National Aeronautics and
Space Administration

NASA earth

Atmospheric Thermodynamics / Dynamics

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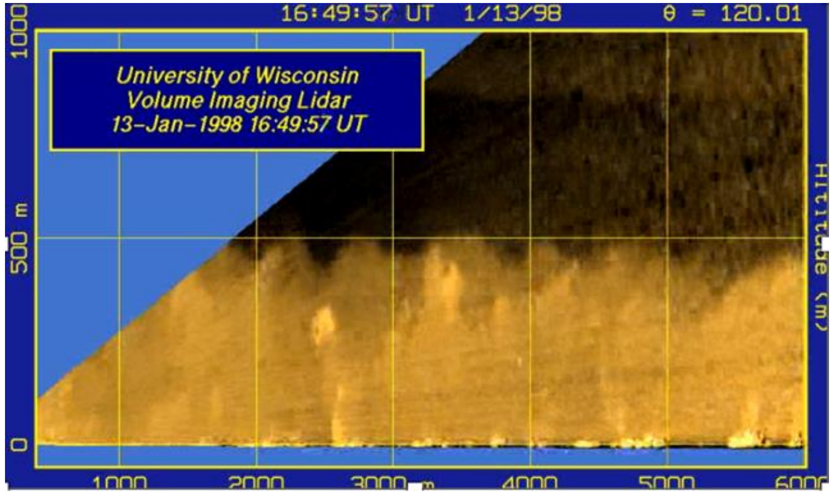
Earth Science Division

April 22, 2026

Setting the context

- Atmospheric thermodynamics and dynamics connect with all of the other pillars of the Sphere
- Traditionally, we have considered thermodynamic profiling and winds to be within the overall “weather” topic area
- Remainder of this session:
  - Brief overview of NASA’s role in weather
  - Summaries of the 2015 Weather focus area report and of the mention of weather in the 2017 ESDS
  - The particular importance of the PBL
  - Guided discussion



Weather at NASA vs NOAA and DoD

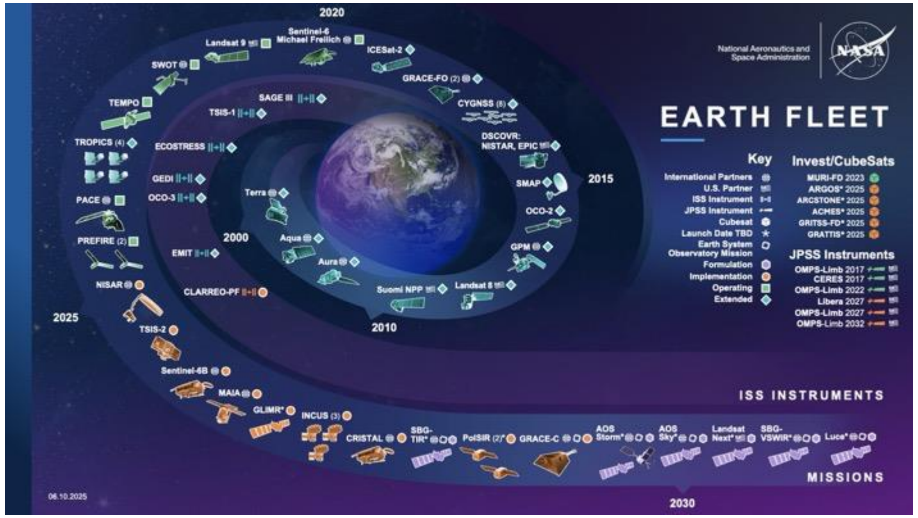
- NOAA and DoD are operational agencies – producing forecasts and state estimates in near real time under strict mandates to satisfy stakeholder needs
- NASA has unique expertise in observing system design and deployment and a mandate for exploration in service of the public good
  - Development of new measurements to increase understanding
  - Expertise in radiative transfer, retrievals, and data assimilation
- **In principle, NASA conducts exploratory development that can then be transitioned to NOAA and industry**

Related Topic: Modeling and Data Assimilation

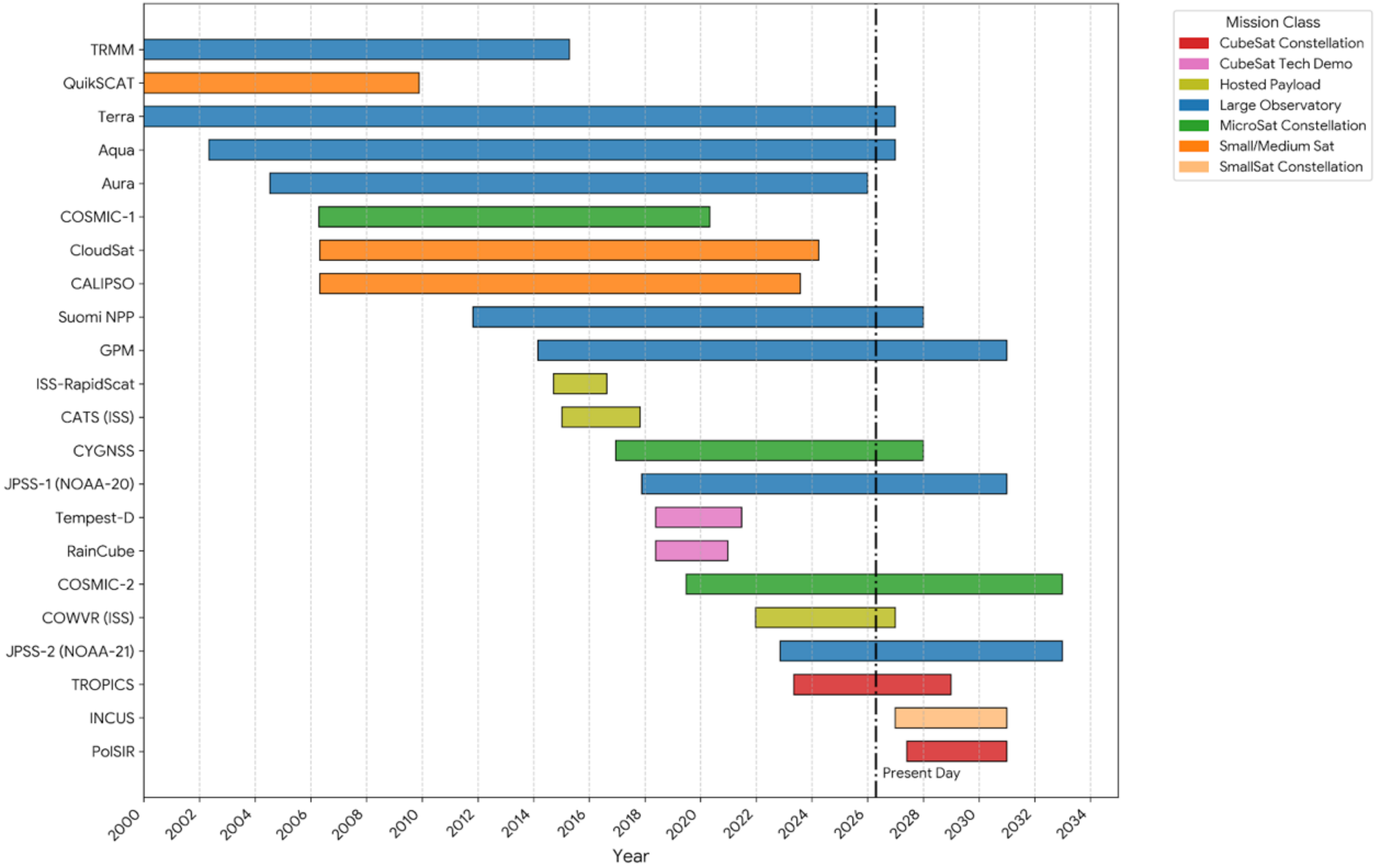
- NASA is unique in infusing observations into models of the Earth system, and with new linkages enabled through IMVI
- Also have significant expertise in high resolution modeling (LES)
- Our Earth system models have rich heritage in data assimilation - optimal integration of model and observations
  - Reanalysis
  - Mission formulation (OSSEs)
  - Scientific discovery (hypothesis testing)
- DA advances within NASA have the potential to translate into significant operational impacts within NOAA and other agencies
  - Successes: clear-sky microwave imager/sounder and hyperspectral IR data
  - Ongoing challenges: all-sky radiances and active (radar, lidar) measurements

Importance of Program of Record

- Routine measurements made now and in the coming decade by operational agencies (NOAA, EUMETSAT, etc) and increasingly commercial partners are increasingly capable
  - LEO constellation of imagers and sounders
  - Commercial GNSS-RO and MW sounders
  - Geo-ring of hyperspectral sounders
  - EPS-Aeolus (Aeolus-2) Doppler wind lidar

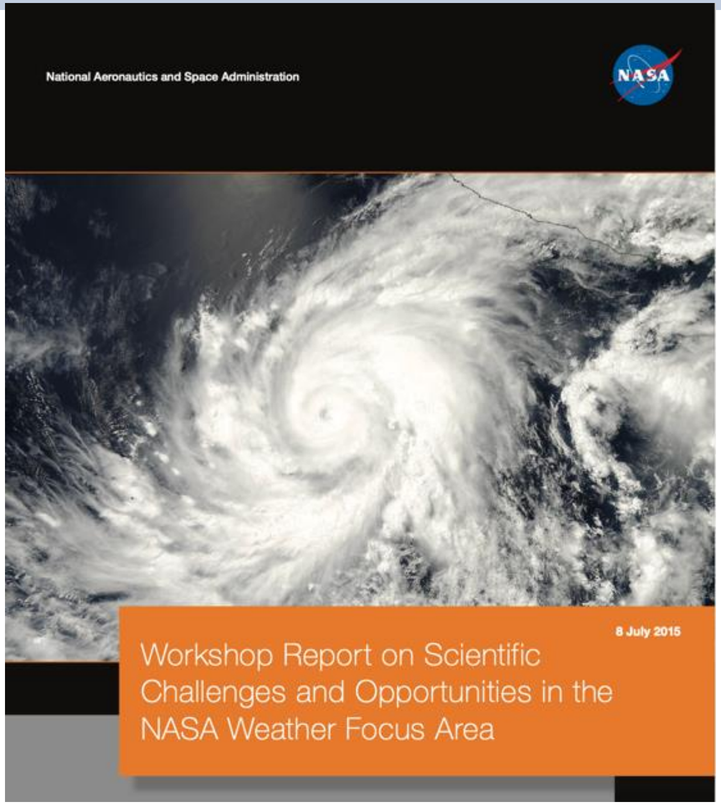


NASA Weather Related Program of Record



2015 Weather Focus Area Workshop Report

- April 2015, ~ 80 people from from NASA HQ/Centers, NOAA, DoD, FAA, OFCM, NGOs, academia, industry, and international organizations
- Purpose: gather NASA Weather Focus Area community leaders to identify the most challenging scientific research and development topics that can be uniquely addressed by the NASA Weather Focus Area
  - Using NASA's satellite, airborne, and surface observations
  - Computational modeling and data assimilation systems and high-end computing facilities.
- Consider new observational, modeling, computational capabilities at present and planned for the future.



CHALLENGES AND OPPORTUNITIES IN NASA WEATHER RESEARCH

BY XUBIN ZENG, STEVE ACKERMAN, ROBERT D. FERRARO, TSENGDAR J. LEE, JOHN J. MURRAY, STEVEN PAWSON, CAROLYN REYNOLDS, AND JOAO TEIXEIRA

Weather Focus Area Workshop Summary I
Key Strengths

- **Technology Development**: NASA is the only U.S. agency with the capability to develop next-generation satellite missions and pioneering instrument technologies.
- **Global Observational Reach**: The agency possesses a unique "global reach" through its extensive suite of satellite, airborne, and sub-orbital platforms.
- **Risk Tolerance**: Unlike operational agencies, NASA is equipped to pursue high-risk fundamental research that explores new measurement concepts.
- **Modeling and Data Assimilation**: NASA maintains high-level modeling systems (like GEOS-5) and produces critical global datasets (such as MERRA) that support the broader research community.
- **OSSE Leadership**: NASA leads in generating high-resolution "nature runs" and instrument simulators for Observing System Simulation Experiments (OSSEs).
- **Computational Infrastructure**: The agency provides massive high-performance computing (HPC) capacity essential for global cloud-resolving simulations.

Weather Focus Area Workshop Summary II
Recommendations I

1. Observing System Simulation Experiments (OSSEs)

- Leadership: The report strongly recommends that the Weather Focus Area take ownership of a dedicated Earth Science OSSE capability.
- Unified Infrastructure: NASA should collaborate with NOAA to evolve shared OSSE elements into a common, unified infrastructure.
- Mission Planning: OSSEs should be performed during the proposal formulation stage—rather than after selection—to ensure mission designs are cost-effective and scientifically impactful.

2. Priority Measurements

- Wind Structure: Developing global 4D measurements of large-scale horizontal wind vectors is considered an urgent priority.
- Temperature and Humidity: Continuous investment is needed for higher spatial and temporal resolution, utilizing synergistic measurements from multiple platforms (LEO, GEO, and CubeSats).
- Cloud and Precipitation: Research should focus on estimating vertical velocity and characterizing cloud microphysical properties, such as particle size distribution and ice mass.

Weather Focus Area Workshop Summary II

Recommendations II

3. Modeling and Computing

- High-Resolution Modeling: NASA should pursue global, convective-permitting models with grid sizes of 1–5 km.
- Coupled Systems: Efforts should prioritize the coupling of the atmosphere with land, ocean, and ice to improve physical balances and predictability.
- Supercomputing Growth: The agency must sustain investment in supercomputing to match the growth of high-resolution models and implement enhanced data-distribution techniques like storage proximal analytics.

4. Scientific Research Questions

- Bridging the Gap: NASA should identify the advances needed to expand the useful range of weather forecasting from two weeks to four weeks.
- Extreme Events: Research must focus on improving the prediction of high-impact events (e.g., hurricanes, floods, and droughts) and quantifying how their frequency varies with climate change.
- Process Studies: Focus on how convective-scale and large-scale circulations interact and what determines the life cycle of convective systems.

Weather in the 2017 ESDS:
Science Questions / Objectives

Weather related "Most Important" questions / objectives:

- Planetary Boundary Layer (W-1): Understanding PBL processes is crucial for modeling air-surface exchanges of energy and mass, which directly impact weather forecasts and air quality simulations.
- Extended Forecasts (W-2): A major goal is to extend environmental predictions to provide seamless forecasts at lead times of one week to two months.
- Convection and Precipitation (W-4): Research focuses on why convective storms and heavy precipitation occur at specific times and locations to improve models of extreme events.
- Integrating Themes: Weather priorities are linked to "Extreme Events," aiming to improve the prediction of hurricanes, flash floods, and droughts through better high-resolution data.

Weather in the 2017 ESDS:
Geophysical Variables

Thermodynamic State: Temperature, Pressure, and Water Vapor

- Temperature and Humidity: 3D profiles of temperature and moisture, especially in the PBL, and for climate variability studies (water vapor feedback, Objective C-2b).
- Surface Pressure: Precise measurements of sea-surface air pressure (within 1 mb) are critical for predicting storm tracks and intensification.

Atmospheric Winds: Horizontal and Vertical

- 3D Horizontal Winds: wind vectors in the troposphere and PBL - for understanding the large scale circulation and the transport of pollutants and water vapor.
- Vertical Motion (Convection): vertical motion within deep convection to within 1 m/s – for improving model representations of convective transport and extreme precipitation.
- Ocean Surface Winds: coincident high-accuracy measurements of ocean surface vector winds and currents to assess air-sea momentum exchange.

We have made progress

- Convection: INCUS and PMM for profiling and vertical motion, plans for FALCON
- PBL: not yet finalized, but a strong strategy is emerging from the incubation activity (PBL is ready for implementation)
- Technology development: maturation of DIAL and DAR, hyperspectral microwave, GNSS-RO, and sensor miniaturization
- OSSEs: evolution from a single type (weather forecast) to a spectrum (retrieval, sampling, forecast, climate); acceleration of time to completion; improvement in fidelity

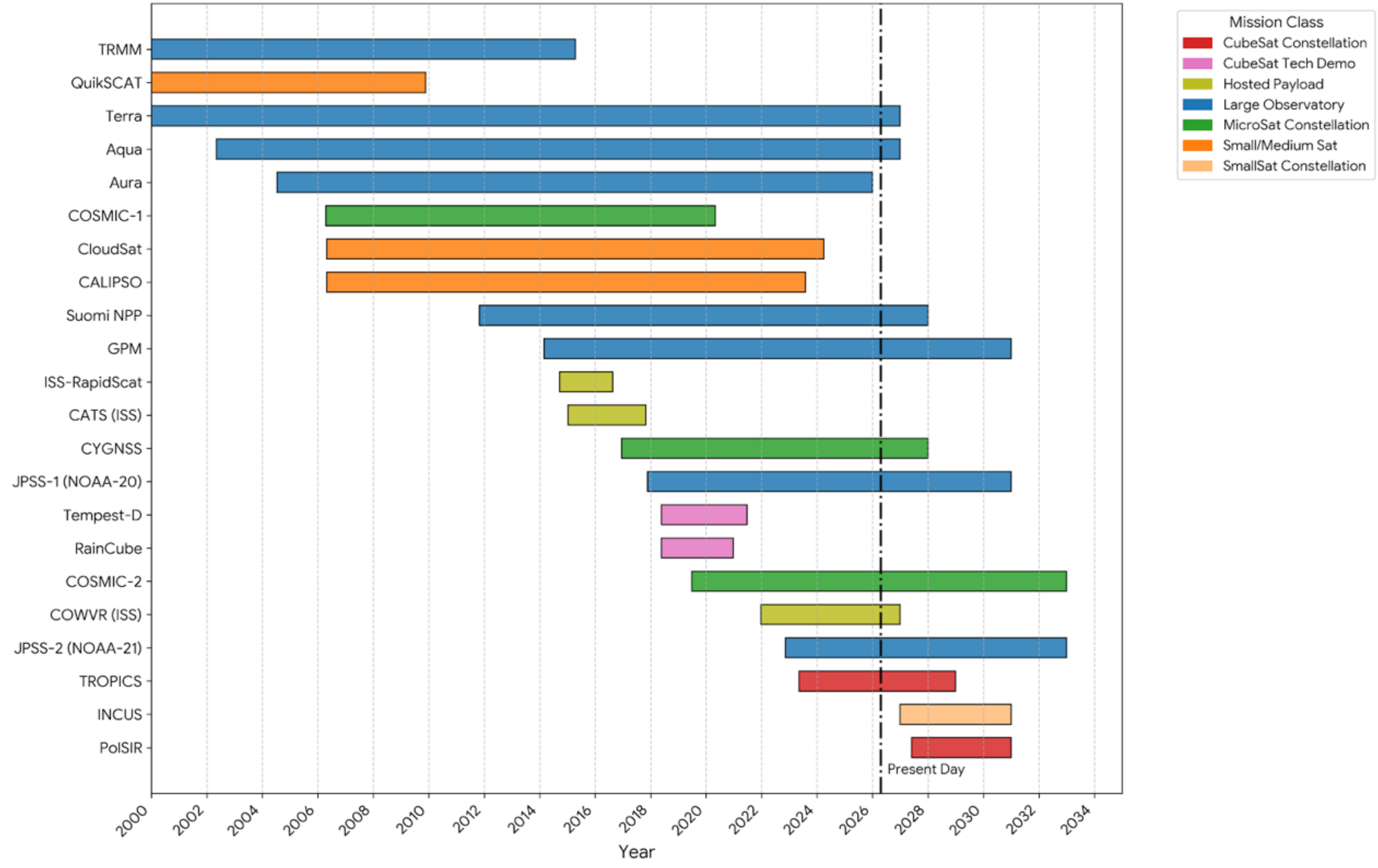
Observing System Simulation Experiments (OSSEs)

- **Modeling systems** are growing ever more complex and computationally expensive
- The **trade space** of what is possible to observe from space, air, and ground has expanded tremendously, and continues to grow
- We are experiencing (and participating in) **rapid advancements** in data science, machine learning, data assimilation, and compute
- The pace of mission design has accelerated – must make formulation ***faster***
- **ESTO solution:** a *spectrum* of OSSEs:
  - **Sampling**: What are the sampling requirements for observing a given feature?
  - **Retrieval**: Do measurements provide enough information to estimate geophysical quantities of interest? What are the uncertainties?
  - **Forecast**: What do new measurements provide relative to the program of record?
  - **Climate:** Do observations contain information that can be used to constrain climate forcing and/or response?

There are as yet unrealized goals…

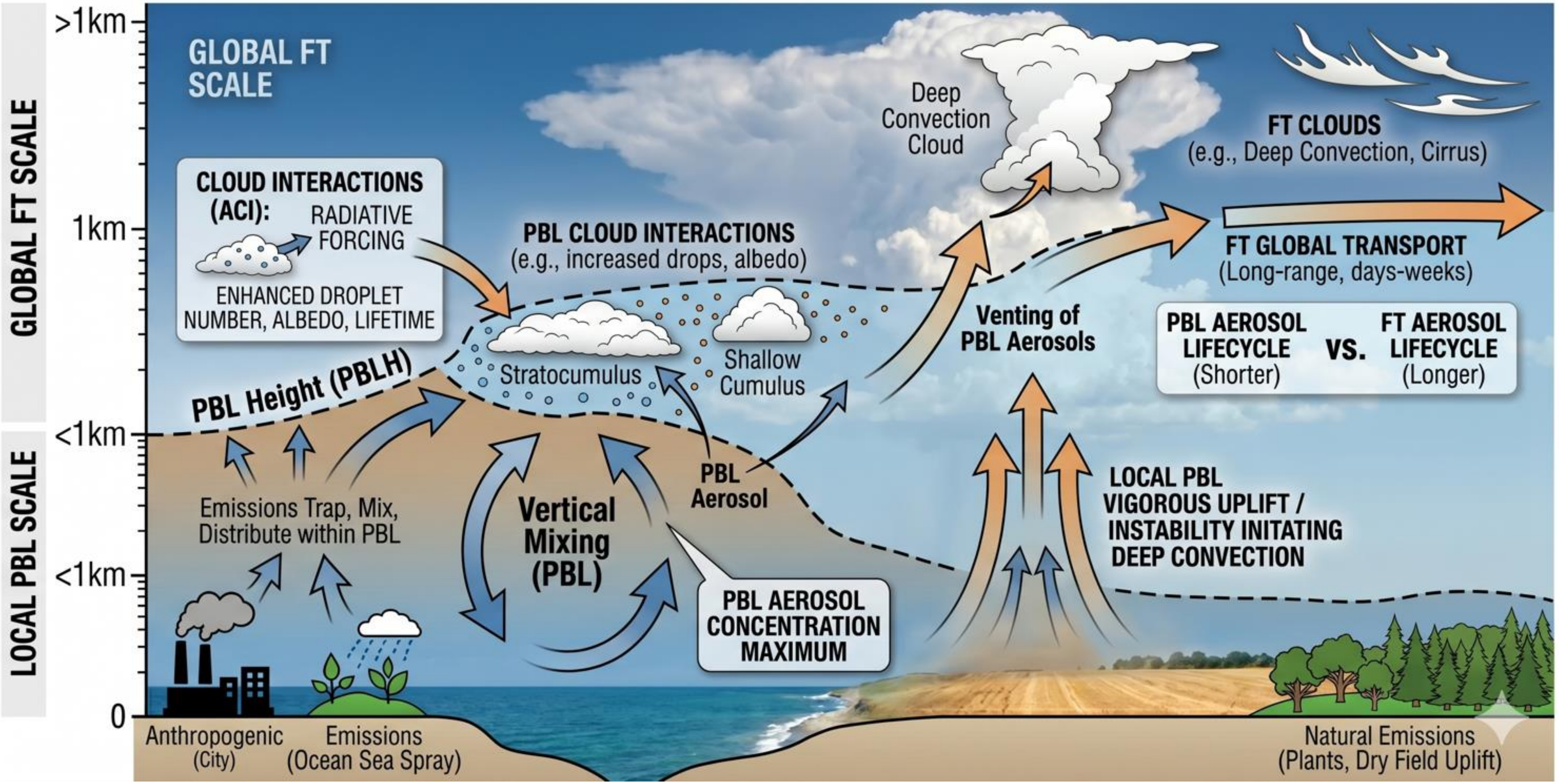
- We are not yet exploiting synergy among agencies
- NASA has the potential to take a stronger role in data assimilation
- We have a new set of OSSE tools, but need to formalize their use
- 3D horizontal winds are a top priority for NOAA and NASA, yet there are no formal plans for space-based implementation in the US
- Advances in winds are coming:
  - Feature tracking from high temporal and spatial resolution Geo IR sounders
  - Follow-on missions to Aeolus
- PBL is a rapidly maturing, yet highly complex, topic – natural laboratory for the design of a highly integrated observing system

NASA Weather Related Program of Record



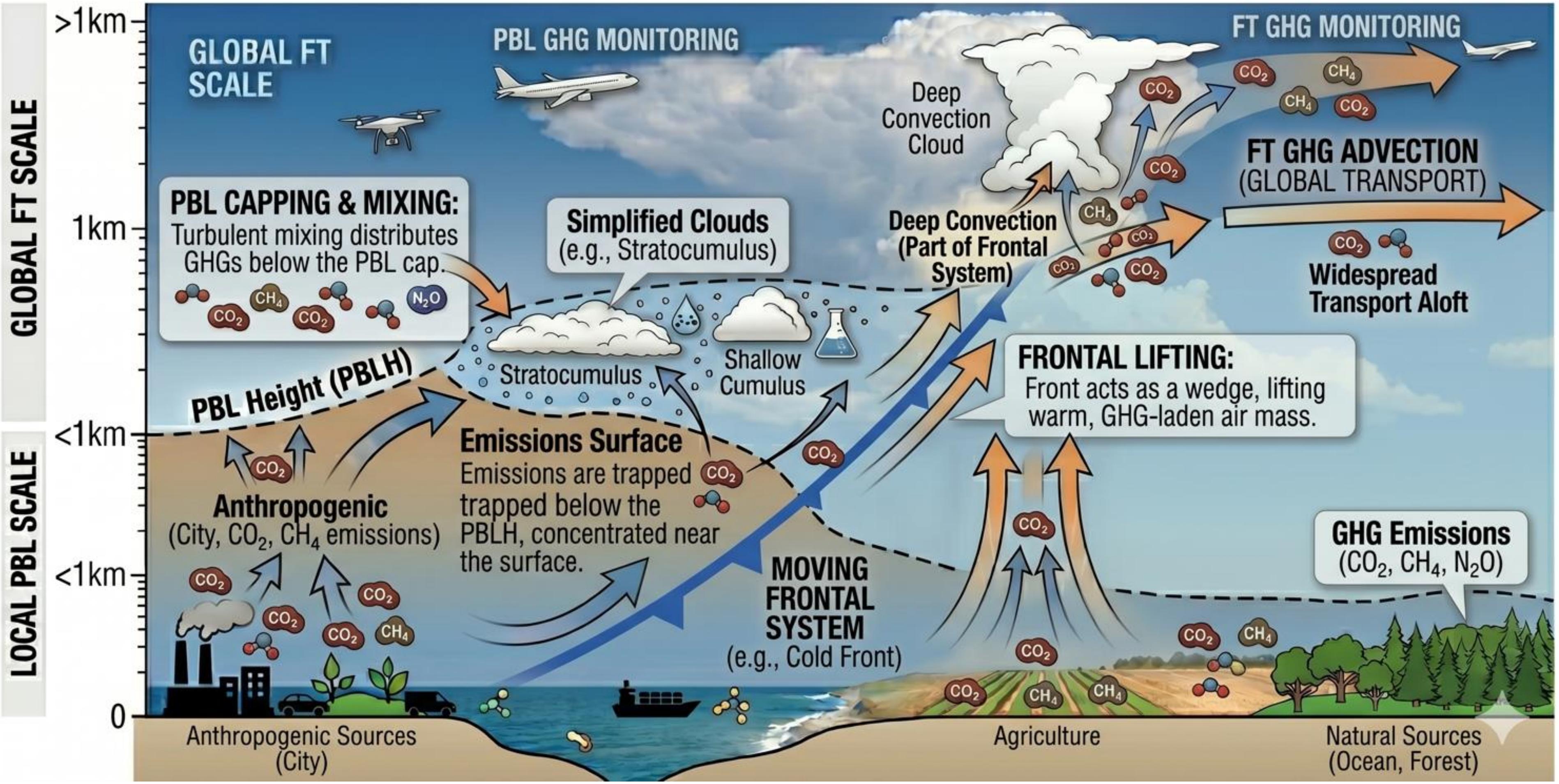
Weather as the Integrator of the Atmosphere

Aerosols and Clouds



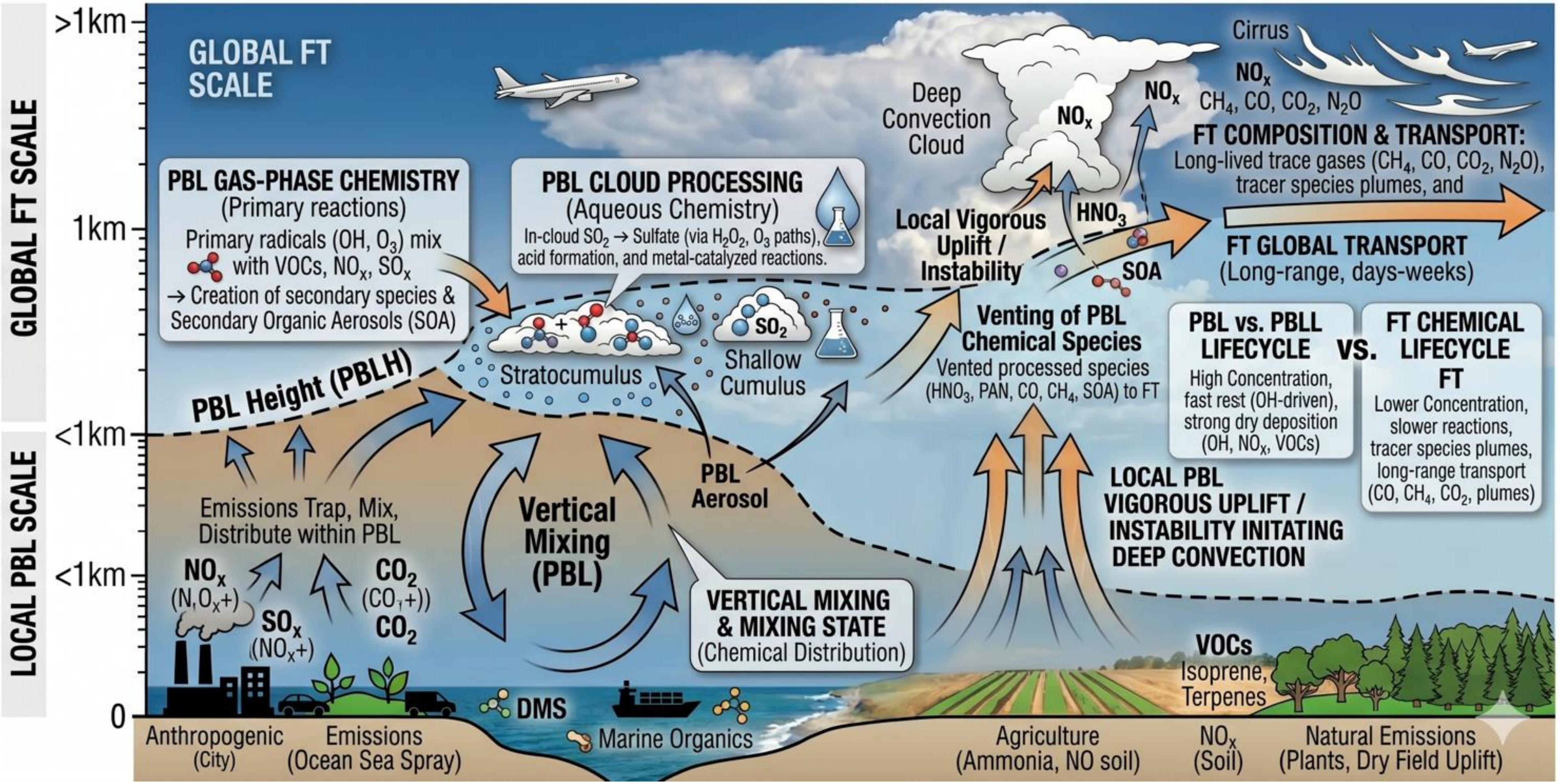
Weather as the Integrator of the Atmosphere

Greenhouse Gases



Weather as the Integrator of the Atmosphere

Troposphere and Stratosphere Composition



Roadmap – Integrated Observing System

2017 Earth Science Decadal Survey

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PBL DSI Study Team

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PBL DSI Study Team Report

National Aeronautics and Space Administration

NASA

TOWARD A GLOBAL PLANETARY BOUNDARY LAYER OBSERVING SYSTEM

THE NASA PBL INCUBATION STUDY TEAM REPORT

João Teixeira [1], Jeffrey R. Piepmeier [2], Amin R. Nehrir [3], Chi O. Ao [1], Shuyi S. Chen [4], Carol A. Clayson [5], Ann M. Fridlind [6], Matthew Lebsock [1], Will McCarty [2], Haydee Salmun [7], Joseph A. Santanello [2], David D. Turner [8], Zhien Wang [9], Xubin Zeng [10]

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[4] University of Washington, Seattle, WA
[5] Woods Hole Oceanographic Institution, Woods Hole, MA
[6] NASA Goddard Institute for Space Studies, New York, NY
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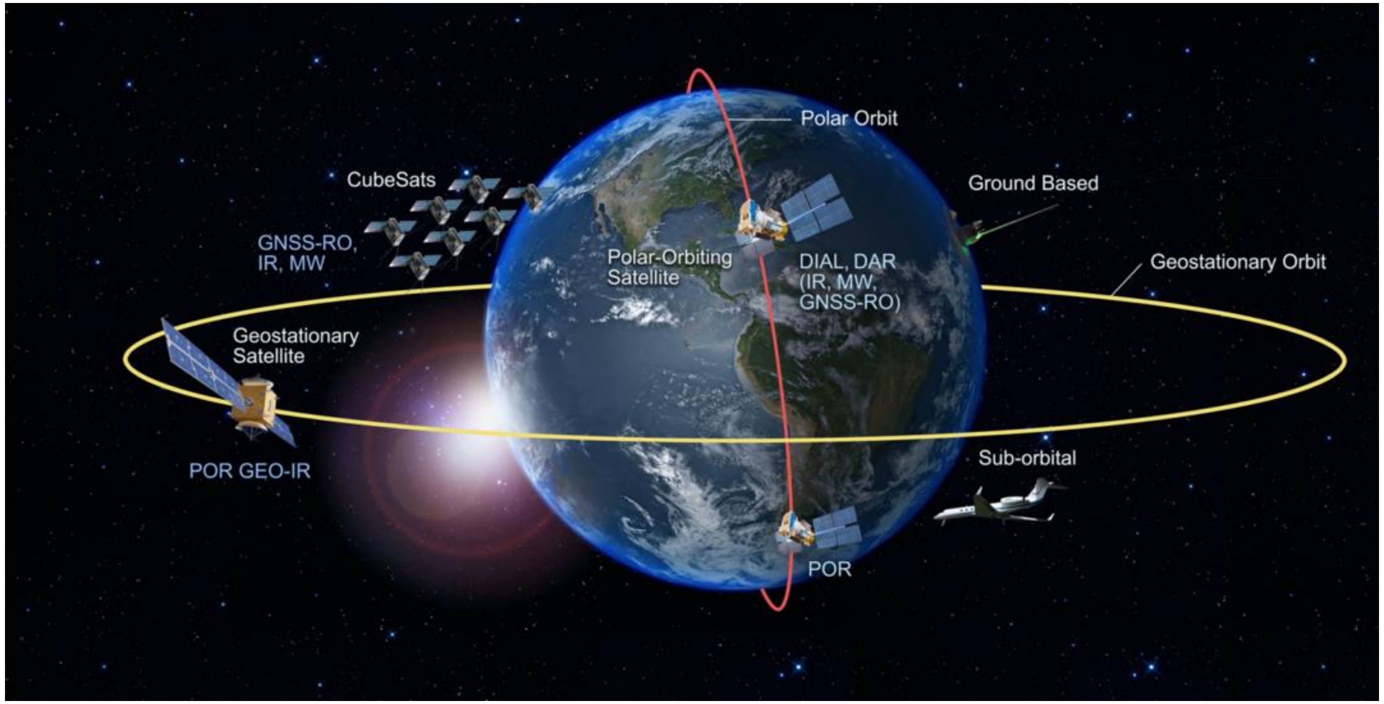

https://science.nasa.gov/earth-science/decadal-surveys/decadal-pbl/

Roadmap – Integrated Observing System

2017 Earth Science Decadal Survey

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PBL DSI Study Team

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PBL DSI Study Team Report

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PBL DSI ROSES-2021

National Aeronautics and Space Administration

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Essential components of a future global PBL observing system illustrated in Figure 1-1 include:

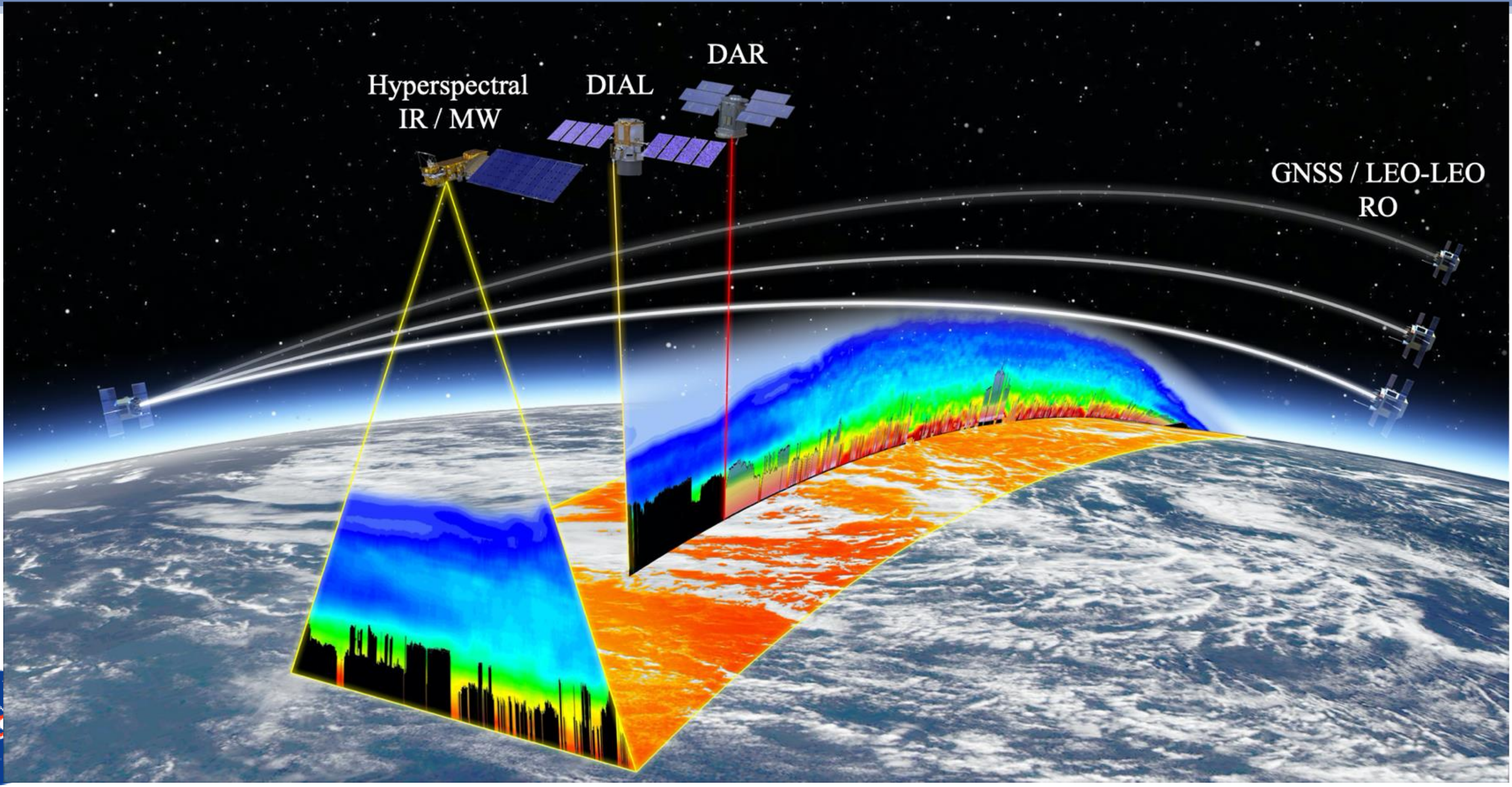
1. **Differential Absorption Lidar (DIAL) and Differential Absorption Radar (DAR) in low Earth orbit (LEO)** to provide high vertical resolution (approximately 200 m) water vapor profiles and high horizontal resolution (1 km) total precipitable water in clear and cloudy conditions, estimates of temperature profiles in liquid phase clouds (DAR), profiles of aerosols and clouds, and high horizontal resolution (1 km) estimates of PBL height (DIAL).
2. **High horizontal resolution hyperspectral infrared (IR) (1 km) and microwave (MW) (5 km) sounders in LEO** to provide 3D temperature and water vapor structure context to DIAL+DAR observations, potentially on SmallSat or CubeSat constellations (to provide higher temporal sampling).
3. **Radio Occultation (RO)** using larger constellations of Global Navigation Satellite System (GNSS-RO) receivers and/or novel orbital configurations and signal frequencies to provide additional high-vertical resolution and temporal sampling of temperature and/or water vapor profiles, and reliable estimates of PBL height.
4. **Geostationary hyperspectral IR sounding**, taking advantage of international (e.g., EUMETSAT) and national inter-agency (NOAA) collaborations, to dramatically increase temporal sampling of temperature and water vapor profiles.
5. **Modeling and data assimilation** capabilities to optimally assimilate these PBL observations to produce the best state estimate of PBL thermodynamics globally (with a potential focus over the continental United States) every day.

Additional key components include:

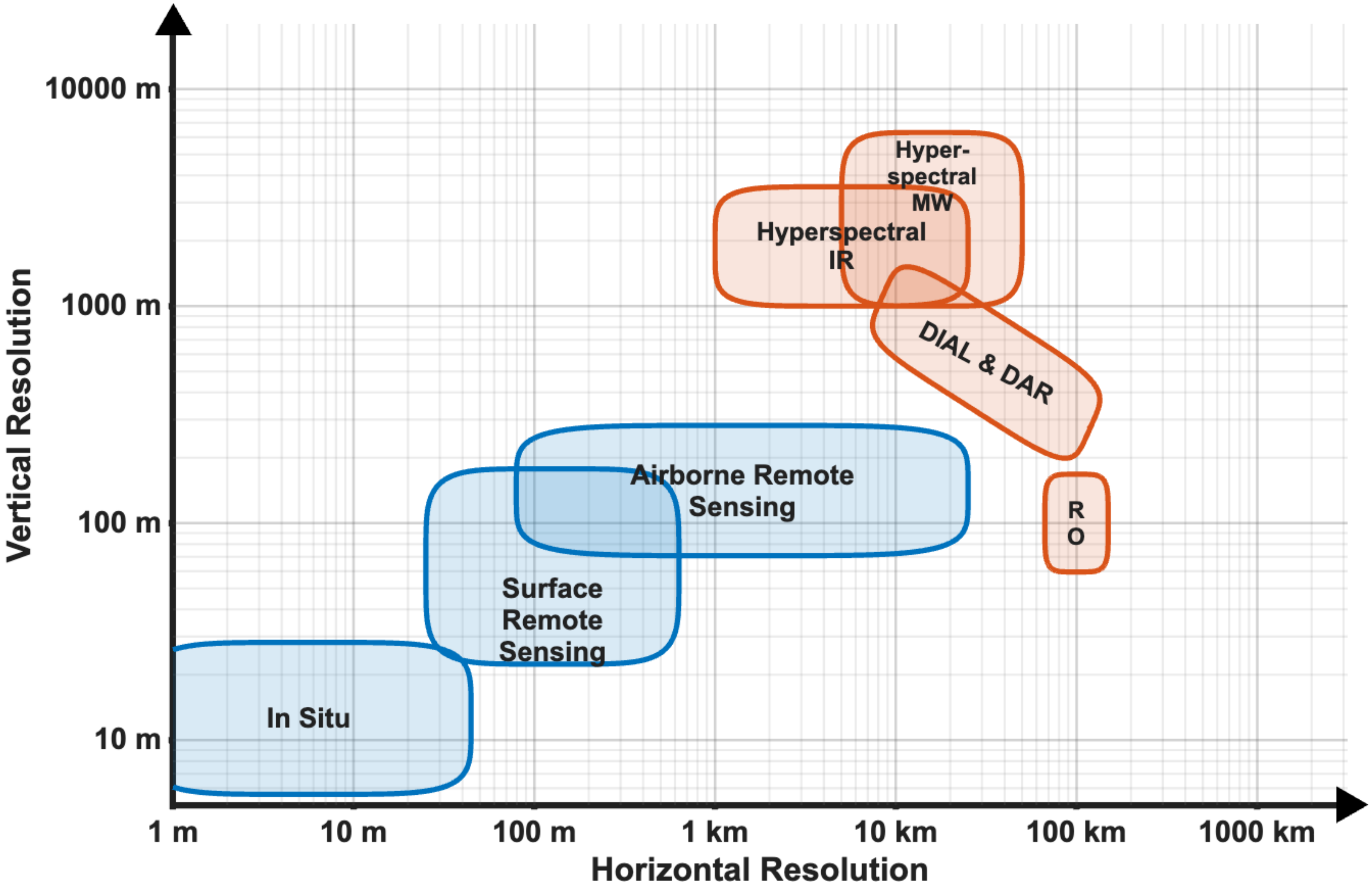
- Program of Record (POR) observations from a variety of platforms (space, suborbital, and surface-based).
- Suborbital campaigns focused on technology demonstrations, data fusion, and process studies in different regions.

https://science.nasa.gov/earth-science/decadal-surveys/decadal-pbl/

Synergistic Observations



Bridging Spatial Scales – Orbital to Suborbital



Community Engagement

- Spring 2023 virtual community meeting
- Fall 2023 community meeting, College Park, MD
- Spring 2024 community meeting, Pasadena, CA
- Fall 2024 Joint Sounder/PBL science team meeting, Pasadena, CA
- Spring 2025 community meeting, Silver Spring, MD
- Fall 2025 community meeting, Hyattsville, Maryland
- Spring 2026 community meeting, Pasadena, CA

DSI – Science Element: Community Engagement

A Global Planetary Boundary Layer Observatory:
The Cloudy PBL White Paper

By

Cloudy PBL White Paper Team

1. Summary

Fundamental planetary boundary layer (PBL) science questions and societal applications urgently require a global PBL observatory based on a core PBL orbital component with strong synergy between orbital, suborbital and surface platforms. The focus of this new global PBL observatory will be on producing novel, global and detailed observations of the PBL thermodynamic structure using innovative observational technologies and architectures, complemented by critical innovations in PBL data science and physical modeling.

Joao Teixeira

NASA PBL Convection and Extreme Weather White Paper Version 2 (10/1/2025)

Authored by the DSI PBL Convection and Extreme Weather Working Group

1. Summary

The planetary boundary layer (PBL) is where convective storms begin and where their greatest impacts are felt. Humidity, stability, and shear in the PBL are essential controls on the occurrence, structure, and intensity of deep, precipitating convection. However, the PBL varies widely in space and time, making it difficult to assess *why convection occurs where and when it does*. Current PBL observations are either made in-situ with high fidelity but poor spatial coverage, or from spaceborne sensors with good spatial coverage but insufficient space-time resolution for resolving many features associated with convective initiation and evolution. The *solution* is a space-based mission that can overcome existing resolution and retrieval limitations with advances in technology, particularly using sensors that can operate in cloudy and precipitating conditions associated with convective storms. Suborbital technology could complement and enhance the science benefits of space-based retrievals to observe processes at scales not possible from space.

Courtney Schumacher

The Importance of Surface-Atmosphere Interactions for a Mission focused on the Planetary Boundary Layer

Authored by the PBL DSI Surface Interactions Working Group

1. Executive summary

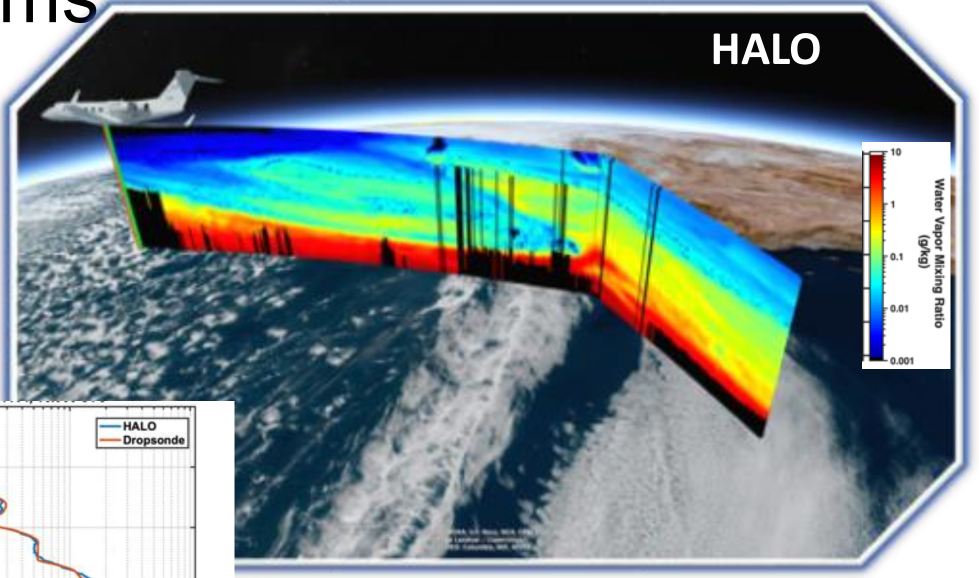
The NASA Planetary Boundary Layer (PBL) mission will be transformational to advancing PBL science and applications. Such a mission will require a significant focus on the key connections of the PBL to the surface and to the lower troposphere across time (diurnal to interannual) as well as across space from point-to-pixel-to-planet. This includes acknowledging and integrating the dynamics of the Earth ***surface*** and especially how the influence of these ***surface dynamics*** feed back to the PBL changes over time and space. These processes can have significant impacts on a variety of natural hazards, including extreme precipitation leading to floods and landslides, droughts that affect the water management and agriculture sectors, as well as wildfires, dust storms, and heatwaves that influence public health and wealth. Therefore, improvement in understanding the PBL and especially its interactions with the surface has direct consequences for decision makers across sectors as prioritized under NASA's Earth Science to Action Strategy.

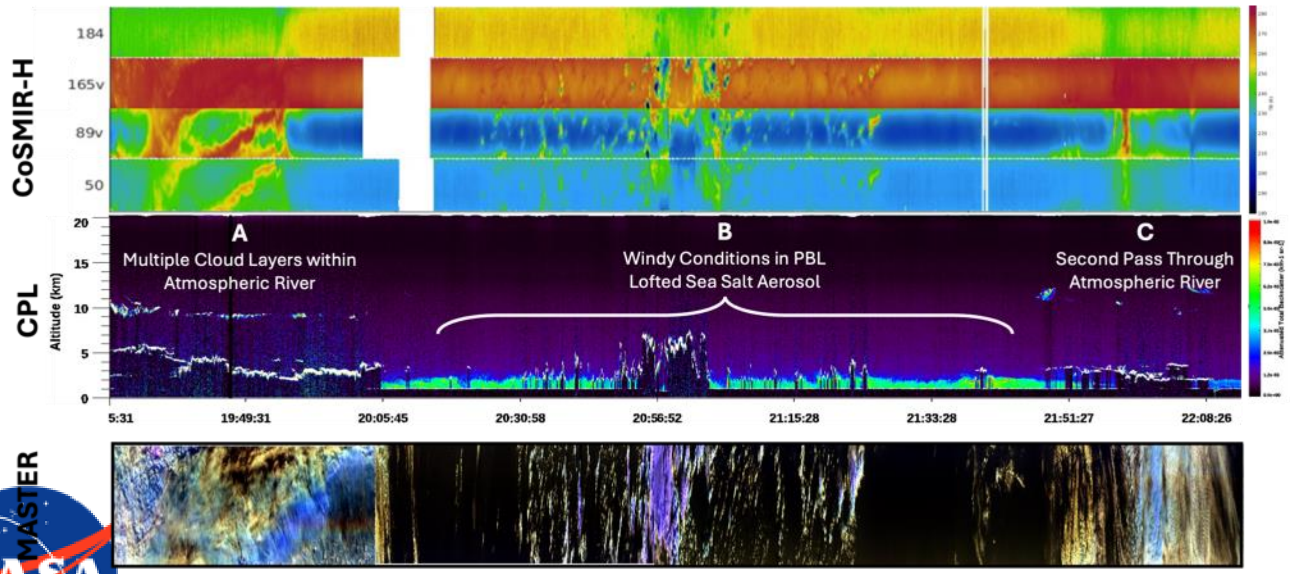
Shawn Serbin

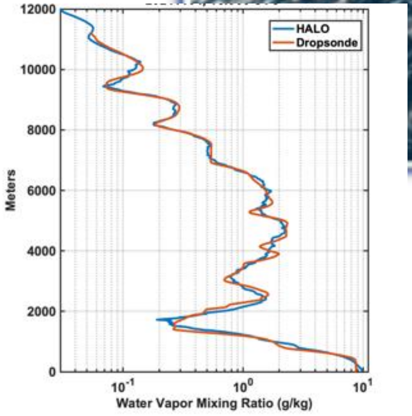
https://science.nasa.gov/earth-science/decadal-surveys/decadal-pbl/

DSI – Technology Element

- Advance subcomponents and subsystems towards enabling new measurement techniques and transitioning mature techniques to flight
- Develop airborne simulators to demonstrate measurement capability, validate fwd. models, and advance algorithms
- Technology Demonstration Flights







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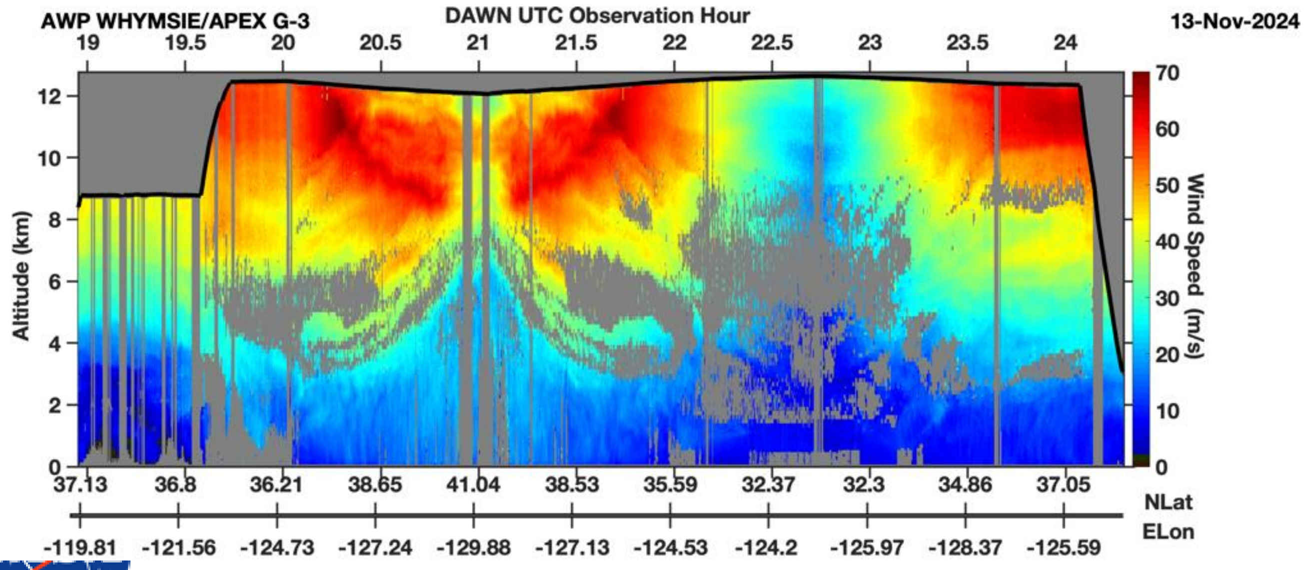

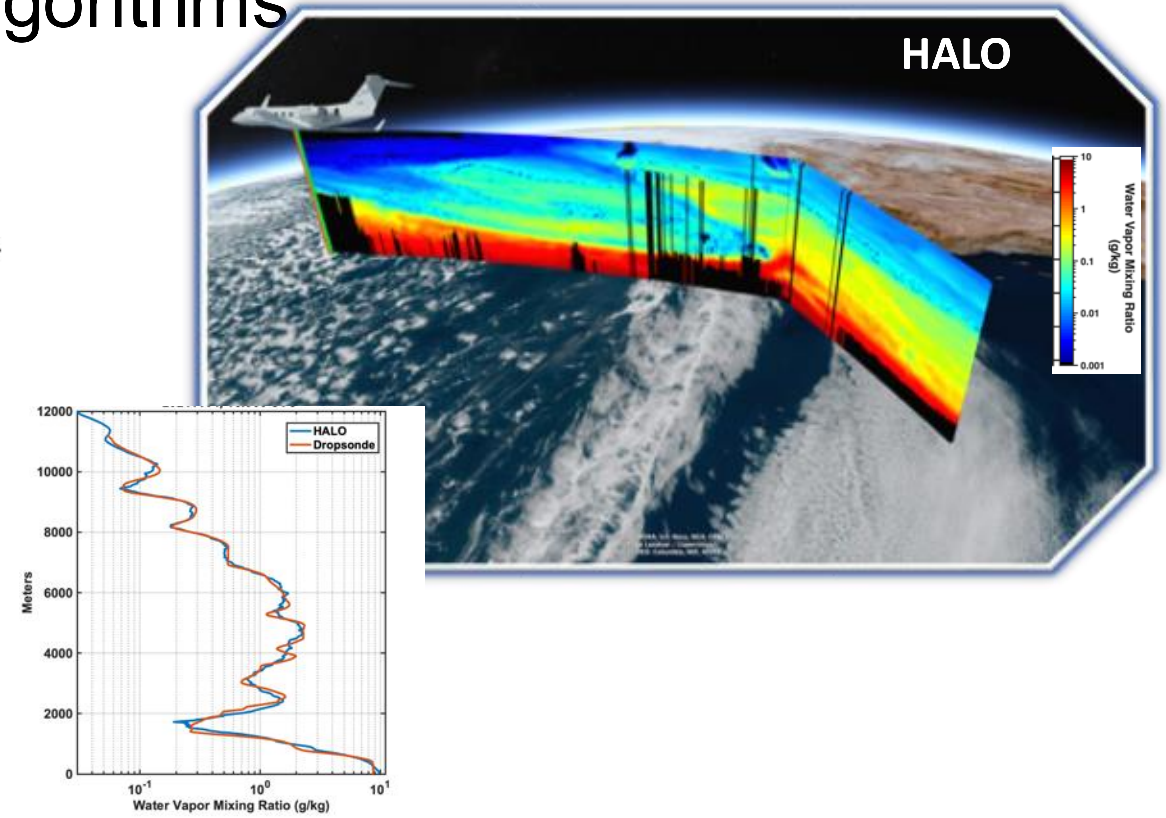

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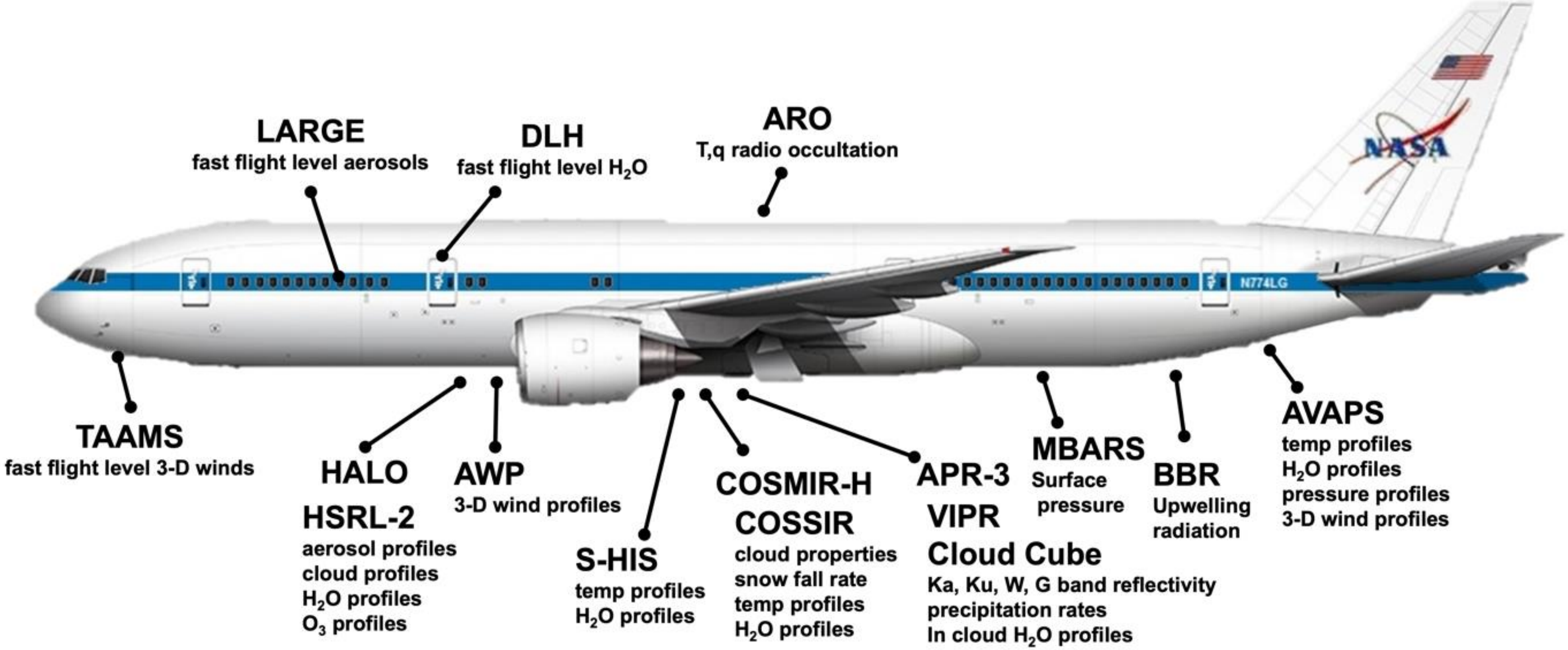
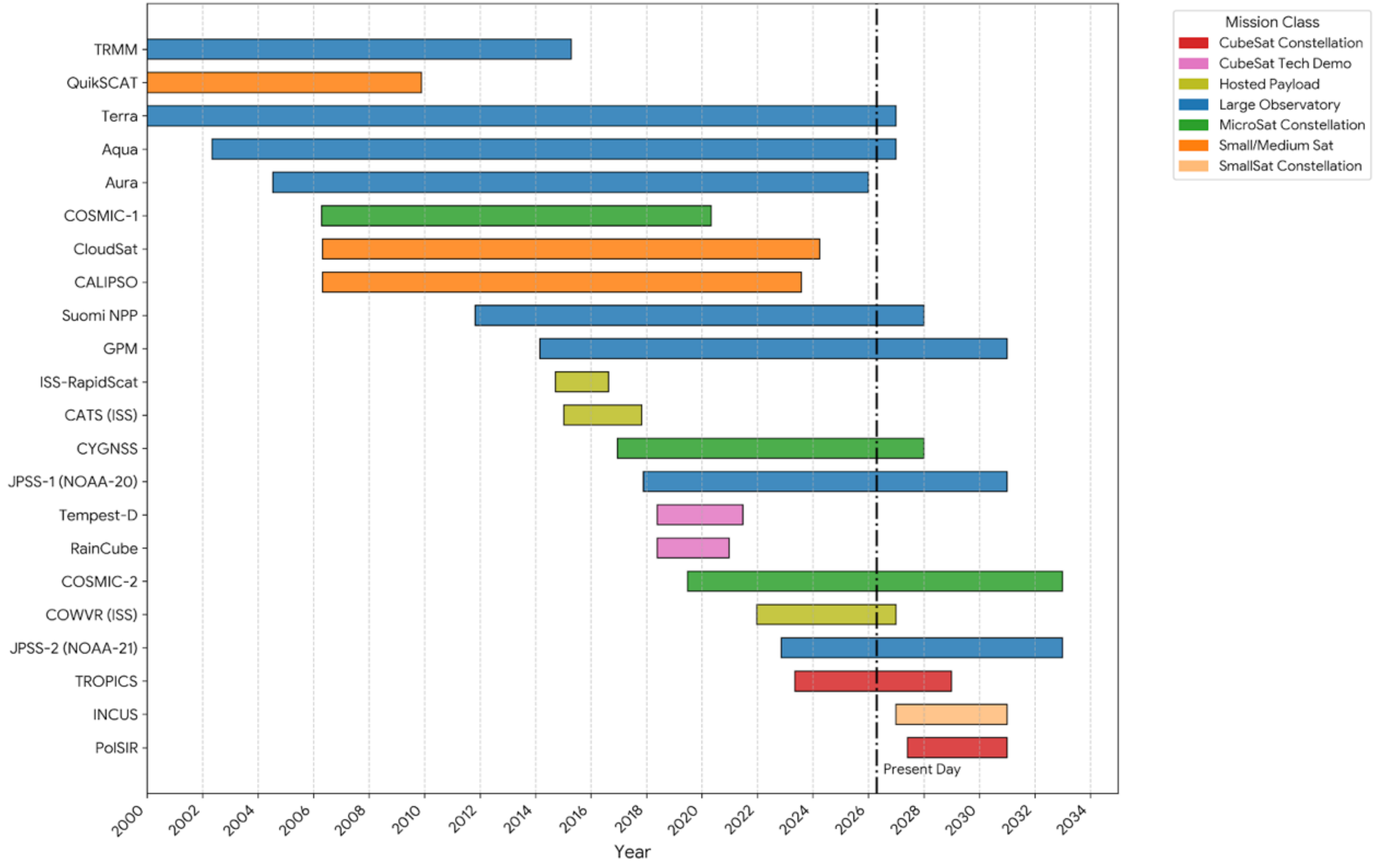
PHILIPPINES EXPERIMENT

Airborne Process Studies



- The PBL is not decoupled from the rest of the atmosphere. Don't focus solely on PBL because it's a program line
- Consider mission architectures that cut across different communities



- The PBL is not decoupled from the rest of the atmosphere. Don't focus solely on PBL because it's a program line
- Consider mission architectures that cut across different communities
- Observing Earth from space is our charter, but doesn't address all our knowledge gaps
- Utilize airborne campaigns to study processes not possible from space. Our aircraft and technologies set us apart from other agencies
- Remember – Weather is the integrator across our sphere. Crosspollinate across communities when and where possible to maximize opportunities
- Undersell, over deliver. Be pragmatic about what can scientifically and technologically be achieved.
- Build community consensus going into the 27 decadal

Overview of 28 Survey Responses

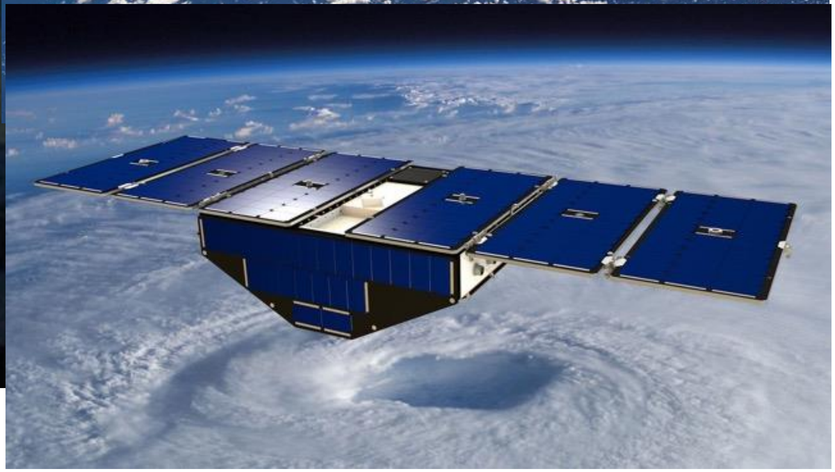
Priorities: Planetary Boundary Layer

- Particular emphasis on the need for concurrent observations of thermodynamic (T/q) and dynamic (wind) profiles.
- Outstanding questions:
  - How does PBL structure and evolution modulate local and remote processes relating to:
    - Convective initiation
    - Extreme hydrological events
    - Diurnal cycle
  - Air-sea interaction
    - What roles do surface wind stress, convergence, and vorticity play in helping convection grow upscale?

- Observables:
  - High-resolution thermodynamic profiles
  - High-resolution 3-D winds

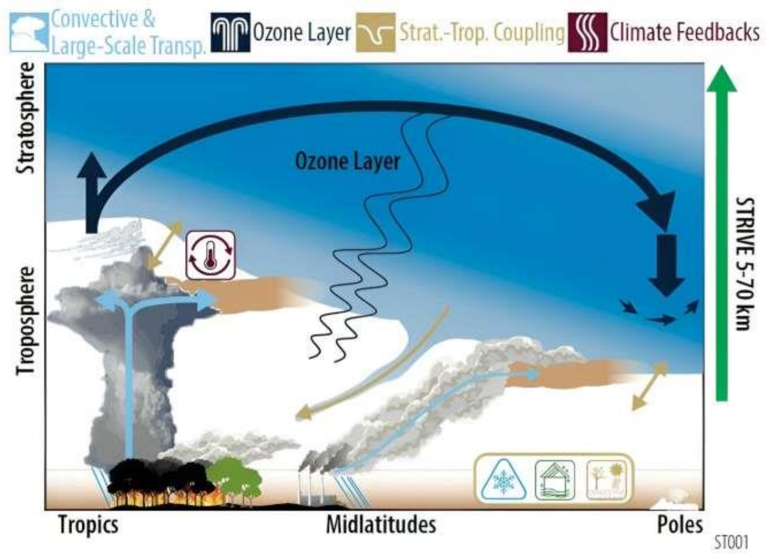
Priorities: Convection and vertical motion

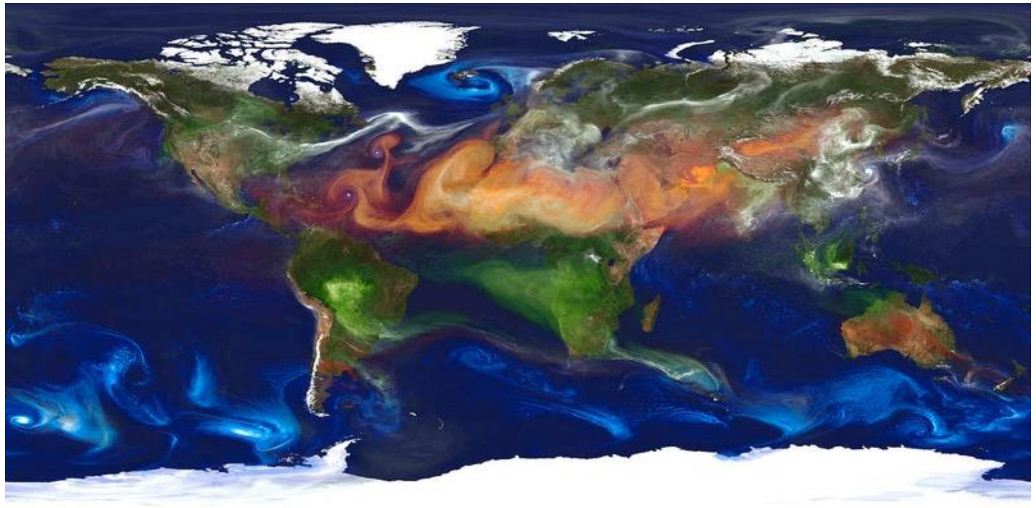
- Particular emphasis on extreme weather events (heatwaves, droughts, severe thunderstorms, winter storms, hurricanes)
  - Outstanding questions:
    - What are the relative roles of the PBL vs. mid/upper-level forcing in convective initiation?
    - What are roles of moist processes and latent heat release in the development of cyclones and atmospheric rivers?
  - Observables:
    - Convective mass flux
    - 3-D wind and thermodynamic profiles
    - Lightning



Your Survey Responses: Interconnections

- Particular emphasis on aerosols, radiation, and troposphere-stratosphere exchange
- Outstanding questions:
  - How does overshooting convection transport water vapor, aerosols, and pollutants into the lower stratosphere?
  - How do aerosols act as cloud condensation nuclei and how does this impact convection and storm intensity?
  - How does convection affect large-scale circulations (Brewer-Dobson, Walker Circulation, Hadley Cell)?

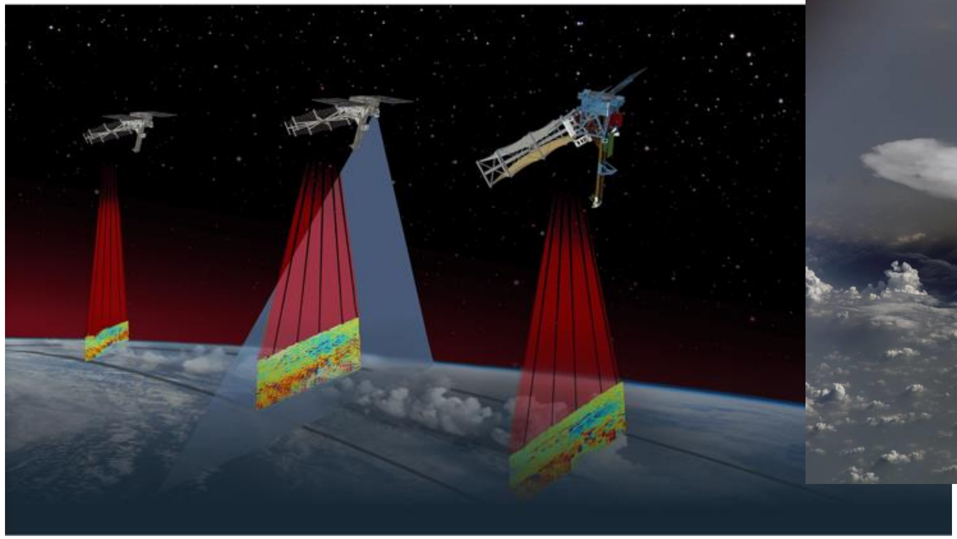




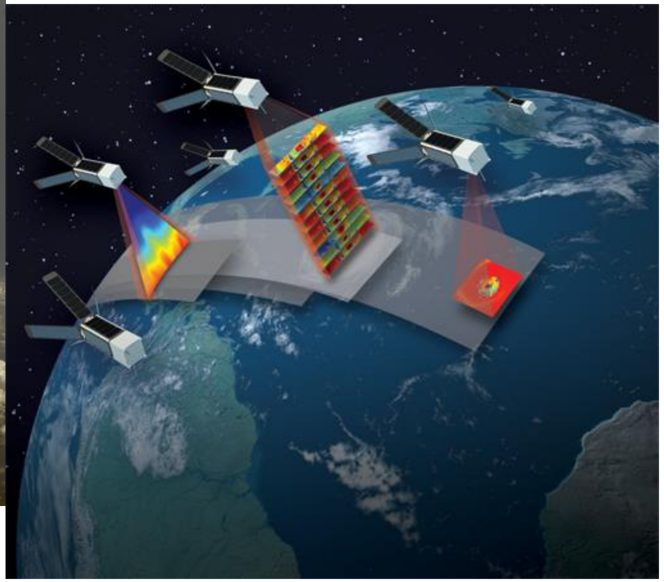
Your Survey Responses: Spaceborne Observing Strategies

- Combine active sensors with passive sensors to retrieve 3-D cloud properties
- Constellations of smallsats to capture rapidly evolving phenomena
- Include lower-frequency microwave channels for precipitation retrievals
- High-resolution thermodynamic profiling (hyperspectral MW/IR)
- 3-D tomographic/stereographic imaging for high clouds
- Global high-resolution lightning mapping

INCUS, incus.colostate.edu

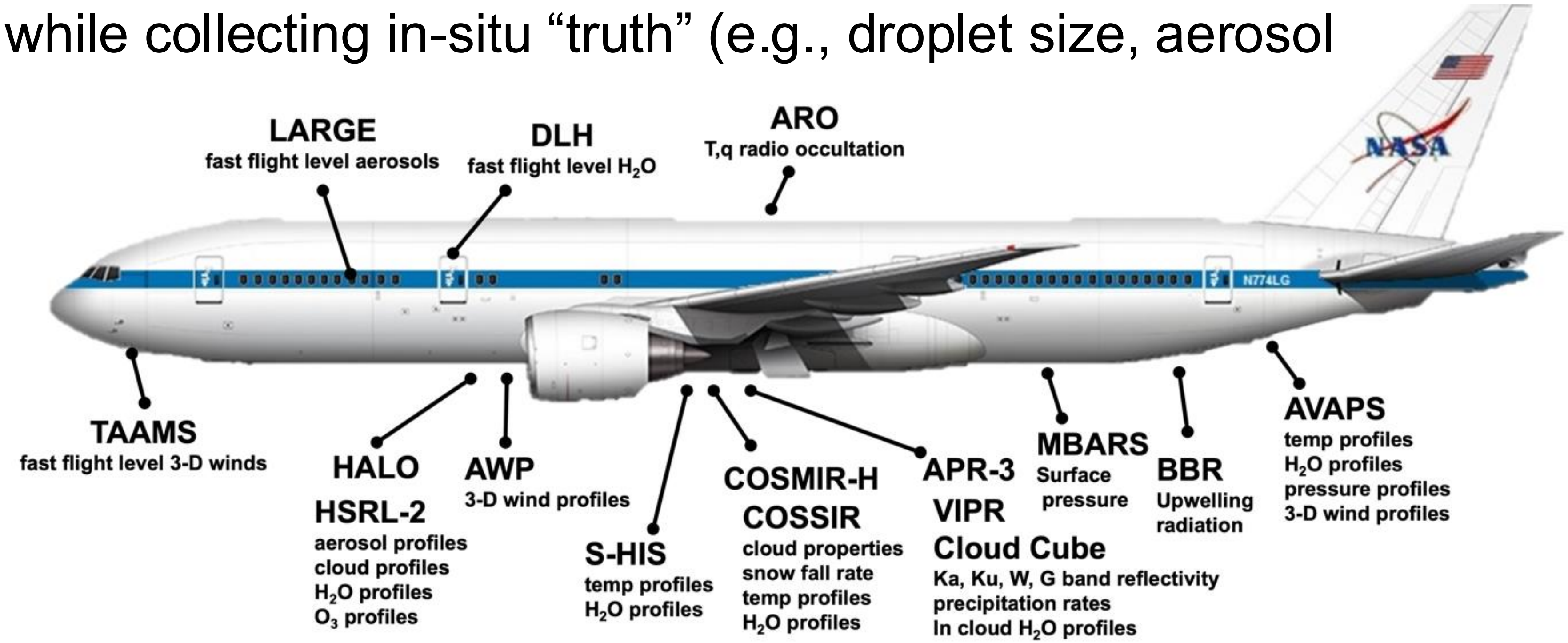


TROPICS,
https://weather.ndc.nasa.gov/tropics/



Your Survey Responses: Airborne Observing Strategies

- Employ the NASA 777 to reach remote regions and employ its large payload capacity to collect collocated thermodynamic and kinematic observations.
- Perform high-altitude sampling with ER-2, WB-57, G-III to observe troposphere-stratosphere exchange.
- Lagrangian process studies that follow air masses as the evolve (e.g., aging wildfire smoke plumes, arctic mixed-phased clouds, marine boundary layer)
- Test new instruments while collecting in-situ "truth" (e.g., droplet size, aerosol composition.)



Your Survey Responses: Modeling Strategies