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Boundary Layer Height Variation over the Savannah River Site during a Heat Wave

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Abstract

With the number of heat waves expect to increase in both in their severity and frequency in the coming years, an insight into their impact on planetary boundary layer (PBL) heights is essential for the development of future emergency and safety plans. Using High-Resolution Rapid Refresh (HRRR) atmospheric model output, an analysis is done on the effects a heat wave has on PBL heights and temperature inversions across the Savannah River Site (SRS). This study showed that due to its adjacency to anthropogenic land use, SRS experiences a non-negligible gradient in its PBL height, with higher heights to the northwest. The singular location PBL height measurement and forecasts for SRS do not account for this gradient, which has potential implications on pollutant and smoke dispersion onsite. During a heat wave this gradient is present but PBL heights are less impacted than surrounding developed areas, possibly attributable to the woody wetlands that surround the Savannah River's banks. Additionally, the heat wave appears to strongly enhance the nocturnal temperature inversions that the site and surrounding areas experience. This is possibly due to increased stability from higher pressure conditions, which are often associated with heat waves. This influence on nocturnal inversions, however, is limited to their intensity, leaving their timing relatively unaltered. The impact a heat wave has on PBL heights and temperature inversions across SRS is seen to be more dependent on adjacent land use and features rather than the unique land use types onsite.

I. INTRODUCTION

With extreme heat events projected to occur with increasing frequency and severity in the coming years[1], there grows an increasing necessity for the understanding of the relationship between these heat waves, the planetary boundary layer (PBL), and urban heat islands (UHI). UHIs are best described as areas of increased atmospheric heat compared to the surrounding rural areas. This phenomenon typically occurs in sprawling metropolitans due to the ability of manmade structures to store and release larger amounts of heat than natural surfaces. Additionally, these surfaces also cool significantly slower and when compounded with emissions from things such as air conditioners and vehicles, UHIs can persist through the nighttime.

An important representor of the interaction between the atmosphere and planetary surface, PBLs describe the point in the atmosphere in which the surface's influence on atmospheric flow becomes essentially negligible. Shortwave light energy emitted by the sun and consequently absorbed by the surface features of the planet are released back into the atmosphere as long wave radiation heat energy. This influx of heat paired with frictional forces from the surface induce turbulent mixing within the lowest layers of the atmosphere, disturbing the otherwise laminar air flow. UHIs' longer lasting and stronger heat emission into the atmosphere force the height at which the air flow is warmed and turned turbulent to increase to much higher levels than surrounding areas.

A deeper insight into how the PBL changes over the Savannah River Site (SRS) and Central Savannah River area (CSRA) is critical for the future development of safety and emergency plans. Being about 20 miles southeast from Augusta, G.A., SRS is expected to experience the effects the Augusta UHI daily. The atmospheric conditions created by the PBL height have a direct effect on the spreading of contaminants and pollutants created by the many industrial processes, controlled burns, etc. on site. PBL's that are exasperated in height due to UHIs would be able to spread contaminants and pollutants in a larger radius, negatively impacting the surrounding communities and ecosystems. Additionally, there exists microscale regions of dense "impervious" surfaces within SRS which leads to the potential of enhanced PBL heights across the PBL. Frequent PBL measurements are taken at SRS through use of a ceilometer, which measures aerosol backscatter. However, it is only located in a singular area of SRS and may not account for the variance of PBL height across the site. SRS forecasts for emergency scenarios or for routine controlled burns rely on this single estimate of PBL height and could be improved through a deeper understanding of how surrounding urban developments affect the PBL.

Much of the US experienced an extreme heat event during June 2022. SRS saw a high of 100.27°F with an average temperature of 79.21°F. An important tool to determine the effect that a temperature can have on the human body is the wet bulb globe temperature (WBGT).

Considering the humidity in the air, the cooling effect sweat has for humans, the cooling due to the wind, and the heating due to solar radiation, WBGT can effectively determine how dangerous the weather is for humans working in it[2]. As seen in Fig. 1(a) and (b), during this heat wave SRS saw a max WBGT of 92.57°F and an average of 75.73°F. This put this period in an extreme heat risk category with the Occupation Safety and Health Administration (OSHA) recommending most types of work be avoided completely. We study model derived PBL heights across SRS and within the CSRA with the purpose of this research to explore the severity of the PBL height gradient above SRS outside of and during this heat wave.

(a) **(b)**

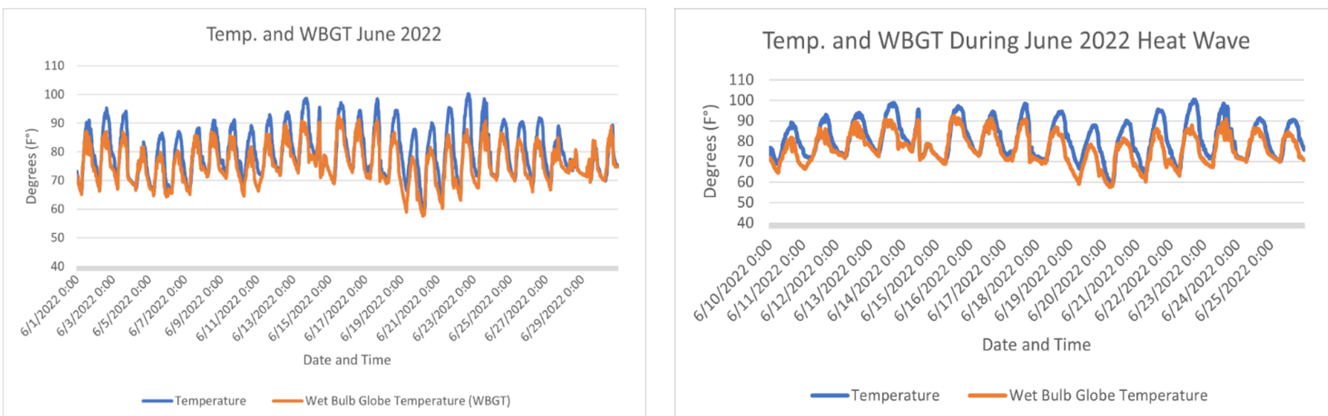

Fig. 1. (a) The hourly temperature and wet bulb globe temperature of the Savannah River Site during the entire month of June 2022. (b) The hourly temperature and wet bulb glove temperature during the heat wave period (June 10th – June 25th).

II. METHODS

This study focuses on the heat wave event that occurred primarily between June 10th to June 25th, 2022. An analysis of modelling data collected by the High-Resolution Rapid Refresh (HRRR) model was done as described below.

A. High-Resolution Rapid Refresh Model

The HRRR data used in this study was produced by the fourth generation of the model, released in December 2020. This model has run operationally at NOAA, producing data for 18-hour forecasts since 2014[3]. With a 3km x 3km grid spacing, the HRRR model assimilates separate radar data with hourly updated data from the 13km Rapid Refresh model every 15 minutes over a 1-hour period. The initial time output for each HRRR simulation rigorously assimilates Automated Surface Observing Station (ASOS) data as well as Next-Generation Weather Radar (NEXRAD) data into the modelled outputs, essentially serving as high resolution re-analysis dataset. Modelled data on the temperature, dewpoint, and vector resolved wind components at different pressure heights can be used to determine PBL heights above different zones of SRS. Additionally, HRRR model derived PBL heights will be used in comparison to analyze calculated heights.

B. PBL Height Calculation Method

Traditionally, there are several methods that are employed to calculate the PBL height using model derived data with no clear consensus on which method best-defines the PBL[4]. A traditional meteorological method uses potential temperature (Θ) gradients as a proxy for stability, with the maximum vertical gradient of potential temperature acting as a "cap" to the surface turbulent mixing, which would act as the PBL height. Many model PBL parameterizations use turbulent kinetic energy (TKE) as a threshold, which is calculated in the form

$$\frac{\partial q^2}{\partial t} = \frac{\partial}{\partial z}\left[lqS_q\frac{\partial q}{\partial z}\right] + P_s + P_b + D$$

where the first term is the vertical transport term, the value inside of the brackets is the set stability function, and P_s, P_b, and D are the shear production, buoyancy production/destruction, and dissipation terms respectively. TKE allows for the calculation of PBL height on the idea that it is the point in the atmosphere in which the turbulence caused by the surface will have become essentially negligible.

The HRRR model employs the Mellor-Yamada-Nakanashi-Niino[5] (MYNN) PBL parameterization to determine mixed layer depths. MYNN is a "hybrid" scheme that utilizes TKE methods in scenarios with low sensible heat fluxes but employs the traditional potential temperature gradient method when sensible heat fluxes are high and large thermally driven boundary layers can be found in vertical soundings. In Fig. 2, the HRRR values for the potential temperature are depicted in the gradient that would typically be used to derive the PBL height. The HRRR derived PBL height is overlaid on this and can be seen to follow the typical trend in sensible heat flux indicative of the PBL height but deviates slightly with its account of the Mellor -Yamada-Nakanashi-Niino parameterization.

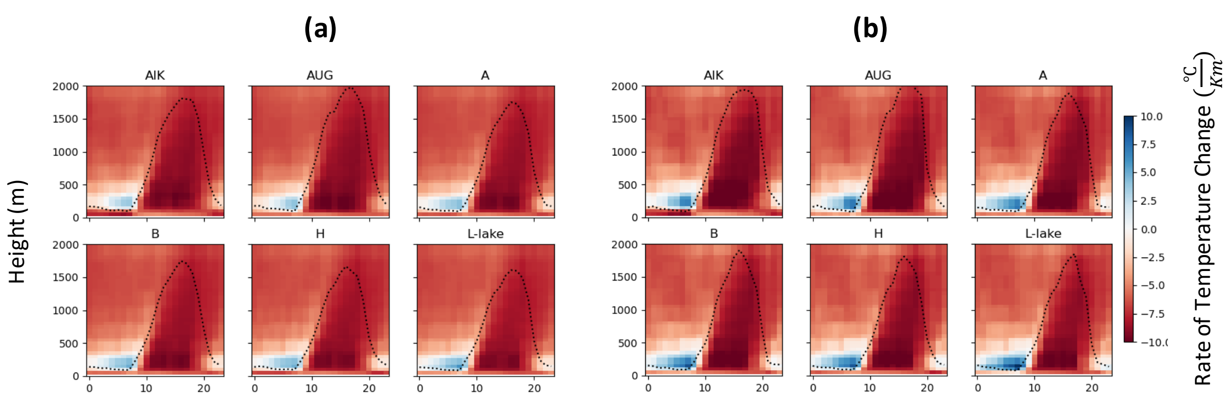

Fig. 2. (a) The average rate of vertical temperature change per kilometer throughout the day for the different areas on and off-site during June 2022 and (b) during the heat wave period of June 2022. The overlaid dashed line represents the HRRR model derived PBL heights.

III. RESULTS

The results analyzed focus on the heat wave period (June 10-25) and the rest of June outside of the heat wave (June 1-9/26-30). June 14th was excluded from the heat wave period dataset due to the high, unexpected convection experienced on this day. By midday, extreme rainfall was experienced and consequently making the PBL height seen this day anomalous from the rest of the days within the heat wave. PBL heights specifically were analyzed at six areas across the CSRA: Aiken, S.C., Augusta, G.A., A-Area, B-Area, H-Area, and L-Lake. Aiken and Augusta each were chosen due to their largely developed areas and proximity to the site. A-Area, H-Area, and L-Lake each provide context to see if PBL height changes within the site due to the extent of development of each. Finally, B-Area is the location of the site's ceilometer and the only place where PBL height is taken at SRS, providing a benchmark to compare the HRRR model-derived PBL heights against.

A. PBL Height Gradient

Across SRS, PBL heights during normal conditions take on a non-negligible gradient due to its adjacency to anthropogenic land use. During typical conditions this gradient can span upwards of 300 m. in difference (Fig. 3a). Higher heights are seen in the northwest and can be attributed to the influence of the nearby Augusta metropolitan area and its UHI. PBL heights gradually decrease to the southeast with the lowest heights being seen on the southern border of SRS with the town of Millet. Again, this decrease in heights can most likely be attributed to the increased distance from Augusta. Additionally, the lack of development in the southern part of the site and surrounding areas promotes this decreased height. During the heat wave conditions of June 2022, it appeared that this gradient still was apparent across the sight with little changes to its severity depicted in Fig. 3b. At SRS, the PBL height determined for the entire site originates from a singular ceilometer measurement at B-Area. As seen in Fig. 2, this singular measurement typically would account for the most extreme PBL heights towards the northern end of the site but doesn't account for the much lower heights to the south. This neglection is the root of a fundamental flaw in safety and emergency measures within SRS, especially due to the higher number of remote workers typically working in the south. Should a contaminant be released, with its plume directed to the south, current estimates would have the dispersion at a much higher altitude and magnitude than would be accurate, necessitating the need for a more inclusive PBL measurement for the site.

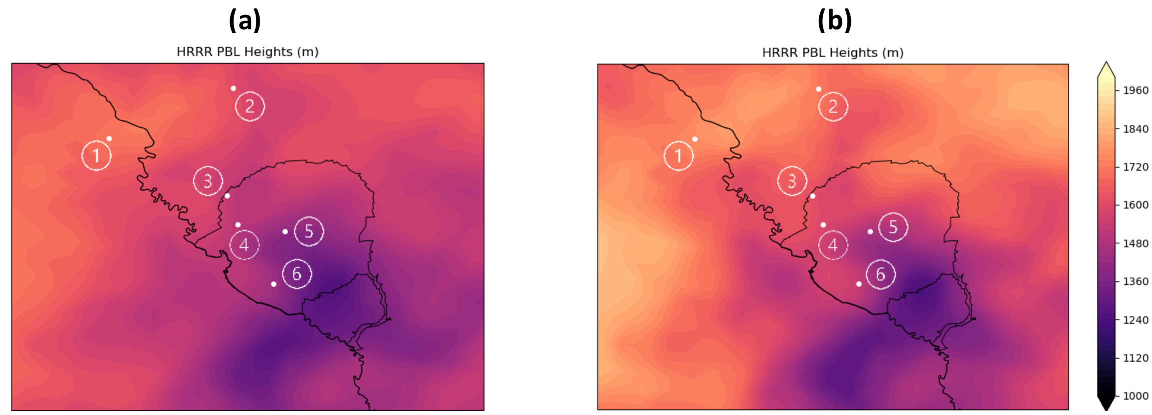

Fig. 3. (a) PBL heights during June 2022 and (b) during the heat wave period of June 2022. Locations: Augusta, GA (1); Aiken, SC (2); A-Area (3); B-Area (4); H-Area (5); L-Lake (6)

B. PBL Height Differences

While the heat wave raised PBL heights universally across the CSRA, the greatest increase in PBL heights was unexpectedly seen at L-Lake around 1600 EDT, seen in Fig. 5. This difference quickly diminished to about nothing by 1800 EDT. Despite the unique case of L-Lake having the greatest increase in PBL heights for about an hour in the late afternoon, SRS seemed to be much less impacted from the heat wave when compared to the surrounding areas. This trend can best be explained through a deeper insight into the conditions present along the western border of SRS. Along this border, the Savannah River flows, bringing with the significant amounts of water needed to sustain the woody wetlands the line its banks. In this study, woody wetlands are defined as areas in which forests and other vegetation account for more than 20% of vegetative cover and occasionally, the soil of these areas are saturated with water[6]. These densely vegetated, saturated areas help mitigate the heat wave's effect on the site through limiting the amount of heat that the overall area retains. The large amounts of moisture present allow for the cooling of the area through latent heat absorption.

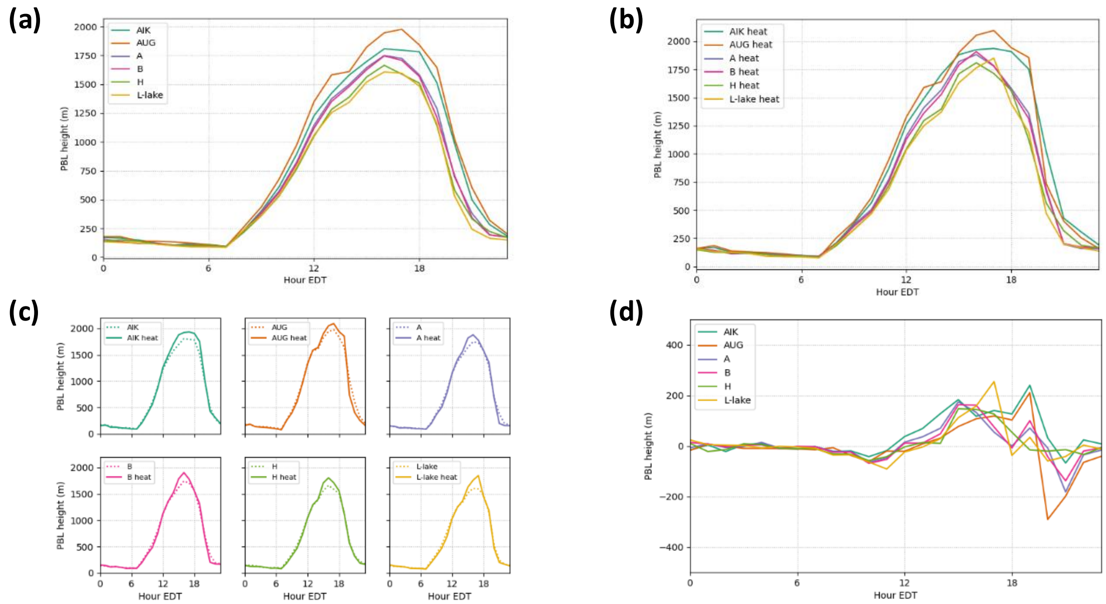

Fig. 4. (a) Average hourly PBL height by area during June 2022 and (b) for the heat wave period of June 2022. (c) Average hourly PBL height by area of the heat wave of June 2022 overlaid with the PBL height of the rest of June 2022. (d) The difference between the PBL height during the heat wave and during the rest of June 2022.

C. Enhancement of Nocturnal Boundary Layer Inversions

A secondary, unanticipated consequence of the heat wave was its effect on the nocturnal boundary inversions across the CSRA. Nocturnal boundary inversions are inversions that form due to the rapid cooling of the immediate surface in comparison to the air above it. This rapid change of air temperature is a useful metric to measure the intensity of these inversions over time. Fig. 5 depicts the average rate of vertical temperature change per kilometer for the first 100-300 m. throughout the day was compared between the heat wave period and rest of June. A trend is quickly apparent between the type of land use and the intensity of the nocturnal boundary inversion above it. As the development on the land increases beneath the inversion, its intensity decreases. This trend seems to be made more apparent because of the heat wave, with intensities in some areas being magnified by a factor of almost 1.5. Despite this intensification, the timing of the nocturnal inversion doesn’t appear to be affected along with the duration of the inversion. This aspect of the heat wave on the local atmosphere conditions most likely ties in with the fact that heat waves inherently are accompanied by periods of high atmospheric pressure. This higher pressure decreases the amount of mixing that the colder, lower layer of air has with the warmer air above it, causing a more severe temperature gradient to form.

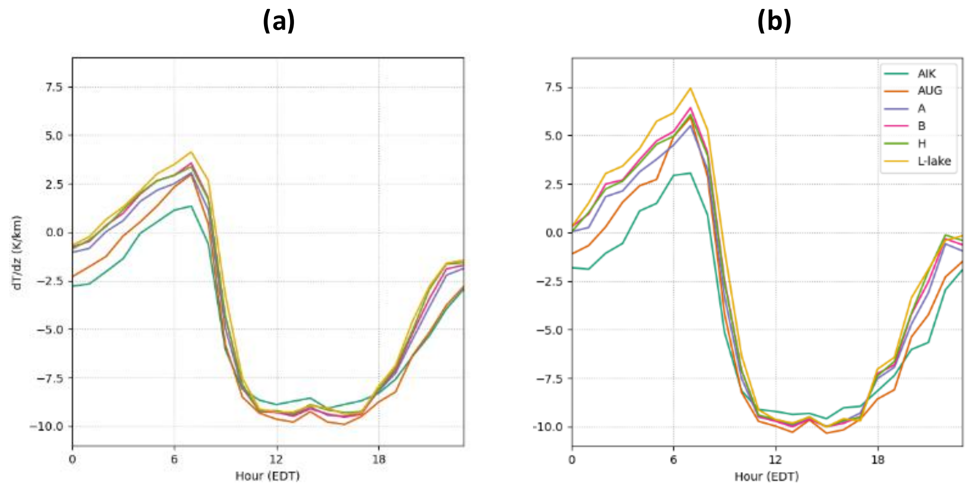

Fig. 5. (a) Average hourly 100-300 m. temperature lapse rate intensities during June 2022 and (b) the heat wave period of June 2022.

IV. CONCLUSIONS

The heat wave of June 2022 at the Savannah River Site (SRS) was studied using the High-Resolution Rapid Refresh (HRRR) model. The model-derived planetary boundary layer (PBL) height above SRS and surrounding areas was analyzed during the entire month of June, the heat wave period (June 10-25), and the periods of June outside of the heat wave. We have shown that both during and outside of heat wave events, a PBL height gradient forms over SRS that isn't considered by the singular ceilometer measurement used by the entire site. This highlights an issue present in current emergency and safety plans in place that rely on accurate PBL measurements for the entire site to predict and act against contaminants and pollutants released into the atmosphere. Furthermore, we explain the elevation of PBL heights across the SRS during a heat wave and the importance of the woody wetlands bordering the Savannah River in mitigating a heat wave's effect. Finally, while daytime PBL heights are elevated due to a heat wave, it is shown that nocturnal boundary inversions are intensified. A result of the increased pressure a heat wave brings, these increased nocturnal inversions lead to periods in the early morning of extremely stable atmospheric conditions. This study only looks at one instance of a heat wave impacting SRS and further research should be done including a larger sample size to see if these findings are universal.

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