The Influence of Teleconnection Patterns on Renewable Energy Resources

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THE INFLUENCE OF TELECONNECTION PATTERNS ON RENEWABLE ENERGY RESOURCES

A Thesis

Presented to

The Faculty of the Department of Meteorology and Climate Science
San José State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by

J. Kyle Bergerson

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The Designated Thesis Committee Approves the Thesis Titled

THE INFLUENCE OF TELECONNECTION PATTERNS ON RENEWABLE ENERGY RESOURCES

by

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SAN JOSÉ STATE UNIVERSITY

December 2021

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ABSTRACT

THE INFLUENCE OF TELECONNECTION PATTERNS ON RENEWABLE ENERGY RESOURCES

by J. Kyle Bergerson

Energy providers are shifting their supply from carbon based forms of energy to renewable sources in response to policy changes aimed at reducing pollution and anthropogenic influence on the environment. Wind and solar energies are notable sources that have been adopted around the globe and are increasing in installation and efficiency, but relying on weather-dependent sources of energy has limitations. Variability in energy supply and demand becomes further dependent on the state of the climate, and thus predictability of that state is critical. Climate modes are correlated with climate variables and are used to make mid-term (>10 days), seasonal, and even decadal climate forecasts. The modes are correlated through teleconnections, which are brought about through changes to the quasi-stationary atmospheric circulation. The research presented herein concerns three climate modes, the El Niño Southern Oscillation, Pacific-North America pattern, and North Atlantic Oscillation, and their teleconnections to wind, sunlight, and temperature on seasonal time scales. We explore these teleconnections through statistical relationships between climate modes and climate variables in the historical record. We look at concurrent relationships to get a better understanding of physical causality and we look at time-lagged relationships to see if there is obvious predictability. It is found that in most locations large scale modes of variability do not provide a major constraint on seasonal wind and solar power and thus their variability is largely a result of internal atmospheric dynamics.
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1. Introduction

Renewable energy is increasing in installation globally as efforts to offset anthropogenic carbon footprint escalate (Panwar et al. 2011) and as advances in engineering improve efficiency. Energy providers around the world are transitioning to a system that is highly penetrated with renewable sources such as wind and sunlight, which are dependent on climate and thus variable and difficult to predict (Wang et al. 2018). This transition demands extensive research in order to manage an efficient, cost-effective energy system. Governments, scientists, and energy industries are faced with the challenging task of restructuring current energy infrastructure, which is reliant on carbon-based and other environmentally hazardous sources, into one that relies on cleaner energy sources in an attempt to meet the goals set by the Paris Agreement.

Reliability will become a major concern as climate-related droughts in power supply are certain to occur (Jurasz et al. 2021). The current North American Electric Reliability Corporation (NERC) standard for electricity reliability is 99.97%, which is equivalent to less than one day per year without power. However, the intrinsic nature of the wind and solar resources are climate driven making maintaining this standard a challenge for energy providers. Climate is defined by long-term trends in weather over an area, of which changes are brought about by the fundamental exchange of energy between the atmosphere, ocean, hydrosphere, biosphere and cryosphere. Climate variables, such as temperature, pressure, precipitation, wind speeds, among many others, fluctuate somewhat regularly. These fluctuations are oscillatory and referred to as “climate modes” (Wang and Schimel 2003). An understanding of climate response to the state of climate modes will improve our ability to accurately forecast related climate extremes that affect energy supply and demand. Such
knowledge will be crucial for maintaining a reliable, robust energy grid. A report by the Carnegie Institution for Science (Shaner et al. 2018) considers geophysical constraints on wind and solar power, finding these sources alone to be capable of providing only about 80% of energy demand in the U.S. using demand data from the period July 2015- July 2016. Their report assumes lossless transmission and considers a variety of storage capabilities and capacity factors (Shaner et al. 2018). Thus, an approximate 20% supply deficit will need to be accounted for. On the other hand, The Department of Civil and Environmental Engineering at Stanford University lays out a plan for providing all global energy with wind, water, and sunlight, claiming that limitations are mostly political and social rather than technological or economic (Jacobson et al. 2014). In this research we will investigate concurrent and time-lagged relationships between climate indices and climate variables over the domain of the entire globe to ask the following research questions:

1. Do climate modes have teleconnection patterns with implications for renewable energy resources?

2. What are the relationships between the El Niño Southern Oscillation (ENSO), Pacific North-America pattern (PNA), and North Atlantic Oscillation (NAO) and temperature, wind speed, solar radiation, and 500 hectopascal (hPa) geopotential height?

3. Are these relationships homogeneous or heterogeneous over the globe?

4. What is the spatial scale over which we need to pool resources in the case of an energy system that is dependent on renewable sources such as wind and solar energy?
2. Background

Climate modes are markedly correlated with weather in certain regions and could potentially predict fluctuations in variables such as wind, solar radiation, and temperature (Krakauer and Cohan 2017). Notable correlations between climate modes and regional weather are known as “teleconnections,” a term used to describe a statistically significant remote response from a forcing region, either concurrent with or time lagged (Yeh et al. 2018). Historically, the main focus of most teleconnection studies has been temperature and precipitation (Diaz et al. 2001; Bartholomew and Jin 2013; Guan et al. 2013). This research will investigate teleconnections to wind speed and solar radiation anomalies, while also considering temperature as a proxy for energy demand via heating and cooling. The occurrence of high and low temperature extremes has a direct influence on energy demand due to heating and cooling demand and therefore is a primary concern for energy production management (Shaner et al. 2018; Millstein et al. 2019; Brown et al. 2020). We consider 500hPa geopotential height anomalies as the mechanism for which anomalies to wind speed, sunlight, and temperature occur. Though the absolute values of these variables will be the main consideration for energy managers’ decision as to where to install wind and solar farms, anomalies are valuable because they provide insight to the departures from climatological averages that may occur in relation to climate modes.

There are a growing number of reports and case studies using California as the setting for reasons including the State’s energy policies, current renewable energy infrastructure, and large population which demands significant energy (Wang et al. 2014). Berg et al. (2013) conducted a study of changes to wintertime winds in Southern California from 1959-2001, finding significant correlations with ENSO. Guan et al. (2013) concluded that the frequency
of atmospheric rivers in California are correlated with several climate modes, including
ENSO, the Arctic Oscillation, which is strongly correlated with the NAO (Ambaum et al.
2001), and the PNA pattern. Another study by Millstein et al. (2019) identifies correlations
between climate modes and wind regime frequency using data collected from wind farms
located in California. They conclude that those linkages provide valuable information about
resource characterization and forecasting. We will further exercise the idea that large scale
modes of variability and climate anomalies are correlated and predictable, specifically as it
relates to the magnitude of relationships with ENSO, the PNA pattern, and the NAO, three
prevalent modes of climate variability with teleconnections in the Northern Hemisphere
(NH).

For energy systems, absolute values in wind, sun, and temperature provide the necessary
perspective for planning where to install infrastructure and when to expect surpluses and
deficits in energy supply and demand. Future energy systems will be designed considering
absolute values and with respect to seasonal cycles (Jacobson and Delucchi 2011). With this
in mind and from a climate standpoint, we are interested in deviations from absolute values.
Additionally, we do not constrain this analysis to current infrastructure and technology, but
instead consider the possibility of harvesting the energy that nature has to offer which far
exceeds the amount needed to fulfill human energy demand (Jacobson and Delucchi 2011).

For temperature related energy demand, positive temperature anomalies may result in
either an increase or a decrease in heating or cooling demand based on the climatological
average for that location and season. Thus it is important to consider the climatology when
interpreting these results.
a. **ENSO**

ENSO was one of the first climate modes to be recognized. It causes global teleconnections that result from changes to global heat transport emanating from the equatorial Pacific (Bjerknes 1966). It is a coupled ocean and atmosphere system that is dependent on sea surface temperatures (SST) and atmospheric pressure anomalies (L’Heureux 2014). On average, when ENSO is neutral, strong easterly winds prevail in the eastern and central equatorial Pacific, which lead to upwelling and a shallow thermocline, resulting in colder SSTs relative to the western Pacific. This generally coincides with higher sea level pressure (SLP) in the east and lower SLP in the west, creating a pressure gradient which is the mechanism responsible for maintaining the equatorial easterly winds. Prolonged changes to eastern and/or central Pacific equatorial SST and changes to the equatorial atmospheric pressure gradient result in major changes to atmospheric circulation which bring about teleconnections impacting climate across the globe. These alterations to global climate are realized through two major atmospheric circulation patterns: The Walker Circulation, which is an east-west overturning feedback loop that dictates zonal flow at the equator; and the Hadley Cell, which is responsible for inducing tropical-extratropical interactions (Bjerknes 1969; Diaz et al. 2001).

Most of the time, when ENSO is neutral and conditions are consistent with the climatological average, vertical columns of rising air incite significant convection in the western Pacific and western Atlantic. A dominant column of subsidence persists in the east Pacific, and strong easterly winds prevail at the surface, which instigates upwelling and keeps SSTs in the central equatorial Pacific relatively cool (Bjerknes 1969). The areas of
convection and subsidence along the equator are connected with and respond to one another, forming a feedback loop named the Walker Circulation (Figures 1 and 2).

**Figure 1.** Global equatorial ENSO neutral Walker Circulation. From Di Liberto (2014).

**Figure 2.** Pacific equatorial ENSO neutral Walker Circulation with sea surface temperature and thermocline cross section. From Pacific Marine Environmental Laboratory (2005).

During the negative phase of ENSO (La Niña), the Walker Circulation is amplified, meaning the columns of convection become more intense as do the columns of subsidence.
(Figures 3 and 4). SSTs in the western Pacific are anomalously warm (yellow shading), thus further enhancing convection in that region and resulting in below average surface pressures. Meanwhile the surface of the ocean becomes even cooler (blue shading) in the east as surface pressures increase and the easterlies intensify. The result is an even stronger pressure gradient across the tropical Pacific Ocean that strengthens the Walker Circulation and is maintained through this ocean-atmosphere feedback. Also typical during La Niña is an increase in convection in the tropical Atlantic, which leads to stronger easterly winds across the Sahara Desert and equatorial Atlantic, which aids tropical cyclone development. It has been shown that ENSO is directly correlated with the Atlantic hurricane season (Xie et al. 2005).

Figure 3. Global equatorial La Niña Walker Circulation. Yellow shading indicates warm SST anomalies while blue shading indicates cold SST anomalies. From Di Liberto (2014).
During the positive phase, El Niño, the opposite patterns of convection and subsidence occur, and the Walker Circulation is essentially reversed. The columns of subsidence become the columns of extreme convection, while the western Pacific and western Atlantic become the areas where subsidence occurs. This is believed to occur as a result of a weakening or perhaps even a reversal of the east-west pressure gradient along the equatorial Pacific Ocean, which results in a shallower thermocline and therefore warmer SSTs in the central and eastern equatorial Pacific (Figures 5 and 6).
Figure 5. Global equatorial El Niño Walker Circulation. Yellow shading indicates warm SST anomalies while blue shading indicates cold SST anomalies. From Di Liberto (2014).

Figure 6. Pacific equatorial El Niño Walker Circulation with sea surface temperature and thermocline cross section. From Pacific Marine Environmental Laboratory (2005).
These anomalies in equatorial heat displacement are well documented and have been recognized to induce tropical-extratropical interactions that have an effect on the global energy balance and give rise to teleconnections all around the globe (Kiladis and Diaz 1989). We expect to see evidence of this in our subsequent analysis as a validation step. The exchange of energy between the tropics and higher latitudes is recognized via the Hadley Circulation, which is described as a cell in each hemisphere that circulates tropical air in the upper atmosphere poleward before descending in the subtropics and flowing back towards the equator down near the surface (Figure 7).

Figure 7. Hadley Cell general circulation. From Barnston (2014).
During El Niño, latent heating in the upper atmosphere released by condensation due to the excess heat provided by increased SSTs strengthens the Hadley circulation. This causes changes to the meridional pressure gradient, which influences the strength and location of the jet stream and causes considerable changes to the atmospheric circulation. This gives rise to a multitude of climate anomalies (Ropelewski and Halpert 1986; Trenberth et al. 1998; Diaz et al. 2001). These processes occur predominantly in the winter hemisphere.

There are four Niño regions, which are located along the central equatorial Pacific; they are the Nino1+2 (0°–10°S, 90°W–80°W), Nino3 (5°N–5°S, 150°W–90°W), Nino3.4 (5°N–5°S, 120°W–170°W), and Nino4 (5°N–5°S, 160°E–150°W). ENSO is tracked using the Oceanic Niño Index (ONI), which is calculated based on SSTs in the Nino3.4 region averaged over a three month period and compared to the recent 30 year SST average. In order to be declared an official El Niño or La Niña, the ONI must exceed an anomaly of ±0.4°C for five overlapping, consecutive three month seasons. But because ENSO is a coupled ocean and atmosphere system, El Niño and La Niña are not officially declared by the National Oceanic and Atmospheric Association (NOAA) unless SLP gradients in the Pacific are strong enough to allow changes to atmospheric circulation that are fundamentally tied to ENSO. In any case, this research does not follow these official declarations for El Niño and La Niña.

Instead, we consider any value above 0 to be El Niño and values below 0 to be La Niña. “El Niño” is the name given to the oceanic measurement of SST anomalies, while the Southern Oscillation, first described by Sir Gilbert Walker in 1923, is measured based on the SLP gradient between Tahiti and Darwin, Australia. It was Bjerknes (1969) who identified the distinct pattern of convection and subsidence in the tropics and referred to this pattern as the Walker Circulation.
Defining accurate El Niño indices has become an issue due to Earth’s warming climate (Figures 8 and 9). A solution to this problem has been proposed by climate scientist Geert Jan van Oldenborgh, who recognized that defining El Niño indices in a warming climate must be done in a way that relativizes SST anomalies in the Nino regions to the SST anomaly of the entire tropics (20ºN-20ºS) (van Oldenborgh et al. 2021). Changes to equatorial convection and subsidence do not occur as a result of locally warm SST unless it is anomalously warm compared to the rest of the tropics. Thus this relative index provides a more accurate representation of ENSO (Figure 10).

Figure 9. 30 year average SST base periods for the Niño3.4 region, starting with 1936-1965 and ending 1991-2020. From Climate Prediction Center Internet Team (CPC 2017).

Figure 10. Regular versus relative ONI, 1950-2021. Top panel shows the time series of the Oceanic Niño Index (ONI). Bottom panel shows the time series of the relative ONI. Red shading depicts El Niño episodes and blue shading depicts La Niña episodes. From L’Heureux (2021).
b. **PNA**

The Pacific-North America (PNA) pattern is a NH climate mode that is active in all months besides June and July (Trenberth et al. 1998). It is the second leading mode of rotated principal component analysis (RPCA) of NH extratropical atmospheric circulation, as determined by Barnston and Livezey (1987). It is directly associated with the winter storm track over North America, therefore having notable implications for U.S. surface climate (Leathers et al. 1991, Leathers and Palecki 1992).

The PNA pattern is defined by pressure anomalies in four regions. There are anomalies of the same sign (negative during the positive phase) near the Aleutian Islands in the North Pacific (NPAC) and in the southeast U.S., and two of the opposite sign located in the subtropical Pacific near Hawaii and spanning much of western North America (positive during the positive phase) (Franzke et al. 2011). This pressure quartet is an example of a planetary wave train which causes major changes to atmospheric pressure and the jet stream (L’Heureux 2019). Planetary waves, also known as atmospheric Rossby waves, naturally occur as a result of the rotation and distribution of heat on Earth, as well as Earth’s geography. These waves transfer heat from the equator poleward and cold air at the poles equatorward in order to maintain atmospheric balance. Rossby waves are slow moving, and their persistence leads to consistent weather patterns that make up Earth’s climate (National Weather Service 2014). Changes in atmospheric pressure are important for renewable energy systems because they influence the general circulation which dictates climatological surface conditions. Furthermore, a pressure anomaly in one region often results in an opposite anomaly nearby (L’Heureux 2019).
The positive and negative phases of the PNA have opposite anomalies because it is determined linearly via RPCA of geopotential height (CPC 2012b). During the positive phase of the PNA pattern, the anomalous high pressure centered in western North America leads to warmer than average temperatures across Canada and the west coast of the U.S. (Figure 11). This often leads to a “blocking high” over the western states, which is described as a persistent area of high pressure responsible for above average temperatures and below average wind power in western North America, as well as an increased likelihood of precipitation drought throughout the southwest (Wallace and Gutzler 1981; L’Heureux 2019).

Research by Feldstein (2000) concludes that accurate predictions of the PNA are limited to about 10 days. We can make seasonal predictions of the PNA during winter to a pretty good degree of accuracy based on the state of the ENSO, though forecasts of the PNA index for a given week (more than 1 week out) are not reliable. The Nino3.4 relative time series and the PNA time series have a correlation $r=0.584$ averaged over all DJF from 1979-2020, with the positive phase favored during El Niño and the negative phase favored during La Niña. The PNA pattern certainly makes up about 10% of atmospheric pressure configuration during the cold months (Barnston and Livezey 1987, Figure 3), and each phase has tangible teleconnections to North American climate, namely in temperature and precipitation. We will take this a step further and compare with wind speeds and solar radiation as well.
The North Atlantic Oscillation (NAO) is recognized as the leading NH climate mode having teleconnections in all 12 months of the year (Barnston and Livezey 1987). It can be defined by pressure anomalies in the geopotential height field (generally SLP, 700hPa, 500hPa, or 200hPa) located over and to the east of Greenland and due south in the central Atlantic from 30°N–35°N, as shown in Figure 12 (Wallace and Gutzler 1981; Barnston and Livezey 1987; Hurrell 1995). The Atlantic center often stretches from the eastern half of the U.S. to western Europe. Pressure anomalies in the central and North Atlantic give rise to major changes in the strength and location of the North Atlantic jet stream, affecting climate
across the Atlantic Ocean and throughout Europe as well as the Middle East and eastern United States (CPC 2012a).

One important feature of the NAO is the relatively low frequency exerted by its time series, meaning that this mode tends to favor one phase for months at a time, sometimes over the course of multiple seasons. The NAO time series also exhibits decadal trends, often preferring one phase over another on the order of 10-15 years (Hurrell 1995). This leads to persistent climate conditions over entire seasons. Therefore the NAO has major implications for energy demand via heating and cooling. Another motivation to analyze this mode and its teleconnections is the relative seasonal predictability of the NAO (Athanasiadis et al. 2020).

The positive phase tends to correlate with warmer temperatures and increased precipitation across northern Europe, while cooler temperatures and decreased precipitation are expected in southern Europe and the Middle East. Because the NAO is determined through linear analysis of geopotential height fields, the negative phase produces the opposite anomalies. The negative phase is a serious concern for North Atlantic blocking, which leads to summer heatwaves and precipitation droughts across Europe (CPC 2012a).
d. Climate change

While a report by Karnauskas et al. (2018) claims that future wind power will decrease over NH mid-latitudes as a result of climate change, other research by Pryor and Barthelmie (2011) states that wind is subject to hourly, daily, seasonal, annual, and decadal changes that are not any more attributable to climate change than the nature variability of climate itself. Their research finds no evidence of a decrease in the wind resource over the contiguous U.S. in the next 50 years, attributing any climate change signals to model weakness. Wang et al.
(2018) suspects shifting wind patterns as a result of climate change, though their analysis finds no evidence of a decrease in the wind resource over the next 50 years.

e. Teleconnection mechanisms

Aside from identifying teleconnections between climate modes and anomalies in wind, sun, and temperature in remote regions, it is useful to discuss the physical mechanisms that result in teleconnections. For ENSO, the physical mechanism is realized through changes to the Hadley Cells’ influence on upper level atmospheric dynamics (Bjerknes 1969). Earth’s rotation and the natural distribution of heat result in a semi-constant west-to-east flow of air in the upper atmosphere of the midlatitudes. This flow has a wave-like motion to it that has semi-consistent features, such as persistent pressure centers like the Aleutian Low, the Icelandic low, the Azores High, etc., which help explain the fundamental aspects of the climate that are observed. The westerly winds are maximized where the pressure gradient is strongest, which is referred to as the jet stream. The strength and location of the jet stream determines the strength and location of the mid-latitude storm track; therefore the phases of ENSO are strongly correlated with climate variables in the mid-latitudes, especially during winter months when pressure gradients are strongest.

Portions of the jet stream are fundamentally affected by the PNA pattern and NAO because they are associated with pressure anomalies in the mid to high latitudes which have a strong influence on the strength and location of the jet stream. The NAO influence on the jet stream causes meridional changes to the storm track, which leads to high latitude North Atlantic blocking during the negative phase, and major blocking events over central Europe during the positive phase (Athanasiadis et al. 2020). This causes prolonged heat waves across Europe and is therefore a concern for energy supply and demand (Hurrell 1995). The PNA
has a downstream effect on the pressure gradient over the U.S., creating a pressure dipole over the nation which shows the need for long-range energy transmission in order to pool resources from areas experiencing opposite climate anomalies. The different phases of the PNA and NAO have direct influence on the position of the jet stream. Therefore they have an influence on the location of mid-latitude storm tracks and surface climate. This is most notable during NH winter months.

When the NAO is positive, the jet stream in the North Atlantic is located further North, causing the storm track to be farther north. During the negative phase, the jet stream and associated storm track are farther south. When the PNA is positive, a large high pressure anomaly forms over much of North America, which generally weakens the jet stream and pushes it farther north. During El Niño, enhanced tropical convection thrusts warm air at the surface up into the upper troposphere and therefore expands the Hadley Cell, which results in a disturbance to the Rossby wavetrain—called Rossby wave breaking, altering the atmospheric circulation in remote regions. A similar process occurs in the NPAC and in the North Atlantic. This led to the naming of these climate modes, the NAO and the PNA, in which pressure anomalies in these regions have a downstream influence which occurs through Rossby wave breaking.

f. **Hypothesis**

There is a dearth of research concerning climate teleconnections with renewable energy resources. Most studies have focused on temperature and precipitation impacts (Guan et al. 2013; Yeh et al. 2018). This thesis project investigates ENSO, PNA, and NAO teleconnections to global climate anomalies, particularly in relation to the wind and solar resources as well as temperature, which is used as a proxy for energy demand. We
hypothesize that these climate modes have heterogeneous relationships to wind and solar power supply and two-meter temperature. We expect that negative (positive) anomalies with 500hpa geopotential height will coincide with negative (positive) anomalies in solar radiation and temperature, and positive (negative) anomalies with wind speed. Furthermore, we predict the spatial scale of climate anomalies will be comparable to the scale of planetary longwaves, on the order of about 3000-6000 kilometers.
3. Data & Methods

This research utilizes the European Reanalysis Assessment volume 5 (ERAv5), covering 42 years of monthly climate data from 1979-2020 over the entire globe with a spatial resolution of 0.25° x 0.25°. We compute the anomalies of two-meter temperature (T2m), ten-meter wind speed (10m wind speed), surface solar radiation (SSR), and 500hPa geopotential height (Z500) for each season (DJF, MAM, JJA, SON) and compare them with the time series of three prominent climate modes. For monthly data, “anomaly” implies that the mean of all January values is calculated and then subtracted from all individual January values, the mean of all Februarys is subtracted from the February values, etc. in order to remove seasonal cycles from the analysis.

We employ the relative Extended Reconstructed Sea Surface Temperature (ERSSTv5) dataset to analyze ENSO teleconnections. The Niño3.4 index is determined by SST anomalies as they compare to the most recent 30-year average; it is the most widely used index for investigating ENSO teleconnections (van Oldenborgh et al. 2021). This time series is relative to tropical (20°S–20°N) SSTs, a minor adjustment designed to offset a global warming trend that causes El Niño events to appear to be strengthening and La Niña events to appear to be weakening over time due to warming temperatures throughout the dataset (section 2a, Figure 10). Monthly indices of the PNA pattern and the NAO are calculated by the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) based on Rotated Principal Component Analysis (RPCA) as in Barnston and Livezey (1987). The RPCA technique is applied to monthly mean standardized 500hPa height anomalies in the region 20°N–90°N. The NAO is recognized as the first rotated empirical orthogonal function of monthly 500hPa height anomalies and the PNA is the second
The time series of the Nino3.4, PNA, and NAO indices used for this research are obtained from the World Meteorological Organization (WMO) Climate Explorer for the inclusive period 1979-2020.

We use correlation coefficients and linear regressions to calculate the strength and magnitude of relationships between climate mode and climate variables. The correlation coefficient value “r” represents the strength of relationship between two variables on a scale of -1 to 1. The equation used to calculate correlation coefficients is

\[ r = \frac{(x_i-\bar{x})(y_i-\bar{y})}{(x_i-\bar{x})^2(y_i-\bar{y})^2}. \]  
(Eq. 1)

R-values close to 0 indicate low magnitude of linear relationships, while results further from 0 indicate more significant inverse or direct relationships, depending on the sign. We then perform a linear regression using each climate index as the independent variable (X) and the climate variables as the dependent variable (Y). The equation used to calculate linear regression is

\[ Y = mX + b. \]  
(Eq. 2)

The slope “m” represents the magnitude of the relationship at each grid point. This is the value plotted in figures 13-20, 22-29, 32-40, and 42. These calculations are performed individually for all 1,038,240 grid points in the reanalysis dataset for each month from 1979-2020 with the three climate indices. We replace all grid points where |r| < 0.3 with a value of zero in order to mute relationships with a correlation coefficient of less than 30%. With 42 years of data (N = 42), a correlation coefficient of \( r > \pm 0.3 \) equates to \( p=0.046 \). Thus all values plotted have a statistical significance above the 95% threshold. We form a visual representation of global teleconnections, both concurrently and as time-lagged relationships.
between the four seasons (DJF, MAM, JJA, SON) and the immediately preceding month. We find that comparing one month’s time series with the following three months’ climate anomalies yields a more significant result than averaging over a three month period and comparing that result with the following season.

We also analyze teleconnections on smaller scales. We provide time series of normalized monthly wind speed over the continental United States (CONUS) plotted together with ENSO, PNA, and NAO time series. We made histograms of CONUS wind speeds when the teleconnections are greater than 1 or less than -1 standard deviation from the mean value. The purpose of this analysis is to present how extreme phases of climate indices impact the wind resource over a region of the globe that is highly populated and will be utilizing the wind resource for energy supply. Furthermore, we provide figures of daily wind speed at wind farms, solar at solar farms, as well as cooling-degree days and heating degree days. This data was provided by Pacific Gas and Electric (PG&E) and collected at solar and wind farms in California. These results show that there are teleconnections to weather on shorter time scales and over a smaller area as well, which support some of the findings from the seasonal analysis.

In order to apply some qualitative analysis of climate modes’ influence on future energy systems to our data, we have created Table 1 to define eight categories to represent relationships with above or below average wind and solar supply and temperature related demand. Category 1 is the best case scenario for renewable energy supply and demand. It applies when there is above average wind power, above average solar power, and below average temperature related energy demand. Surpluses in temperature related energy demand are defined by heating or cooling degree days. Degree days compare the mean temperature to
a standard temperature of 65º Fahrenheit (F). The greater the departure from 65ºF, the greater the value of a heating or cooling degree day. Categories 2 and 3 represent a shifted supply, meaning above average solar with below average wind (category 2) or vice versa (category 3), coupled with low demand. Category 4 is the high supply, high demand scenario, featuring high wind and solar power coupled with high demand. Categories 5 and 6 apply when there is shifted supply, as in categories 2 and 3, though in this case coupled with high demand. Category 7 describes cases of below average wind and solar supply, but with below average demand. Lastly, category 8 represents the worst case scenario. This applies when wind and solar supply are below average, and temperature related demand is high.

Table 1. Qualitative analysis of teleconnection patterns. Green spaces represent below average stress, indicating high wind power, high solar power, or temperatures closer to 65 degrees F. Red spaces represent above average stress, indicating low solar, low wind, or temperatures further away from 65 degrees F.

<table>
<thead>
<tr>
<th>Wind</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dem.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>High supply, low demand</td>
<td>Shifted supply, low demand</td>
<td>Shifted supply, low demand</td>
<td>High supply, high demand</td>
<td>Shifted supply, high demand</td>
<td>Shifted supply, high demand</td>
<td>Low supply, low demand</td>
<td>Low supply, high demand</td>
</tr>
</tbody>
</table>

From this table, we are particularly looking for category 8 scenarios because they pose the greatest threat to energy systems that are highly dependent on renewables. A deficit in wind power and solar radiation coupled with a surplus in demand puts a great deal of stress on energy systems, so forecasting such events is critical. The extent to which we do not find these scenarios in our results is a positive outcome.
a. Limitations

Performing a monthly analysis can be limiting because climate is subject to changes on hourly, daily, weekly, monthly, and seasonal timescales. However, a lull in wind or sunlight averaged over a month or season would be very impactful, so it is a valuable analysis even if there were no instances of this, though we do see several teleconnections on this scale.

Some climate scientists consider ENSO to be nonlinear. Several studies have employed a non-linear cluster analysis approach to investigate ENSO teleconnections. While there are non-linearities involved in ENSO, the majority of teleconnections are linear, which we confirmed through difference comparison of global 500hPa geopotential height during positive and negative phases of the Nino3.4. This difference comparison revealed similar teleconnections to the regression plots that are displayed in the results, which indicates that the majority of ENSO teleconnections are linear, despite some local anomalies that may occur during one phase without an opposite response during the other phase.

Ten-meter wind speed is used here as a proxy for actual wind turbine hub-height wind speed. Nevertheless, over broad areas, windier conditions at the surface translates to windier conditions higher above ground level, especially when diurnal patterns are not considered. Since we are interested in general relationships between wind, sun and temperature this will suffice despite the exact hub-height of wind turbines.

While our current ability to forecast climate modes is limited, ensemble models used to predict climate modes such as the ENSO, PNA, and NAO are improving (Smith et al. 2020). Reanalysis datasets also continue to become more robust with time. We had hoped to have access to the extended ERA5 reanalysis package dating from 1949-present for this research,
but this data was not available in time for completion of this project. Certainly a similar analysis should be performed once that data becomes readily available.

The PNA exhibits changes from week-to-week, rarely remaining in one phase over the course of an entire month. During many months, the value of the PNA may be negative for half of the month before switching to the positive phase for the rest of the month, which would then be averaged out to a neutral value or slightly favor one phase. This may not always portray an accurate depiction of the PNA pattern index. A weekly or even daily analysis of the PNA may offer a different representation of its teleconnections to wind, sunlight, and temperature.
4. Results

This research investigates three major modes of climate variability and their teleconnections to wind speed, temperature and solar radiation. We identify anomalies to 500hPa geopotential height to infer anomalies associated with surface variables on a seasonal timescale using monthly reanalysis data. To achieve this, we conduct statistical analyses comparing each climate variable with the time series of each climate index, repeating this process individually for winter, spring, summer, and fall. The motivation for performing a seasonal analysis, opposed to an annual one, is to provide a more accurate depiction of anomalies because the background circulation changes from season to season. An annual analysis would smooth over seasonal differences and mix anomalies that occur independently as a result of seasonal change. The goal is to identify significant concurrent or time-lagged regressions between synoptic climate variables and climate modes. If certain meteorological anomalies were to recur in response to the state of some climate index, or if some tangible, quantitative recurring climatic or atmospheric phenomena proved to be a good predictor of renewable energy variability, it will be valuable for energy planners to know the degree to which renewable energy resources (and energy demand) are constrained by large scale modes of variability.

The results show that the Nino3.4 index has global climate teleconnections that are concurrent with the time series and are maintained when a one month time-lag is imposed. The NAO and the PNA pattern each have significant concurrent relationships, but the one month time-lagged relationships are nearly non-existent. This is due to the fact that these modes are not persistent from month-to-month therefore their value in one month cannot be used to predict climate anomalies in future months. Temperature and solar radiation are often
correlated on land but are anti-correlated in the tropical oceans because warm SSTs drive convection which leads to cloudy conditions. Relationships with all variables are generally more coherent over the oceans than over land, which can help plan a strategic spatial distribution of offshore wind and solar farms as this technology comes to fruition in the future.

Each figure is made up of four panels. The top two panels, a. surface solar radiation (SSR) and b. 10-meter wind speed (10m wind speed), are used to infer energy supply. Panel c. is used to infer demand from two-meter temperature anomalies (T2m) while panel d. displays anomalies in the upper level circulation, at the 500hpa level (Z500), which we use to understand potential physical causality of surface anomalies. It is important to remember that because we are analyzing anomalies, not absolute values, one must consider the climatology before drawing conclusions about energy supply and demand for a particular region.

a. *Nino3.4 concurrent*

Beginning with DJF, the ENSO-related changes to the Walker Circulation are clearly evident in the plot displaying SSR anomalies (Figure 13a). There is a strong, positive regression between the Nino3.4 and SSR in the Maritime continent and the equatorial Atlantic, and a strong, negative regression in the Nino3.4 region, on the order of 20-25 \( Wm^{-2}C^{-1} \). The relationships with two-meter temperature are consistent with previous ENSO teleconnection research, which reveals positive relationships in the eastern tropical Pacific and in North America (Figure 13c). There is a profound negative relationship with geopotential height in the NPAC and a dipole over North America, featuring a positive anomaly over Canada and negative anomaly over the southern part of the continent (Figure 13d). These height anomalies co-occur with a positive regression with temperature in the
Gulf of Alaska and northern North America and a negative relationship to the south (Figure 13c), which is also consistent with previous ENSO teleconnection research. The most significant relationship with wind speed during DJF takes place in the NPAC (Figure 13b). This relationship supports one of the central arguments of this research: absolute low heights at the 500hPa level induce an increase in wind speed at all levels, a claim that is backed by the fundamental theory that geostrophic flow is stronger around low pressure, and that increased winds aloft translate to an increase in wind near the surface. The opposite is true in the case of absolute high pressure. This result is clear in the research displayed herein and is most pronounced over the oceans. A negative relationship with wind speed in the central equatorial Pacific is evidence of the changes to the equatorial easterly winds that occur during the different phases of ENSO (Figure 13b). In the equatorial Atlantic, there is a negative regression with 10m wind speed that co-occurs with a positive regression with 500hPa geopotential height (Figures 13b,d). There is also evidence of a weak, negative regression with 10m wind speed in the central U.S, though relationships are no greater than 0.5 m s\(^{-1}\) (Figure 13b). Lastly, during DJF the entire tropics, from 20°S-20°N, experience a positive relationship with 500hPa height, which is evidence of ENSO-induced changes to the Hadley Cells caused by latent heating of condensation in the upper atmosphere.
The SSR pattern in conjunction with the Walker Circulation, described above, persists during MAM (Figure 14a). In fact, the magnitude of these relationships becomes even stronger and more expansive than during DJF, extending from the eastern Pacific to the Indian Ocean. The negative relationships with 500hpa heights in the NPAC and southern North America also persist, and the relationships with SSR and T2m are in phase and become more profound (Figures 14a,c). There is a negative regression with wind speed over the western half of the U.S. (Figure 14b). The positive phase of ENSO could be a concern for future energy grids during MAM in the southwestern U.S. as anomalously low SSR and 10m wind speed (Figures 14a,b) cause a supply shortage. However, there is a decrease in temperature in the southern states, which will decrease cooling demand for this region based on the climatology. This adds up to decreases in wind and solar supply and a decrease in energy demand (Category 7). Also during the positive phase in MAM, the northwest U.S.
will experience an increase in solar supply and temperature, decreasing demand (Category 2). This emphasizes the importance of large energy grids capable of supporting long range transmission. Climate is rarely consistent across entire continents, and so while one region experiences supply shortages, another region nearby will likely experience supply surpluses.

![Image of weather patterns and correlation charts]

*Figure 14. Same as figure 13, but for March, April, May (MAM).*

During DJF and MAM, there is a positive correlation with 500hpa heights covering most points between 20°N-20°S (Figures 13d, 14d), but this relationship is beneath the 30% correlation coefficient threshold during JJA and SON (Figures 15d, 16d). Interestingly, there is an area spanning much of eastern Europe with a negative relationship in 500hPa geopotential height (Figure 15d) that coincides with a negative relationship with T2m of about -1.5°C (Figure 15c) and a negative relationship with SSR of approximately 10 Wm⁻² (Figure 15a). This would fall under a shifted supply, low demand category during El Niño years; cooler summer temperatures decrease energy demand while anomalously solar radiation increases stress on supply for that region (Category 3). The opposite would be the case during La Niña (Category 6). Other teleconnections during JJA are mostly insignificant.
on land, but the strengthening effect ENSO has on the Hadley Cells is evident through the negative relationships with 500hPa height in both hemispheres (Figure 15d). At around 30ºS, there is a positive regression with 10m wind speed and a negative regression with 500hpa heights (Figures 15b,d). Here, the descending branch of the southern Hadley Cell is strengthened during the positive phase due to excess tropical heating (and weakened during the negative phase). This leads to an increase in the strength of the subtropical jet stream (Figure 15b).

During SON there is a weak, negative relationship with 500hpa heights extending from the central NPAC to the U.S. southwest (Figure 16d). There is a negative relationship with SSR for much of the southern half of the continental U.S. (Figure 16a), which is likely a result of a more southerly storm track during El Niño. This coexists with a negative relationship in T2m near Texas (Figure 16c). This would lead to a decrease in energy supply and a decrease in demand during El Niño years. There are no significant relationships with 10m wind speed on land in the NH, but there is a positive relationship in the central NPAC

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*Figure 15. Same as figure 13, but for June, July, August (JJA).*
coupled with the negative height anomaly (Figure 16b). The ENSO influence on the Walker Circulation is evident in the SSR plots during all four seasons.

Figure 16. Same as figure 13, but for September, October, November (SON).

b. Nino3.4 time-lagged

The November, February, May, and August Nino3.4 time series’ have strong correlations with climate variables in the following seasons. The strength associated with these regressions can be attributed to the relatively low variability exhibited by the Nino3.4 time series from month to month. In any case, the time-lagged regressions with 500hPa geopotential height are nearly identical to the concurrent ones, though relationships with wind speed are generally weaker. For the Nino3.4, using the value of the last month of each season to predict climate variables for the following season is accurate when compared to concurrent relationships.

Comparing the November Nino3.4 timeseries with climate variables during DJF reveals very similar regressions to the concurrent relationships with DJF (Figure 17). There remain positive relationships with T2m and Z500 in the northern U.S. and Canada (Figures 17c,d).
The pressure anomalies in the NPAC and over North America remain as well. 10-meter wind speed in the NPAC have the opposite relationship to 500hpa height (Figure 17b). The SSR patterns that are associated with the ENSO phases of the Walker Circulation are predicted as well (Figure 17a).

![Image](image_url)

**Figure 17.** Linear regressions between the November Nino3.4 time series and monthly surface solar radiation, 10-meter wind speed, two-meter temperature, and 500hPa geopotential height anomalies averaged over DJF.

When using the February Nino3.4 time series to predict climate anomalies in MAM, we see that relationships are nearly identical to the concurrent ones, albeit slightly less in magnitude (Figure 18). There is about a 10-15% decrease for solar radiation, temperature, and 500hpa heights while the magnitude of relationships with wind speed decrease by a greater amount, about 50% (Figures 17a-c). This tells us that the February Nino3.4 can be used effectively to forecast seasonal climate-related energy supply and demand anomalies in MAM.
Figure 18. Same as Figure 17, but for the February Nino3.4 time series and MAM climate variables.

Figure 19 compares the May Nino3.4 time series to JJA, revealing relationships that do not occur as concurrent relationships. A negative regression with pressure over the western U.S. concurs with negative regressions in surface solar radiation and temperature (Figures 19a-d). Similar relationships occur in eastern Europe. Climatologically speaking, when the Nino3.4 index is positive in May, this would result in a decrease in energy supply from anomalously low solar radiation. However, that would be offset by cooler summer temperatures and therefore a decrease in demand. The opposite relationship, increased solar supply and increased cooling demand, would occur during the negative phase.
Figure 19. Same as Figure 17, but for the May Nino3.4 time series and JJA climate variables.

As displayed in Figure 20, using August to predict SON also depicts negative regressions with geopotential height, temperature, and surface solar radiation in the U.S., but they are shifted further to the south than during JJA (Figures 20a,c,d).

Figure 20. Same as Figure 17, but for the August Nino3.4 time series and SON climate variables.
The motivation for creating Figures 13-20 stems from the histograms of monthly wind speeds over the continental U.S. shown in Figure 21, obtained via personal communication with Dr. Patrick Brown. This figure reveals that below average wind speeds are favored during the positive phase of ENSO, and above average wind speeds are favored during the negative phase. While the departure from the mean is rather small, this is an important finding over a large region at the monthly scale. Furthermore, the probability of extremes is heavily shifted; the most negative extremes in wind speed are much more likely to occur during the negative phase while positive extremes occur during the positive phase. This is not obvious in figures 13-20 but is useful for energy planners to know during strong El Niño and La Niña events.

![Figure 21.](image1)

*Figure 21. (Top panel) Time series of monthly normalized wind speeds over the continental U.S. compared to the Nino3.4 time series. (Bottom panel) Histogram comparison of wind speeds during the positive and negative phases of ENSO. Figure provided from personal communication with Dr. Patrick Brown.*
Figure 22 offers a higher resolution view of Nino3.4 teleconnections over North America during DJF. There are negative regressions with SSR and T2m in the central southern U.S. and Mexico and a positive regression with temperature in the north, and anomalously low wind power in the central U.S. Above average heights occur over Canada and below average heights occur in the NPAC and over southern North America.

![Figure 22](image_url)

*Figure 22. Same as Figure 13, but over North America only.*

c. **PNA concurrent**

Figures 23-26 display the magnitude of the concurrent relationships between the PNA pattern index and the four variables of interest. As expected based on the research of Wallace and Gutzler (1981), PNA teleconnections are most significant during DJF (Figure 23). Pressure relationships are in agreement with observations of the PNA pattern. There is a positive relationship with SSR over the maritime continent and negative relationship in the central equatorial Pacific. Negative relationships with SSR also exists where the southeast pressure center resides near the Gulf of Mexico and the Caribbean. There is a positive relationship near the Hawaiian Islands (Figure 22a). One trivial aspect of SSR relationships is
the positive relationship in the region of the Aleutian Low. Typically, we would expect a negative relationship with SSR to coincide with a strong negative relationship with pressure (Figure 22d). There is a positive relationship with SSR near Alberta, Canada, and a negative relationship in the central U.S. There are weak negative relationships with 10m wind speed in North America. No other relationships with wind speed appear over land surfaces. A strong positive relationship exists in the NPAC where the Aleutian Low is a productive center of cyclogenesis and storm activity which leads to high winds. Most notably, there is a strong positive regression of up to 4°C spanning much of Canada, Alaska, and the U.S. northwest which coincides with a positive relationship with 500hPa geopotential height (Figure 22c).

During MAM, there is still this curious positive relationship with surface solar radiation in the NPAC that now expands to the Bering Sea coastal areas of Alaska and Siberia. This does not agree with the strong negative center in the NPAC and negative relationship with
temperature. Wind speed teleconnections do not occur on land. There is a negative relationship of about 0.5 \( ms^{-1} \) covering much of the equatorial Atlantic and in the North Atlantic as well (Figure 24b). There is now an even larger area of negative relationship with temperature over the southern third of the North American continent, and still a positive relationship with temperature covering much of the northern third of the continent (Figure 24c). These relationships with temperature are consistent with our expectations of the effects of the relative pressure anomalies associated with the PNA pattern during MAM and they appear to extend to the Atlantic, causing remote teleconnections with wind speed, surface solar radiation, and temperature (Figure 24d).

Figure 24. Same as Figure 23, but for MAM.

Figure 25 reveals a positive regression between the PNA pattern and 500hpa height in the tropics and the Arctic (Figure 25d). There are positive regressions with T2m in the tropics (Figure 25c) and a negative regression with SSR in the eastern equatorial Pacific (Figure 25a).
During SON, a positive regression with 500hPa heights in western North America returns along with a positive regression with temperature (Figures 26c,d). This relationship is significant for energy demand because it tells us that this region will be warmer during NH fall, resulting in a decrease in energy demand. A negative regression with 500hPa geopotential height in the NPAC drives a positive regression with 10m wind speed (Figures 26b,d).
Figure 26. Same as Figure 23, but for SON.

d. **PNA time-lagged**

There are not relationships with a correlation coefficient above 30% between the November PNA time series and DJF climate anomalies with implications for renewable energy resources (Figure 27).

Figure 27. Linear regressions between the November PNA time series and monthly surface solar radiation, 10-meter wind speed, two-meter temperature, and 500hPa geopotential height anomalies averaged over DJF.
Comparing February and the following season’s variables, there is a small region that has positive relationships with solar radiation and temperature in central Canada (Figures 28a,c). There is also evidence of the negative regression between the PNA pattern and the Aleutian Low (Figure 28d).

![Image](image.png)

*Figure 28. Same as Figure 27, but for the February PNA time series and MAM climate variables.*

The May PNA time series does not offer predictions of JJA climate anomalies (Figure 29).
Between August and SON, the western U.S. experiences positive regressions SSR with T2m and 500hPa geopotential height (Figures 30c,d).

Overall, the state of the PNA pattern index in February, May, August, and November does not have significant teleconnections with the following season.
In Figure 31, it is evident that the mean wind speed is shifted during the opposite phases of the PNA. The mean wind speed during the positive phase is below average, while the mean wind speed during the negative phase is above average. Additionally, similar to Nino3.4 wind speed teleconnections, the probability of extremes is heavily shifted. The most negative extremes in wind speed occur during the positive phase of the PNA while the positive extremes occur during the negative phase.

Figure 31. (Top panel) Time series of monthly normalized wind speeds over the continental U.S. compared to the normalized PNA time series. (Bottom panel) Histogram comparison of wind speeds during the positive and negative phases of the PNA pattern. Figure provided from personal communication with Dr. Patrick Brown.

Figure 32 offers a higher resolution view of PNA teleconnections over North America during DJF. We see a negative regression with wind speed over parts of the continent and a strong temperature regression over the north half of the continent. In the NPAC, anomalously low 500hPa geopotential height coincides with anomalously strong 10m wind speed.
Figure 32. Same as Figure 23, but over North America only.

e. **NAO concurrent**

The relationships between the NAO index and 500hPa height that occur during DJF are quite profound (Figure 33d). There is a very strong, negative relationship with Z500 about the Icelandic Low and positive relationship due south about the Azores High of nearly the same size and strength. The anomalous low pressure that occurs during the positive phase spans from the Hudson Bay to Scandinavia and the North Sea, while the high pressure to the south spans across the U.S. and the Atlantic to the Mediterranean. This leads to a Northward shift in the Atlantic storm track during the positive phase and a southward shift during the negative phase. This goes along with a strong positive regression with temperature for nearly all of Europe and Russia (Figure 33c). Temperature regressions of up to 4°C exist for much of the area, which is a major concern for energy demand during the negative phase due to a negative temperature anomaly during a climatologically cold season. Meanwhile decreased wind speeds and below average SSR would decrease energy supply from wind and solar farms in the North Sea (Figures 33a,b). The negative phase of the NAO during DJF is a
worst-case scenario for future renewable energy systems in Europe due to increased heating demand, coupled with decreased solar radiation and wind speed (Category 8).

Figure 33. Linear regressions between the Dec-Feb NAO time series (X, independent variable) and Dec-Feb climate anomalies (a. surface solar radiation, b. 10m wind speed, c. 2 meter temperature, d. 500hPa geopotential height) (Y, dependent variables) from the period January 1979-December 2020. Only values at grid points with a correlation coefficient of |r| > 0.3 are shown.

During MAM, the pressure dipole from Greenland to the central Atlantic is weaker at its center but becomes more expansive (Figure 34d). The subtropical pressure anomaly also weakens but extends further from the western U.S. across the Atlantic and onto western and central Europe. The resulting temperature anomalies are positive in the western U.S., western Atlantic and northern Europe and negative in the North Atlantic. There are some scattered relationships with surface solar radiation, most notably there is a positive relationship in the western U.S. of about $15 \text{ Wm}^{-2}$ (Figure 34a). The relationships with 10m wind speed during MAM resemble the same pattern in the Atlantic as during DJF but are weaker in magnitude (Figure 34b).
NAO teleconnections become weaker and less extensive during JJA (Figure 35), though the negative regression with 500hPa geopotential height still encompasses the Arctic. The positive anomaly to the south contracts and shifts eastward towards western Europe. Pressure relationships in the Atlantic are consistent with NAO observations, and regressions with T2m, SSR and 10m wind speed that go with pressure anomalies are in phase, though weak in magnitude (Figures 35a-c).
During SON, NAO relationships with SSR are negligible (Figure 36a). There is a positive regression with wind speed in the North Atlantic (Figure 36b). Temperature relationships are in phase with pressure relationships; there are negative regressions with temperature and pressure extending from Greenland to the Hudson Bay (Figures 36c,d).
f. NAO time-lagged

When it comes to the NAO time-lagged relationships, there are a few key features to point out. Using November to predict DJF confirms that the main geopotential height anomalies occur near the Icelandic low and the Azores High (Figure 37d). This analysis may be useful for predicting wind speed anomalies in northwestern Europe (Figure 37b).

Figure 37. Linear regressions between the November NAO time series and monthly surface solar radiation, 10-meter wind speed, two-meter temperature, and 500hPa geopotential height anomalies averaged over DJF.

The most significant NAO time-lagged regressions occur between the February timeseries and MAM climate variables (Figure 38). There is a positive relationship with 500hPa height in Russia that is the mechanism for positive relationships with SSR and T2m (Figures 38a,c). We observe a similar positive relationship with these variables in western Europe. We also observe negative relationships with T2m and Z500 in the Hudson Bay region (Figures 28c,d).
Figure 38. Same as figure 37, but for the February NAO time series and MAM climate variables.

May relationships with JJA are insignificant (Figure 39) and so are August relationships with SON (Figure 40).

Figure 39. Same as figure 37, but for the May NAO time series and JJA climate variables.
Figure 40. Same as figure 37, but for the August NAO time series and SON climate variables.

In Figure 41, it is evident that there is little departure from the mean wind speed over the continental U.S. during the different phases of the NAO.

Figure 41. (Top panel) Time series of monthly normalized wind speeds over the continental U.S. compared to the normalized NAO time series. (Bottom panel) Histogram comparison of wind speeds during the positive and negative phases of the NAO. Figure provided from personal communication with Dr. Patrick Brown.
Figure 42 offers a higher resolution view of NAO teleconnections over North America during DJF. In the southeastern part of the continent, a positive regression with 500hpa height coincides with positive regressions with T2m and SSR. During the positive phase, this would lead to above average T2m and SSR, which would decrease energy demand while increasing supply. The opposite would occur during the negative phase.

![Figure 42](image)

Figure 42. Same as figure 33, but for North America only.

### g. Diurnal analysis

The following three figures come from a personal communication with Dr. Patrick Brown. They are wind at wind farms, weighed by current wind farm capacity, solar at solar farms, weighed by current solar farm capacity, and degree days, weighed by population, all of which is for California. They show the diurnal cycle in our variables of interest for large positive and negative values of the three modes of variability by season. They are normalized by the mean value across all seasons, therefore a 2 on the y-axis should be interpreted as 2 times the mean value for this variable. Figures 43-45 offer a diurnal comparison of the ENSO, PNA pattern, and NAO time series with the variables of interest. From these, we see that there are teleconnections on a finer scale that would be of interest to energy planners in
California. Furthermore, we are able to confirm some of the findings from this research. For example, the plot in the bottom left corner of Figure 44 shows less heating demand during positive PNA in DJF in California, indicating warmer temperatures in California during the positive phase of PNA in the winter. This is consistent with the results in Figure 23, suggesting that our analysis at the seasonal scale is accurate and can be used to motivate similar research on finer temporal and spatial scales. The majority of relationships in these figures do not reveal strong teleconnections between climate modes and wind and solar energy in the state of California. This is an important finding that tells us that more research will need to be done in order to determine the causes of climate anomalies, specifically those related to renewable energy supply.
Figure 43. Diurnal cycles during all four seasons of (top row) wind at wind farms, (second row from the top) solar at solar farms, (third row from the top) cooling degree days weighed by population, and (bottom row) heating degree days weighed by population as they compare with extreme values (greater than 1, less than -1) of the Nino3.4 time series.
Figure 44. Diurnal cycles during all four seasons of (top row) wind at wind farms, (second row from the top) solar at solar farms, (third row from the top) cooling degree days weighed by population, and (bottom row) heating degree days weighed by population as they compare with extreme values (greater than 1, less than -1) of the PNA pattern time series.
Figure 45. Diurnal cycles during all four seasons of (top row) wind at wind farms, (second row from the top) solar at solar farms, (third row from the top) cooling degree days weighed by population, and (bottom row) heating degree days weighed by population as they compare with extreme values (greater than 1, less than -1) of the NAO time series.
5. Conclusions

Climate sensitive renewable energy variables such as wind, sunlight, and temperature exhibit variability that can in some cases be attributed to the state of large scale modes of atmospheric variability (climate modes). While not all climate variability can be explained this way, the extent to which we do not find relationships between climate modes and these variables is in itself a significant result because, where this is the case, it indicates that energy systems managers will not necessarily need to incorporate forecasts of these modes into their planning. Furthermore, the extent to which we do find anomalous climate activity in relation to departures from the mean state of the ENSO, PNA pattern, and NAO on a seasonal time scale is useful for energy planning as many parts of the world transition to renewable sources of energy that are dependent on climate. In this research, we identify linear regressions between these climate modes and wind, sun, temperature and pressure both as concurrent and time-lagged relationships. Our hope is that the identification of these relationships can be used to prepare for climate related shortages in energy supply and temperature-driven surges in demand, while also serving as a means to determine the spatial distribution of which wind and solar energy farms should be built. While climate variables exhibit changes on all time scales, major anomalies in wind, sunlight, and temperature on a seasonal time scale would be very impactful, hence our decision to investigate them. Referring to Table 1, we are particularly interested in the occurrence of Category 8 scenarios from an energy systems planning perspective because this poses the largest threat to reliability of renewable energy systems. The extent to which we do not find these scenarios is a good outcome for renewable energy systems. Furthermore, we want to identify instances where wind speeds and solar radiation are positively correlated in order to avoid concurrent resource deficits. Identifying
concurrent relationships is helpful for wind and solar infrastructure planning, while time-lagged relationships offer a sense of the predictability of resources as a result of the state of climate modes.

We hypothesized that climate modes would have heterogeneous relationships with wind and solar power supply and two-meter temperature with a spatial distribution of about 3000-6000 kilometers. We also predicted solar radiation and temperature anomalies to be the same sign as 500hPa geopotential height anomalies, while wind speed anomalies would be the opposite. To answer this, we constructed time series comparisons between the ENSO, PNA pattern, and NAO and the wind resource over the continental United States and made histograms of mean monthly wind speed during the positive and negative phases of each climate index (Figures 21, 31, 41). These results motivated calculations of linear regressions between the indices and four climate variables, which we use to infer relationships between climate modes and climate variability as they relate to renewable energy resources. We then looked at wind speed, solar radiation, and heating and cooling demand on a finer scale, comparing observational data from California with the extreme phases of the three modes of variability (Figures 43-45).

The results indicate that renewable energy resources are not heavily constrained by climate modes, therefore more research will need to be performed in order to understand the cause of anomalies. However, there are teleconnections to renewable energy resources and to temperature related energy demand that can be directly attributed to climate modes. Signals are higher over the oceans than on land, which will be useful to future researchers tasked with determining the necessary geospatial distribution of offshore wind and solar farms.

Wind speed, solar radiation, and temperature anomalies were generally in phase with 500hPa
height anomalies, with the exception of temperature anomalies in the tropics. The spatial scale on which signals occur is a few thousand kilometers, and relationships are heterogeneous. A category 8 scenario occurs during the negative phase of the NAO in DJF, which emphasizes the need for appropriate spatial distribution of power generation sites in order to sample resources from regions with positive and negative anomalies. This would ensure that not all power generation sites experience a lull in supply simultaneously. We looked at seasonal predictability based on a one month time-lag between each climate mode and the four climate anomalies. In the case of ENSO, we find that the majority of concurrent relationships are maintained when a one month time-lag is imposed on the calculations. This is not the case when it comes to the PNA pattern and the NAO. This result is expected, due to the fact that the PNA and NAO are atmospheric modes largely driven by internal variability, whereas ENSO is a coupled ocean-atmosphere system controlled by slowly evolving changes in SSTs. The 500 hPa plot often displays the most structure which means there is a lot of uncertainty introduced when trying to infer surface variables from upper level circulation.
6. References


