2B.6 MONITORING ATMOSPHERIC COMPOSITION AND LONG-RANGE SMOKE TRANSPORT WITH NUCAPS SATELLITE SOUNDINGS IN FIELD CAMPAIGNS AND OPERATIONS

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1. INTRODUCTION

The NOAA Unique Combined Atmospheric Processing System (NUCAPS) operationally produces atmospheric soundings of temperature, humidity and trace gases from infrared and microwave instrument pairs on MetOp, Suomi National-Polar-orbiting Partnership (S-NPP) and NOAA-20 polar orbiting satellites. From each satellite, NUCAPS soundings are near-global and twice-daily with similar quality irrespective of time of day. This makes them useful in monitoring diurnal processes, aviation hazards (Weaver et al., 2019) and conditions leading up to severe weather outbreaks (Smith et al., 2019). Recently, we demonstrated how NUCAPS soundings can detect Saharan Air Layers (Barnet et al. 2019). By fostering partnerships with operational meteorologists, researchers, data producers and product developers, we can demonstrate new applications and more effectively identify areas for improvement.

In this manuscript, we explore the value real-time NUCAPS soundings have in monitoring fire weather (i.e., atmospheric conditions leading up to and developing during large fires) and long-range smoke transport. With 'real-time' we mean product latency less than 60 min. Here, we examine two cases from 2019, one of the large bush fires in Australia and a second smaller fire near Kincaid California. We describe where soundings provide value, where they do not, and share the lessons learned from interacting with our partners.

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2. RESULTS AND DISCUSSION

2.1 Regional Smoke Composition and Transport of Australian Bushfires

National Weather Service (NWS) forecasters have access to NUCAPS soundings from S-NPP and NOAA-20 through their Advanced Weather Interactive Processing System (AWIPS) with which day can visualize and query data from many sources in real-time. At first (and since 2014), forecasters could display NUCAPS in the same way as radiosondes, namely as skew-T diagrams. Where this is suitable for radiosondes that are available at fixed times from a sparse network, it soon became evident that this form of display is insufficient for NUCAPS with hundreds of soundings multiple times a day. Forecasters become overwhelmed when they have to query NUCAPS soundings one skew-T diagram at a time. Since 2019, forecasters can display NUCAPS temperature, water vapor and ozone retrievals also as 2-D gridded fields at standard pressure layers from Earth surface to the tropopause. As shown in **Figure 1a** and **b**, gridded NUCAPS retrievals of temperature (as lapse rate) and water vapor (as humidity) have distinct spatial patterns that aid forecasters in identifying risk areas. NUCAPS soundings as 2-D swaths provide real-time situational awareness, give context for finer-scaled in situ measurements and help verify forecast models. AWIPS not only displays NUCAPS retrievals but also derives a suite of relevant meteorological variables, such as the Haines index that indicate fire weather severity.

The aerosol optical depth (AOD) product from VIIRS imagers on S-NPP and NOAA-20 is frequently used to identify and track smoke plumes (**Figure 1c**). From the 2019 Australia bush fire case, we identify a few drawbacks when using this product in isolation:
(1) AOD does not measure the composition or vertical extent of a plume, only the fact that it exists. (2) As the plume disperses AOD decreases and can become undetectable even though the plume continues to

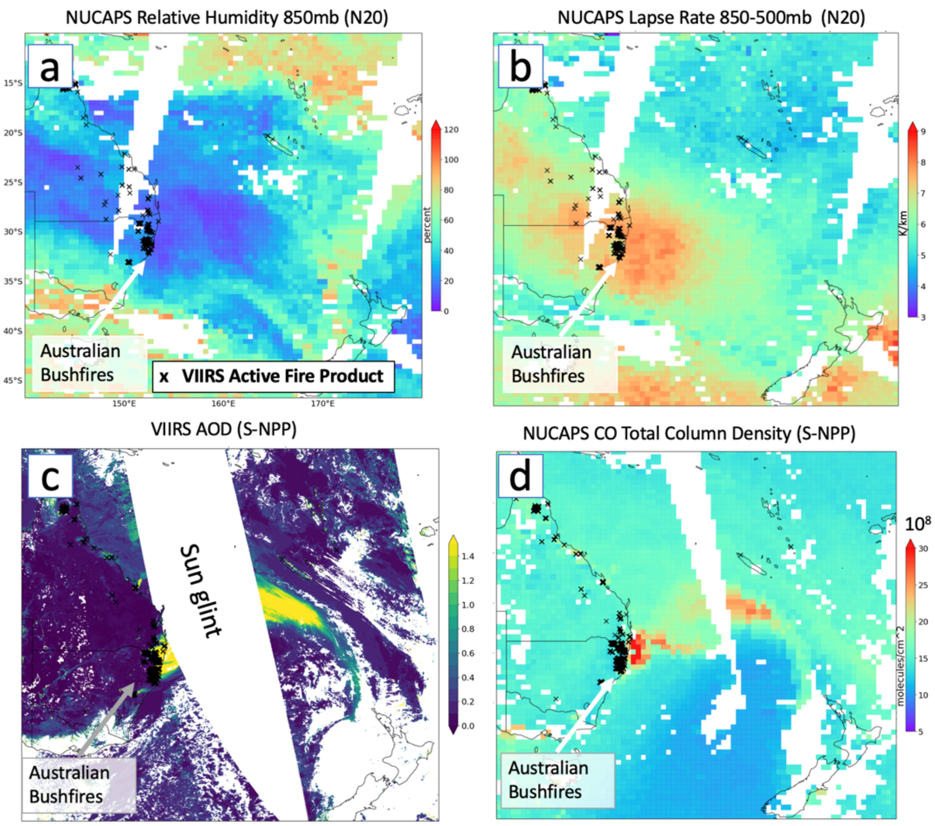

Figure 1 *Australian bush fires on Nov 7, 2019 as measured by instruments onboard NOAA-20 around 01:30 in the afternoon. (a) NUCAPS H_2O retrievals showing very low humidity (< 5%). (b) NUCAPS temperature retrievals showing high lapse rates (> 8 K/km) and thus indicate atmospheric instability ahead of bushfire growth. The burn area increases on Nov 11, 2019, which can be measured by Suomi NPP instruments: (c) VIIRS aerosol optical depth (AOD) highlighting the presence of smoke outside of cloud fields and, (d) NUCAPS total column carbon monoxide (CO indicating smoke plume composition. CO has a 3-5 day lifetime and can be used to track the long range transport of smoke plumes long after the AOD decreased to undetectable values.*

disperse with high trace gas loads and air quality implications for areas downwind. Using AOD as the only metric for smoke transport can thus give false reassurances. (3) AOD is retrieved from spectral channels in the visible range which means that they are unavailable at night when these channels have no information content. Additionally, AOD cannot be retrieved over the ocean in regions with sun glint. We argue here that NUCAPS can complement AOD products and help address these shortcomings by providing a more comprehensive view of smoke plumes, from start to end.

In addition to temperature and humidity, NUCAPS retrieves the following trace gases, carbon monoxide (CO), ozone (O_3,), carbon dioxide (CO_2), methane (CH_4), nitric acid (HNO_3), and nitrous oxide (N_2O). It is CO that is specifically valuable in this context (**Figure 1d**). NUCAPS CO is available from multiple satellites day and night, it has vertical extent and a lifetime of 3-5 days, thus detectible from space long after AOD. NUCAPS CO is not yet available within AWIPS, but we can make a strong case for why it should be included as a real-time product especially as mega-fires become more widespread and frequent.

This said, it is worth spending a moment to understand what exactly we are able to measure about trace gases from space with infrared sounders. In **Figure 2** we plot the NUCAPS-NOAA20 averaging kernels (AK) for temperature, H_2O, O_3, CO and CH_4 (Iturbide-Sanchez et al., 2017; Maddy & Barnet, 2008). AKs are byproducts of the NUCAPS retrieval system and quantify the sensitivity of the retrieved variable to the true state of that variable in the atmosphere. In other words, it is a metric of NUCAPS observing capability, or the ability it has to retrieve the target variable. AKs are available on the same pressure layers as retrievals and vary with pressure and retrieval scene. In **Figure 2** we plot averaging kernel matrix diagonals (i.e., profiles indicating maximum sensitivity at each pressure level) as the mean value for the study area shown in Figure 1 with the error bars as standard deviation. AK values approaching zero (one), indicates low (high) observability. The AKs for moisture indicate sensitivity to the true state throughout the troposphere. For O_3, CO and CH_4, sensitivity is near zero in the boundary layer and low troposphere. The peak sensitivity for CO is around 500 hPa, CH_4 300-400 hPa and in the stratosphere for O_3. This means that when we see regions with high CO from NUCAPS retrievals, they represent mid-tropospheric conditions, only when CO becomes aloft, can we retrieve it with NUCAPS. This is why NUCAPS CO is suitable for measuring and monitoring long-range transport (a mid-tropospheric process) and not air quality (a boundary layer

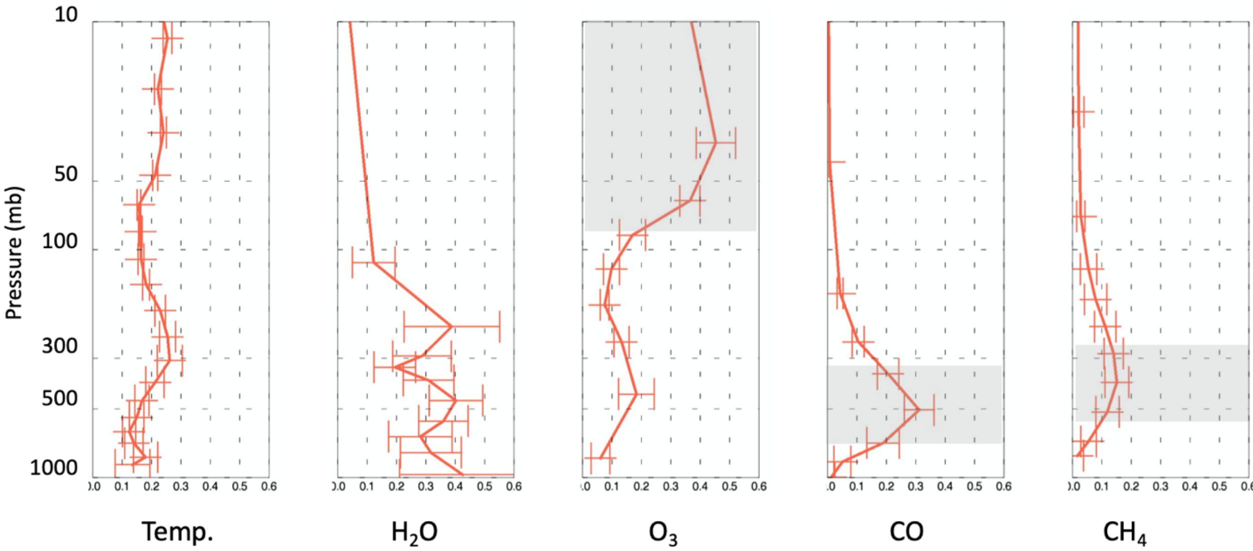

Figure 2 *NUCAPS averaging kernels show vertical information content of temperature, humidity, O_3, CO, and CH_4. Shaded boxes indicate region of maximum sensitivity to the true state for the trace gases. The above is the combined S-NPP am and pm orbits from Nov 11, 2019 over Australia for the domain shown in Figure 1. The solid line is the mean diagonal vector of the averaging kernel matrices for all retrieval scenes and the error bars indicate the standard deviation.*

process). Forecasters and field campaign organizers must make decisions quickly, and should thus know how to interpret NUCAPS sounding correctly. It is our prerogative to distill and communicate information effectively, which is only possible in partnership with different user groups.

2.2 Real time monitoring of Kincaid Fires

The Australian bushfires began on Nov 6, 2019 and are ongoing at the time of writing (with 46 million acres destroyed as of Jan 14, 2020). Such mega-fires produce a lot of smoke easily detectable from space-borne infrared instruments; the plume not only lasts long over a large area but advects to the mid-troposphere from where it is transported to other regions. However, small to moderate sized fires are more common globally and more difficult to detect.

Plumes from small fires are more difficult to retrieve with NUCAPS because they can be smaller than a retrieval footprint (~50 km at nadir and ~150 km at edge of scan) and remain trapped in the lower troposphere where, as previously shown in **Figure 2**, NUCAPS has low observing skill. The Kincaid Fire is such an example where NUCAPS did not retrieve CO for its fire plume. This fire occurred from Oct 23-Nov 6, 2019 (77,758 acres destroyed) and although smaller in size than the Australian bush fires, was considered dangerous and economically costly.

Figure 3a shows VIIRS AOD retrievals next to NUCAPS CO (**Figure 3b**) from NOAA-20. The AOD product detected a clear smoke source and plume, while the NUCAPS CO retrieval is more ambiguous. When compared to the NUCAPS cloud top fraction retrieval (**Figure 3c**) we see the smoke plume downstream from the fire as cloud fraction values greater than 20%. NUCAPS retrieves cloud parameters – fraction and top pressure – for any atmospheric feature with optical thickness high enough to register a radiative effect in the infrared spectrum.

Examining NUCAPS cloud top pressure retrievals for the same scene (**Figure 3d**), the plume appears as a cloud retrieval with pressure greater than 600 hPa. In the previous section, we discussed how the NUCAPS AK for CO indicates highest retrieval sensitivity to true state conditions around 500 hPa. While a total column density value integrates the vertical profile retrieval, most of the CO signal originates from the mid-troposphere. Keeping this in mind, we can interpret **Figure 3b** as retrievals of CO concentrations above (lower pressure) the smoke plume. Thus, the retrieval did not "fail" to detect CO but rather performed as expected, it retrieved CO in the mid-troposphere. Knowing this, we can infer that Kincaid fire plume did not advect into the mid troposphere, but rather stayed closer to the surface, and therefore will not transport over large distances.

Because the fire occurred in California, this fire was monitored in real-time using the Naval Research Lab (NRL) Monterey direct broadcast (DB) station. The Community Satellite Processing Package (CSPP) processes NUCAPS within 20 minutes of a satellite overpass. In addition to lowering latency, the DB

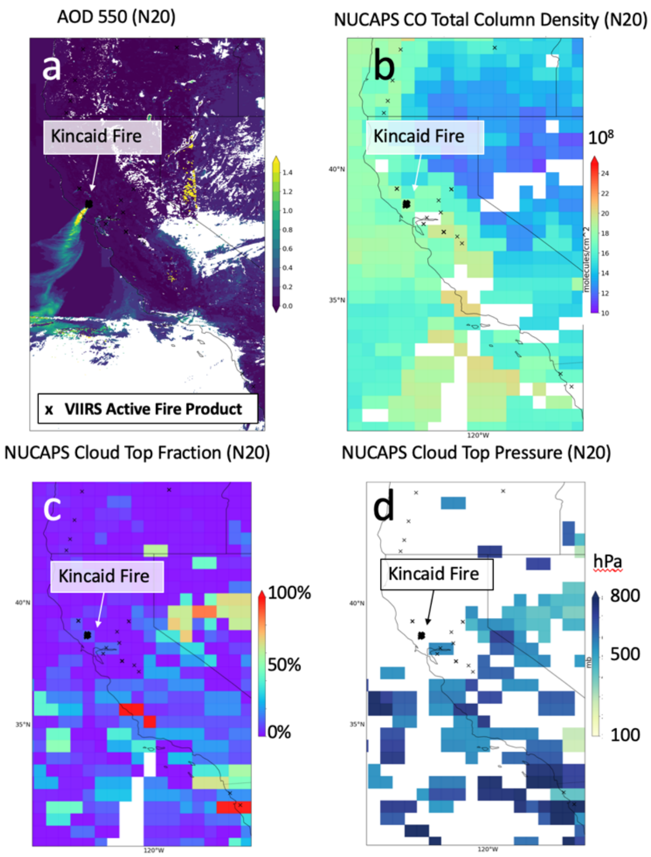

Figure 3 *Kincaid fires in California on Oct 27, 2019 as measured by instruments onboard NOAA-20 around 01:30 in the afternoon. (a) AOD captures smoke from the wildfire that (b) NUCAPS CO does not capture. By examining (c) cloud top fraction and (d) cloud top pressure, we can see that the smoke plume is below the broad 500 hPa layer where the retrieval is sensitive.*

provides sounding data to users outside of NWS. Users can also monitor other fires across the continental United States, Hawaii, Alaska, Puerto Rico in real-time with receivers from other DB partner sites.

3. CONCLUSION

The above examples illustrate potential utility of NUCAPS retrieval products – temperature, moisture, CO and cloud parameters – for fire and smoke monitoring. We supported the FIREX-AQ field campaign in 2019 with real-time visualization to give researchers and meteorologists access to these products while the campaign is on-going and to provide context (situational awareness) for in-situ and aircraft measurements of small and medium fire domains. Our goal was to understand how the design of NUCAPS products can be tailored to better meet the requirements for real-time regional fire-weather forecasting and smoke monitoring.

From our interaction, we learned that NUCAPS potentially has value in:

- Monitoring fire risk ahead of and real-time weather changes (e.g., pyrocumulus cloud formation) during large burning events.
- Tracing long-range smoke transport and composition for large fires, when gases advected to the mid-troposphere.
- Characterizing diurnal conditions with NUCAPS nighttime and daytime retrievals.

However, we also learned that NUCAPS probably does not have value in:

- Measuring boundary layer pollution due to low observability (retrieval sensitivity to the true state) in the lower troposphere.
- Monitoring smaller and moderate sized fires with small spatial extent and short lifetime.

As researchers and product developers, we often focus on validation and meeting statistical requirements to improve satellite retrievals. While quantitative assessment is indispensable, product requirements do not necessarily address user needs. By working directly with users, developers can make refinements to retrieval algorithms that are relevant to the user community. In the case of the fire and smoke community, we can utilize the aircraft measurements from FIREX-AQ to explore, for instance, if using numerical weather models as the retrieval first guess improves plume monitoring. We can also find ways to convey information contained in AKs more simply, so the user can quickly determine where the retrieval has the greatest value. Finally, we can improve training to show how NUCAPS can be combined with existing datasets for more sophisticated monitoring of smoke plumes. While these examples are specific to NUCAPS, we hope to underscore the importance of strengthening partnerships across government agencies, academia, and the private sector for relevant product improvement.

4. REFERENCES

Barnet, C. D., Smith, N., Folmer, M. J., Dunion, J. P., Zawislak, J., Layns, A., Esmaili, R.B., Golderb, M. D., 2019: The use of temperature and water vapor profiles for tropical cyclone weather applications: recent activities within the NOAA/JPSS proving ground sounding initiative. Extended abstract for the 15th Annual Symposium on New Generation Operational Environmental Satellite Systems, Phoenix, AZ: 99th Amer. Meteor.Soc. Annual Meeting, J6.3. https://ams.confex.com/ams/2019Annual/meetingapp.cgi/Paper/353354

Iturbide-Sanchez, F., Liu, Q., Gambacorta, A., Barnet, C., Nalli, N. R., Tan, C., & Santos da Silva, S. R. , 2017: Using averaging kernels to study the vertical resolution of nucaps temperature and water vapor. In 2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS) (pp. 33–35). Fort Worth, TX: IEEE. https://doi.org/10.1109/IGARSS.2017.8126886

Maddy, E. S., & Barnet, C. D., 2008: Vertical Resolution Estimates in Version 5 of AIRS Operational Retrievals. IEEE Transactions on Geoscience and Remote Sensing, 46(8), 2375–2384. https://doi.org/10.1109/TGRS.2008.917498

Smith, N., Barnet, C. D, Berndt, E. B., Esmaili, R. B., & Goldberg, M. D., 2019: Why operational meteorologists need more satellite soundings. Extended abstract for the 15th Annual Symposium on New Generation Operational Environmental Satellite Systems, Phoenix, AZ: 99th Amer. Meteor.Soc. Annual Meeting, 3.7. https://ams.confex.com/ams/2019Annual/meetingapp.cgi/Paper/355319

Smith, N., White, K. D., Berndt, E. B., Zavodsky, B. T., Wheeler, A., Bowlan, M. A., & Barnet, C. D., 2018: NUCAPS in AWIPS–Rethinking information compression and distribution for fast decision making. 22nd Conference on Satellite Meteorology and Oceanography, Austin, TX: 98th Amer. Meteor.Soc. Annual Meeting. Retrieved from https:// ams.confex.com/ams/98Annual/webprogram/Paper336846.html

Weaver, Gail, Smith, N., Berndt, E. B., White, K. D., Dostalek, John. F., & Zavodsky, B. T., 2019: Addressing the Cold Air Aloft Aviation Challenge with Satellite Sounding Observations. Journal of Operational Meteorology, 138–152. https://doi.org/10.15191/nwajom.2019.0710