INjected Smoke and PYRocumulonimbus Experiment (INSPYRE)

White Paper for NASA Earth Venture Suborbital-4 (EVS-4)

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INSPYRE PI Team:

David Peterson (NRL-Monterey)	Principal Investigator
Neil Lareau (University of Nevada Reno)	Deputy Principal Investigator
Olga Kalashnikova (JPL, Caltech)	Deputy Principal Investigator

INSPYRE Management Team:

Will McCarty	Program Scientist
Ken Jucks	Program Scientist
Mike Falkowski	Program Applications Lead
Vidal Salazar	Investigation Manager (ESPO)

EVS-4 Management Team:

Barry Lefer	EVS-4 Program Scientist
Diane Hope	EVS-4 Mission Manager

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Executive Summary

The goals of the INjected Smoke and PYRocumulonimbus Experiment (INSPYRE) are to constrain the role of pyrocumulonimbus (pyroCb) in the warming climate system and characterize their physical links to extreme wildfire behavior. INSPYRE will test the hypothesis that:

Increasing wildfire size and intensity in a warming climate will amplify pyroCb-driven smoke injection into the stratosphere resulting in measurable changes in Earth's radiative balance.

INSPYRE will address three science questions that establish links and feedbacks between the physical processes enabling pyroCb initiation, smoke injection into the upper troposphere and lower stratosphere (UTLS), and downstream consequences:

1. Which fires produce pyroCbs and why?

Threshold: Use airborne measurements and modeling to transform understanding of the variables driving the transition from innocuous pyrocumulus (pyroCu) to dangerous pyroCbs, which is important for improved fire spread and smoke injection altitude modeling.

Baseline: Measure fire-generated winds in the lower-troposphere, including fire inflows and vortices that intensify fires and potentially trigger pyroCbs.

2. What mechanisms determine whether a pyroCb will inject smoke directly into the stratosphere, and what will be the magnitude of the ensuing plume?

Threshold: Measure processes governing smoke lofting in a given pyroCb, how it varies across the full spectrum of observed plume/fire scales, and what conditions are linked to stratospheric smoke injection to provide bounds on the stratospheric impacts expected in a warming climate.

Baseline: Examine potential secondary pathways for stratospheric smoke injection by comparing measurements of traditional storms with pyroCbs in similar environments. A collateral benefit will be improved pyroCb discrimination from space.

3. How do pyroCb-injected smoke plumes modify UTLS composition and radiation budget?

Threshold: Obtain measurements of aerosol properties, trace gasses, and radiative flux in pyroCb smoke for the active and nascent phases (first five days) that will refine assumptions currently employed in numerical modeling studies to constrain the role of pyroCb smoke plumes in the climate system.

Baseline: Measurements needed to understand potential secondary aerosol production after smoke injection into the UTLS and other aspects of plume chemical evolution, such as those associated with stratospheric ozone.

Investigation overview: INSPYRE requires sustained measurements and modeling of co-evolving fire and pyroCb processes including: fire energetics, plume development, pyroCb cloud properties, and smoke plume evolution. Measurements must span the spatial and temporal scales of pyroconvection ranging from non-pyroCb plumes, plumes capped by pyroCu, active pyroCbs, and downstream smoke in the UTLS.

Airborne science platforms: Achieving all threshold objectives requires the NASA ER-2 in combination with the WB-57. The ER-2 payload will include remote sensing instrumentation, while the WB-57 payload will prioritize *in situ* and radiation instrumentation, with a subset of remote sensing measurements.

Ground-based science platforms: Threshold science will be augmented with a baseline investigation that includes ground-based sampling platforms for a smaller sample of fires with the potential to produce pyroCbs, with the goal of filling a measurement gap at the lower portion of pyroconvective columns and obtaining measurements not feasible from aircraft (e.g., fully polarimetric radar). This sampling requires scanning radar and lidar remote sensors, along with other potential instruments (e.g., balloon sondes) to enhance baseline science.

Deployment sites: INSPYRE has flexibility to use multiple deployment sites in western North America based on pyroCb climatology, such as Palmdale, CA, Boise, ID, and Cold Lake, Alberta, which are expected to yield 2-20+ pyroCb events per year during a 6-8-week deployment and many additional large/intense fires. The INSPYRE PI and management teams are currently evaluating the suitability of several potential deployment sites across the western United States and Canada.

Schedule summary: Science deployments are planned for a July to early-September time window during 2026 (Year 1) and 2027 (Year 2). Pre-flight exercises are planned prior to the first deployment, along with two science team meetings. Significant time is devoted to post-flight data analysis and modeling in Years 3, 4, and 5, including annual science team meetings and open data workshops.

NASA relevance: INSPYRE will play a critical role in NASA's Earth Science to Action (ES2A) strategy, which aims to holistically observe, monitor, and understand the Earth system using the most advanced Earth observing capabilities in the world and deliver trusted information to drive Earth resilience activities. The interdisciplinary nature of INSPYRE addresses several "Targeted Observables" in the 2017 NASA Earth Science Decadal Survey: aerosol vertical profiles, aerosol and cloud optical and radiative properties, clouds, convection, and precipitation, greenhouse gases, and atmospheric winds. INSPYRE augments NASA's new and existing wildfire programs and the NASA Earth System Observatory.

This INSPYRE White Paper supersedes the content of a Technical Report that was published by the Naval Research Lab in June 2024: "An Airborne Field Campaign Concept for Studying Pyroconvective Storms and Adjacent Fire Plume Mechanics".

1 Science Goals and Objectives

The goals of the INjected Smoke and PYRocumulonimbus Experiment (INSPYRE, Fig. 1.1) are to constrain the role of pyrocumulonimbus (pyroCb) in the warming climate system and characterize their physical links to extreme wildfire behavior. INSPYRE will test the hypothesis that:

Increasing wildfire size and intensity in a warming climate will amplify pyroCb-driven smoke injection into the stratosphere and induce measurable changes to Earth's radiative balance.

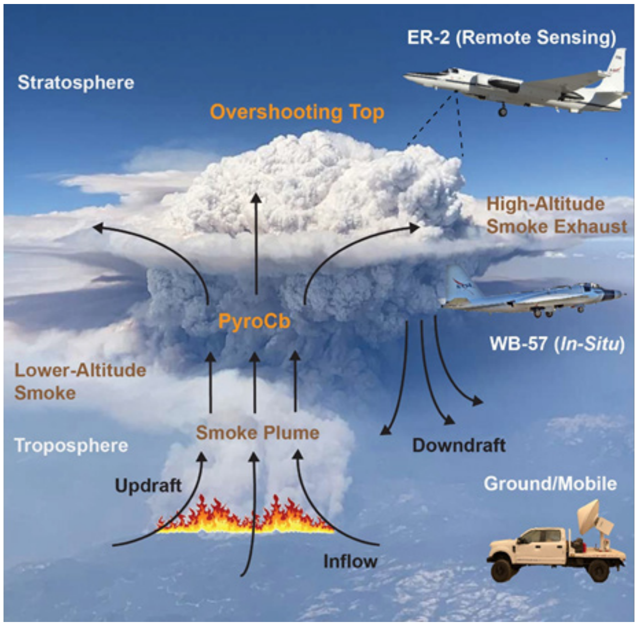

Fig. 1.1: INSPYRE overview, including NASA's ER-2, WB-57, and at least one ground-based platform that will provide remotely sensed and *in situ* measurements for the full spectrum of fire and pyroconvection from the surface to the stratosphere.

To test this hypothesis, we will employ NASA's ER-2 and WB-57 airborne platforms, along with ground-based platforms to obtain the remotely-sensed and *in situ* measurements required to quantify the processes leading to pyroCb development, the downstream consequences of pyroCb-injected smoke on the upper troposphere and lower stratosphere (UTLS), and feedbacks between pyroCbs and extreme fire behavior. Observations will span the full spectrum of wildfire and pyroconvective activity, ranging from precursor pyrocumulus (pyroCu) to large pyroCbs that inject smoke directly into the stratosphere, as depicted in Fig. 1.1.

1.1 Urgent Need for Sustained PyroCb Measurements

PyroCbs are a poorly-understood and inadequately-predicted severe weather phenomenon driven by large and intense fires and unique meteorological conditions. These fire-generated clouds are linked to extreme fire behavior that impedes firefighting efforts and can devastate communities [1, 2]. PyroCbs can also inject volcanic-scale smoke plumes into the stratosphere (Fig. 1.2) [3, 4, 5, 6, 7, 8] that encircle the globe, reside for more than a year, alter stratospheric circulations [9, 10, 11, 12, 13], extend the lifetime and size of the Antarctic ozone hole [14, 15, 16, 17], and affect Earth's radiative balance [18, 19, 20, 21]. **Given the ongoing and projected increases in fire activity and severity linked to a warming climate [22, 23, 24], there is an urgent need to better understand and predict climate- and fire-scale impacts from pyroCb activity.**

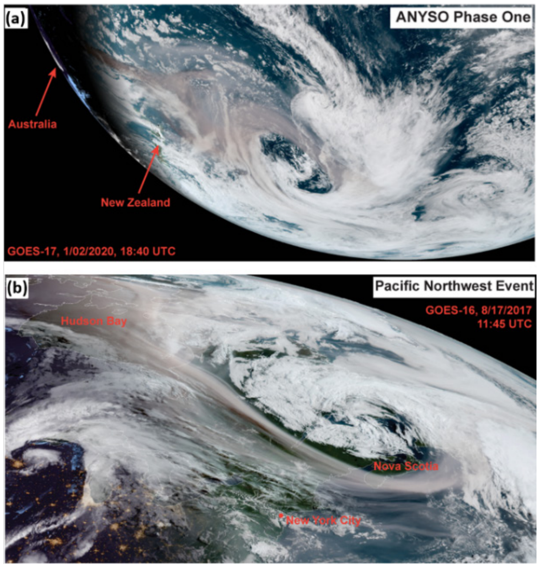

Fig. 1.2: True color imagery of the (a) ANYSO and (b) PNE pyroCb smoke plumes approximately 48 hr after injection into the stratosphere [4].

1.1.1 Climate-Scale Impacts

Recent pyroCb outbreaks in Australia (Australian New Year Super Outbreak; ANYSO) [4] and the Pacific Northwest Event (PNE) of North America [3] produced stratospheric smoke injections rivaling or exceeding the impacts of most volcanic eruptions (Fig. 1.3). Lower stratospheric plumes resulting from large pyroCb outbreaks can disperse in a manner consistent with nuclear winter theory, which is based on combustion from burning cities diabatically rising into the stratosphere and encircling the globe [25, 26, 27]. Yet, the ANYSO and PNE represent only a subset of the 546 pyroCbs occurring worldwide from 2013 to 2021 [7], which combined account for 10-25% of the black carbon and organic aerosols in the lower stratosphere [8].

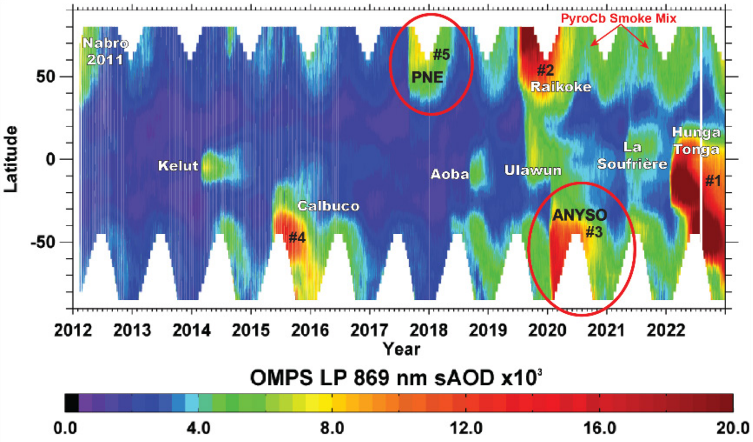

Fig. 1.3: Comparing ANYSO and PNE (red circles) with all significant stratospheric plumes observed during 2012–2022. Shading indicates daily Ozone Mapping and Profiler Suite (OMPS) Limb Profiler (LP) stratospheric aerosol optical depth (sAOD) [4]. White labels indicate volcanic plumes and black indicates pyroCb smoke plumes. Numbers rank the five largest plumes.

Dispersing pyroCb smoke particles (e.g., black carbon) absorb solar radiation, warming the layer where they reside (e.g., [27]), while concurrently cooling earth's surface [19, 21]. The warming aloft yields diabatic lofting of the smoke layer that opposes the mean downward motion of the UTLS Brewer–Dobson circulation [28] and generates anomalous anticyclonic circulations via diabatic destruction/generation of potential vorticity (Fig. 1.4) [9, 10, 11, 12, 13]. As anticyclonic anomalies move upward from the reduced ozone environment in the UTLS, they displace ozone at higher altitudes [10, 11]. On a longer time-scale, pyroCb smoke also depletes stratospheric ozone via heterogeneous chemical reactions on smoke particle surfaces [14, 15, 17, 29, 30, 31]. **Given the scale of these impacts, pyroCbs must be considered as a first-order driver of variations in stratospheric composition and structure. Yet, the community presently lacks the capacity to predict which fires will produce pyroCbs, how much smoke a given pyroCb will inject in the UTLS, and how this smoke alters the Earth's radiative balance.**

1.1.2 Fire-Scale Impacts

PyroCb initiation poses an immediate threat to firefighters and civilians [32], which impedes containment efforts, thereby contributing to increases in fire size and intensity. PyroCb threats include fire-generated tornadoes [1, 2], lightning capable of igniting new fires [33], downdrafts impacting fire spread [7], hail [34], long-range spotting and ember storms [35, 36], and extreme updrafts that threaten fire suppression airtankers and other aircraft unaware of this phenomenon [37]. While recent advances facilitate identification of the synoptic and thermodynamic conditions conducive to pyroCb development with even several days of lead time [38, 39, 40], these approaches only narrow down what regions and fires are candidates for pyroCb development. Significant understanding and modeling gaps still exist at the fire- and convective-scales related to a poorly-observed

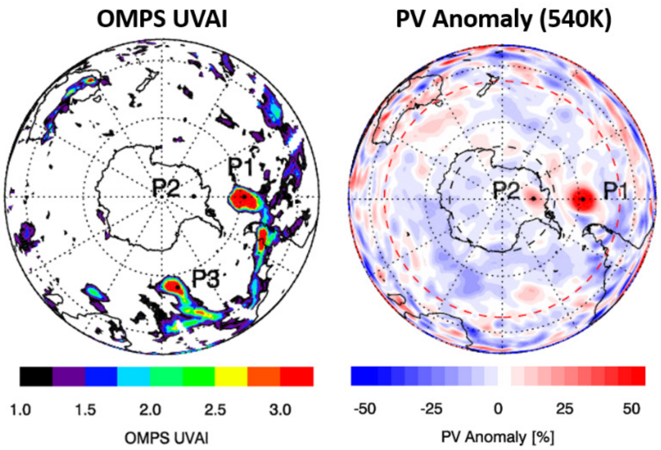

Fig. 1.4: Impact of the large ANYSO smoke plume on meteorology in the Southern Hemisphere stratosphere on 20 Jan 2020 [9]. Left panel displays ultraviolet aerosol index (UVAI) from OMPS, highlighting the locations of three smoke-induced circulation anomalies (P1-P3). Right panel displays potential vorticity (PV) anomalies at a potential temperature surface of 540K, intersecting the altitude of two smoke-induced circulations (P1, P2). P2 was too far poleward form OMPS to observe.

feedback loop coupling fire intensity, updraft dynamics, and moist-convective initiation that yields pyroCbs. **Improved characterization of the processes driving pyroCb initiation is therefore a critical goal for fire management and public safety [7].**

1.1.3 Observational and Modeling Gaps

Despite growing awareness of pyroCbs as drivers of extreme wildfire behavior and climate-altering smoke plumes, process-level measurements and modeling of pyroCb dynamical structure and ensuing UTLS impacts are almost completely lacking. The phenomenon itself was only first introduced to the community within the last 20 years [41]. Satellite observations of pyroCbs are currently used in prototype detection capabilities [42], but they do not resolve co-evolving fire and atmospheric processes leading to pyroCb initiation. These observational gaps are compounded by inadequate parameterization of fire, plume, and pyroCb processes in weather and aerosol/chemistry transport models (e.g., HRRR-Smoke). Even coupled fire-atmosphere models (e.g., WRF-SFIRE) suffer from uncertainties in fire spread and fuel consumption, translating into uncertainties in plume rise and pyroCb development. Worse still, most climate models simply do not represent pyroCbs and their smoke injections, leaving gaps in scientific understanding of their climate-scale, radiative impacts. Regardless of modeling approach, there are presently no comprehensive observational datasets suitable for model evaluation, validation, and refinement related to the pyroCb phenomenon.

1.1.4 Ideal Time for INSPYRE

Given the emerging recognition of climate- and fire-scale impacts from pyroCbs and potential amplification of these processes in a warming climate, the measurements and associated modeling that INSPYRE will provide is critically needed for:

- Understanding plume dynamics linked to high-intensity fire behavior and pyroCb development;
- Quantifying the impact of pyroCb smoke on regional and global-scale radiative forcing;
- Including pyroCb dynamics and ensuing smoke plumes in current Earth System Models;
- Improving fire and pyroCb monitoring from space; and
- Advancing forecasts of pyroCb development for fire managers and community safety.

INSPYRE will build from the recent FIREX-AQ [43], RaDFIRE [44a], and CalFiDE [44b] experiments, which provided first-of-their-kind sampling of dynamical, microphysical, and chemical processes in the upper and lower portions of active pyroCbs. Proceeding from these limited “snap shots”, INSPYRE will provide (1) contextualization via systematic sampling spanning the full spectrum of pyroconvective activity (Fig. 1.5), including larger pyroCbs that inject smoke directly into the lower stratosphere [3, 4], and (2) contemporaneous fire and plume/pyroCb observations capable of establishing coupling and feedbacks between fire processes and atmospheric circulations that make UTLS smoke injection possible.

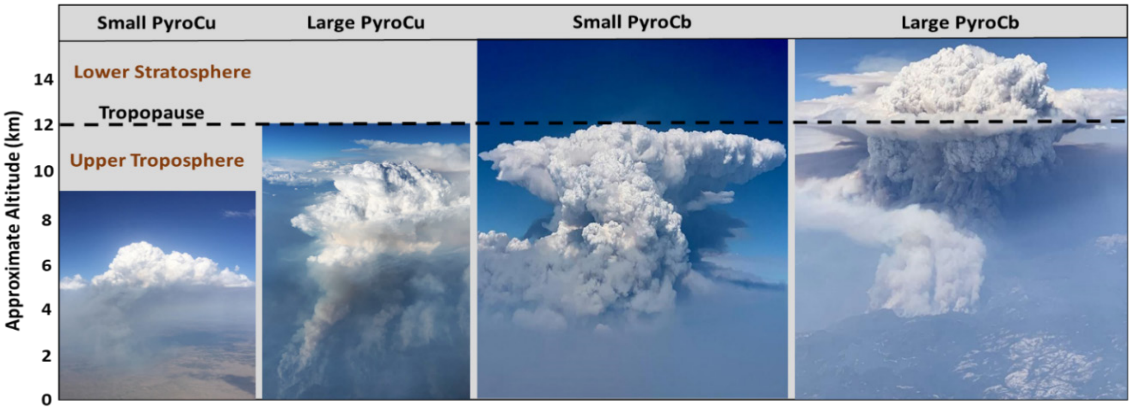

Fig. 1.5: Full spectrum of pyroconvective activity and smoke injection altitudes targeted by INSPYRE.

1.2 Science Questions and Objectives

To test INSPYRE's central hypothesis, we will address three primary science questions that establish links and feedbacks between the physical processes enabling pyroCb initiation, stratospheric smoke injection, and downstream consequences of these injections. The science objectives supporting these questions are separated into threshold (minimum acceptable science) and baseline (needed for a detailed scientific examination). Details and priorities for the corresponding measurements and model simulations are provided in Appendices 1-2.

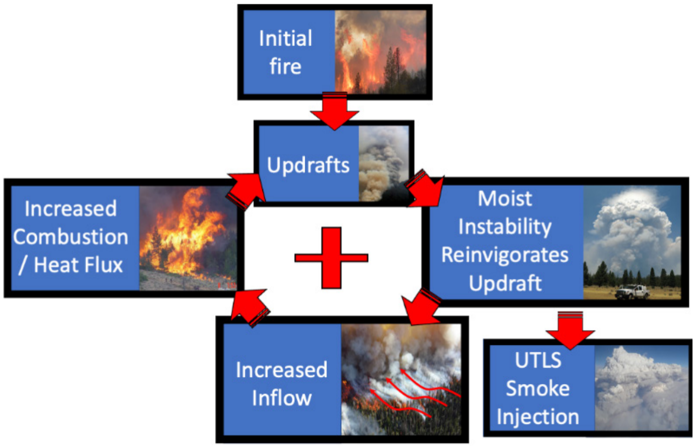

Fig. 1.6: Conceptualized pyroCb feedback loop.

Question 1 (Q1): Which fires produce pyroCbs and why?

To understand how a warming climate will amplify smoke injection into the UTLS, we first need to identify which fires produce pyroCbs. This requires filling gaps in understanding of the process-chain coupling fire intensity, updraft dynamics, and moist-convective initiation. The components of this conceptualized feedback loop for an existing fire with a developing convective column (Fig. 1.6) are:

1. The plume deepens to the condensation level where latent heat release aloft triggers moist instability in the pyro-cloud and reinvigorates the fire's updraft [45, 46];
2. Increased meso-scale inflows near the surface [2] that compensate for increased updraft mass flux;
3. Increased fuel consumption and the onset of mass fire [47] due to the increase in near-surface inflow, which in turn;
4. Yield stronger and broader fire-generated updrafts, and the continued upscale growth of moist convection aloft, resulting in UTLS smoke injection.

Evidence of these "strong and wide" updrafts is provided in Fig. 1.7, which shows radar-observed kilometer-wide updraft cores with speeds of 60 m s^{-1}. Such updrafts rival those in Earth's strongest thunderstorms and hint at the dynamics enabling deep pyroconvection and direct stratospheric injection.

Each step of the feedback loop varies according to a diverse set of fire and atmospheric environmental properties, including sensitivity to fire size and geometry [48, 49], fuel consumption and resulting heat release rates, ambient thermodynamic and wind profiles [38, 40, 50], updraft structure [37], and cloud microphysical processes [45, 46, 51]. The magnitude and sign of feedbacks amongst these processes may vary across different fire and

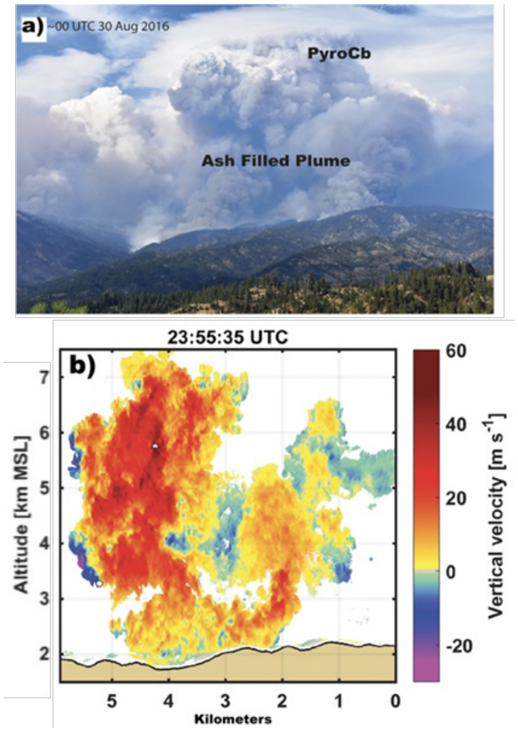

Fig. 1.7: Example of airborne radar (w-band) observations during the Pioneer Fire pyroCb event (2016), revealing extreme updraft speeds [37].

atmospheric environments, yielding multiple pathways to pyroCb development. **The measurements and modeling required to address Q1 (Appendices 1-2) are expected to transform understanding of plume dynamics linked to high-intensity fire behavior, particularly the variables driving the transition from innocuous pyroCu to dangerous pyroCbs, all of which are critically important for developing improved smoke injection altitude parameterizations in numerical modeling applications.**

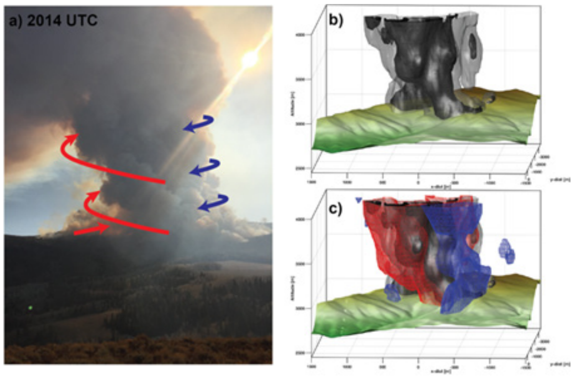

Fig. 1.8: Example Doppler lidar measurements of rotation and inflow winds at the base of a pyroCb-topped plume. (a) Photograph showing anticyclonic rotation. (b) Lidar attenuated backscatter showing plume structure. (c) Out- (red) and in-bound (blue) radial velocity on top of backscatter isosurfaces.

Q1. Threshold Science Objectives:

Airborne measurements and modeling will constrain process uncertainty and co-evolution over the spectrum of fire behavior and environmental conditions that facilitate pyroCb development (Fig. 1.5). This includes infrared (IR) remote sensing of fire processes, such as fire size, distribution, and intensity (e.g., 4 µm brightness temperature, fire-radiative power (FRP), etc.), which must be linked to radar and lidar observations of plume structure, microphysics, and updraft properties. Airborne mm-to-cm wavelength radars (Fig. 1.7) are well suited to measure these plume-kinematic processes (e.g., Doppler velocity in a nadir pointed beam), 3D plume structures (e.g., cross-track or conical scanning radar), and can infer moist processes via polarimetric quantities (e.g., linear-depolarization ratio, correlation coefficient, etc.). Additional measurements, such as pyroCb-induced electric fields and lightning occurrence and polarity will better characterize the moist dynamics of these storms. Finally, these fire and plume processes must be contextualized with *in situ* and/or remotely-sensed (e.g., sounders) thermodynamic profiles near each fire, including stability, moisture content, condensation, and glaciation levels. This suite of observations will resolve the majority of processes in the feedback loop (Fig. 1.6). Coupled-fire atmosphere modeling, driven by observed fire-processes (e.g., forced with IR data), will also help to more-fully constrain components of the feedback loop and process chain such as entrainment and detrainment from the pyrocloud aloft.

Q1. Baseline Science Objectives

Threshold science will be augmented with a baseline investigation that includes ground-based measurements of plume dynamics and vertical profiles of thermodynamic conditions, boundary layer structure, aerosol particle properties, and trace gasses. Recent ground-based instrument deployments (Fig. 1.8) demonstrate the feasibility of obtaining these measurements proximal to pyroCb producing fires [44a, 50, 52, 53]. For example, ground-based scanning Doppler radar and lidar will measure fire-generated winds, including inflows and vortices that are known contributors to high intensity fires and potential triggers for pyroCb [2]. Polarimetric radar observations can differentiate between pyrometeor (ash and debris) and hydrometeor (cloud droplets, graupel, ice, etc.) distributions within pyroCu/Cb topped plumes. Scanning lidars can quantify the cloud base height within plumes and also resolve aspects of the convective boundary layer (CBL) structure proximal to large fires. **When coupled with airborne IR observations, these baseline data will establish links between coevolving fire processes and inflow winds during large wildfires, thereby establishing feedbacks between pyroCb and near-surface processes.** Do to remoteness of some of the fires sampled during INSPYRE, these ground-based measurements will only be available for a subset of fires, likely those in the western US where road networks provide better access to fires.

Question 2 (Q2): What mechanisms determine whether a pyroCb will inject smoke directly into the stratosphere, and what will be the magnitude of the ensuing plume?

Q2 will isolate the subset of mechanics yielding direct stratospheric smoke injection. This distinction is necessary because pyroCb injection altitudes span a range of 8-18 km worldwide, with the majority of injected smoke near the tropopause (Fig. 1.9; 235 events, 47%) and only a subset of injections more than one kilometer into the stratosphere (103 events, 20%) [54]. Estimated aerosol mass in these plumes spans four orders of magnitude, which has significant implications for climate-scale radiative effects.

While pyroCb climatology and conceptual modeling are informative, it is unclear why only some pyroCbs produce large plumes in the UTLS and others are much smaller. Uncertainties are related to:

- The amount and rate of fuel consumed by the fire, which varies directly with fire intensity [55];
- The updraft mass flux;
- Aerosol-cloud interactions and suppression of precipitation [56];
- The penetration altitude above the tropopause, which varies with updraft dynamics and the stability profile in the UTLS; and
- Events with multiple pulses of pyroCb activity (23% of the climatology), which likely influence the overall magnitude of ensuing smoke plumes.

Q2. Threshold Science Objectives:

INSPYRE will measure the key processes governing "smoke uplift efficiency" within a given pyroCb, how it varies across the full spectrum of observed pyroCb scales, and what conditions are closely linked to stratospheric smoke injection. For example, airborne infrared and multi-spectral remote sensing will examine changes in fire expanse and intensity, and thus the "fire-power" ingested by the atmosphere. Airborne radar and lidars on high altitude aircraft will document contemporaneous changes in plume and pyroCb depth and breadth (radar echo tops, lidar backscatter), updraft magnitude (radar Doppler velocity), and elements of the plume's microphysics linked to the latent heating and hydrometeor development (e.g., glaciation of cloud tops). These plume observations must be contextualized with observations of the tropospheric and tropopause structure, including variations in stability, humidity, and wind. Similar overall sampling approaches were demonstrated during FIREX-AQ (Fig. 1.10) [43]. *In situ* measurements (Appendix 1) will then quantify the amount of smoke gas phase and particle pollution (e.g., smoke size and number distributions) and cloud microphysical properties in the upper portion of each pyroCb and how these variables compare with previous studies of lower-altitude smoke (e.g., FIREX-AQ). **These measurements will provide critical bounds on how stratospheric smoke injections from pyroCb activity will change under the fire weather regimes expected in a warming climate.**

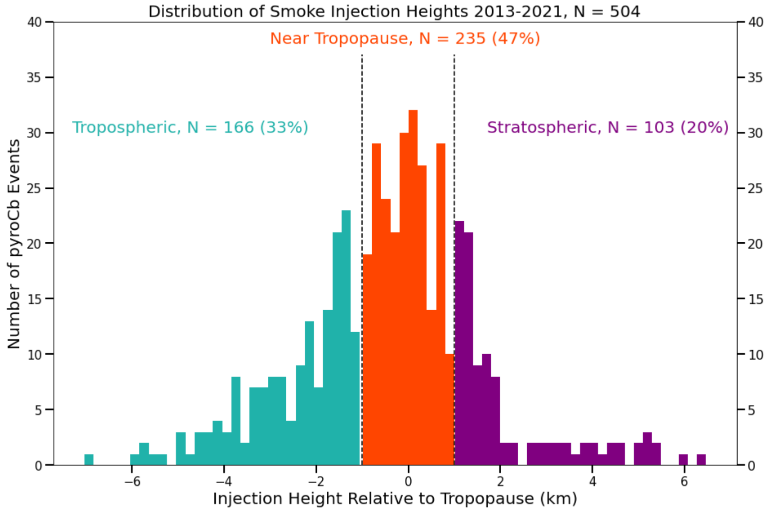

Fig. 1.9: Smoke injection altitude relative to the tropopause for a subset of global pyroCb climatology for 2013-2021 [54].

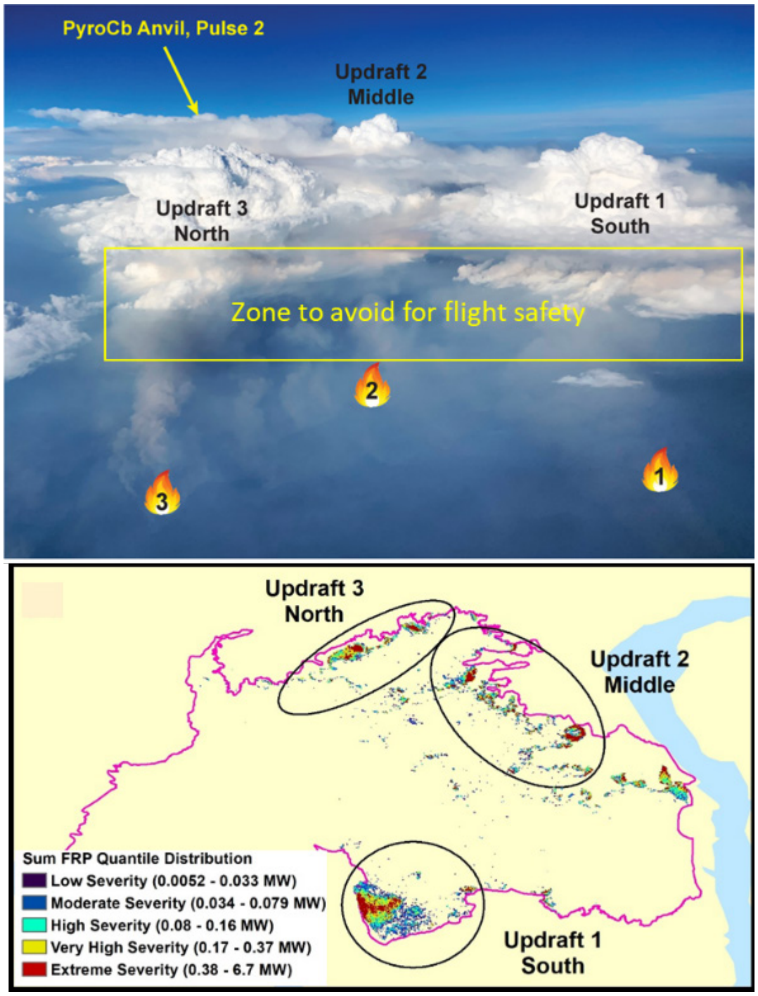

Fig. 1.10: (Top) DC-8 cockpit view of pyroCu/pyroCb activity over three Williams Flats fire updraft regions on 9 Aug 2019. (Bottom) Corresponding MASTER fire radiative power (FRP) data distributed into quintiles, representing the instantaneous energy released from the fire at the overpass time.

Q2. Baseline Science Objective: Are there secondary pathways for stratospheric smoke injection?

Stratospheric smoke plumes have also been attributed to transport pathways independent of direct pyroCb injection, including synoptic weather features and traditional thunderstorms [7, 57, 58, 59]. The thunderstorm pathway is most prominent in recent literature, involving environmental smoke being drawn into the storm and exhausted aloft in a manner analogous to "ordinary" pollution transport into the stratosphere (e.g., DCOTSS and ACCLIP). We hypothesize that secondary-smoke transport pathways are less efficient than the direct pyroCb injection, and contribute much less to stratospheric aerosol loading. For example, we expect traditional thunderstorms ingesting environmental smoke to exhibit weaker aerosol-cloud interaction (Twomey effect; e.g., [56]) compared with more polluted pyroCbs, thereby increasing precipitation scavenging that will ultimately reduce smoke uplift efficiency [60]. A baseline INSPYRE investigation will include sampling focused on these traditional storms to obtain the same set of remotely-sensed and *in situ* measurements described above for pyroCb activity. Opportunities for these comparisons are expected due to the overlap in conditions yielding pyroCbs and traditional high-based dry thunderstorms [38], such that both phenomena are often observed simultaneously [3, 61]. **These comparisons provide the collateral benefit of improved spaceborne detection and characterization of pyroCb activity [42].**

Question 3 (Q3): How do pyroCb-injected smoke plumes modify UTLS composition & radiation budget?

While Q1 and Q2 establish the links between fires and UTLS smoke injection, Q3 investigates the consequence of these injections in the climate system. Earth System Modeling suggests pyroCb smoke causes persistent stratospheric warming (e.g., 1-2 K over 6 months) and surface cooling comparable to major volcanic events [18, 19, 20, 21]. However, these estimates are highly uncertain because the radiative properties (e.g., radiative flux divergence) and composition of pyroCb smoke plumes and smoke-filled anvil clouds have not been measured. This observational deficit limits current understanding of diabatic heating, smoke self-lofting, and ensuing effects on UTLS circulation [7], not to mention an entire swath of chemical reactions and ozone impacts.

Constraining Earth System impacts of pyroCb plumes requires remote sensing (e.g., lidar and polarimeter) and in-situ measurements characterizing aerosol composition, concentration, size distributions, and absorption properties. The ratio of black carbon (BC) to organic carbon (OC) is critically important. BC absorbs UV through IR radiation efficiently (e.g., [62]) and thus yields strong warming. OC also represents a significant absorbing species in the UV, but with less impact at longer wavelengths. Without direct measurements, recent pyroCb smoke radiative forcing studies have used a wide range of BC/OC values (2%–6% BC by mass) based on comparing model simulated diabatic plume rise with satellite observations [19, 20, 21, 27]. The few existing measurements of pyroCb smoke in the UTLS indicate that freshly emitted BC particles in pyroCb plumes are rapidly coated with organics and, over time, grow ten times or more in mass, reaching hundreds of nanometers in radius [8, 63, 64]. This unique pyroCb smoke particle size trajectory has significant implications for accurate modeling of pyroCb smoke plumes in the UTLS.

Recent studies have focused on pyroCb plumes observed weeks-to-months after UTLS injection. The radiative properties of the nascent plume phase (hours to days after injection) are almost completely unconstrained. This period involves a mixture of fresh smoke and residual ice particles, which gradually sublimate in the dry UTLS. Smoke-filled cirrus anvil clouds are known to persist longer than their traditional counterparts [65]. It is important to understand how these young pyroCb plumes perturb UTLS thermodynamics, which requires measurements of all particle types present in the anvil and post-ice smoke plume. These measurements are also essential for improved spaceborne detection of pyroCb activity with potential to inject significant smoke mass into the stratosphere [42].

Q3. Threshold Science Objectives: Particle Properties, Radiative Flux, and Basic Composition

INSPYRE will obtain critical measurements related to the radiative properties of pyroCb smoke for the active and nascent phases of the plumes (e.g., first five days), across as much of the spectrum as possible, including the UV. Emphasis will be placed on both aerosol and ice particles, spanning the range of pyroCb injection altitudes and smoke plume magnitudes available to the experiment. BC concentration and evolution will be quantified, along with measurements of mass extinction efficiency, which are essential for constraining satellite-derived estimates of pyroCb-injected smoke particle mass [3, 4, 6, 66]. INSPYRE will also make direct radiative flux measurements with broadband radiometers above and below nascent pyroCb smoke plumes and anvil clouds [67, 68], thus directly measuring the radiative flux divergence and corresponding heating rates. Additional space on the airborne platforms will be used for additional measurements of aerosol properties, along with basic aerosol and gas phase composition. INSPYRE will target repeat-sampling of the same pyroCb plume to understand its evolution over timespans of hours (same flight) to days (multiple flights). **These data will validate and refine critical assumptions currently employed in numerical modeling studies to ultimately understand the role of pyroCb smoke plumes in the climate system, with an emphasis on radiative forcing and its impact on dynamic circulation in the stratosphere.**

Q3. Baseline Science Objective: Detailed Plume Composition

A baseline INSPYRE investigation will prioritize measurements needed to understand potential secondary aerosol production after smoke injection into the UTLS (e.g., [64]), which is likely a key factor influencing changes in smoke plume mass and evolution during the weeks and months following a large pyroCb event. Observations of other aspects of plume chemical evolution, such as those associated with stratospheric ozone [14, 15, 17, 29, 30, 31], present additional scientific opportunities, depending on platform space and budget constraints.

2 Approach for Addressing INSPYRE Science Questions

Addressing INSPYRE science questions requires sustained airborne measurements, targeted ground-based observations, and process-level modeling of co-evolving fire and pyroCb processes including fire energetics, plume development, pyroCb cloud properties, and smoke plume evolution. Measurements must span the spatial and temporal scales of pyroconvection, ranging from non-pyroCb plumes, plumes capped by pyroCu, active pyroCbs, and downstream smoke processes in the UTLS (Fig. 1.5). Threshold science objectives require airborne infrared remote sensing of fire process and radar and lidar observations of plume processes (Fig. 1.7), as well as *in situ* sampling of smoke composition, radiative processes, and cloud microphysics in the upper portions of pyroCu/Cb. Additional baseline objectives require ground-based measurements of active wildfires. The INSPYRE Science Measurement Requirement Matrix in Appendix 1 provides priority ratings and corresponding performance requirements for all measurement types and platforms.

2.1 Synergy of Measurements and Modeling

INSPYRE will leverage a range of numerical models capturing different aspects of pyroCb science at different scales. The measurement components of INSPYRE will make extensive use of fire-scale (e.g., 100 m, large-eddy resolving simulations) coupled fire-atmosphere models, trajectory models, and regional composition and transport models to derive flight plans and target data collections (Sec. 5.3). Coupled fire-atmosphere modeling will enable process-based, sensitivity, and predictability experiments for Q1 and Q2 that allow INSPYRE to examine a larger portion of the parameter space than is available in observations alone. The science analysis for Q3 will make use of composition and transport models, including full coupling between composition, chemistry, radiation, and dynamics. INSPYRE will measure all parameters required for initialization of pyroCb smoke plumes in aerosol transport, chemistry, and climate models. INSPYRE will also serve as a testbed for pyroCb-specific prediction applications derived from satellite observations and numerical weather prediction (NWP) [38, 39, 40]. The outcome of INSPYRE will be an improved understanding of pyroCb phenomena that can be used to improve the fidelity of these and many other Earth System Models. The Modeling and Forecasting Requirement Matrix (Appendix 2) prioritizes modeling needs.

2.2 Scientific Measurement Platforms

Drawing on recent successes with airborne and ground based pyroCb sampling during FIREX-AQ, RaDFIRE, CalFiDE, FASMEE, and DCOTSS [43, 44a, 44b], INSPYRE will employ the NASA ER-2 and WB-57 airborne science platforms in combination with one or more ground-based platforms (Fig. 1.1). The ER-2 payload will include remote sensing instrumentation, while the WB-57 payload will prioritize in situ and radiation instrumentation, with a subset of remote sensing measurements. Both platforms are required to address the threshold science objectives outlined in Q1-Q3. Ground based measurements from deployable remote sensors proximal to large fires are required to meet baseline objectives for Q1 and Q2. Depending on sampling objective, these platforms will operate in coordination at the same fire or separately. For example, if the WB-57 is focused on *in situ* and radiation measurements of UTLS smoke, the ER-2 can maintain critical remote sensing capabilities for an active pyroCb event or sample a separate fire. When possible, both aircraft will coordinate with ground-based assets, which may also occasionally operate independently for suitable fires. Details of potential flight plans are provided in Sec. 5.2.

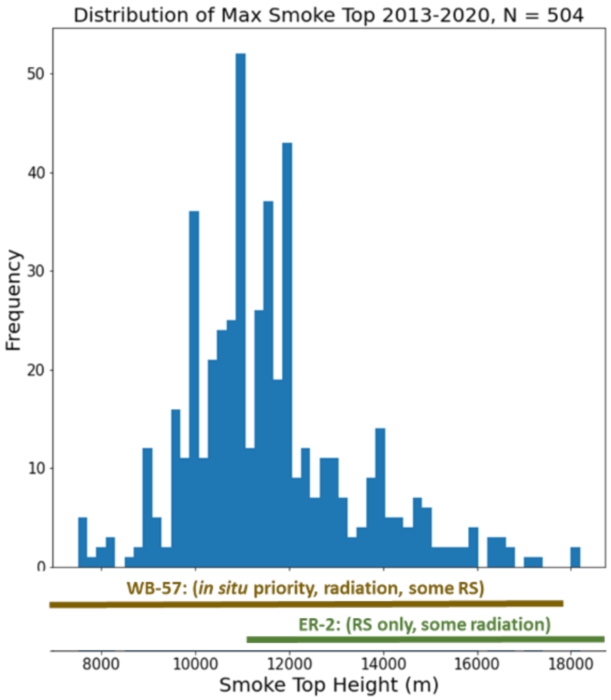

Fig. 2.1: Distribution of pyroCb maximum smoke injection altitudes for 2013-2021 [54] compared with the expected vertical sampling ranges of the ER-2 and WB-57.

2.2.1 ER-2: Airborne Remote Sensing

The ER-2 will serve as a "steerable satellite" flying at an operational altitude of ~20 km, which is above the majority of pyroCb smoke injection altitudes expected (Fig. 2.1). The instrument payload for the ER-2 will include high-altitude radars and lidar systems to observe plume processes (e.g., updraft width and magnitude, plume top heights, etc.), infrared and multi-spectral observations of fire processes (e.g., fire-line geometry, FRP), multi-spectral or hyperspectral VIS-IR imager for providing visual context and smoke optical depth, sounder for thermodynamic profiles, polarimeter for aerosol properties, and instrumentation that provides other measurements of relevance, such as for lightning/electric field and radiative flux (Appendix 1, Table 1). ER-2 has a well-established track record with a remote sensing payload, which was demonstrated during the recent FIREX-AQ and IMPACTS campaigns. INSPYRE will use the ER-2 in its high-altitude sampling mode, flying straight and level for most of the fights. However, this platform will also be capable of providing measurements of radiative flux divergence using broadband radiometers for UTLS smoke layers, which may occasionally require flights at multiple altitudes, as described in Sec. 5.2.3.

2.2.2 WB-57: Airborne In-Situ and Radiation

The WB-57 will provide *in situ* measurements of cloud microphysical processes, aerosol properties, trace gasses, and state variables needed to characterize the environment in which pyroCbs form (Appendix 1, Table 2). Its payload will include cloud probes, aerosol and gas phase instrumentation, meteorological sensors, and a subset of remote sensors, such as an upward and downward pointing lidar. Additional remote sensing packages including radars and thermal imagers may be included if funds and payload requirements allow. Cloud sampling will be conducted in the upper portions of pyroCu/Cb and anvil clouds, but not in hazardous updraft cores. Measurements of radiative flux divergence using broadband radiometers (SW and LW) to address Q3 will be prioritized on the WB-57 due to its flexible flight altitude sampling and collocation with *in situ* cloud probe and aerosol measurements. The WB-57 will operate within most of the expected smoke injection altitude distribution (Fig. 2.1), but it provides a shorter flight duration and range than that of the ER-2.

2.2.3 Ground-Based Science Platforms

Ground-based sampling platforms (Appendix 1, Table 3) will enhance baseline science for a smaller sample of fires with the potential to produce pyroCbs, with the goal of filling a measurement gap at the lower portion of pyroconvective columns and adding measurement capabilities not available from airborne sensors (e.g., polarimetric radar data). This sampling will use scanning radar(s) and lidar(s) remote sensors to observe wildfire plume structure (Q1), fire-generated winds (Q1), and polarimetric properties of pyroCu and pyroCbs (Q1, Q2). Lidar(s) will also provide observations of convective boundary layer structure (e.g., mixing depth, wind profiles, etc.) proximal to large wildfires. Balloon launches may be used, when safety conditions allow, to obtain additional baseline thermodynamic and aerosol profiles. Ground-based sampling draws on recent successes of research teams in obtaining similar measurements during active pyroCb development in the western US (Fig. 1.8). Coordination with deployable and fixed composition instrument networks (e.g., AERONET and MPLNET) will also be facilitated. Sites in the western U.S. are already being scouted to support the study of wildfire smoke. Ground based crews collecting observations proximal to large fires will require fire-line qualifications or other approaches for maintaining team safety.

2.3 Study Region based on PyroCb Climatology

PyroCbs are a significant and endemic feature of the regional summer climate in several highly fire-prone regions of the world [7, 38]. PyroCb climatology reveals that 546 events occurred worldwide during the nine-year period of 2013-2021, with annual totals ranging from 44 to 100, primarily driven by fires in the western United States and Canada (Fig. 2.2) [7]. These two regions are also the primary contributors to total pyroCb activity injecting smoke near and above the tropopause [54]. **Western North America is therefore an ideal region for an intensive study of pyroCb activity and ensuing impacts.** Details on potential deployment sites are provided in Sec. 5.1.

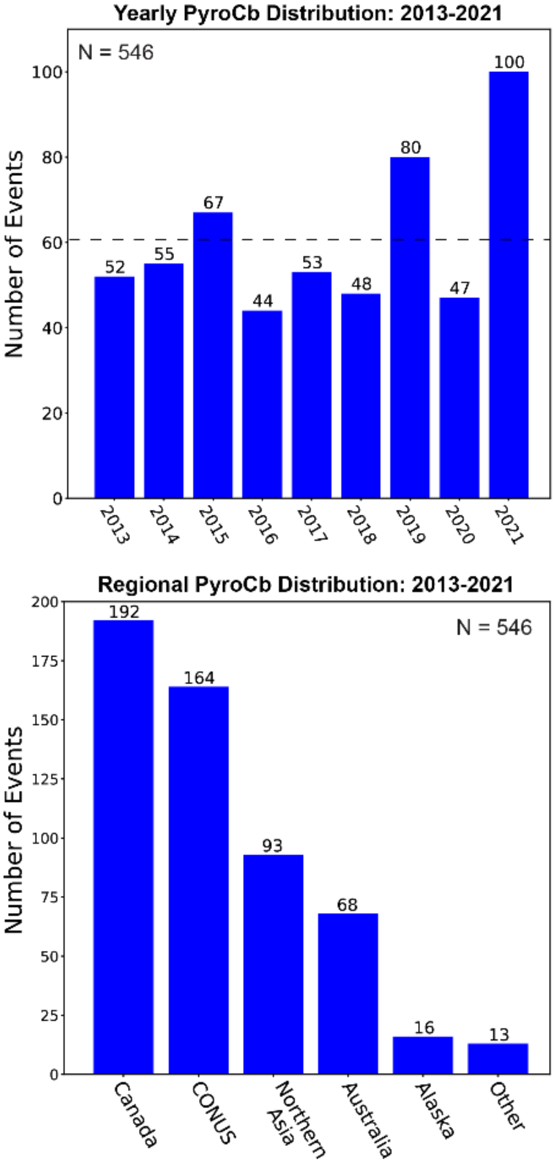

Fig. 2.2: Distribution of worldwide pyroCb activity by year and region for the period of 2013-2021. Both plots include 546 pyroCb events. The mean yearly pyroCb total (61) is displayed as a dashed line.

3 Relevance to NASA's Earth Science Goals

INSPYRE will play a critical role in NASA's Earth Science to Action (ES2A) strategy, which aims to holistically observe, monitor, and understand the Earth system using the most advanced Earth observing capabilities in the world and deliver trusted information to drive Earth resilience activities. INSPYRE will use cutting-edge instrumentation technology to produce integrated and trusted Earth system datasets that are expected to yield many scientific breakthroughs to better understand the role of extreme wildfires and pyroconvection in a warming climate system.

INSPYRE observations of the coupled Earth-surface, fire, and atmospheric system are responsive to NASA's goal of understanding the complexity of the global Earth system. INSPYRE's research falls under Strategic Objective 1.1 in the 2022 NASA Strategic Plan: "Understand the Earth system and its climate", with direct relevance to the following focus areas: Atmospheric Composition, Weather and Atmospheric Dynamics, Climate Variability and Change, and Carbon Cycle and Ecosystems. It directly addresses a longstanding NASA objective to improve understanding and predictive capability for changes in climate forcing and air quality associated with changes in atmospheric composition.

3.1 Value to Advancing NASA's EVS-4 Earth Science Objectives

INSPYRE will advance the three Earth Science Objectives in Section 1 of this EVS-4 program:

1. *Acquiring measurements that address weaknesses in current Earth system models, leading to improvement in modeling capabilities and accuracy:*

INSPYRE data sets will enable evaluation and refinement of emerging models for pyroCb initiation [40], modeling of UTLS smoke plumes, chemical transport, and climate impacts (e.g., [19, 27]), coupled fire-atmosphere models (e.g., WRF-SFIRE), and advances in space-based pyroCb detection [42]. These measurements will facilitate future pyroCb prediction and warning capabilities, ultimately mitigating impacts on firefighting efforts and communities in the wildland-urban interface. These measurements will target the principal source of missed smoke events in a variety of modeling applications, producing an immediate and substantial impact on many research communities.

2. *Producing data sets that identify and characterize important phenomena and/or detecting and characterizing changes in the Earth system:*

INSPYRE will provide the first opportunity to systematically connect meteorology, fire-line geometry, and fire radiative power to pyroCu development, transition to pyroCb, and related cloud-property evolution, including information on the ensuing smoke exhaust in the UTLS. These data are essential for understanding the role of extreme wildfires and pyroCbs in the warming climate system.

3. *Making measurements that contribute to the scientific goals of multiple Earth science focus areas and/or disciplinary programs:*

The observations and analyses needed to answer the INSPYRE science questions requires a multidisciplinary team, fusing meteorology, remote sensing, aerosol-climate, fire science, and multi-scale numerical modeling. The primary "Earth Science Division Focus Area" of INSPYRE is "Weather and Atmospheric Dynamics" with secondary focuses in both "Atmospheric Composition" and "Climate Variability and Change". The interdisciplinary aspect of pyroCb and wildfire science provides relevance to many sub-elements of these focus areas, including Upper Atmosphere Research, Tropospheric Composition, Radiation Sciences, Atmospheric Composition Modeling and Analysis, Atmospheric Dynamics and Precipitation Science, and Modeling, Analysis, and Prediction.

3.2 Relationships between INSPYRE, the NASA Decadal Survey, and other Programs

INSPYRE is directly relevant to several "Targeted Observables" identified in the 2017 NASA Earth Science Decadal Survey as necessary to support priority science and applications objectives: aerosol vertical profiles, aerosol and cloud radiative properties, clouds, convection, and precipitation, greenhouse gases, and atmospheric winds. INSPYRE has direct relevance to NASA's new and existing wildfire programs. INSPYRE is complementary to, but distinct from, NASA's FireSense initiative and FireTech funding opportunities (e.g., A.53 NSPIRES 2022). INSPYRE is also directly relevant to the new NASA Earth System Observatory, especially the following focus areas: *Aerosols and Cloud, Convection, and Precipitation*. INSPYRE compliments and builds upon the results of other NASA funded activities, such as the recent FIREX-AQ and DCOTSS programs. Data collected during INSPYRE will be an important contribution to several focus areas targeted in previous NASA solicitations, such as “High-Impact Natural Hazards”, “Constituents in the Climate System”, and “Extremes in the Earth System”.

4 Baseline and Threshold Science Requirements

Threshold Science Requirements are necessary to achieve the minimum science acceptable for the INSPYRE investment. Baseline Science Requirements are needed to achieve all science objectives.

4.1 Science Platforms and Sampling

All threshold science objectives require an airborne platform capable of 6 hr or longer flight duration over an expansive study region across western North America. INSPYRE airborne platforms must be capable of spanning horizontal scales of 10-60 km during active convection, and 100s-1000s of kilometers during subsequent transport of injected smoke layers. Threshold science objectives require *in situ* sampling over at least half of the expected pyroCb injection altitude depth (Fig. 2.1), which will be accomplished by the WB-57. During the active convection phase, fire and plume processes evolve rapidly, requiring a rate-of-return over the fire of at least 30 min. Threshold science requirements also include at least one period of airborne sampling coincident with ground-based platforms in regions where road networks permit. A full baseline investigation expands *in situ* capabilities over the depth of the troposphere to sample all phases of pyroCu and pyroCb development, while maintaining *in situ* sampling over at least half of the expected pyroCb injection altitude range in the UTLS.

4.2 Deployments

Threshold science objectives require the successful completion of at least two 6-8 week flight missions over the western US and/or Canada during late July-mid-September, focused on periods when forecasting guidance indicates a high potential for pyroCb development. At least 3 flights must sample periods of pyroCu and/or pyroCb activity. One flight is required to sample the lifecycle of a large pyroCb with UTLS smoke injection. At least one flight must sample the anvil cloud/nascent plume of a large pyroCb. **Q1 and Q2 require several flights over fires that do not produce significant pyroCu and pyroCbs in otherwise favorable meteorological conditions. This means that INSPYRE can operate successful science flights even in the absence of pyroCb activity.** Baseline science objectives require additional flights to examine the full range of pyroCb magnitude, smoke plume evolution in the UTLS, and smoke uplift in traditional thunderstorms. Each INSPYRE science deployment will consist of 12-15 science flights. Ground based deployments will focus on the western US, and will opportunistically target a subset of fire’s both with and without pyroCb potential to meet baseline science objectives. At least one deployment coordinated with the ER-2 is required to meet baseline science objectives (Q1). Additional uncoordinated sampling will be possible and will help address the spectrum of fire plume outcomes.

5 Science Implementation and Observing Profile

5.1 Potential Deployment Sites and Timing based on PyroCb Climatology

INSPYRE deployment sites and timing are based on pyroCb climatology for North America [7, 54], which includes 367 pyroCb events from 2013 to 2022, the majority of which occurred during June to mid-September. These data facilitate mission planning based on pyroCb inter-annual, seasonal, sub-daily, and regional variability, including expected injection altitudes (e.g., Fig. 2.1). Figure 5.1 identifies three potential deployment sites in this region, including Palmdale, CA (home base of the ER-2), Boise, Idaho (base for FIREX-AQ, 2019), and Cold Lake, Alberta (base for ARCTAS-B, 2008). Red dots indicate all pyroCbs observed during the period of 03 July to 03 September, which ranks in the top three 8-week periods for all three locations in terms of total pyroCb activity and large/intense wildfires. This example includes a range ring of 1500 km around each location that approximates the airborne sampling domain, allowing for at least 2 hr of loiter time at the edge for the WB-57 and ER-2 (Sec. 2.2). These study domains are expected to yield 2-20+ pyroCb events per year (median of 10-15 events) during this 8-week period, as well as many large and intense fires (based on VIIRS FRP) with weaker pyroconvective plumes, which are required to address Q1 and Q2. Analysis of pyroCb/fire variability in this large domain shows that a deployment based in Canada can expect more fires and pyroCbs by starting in late June, while deployments out of Boise and Palmdale could operate later into mid-September. The INSPYRE PI and management teams are currently evaluating the three sites in Fig. 5.1, along with other potential deployment sites across western North America.

Canada’s boreal forest coincides with the highest percentage of smoke injections above the planetary boundary layer [69]. Proximity to the polar jet stream increases the potential for large and intense pyroCb events [3, 4] and likely simplifies forecasting of periods conducive to pyroCb development [38]. Relatively low mean tropopause heights at these higher latitudes facilitate sampling in the UTLS with the WB-57 and ER-2. This region also increases the opportunity for sampling coincident with the overpass times of polar-orbiting satellites. Long daylight periods provide significant sampling flexibility. However, limited road networks likely limit coincident ground-based sampling. Boise and Palmdale provide more opportunity for coincidence with ground-based and geostationary satellite observations. Palmdale is likely the most cost-effective for the ER-2. However, about half of the domain is devoid of fires (e.g., ocean) and the western location will limit following plumes eastward after injection into the UTLS. The INSPYRE PI Team is currently exploring options to target one domain in the first deployment year (2026) and different domain in the second year (2027).

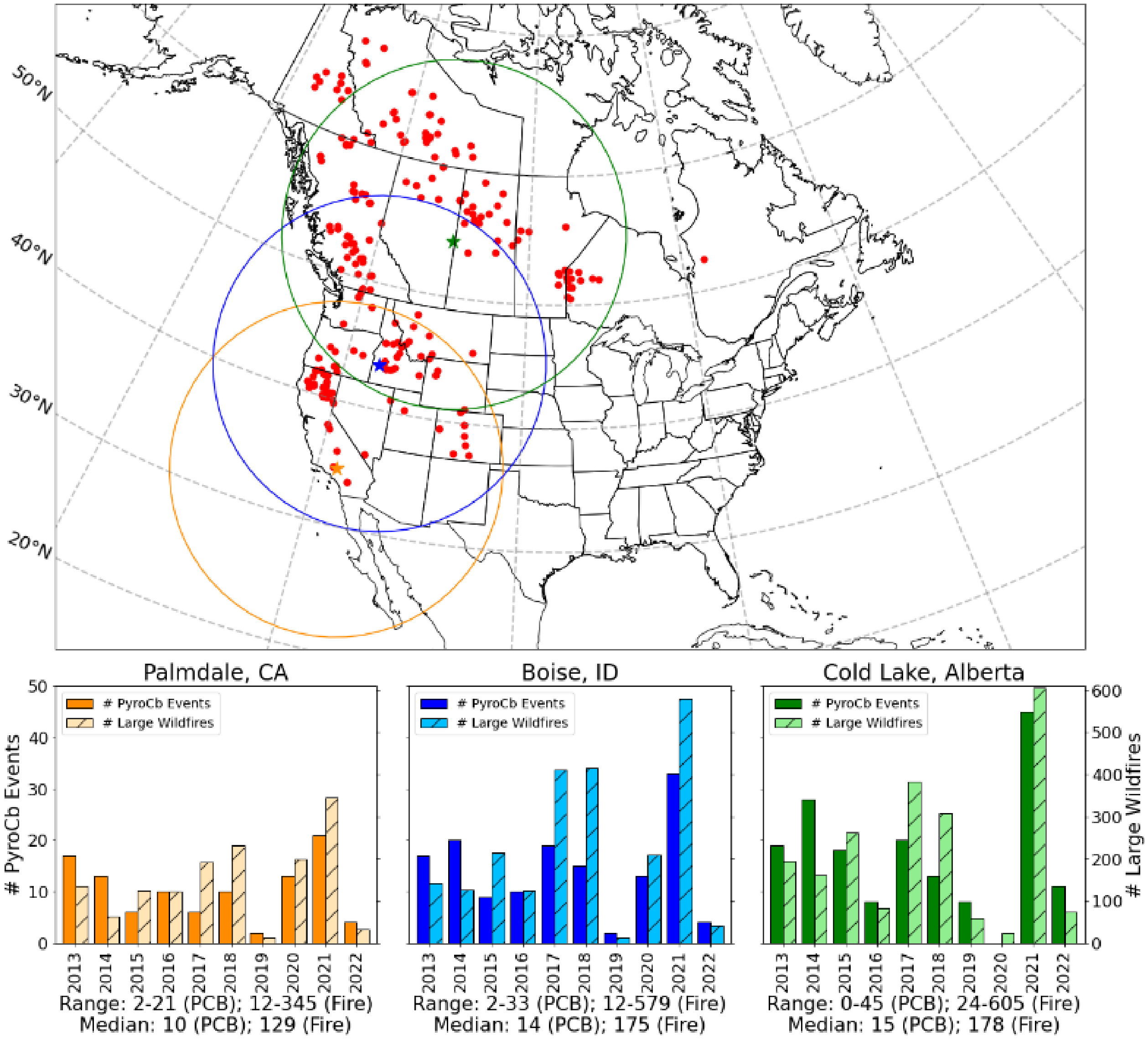

Fig. 5.1: Climatology of pyroCb activity and large wildfires during 03 July to 03 September (2013-2022) for three potential deployment sites. PyroCb locations are displayed in red. Range rings have a 1500 km radius. Large wildfires are defined as total VIIRS I-Band FRP (375 m) exceeding the 75th percentile for clusters of more than 40 fire pixels.

5.2 *Sample Flight Plans*

To address the science questions and objectives described in Sec. 1.2, INSPYRE will employ three notional flight plans, designed with flexibility to execute over a single fire or multiple fires in the same flight. More than one of these flight plans can be combined into a single flight. Actual flight routes will be determined during the campaign based on forecasting and science priorities. Coordination with satellite overpasses will be conducted when possible.

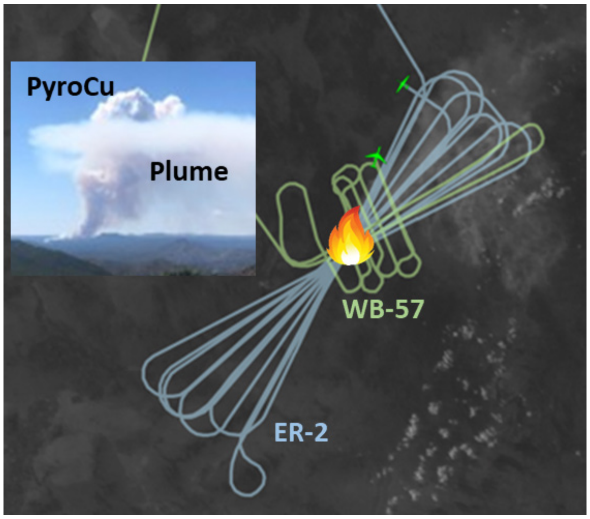

Fig. 5.2: Example ER-2 and WB-57 flight plans for a fire with a deep smoke plume and capping pyroCu, building from a proof-of-concept flight from FIREX-AQ in 2019.

5.2.1 *Flights evaluating fires with deep smoke plumes and capping pyroCu (most common)*

The most common sampling scenario for INSPYRE involves large wildfires with deep (>7 km MSL) smoke plumes and pyroCu formation in an environment that is at least marginally conducive for pyroCb development. Flights in this scenario will focus on repeated sampling with the ER-2 over a specific fire or several fires in close proximity to capture co-evolution in fire processes and plume dynamics. Figure 5.2 provides an example ER-2 flight pattern (blue) that would meet the threshold requirement of repeat sampling at least every 30 min. The WB-57 (green) will provide several transects of *in situ* sampling in the upper portions of the smoke column and/or pyroCu, above the hazardous updraft region shown in Fig. 1.10. WB-57 sampling can also include a remote sensing pass over a given fire or group of fires similar to the ER-2, depending on the final payload instrumentation and science objectives.

5.2.2 *Flights targeting an active pyroCb event (primary target) and/or traditional thunderstorms*

Sampling of active pyroCb events will begin with the methods described above (Fig. 5.2) until the plume reaches the UTLS and an ice anvil cloud develops (Fig. 1.5). In this situation, both platforms will sample at relatively high altitudes to avoid hazardous updrafts in the mid-troposphere [37]. Building from the FIREX-AQ proof-of-concept flight [43], active pyroCb events will require four types of sampling, as color-coded in Fig. 5.3:

- Orange (ER-2): recurring high-altitude remote sensing orbits when injection altitudes permit;
- Brown (WB-57): longitudinal *in situ* passes through the pyroCb cloud tops;
- Red (WB-57): cross-plume *in situ* sampling at multiple altitudes downwind of the updraft core, and;
- Blue (WB-57, ER-2): sampling of older pyroCb exhaust and detached anvil clouds farther downwind.

The ER-2 will operate exclusively as a high-altitude remote sensing platform, providing repeated orbits of the entire pyroCb/fire event at least every 30 min. The WB-57 will provide level longitudinal *in situ* passes through the upper altitudes of smoke and cloud ice outflow, as illustrated in Fig. 5.3. It will also provide cross-plume *in situ* passes at multiple altitudes downwind of the main updraft cores. WB-57 sampling can also operate in a circular pattern that alternates between high-altitude remote sensing passes over the pyroCb and exposed regions of the fire, followed by a set of both types of *in situ* passes. A baseline investigation will employ similar sampling methods to explore potential smoke lofting in traditional thunderstorms using both airborne platforms.

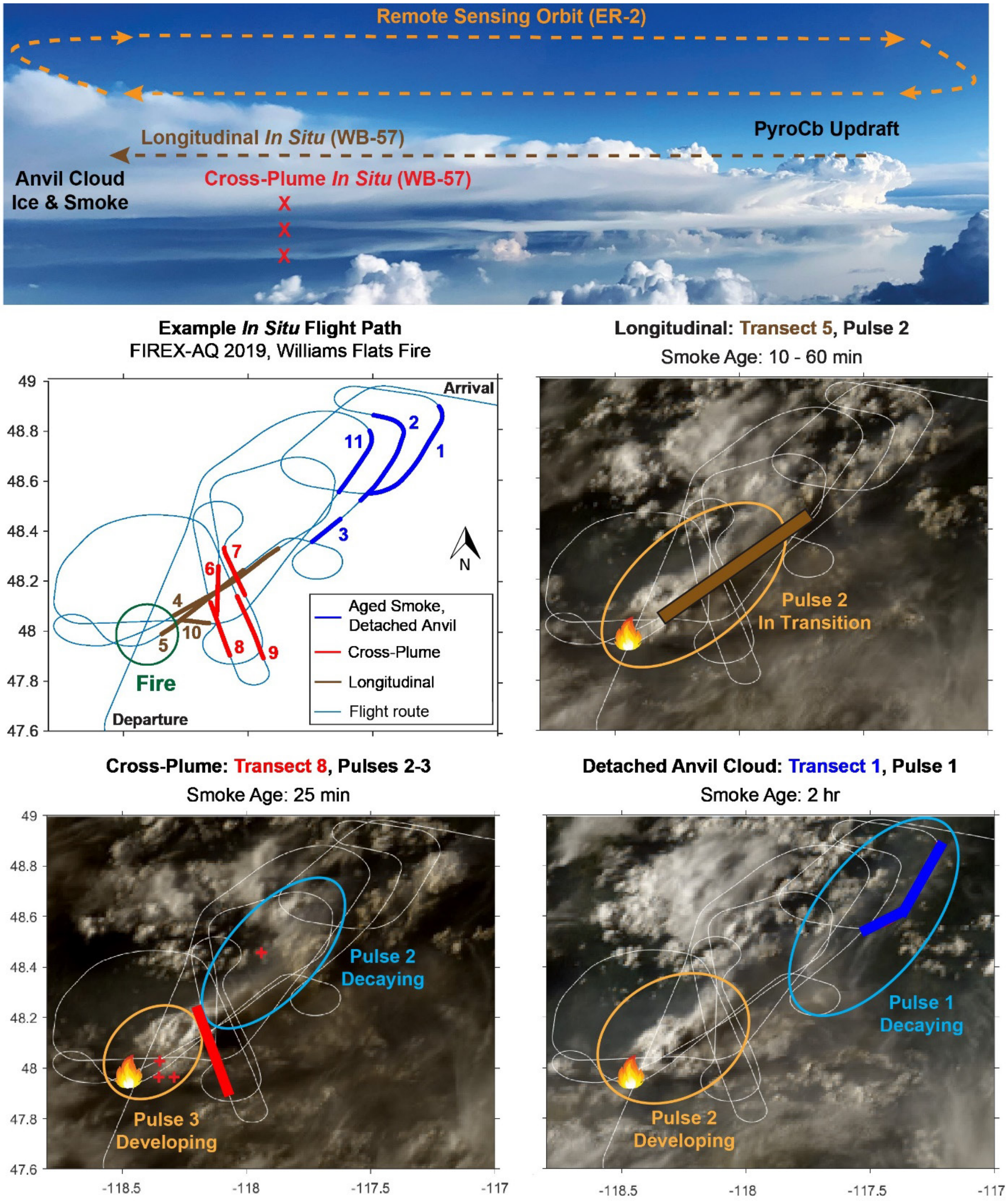

Fig. 5.3: Example airborne sampling for an active pyroCb event, building from the FIREX-AQ proof-of-concept flight over the 2019 Williams Flats fire with the NASA DC-8. Flight route map and satellite images highlight specific types/transects of *in situ* sampling planned for INSYPRE using the WB-57. This example includes three short-lived pulses of pyroCb activity. Red "+" symbols indicate Geostationary Lightning Mapper (GLM) lightning flashes observed within 10 min of each transect midpoint time. Satellite images are not corrected for parallax.

5.2.3 Flights sampling UTLS smoke plumes and/or smoke-filled cirrus anvils

Sampling of young UTLS smoke plumes and decaying pyroCb anvil clouds is targeted at the radiative properties objectives of Q3. INSPYRE will modify a UTLS sampling maneuver originally constructed for sampling the radiative effects of regular cirrus clouds, which was demonstrated during TC-4 in 2007 [70] and ACCLIP in 2022 (Fig. 5.4). It begins with a high-altitude reconnaissance pass for lidar profiling of the plume, followed by a pass at the top of the plume for radiative flux measurements, an *in situ* pass within the plume layer, a second radiation pass below the plume, and a final *in situ* pass while climbing back to cruising altitude. This maneuver can be conducted several times for the same plume. It can also be added to an active pyroCb flight in the anvil region downwind of the fire (Fig. 5.3, blue transects).

The WB-57 is best suited for this sampling due to collocation of lidar, radiation, and *in situ* measurements (Appendix 1, Table 2). However, the ER-2 is a suitable backup/alternative if aerosol and cloud particle information is provided via the remote sensing payload (Appendix 1, Table 1). When possible, INSPYRE will target repeat sampling of the same pyroCb plumes over multiple days to understand their evolution, similar to previous studies of lower-altitude smoke [71, 72, 73]. While the WB-57 can be relocated to a site downwind to follow significant UTLS smoke plumes, this will not be a typical flight planning consideration.

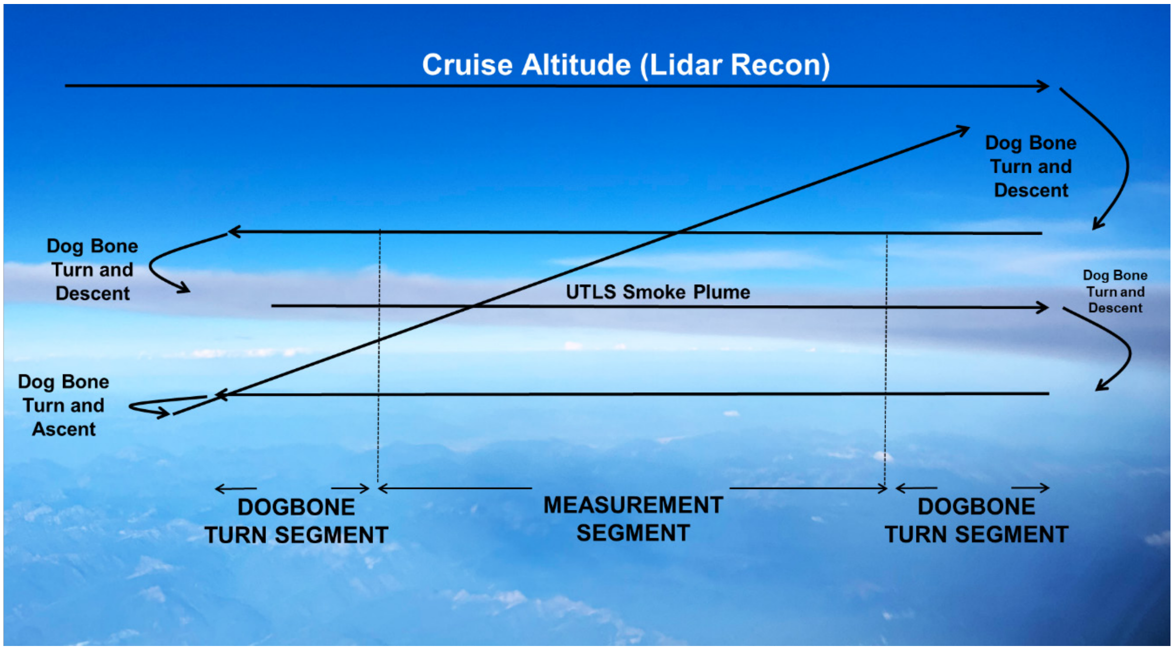

Fig. 5.4: Example sampling maneuver for smoke plumes and/or smoke-filled cirrus anvils in the UTLS based on a method used to sample regular cirrus clouds in ACCLIP 2022. INSPYRE will prioritize this maneuver with the WB-57 payload, and use the ER-2 as a secondary sampling option.

5.3 Ground-Based Sampling

For a subset of fires, ground-based scanning radars and lidars will observe plume structure, fire-generated winds, boundary layer structure, and pyroCb microphysics. An example of coordinated lidar and radar scanning of a pyroCb plume is provided in Fig. 5.5. The scanning radar(s) can rapidly observe the 3D plume structure and the radial components of the wind field, including the updraft core and downdraft regions (Fig. 5.5d). The scanning lidar(s) likewise observe the plume structure, but attenuate at cloud base (Fig. 5.5d, black contours). This attenuation is a useful approach for quantifying pyroCb cloud base properties. Lidar scanning and profiling will also provide airflow near the plume base and can quantify boundary layer depth in the fire-modified environment.

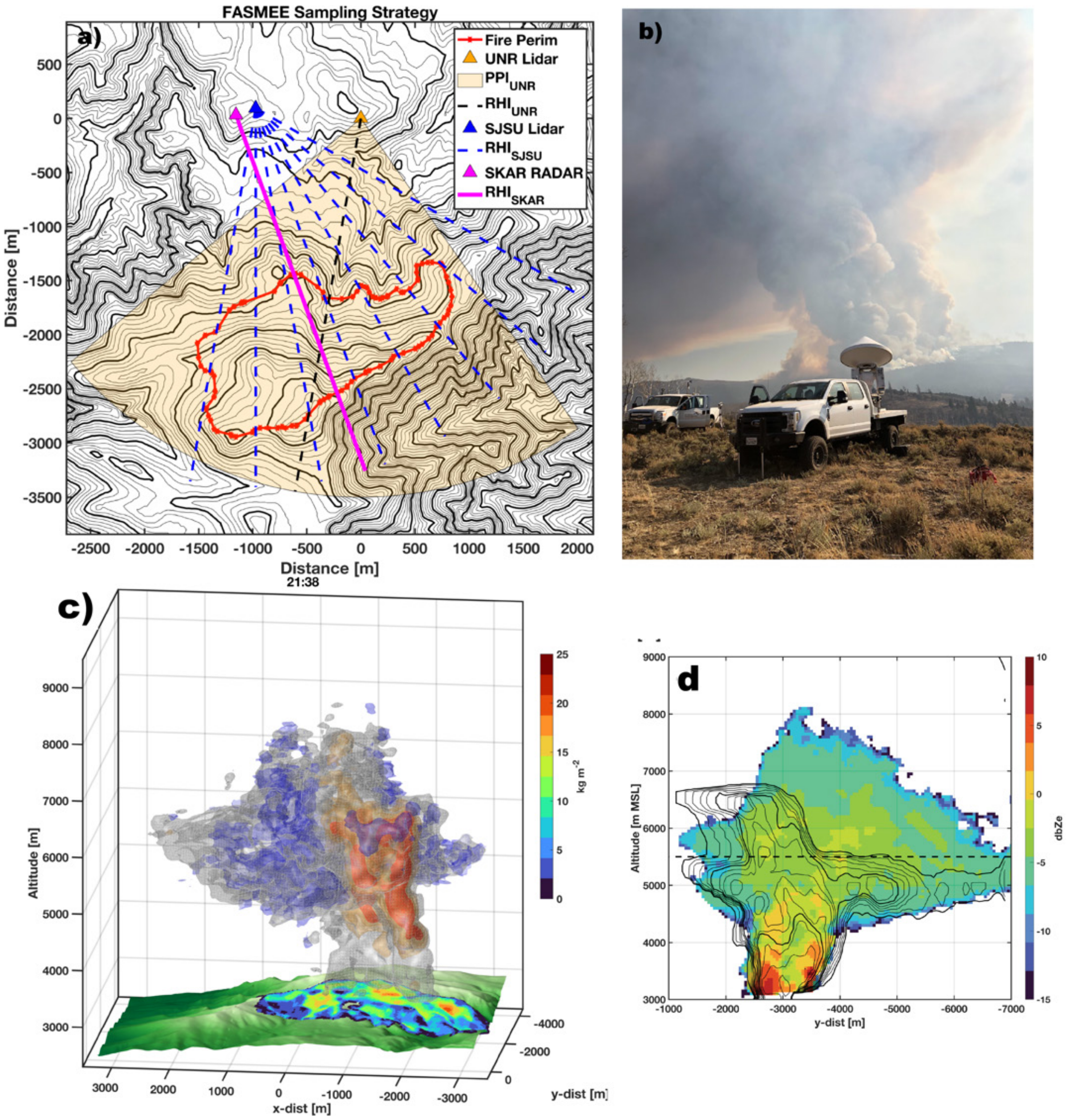

Fig. 5.5: Example of coordinated ground-based sampling with scanning radar and lidar. (a) overlapping scan sectors from multiple sensors. (b) Photograph of radar and lidar vantage point. (c) Radar reflectivity volume (gray) with updraft structure (red) and downdraft structure (blue). (d) Comparison of lidar backscatter (black contours) and radar reflectivity (shaded) showing the lidar's attenuation at cloud base compared to the in-cloud sampling from the radar.

5.4 Fire Selection and Plume Forecasts

Weather conditions supporting pyroconvection are different from those supporting the most rapid fire growth [61]. "Blow up fires" linked to pyroCbs and deep plumes can often be anticipated based on the weather impacting existing fires (wind shifts, convective instability, strong winds, etc.). Focusing on weather changes led to recent successful deployments by the RaDFIRE, FIREX-AQ, and CalFIDE teams. INSPYRE will follow a similar approach for identifying and selecting fires for sampling:

1. *Fire and Plume Monitoring*: Satellite IR (GOES, MODIS, VIIRS) and available aircraft fire perimeters (e.g., NIROPS, FIRIS, etc.) will track day-to-day fire growth. NEXRAD radar, visible satellite, and cameras [74] will track plume development. Fires with potential for large growth will be noted and monitored day-after-day.
2. *Weather:* Daily weather briefings by the INSPYRE forecast team will examine conditions conducive for "blow up" fires including: (a) strong winds, low humidity, and high temperatures, (b) approaching troughs or wind shifts, and (c) mid-level instability conducive to pyroCu/Cb. When appropriate, daily briefings from the National Interagency Fire Center (NIFC) and NWS IMETS will also be incorporated.
3. *Fuels, Topography, and Fire History*: INSPYRE will use maps of topography, fuel type, fuel load, fuel moisture, and fire history to estimate growth *potential* for existing fires. Fuel variables to be examined include 100-hr fuel moisture, Energy Release Component (ERC), and live fuel moisture. In addition, we will examine availability of pre-fire fuels data sets, including airborne laser scanning (ALS), to help select fires for sampling.
4. *Incident Integration:* INSPYRE will work with fire-management stakeholders, including incident command teams, incident meteorologists (IMETs), and fire-behavior analysts (FBANs), to refine our sampling objectives based on expected fire behavior and fire-management tactics (e.g., backfiring).
5. *Simulated growth:* Once a fire of interest is identified, coupled fire-atmosphere models will simulate the expected mesoscale weather, fire growth, and plume behavior for a 48-hour window.
6. *Plume Trajectories:* Trajectory models will simulate plume transport for expected injection altitudes.
7. *Flight Logistics:* We will evaluate the potential for airborne sampling based on non-weather logistics, such as airspace, ongoing fire suppression efforts, etc.

For INSPYRE to be successful, a forecasting team that manages, delegates, and integrates these forecasting components is required. This team should have previous experience in forecasting for large field experiments, especially experiments with components related to prediction of fire behavior and evolution, convective development, and aerosol transport.

5.5 Data Management

INSPYRE requires a data management approach that includes web-based data archives and field catalogs. We anticipate funding a group who will work with NASA to develop and maintain all web-based data archives and field catalogs, help the PI team organize an open data workshops, and answer any data-related questions from science team members for the duration of the project. Examples of comparable field catalogs and data archiving include those from IMPACTS, FIREX-AQ, ASIA-AQ, and ACCLIP.

5.6 Risk Management

INSPYRE is designed to maximize chances for success of all threshold and baseline objectives. For example, Q1 and Q2 require measurements both during and in the absence of large pyroCbs. This means that many science objectives can be addressed even if one of the INSPYRE deployments occurs during an inactive pyroCb period. In many years, it is possible to narrow down regions favored for pyroCb and fire potential several months in advance based on the current and expected weather patterns (e.g., ENSO trends, winter precipitation anomalies, etc.). INSPYRE has some flexibility in deployment location and timing during July to mid-September (e.g., Fig. 5.1), which will mitigate potential delays caused by aircraft maintenance and other logistical issues. Using two airborne platforms allows some threshold measurements to be obtained if one platform becomes unavailable.

5.7 Timeline of Key Milestones

The INSPYRE mission timeline includes an initial year of building the science team and instrument selection (PI Team only). The official 5-year project is expected to begin on 01 October 2025. Science deployments (nominally 6-8 weeks) are planned for Years 1 (2026) and 2 (2027) during a July to early-September time window. Exact deployment dates will be scheduled based on the climatology for the final base location (Fig. 5.1). A potential deployment is also included in Year 3 (2028) to account for potential logistical delays or extra science flights if the budget allows. A series of pre-flight exercises are planned prior to the first science deployment, along with two science team meetings for mission planning. INSPYRE data analysis will begin immediately after the first deployment to refine sampling strategies in subsequent deployments. Significant time is devoted to post-flight data analysis and modeling in Years 3, 4, and 5, including annual science team meetings and open data workshops, to ensure that data are widely disseminated and published before the end of the INSPYRE mission.

Appendix 1: Science Measurement Requirement Matrix

The INSPYRE Science Measurement Requirement Matrix (Tables 1-4) includes remotely-sensed, *in situ*, and ground-based measurements, along with corresponding performance requirements. Airborne measurement requirements are arranged specifically for the ER-2 and WB-57 platforms described in Sec. 2.

Priorities are expressed as follows: 1 = required, 2 = desired, 3 = useful. For Priorities 1 and 2, instruments may be dedicated to a specific need. Uncertainty and resolution specifications must be met or exceeded for a measurement to be useful. The suite of measurements identified as Priority 1 are essential for achieving the minimum science acceptable for the INSPYRE investment. Priority 2 measurements allow for a more detailed examination of all science objectives listed under Q1-Q3 (threshold and baseline). Priority 3 indicates value-added measurements to provide a more complete examination of INSPYRE's science questions, which are typically accomplished by instruments providing higher priority measurements.

The payloads for the ER-2 and WB-57 are expected to contain approximately 8-10 individual instruments or instrument packages that will be managed by approximately 4-7 funded teams for the ER-2 and 5-8 funded teams for the WB-57. Ground-based measurements require at least one multifaceted team, with experience addressing safety and access concerns related to active wildfires. Web-based data archives and field catalogs are essential for the success of the INSPYRE mission.

Table 1. ER-2: Science Measurement Requirement Matrix

v. = vertical; h. = horizontal (x, y); a. t. = along track

ER-2 Remote Sensing	**Priority**	**Uncertainty**	**Resolution**	**Science Qs**
Radar: Updraft properties (Doppler Velocity) • Vertical velocity • Width • Vertical extent	1	2.5 m/s, 25 m	1 m/s, ~500 m h.	1, 2
Radar: 3D Plume structure (Radar Reflectivity) • Plume depth • Plume width as a function of height • Plume geometry (upright, bent-over)	1	2 dbZe, 25 m	Sensitivity -10 dbZe, 10-1000 m h. at surface	1, 2
Radar: Plume hydrometeor/pyrometeor distribution • Pyrometeor loading (reflectivity) • Pyrometeor size (dual-wavelength ratio (DWR)) • Hydrometeor occurrence (linear depolarization (LDR) ratio or polarimetric variables)	1	5% LDR, DWR	1000 m h. at surface	1, 2
Lidar: • Smoke plume vertical profile • cloud top height and phase (nadir)	1	N/A	200 m a. t., 30 m v.	1, 2, 3
UV/VIS-NIR Polarimeter: Cloud droplet size distribution	1	DOLP<0.5% 3 %–5 % radiometric	50 m h.	2
UV/VIS-NIR Polarimeter (if combined with lidar) smoke optical properties and profiles • AOD and extinction profiles • Angstrom exponent • SSA • Refractive index	1	DOLP<0.5% 3 %–5 % radiometric	50 m h.	2, 3
IR imager: Active fire spatial extent, temperature, FRP (non-saturated)	1	3-5%	50 m h.	1, 2
IR imager: Fire rate/direction of spread	1	10%	50 m h., 30 min	1, 2
IR sounder: Temperature profiles	1	2 K	1 km v.	1, 2, 3
IR sounder: Water vapor profiles	1	15%	1 km v.	1, 2, 3
Lightning/Electric Field	1	1000 V/m	1000 V/m	1, 2
Multispectral UV/VIS-NIR Imager: RGB image and Aerosol and Cloud AOD	2	3-5% radiometric	50 m h.	1,3
Radiation: SW and LW broadband flux	2	3%	1s	3
IR Sounder: CO profiles	2	20%	1 km v.	2, 3
Hyperspectral VIS imager: Fuel (vegetation) type	2	5 % radiometric	50 m h.	1, 2

ER-2 *In Situ* Measurements	**Priority**	**Uncertainty**	**Resolution**	**Science Qs**
Meteorology:				
Temperature, pressure	3	0.3 K, 0.3 hPa	0.1 s	1, 2
Flight level wind (u,v)	3	0.5 m/s	0.1 s	1, 2
Vertical velocity	3	0.1 m/s	0.1 s	1, 2

Table 2. WB-57: Science Measurement Requirement Matrix

v. = vertical; h. = horizontal (x, y); a. t. = along track

WB-57 Remote Sensing and Radiation	**Priority**	**Uncertainty**	**Resolution**	**Science Qs**
Lidar: Aerosol backscatter profile (must point up and down)	1	3%	200 m a. t., 30 m v.	2, 3
Radiation: SW and LW broadband flux	1	3%	1s	3
IR imager: Fire Radiative Power (FRP), etc.	3	10%, non-saturated	1 MW	1, 2
IR Sounder (Temp., Water Vapor, CO, etc.)	3	N/A	1 km v.	1, 2, 3
Radar: pyro/hydrometeor reflectivity, Doppler velocity (nadir)	3	See ER-2, Table 1		

WB-57 *In Situ* Measurements	**Priority**	**Uncertainty**	**Resolution**	**Science Qs**
Meteorology:				
Temperature, pressure	1	0.3 K, 0.3 hPa	0.1 s	1, 2
Flight level wind (u,v)	1	0.5 m/s	0.1 s	1, 2
Vertical velocity	1	0.1 m/s	0.1 s	1, 2
Aerosols:				
Accumulation mode number concentration	1	10%	1 s	2, 3
Size distribution (70 nm - 1 μm)	1	20%	1 s	2, 3
Black carbon concentration and mixing state	1	30%	1 s	3
Absorption and extinction, including UV	1	2 Mm-1	1 s	3
Bulk accumulation mode composition	1	100 ng m-3	10 s	3
Refractive index, including UV	2	N/A	N/A	3
Other measurements of relevance	3	N/A	N/A	2, 3
Clouds and Large Particles:				
Droplet, crystal, ash particle number	1	N/A	1 s	1, 2, 3
Size distribution (0.5 μm – 6+ mm)	1	N/A	1 s	1, 2, 3
High-resolution particle images	1	N/A	N/A	1, 2, 3
Total cloud water content	2	20%	1 s	1, 2, 3
Other measurements of relevance	3	N/A	N/A	1, 2, 3
Trace Gases:				
Carbon Dioxide	1	4.0 ppm	1 s	2, 3
Carbon Monoxide	1	10 ppbv	1 s	2, 3
Water Vapor	1	5%	1 s	1, 2, 3
Precursors for secondary aerosol formation	2	N/A	1 s	2, 3
Measurements associated with stratospheric ozone	2	N/A	1 s	2, 3
Other measurements/tracers of relevance	3	N/A	N/A	2, 3

Table 3. Ground-Based: Science Measurement Requirement Matrix

v. = vertical; h. = horizontal (x, y); a. t. = along track

Ground-Based Measurements	Priority	Uncertainty	Resolution	Science Qs
Plume Dynamics (radar and lidar):				
3D plume structure (reflectivity)	1	2 dbZ	1 dbZ, 100 m. h., 1 min	1, 2
Fire-generated winds (Doppler velocity from lidar, radar)	1	2 m/s	1 m/s, 100 m. h.	1, 2
Cloud Processes (radar and lidar):				
Cloud base height (scanning lidar)	1	5%	50 m. v.	1, 2
Polarimetric evidence for hydrometeor development (e.g., radar correlation coefficient, linear depolarization ratio, etc.)	1	5%	20 m. h., 10s of seconds	1, 2
Boundary Layer and Thermodynamic Profiles:				
Boundary-layer/mixing-layer depth proximal to fires (e.g., lidar vertical velocity variance, aerosol backscatter)	1	50 m. v.	20 m. v.	1, 2
Lower tropospheric wind profiles (e.g., lidar VAD)	1	5%	1 m/s, 50 m. v.	1, 2
Temperature and moisture profiles (e.g., balloon soundings, retrieved profiles, etc.)	2	5%	1 K, .1 g/kg	1 ,2, 3
Other measurements of relevance	3	N/A	N/A	2, 3

Appendix 2: Science Modeling and Forecasting Requirement Matrix

The INSPYRE Science Modeling and Forecasting Requirement Matrix (Table 4) prioritizes the modeling and forecasting capabilities necessary to achieve INSPYRE science objectives and address current gaps and uncertainties related to pyroconvection. Priorities are expressed as follows: 1 = required and 2 = desired. The suite of capabilities identified as Priority 1 are essential for achieving the minimum science acceptable for the INSPYRE investment. Priority 2 capabilities allow for a more detailed examination of all science objectives listed under Q1-Q3 (threshold and baseline). Approximately 2-4 separate funded teams are anticipated to cover the modeling and forecasting requirements for INSPYRE.

Table 4. Science Modeling and Forecasting Requirement Matrix

Scientific Modeling/Forecasting Capability	Priority	Scale (Grid Size)	Science Qs
Coupled fire-atmosphere models: • Support for daily forecasting needs during field deployments • Provide process-based sensitivity and predictability experiments after deployments • Include real-time fuel moisture	1	Fire-scale (100 m, LES)	1, 2
PyroCb-specific prediction and nowcasting applications based on satellite data and numerical weather prediction (NWP) inputs: • Support for daily forecasting needs during field deployment • Experiments and analyses after deployments • Work toward development of tools that are useful for firefighting efforts and communities in the wildland-urban interface	1	Regional (< 10 km)	1, 2
PyroCb smoke source development and trajectories: • Initiated from expected pyroCu and pyroCb injection altitudes • Support for daily forecasting needs during field deployment • Experiments and analyses after deployments	1	Regional, global	2, 3
Models with full coupling between composition, chemistry, radiation, meteorology, etc.: • Include a vertical range from the surface to lower stratosphere • Work toward improved pyroCb smoke plume initialization and transport forecasts • Constrain potential feedbacks from pyroCb smoke plumes in the UTLS	1	Regional, global, climate	1, 2, 3
Fire incident expertise and guidance for sampling targets in the western United States and Canada	1	N/A	1, 2, 3
Other aerosol and chemical transport modeling applications and development pathways of relevance	2	Regional, global	2, 3
Aerosol-cloud interaction capabilities	2	Fire-scale, regional	1, 2
Forecast standardization for field deployments (e.g., FLUID framework)	2	Regional, global	1, 2, 3

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