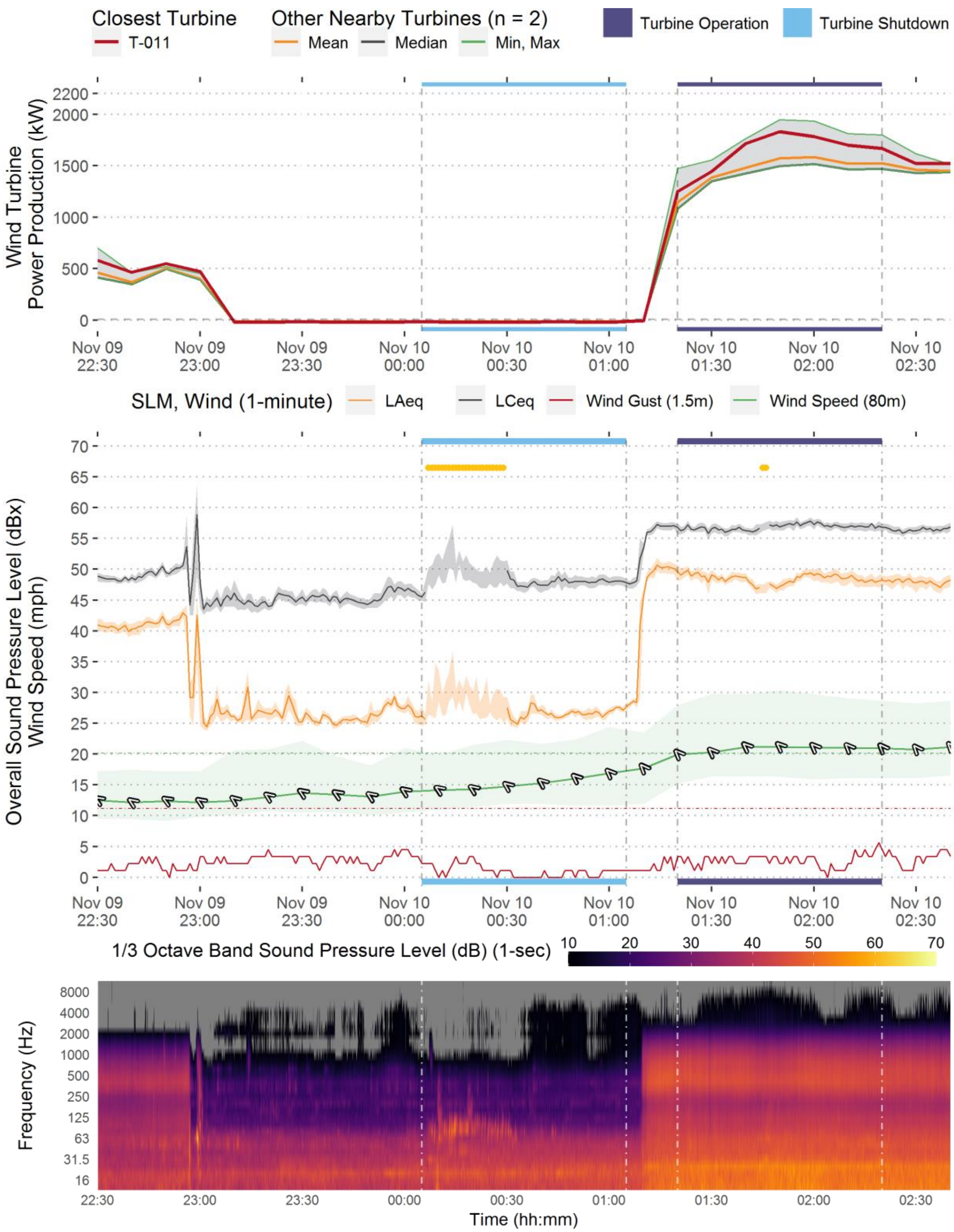

FIGURE 29: GRAPHICAL RESULTS OF SHUTDOWN ID 26 AT THE CENTRAL MONITOR

The yellow points above 65 dBA indicate periods removed due to extraneous anthropogenic noise (i.e., anomalies)

West Monitor

Discrete Shutdowns

A total of 40 valid periods were assessed at the West monitor. A table of with the results for each valid assessment period is provided in Table 11 in Appendix D.

Shutdown ID 37

The worst-case assessment period occurred after 10:00 PM on November 12th (Shutdown ID 37). Detailed results surrounding the shutdown are provided in Figure 30. In Figure 30, total sound levels (L_{eq}) with the turbines operating can be observed to have exceeded 50 dBA for over half of the turbine operation period. The average hub-height wind speed during the Turbine-on period was 10.4 m/s (23 mph) which dropped to 9.4 m/s (21 mph) during the Background period. No ground-level winds were apparent, indicating relatively high wind shear conditions. Winds from the northwest put the West monitor crosswind from T-14 (closest turbine) and directly downwind from T-13 (the next closest turbine – see Figure 7).

The measured L_{50} while the project was in operation was 51 dBA and the measured L_{50} during the shutdown was 38 dBA, resulting in a turbine-only sound level of 50 dBA. This period's Total sound level exceeded the state noise limit.

Binning Method

The binning method analysis at the West monitor consisted of 37 hours of Background periods and 44 hours of Total sound level periods. The distributions of valid binning periods by wind speed bin and period type are provided in Figure 31.

The results of the binning analysis at the West monitor are provided in Table 7. The highest turbine-only sound level of 46 dBA occurred in the 8 m/s wind speed bin. Above 10 m/s, turbine-only sound levels are below background.

While the discrete-shutdown exceedance during Shutdown ID 37 occurred at a wind speed of 10 m/s, the binning analysis shows a Total L_{50} of 47 dBA and a Turbine-only L_{50} of 45 dBA at this wind speed. These levels are below the Permit noise limits.

To assess the frequency of the high wind shear condition that occurred during this shutdown, we evaluated instances of no ground wind gusts with winds at and over 10 m/s. We found that these conditions occurred about 4% over the full monitoring period and for 6% of nighttime periods.

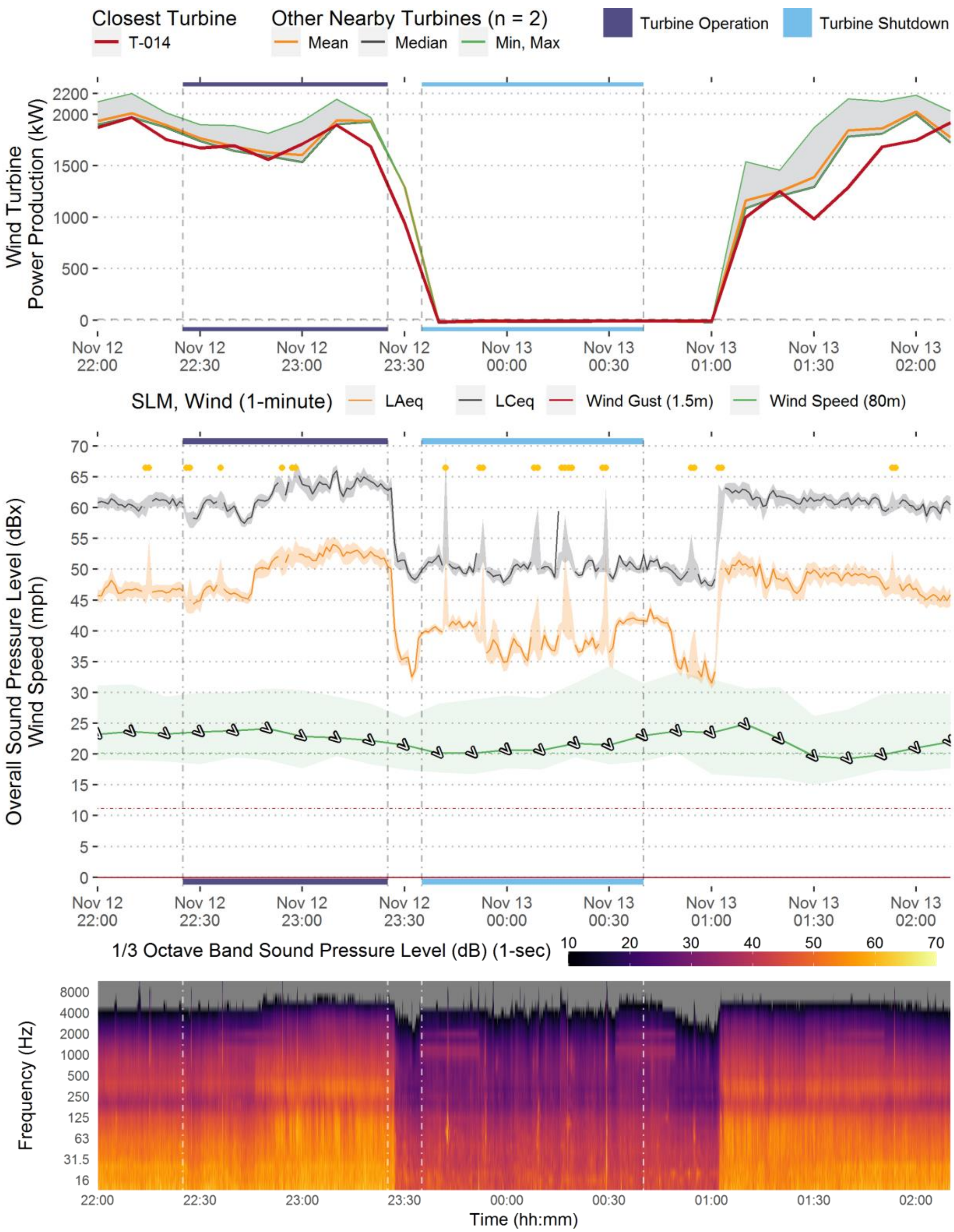

FIGURE 30: GRAPHICAL RESULTS OF SHUTDOWN ID 37 AT THE WEST MONITOR

The yellow points above 65 dBA indicate periods removed due to extraneous anthropogenic noise (i.e., anomalies)

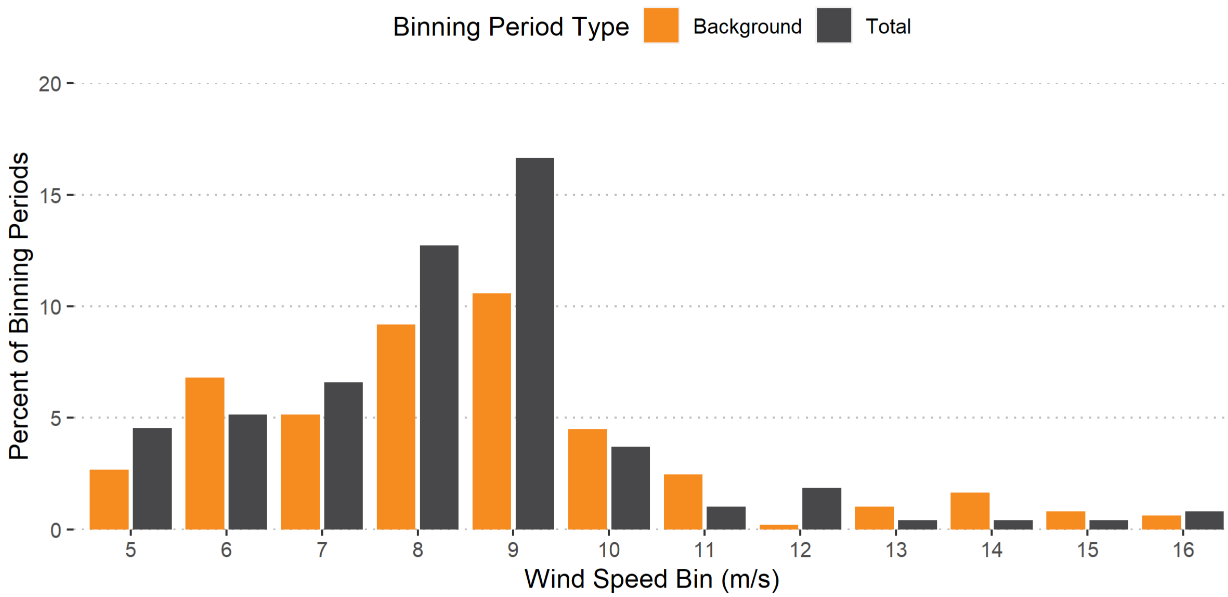

FIGURE 31: DISTRIBUTION OF VALID PERIODS AT EACH HUB-HEIGHT WIND SPEED BIN FOR THE WEST MONITOR

TABLE 7: WEST MONITOR BINNING ANALYSIS L_{50} RESULTS

HUB HEIGHT WIND SPEED BIN (m/s)	WIND SPEED (MPH)	BACKGROUND (dBA)	TOTAL SOUND (dBA)	TURBINE-ONLY (dBA)	PERCENT OF TIME (ABOVE 4 M/S)
5	11.2	35	41	40	7%
6	13.4	40	44	40	12%
7	15.7	38	44	43	12%
8	17.9	40	47	46	22%
9	20.1	41	46	45	27%
10	22.4	41	47	45	8%
11	24.6	45	48	43	4%
12	26.8	44	47	43	2%
13	29.1	46	46	31	1%
14	31.3	47	49	40	2%
15	33.6	49	50	30	1%
16	35.8	50	51	21	1%

South monitor

Discrete Shutdowns

A total of 38 valid periods were assessed at the South monitor. A table of with the results for each valid assessment period is provided in Table 12 in Appendix D.

Shutdown ID 9 was the highest turbine-only and total sound level but gusty winds and conditions not sufficiently similar between turbine operation and background do not allow a precise accounting of background sound during wind turbine operation. Conversely, Shutdown ID 13 was the next highest turbine-only sound level calculated with more consistent conditions. Both are presented in this section.

Shutdown ID 9

Detailed results of Shutdown ID 9 on November 5 and 6 for the South monitor are presented in Figure 32. Gusty ground-level and hub-height wind speeds were observed during the turbine operation period. As the turbines were shutting down, hub height wind speeds decreased 4.5 m/s (10 mph) and a more consistent sound level can be observed to subside during the background period. By the following shutdown operation period (Shutdown ID 10), the gusty winds had subsided. The total sound level during the turbine operation period was 50 dBA. The background period registered a one-hour L_{50} of 45 dBA, resulting in a calculated turbine-only sound level of 48 dBA. The anomalous activity excluded during the evaluation periods consisted of traffic passbys.

Shutdown ID 13

Results for Shutdown ID 13 are provided in Figure 33. Winds were more consistent between the background period and the operational period than Shutdown ID 9, and it provided a better signal-to-noise ratio. During this assessment period, the monitor was downwind of the closest turbine, T-27 located in Iowa. The one-hour L_{50} while the Project was shutdown was 35 dBA while the total one-hour L_{50} level during turbine operation was one-hour L_{50} of 47 dBA. The difference of 12 dB between the background period and turbine operation period indicates the wind-turbine only sound level was 47 dBA.

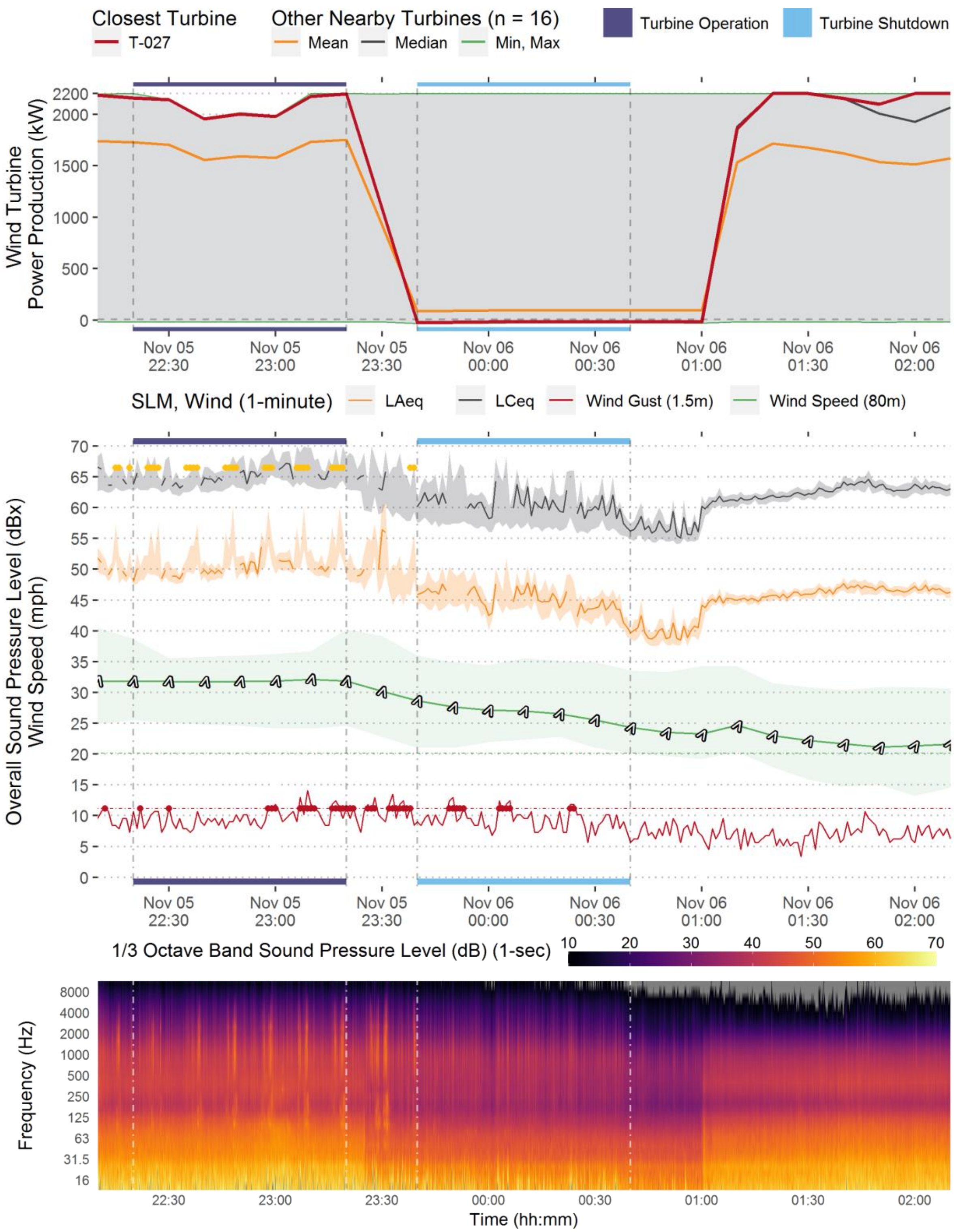

FIGURE 32: GRAPHICAL RESULTS OF SHUTDOWN ID 9 AT THE SOUTH MONITOR

The yellow points above 65 dBA indicate periods removed due to extraneous anthropogenic noise (i.e., anomalies)

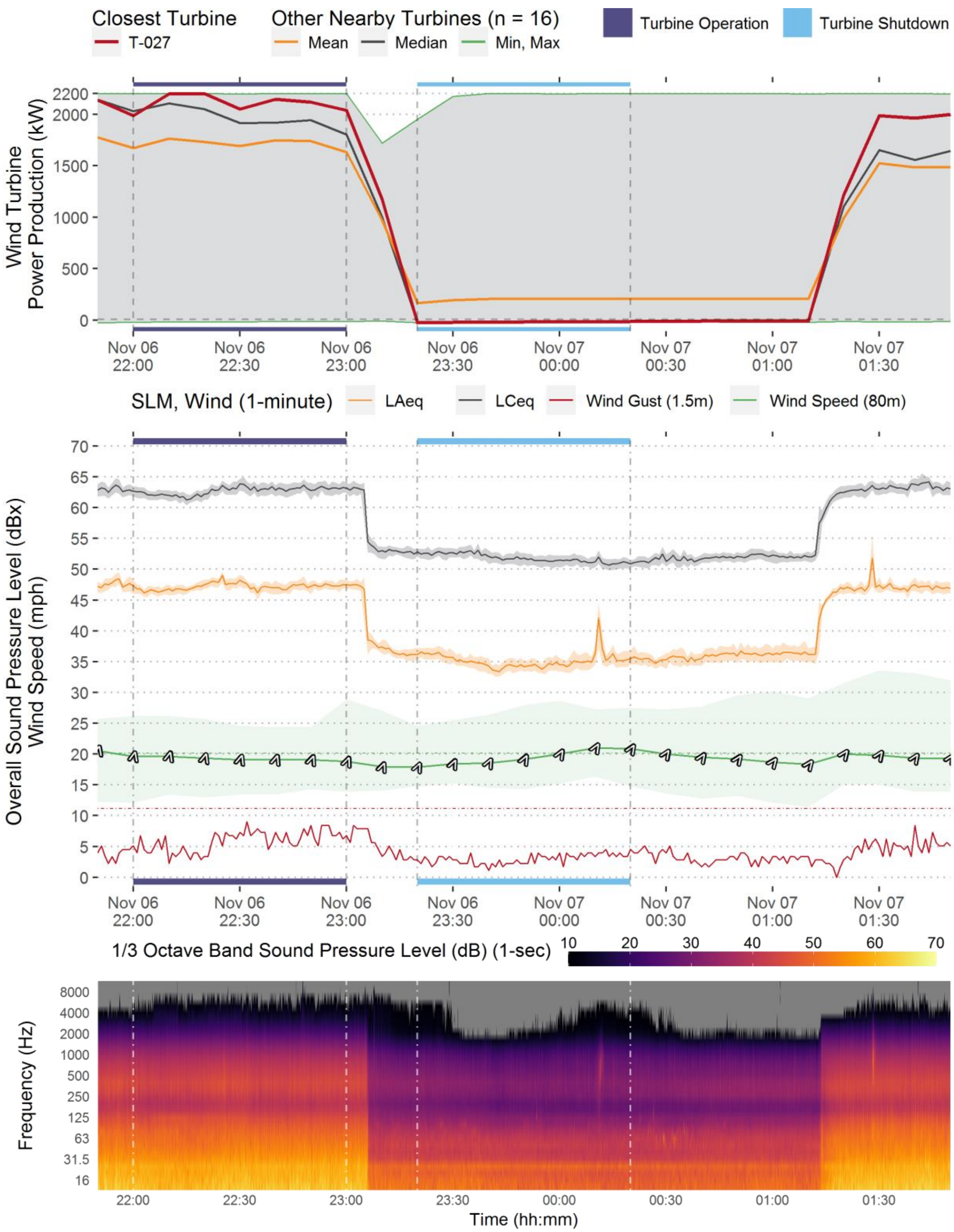

FIGURE 33: GRAPHICAL RESULTS OF SHUTDOWN ID 13 AT THE SOUTH MONITOR

6.3 COMPARISON TO MODELED SOUND LEVELS

As described in Section 2.5, sound levels for the project were modeled prior to construction. In this section, we compare these modeled sound levels to the turbine-only sound levels measured in this report.

The maximum turbine-only sound levels that were monitored at each location were greater than the modeled turbine-only sound levels calculated prior to construction.[15] As shown in Table 8, the maximum monitored turbine-only sound level at the North and West monitor were 5 dB above the updated sound level modeling.[4] At the Central monitor, the maximum measured turbine-only sound level was 4 dB higher than modeled. At the South monitor, the maximum measured turbine-only sound level was 2 dB higher than modeled. Table 8 lists the shutdown identification number and the average power production of the closest turbine. These are the same periods that are graphically represented in Section 6.2.

TABLE 8: COMPARISON OF THE PRECONSTRUCTION MODELED L_{50} WITH THE MAXIMUM TURBINE-ONLY L_{50} CALCULATED FROM THE MEASUREMENTS

MONITOR NAME	SHUTDOWN ID	MEAN PRODUCTION (KW)	MEASURED BACK-GROUND L_{50}	MEASURED TOTAL L_{50}	BACK-GROUND CORRECTED TURBINE-ONLY L_{50}	MODELED TURBINE-ONLY L_{50}
North	14	1,850	30	50	50	45
Central	26	1,630	26	48	48	44
West	37	1,700	38	51	50	45
South	13	2,110	35	47	47	45

The largest factor contributing to the model underestimate is the selection of model parameters used prior to construction.[3] These specific parameters included a ground factor of G=0.5 and a receptor height of 1.5 meters, with no uncertainty factor added to the model results (G=0.5 + 0 dB, h=1.5 m). In other recent pre-construction studies that RSG has conducted in Minnesota for Xcel Energy, we have used a ground factor of G=0.7, a receptor height of 4 meters, and an uncertainty factor of +2 dB (G=0.7 + 2 dB, h=4 m). These modeling parameters have been shown to result in modeled sound levels that are more representative of the highest turbine-only L_{50}, and give results that are approximately 3 to 4 dB higher than G=0.5 + 0 dB, h=1.5.[16] While unusual turbine or weather factors may have also contributed to higher measured sound levels, further investigation would be required to identify these specific factors and their level of influence.

[15] Hankard Environmental, "Pre-Construction noise Analysis (V120 Turbine) for the proposed Freeborn Wind Farm," August 19, 2019 and as-built modeling by Xcel using the same parameters.
[16] Modeling has not been conducted for Freeborn Wind using G=0.7 + 2 dB, h=4 m.

7.0 CONCLUSIONS

The Freeborn Wind Project is subject to Minnesota Rules Chapter 7030, limiting noise from the Project. In conformance with the Project permit and in accordance with the Protocol, this post-construction noise assessment was completed to determine whether the as-built Project complies with those limits.

The conclusions of this assessment are as follows:

- Over the course of the two-week monitoring period, there was one one-hour period that was attributable to the project where total sound levels exceeded the nighttime sound level limit of 50 dBA. This was at the West monitor where the total sound level was 51 dBA and the turbine-only sound level was 50 dBA.
- The exceedance at the West monitor occurred during high wind shear, with ground gusts at 0 m/s and hub height wind speed at 10 m/s. The combination of no ground gust and winds at or over 10 m/s occurred approximately 4% of the monitoring period. This exceedance represents 2% of the discrete nighttime shutdowns at the West monitor.
- All other periods at the West monitor and all other monitoring locations had Total sound levels attributable to the Project at or below the noise limit.
- Under the Protocol, any location with Total sound over the limit attributable to the Project would undergo a “binning” analysis to determine Total and Turbine-only sound levels by wind speed. The highest Turbine-only sound level using this method was 46 dBA at the 8 m/s wind speed bin. There were no periods attributable to the Project that exceeded the sound limits using the binning method.
- The highest calculated Turbine-only sound levels at each monitor location were 2 to 5 dB greater than the turbine-only sound levels modeled during pre-construction. As discussed in Section 6.3, this is primarily due to the modeling parameters that were used in the Pre-Construction Study. Modeling parameters used in other projects RSG has conducted for Xcel projects in Minnesota use more conservative modeling parameters, which would yield sound levels that are more representative of the measured L_{50}.

APPENDIX A. ACOUSTICS PRIMER

Expressing Sound in Decibel Levels

The varying air pressure that constitutes sound can be characterized in many different ways. The human ear is the basis for the metrics that are used in acoustics. Normal human hearing is sensitive to sound fluctuations over an enormous range of pressures, from about 20 micropascals (the “threshold of audibility”) to about 20 pascals (the “threshold of pain”).[17] This factor of one million in sound pressure difference is challenging to convey in engineering units. Instead, sound pressure is converted to sound “levels” in units of “decibels” (dB, named after Alexander Graham Bell). Once a measured sound is converted to dB, it is denoted as a level with the letter “L”.

The conversion from sound pressure in pascals to sound level in dB is a four-step process. First, the sound wave’s measured amplitude is squared and the mean is taken. Second, a ratio is taken between the mean square sound pressure and the square of the threshold of audibility (20 micropascals). Third, using the logarithm function, the ratio is converted to factors of 10. The final result is multiplied by 10 to give the decibel level. By this decibel scale, sound levels range from 0 dB at the threshold of audibility to 120 dB at the threshold of pain.

Typical sound sources, and their sound pressure levels, are listed on the scale in Figure 34.

Human Response to Sound Levels: Apparent Loudness

For every 20 dB increase in sound level, the sound pressure increases by a *factor* of 10; the sound *level* range from 0 dB to 120 dB covers 6 factors of 10, or one million, in sound *pressure*. However, for an increase of 10 dB in sound *level* as measured by a meter, humans perceive an approximate doubling of apparent loudness: to the human ear, a sound level of 70 dB sounds about “twice as loud” as a sound level of 60 dB. Smaller changes in sound level, less than 3 dB up or down, are generally not perceptible.

[17] The pascal is a measure of pressure in the metric system. In Imperial units, they are themselves very small: one pascal is only 145 millionths of a pound per square inch (psi). The sound pressure at the threshold of audibility is only 3 one-billionths of one psi: at the threshold of pain, it is about 3 one-thousandths of one psi.

FIGURE 34: A SCALE OF SOUND PRESSURE LEVELS FOR TYPICAL SOUND SOURCES

Frequency Spectrum of Sound

The "frequency" of a sound is the rate at which it fluctuates in time, expressed in Hertz (Hz), or cycles per second. Very few sounds occur at only one frequency: most sound contains energy at many different frequencies, and it can be broken down into different frequency divisions, or bands. These bands are similar to musical pitches, from low tones to high tones. The most common division is the standard octave band. An octave is the range of frequencies whose upper frequency limit is twice its lower frequency limit, exactly like an octave in music. An octave band is identified by its center frequency: each successive band's center frequency is twice as high (one octave) as the previous band. For example, the 500 Hz octave band includes all sound whose frequencies range between 354 Hz (Hertz, or cycles per second) and 707 Hz. The next band is centered at 1,000 Hz with a range between 707 Hz and 1,414 Hz. The range of human hearing is divided into 10 standard octave bands: 31.5 Hz, 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1,000 Hz, 2,000 Hz, 4,000 Hz, 8,000 Hz, and 16,000 Hz. For analyses that require finer frequency detail, each octave-band can be subdivided. A commonly-used subdivision creates three smaller bands within each octave band, or so-called 1/3-octave bands.

Human Response to Frequency: Weighting of Sound Levels

The human ear is not equally sensitive to sounds of all frequencies. Sounds at some frequencies seem louder than others, despite having the same decibel level as measured by a sound level meter. In particular, human hearing is much more sensitive to medium pitches (from about 500 Hz to about 4,000 Hz) than to very low or very high pitches. For example, a tone measuring 80 dB at 500 Hz (a medium pitch) sounds quite a bit louder than a tone measuring 80 dB at 60 Hz (a very low pitch). The frequency response of normal human hearing ranges from 20 Hz to 20,000 Hz. Below 20 Hz, sound pressure fluctuations are not "heard", but sometimes can be "felt". This is known as "infrasound". Likewise, above 20,000 Hz, sound can no longer be heard by humans; this is known as "ultrasound". As humans age, they tend to lose the ability to hear higher frequencies first; many adults do not hear very well above about 16,000 Hz. Most natural and man-made sound occurs in the range from about 40 Hz to about 4,000 Hz. Some insects and birdsongs reach to about 8,000 Hz.

To adjust measured sound pressure levels so that they mimic human hearing response, sound level meters apply filters, known as "frequency weightings", to the signals. There are several defined weighting scales, including "A", "B", "C", "D", "G", and "Z". The most common weighting scale used in environmental noise analysis and regulation is A-weighting. This weighting represents the sensitivity of the human ear to sounds of low to moderate level. It attenuates sounds with frequencies below 1000 Hz and above 4000 Hz; it amplifies very slightly sounds between 1000 Hz and 4000 Hz, where the human ear is particularly sensitive. The C-weighting scale is sometimes used to describe louder sounds. The B- and D- scales are seldom used. All of these frequency weighting scales are normalized to the average human hearing response at 1000 Hz: at this frequency, the filters neither attenuate nor amplify. G-weighting is a standardized weighting used to evaluate infrasound.

When a reported sound level has been filtered using a frequency weighting, the letter is appended to “dB”. For example, sound with A-weighting is usually denoted “dBA”. When no filtering is applied, the level is denoted “dB” or “dBZ”. The letter is also appended as a subscript to the level indicator “L”, for example “L_A” for A-weighted levels.

Time Response of Sound Level Meters

Because sound levels can vary greatly from one moment to the next, the time over which sound is measured can influence the value of the levels reported. Often, sound is measured in real time, as it fluctuates. In this case, acousticians apply a so-called “time response” to the sound level meter, and this time response is often part of regulations for measuring sound. If the sound level is varying slowly, over a few seconds, “Slow” time response is applied, with a time constant of one second. If the sound level is varying quickly (for example, if brief events are mixed into the overall sound), “Fast” time response can be applied, with a time constant of one-eighth of a second.[18] The time response setting for a sound level measurement is indicated with the subscript “S” for Slow and “F” for Fast: L_S or L_F. A sound level meter set to Fast time response will indicate higher sound levels than one set to Slow time response when brief events are mixed into the overall sound, because it can respond more quickly.

In some cases, the maximum sound level that can be generated by a source is of concern. Likewise, the minimum sound level occurring during a monitoring period may be required. To measure these, the sound level meter can be set to capture and hold the highest and lowest levels measured during a given monitoring period. This is represented by the subscript “max”, denoted as “L_{max}”. One can define a “max” level with Fast response L_{Fmax} (1/8-second time constant), Slow time response L_{Smax} (1-second time constant), or Continuous Equivalent level over a specified time period $L_{eq\ max}$.

Accounting for Changes in Sound Over Time

A sound level meter’s time response settings are useful for continuous monitoring. However, they are less useful in summarizing sound levels over longer periods. To do so, acousticians apply simple statistics to the measured sound levels, resulting in a set of defined types of sound level related to averages over time. An example is shown in Figure 35. The sound level at each instant of time is the grey trace going from left to right. Over the total time it was measured (1 hour in the figure), the sound energy spends certain fractions of time near various levels, ranging from the minimum (about 27 dB in the figure) to the maximum (about 65 dB in the figure). The simplest descriptor is the average sound level, known as the Equivalent Continuous Sound Level. Statistical levels are used to determine for what percentage of time the sound is louder than any given level. These levels are described in the following sections.

[18] There is a third time response defined by standards, the “Impulse” response. This response was defined to enable use of older, analog meters when measuring very brief sounds; it is no longer in common use.

Equivalent Continuous Sound Level - L_{eq}

One straightforward, common way of describing sound levels is in terms of the Continuous Equivalent Sound Level, or L_{eq}. The L_{eq} is the average sound pressure level over a defined period of time, such as one hour or one day. L_{eq} is the most commonly used descriptor in noise standards and regulations. L_{eq} is representative of the overall sound to which a person is exposed. Because of the logarithmic calculation of decibels, L_{eq} tends to favor higher sound levels: loud and infrequent sources have a larger impact on the resulting average sound level than quieter but more frequent sounds. For example, in Figure 35, even though the sound levels spends most of the time near about 34 dBA, the L_{eq} is 41 dBA, having been “inflated” by the maximum level of 65 dBA and other occasional spikes over the course of the hour.

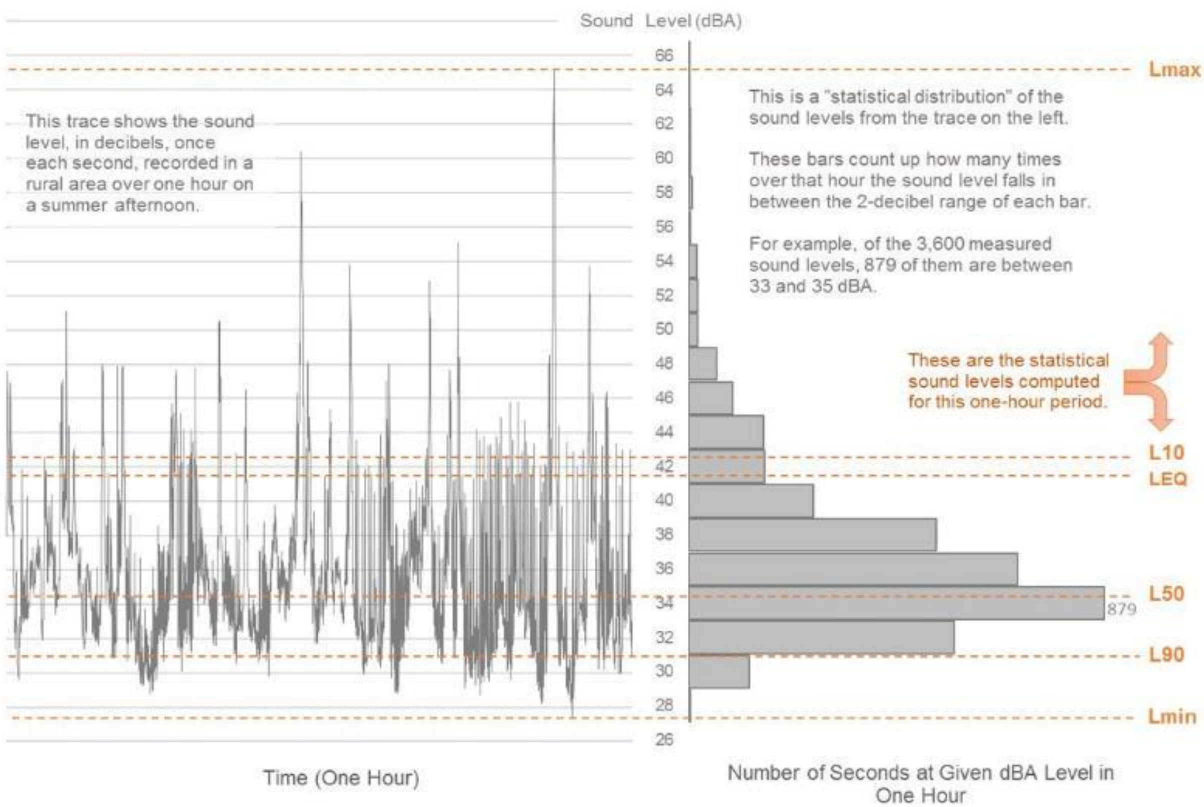

FIGURE 35: EXAMPLE OF DESCRIPTIVE TERMS OF SOUND MEASUREMENT OVER TIME

Percentile Sound Levels – Ln

Percentile sound levels describe the statistical distribution of sound levels over time. “L_N” is the level above which the sound spends “N” percent of the time. For example, L_{90} (sometimes called the “residual base level”) is the sound level exceeded 90% of the time: the sound is louder than L_{90} most of the time. L_{10} is the sound level that is exceeded only 10% of the time. (the “median level”) is exceeded 50% of the time: half of the time the sound is louder than , and half the time it is quieter than . Note that (median) and L_{eq} (mean) are not always the same, for reasons described in the previous section.

L_{90} is often a good representation of the “ambient sound” in an area. This is the sound that persists for longer periods, and below which the overall sound level seldom falls. It tends to filter out other short-term environmental sounds that aren’t part of the source being investigated. L_{10} represents the higher, but less frequent, sound levels. These could include such events as barking dogs, vehicles driving by and aircraft flying overhead, gusts of wind, and work operations. L_{90} represents the background sound that is present when these event sounds are excluded.

Note that if one sound source is very constant and dominates the soundscape in an area, all of the descriptive sound levels mentioned here tend toward the same value. It is when the sound is varying widely from one moment to the next that the statistical descriptors are useful.

APPENDIX B. WIND TURBINE NOISE

Sources of Sound Generation by Wind Turbines

Wind turbines generate two principal types of noise: aerodynamic noise, produced from the flow of air around the blades, and mechanical noise, produced from mechanical and electrical components within the nacelle.

Aerodynamic noise is the primary source of noise associated with wind turbines. These acoustic emissions can be either tonal or broad band. Tonal noise occurs at discrete frequencies, whereas broadband noise is distributed with little peaking across the frequency spectrum.

While unusual, tonal noise can also originate from unstable air flows over holes, slits, or blunt trailing edges on blades. Most modern wind turbines have upwind rotors designed to prevent blade impulsive noise. Therefore, the majority of audible aerodynamic noise from wind turbines is broadband at the middle frequencies, roughly between 200 Hz and 1,000 Hz.

Wind turbines emit aerodynamic broadband noise as the spinning blades interact with atmospheric turbulence and as air flows along their surfaces. This produces a characteristic “whooshing” sound through several mechanisms (Figure 36):

- Inflow turbulence noise occurs when the rotor blades encounter atmospheric turbulence as they pass through the air. Uneven pressure on a rotor blade causes variations in the local angle of attack, which affects the lift and drag forces, causing aerodynamic loading fluctuations. This generates noise that varies across a wide range of frequencies but is most significant at frequencies below 500 Hz.
- Trailing edge noise is produced as boundary-layer turbulence as the air passes into the wake, or trailing edge, of the blade. This noise is distributed across a wide frequency range but is most notable at high frequencies between 700 Hz and 2 kHz.
- Tip vortex noise occurs when tip turbulence interacts with the surface of the blade tip. While this is audible near the turbine, it tends to be a small component of the overall noise further away.
- Stall or separation noise occurs due to the interaction of turbulence with the blade surface.

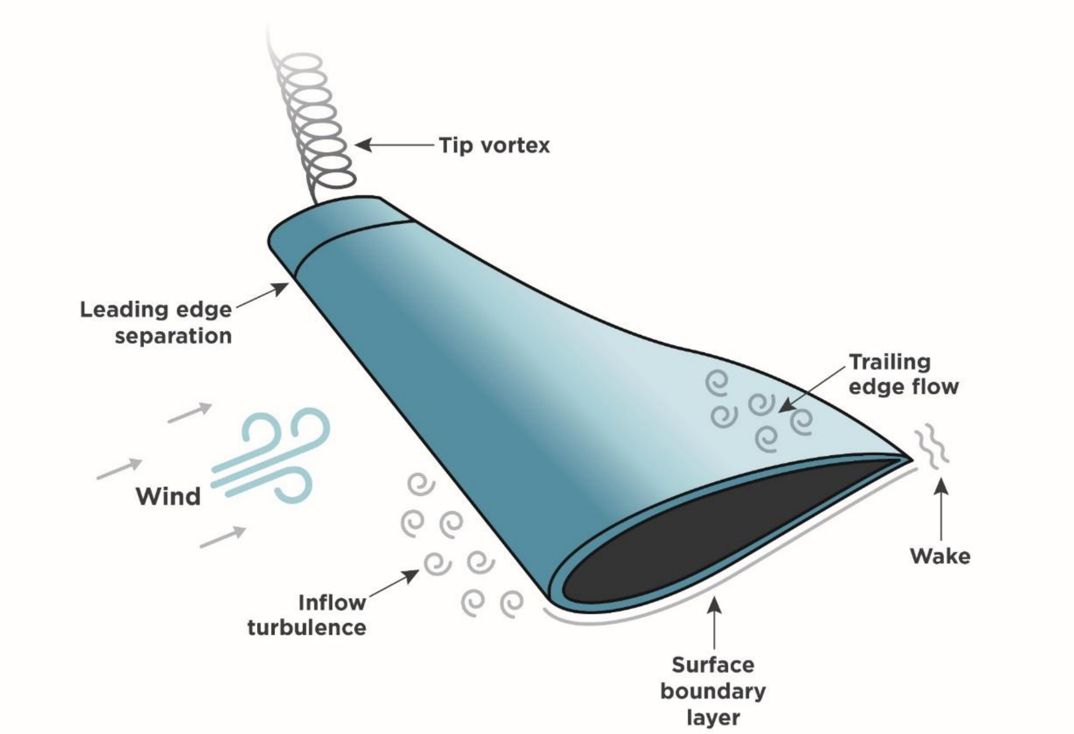

FIGURE 36: AIRFLOW AROUND A ROTOR BLADE

Mechanical sound from machinery inside the nacelle tends to be tonal in nature but can also have a broadband component. Potential sources of mechanical noise include the gearbox, generator, yaw drives, cooling fans, and auxiliary equipment. These components are housed within the nacelle, whose surfaces, if untreated, radiate the resulting noise. However modern wind turbines have nacelles that are designed to reduce internal noise, and rarely is the mechanical noise a significant portion of the total noise from a wind turbine.

Amplitude Modulation

Amplitude modulation (AM) is a fluctuation in sound level that occurs at the blade passage frequency. No consistent definition exists for how much of a sound level fluctuation is necessary for blade swish to be considered AM, however sound level fluctuations in A-weighted sound level can range up to 10 dB. Fluctuations in individual 1/3 octave bands are typically more and can exceed 15 dB. Fluctuations in individual 1/3 octave bands can sometimes synchronize and desynchronize over periods, leading to increases and decreases in magnitude of the A-weighted fluctuations. Similarly, in wind farms with multiple turbines, fluctuations can synchronize and desynchronize, leading to variations in AM depth.[19] Most amplitude modulation is in the mid frequencies and most overall A-weighted AM is less than 4.5 dB in depth.[20]

Many confirmed and hypothesized causes of AM exist, including: blade passage in front of the tower, blade tip sound emission directivity, wind shear, inflow turbulence, and turbine blade yaw error. It has recently been noted that although wind shear can contribute to the extent of AM, wind shear does not contribute to the existence of AM in and of itself. Instead, there needs to be detachment of airflow from the blades for wind shear to contribute to AM.[21] While factors like the blade passing in front of the tower are intrinsic to wind turbine design, other factors vary with turbine design, local meteorology, topography, and turbine layout. Mountainous areas, for example, are more likely to have turbulent airflow, less likely to have high wind shear, and less likely to have turbine layouts that allow for blade passage synchronization for multiple turbines. AM extent varies with the relative location of a receiver to the turbine. AM is usually experienced most when the receiver is between 45 and 60 degrees from the downwind or upwind position and is experienced least directly with the receiver directly upwind or downwind of the turbines.

Meteorology

Meteorological conditions can significantly affect sound propagation. The two most important conditions to consider are wind shear and temperature lapse. Wind shear is the difference in wind speeds by elevation and temperature lapse rate is the temperature gradient by elevation. In conditions with high wind shear (large wind speed gradient), sound levels upwind from the source tend to decrease and sound levels downwind tend to increase due to the refraction, or bending, of the sound (Figure 37).

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[19] McCunney, Robert, et al. “Wind Turbines and Health: A Critical Review of the Scientific Literature.” *Journal of Occupational and Environmental Medicine.* 56(11) November 2014: pp. e108-e130.
[20] RSG, et al., “Massachusetts Study on Wind Turbine Acoustics,” Massachusetts Clean Energy Center and Massachusetts Department of Environmental Protection, 2016
[21] “Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause and Effect.” *RenewableUK.* December 2013.

With temperature lapse, when ground surface temperatures are higher than those aloft, sound will tend to refract upwards, leading to lower sound levels near the ground. The opposite is true when ground temperatures are lower than those aloft (an inversion condition).

High winds and high solar radiation can create turbulence which tends to break up and dissipate sound energy. Highly stable atmospheres, which tend to occur on clear nights with low ground-level wind speeds, tend to minimize atmospheric turbulence and are generally more favorable to downwind propagation.

In general terms, sound propagates along the ground best under stable conditions with a strong temperature inversion. This tends to occur during the night and is characterized by low ground-level winds. As a result, worst-case conditions for wind turbines tend to occur downwind under moderate nighttime temperature inversions. Therefore, this is the default condition for modeling wind turbine sound.

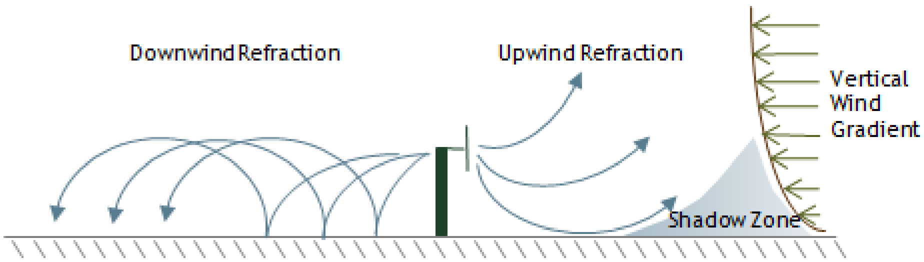

FIGURE 37: SCHEMATIC OF THE REFRACTION OF SOUND DUE TO VERTICAL WIND GRADIENT (WIND SHEAR)

Masking

As mentioned above, sound levels from wind turbines are a function of wind speed. Background sound is also a function of wind speed, i.e., the stronger the winds, the louder the resulting background sound. This effect is amplified in areas covered by trees and other vegetation.

The sound from a wind turbine can often be masked by wind noise at downwind receivers because the frequency spectrum from wind is similar to the frequency spectrum from a wind turbine. Figure 38 compares the shape of the sound spectrum measured during a 5 m/s wind event to that of the Vestas V120-STE wind turbine. As shown, the shapes of the spectra are similar at lower frequencies. At higher frequencies, the sounds from the masking wind noise are higher than the wind turbine. As a result, the masking of turbine noise occurs at higher wind speeds for some meteorological conditions. Masking will occur most, when ground wind speeds are relatively high, creating wind-caused noise such as wind blowing through the trees and interaction of wind with structures.

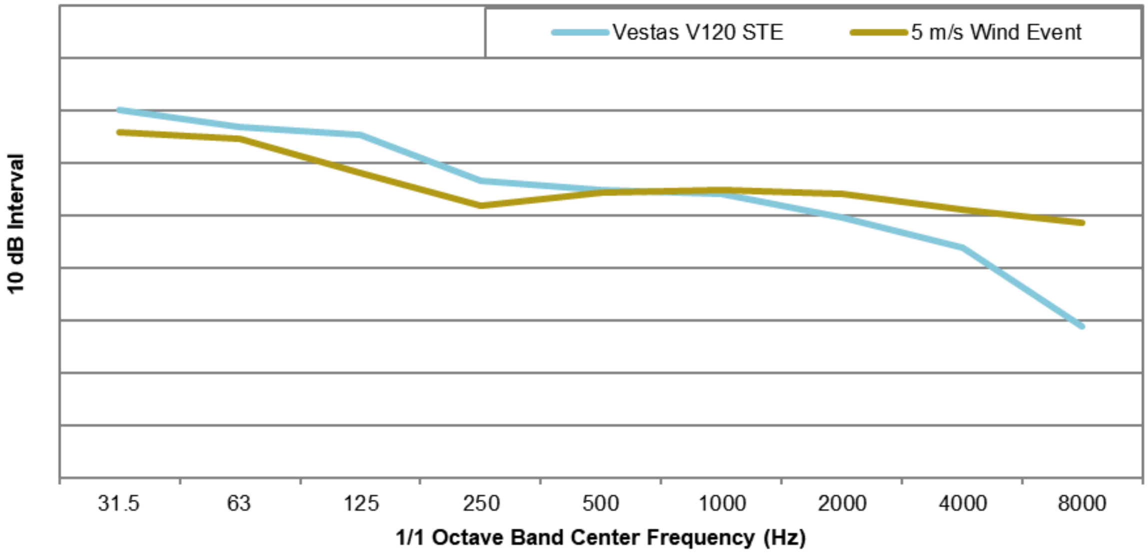

FIGURE 38: COMPARISON OF NORMALIZED FREQUENCY SPECTRA MEASURED FROM THE WIND AND VESTAS V120 STE[22]

It is important to note that while winds may be blowing at turbine height, there may be little to no wind at ground level. This is especially true during strong wind gradients (high wind shear), which mostly occur at night. This can also occur on the leeward side of ridges where the ridge blocks the wind.

[22] The purpose of this Figure is to show the shapes to two spectra relative to one another and not the actual sound level of the two sources of sound. The level of each source was normalized independently.

APPENDIX C. COMPLETE TIME HISTORY PLOTS

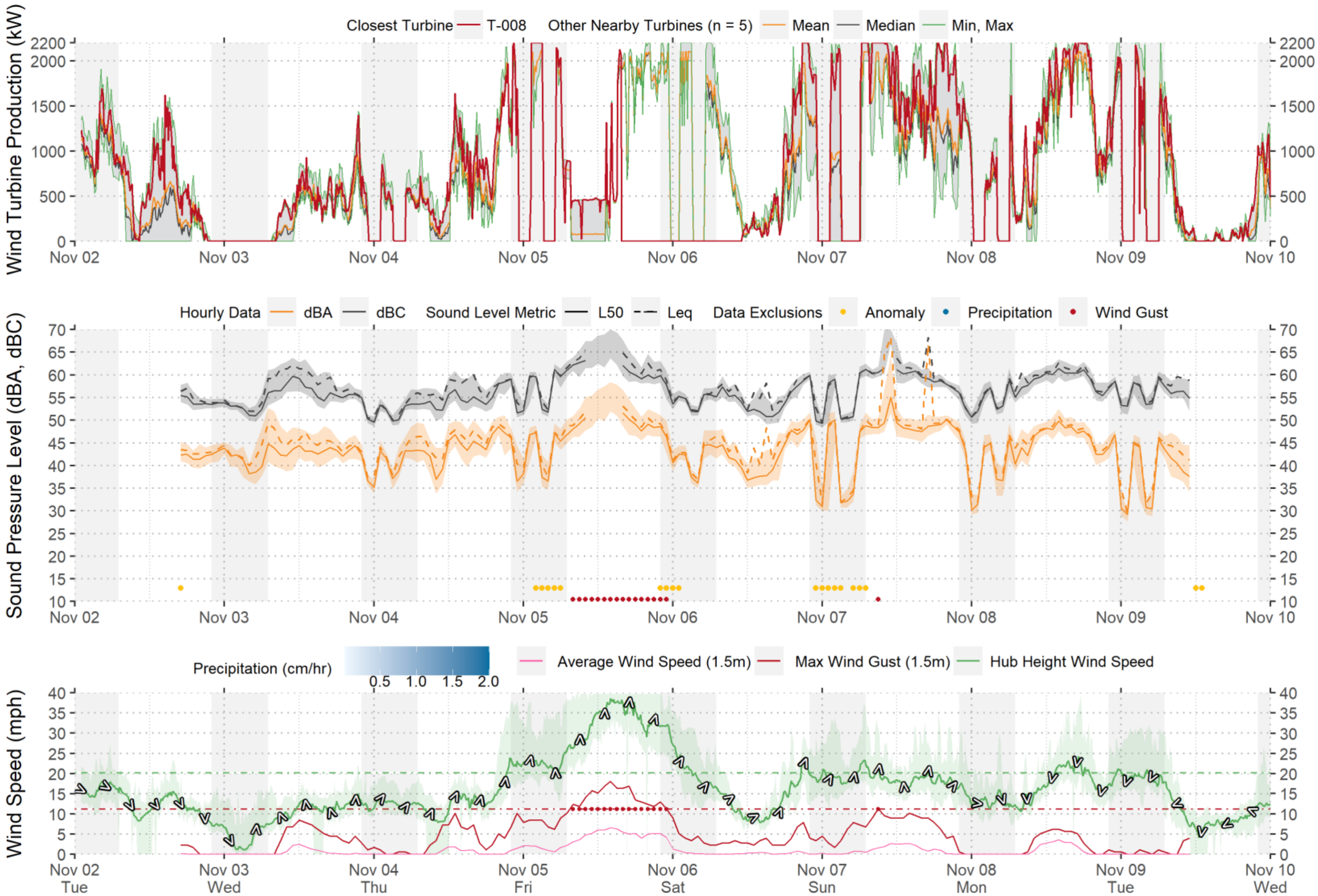

FIGURE 39: NORTH MONITOR, WEEK 1, COMPLETE TIME HISTORY PLOT

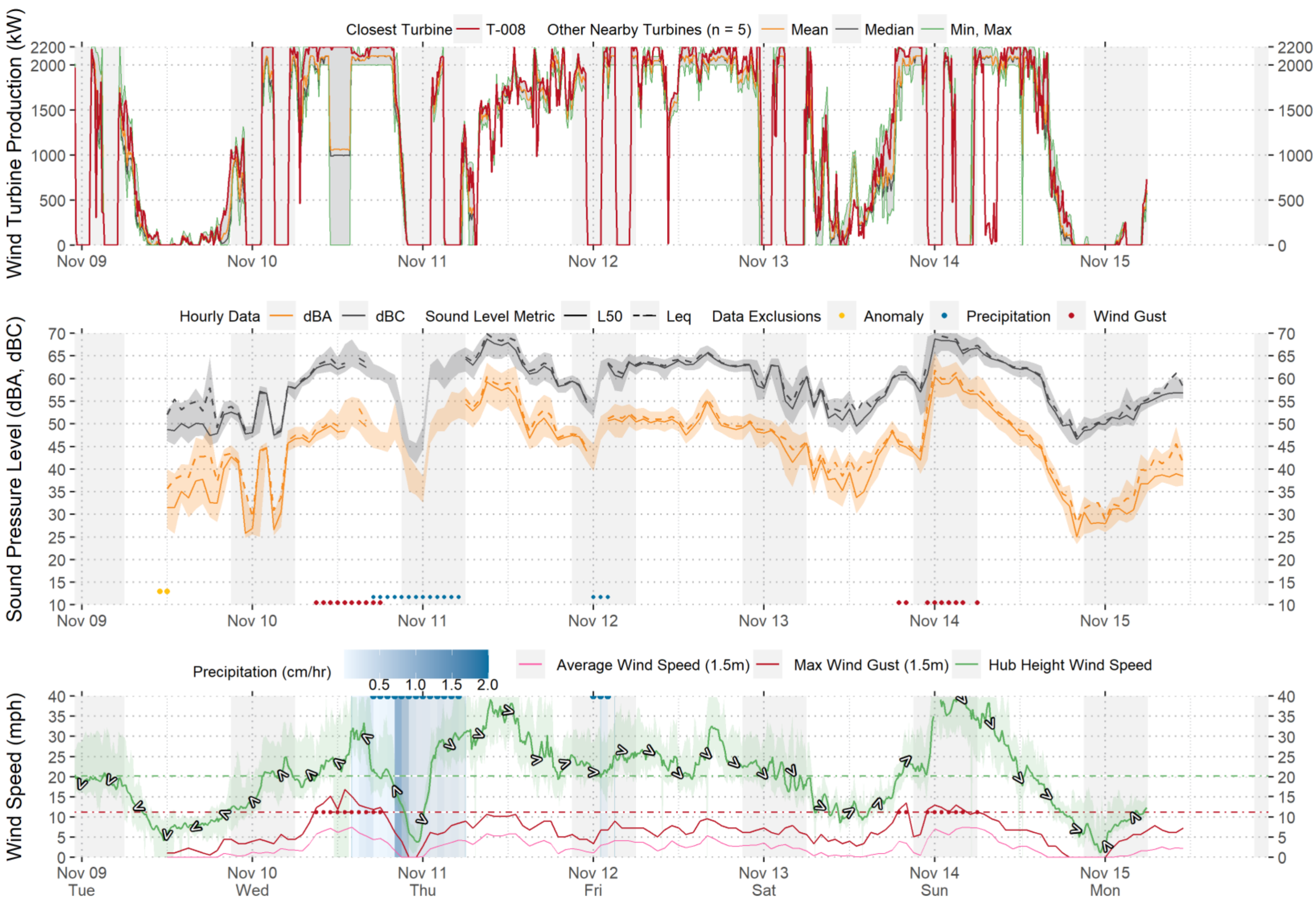

FIGURE 40: NORTH MONITOR, WEEK 2, COMPLETE TIME HISTORY PLOT

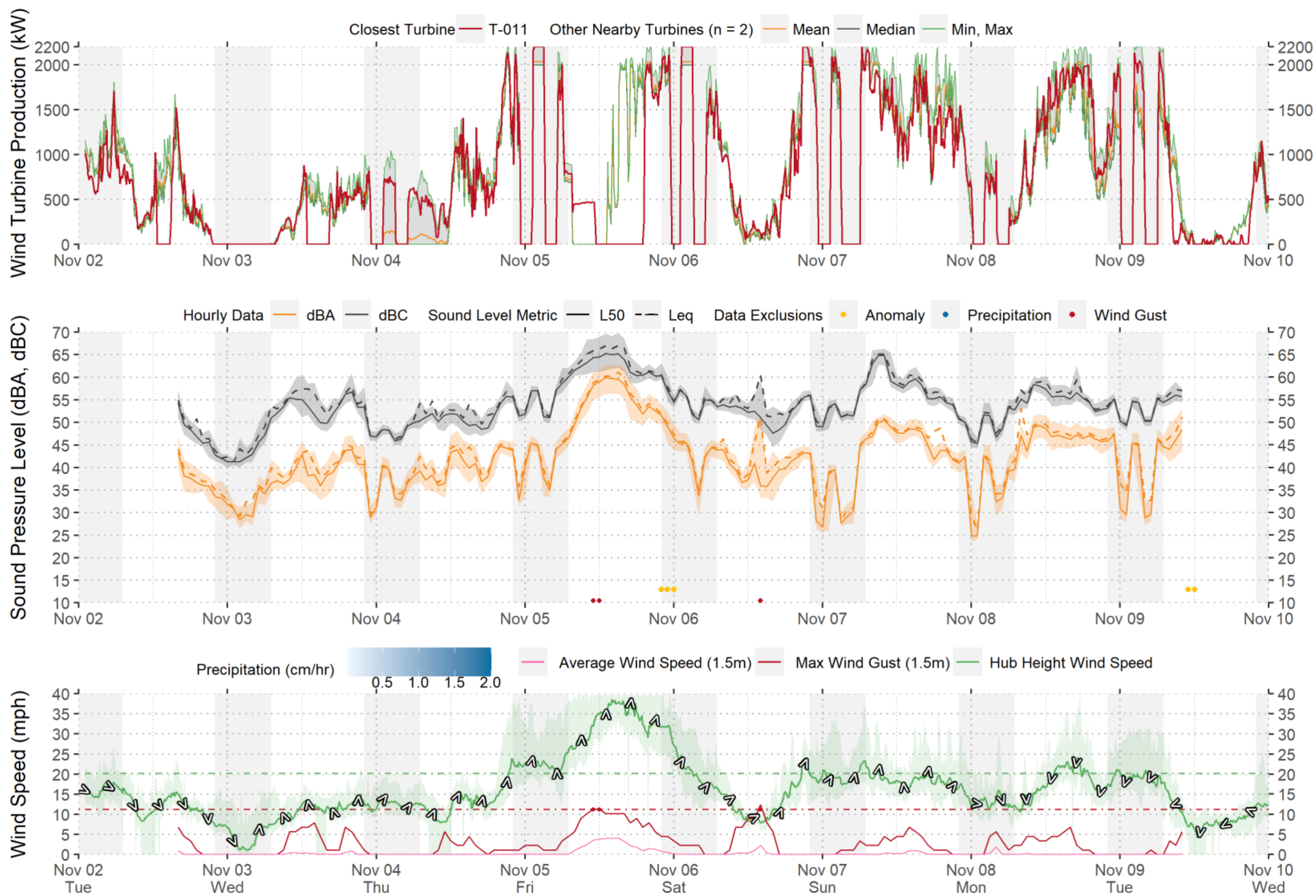

FIGURE 41: CENTRAL MONITOR, WEEK 1, COMPLETE TIME HISTORY PLOT

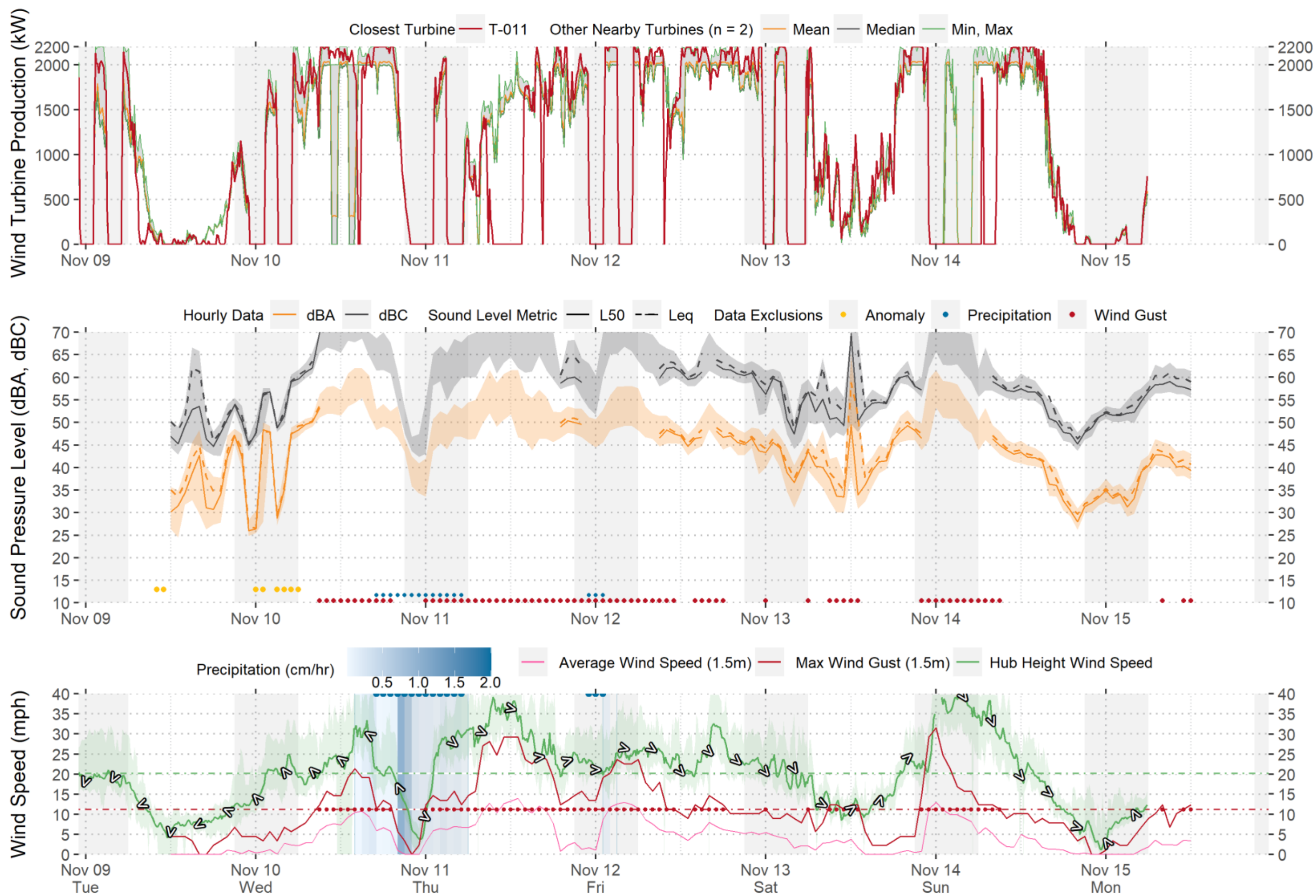

FIGURE 42: CENTRAL MONITOR, WEEK 2, COMPLETE TIME HISTORY PLOT

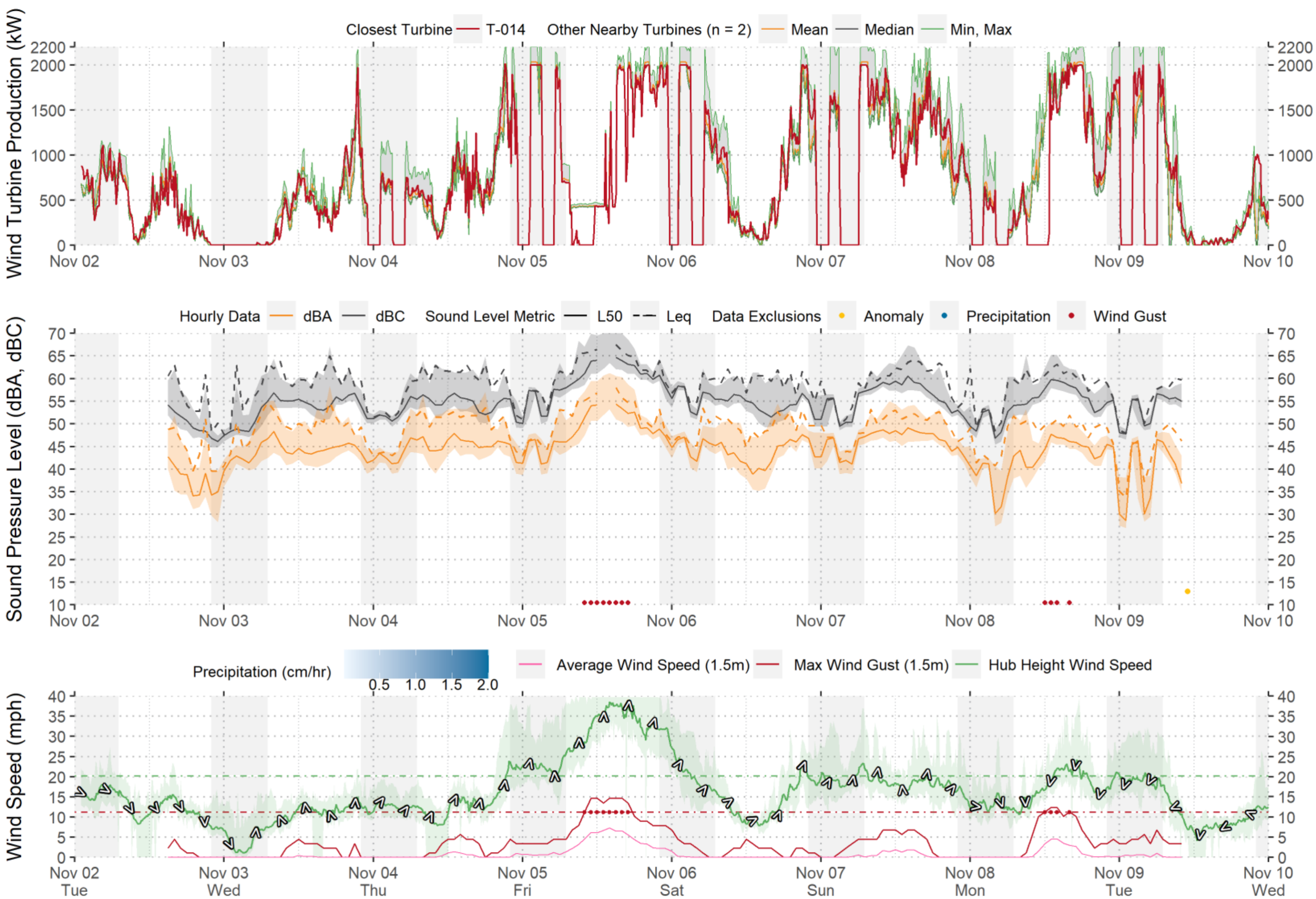

FIGURE 43: WEST MONITOR H17, WEEK 1, COMPLETE TIME HISTORY PLOT

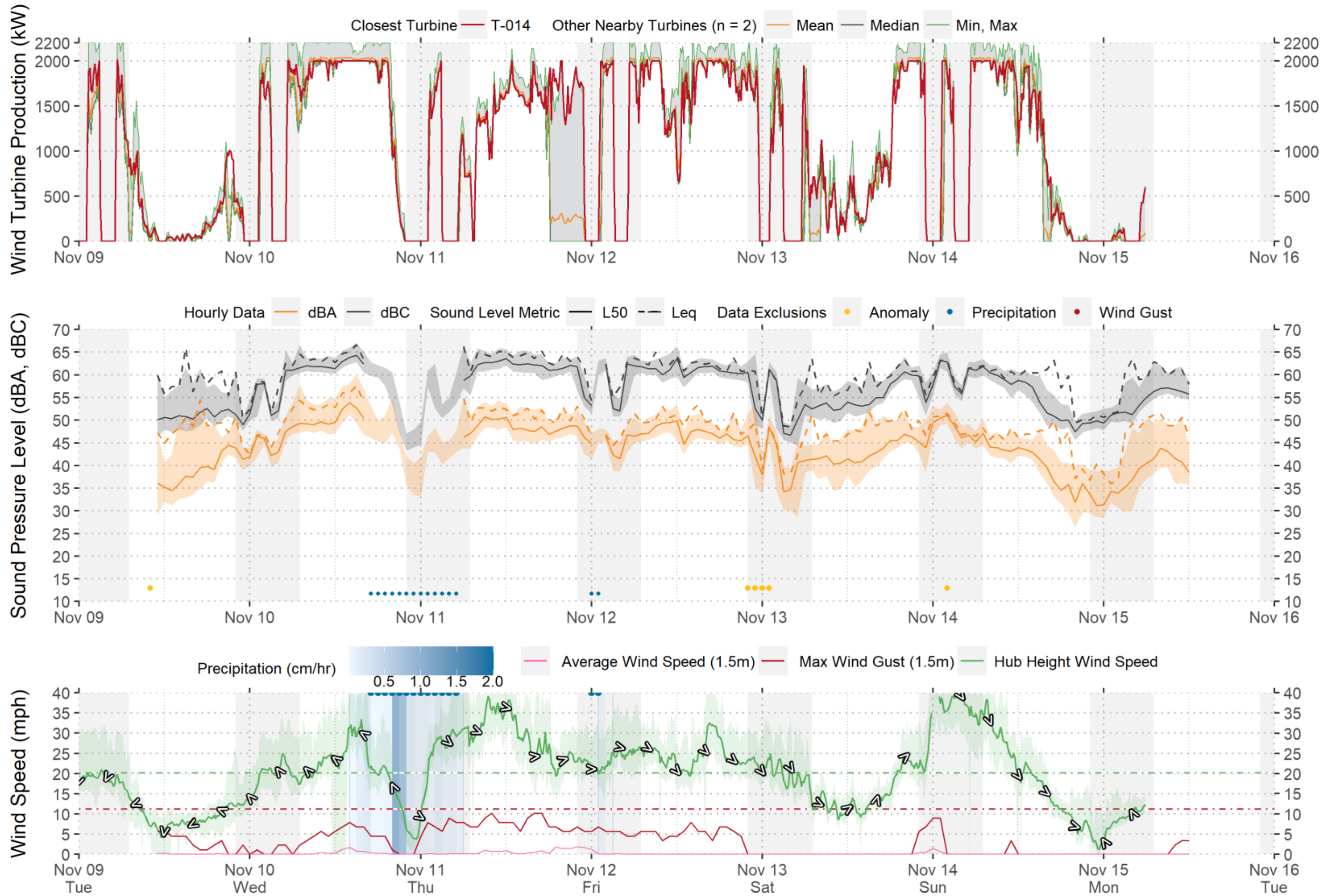

FIGURE 44: WEST MONITOR, WEEK 2, COMPLETE TIME HISTORY PLOT

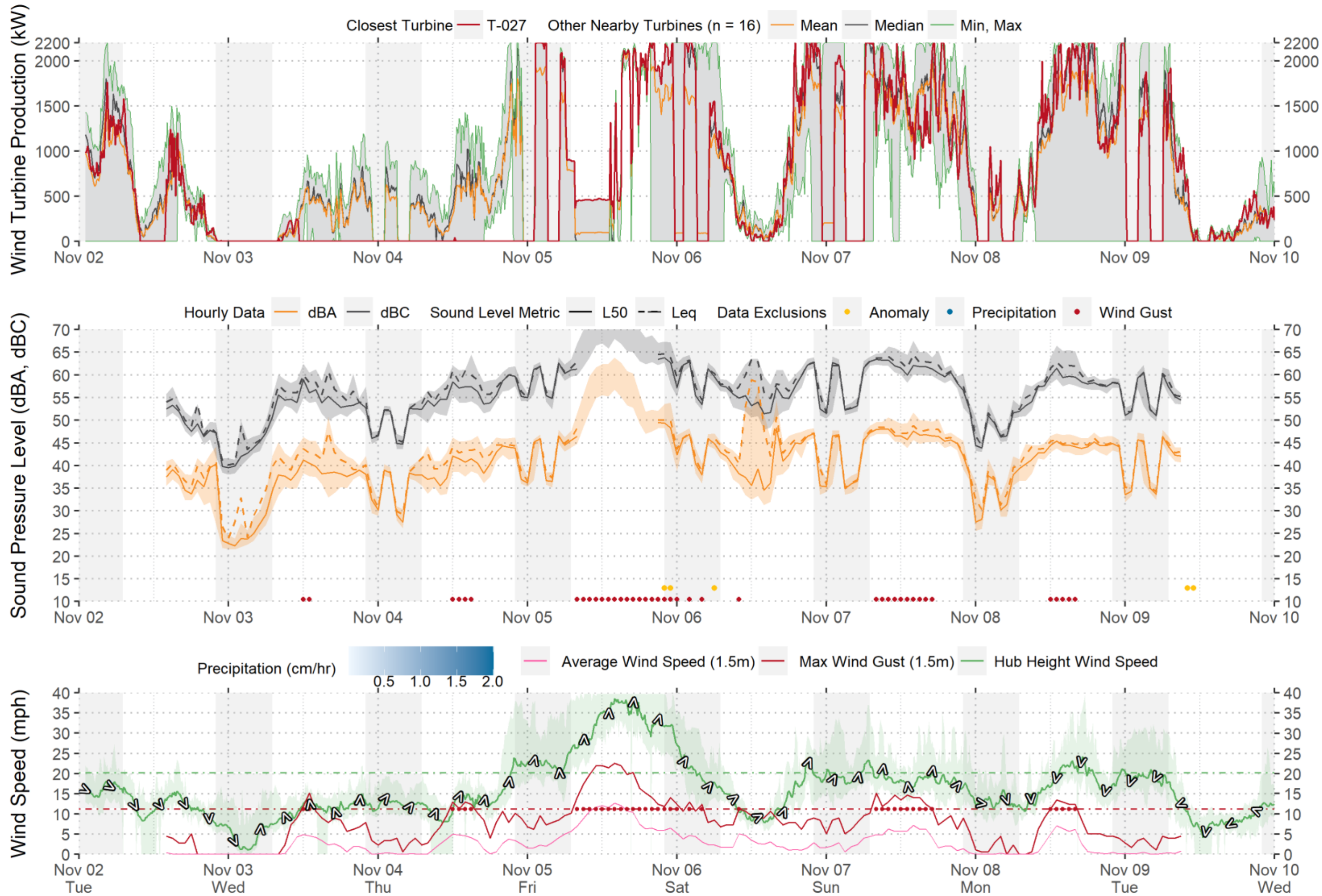

FIGURE 45: SOUTH MONITOR, WEEK 1, COMPLETE TIME HISTORY PLOT

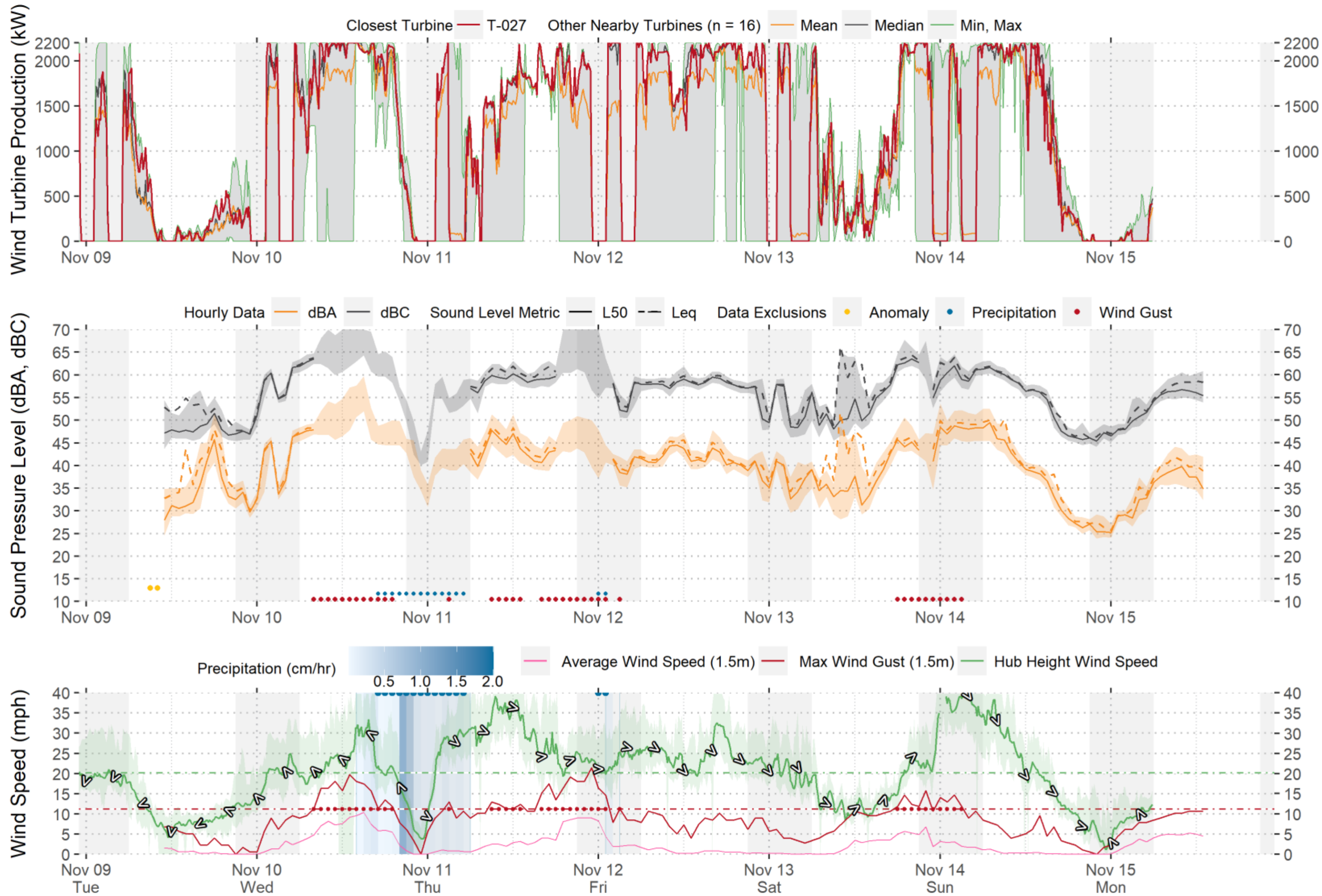

FIGURE 46: SOUTH MONITOR, WEEK 2, COMPLETE TIME HISTORY PLOT

APPENDIX D. SHUTDOWN ANALYSIS RESULTS

The following tables show the valid shutdowns for each monitor. Shutdowns without valid sound levels are not included.

Turbine-only sound levels were calculated on a 1/3 octave band basis, then A-weighted and summed, as noted in Section 6.1, following the procedures of ANSI S12.9 Part 3 Section 6.9. Where turbine-only sound levels are below background (at all 1/3 octaves), “n/a” is indicated.

Note that all times prior to midday on November 9 are in GMT-5 (first monitoring period), while all times after midday on November 9 are in GMT-6 (monitoring period 2). Local time was discontinuous due to daylight savings on November 7 at 2 AM local (Central) time.

TABLE 9: NORTH MONITOR SHUTDOWN RESULTS

SD#	Date & Time	Sound Pressure Level (L_{50}, dBA)			1.5-Meter Mean Wind Speed (m/s)	Hub Height Wind		Production of Closest Turbine (kW)
		Background	Total Sound	Turbine-Only		Mean Speed (m/s)	Mean Direction (deg)	
1	11/03 23:10	35	42	41	0	5	178	512
2	11/04 00:00	33	42	42	0	6	214	631
3	11/04 03:10	36	41	40	0	6	218	462
4	11/04 04:00	37	43	41	0	5	217	550
5	11/04 23:20	36	46	46	1	10	185	1665
6	11/05 00:00	38	47	46	1	10	194	2200
7	11/05 03:20	37	47	47	1	10	193	2200
8	11/05 04:00	37	47	46	0	10	180	1770
9[23]	11/05 23:40	42	49	48	2	13	195	-13
10	11/06 00:00	41	42	35	0	11	212	-13
11	11/06 03:20	37	42	41	0	9	213	-13
12	11/06 04:00	36	44	43	0	8	217	-13
13[23]	11/06 23:20	31	50	50	0	9	198	1848
14[23]	11/07 00:10	31	50	50	0	9	212	1898
15[23]	11/07 03:10	31	50	50	0	8	211	1933
16[23]	11/07 05:00	34	47	47	0	10	185	2200
17	11/08 00:20	30	43	43	0	6	231	1177
18	11/08 01:00	31	44	44	0	6	274	653
19	11/08 04:10	37	45	44	0	6	283	827
20	11/08 05:00	36	44	43	0	5	349	831
21	11/09 00:20	29	47	47	0	9	11	1915
22	11/09 01:00	29	45	45	0	9	21	1632

[23] Anomalous anthropogenic sources evaluated and excluded

SD#	Date & Time	Sound Pressure Level (L_{50}, dBA)			1.5-Meter Mean Wind Speed (m/s)	Hub Height Wind		Production of Closest Turbine (kW)
		Background	Total Sound	Turbine-Only		Mean Speed (m/s)	Mean Direction (deg)	
23	11/09 04:10	30	44	44	0	9	23	1246
24	11/09 05:00	30	45	45	0	8	24	1511
25	11/09 23:10	26	41	41	0	6	122	864
26	11/10 00:05	26	44	44	1	8	135	2196
27	11/10 03:10	27	45	45	1	9	137	2199
28	11/10 04:00	30	46	46	1	10	143	2141
33	11/11 23:10	44	47	44	1	10	252	1973
35	11/12 03:20	51	51	24	2	11	280	2139
36	11/12 04:00	51	52	26	2	11	283	2120
37	11/12 23:35	47	50	44	1	10	310	2043
38	11/13 00:00	48	48	n/a	1	10	319	1772
39	11/13 03:00	44	47	42	1	9	323	2143
40	11/13 04:30	42	46	43	1	8	324	1717
41	11/13 23:00	51	42	n/a	1	12	223	2073
42	11/14 00:00	60	58	n/a	3	17	297	2025
43	11/14 03:00	60	58	n/a	3	17	301	1641
44	11/14 04:00	57	56	n/a	3	16	324	1632

TABLE 10: CENTRAL MONITOR SHUTDOWN RESULTS

SD#	Date & Time	Sound Pressure Level (L_{50}, dBA)			1.5-Meter Mean Wind Speed (m/s)	Hub Height Wind		Production of Closest Turbine (kW)
		Background	Total Sound	Turbine-Only		Mean Speed (m/s)	Mean Direction (deg)	
1	11/03 23:10	29	41	40	0	5	178	624
2	11/04 00:00	31	40	40	0	6	214	709
3	11/04 03:10	33	40	39	0	6	218	696
4	11/04 04:00	33	37	34	0	5	217	590
5	11/04 23:20	33	44	43	0	10	185	1574
6	11/05 00:00	40	45	43	0	10	194	2194
7	11/05 03:20	38	45	44	0	10	193	2200
8	11/05 04:00	35	44	44	0	10	180	1554
9[24]	11/05 23:40	47	51	49	0	13	195	2021
10	11/06 00:00	47	45	11	0	11	212	2170
11	11/06 03:20	38	46	45	0	9	213	2200
12	11/06 04:00	33	43	42	0	8	217	1511
13	11/06 23:20	27	43	43	0	9	198	1837
14	11/07 00:10	26	39	39	0	9	212	1990
15	11/07 03:10	27	40	39	0	8	211	1926
16	11/07 05:00	30	45	45	0	10	185	2081
17	11/08 00:20	25	42	42	0	6	231	751
18	11/08 01:00	25	43	43	0	6	274	673
19	11/08 04:10	32	40	40	0	6	283	702
20	11/08 05:00	33	39	38	0	5	349	281
21	11/09 00:20	30	47	47	0	9	11	1852
22	11/09 01:00	29	45	45	0	9	21	2019
23	11/09 04:10	28	45	45	0	9	23	1915
24	11/09 05:00	29	46	46	0	8	24	1807
25	11/09 23:10	26	42	42	0	6	122	660
26[24]	11/10 00:05	26	48	48	0	8	135	1627
27[24]	11/10 03:10	29	48	48	0	9	137	1673
28[24]	11/10 04:00	35	48	47	1	10	143	1849
37	11/12 23:35	42	47	45	2	10	310	2040
38	11/13 00:00	43	45	38	2	10	319	1905
39	11/13 03:00	39	44	43	2	9	323	2187
40	11/13 04:30	37	43	42	1	8	324	1876

[24] Anomalous anthropogenic sources evaluated and excluded

TABLE 11: WEST MONITOR SHUTDOWN RESULTS

SD#	Date & Time	Sound Pressure Level (L_{50}, dBA)			1.5-Meter Mean Wind Speed (m/s)	Hub Height Wind		Production of Closest Turbine (kW)
		Background	Total Sound	Turbine-Only		Mean Speed (m/s)	Mean Direction (deg)	
1	11/03 23:10	41	43	36	0	5	178	676
2	11/04 00:00	42	43	32	0	6	214	695
3	11/04 03:10	41	42	32	0	6	218	684
4	11/04 04:00	41	44	41	0	5	217	621
5	11/04 23:20	40	45	44	0	10	185	1433
6	11/05 00:00	41	46	45	0	10	194	2000
7	11/05 03:20	41	47	45	0	10	193	2000
8	11/05 04:00	41	46	44	0	10	180	1581
9	11/05 23:40	46	49	46	1	13	195	1893
10	11/06 00:00	45	46	22	0	11	212	1977
11	11/06 03:20	42	47	45	0	9	213	1982
12	11/06 04:00	41	47	45	0	8	217	1413
13	11/06 23:20	42	47	45	0	9	198	1515
14	11/07 00:10	42	47	45	0	9	212	1601
15	11/07 03:10	41	47	46	0	8	211	1577
16	11/07 05:00	41	46	45	0	10	185	2000
17	11/08 00:20	40	43	34	0	6	231	768
18	11/08 01:00	38	41	37	0	6	274	484
19	11/08 04:10	30	41	41	0	6	283	457
20	11/08 05:00	30	39	38	0	5	349	236
21	11/09 00:20	29	45	45	0	9	11	1779
22	11/09 01:00	28	46	46	0	9	21	1829
23	11/09 04:10	29	46	46	0	9	23	1848
24	11/09 05:00	32	47	46	0	8	24	1709
25	11/09 23:10	41	44	38	0	6	122	379
26	11/10 00:05	41	46	45	0	8	135	1684
27	11/10 03:10	42	46	44	0	9	137	1675
28	11/10 04:00	43	48	46	0	10	143	1915
33	11/11 23:10	46	49	44	1	10	252	1773
34	11/12 00:00	45	46	41	0	10	273	1936
35	11/12 03:20	41	47	45	0	11	280	1939
36	11/12 04:00	41	47	45	0	11	283	1902
37[25]	11/12 23:35	38	51	50	0	10	310	1704
38[25]	11/13 00:00	37	48	47	0	10	319	1409
39	11/13 03:00	34	45	45	0	9	323	1636

[25] Anomalous anthropogenic sources evaluated and excluded

SD#	Date & Time	Sound Pressure Level (L_{50}, dBA)			1.5-Meter Mean Wind Speed (m/s)	Hub Height Wind		Production of Closest Turbine (kW)
		Background	Total Sound	Turbine-Only		Mean Speed (m/s)	Mean Direction (deg)	
40	11/13 04:30	31	42	42	0	8	324	1165
41	11/13 23:00	44	45	34	0	12	223	1854
42	11/14 00:00	49	51	37	0	17	297	1921
43[25]	11/14 03:00	49	51	41	0	17	301	1698
44	11/14 04:00	46	46	31	0	16	324	1983

TABLE 12: SOUTH MONITOR SHUTDOWN RESULTS

SD#	Date & Time	Sound Pressure Level (L_{50}, dBA)			1.5-Meter Mean Wind Speed (m/s)	Hub Height Wind		Production of Closest Turbine (kW)
		Background	Total Sound	Turbine-Only		Mean Speed (m/s)	Mean Direction (deg)	
1	11/03 23:10	31	38	37	0	5	178	-22
2	11/04 00:00	30	39	38	0	6	214	-22
3	11/04 03:10	29	38	38	0	6	218	-22
4	11/04 04:00	27	38	38	0	5	217	-22
5	11/04 23:20	36	44	43	1	10	185	-17
6	11/05 00:00	36	45	45	1	10	194	2199
7	11/05 03:20	37	46	45	1	10	193	2189
8	11/05 04:00	36	46	45	2	10	180	1754
9[26]	11/05 23:40	45	50	48	3	13	195	2086
10	11/06 00:00	42	46	43	2	11	212	2130
11	11/06 03:20	40	47	46	2	9	213	2111
12	11/06 04:00	38	46	45	1	8	217	1420
13	11/06 23:20	35	47	47	1	9	198	2105
14	11/07 00:10	36	47	47	1	9	212	1991
15	11/07 03:10	35	47	47	1	8	211	1969
16	11/07 05:00	37	46	46	1	10	185	2196
17	11/08 00:20	27	38	38	0	6	231	437
18	11/08 01:00	28	38	37	0	6	274	590
19	11/08 04:10	30	37	36	0	6	283	608
20	11/08 05:00	31	39	38	0	5	349	495
21	11/09 00:20	34	44	44	0	9	11	2046
22	11/09 01:00	34	46	45	0	9	21	1453
23	11/09 04:10	35	46	45	0	9	23	1533
24	11/09 05:00	34	46	46	0	8	24	1612
25	11/09 23:10	30	34	32	0	6	122	291
26	11/10 00:05	33	44	44	0	8	135	2074
27	11/10 03:10	34	45	45	1	9	137	1984
28	11/10 04:00	37	47	47	1	10	143	1789
35	11/12 03:20	39	41	34	1	11	280	2199
36	11/12 04:00	38	42	40	1	11	283	2120
37	11/12 23:35	34	41	41	0	10	310	2017
38	11/13 00:00	35	41	39	0	10	319	1902
39	11/13 03:00	33	40	39	0	9	323	2064
40	11/13 04:30	35	39	37	0	8	324	1779
41	11/13 23:00	41	43	30	2	12	223	1870

[26] Anomalous anthropogenic sources evaluated and excluded

SD#	Date & Time	Sound Pressure Level (L_{50}, dBA)			1.5-Meter Mean Wind Speed (m/s)	Hub Height Wind		Production of Closest Turbine (kW)
		Background	Total Sound	Turbine-Only		Mean Speed (m/s)	Mean Direction (deg)	
42	11/14 00:00	48	48	n/a	1	17	297	2065
43	11/14 03:00	48	49	25	1	17	301	1772
44	11/14 04:00	48	48	n/a	1	16	324	2151

APPENDIX E. SHUTDOWN PLOTS OF SPECIFIC SHUTDOWNS REFERENCED IN THE REPORT

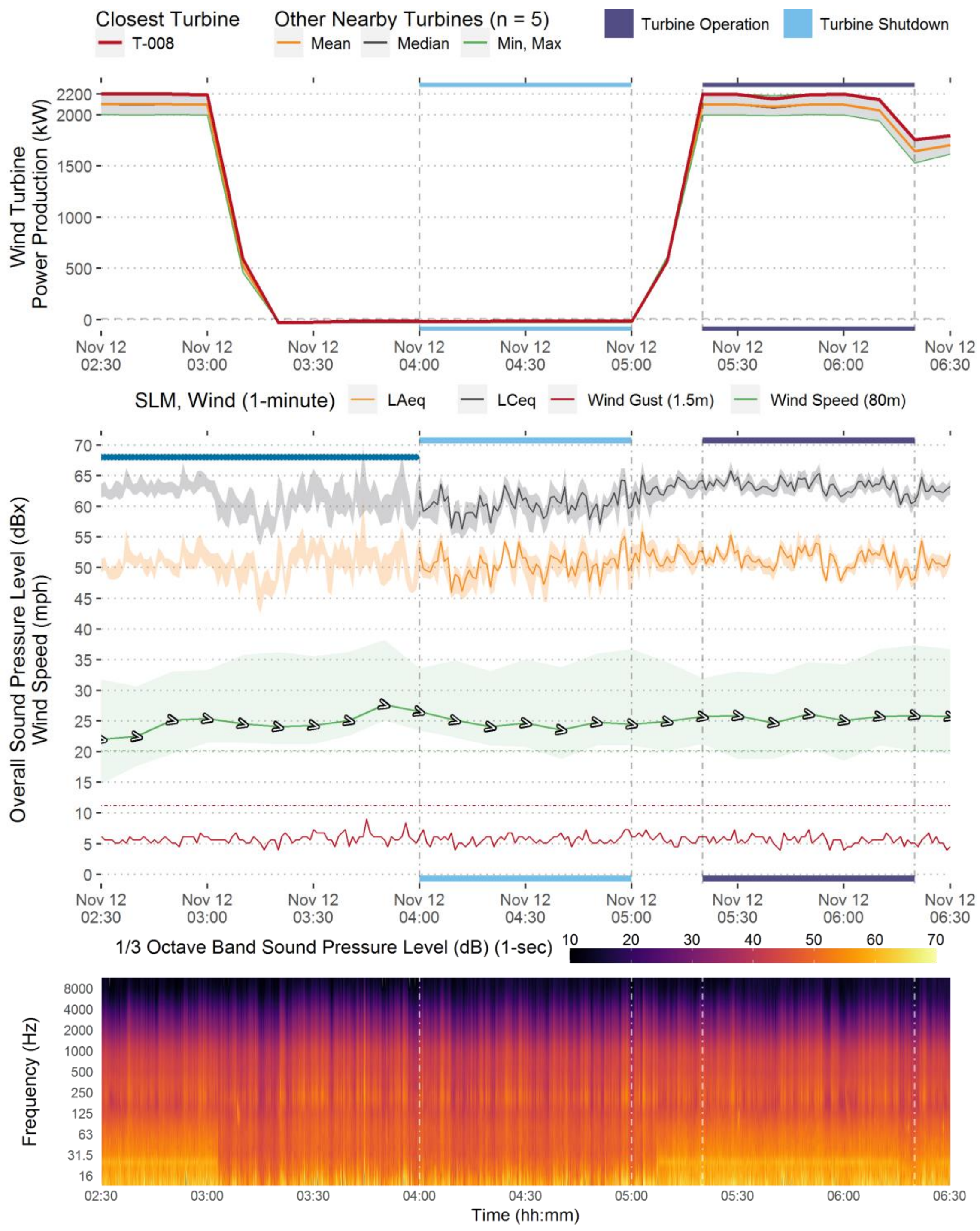

FIGURE 47: SHUTDOWN ID 36 AT THE NORTH MONITOR REFERENCED IN SECTION 5.3

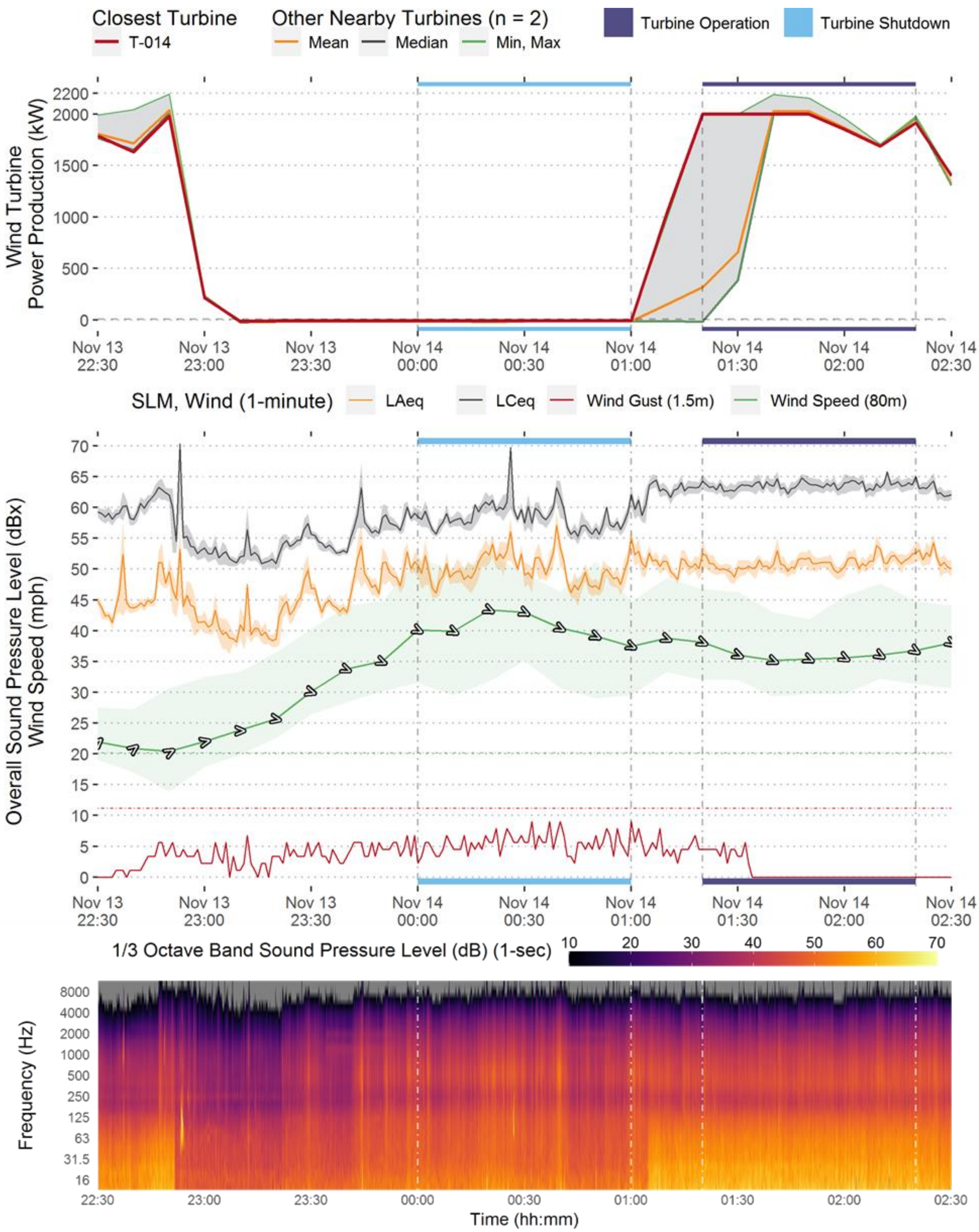

FIGURE 48: SHUTDOWN ID 42 AT THE WEST MONITOR REFERENCED IN SECTION 5.5

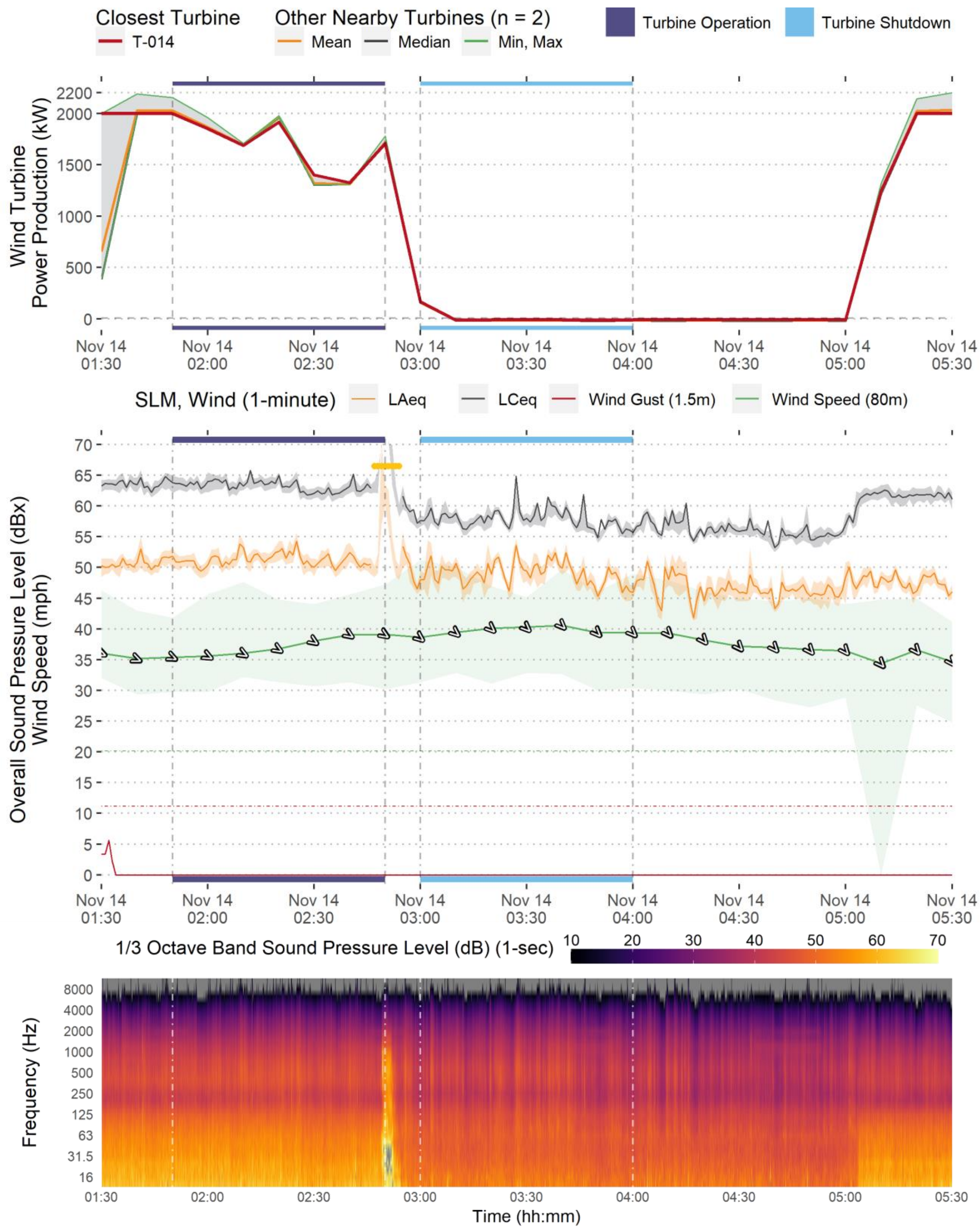

FIGURE 49: SHUTDOWN ID 43 AT THE WEST MONITOR REFERENCED IN SECTION 5.5

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