Evaluation of Atmospheric Conditions Leading to a Fumigation Event

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Abstract

During the afternoon of January 30, 2022, the Savannah River Site experienced unusual temperature conditions leading to a fumigation event that triggered safety alarms and caused considerable confusion about the cause of the event. Normally, it is assumed that fumigation events occur early in the day once surface heating has begun. While most fumigation events are related to the break-up of a nocturnal inversion, this event was related to synoptic atmospheric conditions which provided a more unique scenario that led to the fumigation event. The unusual synoptic atmospheric conditions led to the downwash and fumigation of the elevated plume causing a pollutant to mix rapidly to the surface. These conditions could have potentially harmed workers within the facility since the plume was directed toward a building air intake system. We seek to outline the conditions that led to this unusual fumigation event and provide results of 2-D wind modeling of the event to characterize these conditions for future operational guidance of the facility air intake systems. This work sets the groundwork for future, high-resolution modeling to explore the mechanisms and thresholds affecting fumigation on the facility-specific short distance scales and improve forecasting of non-standard fumigation events to protect human health.

Keywords: Fumigation; Building Downwash; CFD Modeling; Atmospheric Dispersion

Introduction

Fate and transport evaluation of airborne plumes is a key component of facility safety basis modeling used to ensure the health and safety of co-located workers and downwind individuals. Downwind dispersion is the primary mode of plume travel that is considered, but special cases such as fumigation and aerodynamic downwash must also be considered as significant factors impacting plume travel (Bierly and Hewson 1962). These can lead to impacts beyond what plume models typically account for. These additional factors can act to increase the expected surface concentration, creating a risk for harmful plume constituents to enter through building air intakes, potentially exposing interior workers who may be expected to have some measure of protection, and disrupting facility operations. Atmospheric conditions at the Savannah River Site (SRS) near Aiken, SC may have caused a fumigation event on January 30, 2022, prompting investigation into the atmospheric conditions contributing to the event and whether better understanding of the conditions could lead to improved weather forecasts and have operational procedures to respond to future events.

Atmospheric temperature inversions form from a variety of different conditions including nocturnal cooling at ground level; warm air flowing over a large body of cold water; subsidence inversion caused by adiabatic compression in the mid-troposphere; differential warm air advection; and frontal inversion. At the SRS, inversions typically occur due to nocturnal cooling. The remaining atmospheric phenomena associated with temperature inversions are infrequent regional scale phenomena that occur over and across multiple states concurrently. Within this regional scale phenomena, the set of conditions that could lead to a fumigation event occur much less frequently.

Inversions are important to understanding the effects of atmospheric dispersion, because when they occur, plumes are restricted in their ability to disperse or dilute. Dispersion in the layer underneath the inversion is limited by stable (negatively buoyant) air which suppresses turbulence that would otherwise disperse the plume through mixing. Stable conditions at night under an inversion with low wind speed are considered the most restrictive dispersion conditions. Most inversions are caused by nocturnal cooling at the ground and form as outgoing longwave radiation is emitted upward from the surface at night. These situations are the basis of many fumigation event studies and early modeling work (Segal and Pielke, 1983). Nocturnal inversions tend to be shallow, typically on the order of 100-200 m, and subsequently, once the sun rises, a combination of turbulent mixing and daytime heating will quickly mix out the inversion and the plume becomes less concentrated.

Recent work related to fumigation and mixing of plumes to the surface are generally focused on emissions of greenhouse gases or pollutants in urban areas where these can pose a threat to human health (Mushtaq et al. 2020; Hossain 2023). In most cases, it is acknowledged that the key considerations are related to development or break-up of a low-level atmospheric temperature inversion and that the key predictors of a fumigation event are generally low wind speeds and a lack of (or a cap on) thermal buoyancy in the atmosphere.

While work related to the fumigation of plumes in industrial settings is important, little work is being done with this setting in mind. As a result, many industrial applications of fumigation prediction and modeling are still based on decades-old work. Most advancements in this area are related to improving existing models (Warren et al. 2022) or developing machine-learning or other advanced computing techniques to assess these situations (Feng et al. 2020).

This paper examines the atmospheric conditions that are believed to have led to the potential recirculation event and leverages high-resolution computational fluid dynamic modeling to identify whether re-circulation of an elevated plume to the surface may have occurred in the vicinity of the release stack. This event is somewhat unique in that the occurrence of a nocturnal inversion was not solely the cause of the event, as the fumigation event occurred in mid-afternoon, well after sunrise. This work seeks to outline the synoptic meteorological conditions that contributed to the timing of the event and demonstrate an example of a high-resolution 2-D model, which can provide a basis for future work to explore the frequency and industrial hazards associated with re-circulating plumes.

Methods

Analysis of Atmospheric Conditions

The fumigation event being analyzed in this study occurred on January 30th, 2022. The event was identified in an area of a Tritium processing facility which consists of single-story process buildings with the plume being emitted from a 30 m stack located near the center of the facility. Based on measurements at the stack, a release of tritium occurred from the facility at approximately 14:30 LST and lasting for approximately five minutes. Following the release, there were indications that the plume mixed to the surface where it would have had the potential to be taken into the facility through building air intakes within 200 m of the facility and expose individuals inside the facility.

Given the timing of the event as occurring mid-afternoon, this event was not related to a nocturnal surface inversion resulting from nighttime cooling. As such, analysis of the event requires an examination of regional and synoptic-scale weather patterns. This data was obtained from the National Oceanic and Atmospheric Administration (NOAA) using archived synoptic maps of surface and upper air

Figure 1: Map of measurement sites, including: Locations of the Savannah River Site (outlined in white) and regional atmospheric sounding sites at Peachtree City, GA and Charleston, SC (left); Instrumentation sites at the Savannah River Site including the ceilometer, meteorological measurement tower, and tritium facility location (right).

conditions at 925mb and 850mb which were available from www.wpc.ncep.noaa.gov and www.spc.noaa.gov, respectively. Archived upper-air soundings from two nearby sounding sites were also obtained from http://www.weather.uwyo.edu to aid in characterization of the regional atmospheric conditions.

Additional data was obtained from the meteorological monitoring network maintained at the SRS (Figure 1). For this analysis, data from a tower located 4.7 km to the south of the impacted facility was used. This tower is instrumented with RM Young Temperature/Relative Humidity Probes (Model 41382V) mounted in Model 43502 aspirated radiation shield. RM Young Sonic Anemometers (Model 81000) are used to provide temperature and 3-D wind measurements at 18 m, near the level of the stack. Additionally, a Vaisala CL 31 ceilometer is located at the SRS which can be used to provide information regarding boundary layer development leading up to the event. Details of the meteorological monitoring program and data quality assurance procedures are detailed in (Weinbeck, et. al. 2020).

Fluent Modeling

To simulate the event at the SRS, a numerical analysis was carried out to visualize the wind profile around the stack and nearby buildings by simultaneously solving the continuity, momentum, and energy equations, along with the turbulence models represented by the standard k-epsilon using the computational fluid dynamic simulation software ANSYS FLUENT 2021 R1. The air is treated as a continuum by solving the Navier-Stokes and energy equations. As seen in Figure 2, a numerical domain

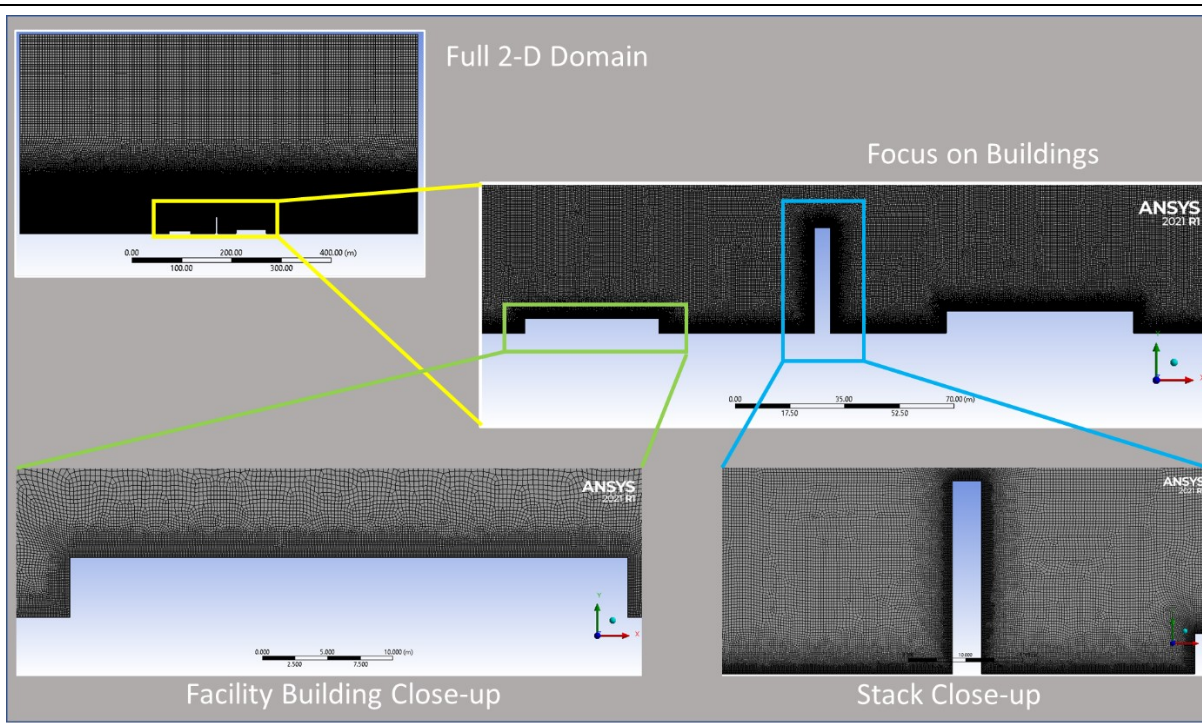

Figure 2. Illustration of the meshes used to simulate flow the release stack and nearby facilities.

having a length and height of 800 m and 400 m, respectively, is constructed in a 2-D rectangular shape. The velocity inlet and pressure outlet boundary conditions are implemented on the left and right side of the domain, respectively, whereas a no-slip boundary condition, with a zero-roughness height, is applied to the ground, walls and roof of the buildings, and sides and top of the stack. Finally, a symmetry boundary condition is applied at the top of the domain to reduce the backflow and improve the convergence of the computation while ensuring that the symmetry boundary condition is sufficiently far away from the buildings so that the wind velocity profile near the area of interest would not be affected.

The buildings mimicking the air blockage are placed far away from the inlet for a fully developed velocity profile. The left building has a height and length of 4.57 m and 42.67 m, respectively, and is placed 300 m away from the domain inlet. The stack height and outlet diameter are 33.50 m and 5.00 m, respectively, and is placed 49.78 m from the left building. The building on the right portion of the domain has a height and length of 7.01 m and 59.83 m, respectively, and is placed 37.13 m away from the stack and about 305 m from the domain outlet. For meshing, the lower part of the domain was meshed finer than the top part of the domain to observe the downwash near the buildings and for computational time. The total number of elements is 532642.

The domain of the model is imported into Fluent with the standard k-epsilon equation solving the turbulence model along with the energy equation. The solution includes a gravitational force and assumes steady state. The wind speed profile at the atmospheric inlet velocity is given by the power law:

$$U = U_{ref}\left(\frac{y}{y_{ref}}\right)^{\alpha}, \tag{1}$$

where, U_{ref}, is the reference velocity at 3 m/s, y, is the node/cell position in the computational domain, y_{ref}, is the reference height at 18 m, and α is the coefficient of the power law. The temperature of the domain remains uniform at 283.15 K, and outlet boundary condition was kept as a static pressure outlet. The simulation involved a coupled pressure-velocity solving method, with a least square cell-based solution method. The pressure, momentum, turbulent kinetic energy, turbulent dissipation rate, and energy equations were solved as second order solutions.

Results and Discussion

January 30th, 2022 Fumigation Event Analysis

On January 29th, 2022, a strong frontal system moved through the Southeast United States. In the wake of the frontal passage, a surface cold airmass moved through South Carolina, illustrated by the 0°C isotherm south of SRS in Georgia and Florida (light blue dashed line in Figure 3), indicating temperatures in South Carolina were below freezing. Simultaneously, warm air advection was occurring at the 925 and 850mb levels, creating a thermal inversion across Florida, Georgia, South Carolina and North Carolina (Figures 4 and 5), illustrated by the wind blowing from warmer air (thicker 500mb heights) to cooler air (shallower 500mb heights) over the Georgia and South Carolina region. Also of importance is that a surface high pressure system covered most of the region, providing clear skies allowing for strong surface heating on January 30th, 2022.

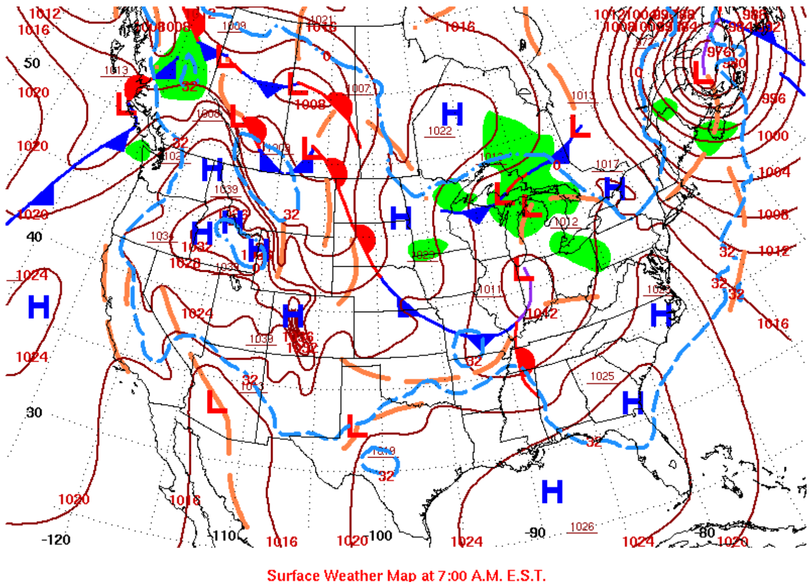

Figure 3. Surface Weather at 7:00AM EST January 30th, 2022. (From https://www.wpc.ncep.noaa.gov/dailywxmap/index_20220129.html)

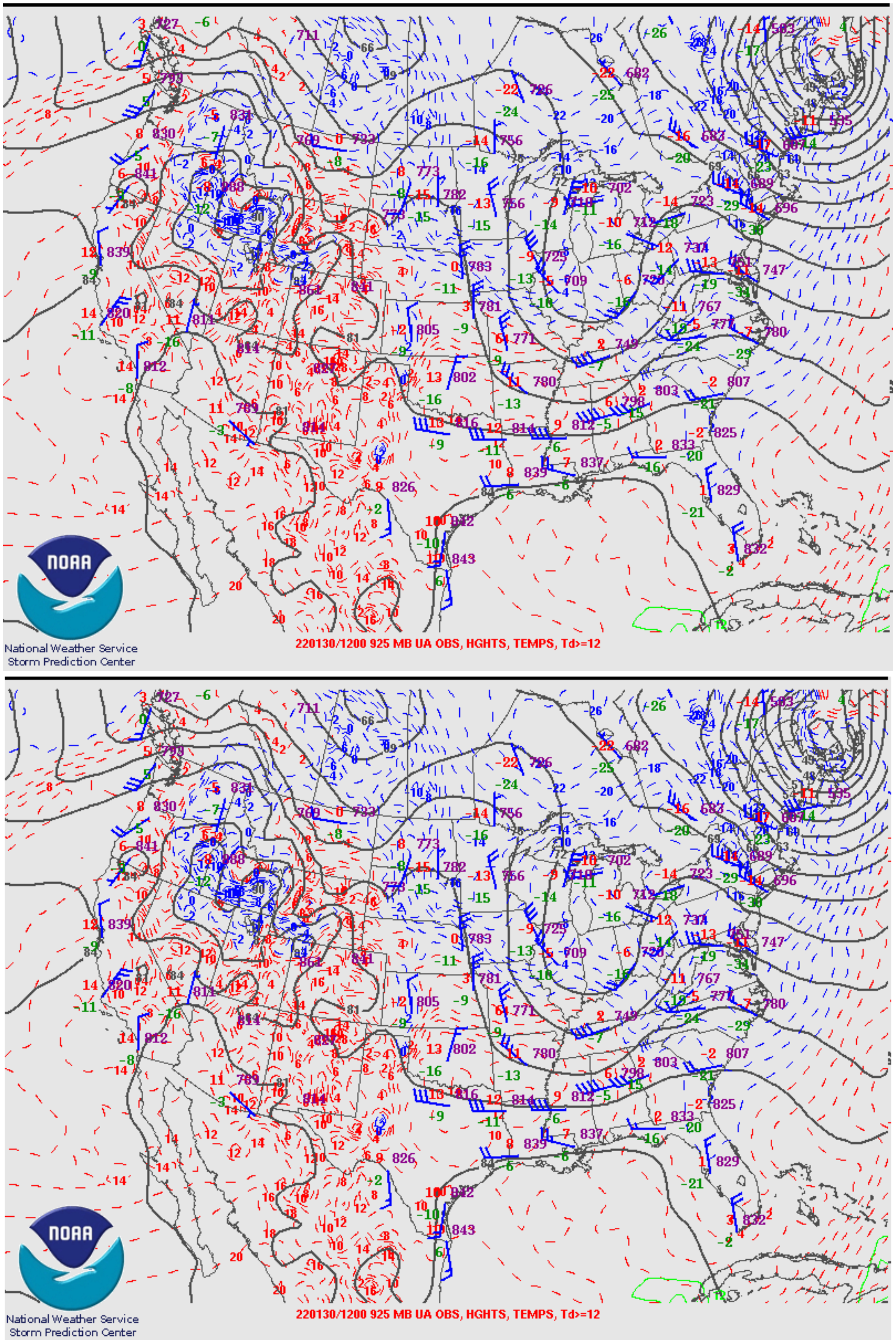

Figure 4. 925 mb analysis for 7 AM Jan 30th (top), and 7 PM Jan 31st, 2022 (bottom). Images obtained from https://www.spc.noaa.gov/obswx/maps/.

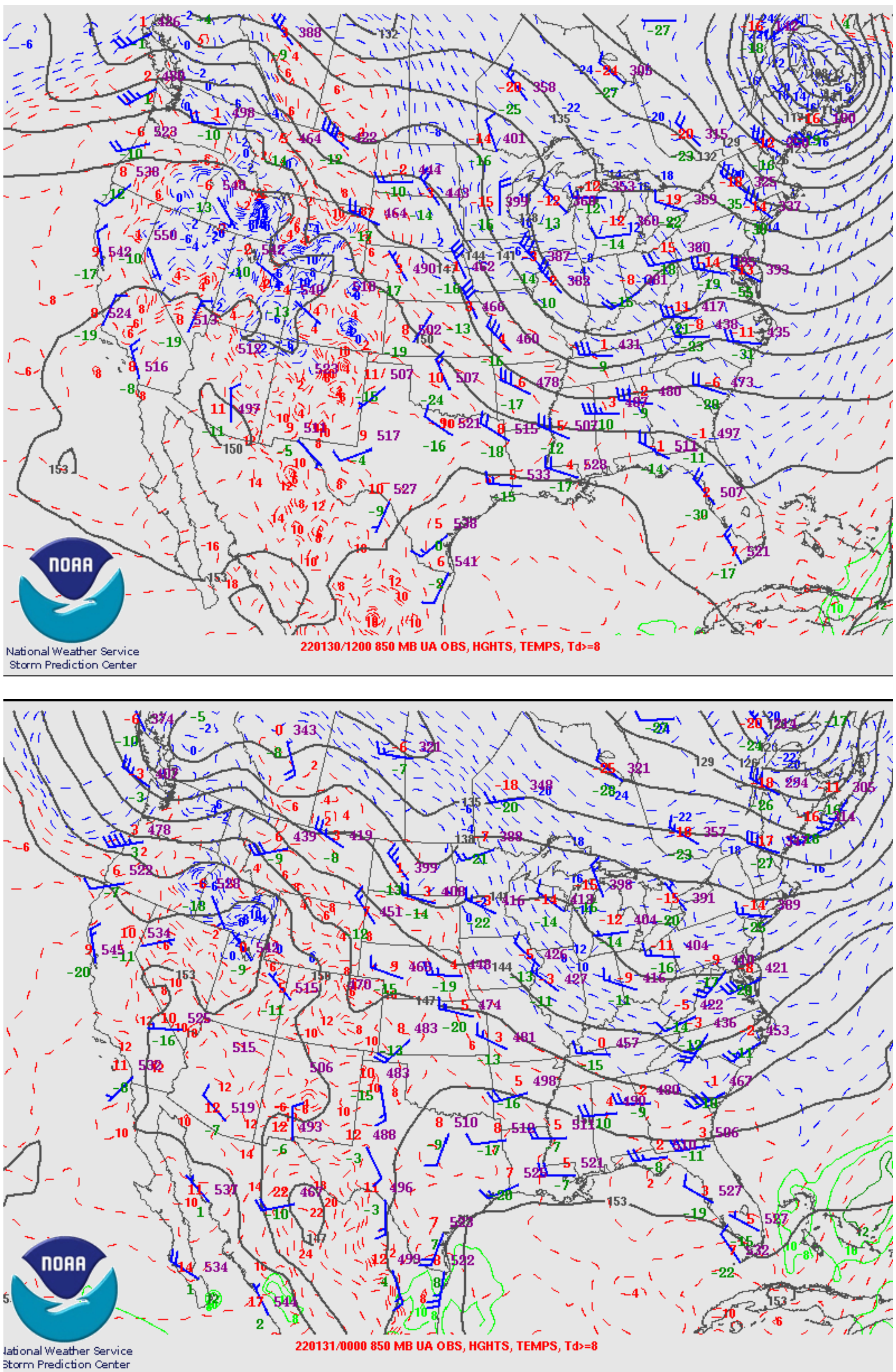

Figure 5. 850 mb Analysis for 7 AM Jan 30th (top), and 7 PM Jan 31st, 2022 (bottom). Images obtained from [https://www.spc.noaa.gov/obswx/maps/.](https://www.spc.noaa.gov/obswx/maps/)

On January 30th, strong surface heating occurred at the surface following sunrise and was paired with the strong, deep inversion aloft. The surface heating initiated vertical thermal mixing near the surface, creating a shallow mixed layer. However, vertical plume movement was trapped by the deep inversion which is seen in the regional atmospheric soundings measured by the National Weather Service (Figure 6). The nearest sounding locations (identified in Figure 1) are located over 100 km away from the SRS, indicating that the inversion condition was a regional event occurring over several states in the region. Figure 6 shows the morning and evening soundings or potential temperature profiles for January 30th, 2022 at 0700 and 1900 LST where the increasing of potential temperature with height indicates a stable layer.

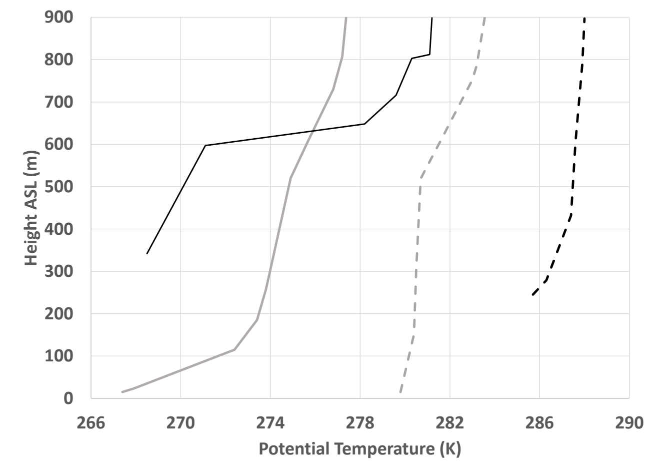

Figure 6: Potential temperature profiles from NWS soundings taken at the Peachtree City, GA (black) and Charleston, SC (gray) sounding sites identified in Figure 1 for 07:00 LST January 30th, 2022 (solid) and for 19:00 LST January 31st, 2022 (dashed).

Both temperature profiles indicate strong and deep stable layers that resulted from a combination of nocturnal cooling, cold air advection behind the cold front that passed through SRS the previous day, and the warm air advection aloft. Both Peachtree City and Charleston soundings have strongly stable layers through 500 m deep while all soundings were stable through the 900 m that was plotted, and remained stable throughout the entire day, indicating that thermal mixing was not sufficient to mix out the deep layer.

Examination of the SRS tower data showed an overnight low temperature of -7°C and is further indication of strong nocturnal cooling at the surface (Figure 7). After sunrise, the temperature increased rapidly, illustrative of the near-surface nocturnal inversion beginning to mix vertically by 0900 LST. SRS ceilometer data suggests that 1130 LST is approximately when the thermal mixing began to gradually deepen (Figure 8), followed by a more rapidly growing mixed layer beginning around 1330 LST. The release from the stack occurred after this point, at approximately 1430 LST. Despite occurring in afternoon, this was still early in the period of mixed layer growth for this day. The mixed

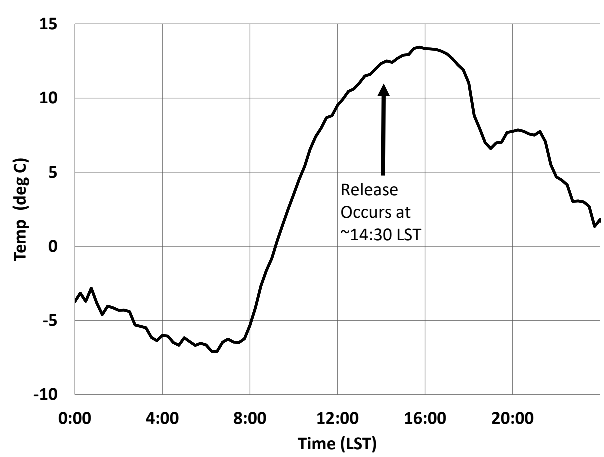

Figure 7. 2m temperature measurements from the SRS meteorological station on January 30, 2022.

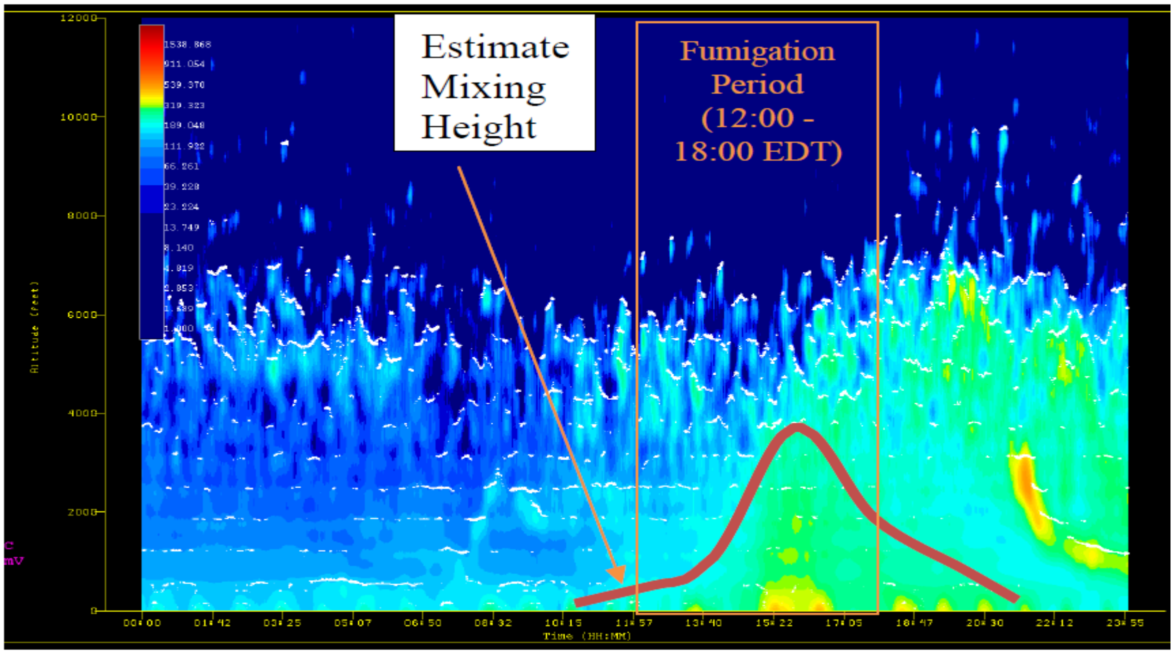

Figure 8. SRS Ceilometer data for January 30, 2022. Colors indicate "backscatter", with the gradients in the colors suggesting where mixing is interrupted. Orange line indicates estimated mixing height. Uniform colors indicate more complete mixing.

layer height was approximately 500 m around this time, meaning that the strong thermal inversion was just starting to break. At this point, it is believed that the plume was still constrained to this depth and that downward mixing occurred as the thermal inversion was mixed out, leading to downward local motion of the plume that led to the plume being brought down to the surface.

An additional contributing factor is believed to be the wind speed, which had increased to around 4.5 ms^{-1} beginning around 1130 LST (Figure 9). This is believed to be significant because stack-tip downwash is more pronounced at higher wind speeds and the increase in wind speed also causes more building induced wake turbulence. Wake models, such as AERMOD (US EPA 2019) or ARCON96 (Ramsdell et al. 1997) usually produce the greatest concentrations with wind speeds of 2-4 ms^{-1}. Within these models, higher wind speeds generally lead to additional mechanical turbulence and dilution of the plume, while lower wind speeds typically do not produce enough turbulence to create a significant downwash effect.

CFD Modeling for 30 January 2022

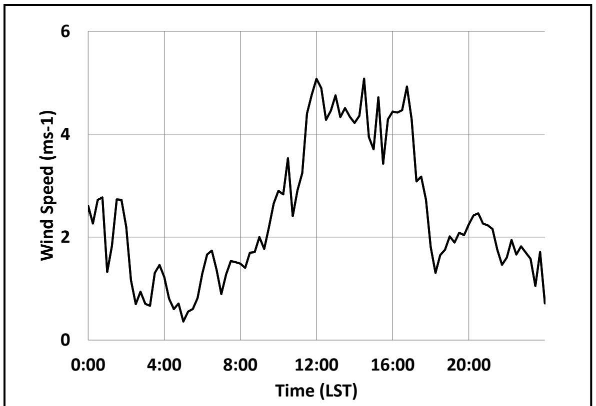

Figure 9. January 30th, 2022 18 m Wind Speed from CLM tower.

The results of a 3 m s^{-1} reference velocity power law are shown in Figure 10. As can be seen in Figure 10a, the obstruction of the stack and the building on the right-hand side of the domain recirculates the air at the ground with a counter-circulation above it and an inflection point near the outlet. The results also show that the velocity profile higher in the atmosphere has a sudden increase in velocity followed by a decrease due to the recirculation. Figure 10b displays a closer view of the wind profile nearby the stack and buildings with wind recirculation occurring at multiple locations with an inflection point on the top of the building on the right. The obstruction of the stack with the wind profile approaching from left to right allows the wind to approach downward both near the buildings and the

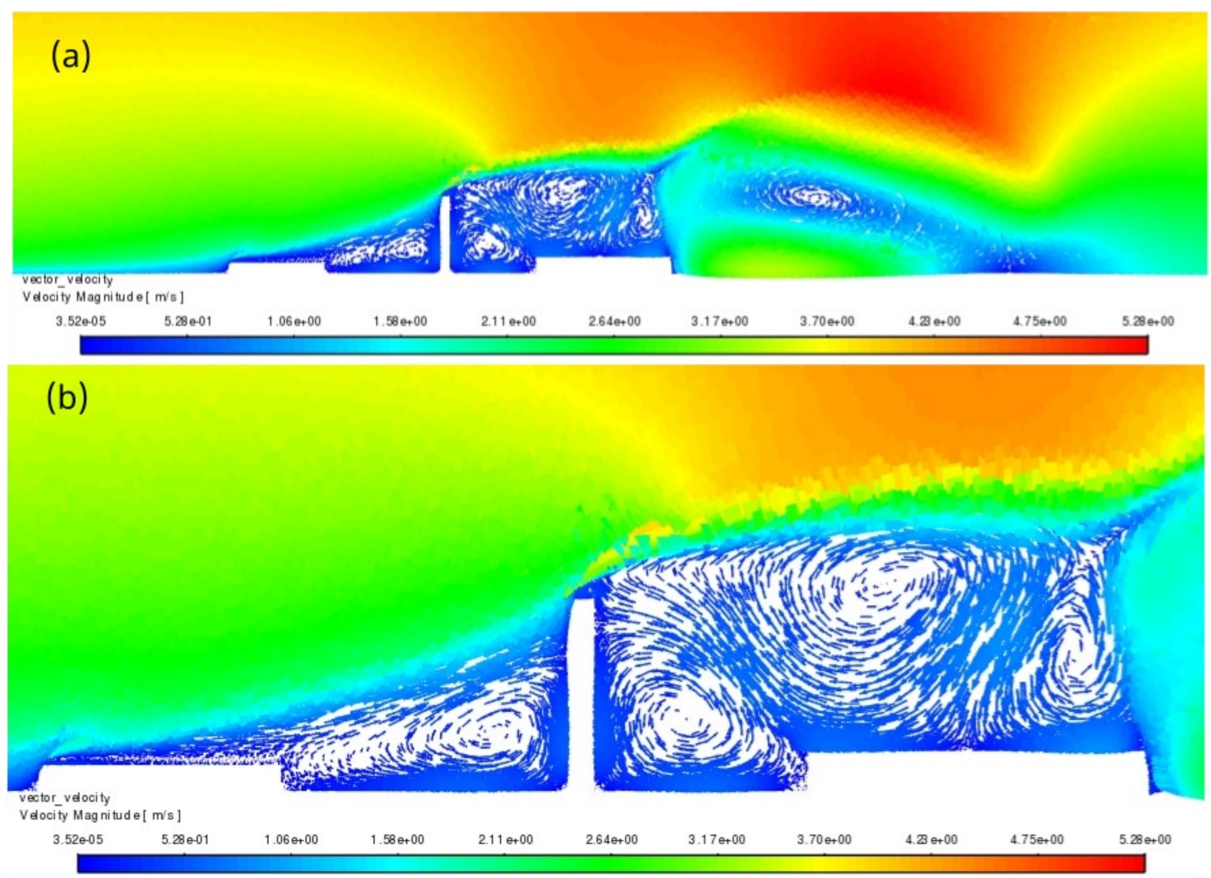

Figure 10. Wind velocity profile in (a) in the lower half of the domain and (b) close up of the stack and buildings.

ground. Therefore, this visualization of the downwash demonstrates it is possible that with the right atmospheric conditions, a plume exiting the stack could possibly be trapped at the ground level and at the top of either building, depending on the direction of the wind.

It should be mentioned that this is an initial step in developing more complex 2-D and/or 3-D studies of the event. Future modeling of the event should include a detailed stack geometry in order to fully capture stack downwash, as illustrated by Cain et al. (2003) when they simulated saturated buoyant plumes with original, choke, and disk geometry designs at the stack exit. Further refinements may include adaptive meshing to improve plume resolution as initial movement of the plume upon release will depend on the outlet radius, as well as humidity of the air output from the stack and the ambient air (Sivanandan et al., 2021, Cizek and Nozicka 2016). Therefore, more sophisticated simulation studies to solve the Navier-Stokes equations would include realizable k-epsilon or large eddy simulations, in which discrete meshing at building surfaces, the ground, and in the atmosphere with plume trajectories are warranted and computational power would be high in demand. Finally, additional physics to condense the plume would require some user defined functions as well as interpolating or extrapolating pressure, temperature, and humidity at varying heights.

Conclusions

In this case, despite an elevated stack, it was found that surface concentrations were leading to sufficient concentrations at the surface to cause alarm regarding uptakes for building air circulation systems. The fact that this event happened in the afternoon during cool, clear conditions with moderate wind speeds raises the question of the event's cause as most fumigation events which could lead to high surface concentrations occur during stable or periods of transition from stable to unstable conditions around or just after sunrise.

Fumigation events resulting from mixing of a near-surface thermal inversion typically occur in the morning after sunrise as a result of an increase in surface sensible heat. The event which occurred on January 30, 2022, is unusual in that the fumigation event occurred in the afternoon but appears to be related to the presence of a strong thermal inversion which was not mixed out until afternoon. A key factor in setting up these atmospheric conditions is the combination of strong surface radiational cooling overnight from January 29 to January 30, with the advection of warm air into the region at heights of approximately 1 km above the surface. This acted to create a much stronger inversion than typically occurs in this region and required a longer period of time to mix out on the following day.

High-resolution modeling demonstrates that re-circulation is plausible based on input and boundary meteorology conditions. The steady state of the boundary conditions will especially be important for plume simulation at the specific time the safety alarms set off on January 30th. For the model itself, additional physics such as heat exchanges, condensation modeling, and meteorological input data should be carefully considered in future studies. Furthermore, a large meshing number should surround the area of interest around the stack and the buildings to capture the turbulent boundary layer, and the plume dynamics. When studying 3-D models, the stack exit may need to be more defined (lip, etc.) and the building air intakes should be treated as sink sources (suck air into the facility). Finally, the turbulent solvers for the event should be worked from realizable k-epsilon and Large Eddy Simulation studies, in which, given their complex designs, will require large computational power for multiple runs. Fortunately, a single event is necessary to study, but there might be additional events to evaluate. Once when these events are studied, additional events seasonal to the SRS site will be simulated to warrant any further action and prediction for worker safety such as redesigning the stack exit and/or cancel any work during events where those specific conditions are observed.

Following an analysis of the event's cause, additional work will need to be pursued aimed at understanding the likelihood of these events occurring in the future and whether surface dynamics such as building downwash or local turbulence play a significant role. Unfortunately, studies developing a climatology of strong inversion events such as the one described here have not been conducted based on the perceived rarity of these events. Such an analysis could provide key data for understanding whether events such as these need to be addressed in more detail for facility safety plans and identify key atmospheric components or patterns that could be used to provide early warning for potential impactful events stemming either from routine or unplanned releases.

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References

Bierly, E. W. and Hewson, E. W., 1962: Some restricitve meteorological conditions to be considered in the design of stacks. *Journal of Appl. Met.*, 1, 383-390.

Cain, Stuart A., Lewis A. Maroti, and Fangbiao Lin. "Prediction of Stack Plume Downwash Using Computational Fluid Dynamics." *Fluids Engineering Division Summer Meeting*. Vol. 36967. 2003.

Cizek, Jan, and Jiri Nozicka. "Cooling tower plume." *AIP Conference Proceedings*. Vol. 1768. No. 1. AIP Publishing LLC, 2016.

Feng, L., Yang, T., Wang, D., Wang, Z., Pan, Y., Matsui, I., ... & Huang, H. (2020). Identify the contribution of elevated industrial plume to ground air quality by optical and machine learning methods. *Environmental Research Communications*, *2*(2), 021005.

Hossain, M., 2022: Fate and transport of stack emissions in the environment and potentail reduction of pollutants in the context of global warming. *J. Environmental Engeineering*, 149, doi.org/10.1061/(ASCE)EE.1943-7870.0002078.

Mushtaq, R., Bandh, S. A. and Shafi, S., 2020: Air pollution and its abatement. Chapter in *Environmental Management*, Springer, 47-93.

Ramsdell, Jr., J. V., Simonen, C. A., Smyth, S. B., Lee, J. Y., 1997: Atmospheric relative concentrations in building wakes. NUREG/CR-6331, Available online at https://inis.iaea.org/collection/NCLCollectionStore/_Public/26/069/26069927.

Segal, M. and Pielke, R. A., 1983: On the evaluation of the mixing layer during elevated plume fumigation. *J. Air Pollution Control Association*, 33, 1190-1192.

Sivanandan, Hrishikesh, et al. "A Study on Plume Dispersion Characteristics of Two Discrete Plume Stacks for Negative Temperature Gradient Conditions." *Environmental Modeling & Assessment* 26.3 (2021): 405-422.

Warren, C. J., Paine, R. J., Connors, J. A., Szembek, C. and Knipping, E., 2022: Evaluation of a revised AERMOD treatment of plume disperison in the daytime elevated stable layer. *J. Air Waste Management Association*, 72, doi.org/10.1080/10962247.2022.2094031.

Weinbeck, S.W., Viner, B.J. and A.M. Rivera-Giboyeaux, 2020: Meteorological Monitoring Program, SRNL-TR-2020-00197, Savannah River National Lab, Aiken, SC, 138 pp. [Available online at https://weather.srs.gov/atg/static/pdf/SRNL-TR-2020-00197.pdf]

U. S. Environmental Protection Agency, 2019: AERMOD: Model formation and evluation. EPA-454/R-19-014, 177pp.