

# FullView®



Site Resource  
Assessment

ANALYSIS OF 14-YEAR RECORD

## Draft Report: Desert Rock, Nevada

FOR  
Client X, Inc.

DATE

May 3, 2011

CONTACT

ph: +1 206.325.1573

fax: +1 206.325.1618

[info@3tier.com](mailto:info@3tier.com)

[www.3tier.com](http://www.3tier.com)

2001 6th Avenue, Suite 2100  
Seattle, WA 98121-2534

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# 1 EXECUTIVE SUMMARY

3TIER has been retained by Client X, Inc. to assess the variability and magnitude of solar irradiance, wind, and temperature at the Desert Rock project site located in Nevada (Latitude: 36.626°N, Longitude: 116.018°W). This report provides a retrospective analysis of the past 14+ years of solar irradiance, wind, and temperature data. The methodology used to derive the solar irradiance from satellite imagery is explained in Section 2. Section 6 explains the methodology used to derive the wind and temperature data.

These data, where indicated, were derived from a model that has been statistically corrected using the observed data during the measurement period at a measurement site that is at or near the project location. Sections 8 and 9 provide details of the comparison of ground and satellite-derived irradiance used in this report.

The expected long-term irradiance (P50) and the probability of exceeding various irradiance values for any continuous 1-year period (1-year P75, P90, P95 and P99) and any continuous ten-year period (10-year P75, P90, P95 and P99) are shown in Section 5. The uncertainty analysis leading to these probability of exceedance values are described in Section 4.

While the data used in this report are comprised of hourly values for the past 14+ years (January 1997 through March 2011), long-term average values are only calculated using complete calendar years. In this report the long-term average period of time is January 1, 1997 through December 31, 2010. Table 1 below shows the long-term average values for MOS-corrected global horizontal irradiance (GHI), MOS-corrected direct normal irradiance (DNI), diffuse horizontal irradiance (DIF), wind speed at 10 meters above ground level (AGL), temperature at 2 meters AGL, surface pressure, and relative humidity at 2 meters AGL.

Variable	Long-term Mean (1997 – 2010)
MOS-corrected Global Horizontal Irradiance (GHI)	238.3 W/m <sup>2</sup> (2087 kWh/m <sup>2</sup> /year)
MOS-corrected Direct Normal Irradiance (DNI)	324.6 W/m <sup>2</sup> (2843 kWh/m <sup>2</sup> /year)
Diffuse Horizontal Irradiance (DIF)	53.20 W/m <sup>2</sup> (466.1 kWh/m <sup>2</sup> /year)
Wind Speed at 10 meters AGL	4.67 m/s
Temperature at 2 meters AGL	15.1 °C
Surface Pressure	89339.1 Pa
Relative Humidity at 2 meters AGL	57.29 %

**Table 1:** Long-term means of several variables at the Desert Rock project site.



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## 2 EXPLANATION OF IRRADIANCE VALUES

The irradiance values presented in this report are from 3TIER's solar dataset. This dataset is based on the past 14+ years (January 1997 through March 2011) of half-hourly high-resolution (roughly 1 km) visible satellite imagery from GOES satellite data (GOES East and GOES West, using the broad-band visible wavelength channel). The satellite imagery has been processed to create 14+ years of hourly values of Global Horizontal Irradiance, Direct Normal Irradiance and Diffuse Horizontal Irradiance at a horizontal resolution of 2 arc minutes. To develop and validate the model, and estimate the error, 3TIER compared the derived irradiance values with observations from the direct surface radiation measurements contained in the National Solar Radiation Database and the Baseline Surface Radiation Network. The error estimates were derived comparing the model data with observations that were not used in training or tuning the modelling system. The error was calculated from the standard deviation of the bias between the satellite estimates and the ground measurements. The standard error estimates provided are computed using all available sites globally and do not include measurement error.

### 2.1 Global Horizontal Irradiance

Global Horizontal Irradiance is the quantity of the total solar radiation per unit area that is intercepted by a flat, horizontal surface. This value is of particular interest to photovoltaic installations. It includes both direct beam radiation (radiation that comes from the direction of the sun) and diffuse radiation (radiation that has been scattered by the atmosphere and which comes from all directions of the sky). The estimate has a standard error of 5.0%.

### 2.2 Direct Normal Irradiance

Direct Normal Irradiance is the quantity of direct beam solar radiation per unit area that is intercepted by a flat surface that is at all times pointed in the direction of the sun. This quantity is of particular interest to concentrating solar installations and installations that track the position of the sun. The estimate has a standard error of 9.0%.

### 2.3 Diffuse Horizontal Irradiance

Diffuse Horizontal Irradiance is the quantity of diffuse solar radiation per unit area that is intercepted by a flat, horizontal surface that is not subject to any shade or shadow and does not arrive on a direct path from the sun. The estimate has a standard error of 15.0%.

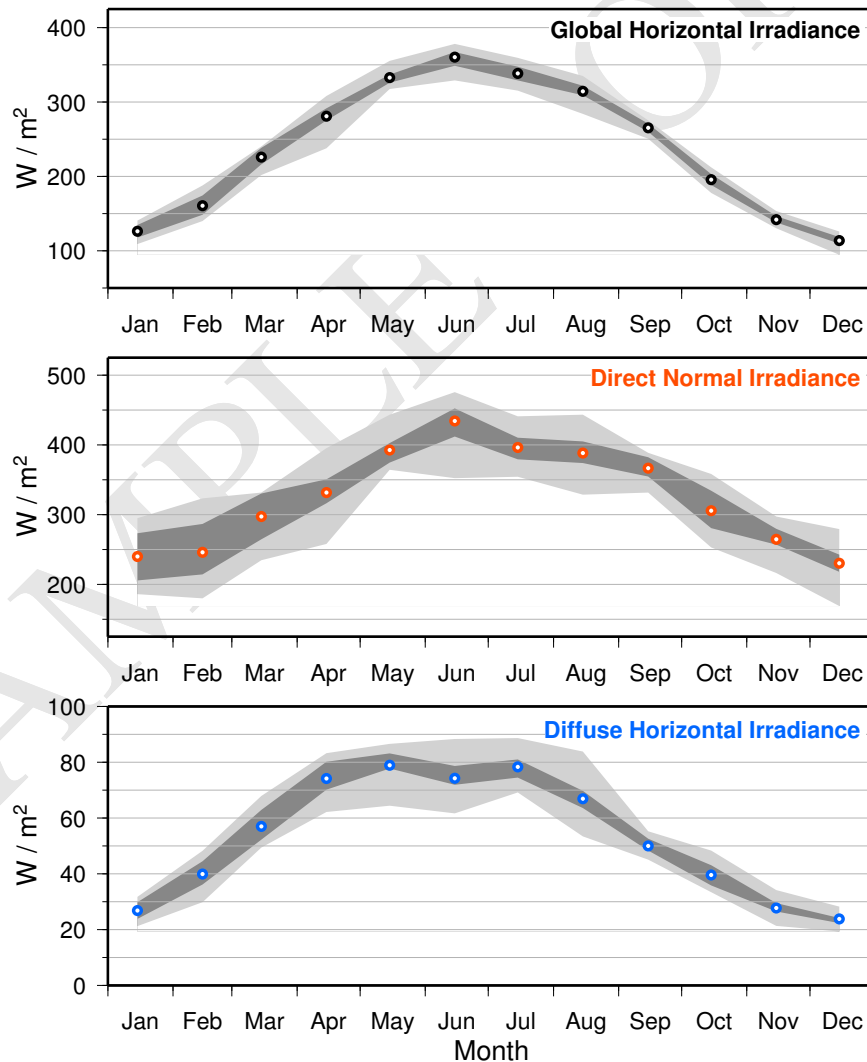
**MOS-correction** was performed on DNI and GHI using the 13 months of onsite observations provided (March 1998 through March 1999). The resulting MOS equations were applied to all calendar months. This correction changed the long-term mean DNI from 300.0 W/m<sup>2</sup> as a raw DNI to 324.6 W/m<sup>2</sup> as a MOS-corrected DNI, and the long-term mean GHI from 230.2 W/m<sup>2</sup> as a raw GHI to 238.3 W/m<sup>2</sup> as a MOS-corrected GHI. Details of the comparison of ground and satellite-derived irradiance can be found in Sections 8 and 9.



### 3 SOLAR RESOURCE ASSESSMENT

This section provides a retrospective analysis of the past 14+ years of solar irradiance data at the Desert Rock project site (Latitude: 36.626°N, Longitude: 116.018°W). All irradiance data presented within this section are valid only for this particular location.

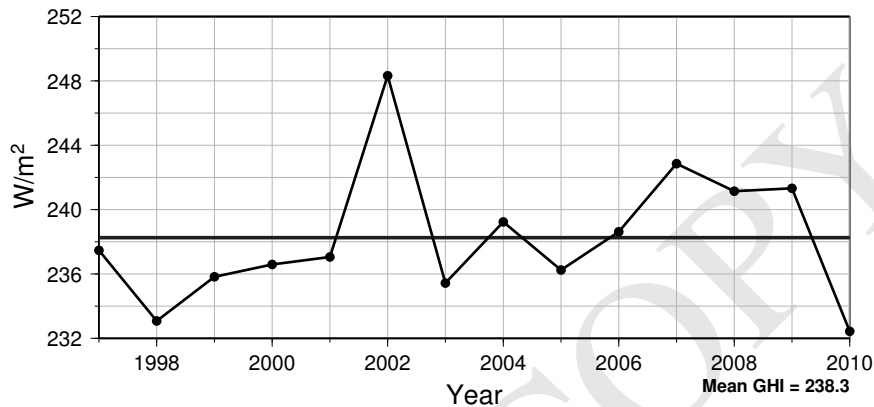
#### 3.1 Monthly-mean Variability of Solar Irradiance



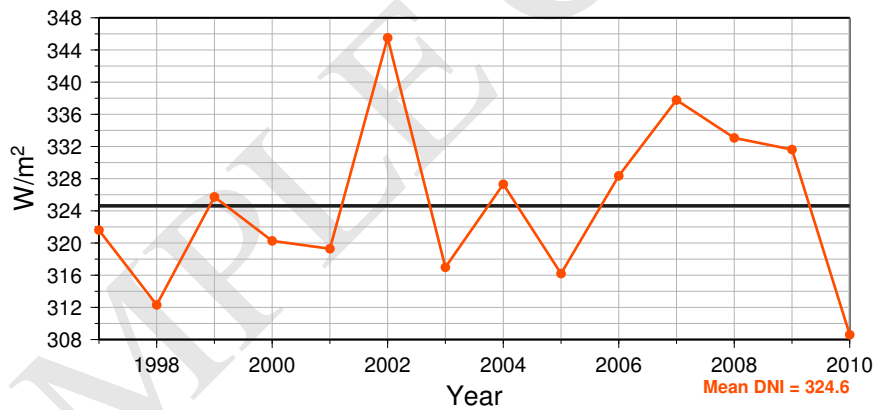
**Figure 1:** Variability of monthly-mean MOS-corrected Global Horizontal [top], MOS-corrected Direct Normal [middle], and Diffuse Horizontal [bottom] irradiance. Long-term monthly-mean values are denoted by colored circles. Upper and lower boundaries of the dark shading correspond to the 75% and 25% quartiles, while the light shading denotes the maximum and minimum monthly-mean irradiance values. Please note that the vertical scale varies between the plots.



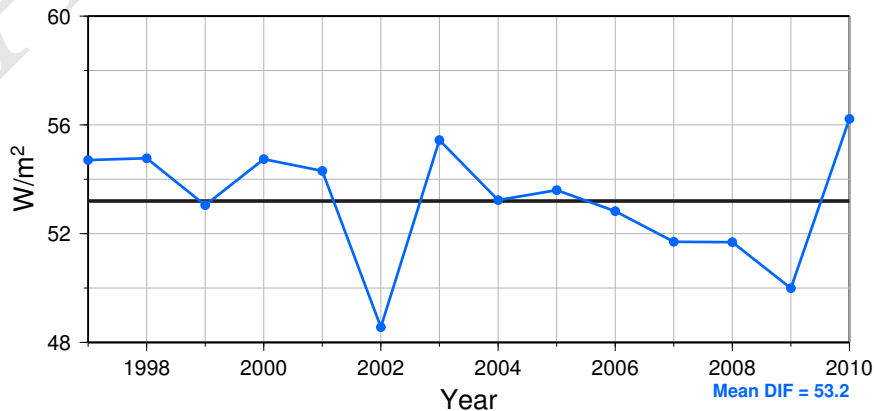
### 3.2 Annual-mean Variability of Solar Irradiance



**Figure 2:** Time series of annual-mean **MOS-corrected Global Horizontal Irradiance**. Black horizontal line denotes the long-term average over the years displayed. Tabular formatted data are available in Table 10 (p. 11).



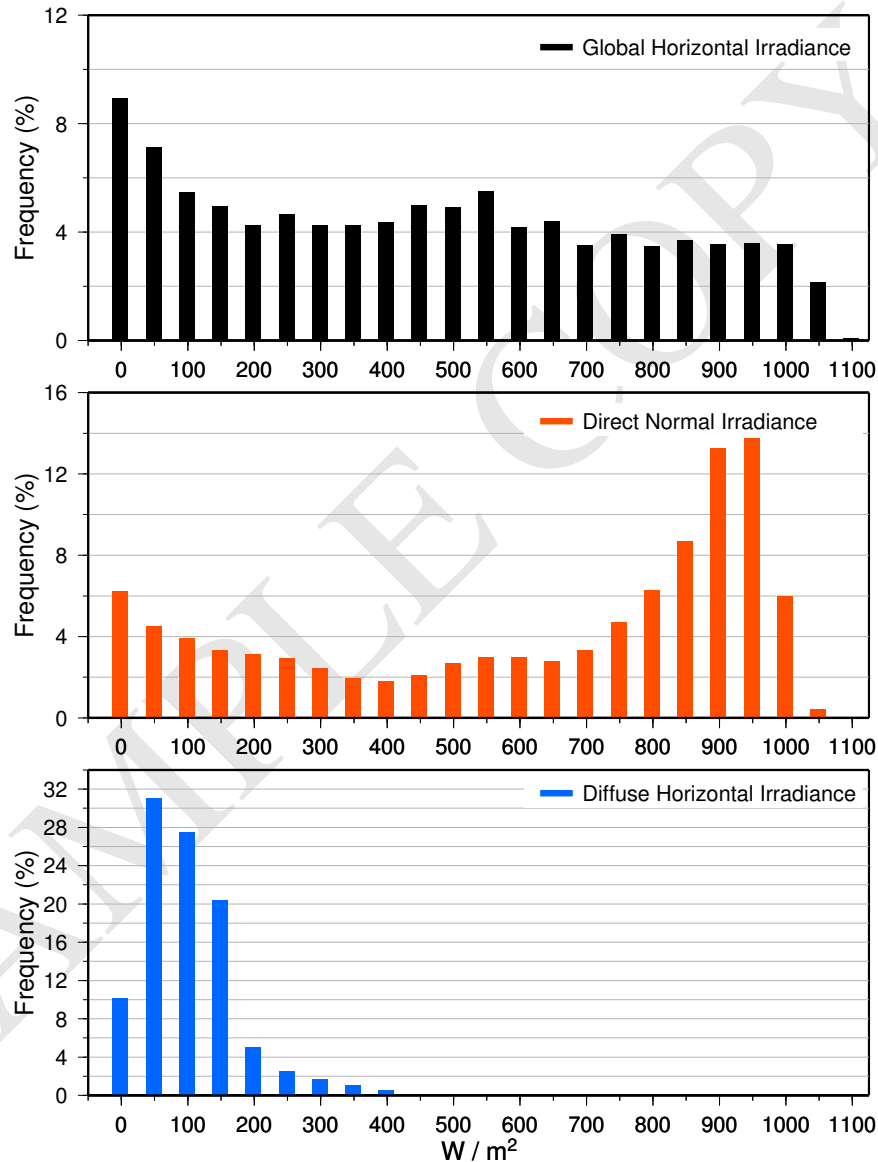
**Figure 3:** Time series of annual-mean **MOS-corrected Direct Normal Irradiance**. Black horizontal line denotes the long-term average over the years displayed. Tabular formatted data are available in Table 11 (p. 12).



**Figure 4:** Time series of annual-mean **Diffuse Horizontal Irradiance**. Black horizontal line denotes the long-term average over the years displayed. Tabular formatted data are available in Table 12 (p. 13).



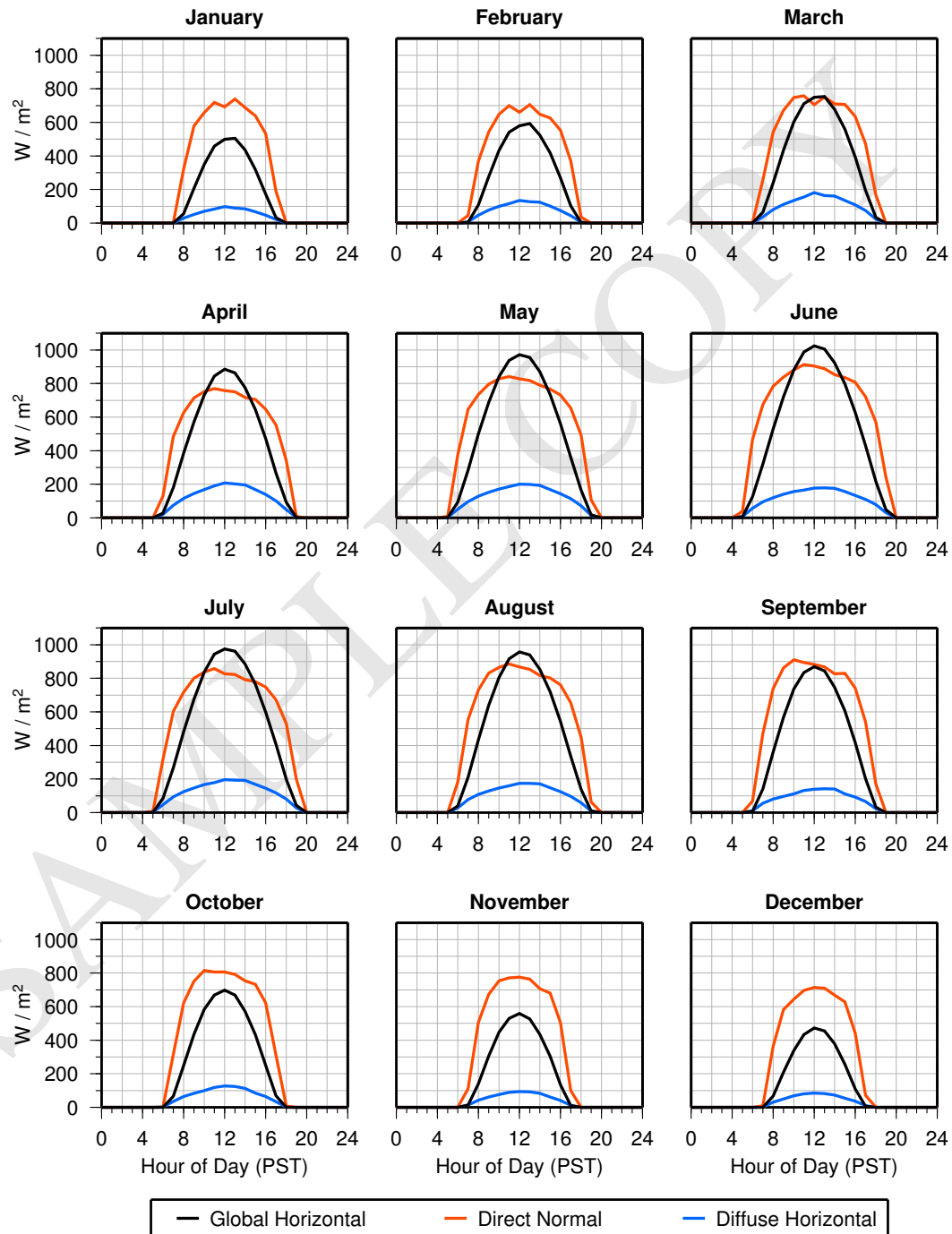
### 3.3 Solar Irradiance Distributions



**Figure 5:** Distribution of hourly MOS-corrected Global Horizontal [top], MOS-corrected Direct Normal [middle] and Diffuse Horizontal [bottom] daylight irradiance values using 50  $W/m^2$  bins. (0  $W/m^2$  bin contains only values  $\leq 25$ .) Each vertical bar represents the frequency of irradiance values occurring within each bin. For example, a vertical bar centered on 200  $W/m^2$  reaching up to 10% means that one-tenth of all daytime values are between 175 and 225  $W/m^2$ . Please note that the vertical scale varies between the plots. Daylight is defined by hours in which the hour-ending mean solar zenith angle is less than 93.0 degrees.



### 3.4 Diurnal Variability of Solar Irradiance



**Figure 6:** Diurnal cycle of MOS-corrected Global Horizontal (black), MOS-corrected Direct Normal (orange) and Diffuse Horizontal (blue) irradiance for each month of the year. The horizontal axis is Pacific Standard Time (PST). Figures 7, 8, and 9 show the diurnal cycle of MOS-corrected Global Horizontal, MOS-corrected Direct Normal, and Diffuse Horizontal solar irradiance, respectively, for each calendar month as a "12 X 24" table.



3.5 Tabular Data

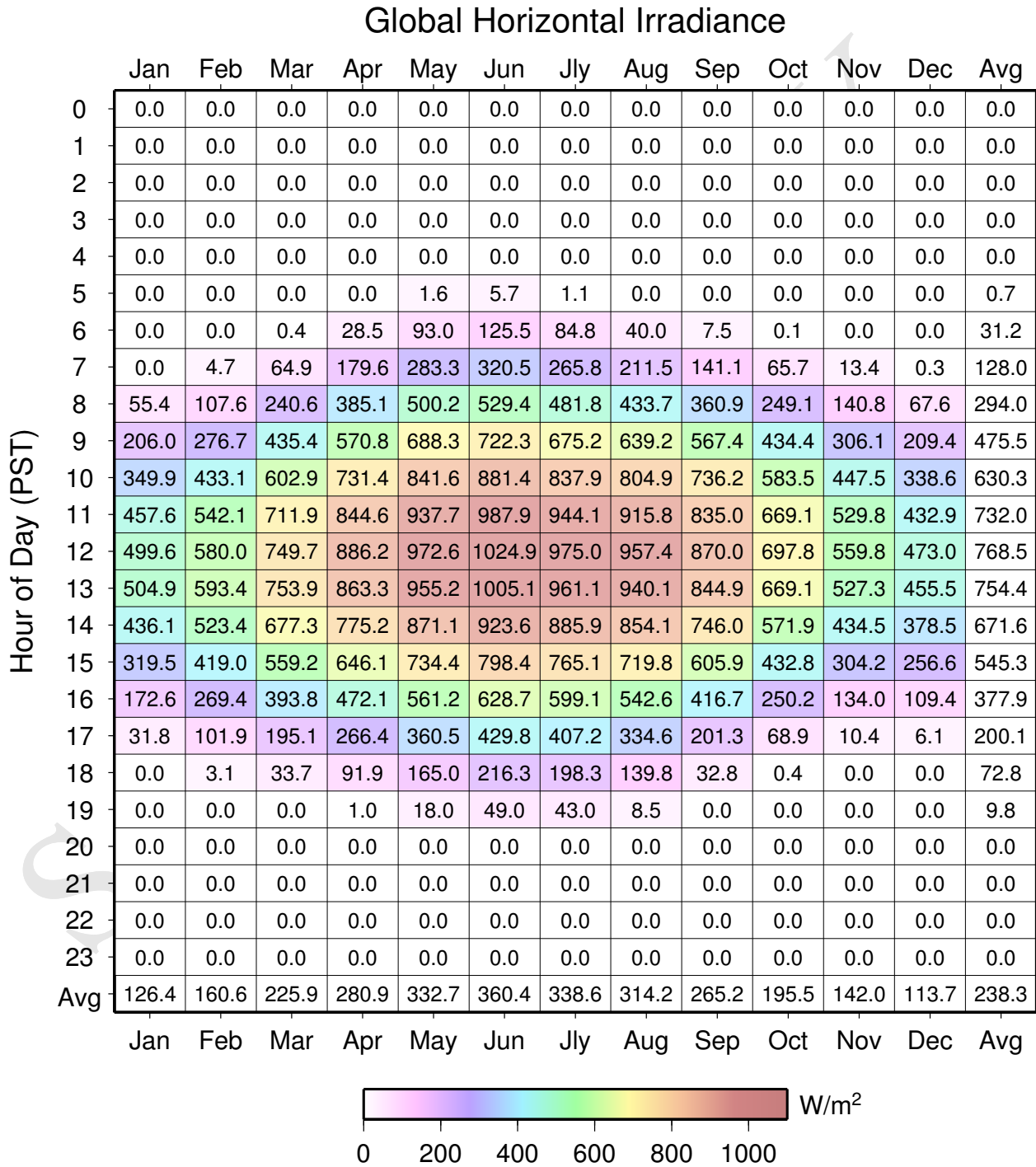
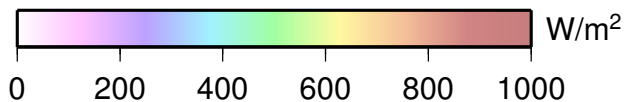


Figure 7: Hourly-mean MOS-corrected Global Horizontal Irradiance values in W/m<sup>2</sup>. The vertical axis is Pacific Standard Time (PST). The overall mean in the bottom right corner is based on complete years only. Time series graph of the diurnal variability is shown in Figure 6.



### Direct Normal Irradiance

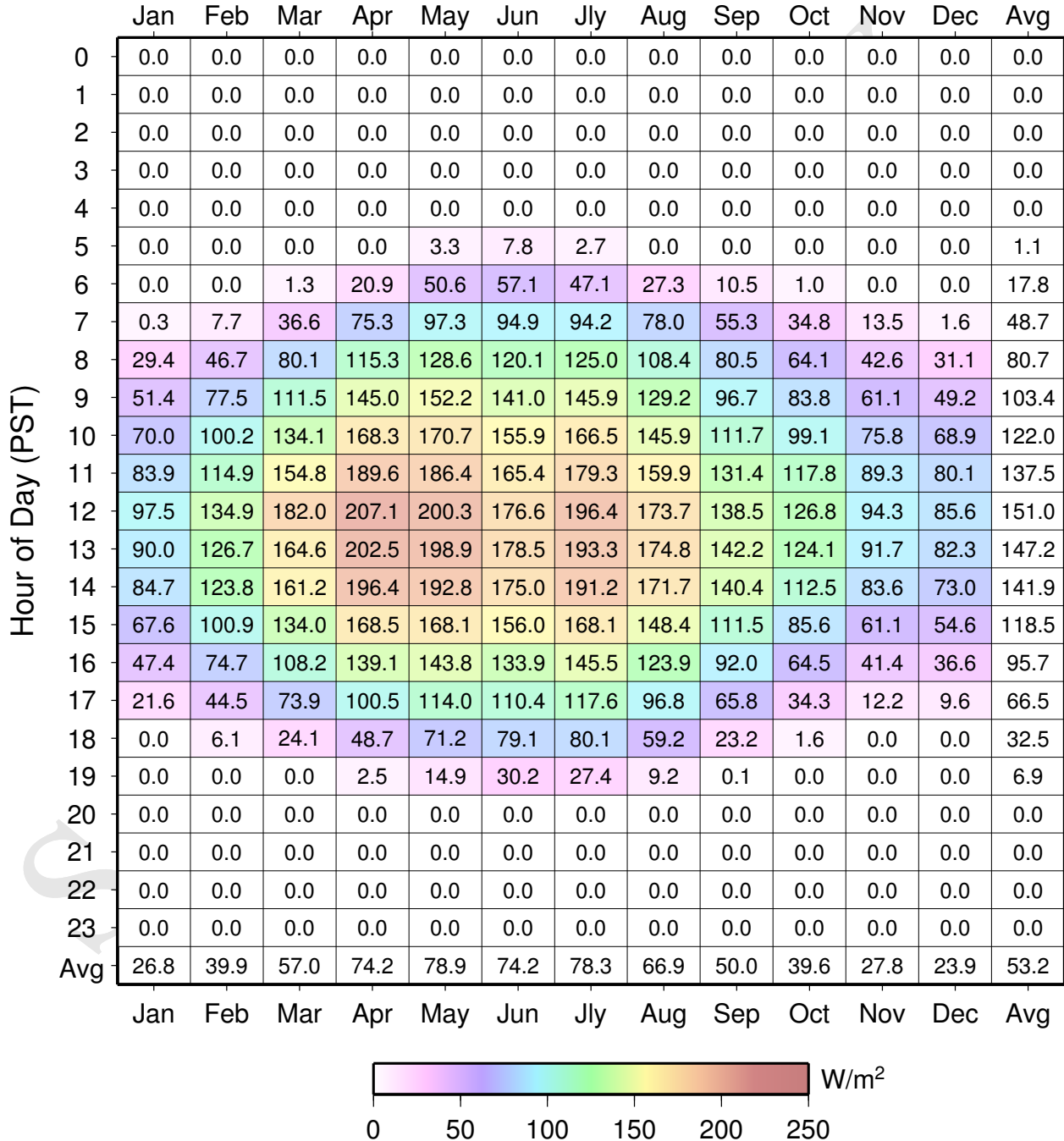
	Jan	Feb	Mar	Apr	May	Jun	Jly	Aug	Sep	Oct	Nov	Dec	Avg
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	9.1	38.2	6.6	0.0	0.0	0.0	0.0	0.0	4.4
6	0.0	0.0	4.1	129.6	374.9	467.4	316.9	181.0	69.1	1.7	0.0	0.0	127.1
7	0.8	45.8	256.4	484.6	647.0	674.4	603.1	554.3	470.7	314.7	111.9	9.4	344.8
8	321.6	368.7	543.1	626.1	735.4	784.0	717.8	730.4	738.5	621.9	507.0	365.0	586.1
9	577.5	543.1	672.5	714.3	796.6	839.0	800.4	831.7	861.8	750.4	673.0	582.9	719.0
10	659.4	648.7	747.7	753.1	827.9	880.9	836.6	864.6	909.8	816.0	754.1	643.6	777.4
11	718.4	699.2	758.9	769.6	841.4	913.2	857.4	884.9	894.4	806.1	771.5	696.9	800.1
12	692.5	659.9	705.4	758.4	828.2	904.9	827.3	868.7	882.0	806.0	775.2	713.9	783.9
13	738.5	705.2	751.6	751.5	818.1	887.8	823.2	853.1	868.5	792.1	763.8	709.8	788.0
14	687.5	647.8	710.1	716.5	790.4	853.2	791.3	817.3	827.3	754.5	707.5	668.6	747.0
15	640.3	626.0	707.0	706.2	766.7	835.4	780.7	802.5	830.0	734.1	680.1	628.3	727.3
16	532.3	553.3	635.6	646.9	731.2	808.3	748.3	761.2	741.6	622.6	505.7	442.0	643.2
17	189.0	369.6	472.6	552.8	654.7	721.9	671.6	654.2	539.8	310.5	100.0	71.5	440.8
18	0.0	34.9	167.1	340.8	493.7	571.1	529.9	450.1	169.2	6.9	0.0	0.0	228.6
19	0.0	0.0	0.0	7.8	106.7	241.6	197.6	62.2	0.0	0.0	0.0	0.0	50.7
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Avg	239.9	245.9	297.3	331.6	392.6	434.2	396.2	388.2	366.8	305.7	264.6	230.5	324.6



**Figure 8:** Hourly-mean MOS-corrected Direct Normal Irradiance values in W/m<sup>2</sup>. The vertical axis is Pacific Standard Time (PST). The overall mean in the bottom right corner is based on complete years only. Time series graph of the diurnal variability is shown in Figure 6.



### Diffuse Horizontal Irradiance



**Figure 9:** Hourly-mean Diffuse Horizontal Irradiance values in W/m<sup>2</sup>. The vertical axis is Pacific Standard Time (PST). The overall mean in the bottom right corner is based on complete years only. Time series graph of the diurnal variability is shown in Figure 6.

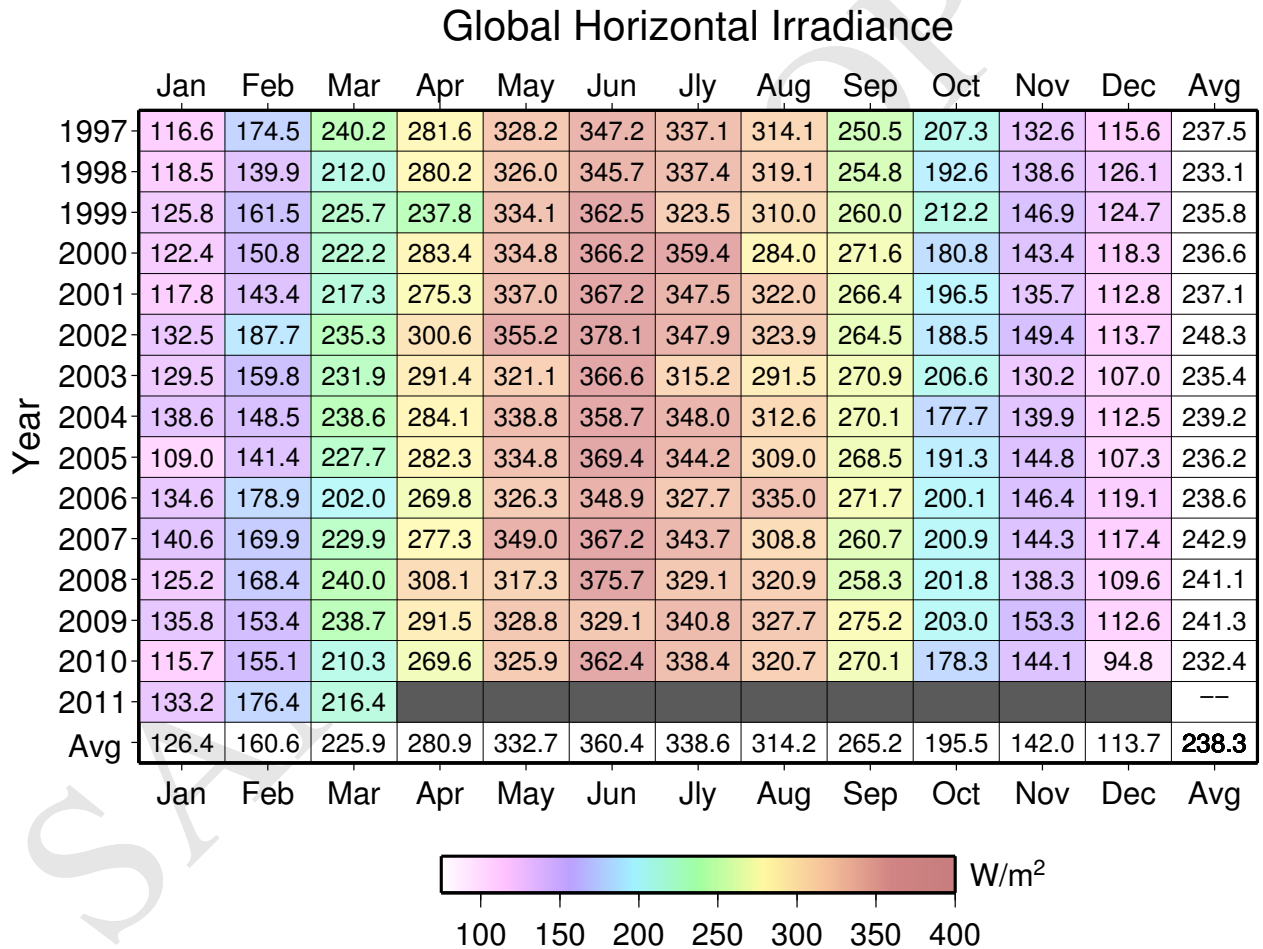


Figure 10: Monthly-mean values of MOS-corrected Global Horizontal Irradiance in W/m<sup>2</sup>. The yearly means in the rightmost column are based on complete years and are shown in Figure 2.

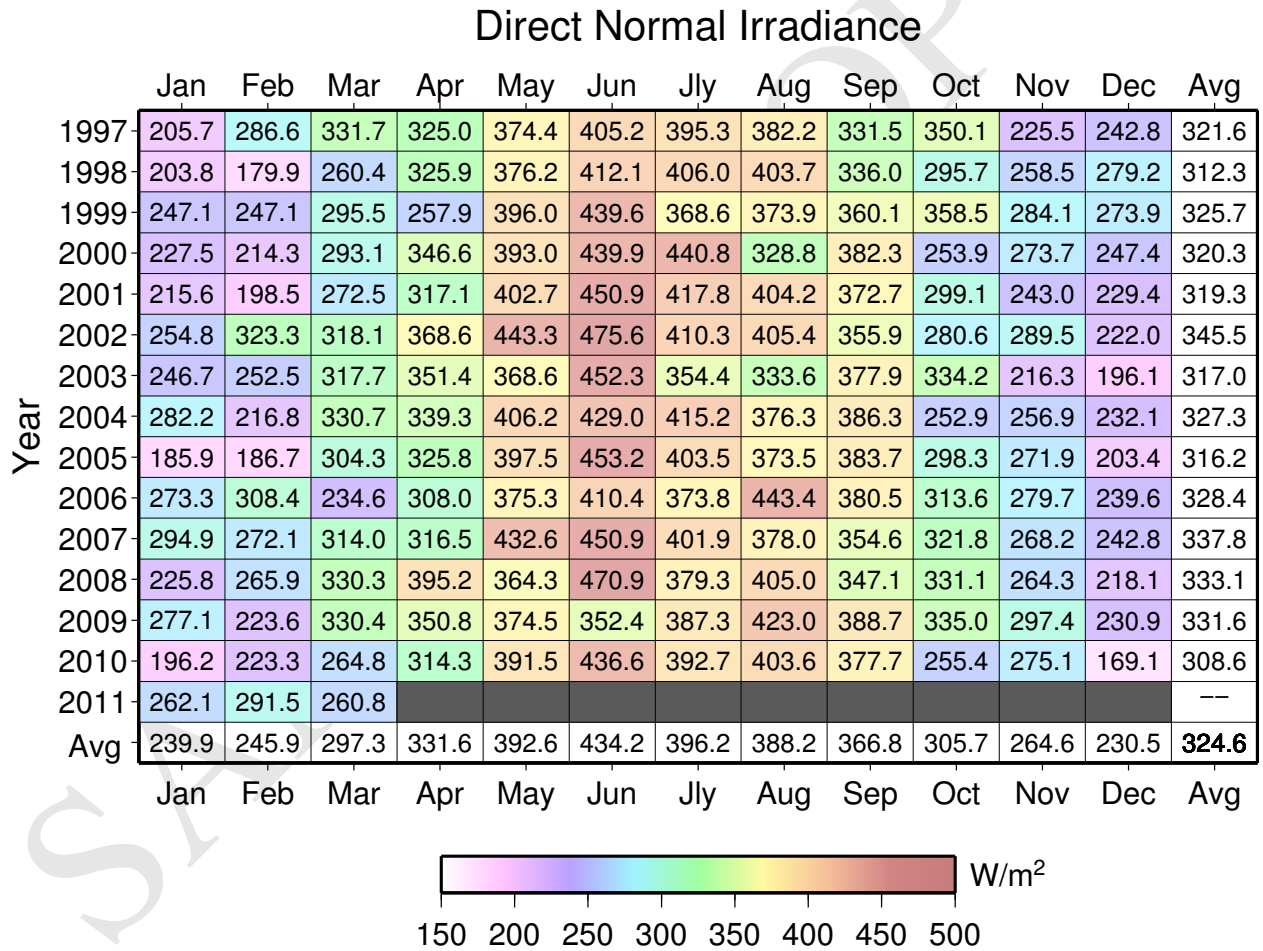


Figure 11: Monthly-mean values of MOS-corrected Direct Normal Irradiance in W/m<sup>2</sup>. The yearly means in the rightmost column are based on complete years and are shown in Figure 3.

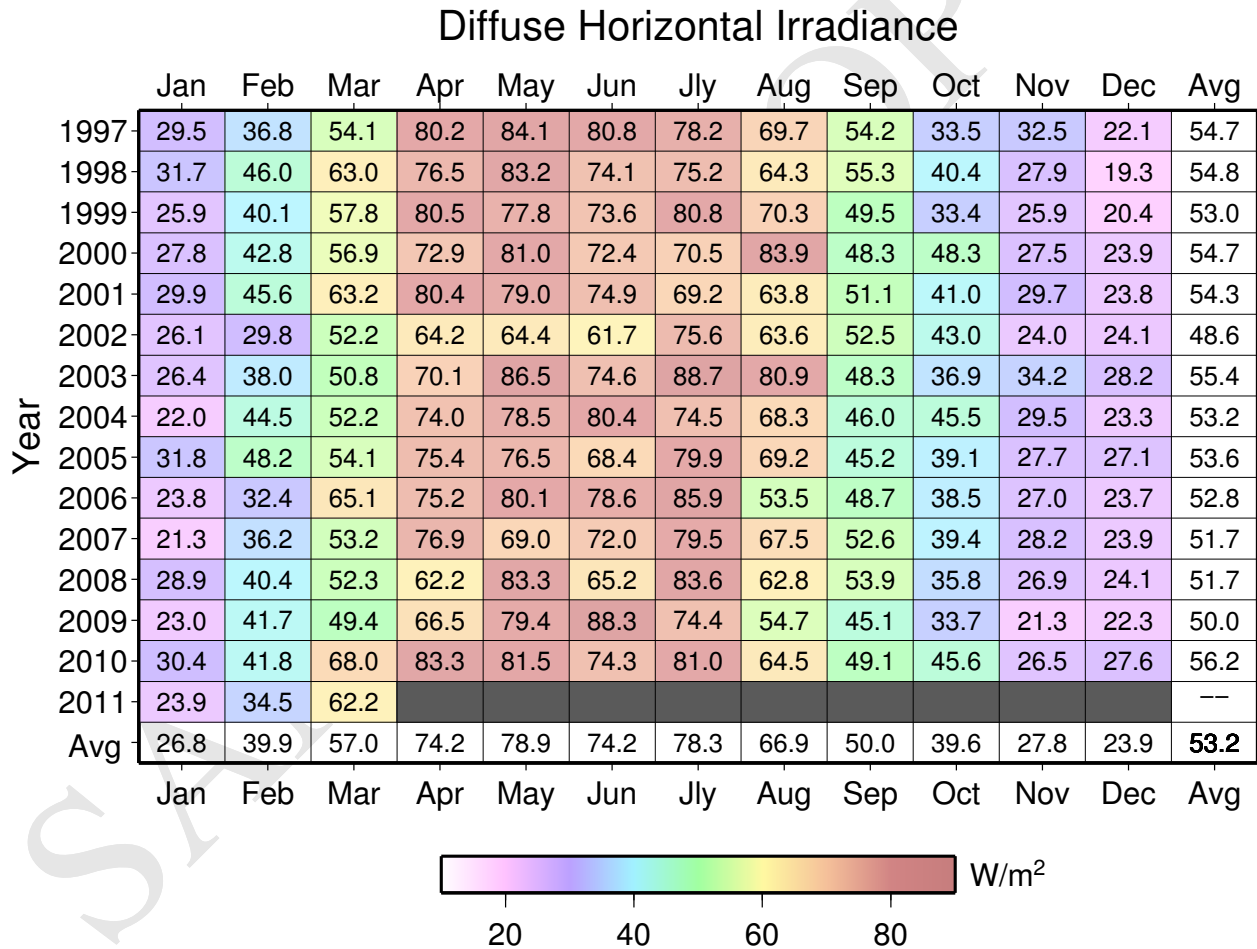


Figure 12: Monthly-mean values of Diffuse Horizontal Irradiance in W/m<sup>2</sup>. The yearly means in the rightmost column are based on complete years and are shown in Figure 4.

## 4 UNCERTAINTY ANALYSIS OF IRRADIANCE

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### 4.1 Measurement Uncertainty

Direct Normal Irradiance and Global Horizontal Irradiance was measured directly at the reference station. Unfortunately, little independent data are available to describe the uncertainty of the sensors employed in estimating the annual average DNI and GHI. Therefore, we accept the measurements and do not attempt to associate a known level of uncertainty with the measurement device.

### 4.2 Model Uncertainty

In the absence of multiple years of ground-based observational data with which to estimate model uncertainty, we use the irradiance model error on the monthly averages as an estimate of the annual error. For months where we have measured data, Root Mean Squared error (averaging over daylight hours) of monthly-mean MOS-corrected DNI and MOS-corrected GHI is used. These values can be seen in the validation analysis sections in Table 5 (p. 27) and in Table 10 (p. 38). For months where we do not have measured data, standard model error, discussed in Section 2 is used. The satellite algorithm error was based on validation of 3TIER's satellite derived data against 92 reference stations across the globe. The error was calculated from the standard deviation of the bias between the satellite estimates and the ground measurements. Table 2 presents the errors, expressed as a percentage of the satellite estimation.

### 4.3 Long-Term Estimate Uncertainty

The solar resource at a given location can vary for a large number of reasons associated with the strength of the solar constant, changes in atmospheric turbidity (e.g. due to volcanic activity, dust storms, etc.), and weather variability from year to year. Two estimates of long-term variability are required in this work. The first is an estimate of the variability for any single year over a long period of time required to estimate the one-year probability of exceedance values. The second is an estimate of the variability over a ten-year continuous period on an annual average basis. To examine the solar resource variability, 3TIER calculated the variability at the Desert Rock project site directly from the interannual variability from 3TIER's multi-year MOS-corrected satellite derived time series. We assume the ten-year variability can be estimated from the one-year variability by dividing by the square root of ten. Table 2 presents the uncertainty associated with 1 and 10-year variability.

#### 4.4 Combining Uncertainty

We assume that all sources of uncertainty described above are independent, and therefore the combined uncertainty can be pooled quadratically. In estimating the difference between the one-year and ten-year probability of exceedance values, we assume that the model uncertainty remains fixed while the uncertainty associated with the long-term variability decreases. The resulting uncertainty analysis for a one-year and ten-year period are summarized in Table 2.

Uncertainty	MOS-corrected GHI	MOS-corrected DNI	DIF
Measurement	–	–	–
Model	1.1	1.4	15.0
1-year Long-Term 10-year Long-Term	1.75 0.55	3.14 0.99	4.01 1.27
Pooled 1-year Pooled 10-year	2.05 1.20	3.44 1.72	15.53 15.05

**Table 2:** Standard error and uncertainty values (% of the mean).

## 5 PROBABILITY OF EXCEEDANCE OF IRRADIANCE

### 5.1 Calculation of Probability of Exceedance Values

Assuming that annual average values are normally distributed, the pooled uncertainty shown in Table 2 results in one-year and ten-year Probability of Exceedance Values (P50, P75, P90, P95 and P99). Results are summarized in Table 3. Using P90 as an example, Desert Rock has a 90 percent chance of exceeding an annual direct normal irradiance of 2718 kWh/m<sup>2</sup>/year for any one-year period and a 90 percent chance of exceeding an annual average direct normal irradiance for a continuous 10 year time period of 2781 kWh/m<sup>2</sup>/year. The 10-year P90 value is larger than the 1-year P90 value due to the decreased impact of inter-annual variability over the longer time period. An example of how the P90 one-year and ten-year probability of exceedance values are calculated is shown below.

$$\text{MOS-corrected DNI 1-year P90} = P50 - 1.282 \times ( 3.44 / 100 ) \times P50 = 2718 \text{ kWh/m}^2/\text{year}$$

$$\text{MOS-corrected DNI 10-year P90} = P50 - 1.282 \times ( 1.72 / 100 ) \times P50 = 2781 \text{ kWh/m}^2/\text{year}$$

	P50	P75	P90	P95	P99
MOS-corrected GHI 1-year	2087	2058	2032	2017	1988
MOS-corrected DNI 1-year	2844	2778	2718	2683	2616
DIF 1-year	466.1	417.2	373.3	347.0	297.7
MOS-corrected GHI 10-year	2087	2070	2055	2046	2029
MOS-corrected DNI 10-year	2844	2811	2781	2763	2730
DIF 10-year	466.1	418.7	376.1	350.7	302.8

**Table 3:** 1-year and 10-year Probability of Exceedance Values (kWh/m<sup>2</sup>/year).

## 6 MODEL SIMULATIONS BY 3TIER

The assessment of the wind resource at the Desert Rock project site presented in this report is based on 14+ years of simulated data (January 1997 through March 2011). The simulated data set is constructed using a state-of-the-art Numerical Weather Prediction (NWP) model that processes coarse-resolution historic gridded data and high resolution topographical and surface data to generate the meteorological time series data.

The NWP model simulated data set is constructed from a 14-year 15km resolution simulation. Some details of the NWP model configuration are shown below in Table 4. The extent of the coarsest grid was selected to capture the effect of synoptic weather events on the wind resource at the site, as well as to allow the model to develop regional, thermally-driven circulations. The increasingly fine 45km, and 15km grids were selected to model the effect of local terrain and local scale atmospheric circulations.

Parameter	Value
Mesoscale numerical weather prediction model	WRF
Horizontal resolution of valid study area	15km
Number of vertical levels	31
Elevation data base	30 second USGS
Vegetation data base	30 second USGS
Surface parameterization	Monin-Obukhov similarity model
Boundary layer parameterization	YSU model (MRF with entrainment)
Land surface scheme	5-layer soil diffusivity model

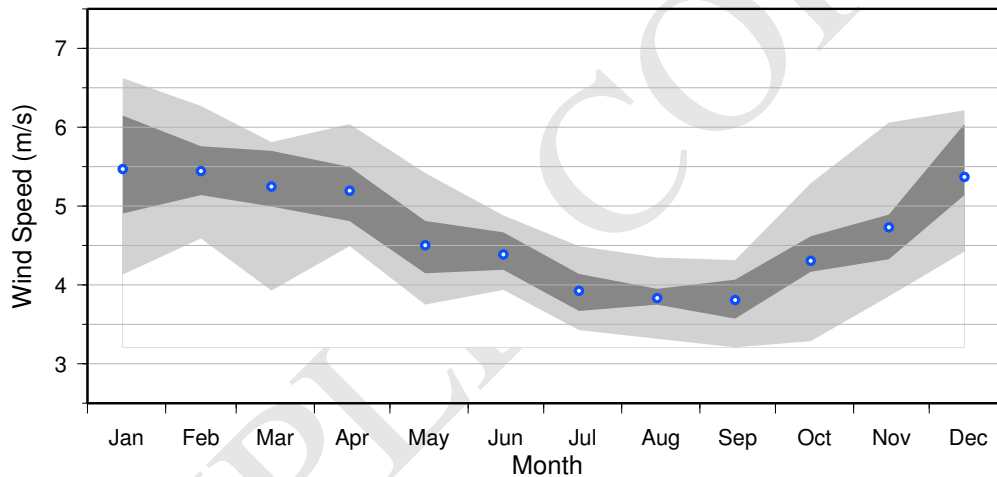
**Table 4:** Numerical weather prediction model configuration.



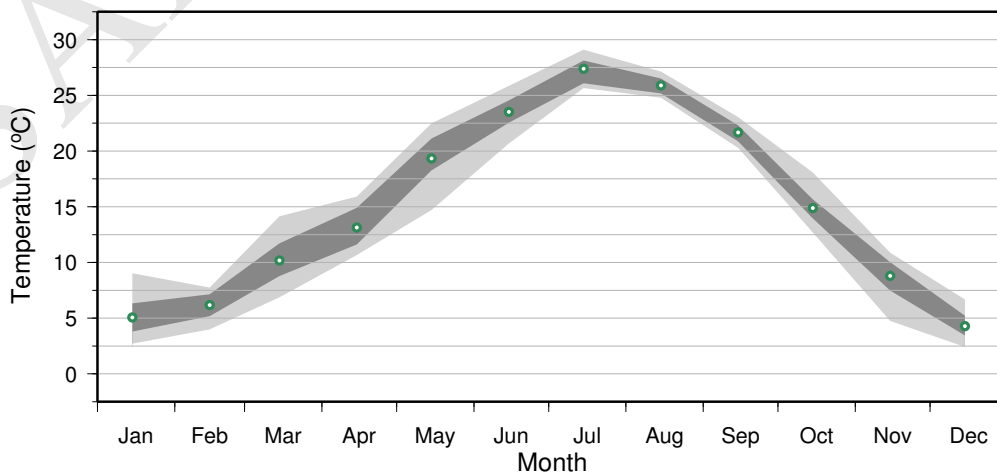
## 7 WIND AND TEMPERATURE RESOURCE ASSESSMENT

This section provides a retrospective analysis of the past 14+ years of wind and temperature data at the Desert Rock project site (Latitude: 36.626°N, Longitude: 116.018°W). All data presented within this section are valid only for this particular location.

### 7.1 Monthly-Mean Variability



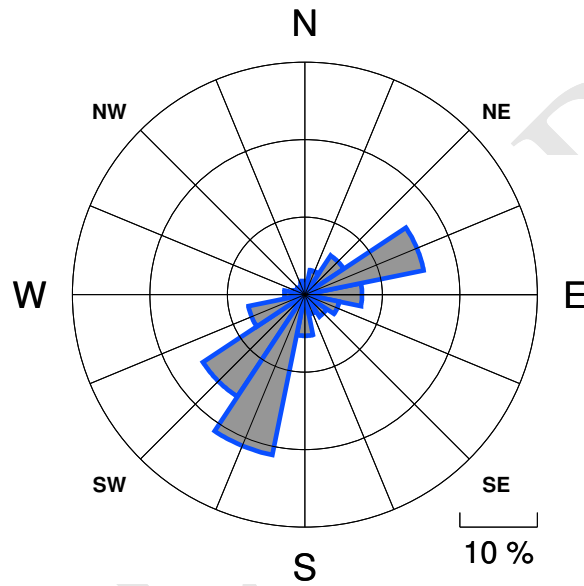
**Figure 13:** Variability of monthly-mean **wind speed** at 10m AGL at Desert Rock. Long-term monthly-mean values are denoted by colored circles. Upper and lower boundaries of the dark shading correspond to the 75% and 25% quartiles, while the light shading denotes the maximum and minimum monthly-mean wind speeds.



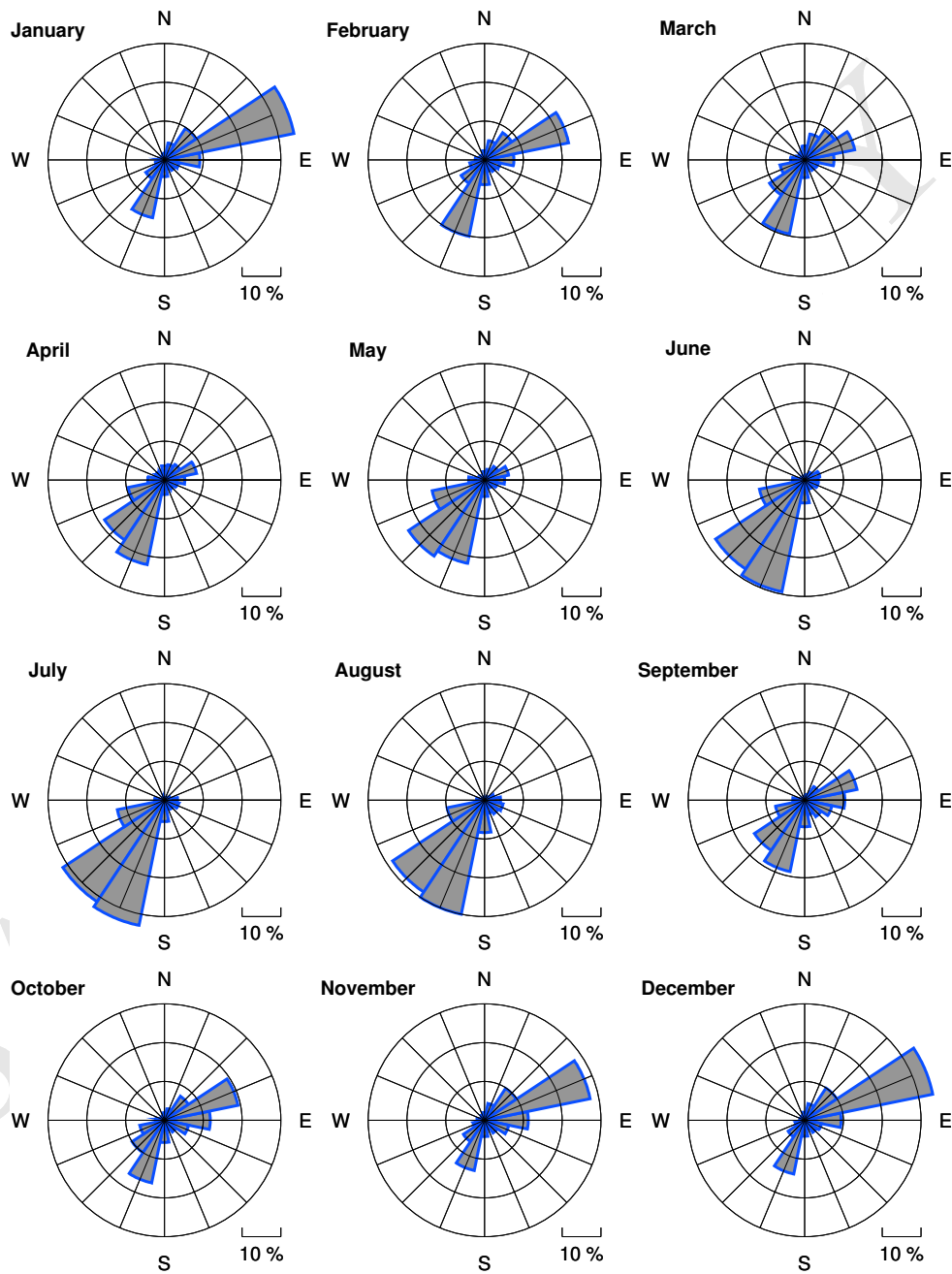
**Figure 14:** Variability of monthly-mean **temperature** at 2m AGL at Desert Rock. Long-term monthly-mean values are denoted by colored circles. Upper and lower boundaries of the dark shading correspond to the 75% and 25% quartiles, while the light shading denotes the maximum and minimum monthly-mean temperature.



## 7.2 Distribution of Wind Direction



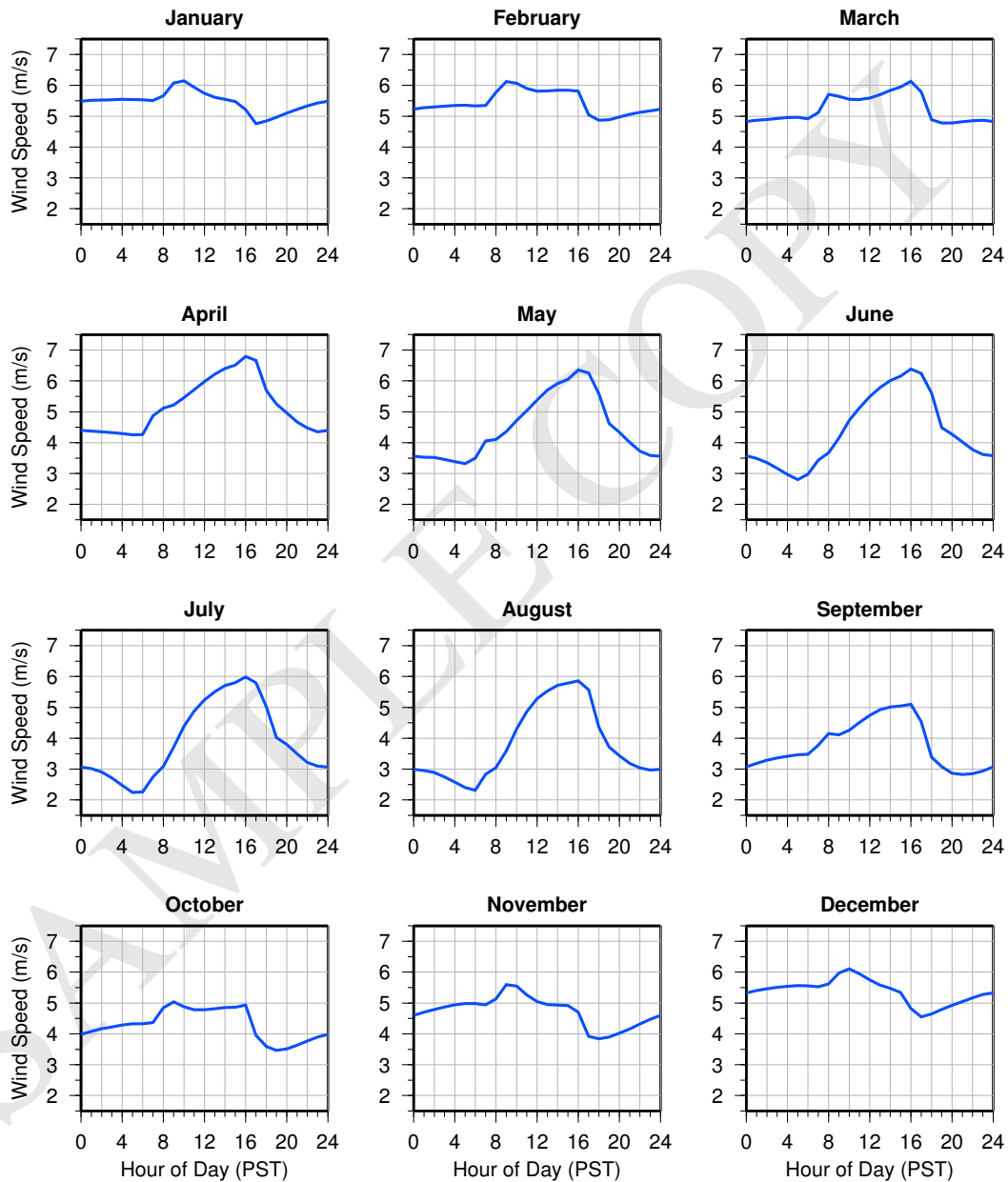
**Figure 15:** Annual wind rose at Desert Rock showing the prevailing **wind directions** at 10m AGL. Directional bins are 22.5° wide, and the radial contour interval is 10%.



**Figure 16:** Monthly wind roses at Desert Rock showing the prevailing wind directions at 10m AGL. Directional bins are 22.5° wide, and the radial contour interval is 10%.



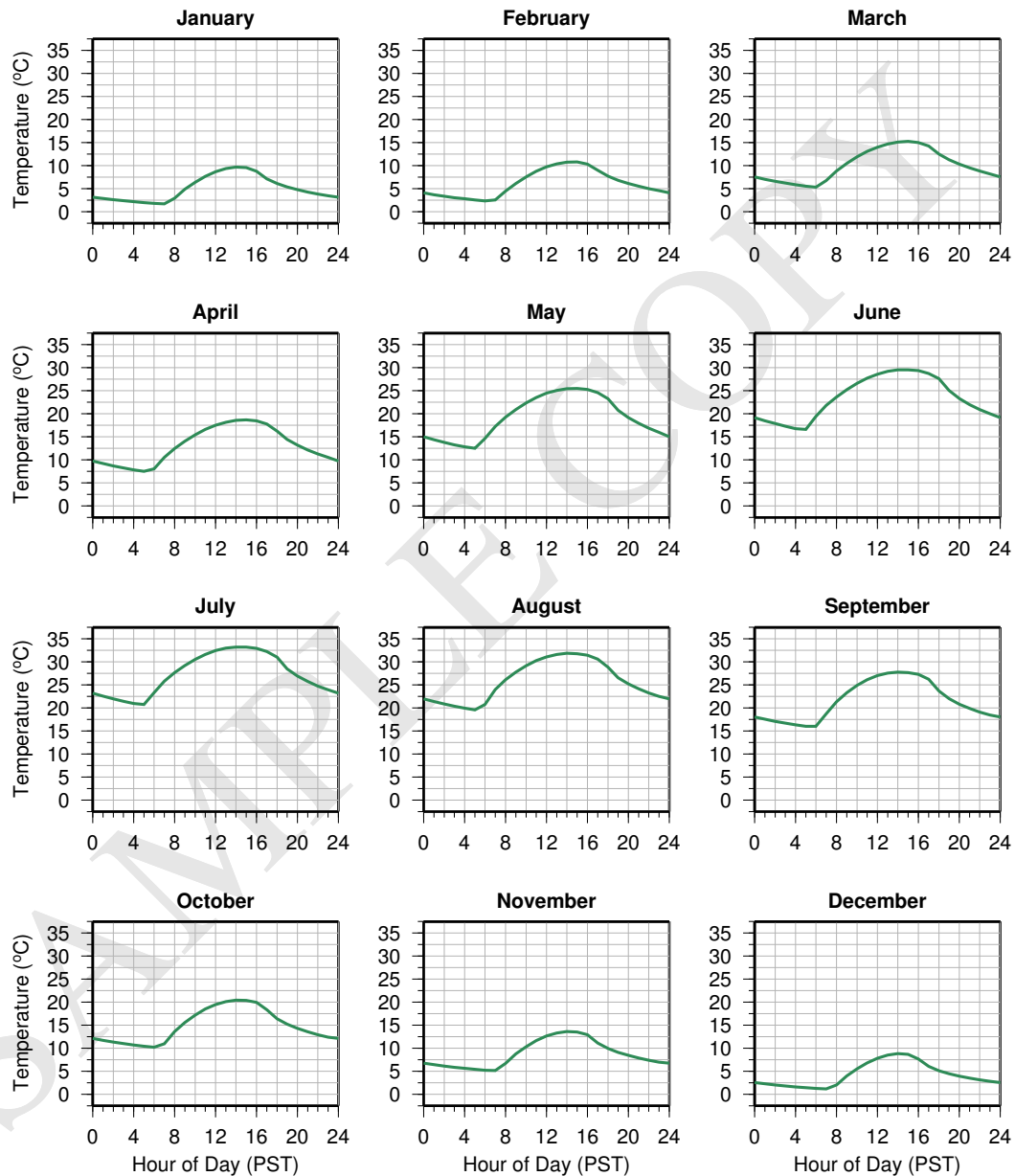
### 7.3 Diurnal Variability of wind speed



**Figure 17:** Diurnal cycle of **wind speed** at 10m AGL for each month of the year. The horizontal axis is in Pacific Standard Time (PST). Figure 19 shows the diurnal cycle of wind speed for each calendar month as a '12 X 24' table.



### 7.4 Diurnal Variability of temperature



**Figure 18:** Diurnal cycle of **temperature** at 2m AGL for each month of the year. The horizontal axis is in Pacific Standard Time (PST). Figure 20 shows the diurnal cycle of temperature for each calendar month as a '12 X 24' table.



7.5 Tabular Data

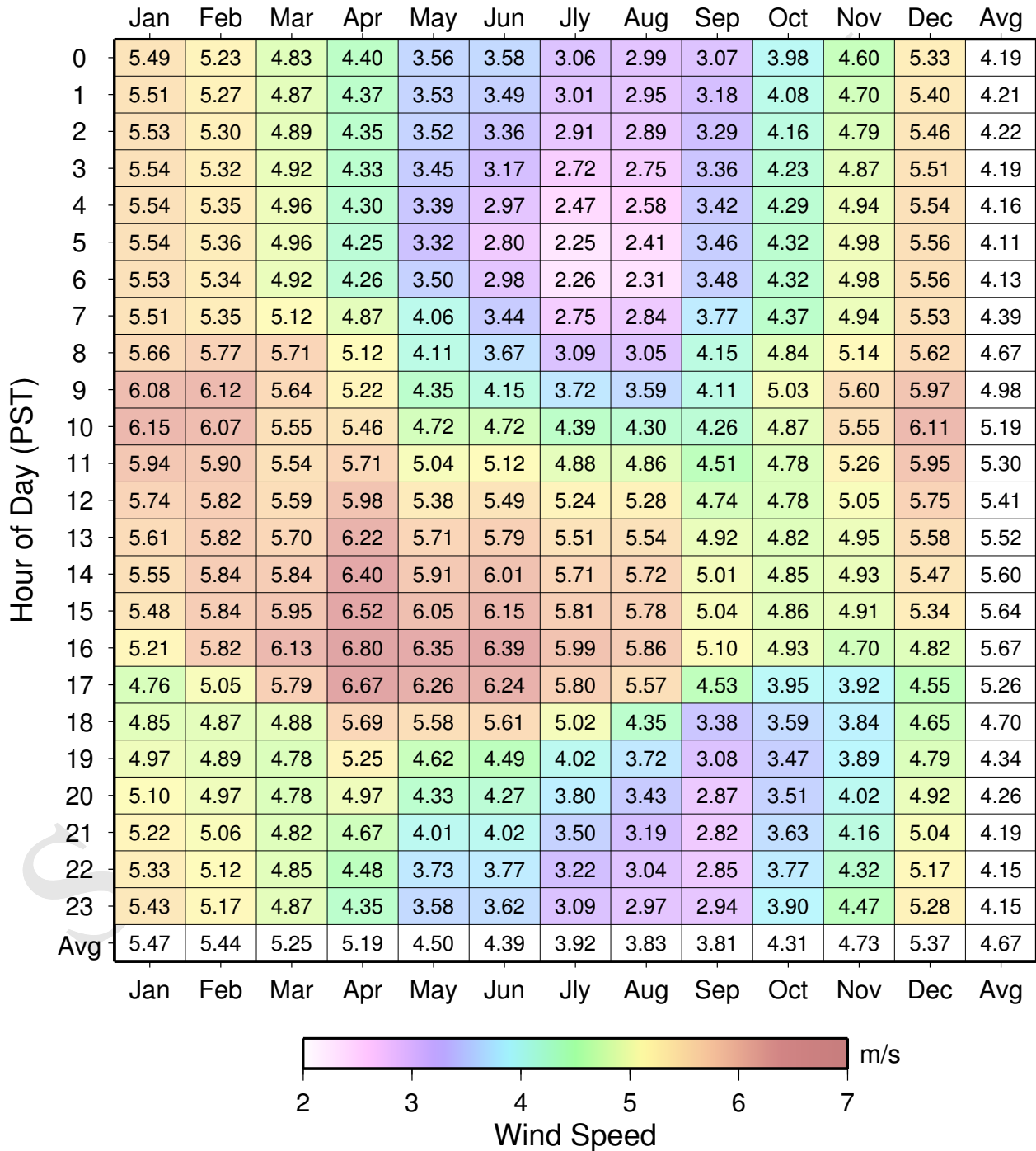
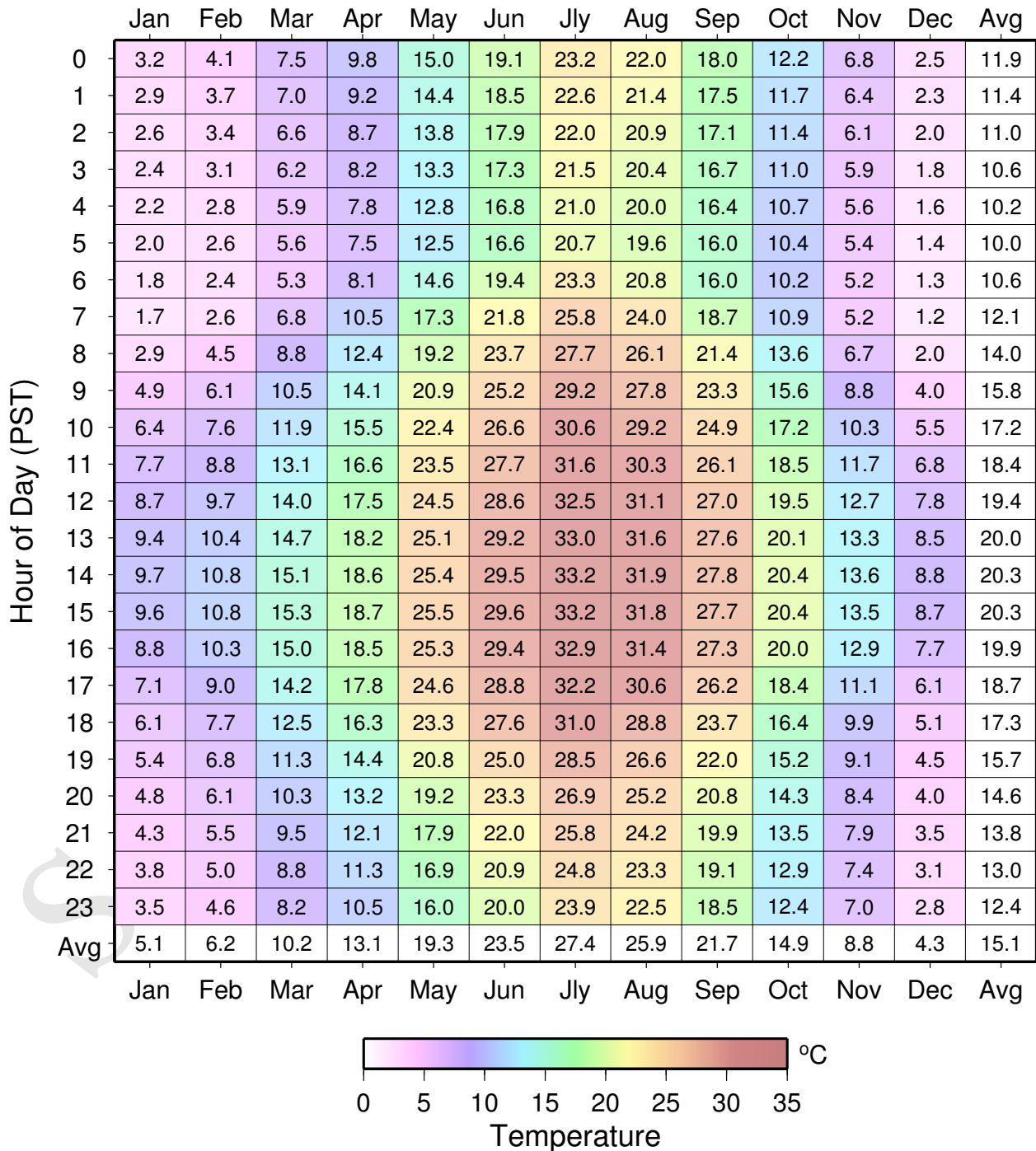


Figure 19: Hourly-mean wind speed values at 10m AGL in m/s. The vertical axis is in Pacific Standard Time (PST). The overall mean in the bottom right corner is based on complete years only. Time series graph of the diurnal variability for each month is shown in Figure 17.



**Figure 20:** Hourly-mean **temperature** values at 2m AGL in degrees Celsius. The vertical axis is in Pacific Standard Time (PST). The overall mean in the bottom right corner is based on complete years only. Time series graph of the diurnal variability for each month is shown in Figure 18.



## 8 VALIDATION OF SATELLITE-DERIVED IRRADIANCE: DNI

---

3TIER has been retained by Client X, Inc. to assess the variability and magnitude of solar irradiance at Desert Rock. This report examines the quality of the satellite observational data used for that assessment at a single point within the study area. Ground observations were taken at Desert Rock in Nevada (Latitude: 36.626°N, Longitude: 116.018°W).

The average observed direct normal irradiance (DNI) value for all valid **daylight observational times** at the ground during the 13 months of the period of record (March 1998 through March 1999) is **596.4 W/m<sup>2</sup>**. This compares to the raw satellite direct normal irradiance mean value of **551.5 W/m<sup>2</sup>** for these same times.

A multilinear regression model (called "MOS") was constructed to reduce bias in the mean and variance of the raw satellite data with respect to the ground observations. After applying this statistical model to the raw satellite data, the MOS-corrected direct normal irradiance mean is **595.2 W/m<sup>2</sup>** for the same times as above.



## 8.1 Observational data

Approximately 13 months of data (March 1998 through March 1999) from a ground observation station at Desert Rock (Latitude:  $36.626^{\circ}\text{N}$ , Longitude:  $116.018^{\circ}\text{W}$ ) were used in this analysis. This station will be referred to as the reference station. The solar radiation sensor employed at the reference station is a pyroheliometer used for the measurement of DNI. The data at the reference station were used to assess the quality of the raw satellite data. It should be noted that on-site ground observations provided to 3TIER are not allowed to influence the raw satellite results. However, the ground observations are used to develop Model Output Statistics (MOS), which is a multi-linear regression model designed to remove bias and adjust the variance of the raw satellite data to better match the ground observations. Data with the statistical model applied are referred to as MOS-corrected data.

The observational data are transformed into an hour-ending mean hourly time series before any additional processing takes place. This is done so that an even comparison can be made between the raw satellite data, which are derived as an hour-ending mean hourly time series, and the provided ground observational data. By transforming the observational data, this also ensures that the resulting MOS-corrected time series data are also an hour-ending mean hourly time series. Observational data that is found to be incomplete or erroneous due to a malfunction or improper cleaning of the sensor is removed from the analysis for that day.

## 8.2 Validation Statistics

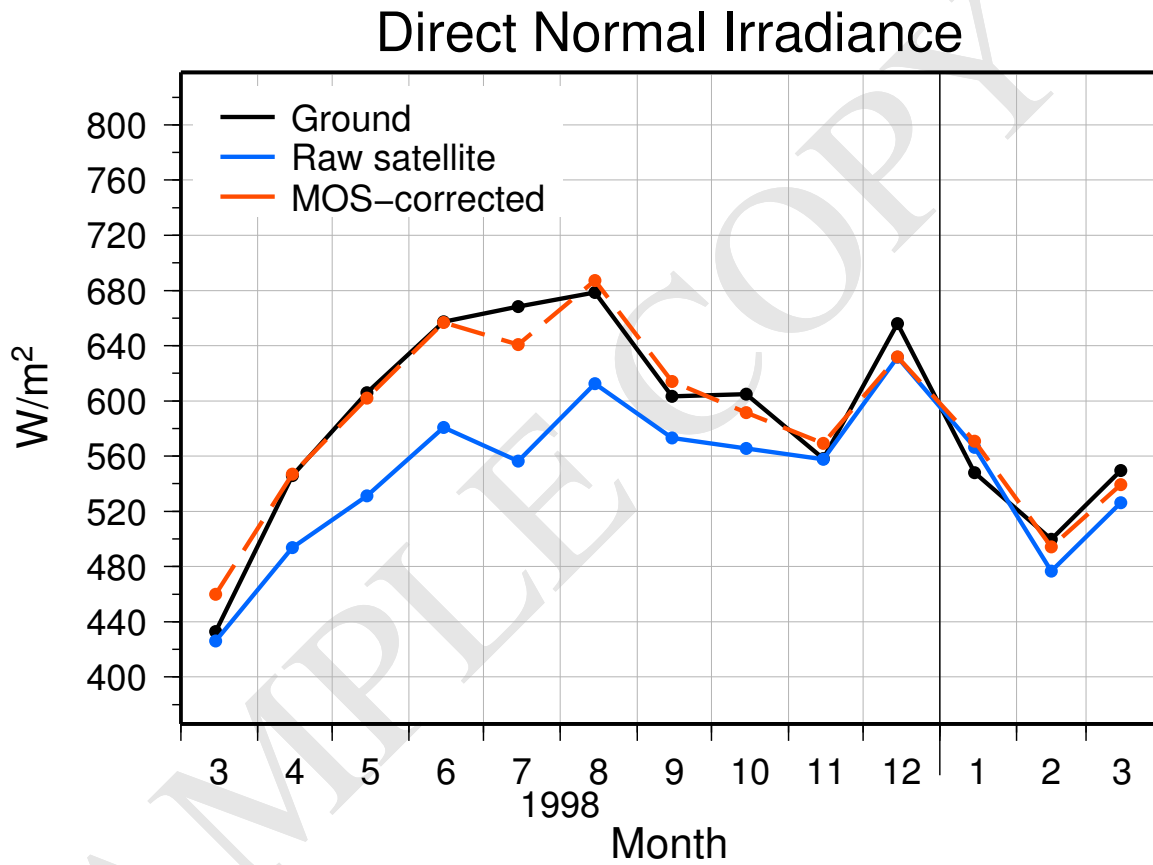
The observed, raw satellite, and MOS-corrected irradiance data shown in within this section represent the values for all **daylight times** when a valid irradiance observation was available. Therefore, values shown within this section should not be interpreted as estimates of the true irradiance values at the site, but rather a verification of the satellite-derived data used to reproduce the available ground observations. Any month or hour missing greater than 30% of the available daylight observations is omitted from the following figures, tables, and statistics. Daylight is defined by hours in which the hour-ending mean solar zenith angle is less than 93.0 degrees.

Table 5 presents some basic statistical measures of the raw satellite performance relative to the measured irradiance values at the reference station during the observational period. Also shown are values (labeled “MOS-corrected”) for satellite data with the statistical model applied. For reference, the correlation of the reference station data to itself is perfect and hence the explained variance ( $r^2$ ) value is 1.0.

Statistic	Value
Correlation of monthly-mean raw satellite DNI to reference station	0.87
RMS error of monthly-mean raw satellite DNI	52.3 W/m <sup>2</sup>
Correlation of monthly-mean MOS-corrected DNI to reference	0.98
RMS error of monthly-mean MOS-corrected DNI	15.8 W/m <sup>2</sup>
Correlation of daily-mean raw satellite DNI to reference station	0.92
RMS error of daily-mean raw satellite DNI	96.9 W/m <sup>2</sup>
Correlation of daily-mean MOS-corrected DNI to reference station	0.96
RMS error of daily-mean MOS-corrected DNI	66.5 W/m <sup>2</sup>

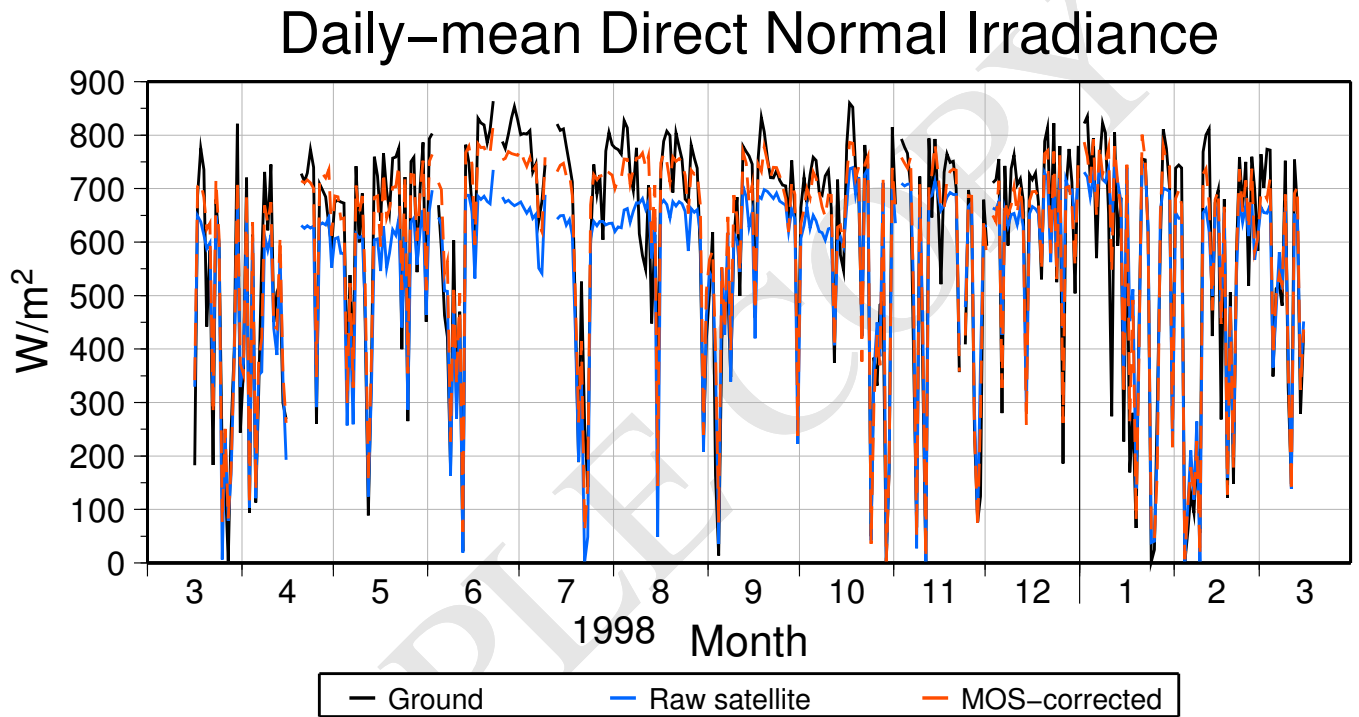
**Table 5:** Correlation and root mean square (RMS) error statistics of satellite irradiance data for daylight times.

8.3 Monthly-mean Irradiance



**Figure 21:** A comparison of the ground observed, raw satellite, and MOS-corrected monthly-mean **direct normal** irradiance at Desert Rock for daylight times. Months missing greater than 30% of the available daylight observations are not plotted.

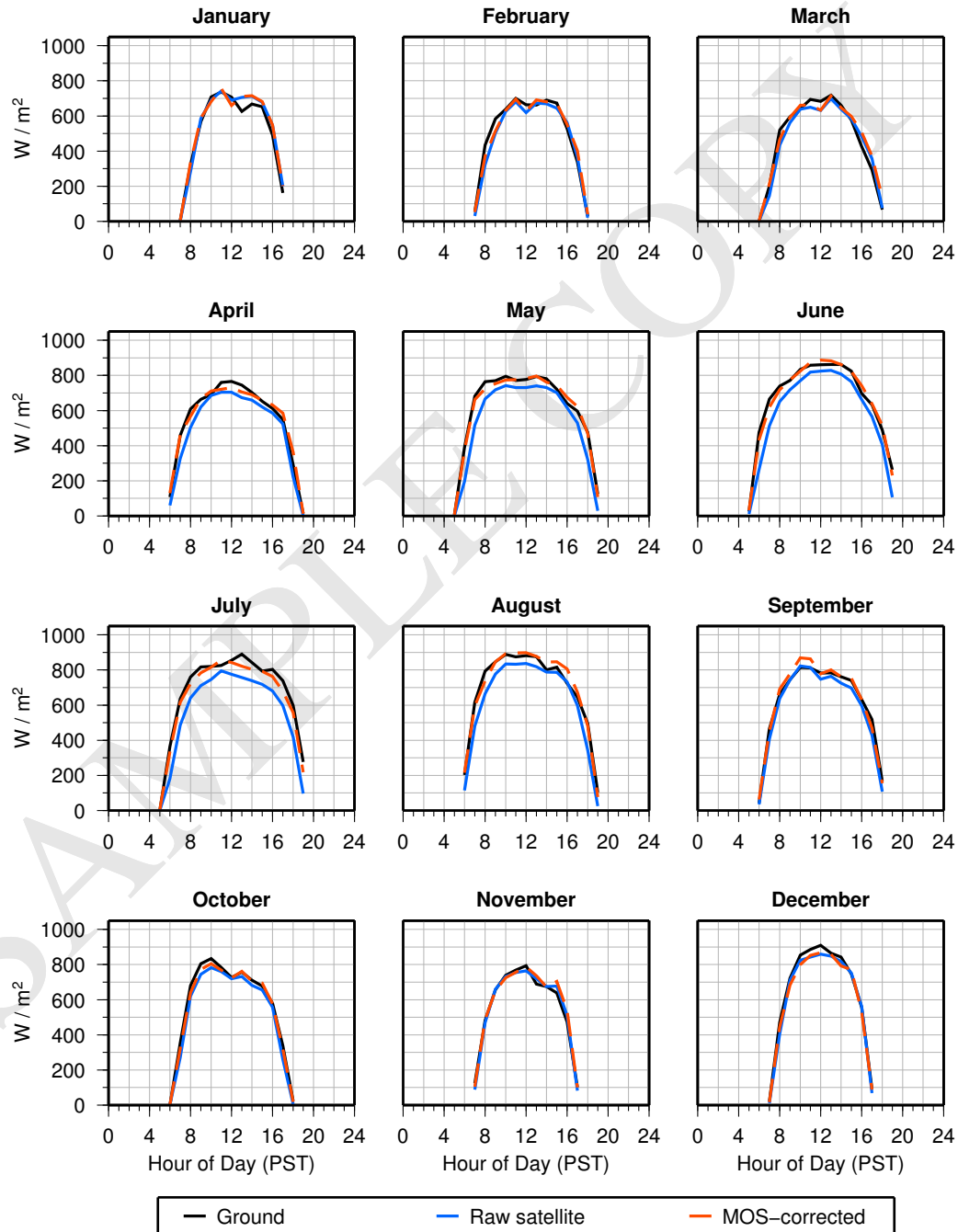
8.4 Daily-mean Irradiance



**Figure 22:** A comparison of the ground observed, raw satellite, and MOS-corrected daily-mean **direct normal** irradiance at Desert Rock for daylight times. Individual days missing greater than 30% of the available daylight observations are not plotted.

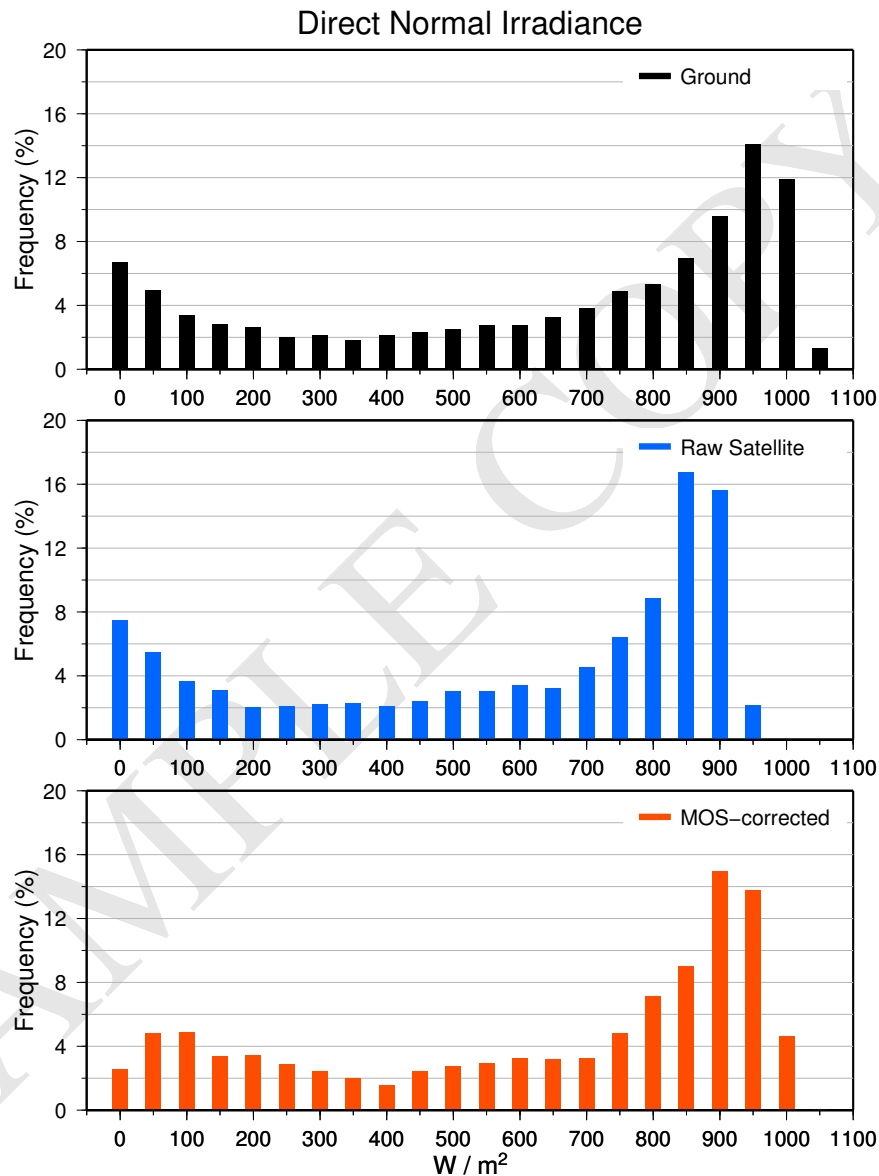
### 8.5 Diurnal Variability of Irradiance

#### Direct Normal Irradiance



**Figure 23:** A comparison of the diurnal cycle of ground observed, raw satellite, and MOS-corrected **direct normal** irradiance for each month at Desert Rock. Individual hours missing greater than 30% of the available daylight observations are not plotted. The normal axis is Pacific Standard Time (PST). Tabular formatted data available in Tables 7 and 9 (p. 33 and 35).

### 8.6 Histograms of Irradiance



**Figure 24:** A comparison of the ground observed, raw satellite, and MOS-corrected hourly daylight **direct normal** irradiance distributions at the reference station during the period of record, using  $50 \text{ W/m}^2$  bins. ( $0 \text{ m/s}$  bin contains only values  $\leq 25$ ). Each vertical bar represents the frequency of irradiance values occurring within each bin. For example, a vertical bar centered on  $200 \text{ W/m}^2$  reaching up to 10% means that one-tenth of all daytime values are between  $175$  and  $225 \text{ W/m}^2$ .

## 8.7 Tabular data

Month	Observed	Raw	Bias	MOS-corrected	Availability(%)
03/1998	432.75	426.10	-6.65	459.76	53.7
04/1998	545.96	493.69	-52.27	546.99	86.6
05/1998	605.88	531.15	-74.73	601.89	100.0
06/1998	657.28	580.84	-76.44	656.85	90.0
07/1998	668.33	556.31	-112.02	640.93	90.3
08/1998	678.50	612.48	-66.02	687.34	100.0
09/1998	603.27	573.13	-30.14	614.08	100.0
10/1998	605.00	565.59	-39.41	591.43	100.0
11/1998	558.28	557.58	-0.70	569.32	93.3
12/1998	656.01	631.52	-24.49	631.78	96.7
01/1999	547.88	566.47	18.58	570.75	96.9
02/1999	499.81	476.53	-23.28	494.25	100.0
03/1999	549.53	526.12	-23.41	539.34	47.9
All	596.42	551.50	-44.92	595.22	88.9

**Table 6:** Monthly-mean daylight **direct normal** irradiance ( $W/m^2$ ) at the reference station. Time series graph of data is available in Figure 21 (p. 28).

Observed = mean of all available daylight DNI observations

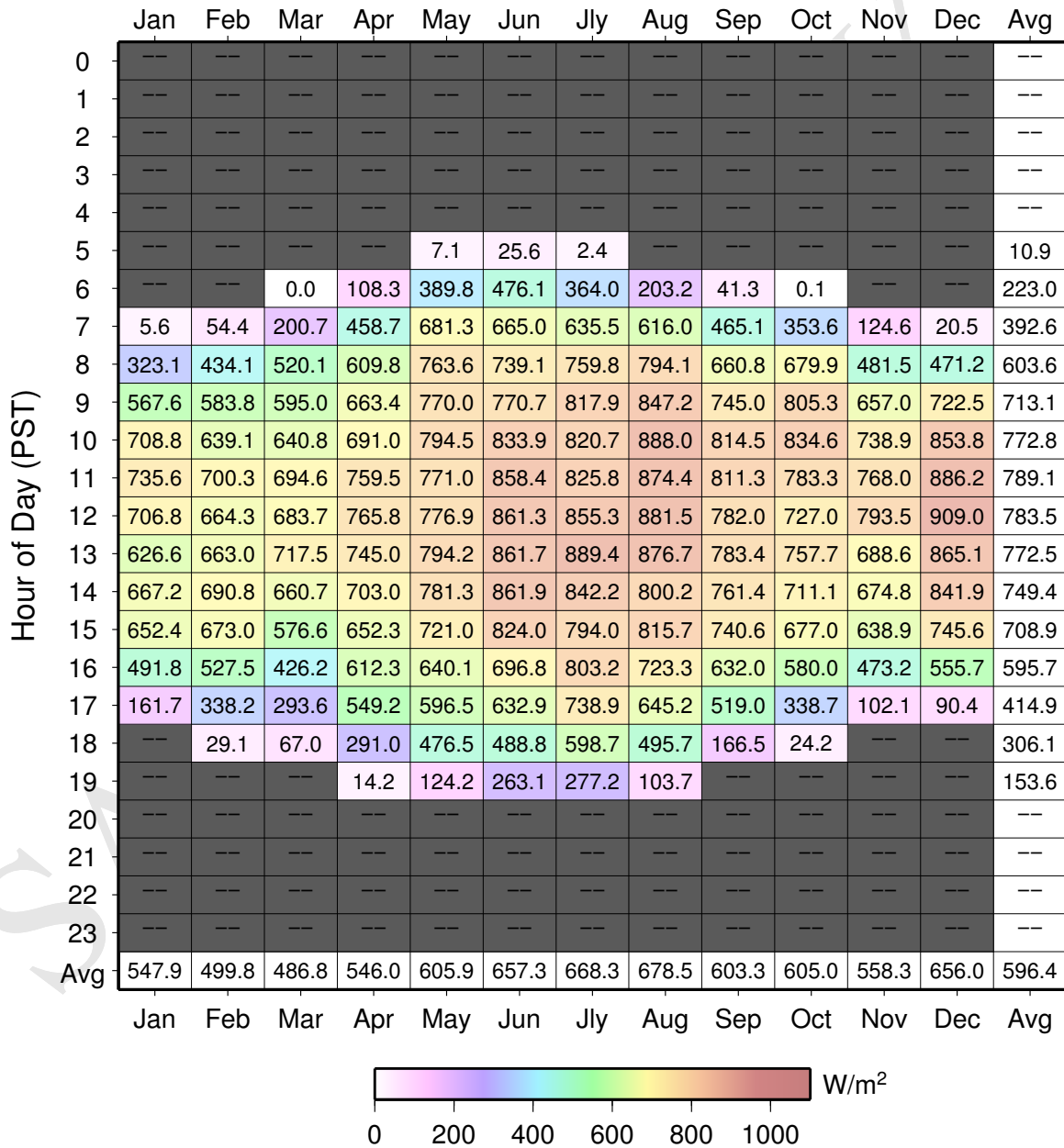
Raw = mean of satellite-derived irradiance for daylight times with observations

Bias = Raw – Observed

MOS-corrected = mean of MOS-corrected output for daylight times with observations

Availability(%) = percent of available observations during daylight hours

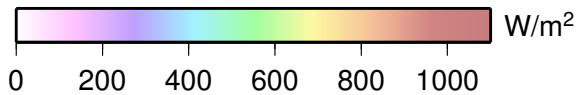
### Ground Observed Direct Normal Irradiance



**Table 7:** Hourly-mean values of ground observed **direct normal** irradiance. Hours missing greater than 30% of the available observations are not plotted. The vertical axis is Pacific Standard Time (PST). Time series graphs of data are available in Figure 23 (p. 30).

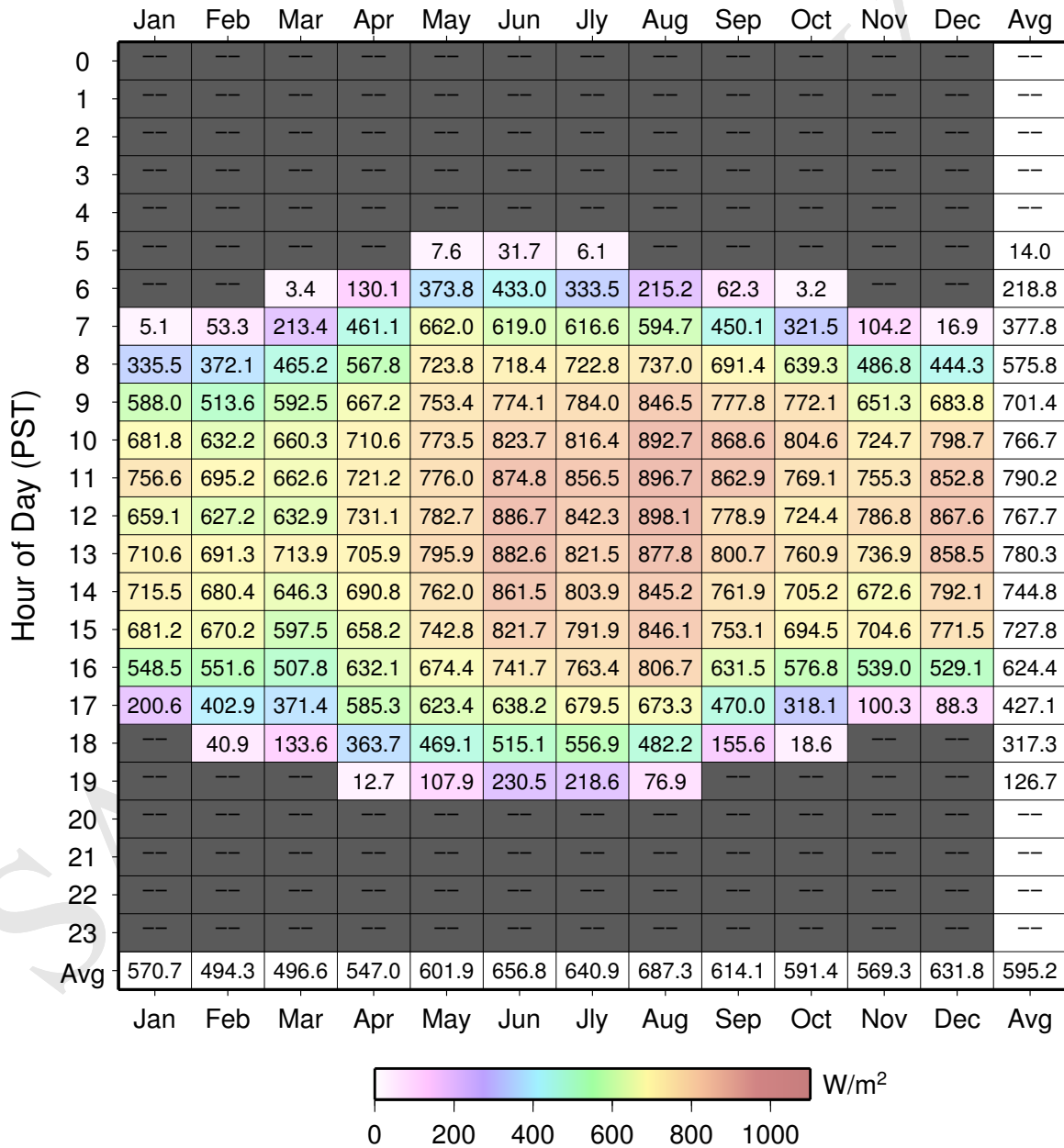
### Raw Satellite Direct Normal Irradiance

	Jan	Feb	Mar	Apr	May	Jun	Jly	Aug	Sep	Oct	Nov	Dec	Avg
0	--	--	--	--	--	--	--	--	--	--	--	--	--
1	--	--	--	--	--	--	--	--	--	--	--	--	--
2	--	--	--	--	--	--	--	--	--	--	--	--	--
3	--	--	--	--	--	--	--	--	--	--	--	--	--
4	--	--	--	--	--	--	--	--	--	--	--	--	--
5	--	--	--	--	1.9	11.6	1.3	--	--	--	--	--	4.5
6	--	--	2.3	60.2	195.2	264.4	181.2	114.9	34.5	0.8	--	--	120.0
7	2.2	30.7	145.4	326.6	516.3	513.3	486.7	481.2	407.2	270.8	88.5	11.6	301.5
8	283.8	322.7	433.6	504.2	666.6	651.6	641.4	665.1	637.5	620.2	469.6	403.2	525.7
9	585.4	502.3	561.2	621.0	717.6	717.7	710.8	777.1	743.2	745.4	659.8	711.9	672.4
10	690.8	626.2	638.3	686.2	741.9	770.3	745.6	833.7	822.8	782.0	731.6	824.2	742.3
11	741.4	680.4	649.8	703.8	730.7	818.3	795.1	832.6	814.9	759.8	753.8	842.0	760.5
12	689.6	619.1	631.3	703.9	730.8	824.3	775.1	837.1	746.9	719.6	764.6	859.8	741.8
13	705.5	673.7	698.6	673.6	740.1	828.0	757.4	818.4	763.9	732.4	719.8	847.4	747.2
14	712.5	668.6	639.2	659.6	730.4	808.3	738.5	788.5	725.8	681.9	674.2	816.8	720.6
15	678.2	644.0	583.8	620.1	700.8	764.1	717.8	786.7	696.9	654.6	678.3	751.4	690.0
16	547.3	563.0	481.6	585.4	615.7	662.6	680.2	732.0	596.1	557.1	510.2	561.3	590.7
17	199.6	366.7	357.2	524.0	529.0	565.5	597.9	597.9	429.1	259.9	83.0	69.1	379.6
18	--	21.2	75.8	222.4	320.8	406.6	418.7	343.1	108.3	6.1	--	--	223.2
19	--	--	--	1.8	29.4	106.1	96.8	25.7	--	--	--	--	50.5
20	--	--	--	--	--	--	--	--	--	--	--	--	--
21	--	--	--	--	--	--	--	--	--	--	--	--	--
22	--	--	--	--	--	--	--	--	--	--	--	--	--
23	--	--	--	--	--	--	--	--	--	--	--	--	--
Avg	566.5	476.5	472.4	493.7	531.1	580.8	556.3	612.5	573.1	565.6	557.6	631.5	551.5



**Table 8:** Hourly-mean values of raw satellite **direct normal** irradiance. Hours missing greater than 30% of the available observations are not plotted. The vertical axis is Pacific Standard Time (PST). Time series graphs of data are available in Figure 23 (p. 30).

### MOS-corrected Direct Normal Irradiance



**Table 9:** Hourly-mean values of MOS-corrected **direct normal** irradiance. Hours missing greater than 30% of the available observations are not plotted. The vertical axis is Pacific Standard Time (PST). Time series graphs of data are available in Figure 23 (p. 30).

## 9 | VALIDATION OF SATELLITE-DERIVED IRRADIANCE: GHI

---

3TIER has been retained by Client X, Inc. to assess the variability and magnitude of solar irradiance at Desert Rock. This report examines the quality of the satellite observational data used for that assessment at a single point within the study area. Ground observations were taken at Desert Rock in Nevada (Latitude: 36.626°N, Longitude: 116.018°W).

The average observed global horizontal irradiance (GHI) value for all valid **daylight observational times** at the ground during the 13 months of the period of record (March 1998 through March 1999) is **440.4  $W/m^2$** . This compares to the raw satellite global horizontal irradiance mean value of **426.4  $W/m^2$**  for these same times.

A multilinear regression model (called "MOS") was constructed to reduce bias in the mean and variance of the raw satellite data with respect to the ground observations. After applying this statistical model to the raw satellite data, the MOS-corrected global horizontal irradiance mean is **440.4  $W/m^2$**  for the same times as above.

## 9.1 Observational data

Approximately 13 months of data (March 1998 through March 1999) from a ground observation station at Desert Rock (Latitude: 36.626°N, Longitude: 116.018°W) were used in this analysis. This station will be referred to as the reference station. The solar radiation sensor employed at the reference station is a pyranometer used for the measurement of GHI. The data at the reference station were used to assess the quality of the raw satellite data. It should be noted that on-site ground observations provided to 3TIER are not allowed to influence the raw satellite results. However, the ground observations are used to develop Model Output Statistics (MOS), which is a multi-linear regression model designed to remove bias and adjust the variance of the raw satellite data to better match the ground observations. Data with the statistical model applied are referred to as MOS-corrected data.

The observational data are transformed into an hour-ending mean hourly time series before any additional processing takes place. This is done so that an even comparison can be made between the raw satellite data, which are derived as an hour-ending mean hourly time series, and the provided ground observational data. By transforming the observational data, this also ensures that the resulting MOS-corrected time series data are also an hour-ending mean hourly time series.

## 9.2 Validation Statistics

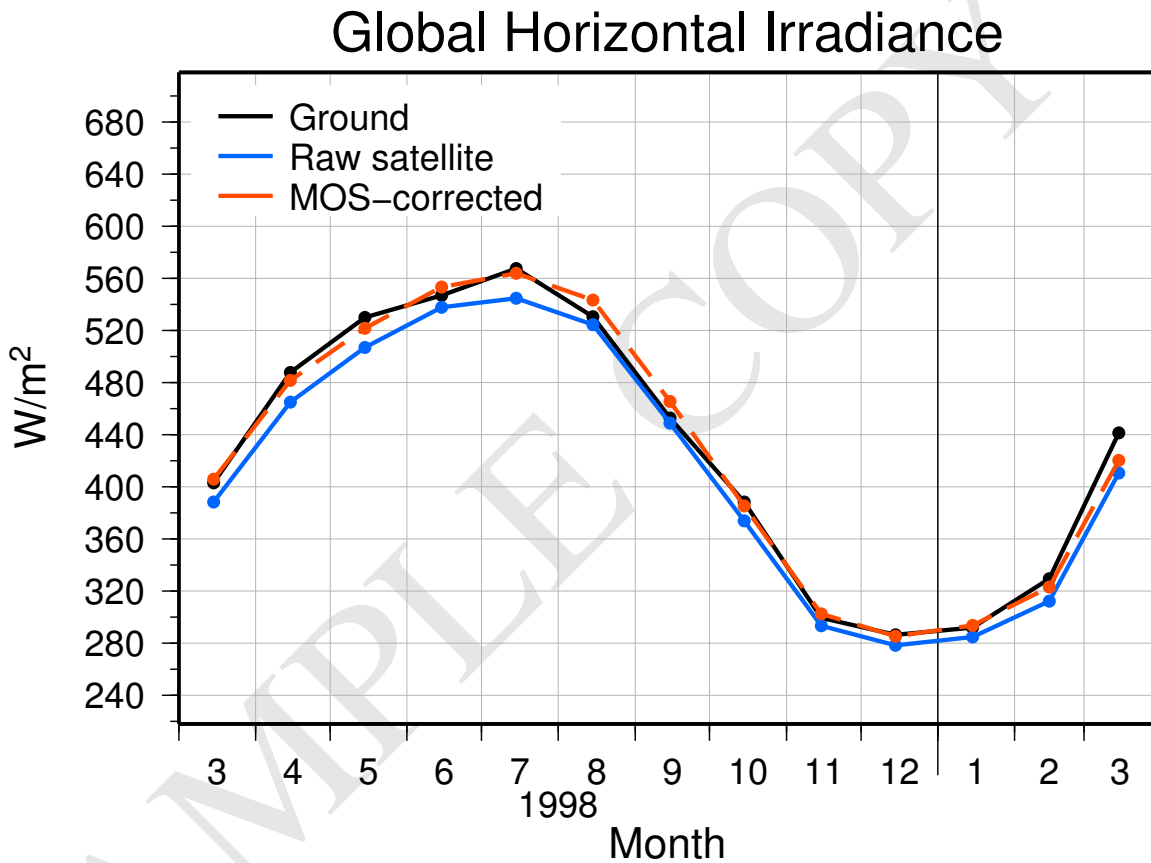
The observed, raw satellite, and MOS-corrected irradiance data shown in within this section represent the values for all **daylight times** when a valid irradiance observation was available. Therefore, values shown within this section should not be interpreted as estimates of the true irradiance values at the site, but rather a verification of the satellite-derived data used to reproduce the available ground observations. Any month or hour missing greater than 30% of the available daylight observations is omitted from the following figures, tables, and statistics. Daylight is defined by hours in which the hour-ending mean solar zenith angle is less than 93.0 degrees.

Table 10 presents some basic statistical measures of the raw satellite performance relative to the measured irradiance values at the reference station during the observational period. Also shown are values (labeled “MOS-corrected”) for satellite data with the statistical model applied. For reference, the correlation of the reference station data to itself is perfect and hence the explained variance ( $r^2$ ) value is 1.0.

Statistic	Value
Correlation of monthly-mean raw satellite GHI to reference station	1.00
RMS error of monthly-mean raw satellite GHI	16.5 W/m <sup>2</sup>
Correlation of monthly-mean MOS-corrected GHI to reference	1.00
RMS error of monthly-mean MOS-corrected GHI	8.8 W/m <sup>2</sup>
Correlation of daily-mean raw satellite GHI to reference station	0.98
RMS error of daily-mean raw satellite GHI	28.4 W/m <sup>2</sup>
Correlation of daily-mean MOS-corrected GHI to reference station	0.99
RMS error of daily-mean MOS-corrected GHI	22.0 W/m <sup>2</sup>

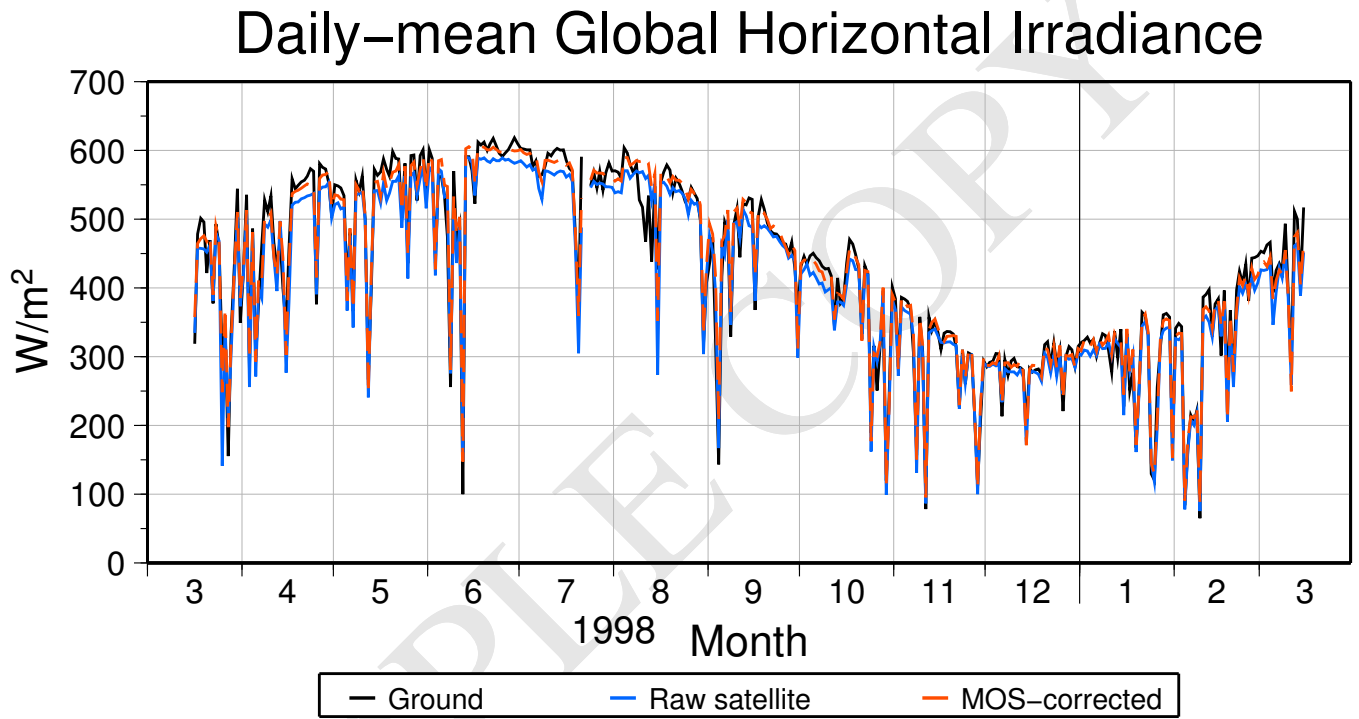
**Table 10:** Correlation and root mean square (RMS) error statistics of satellite irradiance data for daylight times.

9.3 Monthly-mean Irradiance



**Figure 25:** A comparison of the ground observed, raw satellite, and MOS-corrected monthly-mean **global horizontal** irradiance at Desert Rock for daylight times. Months missing greater than 30% of the available daylight observations are not plotted.

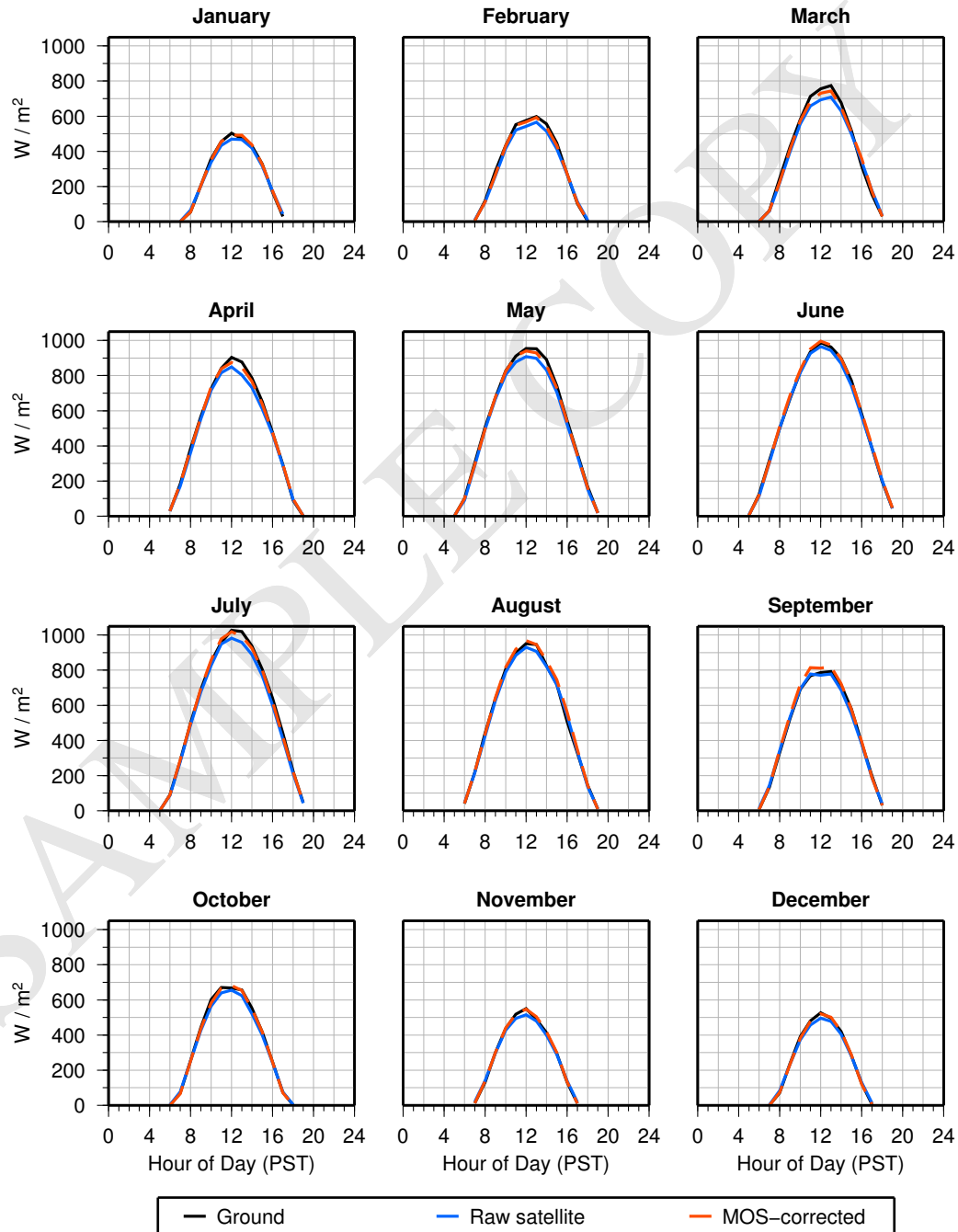
9.4 Daily-mean Irradiance



**Figure 26:** A comparison of the ground observed, raw satellite, and MOS-corrected daily-mean **global horizontal** irradiance at Desert Rock for daylight times. Individual days missing greater than 30% of the available daylight observations are not plotted.

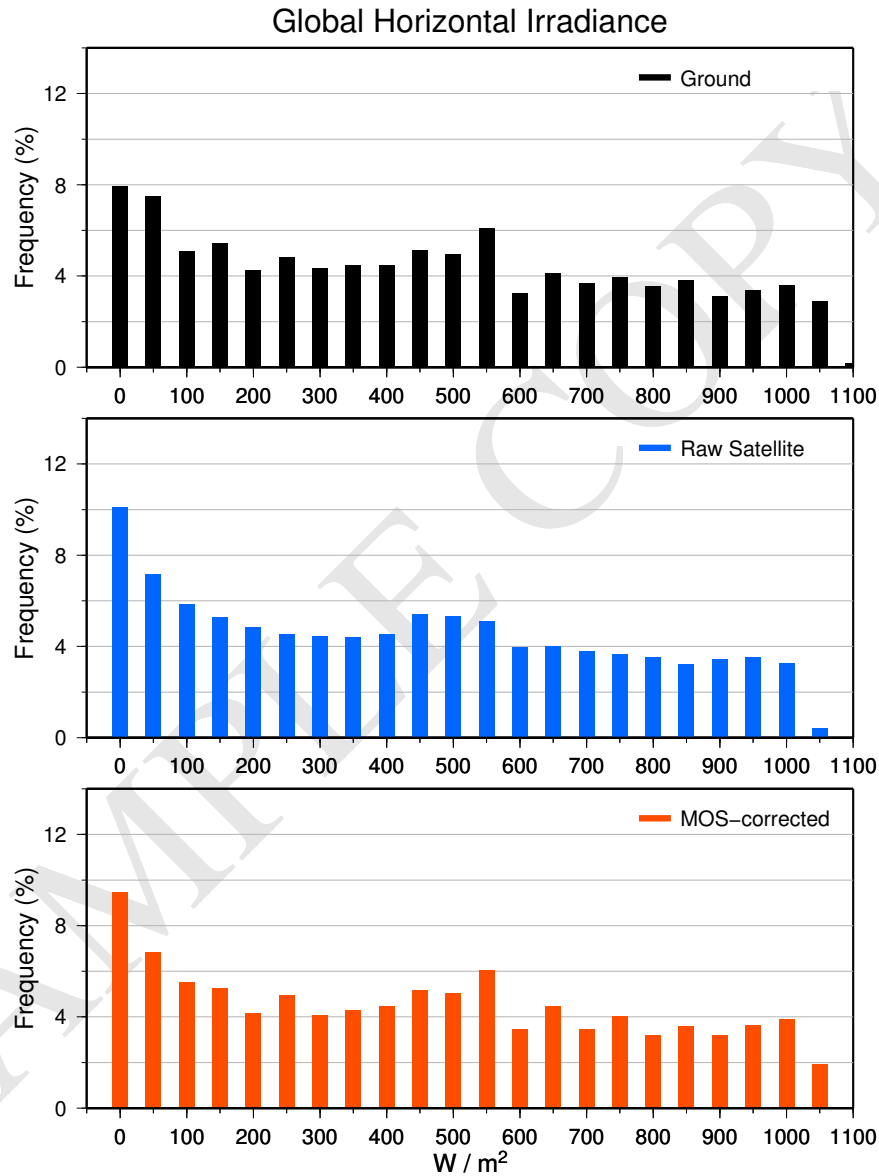
### 9.5 Diurnal Variability of Irradiance

#### Global Horizontal Irradiance



**Figure 27:** A comparison of the diurnal cycle of ground observed, raw satellite, and MOS-corrected **global horizontal** irradiance for each month at Desert Rock. Individual hours missing greater than 30% of the available daylight observations are not plotted. The horizontal axis is Pacific Standard Time (PST). Tabular formatted data available in Tables 12 and 14 (p. 44 and 46).

9.6 Histograms of Irradiance



**Figure 28:** A comparison of the ground observed, raw satellite, and MOS-corrected hourly daylight **global horizontal** irradiance distributions at the reference station during the period of record, using 50 W/m<sup>2</sup> bins. (0 m/s bin contains only values ≤ 25). Each vertical bar represents the frequency of irradiance values occurring within each bin. For example, a vertical bar centered on 200 W/m<sup>2</sup> reaching up to 10% means that one-tenth of all daytime values are between 175 and 225 W/m<sup>2</sup>.

## 9.7 Tabular data

Month	Observed	Raw	Bias	MOS-corrected	Availability(%)
03/1998	403.06	388.23	-14.83	405.75	53.7
04/1998	487.85	464.89	-22.96	481.53	100.0
05/1998	529.97	506.96	-23.01	521.55	100.0
06/1998	546.80	537.72	-9.08	553.18	100.0
07/1998	567.45	544.59	-22.86	563.74	93.5
08/1998	530.55	524.37	-6.17	543.24	100.0
09/1998	452.65	448.82	-3.83	465.62	100.0
10/1998	388.21	373.72	-14.49	385.21	100.0
11/1998	299.27	293.15	-6.13	302.33	100.0
12/1998	286.31	278.19	-8.12	285.12	100.0
01/1999	291.95	284.75	-7.21	293.51	100.0
02/1999	329.28	312.03	-17.24	323.01	100.0
03/1999	441.26	410.54	-30.72	420.25	47.9
All	440.38	426.40	-13.98	440.39	91.9

**Table 11:** Monthly-mean daylight **global horizontal** irradiance ( $W/m^2$ ) at the reference station. Time series graph of data is available in Figure 25 (p. 39).

Observed = mean of all available daylight GHI observations

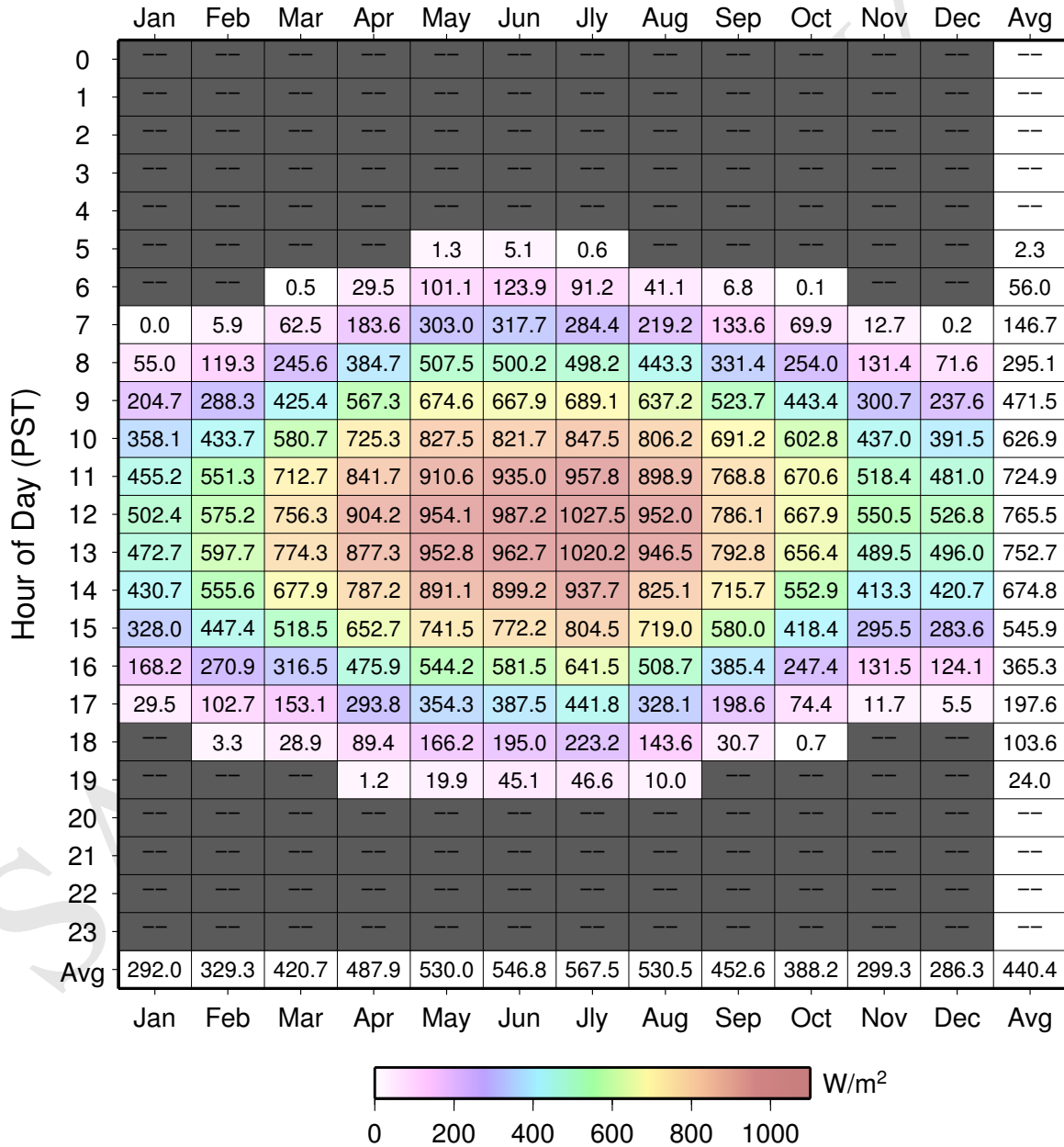
Raw = mean of satellite-derived irradiance for daylight times with observations

Bias = Raw – Observed

MOS-corrected = mean of MOS-corrected output for daylight times with observations

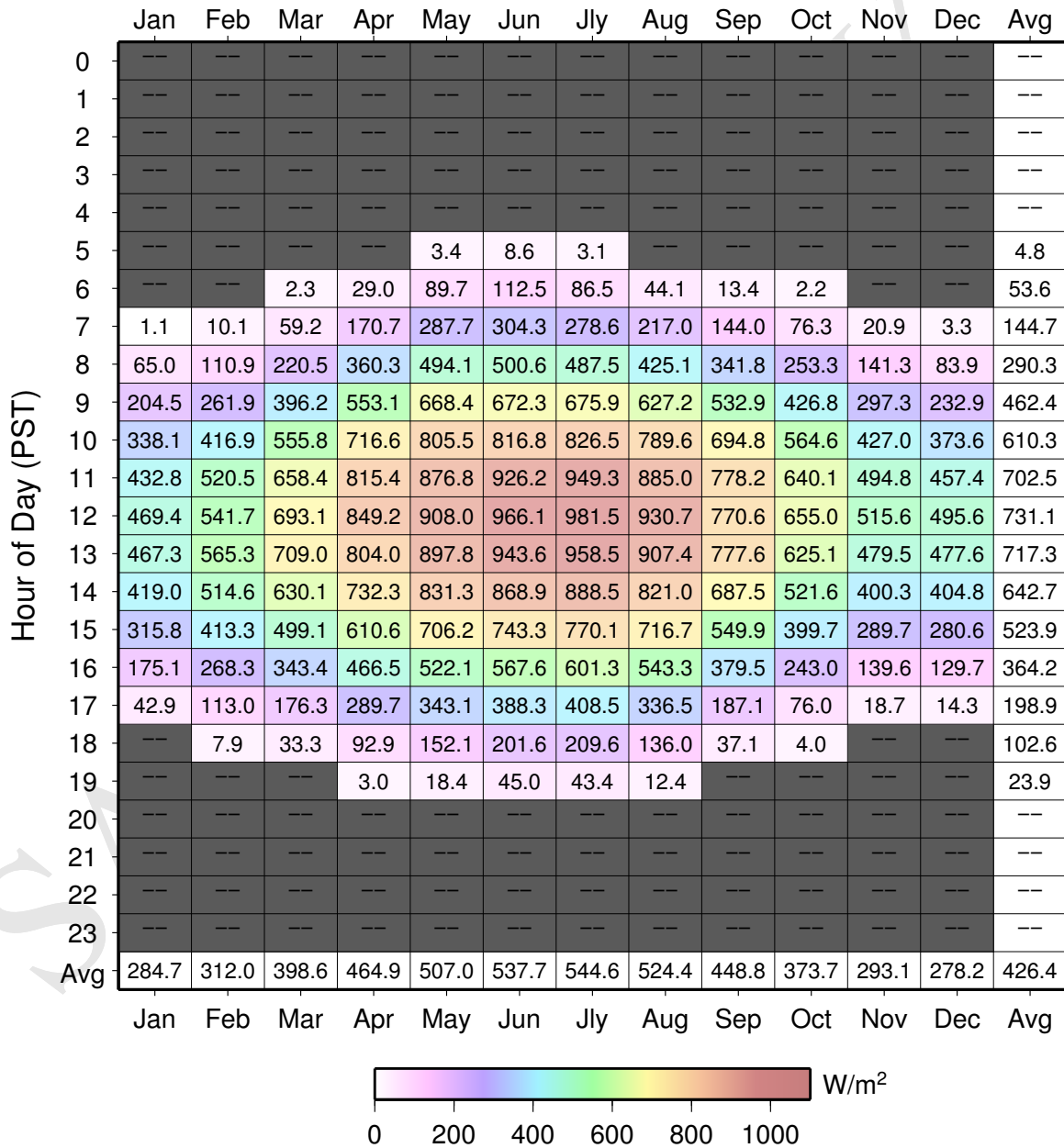
Availability(%) = percent of available observations during daylight hours

### Ground Observed Global Horizontal Irradiance



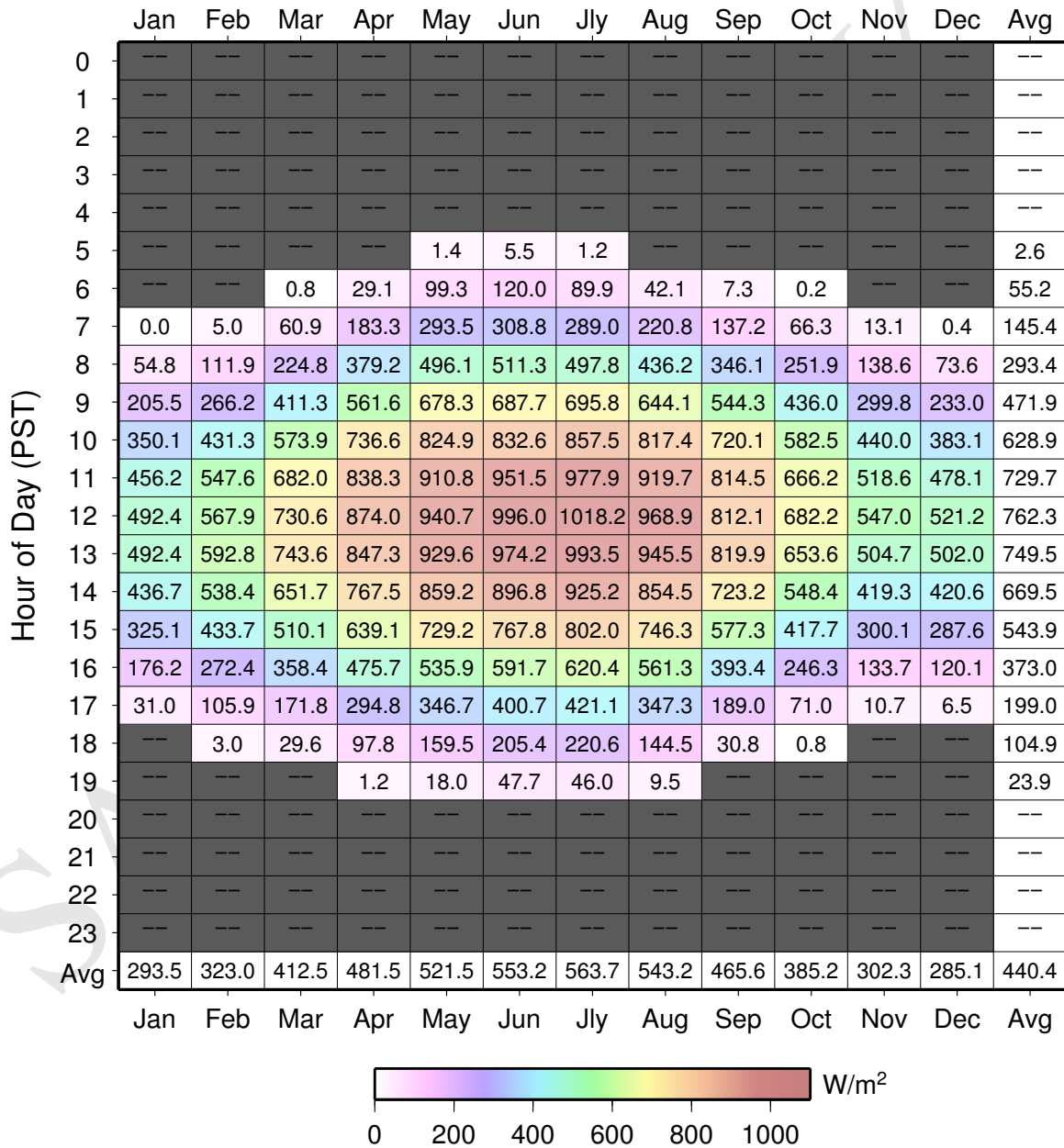
**Table 12:** Hourly-mean values of ground observed **global horizontal** irradiance. Hours missing greater than 30% of the available observations are not plotted. The vertical axis is Pacific Standard Time (PST). Time series graphs of data are available in Figure 27 (p. 41).

### Raw Satellite Global Horizontal Irradiance



**Table 13:** Hourly-mean values of raw satellite **global horizontal** irradiance. Hours missing greater than 30% of the available observations are not plotted. The vertical axis is Pacific Standard Time (PST). Time series graphs of data are available in Figure 27 (p. 41).

### MOS-corrected Global Horizontal Irradiance



**Table 14:** Hourly-mean values of MOS-corrected **global horizontal** irradiance. Hours missing greater than 30% of the available observations are not plotted. The vertical axis is Pacific Standard Time (PST). Time series graphs of data are available in Figure 27 (p. 41).

## 10 DESCRIPTION OF DATA FILES

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This section provides a description of data files that were delivered with this report. All data presented within this section are valid only at the Desert Rock project site (Latitude: 36.626°N, Longitude: 116.018°W).

### 10.1 Time series Data

3TIER has created a time series data file with 14+ years of solar irradiance and weather data from January 1997 through March 2011. The data period is hourly where each value represents the hour-ending mean of the previous hour. The variables in the file are MOS-corrected global horizontal irradiance (GHI), MOS-corrected direct normal irradiance (DNI), diffuse horizontal irradiance (DIF), zenith angle, azimuth angle, wind speed and direction at 10 meters above ground level (AGL), temperature at 2 meters AGL, surface pressure, and relative humidity at 2 meters AGL. The time series data is presented as standard CSV files in local time (PST: Pacific Standard Time) and in UTC.

### 10.2 TMY Data

3TIER has created a TMY (Typical Meteorological Year) dataset using an empirical approach that selects four-day samples from the full times series to create a "typical year" of data with 8760 hours, while preserving the following characteristics of MOS-corrected global horizontal irradiance: monthly means, monthly cumulative distribution of daily means, monthly diurnal cycles and the annual mean. The values of MOS-corrected DNI, DIF, air temperature, wind speed, wind direction, surface pressure, and relative humidity were not used in the selection process but were sampled to preserve temporal correlation. The TMY data is presented in local time (PST: Pacific Standard Time) in TMY2 format (.tm2) and in a standard CSV file.