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Evaluating Atmospheric Mixing Height Estimations in the Western United States

DEVELOP Technical Report

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1. Abstract

Wildfires in the western United States have caused immense infrastructure damage and loss of human life in recent years. Wildfire smoke, which travels far from its original source, is also harmful to human health. Mixing height, which acts as a lid and prevents smoke from rising above a certain altitude in the lower troposphere, is a critical input in smoke dispersion and air quality models used by agencies that monitor wildfires. These models, coupled with forecaster expertise, are also used to decide when it is safe to execute a prescribed burn. The DEVELOP ID team partnered with the National Weather Service (NWS) Fire Weather Program, Bureau of Land Management (BLM), National Interagency Fire Center (NIFC), and National Park Service (NPS) Fire Management Program Center (FMPC) to help improve reliability and confidence in mixing height estimations, and therefore the burn prescription decision-making process. To that end, the team developed a toolbox for measuring smoke-related aerosol mixing heights using Cloud-Aerosol LiDAR and Infrared Pathfinder Satellite Observations (CALIPSO) Vertical Feature Mask granules. CALIPSO mixing heights and NWS estimations covaried significantly and positively. However, substantial disagreement between the methods stymied the team's attempts to quantify systematic bias in a meaningful way. The relative error between the methods was especially large at low mixing heights, which suggests that this method of validation may only be suitable at higher altitudes.

Key Terms

Wildfires, smoke pollution, mixing height, aerosol dispersion, CALIPSO, remote sensing, Western US

2. Introduction

2.1 Background Information

In recent decades, wildfire events in the western United States have increased in frequency due to changes in climate, severe droughts, invasive plant species, and consequences from historic fire management and fire suppression (Dennison et al., 2014). While fires can damage infrastructure, the smoke from these events is also harmful. Wildfire smoke has been linked to decreased environmental productivity (Yue & Unger, 2018), and is known to have adverse effects on human respiratory health, particularly in older adults and those with other health conditions such as asthma and chronic obstructive pulmonary disease (Reid & Maestas, 2019). With an aging population and increasing asthma rates, more Americans will be especially vulnerable to these negative health effects in the coming years (Jones & Berrens, 2017). Thus, accurate air quality forecasts are essential in reporting public safety recommendations, as well as determining the safety of prescribed burns. Prescribed burns have the potential to substantially reduce fuel loads, limit the spread of wildfires, and reduce wildfire potential, yet this management tool is often rejected due to smoke concerns (Williamson et al., 2016).

One of the key indices for smoke pollution forecasting is mixing height. Mixing height is defined as the maximum height below which rapid vertical mixing takes place in the atmosphere and is expressed as an altitude measurement above ground or sea level (Figure 1). Mixing height estimation is critical in predicting the movement and dispersal of wildfire smoke plumes (Zilitinkevich & Baklanov, 2002). Lower mixing heights are also associated with less dispersal of PM2.5 and other pollutants, leading to poorer surface-level air quality (Murthy et al., 2020).

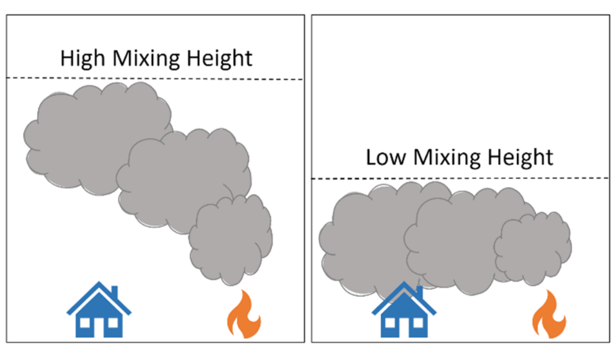

Figure 1. Mixing height is the altitude below which smoke is vertically well-mixed. The atmospheric boundary denoted by the mixing height is determined by atmospheric temperature and can be observed as the maximum altitude of smoke aerosols.

Satellites, such as Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), can be used to calculate observed mixing height. Previous studies have used CALIPSO Level 2 LiDAR vertical feature mask (VFM) data to calculate mixing heights because the CALIPSO VFM data product (Figure A1) describes the vertical and horizontal distribution of cloud and aerosol layers and can detect many air quality feature types, including tropospheric aerosols (NASA, 2018). Smoke plumes that are contiguous to the Earth's surface are classified as tropospheric aerosols, and the maximum altitude of these aerosols is used a proxy for mixing height (Fearon et al., 2015).

The previous team working on this project wrote a script that uses CALIPSO VFM data to calculate mixing height where wildfire smoke plumes are transected by a CALIPSO pass. They focused on wildfires in the southern Idaho region between 2013 and 2020 but found few smoke plumes for which CALIPSO data were available. For this reason, the study area was expanded in the second term of the project to include the entire western United States: Arizona, California, Colorado, Idaho, Nevada, New Mexico, Montana, Oregon, Utah, Washington, and Wyoming (Figure 2). Given that CALIPSO was launched in 2006, the study period for this term was also expanded to include fires between 2006 and 2020. This team identified smoke plumes in July, August, and September across the western United States study area. The expanded region and period allowed for a much larger data set of smoke plumes to analyze.

Figure 2. The study area: the western United States. Smoke plumes in these western states from July-September 2006-2020 were identified for mixing height comparison.

2.2 Project Partners & Objectives

This project partnered with the National Weather Service (NWS) Fire Weather Program (FWP) and the Bureau of Land Management (BLM), National Interagency Fire Center (NIFC) and the National Parks Service (NPS) Fire Management Program Center (FMPC) to increase confidence in mixing height estimation methods by verifying current methodologies against satellite-observed estimates. The dearth of research in this area has led to the adoption of non-uniform mixing height estimation models among NWS forecasting offices, which is a major issue that detrimentally impacts the accuracy of air quality data. At the time of this study, NWS Fire Weather forecasters employ a multi-step process in calculating mixing height estimations, which involves an initial estimation based on outputs from the Advanced Weather Interactive Processing System (AWIPS) that is subsequently adjusted through use of model- or radiosonde-based upper air soundings and individual forecaster knowledge. The AWIPS mixing height input to the Fire Weather forecasts was calculated using a modified Stull method which, to our knowledge, has only had its accuracy assessed in the single study by Fearon et al. 2015 (Craven et al., 2019, Griffith et al., 2020). In light of this, the FWP was interested in conducting a study to understand whether systematic biases existed in Stull-based mixing height estimations and statistically quantify these biases.

NIFC provides decision-support for conducting prescribed burns, and mixing height estimations are essential to downstream modeling of air quality impacts. The decision to ignite a fire is based on mixing height estimations and the NIFC cannot permit a prescribed burn if the estimated mixing height is so low that it may lead to possible downwind air quality hazards. A validation study will therefore allow NIFC to make better-informed decisions about the air quality implications of prescribed burns. Lastly, the NPS Fire Management Program Center maintains national lands in regions of the United States that are subject to frequent wildfires. They are interested in a verification study of NWS mixing height estimation methods because they rely on these estimates to determine the safety of prescribed burns and report on air quality in their parks.

3. Methodology

3.1 Data Acquisition

We used several remotely sensed data products and an ancillary mixing height dataset to estimate and validate smoke plume mixing height, which are illustrated in Tables 1 and 2, below.

Table 1

Primary Earth observational data acquired pertaining to mixing height estimation and validation.

Data Acquired	Temporal Coverage	Spatial Coverage	Source	Description
CAL_LID_L2_VFM-Standard-V4 20, CALIPSO LiDAR Level 2, 5km Vertical Feature Mask (VFM) V4-20	2006-2020	Western US	NASA EarthData Portal	The CALIPSO LiDAR Vertical Feature Mask product contains the observed vertical and horizontal distribution of cloud and aerosol layers.
National Weather Service Mixing Height estimations	2006-2020	National Weather Service forecasting zones	Archive of National Weather Service Forecasts from the Iowa Environmental Mesonet	These estimations are produced internally by the National Weather Service's standard Advanced Weather Interactive Processing System (AWIPS), and then adjusted by forecasters based on balloon soundings and individual expertise.

MOD07_L2, MODIS Terra Vertical Temperature and Water Vapor Profiles, 5-min Level-2, Swath 5km	2006-2020	Specific areas of interest in the Western US	NASA Level-1 LAADS DAAC	These data contain temperature and moisture profiles produced at 20 vertical levels at 5km grid spacing.

Table 2

Ancillary datasets used for geospatial analysis.

Ancillary Dataset	Temporal Coverage	Spatial Coverage	Source	Description
Historic Fires Database (HFD)	1950-2020	Western US	Idaho State University GIS Training and Research Center. 2020. Historic Fires Database (HFD) version 3.0. Downloaded from http://giscenter.isu.edu/research/Techpg/HFD/ October 1, 2020	This dataset contains GIS data for wildfires in the western U.S. Used to identify burn scars of wildfires in the study area.
CALIPSO-CIMSS Surface Attached Aerosol Layer (SAAL)	2006-2012	Global CALIPSO transects	Downloaded from the Cooperative Institute for Meteorological Satellite Studies (CIMSS) website http://cimss.ssec.wisc.edu/calipso/ Feb. 20, 2021	This data product contains Surface Attached Aerosol Layer Height (a proxy for Mixing Layer Height) which is calculated using a wavelet covariance transform applied to the CALIPSO LiDAR backscatter profiles.
Western US Digital Elevation Model (DEM)	2013-2017	Western US	Idaho State University GIS Training and Research Center. Accessed March 10, 2021	This DEM is a 10-meter resolution seamless surface elevation model. Originally designed for the NASA RECOVER wildfire decision support system. Generated using USGS NED data.

3.2 Data Processing

The CALIPSO Vertical Feature Mask data is binned differently at different altitudes. Here, we study the lower troposphere (Block A, Figure 3) where each 5km x 5km block is divided into 15 granules horizontally, with a vertical resolution of 30m. The mixing heights detected within these 15 granule blocks (Block A, Figure 3) are output into a table containing the latitude, longitude, and altitude of the mixing height and exported into comma-separated values (CSV) files. We automated and applied the A-SMOKRE tool to calculate mixing heights from the CALIPSO transects that overlapped with smoke plumes, identified visually using the NASA WorldView Interactive Interface with the Terra & Aqua MODIS Corrected Reflectance (True Color), the MODIS Fires and Thermal Anomalies, and the VIIRS/Suomi NPP Fires and Thermal Anomalies layers. We manually recorded the geographic extent of the daytime CALIPSO transects that overlapped with smoke plumes from fire anomalies as well as the time of the pass.

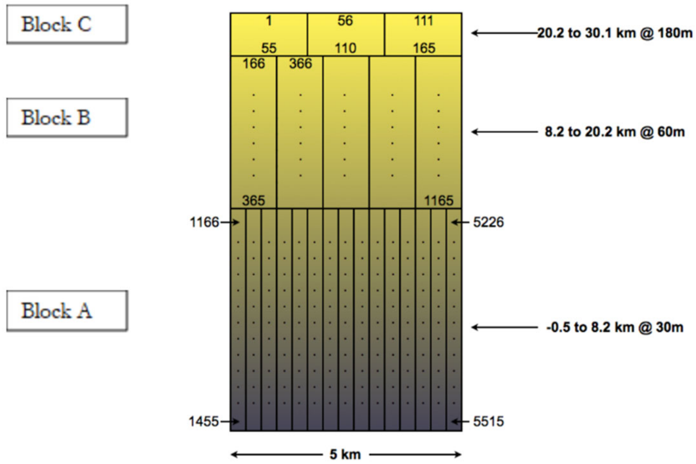

Figure 3. Diagram showing the CALIPSO Vertical Feature Mask granule block structure from the CALIPSO User Guide (NASA, 2018). The swath is 5 km wide and the vertical layers of the atmosphere are separated into granule blocks with different resolution.

We acquired historic National Weather Service mixing height forecasts (Figure 4) from the Iowa Environmental Database National Weather Service Text Product archive using a Python-based web scraper. Two types of forecasts were acquired: Fire Weather Forecasts, which are associated with specific Fire Weather Zones indicated in Figure 4, as well as Spot Forecasts, which were issued for specific locations where wildfires occurred.

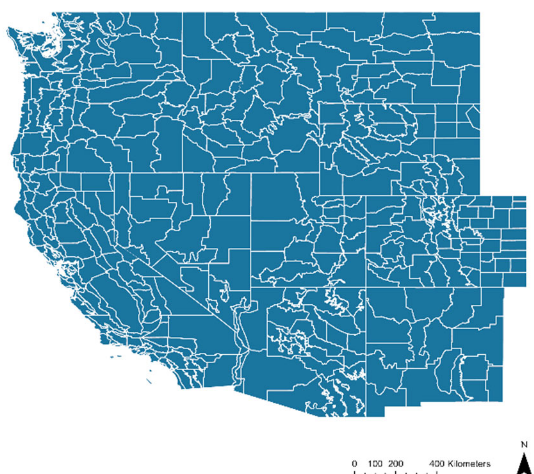

Figure 4. National Weather Service forecasting zones (also known as Fire Weather Zones) in the western U.S.

We extracted Terra MODIS Atmospheric Profiles over each area of interest using the gridded latitude and longitude data fields. We then analyzed the water vapor mixing ratio vertical profiles, which are provided at 20 pressure levels in the atmosphere: 1000, 950, 920, 850, 780, 700, 620, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10, 5 mbar. Following the sounding-validated methodology in Feng et al. (2015), we calculated the gradient of the water vapor mixing ratio and identified where an abrupt decrease was observed in the water vapor mixing ratio (Figure 5). This represents the transition into the mixing layer, and was accomplished using an automated script. The atmospheric pressure associated with the decrease in water vapor mixing ratio was then converted to altitude using the same pressure altitude conversion formula used by the National Weather Service. These altitudes represent the mixing heights estimated from this method.

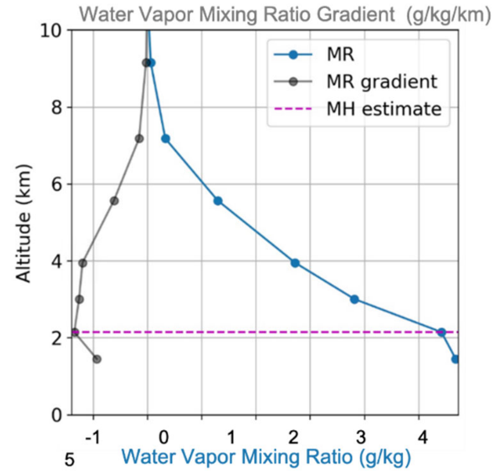

Figure 5. Water vapor mixing ratio (MR) and gradient in the mixing ratio used to estimate mixing heights (MH) from August 20, 2020 Terra MODIS Atmospheric Profile over Eastern Oregon.

The CALIPSO-CIMSS Surface Attached Aerosol Layer (SAAL) data are attributed with latitude, longitude, and the Planetary Boundary Layer Height (PBLH) calculated for the SAAL along the global CALIPSO transects from 2006-2012. The SAAL is a proxy for the height of the mixing layer. We used the latitude and longitude data to identify mixing height estimates over each area of interest and compared these to mixing height estimates derived from the CALIPSO vertical feature masks.

The CIMSS, MODIS, and National Weather Service forecasted mixing heights are expressed as the altitude above ground level in kilometers. The CALIPSO mixing heights, provided as altitude above mean sea level, were corrected to units above ground level using the western topography Digital Elevation Model for the comparison. There are multiple satellite-derived mixing heights within each of the NWS Fire Weather Zones for which there is a single forecasted mixing height, so we calculated a mean of the mixing height from each satellite-based method for each NWS Fire Weather Zone.

3.3 Data Analysis
We validated the mixing height estimates generated by NWS partners by comparing them to the mixing heights we calculate from the CALIPSO Vertical Feature Masks, the mixing height estimates from the CIMSS SAAL product, and the mixing heights estimated from MODIS vertical Atmospheric Profiles. Where the datasets overlap spatially and temporally, we calculated the differences in mixing height and generated summary statistics to report on the accuracy of the NWS mixing height estimates. Furthermore, we generated scatter plots to visualize the mixing height estimates from the different methods and interpret the results. We also generated plots of mixing height corresponding to specific fire events, which will give our partners a visual representation of our validation results in the context of wildfire management.

4. Results & Discussion
The mixing height of aerosols determined from the CALIPSO Vertical Feature Masks was compared to the Fire Weather Zone forecast and the average MODIS mixing height estimate for a smoke plume event case study from Northern Idaho in 2015 (Figure 6). Additionally, the resulting mixing heights determined from CALIPSO Vertical Feature Masks (Figure 7), MODIS Terra atmospheric profiles (Figure 8), and the values determined from the CALIPSO-CIMSS Surface Attached Aerosol Product were all compared to each other.

4.0a Case Study

To provide partners with a specific case study of our mixing height comparisons, we visualized the mixing height estimates produced for a smoke plume event in northern Idaho from August 2015 (Figure 6). The CALIPSO transect overlapped the smoke plume on August 27, 2015 in Fire Weather Zone ID101 (Figure 6A). Mixing height estimates from MODIS were also available in the Fire Weather Zone from that date. The mixing heights calculated from A-SMOKRE along the CALIPSO transect is shown by aerosol classification along with the mean MODIS mixing height the FWF forecasted mixing height for the zone (Figure 6B). For this case study, mixing heights from A-SMOKRE and the mean mixing height estimate from MODIS are higher on average than the National Weather Service FWF forecasted value, suggesting an underprediction in the forecast.

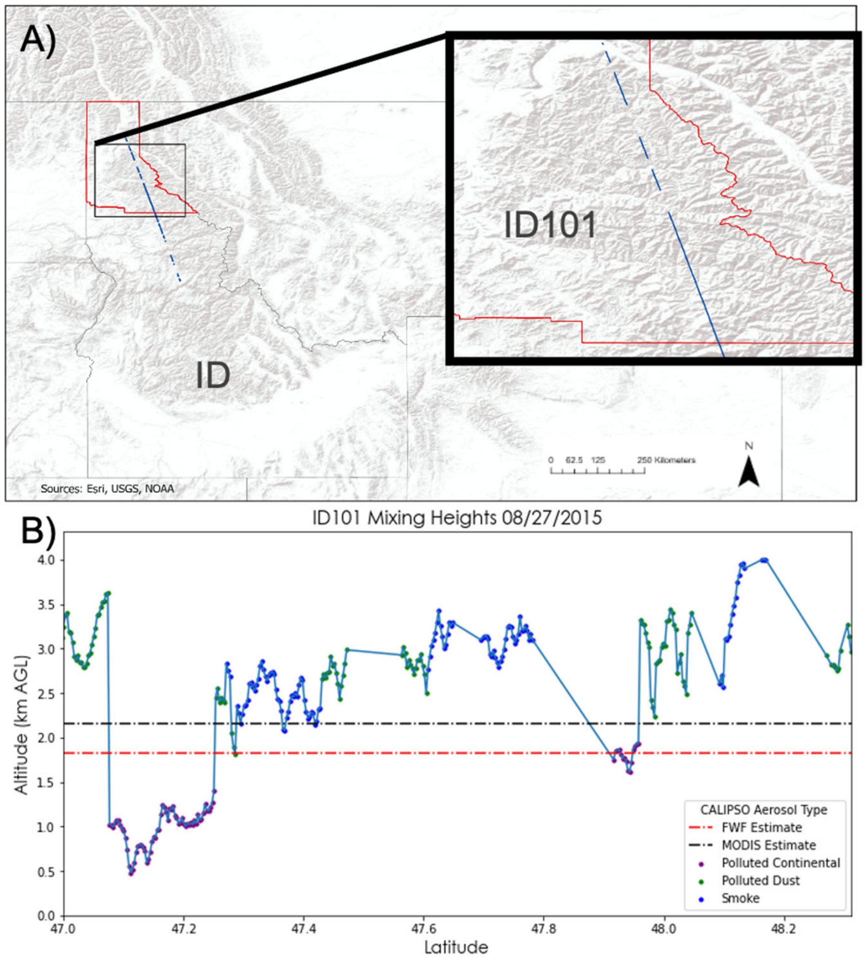

Figure 6. Case study of smoke plume event in northern Idaho on August 27, 2015 in Fire Weather Zone (FWZ) ID101. A) Red polygon indicates extent of FWZ ID101. Blue line shows the CALIPSO transect. B) Mixing heights for the case study. The plot shows the National Weather Service Fire Weather Forecast mixing height for the FWZ (red dash-dot line), the mean MODIS estimate over zone ID101(black dash-dot line), A-SMOKRE outputs for three aerosol sub-types (purple dots: polluted continental; green dots: polluted dust; and blue dots: smoke). Blue line segments are added where A-SMOKRE outputs are not available.

4.0b Broader Results

We examine the overall distribution of mixing heights generated from each dataset (Figure 7). The distribution of mixing heights from A-SMOKRE and the NWS forecasts appear similar and have higher mixing height estimates than those generated from the other methods. Interestingly, the two types of NWS forecasts appear to have slightly different distributions. The two CALIPSO-derived mixing heights maintain very different distributions. CIMSS mixing heights have a much narrower spread than A-SMOKRE and show a more similar distribution to MODIS estimates, with neither of these two datasets producing any mixing height estimates above 3km. CIMSS and A-SMOKRE both use CALIPSO data, so their dramatic difference in estimation is curious. One possible reason for this difference may be the assumptions made about smoke aerosol profiles. In CIMSS, only aerosol plumes that are attached to the surface are considered, whereas in A-SMOKRE, plumes which are slightly detached or discontinuous are considered.

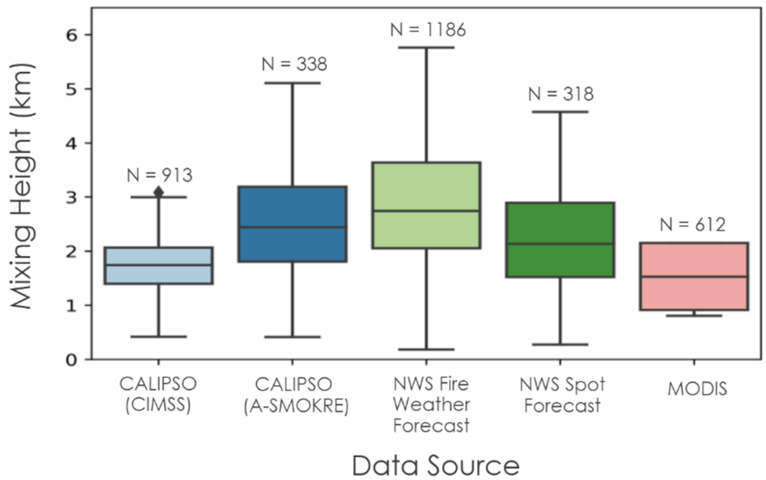

Figure 7. Box plots showing the distribution of mixing heights estimated from each method. The box corresponds to the 25th, 50th, and 75th percentiles, while the whiskers correspond to the range of the data. Diamonds indicate outliers, which are more than 1.5 times the interquartile range away from the 25th and 75th percentiles. The estimates from CIMSS, A-SMOKRE, and MODIS were computed as means over the Fire Zones to avoid weighting longer transects more heavily. While datapoints for MODIS and A-SMOKRE correspond to the same Fire Weather Zones, CIMSS data presented does not necessarily align spatially with those products.

4.1a Analysis of Results

The relationship between MODIS- and CALIPSO-derived mixing height estimations along with National Weather Service estimations were examined for potential systematic bias (Figure 8). We examined potential systemic bias in the NWS estimations and factors influencing accuracy.

Though the scatter plot points (Figure 8A) demonstrate a sizeable spread, the positive correlation trend indicated by coherence with the one-to-one line suggests the A-SMOKRE output was generally aligned with NWS forecasts. On the other hand, scatterplots 8B and 8C demonstrate mixing height overestimation by the NWS methodology compared to CALIPSO-CIMSS and MODIS. Given that these two satellite products only produced mixing heights below 3km, it remains unclear whether they provide meaningful comparisons for NWS forecasts above 3km. Figure 8C illustrates how the limited vertical resolution of MODIS water vapor profiles to just a few discrete pressure levels in the lower troposphere eliminated its utility beyond 2.5km; however, for lower NWS mixing height forecasts, there appears to be general coherence between these datasets.

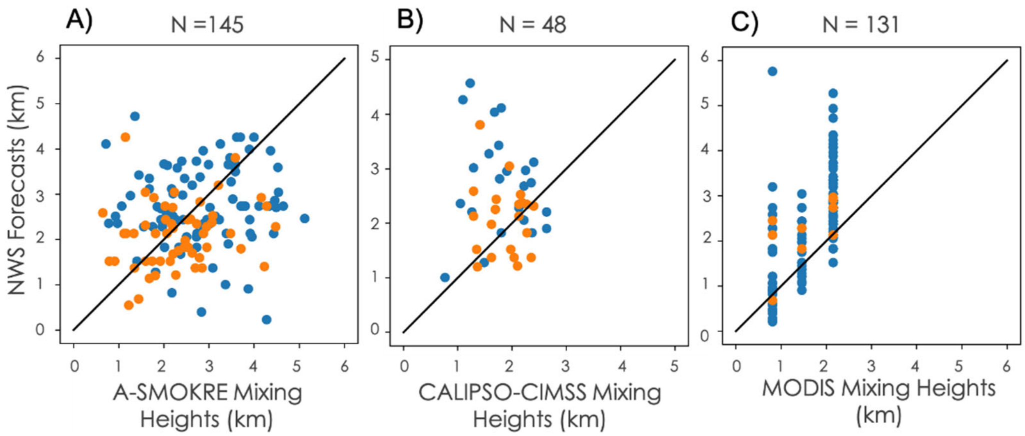

Figure 8. Comparisons of NWS forecasted mixing heights against the remotely sensed datasets: A) A-SMOKRE, B) CALIPSO-CIMSS, and C) MODIS. Blue points correspond to NWS Fire Weather Forecasts while orange points correspond to NWS Spot Forecasts. 1-to-1 lines indicate perfect coherence between the two compared mixing heights for a smoke plume event. Note that N values differ from Figure 7 because N values in Figure 7 indicate the total number of observations for each source, whereas the N values in Figure 8 are a subset of those representing the intersection between the datasets listed on the x and y axis.

Figure 9A indicates general coherence between A-SMOKRE and CALIPSO-CIMSS for the polluted dust, continental, and undetermined aerosol types. Figures 9A and 9B indicate that smoke seems to have higher mixing heights than the other aerosol types, which are even further from the capabilities of both CALIPSO-CIMSS and MODIS. This result suggests one of three things: (1) that the VFM smoke aerosol classifications are not accurate and actually overestimating mixing heights, (2) that CIMSS and MODIS are only able to accurately predict mixing heights for non-smoke aerosols which may be a function of the size of specific particulate matter, or (3) that the underlying methodology of these two datasets constrains their mixing height observations between 0.5 and 3km, therefore rendering them inappropriate when examining higher mixing heights.

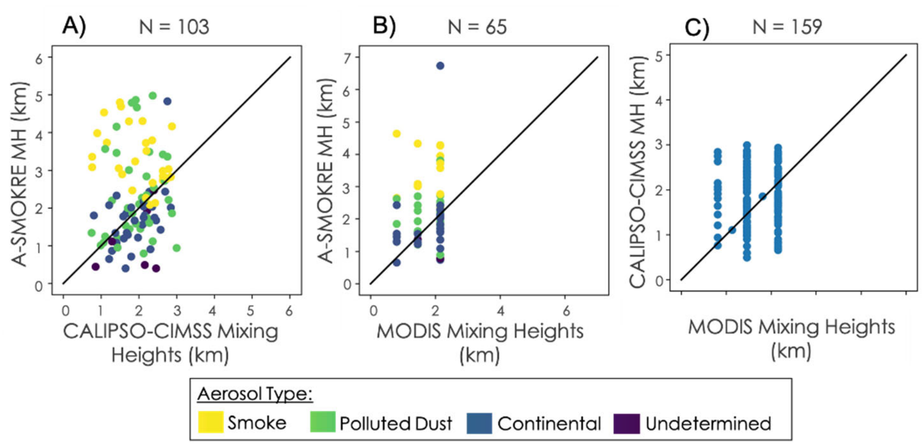

Figure 9. Intercomparison of the mixing heights generated from MODIS and CALIPSO data: A) A-SMOKRE vs. CALIPSO-CIMSS, B) A-SMOKRE vs. MODIS, and C) CALIPSO-CIMSS vs. MODIS. The aerosol type classifications correspond to the modal aerosol classification for the A-SMOKRE mixing heights within the corresponding Fire Weather Zone.

Comparing the A-SMOKRE output and NWS mixing heights, we see a general trend of agreement, or at least an ovular shape with increasing upper and lower bounds (Figure 10). The corresponding orthogonal distance regression shows that the regression is statistically significantly different from a slope of zero. Moreover, the

Pearson's r test of covariance (which is independent of the regression) shows that the data covary in a significant way (Table A1). One factor of interest is the lack of heteroscedasticity, which leads to significantly higher relative errors at lower values (Figure 11). Especially at lower mixing heights, the relative error is very high, and overwhelmingly positive. Meanwhile, at higher mixing heights, the relative error tends to be lower, and more often negative. The latter phenomenon is particularly clear in Figure 11B, where the relative error is calculated with respect to A-SMOKRE. Although the absolute number of underestimates seems to remain constant across mixing heights, a greater portion of NWS predictions are underestimates at higher mixing heights. Figure 11A, where relative error is calculated with respect to NWS predictions, also exhibits this shift in the proportion of under- or over-estimates as mixing height increases. These similar trends in the relative error seem to be a product of the unimodal distribution of each dataset and disagreement on the tails of that distribution; i.e., both are more likely to predict mixing heights from 1.5-3 km, and when one predicts a value outside that range, the other is more likely to fall closer to the mean. Generally, NWS zonal forecasts were lower than A-SMOKRE observations, with a median relative error of –10.7%.

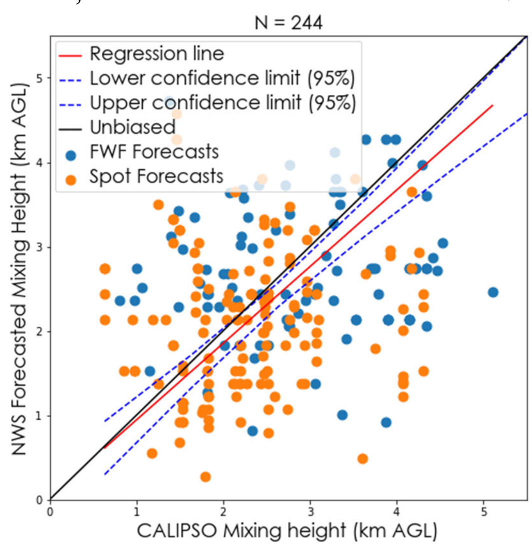

Figure 10. Zonal mean mixing heights (defined as the mean across each NWS Fire Weather Zone) from A-SMOKRE vs National Weather Service zonal forecasts. Orthogonal distance regression, which accounts for variability in both measurements, was used analyze the trend in the data.

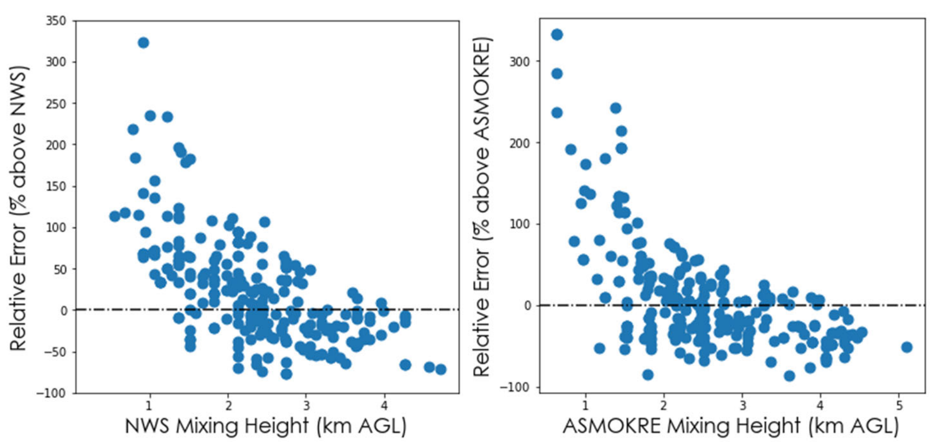

Figure 11. Left: Percent error relative to NWS forecast estimates (median = 12.1 %). Right: Percent error relative to A-SMOKRE observations (median = -10.7 %).

Because the box plots showed differences between the NWS Fire Weather Forecasts and spot forecasts, we plotted these forecasts against each other for days and locations where both were available. Figure 12 shows there is some variation between the two forecast types, and while there is general agreement, many of the spot forecasts predict lower mixing heights than the Fire Weather forecasts at the same location on the same day.

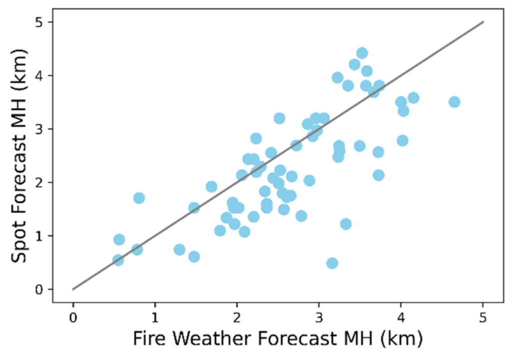

Figure 12. National Weather Service Fire Weather Forecasts plotted against National Weather Service spot forecasts at the same location on the same day. The Fire Weather Forecasts are general forecasts that are released every day. The spot forecasts are released when a wildfire smoke is expected to be a concern in a particular area. Fire Weather Forecasts cover fire weather zones and spot forecasts cover larger areas called PILs, so the Fire Weather Forecasts here have been averaged over PILs on a given day. The 1:1 line indicates perfect agreement between the two forecasts.

Mapping relative error across the study area revealed an apparent trend of NWS FWF to underestimate mixing heights originating in the Pacific Northwest (Figure 13). While adjacent Fire Weather Zones in other states such as Oregon, Idaho, and Wyoming display similar values to one another, the majority of these relative errors are less extreme, lying closer to zero than either end of the spectrum. However, the sparseness of the dataset (just 12% coverage across Fire Weather Zones in the western United States) limits any definitive conclusions about this pattern. This map (Figure 13) along with closer inspection of the data, show that several of the Fire Weather Zones tend to either under- or over-estimate, but not both.

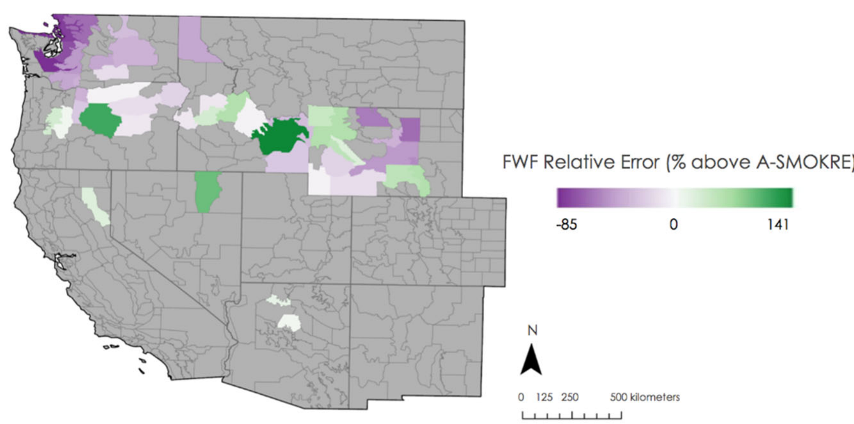

Figure 13. Percent error of NWS FWF relative to A-SMOKRE observations. The largest underestimates occurred in the Seattle, WA area while the largest overestimates occurred in southeastern Idaho.

Mean absolute error (MAE) was calculated for mixing height estimates among the NWS Fire Weather Forecasts, NWS Spot Forecasts, A-SMOKRE, MODIS, and CIMSS (Table 3). Of the two NWS products, the Spot Forecasts show greater agreement with all of the satellite-derived mixing height observations than the NWS Fire Weather Forecasts. The MODIS mixing heights seemed to correspond the best to the mixing heights from all other methods, including the two types of NWS forecasts. Table A2 displays MAE of remotely sensed products compared with the combined NWS forecasts, which indicates midpoint values between the two.

Table 3
Confusion matrix showing the Mean Absolute Error (MAE) in mixing height estimates in kilometers above ground level between A-SMOKRE, MODIS, CIMSS, NWS Spot Forecasts, and NWS Fire Weather Forecasts. Since NWS Spot Forecasts did not overlap with NWS Fire Weather Forecasts in this study, no MAE is calculated between the two.

	A-SMOKRE	MODIS	CIMSS	NWS Spot Forecast	NWS Fire Weather Forecast
A-SMOKRE		0.84 (n=58)	0.94 (n=96)	0.87 (n=53)	0.97 (n=79)
MODIS			0.70 (n=94)	0.72 (n=9)	0.83 (n=120)
CIMSS				0.58 (n=22)	1.16 (n=24)
NWS Spot Forecast					N/A
NWS Fire Weather Forecast					

Other researchers in this field found similar results to our team. In their study verifying NWS spot forecasts using atmospheric sounding observations, Nauslar et al. 2016 found that mixing height spot forecasts exhibited large mean absolute errors compared to atmospheric soundings and were biased toward overforecasting. In comparison to Stull-based atmospheric soundings, spot forecasts exhibited a mean absolute error of 0.618km for the Western United States (Nauslar et al. 2016). We found similar mean absolute errors between spot forecasts and our remotely sensed observations which serve as a proxy for atmospheric soundings: CIMSS (0.58km), MODIS (0.72km), and A-SMOKRE (0.87km).

4.1b Uncertainties and limitations

A limitation in this study was the sparseness of data. A sun-synchronous satellite, CALIPSO only passed over the same location once every 16 days, which decreased the likelihood of a pass intersecting a smoke plume. Moreover, given that certain state NWS Forecasting offices are not mandated to report mixing heights, there were many states for which we did not have any historic mixing height data for comparison.

Important to mention, in relation to A-SMOKRE outputs, is the propagation of error inherent in CALIPSO CALIOP LiDAR data. Due to atmospheric effects, there is reduced certainty in lower mixing height estimations as a result of backscatter interactions. During the 10-week term, our team did not have enough time to quantify this uncertainty and explore how potential impacts on outputs, however it is important to mention as a caveat, especially in regard to the discrepancies between NWS and A-SMOKRE for mixing heights below 3km.

4.2 Future Work

NWS and NPS partners are interested in further understanding the influence of climate and moisture on mixing heights. Future research could incorporate environmental variables such as humidity to determine whether their estimates are more or less accurate in certain environments. Given the poor temporal and spatial resolution of CALIPSO, it would be constructive to consider alternative instruments for observing mixing height. Additionally, optimizing the WorldView workflow of identifying smoke plumes could increase the likelihood of wildfire event inclusion while simultaneously improving the temporal efficiency of CALIPSO transect identification.

Lastly, while NASA Earth observations can serve as effective tools for evaluating NWS mixing height forecasts, the inclusion of *in situ* radiosonde data would strengthen comparative results from this study and serve as a valuable validation resource. Therefore, we encourage future researchers to include ground truth data by identifying locations and time windows where states report mixing heights for Fire Weather Zones which are also areas with reliable CALIPSO overpasses in order to coordinate weather balloon launches specifically at those sites/times.

5. Conclusions

This project partnered with the National Weather Service Fire Weather Program to conduct a study evaluating the accuracy of their mixing height estimates. While we did not find evidence supporting systematic biases in NWS estimates, we did find meaningful differences between NWS forecasts and our A-SMOKRE outputs. The disagreement between these two sources was especially evident at low mixing heights, which may be when accurate forecasts are most important. However, substantial disagreement among the methods stymied the team's attempts to quantify systematic bias in a meaningful way

While this work did not directly improve NWS estimates, our research provided evidence supporting a reevaluation of current estimation techniques, particularly at low mixing heights. Additionally, we provided the NWS with scripting tools for conducting future studies validating mixing height estimates, which will enable them to compare future forecasted estimates to those retrieved from NASA Earth observations CALIPSO and Terra MODIS. This feasibility study successfully identified potential areas for improvement in NWS mixing height forecasts, which, if taken into consideration, could increase accuracy of air quality monitoring, thereby enabling partners at the National Park Service and the Bureau of Land Management to conduct prescribed burns under the safest possible conditions. Fuel reduction treatments such as prescribed burns could decrease wildfire risk, lessening damage to property and natural resources while protecting public health by reducing harmful air quality emissions.

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7. Glossary

Mixing Height – represents the top of the planetary boundary layer
NWS – National Weather Service
NPS – National Park Service
BLM – Bureau of Land Management
FWP – Fire Weather Program. Branch of NWS.

FMPC – Fire Management Program Center. Branch of NPS
FWF – Fire Weather Forecasts, issued for Fire Weather Zones
FWS – Fire Weather Spot Forecasts, issued on the spot for specific wildfires
Planetary Boundary Layer (PBL) - the part of the troposphere that is directly influenced by the presence of the Earth's surface, and responds to surface forcings with a timescale of about an hour or less (Stull 1988).
CALIPSO – The Cloud-Aerosol LiDAR and Infrared Pathfinder Satellite Observations (CALIPSO) satellite launched in 2006 to monitor clouds and aerosols globally. The satellite contains passive and active remote sensing instruments, including CALIOP, a LiDAR instrument that provides vertical profiles of aerosols and clouds.
MODIS – Moderate resolution Imaging Spectroradiometer, an instrument aboard the Terra (day) and Aqua (night) satellites, which cover the Earth surface every 1 to 2 days.
NIFC – National Interagency Fire Center
VIIRS – Visible Infrared Imaging Radiometer Suite, one of the instruments aboard the Suomi National Polar-Orbiting Partnership (Suomi NPP) satellite launched in 2011.
VFM – Vertical Feature Mask, CALIPSO product
LAADS DAAC – Level-1 and Atmospheric Archive & Distribution System (LAADS) Distributed Active Archive Center (DAAC)
CIMMS – University of Wisconsin's Cooperative Institute for Meteorological Satellite Studies
AWIPS – Advanced Weather Interactive Processing System

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9. Appendices

Appendix A

This appendix contains supplementary figures and tables related to analysis for the project. Table A1 and Figure A1 relate to results as shown in Figure 10, while Table A2 relates to results as shown in Figure 7.

Statistic	Value
Beta0 (slope)	0.908
Beta1 (intercept)	0.035
T-test p-value	2.87 e-06
RMSE_x (km)	0.617
RMSE_y (km)	0.561
Pearson's r	0.178
Pearson's r p-value	0.0052
R2 (distance-wise)	0.172

Table A1. Regression statistics (A-SMOKRE vs NWS) show a statistically significant regression, with a p-value < 0.05. Additionally, the Pearson's r p-value, which is independent of the regression, indicates that the A-SMOKRE and NWS data covary in a significant way.

Datasets compared	MAE in mixing height (km)
NWS to A-SMOKRE	0.93
NWS to MODIS	0.82
NWS to CIMSS	0.88
A-SMOKRE to MODIS	0.84
A-SMOKRE to CIMSS	0.94

Table A2. Mean Absolute Error (MAE) in mixing height estimates in kilometers above ground level between MODIS, CALIPSO, and NWS products (which include Fire Weather Forecasts in addition to Spot Forecasts). By grouping NWS products together, this table differs from Table 3 because it indicates midpoint values between the FWF and FWS, which vary from one another as the former generally is higher than the latter.

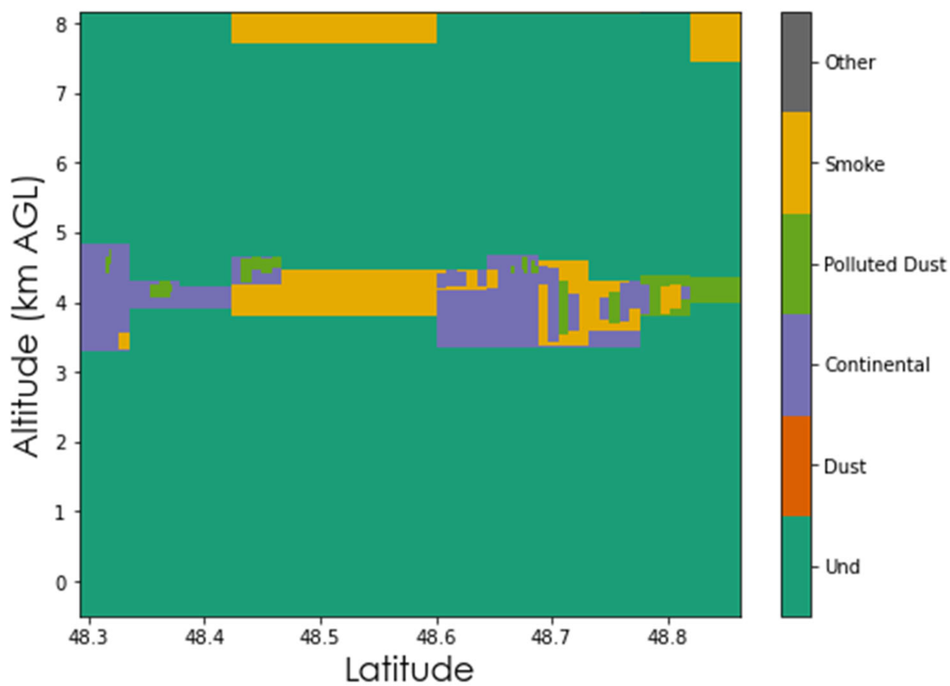

Figure A1. A case study that identifies the altitudes where different types of aerosols are found across the Elk Complex Fire in Southern Idaho on August 12, 2013. This plot represents the types of visualizations output by our tool A-SMOKRE, which uses CALIPSO Vertical Feature Mask data to classify aerosols by type. Here, a bulk majority of altitudinal space is classified as undetermined, which could represent interference with the LiDAR backscatter signal on this particular day.