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Comparing measurements of the mixing layer height to modeled values

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ABSTRACT:

The mixing layer height (MLH) is the top layer of turbulent mixing within the lower atmosphere, above the Earth's surface. Estimates of the mixing layer height allow us to determine the volume available for the dispersion of pollutants throughout the atmosphere. Our goal is to identify the most suitable mixing layer height input for our dispersion modeling tool (AERMOD). For this project we evaluated two different methods of estimating the local mixing layer height. First, we use 3 estimates of the mixing layer height obtained from a ceilometer, each height estimate corresponds to a different gradient in aerosol backscatter which is used as a proxy for mixing layer height identification. Second, we use AERMET, our AERMOD modeling system pre-processor for meteorological data, which estimates the mixing layer height using several equations combined with measured meteorological data. We evaluate the ceilometer and AERMET estimates over a 5-year period (2015-2019) to see how well aligned the estimated mixing layer heights are. Our results suggest that our model, AERMET, is on average, aligned with ceilometer estimates during the daytime hours. However, daily maximum MLH estimates by AERMET occur earlier in the day than those estimated by the ceilometer. We believe that the ceilometer struggles with accurately measuring the MLH during nighttime hours as a result of sensor limitations.

I. INTRODUCTION

The mixing layer is a layer of turbulent mixing within the lower atmosphere, above Earth's surface. Pollutants or other material emitted within this layer become dispersed throughout the layer by convective or mechanical turbulence. Convective turbulence is turbulent vertical motions that result from convective currents and the subsequent rising and sinking of air. Mechanical turbulence is turbulence caused by obstructions to the wind flow, such as trees, terrain, or man-made structures. The mixing layer *height* (MLH) is then defined as the upper bound to the region of active mixing at a given time.

The MLH allows us to determine the volume available in the atmosphere for pollutant dispersion and helps us to model and assess downwind pollutant concentrations (Reference: Seibert et al. 1999). If the mixing layer height is lower, that means there is less room for pollutant dispersion and therefore a higher concentration of the pollutant in that area. If the mixing layer height is higher, that means there is more room for pollutant dispersion and therefore a lower concentration of the pollutant in that area. During the daytime hours, the sun heats the ground surface which causes more turbulence, so the mixing layer height increases. During the nighttime, there is no surface heating of the ground which generally means less turbulence, so the mixing layer height tends to decrease overnight. Different meteorological conditions can also drive the height of the mixing layer height. During very stable nighttime conditions, the mixing layer height can be as low as less than 500 meters in height, while during warm unstable days it can reach up to 2000 meters (~6000 ft). A climatology of mixing height estimates for the US conducted by Holzworth (1972) demonstrated that average values of both morning and afternoon mixing height estimates display seasonal variation. The average morning mixing heights for the southeast US are around 300-400 meters, while the average afternoon mixing height ranges from 1000 – 1800 meters (Holzworth, 1972).

Although all this information is known about mixing height behavior, there is no direct method to measure the MLH. Over the years different methods to estimate this value have been employed, some are based on measurements of vertical atmospheric temperature or aerosol profile and others are model parametrizations based on surface measurements. Each method has advantages and disadvantages under different meteorological conditions. On this study we focus on two methods of estimating the MLH: model parametrization and ceilometer estimates. Our model parametrized estimates are from AERMET which estimates the MLH through parametrization using surface measurements of wind and temperature from our local meteorological tower, combined with model estimates of turbulence, heat flux, surface roughness, surface moisture, and reflectivity. AERMET estimates both the convective and mechanical turbulence and creates an estimate of the mixing layer height from each. However, as AERMET uses measurements of only wind and temperature of the lower atmosphere to create subjective estimations of the MLH, these estimations may not be accurate as a result of changing or unforeseen weather conditions (Seibert et al. 1999). Our ceilometer is a type of lidar measurement, which take measurements of the aerosol concentration profiles in the atmosphere to get a value of the MLH. However, lidar systems have trouble measuring the aerosol concentration when there is not a well-defined discontinuity in the backscatter intensity profile (Seibert et al. 1999). Other types of measurements include sodar and radar. Each of these measurement types have different limitations in their ability to measure the MLH accurately. This means that there is no method that allows us to get an accurate MLH measurement, but we can compare our different measurement types to see how the data compares and determine from that a very close MLH estimate.

Our goal is to evaluate how estimates of the MLH derived from ceilometer measurements compare to model parametrization estimates. This will help identify the most suitable type of input value for our dispersion modeling tool (AERMOD). Similar studies that have looked at different estimates to calculate the MLH include Khandokar. In Khandokar's study, their data was collected over a period of 6 months, their results suggest that summer days have more variability in MLH compared to winter. While our work is like other work done before, our data set is from a 5-year period and we are looking at an hourly, daily, monthly, seasonal, yearly, and yearly averages for our data versus just one of these at once. Another study done by Simpson was used to test AERMET. They compared AERMET estimates to observed mixing heights from July 1, 2003 to July 31, 2003 and their results conclude that AERMET is able to reasonable estimate mixing heights over a wide range of atmospheric conditions and that model estimations of the height of the late afternoon mixed layer also correspond well with observations. So far, compared to other studies, ours uses data from a much longer time period and we do multiple tests in our study including looking at days, seasons, year, and hours. The fact that we observe a 5-year dataset, allows us to have more of a climatology of the MLH at SRS, rather than an event-based case study as most of these previous studies provide.

II. MEASUREMENTS AND ESTIMATES

1. Ceilometers estimates.

We obtained hourly estimates of the mixing layer height at the Savannah River Site by using a ceilometer. The ceilometer essentially shoots a laser beam into the atmosphere to determine cloud base height and can also be used to measure aerosol concentration (backscatter) within the atmosphere. Although ceilometers were not originally designed as instruments to measure the MLH, the vertical profile of backscatter intensity indicates gradients in the volume of aerosol in the atmosphere. This gradient is used as a proxy for the mixing layer height, as regions with uniform aerosol loading indicate regions of constant mechanical or convective turbulence, whereas large differences in aerosol loading indicate a drastic change in mixing conditions and can indicate a boundary between layers in the atmosphere.

At SRS we operate a Vaisala CL31 Ceilometer to obtain backscatter profiles which are integrated over 30 seconds (Weinbeck, et al., 2020). An automated algorithm based on Brooks, et. al. (2003) searches for strong gradients in the aerosol backscatter profile and identifies the respective heights as the MLH. Currently three estimates of the MLH are obtained following this method: MLH1 corresponds to the height of the largest gradient, MLH2 corresponds to the height of the second largest gradient, and MLH3 corresponds to the height of the third largest gradient. Because there is no direct way to measure the MLH, we obtain multiple values for what it could be to try and encompass the MLH within these estimates.

2. AERMET estimates.

We obtained hourly estimates of the MLH from AERMET, our AERMOD modeling system pre-processor for meteorological data. AERMET estimates the MLH through parametrization using surface measurements of wind and temperature from our local meteorological tower, combined with model estimates of turbulence, heat flux, surface roughness, surface moisture, and reflectivity. AERMET estimates both the convective and mechanical turbulence and creates an estimate of the mixing layer height from each. Zic is the estimated mixing layer height from AERMET's estimate of the convective turbulence. Zim is the estimated mixing layer height from AERMET's estimate of the mechanical turbulence. To obtain a final value of the MLH, Zi, that the dispersion model can use, AERMET uses the logic shown in Figure 1 to choose whether the Zic or Zim value is the most accurate for each hour of the day.

$$z_i = MAX\left[z_{ic};\ z_{im}\right] \qquad for\ \ L < 0\ \ (CBL)$$
$$z_i = z_{im} \qquad for\ \ L > 0\ \ (SBL)$$

FIG1: Equation used by AERMET to select which value (Zic or Zim) is most representative of the MLH for each hour of the day. Where L is the Monin-Obukhov Length, CBL refers to Convective Boundary Layer, and SBL refers to Stable Boundary Layer.

AERMET also has logic to consider changes in turbulence during transitional periods (dusk and dawn) and to avoid sudden and unrealistic drops in the MLH during these periods (EPA 2022).

III. METHODS

We calculated daily averages of MLH1, MLH2, MLH3, Zic, and Zim each day from 2015 to 2019. This allowed us to see how similar our ceilometer estimates and AERMET estimated values of the mixing layer height are to each other. We wanted to assess whether there was any obvious trend or relationship between the any of the ceilometer estimates and the convective (Zic) or mechanical (Zim) estimates from AERMET. In order to do this, we took our hourly values, separately measured by each of the 5 data sets, and separated them by month for each year. This allowed us to see the general daily progression of the measured values day-by-day, over each year. Along with this, we separated the values into seasons: winter being December (previous year)-February, spring being March-May, summer being June-August, and fall being September-November. This allowed us to see how the different seasons and weather patterns affected the amount of turbulence in the atmosphere and the mixing layer height estimates provided by both AERMET and the ceilometer. By having the values sorted by daily averages, we can also spot days with good agreement or days where the values disagree, which we hypothesize are associated to specific weather events, as these days tend to have large rises or drops in mixing layer height.

We also took hourly averages of the entire 5-year dataset, which was used in a different manner than the daily averages. We sorted this data by using MLH1 and Zi, MLH2 and Zi, and MLH3 and Zi together. We used this data to show how the hourly progression of the mixing layer height changes as estimated by each method. This allowed us to see how the two estimates compare in daytime progression of the MLH growth. We also evaluated the hourly average standard deviation for MLH1 to illustrate how our ceilometer estimates fluctuate hour-to-hour throughout the day and determine if there are hours where there is more spread on the ceilometer estimates.

IV. RESULTS

1. Daily Averages

We started by taking daily averages of our ceilometer and AERMET hourly data. This allowed for us to see what the MLH was on each day from 2015-2016 and how the MLH changed between different seasons of the year. From our daily averages, we found that the measurements and estimates are much more aligned during the summer months than the winter months, these results can be seen in our data each year and can be shown in Figure 2. This alignment can be seen between the measurements of MLH1, MLH2, MLH3, and Zic with the only difference being Zim, which stays at about the same value for all of the seasons. In all four seasons, it seems that our ceilometer estimates, MLH1, MLH2, MLH3, are all very close in MLH, with Zic being a little bit lower, and then Zim being the lowest.

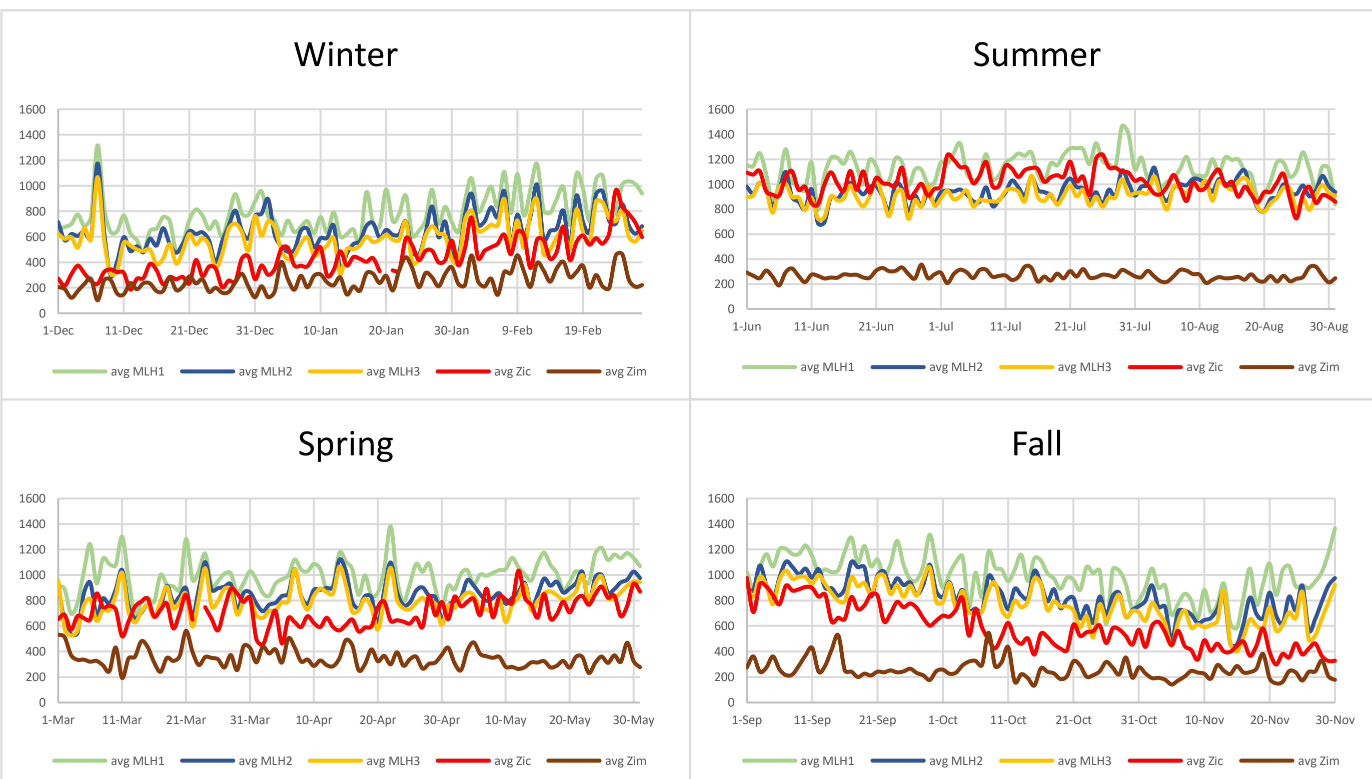

FIG 2: Daily averages of all four seasons averages over all 5 years.

2. Hourly Averages

From our 5-year hourly averages (Figure 3), we can see that MLH1 and Zi line up very well during the daytime hours. In Figure 4, we can see that Zi slightly overestimates MLH2 during the daytime hours, and in Figure 5, we can see that Zi overestimates MLH3 during daytime hours. Therefore, the MLH estimates obtained from the strongest and second strongest gradient in backscatter from our ceilometer data seem to align well with AERMET parametrization estimates of the daytime MLH. However, we note that the maximum hourly average value for each MLH estimate obtained from the ceilometer occurs later in the day than the maximum hourly average value of Zi, obtained from AERMET. We believe that this could be a result of the nature of the ceilometer measurements. The ceilometer measures suspended aerosols and might be measuring aerosols above the MLH (in what is known as the residual layer), not able to capture a more stable layer developing near the ground as the sun sets.

Figures 3, 4, and 5 also demonstrate that on average, the MLH estimates from the ceilometer align quite well with AERMET estimates from dawn to dusk. However, from dusk to dawn, we can see that the results of the ceilometer and AERMET estimates exhibit large differences of the MLH. The ceilometer and AERMET estimates of the MLH exhibit differences of about 600 meters during the winter and spring months and differences up to 1000 meters during the spring and summer months (Figures 3, 4, and 5). We believe these results could be a reflection of our ceilometer capturing suspended aerosols above the lower stable layer that develops near the ground overnight. If this is the case, the ceilometer estimates would be providing an unrealistically high MLH value overnight. Alternatively, it is also possible that the ceilometer estimates are accurately representing the real MLH over SRS and that the AERMET parametrization scheme is underestimating this height. The AERMET methodology automatically selects the Zim value as the MLH for nighttime conditions, and this value is derived based on a series of assumptions on the mechanically generated turbulence, friction velocity, drag coefficient (EPA 2022). The transition from daytime conditions (represented in AERMET as convective boundary layer) to nighttime (represented as stable boundary layer) is driven by assumptions of heat flux change when a critical solar angle is reached. At SRS we have a significant amount of tree canopy coverage, which is not necessarily well represented by these parametrizations and assumptions used by AERMET. Tree canopy has a daily heating and cooling cycle that is different (and potentially out of phase) from that of a flat surface – as it is assumed by AERMET. Hence, the discrepancy between MLH estimates obtained from our local ceilometer data and those obtained from AERMET calculations, could be attributed to canopy effects in mixing conditions overnight. The impacts of vegetation on site can also explain why we observe the maximum values of MLH from the ceilometer occurring at a later time than those from AERMET estimates. Further work is needed to address these potential interactions.

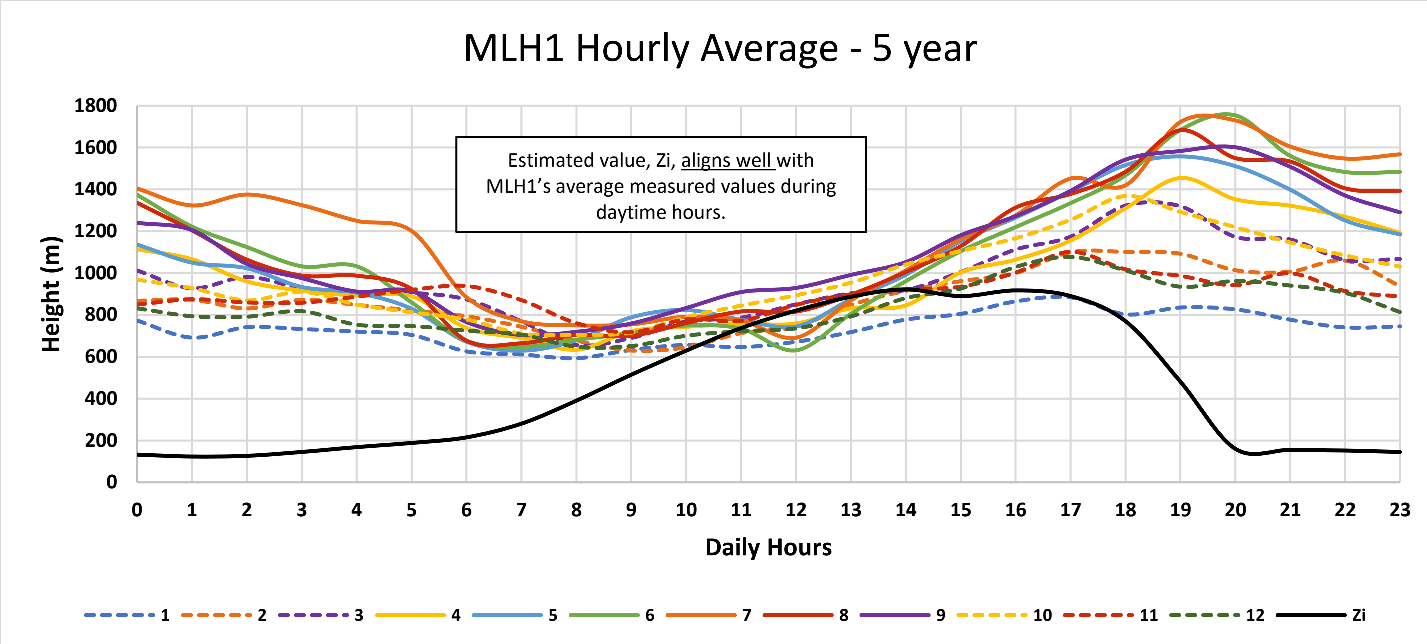

FIG 3: MLH1 hourly average over the 5-year period. The colored lines represent each month of the year.

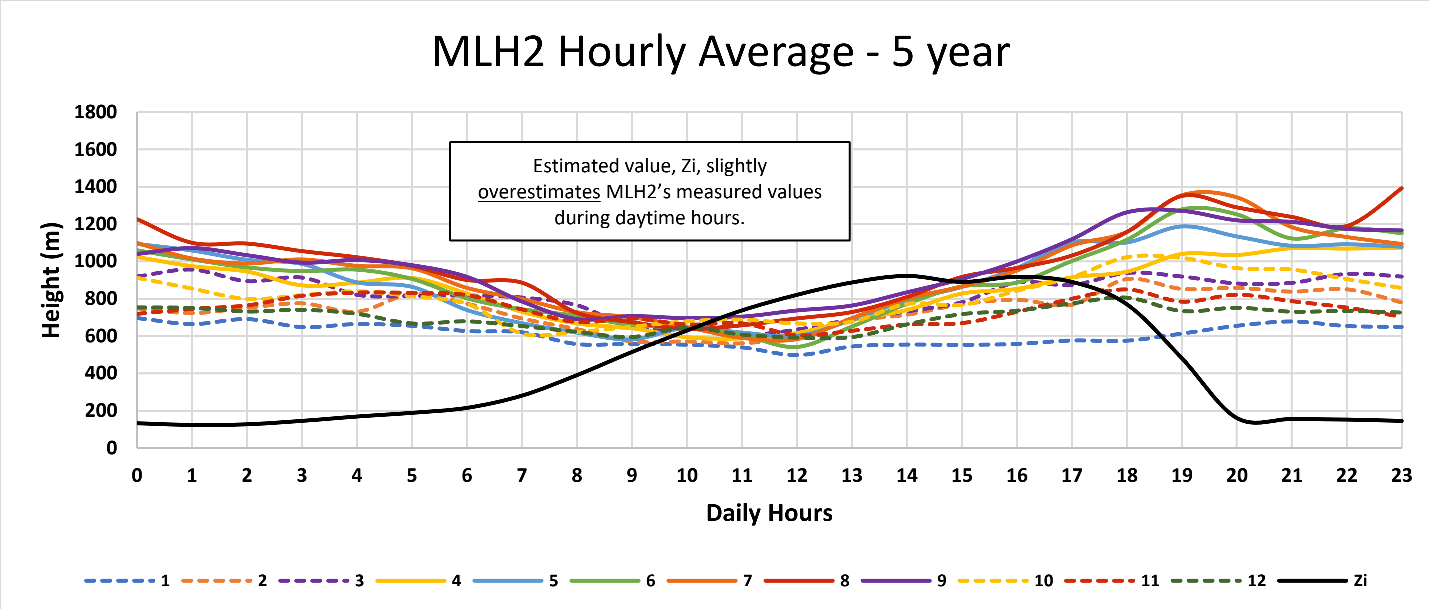

FIG 4: MLH2 hourly average over the 5-year period. The colored lines represent each month of the year.

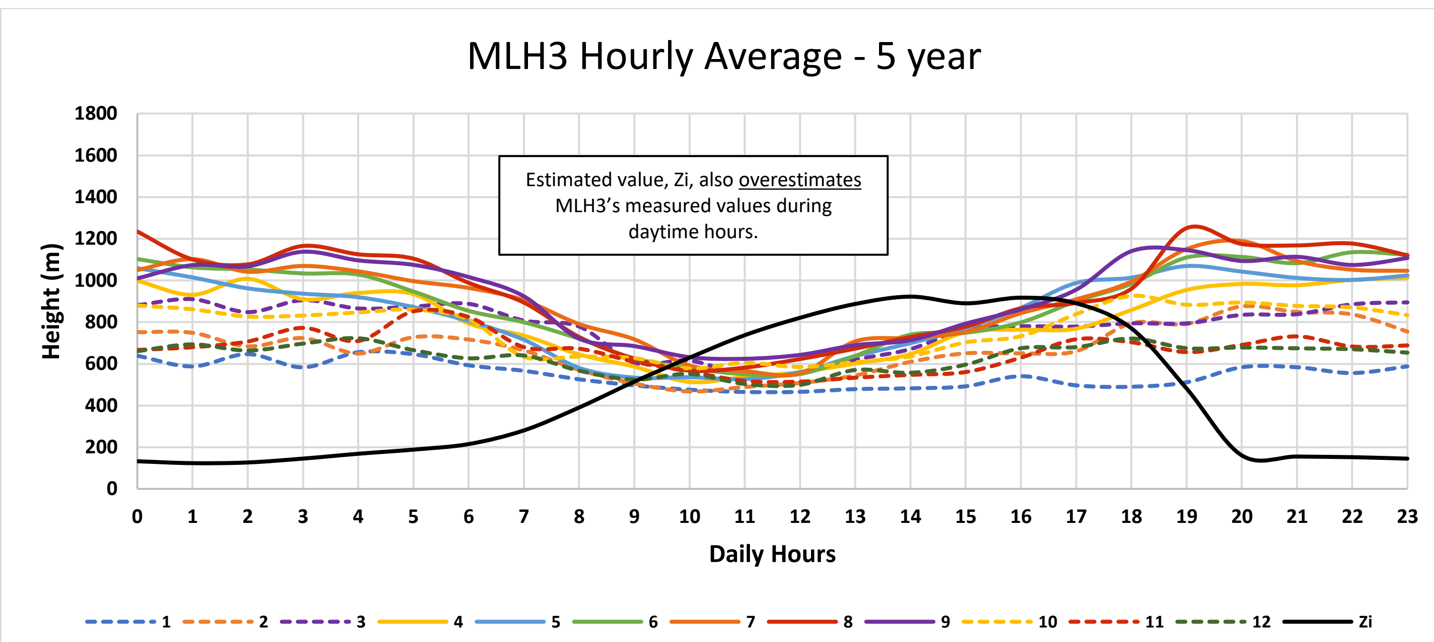

FIG 5: MLH3 hourly average over the 5-year period. The colored lines represent each month of the year.

3. Standard Deviation

After looking at our 5-year hourly averages, we decided to also look at the hourly standard deviation of the hourly estimates from the ceilometer (MLH1). Figure 6 shows that larger values of standard deviation occur during the nighttime and correspond to the periods where the ceilometer estimates produce higher MLH values than AERMET parametrization (Figures 3, 4, 5). Based on our knowledge on how the ceilometer generates the MLH estimates, we believe that our ceilometer has trouble identifying the low mixing layer heights that can occur during stable nighttime conditions, as mentioned on the previous section. Additionally, during the transition period of dusk and dawn the gradient and the rate of change in turbulent conditions is large. Therefore, the large standard deviation in hour-to-hour estimates from the ceilometer during these particular hours of the day was expected and suggest that the cause might be a combination of instrument sensitivities to suspended aerosols in the residual layer as well as fast changes in turbulence occurring as the atmosphere transitions from convective to stable. These results indicate that further work must focus on better understanding the local processes occurring at these times and how sensible our estimates of MLH are to these fast transitions in the lower atmosphere.

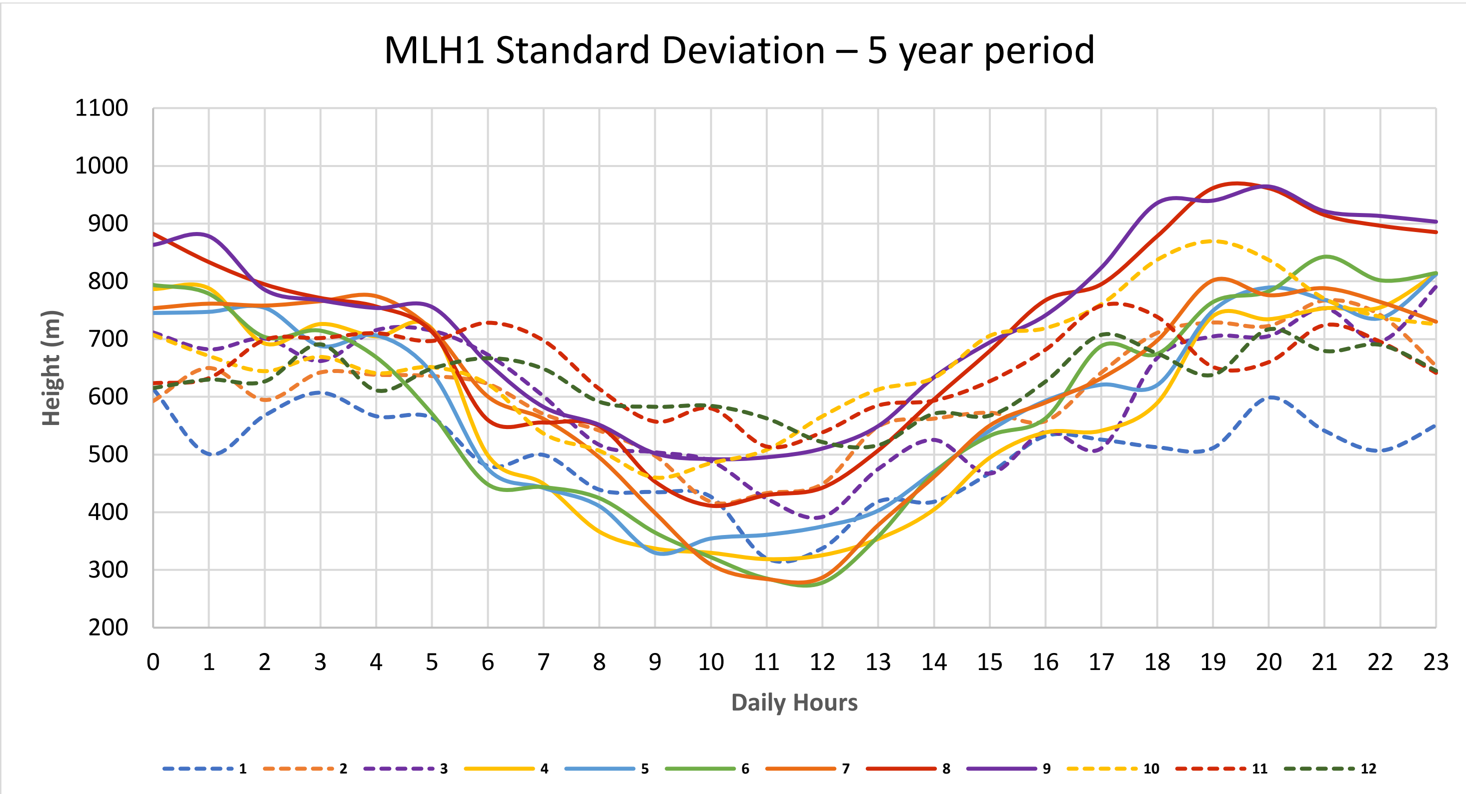

FIG 6: MLH1 standard deviation of hourly average values over the 5-year period. The colored lines represent each month of the year.

V. CONCLUSIONS

Based on our findings, we can conclude that our model, AERMET, is on average, better aligned with MLH1 and MLH2 values during the daytime hours. We can also conclude that our daily maximum mixing layer height estimates by AERMET occur earlier in the day than our ceilometer measurements. During overnight hours, the two methodologies begin to disagree with estimates from our ceilometer suggesting a higher MLH than the height estimated by AERMET. We believe that is possible the ceilometer struggles with accurately measuring the mixing layer height during the nighttime hours as a result of sensor limitations not being able to detect the lower stable layers that develop overnight. However, further work should focus on estimates during this time as it could be possible that the ceilometer estimates are accurately representing the MLH over the heavily forested SRS while AERMET's assumptions on mechanically generated turbulence might not be representative of overnight turbulence conditions at SRS.

From these findings, we believe that more testing is needed in order to complete the goal of identifying the most suitable type of input value for our dispersion modeling tool and testing the hypothesis of our ceilometer having difficulties measuring the mixing layer height during times when this height is too close to the ground.

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