

FullView®



Site Climate
Variability Analysis

ANALYSIS OF 13-YEAR RECORD
Seattle, WA

FOR
Client X, Inc.

DATE

November 29, 2010

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1 INTRODUCTION

3TIER has been retained by Client X, Inc. to assess the variability and magnitude of solar irradiance, wind, and temperature at the Seattle project site located in WA (Latitude: 47.621°N, Longitude: 122.312°W). This report provides a retrospective analysis of the past 13+ 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 7 explains the methodology used to derive the wind and temperature data.

While the data used in this report is comprised of hourly values for the past 13+ years (January 1997 through June 2010), 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, 2009. Table 1 below shows the long-term average values for global horizontal irradiance (GHI), direct normal irradiance (DNI), diffuse horizontal irradiance (DIF), wind speed at 10 meters above ground level (AGL), temperature at 2 meters AGL, and surface pressure.

Variable	Long-term Mean (1997 – 2009)
Global Horizontal Irradiance (GHI)	152.3 W/m ² (1333 kWh/m ² /year)
Direct Normal Irradiance (DNI)	172.0 W/m ² (1506 kWh/m ² /year)
Diffuse Horizontal Irradiance (DIF)	60.37 W/m ² (528.8 kWh/m ² /year)
Wind Speed at 10 meters AGL	2.36 m/s
Temperature at 2 meters AGL	11.5 °C
Surface Pressure	101281.0 Pa

Table 1: Long-term means of several variables at the Seattle project site.

No on-site observations were provided at this project location; thus, all data presented within this report are purely processed satellite output and raw model output. If observational data become available, 3TIER can incorporate the data via additional analysis and provide statistically-corrected results.



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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 13+ years (January 1997 through June 2010) 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 13+ 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%.

3 SPATIAL MAPS OF IRRADIANCE

3.1 Annual-mean Maps

This section presents spatial maps of the solar irradiance across the Seattle project region. All annual-mean maps within this section are calculated using 13+ years of satellite-based irradiance data.

Annual-mean Maps are provided for Global Horizontal, Direct Normal and Diffuse Horizontal Irradiance across an area of approximately $50km$ by $50km$ centered at Latitude: $47.621^{\circ}N$, Longitude: $122.312^{\circ}W$. These maps are displayed in Figures 1–3.

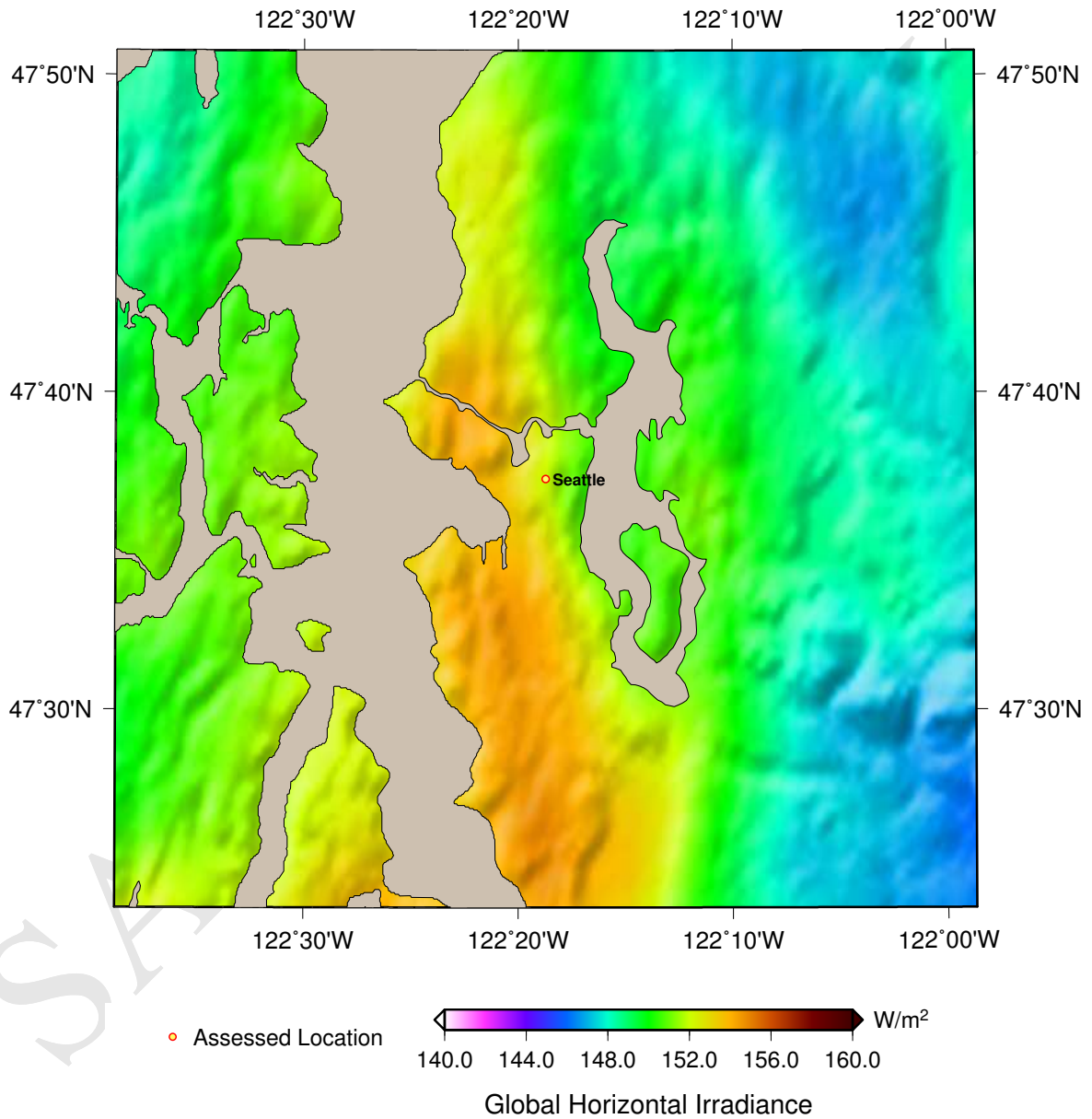


Figure 1: Annual-mean **Global Horizontal Irradiance**. The yellow dot denotes the location of the Seattle project site analyzed in Sections 4 and 8.

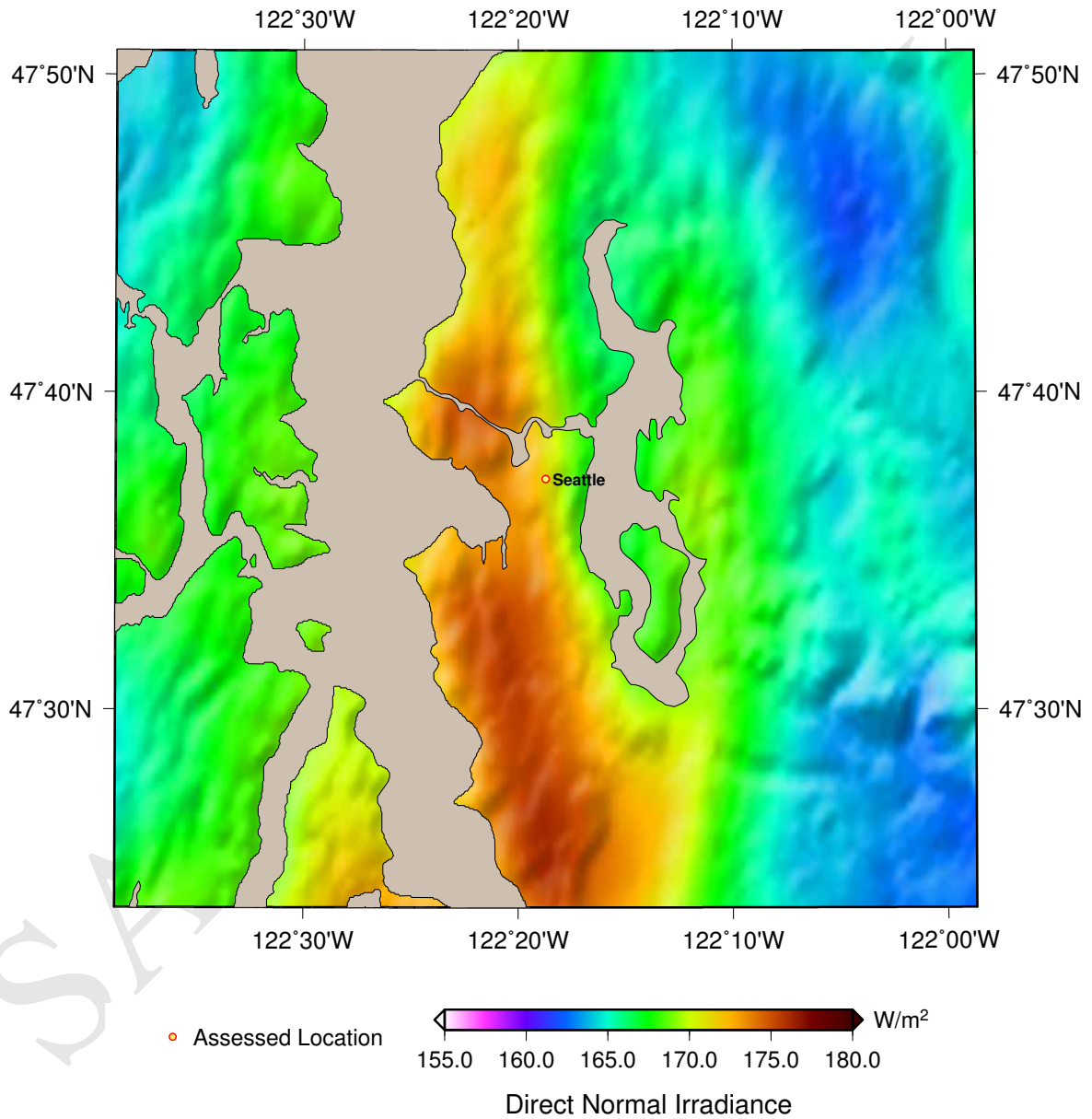


Figure 2: Annual-mean **Direct Normal Irradiance**. The yellow dot denotes the location of the Seattle project site analyzed in Sections 4 and 8.

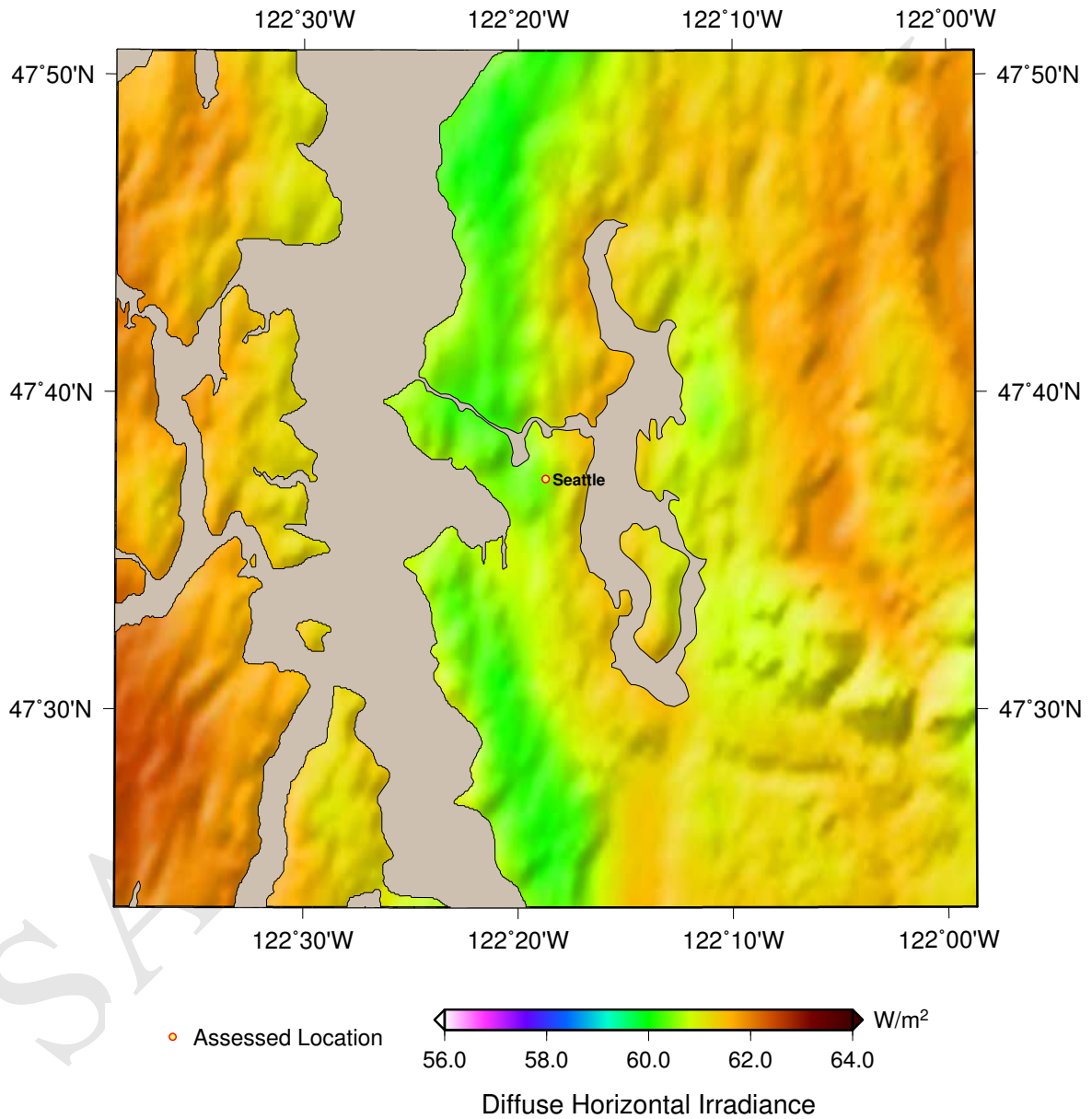


Figure 3: Annual-mean **Diffuse Horizontal Irradiance**. The yellow dot denotes the location of the Seattle project site analyzed in Sections 4 and 8.



4 SOLAR RESOURCE ASSESSMENT

This section provides a retrospective analysis of the past 13+ years of solar irradiance data at the Seattle project site (Latitude: 47.621°N, Longitude: 122.312°W). All irradiance data presented within this section are valid only for this particular location.

4.1 Monthly-mean Variability of Solar Irradiance

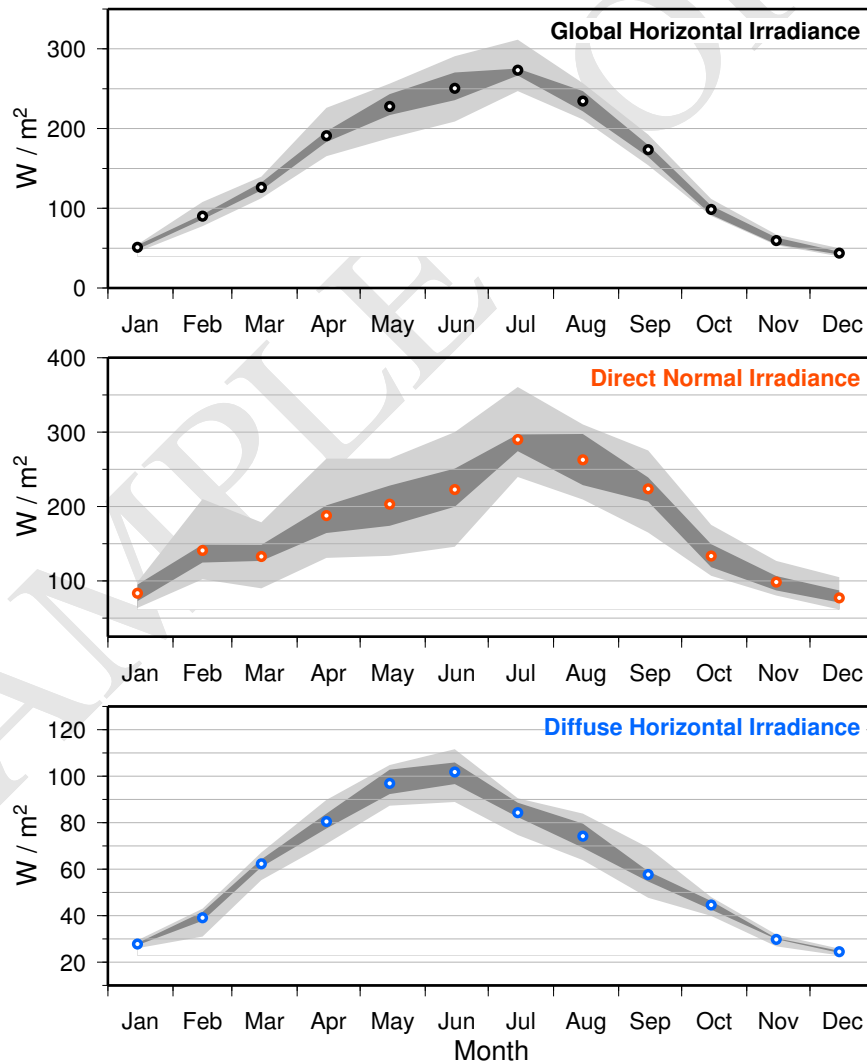


Figure 4: Variability of monthly-mean **Global Horizontal** [top], **Direct Normal** [middle], and **Diffuse Horizontal** [bottom] irradiance. Long-term monthly-mean values are denoted by colored circles. Upper and lower boundaries of the dark shading correspond to the 75% and 25% quartiles, while the light shading denotes the maximum and minimum monthly-mean irradiance values. Please note that the vertical scale varies between the plots.



4.2 Annual-mean Variability of Solar Irradiance

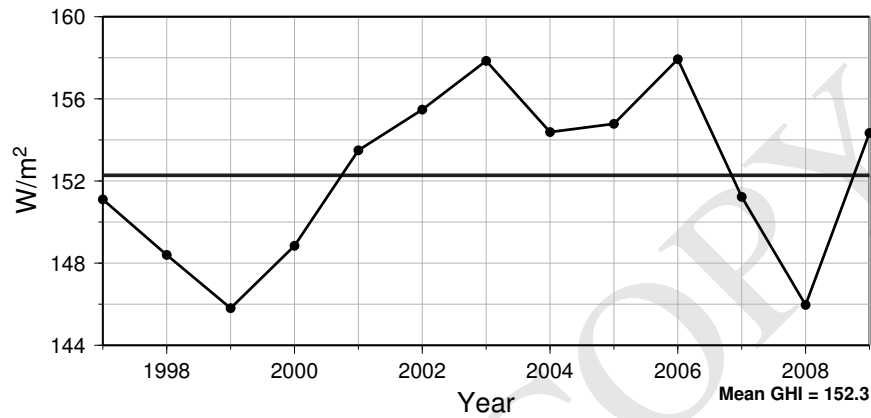


Figure 5: Time series of annual-mean **Global Horizontal Irradiance**. Black horizontal line denotes the long-term average over the years displayed. Tabular formatted data are available in Table 13 (p. 15).

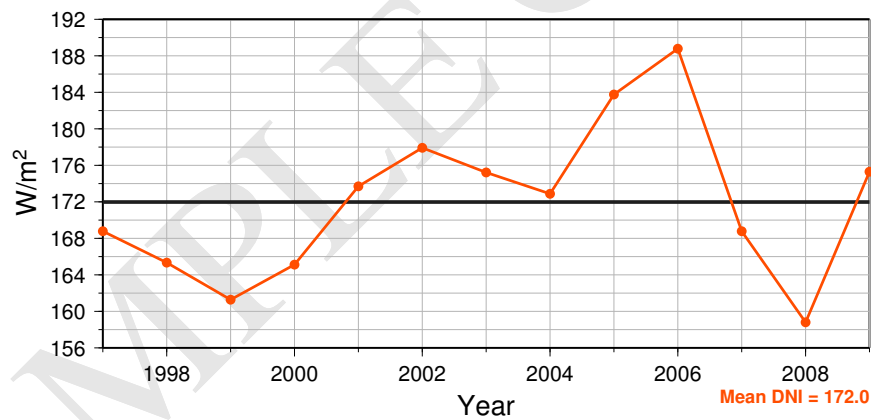


Figure 6: Time series of annual-mean **Direct Normal Irradiance**. Black horizontal line denotes the long-term average over the years displayed. Tabular formatted data are available in Table 14 (p. 16).

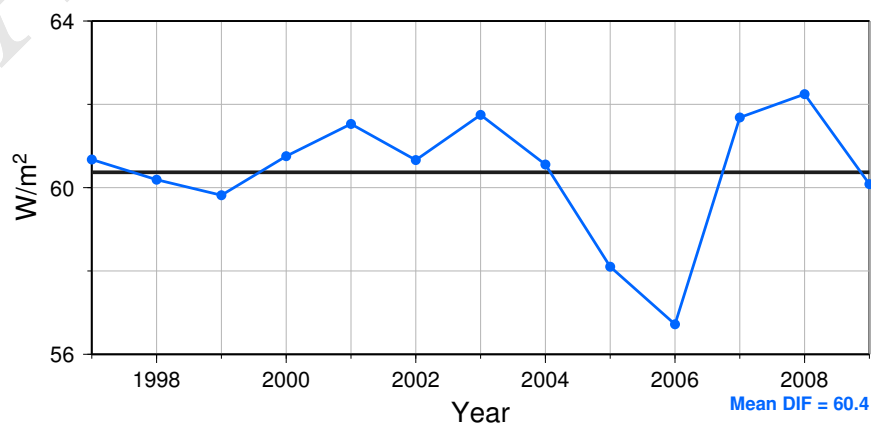


Figure 7: Time series of annual-mean **Diffuse Horizontal Irradiance**. Black horizontal line denotes the long-term average over the years displayed. Tabular formatted data are available in Table 15 (p. 17).



4.3 Solar Irradiance Distributions

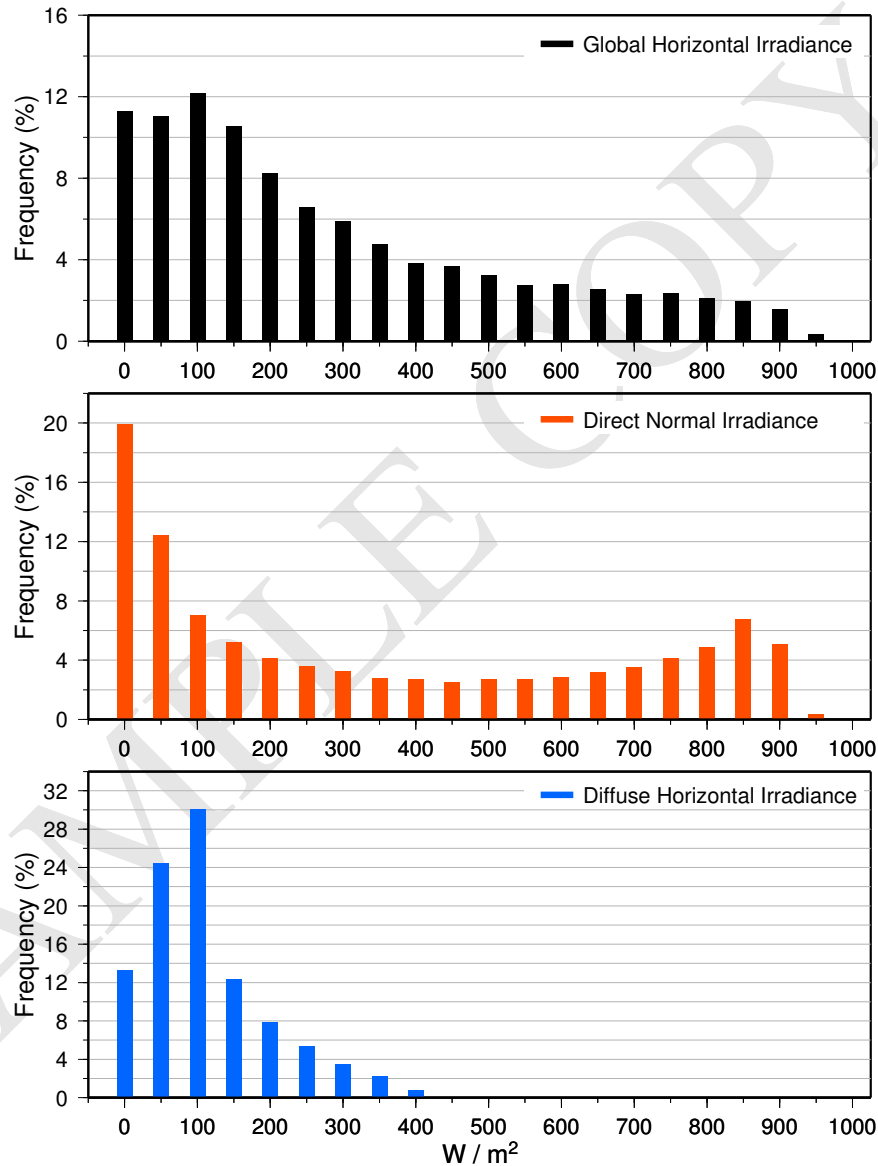


Figure 8: Distribution of hourly **Global Horizontal** [top], **Direct Normal** [middle] and **Diffuse Horizontal** [bottom] daylight irradiance values using 50 W/m² bins. (0 W/m² bin contains only values ≤ 25.) Each vertical bar represents the frequency of irradiance values occurring within each bin. For example, a vertical bar centered on 200 W/m² reaching up to 10% means that one-tenth of all daytime values are between 175 and 225 W/m². Please note that the vertical scale varies between the plots.



4.4 Diurnal Variability of Solar Irradiance

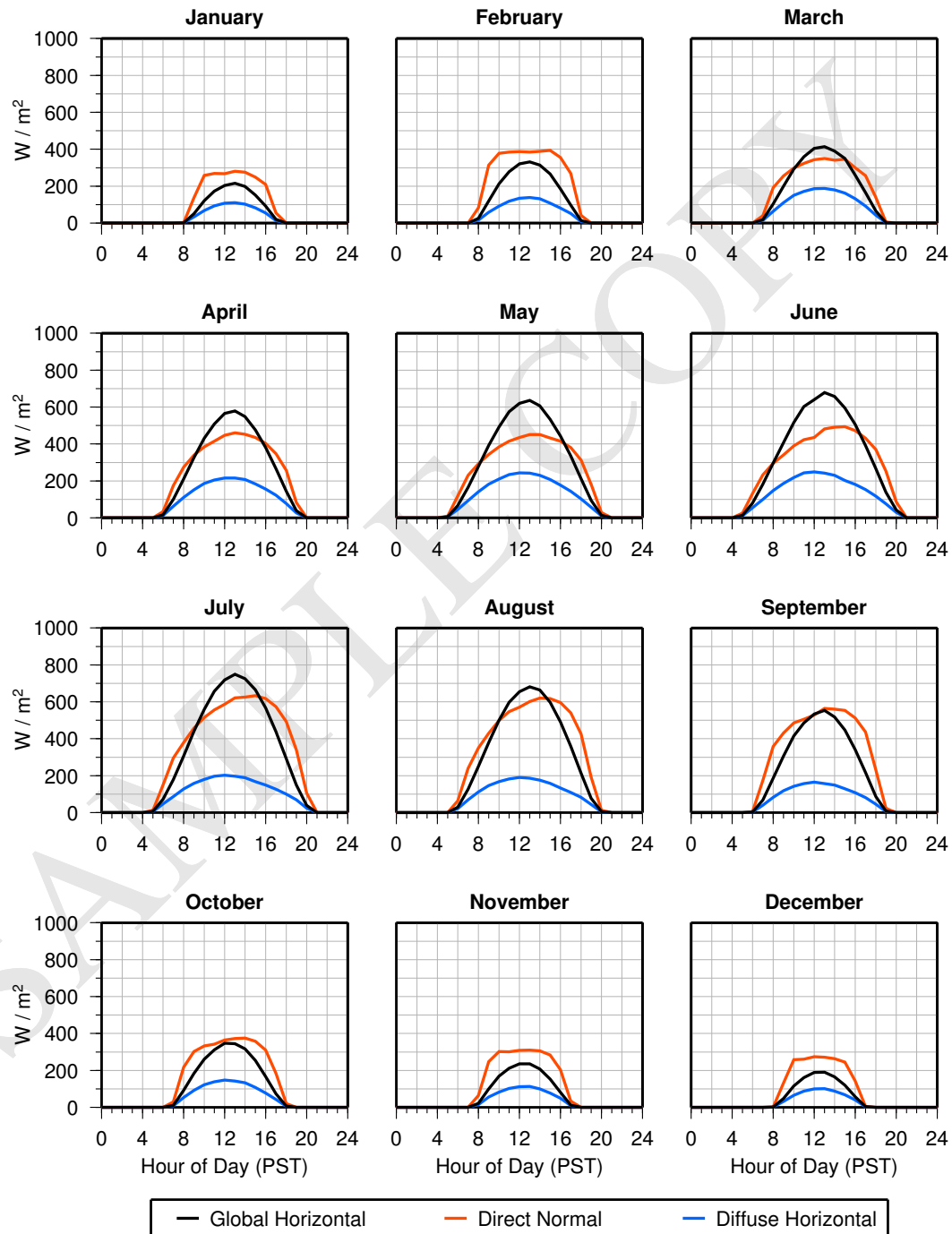


Figure 9: Diurnal cycle of **Global Horizontal** (black), **Direct Normal** (orange) and **Diffuse Horizontal** (blue) irradiance for each month of the year. The horizontal axis is Pacific Standard Time (PST). Figures 10, 11, and 12 show the diurnal cycle of Global Horizontal, Direct Normal, and Diffuse Horizontal solar irradiance, respectively, for each calendar month as a "12 X 24" table.



4.5 Tabular Data

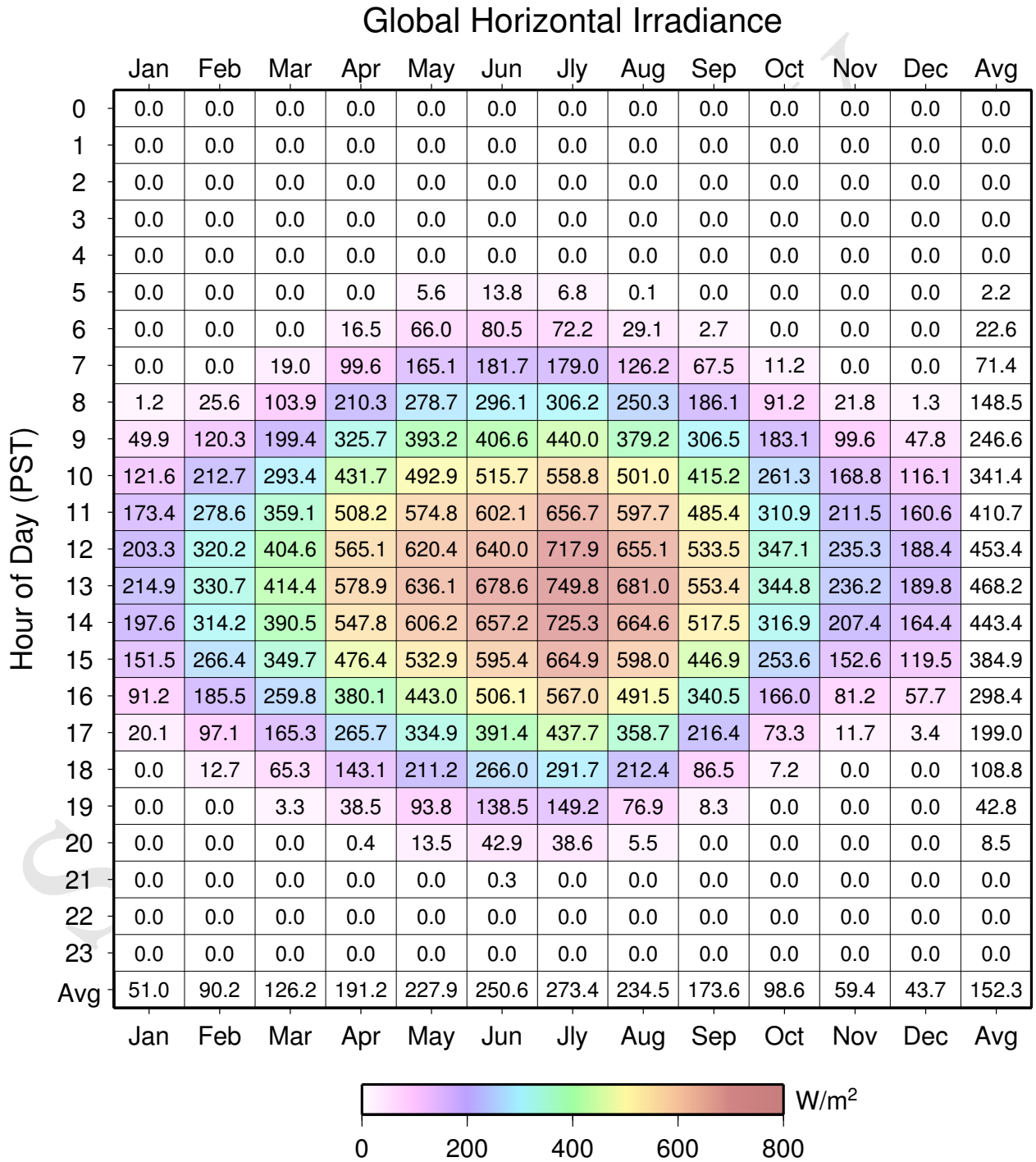


Figure 10: Hourly-mean Global Horizontal Irradiance values in W/m². The vertical axis is Pacific Standard Time (PST). The overall mean in the bottom right corner is based on complete years only. Time series graph of the diurnal variability is shown in Figure 9.



Direct Normal Irradiance

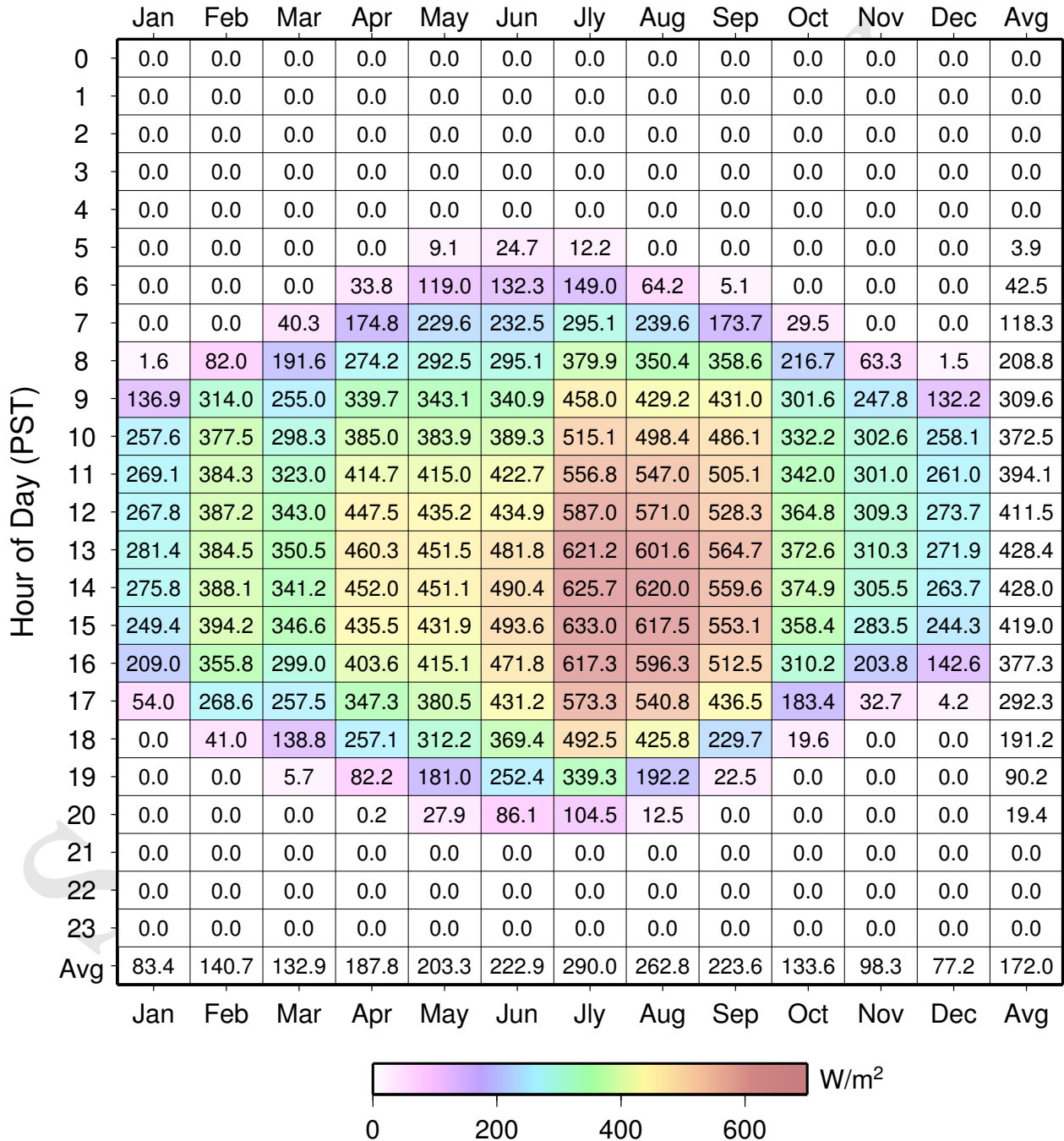


Figure 11: Hourly-mean Direct Normal Irradiance values in W/m². The vertical axis is Pacific Standard Time (PST). The overall mean in the bottom right corner is based on complete years only. Time series graph of the diurnal variability is shown in Figure 9.



Diffuse Horizontal 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	4.8	11.2	5.8	0.1	0.0	0.0	0.0	0.0	1.9
6	0.0	0.0	0.0	12.5	45.7	54.5	46.5	20.7	2.4	0.0	0.0	0.0	15.4
7	0.0	0.0	14.1	62.0	92.6	100.2	86.3	69.2	40.1	8.3	0.0	0.0	39.8
8	1.1	15.6	64.3	110.6	140.7	147.4	127.7	112.4	82.7	53.2	14.5	1.2	73.1
9	32.8	59.0	111.0	151.2	181.8	186.5	158.3	146.2	118.7	92.3	56.0	32.0	111.1
10	67.6	92.0	150.1	185.7	210.7	218.2	179.4	168.2	142.1	122.0	83.0	65.8	141.1
11	92.5	118.2	172.1	205.4	234.4	242.9	196.5	181.8	156.9	138.8	102.7	88.0	161.6
12	108.1	134.1	186.4	215.2	242.9	249.4	201.9	190.5	164.4	147.6	111.3	100.1	171.8
13	110.7	138.9	187.5	216.0	242.7	242.5	197.3	186.1	157.7	142.9	112.9	101.0	170.5
14	103.1	131.4	180.2	208.0	230.7	230.5	189.2	175.8	149.1	132.4	100.3	88.3	160.8
15	82.8	108.2	162.1	183.8	207.2	202.3	167.9	157.9	129.6	107.9	77.5	67.7	138.7
16	54.2	80.9	131.3	155.4	176.8	181.5	148.6	133.4	107.9	77.8	48.8	39.5	112.1
17	13.6	51.9	91.3	122.2	143.7	152.7	126.3	109.6	81.6	42.0	8.7	3.2	79.6
18	0.0	8.6	43.0	77.3	102.7	117.3	99.5	82.0	45.8	5.2	0.0	0.0	49.0
19	0.0	0.0	2.8	26.9	57.8	75.6	69.0	43.5	5.9	0.0	0.0	0.0	23.7
20	0.0	0.0	0.0	0.4	10.4	29.3	23.3	4.4	0.0	0.0	0.0	0.0	5.7
21	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
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	27.8	39.1	62.3	80.5	96.9	101.8	84.3	74.2	57.7	44.6	29.8	24.5	60.4

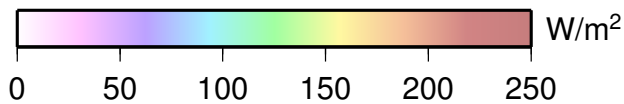


Figure 12: Hourly-mean Diffuse Horizontal Irradiance values in W/m². The vertical axis is Pacific Standard Time (PST). The overall mean in the bottom right corner is based on complete years only. Time series graph of the diurnal variability is shown in Figure 9.

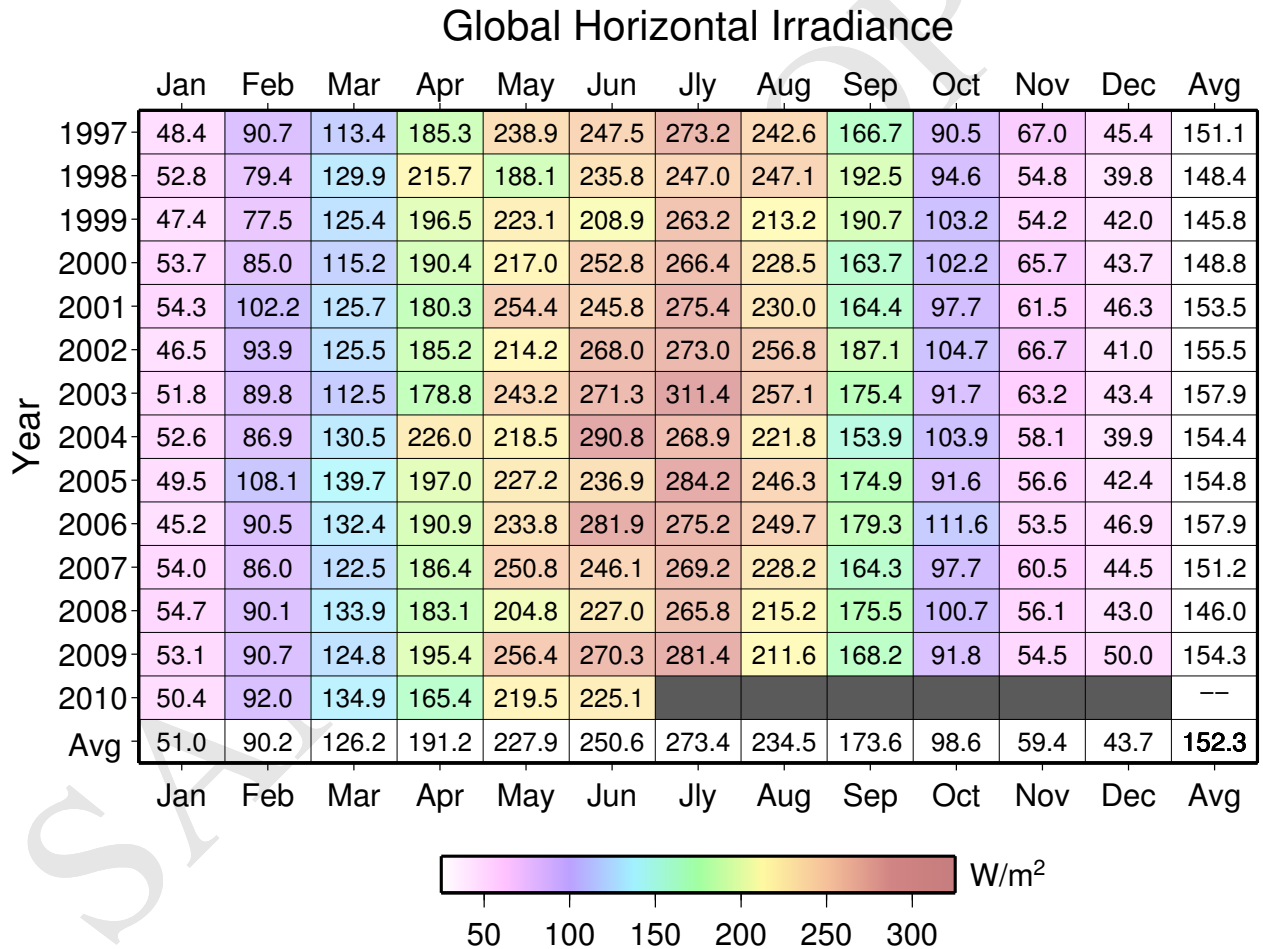


Figure 13: Monthly-mean values of **Global Horizontal Irradiance** in W/m². The yearly means in the rightmost column are based on complete years and are shown in Figure 5.

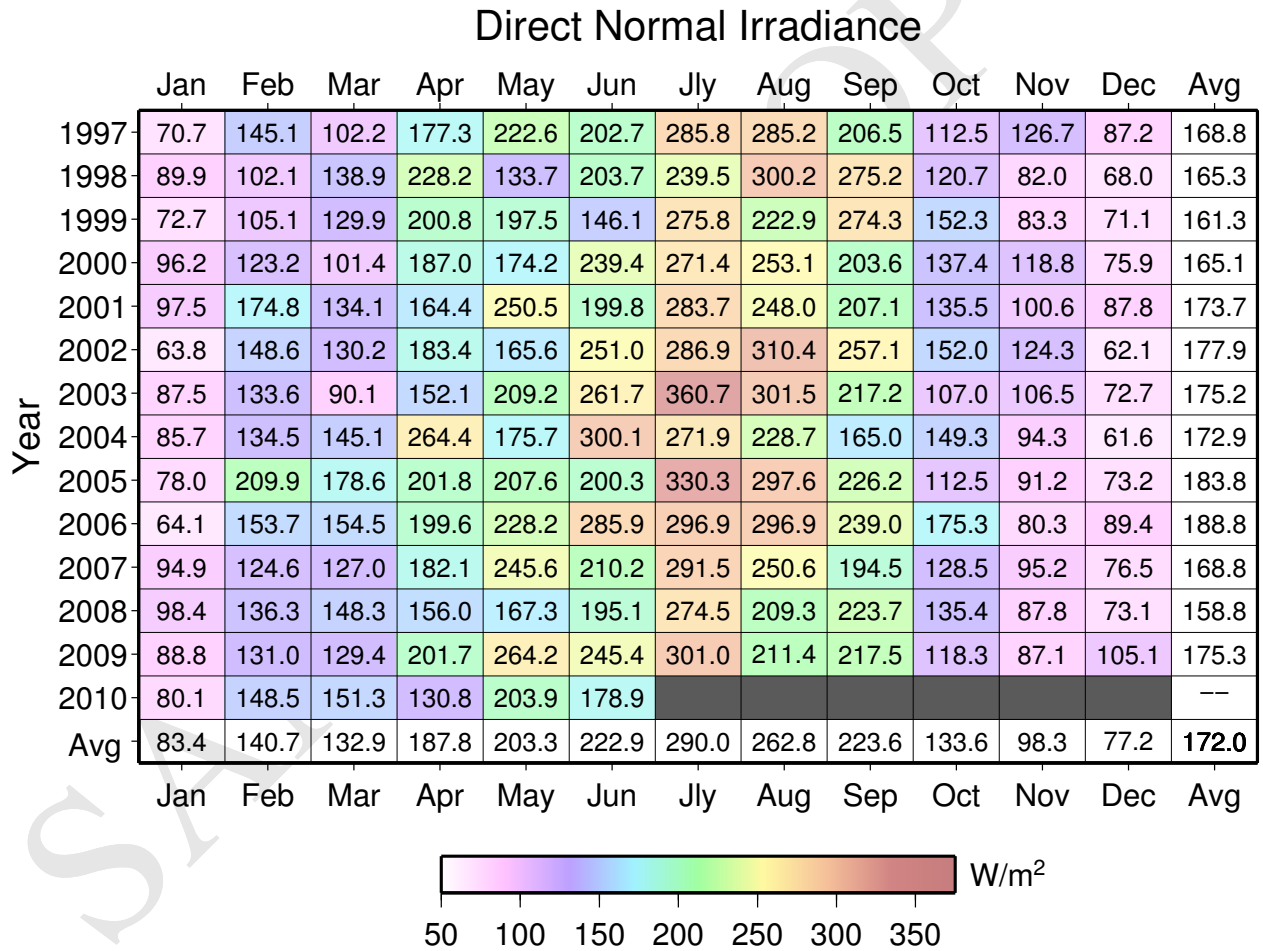


Figure 14: Monthly-mean values of Direct Normal Irradiance in W/m². The yearly means in the rightmost column are based on complete years and are shown in Figure 6.

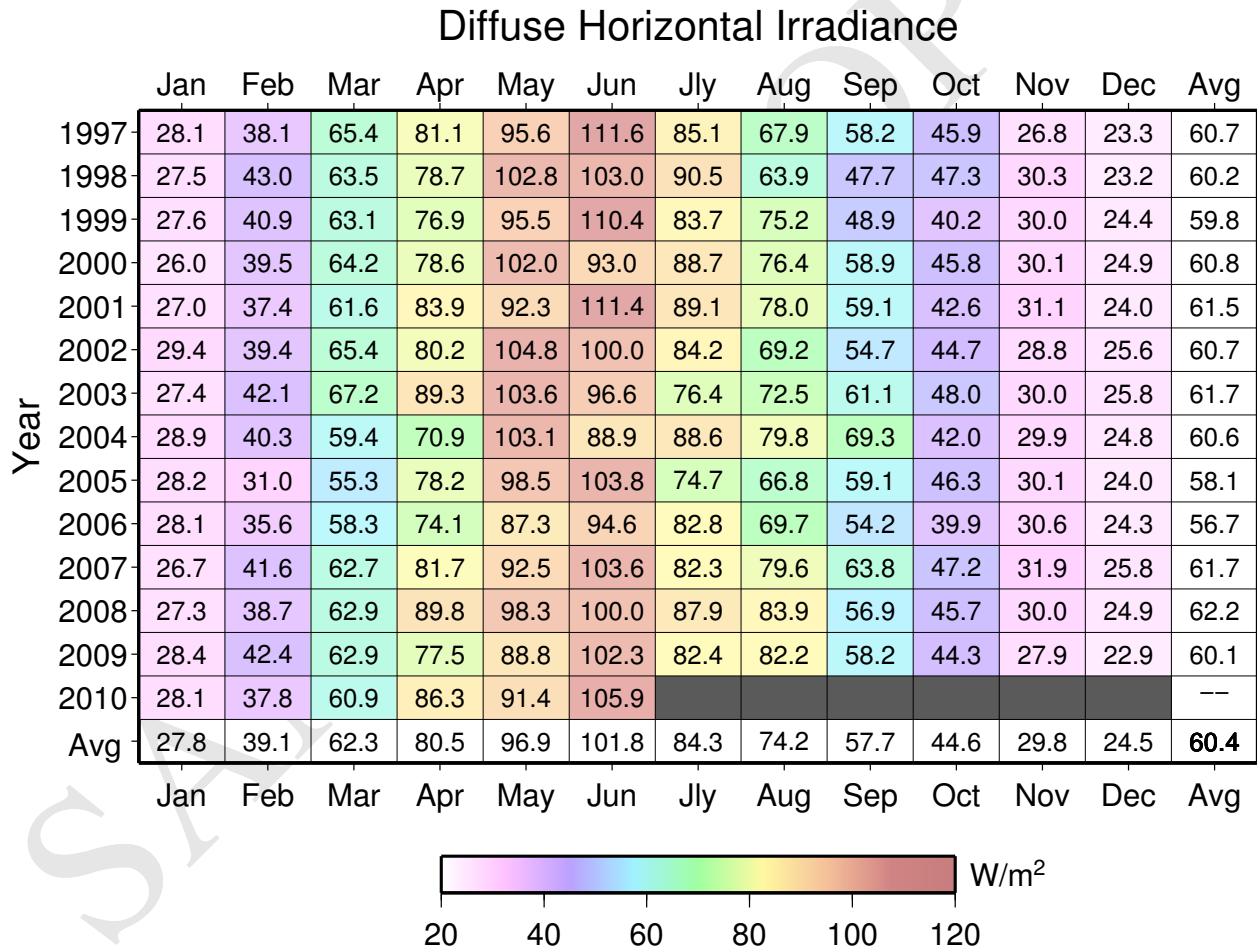


Figure 15: Monthly-mean values of Diffuse Horizontal Irradiance in W/m². The yearly means in the rightmost column are based on complete years and are shown in Figure 7.

5 UNCERTAINTY ANALYSIS OF IRRADIANCE

5.1 Model Uncertainty

The satellite algorithm error was based on validation of 3TIER's satellite derived data against 92 reference stations across the globe, and is discussed in Section 2. 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.

5.2 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 Seattle project site directly from the interannual variability from 3TIER's multi-year 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.

5.3 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	GHI	DNI	DIF
Model	5.0	9.0	15.0
1-year Long-Term	2.69	4.98	2.52
10-year Long-Term	0.85	1.58	0.80
Pooled 1-year	5.68	10.29	15.21
Pooled 10-year	5.07	9.14	15.02

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



6 PROBABILITY OF EXCEEDANCE OF IRRADIANCE

6.1 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, Seattle has a 90 percent chance of exceeding an annual global horizontal irradiance of 1237 kWh/m²/year for any one-year period and a 90 percent chance of exceeding an annual average global horizontal irradiance for a continuous 10 year time period of 1247 kWh/m²/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.

$$\text{GHI 1-year P90} = \text{P50} - 1.282 \times (5.68 / 100) \times \text{P50} = 1237 \text{ kWh/m}^2/\text{year}$$

$$\text{GHI 10-year P90} = \text{P50} - 1.282 \times (5.07 / 100) \times \text{P50} = 1247 \text{ kWh/m}^2/\text{year}$$

	P50	P75	P90	P95	P99
GHI 1-year	1334	1283	1237	1209	1158
DNI 1-year	1506	1402	1308	1252	1146
DIF 1-year	528.8	474.6	425.7	396.5	341.7
GHI 10-year	1334	1288	1247	1223	1177
DNI 10-year	1506	1414	1330	1280	1186
DIF 10-year	528.8	475.2	427.0	398.2	344.0

Table 3: 1-year and 10-year Probability of Exceedance Values (kWh/m²/year).

7 MODEL SIMULATIONS BY 3TIER

The assessment of the wind resource at the Seattle project site presented in this report is based on 13+ years of simulated data (January 1997 through June 2010). 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 13-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	3 second SRTM
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.



8 WIND AND TEMPERATURE RESOURCE ASSESSMENT

This section provides a retrospective analysis of the past 13+ years of wind and temperature data at the Seattle project site (Latitude: 47.621°N, Longitude: 122.312°W). All data presented within this section are valid only for this particular location.

8.1 Monthly-Mean Variability

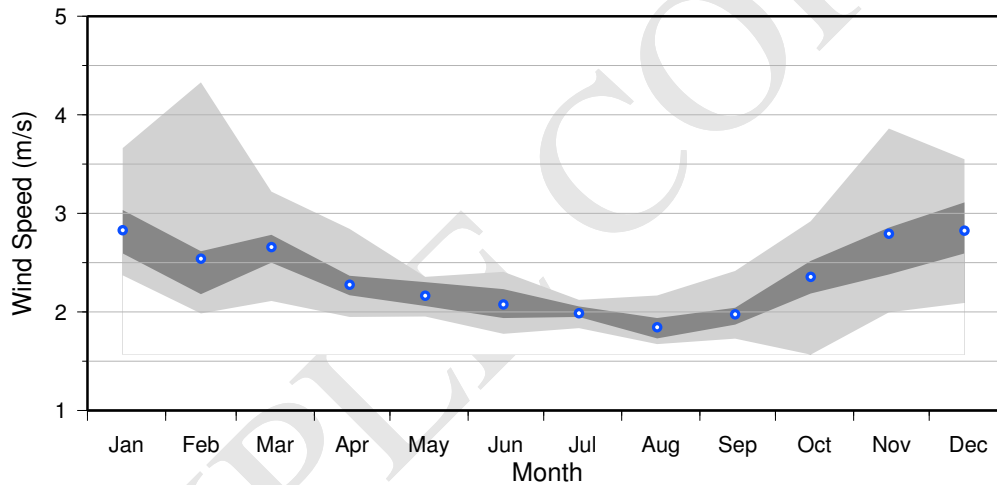


Figure 16: Variability of monthly-mean **wind speed** at 10m AGL at Seattle. Long-term monthly-mean values are denoted by colored circles. Upper and lower boundaries of the dark shading correspond to the 75% and 25% quartiles, while the light shading denotes the maximum and minimum monthly-mean wind speeds.

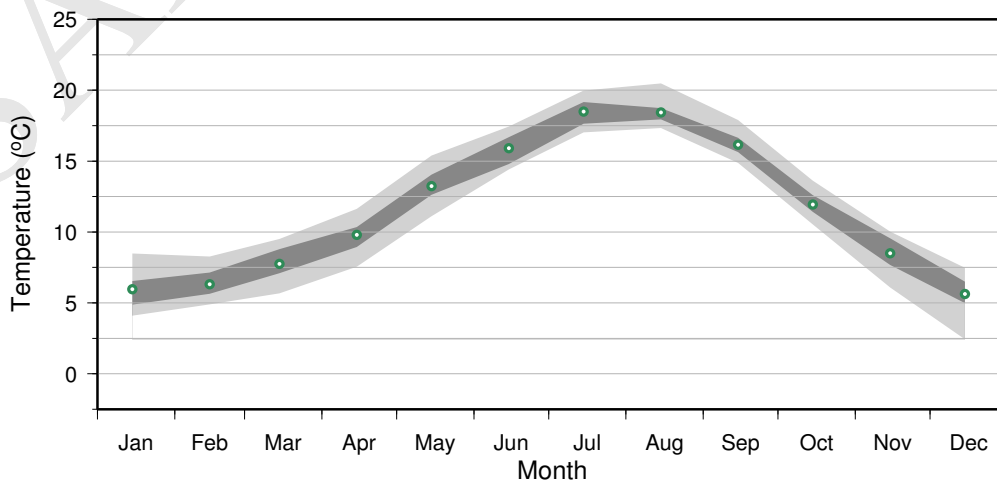


Figure 17: Variability of monthly-mean **temperature** at 2m AGL at Seattle. Long-term monthly-mean values are denoted by colored circles. Upper and lower boundaries of the dark shading correspond to the 75% and 25% quartiles, while the light shading denotes the maximum and minimum monthly-mean temperature.



8.2 Distribution of Wind Direction

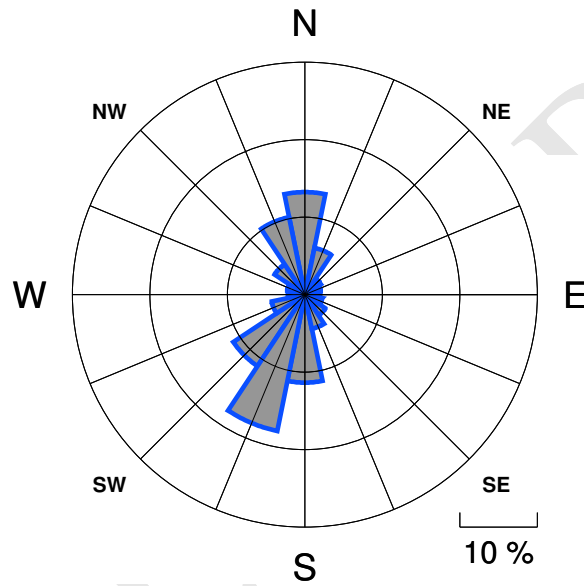


Figure 18: Annual wind rose at Seattle showing the prevailing **wind directions** at 10m AGL. Directional bins are 22.5° wide, and the radial contour interval is 10%.

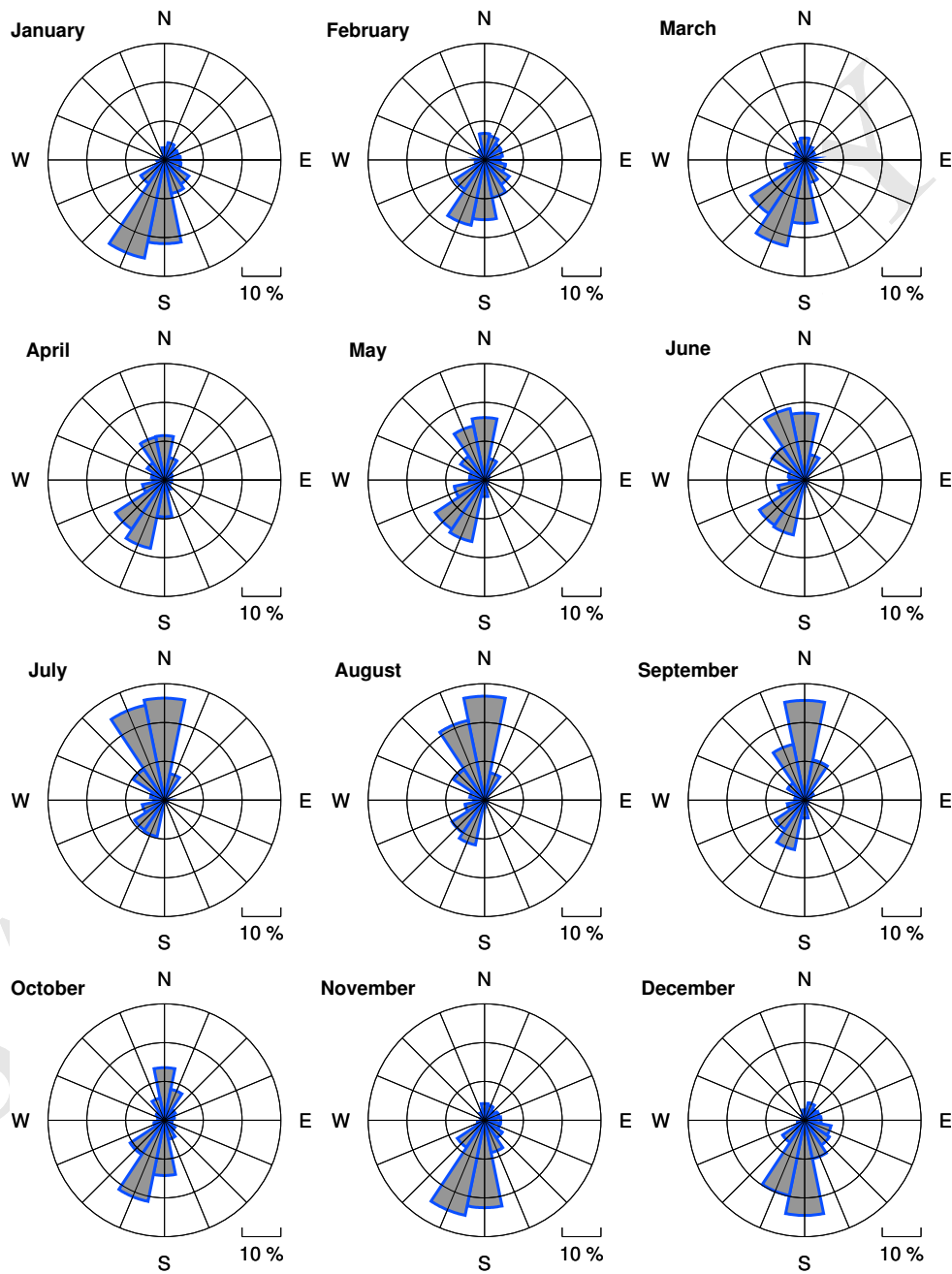


Figure 19: Monthly wind roses at Seattle showing the prevailing **wind directions** at 10m AGL. Directional bins are 22.5° wide, and the radial contour interval is 10%.



8.3 Diurnal Variability of Wind Speed

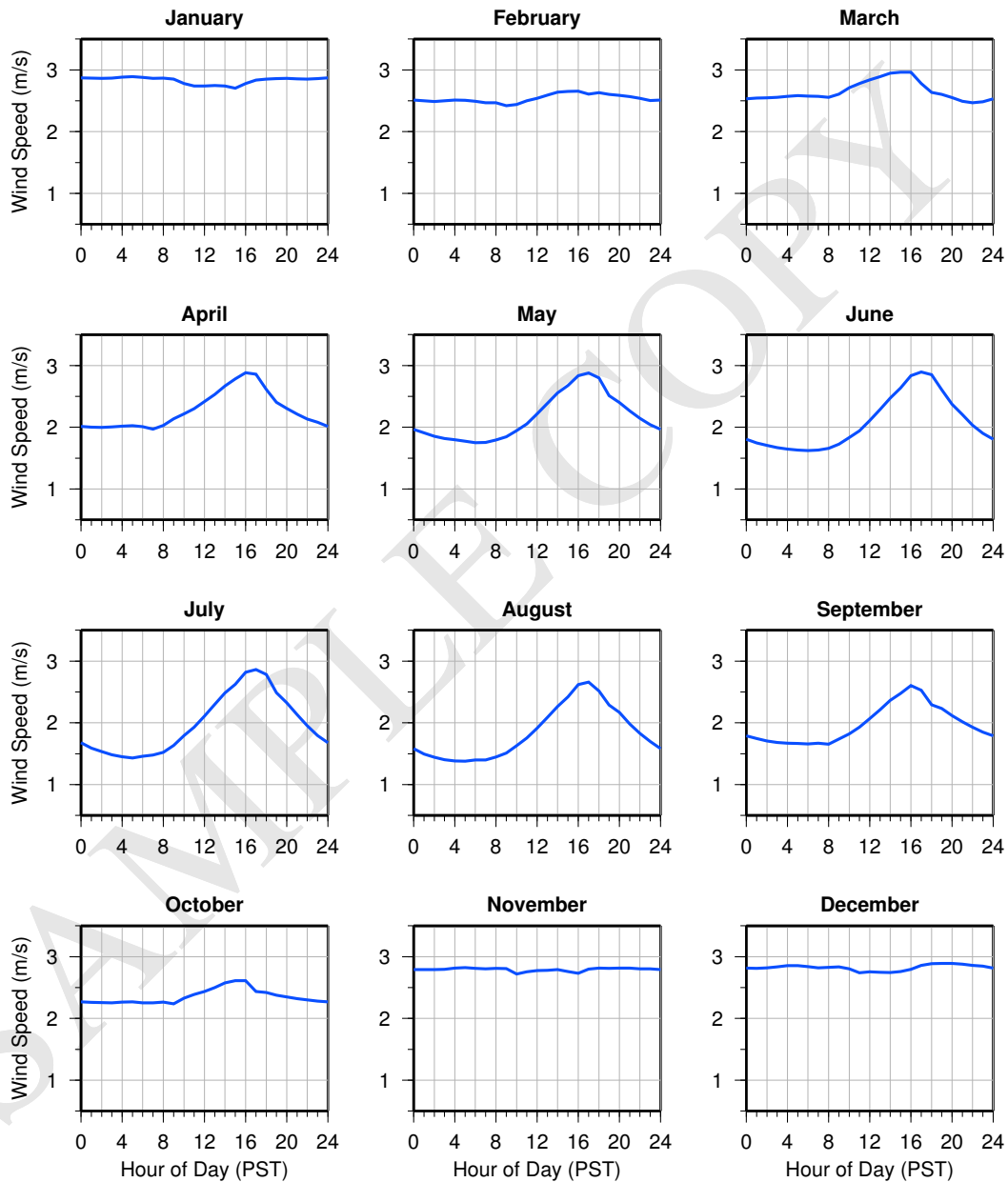


Figure 20: Diurnal cycle of **wind speed** at 10m AGL for each month of the year. The horizontal axis is in Pacific Standard Time (PST). Figure 22 shows the diurnal cycle of wind speed for each calendar month as a '12 X 24' table.



8.4 Diurnal Variability of Temperature

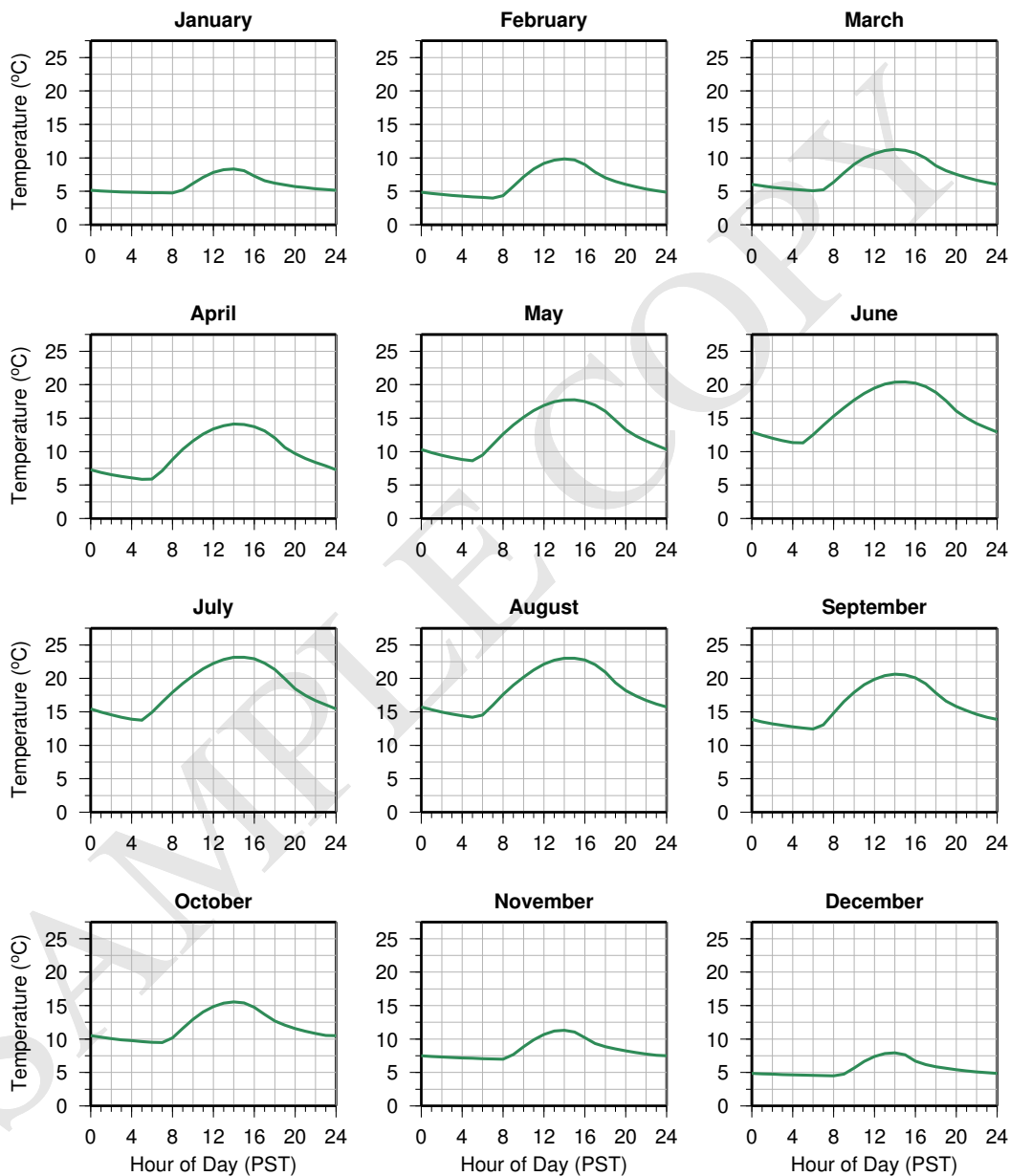


Figure 21: Diurnal cycle of **temperature** at 2m AGL for each month of the year. The horizontal axis is in Pacific Standard Time (PST). Figure 23 shows the diurnal cycle of temperature for each calendar month as a '12 X 24' table.



8.5 Tabular Data

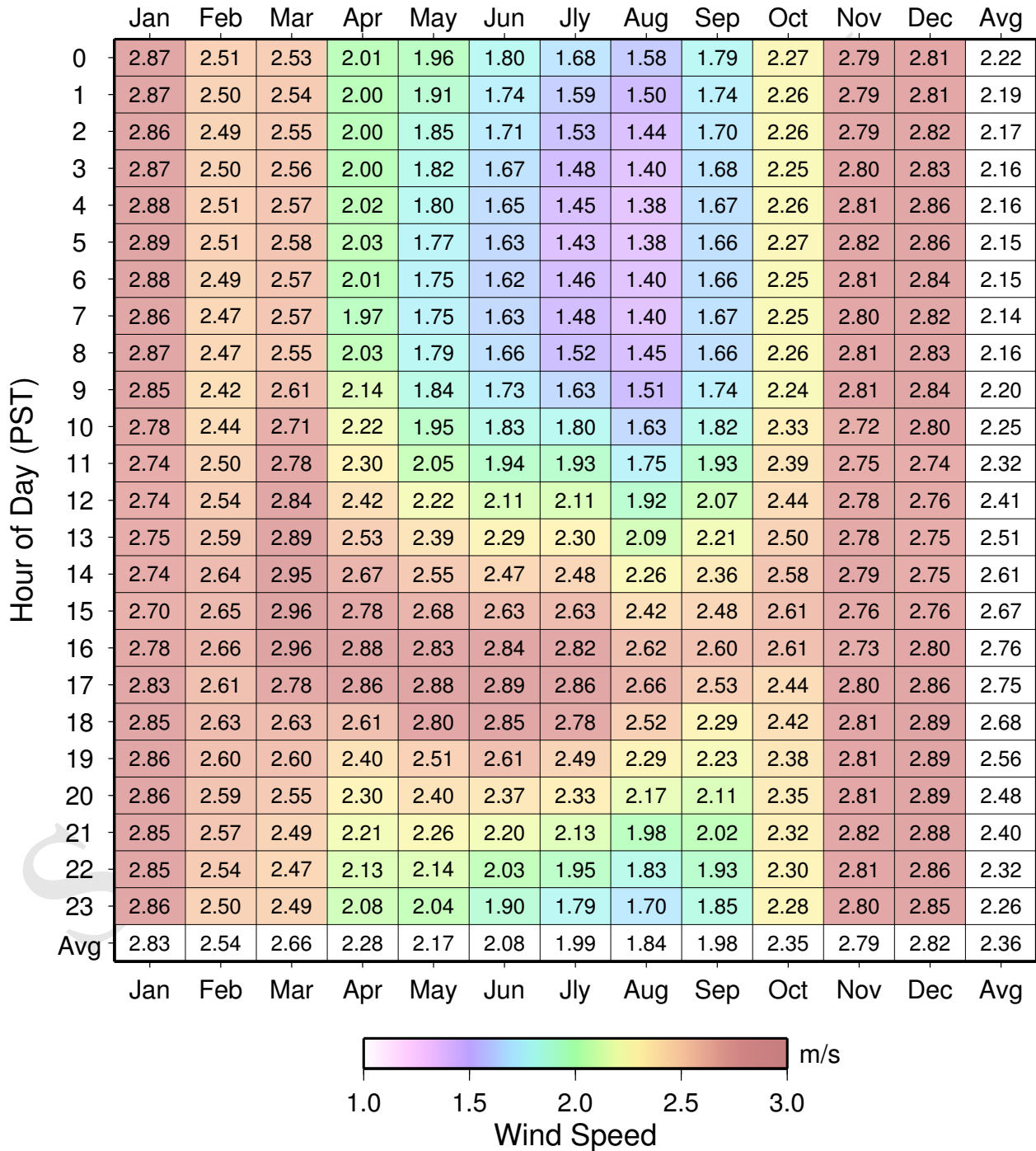


Figure 22: Hourly-mean wind speed values at 10m AGL in m/s. The vertical axis is in Pacific Standard Time (PST). The overall mean in the bottom right corner is based on complete years only. Time series graph of the diurnal variability for each month is shown in Figure 20.

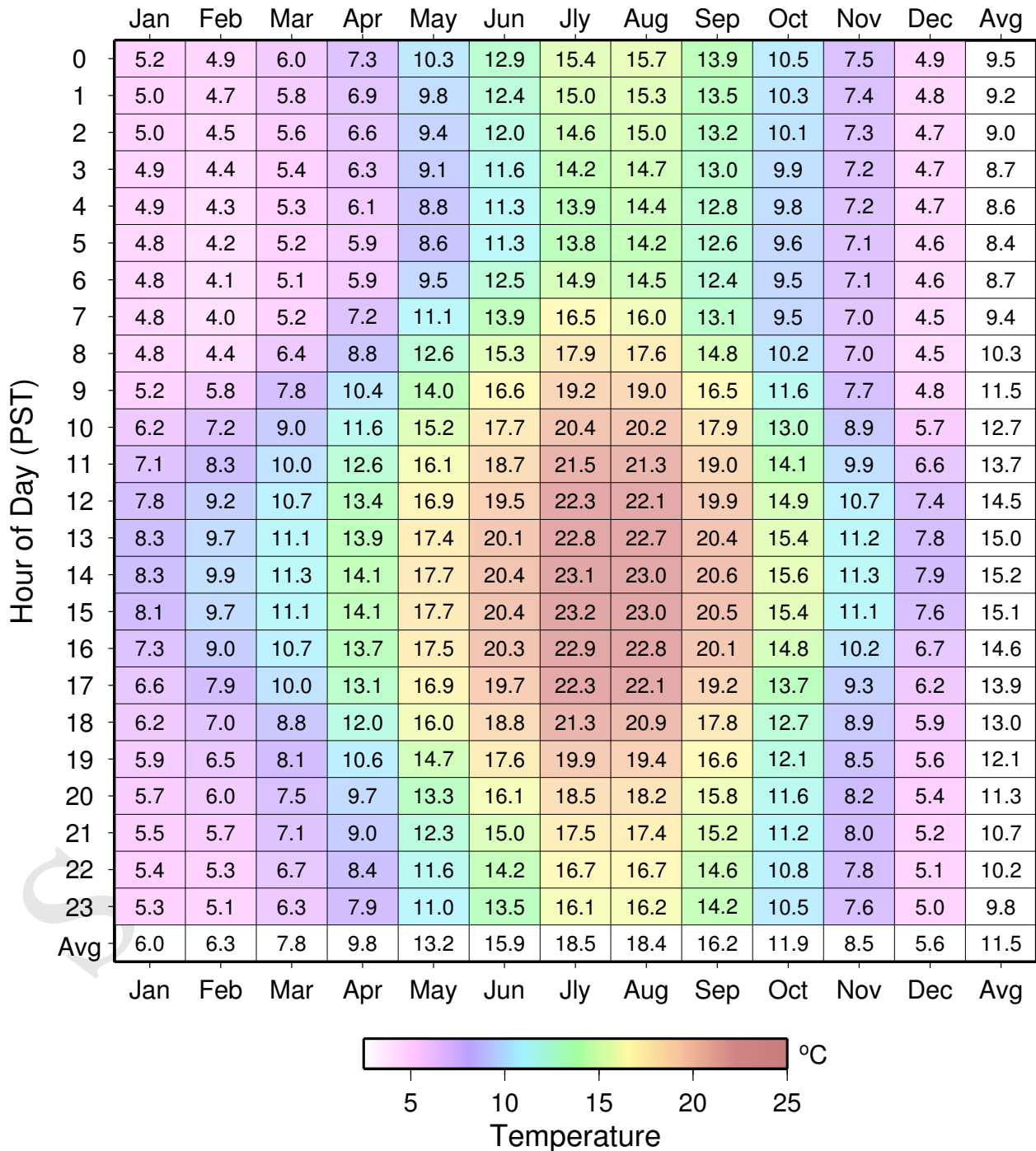


Figure 23: Hourly-mean temperature values at 2m AGL in degrees Celsius. The vertical axis is in Pacific Standard Time (PST). The overall mean in the bottom right corner is based on complete years only. Time series graph of the diurnal variability for each month is shown in Figure 21.