



TO PRESERVE THE MAGNIFICENT DARK SKIES OF
OREGON AND DIMINISH LIGHT POLLUTION FOR THE
HEALTH, SAFETY AND WELL-BEING OF ALL LIFE

Oregon Skyglow Measurement Network
Technical Report Edition #5
Data from 2019 to November 2021
April 16, 2022

Summary

Outdoor light shining upward brightens the sky at night, which is known as light pollution or skyglow. Light pollution hides the starry night sky and has negative environmental consequences for people and the wild ecosystem. State and Federal organizations measure air, water and soil pollution, but do not directly measure light pollution. We are running a multi-year project to measure light pollution in Oregon, to bring attention to this environmental issue and to support parks and communities working toward certification as [Dark Sky Places](#).

With support from 20 volunteer individuals and groups, we are currently measuring the absolute level of skyglow directly overhead at 35 sites around Oregon and also track change of the light pollution over time.

Two sites in the City of Bend show the most light pollution and it is increasing there by 5% to 6% per year, which is 2x greater than the estimated global increase of light pollution. Measurements from Sisters High School show an increase of about 10% per year over the past year and a half. Other moderately light-polluted sites nearby to Oregon cities are experiencing light pollution increases of several percentage points per year. The sites with the darkest natural skies furthest from the cities show little change.

The measurements show that the two current [Dark Sky Places](#) in Oregon, the community of Sunriver and Prineville Reservoir State Park, retain dark skies. Measurements at sites currently working toward Dark Sky Place certification also meet Dark Sky Place criteria. These locations include Cottonwood Canyon State Park, Wallowa Lake State Park, Black Butte Ranch, Oregon Caves National Monument, the City of Sisters, the Pine Mountain Observatory and large areas of the Outback of southeastern Oregon. Measurements in the Oregon Outback document pristine night skies overhead.

We are expanding the network monthly. We solicit your help to install and maintain additional sites. We would especially like to expand coverage in the Willamette Valley, in the Columbia River Gorge and along the Oregon Coast.

Background

Light pollution at night has been shown to have a negative effect on people and the larger environment, in addition to being a waste of energy. Light pollution, especially blue light at night, disrupts the circadian rhythm of people and other organisms. The impact on humans includes lack of sleep and probable increase in cancers and other diseases. Various animal species – birds, amphibians, mammals, invertebrates and primates – are adversely impacted by: confusion of celestial navigation, misorientation at night, attraction/repulsion to artificial light, impact on predator/prey relationships, effects on timing of breeding, nesting, migration and foraging. Here's a good presentation of this topic by IDA Oregon Board Member, Mary Coolidge, [From the Desert to the Coast, the Case for Dark Skies](#).

State and Federal organizations measure air, water and soil pollution, but do not directly measure light pollution. In part, to show what is possible, and to bring attention to this environmental issue, the Oregon Chapter of the International Dark-Sky Association (IDA), with support from other groups, are running a multi-year project to measure light pollution in Oregon. We operate a network of continuously-recording [Sky Quality Meters](#) (SQMs) in Oregon.

Volunteers gather data every 3 months from the measurement sites. Every six months we update this report to include all the data acquired and incorporate new stations too. This report is Edition #5 and incorporates data from 9 new SQMs. Figure 1 shows the locations of the 30 SQMs with data up to the November 2021 deadline of this report. Appendix A shows a chart of the time ranges of data available from each of these 30 SQM sites.

Five additional meters have been installed since November 2021. The locations of all 35 meters as of March 2022 are shown in [this map online](#).

Skyglow is literally the glowing sky at night, due to both man-made artificial light and natural light. SQMs measure the brightness of the night sky directly overhead and provide a measure of both light pollution and natural light at night. SQMs are widely used around the world for this kind of survey ([Kyba and others, 2015](#)).

Other measurement tools designed to measure skyglow, such as calibrated all-sky cameras ([Jechow and others, 2017](#)), provide additional information about skyglow, namely a complete picture of how the skyglow varies across the sky at a given location. Our SQM measurements document the skyglow directly above. Changes of skyglow may be more readily identified by including changes nearer the horizons. We anticipate augmenting the SQM zenith measurements by all-sky camera data going forward.

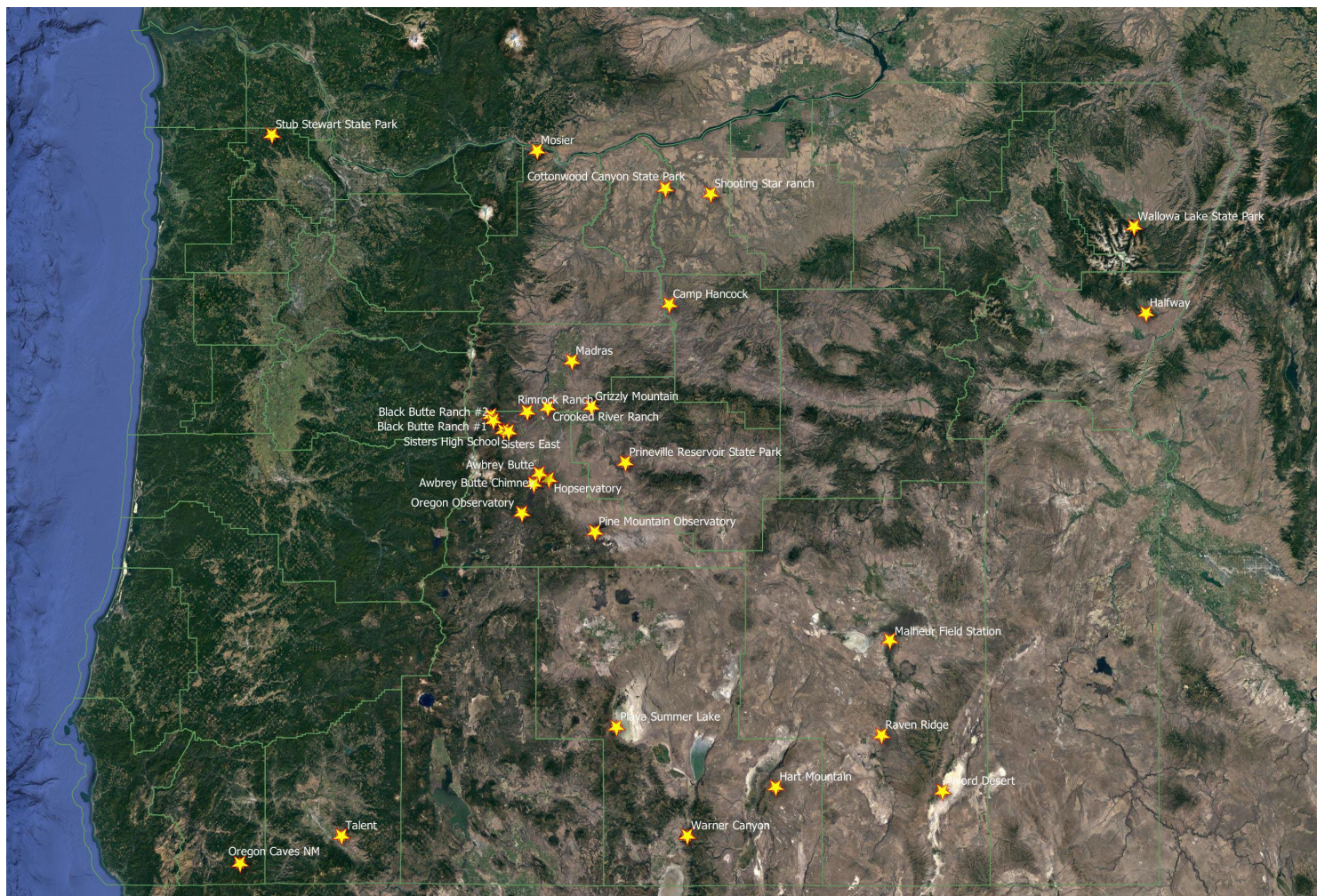


Figure 1. Yellow stars show the locations of the 30 SQM monitoring sites in Oregon with data as of November 2021. The green outlines demarcate the counties of Oregon. We solicit your help to install and maintain additional sites. We would especially like to expand coverage in the Willamette Valley, in the Columbia River Gorge and along the Oregon Coast. The background image is from Google Earth.

Explanation of Skyglow Measurements

Each SQM is enclosed inside a weather proof case and is attached to a fixed support, pointed directly upwards. The SQMs are set to record a skyglow measurement every five minutes. Figure 2 shows examples of SQMs installed at various sites in Oregon.



Figure 2. Examples of SQMs installed at sites in Oregon. The meter resides inside a weatherproof case and point vertically toward the sky.

Figure 3 shows typical data from five SQMs during the night of August 1-2, 2019, which was a mostly cloud-free night during a new moon period.

Data units in Figure 3 and elsewhere in this report are in a logarithmic scale used by astronomers -- magnitude per arc second squared (mags/arcsecond^2). This unit of measure, for example, 21.5 mags/arcsecond^2 , is like saying that the sky glows as though the light of one 21.5-magnitude star, a very dim star, were smeared out across each square arcsecond (a very small 2-dimensional area) of sky. Because this scale is logarithmic, small changes in value of mags/arcsecond^2 represent larger changes in a linear brightness scale. See Table 1 below for additional information.

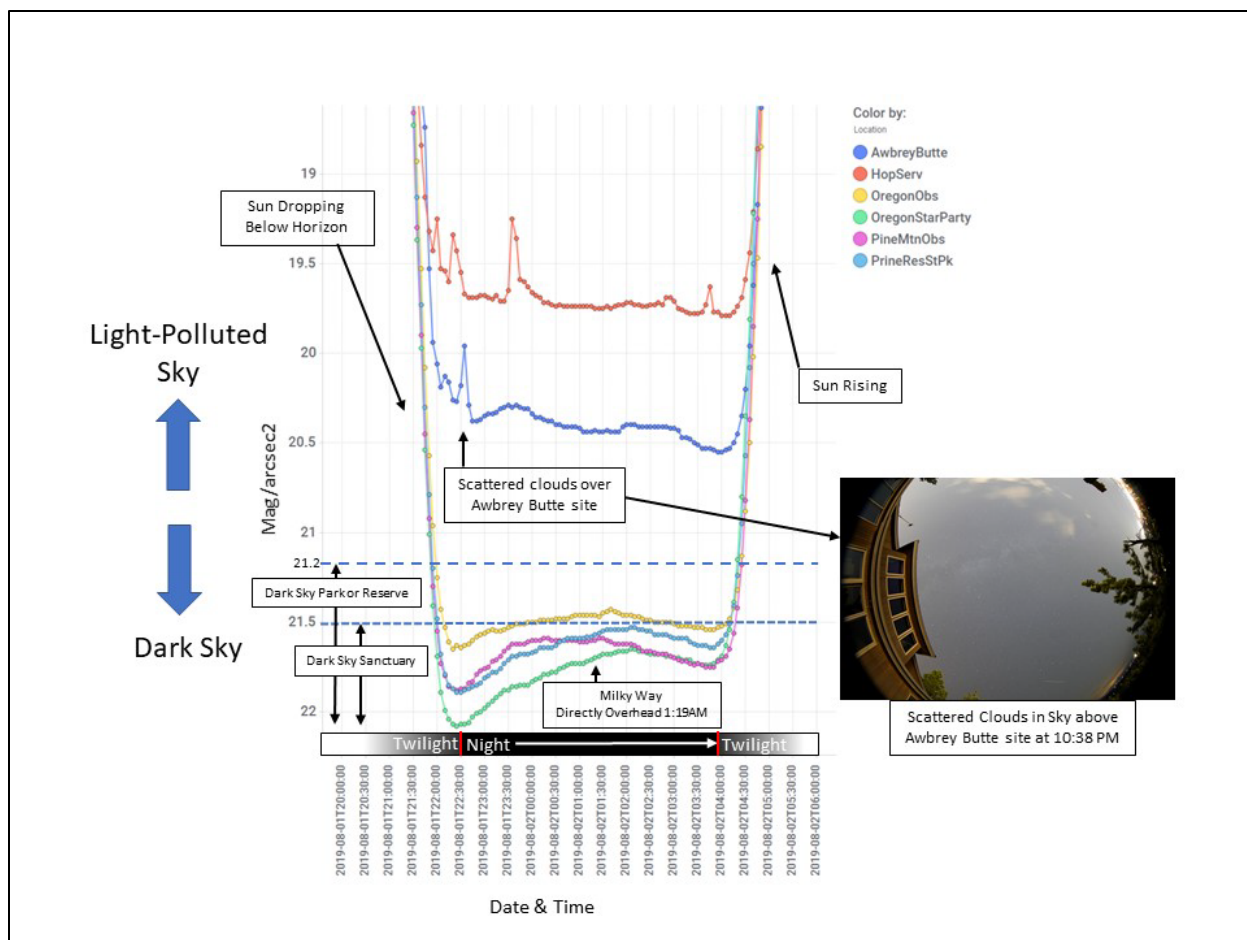


Figure 3. Typical data from SQMs at six different locations for the same single night of August 1-2, 2019.

The vertical axis in Figure 3 displays the SQM measurements – larger numbers are toward the bottom and represent measurements of darker sky. The horizontal axis is Date and Time, over the night of August 1-2, 2019, with labels one hour apart. The colored lines show the recorded data from five SQM locations and additional data recorded at a temporary site during the Oregon Star Party at Indian Trail Spring – the green line.

The data in Figure 3 show that the night sky, directly overhead at the Hopservatory and Awbrey Butte sites (the uppermost red and blue lines), are light-polluted compared to the other sites. These two light-polluted sites are located within the light-dome over the city of Bend. The other four sites have darker skies – they are far away from light-polluted cities. The Oregon Star Party site east of Prineville (green line) had the darkest night sky among these six locations on August 1 – 2 and is furthest of all the sites from the Central Oregon cities.

The International Dark-Sky Association (IDA) has a program to recognize areas that are still mostly unaffected by light pollution. Three categories of such dark sky places are known as Dark Sky Parks, Reserves and Sanctuaries. As shown by the horizontal dashed lines Figure 3, a Dark Sky Park or Reserve must have SQM readings of at least 21.2 mags/arcsecond². Dark Sky Sanctuaries must meet a more strict night sky darkness of at least 21.5 mags/arcsecond². The data suggest that all four of the darkest Central Oregon SQM locations in Figure 3 may meet the stricter criterion. In fact, Prineville Reservoir State Park is now certified as the first Dark Sky Park in Oregon. Note that other significant criteria must also be met to obtain status as a [Dark Sky Park](#), [Dark Sky Reserve](#) or [Dark Sky Sanctuary](#).

Figure 3 shows that the sky overhead at the four dark sites brightens as the Milky Way rises directly overhead, and then darkens as the Milky Way begins descending through the early morning hours. The effect of the Milky Way brightening in the data for the two sites under the City of Bend light dome (Awbrey Butte and Hopservatory), is not obvious because the Milky Way is washed out by the light-polluted skies at those two sites. Instead, we see a gradual darkening through the night hours, which we presume is due to some outside lights in the City, being dimmed or turned off, and fewer car headlights as most people are sleeping.

Project Goals & Data Processing Steps

This project has two main Goals: 1) to support certification of Dark Sky Places and 2) to document the level of light pollution and to track its change over time. Processing of the SQM data differs according to these goals, as described below.

Under Goal #1, the skyglow data support local efforts to nominate sites under IDA's [International Dark Sky Place Program](#). So far, these Oregon data have been instrumental in helping to certify the community of Sunriver as a Dark Sky Development of Distinction (Aug 2020) and Prineville Reservoir State Park as the first Dark Sky Park in Oregon (May 2021). Night time measurements are currently underway at four other potential Dark Sky Parks in Oregon -- at Cottonwood Canyon State Park, Wallowa Lake State Park, Oregon Caves National Monument and Pine Mountain Observatory. Volunteers are also measuring skyglow at two possible future Dark Sky Communities in Oregon -- at Black Butte Ranch and the City of Sisters. The skyglow data from six sites in southeastern Oregon will be submitted by the [Oregon Outback Dark Sky Network](#) to IDA in support of certification of a Dark Sky Sanctuary in that large area.

Under Goal #2, we want to document the level and any changes in light pollution over a five-year period at each site. As scientific measurements, the skyglow data will inform responsible local officials of the level of the light pollution problem, ideally leading to change for healthier and safer communities. IDA has identified [five principles of responsible outdoor lighting](#) which, when followed, will reduce light pollution.

Processing of the SQM data for Goals #1 and #2 begins with the same first steps, then diverges in subsequent steps to accommodate each of the two project goals.

Goal #1 - We process the SQM data suitable for Dark Sky Place certification along these steps:

- 1) Remove influence of the sun, moon and clouds
- 2) Adjust data for SQM hardware conditions -- presence of the weather proof case and aging of the SQM
- 3) Exclude any data values greater than 22.0 magnitudes per arc second squared
- 4) Minimize influence of the brightness of the Milky Way -- filter out data acquired when the Milky Way is overhead

Goal #2 - We process data for the level of light pollution and detection of long-term change of skyglow due to artificial sources, along these steps:

- 1) Same as for Goal #1
- 2) Same as for Goal #1
- 3) Same as for Goal #1
- 4) Minimize Milky Way influence by normalizing the data to a Milky Way position at a specific galactic latitude, 30 degrees off the zenith
- 5) Understand variation due to local seasonal effects and minimize those which vary year-to-year
 - a. Consider time of darkness of winter versus summer nights; eliminate early evening winter hours.
 - b. Consider snow cover - use satellite data to eliminate nights when snow cover was present
 - c. Consider atmospheric character - particulates, humidity
- 6) Consider the increase of airglow due to increase of solar flux

So, the processing of the SQM data toward each goal diverges at step 4, the handling of the effect of the Milky Way. For Goal #1, processing for Dark Sky Place certification, we exclude data samples acquired with the Milky Way overhead, which is consistent with IDA advice to not include the Milky Way in any SQM readings, to avoid biasing the data. Also, for Goal #1, consistent with IDA advice, we include data from all seasons without adjustment, to characterize the annual night sky brightness at a site.

For Goal #2, long-term tracking, instead of discarding the Milk Way data, we choose to normalize the effect of the Milky Way, to minimize seasonal variation. And further for Goal #2, in steps 5 and 6, we seek to understand and to minimize seasonal and other long-term variations that may also bias the skyglow trends over time.

Goals #1 and #2

Processing Step 1 – Remove the Influence of the Sun, Moon and Clouds on Skyglow Measurement

Eliminating the effects of sunlight and moonlight is straightforward. To eliminate issues with sunlight, we only consider data recorded after astronomical twilight (dusk) and before the start of astronomical twilight (dawn) – defined as the period during which the Sun is 18 degrees or more below the horizon. To eliminate issues with moonlight, we only consider SQM data recorded when the Moon is 10 degrees or more below the horizon.

Clouds at night significantly affect the brightness of the sky recorded by the SQMs. Figure 4 shows details of SQM data from five sites recorded during the night of August 10-11, 2019, which was a particularly cloudy night across Central Oregon. The data show rapid variation at the 5-minute sampling interval due to changing cloud conditions overhead during that night. The rapid variation over time, caused by clouds is quite different from the smooth track of data acquired during clear nights, as shown in Figure 3.

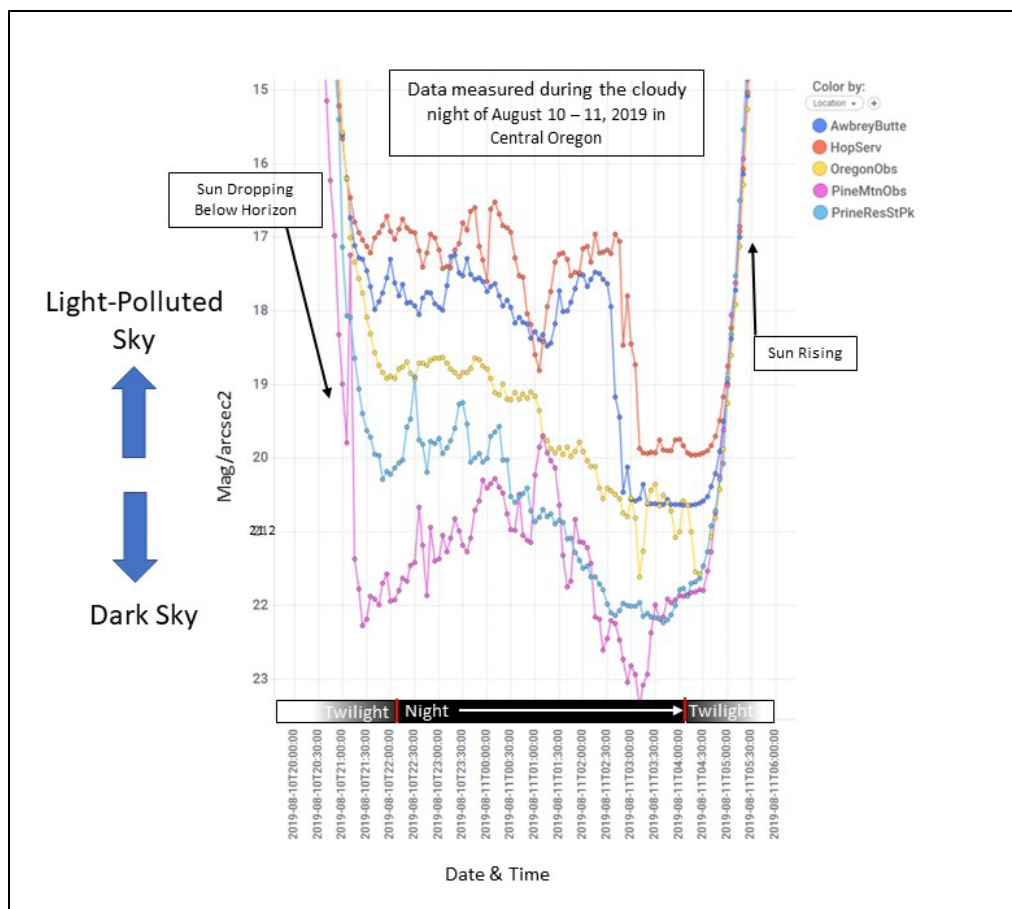


Figure 4. SQM data recorded during a particularly cloudy night across Central Oregon. The data show rapid variation at the 5-minute sampling interval due to changing cloud conditions overhead during that night.

To eliminate skyglow measurements taken during cloudy periods, we use an algorithm that measures the “jaggy” of the skyglow data over a 90-minute period. If the skyglow data are relatively smooth over a 90-minute period, we assume that clouds are not present, and we include the center point of that period as a clear sky measurement. This algorithm is based on one used by Grauer and others, 2019, but modified to employ the Residual Standard Error (RSE) as a measure of deviation from a linear fit. See Appendix B for details. We use a RSE cutoff of 20 to exclude cloudy, that is “jaggy”, data. Points at the center of each 90-minute segment are excluded if the RSE for that segment is larger than 20, otherwise the point is considered to be measured during clear sky conditions. Note that in the previous report, Edition #4, we used an RSE cutoff of 50, but as explained in Appendix B, now choose a more conservative cutoff, 20.

Note in Figure 4 that the clouds cause quite bright skyglow readings at the Awbrey Butte and Hopservatory light-polluted sites – the artificial light from the ground reflects from the clouds downward. The opposite tends to occur at the dark sky sites – the clouds block the starry night sky so we record a darker sky than usual. Note that clouds at the Pine Mountain site caused readings greater than 22 mags/arcsecond² in the early morning hours, an unreasonably dark reading for a natural sky – caused by black-appearing clouds blocking the stars. See Appendix C for detailed data plots of this phenomenon and a discussion of the skyglow signature of a site.

Goals #1 and #2

Processing Step 2 - Adjust data for SQM hardware conditions –the weather proof case and SQM aging

The SQM hardware resides inside a weather proof case during deployment. The top of the case has a clear window that darkens each measurement. Unihedron, the manufacturer, specifies that users should subtract

0.11 magnitudes per arc second squared from the data to account for the presence of this window. Accordingly, we do so.

Recent research (Puschnig and others, 2020) using SQMs from three different locations, documents that as the SQM device and weather proof enclosure age, that there is a darkening effect on measured data, in their case an average of about .04 mags/arcsecond² per year. This aging effect increases the skyglow measurements over time, making the sky seem slightly darker than reality.

To understand this phenomenon better, we obtained two new SQMs and installed them to run in parallel to two SQMs which had been running for several years. The results from our experiment suggest that a darkening effect is present, but a smaller one compared to the estimate from Puschnig and others. Our estimate is .019 mags/arcsecond² per year. Accordingly, we subtract values proportional to this assumed aging effect from our data, based on the progressive, serial exposure over time of measurements from each SQM in our network. See details in Appendix D.

Goals #1 and #2

Processing Step 3 - Eliminate out of bounds values

It is widely considered that the darkest clear night sky should not have any zenith brightness values greater than 22 mags/arcsecond². Accordingly, we filter out those few values greater than 22.0 from our data.

Goal #1

Processing Step 4 - Filter out measurements taken when the Milky Way is overhead

As noted above, when processing the SQM data for Dark Sky Place certification, we exclude data samples acquired with the Milky Way overhead, which is consistent with IDA advice to not include the Milky Way in any SQM readings, to avoid biasing the data. Accordingly, we eliminate any data points acquired when the plane of the Milky Way is within 30 degrees of the zenith. We choose thirty degrees to accommodate the 20-degree FOV of the SQM, plus 10 more degrees to take a conservative approach.

After Steps 1-4, the processing for Goal #1, Dark Sky Place measurements, is complete. We have removed the effects of the sun, moon, clouds, weatherproof cover, SQM aging, out of bounds data and presence of the Milky Way. So, we can compare the brightness of the clear night skies at the current sites (Figure 5).

The sites are organized in Figure 5 by the highest amount of light pollution on the top to the least on the bottom. The sites on the very bottom, beginning with Hart Mountain, have essentially pristine night skies.

As we acquire additional data over time, the exact order of the sites may change, as several of the sites have a limited number of data points so far. In fact, one of the sites, Grizzly Peak, is not shown in Figure 5 because of no data remaining after filtering.

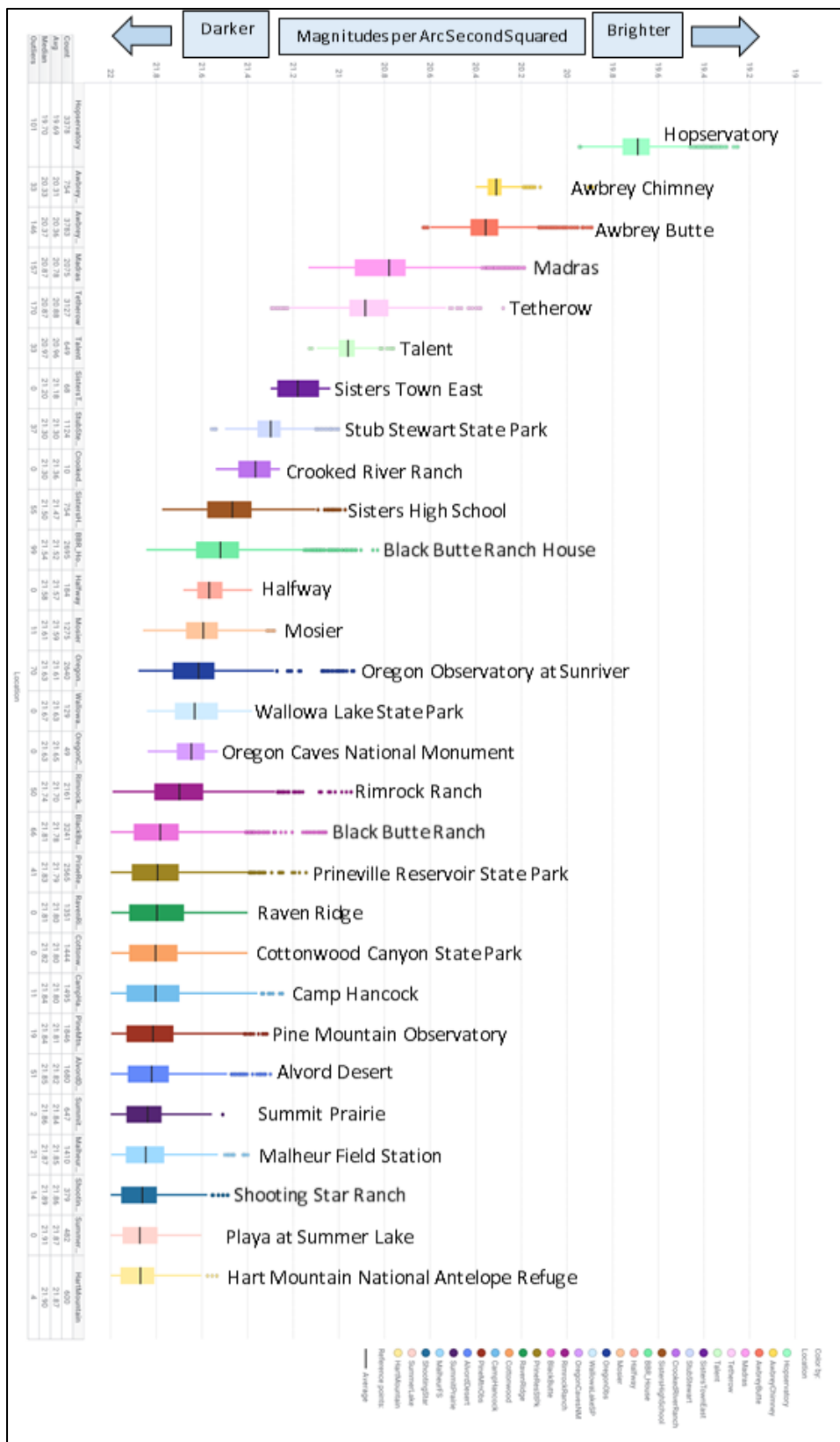


Figure 5. Box plot showing the clear sky measurements of the current sites. The vertical black line in each box marks the average value. The horizontal size of the box marks the central two quartiles (central 50% of data). The vertical lines that extend up and down from each box show the limits of the upper and lower quartile of the data. Table 1 provides the summary statistics at each site.

Table 1 lists the average brightness of the night sky for each site in the mags/arcsecond² scale. The “X Brighter” column in Table 1 on the far right shows how much brighter, on a linear scale, each site is compared to Hart Mountain, the darkest night sky site in our data set to date. The clear night skies in and near the cities of central Oregon are 3x to 7x brighter, that is, 3x to 7x more light polluted, than the pristine night skies at Hart Mountain.

Location	Age of SQM (Days Exposed)	Age-Corrected Mean (mag/arc second squared)	Age-Corrected Mean (microCandelas/ meter squared)	X Brighter
Hopservatory	831.92	19.69	1438.04	7.45
Awbrey Chimney	206.63	20.31	812.00	4.21
Awbrey Butte	965.63	20.36	777.42	4.03
Madras	759.81	20.78	526.74	2.73
Tetherow	720.39	20.88	478.15	2.48
Talent	175.65	20.96	446.69	2.32
Sisters Town East	74.59	21.18	364.07	1.89
Stub Stewart State Park	249.72	21.30	326.38	1.69
Crooked River Ranch	143.89	21.36	307.34	1.59
Sisters High School	498.06	21.47	279.71	1.45
Black Butte Ranch House	675.27	21.52	266.31	1.38
Halfway	161.83	21.57	254.96	1.32
Mosier	781.91	21.59	248.85	1.29
Oregon Observatory	840.05	21.61	244.08	1.27
Wallowa Lake State Park	161.65	21.63	240.46	1.25
Oregon Caves NM	106.06	21.65	236.79	1.23
Rimrock Ranch	557.60	21.70	226.18	1.17
Black Butte Ranch	795.90	21.78	209.34	1.09
Prineville Reservoir State Park	856.96	21.79	206.79	1.07
Raven Ridge	326.06	21.80	206.56	1.07
Cottonwood Canyon State Park	312.02	21.80	205.03	1.06
Camp Hancock	367.96	21.80	205.35	1.06
Pine Mountain Observatory	851.73	21.81	203.32	1.05
Alvord Desert	344.81	21.82	201.87	1.05
Summit Prairie	184.40	21.84	198.65	1.03
Malheur Field Station	343.72	21.85	197.42	1.02
Shooting Star	215.78	21.86	194.46	1.01
Playa at Summer Lake	238.30	21.87	192.76	1.00
Hart Mountain	239.21	21.87	192.92	1.00

Table 1. Summary of SQM **clear night data** at each location. The clear night skies near the central Oregon cities of Bend and Madras are 3x to 7x brighter than at Hart Mountain. The mean values in the second data column are in the logarithmic units of **mags/arcsecond²**. These data have been adjusted for the age of each SQM and filtered to remove data acquired when the Milk Way is within 30 degrees of zenith. Any data values higher than 22.0 mags/arc second squared was also eliminated. The third data column lists the mean values after conversion to a linear brightness scale. The “X Brighter” column shows how much brighter is the clear night sky at each site compared to the current darkest site – Hart Mountain. ([See this link](#) for information about converting from the logarithmic **mags/arcsecond²** scale to candelas.)

Skyglow from Cloudy Nights – the Second Part of the Signature

The previous section summarized the clear night data from each measurement site. We also want to characterize each site’s measurements during cloudy conditions. We achieve that by selecting the “jaggy” data – namely points that have a RSE value greater than the cutoff of 20.

Table 2 summarizes the statistics for these measurements taken during cloudy conditions. The “X Brighter” column in Table 2 shows that under clouds, the sites near the central Oregon cities of Bend, Redmond and Madras are 11x to 35x brighter than are cloudy conditions at Hart Mountain. Clouds near cities reflect light pollution back down to the environment while clouds at a dark sky site like Hart Mountain appear black because there is no artificial light pollution coming from the ground, and because the clouds block out starlight. Because several of the sites have only been recording for several months, we can expect the statistics to improve as more data become available.

We can consider the skyglow at Hart Mountain to be the natural case, and the skyglow over the central Oregon cities to be quite un-natural. The impact on the wild ecosystem of light pollution in cloudy conditions is likely significant.

Location	Age of SQM (Days)	Age-Corrected Mean (mag/arc second squared)	Age-Corrected Mean (microCandelas/ meter squared)	X Brighter
Hopservatory	831.92	18.40	4700.61	35.22
Awbrey Chimney	206.63	19.38	1909.36	14.31
Awbrey Butte	965.63	19.11	2448.07	18.34
Madras	759.81	19.63	1522.29	11.41
Tetherow	720.39	19.63	1518.59	11.38
Talent	175.65	20.15	943.37	7.07
Sisters Town East	74.59	20.85	492.16	3.69
Stub Stewart State Park	249.72	21.13	381.00	2.85
Crooked River Ranch	143.89	21.10	392.75	2.94
Sisters High School	498.06	20.64	600.29	4.50
Black Butte Ranch House	675.27	21.31	322.65	2.42
Halfway	161.83	21.40	298.52	2.24
Mosier	781.91	21.17	366.58	2.75
Oregon Observatory	840.05	20.61	617.69	4.63
Wallowa Lake State Park	161.65	21.57	253.22	1.90
Oregon Caves NM	106.06	21.74	217.92	1.63
Rimrock Ranch	557.60	21.65	236.51	1.77
Black Butte Ranch	795.90	21.68	228.94	1.72
Prineville Reservoir State Park	856.96	21.72	221.40	1.66
Raven Ridge	326.06	22.25	135.45	1.01
Cottonwood Canyon State Park	312.02	22.07	161.09	1.21
Camp Hancock	367.96	22.20	142.43	1.07
Pine Mountain Observatory	851.73	22.17	145.93	1.09
Alvord Desert	344.81	22.17	146.91	1.10
Summit Prairie	184.40	21.88	191.12	1.43
Malheur Field Station	343.72	22.16	147.56	1.11
Shooting Star	215.78	21.86	193.94	1.45
Playa at Summer Lake	238.30	22.06	162.02	1.21
Hart Mountain	239.21	22.27	133.46	1.00

Table 2. Summary of SQM **cloudy night data** at each location. The sites are listed in the same order as in Table 1. The cloudy night skies near the central Oregon cities of Bend and Madras are 11x to 35x brighter (top five rows of the table) than cloudy nights at Hart Mountain. The mean values in the second data column are in the logarithmic units of **mags/arcsecond²**. These data have been adjusted for the age of each SQM and filtered to remove data acquired when the Milk Way is within 30 degrees of zenith. Values higher than 22.0 mags/arc second squared are included because they record the fact that clouds will block the stars and are representative of cloudy conditions. The third column lists the mean values after conversion to a linear brightness scale. The “X Brighter” column shows how much brighter is the cloudy night sky at each site compared to the current darkest site – Hart Mountain.

Goal #2

Processing Step 4 - Adjust Clear Sky SQM Data for the Position of the Milky Way

When the Milky Way is overhead, the SQM will record a brighter night sky. Instead of eliminating those measurements as we did for Goal #1, we instead keep those data and normalize out that effect in processing toward Goal #2. By this method, we minimize the seasonal nature of the Milky Way pattern and also avoid loss of data. This process is described in Appendix E.

Goal #2

Processing Step 5 - Minimize other seasonal effects in the data

One seasonal pattern to minimize is the time of darkness during winter versus summer nights. In our northern hemisphere winter, we experience much longer evening hours of darkness, versus the summer months. That is, darkness in the winter begins much earlier in the evening. For light polluted sites, this early evening skyglow is quite bright, due to most outdoor lights being on and people driving about with car headlights lights on. As the evening hours pass, the light pollution and skyglow decrease. This effect is more pronounced in the winter than summer and more significant for light polluted sites too.

While this effect is consistent from year-to-year and may be considered a known and constant influence on the seasonal skyglow trend, on the other hand, the time of acquisition of our data from various SQM locations does not include complete seasonal cycles, so the trend over years will be influenced by which seasons are covered by each SQM data set. So, a safer solution is to filter all data to the summer night hours.

We removed this seasonal bias by filtering data on a nightly basis -- to only include data from 10:30PM local time to 4:30AM local time, which is the time range of the summer nights in our latitude range. See additional discussion and figures in Appendix F.

Other seasonal effects that will affect skyglow include snow cover in winter and variations in character of the atmosphere such the particulate concentration and humidity. In the high desert environment of most of our SQM sites, humidity tends to be higher in the winter than in summer, which qualitatively suggests that we should measure brighter skies in winter, which is what our data show. Atmospheric particulates increase in late summer, largely due to forest fire activity. There is also a trend of increased particulates since the beginning of our SQM study, which will likely contribute to increased skyglow, although complex competing influences are present (Cinzano and Falchi, 2012; Kocifaj and Komar, 2016).

Currently we apply an estimate of the effect of the snow cover by subtracting 1% from the annual skyglow trends. We don't attempt any adjustment for the probable atmospheric effects. As we expand the SQM network into non-arid regions of Oregon, with different seasonal atmospheric properties, we expect to better understand these effects. See discussion on winter snow, humidity and atmospheric particulates in Appendix G.

Goal #2 - Processing Step 6 – Consider the increase of airglow due to increase of solar flux

Another factor to consider in zenith skyglow trends over long periods is variations due to airglow, the light emitted from the atmosphere itself due to the impact of space weather on Earth (Grauer and others, 2019). Airglow is known to vary on a wide range of time scales, from rapid variation in minutes and across one night, to strong, years-long changes correlated to the 11-year solar sunspot cycle.

The sun is currently rising out of a solar sunspot minimum, toward a predicted sunspot maximum in July 2025. So, space weather may cause our SQM data to read brighter since our SQM project began in mid-2019, by increased airglow, independently of any changes in light pollution from the ground. The analysis described in Appendix H implies a trend increase of visible light at the zenith of about 0.7% per year due to increased solar flux. Accordingly, we subtract 0.7% per year from each trend of skyglow measurement data, described below. Also see Appendix H.

Changes of Skyglow over Time

After processing the SQM data for Goal #2, we plot the corrected data over the time since we began recording data. Figure 6 shows the clear night sky data for the twelve sites for which we have at least a year and a half of data, plotted over time. The data in Figure 6 appear as patches -- there is one patch for each new moon period. Some months of data are missing from individual sites due to failure of batteries and in the case of Pine Mountain Observatory, due to a winter storm which blew the SQM mounting pole off the zenith direction.

The solid line across each data subset in Figure 6 is a linear regression fit to the sky brightness recorded over time. Despite the monthly scatter of data about the regression lines, the 95% confidence band of the regression lines is quite similar to the black lines in Figure 6. (See discussion in Appendix I).

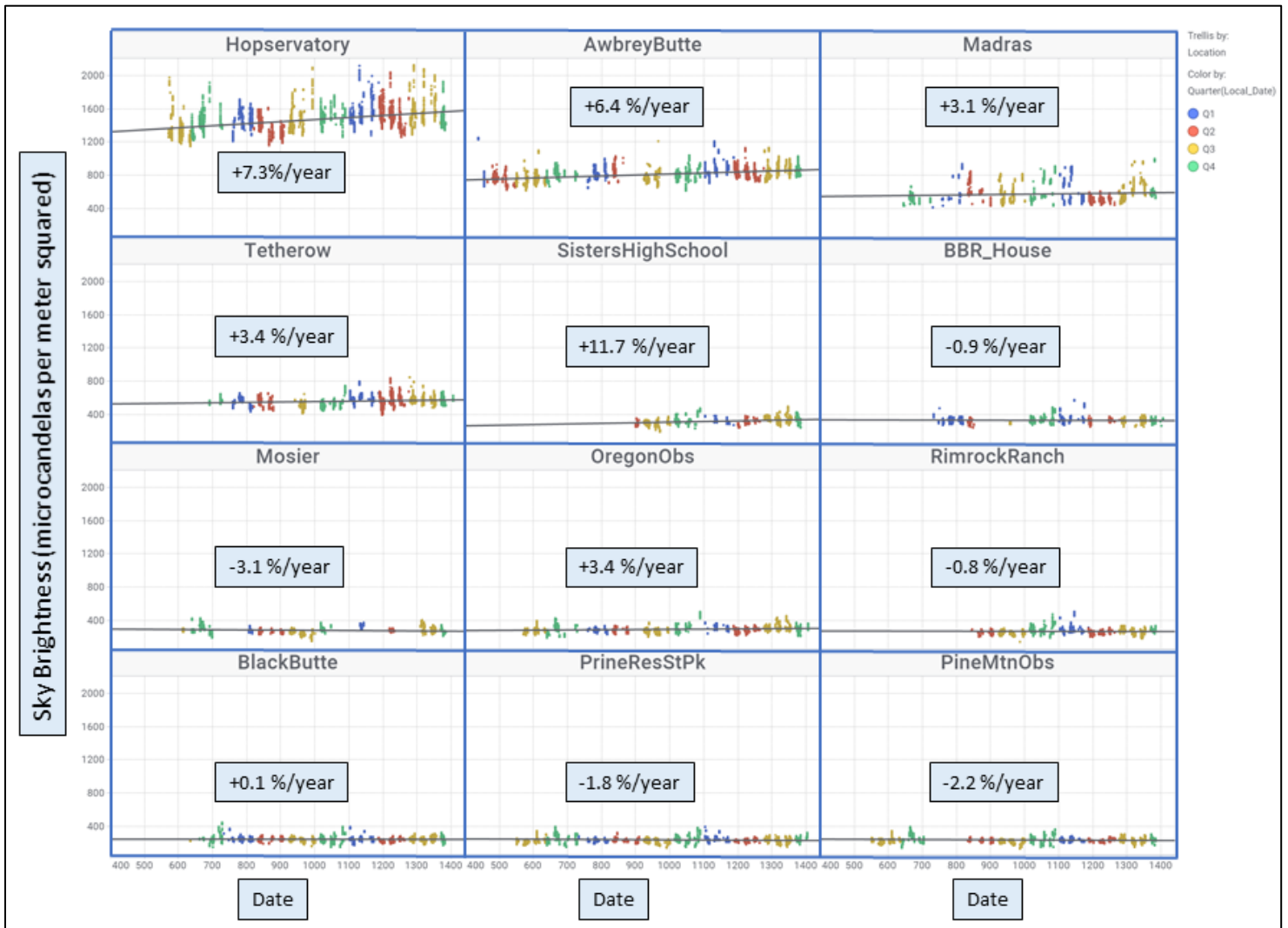


Figure 6. The clear sky data for the sites with at least 1.5 years of data, plotted over time. The solid line across each data subset is a linear regression fit. The percentage changes of skyglow are shown for each site over the time period of each site's survey period. This period ranges from 1.5 years to 3 years. The data are corrected according to Goal #2 as described above, except they are not yet adjusted for the presence of snow cover and solar flux change over time. See Table 3.

Note that the patches in Figure 6 are colored by quarter of the year. The winter – Q4 and Q1 – are colored green and blue respectively. Skyglow measurements during the winter quarters still tend to be brighter than during the summer, despite the adjustments that we have made for the position of the Milky Way and

for hours of night, winter versus summer. We anticipated that the winter brightening is due to reflective snow cover in winter causing more light to reflect upward and subsequently scattered back down as skyglow, compared to summer during which leaves on deciduous trees and plants cause the reflection of the ground to decrease. After eliminating the days with snow on the ground, we previously found a 1% change of the trends, but the seasonal pattern is still present in the data.

Figure 6 suggests that the two sites within the City of Bend (Hopservatory and Awbrey Butte) increased by about 6% to 7% per year since the summer of 2019. However, these data are not yet adjusted for the presence of snow cover and solar flux change over time, which drops them to the range of 5% to 6% per year. That is, based on the snow cover analysis performed in Edition #4 of this report, plus the updated estimate of airglow due to increasing solar flux output (Appendix H), we subtract 1.7% from each yearly estimates as shown in Table 3.

Location	Trend from Skyglow Data (% per year)	After Snow Cover and Solar Flux Adjustment (% per year)
Hopservatory	7.3	5.6
Awbrey Butte	6.4	4.7
Madras	3.1	1.4
Tetherow	3.4	1.7
Sisters High School	11.7	10.0
Black Butte Ranch House	-0.9	-2.6
Mosier	-3.1	-4.8
Oregon Observatory	3.4	1.7
Rimrock Ranch	-0.8	-2.5
Black Butte Ranch	0.1	-1.6
Prineville Reservoir State Park	-1.8	-3.5
Pine Mountain Observatory	-2.2	-3.9

Table 3. Percentage change of skyglow over time at the 12 sites with at least 1.5 years of data. The first column shows the trends of measured skyglow from Figure 6. The second column show the trends after subtracting the estimated impact of winter snow cover and increased solar flux, both of which increase the skyglow trend beyond that due to artificial light at night. Additional factors, not currently adjusted for, may also play a role in the trends, such as the increase in atmospheric particulates over the time frame of the ongoing SQM study (Appendix G).

The increase of 5% to 6% per year is about 2x faster than the estimated average increase of light pollution globally and seems due to the increase in population of central Oregon over the past few years along with ineffective enforcement of the existing lighting ordinances. Skyglow at Sisters High School increased even more (+10%) over the survey period. That increase may be due to local lighting associated with nearby developments in a formerly relatively dark environment.

The darker sky sites (bottom 7 rows of Table 3) tended to be flat or to decrease in adjusted skyglow with time. This is unexpected considering their proximity to areas of increased skyglow. Three of the sites with the largest negative trends, Black Butte Ranch House, Mosier and Pine Mountain Observatory, have missing data which may bias their trends.

Other factors to consider in seasonal variation are the effects of humidity and particulates on the aerosol depth of the atmosphere in our high desert environment. We suspect that variation in humidity in our high-desert environment – more humid air in the winter versus drier air in the summer – contributes to the seasonal brightening of skyglow in the winter. Particulates in the atmosphere likely also play a role and affect the long-term trend too. Currently we don't attempt an adjustment for humidity or particulate concentrations. (See Appendix G.)

We may be at the limit of SQM technology for detecting changes in zenith skyglow at the darkest sites, considering other factors at play, especially seasonal effects which are still present in our adjusted data and may swamp slight changes of skyglow at the zenith.

At the darker sites, changes of skyglow will be more evident near the horizon. This calls for an additional measuring system, such as a calibrated all-sky camera. This could be either a tripod-mounted system used at key sites during cloud-free, new moon conditions or an all-weather camera, always operating, acquiring images and periodically calibrated to further understand seasonal patterns and other issues that may become evident.

Acknowledgements

IDA Oregon acknowledges and thanks the representatives at the public and private SQM sites for their continued support on this project -- the Hop Observatory, Tetherow, Madras, the Oregon Observatory at Sunriver, Black Butte Ranch, Prineville Reservoir State Park, the Pine Mountain Observatory, Rimrock Ranch, Sisters High School, Astronomy Club of City of Sisters, Crooked River Ranch, Grizzly Mountain, Camp Hancock, the Malheur Field Station, Raven Ridge, Southern Oregon Travel, Oregon Outback Dark Sky Network, Stub Stewart State Park, Shooting Star Ranch, Summer Lake, Summit Prairie, Alvord Desert, Hart Mountain National Antelope Refuge, Halfway, Cottonwood Canyon State Park, Wallowa Lake State Park and Oregon Caves National Monument.

We also appreciate the ongoing support of the Rose City Astronomers, the Sisters High School Astronomy Club and the City of Sisters Astronomy Club.

We also acknowledge the free-to-nonprofit availability and use of Tibco's exceptional Spotfire software which has been critical to our analyses of the SQM data.

Project Contacts:

Bill Kowalik	bill.kowalik@darksky.org
Mike McKeag	michael.mckeag@darksky.org

References

Cinzano, P., Falchi, F., 2012, [The Propagation of Light Pollution in the Atmosphere](#), Monthly Notices of the Royal Astronomical Society, Vol 427, Issue 4, pp 3337-3357.

Coolidge, M., 2021, [From the Desert to the Coast, the Case for Dark Skies](#), video presentation to the Cape Perpetua Collaborative, Oregon.

Grauer, A.D., Grauer P.A., Davies, N. and Davies G., 2019, [Impact of Space Weather on the Natural Night Sky](#), Publications of the Astronomical Society of the Pacific.

IDA, [International Dark Sky Places Program](#).

Jechow, A, Kollath, Z, Ribas, SJ, Spoelstra H, Hölker, F and Kyba, CCM, 2017, [Imaging and Mapping the Impact of Clouds on Skyglow with All-Sky Photometry](#), Scientific Reports.

Kocifaj, M., and Komar, L, 2016, [A Role of Aerosol Particles in Forming Urban Skyglow and Skyglow from Distant Cities](#), Monthly Notices of the Royal Astronomical Society, Vol 458, Issue 1, pp 438-448.

Krisciunas, K., 1997, [Optical Night-Sky Brightness at Mauna Kea over the Course of a Complete Sunspot Cycle](#), Journal of the Astronomical Society of the Pacific, 109, pp 1181-1188.

Krisciunas, K., Semler, D.R, Richards, J., Schwarz, H.E., Zuntzeff, N.B., Vera, S., and Sanhueza, P., 2007, [Optical Sky Brightness at Cerro Tololo Inter-American Observatory from 1992 to 2006](#), Publications of the Astronomical Society of the Pacific, 119, pp 687-696.

Kyba, C., Tong, K., Bennie, J. et al., 2015, [Worldwide Variations in Artificial Skyglow](#). Sci Rep 5, 8409.

Puschnig, J., Posch, T. and Uttenthaler, S., 2013, [Night Sky Photometry and Spectroscopy Performed at the Vienna University Observatory](#).

Puschnig, J., Naslund, M., Schwöpe, A., and Wallner, S., 2020, [Correcting Sky Quality Meter measurements for Aging Effects Using Twilight as Calibrator](#), MNRAS, 000, pp 1-6.

Schnitt, S., Ruhtz, T., Fischer, J., Holker, F. and Kyba, C.C.M., 2013, [Temperature Stability of the Sky Quality Meter](#), Sensors (Basel), 13 (9), pp 12166-12174.

[Sky Quality Meters](#), Unihedron.

Appendix A – Time duration of data from each SQM

Figure A1 show the data coverage over time of each SQM site as of this Edition (#5) of the report on the Oregon Skyglow Measurement Network. The chart is color-coded by the quarter of the year. Data gaps are caused by battery failure and adverse weather conditions that prevented timely access.

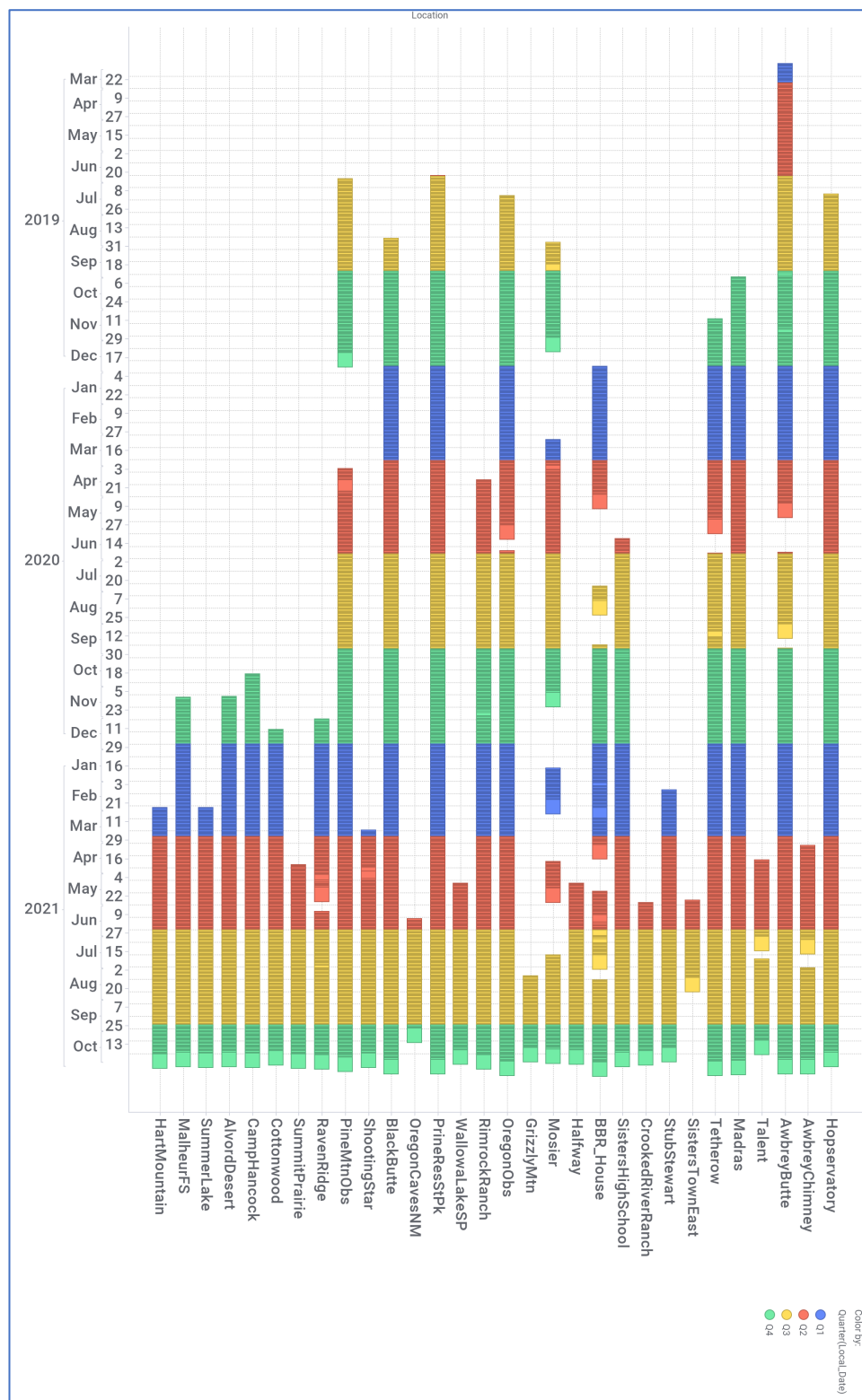


Figure A1. Time range of data available from each SQM as of November 2021. Plot is colored by quarter of the year.

Appendix B - Cloud Removal Algorithm

To eliminate skyglow measurements taken during cloudy periods, we use an algorithm that measures the “jaggy” of the skyglow data over a 90-minute period. If the skyglow data are relatively smooth over a 90-minute period, we assume that clouds are not present, and we include the center point of that period as a clear sky measurement. Figure B1 shows a diagrammatic explanation. Figure B2 shows data examples.

This algorithm is based on one used by Grauer and others, 2019, but modified to employ the Residual Standard Error (RSE) as a measure of deviation from a linear fit. This algorithm is now implemented in Unihedron’s UDM software, under the processing option “Tools/.dat to Sun-Moon-MW-Clouds.”

We use a RSE cutoff of 20 to exclude cloudy, that is “jaggy”, data. Points at the center of each 90-minute segment are excluded if the RSE for that segment is larger than 20, otherwise the point is considered to be measured during clear sky conditions.

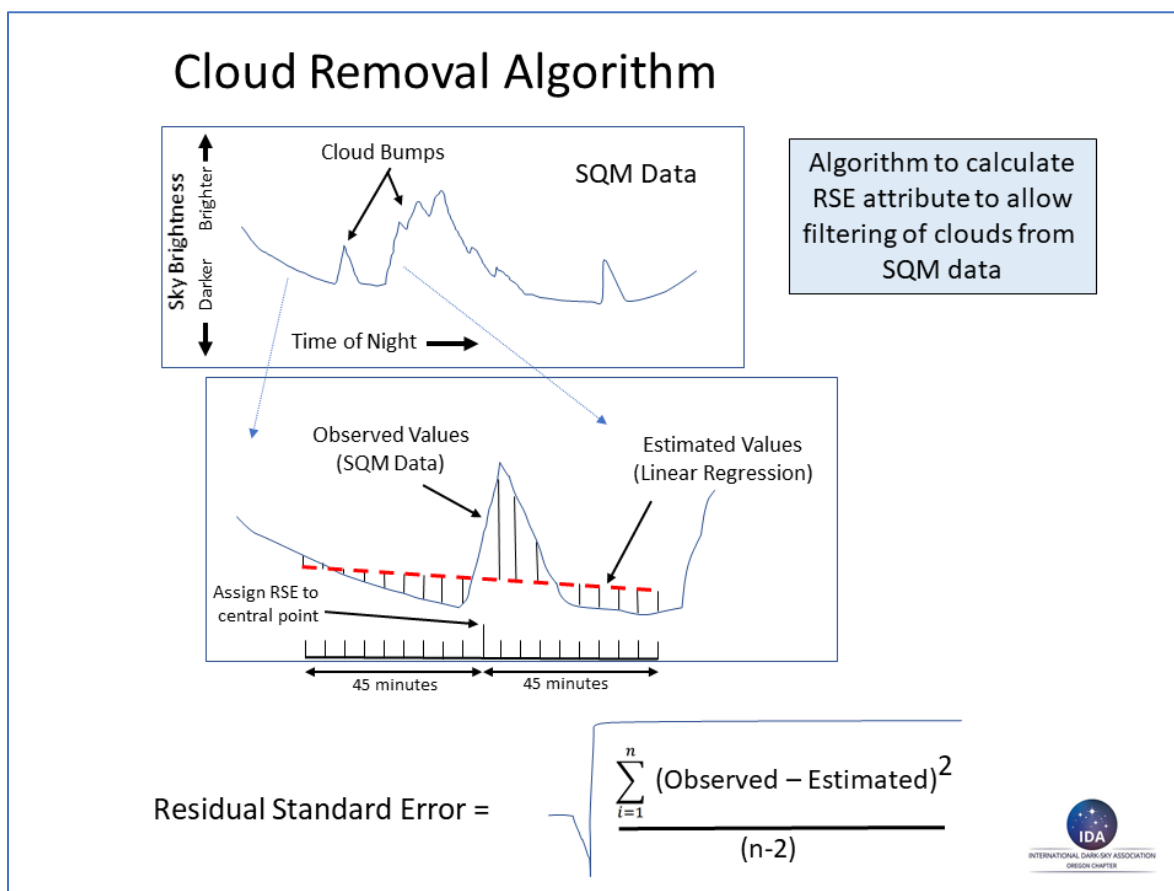


Figure B1. Diagrammatic explanation of the calculation of residual standard error which is used as the statistic to gauge the presence of clouds at each data point. We fit a linear regression to a sliding 90-minute interval of SQM data and assign the residual standard error to the center point of the time interval.

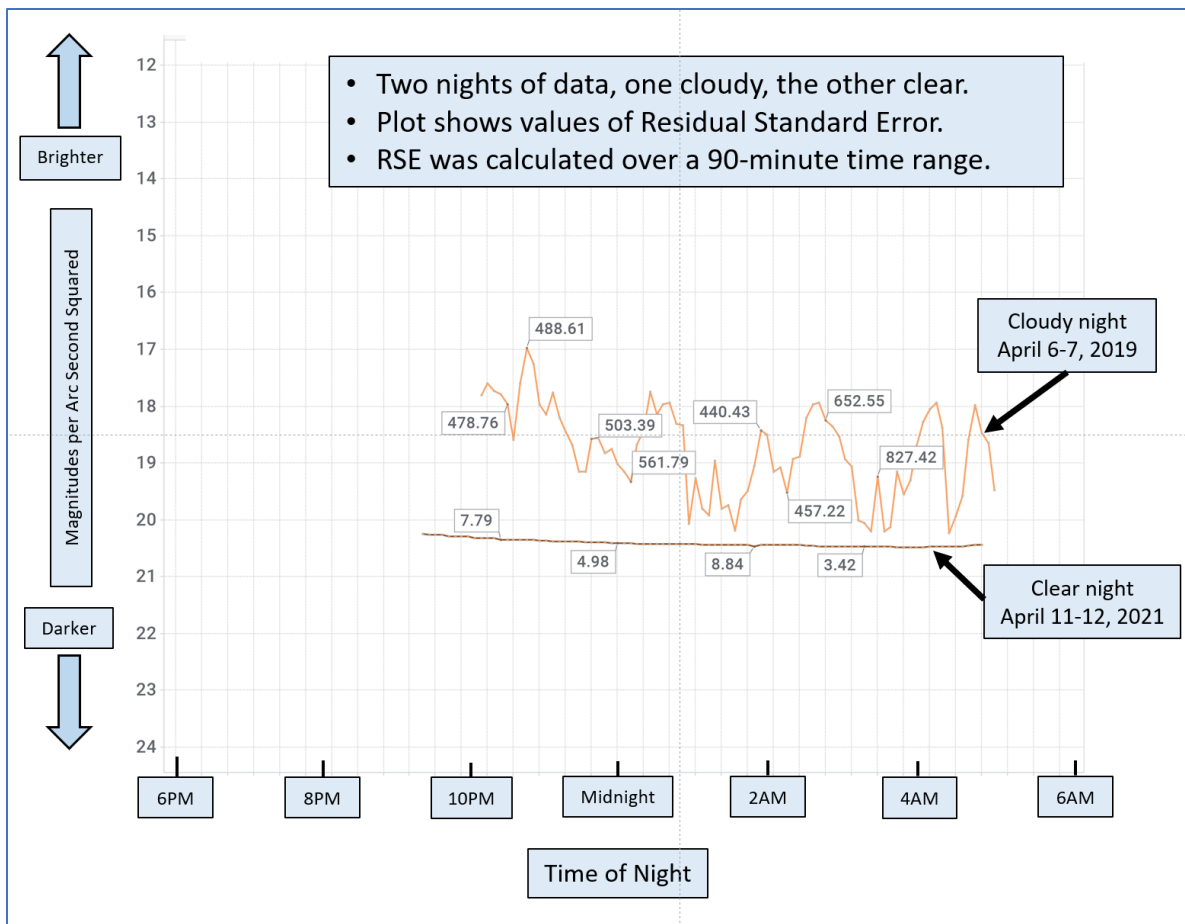


Figure B2. Data from two different nights, one cloudy, the other clear. The residual standard error values are shown at several point along the profiles. The clear night data has much smaller RSE values compared to data acquired during the cloudy night.

Filtering out cloudy data samples requires a choice of a cutoff RSE value. Previously we used a cutoff value of 50, but after studying density plots of RSE data (Figure B3), we chose a more conservative RSE value of 20. Figure B3 shows that a cluster of data points lies below the RSE value of 20. We take this as a natural clustering of cloud-free data, and accordingly use the RSE value of 20 to separate clear from cloudy data samples.

This algorithm effectively filters out SQM measurements acquired when cloud conditions vary during the 90-minute time span. However, it fails to remove cloudy data from periods of uniform overcast or fog. To fix this, we manually delete those data from each site. See explanatory figures and further discussion on this in Appendix C.

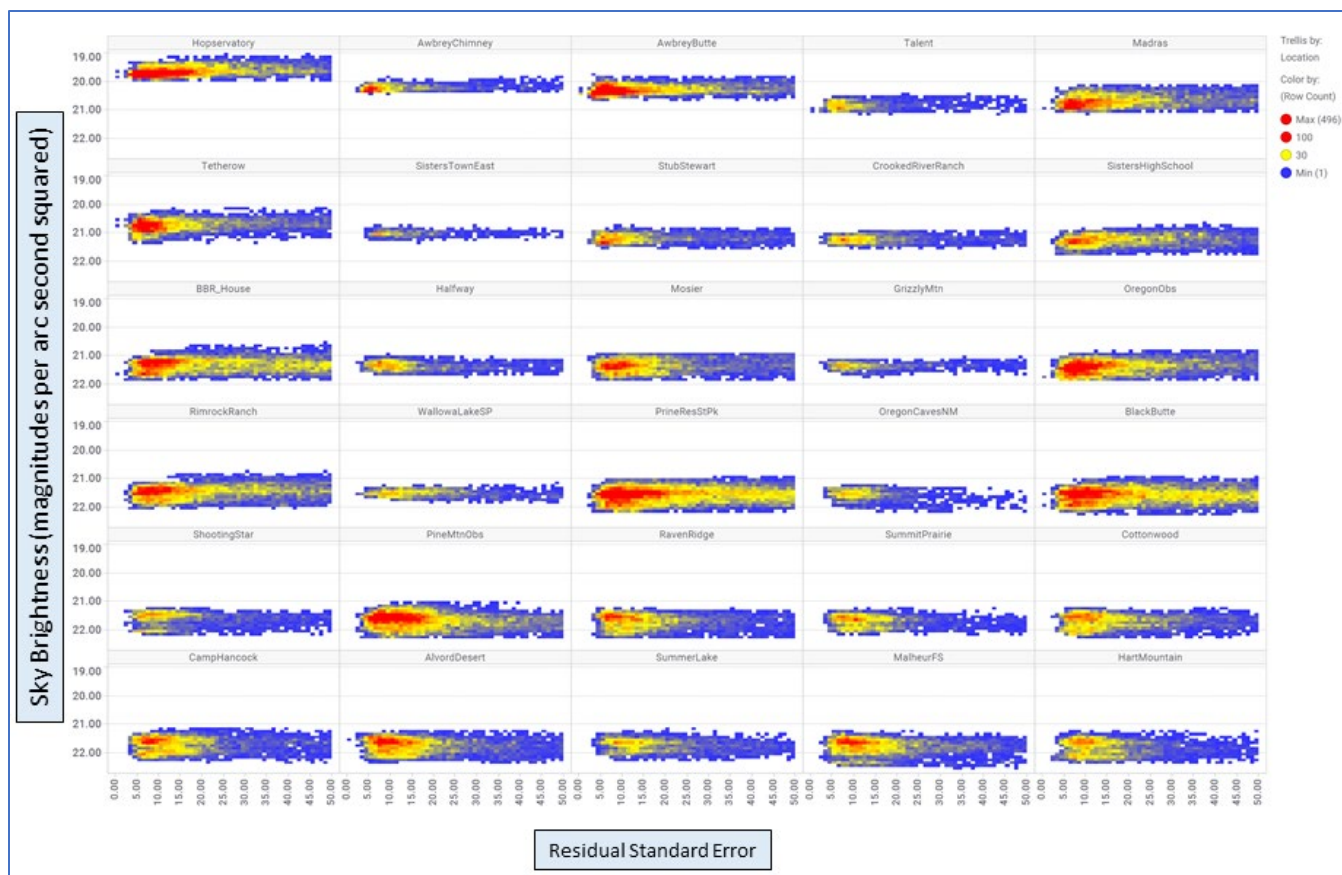


Figure B3. Density plot of residual standard error values versus sky brightness for all 30 SQM sites. All of the sites show a cluster of values at the short end of the RSE scale. We choose a cutoff value of 20 to include those clustered values as clear sky data points.

Appendix C - Skyglow Signature of a Site

Skyglow data acquired over months and years provides a cumulative signature which is characteristic of the amount of light pollution at each measurement site. We summarize two main features of that signature: (1) the brightness of the clear night sky and (2) the brightness of the night sky during cloudy conditions.

Measurements of the darkness of the **clear night sky** are useful to satisfy Dark Sky Place criteria and for comparison between sites without the complication of variable cloud cover. The darkness of the night sky **during cloudy conditions** provides an enhanced measure of the environmental impact of light pollution. At light polluted sites, the clouds are lit up from below and cast much more light downward into the environment, compared to sites without light pollution -- where clouds overhead appear black and compound the natural darkness.

Figure C1 shows the SQM measurements acquired at the Awbrey Butte neighborhood of the City of Bend, from July 2019 to September 2020. The vertical axis is the SQM brightness reading. The horizontal axis is local time of the night, in minutes since 3PM of the previous daytime. Data are from all of the nights, whether clear nights or cloudy nights, and only if the Sun is at least 18 degrees below the horizon, and the Moon is at least 10 degrees below the horizon.

Figure C1 is a density plot -- each small square in the plot shows how many measurements fall into that position. (See [Puschnig and others \(2013\)](#) for another example of a density plot of SQM data.) So, each small square includes one or more of the SQM measurements. The number of SQM measurements in each small square is color-coded based on the percentage of the total number of data points available.

The red and yellow trend in the plot across the darkest sky measurements at the bottom of the plot identifies the very frequent measurements over the time period. We call that red trend the “Most Common Clear Dark Sky Night” or MCC for short. The large sparse, scattered area of blue and yellow color above the red trend represents SQM measurements taken under cloudy skies at night. Both features of the density plot, the dense red trend and the sparse blue pattern above, and other subtleties present, represent the skyglow signature of the site.

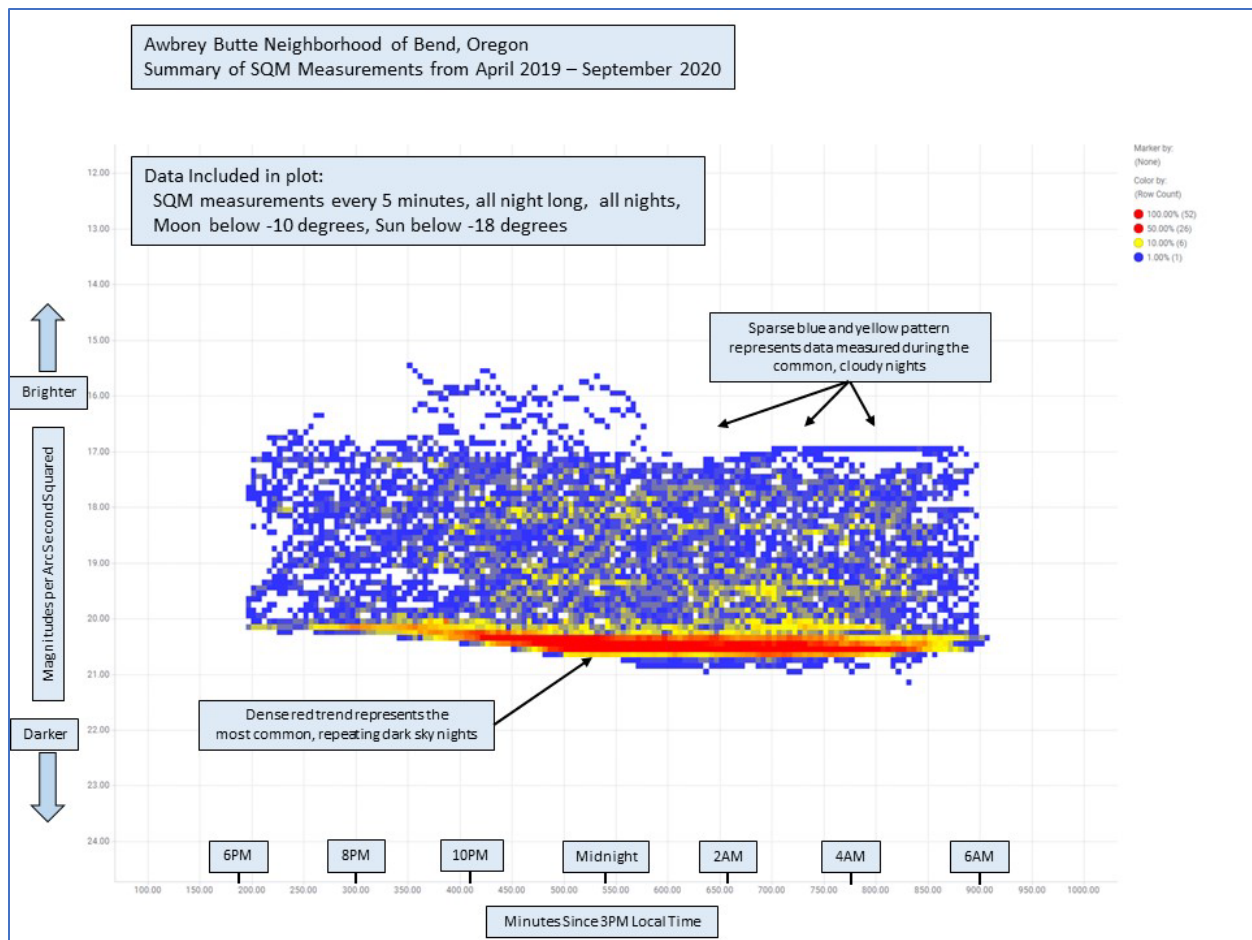


Figure C1. Density plot of SQM data from the Awbrey Butte Neighborhood site. Each small square represents the percentage of 5-minute SQM samples that fall into that zone. We take the dense red trend across the bottom of the data as the Most Common Clear Dark Sky Nights (MCC). The sparse blue and yellow pattern at brighter skyglow values are due to measurements under cloudy skies at night.

Figure C2 shows an SQM signature density plot with an entirely different character – from the Pine Mountain Observatory (PMO) site which has very little light pollution overhead. The red and yellow streak of MCC at this site is positioned between 21 and 22 mags/arcsecond², which is about 4x darker than the Awbrey Butte site (20 – 21 mags/arcsecond²). Moreover, the sparse blue pattern of clouds is entirely below the clear night MCC red streak, instead of above it.

This signature is characteristic of dark sky sites -- there is very little light pollution coming from the ground at the PMO site, so any clouds overhead are not lit up from below – instead, the clouds appear black and block the starlight. Because the clouds appear black, the data from cloudy nights plot below the clear night MCC red streak on the plot.

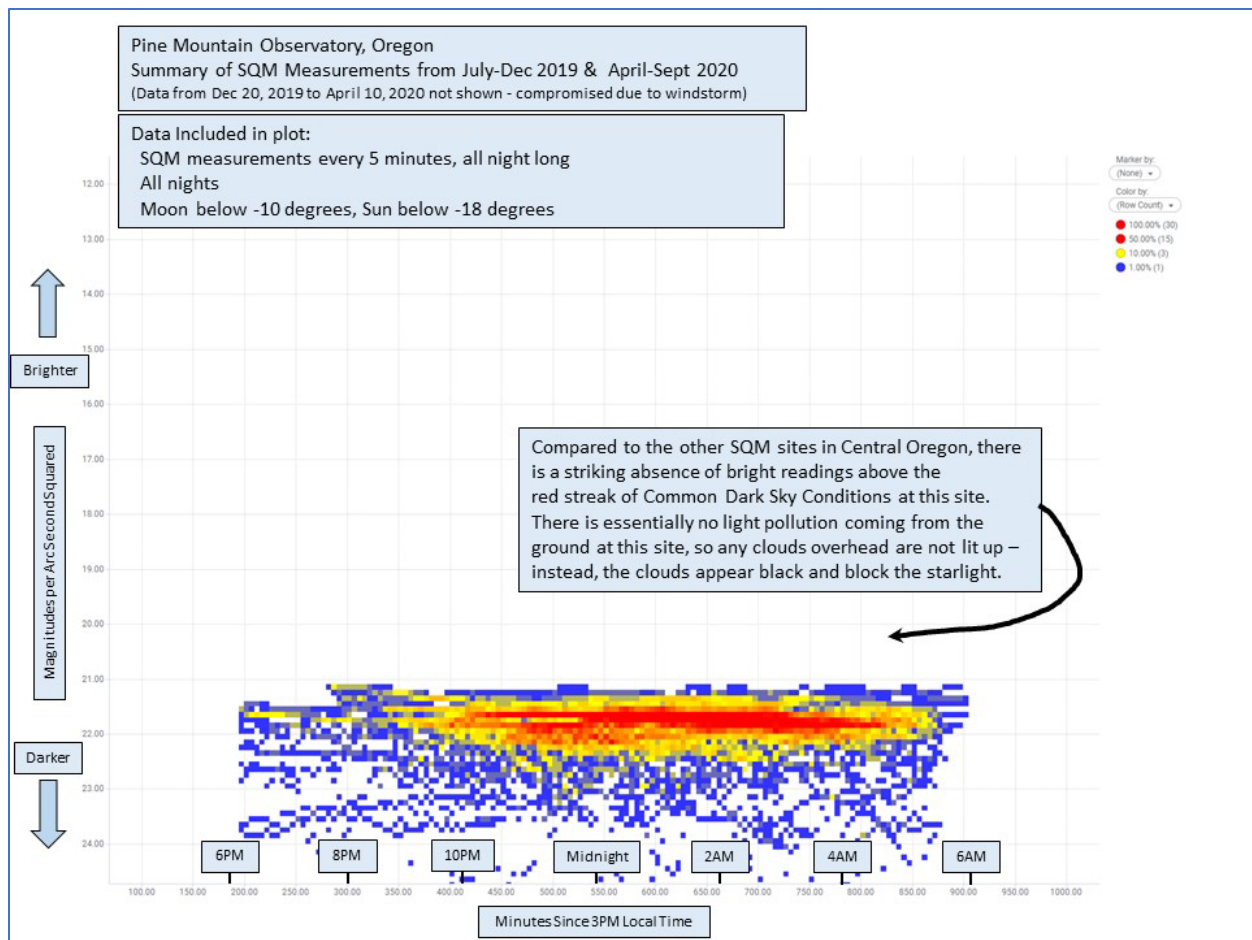


Figure C2. Density plot of SQM data from the Pine Mountain Observatory site. Note the absence of bright readings above the red and yellow streak of MCC at this site. See explanation in the figure and in the text.

Figure C3 summarizes the density plots for all of the SQM sites in the Oregon SQM Network which have been recording up to November 2021. The plots are arranged from top left to bottom right, from most light-polluted to least light-polluted. Some sites have been recording for shorter periods, so they show more sparse density plots. Appendix A summarizes the data available over time for each site.

Notice that the red streak in each successive plot of Figure C3 falls lower, toward darker readings, and that along the bottom row of least light-polluted sites toward the lower right, the sparse blue points which represent measurements taken during cloudy conditions tend to progressively appear below the red and yellow streak.

The characteristic red and yellow streak of each of these sites in Oregon may be a feature of the relatively dry, high desert environment of this part of Oregon which has many clear nights throughout the year. Other climatic areas may not show such pronounced high-density streaks in SQM density plots.

Also notice that the Madras and Tetherow sites show yellow streaks at much brighter values above the red streaks. The yellow streaks represent a recurring, probably cloudy condition, which is much less frequent than the clear night condition represented by the dominant combined red and yellow streaks.

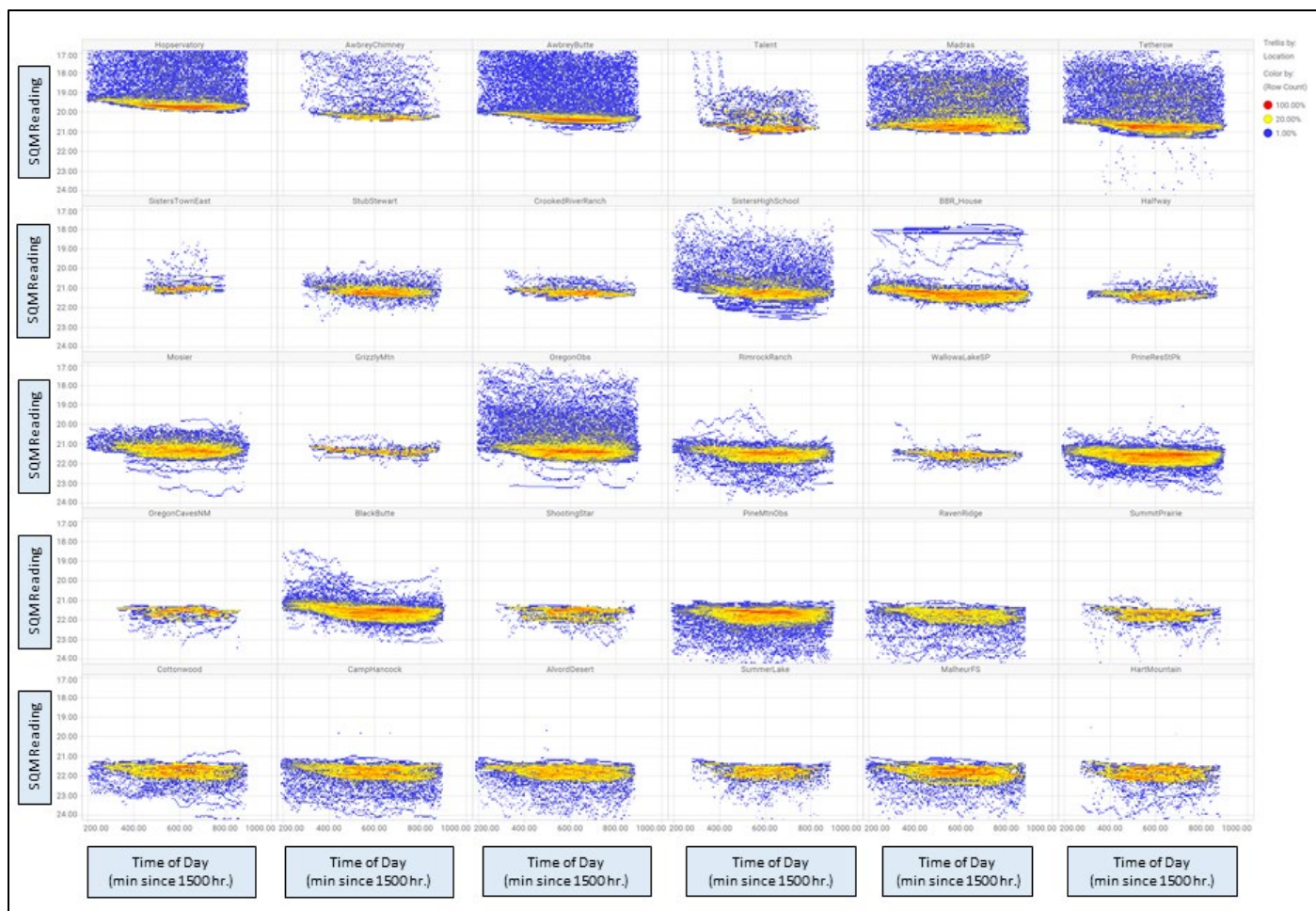


Figure C3. Density plots of SQM data from the thirty sites with data available to November 2021.

Figure C4 shows the data for all of the sites after “jaggy” data – cloudy data – removal by the algorithm described in Appendix B. Note that the algorithm failed to remove cloudy data from periods of uniform overcast or fog – there are smooth blue lines above and below the high density points at many of the sites in Figure C4. To fix this, we manually deleted those points above and below the high-density red/yellow zones at each site. The cleaned, cloud-free data are shown in Figure C5.

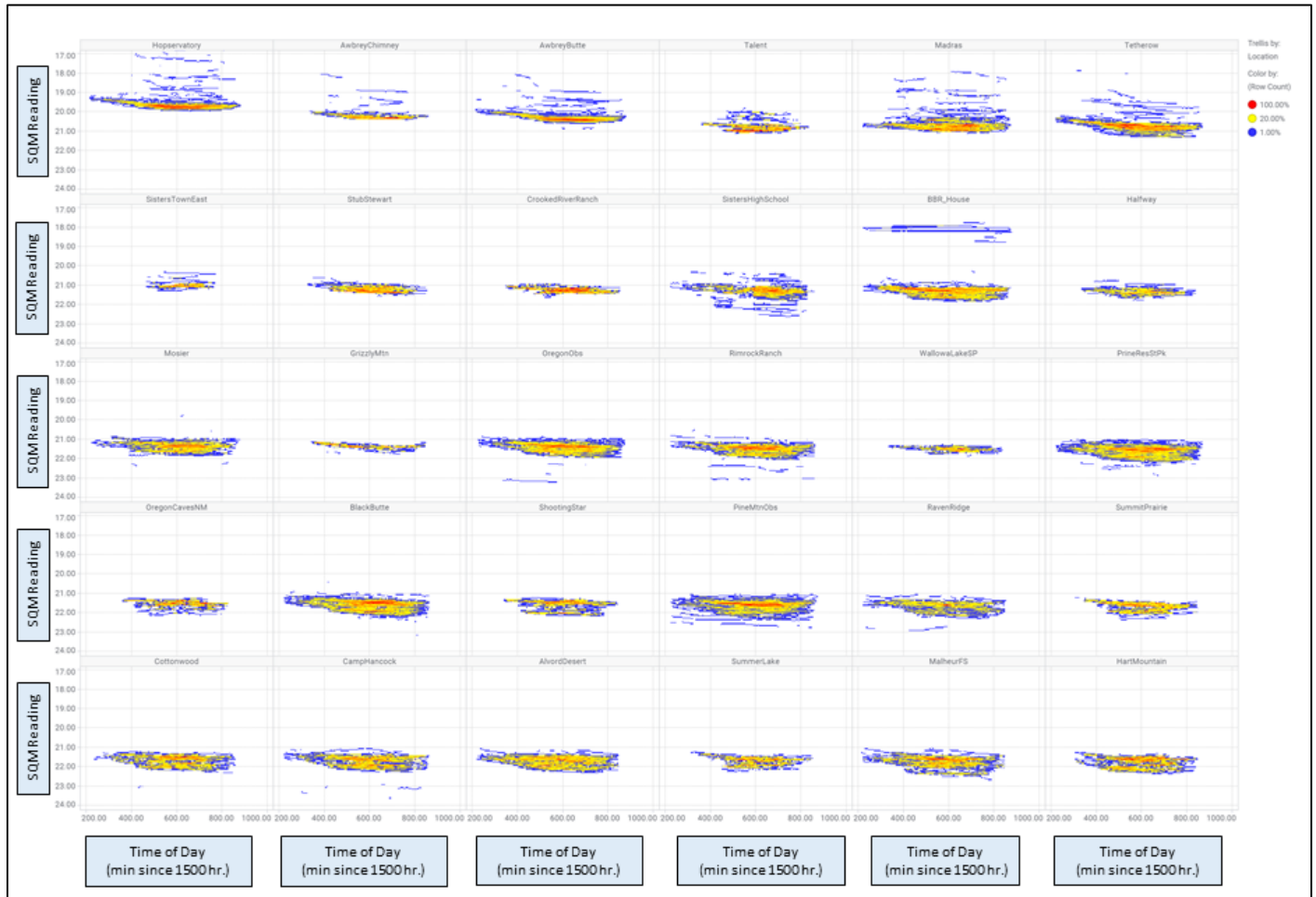


Figure C4. Density plots of SQM data from all thirty sites after application of the cloud removal algorithm. The algorithm fails to remove cloud cover that is consistent over time.

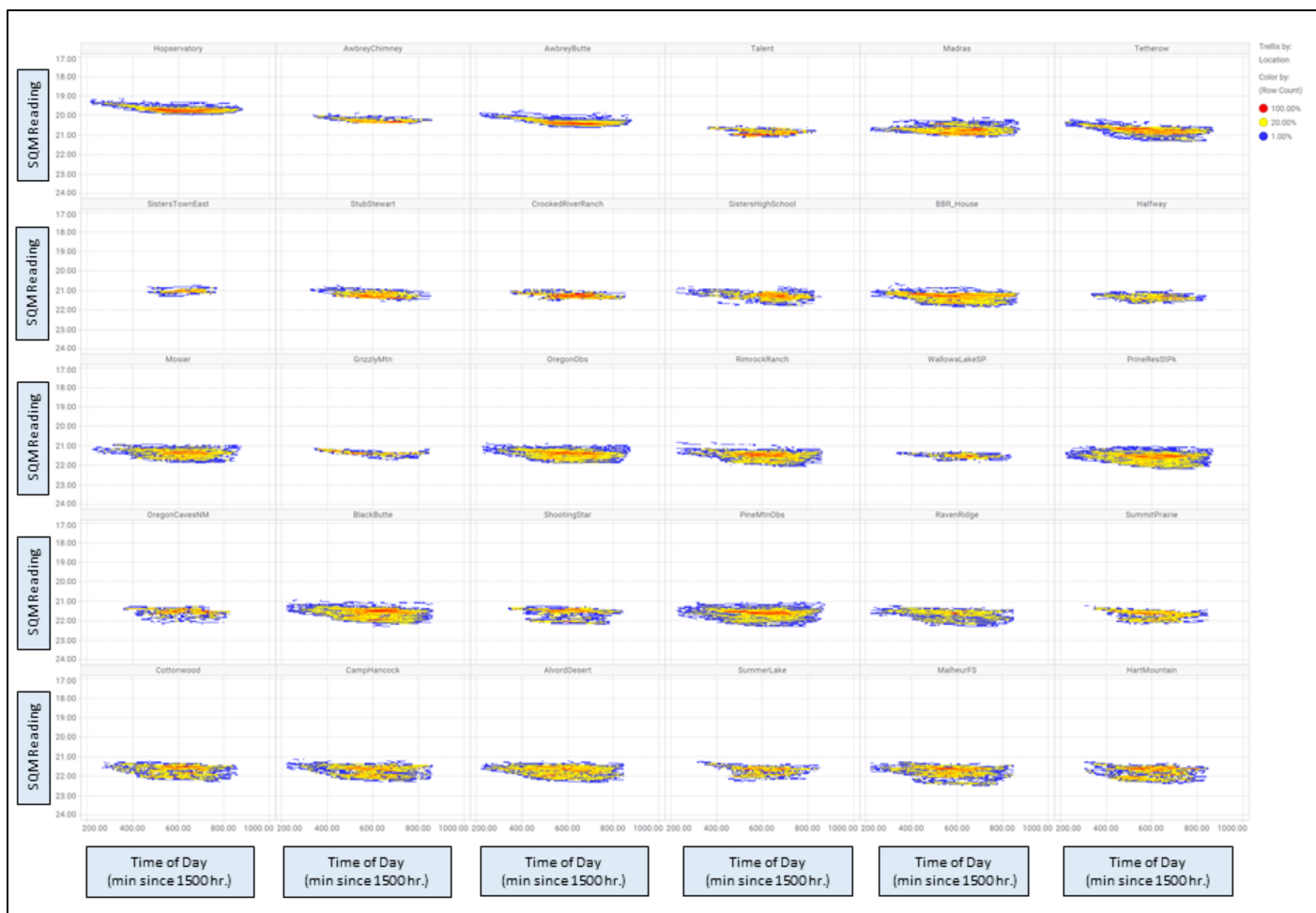


Figure C5. Density plots of SQM data from all thirty sites after manual cleaning of the smoothly-varying cloudy data.

Appendix D – Darkening over time with aging of SQMs

Recent research (Puschig and others, 2020) documents that as the SQM device and weather proof enclosure age, that there is a darkening effect on measured data, in their case an average of about .04 mags/arcsecond² per year. This aging will darken the skyglow measurements over time.

To understand this phenomenon better, we obtained two new SQMs and installed them to run in parallel to two SQMs which had been running for about three years. We installed one at a light polluted site (Awbrey Butte) and the other at a dark sky site (Prineville Reservoir State Park). Both ran in parallel for several weeks.



Figure D1. New and old SQMs running in parallel at two different sites, with the goal of assessing aging phenomena of the SQM unit. Awbrey Butte site on the left, Prineville Reservoir State Park on the right.

Figure D2 shows the results of this experiment.



Figure D2. Box plot comparing data recorded by the two sets of parallel-running SQMs. In both cases, the older SQMs recorded slightly darker skies on average.

Table D1 summarizes the statistics of this experiment.

SQM	SQM ID	Install Date	End of Test Date	SQM Exposure (days)	SQM Exposure (Years)	Difference of Exposure (years)	Count	Average	Median	Msas Difference of Average	Msas difference per Exposure Year
Awbrey Butte Old SQM	A5055IWP	13-Mar-19	2022-02-20	1075	2.9452		819	20.404090	20.44		
Awbrey Butte New SQM	ABSCDE1J	22-Jan-22	2022-02-20	29	0.0795	2.8658	814	20.351351	20.38	0.052739	0.018403188
Prineville Old SQM	AK06E3YZ	30-Jun-19	12-Feb-22	958	2.6247		366	21.766366	21.81		
Prineville New SQM	ABSCDQTV	30-Jan-22	12-Feb-22	13	0.0356	2.5890	373	21.715764	21.76	0.050602	0.019544688
										Mean	0.018973938

Table D1. The older SQM in each case recorded an average value .05 magnitudes per arc second squared darker than the new SQM in parallel. This amounts on average to .019 per year of exposure.

Distributed over the time range of exposure difference, we estimate a darkening of about .019 magnitudes per arc second squared per year of exposure. Accordingly, we subtract values proportional to this assumed aging effect progressively from our data, based on the serial exposure time of each data point of each SQM in our network.

Puschnig and others 2020 had three SQM sites at widely different locations, ranging from about 48 to 60 degrees North latitude. They noted aging proportional to the latitude of exposure, with less darkening at higher latitudes, related to the amount of sunlight exposure at each site. Figure D3 plots the Puschnig and others aging data versus latitude. Given that data, the Oregon SQMs at about 44 degrees north latitude should have a darkening at about .06. Instead, we find a darkening of less than .02.

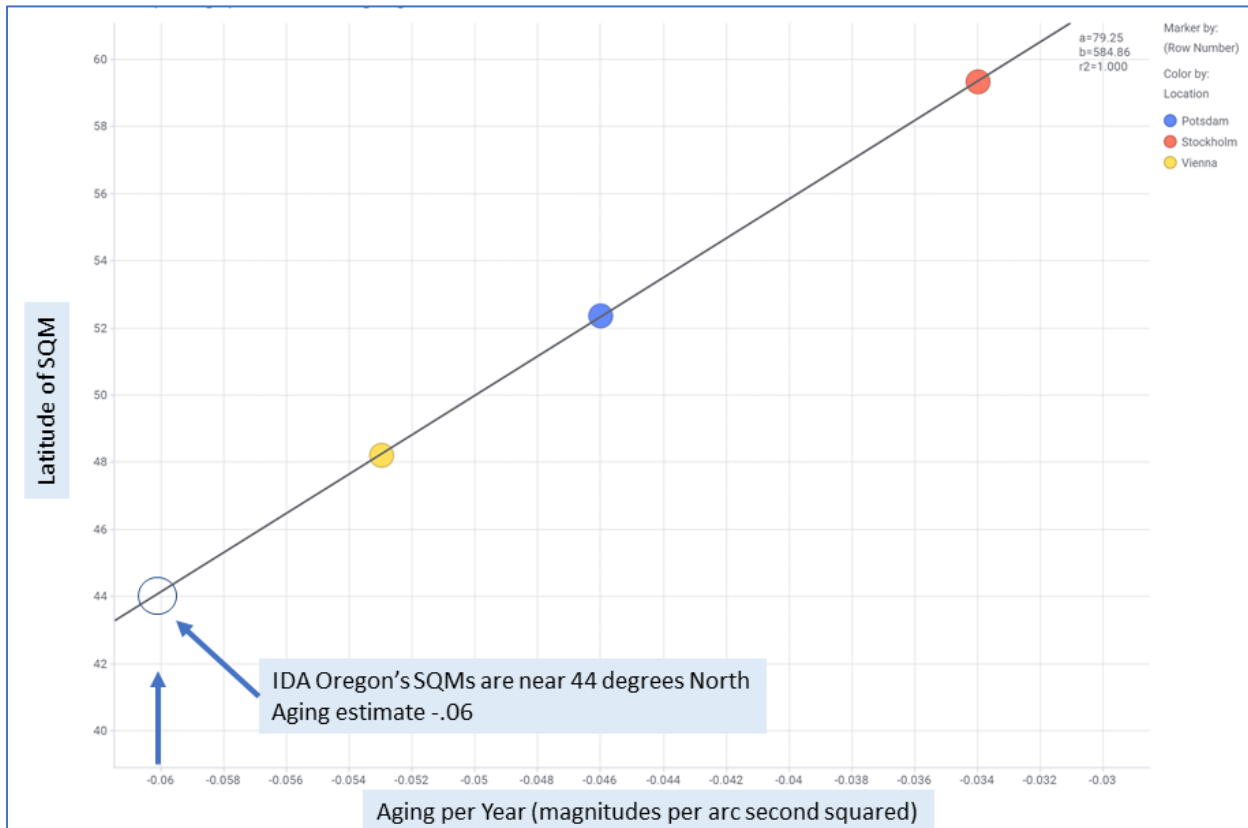


Figure D3. Data on aging of SQMs from Puschnig and others, 2020. There is a strong relationship of latitude on the rate of aging. Based on the three SQMs in their data set (colored dots) the Oregon SQMs should have an aging rate of about .06 per year. Our current experimental data suggest a smaller aging rate of slightly less than .02 per year.

Our parallel SQM experiment only involved two pairs of SQMs. Additional experimental data along with re-calibration of older SQMs should shed additional light on this. It could be that our observations of older SQMs recording darker values are not caused by darkening, but by some other calibration issue. We currently attribute the difference to aging of the older SQM. We have implemented the approximately .02 per year aging adjustment in our data processing in this report.

Appendix E - Adjustment for Brightness of the Milky Way

When the Milky Way is overhead, the SQM will record a brighter night sky. Instead of eliminating those measurements as we did for Goal #1 (measurements in support of Dark Sky Places), we instead keep those data and normalize out that effect in processing toward Goal #2. By this method, we minimize the seasonal nature of the Milky Way pattern and also avoid loss of data.

In the following, “galactic latitude” refers to the angle between the zenith at an SQM site and the center of the highest arc of the Milky Way in the night sky. A galactic latitude of zero signifies that the SQM is pointed directly into the Milky Way overhead.

The left side of Figure E1 shows a plot of the SQM measurements (after conversion to the linear candelas scale) from the clear sky data on the vertical axis versus the galactic latitude of the SQM pointing direction. These data are for two sites, Awbrey Butte and Black Butte Ranch. The data is colored by the galactic latitude – reds correspond to galactic latitudes around zero.

The black line through the data on the left side of Figure E1 is a 4th order polynomial fit to the data, which shows a broad maximum of SQM-measured brightness near galactic latitudes around zero. We measured a brighter sky when the Milky Way was overhead.

The polynomial fit allows an adjustment for galactic latitude, which is shown on the right side of Figure E1. After adjustment, the polynomial fit to the data is now horizontal. We adjusted the data to a galactic latitude of 30 degrees, which is midway between the high and low of the original data across the range of galactic latitude.

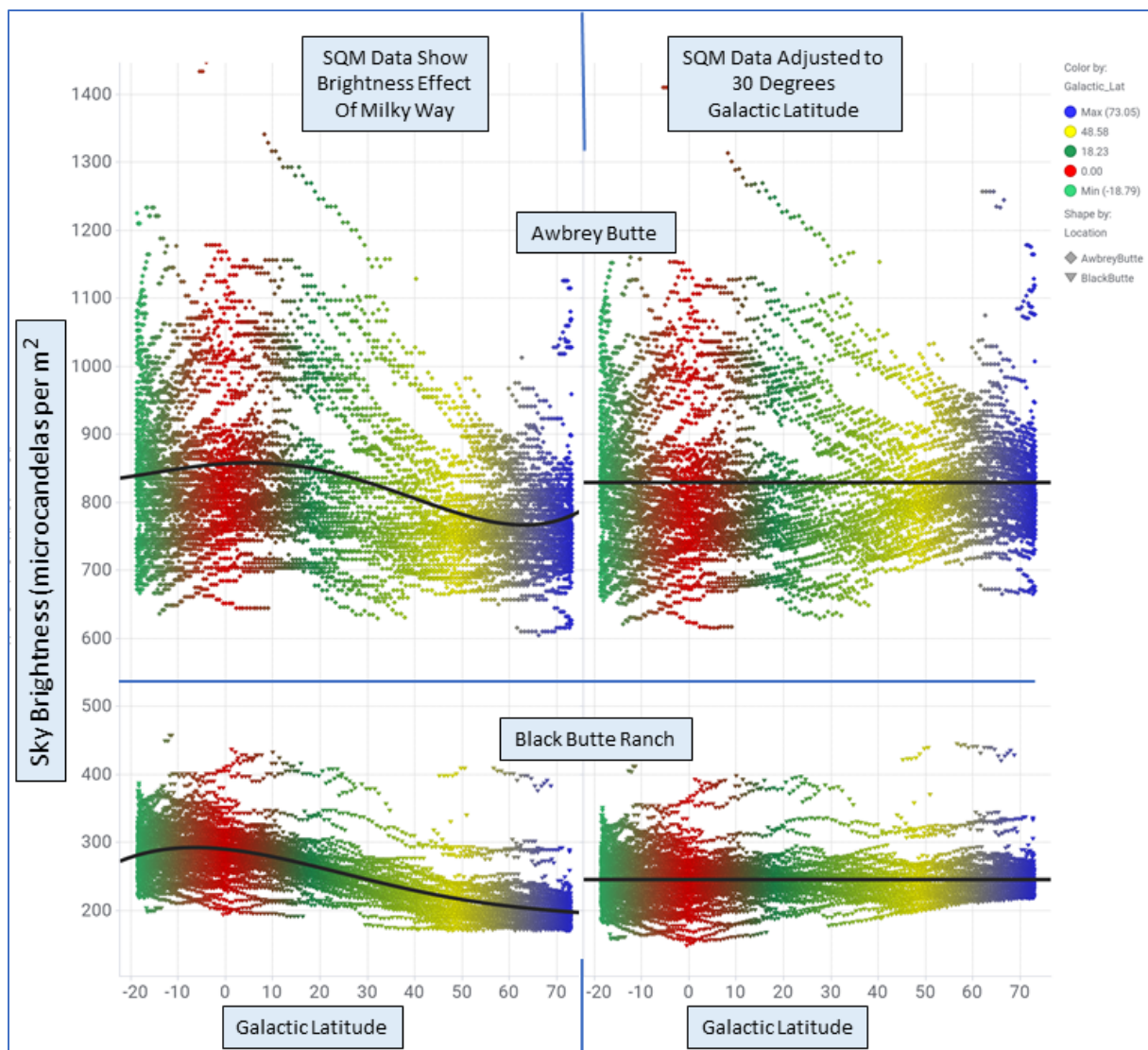


Figure E1. Adjustment of SQM data for the position of the Milky Way in the sky for the Awbrey Butte and the Black Butte Ranch sites. The left part shows the original data, the right part shows the data after adjustment for galactic latitude. See text for explanation.

Figure E2 shows histograms of the amount of adjustment of the SQM data for the 12 long term sites with at least 1.5 years of data, colored by galactic latitude.

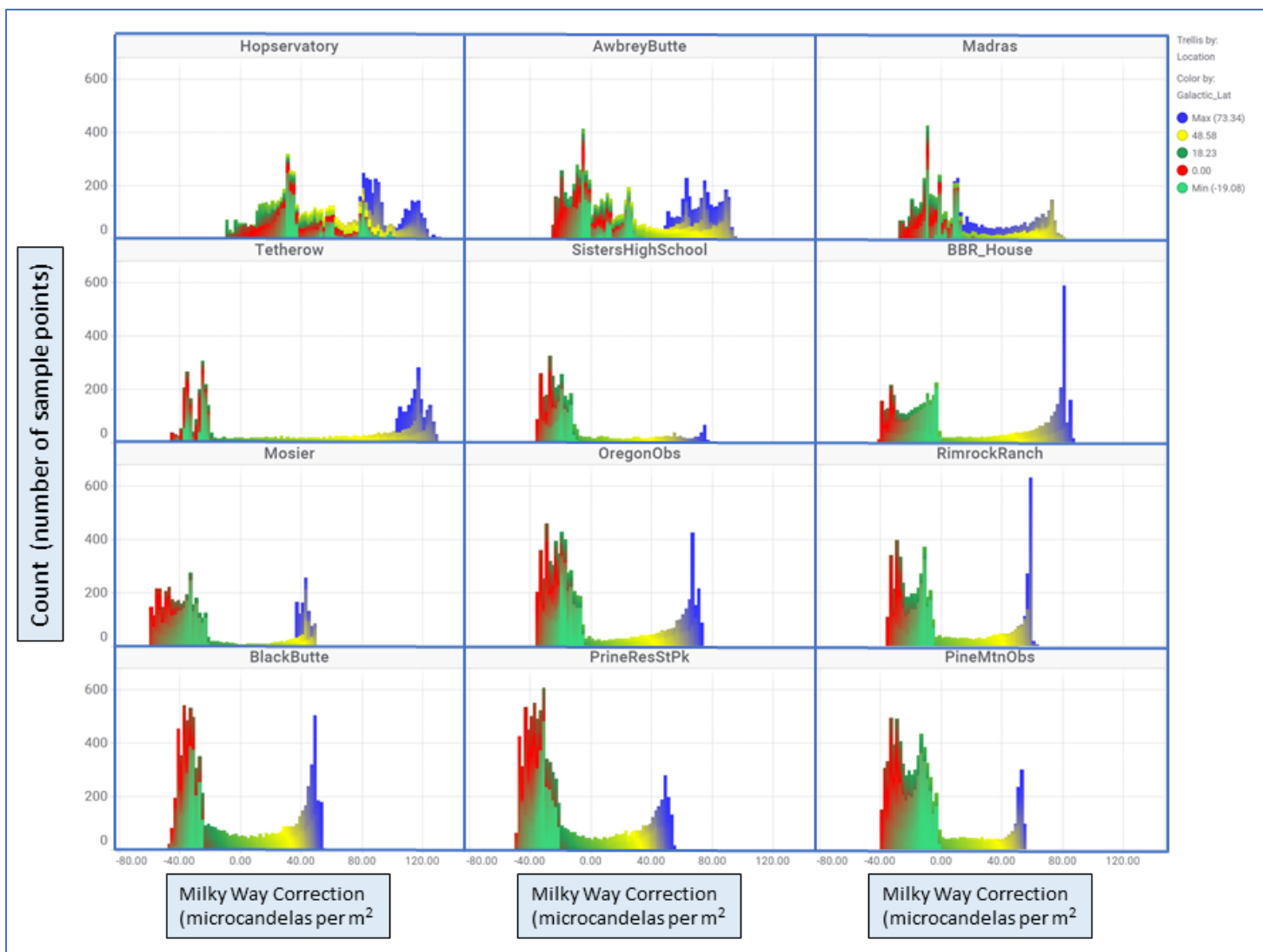


Figure E2. Histograms of the amount of adjustment introduced by normalization for the presence of the Milky Way in the sky brightness measurements. These are the 12 sites with at least 1.5 years of data.

Appendix F - Filter data to summer night time hours

We wish to minimize the seasonal pattern in time of darkness during winter versus summer nights. In our northern hemisphere winter, we experience much longer evening hours of darkness, versus during the summer months. That is, darkness in the winter begins much earlier in the evening.

Figure F1 shows data acquired during the winter (annual quarters 4 and 1) for the Hopservatory site which is light polluted. At the beginning of the winter evening, the skyglow is quite bright, we expect due to most outdoor lights being on and people driving about with car headlights lights on. As the evening hours pass, the light pollution and skyglow decrease.

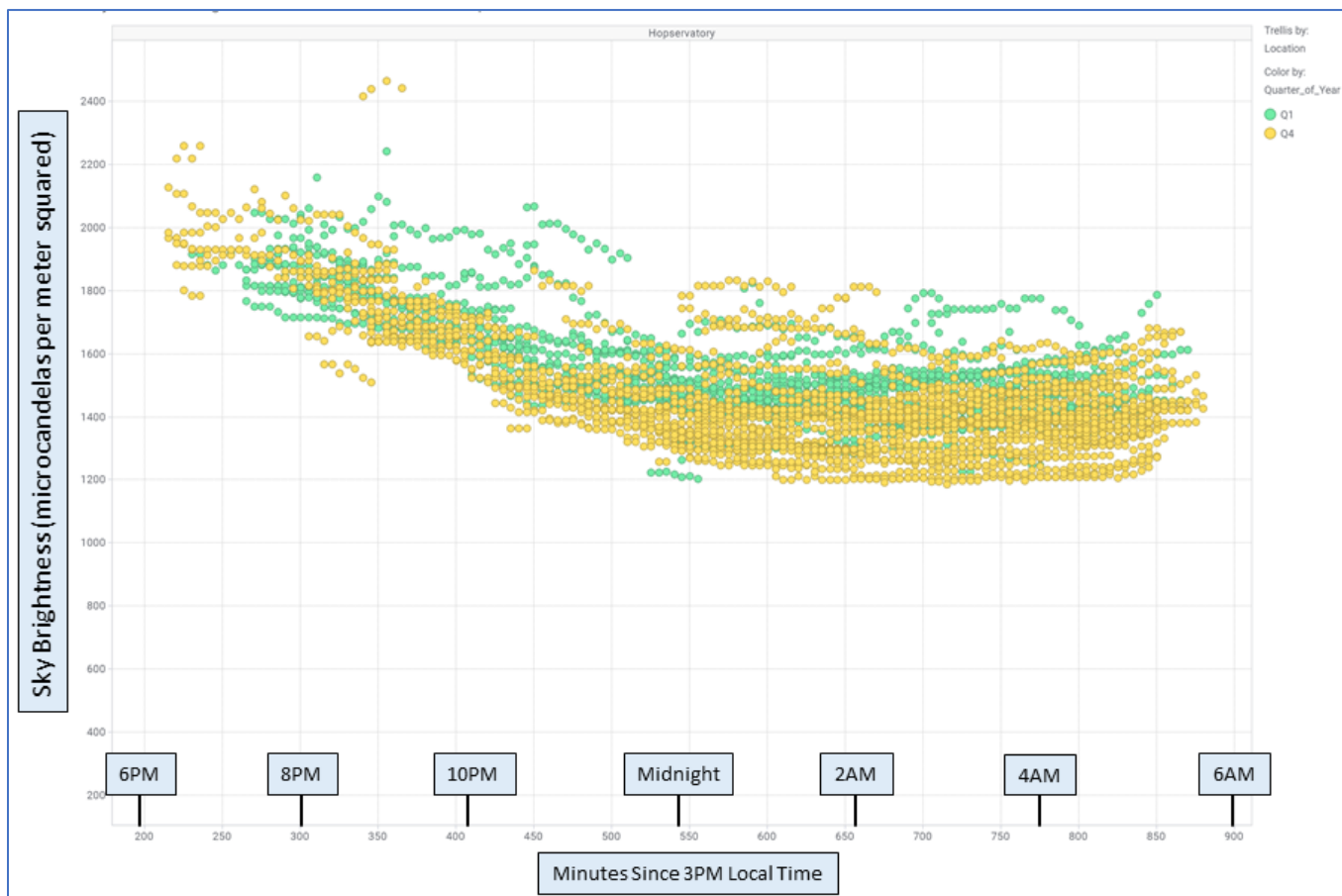


Figure F1. Data acquired at the Hopservatory, a light polluted site, during winter. There is a pronounced drop in sky brightness from the early evening toward midnight. Points are colored by quarter of the year. Q1 (Jan, Feb, Mar) points are green. Q4 (Oct, Nov, Dec) points are yellow.

Figure F2 shows the data acquired during the spring and summer (annual Quarters 2 and 3, April - Sept) for the same site. The hours of darkness begin much later in the spring and summer and do not show as pronounced a drop in brightness over time.

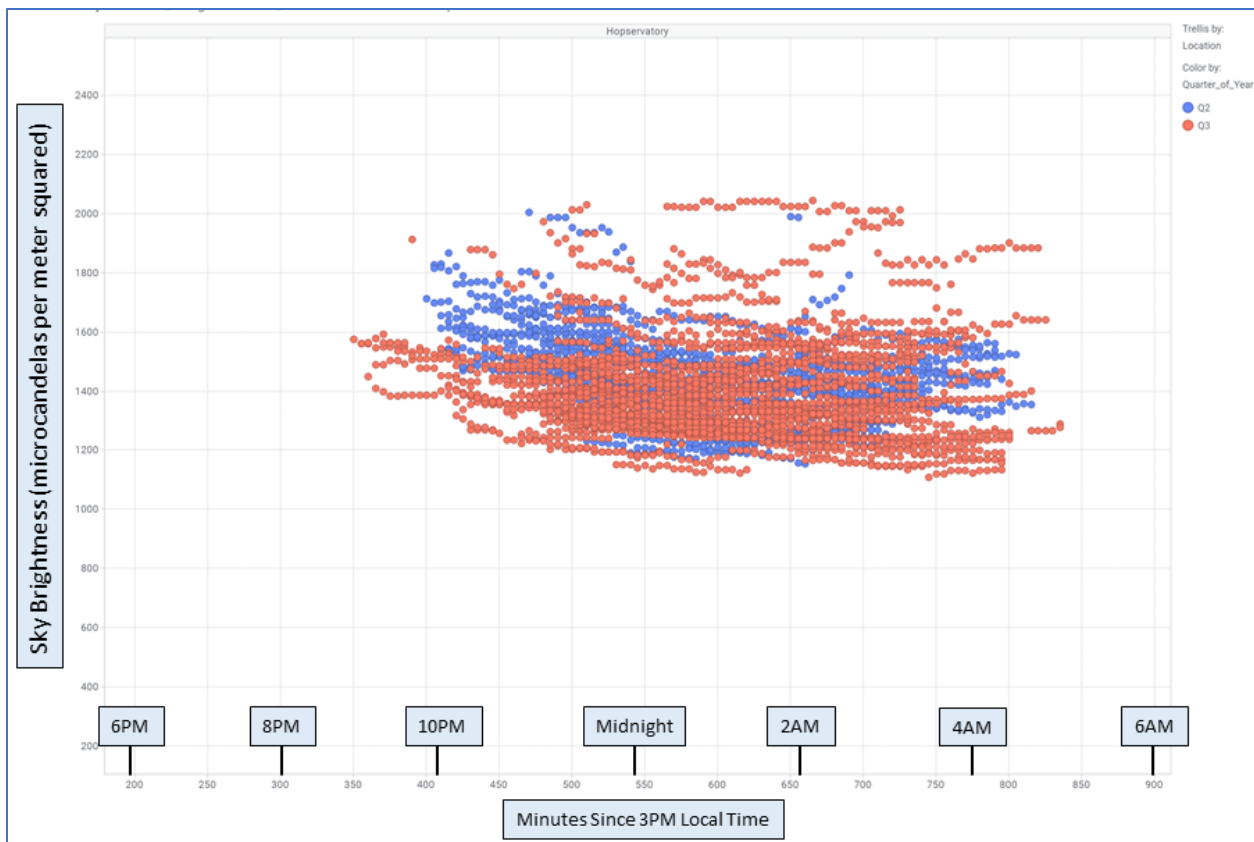


Figure F2. Data acquired at the Hopobservatory, a light polluted site, during summer. The sky brightness from initial darkness onward does not decrease as much as in winter (Figure F1). Points are colored by quarter of the year. Q2 (Mar, Apr, May) points are blue. Q3 (July, Aug, Sep) points are red.

While this winter versus summer evening effect is consistent from year-to-year and may be considered a known and constant influence on the seasonal skyglow trend, on the other hand, the time of acquisition of our data from various SQM locations does not include complete seasonal cycles, so the trend over years will be influenced by which seasons are covered by each SQM data set. So, instead of ignoring this regular seasonal pattern, we choose to filter all data to the summer night hours.

We removed this seasonal bias by filtering data by hours on a nightly basis -- to only include data from 10:30PM local time to 4:30AM local time, which is the time range of the summer nights in our latitude range. Figure F3 shows the data for the Hopobservatory site after filtering to the summer time range.

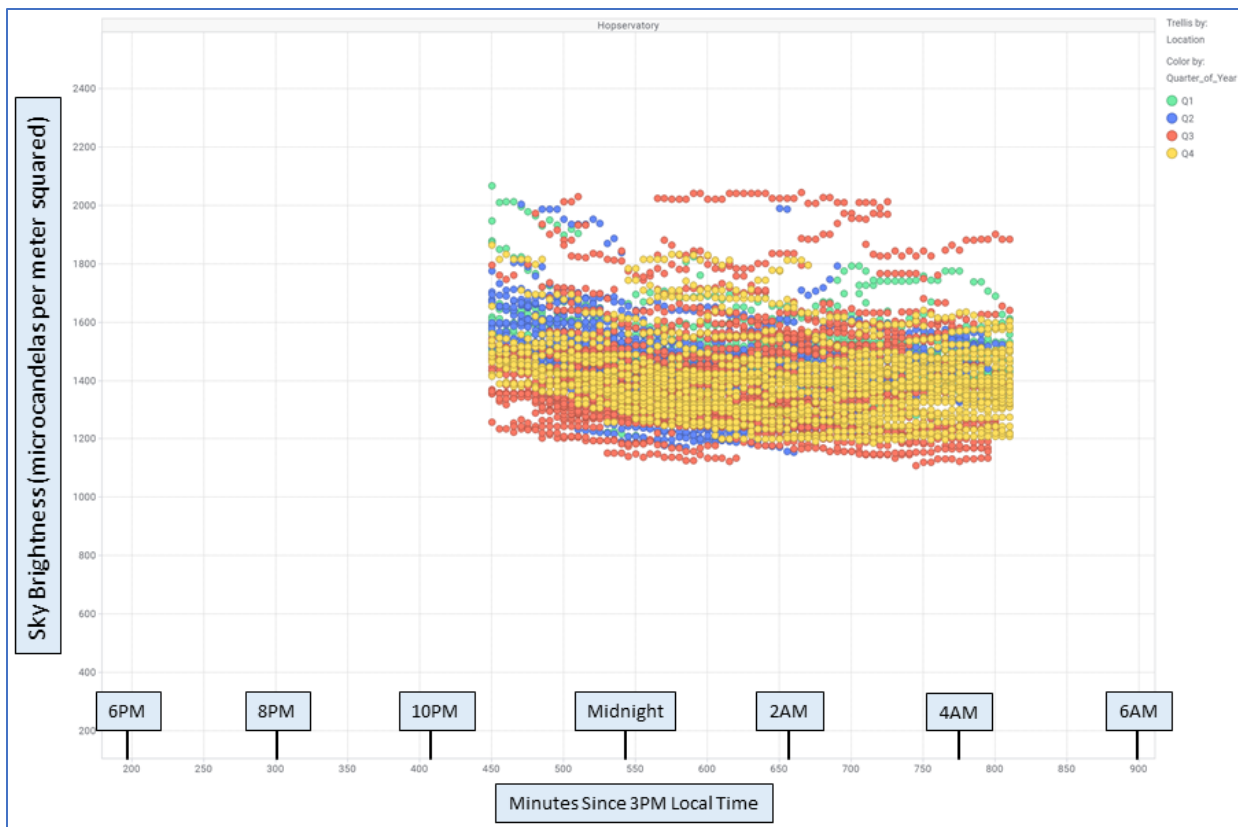


Figure F3. Data acquired at the Hopobservatory, a light polluted site, after filtering to only include data between 10:30PM and 4:30AM local time. Data from all quarters of the year are shown by colors. Points are colored by quarter of the year.

Appendix G - Seasonal variation in ground cover and the atmosphere

Snow cover - Might variable snow cover during the winters of our data acquisition explain the seasonal pattern of bright readings in the winter? To evaluate the effect of snow cover on our skyglow trends, in Edition #4 of this report series, we used the archived day-by-day snow cover data available for the central Oregon region from the National Operational Hydrologic Remote Sensing Center (<https://www.noahrs.noaa.gov/interactive/html/map.html>). After eliminating data from any night which had a trace or more of snow cover on the ground, we find small changes in the trends – an average decrease in the trends of about 1% per year. We conclude that the snow cover does not play a large role in the observed trends and further that the summer to winter skyglow variation is largely not due to snow cover alone.

Temperature - The SQM device is internally temperature compensated. Schnitt and others, 2013, demonstrate by a laboratory experiment that despite the temperature compensation circuitry, that two SQMs they used recorded larger magnitudes/arcsecond² values (darker) when hot and vice versa (brighter) when cold. The difference in SQM readings between +35C and -15C was 7% to 10% (their Figure 3). In Edition #4 of this report series, we showed a rough correlation between temperature and SQM readings, in a trend consistent with Schnitt and others, 2013. In that report we applied a normalization via the temperature in an effort to subdue the seasonal variation. Figure G1 is taken from the Edition #4 report.

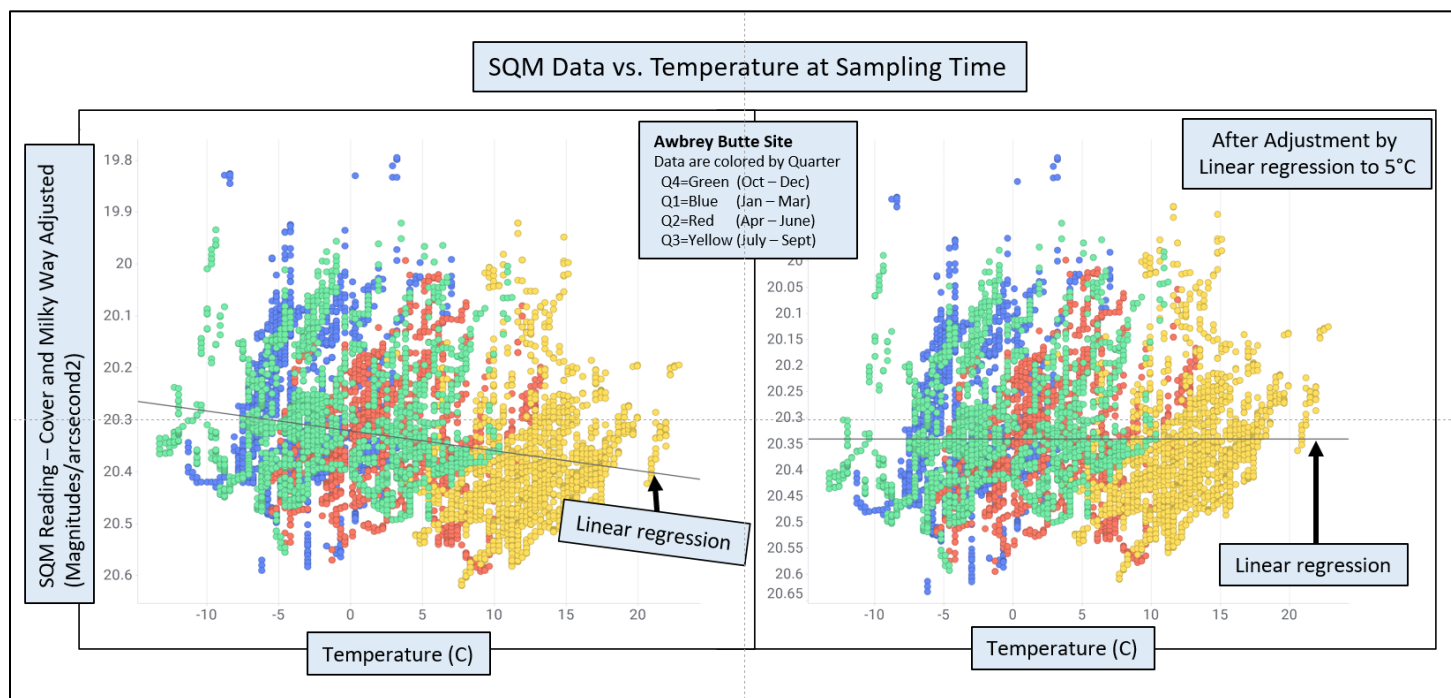


Figure G1 (from Edition #4 report). The left side shows SQM data from clear nights, Milky Way adjusted, when no snow was on the ground, from the Awbrey Butte site, versus temperature at acquisition. Data points colored green and blue were acquired during the cold season (Quarters 4 and 1). Red and yellow data points were acquired during the warm season (Quarters 2 and 3). The SQM recorded darker readings when temperatures were higher, and vice versa. The right side shows the same data after adjustment by linear regression to 5°C.

Humidity - In this report (Edition #5) we have not applied a temperature adjustment because we realize that atmospheric humidity may also be a main source of the brighter dark sky values in winter, along with the early evening hours of brighter night skies as described in Appendix F. In our high desert environment, humidity values are much higher in winter than in summer (Figures G2 and G3). Higher humidity will cause more atmospheric scattering and therefore brighter dark sky measurements. Or, perhaps both temperature and humidity work in tandem to give brighter dark sky readings in winter versus summer.

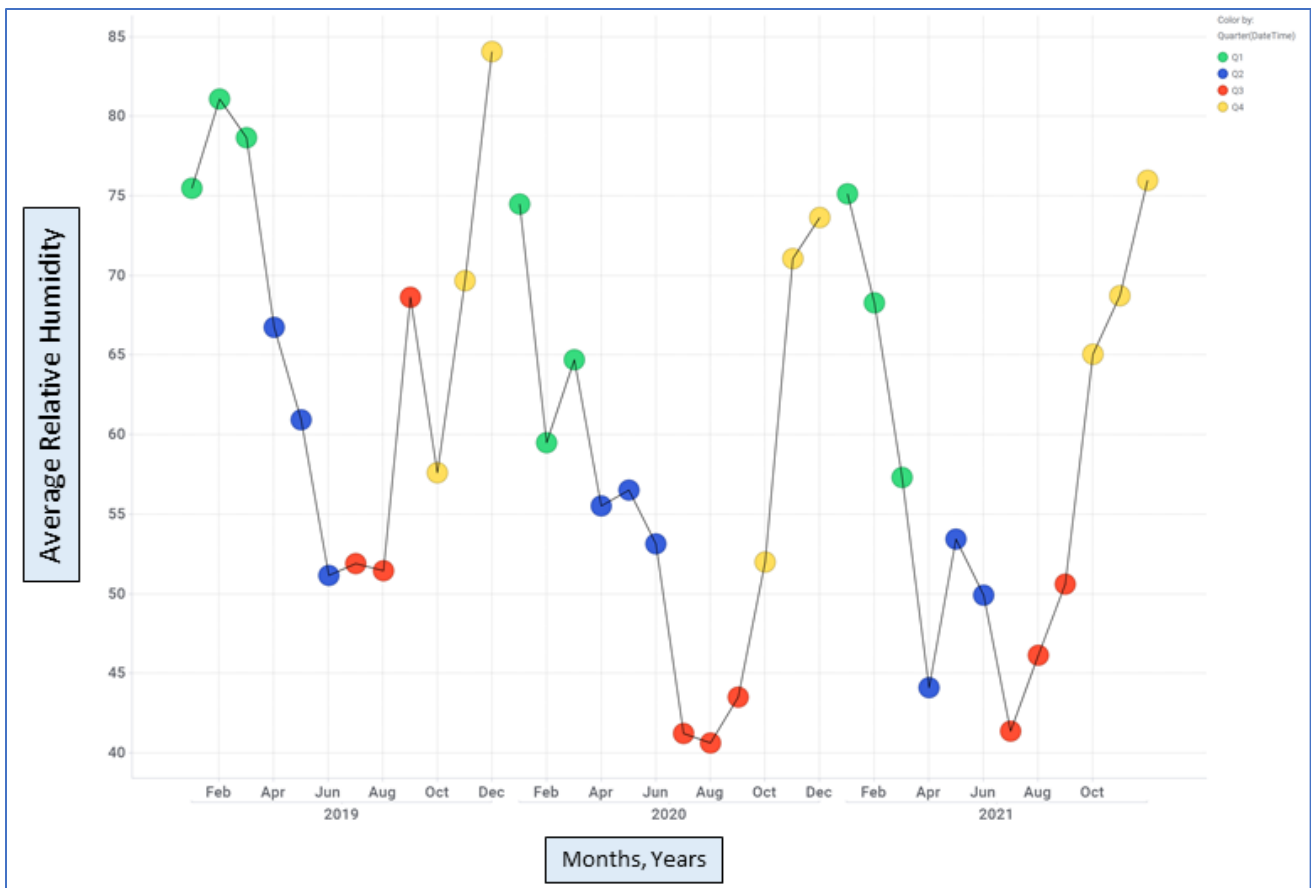


Figure G2. Average relative humidity recorded in Bend, Oregon over the three years for which we have SQM data. The relative humidity is notably higher during the winter than summer. Points are color-coded by quarter of the year. winter point (Q1, Q4) are green and yellow. Spring and summer points (Q2, Q3) are blue and red.

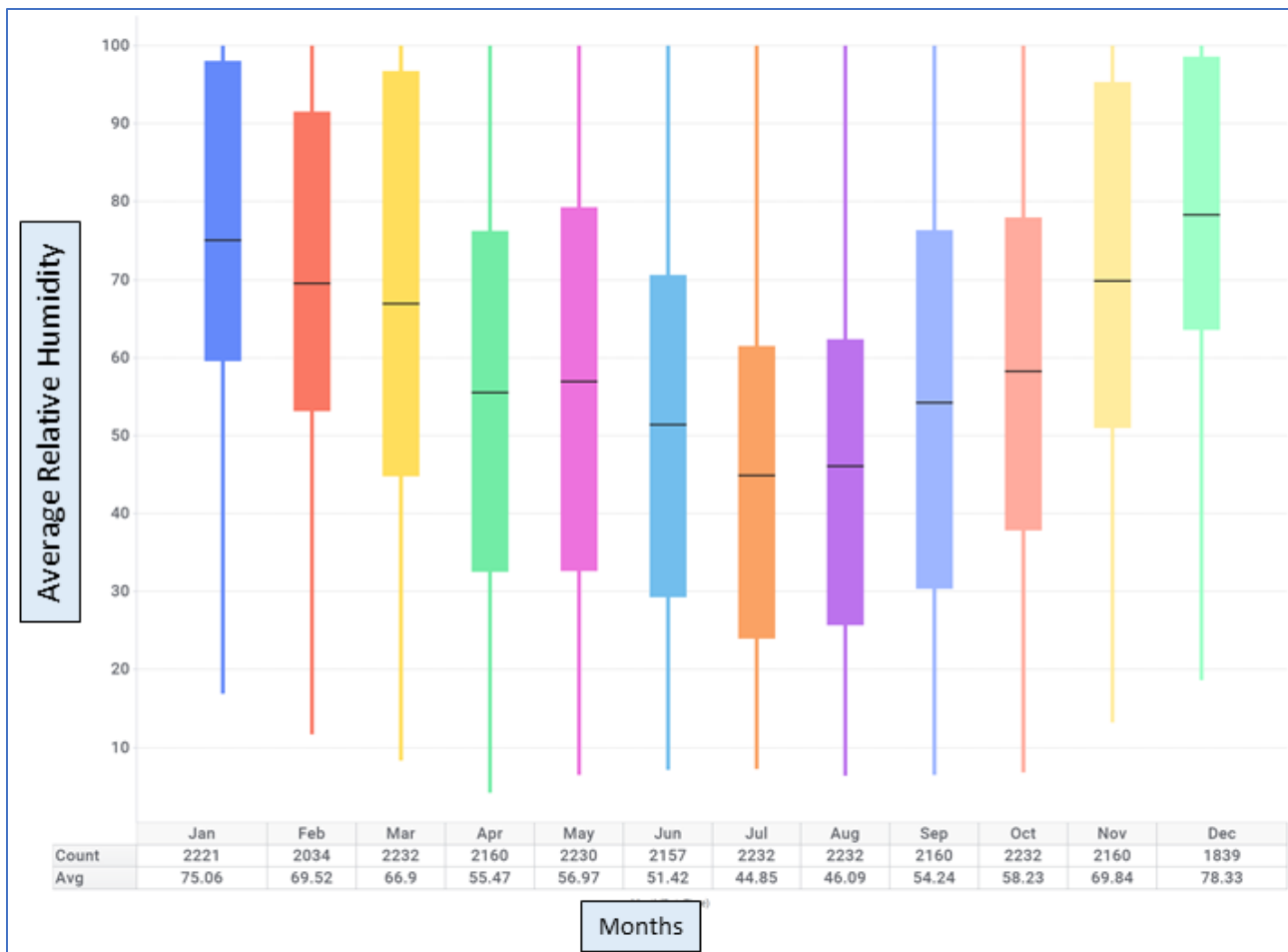


Figure G3. Boxplot of average relative humidity by month recorded in Bend, Oregon over the three years for which we have SQM data. The humidity is lowest in the spring and summer (April-Sept) and highest in winter months (Nov-Feb)

Atmospheric quality - Might variable atmospheric particulate concentrations over the course of our data acquisition period play a role in our sky brightness? To evaluate this, we acquired Purple Air (<https://www2.purpleair.com/>) air quality data from the vicinity of seven long term sites and associated that data into the 5-minute sample times of the SQM data. The sites are Awbrey Butte, Hopservatory, Black Butte Ranch, Oregon Observatory, Rimrock Ranch, Sisters High School and Tetherow. After filtering the data to the clear data under Goal #1 (filtered for sun, moon, clouds and time of night) the data show a gradual increase of particulates over the duration of our SQM data.

Figures G4, G5 and G6 show the PM1.0, PM2.5 and PM 10.0 data respectively, averaged by month over all the seven Purple Air sites adjacent to the SQM locations. The trends are upward, especially for the larger diameter particulates. This may be a result of increased forest fire activity, especially in August and September, since 2019 in the area of our study. We expect that high concentrations of large particulates will block skylight and result in darker readings. However, increases in the smaller particulates are likely to yield an increase in skylight. It seems likely that we have a case of competing influences of atmospheric effects on the skylight data.

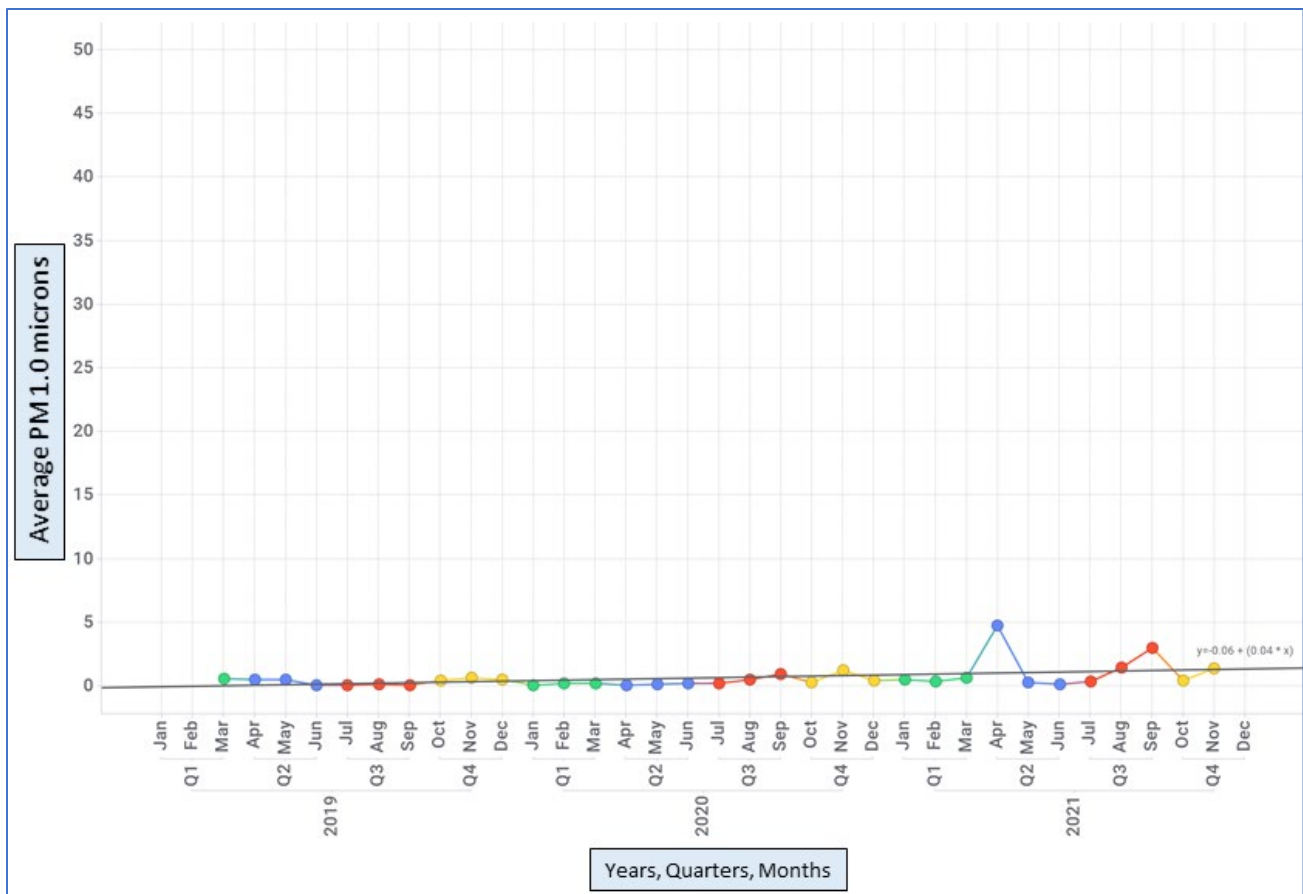


Figure G4. Average PM 1.0-micron air quality data averaged by month from the vicinity of seven long term SQM sites. Data are filtered according to criteria of Goal #1. The line shown is the linear regression fit.

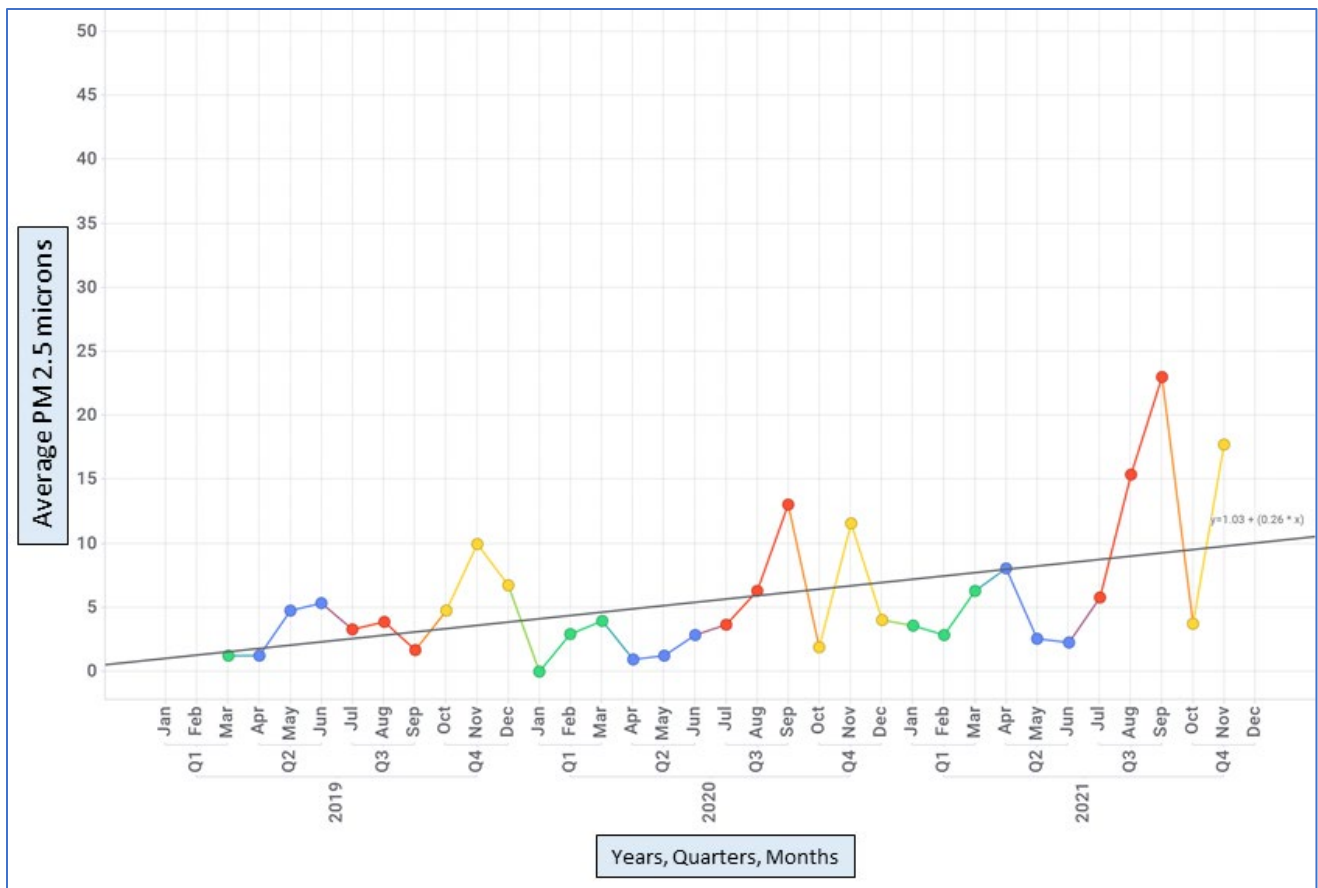


Figure G5. Average PM 2.5-microns air quality data averaged by month from the vicinity of seven long term SQM sites. Data are filtered according to criteria of Goal #1. The line shown is the linear regression fit.

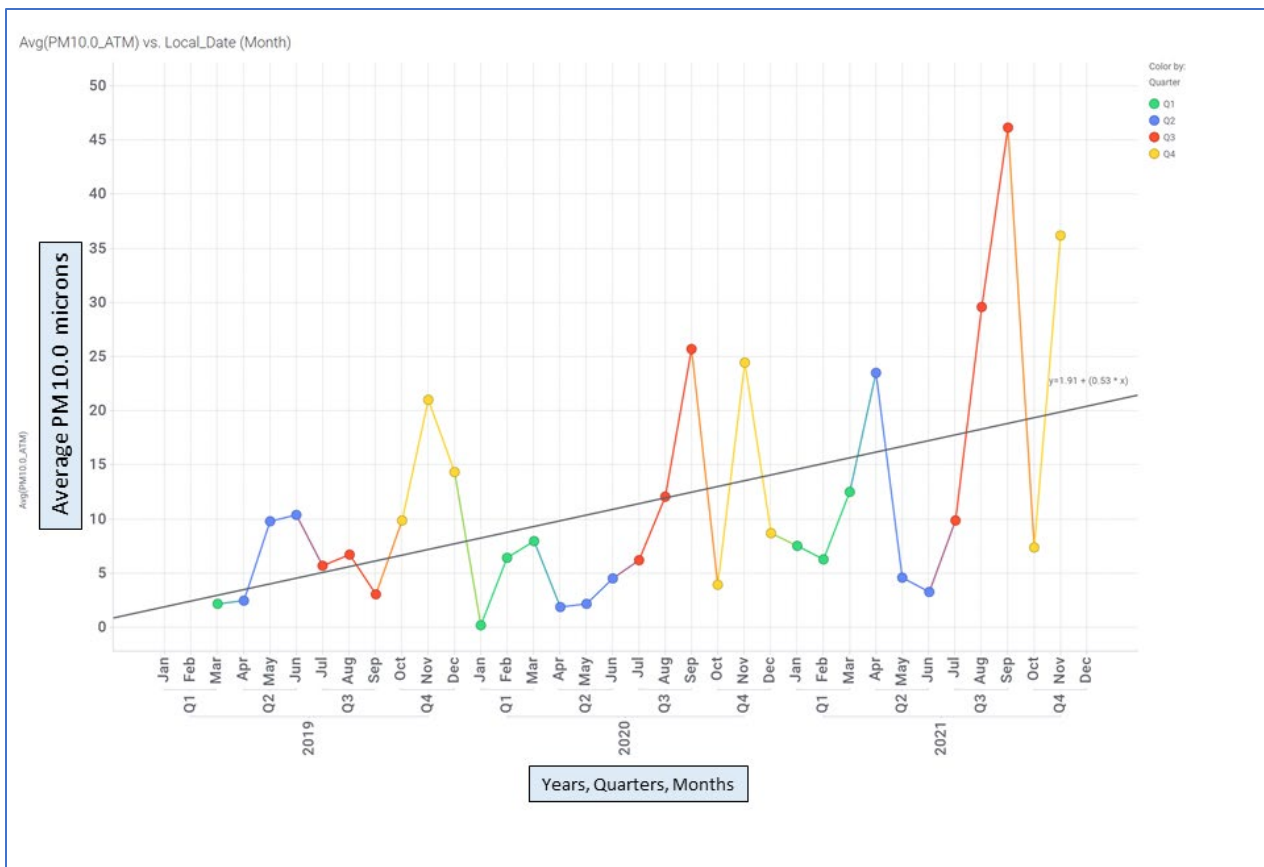


Figure G6. Average PM 10.0-microns air quality data averaged by month from the vicinity of seven long term SQM sites. Data are filtered according to criteria of Goal #1. The line shown is the linear regression fit.

The intensity of skyglow is a complex function of atmospheric character, including size and shape distributions of particles, layering in the atmosphere, distance from light source, spectral character of the light source, etc (Cinzano and Falchi, 2012; Kocifaj and Komar, 2016).

It is apparent that fairly detailed temperature, humidity and atmospheric particulate data along with atmospheric modeling will be needed to understand and adjust the seasonal patterns of skyglow and the impact of change of atmospheric character over time. Given all of the above, at present, we choose to not attempt adjustments over time for atmospheric quality or temperature or humidity.

Appendix H – Change of airglow over time related to changing solar flux

Another factor to consider in zenith skyglow trends over long periods is change of airglow, the light emitted from the atmosphere itself due to the impact of space weather on Earth (Grauer and others, 2019). Airglow is known to vary on a wide range of time scales, from rapid variation in minutes and across one night to strong, years-long changes correlated to the 11-year solar sunspot cycle.

The sun is currently rising out of a solar sunspot minimum, toward a predicted sunspot maximum in July 2025. So, space weather may cause our SQM data to read brighter since mid-2019 by increased airglow, independently of any changes in light pollution from the ground.

Krisciunas and others, 2007 showed that visible light measured at the zenith is correlated to the 10.7cm radio flux recorded 5 days prior to the night in question (their Figure 5). A plot of monthly averages of the 10.7cm radio flux (Figures H1 and H2) shows a decrease from the beginning of our SQM data in April 2019, a peak in late 2020, followed by a general increase to November 2021.

We fit a linear regression line to the data in Figure H2, which shows an estimated 23% increase in solar flux during our SQM study so far. Using the relationship in Figure 5 of Krisciunas and others, 2007, there is an expected 1.8% increase in visible band brightness of the sky at zenith, from the solar flux low at March 2019, to the solar flux value in November 2021. This amounts to about 0.7% per year increase of visible band brightness during that period. We take this into account by subtracting 0.7% per year from the long-term trends of skyglow data itself, to improve our estimates of skyglow change due to artificial light sources.

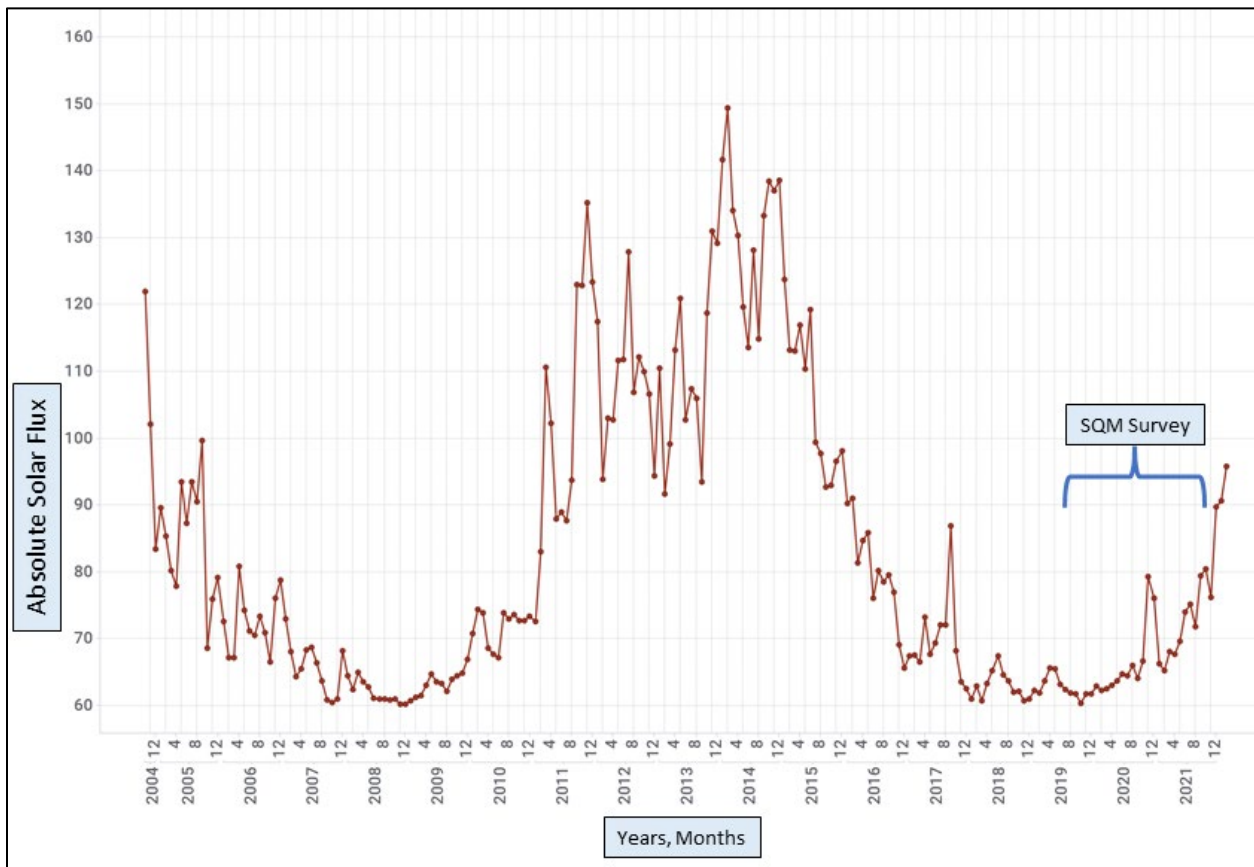


Figure H1. Absolute solar flux at 10.7cm, averaged by month, from 2013 to 2023. Data from National Research Center of Canada (<https://spaceweather.gc.ca/forecast-prevision/solar-solaire/solarflux/sx-5-mavq-en.php>).

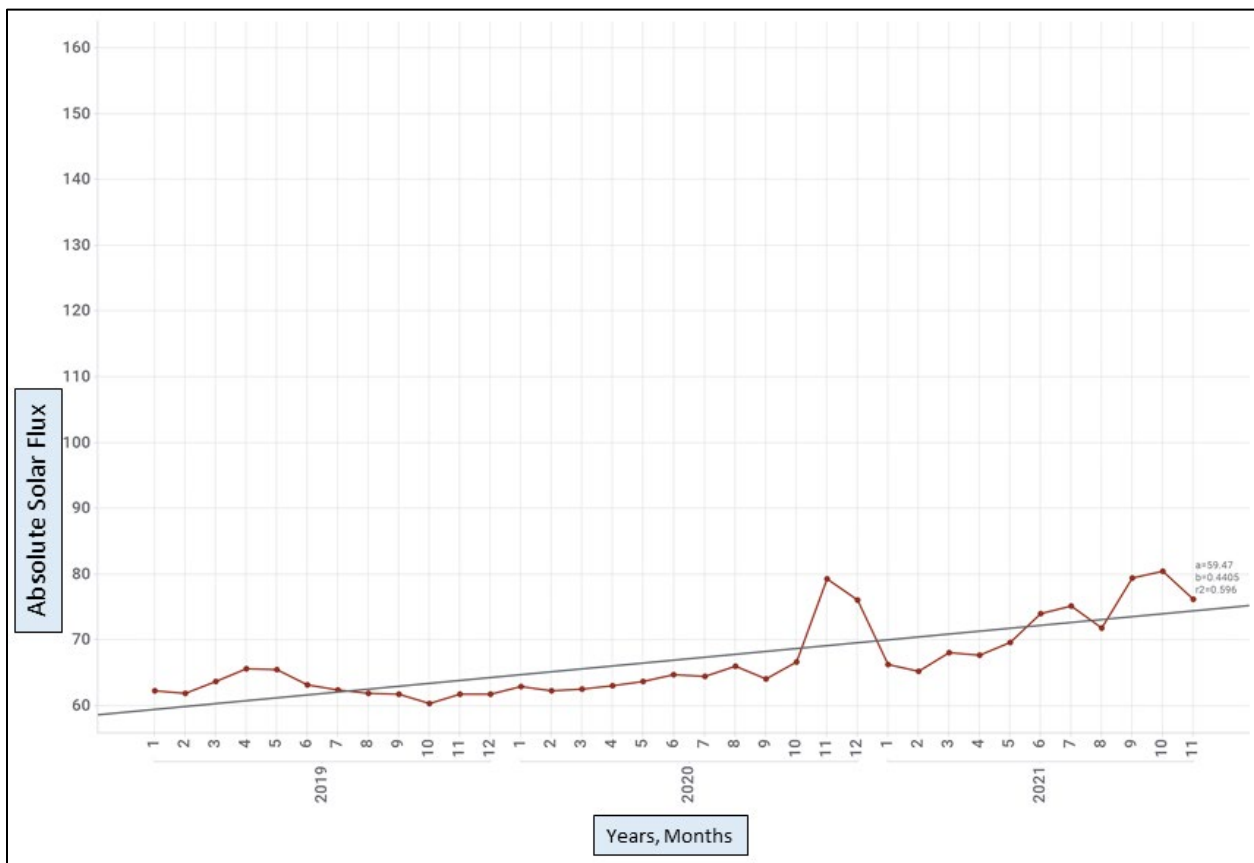


Figure H2. Absolute solar flux at 10.7cm, averaged by month, showing the time range of the SQM survey. The black line is a linear regression fit to these data. The solar flux increased about 23% from March 2019 to November 2021 during the time range of our SQM survey.

Appendix I – Confidence intervals of long-term sky brightness trends

In statistical regression analyses it is useful to quantify the confidence of the results. Two criteria are

- 1) Confidence bands about the regression line and
- 2) Prediction ellipse for new data that may later be added.

The figures and results in this Appendix were created by the Statistica software.

Figure I1 shows a plot of the sky brightness processed according to Goal #2, versus nights over time for the Awbrey Butte site. The 95% regression confidence band is quite tight around the regression line, indicating that we have confidence in the regression slope. Note that R-squared in Figure I1 is about .20, indicating that only 20% of the variation in sky brightness is explained by the trend over time. Clearly, other attributes not controlled so far affect the vertical range of sky brightness variation that we see in each month's clump of data.

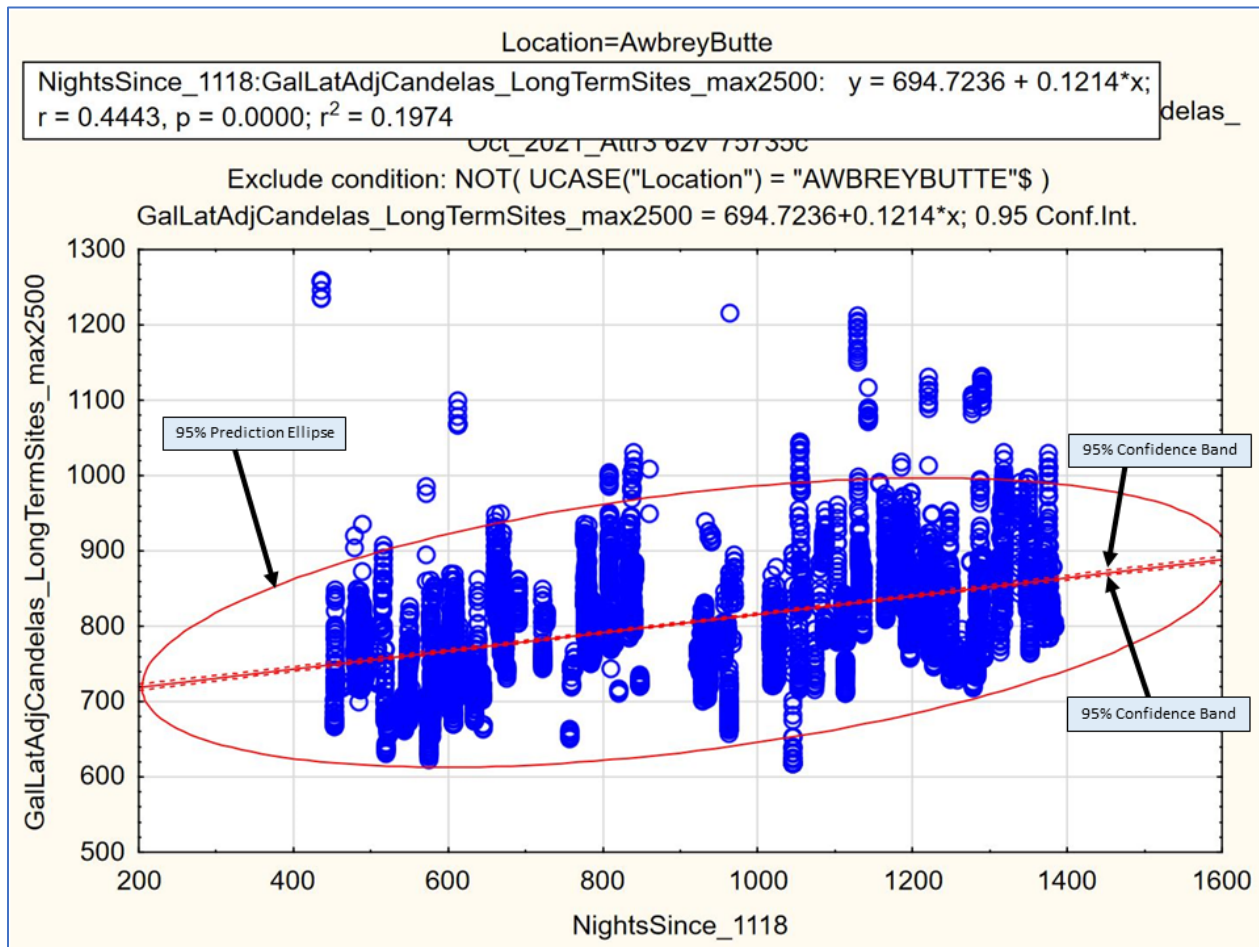


Figure I1. Plot shows sky brightness on the vertical axis versus nights of time. The dashed-red lines show the 95% confidence band on either side of the linear regression solid red line. The red ellipse predicts the region in which new data will appear, with 95% confidence. Data analysis is via the Statistica software.

Figure I2 shows the same plot of Figure I1, along with plots for the other of our 11 long-term sites. The 95% confidence band on the regression line is similarly tight for the other SQM sites.

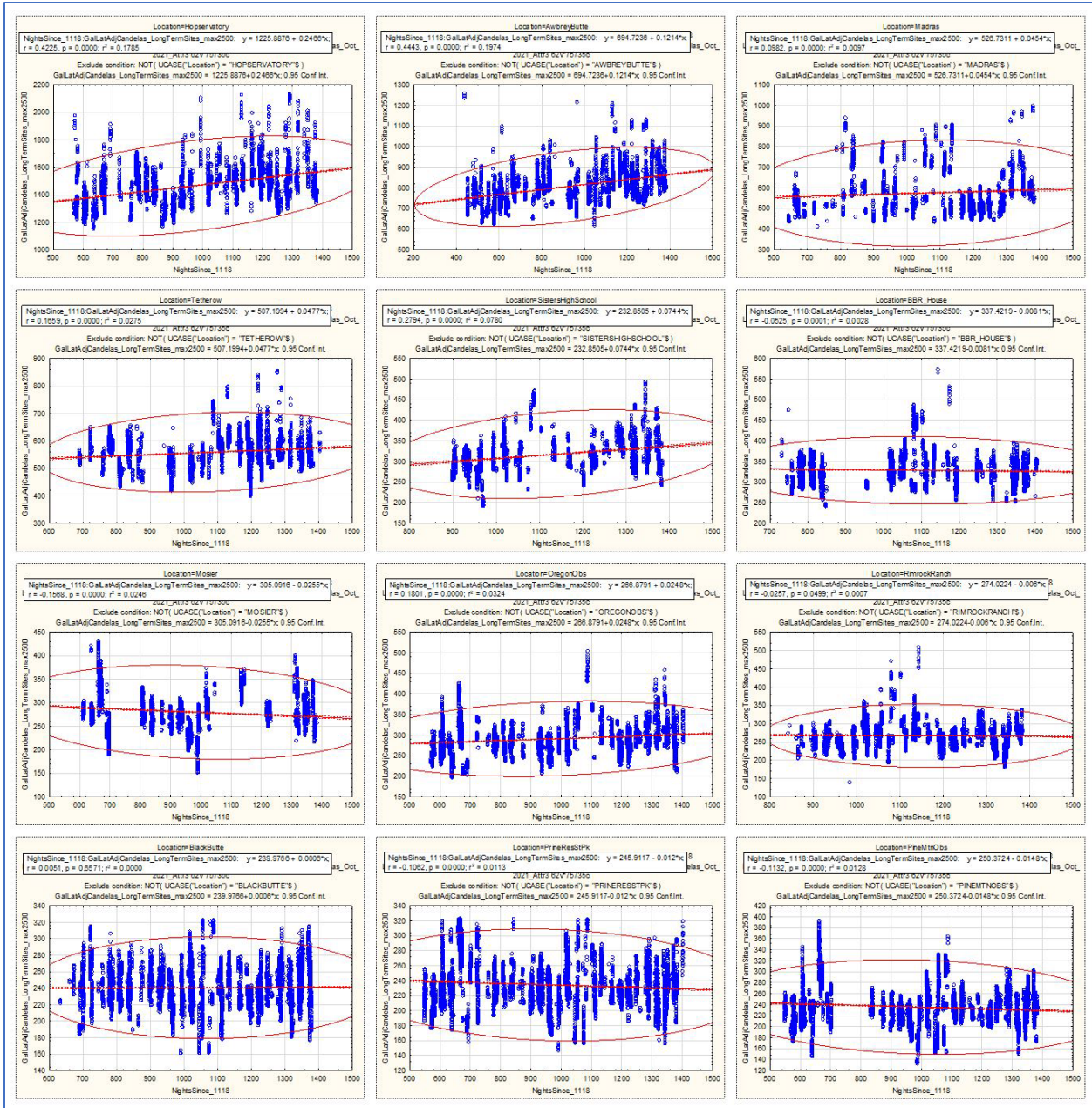


Figure 12. Plot of all the 12 long-term sites of sky brightness on the vertical axis versus nights of time. The dashed-red lines show the 95% confidence band on either side of the linear regression solid red line. The red ellipse predicts the region in which new data will appear, with 95% confidence. Data analysis is via the Statistica software.