model forced by observed meteorological conditions to estimate the land surface hydrology and surface fluxes of water and energy (Rodell et al. 2004; Sheffield and Wood 2006). All analyses cover the 1961 to 2012 period and anomalies, when used, are with respect to a climatology over this period.

3. Climatology of vapor pressure deficit across the U.S.

Figure 1 shows the VPD, e_s and e_a for the four seasons of October to December (OND), January to March (JFM), April to June (AMJ) and July to September (JAS), which correspond to the hydrological year and which we shall refer to as fall, spring, summer and fall. The VPD is lowest in the winter season, that is, the air is closest to saturation at this time. This is partially caused by the low e_s, following on the coldest temperatures of the year, which places an upper bound on how large VPD can be. A vast area of western North America and northern central and eastern North America has e_s below 5mb in the winter. The VPD pattern is largely zonal in winter because the warmer west coast areas with higher e_s are also areas of higher e_a. The coastal eastern regions have less of a maritime climate and a more continental climate because of the prevailing westerlies and VPD, e_s and e_a here are contiguous with the interior U.S. to the west.

By spring the VPD has climbed above 5mb across most of the U.S. except for parts of the northwest, some areas south of the Great Lakes and northern Maine. What is striking is the area of $20-30mb$ VPD in the interior southwest U.S. This is driven by a sharp rise in e_s. However, e_s rises by just as much across the southern central and southeast U.S.. However, in these regions this does not translate into a similar rise in VPD because e_a also rises to keep track while it does not in the interior southwest. These differences are, in turn, related to the development of the Atlantic subtropical high and moisture convergence in southerly flow over the southern U.S. (e.g. Seager et al. (2003b)) whereas moisture flow into the interior southwest awaits the reach of the North American Monsoon (Adams and Comrie 1997). The switch from winter with northerly flow to spring with southerly flow, associated with development of the Atlantic subtropical high, is evident in the rise of e_a across the U.S. from the Plains to the Atlantic coast.

In going from spring to summer VPD increases modestly over the eastern U.S., especially in the northern region but climbs strongly in the southwest. The highest monthly mean values that ever occur in the U.S. (close to 50mb) occur in summer in southeastern California, southern Nevada and southwestern Arizona. This is related to high temperatures driving high e_s and outstripping the increase in e_a. Texas is the other region of widespread high VPD which arises from very high e_s and relatively low e_a away from the Gulf coast. High e_a across the remainder of the southern U.S. and the southeast balances high e_s and keeps VPD relatively low. The northwest, north central and northeastern U.S. have their maximum VPD in summer as e_a fails to keep up with the highest values of e_s driven by the warmest temperatures of the year. In fall all quantities are well on their way, after summer, to re-establishing their winter states.

4. Interannual variability of VPD across the U.S.

While the climatology of VPD is interesting, ecosystems are presumably largely evolved to deal with this. They will also be able to adapt, to some extent, to year-to-year variability. However extreme high VPD years are expected to exert considerable water stress on vegetation risking disease, fire and mortality. Hence we next turn to examine the variability of VPD and its causes over the post 1961 period. To do this we computed the variance of VPD, e_s and e_a for each month and then averaged these monthly variances to form seasonal mean variances which are shown in Figure 2.

In no season is the VPD variance simply proportional to the VPD climatology. In the fall and winter the VPD variance has a southwest maximum, northeast minimum pattern with lines of equal variance oriented in a roughly northwest to southeast manner. This is in contrast to the more zonal pattern of the VPD climatology. This VPD variance pattern is quite distinct from that of the e_s and e_a variances which are maximum over the southeastern U.S. Since these do not translate into a VPD variance maximum it must be because they vary together, i.e. $e_s' \approx e_a', (e_s - e_a)' \approx 0$. One reason for this is that in these seasons transient eddies dominate the moisture convergence into the southeastern and eastern U.S (Seager et al. 2014b). The eddies act to diffuse temperature and moisture such that, in southerly flow they will both warm, increasing e_s, and moisten, increasing e_a, and vice versa for northerly flow, minimizing the change in VPD. In contrast, in the southwest the e_s variance is large and must not be compensated for by e_a variance. These comparisons make clear that, in general, the VPD variance can not be explained as being purely temperature driven with, for example, e_s varying and the VPD variations simple related to this according to fixed RH.

In the spring the southwest region of climatological high VPD is also a region of high VPD variance and this seems driven by high e_s variance, i.e. by temperature variance, while the e_a variance is quite low. There is also a central U.S. maximum of VPD variance that stretches from Texas north to Canada which arises from a maximum of e_s, i.e. temperature, variance. In the summer many of the features of VPD and e_s variances seen in spring remain but are amplified. Maximum VPD variance occurs in the Mojave, Sonora and Chihuahua Desert portions of the southwest U.S. These are all regions of high e_s variance. In summer an e_a variance maximum develops in southeast California and southwest Arizona which is likely due to variance of moisture convergence in the North American Monsoon.

The regions of low spring and summer e_s variance in the interior west, which translate into lower VPD variance are related to high topography where the climatological e_s and e_a are lower than in lower-lying surrounding areas (Figure 1). This can be understood as follows. The e_s variance for a given month is given by:

$$\sigma_{e_s} = \frac{1}{N}\sum_{n=1}^{N} e'^2_{s,n}, \tag{7}$$

where n indicates year and N is the total number of years. e'_s can be linearized as:

$$e'_s \approx \frac{de_s}{dT}\Big|_{\overline{T_a}} T'_a, \tag{8}$$

that is, the gradient of e_s with respect to T evaluated at the climatological mean air temperature, $\overline{T_a}$, multiplied by the air temperature anomaly, T'_a. Substituting Eq. 8 into Eq. 7 we get:

$$\sigma_{e_s} = \frac{1}{N}\sum_{n=1}^{N}\left(\frac{de_s}{dT}\Big|_{\overline{T_a}} T'_a\right)^2. \tag{9}$$

Since de_s/dT increases with T, the same temperature variance will give lower e_s variance at lower climatological mean temperatures. When e_s variance is estimated with Eq. 9 (not shown) it is clear that this effect, in combination with lower temperature variance at colder temperatures, explains the low e_s and VPD variance at higher elevations in western North America.

The clear and expected increase of variance of vapor pressure quantities with the mean values suggest that normalized variance may be a more informative measure. Hence Figure 3 shows the variances normalized by their climatological values and expressed as a fraction. In this case large values show that the variance is unusually large in comparison to its climatological value while small values show the opposite. The southwest desert maximum of VPD variance does not appear in the maps of normalized variance. Instead the normalized variance of VPD emphasizes the southern Plains in spring, the entire Plains in summer and many southwestern areas in California, Arizona, New Mexico, Colorado and Utah. Also some areas of relatively low absolute VPD variance in the Pacific northwest states appear as high areas of relative variance. The normalized variances of e_a are also different to those of absolute e_a. While the latter track the climatological e_a, the former shows the southwest areas of high VPD variances to be ones of high e_a variance. Looked at in this way, it appears that high VPD variance in regions of the southwest does not just arise from high temperature, e_s, and e_s variance but also from relatively high e_a variance. This is suggestive of a potential role for driving of atmospheric humidity variability by locally strong atmospheric circulation variability, that is, a role for atmospheric dynamics as well as thermodynamics.

Figure 4 shows all areas that have burned across the western U.S. from 1984 to 2011 based on the Monitoring Trends in Burn Severity data (`www.mtbs.gov`, Eidenshink et al. (2007)). This can be qualitatively be compared with the climatology and variance figures above. Clearly the area in the deep southwest at the California-Arizona border that has high climatological and absolute (but not normalized) variance of VPD is not an area of frequent and widespread burns which is probably because of the lack of fuel. Burns are common and widespread in a swath of land across southern and central Arizona and New Mexico, western Texas, Oklahoma and eastern Kansas, extend north through the Plains, Nebraska and Montana linking to an area of widespread burns in Idaho, eastern Washington and Oregon and northern Nevada. Other areas of widespread burns are the coastal and Sierra Nevada ranges of California. This bears some similarity to the maps of spring and summer normalized VPD variance. A perfect match would not be expected given the control that fuel availability, for example, and other factors will exert on burned area (Swetnam and Betancourt 1998; Westerling et al. 2002, 2003; Littell et al. 2009; Abatzoglou and Kolden 2013). So, for example, the tremendous maximum of variance in Texas and the southern to central Plains does not translate into a similarly impressive maximum in burned area. That may be because this is an area of grasslands rather than forest but, nonetheless, this is a local maximum of burned area. Similarly the general donut of burn areas in the Plains, northern states, California and the southwest, ringing a burn area donut hole in the interior west, is also seen in VPD variance. Much of this donut hole is very high altitude with low climatological and variance of temperature or high desert with little vegetation to burn. Another notable feature is that, despite the relatively low climatology and variance of VPD in the northwestern states, the relatively high normalized VPD variance matches the high burned area in this region. The exception is the coastal northwest where low burned area corresponds to low normalized VPD variance. All these relations make clear the importance to fire incidence and spread of VPD and how its variance compares to the mean conditions. Areas with lower mean VPD but relatively high variance seem to be able to have greater burned area than those with higher VPD and relatively lower variance.

5. Relationship of VPD variability in the southwest U.S. to SST and circulation variability

As shown in Williams et al. (2014b,a), interannual VPD variability is the best predictor of burned forest area in the southwest U.S. The analysis above has shown that VPD variability is largest in the southwest U.S. at the California-Arizona border. However this is a very arid region, with high climatological VPD, and not one with extensive fire occurrence due to the absence of extensive vegetation. Fire occurrence is more common in regions of lower climatological VPD that are less arid and can sustain vegetation that is nonetheless susceptible to burning. We have already shown that VPD variability is large in these intermediate aridity regions in the spring and summer seasons critical for fires and that this is influenced strongly by e_s variability but also by e_a variability. But what controls VPD, e_s and e_a variability?

To look at this we examine relations between VPD, e_s and e_a and atmospheric circulation, as measured by the 700mb geopotential height, and sea surface temperature (SST) variability. We focus in on the region of high fire occurence identified by Williams et al. (2014b,a). This southwest area lies to the east of the region of very high VPD climatology and variance at the California-Arizona border and includes the parts of Arizona, New Mexico, Texas, Oklahoma, Colorado and Utah bounded by $28.5°N$ and $38°N$ and to the west of $100°W$. The 700mb level is chosen since this more closely corresponds to the level in the atmosphere where significant moisture transport occurs. Results are shown in Figure 5. In fall, winter and spring high VPD in the southwest correlates with local high pressure. In fall this is part of a zonal wave pattern and in winter and spring it is part of a general mid-latitude ridge that extends across the Pacific, North America and the Atlantic. High VPD is also correlated with cool tropical Pacific SSTs in winter and spring and, to a lesser extent, in fall. The circulation patterns are what is expected given the La Niña SST pattern (Seager et al. 2003a, 2005, 2014a). These relations make clear that high VPD in the southwest is promoted by La Niña conditions. This relation breaks down in the summer which is expected given the general weakness of tropical-mid-latitude teleconnections in the summer (Kumar and Hoerling 1998).

High e_s is also correlated with high geopotential heights and La Niña SST conditions and the patterns of each are quite similar to those for the VPD correlations. This indicates that high VPD anomalies are being driven, in large part, by an increase in temperature causing high e_s. The correlations with e_a are opposite in fall and winter: that is, low e_a, which would contribute to high VPD, also arises from La Niña conditions. The La Niña connection to low e_a is also clear in the spring though the associated height anomaly pattern is different to that for the VPD and e_s correlations. The summer e_a correlation, as expected, does not have a feature in the tropical Pacific and the circulation anomaly indicates high e_a corresponding to low pressure off Baja California and high pressure over the Rocky Mountains.

These relations are fairly easy to explain. During La Niña conditions in the fall, winter and spring high pressure develops over the southwest which favors subsidence beneath causing both high temperatures and high e_s, via warming due to compression, and low e_a due to the subsidence of dry air. Both effects drive the VPD to be high. In summer, when the connection to the tropical oceans is weak, high VPD and e_s in the southwest are still favored by local high pressure (and, presumably, subsidence warming) while low e_a appears to be favored by flow anomalies from the north and west, which makes sense since the moisture sources for the southwest lie to the south over the Gulfs of California and Mexico.

6. Relationship of variability of VPD to land surface conditions

While atmospheric circulation anomalies are expected to be able to influence VPD instantaneously via subsidence of warm, dry air, it is also expected that previous reductions in precipitation could dry out the soil and lead to an increase in VPD. As the soil dries out incoming solar radiation needs to be increasingly balanced by sensible and long wave radiative heat loss, and less by evapotranspiration, and this requires an increase in surface temperature at the same time as less moisture flux from the surface to the atmosphere, both effects increasing VPD. One measure of soil dryness is the Bowen ration, $B = SH/LH$, where SH is surface sensible heat flux and LH is surface latent heat flux.

The previous section showed that VPD increases as atmospheric circulation anomalies cause warming and/or drying. In the absence of a surface moisture anomaly, subsidence warming and drying would be expected to increase LH and reduce SH, surface flux changes that would offset the circulation-induced changes in VPD. This would cause a reduction in the Bowen ratio to accompany the increase in VPD.

Figure 6 shows the correlation across North America between seasonal VPD and Bowen ratio. In the southwest and coastal western North America, the Bowen ratio increases with VPD throughout the year. There are negative correlations across the central northern U.S. in fall and most of the central and eastern U.S. in spring. The strongest positive correlations are in the interior West and the Gulf Coast in summer.

The cause of these correlations can be understood in terms of the correlation of Bowen ratio with e_s and e_a also shown in Figure 6. The correlation between Bowen ratio and e_a is simple and essentially always negative (except for Pennsylvania, New York and New England in summer). That is as latent heat flux goes up, and Bowen ratio drops, the atmospheric water vapor rises. This suggests the atmospheric vapor pressure responding to changes in evapotranspiration. The relation of Bowen ratio with e_s is more spatially variable. In the central and southern parts of the West Bowen ratio tends to rise as temperature rises while in the central to eastern U.S. and the northwest the Bowen ratio tends to decrease as temperature rises. In winter across most of the U.S. the Bowen ratio tends to decrease as e_s, i.e. temperature, rises.

Away from the southwest, the winter relations between Bowen ratio and e_s and e_a can be understood in terms of atmospheric driving. During this season of low evapotranspiration and high surface moisture availability, a warm anomaly (of whatever origin) will cause an increase in e_s, an increase in latent heat flux, a drop in the Bowen ratio, and an increase in e_a. The east-west correlation contrast in summer probably reflects the east-west high-low precipitation/dryness contrast. That is, the eastern half receives considerable precipitation in summer and generally has ample surface moisture supply while the west receives little summer precipitation and the surface dries in summer. As such, warm temperature anomalies can drive higher latent heat flux and lower Bowen ratio during summer in the eastern half of the country. In contrast, across the west throughout the year, moisture is in shorter supply and drying (due for example to a precipitation reduction) can cause a reduction in latent heat flux and both an increase in Bowen ration and warming as sensible and long wave heat flux rise to balance incoming solar radiation while latent heat flux is reducing. The Bowen ratio-temperature and e_s correlations are, therefore, driven by the atmosphere in the east and by the land surface in the west.

The correlation between VPD and Bowen ratio combines the influences of the correlations of Bowen ratio with e_s and e_a. Over the west, in winter, an increase in latent heat flux drives a drop in Bowen ratio, an increase in e_a and drop in VPD. Further east in winter the Bowen ratio and VPD are less correlated while in spring there are areas around the Ohio River valley of negative correlation. This can be explained if a warm anomaly increases latent heat flux and decreases the Bowen ratio and at the same time causes e_s to rise by more than e_a

thus increasing the VPD. In the summer, by contrast, VPD and Bowen ratio are positively correlated essentially everywhere but this is for different reasons in the central to eastern U.S. and the west because of the opposite sign correlations between e_s and Bowen ratio. In the moist central to eastern U.S., an increase in surface moisture (say, due to an increase in precipitation) can cause an increase in latent heat flux and a drop in Bowen ratio but an increase in e_a and a drop in VPD. The positive VPD- Bowen ratio relation is, however, much stronger in the dry west. Here a decrease in surface moisture (say, due to a decrease in precipitation) causes a decrease in latent heat flux and an increase in Bowen ratio but also an increase in surface temperature and e_s (as less of the incoming solar is balanced by latent heat flux) and a decrease in e_a and, hence, an increase in VPD.

Hence it might be expected that VPD will rise following a period of reduced precipitation that dries the surface. In contrast changes in atmospheric circulation that cause warming and/or drying of surface air will near instantaneously cause an increase in VPD. Thus the land surface and atmospheric circulation mechanisms of altering VPD can work on different timescales with the former offering potentially longer term predictability.

7. Relation of Southwest and Colorado region VPD to the combined effects of land surface and atmospheric conditions

To illustrate the effects of land surface and atmospheric conditions we conducted a multiple linear regression of VPD, Bowen ratio and 700mb geopotential height all averaged over the Southwest box and a Colorado box $(109° - 101°W, 37° - 41°N)$. The Colorado region was chosen as it encompasses the area of the 2002 Hayman fire discussed below. First we used linear regression to determine the relation between VPD and Bowen ratio, B, as follows:

$$VPD(t) = VPD_B(t) + \epsilon(t) = aB(t) + c + \epsilon(t) \qquad (10)$$

where $VPD_B(t)$ is the VPD reconstructed on the basis of B alone and ϵ is the unexplained residual. We then performed a multiple regression between VPD, B and the 700mb geopotential height H, as follows:

$$VPD(t) = VPD_{BH}(t) + \epsilon'(t) = a'B(t) + b'H(t) + c' + \epsilon'(t) \quad (11)$$

where $VPD_{BH}(t)$ is the VPD reconstructed on the basis of B and H, the values of a' and a and c' and c need not be the same and ϵ' is the residual unexplained by the multiple regression. The time series of AMJ seasonal means of VPD_B, VPD_{BH} and the actual AMJ VPD are shown in Figure 7 for the Southwest and Colorado area averages. The reconstructions of VPD based on Bowen ratio alone are not very accurate but the reconstructions based on Bowen ratio (the land surface influence that builds in prior precipitation) and geopotential height (the contemporary atmospheric circulation influence) are reasonably accurate. Bowen ratio and geopotential height together explain 70% and 59% of the variance of AMJ seasonal means of VPD in the southwest and Colorado regions, respectively. Not shown here, but the explained variances were only slightly weaker for summer JAS seasonal means. We are not proposing that such a simple model be used as a potential means for predicting VPD in early fire season but simply wish to better illustrate the land surface and atmosphere controls on VPD. It is quite likely that a more extensive search for predictor variables will lead to better relations than shown here.

8. Trends in VPD across the U.S.

Next we consider whether there are long term trends in VPD and its contributors. Trends are evaluated via a straightforward least squares regression of seasonal mean VPD, e_s and e_a for the 1961 to 2012 period and results are shown in Figure 8. Trends in e_s are overwhelmingly positive in all seasons, strong in the spring and summer and especially strong in the southwest. These reflect warming trends. In contrast the trends in actual vapor pressure, e_a, are not uniformly positive. e_a has been rising in the southeast in fall, in the south central U.S. in winter, across the whole eastern U.S. in spring and the whole eastern U.S. plus northern Plains in summer. However, e_a has actually been falling in the southwest in summer, as noted before by Isaac and van Wijngaarden (2012) using station data from 1948 to 2010. As a consequence of the rise in e_s and drop in e_a there has been a strong trend to increased VPD in the southwest in spring and summer. Elsewhere in the west in summer VPD has also increased due to the rise in e_s. In the northern Plains (and to a lesser extent across the north U.S.) VPD has actually decreased as e_a has risen but e_s (and hence temperature) has stayed steady. These trends in the West are consistent with identified trends in wildfires (Dennison et al. 2014).

9. Changes in VPD up to and during the June 2002 Hayman and Rodeo-Chediski fires

As mentioned in the Introduction, a main motivation of this paper is the previously demonstrated importance of VPD to the occurrence of forest fires in the western U.S. Two important fires of the past decade are the Rodeo-Chediski fire in Arizona and the Hayman fire in Colorado, both of which began in June 2002, in the heart of a major multiyear western drought (Seager 2007; Weiss et al. 2009; Cayan et al. 2010). The Rodeo-Chediski fire burned from June 18 to July 7 2002 and burned 189,095 hectares of ponderosa pine and mixed conifers in northern Arizona, worse than any previous recorded Arizona fire (Schoennagel et al. 2004). The Hayman fire was smaller and burned 55,915 hectares to the southwest of Denver beginning on June 9 2002 (Schoennagel et al. 2004) and remains the worst fire in recorded Colorado history. Further, based on dendroecological records Williams et al. (2013) found 2002 to be the most severe year for forest drought stress in the Southwest since at least 1000 C.E. These facts motivate the presentation here of meteorological conditions and VPD anomalies in the months preceding the June 2002 fires.

Figure 9 shows conditions during the previous winter, JFM 2002, in terms of standardized anomalies. Very high VPD was evident across the southwest in JFM 2002 with maximum values in Arizona but not widespread in Colorado. Precipitation was below climatological normal across almost all of western North America. The Bowen ratio was high in the interior southwest in Arizona, New Mexico and Colorado consistent with a drier than normal land surface. Subsidence was also widespread across western North America occurring within northwesterly flow. All of these prior winter conditions are conducive to elevating fire risk with both land surface and atmospheric drying being responsible. Figure 10 shows the same conditions for AMJ 2002. By spring high VPD anomalies had spread across the western U.S. centered on Arizona, New Mexico, Utah and Colorado, reaching three standard deviations in most locations. Precipitation was also below normal by two or more standard deviations across the western U.S. and the Bowen ratio was elevated by two or more standard deviations across the southwest. Unlike in the previous season, a southwesterly flow anomaly was associated with anomalous ascent. The precipitation, land surface conditions and VPD state remained conducive to elevated fire risk as in the previous season. These relations, within the context of two specific historic fires, support the idea of VPD exerting an influence on fire and also the influence of contemporary and prior atmosphere and land surface conditions on the VPD.

10. Conclusions

To our knowledge this is the first comprehensive study of vapor pressure deficit (VPD) which was recommended by Anderson (1936) as a more useful measure of the moisture state of the atmosphere than relative humidity (RH). Unlike RH, for which the same value can be associated with very different moisture conditions depending on the air temperature, VPD is an absolute measure of the moisture deficit of the atmosphere. Hence, VPD, is more closely related to the water stress on vegetation. Indeed, prior work has shown the relationship between VPD variability and burned forest area in the southwest U.S (Williams et al. 2014b). That relation is the prime motivation for this study since it makes clear that a better understanding of the climatology, variability and trends of VPD is needed.

- VPD follows a notable seasonal cycle with minimum values in the winter and maximum values in the summer. This is controlled by both the seasonal cycles of temperature and humidity. Because of the development of the subtropical anticyclones, which moisten the eastern U.S. and dry the western U.S., actual vapor pressure has a summer maximum in the southeast but remains low in the west. In contrast, saturation vapor pressure in summer maximizes in the interior southwest, southern and central Plains and the southeast. Combining these influences, VPD in summer is far greater in the west than in the east. VPD reaches its all-U.S. maximum in summer at the California-Arizona border but more general maxima extend across the southwest U.S.

- The variance of VPD has a minimum in fall and then strengthens into winter and then to spring and to summer. The southwest and the southern Plains stand out as maxima of variance in spring and summer. The VPD variance quite closely tracks the saturation vapor pressure variance but the southwest and the southern Plains are also regions of relatively strong variance of actual vapor pressure. Hence it appears that VPD variability can be influenced by both thermodynamic and dynamic processes.

- High VPD in the interior southwest U.S. is associated with La Niña conditions in the tropical Pacific Ocean in fall, winter and spring. This association works via ocean forcing of circulation anomalies that involve high pressure and northerly, subsiding flow over the southwest. Such flow warms, increasing saturation vapor pressure, and dries, decreasing actual vapor pressure, and, hence, causes VPD to increase. Summer VPD anomalies in the southwest are controlled by more local circulation anomalies that influence saturation vapor pressure.

- High VPD in spring and summer can also be caused by an increase in Bowen ratio, that is an increase in sensible heat flux relative to latent heat flux, although the causes of this are distinct in the eastern and western U.S. In the western U.S. low surface moisture, following a drop in precipitation for example, can cause an increase in Bowen ratio and VPD.

- A case study of conditions in advance of the June 2002 Rodeo-Chediski and Hayman fires in Arizona and Colorado, respectively, shows very high VPD that was caused by precipitation drops, an increase in Bowen ratio and anomalous subsidence in the preceding months. This reveals the complexity of meteorological processes that can increase drying of the land surface and vegetation and set the stage for serious fires.

- Since 1961 VPD has increased notably across the western U.S. with the strongest increases in the southwest. These trends have been primarily driven by warming that increases the saturation vapor pressure but have also been contributed to by a decrease in actual vapor pressure. Actual vapor pressure has increased elsewhere in the U.S. such that VPD has declined in the northern Plains and midwest.

This is the first comprehensive study of vapor pressure deficit since Anderson (1936) argued for its use instead of relative humidity as a measure of the moisture state of the atmosphere. As an absolute measure of the difference between actual and potential water vapor holding capacity of the atmosphere, VPD is a useful indicator of the ability of the atmosphere to extract moisture from the land surface and, hence, is of relevance in studies of the links between meteorological conditions and forest fires. Here we have sought to achieve a basic understanding of the climatology and variability of VPD across the United States and have explained these in terms of atmospheric and land surface conditions. Future work will investigate closely the links between fires and VPD variability and the surface and atmospheric conditions that control them.

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List of Figures

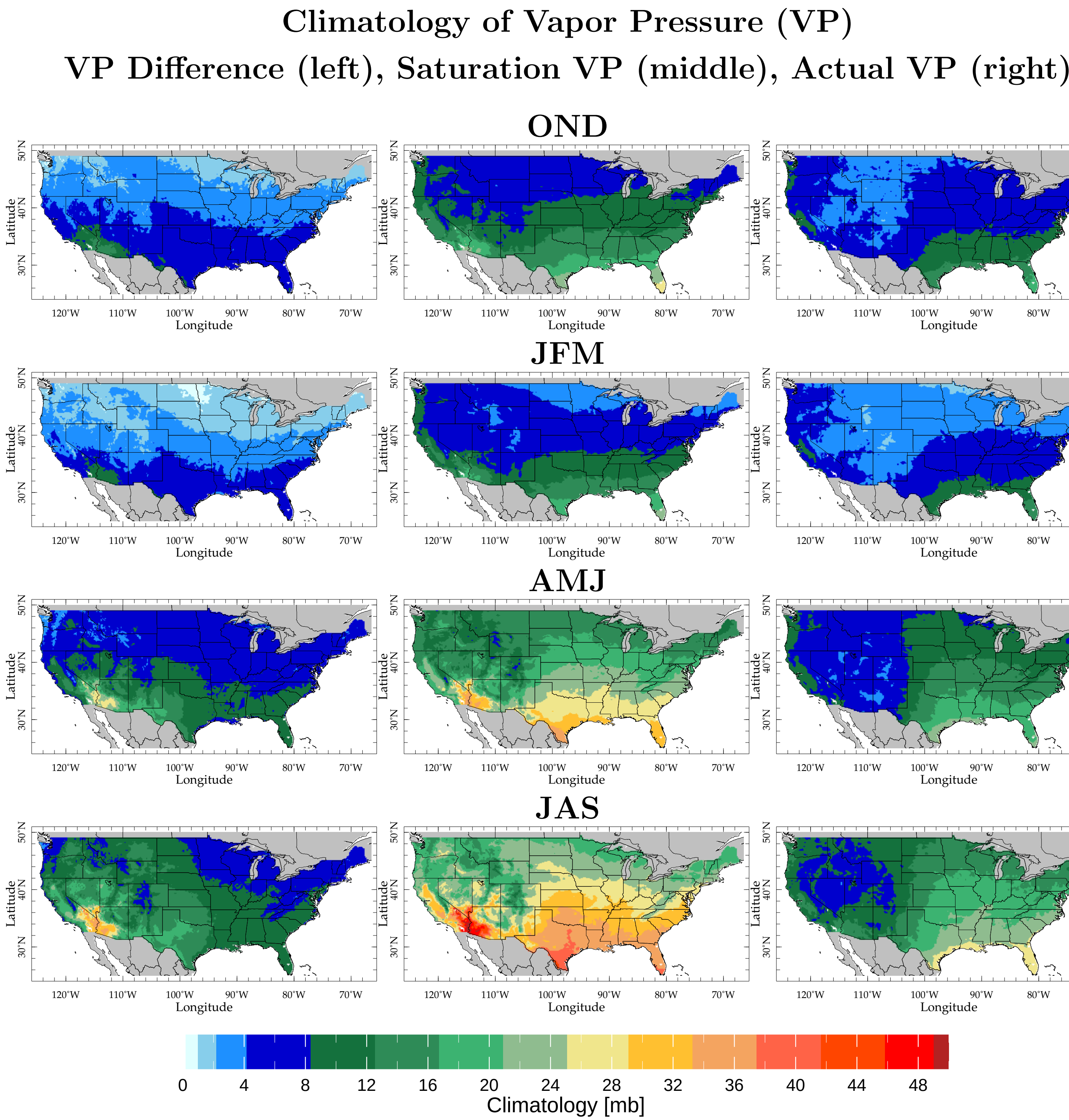

FIG. 1. The climatology of vapor pressure deficit VPD (left), saturation vapor pressure e_s (middle) and actual vapor pressure e_a (right) for the October to November (fall, top), December to February (winter, upper middle), March to May (spring, lower middle) and June to July (summer, bottom) seasons. Units are hPa (or mb).

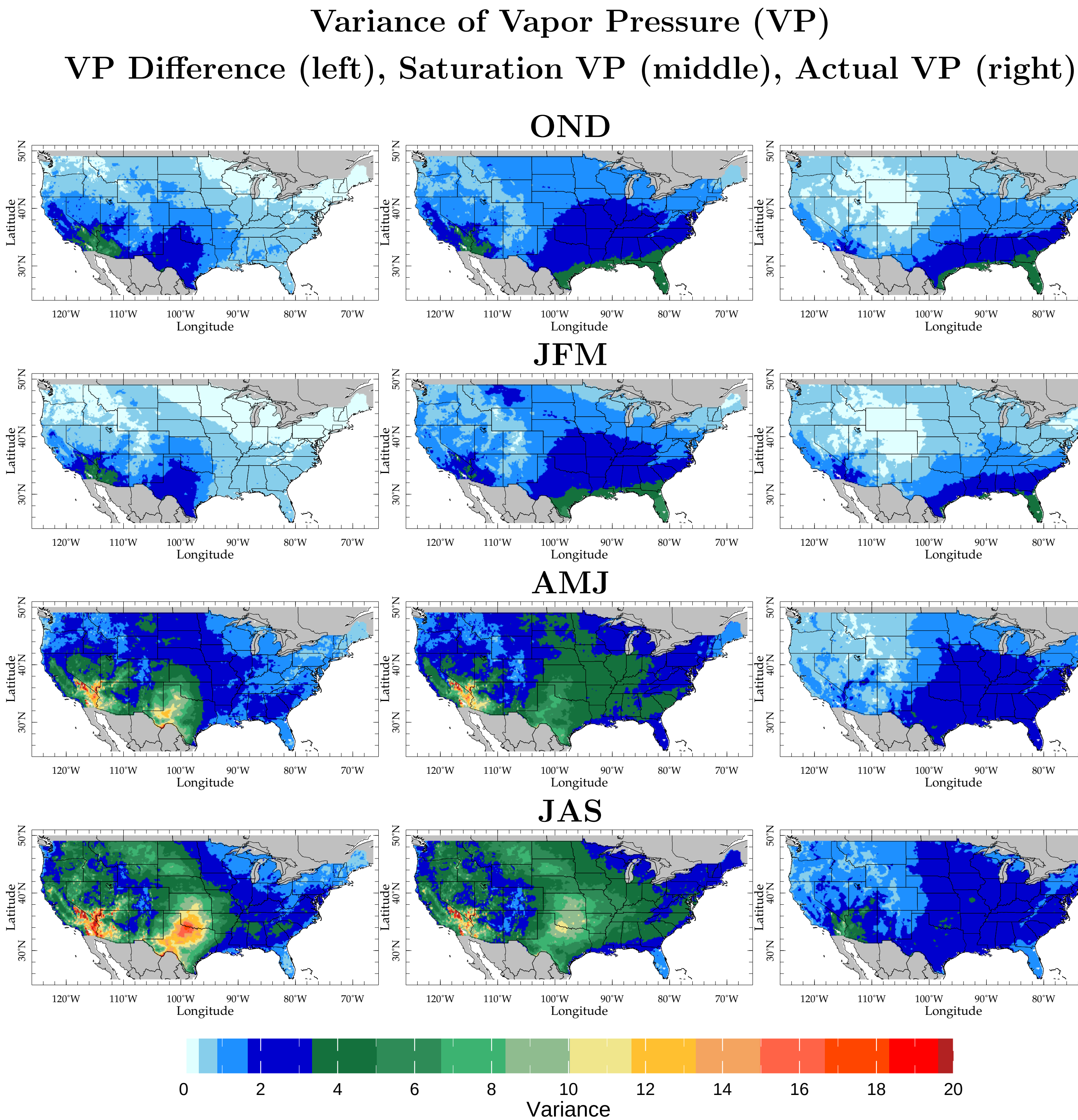

FIG. 2. Same as Figure 1 but for variances. Units are hPa squared.

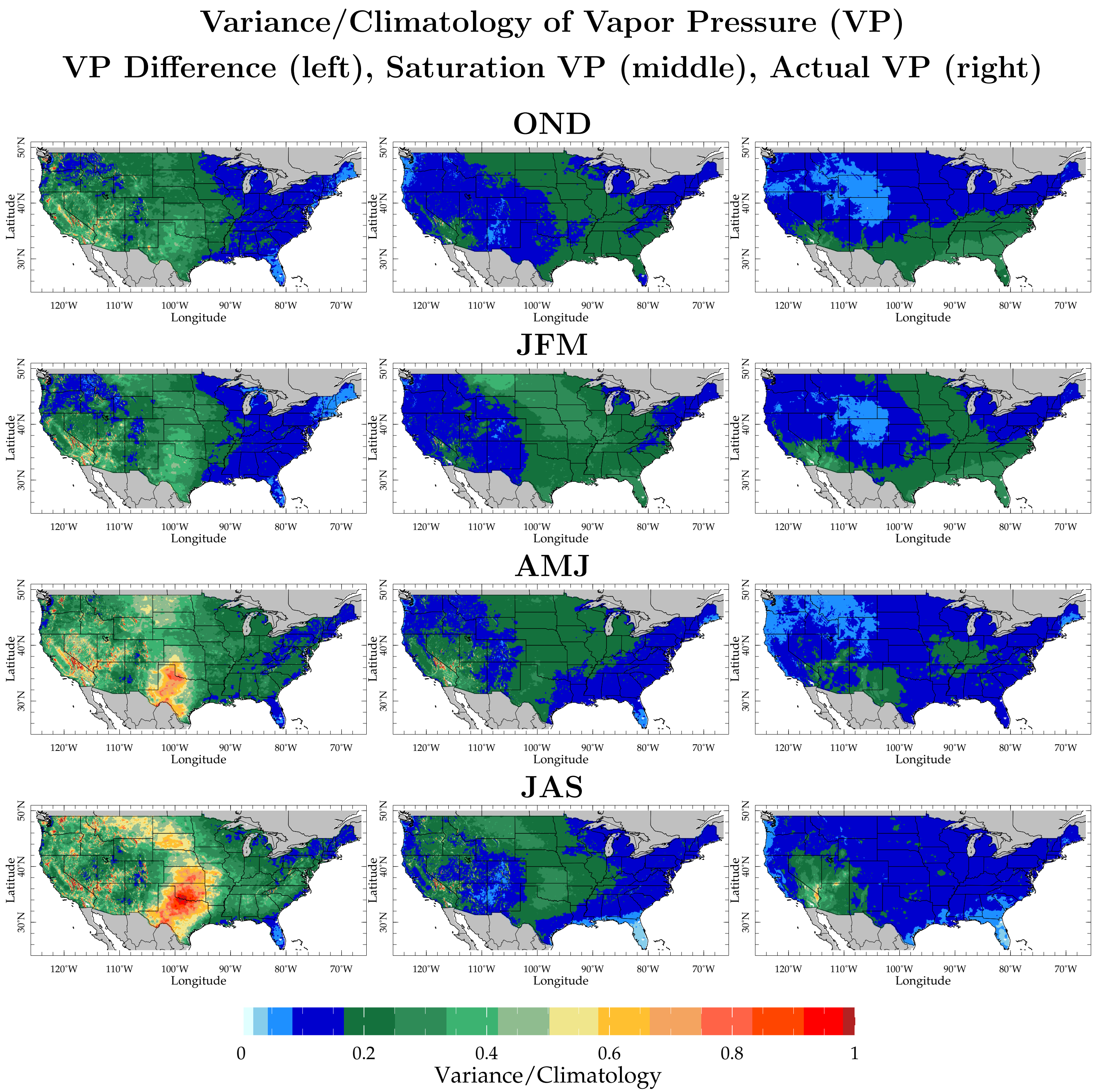

FIG. 3. Same as Figure 2 but with the variances divided by the climatological values.

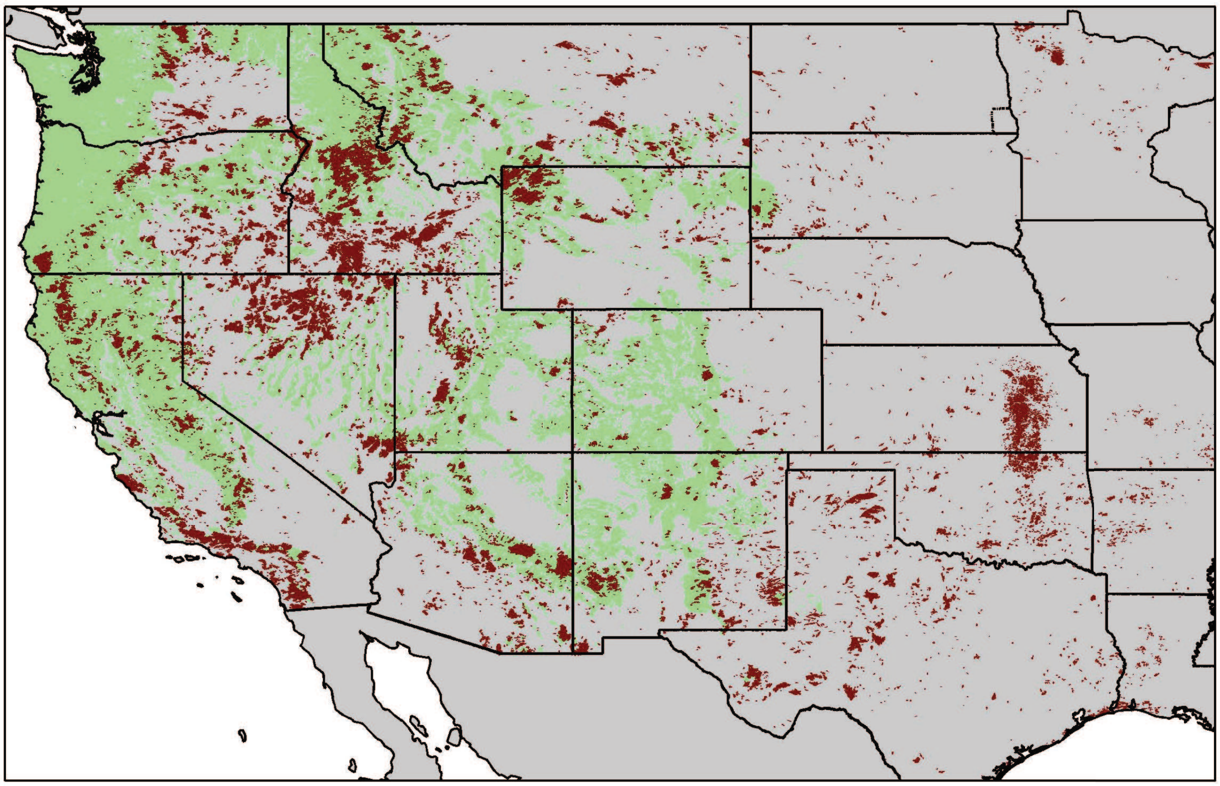

Fig. 4. Areas burned over 1984 to 2011 marked as brown on top of forest areas marked as green. Data from the Monitoring Trends in Burn Severity program.

Correlation of Vapor Pressure (VP) on SSTA (colors), 700 mb Heights (contours)

VP Difference (left), Saturation VP (middle), Actual VP (right)

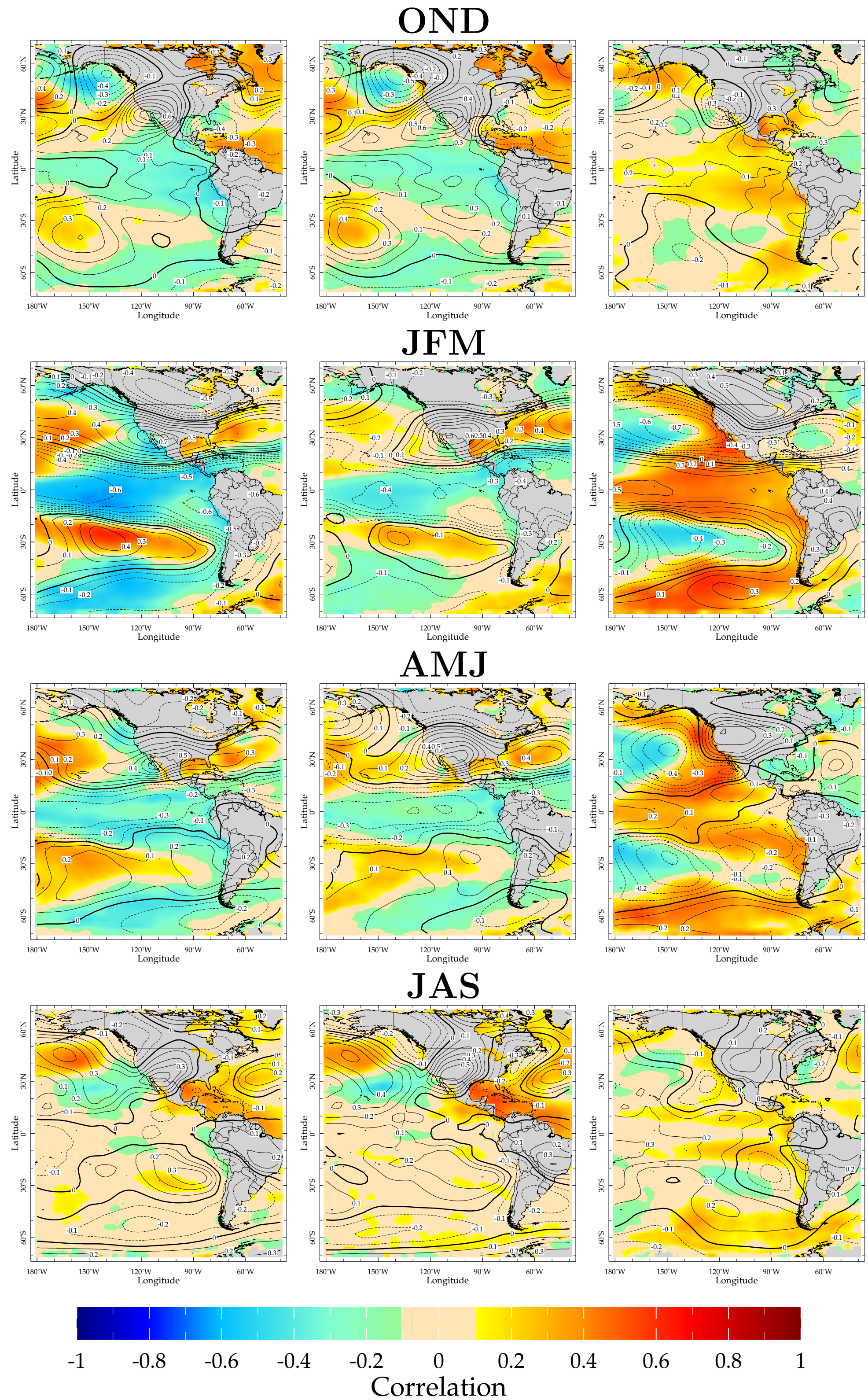

FIG. 5. The correlations between VPD (left), e_s (middle) and e_a (right) in the U.S. Southwest and 700hPa geopotential heights (contours) and SST (colors) anomalies for fall (top), winter (upper middle), spring (lower middle) and summer (bottom).

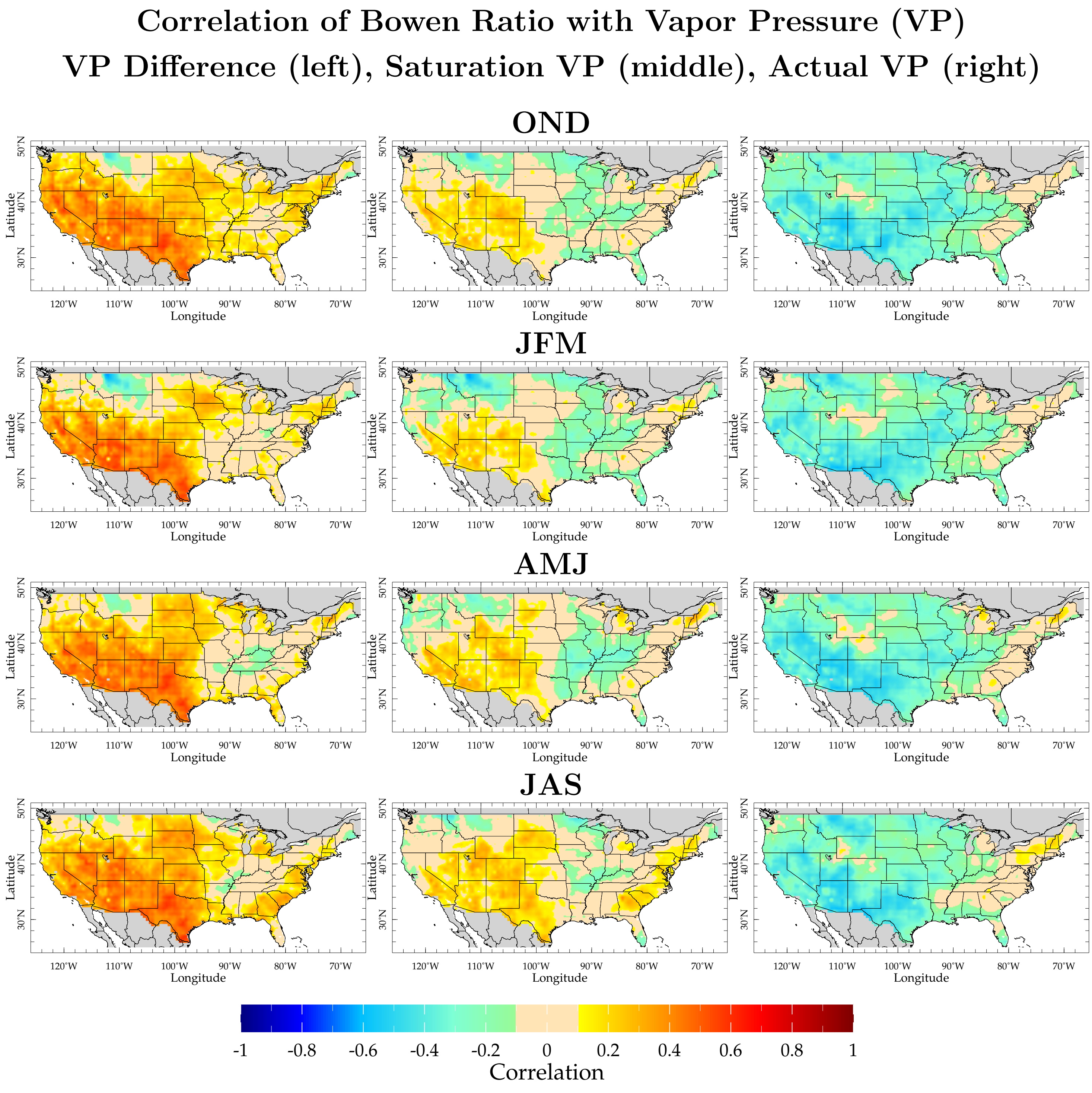

FIG. 6. The correlations between Bowen ration and VPD (left), e_s (middle) and e_a (right) for fall (top), winter (upper middle), spring (lower middle) and summer (bottom).

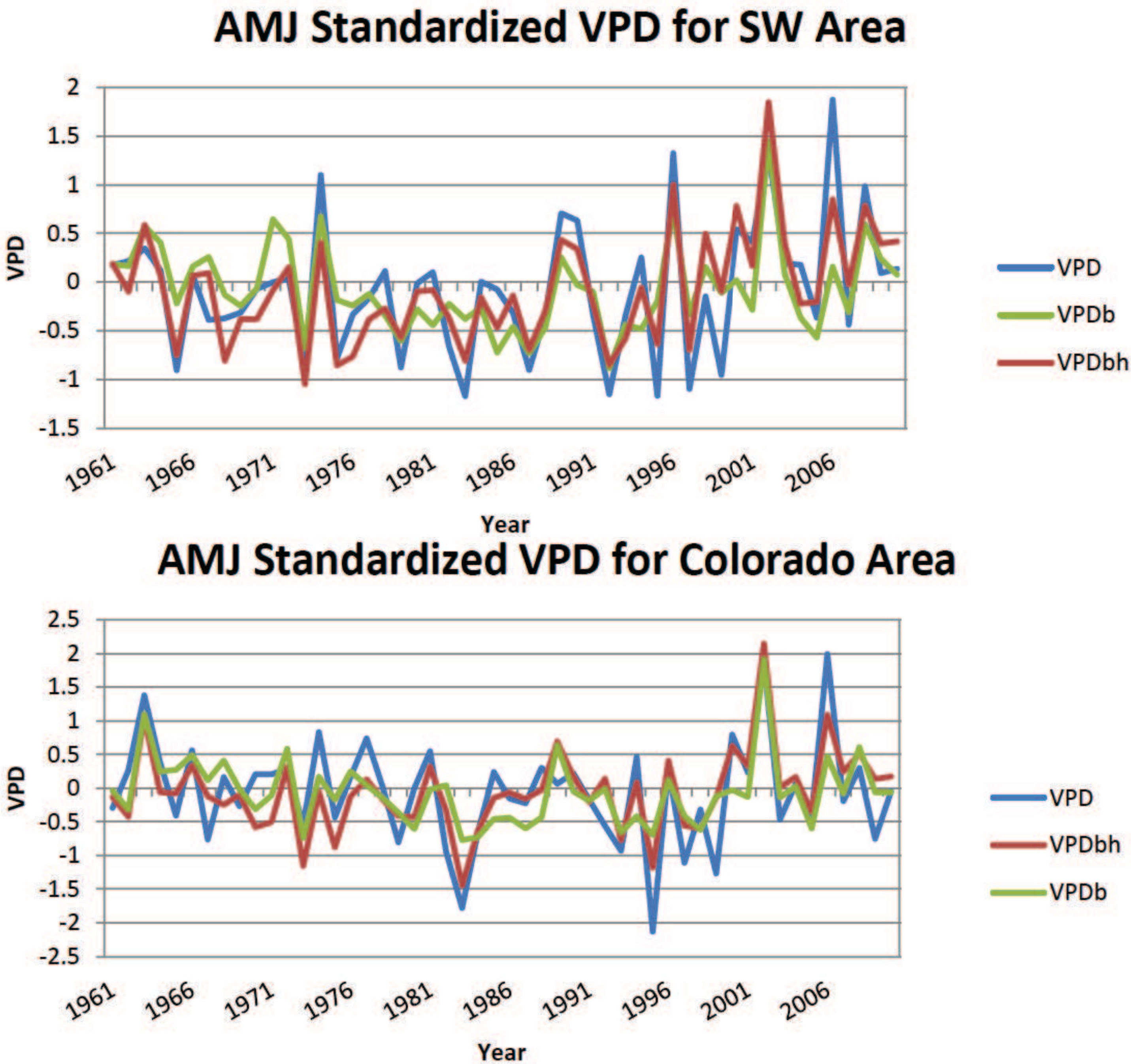

FIG. 7. The actual VPD for AMJ and its reconstruction via linear regression based on AMJ Bowen ratio alone (V_b) and both AMJ Bowen ratio and AMJ 700mb geopotential height (V_{bh}).

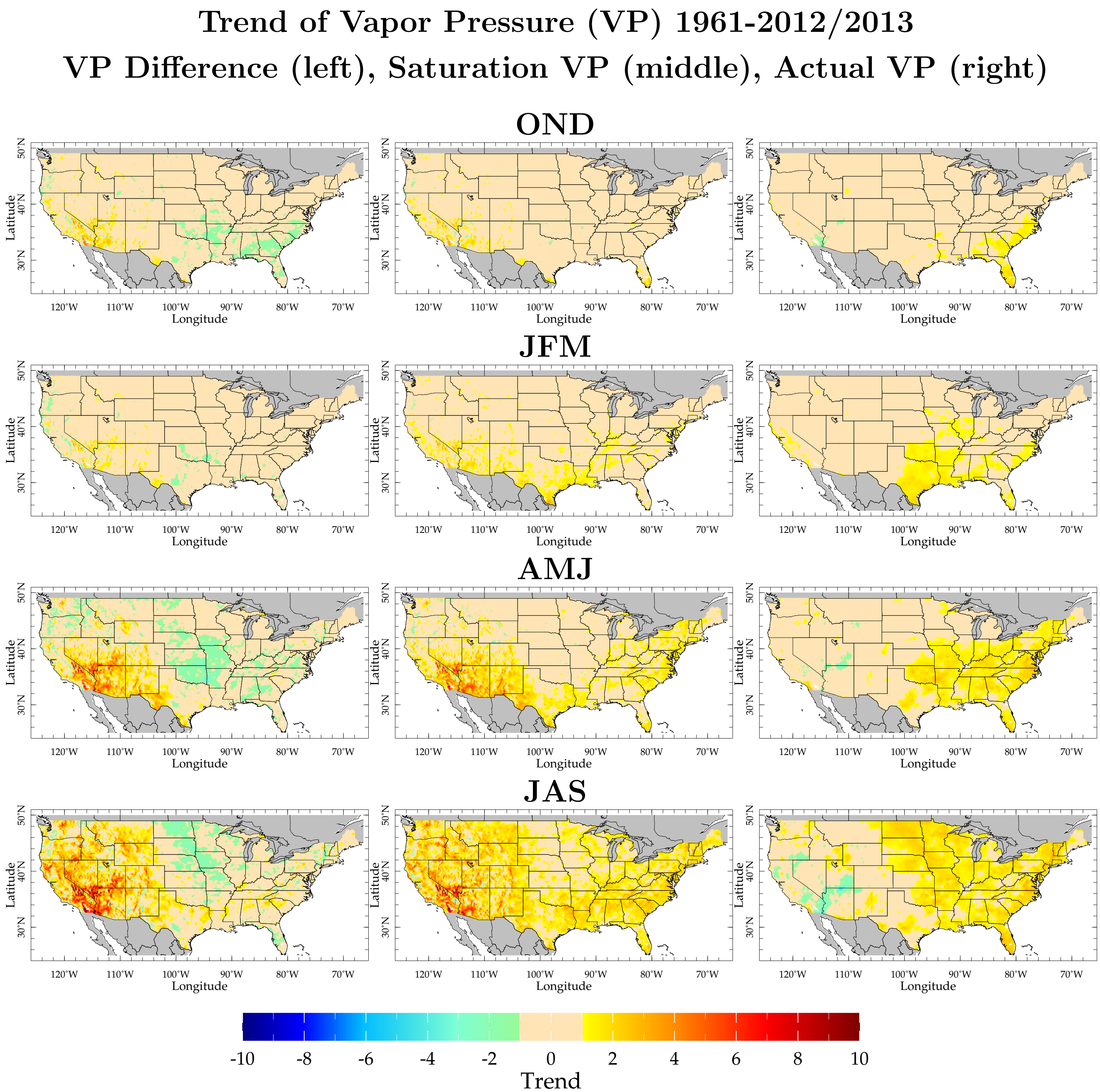

FIG. 8. Linear trends in VPD, e_s and e_a for 1960 to 2012 for fall (top), winter (upper middle), spring (lower middle) and summer (bottom). Units are hPa change over the 53 year period.

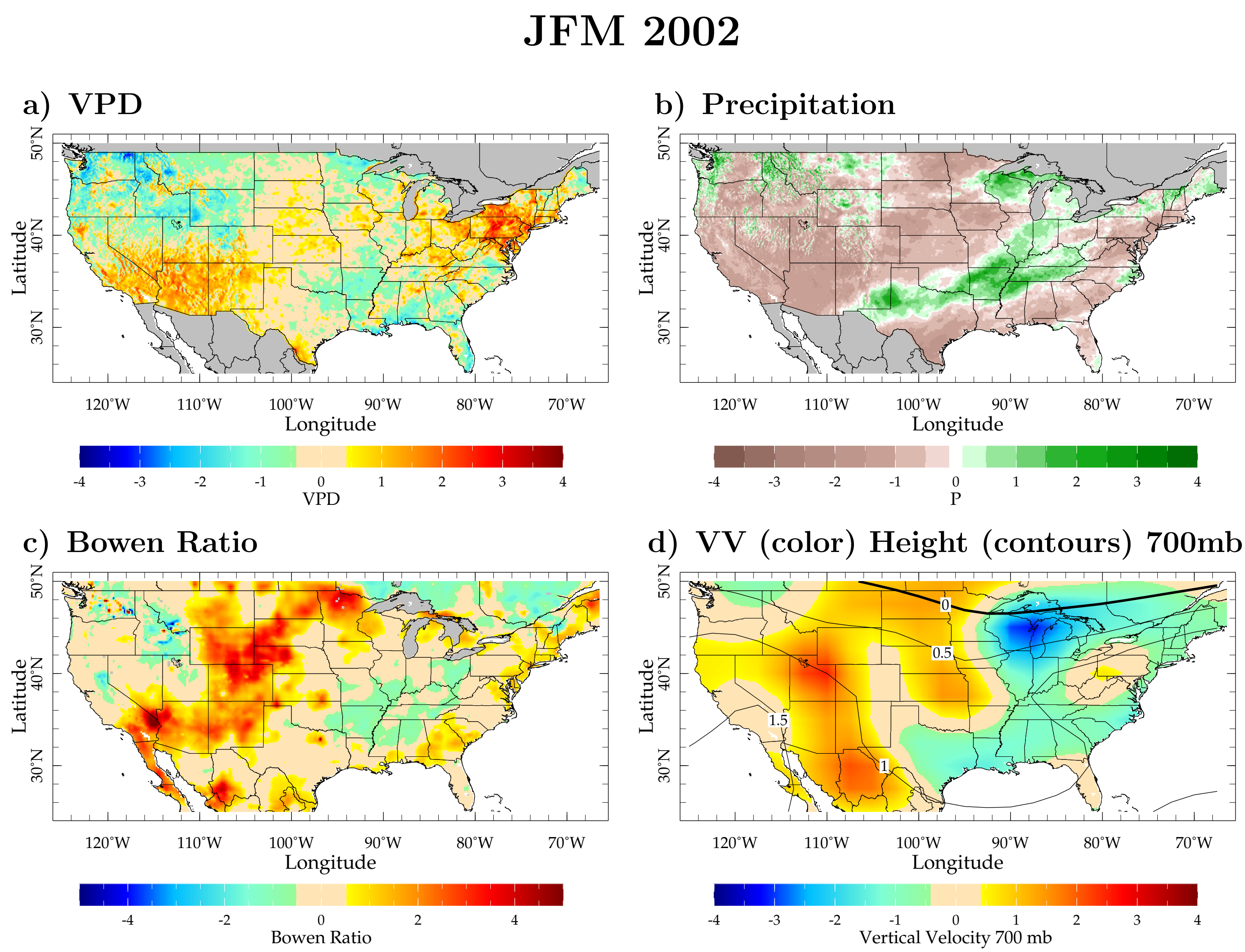

FIG. 9. Conditions in the winter before the Rodeo-Chediski and Hayman fires of June 2002. Shown for JFM 2002 are the standardized anomalies of VPD (upper left), precipitation (upper right), Bowen ratio (lower left) and 700mb vertical velocity (colors) and geopotential heights (contours) (bottom right).

AMJ 2002

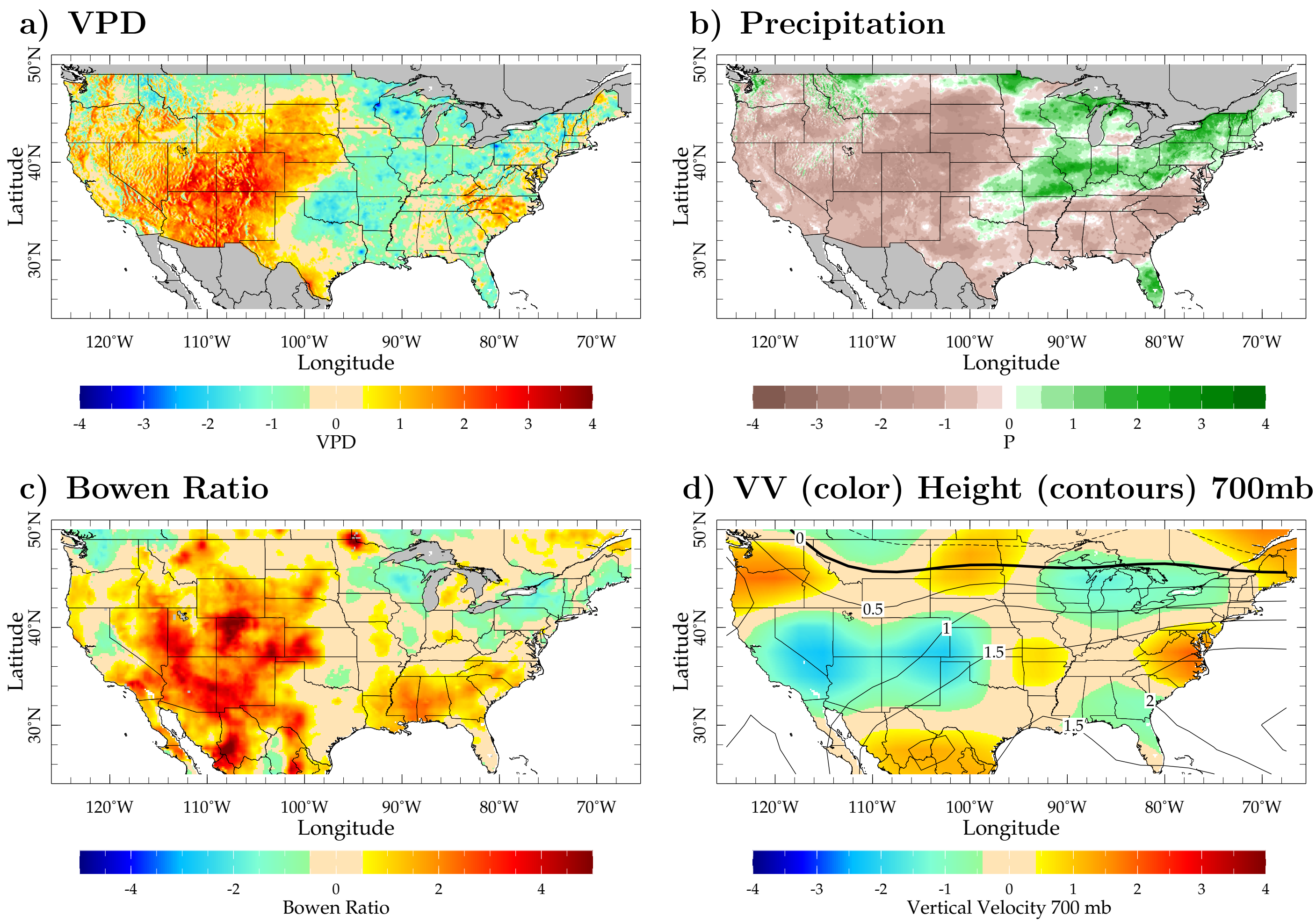

FIG. 10. Same as Figure 9 but for AMJ 2002.