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Monitoring of Volcanic Eruptions, Pyrocumulonimbus (PyroCb), and Ensuing Impacts on the UTLS Worldwide

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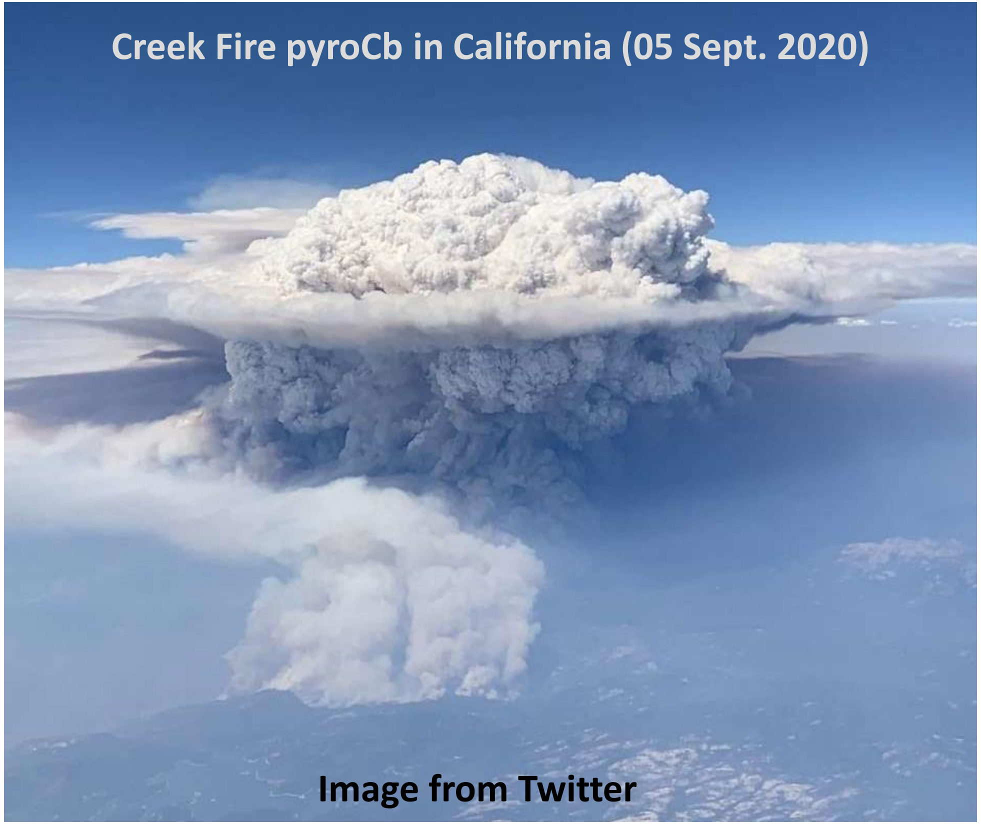
Many contributions from members of the FIREX-AQ Science Team

NASA AOS Applications Seminar, 27 October 2022

Pyrocumulonimbus (PyroCb)
Dangerous & Severe Type of Fire Weather



Near-fire, Firefighting:
- Erratic wind behavior near fires, enhanced spotting
- Extreme fire whirls likely
- Lightning strikes can ignite new fires

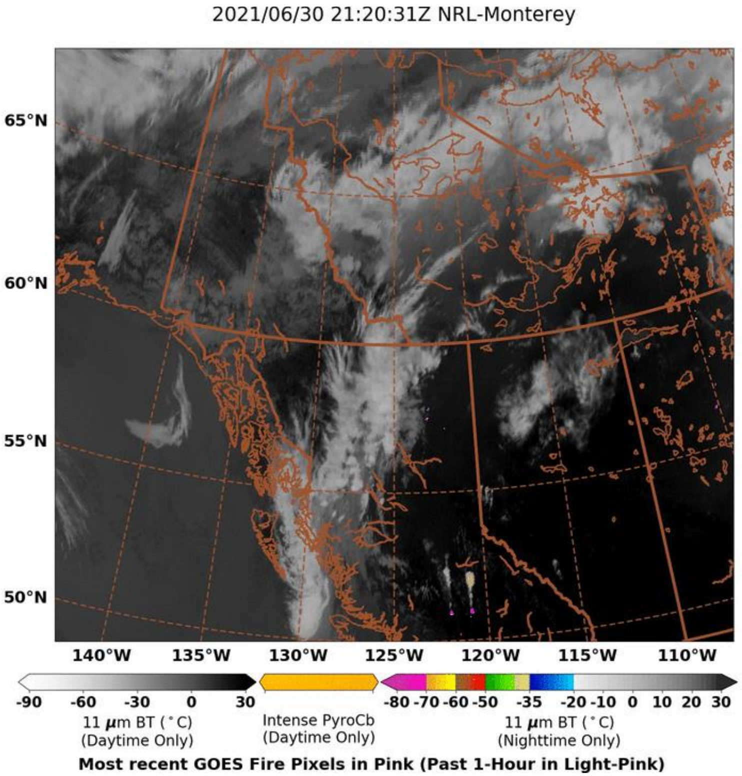
Aviation:
- Airborne fire suppression impossible
- PyroCbs may not appear hazardous in aircraft radar displays. Pilots might inadvertently fly into storm core.

Smoke Transport:
- Smoke injected at and above aircraft cruising altitudes
- No prediction available for long-distance smoke transport induced by pyroCbs

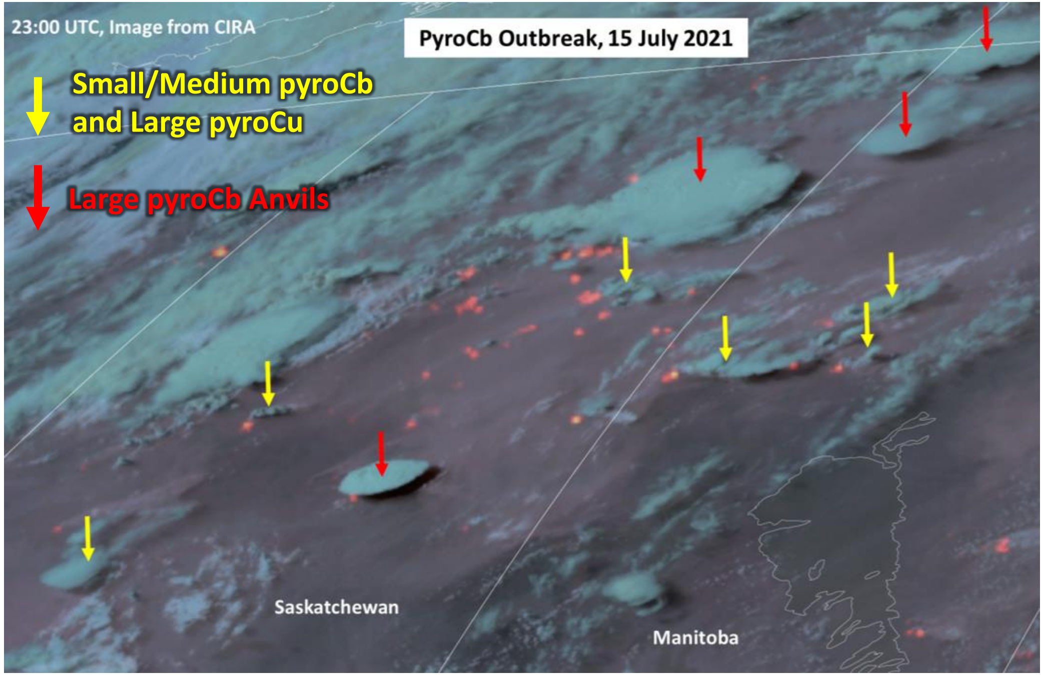
Climate:
- PyroCbs often inject smoke into the stratosphere
- Plume magnitude can rival volcanic eruptions
- Potential feedbacks on radiative forcing, ozone loss, dynamic circulation, etc.

2021 PyroCb Season
83 PyroCbs in North America, 100 Worldwide

"Monster PyroCb" (30 June)



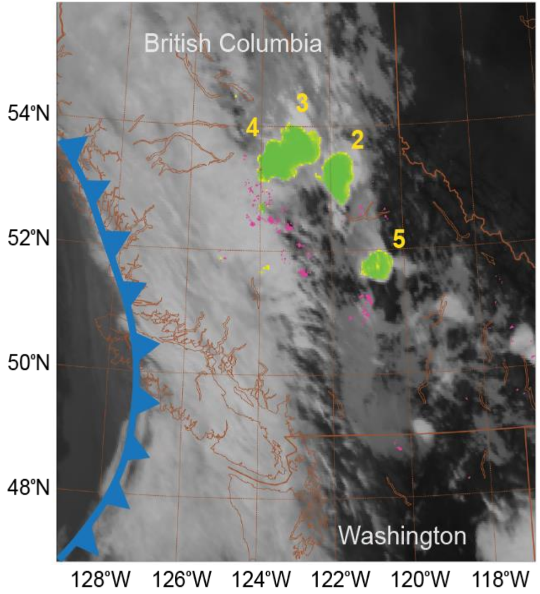
Largest known pyroCb outbreak in North America (15 July)



New Class of Large Smoke Plumes in the Stratosphere

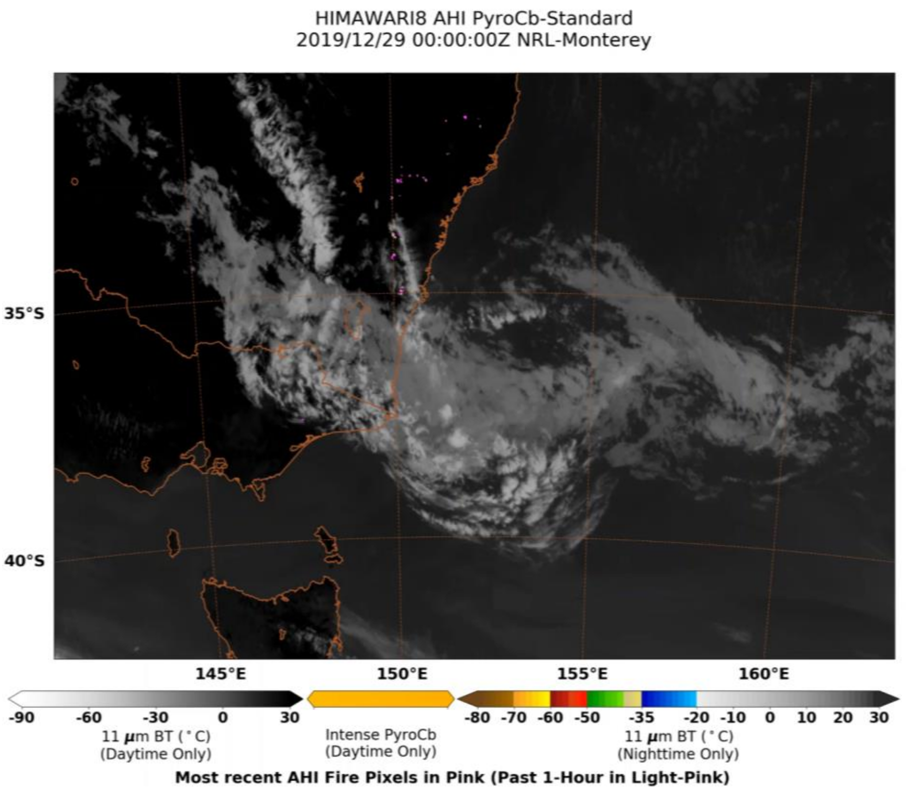
2017 Pacific Northwest Event (PNE)

Active PyroCb (8/12/17)
Green = PyroCb Microphysics



How does pyroCb activity compare to volcanic eruptions?

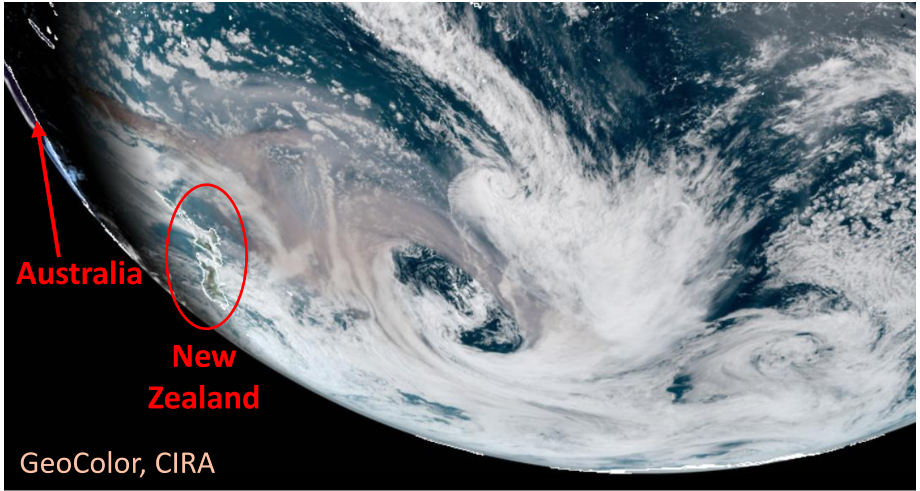
Australian New Year Super Outbreak (ANYSO)
Phase #1: 29-31 December 2019



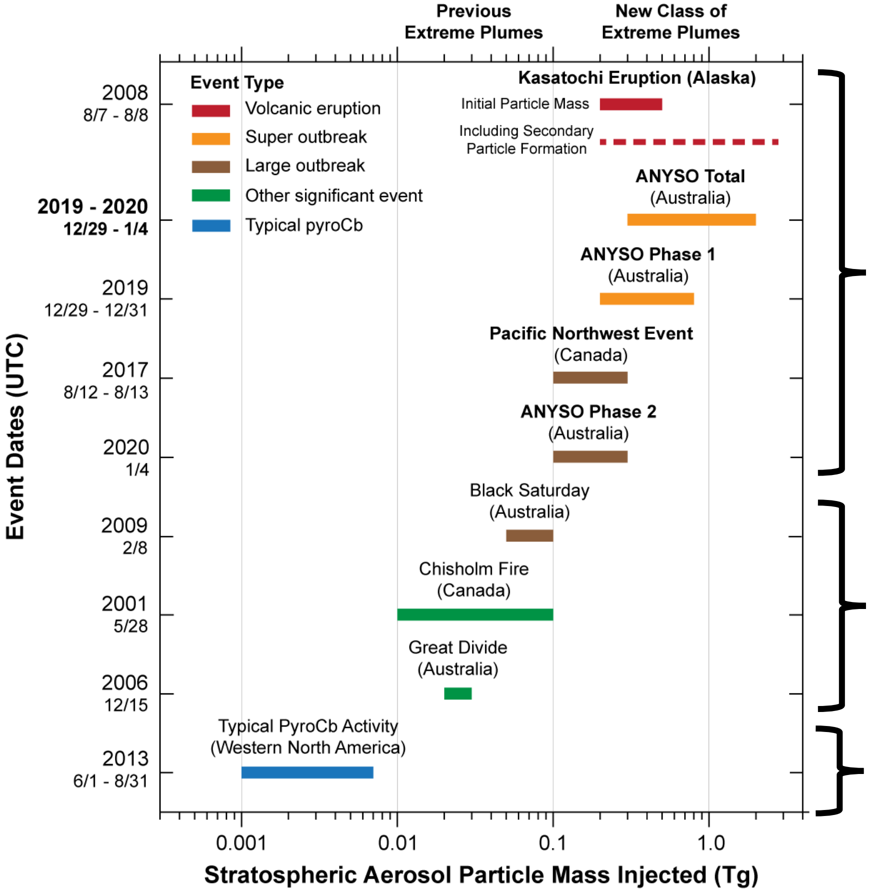
Peterson et al. 2021 (Nature PJ, Climate & Atmos. Sci.)

- longest duration of near-continuous pyroCb activity
- 33 pyroCbs observed over ~45 hr
- PyroCbs developed both during day and night
- Total stratospheric aerosol mass: 0.2 - 0.8 Tg
- **Largest smoke particle injection on record!**

Stratospheric Plume: GOES-17 1/2/20 (18:40 UTC)



Significant Stratospheric Aerosol Particle Injections



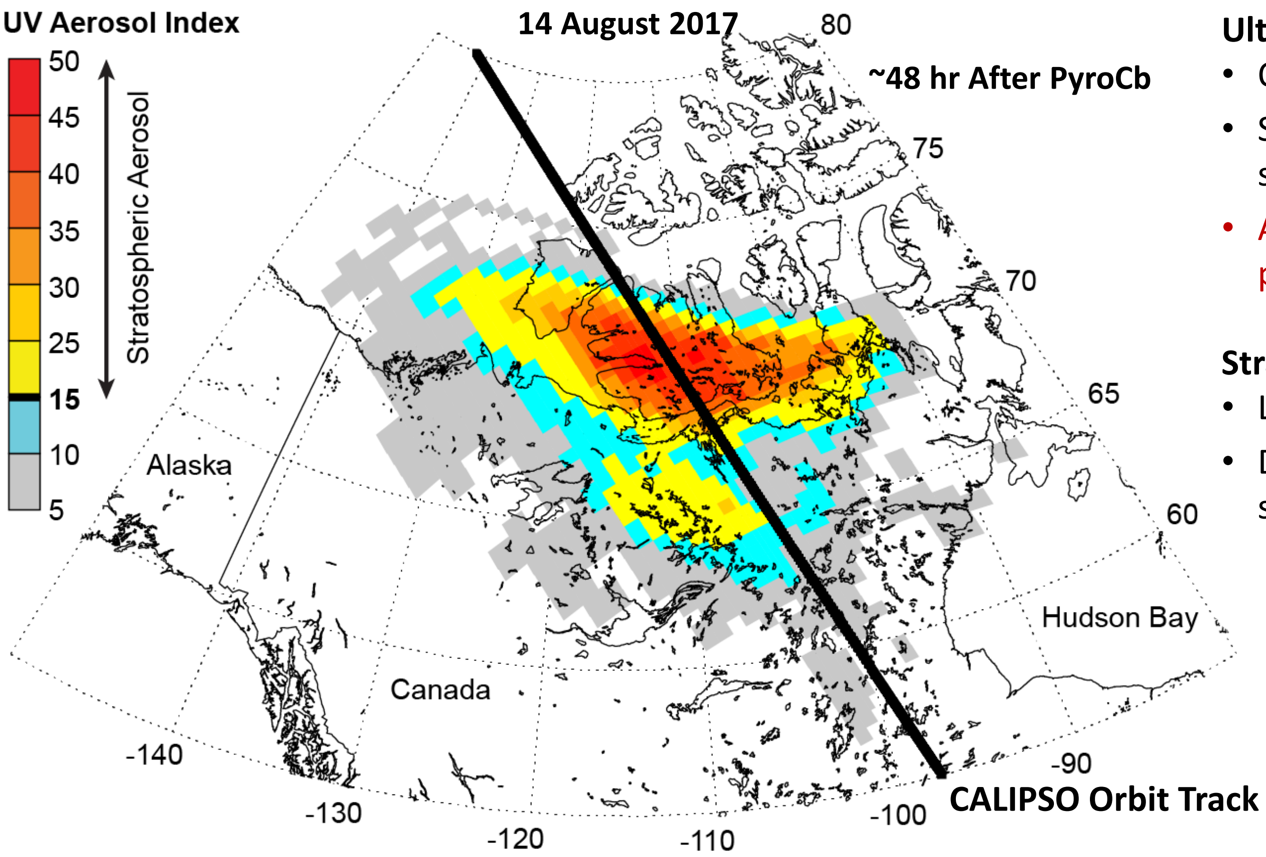
- **Australian and Pacific NW Event smoke plumes are comparable to plumes ensuing from moderate volcanic eruptions**
- **Two stratospheric smoke plumes of volcanic scale in less than 3 years!**
- **Preliminary estimate for the combined Australian plume (0.3-1.1 Tg) is at least three times larger than the 2017 Pacific NW Event (0.1-0.3 Tg)**

Significant pyroCb events prior to 2017

“typical” pyroCb events

Peterson et al. 2021
(Nature PJ, Climate and Atmos. Science)

Quantity of smoke aerosol mass injected into the stratosphere?



Ultra-Violet Aerosol Index (UVAI):

- Ozone Mapping Profiler Suite (OMPS)
- Sensitive to altitude of light-absorbing smoke aerosols
- AI exceeded all known pyroCb & volcanic plumes!

Stratospheric plume area:

- Lidar (CALIOP) vertical profiles required!
- Derive an UVAI threshold for stratospheric aerosol: AI > 15

Nascent stratospheric plume area nearly 800,000 km²

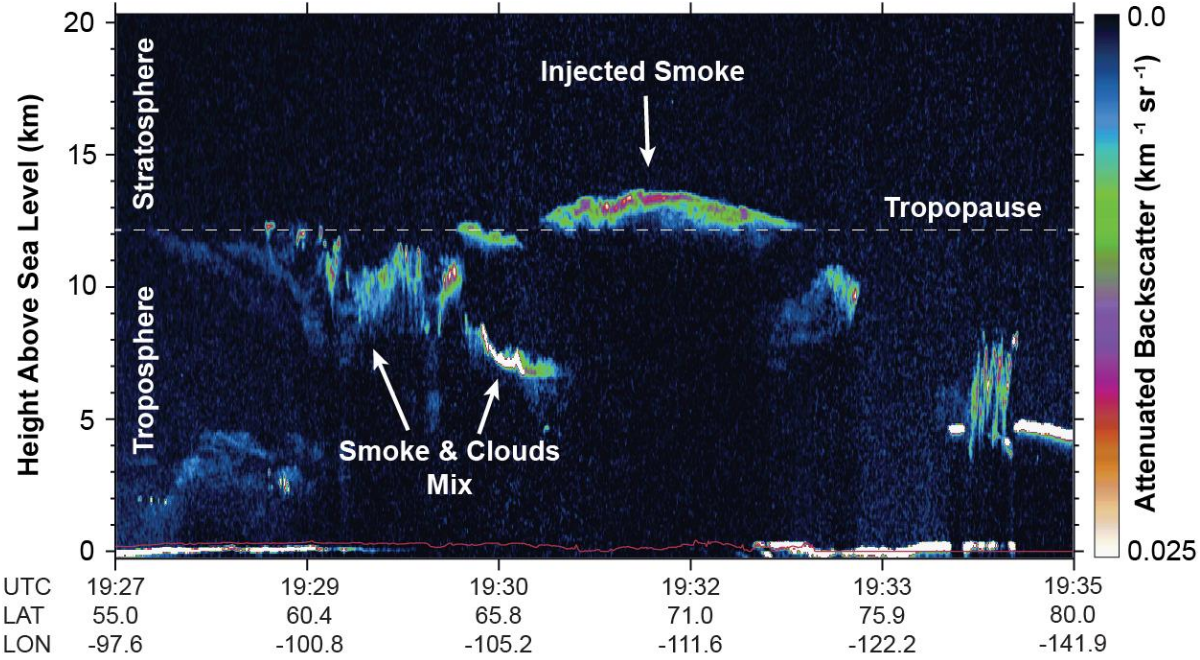
Peterson et al. 2018
(Nature PJ, Climate and Atmos. Science)

Stratospheric Aerosol Mass Calculations

Total mass injection = mass density x stratospheric plume volume

$$Mass\ Density = \frac{\beta R}{\varepsilon}$$

CALIOP 14 August 2017 (~48 hr after pyroCb)



β: Lidar backscatter ($m^{-1}sr^{-1}$)
ε: Smoke mass extinction coefficient (m^2kg^{-1})
R: Lidar ratio (sr), extinction-to-backscatter

Methods:

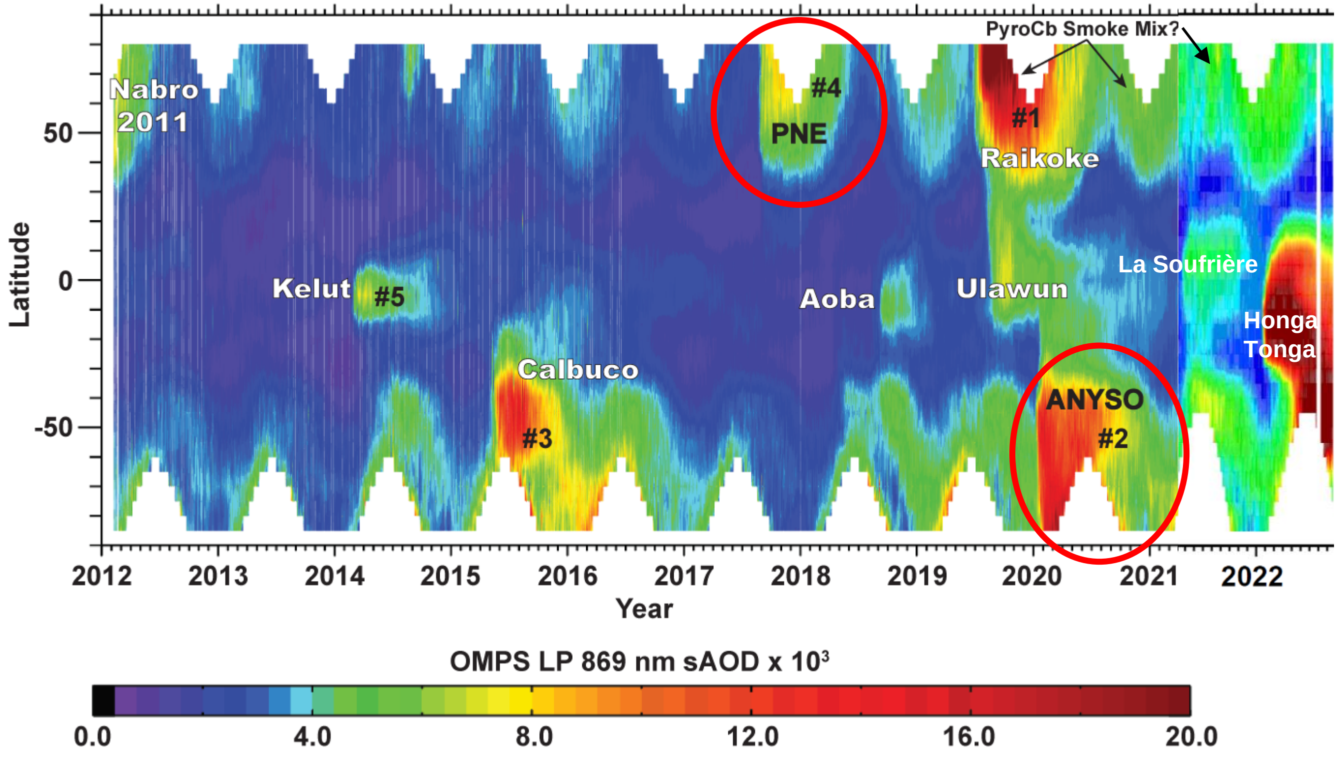
- Range of values used for ε and R
- Account for potential mix of smoke particles, water/ice, and mineral dust

Results:

- Smoke mass density: 73-220 μg m^{-3}
- **Total stratospheric aerosol mass: 0.1 to 0.3 Tg**

Comparison and Potential Interaction with Volcanic Plumes

OMPS LP stratospheric aerosol optical depth (sAOD)



- Two of the five largest plumes since 2012 are from pyroCbs
- 2019-2020 featured the highest levels of sAOD during the entire 25 year, post-Pinatubo era:
  - ANYSO played a significant role
  - Impact from additional pyroCb activity in N. Hemisphere?
- Potential interactions between pyroCb smoke and sulfate-based volcanic plumes?

Updated by Ghassan Taha, 2022

Diabatic Lofting of Smoke in the Stratosphere

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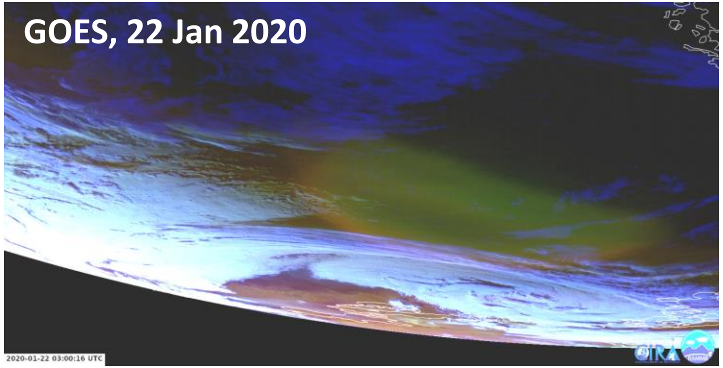
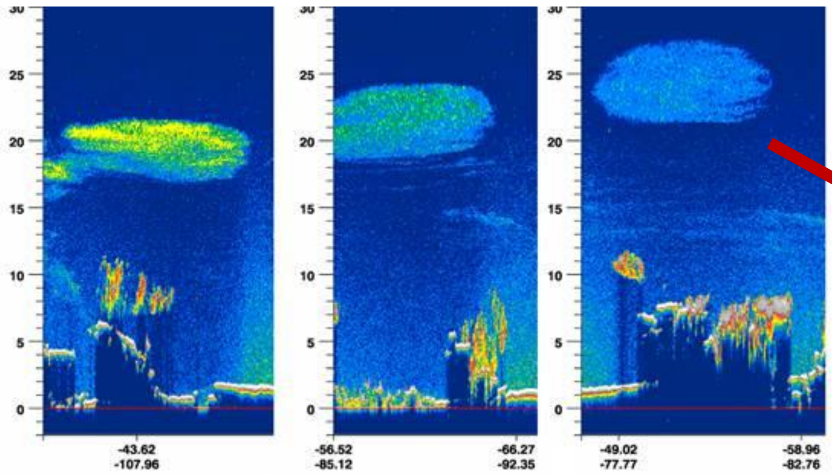
Multiple Injections = Complex Plume in the Stratosphere

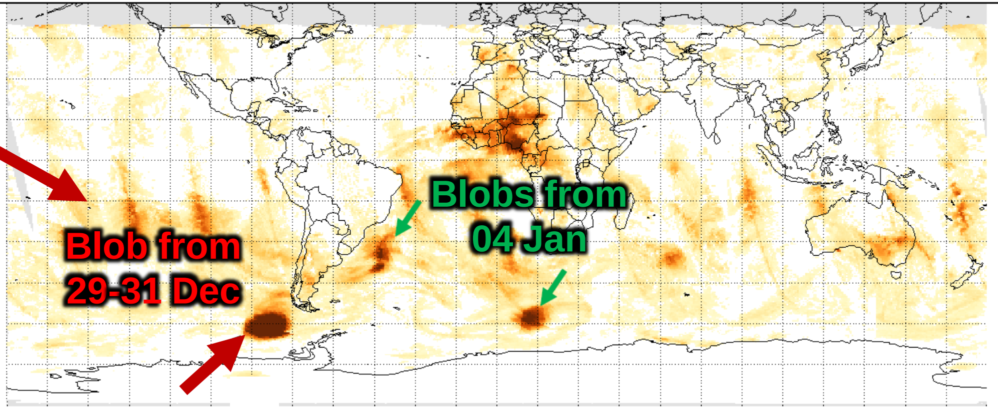
- Considerable diabatic lofting from absorption of solar radiation
- Smoke “blob” observed up to 30 km by early February (Dec. injection)
- Transport speed and direction changed with smoke altitude
- Evolution of the blobs vs. diffuse smoke layers?



11 Jan 2020 | 21 Jan 2020 | 31 Jan 2020

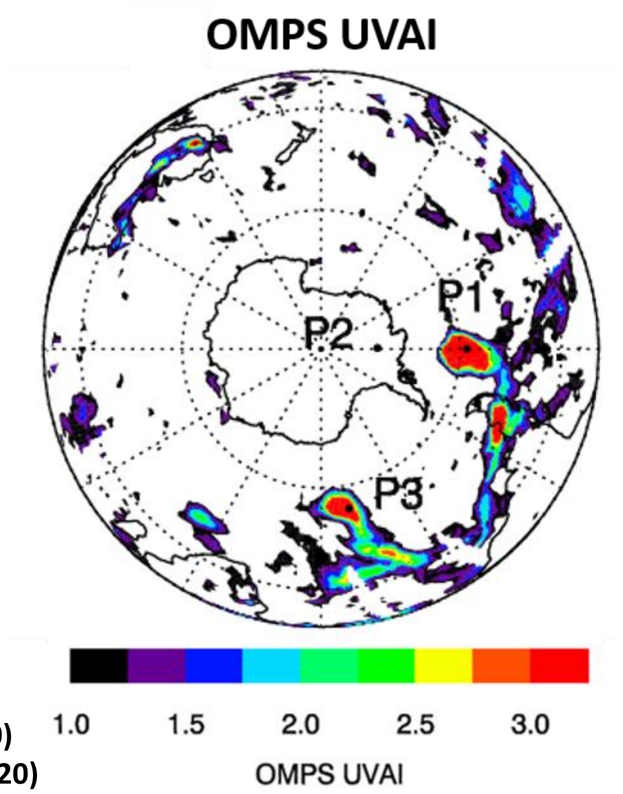


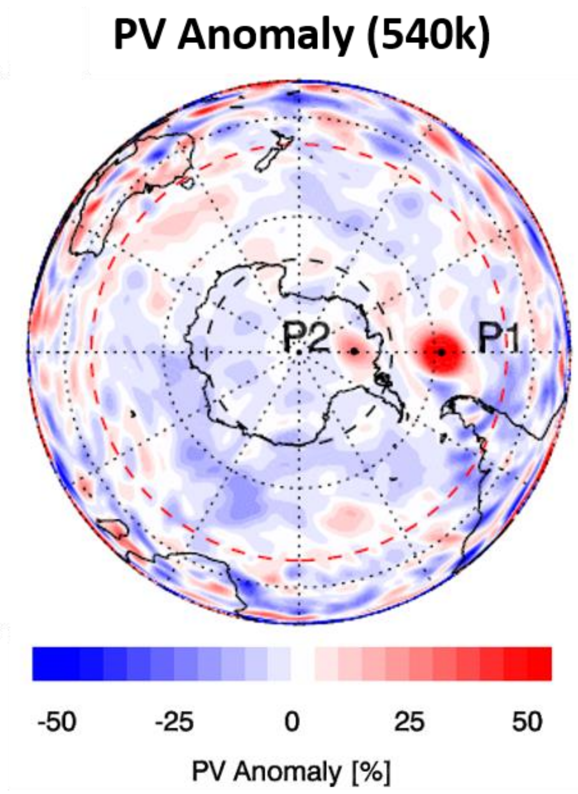
On 21 Jan the three most distinctive AI blobs consist of the Dec blob over the Pacific and two 4 Jan blobs over the Atlantic.



PyroCb Smoke Plumes Affect Dynamic Circulation
20 January 2020

Absorbing smoke layers generate anticyclonic circulations in the lower stratosphere…



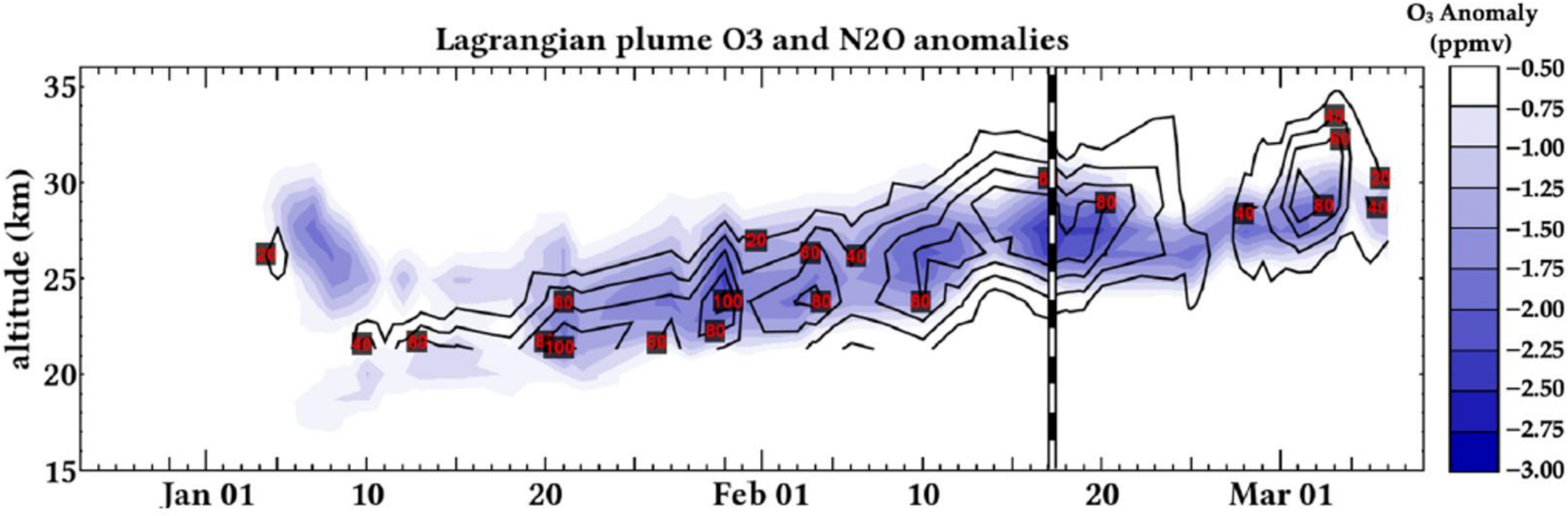


Allen et al. (2020)
Kablick et al. (2020)

PyroCb Smoke Plumes Perturb Stratospheric Ozone

Recent discoveries via Aura MLS, SAGEIII/ISS, OMPS and other sensors:

1. Rapid vertical transport of contained circulation anomalies can displace local ozone
2. Anomalies of stratospheric ozone from heterogeneous chemistry on smoke particle surfaces



Kablick et al. 2020; Rieger et al. 2021; Santee et al. 2022; Solomon et al. 2022; Bernath et al. 2022

Blow-Up Fires Contributing to a PyroCb Super Outbreak

Requires NASA Fire Detections

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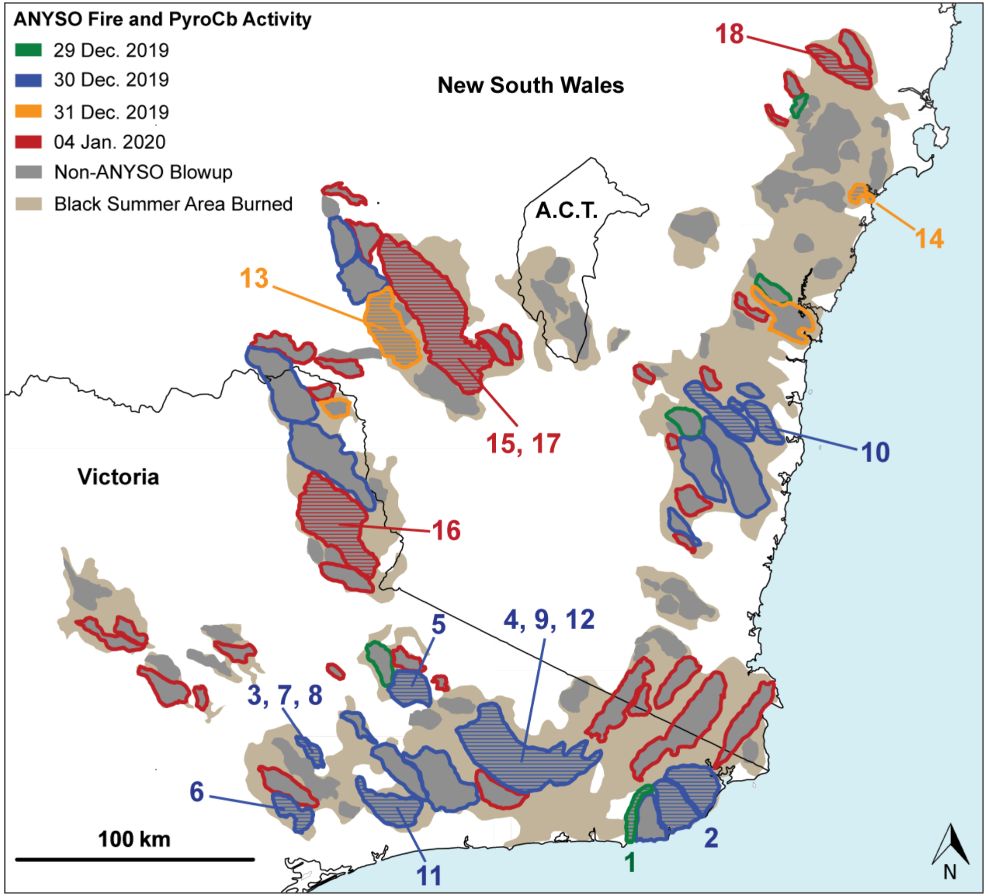

What is a "blow-up fire"?

- Rapid increases in rate of spread and intensity
- Significant vertical smoke plume growth that extends above the planetary boundary layer

Unprecedented fire activity

- Australia's "Black Summer" fire season burnt a record area of land, including 109 significant blow-up fires
- ANYSO was driven by 13 fire blow-ups:
  - Burned 530,000 ha, larger than Delaware (land area)
  - Energy release of approximately 1.3-5.1 x 10^{11} MJ
  - 2,000 times the Hiroshima atomic explosion
- PyroCb activity was extremely complex:
  - Divided into 18 smaller pyroCb "sub-events"
  - Individual pyroCb pulse or chain of several "pulses" anchored to one of the 13 blow-up initiation points

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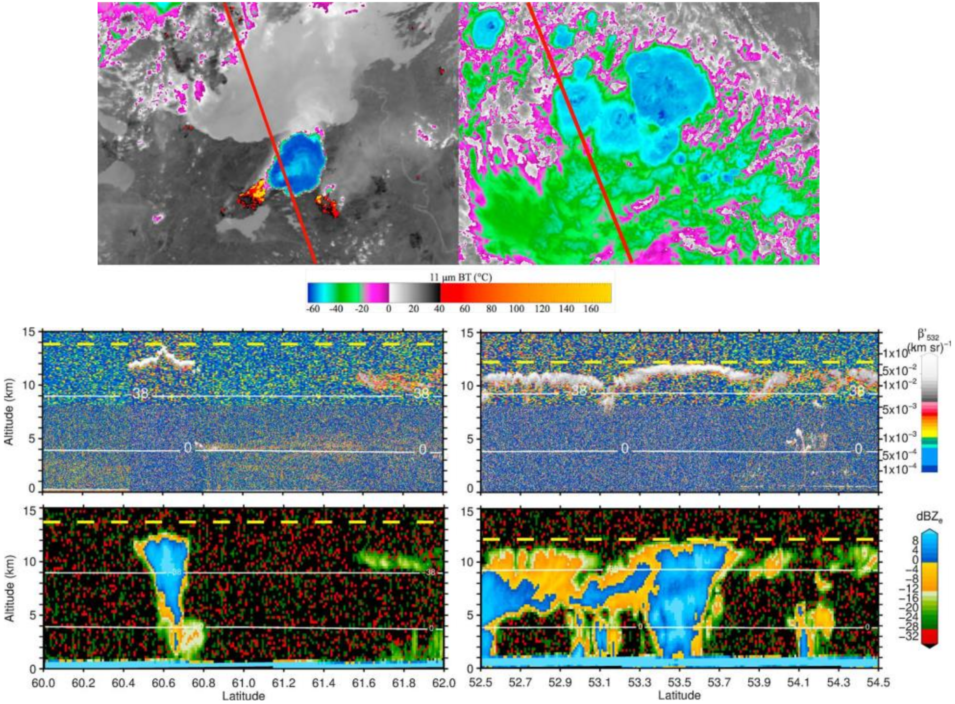
Convective Cloud Properties and MISR Plume Heights

Convective Cloud Study (Kablick et al. 2018)

MODIS + CALIPSO + CLOUDSAT

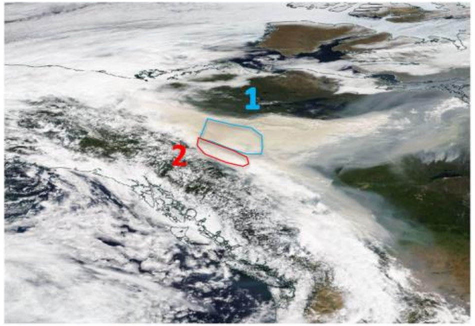
PyroCb **Traditional Cb**

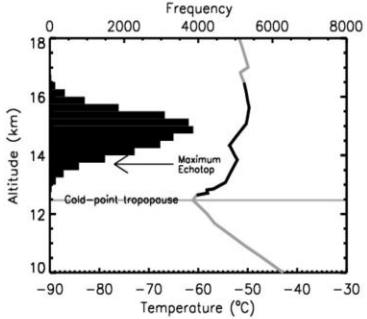


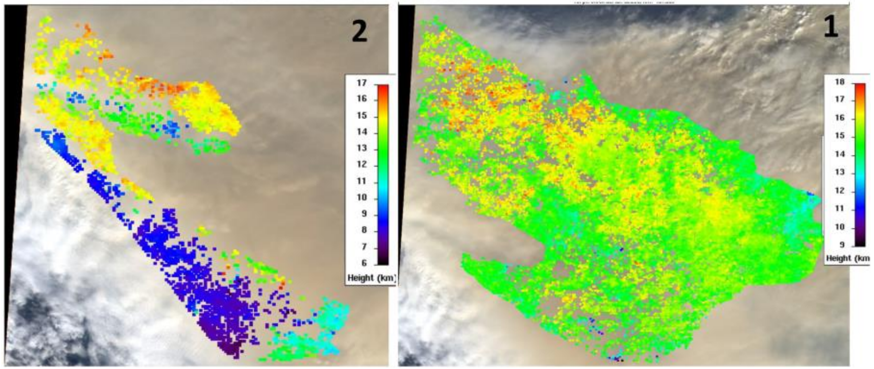
PyroCb Plume Altitude (Fromm et al. 2021)

MISR stereo heights

PNE Plume, 13 Aug. 2017

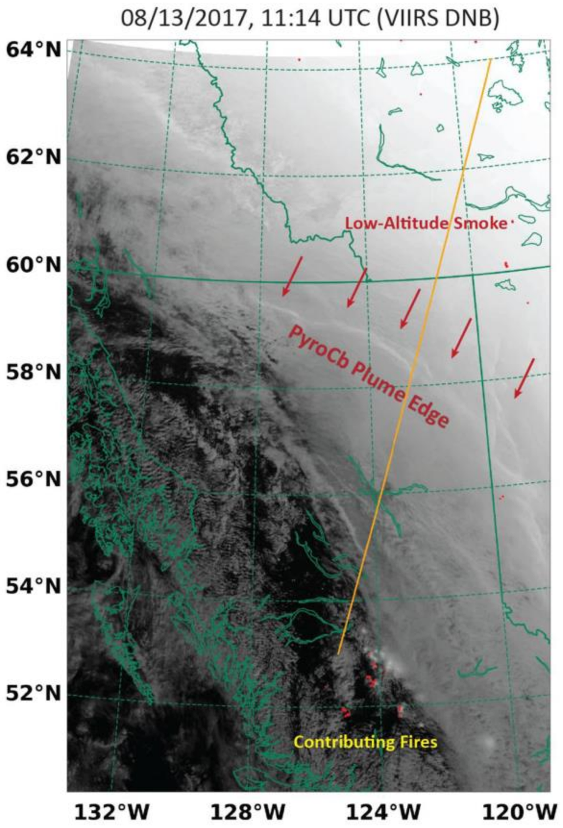




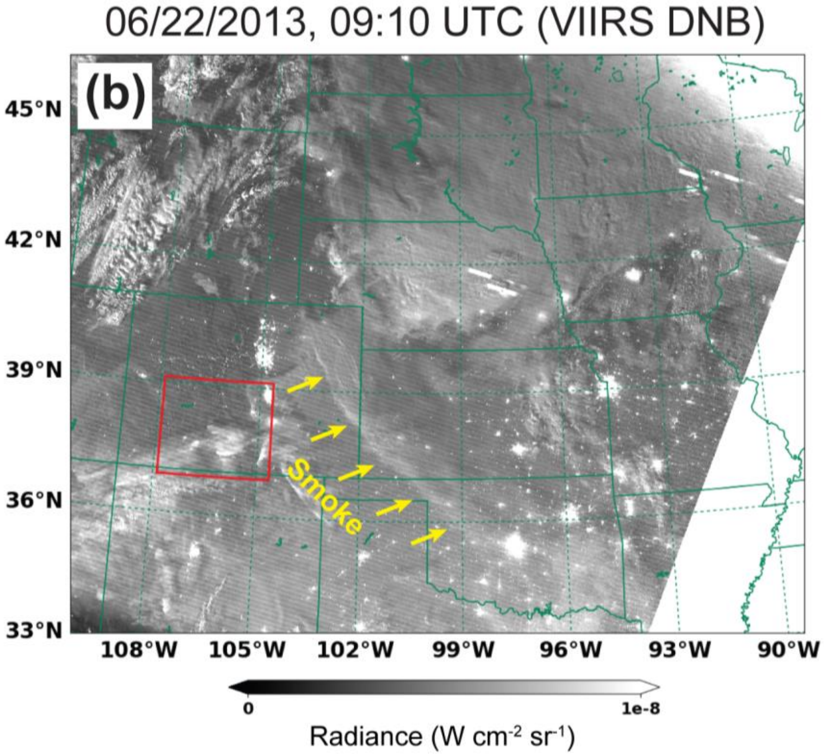


VIIRS Day/Night Band (DNB)
Tracking pyroCb smoke plumes at night

Fromm et al. 2021

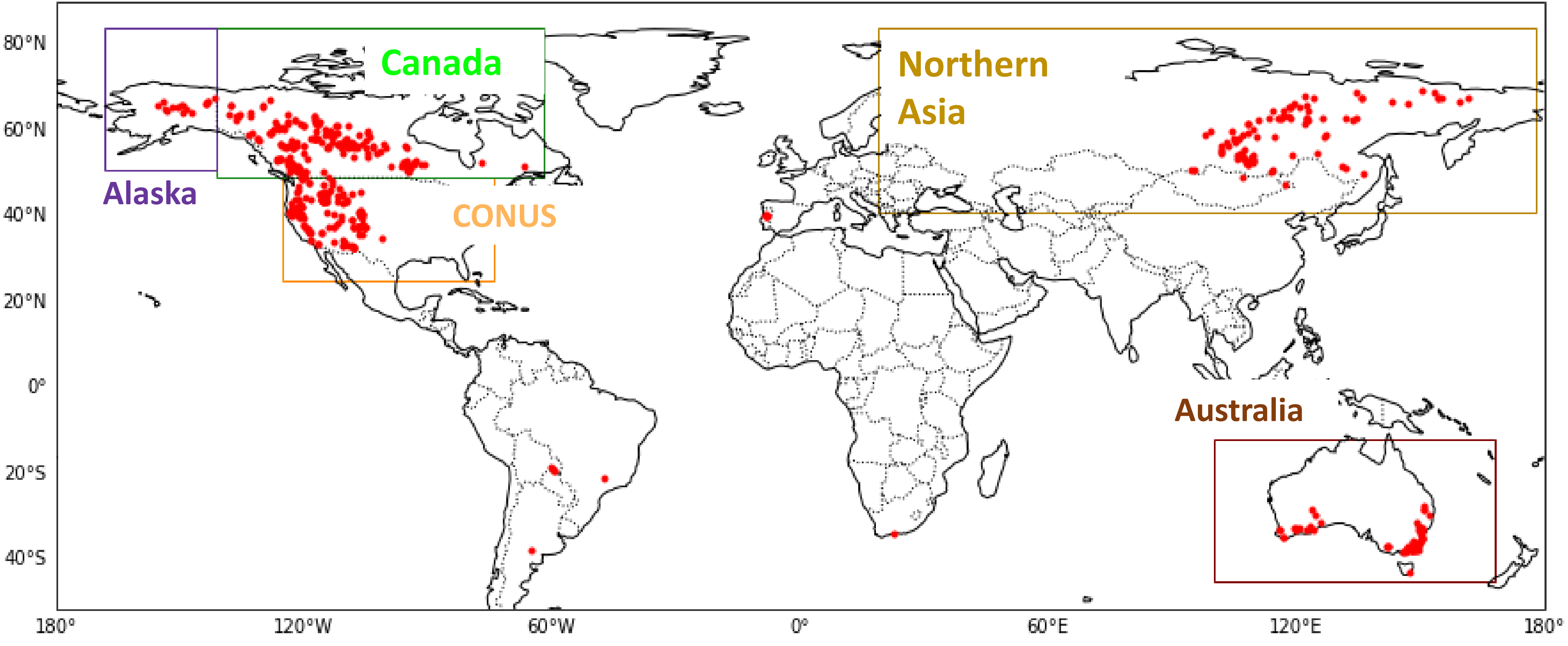


Fromm et al. 2019



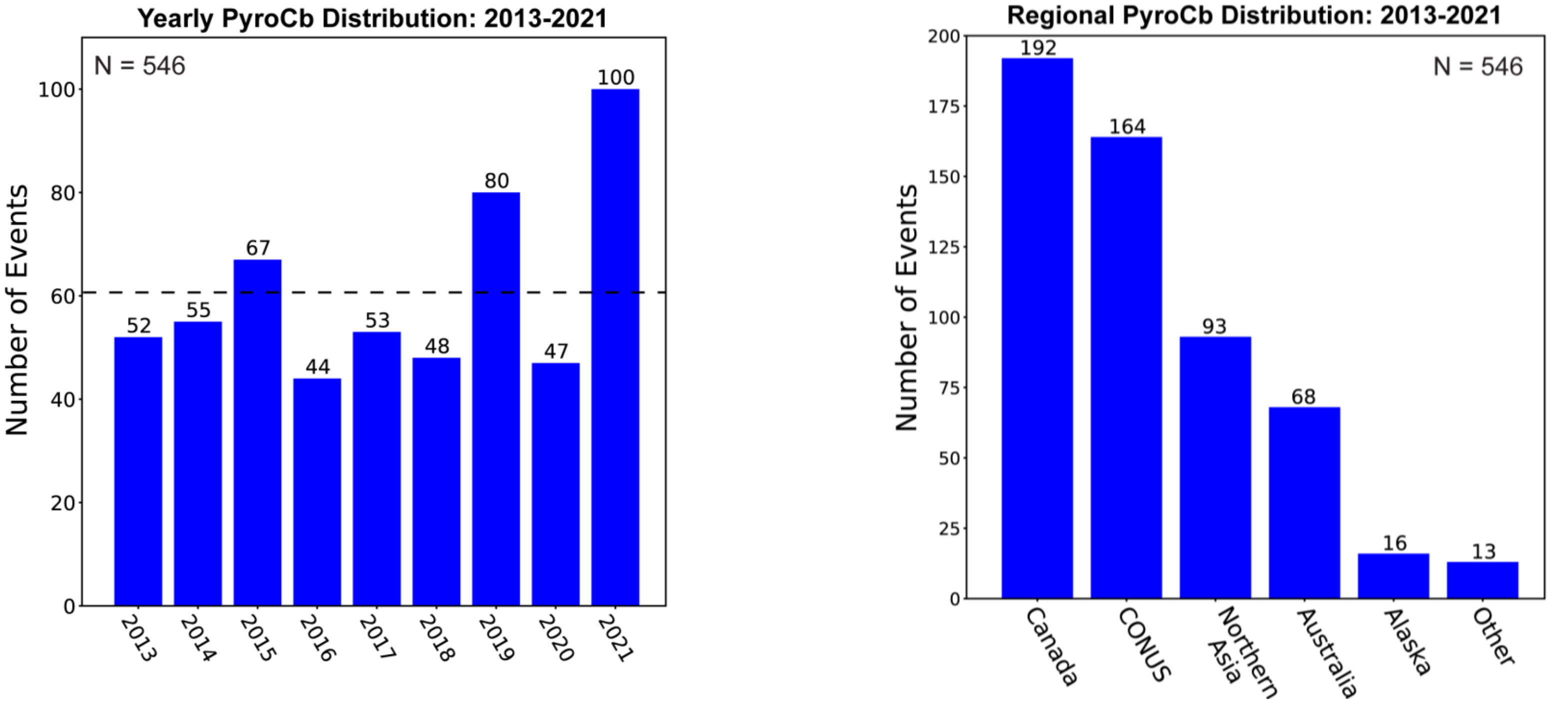
NRL PyroCb Inventory

Location of 546 pyroCbs during 2013-2021



Peterson, Berman et al. (in prep)

NRL PyroCb Inventory

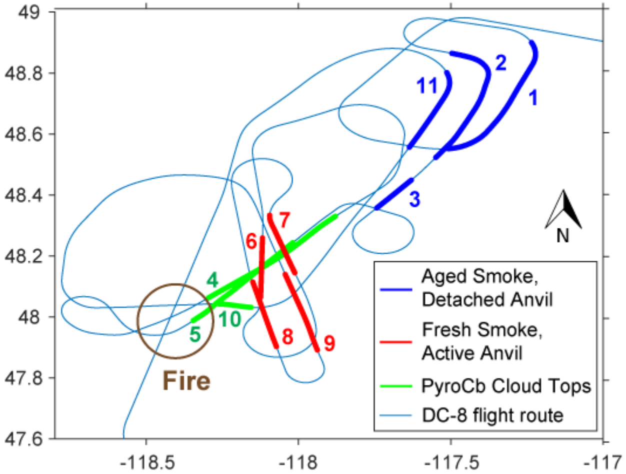


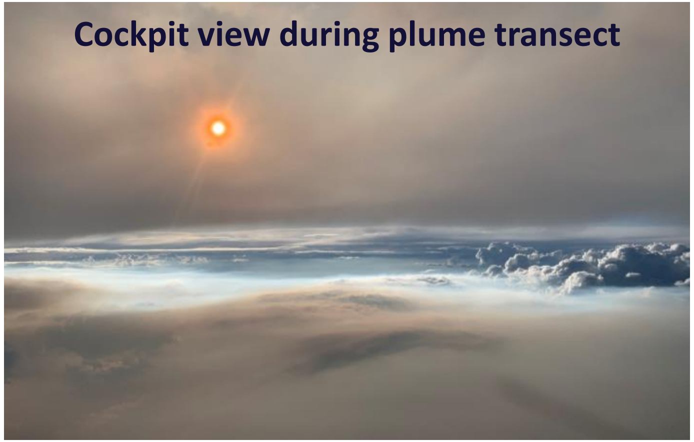
Fromm et al. 2022 (Nature Comm. Earth & Environment)

First in-situ measurements from the top of an active pyroCb and young smoke outflow

NASA's DC-8
Airborne Science Laboratory

Williams Flats Fire
08 Aug. 2019





Peterson et al. 2022 (BAMS)

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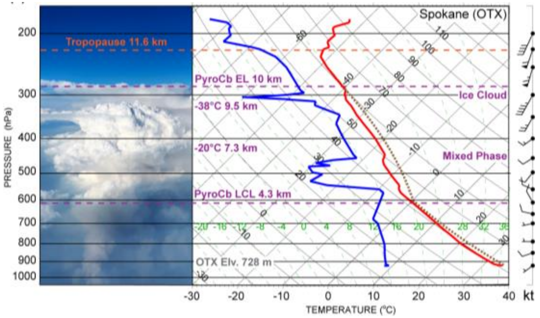
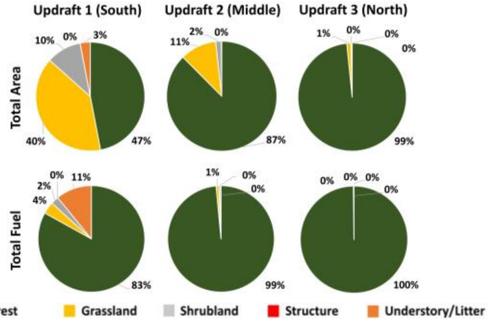
Significant Advancement in PyroCb Research

First opportunity to connect meteorology, fuels, fire-line geometry, and fire radiative power to pyroCb development and cloud property evolution, including chemistry of the ensuing smoke exhaust…

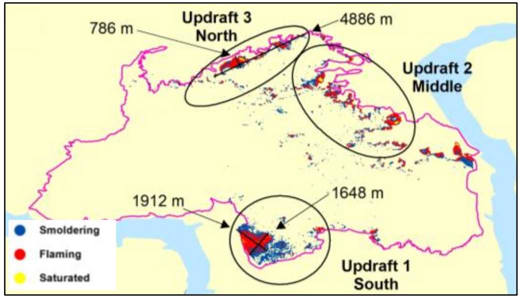
Meteorology



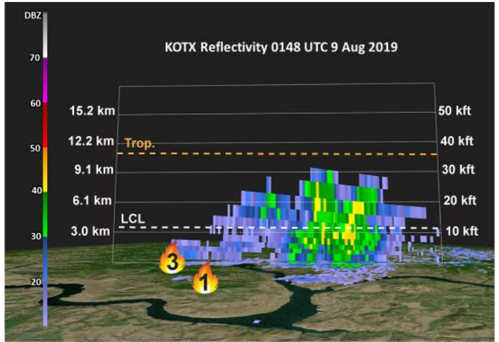
Fuels



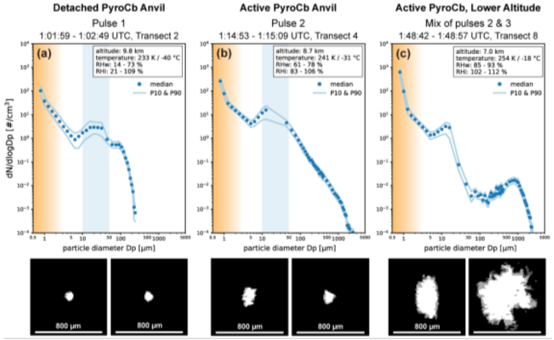
Fire Characteristics



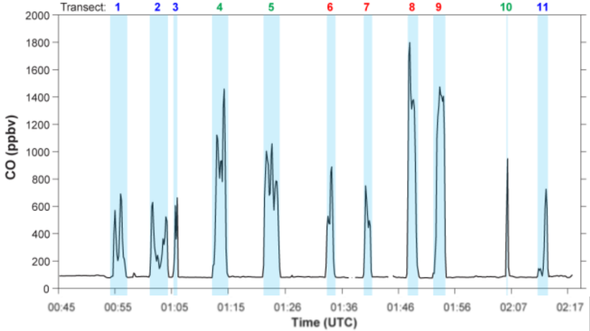
PyroCb Development



Cloud Property Evolution



Smoke Plume Chemistry



Summary and Conclusions

Contact: david.peterson@nrlmry.navy.mil, Twitter: @DrDavePeterson

New Class of Extreme PyroCb Events

- Pacific Northwest Event (PNE, 12 August 2017)
- ANYSO (29-31 December 2019 and 04 January 2020)
- Ensuing smoke plumes **exceeded the stratospheric impact from the majority of volcanic eruptions observed during 2012-2020**

Other Discoveries

- PyroCb smoke plumes can alter dynamic circulation
- Perturbations of stratospheric ozone
- Natural phenomenon to validate nuclear winter theory

It is now relevant to ask:

- Are the PNE and ANYSO harbingers of even larger pyroCb outbreaks?
- Potential for pyroCb super outbreaks increasing in a warming climate?
- Significant source of stratospheric aerosols each year?
- Potential impacts on radiative forcing and circulation?

Future Opportunities

- Account for pyroCb activity in aerosol transport models
- Improved tactical fire weather support

Williams Flats PyroCb, FIREX-AQ

References:

Peterson et al., 2022: Measurements from inside a Thunderstorm Driven by Wildfire: The 2019 FIREX-AQ Field Experiment. *BAMS*.

Peterson et al., 2021: Australia's Black Summer Pyrocumulonimbus Super Outbreak Reveals Potential for Increasingly Extreme Stratospheric Smoke Events. *Npj Climate & Atmos. Sci.*

Peterson et al., 2018: Wildfire-Driven Thunderstorms Cause a Volcano-Like Stratospheric Injection of Smoke. *Npj Climate & Atmos. Sci.*

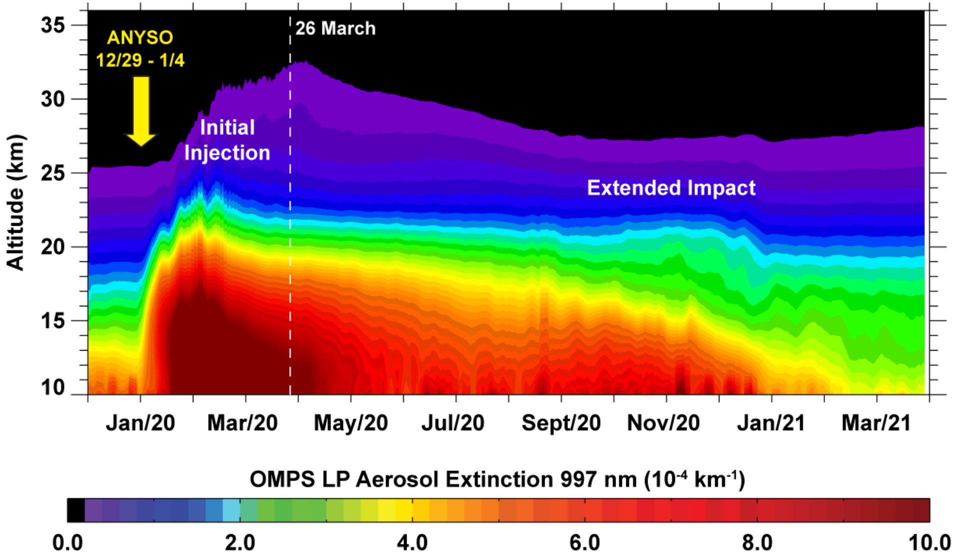
NRL PyroCb Website:
http://www.nrlmry.navy.mil/pyrocb-bin/pyrocb.cgi

Extra Slides

Smoke Plume Evolution and Persistence in the Stratosphere

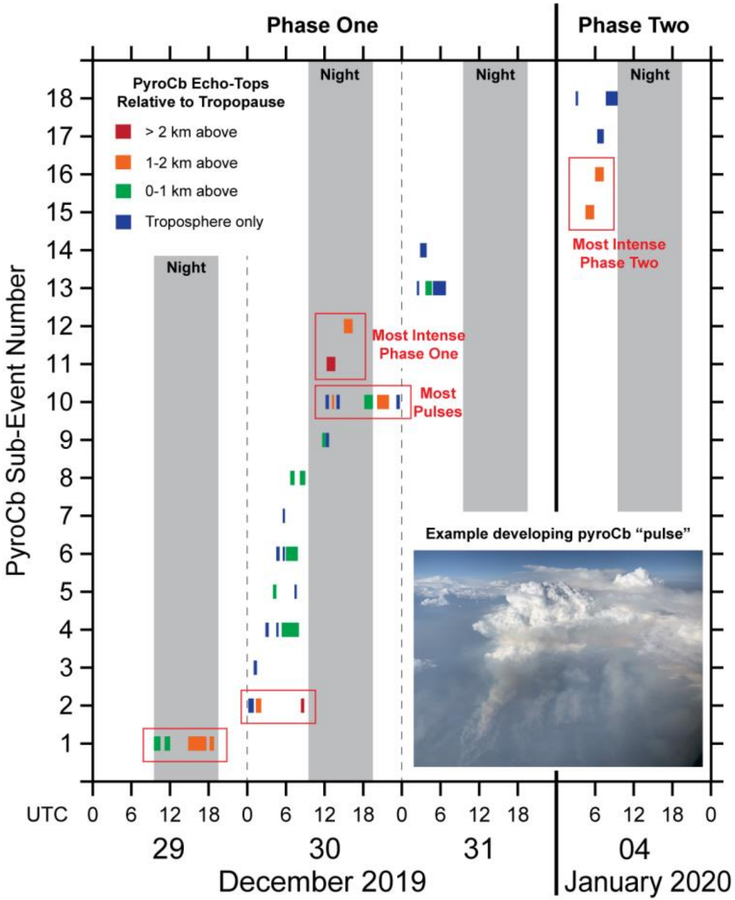
Daily OMPS LP aerosol extinction profiles (997 nm)

Stratosphere, 20S to 90S, Dec. 2019 to March 2021



- **ANYSO set a new benchmark for detectable smoke plume residence time in the stratosphere:**
  - **At least 15 months!**
  - PNE plume lasted 10 months
- The two initial stratospheric plumes merged
- Encircled a portion of the Southern Hemisphere
- Plume altitude increased from its initial injection at 15-17 km to more than 30 km within 40 days
  - Extended well into the ozone layer
  - Comparable with the sulfate plume altitude following the 1991 Pinatubo eruption
- Validation of nuclear winter theory?

Timeline of ANYSO PyroCb Activity
18 sub-events, with 38 individual pulses



PyroCb "pulse" = distinct, ice-capped convective column

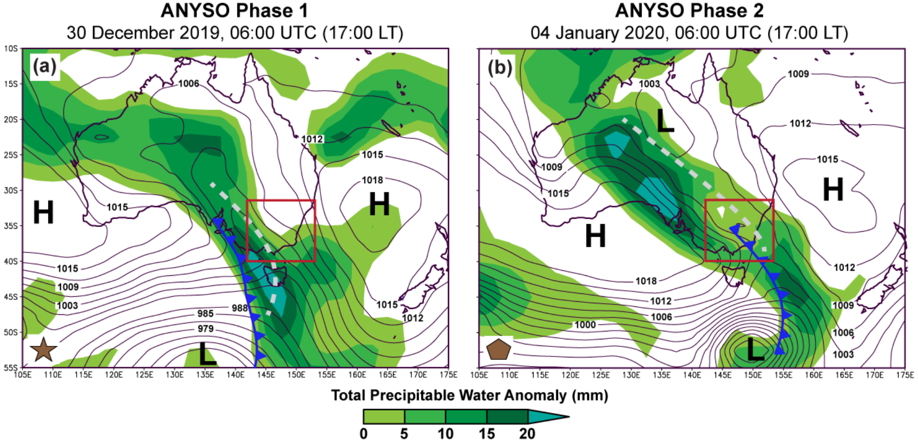
Why was ANYSO a Super Outbreak?

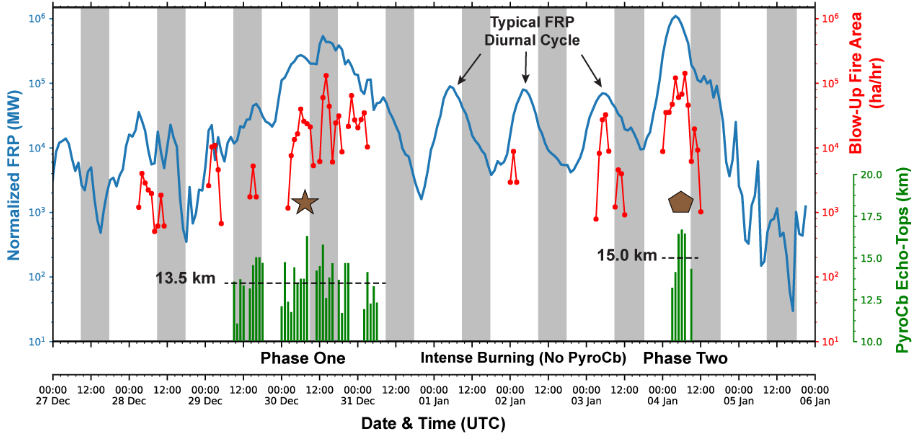
- 38 pyroCb pulses over 51 non-consecutive hours
- 20 of the pulses (53%) reached the lower stratosphere
- Three pulses extended directly into the stratospheric "overworld", potential temperature > 380 K
- First known occurrence of continuous pyroCb activity over an entire 24 hr period (Phase #1)

Comparison with previous events

- All featured fewer than 10 pyroCb pulses
- Less than 24 hr duration
- 2017 PNE included 7 pulses, with ~4 contributing fires

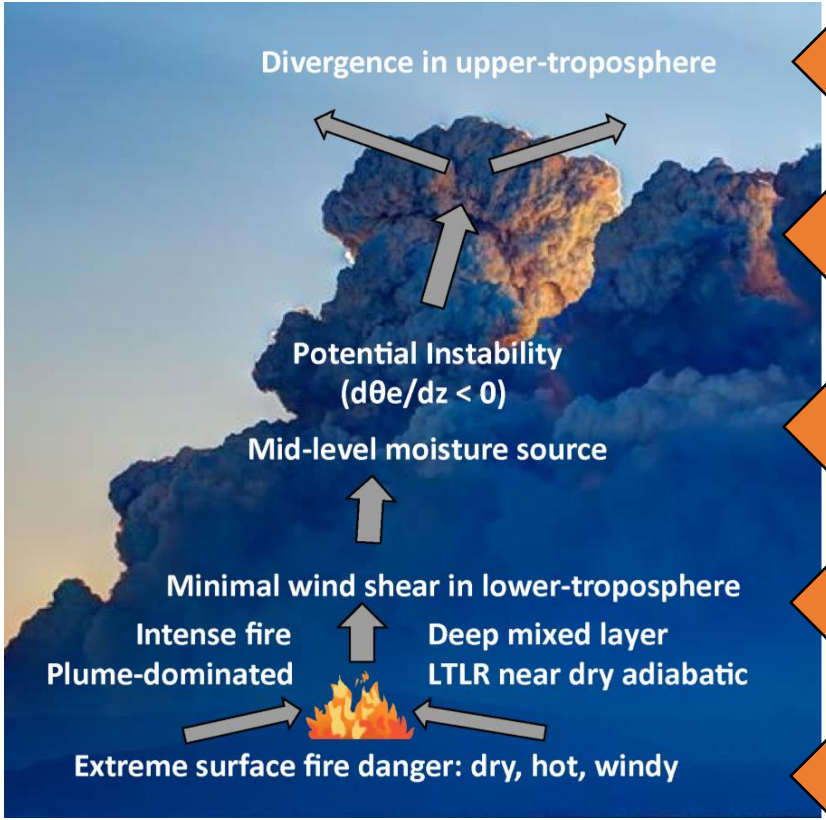
Meteorology Supporting a PyroCb Super Outbreak





- Both ANYSO phases developed as a strong high pressure began to weaken
- Ahead of an approaching low pressure trough and its associated low-level frontal boundary
- Favors a deep, dry, and unstable near-surface mixed layer surmounted by a moisture source and decreased stability in the mid-troposphere
- Approaching weather disturbances sustained conditions suitable for extreme fire and pyroCb activity well after sunset (e.g., Saide et al. 2015)
- ANYSO's first phase associated with anomalous and persistent transport of moisture in mid-troposphere
- Rapidly evolving synoptic weather features are a key factor limiting the duration of pyroCb outbreaks

Drivers of Stratospheric Smoke Composition: Unknowns



Peterson et al., 2017 (Mon. Wea. Rev)

- Photochemical reactions that influence ozone chemistry?
- What are the rules for secondary aerosol when precursors are way up here?
- Aerosol/gas phase chemistry of smoke plumes in the UTLS?
- How much liquid processing of particles?
- Characteristics of the contributing fire?