Lidars:
CALIPSO, EarthCARE, ACCP

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with input from
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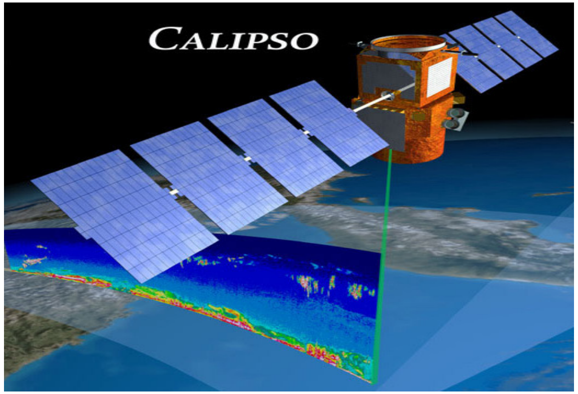
CEOS AC-VC #17
7-11 June 2021
Virtual Meeting

Lidars in Space: Now, Next & Beyond

CALIPSO: 2006-2023



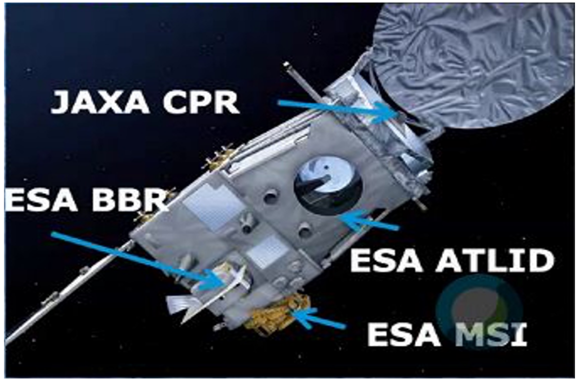
Launch date: April 28, 2006

Mission duration: 15+ years …

Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) backscatter lidar that provides high-resolution vertical profiles of aerosols and clouds

- Instrument and spacecraft are healthy and operating nominally
- Do not anticipate ops beyond 2023
- CALIOP v4.5 products planned for Fall
- Data quality issues over SAA since 2019

EarthCARE: 2023-27



Expected Launch date: March 2023

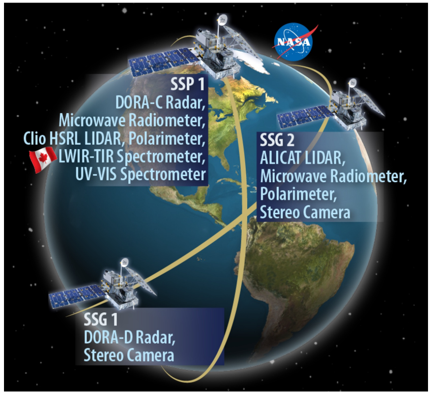
Mission duration: 3 years + 1

Payload: 2 active (ATLID & CPR), 2 passive (BBR & MSI) instruments

ATmospheric LIDar (ATLID) – UV HSRL lidar with depolarization providing high resolution profiles of aerosols

- ATLID is complete and passed functional and performance tests
- ATLID was integrated last year
- Level 2 products expected right after launch
- CPR Doppler radar, W-band

ACCP: 2028-2031+



Expected Launch dates: 2027, 2028

Mission duration: 3+ years

Payload: Lidars, Doppler radars, polarimeters, microwave radiometers, stereo cameras, spectrometers for ***Aerosols, Clouds, Convection and Precipitation***

ALICAT backscatter lidar: inclined orbit

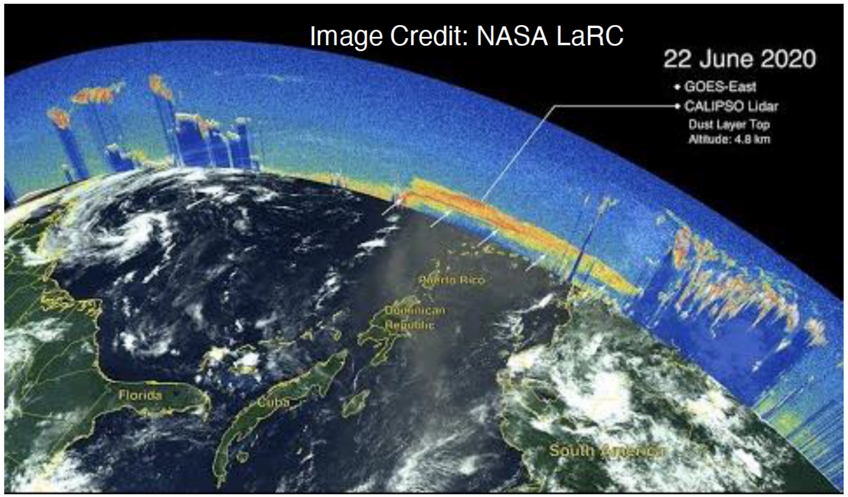
Clio VIS HSRL lidar: polar orbit

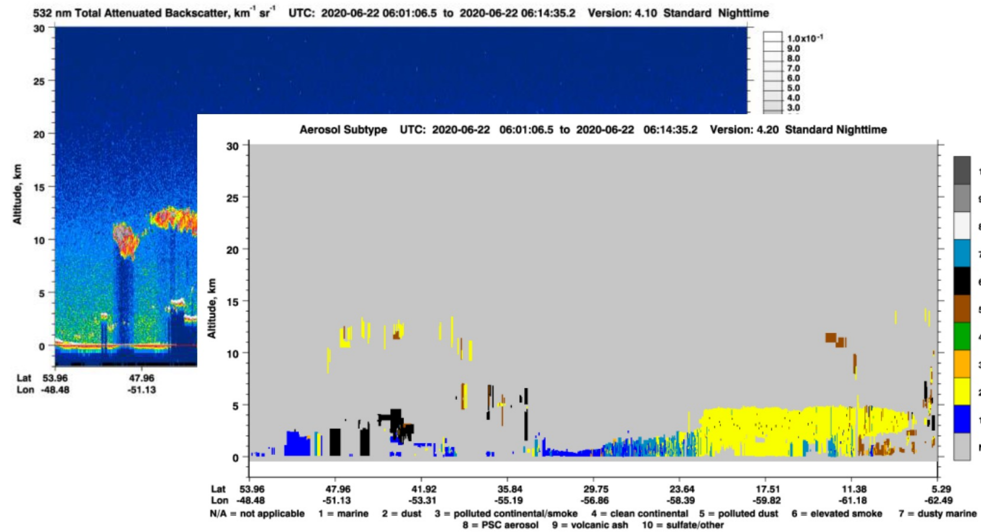
- Recommended by 2017 Decadal Survey
- Pre-formulation Study concluded in 2021
- Currently in Pre-phase A

Relevant URLs

- CALIPSO: https://www-calipso.larc.nasa.gov
- EarthCARE
  - ESA: https://earth.esa.int/eogateway/missions/earthcare
  - JAXA: https://global.jaxa.jp/projects/sat/earthcare/
- ACCP: https://vac.gsfc.nasa.gov

Current: Lidars for Aerosols





- CALIOP, flying in NASA A-Train, observes vertical structure of aerosols in atmosphere
- **Advantages**: Vertical distribution of aerosol types (i.e., coarse dust vs fine particles) and concentrations, including in lower troposphere where people live
- **Limitations**: Limited spatial coverage with lidar curtain, large uncertainties separating between fine mode aerosols (e.g., smoke) and aerosol mixtures

CALIPSO Status

- CALIOP and CALIPSO spacecraft
  - both healthy and operating nominally
  - except that propellant has been depleted
- Don’t anticipate operation beyond September 2023
- Plan to release CALIOP V4.50 data products in the fall
  - improved calibration and improvements in aerosol products
- Experiencing data quality issues over the SAA since 2019
  - a future data product release will improve data quality within the SAA

EarthCARE Satellite

Orbit:

- 393 km mean altitude
- Sun Synchronous frozen orbit
- 97° Inclination
- 14h00 DSN MLST
- 25-days repeat cycle

Lifetime:

- 3 years + 1 (incl. 6-months commissioning)
- Launch date MARCH 2023

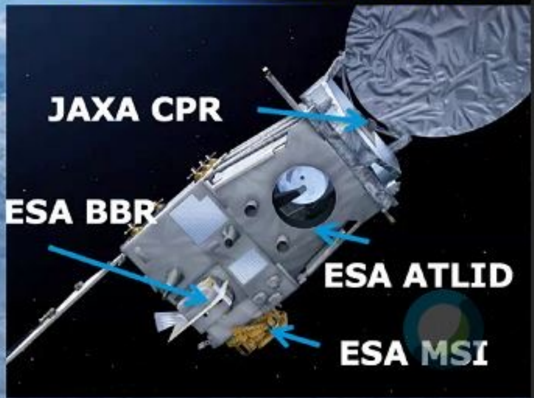
Space Links:

- S-Band:
  - Kiruna KIR1 / KIR2 Ground stations
  - 64 kbps uplink
  - 128 kbps / 2 Mbps downlink (with/without ranging)
- X-Band:
  - Kiruna-Esranges & Inuvik Ground stations
  - 150 Mbps downlink

Satellite:

- 2350 kg (incl. 313 kg propellant)
- 3-axis stabilized / yaw-steering
- 1700W
- On-board data rates average:
  <15 kbps (HKTM)
  <2.5 Mbps (science)

Payload:
2 active instruments (ATLID & CPR)
2 passive instruments (BBR & MSI)



EarthCARE Spacecraft Status

EarthCARE integrated at Airbus. System level functional and performance tests ongoing.

Open Work: 2021 Complete CPR testing, MSI modifications, Perform all system level tests, including System Validation Tests. **2022** Environmental test campaign @ESTEC, CPR HPT-A integration, Acceptance Review.

CPR Status

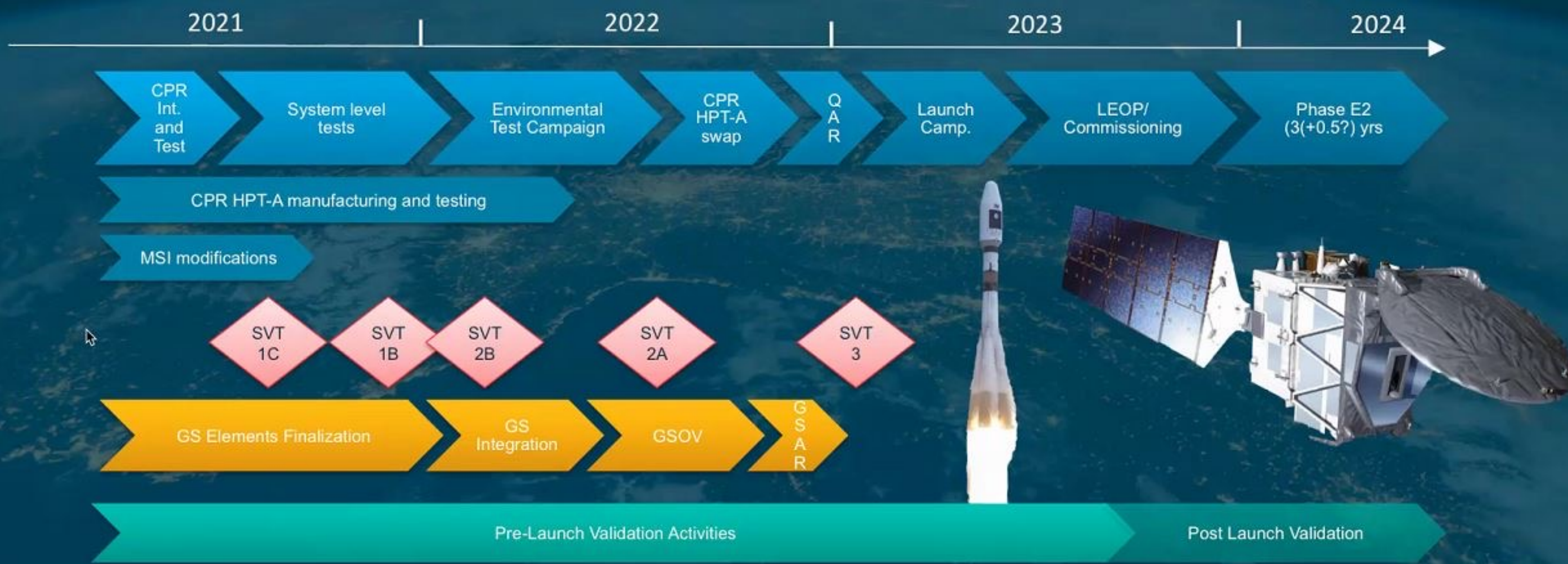
HVGM potting. Image courtesy Leonardo

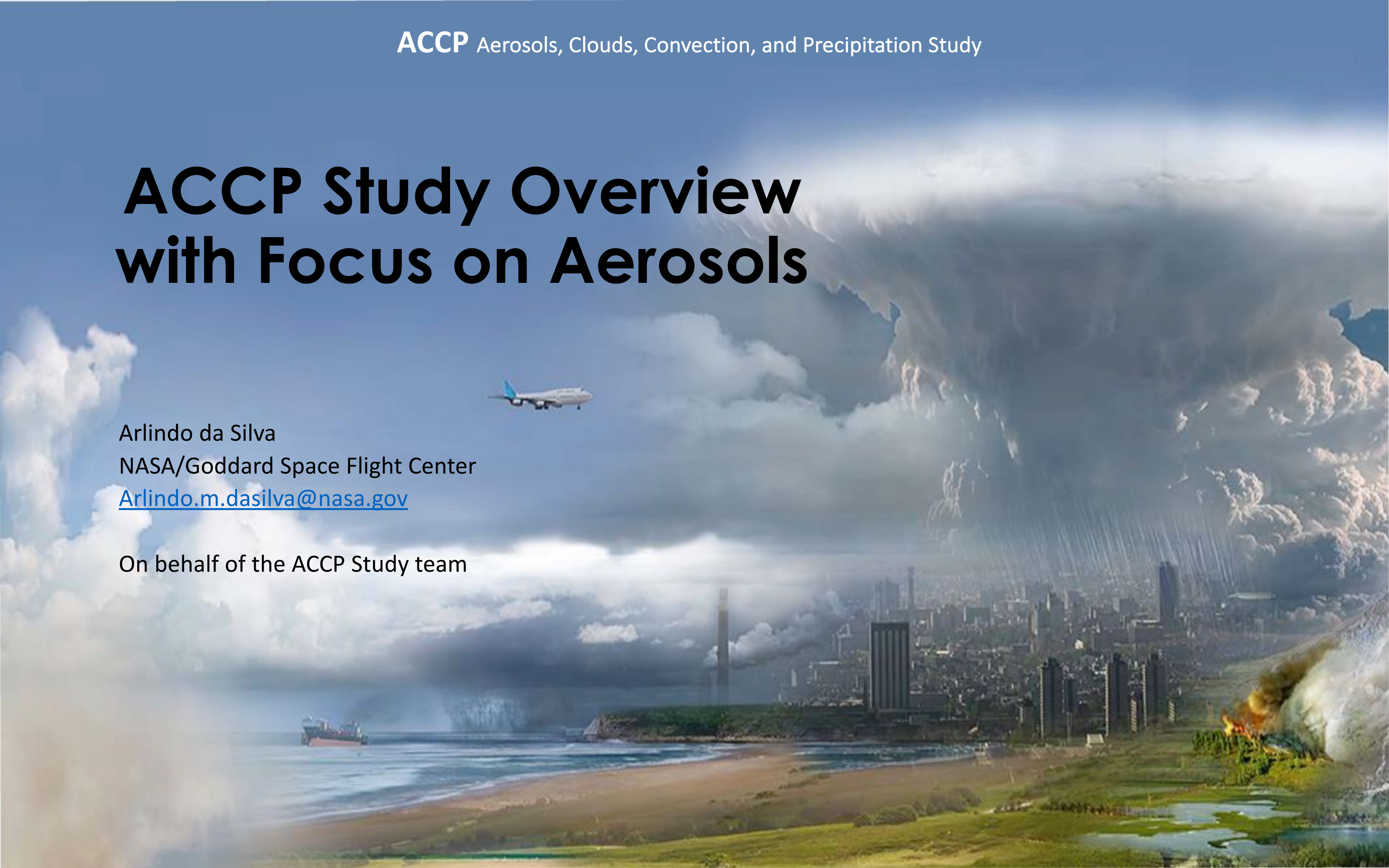
Movie and image courtesy Airbus

CPR mechanically and electrically integrated on spacecraft.

Open Work: Instrument Performance Check, Integrated System Tests and deployment test ongoing in Q2 2021. Manufacturing of redundant HPT ongoing for later integration in CPR.

EarthCARE planned activities





ACCP Study Overview with Focus on Aerosols

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On behalf of the ACCP Study team

Thriving on Our Changing Planet

A Decadal Strategy for Earth Observation from Space

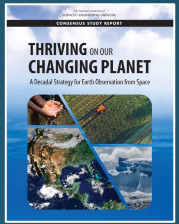
Available from http://sites.nationalacademies.org/DEPS/ESAS2017

Recommended NASA Flight Program Elements

Program of Record. The series of existing or previously planned observations, which **should be completed as planned**. Execution of the ESAS 2017 recommendation requires that the total cost to NASA of the Program of Record *flight missions from FY18-FY27 be capped at $3.6B.*

- ***Designated.*** A new program element for ESAS-designated cost-capped medium- and large-size missions to address ***observables essential to the overall program*** and that are outside the scope of other opportunities in many cases. Can be competed, at NASA discretion.
- ***Earth System Explorer.*** A new program element involving competitive opportunities for medium-size instruments and missions serving specified ESAS-priority observations. ***Promotes competition among priorities.***
- ***Incubation.*** A new program element, focused on investment for priority observation opportunities needing advancement prior to cost-effective implementation, including an Innovation Fund to respond to emerging needs. ***Investment in innovation for the future***.
- ***Venture.*** Earth Venture program element, as recommended in ESAS 2007 with the addition of a new Venture-Continuity component to provide ***opportunity for low-cost sustained observations***.

Scientific and Programmatic Basis



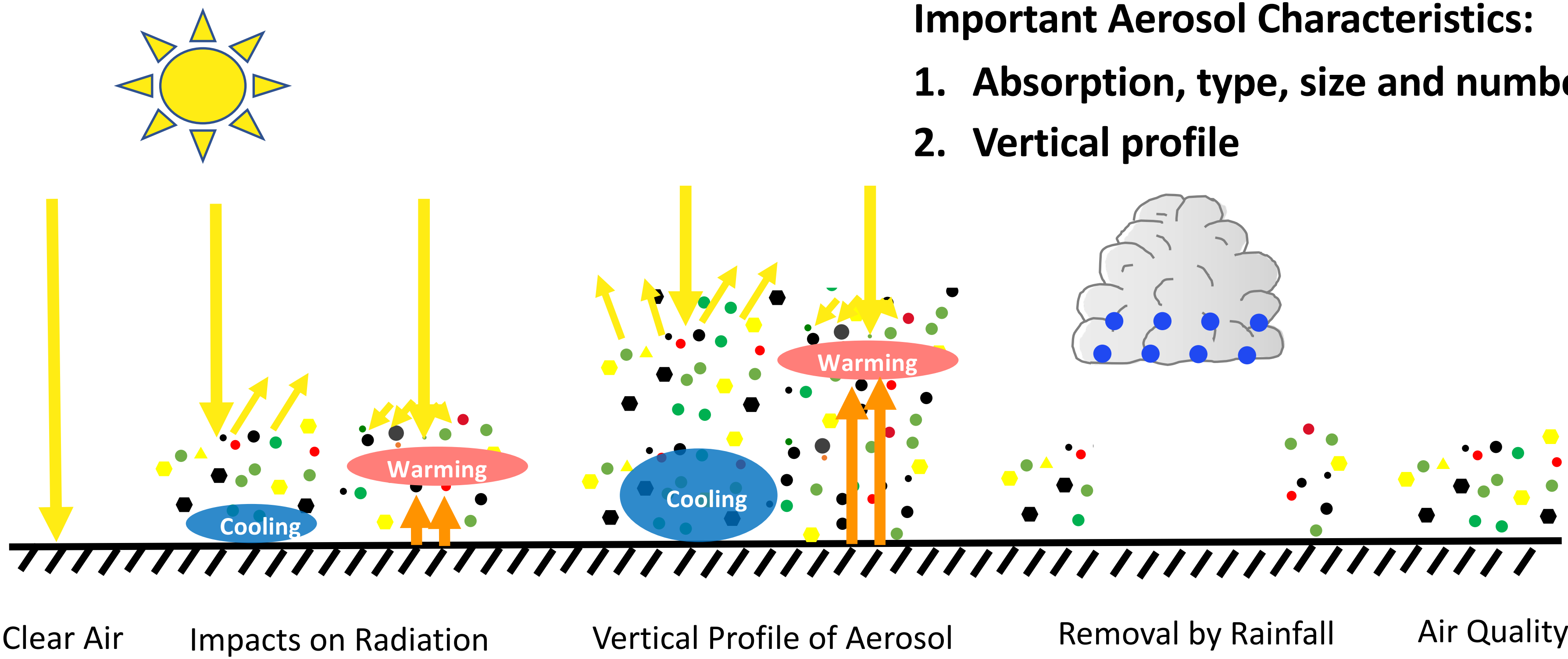
- The 2017 Decadal Survey recommended a new program element called *Designated Observables* with cost-caped missions to provide measurements essential to a comprehensive collection of Earth Science questions.
- ACCP combines 2 Designated Observables

	Aerosols	**Clouds, Convection, and Precipitation**
Observable Priorities	Aerosol properties, aerosol vertical profiles, and cloud properties to understand their effects on climate and air quality	Coupled cloud-precipitation state and dynamics for monitoring global hydrological cycle and understanding contributing processes including cloud feedback
Desired Observables	Backscatter lidar and multi-channel, multi-angle imaging polarimeter	Radar(s), with Doppler, with multi-frequency passive microwave and sub-mm radiometer

Profiles of Aerosol Properties

Important Aerosol Characteristics:

1. **Absorption, type, size and number**
2. **Vertical profile**

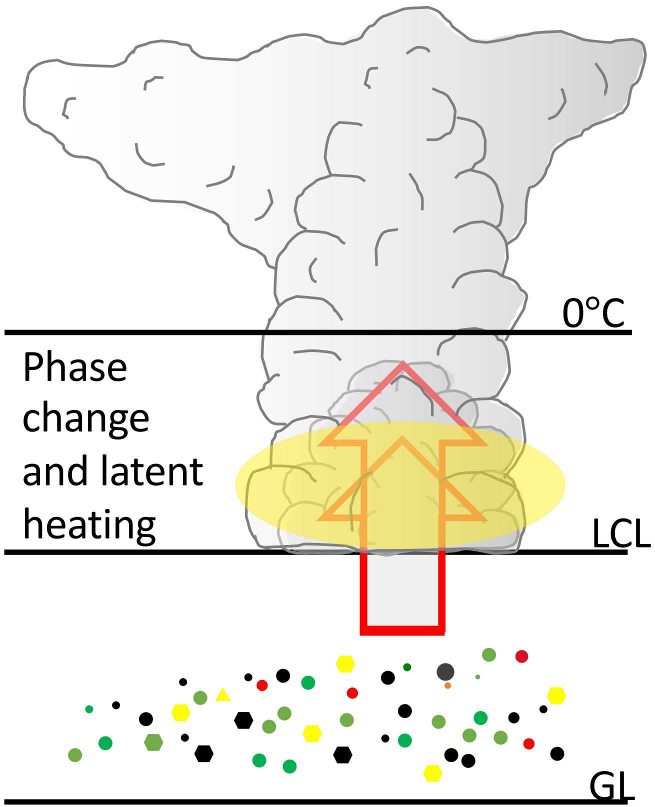


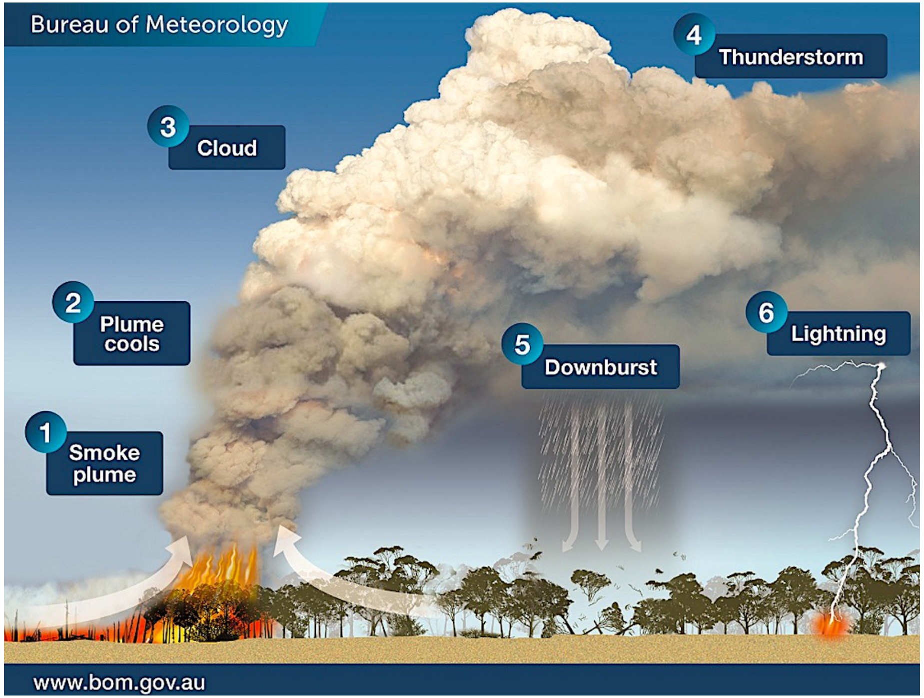
Slide Credit: Sue van den Heever

Needed Measurements

- **High-resolution profiles of aerosol properties**, including absorption and types → better quantify warming and anthropogenic contributions to forcing
- **Aerosol observations in the boundary layer** → advance our capabilities of identifying anthropogenic aerosols and links to human health
- **Simultaneous measurements of aerosol and precipitation processes** → better understanding of removal and redistribution processes

Dynamics, μphysics and Aerosol Characteristics





The storms developing in association with recent fires demonstrate links between vertical motion, aerosols, cloud and precipitation processes

DS Science Related to ACCP

Weather & Air Quality

W-1 (MI): Planetary Boundary Layer Dynamics. What PBL processes are integral to the air-surface exchanges of energy, momentum, and mass, and how do these impact weather forecasts and AQ simulations?

W-2 (MI): Larger Range Environmental Predictions. How can environmental predictions of weather and air quality be extended to lead times of 1 week to 2 months?

W-4 (MI): Convective Storm Formation Processes. Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?

W-5 (MI): Air Pollution Processes and Distribution. What processes determine the spatio-temporal structure of important air pollutants and their concomitant adverse impact on human health, agriculture, and ecosystems?

W-6 (I): Air Pollution Processes and Trends. What processes determine long-term variations and trends in air pollution and their subsequent long-term recurring and cumulative impacts on human health, agriculture, and ecosystems?

W-9 (I): Role of Cloud Microphysical Processes. What processes determine cloud microphysical properties and their connections to aerosols and precipitation?

W-10 (I): Clouds and Radiative Forcing. How do clouds affect the radiative forcing at the surface and contribute to predictability on time scales from minutes to subseasonal?

Climate Variability & Change

C-2 (I-MI): Climate Feedback and Sensitivity. How can we reduce the uncertainty in the amount of future warming of Earth, improve our ability to predict local and regional climate response to natural and anthropogenic forcings, and reduce the uncertainty in global climate sensitivity?

C-5 (I-VI): Aerosols and Aerosol Cloud Interactions. A. How do changes in aerosols (including their interactions with clouds) affect Earth's radiation budget and offset the warming due to greenhouse gases? B. How can we better quantify the magnitude and variability of the emissions of aerosols so that we can better understand the response of climate to its various forcings?

Most Important

Very Important

Important

Hydrological Cycle

H-1 (MI): Coupling the Water and Energy Cycles. How is the water cycle changing and how are these changes expressed in the space-time distribution of rainfall, snowfall, and the frequency and magnitude of extremes?

C-8 (I): Causes and Effects of Polar Amplification. What will be the consequences of amplified climate change in polar regions on global trends of sea-level rise, atmospheric circulation, and extreme weather events?

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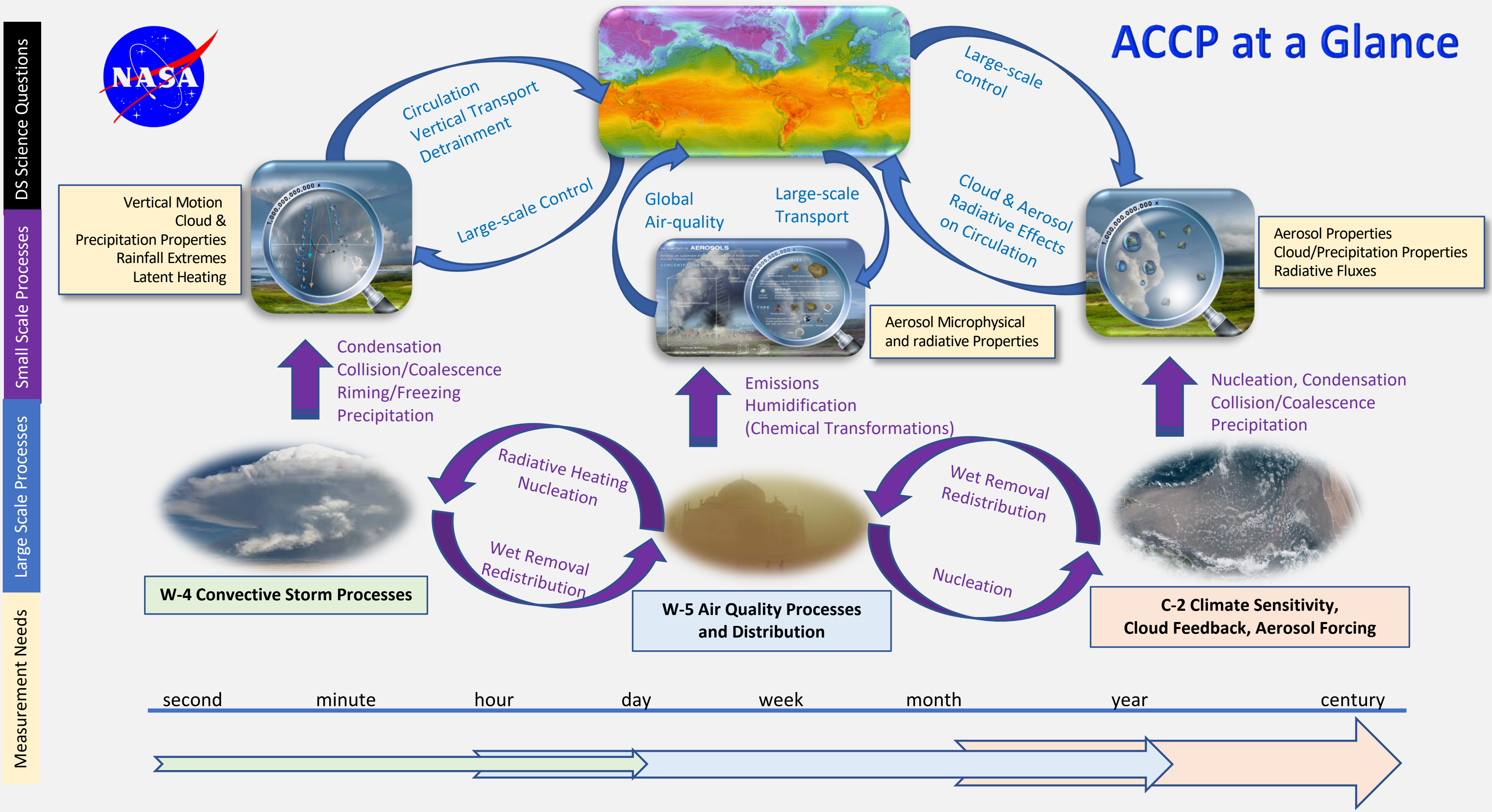
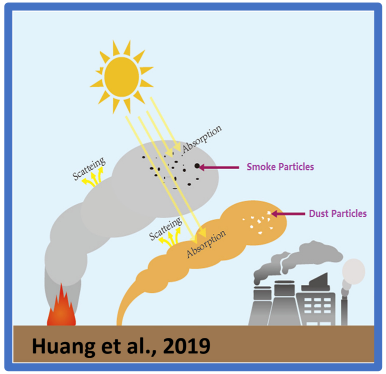
ACCP at a Glance

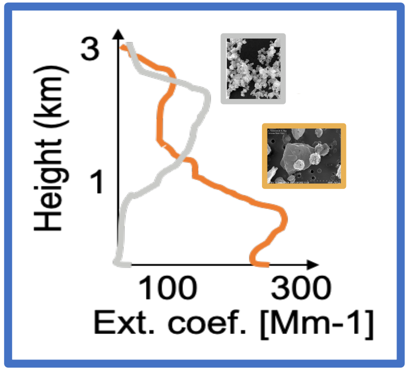


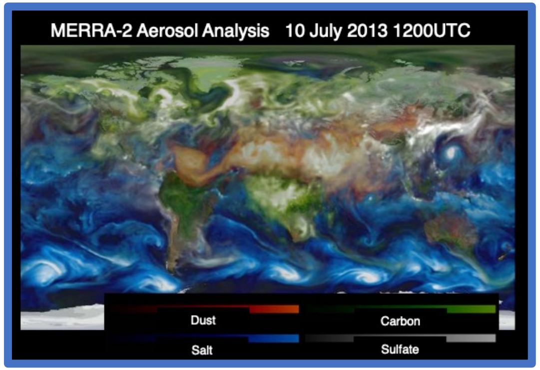
ACCP Science Objectives

O5: Attribution & AQ



Huang et al., 2019

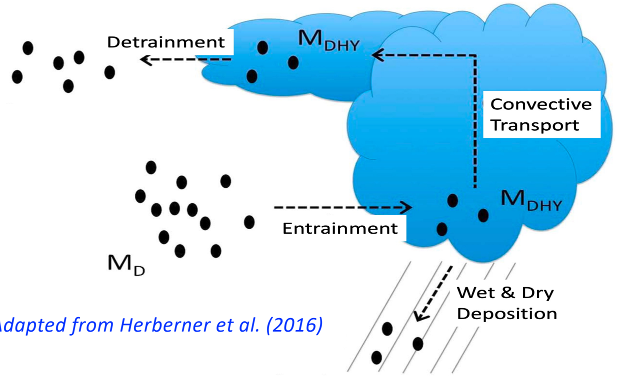




- **Minimum:** Vertical aerosol attribution (PBL, above PBL), improved estimates of emissions –> better predictions
- **Enhanced:** changes in aerosol properties in space and time –> better process understanding

- **$PM_{2.5}$ on Health --** Poor AQ is leading cause of premature death; linkage between speciated $PM_{2.5}$ and health is insufficient
- **Inter-model diversity** in vertical aerosol attribution and near-surface $PM_{2.5}$ is due to uncertain emissions, speciation and processes (e.g., PBL, precipitation, transport, deposition and scavenging)
- Need to constrain model with **observations** to improve predictions of speciated aerosol profile:
  - **Space sensors:** Optical and microphysical aerosol properties in PBL and FT -- vertically/spectrally resolved (e.g., aerosol absorption and extinction, fine mode fraction, lidar ratio etc.)
  - **Program of Record:** GEO & LEO for off-swath total-column aerosol meas. and diurnal cycle; suborbital for processes, enhanced meas. and optical-chemical linkage to PM mass

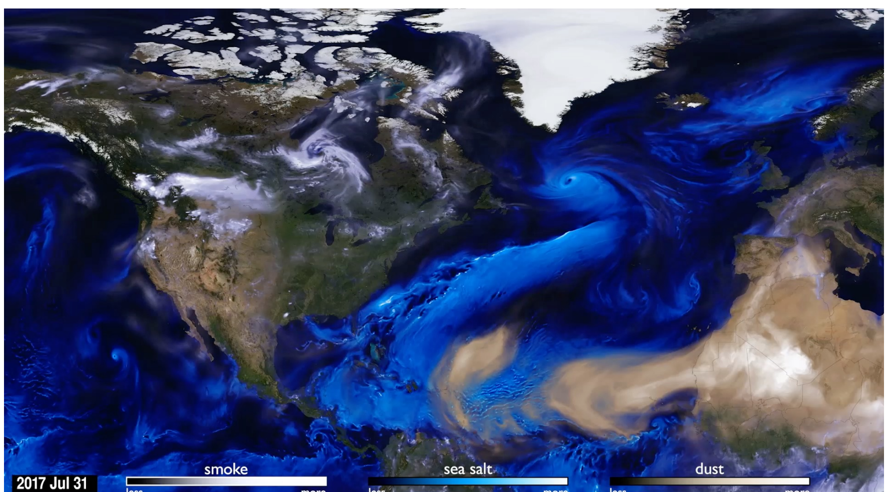
O6: Aerosol Removal and Redistribution



Adapted from Herberner et al. (2016)

- Earth-system models including atmospheric constituents and their interactions with the circulation inform past, present and future location, loading and species of aerosols and their impact on the climate system.
- Representation of aerosol processes in these models, most notably processing by clouds and microphysical processes that remove and transport aerosols can be advanced by ***nearly simultaneous*** vertically resolved observations of aerosols, clouds and precipitation microphysical properties.

ACCP will provide transformative measurements of aerosols and convective cloud vertical motion (w)



Important Geophysical Variable(s):

- Global profiles of aerosol extinction, including information on size and particle microphysical properties
- Global profiles of convective vertical motion, liquid/ice water path, profiles of precipitation rate, phase (ice, mixed, liquid), and type (C/S), cloud top height/temp, cloud top phase

ACCP enables and enhances science by PoR:

- GEO, LEO: vertically integrated/single level ACP properties and <u>time evolution</u>, organization and time/spatial coverage
- Suborbital: higher fidelity remotely sensed aerosol, cloud and precip measurements and verifying in-situ observations. Below cloud A measurements, diurnal evolution.

O7: Aerosol Direct Effect and Absorption

Background

- Aerosols continue to be responsible for the largest uncertainty in determining the anthropogenic radiative forcing of the climate (IPCC, 2014)
- There is evidence that IPCC underestimated uncertainty in aerosol DRF
- Current observational estimates of aerosol DRE/DRF
  - Are hampered by measurement uncertainties in aerosol properties, especially aerosol absorption (e.g. single scattering albedo – SSA) and aerosol optical depth (AOD)
  - Significantly underestimate aerosol DRE uncertainty
- **Decadal Study Most Important Recommendation** - (Reduce the IPCC AR5 total aerosol radiative forcing uncertainty by a factor of 2).

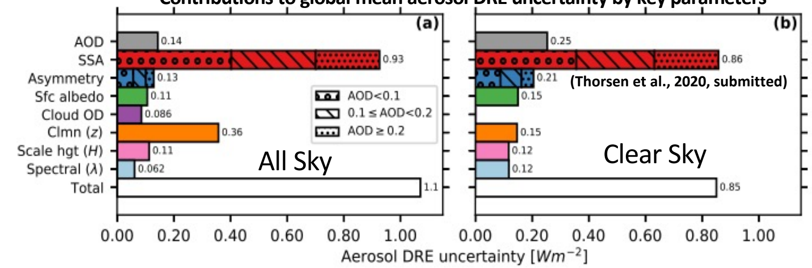
ACCP approach enables transformative science centered on:

- Quantifying aerosol's role in radiation budget to provide tighter constraints on
  - Aerosol DRE/DRF – aerosol absorption
  - Anthropogenic aerosol – aerosol type/speciation/size
  - Aerosol DRE under thin cloud – aerosol extinction under thin cirrus
- Vertical profiles of aerosol absorption and speciation/type
  - Provide insight of how sources impact forcing regionally
  - Assess aerosol impact on radiative heating – impact on stability/cloud cover/precipitation

ACCP Approach

- Provide accurate aerosol, cloud, environmental parameters as input
- Use radiative transfer (RT) models - to compute aerosol DRE/DRF, heating rates, spectral and angular radiances
- Evaluate model results (closure) – Compare:
  - Computed radiative to observed broadband flux observations from PoR
  - Computed and measured spectral and angular radiances
- Compute regional/local aerosol DRE/DRF
  - Use satellite and suborbital measurements in conjunction with models
  - Compare with suborbital measurements of aerosols and radiance/irradiance

Contributions to global mean aerosol DRE uncertainty by key parameters



Key Advances of ACCP over A Train

- **AOD** - A Train: ±0.04 (500 nm); ACCP: ±0.02-0.03 (500 nm)
- **Fine mode fraction (~anthropogenic portion)** - A Train: MODIS uncertainty ~ 50% and primarily limited to over ocean; ACCP: Uncertainty ~ 20%, over land and ocean
- **AAOD (or aerosol single scattering albedo)** - A Train: SSA uncertainty ~ ±0.05 (limited retrievals); ACCP: SSA uncertainty ~ ±0.03-0.04
- **Daytime lidar aerosol backscatter detection sensitivity** - A Train (CALIOP): 1.5×10^{-3} $(km\text{-}sr)^{-1}$ (532 nm); ACCP: $3\text{-}4\times10^{-4}$ $(km\text{-}sr)^{-1}$ (532 nm)
- **Spectrometer measurements of spectral radiance for closure with RT computations** – A train (none), ACCP: spectrometer

O8: Aerosol In direct Effect

The DS recognizes aerosol interactions with clouds as a major uncertainty in predicting climate change. ACCP will advance the science with a suite of co-located observations providing improved accuracy and new variables to better inform process understanding

"Processes" - physics that couple clouds, precipitation, and radiation with the ambient environment are modulated by aerosol to alter TOA radiation

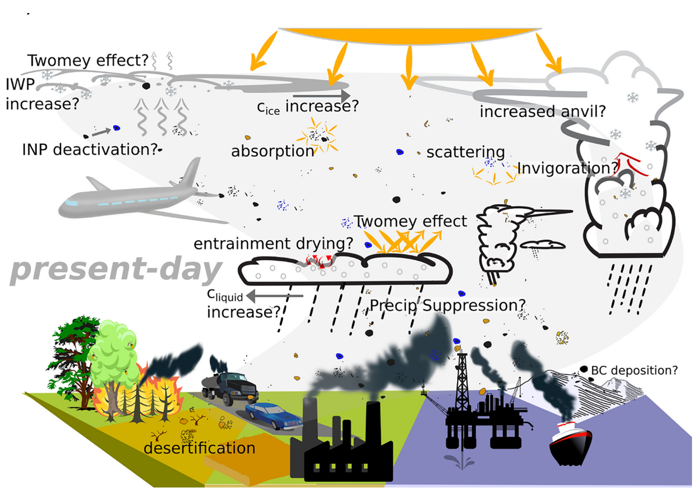
Cloud microphysical interactions

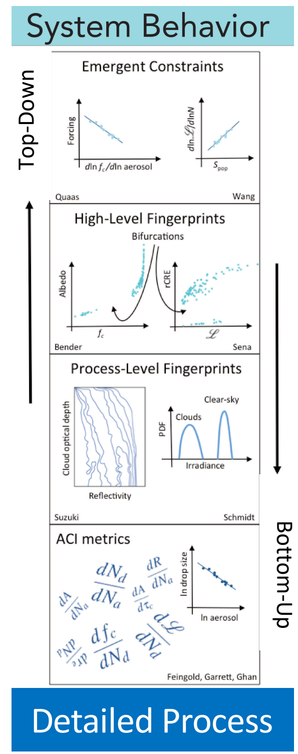
$$\varepsilon = \Delta \ln(N_d) \frac{dR}{d\ln(N_d)}$$

Cloud-radiation interactions

$$\varepsilon = \Delta\tau_a \frac{dR}{dR_{atm}} \frac{dR_{atm}}{d\tau_a}$$

(Bellouin et al. Rvws Geophys 2019)





Process understanding comes from joint statistics which characterize relations between key variables.

$$\mathrm{ACI} = \frac{\partial(cloud)}{\partial(aerosol)}, \quad \frac{\partial(radiation)}{\partial(aerosol)}$$

These metrics can constrain processes at various levels of detail, from microphysical processes to system-wide behavior.

Key Geophysical Variables

- Aerosol: particle size, concentration, absorption
- Cloud: LWP, particle size and concentration
- Radiation: cloud albedo, aerosol heating, LW cooling

(Mulmenstadt and Feingold CCCR 2018)

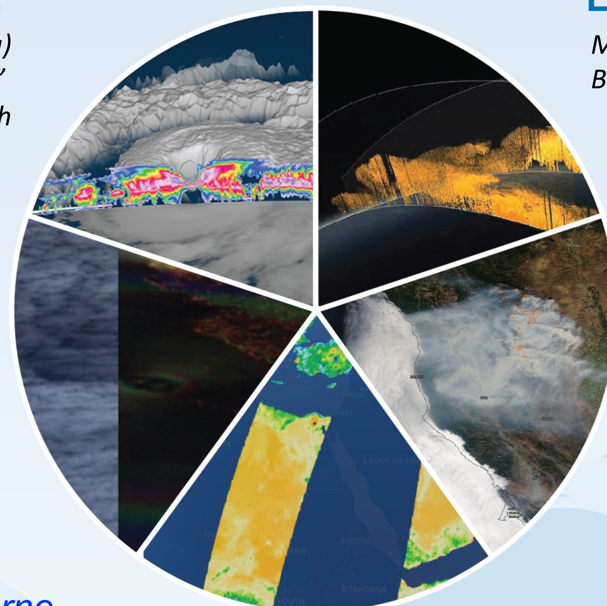
Key ACCP INSTRUMENTS

RADAR

Multi-wavelength (W, Ka and/or Ku)
Doppler or "Delta-T"
Ku radar may have swath

LIDAR

Multi-wavelength (532 and 1064 nm, maybe 355 nm)
Backscatter and/or HSRL (532 nm, maybe 355 nm)



POLARIMETER

Multi-wavelength (UV-VNIR-SWIR)
Multi-angle, 500m or 1 km footprint
Swath: 600 km or 1,100 km

SPECTROMETER

Multi-wavelength (UV-VIS-NIR-SWIR-LWIR-FIR) reflectances and brightness temperatures

ACCP requires a suite of spaceborne instruments to measure and characterize the complexity of hydrometeors and aerosols.*

RADIOMETER

Multi-wavelength Microwave (~100-900 GHz)

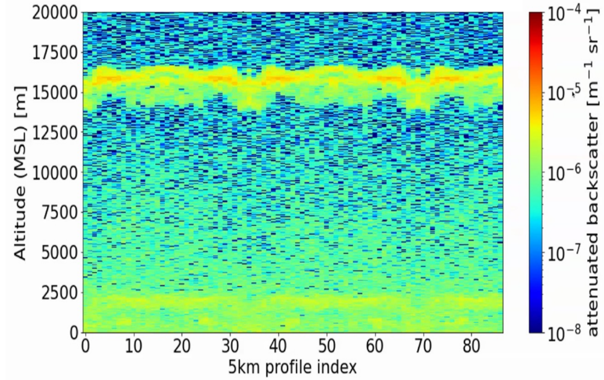
**To also include as, or more capable, airborne in-situ and remote sensing instruments, deployed in synergistic/complementary suborbital campaigns.*

Lidar Capabilities

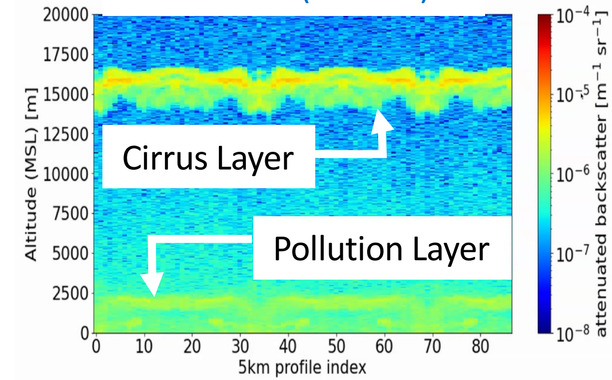
Simulated Daytime Conditions

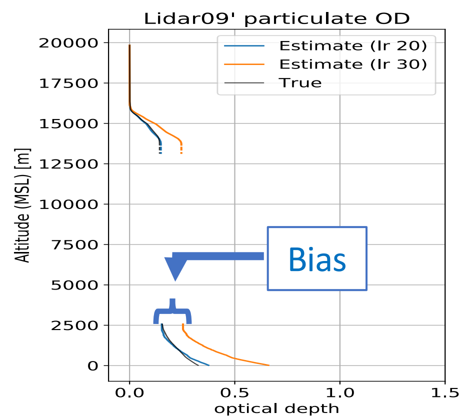
- Backscatter Lidar9er provides improved signal to noise (SNR) compared to CALIPSO
- HSRL Lidar05 provides exceptional SNR and direct measurement of particulate backscatter for improved characterization of vertically-resolved aerosol properties
- HSRL's direct measurement of particulate backscatter critical for near surface estimates of aerosol optical depth in the presence of a cirrus layer above.

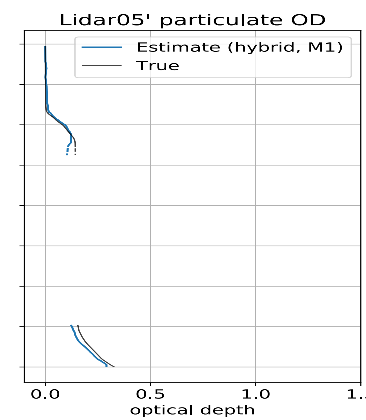
Backscatter Lidar (Lidar9er)



HSRL (Lidar05)



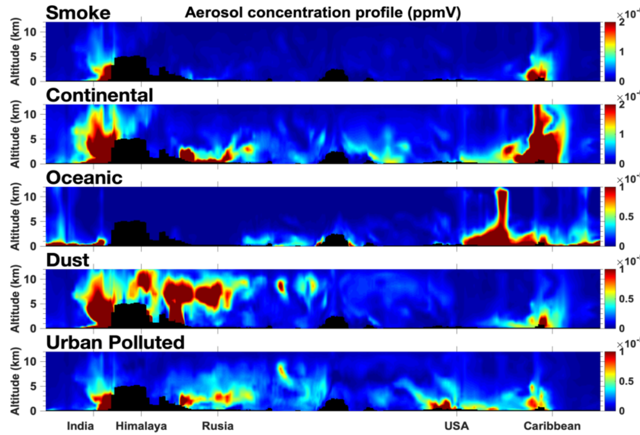




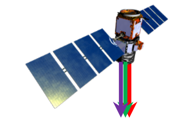
Simulations produced ACCP Lidar Working Group

Lidar06 adds UV channel (355 nm) for improved retrievals of intensive properties and aiding aerosol speciation.

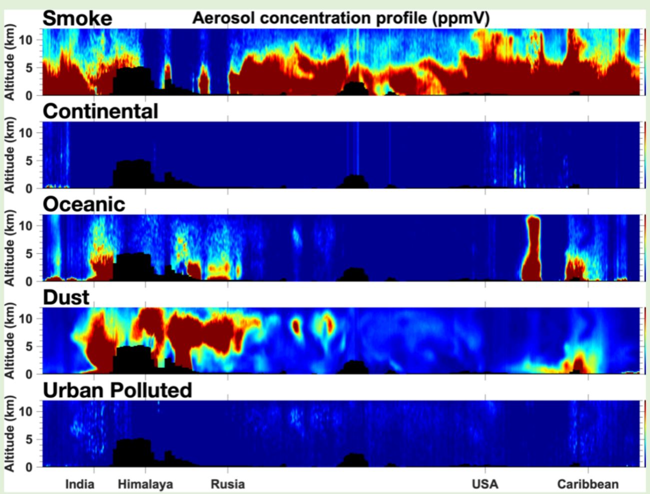
Retrieval Simulations



Prescribed “Truth”:
Transects of profiles of 5 aerosol types, with noise and variability of aerosol properties

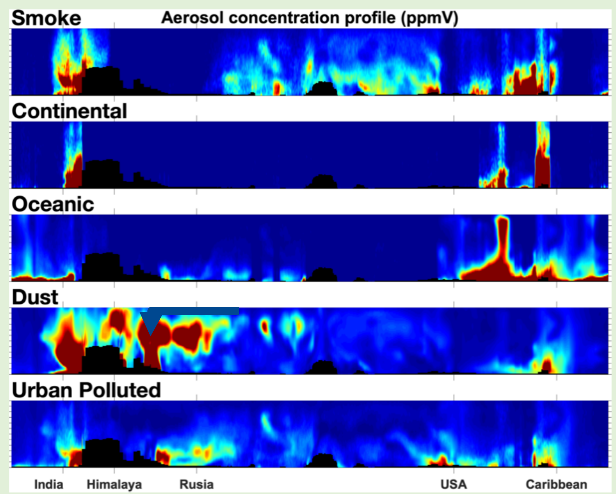


Backscatter Lidar09 (VIS-NIR)



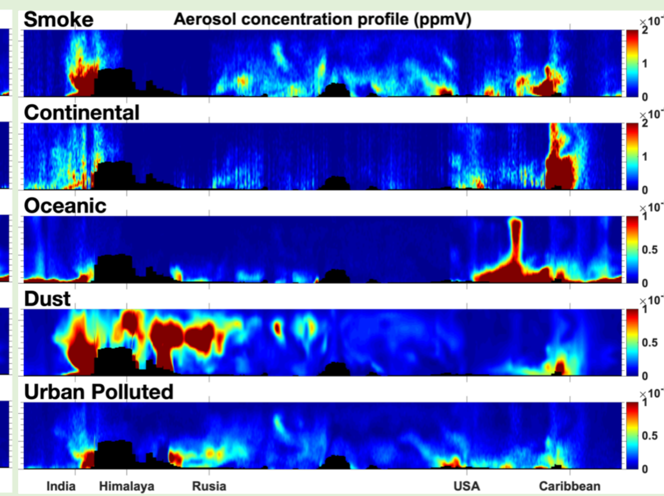
Unable to speciate, except for dust

HSRL Lidar05 (VIS-NIR)



Good performance

HSRL Lidar06 (UV-VIS-NIR)

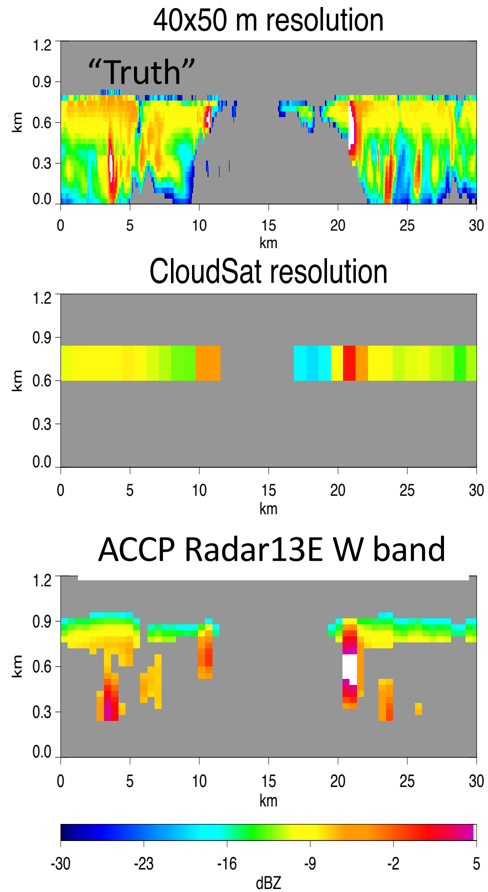


Best performance

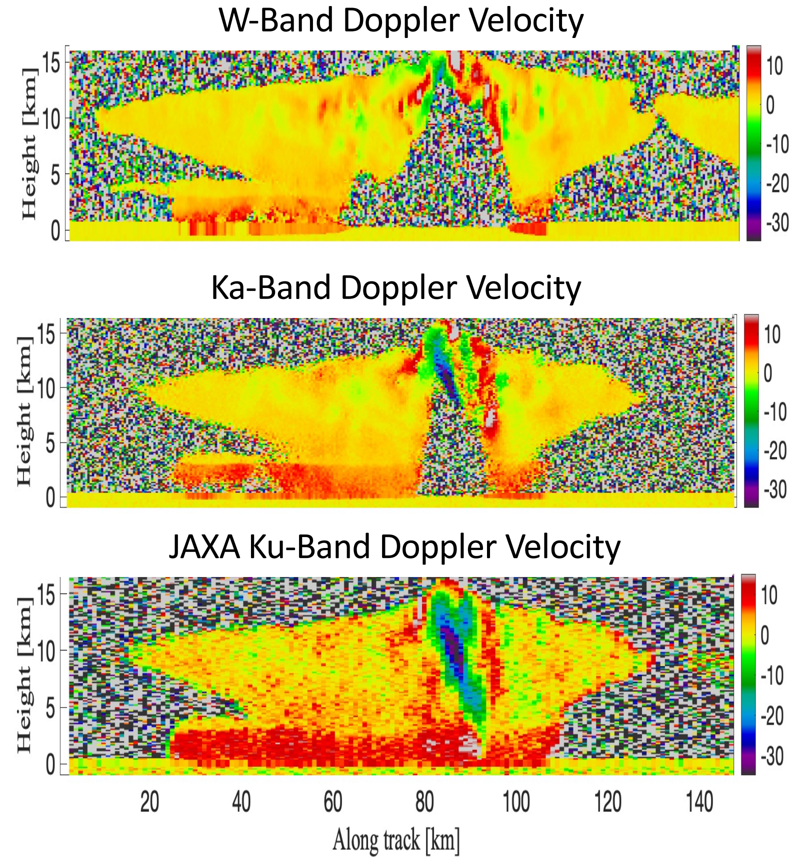
Radar Capabilities

- Radar13E provides W and Ka band profiling, advances on CloudSat with profiling to near the surface, Doppler capability, and second frequency for stronger precipitation rates
- Radar17 (JAXA contribution) and Radar13+1 provide Ku band Doppler for measurements in heavy precipitation
- Radar12 (inclined orbit) will not profile to near surface, won't address low clouds, heavy precipitation in convection

Low Cloud Profiling



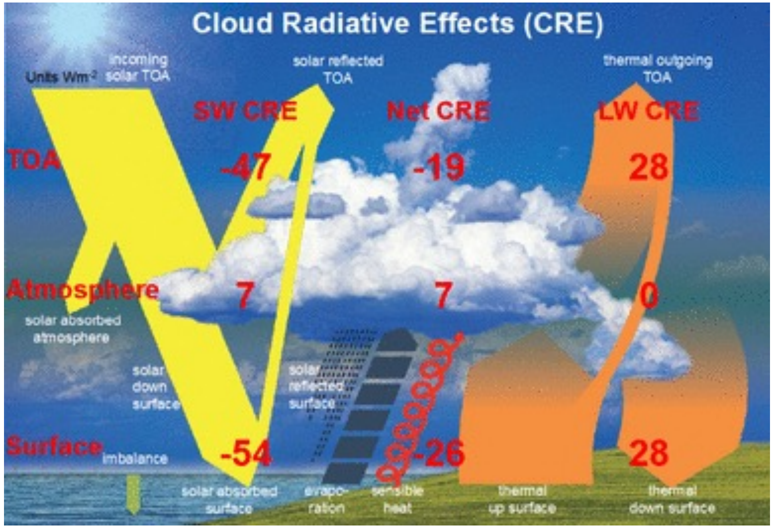
Doppler Motions In Deep Convection



Spectrometer Capabilities

- Two spectrometers included in every polar orbit configuration
- Spec03 is CSA contribution
- Essential to measuring cloud and aerosol radiative effects

Spectrometer	Spectral Regions	Wave-lengths (μm)	ΔX at nadir	Swath (km)
Spec03 (CSA)	LWIR, FIR	8.7, 10, 11, 13, 17.75, 19.5, 21.5, 25, 40	5 km (~1 km at 10 μm)	400
Spec04	LWUV, VIS, NIR, SWIR	0.35 – 2.3 (contiguous)640 channels	0.5 km	200

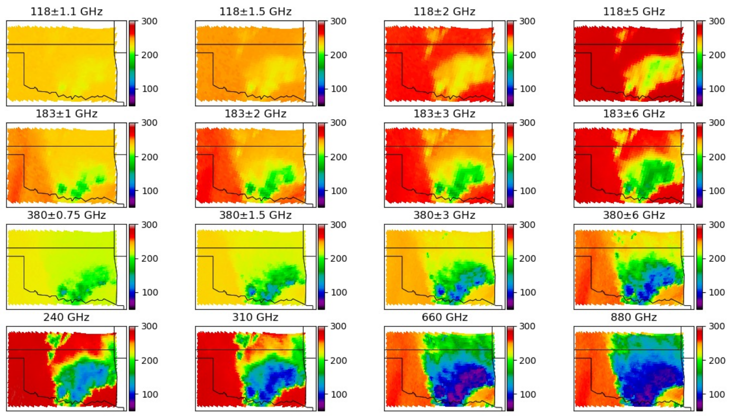


Passive Microwave Radiometer Capabilities

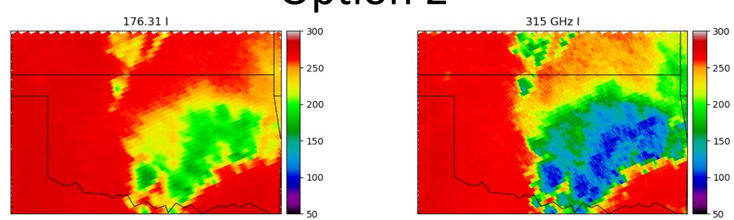
Two radiometers have featured prominently in architectures

- **Option 1** (RadioO7)
  - 118 (4), 183 (4), 240, 310, 380 (4), 660, 880 GHz
  - Conical scanning
  - 750 km swath width
  - IFOV 16x24 to 6x10 km
- **Option 2** (RadioO9b')
  - 183 (6), 325 (3) GHz
  - Cross-track scanning
  - 770 km swath width
  - IFOV 5x5 and 3x3 km at nadir
- Radio09c adds 664 GHz to Radio09b
- Radio09d adds 89 GHz to Radio09b

Option 1



Option 2

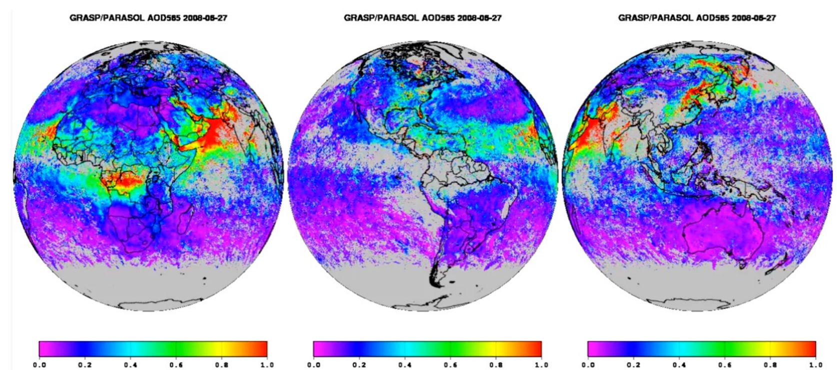


Simulations produced by Joe Munchak

Polarimeter Capabilities

- Polarimeter retrievals for cloud-top microphysics and aerosol retrievals
- Polarimeter provides constraints for improve aerosol property retrievals
- Polar07 preferred due to smaller footprint, but Polar04b offers lower cost option

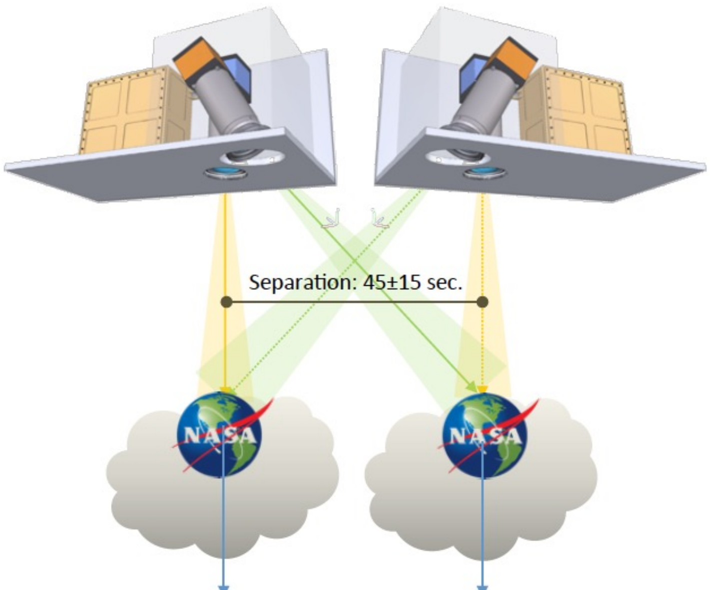
Polarimeter	UV-VIS (nm)	VNIR-SWIR (nm)	ΔX at nadir	Swath (km)	# Angles
Polar04b	360, 380, 410, 550, 670	870, 1230, 1380, 1550, 1650	1 km	1130	60 at 670 nm, 10 at others
Polar07	360, 380, 410, 550, 670	870, 940, 1230, 1380, 1550, 1650	0.5 km	550	60 at 670 nm, 10 at others



AOD

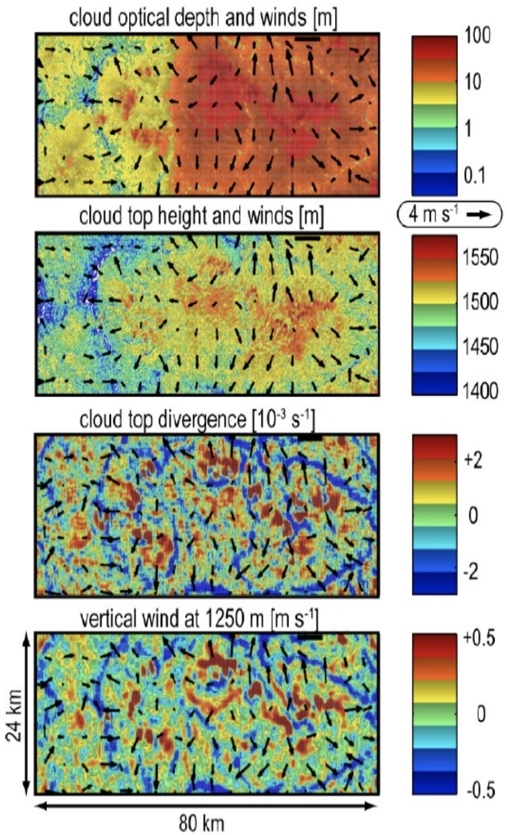
Example taken from POLDER instrument on the Parasol satellite

Time-Differenced Stereo Cameras

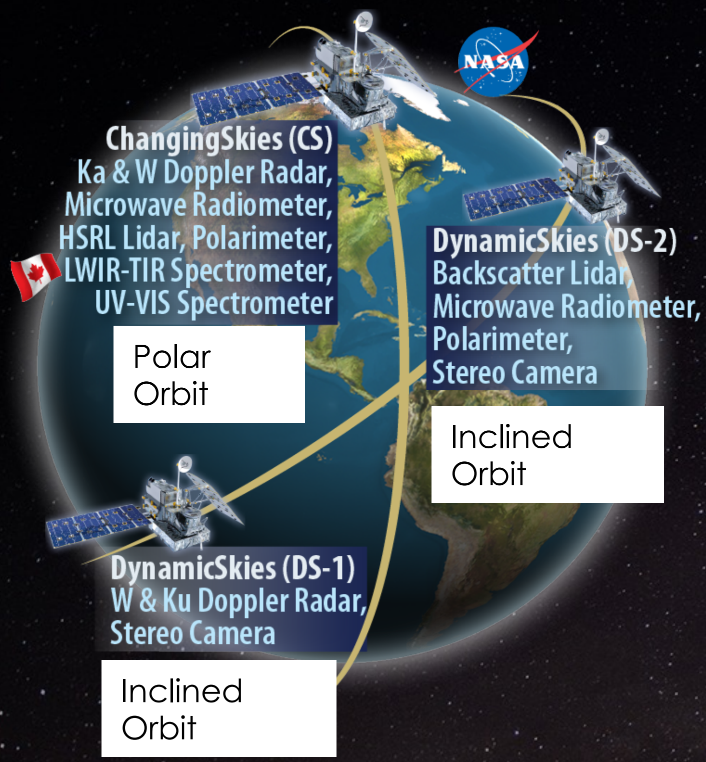


Same cloud feature is observed from 2 view angles (stereo/3D image) twice (cloud motion after 45 sec.).

From R. Marchand, A. Davis, L. Forster, and M. Kurowski



Architecture Recommendation—Dual Orbit Constellation



1st launch of inclined orbit ~2028

2nd launch of polar orbit ~2029-30

Inclined Orbit

- W-, Ku-band Doppler radar
- Microwave radiometer (118-880 GHz)
- 532 and 1064 nm backscatter lidar
- Polarimeter (1130 km swath, 1 km resolution)
- Time-differenced stereo camera measurements

Polar Orbit

- W-, Ka-band Doppler radar
- Microwave radiometer (118-880 GHz)
- 532 nm HSRL, 1064 nm backscatter lidar
- Polarimeter (550 km swath, 0.5 km resolution)
- Spectrometers (LWUV, VIS, NIR, SWIR, LWIR, FIR)

Summary

- The ACCP science goals are tightly connected to 2017 Decadal Survey questions and combines the science of 2 Designated Observables:
  - Aerosols
  - Clouds, Convection and Precipitation
- ACCP is a component of NASA's Earth System Observatory
- The cornerstone of the ACCP orbital component are active sensors (lidars, radars) complement by very capable passive instruments (polarimeters, radiometers, spectrometers)
- ACCP includes both orbital and suborbital components
  - ➢ A second suborbital workshop took place in March—April 2021
  - ➢ Suborbital measurements will be a major contributor to addressing the A/Q science objectives.
- The ACCP Study officially started on October 2018 and it has now concluded
  - ➢ pre-Phase A started in June 2021, with KDP-A in early-mid 2022
  - ➢ Launches in ~2028 (inclined), ~2029 (polar)
- Internally at NASA, ACCP is sometimes referred to as

AtmOS: The Atmosphere Observing System