CLIMATE-REGIME COSPECTRUM ANALYSIS: SHORTWAVE SOLAR IRRADIANCE WITH OTHER METEOROLOGICAL PARAMETERS FOR REGIONALLY SPACED LOCALES

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Abstract

Solar irradiance has both short-term (less than 12 hour) and long-term (intra-seasonal) variations. Understanding these fluctuations is crucial for improving solar resource forecasting and evaluating co-production strategies for solar-fossil power technologies. Downwelling shortwave solar irradiance data (DWS; 3-minute averaging) were used for a three-year period from 2007-2009. Six USA sites were selected from the Integrated Surface Irradiance Study (ISIS) and Surface Radiation (SURFRAD) budget network. Power spectral density was used to analyze the short term and long term variations in DWS. To assess the long-term variations, the data was analyzed in seasonal periods: winter, spring, summer, and fall. Additionally, the cospectrum was evaluated to compare the variation between sites. The three pairs of locations included a mid-Atlantic region: Rock Springs, PA with Sterling, VA; a southwest region: Desert Rock, NV with Hanford, CA; and mid-continent region: Fort Peck, MT with Bismarck, ND. The SURFRAD sites were analyzed in greater detail looking at DWS against several other meteorological parameters using the cospectral analysis. Surface observations of Relative humidity (RH), ambient temperature, wind speed, and air pressure were all analyzed with respect to the DWS. The inter-site coherence and phase analysis allows geographic dispersion of the solar resource to be evaluated. The coherence spectra showed high correlation between downwelling solar and relative humidity.
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Although currently a small contributor in the total mix, solar energy is developing significant potential to diversify the global power production portfolio. Developing constraints on fuel combustion linked to limits on greenhouse gas emissions will increase traditional combustion energy costs. Recent policy allowances to subsidize solar energy along with other forms of renewable energy has resulted more photovoltaics and solar thermal projects being designed and deployed across the United States.

Costs of power production at the systems level is still a barrier however. The intermittency of power output and consequential demand for fast-ramping power technologies to complement photovoltaics are key concerns for increasing grid-connected PV deployment. Curtright and Apt have shown that knowledge of the characteristics of both short term and long term variations in PV power can be used to minimize the cost of energy [1]. Hence, research to assess and understand both the short-term (less than 12 hour) and long-term (intra-seasonal) variation of the available solar resource is essential to addressing this concern.

This research will demonstrate that much more information can be obtained from similar data sets given a combined approach of power spectral analyses and co-spectral analyses. The resulting assessments will be demonstrated as beneficial to energy co-production schemes, both for regionally distributed solar power schemes, and regionally distributed solar-fossil fuel hybridization schemes.
Recent work by Lave and Kleissl has demonstrated that a network of PV systems spaced less than 200km apart in Colorado dispersed over the region has a smoothing effect on the daily combined output power and that the average of the sites are less likely to experience large fluctuations [2]. Even though annual irradiation for the continental USA is high across the continent, within $\sim$14-21 MJ/m$^2$, seasonal and intra-seasonal variations will be different for each locale. Such differences occur because each locale is affected by the variable synoptic, mesoscale/microscale, and diurnal patterns, with the resulting meteorological conditions leading to fluctuations in irradiance (incident shortwave solar radiance, W/m$^2$). It has been suggested by Gueymard that 3 years or more of data are recommended to validate a solar resource model [3].

The impact of these meteorological phenomena is partially dictated by the Taylor Frozen Wave Hypothesis. The Taylor Frozen Wave Hypothesis states that turbulence or waves can be viewed as being frozen as they passes by a site, which allows measurements in time to be converted to movement in space, essentially that a change in measurement over time result from the lateral change in the conditions across the wave [4].

The first section of this study focuses on three pairs of locations around the continental United States using three-minute, time-averaged downwelling shortwave solar irradiation data from the Integrated Surface Irradiance Study (ISIS) network and the Surface Radiation budget network (SURFRAD) for several months over several years. The sites were selected as representative of various geographic regions in the US. The second section of this study focuses on the three locations from the SURFRAD network. The analysis of these locations also includes the power spectral density, and coherence and phase spectra for downwelling short-wave radiation with temperature, relative humidity, wind speed, and pressure.
Chapter 2

Background and Literature Review

The study of solar energy and solar energy systems is an extremely complicated science. Solar energy analysis includes the solar resource, models for solar resource analysis, spectral modeling, irradiance component analysis, light-matter interactions, meteorology and various physical and empirical modeling technologies for data processing. In addition to the breadth of knowledge and information required, there are numerous sets of terminology to describe the many branches of the science depending on the viewpoint and source of information.

2.1 The Solar Resource

The solar resource analysis covers a wide range of concepts and modeling techniques. Understanding the solar resource can be viewed as the study of the fuel source for solar energy technologies. Where fossil fuels are the source for many technologies like coal-fired power plants and natural gas burners, the solar resource is the fuel source for photovoltaics, solar thermal systems and passive solar systems. The solar resource requires an understanding of the types of radiation emitted from the sun in both broadband and spectral terms, the relationship between the earth and the sun via solar geometry, and the numerous models that have been developed to model the solar resource. The interaction of the solar radiation with a wide variety of materials to provide the energy conversion to electricity or thermal energy is also a crucial component. As this research focuses on irradiance, the light-matter interaction on the device level is beyond the scope of this work.
2.1.1 Insolation, Irradiance, and Irradiation

Understanding the solar resource is the first step in planning for increased deployment of solar energy generation technologies. The sun produces an immense amount of radiation every second, (about \(3.8 \times 10^{26}\) W). Radiation from the sun is also called insolation. The amount of insolation that reaches the earth is inversely proportional to the square of the distance between the sun and earth via the Inverse Square Law. The average distance is one astronomical unit or about \(1.495 \times 10^{11}\) m [5]. Equation 2.1 shows this relationship.

\[
I = \frac{S}{4\pi r^2} = \frac{3.8 \times 10^{26} \text{ W}}{4\pi (1.495 \times 10^{11} \text{ m})^2} \approx 1353 \frac{\text{W}}{\text{m}^2} \tag{2.1}
\]

Where \(I\) is intensity, \(S\) is the strength of the source, and \(r\) is the radius or distance from the source. This relationship defines the solar constant \(G_{sc}\). Since the solar constant is defined as instantaneous energy per unit area the quantity is called irradiance. The value of 1353 W/m\(^2\) was the accepted solar constant until around 1977 when it was determined there were errors in instrument calibrations. The solar constant has since be changed to the accepted value of 1366.1 W/m\(^2\) [7]. Despite being called the solar constant, it varies throughout the year as the distance between the earth and sun change, and on time-scales longer than a year due to varying intensity of radiation output from the sun. Figure 2.1 shows the variability of the extraterrestrial total solar irradiance from 1978 to 2000 with data collected from various sources.

The most prominent source of the variability shown here arises from the solar cycle. This cycle originates from the differential rotation of the sun. As the sun rotates, it’s polar and equatorial regions do so at different rates causing it’s magnetic field lines twist. This allows for varying levels of radiation to be emitted. The cycle has a full period of about 22 years with the polarity changing twice. This is indicated by a maximum amplitude occurring twice, once for each polarity before the sun’s differential rotation causes it to realign again [9].

Figure 2.2 shows the annual average irradiation across the united states. Irradiation is energy per unit area per time. Maps like the ones shown here are produced by the National Renewable Energy Laboratory for both annual and monthly irradiation. The values shown are in kilowatt-hours per meter squared per day.
Irradiation varies widely across the United States from around 3.5kWh/m²/day in the northeast to more than 6kWh/m²/day in the southwest. The photovoltaic solar resource map contains total shortwave downwelling solar irradiation. The concentrating solar resource map contains only direct and circumsolar irradiation. These are the various components for broadband irradiance models. There are numerous broadband component and spectral models used to describe the solar resource. The solar constant is a broadband term, quantitatively describing the solar resource.
2.1.2 Broadband Irradiance

Many solar resource models break down irradiance into components. These component models are called broadband models as opposed to spectral emission models. The components describe the quality or irradiance in “lump sum” terms, with the various components describing the source of irradiance inside of the atmosphere. The solar constant is a broadband term for extraterrestrial irradiance. Figure 2.3 shows a hemispherical view of the terrestrial broadband components.

![Diagram of broadband irradiance components](image)

**Figure 2.3.** Anisotropic sky model shown in a hemispherical view with labeled components [11].

The general components of the solar resource are total solar irradiance, direct or beam irradiance, circumsolar irradiance, sky diffuse irradiance, and ground-reflected diffuse irradiance. Terrestrial total solar irradiance describe all of the irradiance that has passed through the atmosphere. Direct irradiance describes the irradiance that has not been scattered by particles or gases in the atmosphere. This is generally considered to encompass a a 0.53° half-angle cone around the center of the sun. Circumsolar irradiance is the radiation emitted from a 3° half-angle cone around the sun [12]. Diffuse irradiance describes the irradiance that has been scattered by the atmosphere.
2.1.3 Wavelength and Energy

Electromagnetic radiation, such as insolation, can be described by either its wavelength or energy. Equation 2.2 shows the Planck-Einstein relationship that describes the relationship between wavelength and photon energy in electron-volts.

\[
E(eV) = \frac{hc}{\lambda} = \frac{1239.8}{\lambda(\mu m)} \quad [6] \tag{2.2}
\]

Where \( h \approx 6.626 \times 10^{-34} m^2 kg/s \) is Planck’s constant, \( c \approx 3.0 \times 10^8 m/s \) is the speed of light in a vacuum and \( \lambda \) is the wavelength of radiation. The value shown in the numerator is valid if wavelength is given in micrometers. The numerator has a different value if a different scale is used for wavelength.

2.1.4 Blackbody Radiation

The sun’s emission spectra can be estimated by modeling the sun as a blackbody radiator. A blackbody radiator is a perfect emitter of radiation. Planck’s equation was derived to describe the spectral emission of a blackbody radiator as a function of temperature and wavelength. The relationship is shown in equation 2.3.

\[
e_{b\lambda}(\lambda, T) = \frac{2\pi hc^2}{\lambda^5 e^{\frac{hc}{\lambda kT}} - 1} \quad [6] \tag{2.3}
\]

Where \( h \) is Planck’s constant, \( c \) is the speed of light in a vacuum, \( k \approx 1.38 \times 10^{23} m^2 kg/s^2 K \) is the Boltzmann constant, \( \lambda \) is wavelength, and \( T \) is temperature (in Kelvin). The total power emitted by a blackbody can be determined by integrating over the entire spectrum by wavelength or energy. Figure 2.4 shows the blackbody radiation curve for a body at 5800K and 300K. The values were calculated in 10nm increments.

The top axis is shown by energy and the bottom axis is shown by wavelength. The magnitude of the emission spectrum from the sun was scaled by \( 10^{-6} \) in order to better compare the emissions from the sun and earth on the same plot. For blackbody radiators, the spectra bodies at lower temperatures will fit entirely inside of the spectra from hotter bodies.

The total energy output by a blackbody radiator is estimated by the Stefan-Boltzmann Law shown in equation 2.4.
Figure 2.4. Planck’s law for blackbody radiation at 5800K as an estimation of the emission spectrum from the sun and 300K as an estimation of the emission spectra from earth.

\[
\frac{P}{A} = \sigma \ast T^4
\]

Where \( P \) is the total power, \( A \) is the surface area of the body, \( \sigma \approx 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4 \) is the Stefan-Boltzmann constant, and \( T \) is the temperature (in Kelvin). The Stefan-Boltzmann constant is derived from several known constants in nature which arise by integrating Planck’s equation over wavelength using the substitution method.

2.1.5 Spectral Radiation

For most solar energy conversion devices, understanding the spectrum is just as important as understanding the magnitude of irradiance. Devices react differently to different portions of the electromagnetic spectrum. Approximately 99% of the emission spectrum from the sun is shortwave radiation, spanning from around 300nm to 3,000nm. The shortwave band is further subdivided into near infrared which accounts for 37% of insolation, visible light which accounts for 44% of insolation and ultraviolet which accounts for 7% of insolation.

The solar constant approximated in equation 2.1 is for extraterrestrial radia-
tion. The current accepted value was adopted in 2000 as laid out in the American Society for Testing and Materials (ASTM) E-490 [13]. The standard for the solar constant is based on the integral over the entire air mass zero, AM0, spectrum. Air mass describes the average length of atmosphere through which the irradiance has traveled. AM0 refers to extraterrestrial, outside of the atmosphere, radiation. The AM0 spectrum is shown in figure 2.5.

Figure 2.5. The AM0 spectrum defined in ASTM standard E490 and the AM1.5 spectra defined in ASTM G173 adapted from [14].

Figure 2.5 also shows the reference spectra for AM1.5. This is the terrestrial spectra from when passing through the atmosphere at 48.19° which is an average approximation for the length of the atmosphere for most of the day. The dips in the spectra occur from absorption by various gases in the atmosphere.

2.1.6 Solar Geometry

In addition to the sun having it’s own variability, as shown in figure 2.1, the sun-earth system causes additional variability in the intensity of irradiance received at the earth. The earth rotates around the sun with an average orbit lasting 365.24 days. There are two parameters that correspond to the orbital geometry of the sun-earth system; equation of time and declination. The length of day varies with the angle of the normal vector towards the sun with respect the the plane of earth’s
orbit and the size of the angle covered by the earth during any period of time.

The actual time of day and year with relationship to the sun is constantly changing. Since human beings have established our own standard time with 24 hours in a day, our standard time varies from actual solar time. The difference between these two scales of time is defined by the equation of time. There are numerous models to describe the equation of time by Woolf (1968), Lamm (1981), and Yallop (1992) [15] [16] [17].

Declination, $\delta$, is defined as the angle between the earth-sun vector and the plane of the equator. Declination varies throughout the year from $\delta = -23.45^\circ$ during the winter solstice to $\delta = 23.45^\circ$ during the summer solstice. Figure 2.6 illustrates the equation of time and declination using Yallop’s algorithm for State College, PA located at 40.72 N, 77.93 W. The code for this algorithm is shown in appendix A.

\[\sin(\alpha_s) = \sin(LAT) \cdot \sin(\delta) - \cos(LAT) \cdot \cos(\delta) \cdot \cos(GHA) \quad [18] \quad (2.5)\]

Where $LAT$ is the latitude, $\delta$ is declination and $GHA$ is the Greenwich Hour Angle. The solar azimuth angle, $\gamma_s$, describes the angular displacement of the
project of the beam component of radiation on the horizontal plane. Depending on the source, solar azimuth is defined with either north or south equal to an azimuth of $0^\circ$. Equation 2.6 describes the solar azimuth.

\[
\cos(\gamma_s) = \frac{\cos(\delta)(\cos(LAT) \cdot \tan(\delta) + \sin(LAT) \cdot \cos(GHA))}{\cos(\alpha_s)} \tag{2.6}
\]

The plot of solar altitude angle vs. solar azimuth angle is called a sun path diagram. Generally, the plot will be created from hourly data from one day from each month for a year. The corresponding traces show the position of the sun throughout the year when viewed from the earth’s surface. The sun path diagrams for the three SURFRAD locations are shown in figure 2.7.

**Figure 2.7.** Sun path diagram for Rock Springs, Pennsylvania, Fort Peck, Montana, and Desert Rock, Nevada with points for every hour during the 21st of every month cut off at the horizon.

The three locations shown are Rock Springs, PA (40.72N 77.93W), Fort Peck, MT (48.31N 105.10W), and Desert Rock, NV (36.63N 116.02W). The smallest arc at the bottom is for the winter solstice, December, 21st, and the largest arc is for the summer solstice, June, 21st. The general shape of the plot is based on
the latitude of the locations. Montana is the furthest north so the sun reaches the smallest altitude whereas Nevada is the furthest south so the sun reaches the highest altitude. Frequently, these plots are used in shading analysis for potential solar energy systems. Potential shading objects can be drawn onto the plots to observe times throughout the year during which shading of the system will occur.

2.1.7 Solar Resource models

Throughout the years there have been many attempts at creating solar resource models to aid in systems design. The initial attempt at a solar resource mode was the isotropic sky model created by Lui and Jordan [19]. The isotropic diffuse model assumes that all diffuse radiation is uniformly distributed over the sky. This model was an attempt to determine the instantaneous diffuse radiation on a sloped surface given actual measurements, or estimations of total solar irradiance on a horizontal surface for clear sky days. This model is based on three components, direct, diffuse and ground reflected irradiance. For consistency the following equations use the nomenclature from Duffie and Beckman [5].

\[
I_T = I_b R_b + I_d \left( \frac{1 + \cos(\beta)}{2} \right) + I \rho_g \left( \frac{1 - \cos(\beta)}{2} \right) (2.7)
\]

Where \( I_T \) is the total radiation on a sloped surface, \( I_b \) and \( I_d \) are direct/beam and diffuse radiation, \( R_b \) is the the ratio of horizontal diffuse to diffuse on a sloped surface, \( \rho_g \) is the ground reflectance, and \( \beta \) is the slope of the surface. The isotropic model is a very simple model assuming ideal conditions.

To refine this model there have been numerous anisotropic sky models developed that have much greater accuracy. The Hay-Davies model was created in 1980 as one of the first anisotropic models. Since then there have been several revisions by Klucher and Reindl to improve it’s validity [20] [21]. The model is now known as the Hay-Davies-Klucher-Reindl (HDKR) model. Equation 2.8 shows the HDKR model for calculating radiation on a sloped surface.

\[
I_T = (I_b + I_d A_i) R_b + I_d (1 - A_i) \left( \frac{1 + \cos(\beta)}{2} \right) [1 + f \sin^3 \left( \frac{\beta}{2} \right)] + I \rho_g \left( \frac{1 - \cos(\beta)}{2} \right) (2.8)
\]
Where $A_i$ is the anisotropy index, and $f$ is a modulation factor. This model includes a more accurate description of the circumsolar irradiance and a component for horizon brightening.

The Perez model was designed to overcome issues facing clear sky only models like the isotropic and anisotropic sky models. The model focuses on both energy and daylighting for systems and the built environment with sets of derived coefficients based on the location. Additionally, this model accounts for the angular distribution of diffuse irradiance across the sky [22]. The basic format of this model is shown in equation 2.9.

$$I_{d,T} = I_d \ast [(1 - F_i) \frac{1 + \cos(\beta)}{2} + F_1 \frac{a}{b} + F_2 \sin(\beta)] \quad (2.9)$$

Where $I_{d,T}$ and $I_d$ are the tilted and horizontal irradiance or illuminance, $\beta$ is the surface slope, and $F_1$ and $F_2$ are brightness coefficients derived from the anisotropy of the circumsolar and zenith, both of which are function of the condition of the sky. $F_1$ and $F_2$ were calculated for both irradiance and illuminance by Perez to increase the usability of this model.

The Muneer model, another model that focuses more on atmosphere transmission and meteorological parameters, uses based on the Meteorological Radiation Model (MRM), Cloud-Cover Radiation Model (CRM), and Diffuse Ratio Model (DRM) [23].

The REST2 models, developed by Gueymard et al., is a rigorous model to predict solar irradiance with great attention to the effect of atmospheric transmission via aerosols [24]. The REST2 Model shown in equation 2.10 calculates direct irradiance from numerous transmission parameters.

$$E_{bni} = T_{Ri}T_{gi}T_{oi}T_{ni}T_{wi}T_{ai}E_{0ni} \quad (2.10)$$

Where $T_{Ri}$, $T_{gi}$, $T_{oi}$, $T_{ni}$, $T_{wi}$, and $T_{ai}$ are the band transmittances for Rayleigh scattering, uniformly mixed gases absorption, $O_3$ (ozone) absorption, $NO_2$ (nitrogen dioxide) absorption, $H_2O$ (water vapor) absorption and aerosol extinction, respectively. $E_{bni}$ and $E_{0ni}$ are direct and total irradiance respectively. The model provides design conditions for every month rather than annual parameters and is based off of ground or satellite sensor data. The REST2 model has been devel-
oped in conjunction with SMARTS (Simple Model for Atmospheric Transmission of Sunshine), also created by Gueymard. SMARTS is a spectral radiation model, used to develop the modern ASTM spectra. Additionally, it is used to calculate the atmospheric transmission parameters used in REST2 [25].

The REST2 model is a parametric model and has been proposed to be the new ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers) standard model for solar radiation [26]. It is an improvement on previous parametric models such as the Iqbal model [27]. The details of these models are beyond the scope of this research, but provide very useful methodologies for calculating solar resource assessment parameters.

2.1.8 Solar Resource Forecasting

While solar resource models are useful for the planning and design stages of solar energy power generation technologies, solar resource forecasting is crucial for short term planning of actual energy generation capabilities. Forecasting is generally broken up into three time scales; short-term, less than one hour to six hours, mid-term, one to three days, and long-term, intra-seasonal and annual changes in the resource. Long-term forecasting is performed through long-term measurements of the solar resource such as the methods described in this research. Short-term and mid-term forecasting methodologies are currently being explored by numerous national laboratories and individual researchers [28].

Two of the key methods to date are numerical weather prediction (NWP), artificial neural networks (ANN). NWP uses data from radiosondes (soundings) and satellites to initialize numerical solutions to the equations of atmospheric evolution, while ANN generally focuses on extrapolation from ground station measurements. Figure 2.8 shows a sample methodology for solar resource forecasting.

The model in figure 2.8, the European Centre for Medium-Range Weather Forecast mode, is described in full by Lorenz et al. and is based on the NWP methods [29]. NWP used mathematical models to describe the atmosphere and ocean conditions to predict future conditions. Perez et al. describe numerous models based on NWP [30]. Pelland et al. also describe a methodology using NWP with the Environment Canadas Global Environmental Multiscale (GEM)
model [31]. Both Perez et al. and Pelland et al. validated their results with the SURFRAD budget network ground station measurements. Models using NWP frequently utilize model output statistics for post processing and removing errors from the numerical predictions.

ANN focuses on using actual time-series data to predict future conditions of the solar resource. Paoli et al. describe several popular methods of using ANN for solar resource forecasting. Paoli et al. found that models based on the clearness index and clear sky index performed better by 5 to 6% than models that assume a clear sky [32].
2.2 Meteorology

Meteorology is defined by the National Oceanic and Atmospheric Administration’s National Weather Service as the science dealing with the atmosphere and its phenomena [33]. There is a distinction between meteorology, the current, or at any given time state, of the atmospheric conditions or weather, and climatology, the long term average conditions of the atmosphere. There is also a distinction between the solar engineering air mass, the length of atmosphere irradiance must travel through, and meteorological air mass which refers to a physical body of air with a certain uniformity of conditions. The equations shown here are from Meteorology Today for Scientists and Engineers [4].

2.2.1 Air Masses

Air masses are described by their origins. There are five main types of air masses common to the United States; continental Arctic (cA), continental Polar (cP), continental Tropical (cT), maritime Polar (mP), and maritime Tropical (mT). Figure 2.9 shows the air masses common to the U.S.

![Figure 2.9. The five air masses common to the United States [34].](image)

The air masses are named after the region over which they form. Generally forming around high pressure centers, which allow the air mass to remain relative
still to allow some uniformity to occur within them, the region in which they form will generate varying conditions. Arctic air masses form over the frigid polar ice caps, while maritime air masses form over oceans, yielding high relative humidity compared with continental air masses [4].

2.2.2 Weather Types

*Synoptic-scale weather* is large scale meteorology, with common atmospheric conditions spanning several hundred to several thousand kilometers, also termed cyclonic scale as this is the scale on which cyclones and anti-cyclones occur. Weather on this scale is largely impacted by the Coriolis effect, a force exerted by the rotational motion of the earth. *Meso-scale weather* is medium scale meteorology, with common atmospheric conditions spanning from one to several hundred kilometers. *Micro-scale weather* is the smallest scale weather, with common atmospheric conditions spanning anywhere from a few millimeters up to 1 km. Meso- and microscale weather are not affected significantly by the Coriolis effect [35].

Local weather observations are frequently reported on what is known as a station model. Figure 2.10 shows a sample annotated station model.

![Sample station model.](image)

The station models show numerous weather conditions, like temperature, dew point, pressure and the pressure trend, and the current weather conditions. The symbol labeled weather indicates thunderstorms. There are a wide variety of symbols to illustrate the current weather condition. The following sections describe these parameters in greater detail.
2.2.3 Relative Humidity

Relative humidity is a ratio between the actual amount of moisture in an air mass and the amount of moisture that would be present if the air was completely saturated. Equation 2.11 shows the calculation of relative humidity.

\[ RH = \frac{\text{actual vapor density}}{\text{saturation vapor density}} \times 100\% \quad (2.11) \]

Essentially, a relative humidity value of 100% indicates that the air is completely saturated and will not allow any net evaporation of water to occur. The saturation vapor density is dependent on air temperature.

2.2.4 Temperature

Temperature is a measure of the internal energy contained within a substance. When referring to meteorology, this is the average kinetic energy of the molecules in a surrounding airmass. Higher temperatures are associated with a higher level of average speeds dictated by equation 2.12.

\[ T = am_wv^2 \quad (2.12) \]

Where \( T \) is temperature in Kelvins, \( a \) is a constant that equals \( 4.0 \times 10^{-5} \) Km\(^{-2}\)s\(^2\), \( m_w \) is the molecular weight, and \( v \) is the average speed. This describes the dry-bulb temperature. **Wet-bulb temperature** is a measure of the relationship between temperature and humidity. It is measured by covering a thermometer with a wet cloth in order to account for the latent heat of evaporation. This has a cooling effect on the feel temperature as drier air will absorb more water, making the air actually feel cooler.

Fundamentally, temperature is controlled by the earth’s energy budget. Insolation warms the planet and hence the air close to the surface. The earth emits long-wave radiation that also heats the air and eventually is lost to space. These two forces strike a balance that produces the average temperature.
2.2.5 Wind Speed

Wind speed is the rate at which air is moving horizontally past a given point as either a two minute average or instantaneous value. The driving force behind wind motion is the macroscopic velocity of air particles. Where temperature is concerned with the random motion of the air, wind is concerned with air moving in one direction. Wind is described as a vector quantity, describing both the speed and direction of the wind. The wind direction is customarily described in the direction from which it blows with north equal to $0^\circ$ and south equal to $180^\circ$. Thus, the wind direction shown in figure 2.10 is blowing from the northeast or $45^\circ$ at 5 knots.

2.2.6 Dew Point Temperature and Cloud Levels

The dew point temperature is the temperature at which air must be cooled in order to reach saturation, given that pressure remains constant. Dew point temperature can be measured very accurately and provides the most accurate measure of moisture content in the air. Dew point temperature can be calculated with equation 2.13.

$$T_d = \left[ \frac{1}{T_0} - \frac{R_v}{L} \times ln\left( \frac{e}{e_0} \right) \right]^{-1} \quad (2.13)$$

By analyzing the dew point and vertical temperature profile one can deduce the height at which clouds will form. Lifting condensation level describes the height at which saturation will occur, allowing clouds to form from a near surface air parcel. This is given by equation 2.14.

$$z_{LCL} = a(T - T_d) \quad (2.14)$$

Where $z_{LCL}$ is the vertical distance, $a$ is a constant (0.125km/$^\circ$C), and $T$ and $T_d$ are temperature and dew point temperature respectively [4].

2.2.7 Air Pressure

Air pressure is the total force of all of the air molecules in an air column from the top of the atmosphere to the surface per unit area. It has been convention in
meteorology to use the units of millibars to describe air pressure since 1929. Typical sea-level pressure levels range from low pressure, between 960mb and 980mb, to high pressure, between 1035mb to 1050mb. Recorded pressure levels are frequently converted to sea-level pressure to allow comparison between locations. Figure 2.10 shows the sea-level pressure using only three digits. The three value shown, 059 could describe various pressure such as 905.9mb or 1005.9mb. Since 905.9mb is far out of the range of typical air pressure it actually describes a pressure of 1005.9mb. As elevation increases, air pressure drops following a logarithmic gradient. This gradient can be seen on the left axis in figure 2.11

### 2.2.8 Layers of the Atmosphere

Most clouds and weather are only present inside of the troposphere which covers from the earth’s surface to around 11km. The additional layers of the atmosphere are the Stratosphere, the Mesosphere, and the Thermosphere. The Stratosphere

![Figure 2.11. Sounding for State College, PA on June 21st, 2009. Also shown is the sounding for the nearest weather station in Pittsburgh, PA [36].](image-url)
spans from 11km to 47km, the mesosphere spans from 47km to 85km, and the Thermosphere is above 85km [37].

_Soundings_ are measurements taken by a weather balloon as it ascends through the various layers of the atmosphere. Generally, soundings are taken at many locations around the United States every 12 hours. Readings are taken periodically as the balloon ascends and plotted in a figure like the one shown in figure 2.11.

Soundings show the vertical variations in temperature, relative humidity, and wind speed related to air pressure. Since pressure decreases directly with elevation, the pressure scale is indicative of height. The air speed is shown on the right-hand side.
2.3 Spectral Analysis of Time-Series Data

Analysis of time-series data relies on numerous complex computer based models. Frequently the data sets are thousands, to hundreds of thousands of lines of data. Many solar energy models rely on irradiance measurements as well as numerous meteorological conditions for both prediction and analysis. Spectral analysis converts time-series data to the frequency domain.

2.3.1 Time-Series Data

Data series can either be continuous or discrete in nature. Continuous time-series data are measured continuously from a source such as voltage or current fluctuations from electronics. Discrete time-series data are obtained by sampling a continuous time-series at discrete intervals in time. Many parameters used to describe the solar resource and meteorology are only sampled in discrete intervals to cut down on the size of the data for continuous signals [38].

2.3.2 Power Spectral Density

Fourier analysis is one of the most commonly used techniques for converting between the time and frequency domains. Fourier analysis can be performed on either continuous or discrete data. Equations 2.15 and 2.16 show a Fourier transform (FT) pair for continuous functions.

\[ H(f) = \int_{-\infty}^{+\infty} h(t) \times e^{2\pi ift} dt \quad [35] \]  

\[ h(t) = \int_{-\infty}^{+\infty} H(f) \times e^{-2\pi ift} dt \quad [35] \]

Where \( H(f) \) and \( h(t) \) are functions of frequency and time respectively. Discrete FTs are performed using summation over a series of data rather than integration. Using Euler’s formula, the Fourier transform can be broken into real and imaginary components. For computer algorithms the Fourier transform is related by the Fast Fourier Transform (FFT). This normalizes the real and imaginary components into a series of amplitude data known as the amplitude spectrum.
The spectral power or power spectral density is a variation of the spectral amplitude. Specifically it is the FT of the auto-covariance function. The equation for calculating discrete power spectral densities is shown in the Methodologies in equation 3.1. The power spectral density is a symmetric function.

### 2.3.3 Co-spectrum

The cross power spectral density or co-spectrum is the FT of the cross-covariance function. The co-spectrum is calculated for a pair of continuous signals by the relationship in equation 2.17.

\[
S_{xy}(\omega) = \int_{-\infty}^{+\infty} (x(t) \times e^{-j\omega n})(y(t) \times e^{-j\omega n} dt)^* \tag{38} \]

Where \( S_{xy} \) is a complex valued number. The equation for calculating discrete cross-power spectral densities is shown in the Methodologies in equation 3.4. The co-spectrum is an asymmetric function about zero, where \( S_{xy}(\omega) = -S_{xy}(-\omega) \). The co-spectrum is particularly useful for determining whether different time-series data have frequency components that occur at the same time, or with a phase lag between them.

### 2.3.4 Coherence and Phase Spectra

The co-spectrum can be decomposed into coherence and phase components. Equation 2.18 shows the discrete co-spectrum and it’s decomposition into coherence and phase.

\[
S_{xy}(\omega) = \frac{1}{N} \left( \sum_{n=0}^{N-1} x(n)e^{-jn\omega} \right) \left( \sum_{n=0}^{N-1} y(n)e^{-jn\omega} \right)^* = \alpha_{xy}(\omega) * e^{j\phi_{xy}(\omega)} \tag{38} \]

Where \( \alpha_{xy}(\omega) \) is the coherence, a real number with values between 0 and 1, where 1 indicated perfect coherence and 0 indicated non-coherence, and \( \phi_{xy}(\omega) \) is the phase, a real number with values between \( \frac{\pi}{2} \) and \(-\frac{\pi}{2} \), where positive values indicate \( x \) leads \( y \) and negative values indicate \( x \) lags \( y \).
Chapter 3

Methodologies

3.1 Data Collection

The raw irradiation data were collected from the ISIS level 1 and ISIS Level 2: Surface Radiation (SURFRAD) Budget Management networks. The ISIS Network, established by the National Oceanic and Atmospheric Administration’s Earth System Research Laboratory Global Monitoring Division, has been reporting irradiation measurements since 1995. The ISIS level 1 stations monitor incoming radiation only while the ISIS level 2 SURFRAD stations more completely monitor the surface radiation balance [39] [36]. Beginning in 2009 the SURFRAD stations converted from reporting three-minute data to one-minute data. Three regional location-pairs were selected. The three location-pairs included in this study are Fort Peck, MT and Bismarck, ND, Rock Springs, PA and Sterling, VA, and Desert Rock, NV and Hanford, CA. Table 3.1 lists the longitude and latitude of all of the locations and the distance between the location-pairs.

<table>
<thead>
<tr>
<th>Region</th>
<th>ISIS site</th>
<th>Lat./Long.</th>
<th>SURFRAD site</th>
<th>Lat./Long.</th>
<th>Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-Continent</td>
<td>Bismarck, ND</td>
<td>46.77N 100.77W</td>
<td>Fort Peck, MT</td>
<td>48.31N 105.10W</td>
<td>320.3</td>
</tr>
<tr>
<td>Mid-Atlantic</td>
<td>Sterling, VA</td>
<td>39.98N 77.47W</td>
<td>Rock Spring, PA</td>
<td>40.72N 77.93W</td>
<td>185.9</td>
</tr>
<tr>
<td>Southwest</td>
<td>Hanford, CA</td>
<td>36.31N 119.63W</td>
<td>Desert Rock, NV</td>
<td>36.63N 116.02W</td>
<td>362.6</td>
</tr>
</tbody>
</table>

All of the diffuse irradiance measurements at the ISIS and SURFRAD locations are measured with Eppley black and white model 8-48 pyranometers. The data is reported in three-minute averaging intervals from one second sampling. Addi-
tionally, dry-bulb temperature, relative humidity, wind speed, and pressure were all collected from the SURFRAD budget network. Figure 3.1 shows a schematic of the basic SURFRAD station layouts.

3.2 Data Processing

The raw downwelling solar irradiation (W/m²), temperature (°C), relative humidity (%), wind speed (mph), and pressure (mb) data had to be edited to remove erroneous data. Both networks follow the same methodology of reporting flawed data. For all reported parameters, if the sensor malfunctioned at a point of time, hence missing data, the reported measurement is -9999.9. For this study, erroneous values are corrected by interpolating between the surrounding correct data. Large gaps in data longer than a few days during the selected months were omitted for this study. The radiation parameters are flagged as errors if there is any negative data present that is outside the range of noise; these values are set to zero. The meteorological parameters were also interpolated between surrounding data to correct any errors. Additionally, the one-minute data from the SURFRAD stations after 2009 were converted to three-minute averages. Several programs were written using SciLab in order to process the data. SciLab is an open source software
for numerical calculations. The software has hundreds of mathematical models and both two and three dimensional graphing capabilities. The program used to process the data and remove errors is shown in appendix C.

The downwelling solar irradiation and various meteorological parameters were compiled into arrays of three consecutive years: 2007, 2008 and 2009. The years were divided by season, with Winter spanning December, January and February, Spring spanning March, April and May, Summer spanning June, July and August and Fall spanning September, October and November.

3.3 Power Spectral Density

The power spectral density is a measure of the strength of variation of the power contained in a signal as a function of frequency. The power spectrum of a signal is defined as the square of the magnitude of the Fourier transform shown in equation 3.1.

\[
S_x(\omega) = \left| \frac{1}{N} \sum_{n=0}^{N-1} x(n)e^{-j\omega n} \right|^2 [38]
\]  

(3.1)

Where \(x(n)\) is the signal with a total number of points \(N\) and \(S_x(\omega)\) is a real valued number.

Once PSD was plotted for the irradiance data, linear best fit slopes were evaluated for each spectra in both the synoptic-scale and meso-/microscale weather regions. For the synoptic-scale, a 90% confidence interval was used, while a 95% confidence interval was used for the meso-/microscale data regions. A full table of fit data is available appendix D.

3.4 Irradiance Statistical Analysis

For each location the values of the slopes and intercepts were plotted against each other. The figures also show the 90% and 95% confidence intervals respectively. An algorithm was created to predict the synoptic-scale weather slopes and intercepts based on the meso- and micro-scale weather slopes and intercepts to find a
correlation between the weather types. A systems of equations of the form shown in equation 3.2 and 3.3 were created.

\[ S_{syn} = a \times S_{mm} + b \times I_{mm} + c \] (3.2)

\[ I_{syn} = d \times S_{mm} + e \times I_{mm} + f \] (3.3)

Where \( S_{syn} \) is the synoptic-scale slope, \( S_{mm} \), is the meso- and micro-scale slope, \( I_{mm} \) is the meso- and micro-scale intercept, \( I_{syn} \) is the synoptic-scale intercept, and \( a-f \) are calculated parameters. Most analysis focus on only meso- and micro-scale data sets. By allowing calculation of the synoptic-scale slopes and intercepts the character of the long-term variations can be calculated.

### 3.5 Cospectral Analysis

The cross power spectral density between two arrays of data is also called the cospectrum, the measure of similarity between the respective power spectral densities. The co-spectrum is a product of the complex valued phase spectrum, a measure of the phase offset, lagging or leading, between the two arrays and the cross amplitude spectrum or coherency spectrum, a measure of the similarity of the magnitudes of the frequency components. The co-spectrum is defined by the relationship shown in equation 3.4.

\[ S_{xy}(\omega) = \frac{1}{N}(\sum_{n=0}^{N-1} x(n)e^{-j\omega n})(\sum_{n=0}^{N-1} y(n)e^{-j\omega n})^* \]

\[ = \alpha_{xy}(\omega) \times e^{j\phi_{xy}(\omega)} \] [38] (3.4)

Where \( x(n) \) is the first time-series and \( y(n) \) is the second time-series, and \( S_{xy}(\omega) \) is a complex valued number whose magnitude is the coherency spectrum \( (\alpha_{xy}(\omega)) \) and angle is the phase spectrum \( (\phi_{xy}(\omega)) \). The program used to calculate the power spectral densities and coherence and phase spectra is shown in appendix C.
Chapter 4

Results

4.1 Inter-Site Analysis

The first section of this research focuses on the location pairs in the southwest, mid-atlantic, and mid-continental regions. The power spectral densities and coherence and phase spectra are calculated for each location and location pairs.

4.1.1 Irradiance Power Spectral Density

The power spectral densities were calculated for each month and averaged into the intra-seasonal plots. Each subsequent plot shows a 30 day period for irradiance over three months for three years.

The sample schematic in figure 4.1, shows that the x-axis displays periodicity in terms of days rather than Hz (seconds\(^{-1}\)). This new convention conveniently separates diurnal cyclic data from other distinctive scales of meteorological phe-

![Figure 4.1. Schematic illustrating the weather scales and diurnal phenomena on a frequency plot of power spectral density (PSD).](image)
Figure 4.2. Power Spectral Density for Fort Peck, MT and Bismarck, ND using 3 minute averaged downwelling solar irradiance for Winter, Spring, Summer and Fall including the slopes of the synoptic-scale weather (left) and meso- and micro-scale weather (right) in the legends.

Nominal weather phenomena, as all seasons and locations show trivial peaks at periods corresponding to 1 day and 12 hours. The peaks and the subsequent harmonics in some figures represent spectral decomposition of the diurnal cycle. Information to the left of 1 day corresponds to synoptic weather. Information to the right of the diurnal patterns (spanning to high frequency), is the range of meso- and micro-scale weather. Figures 4.2 through 4.4 show the power spectral densities for the three location-pairs.

Mid-Continental:

Figure 4.2 shows the power spectral densities for Montana and North Dakota in the mid-Continental region. The only months that contained too many errors for use are November and December 2009 from North Dakota. The winter and
Figure 4.3. Power Spectral Density for Rock Springs, PA and Sterling, VA using 3 minute averaged downwelling solar irradiance for Winter, Spring, Summer and Fall including the slopes of the synoptic-scale weather (left) and meso- and micro-scale weather (right) in the legends.

fall power spectral densities were averaged for 8 months rather than nine. The synoptic-scale weather is described by a best-fit line from 15 days through 2 days. The slope is shown for each location as the first frequency exponent. The steepest slope for the synoptic-scale weather occurred in the summer for Montana, $f^{-0.60}$ and the winter and spring for North Dakota, $f^{-0.85}$. The smallest slopes occurred in the spring for Montana, $f^{-0.32}$ and the fall for North Dakota, $f^{-0.40}$. The plots for each season also contain the best fit line for the linear portion ($< 9$ hours or 0.37 days) of the high frequency power spectral densities. The winters had the largest slopes of $f^{-1.59}$ and $f^{-1.61}$. The summers had the smallest slopes of $f^{-1.18}$ and $f^{-1.25}$ respectively with a 25% and 22% change between the high and low slopes throughout the year.
Pennsylvania at and fall all had much steeper slopes with the maximum reached in summer for the diurnal pattern showed much fewer harmonics in the mid-Atlantic sites than in over a long time period the impact on the available irradiance increases. The low frequency are much smaller than the diurnal variations, but as they occur in the power spectral densities changed between the seasons. These variations in showed extremely low slopes,

The synoptic weather in Pennsylvania and Virginia both including the slopes of the synoptic-scale weather (left) and meso- and micro-scale weather (right) in the legends.

Mid-Atlantic:

Figure 4.3 shows the power spectral densities for Pennsylvania and Virginia in the mid-Atlantic region. The synoptic weather in Pennsylvania and Virginia both showed extremely low slopes, $f^{-0.19}$ and $f^{-0.03}$, in the winter. Spring, summer, and fall all had much steeper slopes with the maximum reached in summer for Pennsylvania at $f^{-0.85}$ and fall for Virginia at $f^{-0.77}$. The long term variations in the power spectral densities changed between the seasons. These variations in the low frequency are much smaller than the diurnal variations, but as they occur over a long time period the impact on the available irradiance increases. The diurnal pattern showed much fewer harmonics in the mid-Atlantic sites than in the southwest sites. The best fit for the high frequency varies from $f^{-1.43}$ in the

Figure 4.4. Power Spectral Density for Desert Rock, NV and Hanford, CA using 3 minute averaged downwelling solar irradiance for Winter, Spring, Summer and Fall including the slopes of the synoptic-scale weather (left) and meso- and micro-scale weather (right) in the legends.
winter to $f^{-1.19}$ for PA and $f^{-1.25}$ in the summer. This indicates that the high frequency variations in the summer are the largest and the winter variation are the smallest.

**Southwest:**

Figure 4.4 shows the power spectral densities for Nevada and California in the Southwest region. Winter, spring and fall all showed similar slopes on the synoptic-scale from $f^{-0.8}$ to $f^{-1.0}$. Summer showed the least steep slopes of $f^{-0.64}$ in Nevada and $f^{-0.41}$ in California. These two locations showed the most prominent harmonics of the diurnal pattern with additional peaks at 8, 6, 4.8, 4 and 3 hours. The peaks vary in intensity and width throughout the seasons. The 8 hour peak has the largest width of the diurnal pattern harmonics in the winter. The flatness, closeness to zero, of the spectrum slope indicates larger variations in the high frequency irradiation. The Winter has the largest slope of $f^{-1.46}$ and $f^{-1.44}$. Nevada showed the smallest slope in the fall at $f^{-1.33}$ and California in the spring at $f^{-1.29}$. Tables 4.1 to 4.3 show the slopes and intercepts with their respective confidence intervals for the six locations.

**Table 4.1.** Slopes and intercept with confidence intervals of PSD for Montana and North Dakota.

<table>
<thead>
<tr>
<th>Location</th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Montana</td>
<td>$10^{0.19}(\pm0.214)$</td>
<td>$10^{0.28}(\pm0.187)$</td>
<td>$10^{0.11}(\pm0.124)$</td>
<td>$10^{0.88}(\pm0.267)$</td>
</tr>
<tr>
<td>Syn Int</td>
<td>-0.54(\pm0.315)</td>
<td>-0.32(\pm0.278)</td>
<td>-0.60(\pm0.184)</td>
<td>-0.34(\pm0.400)</td>
</tr>
<tr>
<td>Syn Slope</td>
<td>-1.59(\pm0.011)</td>
<td>-1.24(\pm0.010)</td>
<td>-1.18(\pm0.010)</td>
<td>-1.35(\pm0.011)</td>
</tr>
<tr>
<td>North Dakota</td>
<td>$10^{0.27}(\pm0.209)$</td>
<td>$10^{0.30}(\pm0.259)$</td>
<td>$10^{0.17}(\pm0.242)$</td>
<td>$10^{0.70}(\pm0.171)$</td>
</tr>
<tr>
<td>Syn Int</td>
<td>-0.85(\pm0.315)</td>
<td>-0.85(\pm0.386)</td>
<td>-0.60(\pm0.306)</td>
<td>-0.40(\pm0.237)</td>
</tr>
<tr>
<td>Syn Slope</td>
<td>-1.61(\pm0.011)</td>
<td>-1.27(\pm0.010)</td>
<td>-1.25(\pm0.010)</td>
<td>-1.39(\pm0.011)</td>
</tr>
<tr>
<td>Micro Int</td>
<td>$10^{0.02}(\pm0.022)$</td>
<td>$10^{0.02}(\pm0.021)$</td>
<td>$10^{0.01}(\pm0.019)$</td>
<td>$10^{0.02}(\pm0.022)$</td>
</tr>
<tr>
<td>Micro Slope</td>
<td>-1.35(\pm0.001)</td>
<td>-1.35(\pm0.001)</td>
<td>-1.35(\pm0.001)</td>
<td>-1.35(\pm0.001)</td>
</tr>
</tbody>
</table>

**Table 4.2.** Slopes and intercept with confidence intervals of PSD for Pennsylvania and Virginia.

<table>
<thead>
<tr>
<th>Location</th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pennsylvania</td>
<td>$10^{0.32}(\pm0.079)$</td>
<td>$10^{0.22}(\pm0.11)$</td>
<td>$10^{0.21}(\pm0.211)$</td>
<td>$10^{0.177}$</td>
</tr>
<tr>
<td>Syn Int</td>
<td>-0.19(\pm0.119)</td>
<td>-0.84(\pm0.347)</td>
<td>-0.85(\pm0.313)</td>
<td>-0.73(\pm0.266)</td>
</tr>
<tr>
<td>Syn Slope</td>
<td>-0.93(\pm0.322)</td>
<td>-0.74(\pm0.294)</td>
<td>-0.62(\pm0.279)</td>
<td>-0.77(\pm0.222)</td>
</tr>
<tr>
<td>Micro Int</td>
<td>$10^{0.02}(\pm0.020)$</td>
<td>$10^{0.01}(\pm0.019)$</td>
<td>$10^{0.17}.(\pm0.019)$</td>
<td>$10^{0.17}.(\pm0.019)$</td>
</tr>
<tr>
<td>Micro Slope</td>
<td>-1.59(\pm0.011)</td>
<td>-1.24(\pm0.010)</td>
<td>-1.18(\pm0.009)</td>
<td>-1.35(\pm0.011)</td>
</tr>
<tr>
<td>Virginia</td>
<td>$10^{0.36}(\pm0.214)$</td>
<td>$10^{0.18}(\pm0.197)$</td>
<td>$10^{0.18}(\pm0.187)$</td>
<td>$10^{0.18}(\pm0.187)$</td>
</tr>
<tr>
<td>Syn Int</td>
<td>-0.32(\pm0.322)</td>
<td>-0.74(\pm0.294)</td>
<td>-0.62(\pm0.279)</td>
<td>-0.77(\pm0.222)</td>
</tr>
<tr>
<td>Syn Slope</td>
<td>-1.59(\pm0.011)</td>
<td>-1.24(\pm0.010)</td>
<td>-1.18(\pm0.009)</td>
<td>-1.35(\pm0.011)</td>
</tr>
<tr>
<td>Micro Int</td>
<td>$10^{0.02}(\pm0.020)$</td>
<td>$10^{0.01}(\pm0.019)$</td>
<td>$10^{0.17}.(\pm0.019)$</td>
<td>$10^{0.17}.(\pm0.019)$</td>
</tr>
<tr>
<td>Micro Slope</td>
<td>-1.59(\pm0.011)</td>
<td>-1.24(\pm0.010)</td>
<td>-1.18(\pm0.009)</td>
<td>-1.35(\pm0.011)</td>
</tr>
</tbody>
</table>
Table 4.3. Slopes and intercept with confidence intervals of PSD for Nevada and California.

<table>
<thead>
<tr>
<th>Region</th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nevada</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syn Int</td>
<td>$10^{0.34}(±0.249)$</td>
<td>$10^{0.80}(±0.176)$</td>
<td>$10^{0.82}(±0.219)$</td>
<td>$10^{0.39}(±0.118)$</td>
</tr>
<tr>
<td>Syn Slope</td>
<td>-0.84(±0.375)</td>
<td>-0.88(±0.263)</td>
<td>-0.64(±0.326)</td>
<td>-1.03(±0.176)</td>
</tr>
<tr>
<td>Micro Int</td>
<td>$10^{0.34}(±0.020)$</td>
<td>$10^{0.80}(±0.020)$</td>
<td>$10^{0.82}(±0.020)$</td>
<td>$10^{0.39}(±0.021)$</td>
</tr>
<tr>
<td>Micro Slope</td>
<td>-1.46(±0.010)</td>
<td>-1.36(±0.010)</td>
<td>-1.34(±0.010)</td>
<td>-1.33(±0.010)</td>
</tr>
<tr>
<td>California</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syn Int</td>
<td>$10^{0.34}(±0.132)$</td>
<td>$10^{0.47}(±0.153)$</td>
<td>$10^{0.79}(±0.206)$</td>
<td>$10^{0.20}(±0.239)$</td>
</tr>
<tr>
<td>Syn Slope</td>
<td>-0.99(±0.198)</td>
<td>-0.91(±0.227)</td>
<td>-0.41(±0.307)</td>
<td>0.91(±0.358)</td>
</tr>
<tr>
<td>Micro Int</td>
<td>$10^{0.34}(±0.022)$</td>
<td>$10^{0.47}(±0.197)$</td>
<td>$10^{0.79}(±0.020)$</td>
<td>$10^{0.20}(±0.198)$</td>
</tr>
<tr>
<td>Micro Slope</td>
<td>-1.44(±0.011)</td>
<td>-1.29(±0.010)</td>
<td>-1.37(±0.010)</td>
<td>-1.43(±0.010)</td>
</tr>
</tbody>
</table>

4.1.2 Irradiance Statistical Analysis

Figure 4.5. Slopes and intercepts for the mid-continental region, synoptic-scale (a) and meso- and micro-scale (b) for Montana and synoptic-scale (c) and meso- and micro-scale (d) for North Dakota.

Figures 4.5 through 4.7 show the scatter plots of the slopes vs. the intercepts for the location pairs by region of the form $y = mx + b$ with the 90% for synoptic-scale and 95% for meso- and micro-scale confidence intervals. These values were used to calculate fit coefficients for equations 3.2 and 3.3.

The coefficients were calculated with the program shown in appendix D. The program calculates two arrays, $coeff_1$ and $coeff_2$, where $coeff_1$ is a matrix whose elements are $[a \ b \ c]$ corresponding to equation 3.2 and $coeff_2$ is a matrix whose elements are $[d \ e \ f]$ corresponding to equation 3.3. The coefficients calculated to relate synoptic-scale slopes and intercepts with meso- and micro-scale slopes and intercepts are shown in equations 4.1 and 4.2.
**Figure 4.6.** Slopes and intercepts for the mid-Atlantic region, synoptic-scale (a) and meso- and micro-scale (b) for Rock Springs, PA and synoptic-scale (c) and meso- and micro-scale (d) for Sterling, VA

**Figure 4.7.** Slopes and intercepts for the southwest region, synoptic-scale (a) and meso- and micro-scale (b) for Desert Rock, NV and synoptic-scale (c) and meso- and micro-scale (d) for Hanford, CA

$$S_{syn} = -0.122(\pm 1.047) \times S_{mm} + 0.060(\pm 0.223) \times I_{mm} + 0.209(\pm 2.952) \quad (4.1)$$

$$I_{syn} = -0.861(\pm 0.972) \times S_{mm} + 1.009(\pm 0.207) \times I_{mm} + 1.013(\pm 2.230) \quad (4.2)$$
Table 4.4. Calculated slopes and intercepts based on the modeled coefficients from predicting synoptic-scale slopes and intercepts from meso- and micro-scale and the % errors for the values.

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These coefficients were averaged from the slopes and intercepts from all six locations and their 95% confidence intervals are shown in parentheses following each coefficient. The analysis shows that both of the constant term are not statistically different from zero. The intercept coefficient for I<sub>mm</sub> for predicting the intercept I<sub>syn</sub> is statistically different than zero, while the slope coefficients are not statistically different than zero.

Table 4.4 shows the actual slopes and intercepts, calculated synoptic slopes and intercepts (not including the confidence intervals), and the % error calculations. This method does not account for the confidence intervals shown in the figures above, but rather the individual points of data. The data is separated by region starting with mid-continental, followed by mid-Atlantic, and last, southwest.

The results indicated that this method and system of equations was fairly
accurate in predicting the intercepts of the synoptic-scale weather. The average total % error for the synoptic intercept was only 1.96%. The synoptic slope however was much less accurate. Many of the outliers showed very large errors. Several individual points showed errors over 100%. Excluding the 3 significant outliers, noted by *, the average error for the synoptic slope was 25.95%. The details of these analysis are shown in appendix D.

A similar analysis was performed to predict meso- and micro-scale slopes and intercepts from the synoptic-scale information. The equations used for this analysis are shown in equations 4.3 and 4.4.

\begin{align*}
S_{mm} &= -0.065(\pm 0.168) \times S_{syn} - 0.069(\pm 0.074) \times I_{syn} + 2.105(\pm 0.795) \quad (4.3) \\
I_{mm} &= 0.660(\pm 0.240) \times S_{syn} + 0.837(\pm 0.106) \times I_{syn} + 1.294(\pm 1.129) \quad (4.4)
\end{align*}

The analysis shows that both of the constant term are statistically different from zero. The intercept coefficient for \( I_{syn} \) for predicting the intercept \( I_{mm} \) is statistically different than zero, while the slope coefficients are not statistically different than zero. The analysis for predicting meso- and micro-scale slopes and intercepts yielded much lower average errors than predicting synoptic-scale from meso- and micro-scales. The average error for slope was 5.78% and for intercept was 1.72% for all of the locations. The results are shown in table 4.5. These analyses showed that one can predict either the meso- and micro-scale intercept values or the synoptic-scale intercept values fairly accurately, but there is a very large error associated with calculating the slope values for both scales.
Table 4.5. Calculated slopes and intercepts based on the modeled coefficients from predicting meso- and micro-scale slopes and intercepts from synoptic-scale and the % errors for the values.

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4.1.3 Irradiance Cospectral Analysis

Figures 4.8 through 4.10 show the coherence and phase spectra for the three location-pairs. The weather types shown in figure 4.1 correspond to the same periods in the cospectral analysis. The diurnal pattern is visible in the coherence spectrum for all of the locations. The high frequency becomes nearly incoherent and out of phase at periods smaller than a few hours.

Mid-Continental:

Figure 4.8 shows the coherence and phase for Montana and North Dakota. Winter and summer show moderate coherence around 5 and 6 days. Despite the minimal summer phase offset from 30 days to 4 days, coherence is low for most of this period. The coherence drops to almost zero for periods near 2 days with
Figure 4.8. Coherence spectra (red) and phase spectra (gray) for Fort Peck, MT and Bismarck, ND using 3 minute averaged downwelling solar irradiance for Winter, Spring, Summer and Fall.

A resulting randomization of phase lags. Spring and fall are nearly incoherent through the synoptic-scale weather. All seasons are nearly incoherent around 2 days. The monthly coherence, the coherence around the 30 day period, is the highest in the spring at 0.61 followed by winter, 0.44, fall, 0.26, and summer 0.04.

The magnitude of the phase offset between the sites is very large throughout most of the year with the exception being summer. The lags (negative phase) and leads (positive phase) are relatively small until 2 days where the coherence falls apart. The other seasons are out of phase until the 24 and 12 hours peaks where the diurnal pattern takes over.

Mid-Atlantic:

Figure 4.9 shows the phase and coherence spectra for Pennsylvania and Virginia. The winter synoptic weather shows a few peaks around 2 days and 10 days
but becomes nearly incoherent at periods larger than 10 days. Spring and summer show high coherence from 4 and 5 days to 10 days. Fall shows high coherence at the widest range around 1 day and from 2 to 5 days. The monthly coherence is the highest in the spring at 0.74 followed by fall, 0.50, summer, 0.45, and winter 0.25.

The phase offset in all the seasons is close to zero until almost 12 hours. The high coherence in the spring, summer, and fall and close to zero phase lag indicates that any networked solar production between the two sites would be less effective at countering the intermittancy of irradiance on the synoptic-scale.

Southwest:

Figure 4.10 shows the coherence and phase spectra for Nevada and California. The winter synoptic weather shows a few peaks around 3 to 5 days and 6 to 8
Figure 4.10. Coherence spectra (red) and phase spectra (gray) for Desert Rock, NV and Hanford, CA using 3 minute averaged downwelling solar irradiance for Winter, Spring, Summer and Fall.

days, but becomes nearly incoherent at periods larger than 8 days. The summer and fall are nearly incoherent between 1 and 4 days but become slightly coherent at frequencies greater than 10 days. Spring shows small peak at 2.5 and 3.5 days. The monthly coherence is the highest in the summer at 0.62 followed by fall, 0.59, spring, 0.55, and winter 0.15.

The phase offset between the two locations is minimized during the fall until 3 days where they become out of phase and non cohere until the 24 hours peak. Winter is all out of phase for the majority of the synoptic weather. Spring and summer are in phase from 30 days to around 10 days. Fall also shows the most harmonics in the diurnal pattern at 8, 6 and 4.8 hours. The 8 and 6 hour peaks are also visible in the spring and summer.
Figure 4.11. Power spectral densities for Fort Peck, MT for winter, spring, summer, and fall

4.2 Intra-Site Analysis

The second section of this research focuses on the location from the SURFRAD budget network only. The locations are Desert Rock, NV in the southwest, Rock Springs, PA in the mid-atlantic, and Fort Peck, MT in the mid-continental regions. The power spectral densities for temperature, relative humidity, wind speed, and pressure are calculated. Additionally, the cospectra between down-welling solar and the meteorological parameters are shown for each location and season.

4.2.1 Meteorology Power Spectral Density

Fort Peck, MT:

Figure 4.11 shows the power spectral densities for temperature, relative humidity, wind speed, and pressure for Fort Peck, Montana for the four seasons. The
figures show the 5 parameters in seasonal plots. DWS has already been discussed in section 4.1.1.

Air pressure showed the least variability in synoptic, diurnal, and meso- and micro-scales. The summer showed very little variation peaks throughout the spectrum. Summer and fall showed much larger peaks than winter and spring throughout the diurnal cycle. Relative humidity shows large variations on the diurnal pattern throughout the year. Winter and fall show slightly less variation than spring and summer. The meso- and micro-scale variations are much smaller than many of the other variables.

Compared with DWS, temperature shows much less variation on synoptic-scale weather year-round. In the diurnal pattern, temperature shows higher variation during the spring, summer, and fall. This is consistent with larger temperature changes over the period of one day and 12 hours. Winter shows the smallest
variation during both the diurnal patterns and meso- and micro-scale weather.

There is much less dependence of wind speed on the diurnal pattern than relative humidity and temperature. The spring and summer showed minor peaks at one day while the winter and fall showed almost no peaks in the diurnal cycle. The wind power spectral densities for Montana showed spectra different from the Kolmogorov spectrum ($f^{-1.667}$). The closest to the Kolmogorov spectrum was the winter. The slopes of the spectra for less than 9 hours were $f^{-1.543}$ in the winter, $f^{-1.204}$ in the spring $f^{-1.203}$ in the summer, and $f^{-1.351}$ in the fall.

**Rock Springs, PA:**

Figure 4.12 shows the power spectral densities for temperature, relative humidity, wind speed, and pressure for Rock Springs, Pennsylvania for the four seasons. Pressure showed smaller variations throughout the year than in Montana. Winter, spring, and fall showed very little variation on the diurnal cycle. The summer
showed almost several peaks in the diurnal cycle. The high frequency slopes for pressure, meso- and micro-scale, is steeper than the other variables. Winter, spring, and fall shows similar peaks distributions with smaller magnitudes during the diurnal cycle for relative humidity compared to the DWS. In the summer relative humidity showed a similar slope through the diurnal cycle and into the meso- and micro-scale weather.

Temperature showed more variation on both the synoptic-scale and diurnal cycle than in Montana, especially in spring and fall. The high frequency slope for the winter continued through the diurnal cycle, while spring and fall had a change in slope on the diurnal period.

Wind speed showed similar character to Montana with small peaks through the diurnal cycle in spring, summer, and fall. The wind power spectral densities for Pennsylvania showed spectral slopes much less than the Kolmogorov spectrum. For less than 9 hours the slopes were $f^{-1.102}$ in the winter, $f^{-1.083}$ in the spring, $f^{-1.346}$ in the summer, and $f^{-1.057}$ in the fall.

Desert Rock, NV:

Figure 4.13 shows the power spectral densities for temperature, relative humidity, wind speed, and pressure for Desert Rock, Nevada for the four seasons.

Pressure showed more variation throughout the diurnal cycle than the other locations. Winter, spring, and summer showed a flattening in the high frequency range. Fall showed peaks at both one day and 12 hours. Spring and summer showed peaks at one day, 12 hours, and several shorter period harmonics.

Relative humidity showed very strong dependence to the diurnal cycle, showing very large peaks in winter, summer, and fall. The short period variations were smaller than the diurnal variations. Synoptic, diurnal, and meso- and micro-scale variations throughout the spring were smaller than the other seasons.

Temperature showed very large variations on the diurnal cycle. Winter, spring, summer, and fall also showed more harmonics throughout the diurnal cycle than in either Montana or Pennsylvania. The high frequency variations are larger than the other meteorological parameters as well.

Wind speed showed much more variation on the diurnal cycle than in either Pennsylvania or Montana. Diurnal peaks are visible in all of the seasons with the
exception of spring. The wind power spectral densities for Nevada showed spectra similar to the Kolmogorov spectrum in winter and spring at $f^{-1.617}$ and $f^{-1.707}$ respectively. The slopes of the spectra for less than 9 hours in the summer and fall were $f^{-1.083}$ and $f^{-1.240}$ respectively. Table 4.6 shows the slopes and 95% confidence intervals for all of the wind speed spectra.

**Table 4.6.** Meso- and micro-scale slopes of the form $f^x$ and 95% confidence intervals for wind speed.

<table>
<thead>
<tr>
<th></th>
<th>Montana</th>
<th>Pennsylvania</th>
<th>Nevada</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wi</td>
<td>-1.5431 ± 0.00945</td>
<td>-1.1024 ± 0.00915</td>
<td>-1.6171± 0.00881</td>
</tr>
<tr>
<td>Sp</td>
<td>-1.2038 ± 0.00944</td>
<td>-1.0827 ± 0.00892</td>
<td>-1.7074± 0.00533</td>
</tr>
<tr>
<td>Su</td>
<td>-1.2034 ± 0.00914</td>
<td>-1.3455 ± 0.00894</td>
<td>-1.0827 ± 0.00992</td>
</tr>
<tr>
<td>Fa</td>
<td>-1.3514 ± 0.00954</td>
<td>-1.0572 ± 0.00941</td>
<td>-1.2396 ± 0.0092</td>
</tr>
</tbody>
</table>
4.2.2 Irradiance and Meteorology Cospectral Analysis

Figures 4.14 through 4.29 show the cospectral analysis for down-welling solar irradiance vs. temperature, relative humidity, wind speed, and pressure. Each figure shows the coherence and phase spectra for the three locations for one season.

Temperature:

Figure 4.14 through 4.17 show the coherence and phase plots for down-welling solar versus temperature. Temperature showed very low coherence throughout all three weather types. Nevada showed high coherence around the diurnal cycle at one day and 12 hours. Neither Montana nor Pennsylvania had any significant coherence throughout the diurnal cycle. There are small peaks in the synoptic-scale in Montana and Nevada from 5 to 8 days but this coherence is not large enough to be significant. Pennsylvania also had 2 insignificant peaks during the synoptic scale from 5 to 8 days and around 15 days.

Spring, shown in figure 4.15, shows some significant coherence in the synoptic-scale. Montana showed moderate coherence from 5 to 15 days that is mostly out of phase until 8 days. There was also strong coherence on the monthly scale reaching around 0.75. Pennsylvania had a slightly lower coherence peak for the same
Figure 4.15. Coherence and phase between DWS and temperature spring.

Figure 4.16. Coherence and phase between DWS and temperature for summer.
Figure 4.17. Coherence and phase between DWS and temperature for fall.

period with a lower monthly coherence or around 0.4. Nevada showed coherence of around 0.5 starting at 6 days through 15 days after which it dropped slightly. The coherence is mostly in phase after about 10 days. The diurnal cycle showed much strong coherence in the spring than in the winter. Montana and Pennsylvania showed a wider band of high coherence around one day than Nevada. All three locations show a consistent phase lag between temperature and DWS indicating that the temperature variations occur before the changes in DWS. There is little evidence of high coherence below 12 hours.

Summer, shown in figure 4.16, shows less coherence throughout the synoptic-scale weather than the spring. Montana shows slightly higher coherence from 5 to 20 days, but had a much lower monthly coherence. There was a significant phase lag over this peak until around 10 days. Pennsylvania showed no significant coherence on the synoptic-scale. Nevada showed several peaks from 2 days to 4 days which were mostly out of phase. There was another peak of a coherence around 0.4 at 15 days. Montana showed a large band around one day through the diurnal cycle and a harmonic peak around 8 hours. Nevada showed very narrow bands of high coherence through the diurnal cycle with peaks at one day, 12 hours, and 8 hours. There was no strong coherence throughout the meso- and micro-scale
Figure 4.18. Coherence and phase between DWS and relative humidity winter.

Fall, shown in figure 4.17, in Pennsylvania and Nevada show very low coherence between temperature and DWS throughout most of the synoptic-scale. Montana shows a peak around 2 days and 5 to 9 days. The two day peak covers a wide frequency band and has a coherence of around 0.8. Both Montana and Nevada peaks in the diurnal cycle with narrow frequency bands. Pennsylvania has peaks at one day and 12 hours with much wider frequency bands but a lower coherence of around 0.8. There is significantly more noise throughout the meso- and micro-scale range.

Relative Humidity:

Figures 4.18 through 4.21 show the coherence and phase plots for down-welling solar versus relative humidity. In winter, with the exception of Montana, the sites showed moderate coherence throughout the synoptic-scale range. Montana showed a few insignificant peaks around 2 days and from 5 to 9 days. Pennsylvania had a coherence peak at 2 days and from 4 days through the month. The monthly coherence was around 0.5 with very little phase offset. Nevada showed a few peaks around 2 days and strong coherence of between 0.6 and 0.8 from 6 days through the month. All three locations showed peaks in the diurnal cycle around one day
Figure 4.19. Coherence and phase between DWS and relative humidity for spring.

Figure 4.20. Coherence and phase between DWS and relative humidity summer.
Figure 4.21. Coherence and phase between DWS and relative humidity for fall.

and 12 hours.

Figure 4.19 shows the coherence and phase for relative humidity in the spring. Both Montana and Pennsylvania showed very high coherence throughout the synoptic scale weather. Montana had a monthly coherence of 0.72 and remained high until around 4 days. There were also a few smaller peaks between one day and 3 days. Pennsylvania showed even higher coherence throughout the synoptic-scale with a monthly coherence of 0.85. The high coherence spans until 3 days with a minor dip around 10 days. Nevada had much lower coherence throughout the synoptic-scale. There were a few minor peaks around 2 days and from 4 to 5 days. The diurnal cycle showed high coherence with a moderate phase lead in both Montana and Pennsylvania. Nevada showed a slightly lower coherence around one day and the harmonic peaks were much less pronounced.

Summer, shown in figure 4.20, showed lower coherence in the synoptic-scale for Montana and Pennsylvania but Nevada had much stronger coherence. Montana showed a large peak between 6 and 15 days with a magnitude of around 0.7. The magnitude between 5 and 2 days were around 0.5. The monthly scale around 30 days was nearly incoherent in Montana and Pennsylvania. Pennsylvania showed very strong coherence between 3 days and 15 days. There was also a moderate
peak around 2 days. Nevada showed much higher coherence than in the spring. There was a strong coherence peak from 6 days through the month with a peak magnitude of around 0.85. The diurnal coherence was high at one day at all three locations and at 12 hours in Pennsylvania and Nevada. Pennsylvania showed the widest band of high coherence around one day.

Fall, shown in figure 4.21, showed the largest coherence in Nevada while Montana and Pennsylvania showed much lower coherence than the spring and summer throughout the synoptic-scale weather. Montana showed a few small peaks around 2 days, 5 to 10 days, and 15 days all with magnitudes less than 0.4. Pennsylvania showed moderate coherence around 10 days and between 2 and 3 days. Nevada had significant coherence from 5 days to 20 days with a magnitude of around 0.8. The diurnal cycle showed peaks at one day and 12 hours at all three locations. There were a few less significant peaks in Montana at 8 hours and 6 hours. Nevada showed one additional peak at 8 hours.

Wind Speed:

Figures 4.22 through 4.25 show the coherence and phase plots for down-welling solar versus wind speed. Winter, figure 4.22, shows a few minor peaks in coherence through the synoptic-scale weather. Montana has moderate coherence that
Figure 4.23. Coherence and phase between DWS and wind speed for spring.

Figure 4.24. Coherence and phase between DWS and wind speed for summer.
Figure 4.25. Coherence and phase between DWS and wind speed for fall.

is mostly in phase at 3 days and between 5 to 9 days. Pennsylvania is nearly incoherent through the synoptic scale. Nevada has moderate coherence that is slightly out of phase around 15 days. All three locations showed moderate coherence in the diurnal cycle around one day and 12 hours, but the diurnal coherence was much lower than with the other meteorological conditions with a peak magnitude of around 0.6 in Montana and less than 0.8 in Pennsylvania and Nevada.

Spring, figure 4.23, shows slightly higher coherence in Pennsylvania and Nevada compare with the winter. Pennsylvania had a peak magnitude of 0.6 from 5 days to 15 days. Nevada had a small peak between 2 and 4 days. Montana showed a few minor peaks in coherence with a magnitude of 0.4 around 2 days and from 4 to 8 days. All three locations had very low monthly coherence. Montana and Pennsylvania showed peaks in the diurnal cycle around one days covering narrow frequency bands.

Figure 4.24 shows the coherence and phase spectra for summer. There were only minor peaks in the magnitude of coherence in the synoptic-scale weather. Montana shows the largest peaks between 3 and 4 days with a magnitude of around 0.6, and 5 to 15 days with a magnitude of 0.4. Pennsylvania has insignificant peaks from 4 to 10 days. Nevada was nearly incoherent through the synoptic-scale. The
coherence in the diurnal cycle had peaks around one day in all three locations with narrow frequency bands. Montana showed secondary peaks at 8 and 4.8 hours. Pennsylvania had one additional peak at 12 hours and Nevada had two additional peaks at 12 hours and 8 hours.

Fall, figure 4.25, was mostly incoherent throughout the synoptic-scale weather. There were a few small peaks around 2 and 3 days but they are not significant. The diurnal cycle showed moderate coherence in all three locations around one day and 12 hours with Montana having additional peaks at 8 hours and 4.8 hours.

**Pressure:**

Figures 4.26 through 4.29 show the coherence and phase plots for down-welling solar versus pressure. Winter, shown in figure 4.26 shows only moderate coherence through the synoptic-scale weather. Montana shows several peaks around 2 and 3 days with magnitudes of 0.5, and from 5 to 20 days with a magnitude of around 0.4 to 0.5; these peaks showed a phase lag. Pennsylvania had a peak with a magnitude of 0.6 around 4 days that was mostly in phase. Nevada showed several peaks at 2 days and over a wide range around 10 days. Neither of these peaks had large magnitudes, barely reaching 0.4. The diurnal cycle showed several peaks. Nevada was the only location with a one day peak while all three locations had 12 hour...
Figure 4.27. Coherence and phase between DWS and pressure for spring.

Figure 4.28. Coherence and phase between DWS and pressure summer.
and 8 hour peaks. Montana showed two additional peaks at 6 hours and 3 hours with large magnitudes of around 0.7.

Spring, shown in figure 4.27, had the largest magnitudes of coherence throughout the synoptic-scale weather. Montana had a few small peaks around 2 days and 6 days with magnitudes of 0.4 and 0.5 respectively. Pennsylvania had relatively high coherences from 6 days through the monthly scale. The synoptic-scale coherence was the highest at 15 days with a magnitude of 0.7. There was also a peak around 3 days. Nevada had lower coherence than Pennsylvania but still showed 2 significant peaks at 3 days and 10 days reaching magnitudes of 0.68 and 0.66 respectively. Nevada showed very low monthly coherence after the 10 day peak. All three locations showed high coherence in the diurnal cycle at one day and 12 hours. The few secondary peaks in the diurnal cycle had much lower magnitudes.

Summer, shown in figure 4.28, showed only moderate coherent throughout the synoptic-scale weather at all three locations. Pennsylvania and Nevada showed insignificant peaks between one day and 3 days with magnitudes approaching 0.4. Montana and Pennsylvania showed minor peaks with magnitudes of around 0.5 from 2 to 6 days. Nevada also had a peak at 10 days with a magnitude of 0.4. All three locations showed large coherence peaks at one day and 12 hours. Montana
and Nevada also showed peaks at 8 hours.

Fall, shown in figure 4.29 was mostly incoherent throughout the synoptic-scale weather with the exception of Pennsylvania which had a few peaks with magnitudes reaching 0.4 between 2 and 4 days and a wide band around 15 days. All three locations had significant peaks throughout the diurnal cycle at one day, 12 hours, and 8 hours.
Chapter 5

Discussion and Conclusions

Analyzing the character of both the power spectral density and the inter-site co-spectrum of shortwave solar irradiance in mid-latitude climate regimes of the USA gives further insight to the time-space scales of variation of the available solar resource. The degree of synoptic scale variability varies with both climate region and season, as does the meso- and microscale variability. The analyzed power spectral densities for mid-continent, mid-Atlantic, and Southwest regimes exhibit evidence that synoptic weather (periods of days) behavior impacts the magnitude and frequency dependence of meso- and microscale (periods of hours and minutes) variations. Thus, the degree of short-period variation in solar irradiance could be inferred from the long-period variation captured by conventional low-frequency observations.

This information is potentially useful for distribute power generation planning for multi-site, networked solar power installations. Likewise, because of the rough correspondence between temporal and spatial spectra captured in Taylors Frozen Wave Hypothesis, this information could also be exploited to help estimate the variation of aggregate power production from a spatially distributed solar resource.

While analyzing the character of the down-welling solar can be beneficial to long term solar energy generation planning, analyzing the character of the DWS in conjunction with meteorological conditions (temperature, relative humidity, pressure, and wind speed) can be beneficial to short-term and mid-term solar resource forecasting. There are frequent analyses of the condition of the weather performed with great accuracy. Incorporating the solar resource into these analyses requires
knowledge of the relationship between irradiance and the various meteorological conditions.

The variability of the meteorology parameters is closely related to the sites’ locations distributed across the United States. The mid-continental, mid-Atlantic, and southwest locations showed very different conditions throughout the seasons. A large analysis including more sites would be useful to fully understanding the variations across the United States. An additional affect of Taylor’s Frozen Wave Hypothesis is that the character of the meteorology conditions could be extrapolated across relative proximity around many observation stations that already exist across the United States.

The distributed solar resource issues can be addressed more directly using coherence and phase spectra between pairs of sites. The diurnal variability is, of course, highly coherent between sites. The synoptic scale variability is less so, but remains large in the 3 to 6 day range typical of air mass and cyclone passage. Thus, solar irradiance variations are strongly correlated between sites at these time scales. In contrast, coherence is weak at the meso- and microscale. Thus, site aggregation could greatly reduce power variability on these shorter time scales. This result is expected to be sensitive to the spacing between sites, another consequence of the Taylor Frozen Wave Hypothesis.

The cospectral analysis of the meteorological parameters showed that relative humidity had the highest coherence with down-welling solar throughout the synoptic-scale. Wind speed and pressure showed the least coherence with down-welling solar throughout all weather scales and the seasons. Additionally there were much stronger phase offsets between DWS and meteorological conditions than between the inter-site DWS analysis. Understanding of the phase offset could aid in short-term and mid-term forecasting of the solar resource based on known weather conditions.

Information on the characteristics of the irradiation with frequency longer than one day is relevant to slow ramping technologies for long term forecasts. Information on the characteristics of the irradiation with frequency shorter than one day is relevant to fast ramping technologies. If there is a high degree of coherence on long time scales (the sites are either both receiving sunlight or both not receiving sunlight) alternative forms of energy generation are required to offset production.
Appendix A

Program for Equation of time and Declination

The function shown here calculates the declination, equation of time, Greenwich hour angle, and solar hour angle for a specific time. In order to produce a yearly plot of the data a frame program was also written to control the flow of time.

function [DEC, EoT, NGHA, SHA, YRT] = . . DEC_EoT(wDY, wMN, sYR, wHR, SLONG)
//Calculates declination and the equation of time using
//Yallop’s method
funcprot(0)
if wMN > 2 then
  NYR = sYR; NMN = wMN - 3;
else NYR = sYR - 1; NMN = wMN + 9;
end

//Calculates time of year
YRT = (((wHR + SLONG/15)/24) + wDY + int(30.6*NMN + 0.5) + . .
.. int(365.25*(NYR - 1976)) - 8707.5)/36525.0;
G = 357.528 + 35999.05*YRT;
if G > 360 then
  NG = G - int(G/360)*360;
else NG = G;
end

C = 1.915*sin(NG*DEGRAD) + 0.020*sin(2*NG*DEGRAD);
L = 280.460 + 36000.770*YRT + C;
if L > 360 then
    NL = L-int(L/360)*360;
else
    NL = L;
end

alph = NL - 2.466*sin(2*NL*DEGRAD) + 0.053*sin(4*NL*DEGRAD);
eps = 23.4393 - 0.013*YRT;
GHA = 15*wHR - 180 - C + NL - alph;
if GHA > 360 then
    NGHA = GHA-int(GHA/360)*360;
else
    NGHA = GHA;
end

DEC = atan(tan(eps*DEGRAD)*sin(alph*DEGRAD))/DEGRAD;
EoT = (NL-C-alph)/15;
SHA = NGHA-LLONG;
endfunction
Program for Data Processing

The function shown here processes data from the SURFRAD and ISIS networks. The data must be in three minute time steps for this program to function properly.

```
function [processedData] = dataProcessing(data,total,type);
    funcprot(0);
    //Data Processing for SURFRAD and ISIS network radiation and
    //meteorology measurements. Removes negative noise and
    //erroneous data points.
    clear processedData;
    clear dataArray;

    for i = 1:(total)/480
        for j = 1:480
            k = (i-1)*480+j;
            if data(k) <= -3000 then
                if type == 'rad' then
                    if k == 1 | k == total then
                        dataArray(k) = 0;
                    elseif j < 340 & j > 100 then
                        dataArray(k) = dataArray(k-1)...
                        +abs((dataArray(k-1)-dataArray(k-2)));
                    else
                        dataArray(k) = dataArray(k-1)...
                        -abs((dataArray(k-1)-dataArray(k-2)));
                    end
                if dataArray(k) < 0 then
                    dataArray(k) = 0;
                end
            end
    end
```
else
    if k == 1 | k == 2 | k == total then
        dataArray(k) = 0;
    else
        if dataArray(k-1) <= dataArray(k-2) then
            dataArray(k) = dataArray(k-1) - abs((dataArray(k-1) - dataArray(k-2)));
        else
            dataArray(k) = dataArray(k-1);
        end
    end
    if dataArray(k) < 0 then
        dataArray(k) = 0;
    end
elseif (data(k) < -10) then
    dataArray(k) = 0;
else
    dataArray(k) = data(k);
end
end

processedData(:) = dataArray(:);

endfunction
Program for PSD and Coherence and Phase Spectra

//Function that calculates the coherence and phase for two input data arrays.
function [psd1, psd2, dcohere, dphase, coh] = CoherenceAndPhase(dataArray1, dataArray2, total)
  funcprot(0);

m = 9;
nw = total/m;
startpt = 1;
endpt = nw;
gasum = zeros(nw,1);
gbsum = zeros(nw,1);
psd1 = zeros(nw,1);
psd2 = zeros(nw,1);
gabsum = zeros(nw,1);
gsyhan = window('hm', nw);
qsum = zeros(nw,1);
cosum = zeros(nw,1);

gsyhanCol(:,1) = gsyhan;

for i = 1:m
    ap = detrend(dataArray1(startpt:endpt,1))
    ap = ap.*gsyhanCol;
    bp = detrend(dataArray2(startpt:endpt,1))

bp = bp .* gsyhanCol;

fap = fft(ap);
fbp = fft(bp);
fftpsd1 = abs(fft(dataArray1(startpt:endpt,1)))^2;
fftpsd2 = abs(fft(dataArray2(startpt:endpt,1)))^2;
fap = fftshift(fap);
fbp = fftshift(fbp);
cop = (real(fap) .* real(fbp) + imag(fap) .* imag(fbp));
qp = (imag(fap) .* real(fbp) - real(fap) .* imag(fbp));

gap = abs(fap) ^ 2;
gbp = abs(fbp) ^ 2;

gasum = gasum + gap;
gbsum = gbsum + gbp;

psd1 = psd1 + fftpsd1;
psd2 = psd2 + fftpsd2;
gabp = conj(fap) .* fbp;
gabsum = gabsum + gabp;
qsum = qsum + qp;
cosum = cosum + cop;

startpt = startpt + nw
endpt = endpt + nw

end

dcohere = (conj(gabsum) .* gabsum) ./ (gasum .* gbsum);
lcohere = linspace(1, total/m, total/m);
coh(:, 1) = lcohere;
dphase = atan(qsum ./ cosum);
Appendix D

Regression Analysis Program and Results

The program shown here calculates the coefficients for calculating the synoptic-scale slope and intercept from meso- and micro-scale data. The same format was used for the analysis to calculate meso- and micro-scale slope and intercepts from synoptic-scale data.

\[
\text{[n,I\_syn, S\_syn, I\_mm, S\_mm]} = \text{mfscanf(-1,fid, "\%f \%f \%f \%f")};
\]

\[
\text{total=size(I\_syn,1)};
\]

\[
\text{//S\_syn = aCoeff*S\_mm + bCoeff*I\_mm + cCoeff}
\]

\[
\text{//I\_ss = dCoeff*S\_m + eCoeff*I\_mm + fCoeff}
\]

\[
\text{//x1=a,x2=b,x3=c}
\]

\[
\text{ax=linspace(1,1,24)};
\]

\[
\text{a3(:,1)=ax}
\]

\[
\text{//coeffs = [aCoeff;bCoeff;cCoeff];}
\]

\[
\text{A=[S\_mm,I\_mm,a3]};
\]

\[
\text{B=[S\_syn]};
\]

\[
\text{coeffs=A\textbackslash B}
\]

\[
\text{D=[S\_mm,I\_mm,a3]};
\]

\[
\text{E=[I\_syn]};
\]

\[
\text{coeffs2=D\textbackslash E}
\]
Bibliography


