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Association of direct normal irradiance with El Niño Southern Oscillation and its consequence on concentrated solar power production in the US Southwest

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HIGHLIGHTS

- Influences of ENSO on DNI and CSP plants productions in four US southwest states are investigated.
- Responses of DNI to ENSO events are both location and seasonal dependents.
- Each ENSO event has unique influence on variability, characteristics and magnitude of DNI.
- Occurrence of ENSO events results in changing the anticipated outputs of CSP plants.

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ABSTRACT

The US Southwest is among the most suitable regions for the employment of concentrated solar power (CSP). The high fluctuations of direct normal irradiance (DNI) lead to significant variabilities in CSP plants power output. El Niño Southern Oscillation (ENSO) has been proven as a large-scale climate phenomenon that influences the climatic behaviors and meteorological variables in the US southwest. In this study, the impacts of ENSO on DNI and CSP plants electricity production are investigated in four US southwest States of Arizona, California, Nevada and New Mexico, using 50 years (1961–2010) collected DNI data. The results demonstrate that responses of DNI to ENSO are both location and seasonal dependent due to the specific climate and DNI features of each site. Furthermore, the conducted analysis shows that each ENSO type and intensity has distinct impacts on DNI. The changes in the variability, distribution and magnitude of DNI during ENSO events can be due to changes in the atmospheric contents, cloud amounts and precipitation level caused by ENSO events. These changes lead to magnitude and continuity variations of CSP plants power output. Such variations necessitate optimizing the thermal energy storage utilization schedule and back-up energy source requirements for CSP power plants.

1. Introduction

The US Southwest is among the best regions in the world in terms of solar energy potential. In the Mojave Desert, the solar radiation level is up to two times more than other regions of the US. This enormous solar energy potential facilitates developing solar power plants as a clean alternative to conventional power plants such as natural gas and coal [1].

Solar electricity can be generated using photovoltaics (PV) and concentrated solar power (CSP) technologies [2,3]. CSP technologies utilize mirrors to concentrate solar energy in the form of direct normal irradiance (DNI) and convert it to heat in order to create steam and drive a turbine for generating electricity [4–6]. A high level of DNI is the most important parameter to power CSPs for electricity generation, and so the most appropriate sites for CSP development are in regions with clear sky conditions and high DNI such as those in the US Southwest [7].

DNI is highly variable; different atmospheric phenomena such as clouds covering the sun temporarily impact the level of DNI. High fluctuations of DNI result in variable power output of CSP plants. The intermittency in DNI brings uncertainty in the electricity production of CSP plants and risk of unpredicted imbalance in supply and demand. This potentially causes the network voltage and frequency to exceed the safe operation limits, and thus decreases the reliability of the network and increases the maintenance costs [8,9]. Since CSP plants require DNI to heat water and generate steam for producing electricity, anything that reduces the level of DNI in the sky can influence the steam conditions that can then damage equipment and lead

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to unsafe conditions. Industry-wide models suggest that a 5% negative anomaly in DNI during summer for a CSP plant can lead to approximately 1–1.5% decline in annual revenue for a CSP developer or operator [10]. Frequent and substantial departures from long-term average DNI highlight the necessity of analyzing the influence of DNI variability on both over- and under-performance of CSP plants.

Understanding the DNI variations throughout the year is valuable for CSP developers and decision makers. This can also be utilized to optimize the thermal energy storage charging/discharging schedules which can lead to financial benefits [11,12]. Furthermore, understanding the DNI variations can be helpful for optimizing the CSP plants by decreasing the heat loss and increasing the solar-to-electricity conversion efficiency [8,13,14]. Equally important, it is vital to determine the factors that influence the fluctuations of DNI in different time scales. Factors such as clouds, jet contrails, aerosol and climate have a higher influence on the plant production than what owners may expect [15].

There are different climate phenomena such as El Niño-Southern Oscillation (ENSO) that cause variability and influence global seasonal climate. ENSO is currently regarded as a key element for predicting different parameters in the US Southwest such as precipitation, drought, air temperature, wind speed, etc. [16–22].

Predictions based on the ENSO events are linked to the strength of an event such that stronger events provide higher predictive signals [23]. ENSO is a large-scale climatic variable pattern that is characterized by a periodic shift in the ocean-atmosphere conditions, especially the sea surface temperature (SST) across the equatorial Pacific Ocean. ENSO is a natural but largely unpredictable condition that results from complex interaction of clouds and storms, regional winds, oceanic temperatures, and ocean currents along the equatorial Pacific. It ranges from a warm phase called El Niño to a cold phase called La Niña, which both heavily influence the climate patterns in the US Southwest [19]. The condition is called Neutral when there is no El Niño or La Niña. Generally, El Niño is described with an abnormal increase of SST in the central and/or eastern equatorial Pacific Ocean, while the atmospheric component (Southern Oscillation) relates to an increase in the sea atmospheric pressure in the western Pacific Ocean. La Niña is the opposite phenomenon characterized by an abnormal decrease in the SST [24].

Recent studies presented in the literature discussed high influence of ENSO on renewable energy resources, especially solar and wind. Yip et al. [25] discussed potential impacts of ENSO on wind energy resources in Arabian Peninsula. Fant et al. [26] pointed out wind speed is largely influenced by large-scale oscillations such as ENSO. Bianchi et al. [27] studied the impacts of different large-scale climate phenomena such as ENSO on wind resources in southern parts of the South America. They discussed that ENSO events can be predicted on seasonal timescales. The results of this study demonstrated that ENSO may be utilized as a predictor of wind energy production on monthly and seasonal scales in many southern regions of South America. Prasad et al. [28] discussed high dependency of solar and wind energy resources on ENSO in Australia. In some studies, it was shown that ENSO has a direct influence on solar radiation variations. Mohammadi and Goudarzi [29] explored the sensitivity of different climatic parameters such as total solar radiation, wind speed and participation to ENSO events in California. Their conducted analysis illustrated that occurrence of ENSO events causes distinct impacts on the magnitude and distribution of the studied climatic variables. They found that the impact of each ENSO event on these variables is geographically and seasonally dependent. Based on the conducted study, ENSO was suggested as a useful prognostic tool for solar and wind energy and hydropower planning in California. Davy and Troccoli [30] studied the influence of ENSO on total solar radiation in Australia during summer and winter seasons, using a 20-year dataset from 1989 to 2008. They found out that the impact of ENSO on total solar radiation is an increase in the average total solar radiation in El Niño years compared to La Niña years. The results showed while there is generally a small variation in solar radiation due to ENSO during summer, it can lead to more than 10% variations in some locations during winter. Whitlock et al. [31] investigated the anomaly in total solar radiation due to El Niño and La Niña. They used a 10-year solar radiation data from 1983 to 1993 to generate global maps of locations with significant solar radiation variations. It was shown that most of the regions had a ± 15% year-to-year solar radiation variability; some regions had a higher variability for only several months. Prasad et al. [32] used DNI data from January 1990 to June 2012 to investigate the impact of ENSO on temporal and spatial variability of DNI across Australia and its importance for future CSP plants developments. It was demonstrated that ENSO has a significant impact on DNI variability in the North and Northeast of Australia with a greater impact during winter compared to summer.

The literature lacks detailed studies on the influence of ENSO on the level of solar radiation and in particular the DNI. The importance of such analysis can be better understood when regions with substantial DNI potential are studied. One example is the US Southwest where there is a large number of CSP plants. Therefore, considering the growing development of CSP power plants and proved influence of ENSO on renewable energy sources, the main objective of this study is to identify the relationship of the ENSO phenomenon with DNI in four US Southwest states of Arizona (AZ), California (CA), Nevada (NV), and New Mexico (NM). The selected case studies cover different climate conditions and DNI characteristics. The influence of ENSO events on variability, characteristic, magnitude, and distribution of DNI in this area and potential consequences on CSP plants yields is explored. This study also investigates the influence of intensities of El Niño and La Niña events on DNI level. To fulfil these objectives, very strong and strong El Niño as well as strong and moderate La Niña events are studied. Hourly averaged DNI datasets for a long-term period of 50 years from January 1961 to December 2010 provided by National Renewable Energy Laboratory (NREL) have been utilized for this study.

The main originality of this work, that has not been carefully addressed in previous studies, is a detailed study on the impact of ENSO events with different intensities on DNI with a focus on possible consequences on CSP plants power output. This study brings new contributions and useful insights to the risks associated to the CSP power plants when ENSO events occur. It can be utilized to anticipate the over and underperformance of CSP plants during ENSO events and perform financial and technical risk assessment. The analysis conducted in this work is valuable for project developers, power system operators and central planners.

2. Case study, data and methods

The Southwest, with substantial solar energy potential throughout the year, is the most suitable region for CSP development in the US. This region includes approximately 139,500 km^2 of suitable lands for CSP development, out of which 121,700 km^2 is located in four States of Arizona (AZ), California (CA), Nevada (NV) and New Mexico (NM) [33]. The existing CSP power plants are mainly constructed in AZ, CA, and NV [34]. Despite the substantial potential capacity for electricity generation using CSPs in NM, there is not currently any CSP plant operating in this State.

The US Southwest is the hottest and driest region in the US with a wide range of climates and climatic behaviors. It includes a wide range of geographical features ranging from valleys that are below the sea level to mountains with some of the highest peaks in the contiguous US. Except the North Pacific coast, most regions feature an arid or semi-arid climate in which high share of annual precipitation often happens during a particular time of the year. The seasonal cycle of precipitation is quite variable and it is mainly centered in the winter season in most regions [35].

To fulfill the study objectives, ten sites from four States that cover different climate conditions and different DNI intensities and characteristics are selected: Phoenix (AZ), Prescott (AZ), Tucson (AZ), Bakersfield (CA), Daggett (CA), Ely (NV), Reno (NV), Tonopah (NV), Las Vegas (NV), and Albuquerque (NM). The selected locations, with

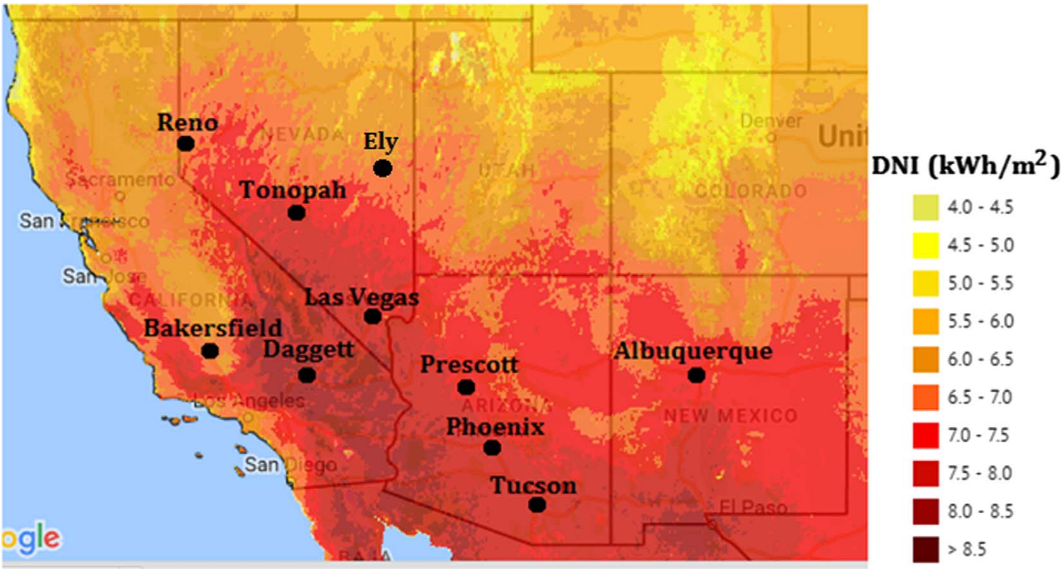

Fig. 1. Geographical location and annual DNI in kWh/m^2 of ten selected sites (DNI map was adapted from [36]).

their geographical positions and DNI intensities are illustrated in Fig. 1.

Hourly averaged DNI data for 10 selected locations have been sourced for this study. We used National Solar Radiation Data Base (NSRDB) data from the National Renewable Energy Laboratory (NREL) for the period of 1961–2010 [37]. NREL's DNI data includes two data series for the period of Jan. 1961 to Dec. 1990 and Jan. 1991 to Dec. 2010. The selected sites have a complete set of data for the whole period of 1961–2010. Also, many of the CSP power plants in Southwest are in the selected sites, and the significant solar resource throughout the year enables future CSP plant developments in these sites. The long-term datasets from 1961 to 2010 enables large-scale analysis of DNI for a large number of El Niño and La Niña years. The complete description and information regarding the NREL solar radiation data have been documented in [38–40].

Different indices have been developed for characterizing the ENSO events. The Oceanic Niño Index (ONI), frequently used for this purpose, is defined as a three-month running mean of SST anomalies in the Niño 3.4 region (5°S–5°N, 170°W–120°W). Warm phase (El Niño) and cold phase (La Niña) are defined based on a threshold of anomaly $> +0.5\,^{\circ}\mathrm{C}$ and anomaly $> -0.5\,^{\circ}\mathrm{C}$ for the ONI, respectively. The intensities of El Niño and La Niña can be defined based on the level of Niño 3.4 region SST anomaly. El Niño intensities classification based on this definition is shown in Table 1. These definitions have been utilized by the NOAA Climate Prediction Center [41] and have been also broadly used in previous studies to evaluate the influence of ENSO on climate patterns in different regions in the US [20,22,42].

The greatest influence of ENSO on the climate in the US Southwest is typically observed in fall (Sep-Nov) and winter (Dec-Feb). Previous studies demonstrated a significant control of ENSO on climate variables over seasonal timescales [21,22,27,30]. Thus, this study only focuses on fall and winter ENSO impacts. Furthermore, in this study, very strong and strong El Niño and also strong and moderate La Niña are considered for analysis; these events are expected to have higher signals and correlations with DNI. Table 2 provides the list of El Niño and La Niña events during the studied period of 1961–2010 [41].

The variability and behavior of DNI under the influence of El Niño and La Niña events are analyzed using coefficient of variation (COV), histogram, and probability distribution plots as well as dimensionless median absolute deviation (DMAD) analysis. The COV describes the amount of variability relative to the mean which is defined as the ratio of standard deviation to the mean value. It measures the variability of DNI data independent of the unit and magnitude. Using COV, it is possible to examine whether the variability of DNI varies with ENSO events. A histogram plot provides a graphical representation of the DNI data distribution and examines how different intervals of DNI respond to El Niño and La Niña events. The median absolute deviation (MAD) is a robust measure of the statistical dispersion and central tendency. MAD is defined as the median of the absolute deviations from the data median [43]:

$$MAD = median(|X_i - median(X)|) \tag{1}$$

where, for each specific variable, X is the vector of all data for each specific variable and X_i is the individual data for the specific time of i.

In order to examine the influence of El Niño and La Niña events, a dimensionless MAD (DMAD) parameter is defined by dividing the difference between $X_i - median(X)$ to MAD:

$$DMAD = \frac{X_i - median(X)}{MAD} \tag{2}$$

Using DMAD, it is possible to generate sets of standardized indexes that vary between negative and positive values. DMAD can be positive or negative, and shows the number of MADs the data is from the median.

3. Results and discussion

3.1. Seasonal variability of DNI

To understand the seasonal features and variability of DNI, the data were sorted according to the definition of northern hemisphere's fall (September-November) and winter (December-February) seasons. The

Table 1
El Niño and La Niña events classification based on the Niño3.4 region SST anomaly [41].

	Very strong	Strong	Moderate	Weak
El Niño	anomaly ≥ 2.0 °C	1.9 °C > anomaly > 1.4 °C	1.4 °C > anomaly > 1.0 °C	0.9 °C > anomaly > 0.5 °C
La Niña	–	−2.0 °C > anomaly ≥ −1.5 °C	−1.4 °C > anomaly > −1.0 °C	−0.9 °C > anomaly > −0.5 °C

Table 2
El Niño and La Niña events during 1961–2010 analyzed in this study [41].

Very strong El Niño (VSE)	1982 (fall), 1983 (winter), 1997 (fall), 1998 (winter)
Strong El Niño (SE)	1965 (fall), 1966 (winter), 1972 (fall), 1973 (winter)
Strong La Niña (SL)	1973 (fall), 1974 (winter), 1975 (fall), 1976 (winter), 1988 (fall), 1989 (winter)
Moderate La Niña (ML)	1970 (fall), 1971 (winter), 1998 (fall), 1999 (winter), 1999 (fall), 2000 (winter), 2007 (fall), 2008 (winter), 2010 (fall)

coefficient of variation (COV) was calculated to determine and characterize the seasonal variability of DNI under the influence of El Niño and La Niña events. For this aim, the mean and standard deviation of daily averaged DNI were computed over each season for all sites; then COV was calculated.

Fig. 2 illustrates the seasonal COV of DNI for very strong El Niño (VSE), strong El Niño (SE), strong La Niña (SL) and moderate La Niña (ML) events in the fall (F) and winter (W) seasons for the whole period of 1961–2010. The category “All” refers to the COV of the whole period of analyzed data in each season. It is observed that DNI variability depends on the ENSO events; however, the responses are not the same for all selected locations. Despite the tendency for ENSO events to affect the DNI variability, the location dependency of the responses is evident due to differences in the climate conditions and DNI characteristics of the locations. This highlights the distinct impacts of each El Niño and La Niña events on DNI variability in each location.

For fall seasons, it is observed that the VSE and SE events increase the variability in all selected locations. A reverse influence is observed for La Niña events on DNI variability in the fall season for all locations. As shown in Fig. 2, the DNI variability decreases when SL and ML events occur. Despite the higher signal of SL, for some locations, ML causes a further variability reduction compared to that from SL. The same pattern has also been observed for the VSE and SE events. The highest and most consistent responses of DNI variability to the El Niño and La Niña events are observed in CA and AZ states. This could be an indication of higher influences of ENSO events on climate patterns in these states. In contrast, the lowest responses are noticed in Ely and Reno, located in the northern areas of Nevada.

The conducted analysis shows that there are some differences in the seasonal DNI variability of the selected locations due to changes in the climate conditions between fall and winter seasons. Changes in different meteorological parameters such as temperature, humidity, precipitation and atmospheric pressure may induce feedbacks in the climate systems. For all locations, the COV of DNI is higher in winter compared to that in fall. Nevertheless, there is a smaller impact of ENSO events on DNI variability, especially during VSE and SE events. For some locations such as Bakersfield, Phoenix, Reno and Tucson, there is almost no influence of VSE and SE events on DNI variability in winter. This smaller impact of VSE and SE events in winter indicates a lower negative influence on CSPs yields.

The changes in the level of variability of DNI in the studied sites can be related to the variations of the atmospheric patterns and cloud amount, as well as precipitation level as a consequence of El Niño and La Niña events. These variabilities of DNI impact the energy production of CSP plants; a higher DNI variability leads to reduction in the magnitude and consistency of CSP electricity generation. It necessitates careful utilization of thermal energy storage and back-up sources. In contrast, a lower variability of DNI due to SL and ML events could be a positive factor for CSP plants operation.

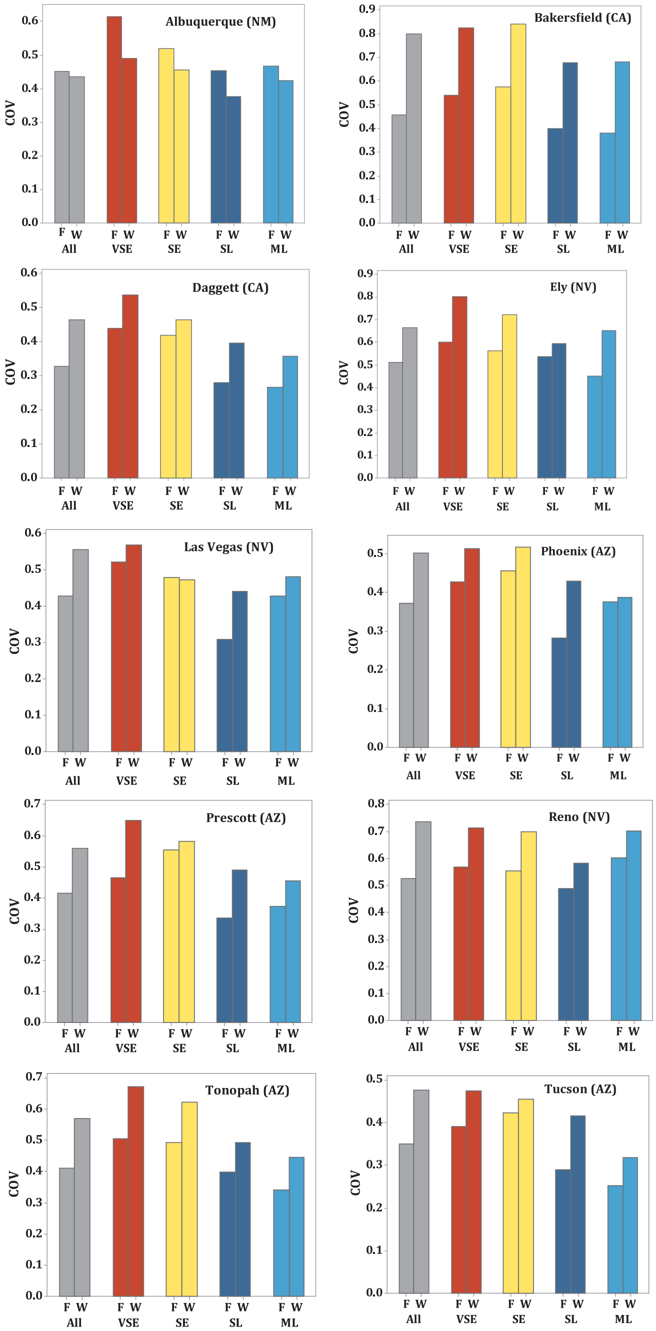

Fig. 2. COV indicating the DNI variability in different events in fall (F) and winter (W).

3.2. Distribution and probability occurrence of DNI

The histograms of hourly DNI data (Wh/m^2) in all fall seasons from 1961 to 2010 are compared to those for all ENSO events, as illustrated in Fig. 3. These plots illustrate the frequency in percentage of total number of hours falling within different intervals of DNI. One of the most important findings from this analysis is the location and seasonal dependency of DNI to ENSO events. It is observed that ENSO changes the probability distribution of DNI in fall so that some shifts in the probability occurrence of DNI at different ranges are noticeable. The shifts and responses are different when either El Niño or La Niña occurs. VSE events decrease the probability of higher levels of DNI. In all locations, VSE events cause a decrease in the probability of DNI values greater than 800 Wh/m^2. While these changes are very minimal for some locations such as Albuquerque, Bakersfield, Ely and Reno, other locations experience significant shifts due to VSE events. While small responses to VSE events are observed in northern parts of CA, NM, and NV, bigger responses are observed in AZ, southern CA, and NV. In SE events, only small changes in the probability occurrence of the DNI values are observed for most of the studied sites.

The analysis also reveals that La Niña (either SL or ML) events generally cause opposite impacts on the probability of higher ranges of DNI compared to those from El Niño events. The La Niña impacts on the distribution of DNI are site dependent. For instance, while SL might

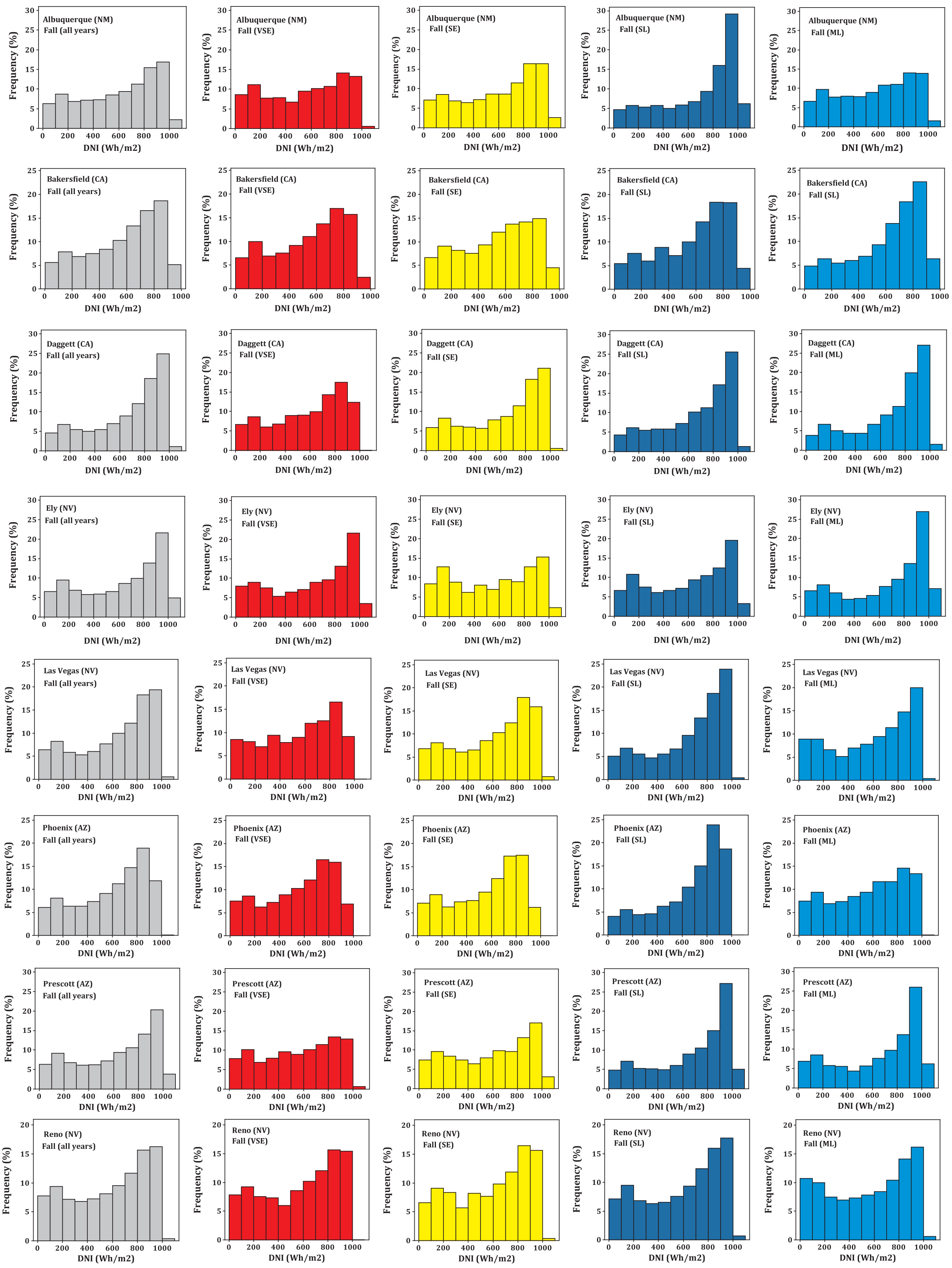

Fig. 3. Histogram of hourly DNI (Wh/m^2) in all fall seasons compared to the fall seasons with VSE, SE, SL and ML events.

impact the probability distribution in one site, ML might not have any impact; or an opposite behavior could be observed in another site.

Similar histograms as those of Fig. 3 are presented in Fig. A1 in Appendix A for winter seasons. For winter seasons, similar conclusions as those of fall seasons can be drawn regarding the general influences of El Niño and La Niña events on the probability distribution of DNI. VSE

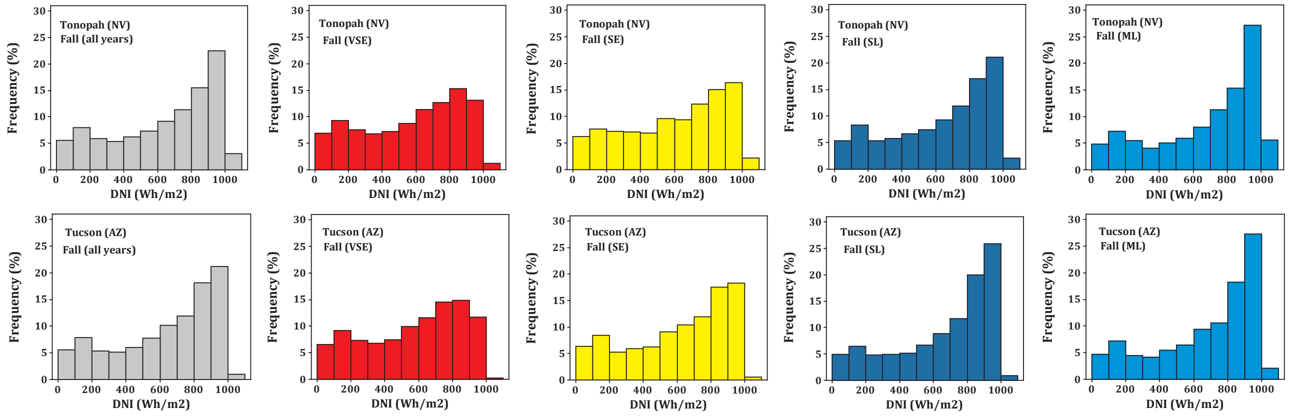

Fig. 3. (*continued*)

Table 3
Probability of DNI of lower than 400 Wh/m^2 for fall seasons.

Location	All	VSE	SE	SL	ML
Albuquerque	29.12%	35.29%	28.85%	21.65%	32.02%
Bakersfield	27.78%	31.10%	31.47%	27.15%	22.69%
Daggett	21.90%	28.00%	26.46%	21.71%	19.95%
Ely	28.74%	29.81%	36.34%	31.12%	25.27%
Las Vegas	25.84%	32.93%	27.84%	22.11%	29.56%
Phoenix	26.89%	29.47%	29.66%	18.69%	31.04%
Prescott	28.44%	32.94%	32.97%	22.36%	26.77%
Reno	31.14%	32.09%	29.86%	29.81%	35.11%
Tonopah	24.97%	30.61%	28.20%	24.70%	21.55%
Tucson	23.92%	29.82%	26.04%	21.16%	20.63%

Table 4
Probability of DNI of lower than 400 Wh/m^2 for all winter seasons compared to different ENSO events.

Location	All	VSE	SE	SL	ML
Albuquerque	33.02%	35.84%	34.23%	28.02%	33.53%
Bakersfield	45.07%	55.05%	47.15	43.69%	36.35%
Daggett	28.91%	38.26%	32.13%	28.95%	25.10%
Ely	35.40%	40.01%	44.20%	36.18%	32.35%
Las Vegas	31.38%	35.72%	31.87%	25.44%	32.96%
Phoenix	32.09%	35.28%	32.44%	26.97%	30.19%
Prescott	33.28%	40.72%	33.81%	31.00%	29.41%
Reno	44.96%	47.91%	47.45%	40.11%	46.27%
Tonopah	32.58%	45.11%	38.30%	31.61%	29.02%
Tucson	27.98%	33.13%	30.17%	26.81%	21.99%

events decrease the probability of higher levels of DNI. Similar to fall seasons, SE events in most of the locations cause only small changes in the probability of the DNI values during winter seasons. The results reveal that either SL or ML increases the probability of higher levels of DNI in comparison to those from El Niño events. This impact is small for some sites such as Daggett in CA (see Fig. A1 in Appendix A for further details).

Atmospheric phenomena have more impacts on DNI than total (global) solar radiation. There is a direct relationship between the magnitude of DNI and the amount of generated electricity from CSP plants. Thus, in the case of higher DNI levels, more electricity generation from CSP plants can be expected and vice versa. Regardless of the DNI level, the thermal losses in the receiver of a CSP plant and the parasitic consumption of electrical auxiliaries are constant. There is normally a DNI threshold of 400 W/m^2 for an efficient CSP plant operation such that no net electricity is expected at values lower than that [44]. During El Niña or La Niña events, the distribution and probability occurrence of DNI at higher ranges change; it leads to power variations in the CSP plant. A comparison between histogram analysis of fall and winter seasons indicates that the probability of DNI of lower than 400 Wh/m^2 in winter is much higher than fall for most locations; meaning a higher probability of no net electricity output by CSP plants. It is possibly due to higher precipitation and cloud amounts in winter than fall causing a reduction in the DNI level. It is worth noting that when El Niño or La Niña events change the probability occurrence of DNI at higher ranges, the opposite change normally occurs in the probability occurrence of DNI values which are lower than 400 Wh/m^2. For example, when VSE events happen, the probability of DNI occurrence at higher ranges decrease whereas the probability occurrence of DNI of lower than 400 Wh/m^2 increases. Therefore, the VSE events could result in a decline in the CSP plants' electricity outputs during fall and winter seasons. This negative impact on the CSPs' outputs is because of lower power production of the plant due to two main reasons: (1) a lower probability of higher DNI ranges and (2) a higher probability of low DNI values, lower than 400 Wh/m^2 which increases the number of hours or days that the net output of CSP plants is null. In contrast, during SL or ML events, a positive influence on the CSP plants output or higher than normal anticipated range of electricity generation may be expected. The reason is SL or ML events cause an increase in the probability occurrence of higher ranges of DNI and/or a decrease in the probability occurrence of DNI of lower than 400 Wh/m^2. The probability of DNI of lower than 400 Wh/m^2 for all years compared to ENSO events in fall seasons and winter seasons, are presented in Tables 3 and 4, respectively. Tables 3 and 4 provides numerical values of the analysis given in Fig. A1.

It is noticed that an occurrence of VSE events causes an increase in the probability of lower DNI than 400 Wh/m^2 in all studied sites in fall seasons. For most locations, SE events leads to an increase in this probability but mostly with a lower intensity compared to the observed influence of VSE events. The exception is Ely for which the impact of SE events is higher than VSE events. For Albuquerque and Reno, SE events cause a decreases in this probability. For all locations except Ely, a reduction in the probability is noticed when SL events occur; however, the intensities are different. Table 3 shows that the impacts of ML events are inconsistent; while for some locations an increase in the probability is noticed, for other ones a reverse impact is observed.

Table 4 shows that similar to fall seasons, VSE and SE events increase the probability for all studied sites. Again, for a majority of locations, a higher impact is noticed during VSE events. For some locations such as Bakersfield, Daggett and Tonopah, VSE has a noticeable effect on DNI probability of lower than 400 Wh/m^2. For most locations, SE has a lower impact on probability; however, Ely is found as an exception. It is noticed that for most locations, SL events lead to a reduction in the probability; however, the impact is not noticeable mostly. For ML events, depends on the location, the impact can be observed as both increase and decrease. The highest impact, which is an increase in the probability, is observed for Bakersfield and Tucson.

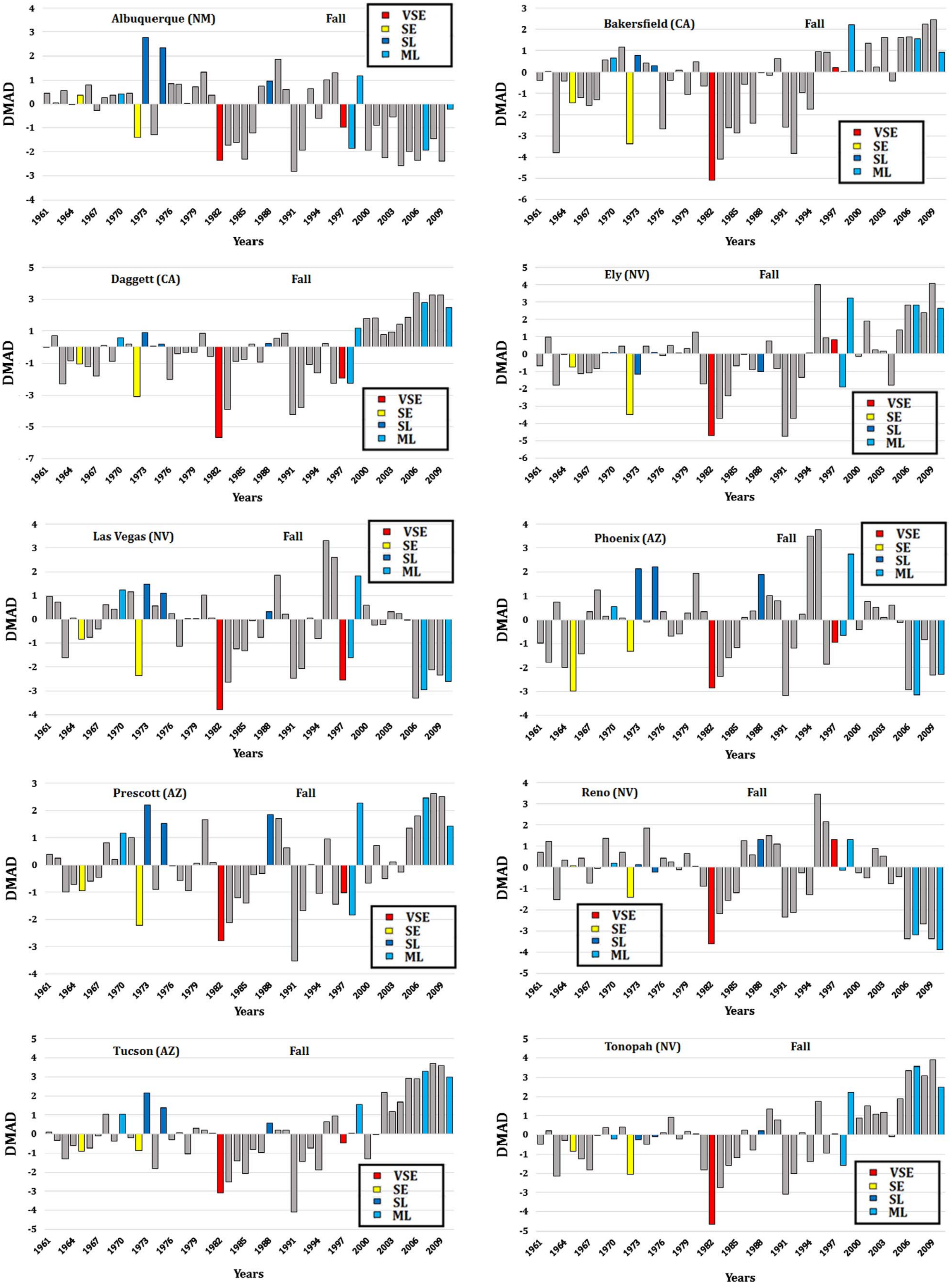

Fig. 4. Calculated DMAD of DNI for different El Niño and La Niña events for fall season.

3.3. Overall changes and anomalies of DNI

The sensitivity of DNI to different intensities of El Niño and La Niña events is further assessed via calculating the DMAD of DNI. Fig. 4 shows the calculated DMAD of DNI from 1961 to 2010 in fall seasons. Similar results for winter seasons are shown in Fig. B1 in Appendix B. The years with VSE, SE, SL and ML events are shown with different colors.

The conducted analysis shows that during VSE events in both fall and winter seasons, the magnitude of DNI highly decreases in all locations. This implies the influence of VSE events on the level of DNI in all selected sites. However, as discussed in Sections 3.1 and 3.2, this effect is different from one site to another one due to changes in the climate and DNI characteristics as well as response to VSE events. This analysis reveals that responses of DNI to the SE phenomenon are different when both locations and seasons change. In fall seasons, almost no overall impact can be reported for two selected locations of CA (Bakersfield and Daggett); it might come from both increasing and decreasing the DNI due to SE events. For Ely and Tonopah in NV, SE events decrease the DNI level in fall seasons. For other selected sites, the influence of SE events in fall seasons is mainly an increase in the DNI magnitude. The obtained results for SE events in fall seasons indicate the specific response of DNI to SE phenomenon in each site. In winter seasons, the impact of SE is mostly a slight decrease in the DNI level. The conducted analysis also reveals that both La Niña events (SL and ML) mostly increase the magnitude of DNI in all selected sites in fall and winter seasons. While in both fall and winter seasons the magnitudes of DNI may both increase and decrease when La Niña events occur, the overall impact of La Niña should be introduced as an increase in the DNI level (refer to both Figs. 4 and B1 for clarity).

Based on Figs. 4 and B1, the impacts of ENSO events on DNI may not be consistent and follow a specific pattern for all years and selected case studies. Although the DMAD values in ENSO years are not always in contrast to the surround years, there are still interesting patterns for most case studies; especially when the ENSO has a strong signal such as VSE.

Lower than the historical average DNI during fall and winter seasons results in lower than anticipated electricity production by CSP plants and vice versa. In this context, the occurrence of VSE events in both fall and winter seasons causes a reduction in the net output of the CSP plants in all studied sites. The SE events impact is both location and seasonal dependent; thus, the overall CSP plants' outputs can be both higher or lower than a typical expected range. In contrast, during the SL and ML events, a higher amount of electricity generation from CSP power plants can be expected; although in some SL and ML events the impact is declining the level of DNI and CSP plants output.

One of the main consequences of lower or higher than normal expected output electricity from CSP plants is a change in the requirements of back-up sources. When VSE events occur, the CSP plants may require more back-up energy source such as natural gas or non-intermittent renewable energy resources (e.g. biomass and geothermal) in order to reach the expected power production target. As a majority of the US southwest CSP plants use natural gas as a back-up source, more natural gas might be needed to meet the baseload/targeted seasonal demands. In addition to a higher cost for the required back-up source, this makes CSP plants less green and environmentally friendly. During the SL and ML events, an opposite situation regarding the need to supplementary fuel is anticipated.

4. Summary and conclusions

In this study, the impacts of ENSO phenomenon on the DNI were examined in four US Southwest states of AZ, CA, NV and NM. As literature clearly lacks details and enough studies on the relationship of ENSO with DNI, the major motivations behind this study were to find out whether ENSO has an impact on DNI in the US southwest and whether ENSO types and intensities are matters in this regard.

The conducted analysis revealed that the responses of DNI to ENSO are contingent upon both location and season; each location represents specific climate and DNI features. The types and intensities of ENSO were found as important matters in terms of impacts on DNI. The results showed that each examined ENSO event consisting of VSE, SE, SL and ML events has a unique influence on variability, characteristics and magnitude of DNI as well as its probability distribution. It was found that VSE events increase the DNI variability and the probability occurrence of DNI; particularly at higher ranges. They reduce the probability occurrence at ranges lower than 400 Wh/m^2 and in general, reduce the magnitude of DNI in both fall and winter seasons. La Niña (either SL or ML) showed an opposite impacts compared to those from VSE events. Also, the analysis indicated that SE events do not bring consistent impacts on DNI variability, distribution and magnitude; such that the impacts varied with locations and seasons.

Changes in the DNI variability, distribution and magnitude during ENSO events can happen because of changes in the atmospheric contents, cloud amounts and precipitation level as feedbacks to ENSO occurrence. DNI variabilities result in changing the expected electricity outputs from CSP due to the direct relationship between the magnitude of DNI and the amount of electricity that can be generated by CSP power plants. In regards to the changes in CSPs outputs, to supply the expected demands, the thermal energy storage charging/discharging schedule and back-up energy source requirements for CSP power plants should be adjusted accordingly. The consequence of VSE events could be a reduction in the CSP plants' electricity output during fall and winter seasons; SL or ML would increase the electricity outputs of CSP power plants. However, during SE events CSP power plants' output could be expected to either increases or decreases. Change in the back-up source requirements is among the important consequences of lower or higher than normal anticipated output electricity from CSP power plants. During VSE events, to meet the required output electricity, more auxiliary heating backup source such as natural gas or biomass and geothermal as non-intermittent renewable energy resources would be required. The contrary situation regarding the need to supplementary fuels can be expected during the SL and ML events. Such changes in the DNI level and back-up energy requirements at different years throughout the lifetime of the project impact the economic and the revenue from CSP projects. The knowledge of those anomaly behaviors would provide information on the changes in the CSP plants profitability when the ENSO events occur.

The analysis suggests that general impacts of El Niño or La Niña events on DNI and CSP plants outputs in the US Southwest can be anticipated in advance to construct a portfolio for balancing the ENSO impacts. Thus, the obtained results would be valuable to project developers, power system operators and central planners to foresee whether CSP power plants might either over perform or under perform in terms of electricity production during ENSO events and to assess the related financial and technical risks. They also offer insights in terms of thermal energy storage charging/discharging schedule and back-up fossil fuel source requirements.

Appendix A

Fig. A1 illustrates the histograms of hourly DNI data (Wh/m^2) in all winter seasons from 1961 to 2010. Similar to Fig. 3, it shows the frequency in percentage of total number of hours falling within different intervals of DNI. For complete explanations and discussion of Fig. A1, it is referred to the explanations given along with Fig. 3 in Section 3.2.

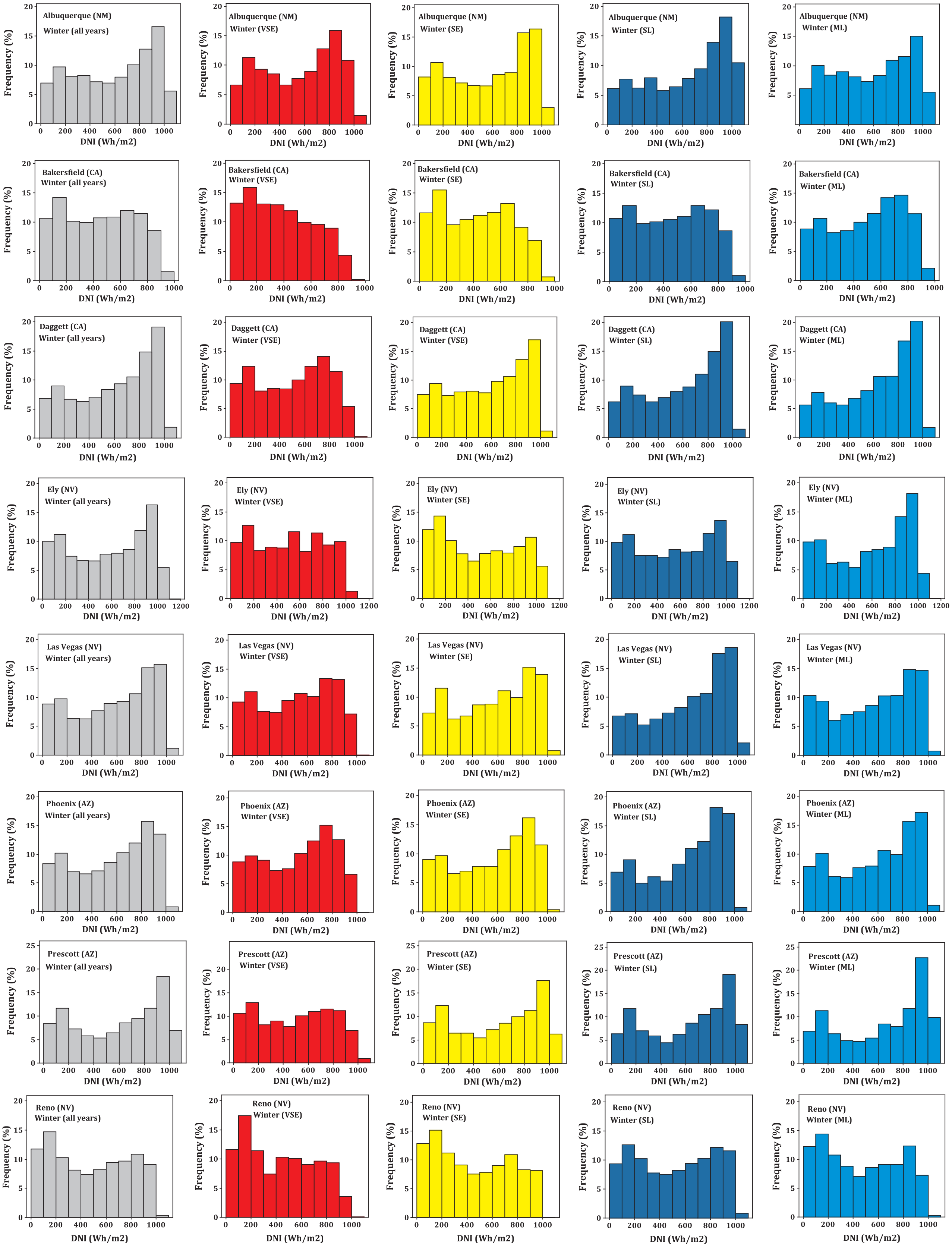

Fig. A1. Histogram of hourly DNI (Wh/m^2) in all winters compared to the winters with VSE, SE, SL and ML events.

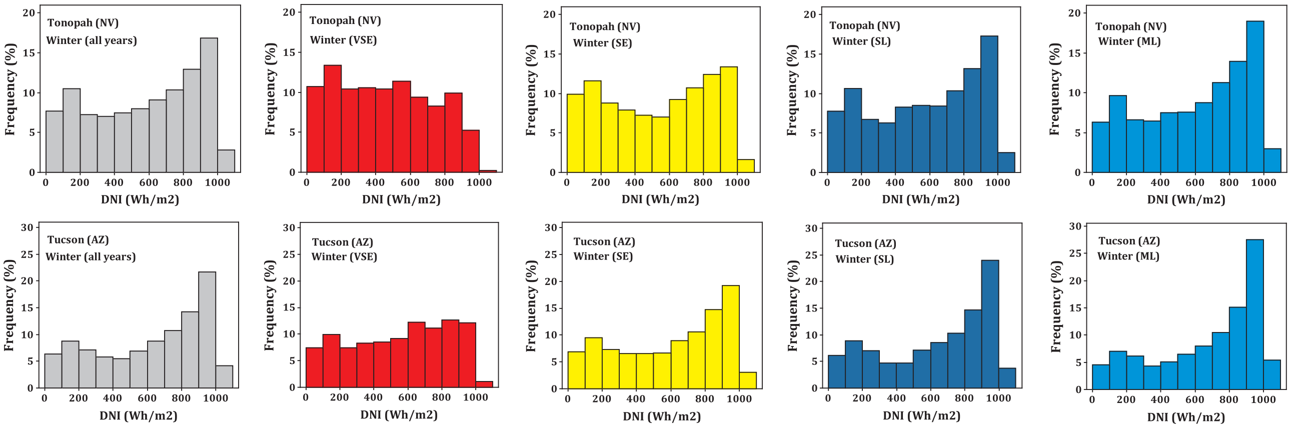

Fig. A1. (*continued*)

Appendix B

The calculated DMAD of DNI from 1961 to 2010 in winter seasons is shown in Fig. B1 for all studied sites. Explanations of Fig. B1 was presented in Section 3.3 along with those of Fig. 4 for fall seasons.

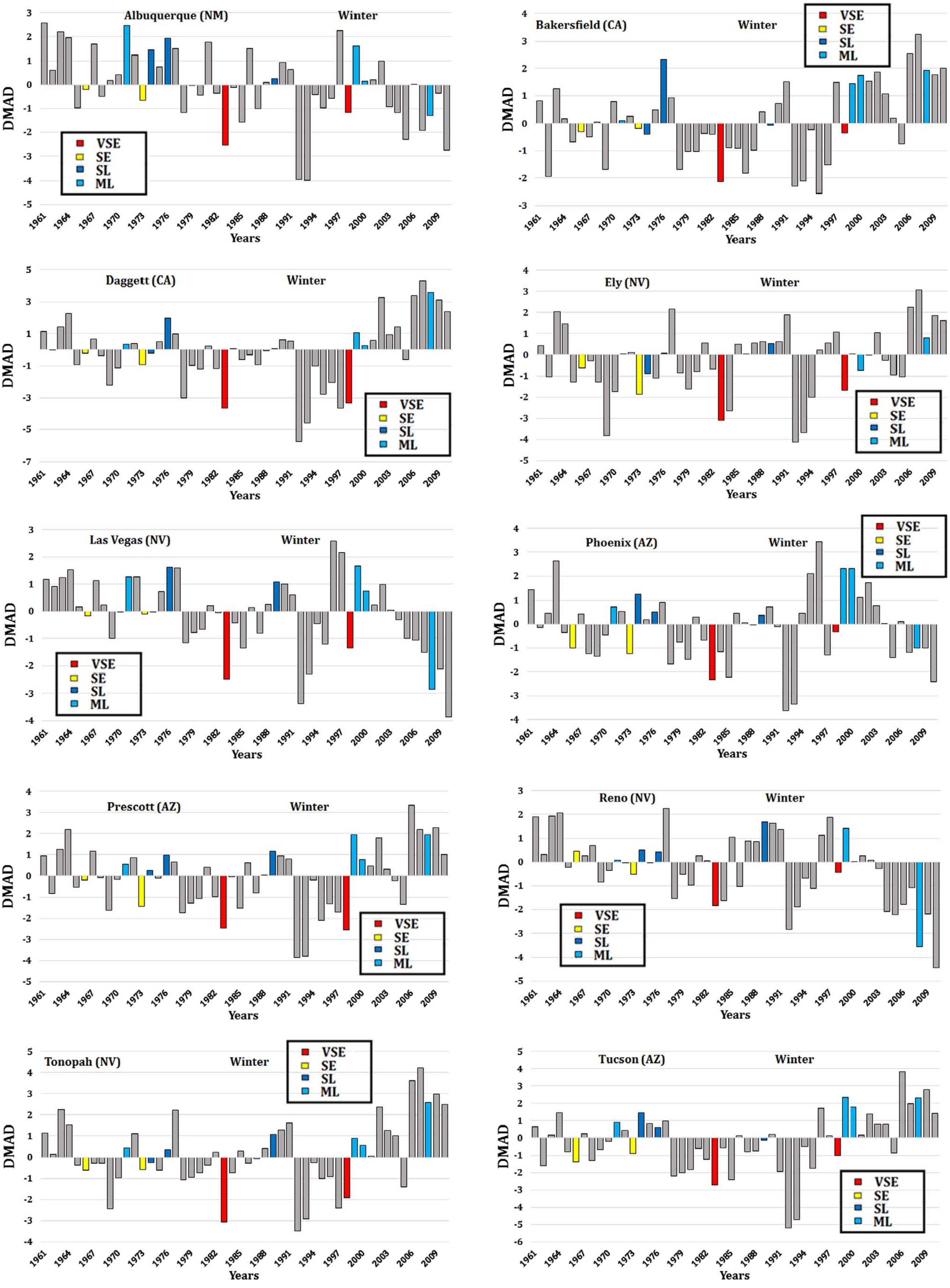

Fig. B1. Calculated DMAD of DNI for different El Niño and La Niña events for fall season.

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