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# Weather Extremes Induced by Large Pyrocumulonimbus Smoke Events

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# Contents

Abstract.....	1
1. Project Objective.....	1
2. Introduction .....	1
3. Data and Methods .....	3
3.1 NAAPS.....	3
3.2 NAVGEM.....	4
3.3 Smoke Plume Initialization.....	4
4. Results .....	5
4.1 Horizontal Plume Transport.....	5
4.2 Vertical Plume Profiles .....	6
4.3 Radiative Coupling and Impact on Atmospheric Dynamics .....	7
5. FY20 Summary .....	7
6. Future Work .....	9
7. Papers: Published or in Prep .....	9
8. Presentations .....	9
9. References.....	10

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# Weather Extremes Induced by Large Pyrocumulonimbus Smoke Events

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## Abstract

Towering thunderstorms triggered by intense wildfires (known as pyrocumulonimbus or pyroCb) act as giant chimneys, injecting large quantities of smoke particles high into the atmosphere every year. These smoke particles absorb solar radiation, thereby altering temperature, vertical motion, and horizontal circulation. On 12 August 2017, a large pyroCb event injected smoke directly into the lower stratosphere during a historic forest fire event in British Columbia, Canada, with total aerosol mass rivaling the magnitude of a moderate volcanic eruption. A portion of the dispersing smoke plume stagnated over northern Canada embedded within a deep anticyclonic circulation for days after the event. On 25 August 2017, just a few days after the pyroCb event, Hurricane Harvey made landfall over southeastern Texas and meandered for days along the Gulf of Mexico coastline causing equally-historic levels of destruction. Harvey stalled because there was no significant westerly circulation to pull the storm northward and push it away from Texas. Here, we examine if the heating perturbation induced by large smoke plumes in the lower stratosphere significantly influenced dynamic circulation in the atmosphere, including the slow movement and destructive impact of Hurricane Harvey in August 2017. We also set a foundation for future analysis of a recent pyroCb event in Australia (Dec. 2019 – Jan. 2020) that injected a plume three times larger into the stratosphere.

## 1. Project Objective

Determine if the heating perturbation induced by large smoke plumes in the lower stratosphere significantly influences dynamic circulation in the atmosphere, including the slow movement and destructive impact of Hurricane Harvey in August 2017.

## 2. Introduction

Towering thunderstorms triggered by intense wildfires (known as pyrocumulonimbus or pyroCb) act as giant chimneys (Fig. 1), injecting large quantities of smoke particles high into the atmosphere every year. When compared with typical convective storms, intense pyroCbs are characterized by relatively smaller cloud droplet and ice particle size distributions, caused by an overabundance of smoke particles that dominate nucleation, condensation, and freezing processes (Rosenfeld et al. 2007).



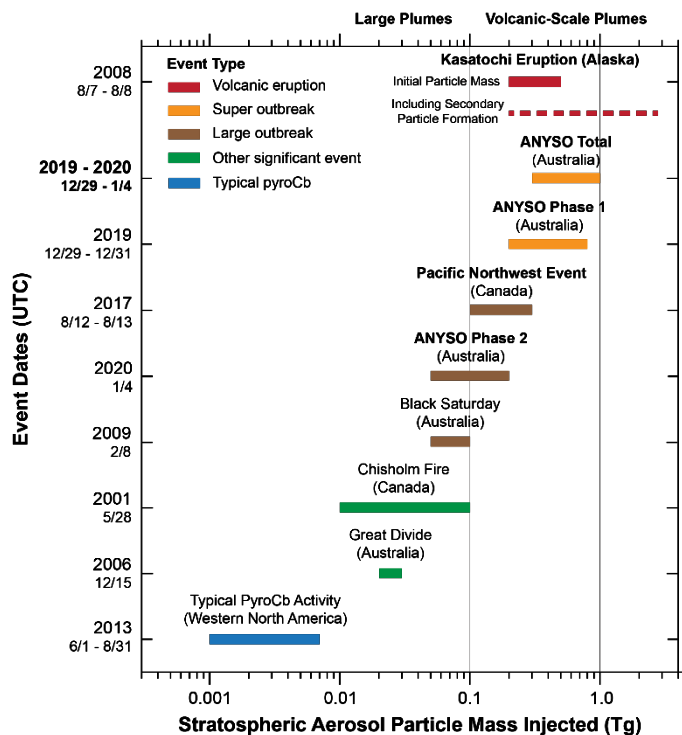
**Figure 1. Intense pyroCb observed in Australia on 04 Jan. 2020, injecting smoke directly into the stratosphere.**

Smaller inherent size distributions within the inner storm core suppress precipitation (Reutter et al. 2014; Chang et al. 2015), which inhibits significant scavenging and redistribution of smoke downward toward the ground. A considerable quantity of smoke particle mass is therefore exhausted from the top of pyroCbs through the high-altitude anvil outflow region, forming an efficient vertical smoke-transport pathway (Fromm et al. 2019). Intense pyroCb events are often characterized by extreme updraft velocities (e.g., 35 to 58 ms<sup>-1</sup>, Clements et al. 2018; Rodrigues et al. 2020) that can rapidly transport smoke particles directly from the surface to the lower stratosphere, with the ensuing smoke plumes resembling the initial stages of a moderate volcanic eruption (Peterson et al. 2018).

PyroCb smoke plumes reaching the lower stratosphere often result from multiple large wildfires in close proximity that produce several intense convective updrafts over a period of only a few hours (Cruz et al. 2012; Peterson et al. 2018). PyroCb intensity and ensuing stratospheric plume impacts therefore vary with the distribution and intensity of regional wildfire activity, the favorability of background meteorology, and the duration that both remain synchronized. While this regional “pyroCb outbreak” phenomenon deviates from a typical volcanic eruption point source, the ensuing smoke plumes exhibit many similarities, traveling thousands of kilometers in both the upper troposphere and lower stratosphere (UTLS), even encircling an entire hemisphere (Peterson et al. 2018; Fromm et al. 2008; Kablick et al. 2020; Khaykin et al. 2020).

The recent “Australian New Year Super Outbreak” (ANYSO) of pyroCb activity resulted in nearly 1.0 Tg of cumulative smoke particle mass being injected into the lower stratosphere (Fig. 2), consistent in magnitude with the initial stages of a significant volcanic eruption (Peterson et al. 2018). ANYSO comes less than three years after the “Pacific Northwest Event” (PNE) in western North America (12 August 2017), which served as the previous benchmark for an extreme, lower-stratospheric pyroCb smoke mass injection (albeit three times smaller). Smoke plumes ensuing from these events reached unprecedented altitudes in the mid-stratosphere (20-35 km) (Allen et al. 2020; Khaykin et al. 2020), where smoke particles absorb solar radiation and heat the layer they reside within. (Christian et al 2019).

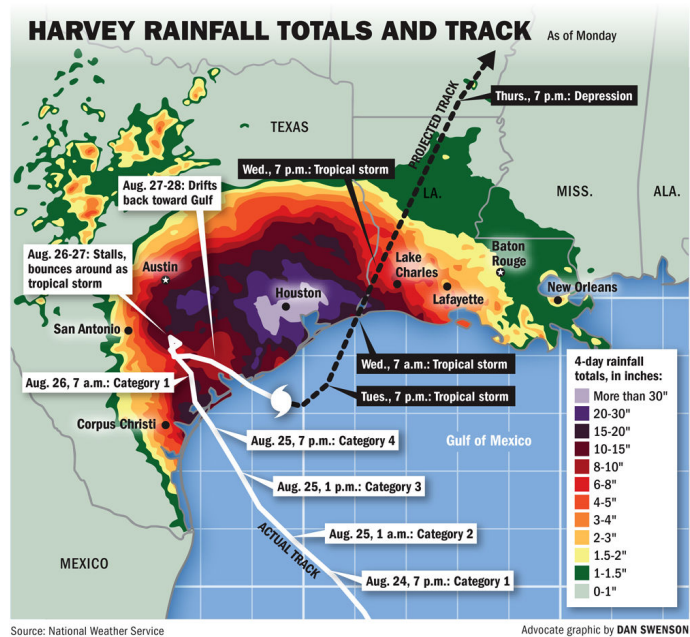
On 25 August 2017, just a few days after the PNE, Hurricane Harvey made landfall over southeastern Texas and meandered for days



**Figure 2. Comparing recent pyroCb smoke plumes in the stratosphere with a volcanic eruption. Bars indicate the approximate uncertainty range of stratospheric aerosol particle mass injected. All mass estimates are displayed using a logarithmic scale (x-axis). Color scheme indicates event type and characteristics.**

along the Gulf of Mexico coastline, causing historic flooding (Fig. 3). Harvey stalled because there was no significant westerly circulation over North America to pull the storm northward and push it away from Texas. A portion of the PNE smoke plume stagnated over northern Canada during this same time interval. It is therefore relevant to ask:

1. *How does the heating perturbation induced by pyroCb smoke plumes affect atmospheric dynamics?*
2. *Did the PNE plume enhance downstream “blocking” that allowed Hurricane Harvey to persist?*



**Figure 3. Hurricane Harvey track and total rainfall during 24-28 August 2017.**

This project addresses these questions by simulating the stratospheric smoke impacts from the PNE in the Navy’s environmental prediction models and preparing for future simulations of the larger ANYSO plume. The methodology employed here sets a foundation for including all types of stratospheric aerosol plumes in Navy forecasting systems, thus positioning NRL at the forefront of future aerosol-modeling applications.

### 3. Data and Methods

This project employed the Navy’s aerosol modeling capabilities (see detailed descriptions below) to quantitatively determine how the incorporation of a proper pyroCb injection profile and aerosol radiative coupling influences dynamic circulation. Experiments are required with three model states:

- a) Control Run - Baseline global model fields with no pyroCb smoke plume or radiative coupling,
- b) Aerosol Run #1 - Aerosol radiative coupling is activated, with no pyroCb plume, and
- c) Aerosol Run #2 - Aerosol radiative coupling is activated, with proper pyroCb injection profile.

Aerosol Run #2 is the key aspect of this project. We began with the parameters derived from our previous investigation of the 2017 PNE, providing the initial plume location, areal size, altitude, depth, particle mass, and basic chemistry (Peterson et al. 2018). Aerosol Run #1 is required to isolate the radiative effect from the current operational forecasting scheme, which assumes that all smoke is injected near the ground. We compared the results of these simulations to the control run.

#### 3.1 NAAPS

Navy Aerosol Analysis and Prediction System (NAAPS) is an offline aerosol transport model, which has seen wide use in the community for global aerosol lifecycle research, contextual information, field

mission planning, and operations. NAAPS has been run quasi-operationally at NRL since 1998, and became the world's first operational global aerosol model in 2006 with implementation at the Fleet Numerical Meteorology and Oceanography Center (FNMOC). In its current operational configuration, NAAPS makes six-day forecasts of aerosol concentrations and optical properties, four times a day at 1080x540 global (1/3 degree) spatial resolution, with 42 vertical levels driven by truncated T425L60 resolution Navy Global Environmental Model (NAVGEM) meteorology (Hogan et al. 2014).

NAAPS characterizes anthropogenic and biogenic fine (ABF, including sulfate, and primary and secondary organic aerosols), dust, biomass burning smoke and sea salt aerosols. Smoke from biomass burning is derived from near-real time satellite based thermal anomaly data used to construct smoke source functions as in the Fire Locating and Modeling of Burning Emissions (FLAMBE1.0; Reid et al. 2009). In this project, pyroCb smoke sources were specifically derived with additional observations. Detailed description of NAAPS and its performance statistics can be found in Lynch et al. (2016).

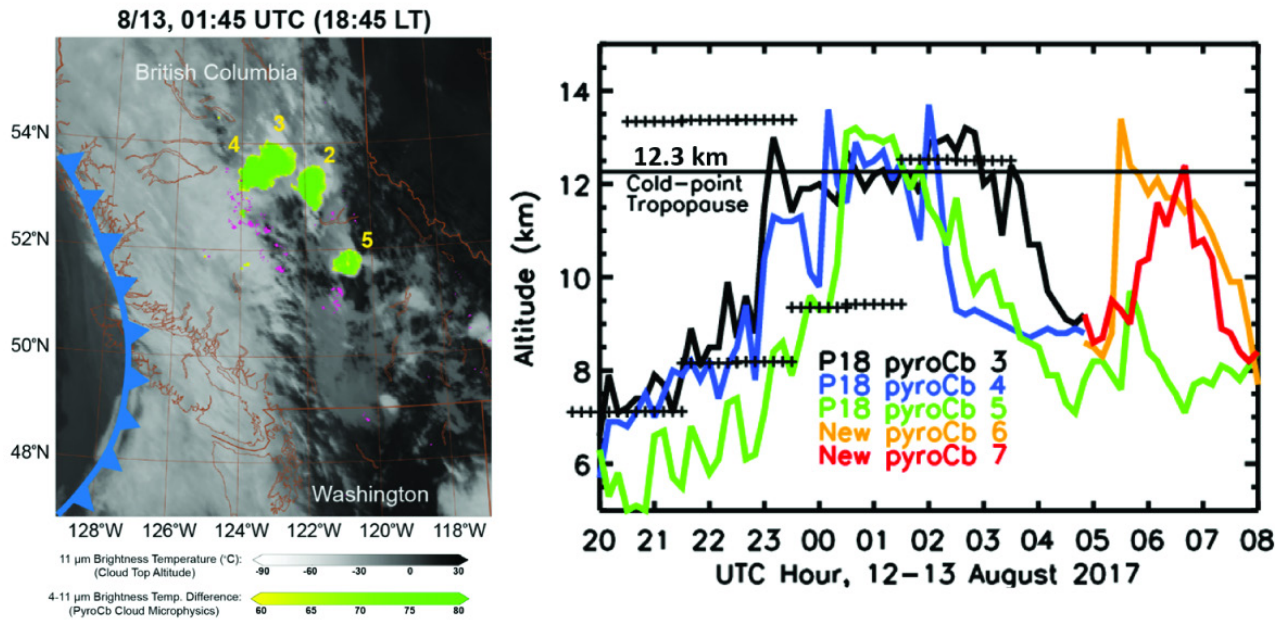
### **3.2 NAVGEM**

Navy's operational global weather forecast model NAVGEM (the Navy Global Environmental Model, Hogan et al. 2013) was also used to quantify the impact of radiative heating on atmospheric dynamics. NAVGEM allows modeled aerosol particles to directly heat and/or cool their surrounding air, which enables smoke aerosol radiative effects to directly couple with and modulate forecasts of temperature, pressure, humidity and winds. This aerosol "inline" with weather modeling capability is driven by NAVGEM large-scale transport and turbulent mixing at each grid point in each time step, and goes through aerosol life cycle of sedimentation, wet removal and dry deposition. It is simulated in the successive 6-hr forecasts along with the atmospheric data assimilation update cycles.

### **3.3 Smoke Plume Initialization**

The project team developed the first vertical smoke injection capability for intense pyroCb activity in Navy forecast models. FY20 work focused on developing the smoke source information required for simulating the PNE plume. Figure 4 provides a snapshot of the PNE pyroCb activity near maximum intensity on 13 August 2017 using a unique algorithm developed by NRL to distinguish pyroCb from other convective cloud types using satellite observations (Peterson et al. 2017). This display also provides a corresponding time series of individual pyroCb echo tops from local weather radar observations (partnership with Fromm et al. in NRL 7227).

The combination of these tools was employed to examine the seven pyroCb updrafts observed during the PNE, revealing that six pyroCbs injected smoke directly into the stratosphere (above the tropopause altitude). The corresponding 0.3 Tg of total stratospheric smoke particle mass attributed to the PNE (Fig. 2, upper bound) was then partitioned to the locations of these six pyroCbs based on injection duration and maximum altitude. This analysis discovered that three of the PNE pyroCbs were especially intense, injecting ~88% of the total stratospheric plume mass.



**Figure 4. (Left) Snapshot of the 2017 PNE pyroCb activity from satellite. Grayscale shading indicates the thermal infrared (11 μm) brightness temperature (GOES-16), with colder, high altitude cloud tops displayed in white. Green shading indicates active, smoke-infused pyroCb updrafts. Pink shading indicates active wildfires. (Right) Radar echo-top time series for seven individual pyroCbs observed during the PNE. Horizontal line denotes the cold point tropopause.**

Initial testing this new pyroCb smoke source capability focused on NAAPS because it provides a baseline for inline NAVGEM aerosol simulations. It is also computationally much less expensive than inline NAVGEM, so sensitivity tests could be performed relatively easily. In order to translate the observationally-based smoke source into NAAPS, sensitivity tests were performed where the same smoke aerosol mass was injected into different vertical layer(s) of the model. Eventually, a single-layer emission method was selected for the idealized NAAPS and subsequent NAVGEM simulations. To isolate impacts from the PNE plume, only stratospheric smoke was released into the model and other smoke sources were turned off.

## 4. Results

### 4.1 Horizontal Plume Transport

After initializing the pyroCb smoke sources in NAAPS/NAVGEM, the team showed that Navy forecast models are capable of simulating the horizontal transport of the ensuing volcanic-scale smoke plumes in the stratosphere. Aerosol Index (AI) observations from the Ozone Mapping Profiler Suite (OMPS), flown aboard the Suomi National Polar-orbiting Partnership (S-NPP) satellite, reveal that the PNE smoke plume split into two branches a few days after the initial injection of smoke into the stratosphere (Fig. 5). AI is sensitive to the altitude of the light-absorbing smoke particles that make up pyroCb plumes (e.g., black and brown carbon), with stratospheric layers corresponding to the largest values (Fig. 5,

yellow/red). One branch lingered over north of Hudson Bay, while the other was transported to the east of Hudson Bay and then over the North Atlantic and Europe. Idealized NAAPS and NAVGEM simulations of pyroCb smoke in the lower stratosphere successfully captured this spatial bifurcation of the plume. The NAAPS smoke transport example in Fig. 5 is displayed using smoke aerosol optical depth (AOD).

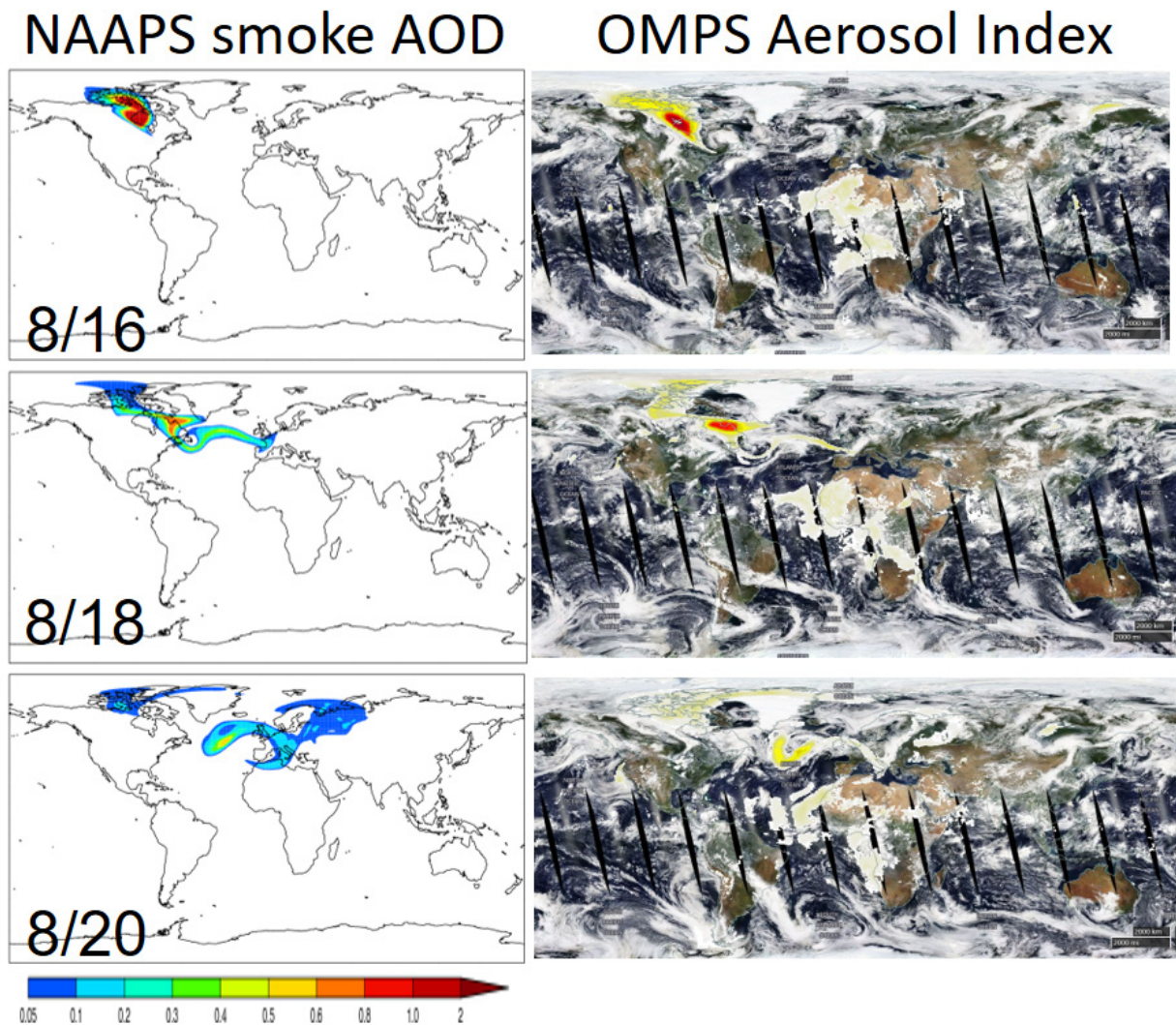


Figure 5. Evolution of smoke AOD resulting from the 2017 PNE smoke plume in North America using idealized NAAPS simulation (left) and the corresponding observed OMPS Aerosol Index (right).

#### 4.2 Vertical Plume Profiles

Quantitative validation smoke plume vertical profiles is challenging because stratospheric aerosols are often concentrated in a narrow vertical layer. Here, the team employed observed profiles from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), flown aboard NASA's polar-orbiting CALIPSO satellite. CALIOP laser-backscatter observations were used to verify the vertical profiles of NAVGEM output during the plume transport on Aug. 14, 22, and 24. As highlighted in Fig. 6, NAVGEM simulations

captured the altitude of the observed smoke plumes well. NAVGEM also successfully simulated the narrow, high-altitude plume characteristics identified by CALIOP. However, the maximum simulated backscatter coefficient was slightly smaller than the CALIOP observations at longer durations after the pyroCb event (e.g., 24 Aug).

While there was some initial concern that vertical diffusion and removal processes in NAVGEM may limit the accuracy of these simulations, the results for the PNE smoke plume in Fig. 6 are extremely encouraging. Minor offsets may be as much due to errors in the modeling run as they are uncertainties in our initial source function. The point here is that the aerosol is generally in the right place, which is a key step toward evaluating our hypothesis.

Our FY20 work has greatly increased confidence in the ability of NAVGEM to successfully simulate the vertical profile of pyroCb smoke plumes, which is essential for accurate modeling of radiative feedbacks. NRL becomes one of the only laboratories in the world capable of this endeavor, making our investment in this work unit a successful one. This analysis step sets a foundation for routine forecasting of stratospheric aerosol plumes in the Navy's weather models, including pyroCb smoke and volcanic eruptions.

#### ***4.3 Radiative Coupling and Impact on Atmospheric Dynamics***

After addressing the pyroCb smoke initialization and 3-D plume transport, the team is well positioned for the final step in this project, which requires using the radiative coupling capability in NAVGEM for evaluating our hypothesis. The heating effect generated by absorption of solar radiation within the smoke plume must be isolated to ultimately determine how pyroCb plumes can impact large-scale meteorology over the days and weeks following the event. While the team conducted initial testing in FY20, future work is required to employ the three modeling experiments outlined above that will ultimately answer the project science questions.

### **5. FY20 Summary**

The project team made significant progress during FY20. A pyroCb smoke source capability was developed and tested for NAAPS and NAVGEM, representing the most precise pyroCb plume initialization ever attempted in an aerosol model. Vertical and horizontal plume transport were validated using a suite of available satellite observations. Initial testing of the radiative coupling in NAVGEM is currently in progress through FY21, which will allow us to understand the role of the 2017 Pacific Northwest Event in influencing the track of Hurricane Harvey. Our results from FY20 have positioned NRL to lead future modeling initiatives on large pyroCb smoke plumes. We remain committed understanding the role of the pyroCb phenomenon in the climate system, and its potential impact on naval weather forecasts and field operations.

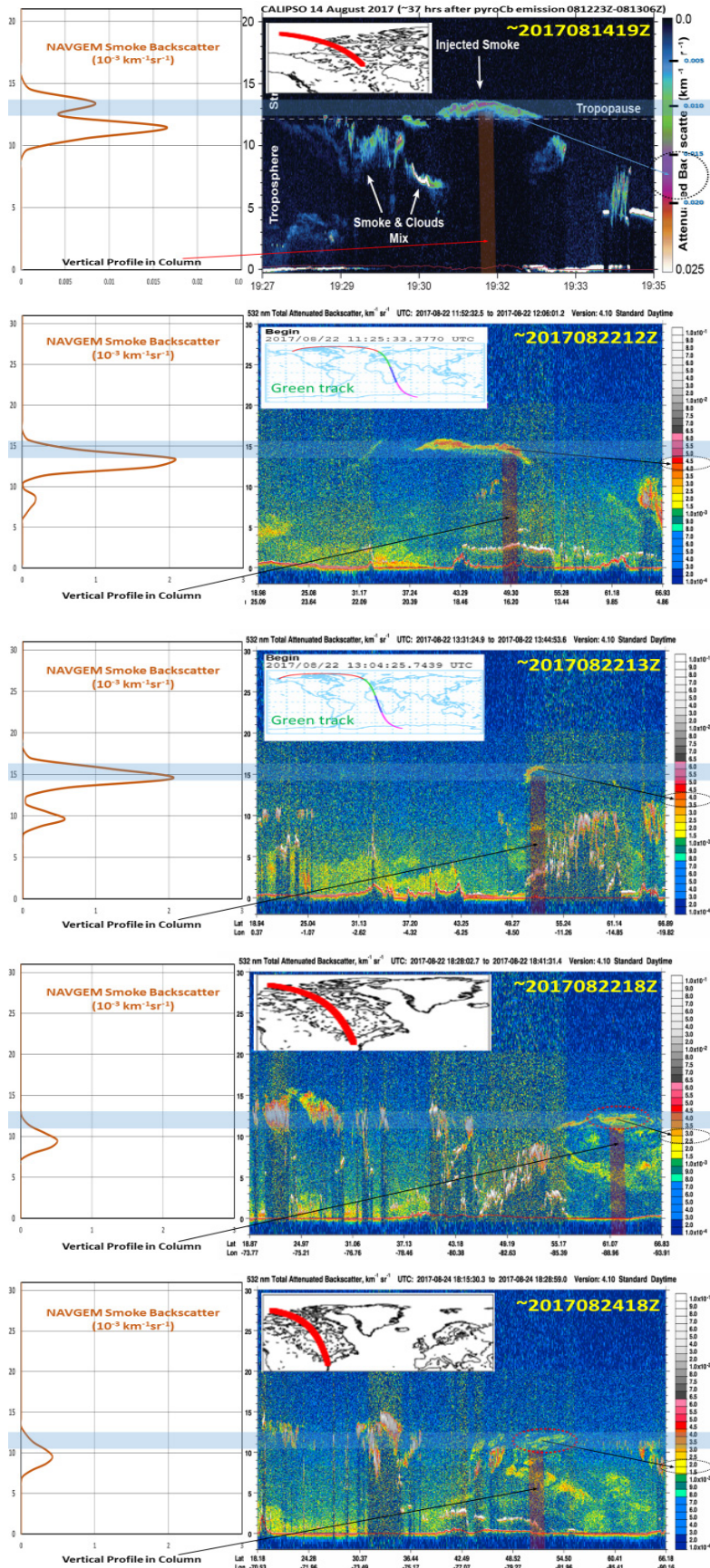


Figure 6. NAVGEM vertical distribution of smoke backscatter coefficient output from model grid columns (left) at the locations of maximum backscatter observed on CALIPSO satellite scan tracks (right) during the 2017 PNE.

## 6. Future Work

Future work (originally planned under FY21 NISE funding) will quantify differences in the hemispheric longwave weather patterns induced by the PNE and ANYSO smoke plumes. For example, we will examine differences in geopotential heights at a variety of levels, as well as perturbations in temperature and potential vorticity. We will first complete our analysis of the PNE plume, with the goal of a high-impact publication. Subsequent work will focus on the more complex Australian ANYSO event, with the goal of preparing the Navy for atmospheric impacts ensuing from future pyroCb “super outbreaks”.

The smoke source for the ANYSO plume is much more complicated than the PNE, featuring 38 individual pyroCb updrafts, with many injecting smoke directly into the stratosphere (paper in prep). In fact, ANYSO was so complex that we had to divide it into 18 smaller pyroCb events that developed over 13 intense wildfires. ANYSO also included two distinct phases of pyroCb activity (29-31 December 2019 and 04 January 2020). For these reasons, NAAPS and NAVGEM simulations focused exclusively on the easier PNE plume in FY20. ANYSO will be examined in more detail in future studies.

## 7. Papers: Published or in Prep

Fromm, M. D., Kablick, G. P., **Peterson, D. A.**, Kahn, R. A. (in prep). Quantifying the source term and uniqueness of the 12 August 2017 Pacific Northwest pyroCb event. *Journal of Geophysical Research*.

**Peterson, D. A., Xian, P., Liu, M.** (in prep). Weather Extremes Induced by Large Pyrocumulonimbus Smoke Events. *Journal TBD*.

**Peterson, D. A.**, Fromm, M. D., McRae, R., Campbell, J. R., Hyer E. J. (in prep). Australia’s 2019/20 super outbreak of fire-induced thunderstorms and its connection to an unprecedented stratospheric smoke plume. *npj Climate and Atmospheric Science (invited)*.

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Meteorology Influencing Fire Activity and Smoke Plume Evolution during FIREX-AQ. Peterson, D.A., FIREX-AQ Science Team Meeting, virtual, 02 April 2020.

Quantifying the Impact of Intense Pyroconvection on Stratospheric Aerosol Loading, Peterson, D.A., Third International Smoke Symposium, virtual meeting, 22 April 2020.

Analysis of the Williams Flats PyroCb Events, Peterson, D.A., FIREX-AQ Science Team Meeting, virtual, 25 June 2020.

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