COMMUNITY CHALLENGES AND PROSPECTS IN THE OPERATIONAL FORECASTING OF EXTREME BIOMASS BURNING SMOKE

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ABSTRACT

Various forms of global compositional forecasting are now commonplace across the world's operational centers. Biomass burning smoke is often forecast just like other aspects of our weather to support numerous applications such as air quality, transportation, and climate. Recent developments in the field have been bolstered by a new generation of advanced satellite sensors and algorithms on an international constellation of geostationary and polar orbiting satellites. The academic community frequently solicits operational developers for input on development needs and what should be operationalized. Yet, the volume of new data sources is currently outpacing Moore's Law and the forecasting community's ability to process and utilize new data sources data. Targeted to the academic community and using the 2020 western biomass-burning season as an example, this presentation will provide a brief review of how developers view next generation products for use in coupled observational and data assimilation systems that may be required to meet challenges posed by global extreme smoke event forecasting.

Index Terms— Fire, smoke, forecasting, air quality

1. INTRODUCTION

By definition, extreme hazard events are just that, rare occurrences with significant impact on the population and/or environment. In the field of air quality, perhaps biomass-burning smoke dominates this category more than any other aerosol category. High aerosol events occur throughout the globe on a fairly regular basis, including haze formation over South Asia and the West China Plain and dust events over the Saharan, Taklimakan and Gobi Deserts. Significant biomass burning plumes are a recurring feature on global aerosol maps dominated by Africa, the Amazon, and Peninsular Southeast Asia. However, due to their seasonality and frequency of occurrence the most appropriate classification for these events might be highly polluting instead of extreme. With their regular occurrence, it is possible for aerosol monitoring and forecasting systems to successfully track aerosol loadings for these regions. In contrast, boreal and mid latitude wildfire events are more episodic, have strong nonlinear physics, and can have exceptional amplitudes and spatial extents that overtake all other high AOD events from other aerosol classes by a wide margin. The nature of such biomass events challenges automated observing and data assimilation systems that support numerical composition prediction (NCP). Indeed, it is little wonder that NOAA manages a watch floor that uses human input to monitor such events (https://www.ospo.noaa.gov/Products/land/hms.html#maps).

The International Cooperative for Aerosol Prediction (ICAP) community is a grass roots organization to promote community development of global aerosol observations, data assimilation, and prediction technologies that can support operational aerosol forecasting. Members are frequently solicited by the academic and satellite production community on what is needed and whether particular products have operational forecasting value. In this short presentation, we use the 2020 Western United States fire systems to express consensus opinions on the need for a paradigm shift from more typical observation and assimilation practices to next generation solutions that can support global wildfire forecasting. While this material is all drawn from the peer-reviewed literature, here we provide context from the ICAP developer's point of view in order to encourage future development within the academic community of products that can potentially be applied to operational systems.

2. BASELINE CONSIDERATIONS

There are hundreds of papers written every year on wildfires that increase our knowledge of the fire system. While such findings are important, their influence on smoke forecasting development is dependent on the mapping of the observations and distilled findings onto aerosol lifecycle, such as, emissions, observations, microphysics, transport/transformation, sinks and environmental prediction feedbacks. An additional complexity is that these components are interrelated within the model physics, initialization, and data assimilation within the NCP and associated Numerical Weather Prediction (NWP) systems. This leads to challenges for developers who must consider the balanced whole, as modification to one component will likely impact the others. This is especially true for strongly forcing, low frequency extreme events such as large wildfires. The coupled nature of large wildfire events, with interdependencies between aerosol lifecycle and meteorology, points to the compelling need for coupling between observations, data assimilation, and atmospheric and aerosol physics as well as between the atmosphere and surface properties such as vegetation, fuel moisture and hydrology. However, coupled systems are complex, requiring joint error analysis and the consideration of development that varies vastly by scale- ranging from local monitoring and nowcasting (what is the likelihood of a blow up or pyroCB event in the hour to day?) to seasonal to sub-seasonal prediction (S2S; Will it be a bad fire year and will that feedback into my seasonal forecast?). For reanalysis applications, temporal stability of products is also of paramount importance.

The aerosol community recognizes the highly diverse datasets available and is reluctant to set specific data requirements, which become even more complex for coupled observations (e.g., say simultaneous AOD and wind). Coverage and frequency are certainly valued, but the inevitable trade space between coverage and information content is well recognized (e.g., a polar orbiting imager like VIIRS versus a lidar like CALIOP). However, with next generation systems, high temporal resolution imagery coupled with advanced data assimilation may allow developers to have the best of both worlds. Nevertheless, there are three primary considerations for data providers when developing products that support operations, regardless of the nature of the product[1]: 1) The data must be easily accessible and well formatted (e.g., CF compliant NetCDF on an easily accessible site); 2) It must have reliable and rapid production: Minutes for nowcasting, up to three hours for data assimilation; 12 hours for late runs; a day for regular verification or some S2S applications; and 3) It must be well characterized, including biases and error correlations in space, especially for high resolution geostationary data, and in the case of coupled products, joint error estimates. The community can cope with uncertain data, but the utility of the product in numerical applications is dependent on understanding and quantifying those uncertainties. In addition to these data requirements, there are constraints on data assimilation and model physics, including consistency of data products under varying domain conditions, sophistication of the model physics required to forward model the observations, and ultimately computational cost. The products most likely to be used follow these guidelines. Examples of successful product adaptation for near real time use include the development of near real time AERONET and CALIOP products. Neither of these systems was originally intended for data assimilation, but both can now be usefully ingested into a number of models.

3. 2020 WESTERN UNITED STATES AS AN EXAMPLE OF CHALLENGES AND PROSPECTS

The 2020 fire season of the Western United States is an excellent example of extreme events that challenge operational forecast systems. While it is relatively easy to generate a narrative of "What happened?" for the individual massive events that occurred this season, automated forecast systems were in many cases overmatched by the extremes witnessed.. And while data assimilation systems can bring together a variety of data products, correlated errors or time differences between observations of rapidly evolving wildfire can be problematic, even with advanced data assimilation algorithms such as 4DVAR.

Beginning with source functions, while there were periodic and climatologically expected fire events throughout the summer of 2020, the first regional event occurred in association with a mostly dry lightning subtropical disturbance on the early morning hours on August 16, 2020 (Figure 1). Single pixel fire detections from VIIRS on that day provided early detections of fire. Due in part to the high number of initiated fires, suppression crews were overwhelmed and the fires grew rapidly. With meteorology conducive for burning, the smoke spanned a total of 2000

Figure 1. Soumi NPP Imagery and fire detects of biomass burning plumes following a dry lighting event over California. Imagery from NASA Worldview, https://worldview.earthdata.nasa.gov/

km a day later. In this scenario, the operational models are constantly playing "Catch up" with emissions. This demonstrates the pressing need for high fidelity prognostic emissions modelling to be incorporated into large-scale systems. While coupled mesoscale-wildfire systems exist, they are not global or configured for operational use. This case demonstrates the need for near real time output. At the same time, S2S applications are also of concern to developers-e.g., in a given season, what are the probabilities of dry lighting events? This demonstrates the need for large-scale coupled fire-meteorology modeling. Given the strong nonlinearity and stochastic nature of the relationships, this puts forth challenging requirements for seasonal weather prediction.

Assimilation of observations of plume extent and AOD can in part correct for emission deficiencies in operational models, but again extreme wildfires pose unique challenges to the system. Further into the wildfire season, fire prevalence and strength intensified (e.g., September 11, 2020, Figure 2 (a)), with aerosol optical depths (AOD) at AERONET sites in California estimated to be in excess of 10. This case represents an excellent example of the coupled problem, with the highly varied model simulations between centers even after the assimilation[3](Figure 2(b)). These extreme differences between models and observations, challenges data assimilation. Further, AODs are semi-infinite, plume radiances have strong dependencies on single scattering albedo, and advection is driven by a cutoff low with corresponding cloud cover. This leads to sampling biases and retrieval failures of the densest smoke (Figure 2(c)). Owing to evolving fire characteristics and PyroCB development, plume injection heights are highly variable from near surface to 12 km with significant attenuation and mid to upper level smoke being misclassified as cirrus (e.g., CALIOP, Figure 2(d)), leading to model misrepresentation and advection errors. The UV based aerosol index, a mainstay of significant UTLS biomass burning event monitoring, is nevertheless semi quantitative in regard to assimilation due to interdependencies on underlying clouds, single scattering albedo and height[5] (e.g., OMI Aerosol index, Figure 2(e)). Ultimately, models benefit from assimilation but are challenged by the diversity of products, their sampling and retrieval biases, and overall data management.

Next generation products and assimilation systems are coping with the complexity of the wildfire system in innovative ways, including the use of convolutional neural network of multi spectral spatial texture instead of just pixel level retrievals to identify high AOD cases[2](; optical flow for simultaneous retrieval of aerosol loading, plume and wind vectors from which some information on height can also be extracted; multi sensor UV, visible, and IR retrievals of single scattering albedo and AOD; oxygen A plume height[4]; and visible and IR retrievals for fire phase. Ensemble and hybrid data assimilation systems are likewise being developed to make use of these datasets, with coupled data assimilation where meteorology and composition observations can influence both meteorological and composition analysis is now in its infancy. Yet, while each of these observations and techniques have been shown to be useful on a case-by-case basis, their complexity and computational expense requires additional development, simplification, and characterization.

The above observations leads us back to the baseline considerations discussed earlier. We look to the academic community to continue to be innovative but systems developers need robust, well characterized, and accessible datasets. Case studies can show sensitivity and can tell a good story, but consistent and sustainable performance is arduous as is coupling observations to the underlying model physics. Thus operations developers will be drawn to a particular product line that not only can characterizes the complex wildfire cases shown here, but do it in a sustainable fashion amenable to automation with limited human maintenance within a preferable coupled model framework.

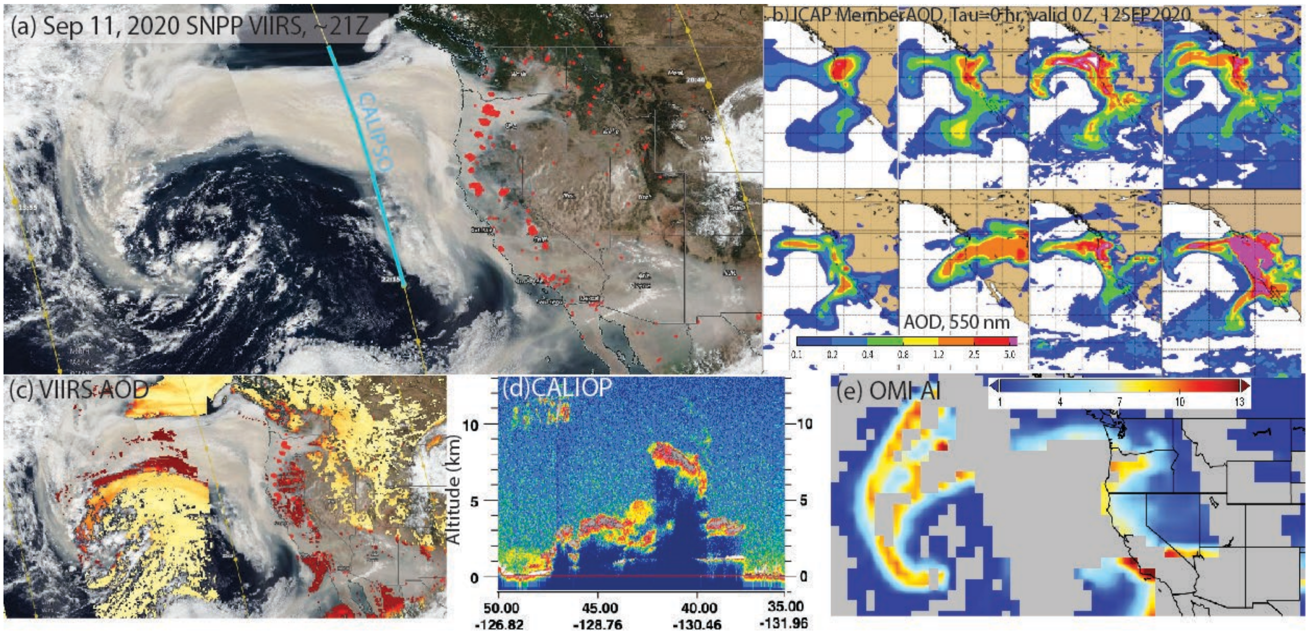

Figure 2. (a) Soumi NPP Imagery and fire detects of biomass burning plumes for 11SEP2020, 21 Z; (b) 12SEP2020 0Z AODs from ICAP member models; (c) VIIRS AOD; (d) CALIOP browse image backscatter profiles of smoke; (e) OMI Aerosol Index. Imagery from NASA Worldview, https://worldview.earthdata.nasa.gov/; CALIOP from https://www-calipso.larc.nasa.gov/products/lidar/browse_images/production/

This requires extensive verification with large sample sizes that can account for nonlinearities in coupled systems and partnerships to provide a rapid feedback cycle between basic research and operations. Data harmonization efforts, perhaps in cloud environments, may provide the venue for such a workflow.

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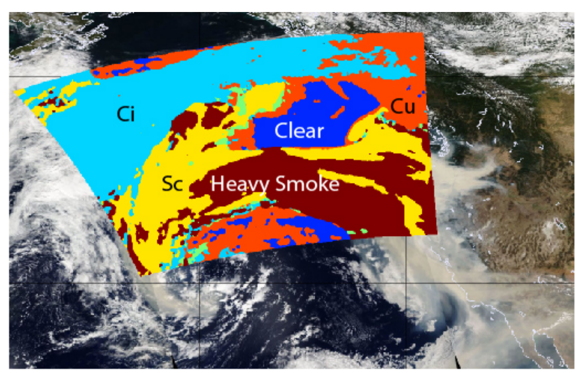

Figure 3. Dominant top of atmosphere cloud and aerosol features for the 11 September, 2020 case using CNN scene classification on Aqua MODIS data.