Figure 3.3: Synthetic risk diagrams of global and sectoral assessments and examples of regional key risks. The burning embers result from a literature based expert elicitation. **Panel (a): Left** - Global surface temperature changes in °C relative to 1850–1900. These changes were obtained by combining CMIP6 m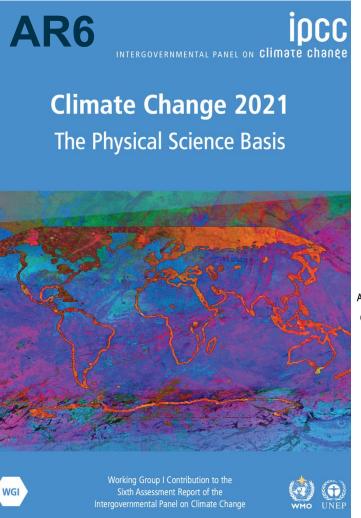odel simulations with observational constraints based on past simulated warming, as well as an updated assessment of equilibrium climate sensitivity. *Very likely* ranges are shown for the low and high GHG emissions scenarios (SSP1-2.6 and SSP3-7.0). **Right** - Global Reasons for Concern, comparing AR6 (thick embers) and AR5 (thin embers) assessments. Diagrams are shown for

Climate forcing, feedbacks, and sensitivity

AR6

ipcc
INTERGOVERNMENTAL PANEL ON climate change

Climate Change 2021
The Physical Science Basis

Working Group I Contribution to the
Sixth Assessment Report of the
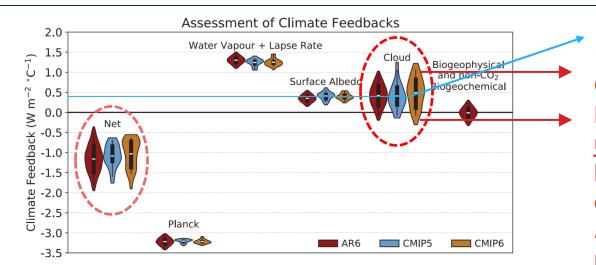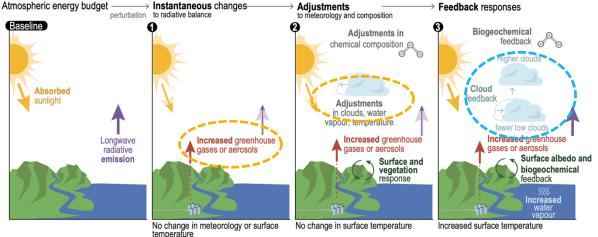Intergovernmental Panel on Climate Change

WGI   WMO   UNEP

Figure 7.10 | Global mean climate feedbacks estimated in *abrupt4xCO2* simulations of 29 CMIP5 models (light blue) and 49 CMIP6 models (orange), compared with those assessed in this Report (red). Individual feedbacks for CMIP models are averaged across six radiative kernels as computed in Zelinka et al. (2020).

Figure TS.14 | Schematic representation of changes in the top-of-atmosphere (TOA) radiation budget following a perturbation. *The intent of this figure is to*

Net **cloud feedback** positive (*high confidence*).

Cloud feedbacks remain **largest contributor** to uncertainty of net feedback, but the uncertainty is reduced compared to AR5 (by ~50%). *High confidence* that **radiative feedbacks** are largest source of uncertainty in **project global warming** out to 2100 under increasing or stable emission scenarios.

Uncertainty is dominated by **aerosol ERF** in strong mitigation scenarios. [chapter 7.5]

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Major advances since AR5
- Comprehensive assessment of feedbacks in different cloud regimes (cf. Table 7.9)
- Increased confidence of the positive low-cloud amount feedback
- Improved understanding of the cloud phase change feedback

Rising of Tropopause
Rising high clouds (+)
Fewer anvil clouds (-)
Enhanced stability
Rising of tropopause
Enhanced stability
Fewer low clouds (+)
More liquid from ice (-)
Destabilization

Equator — 30° — 60° — Pole
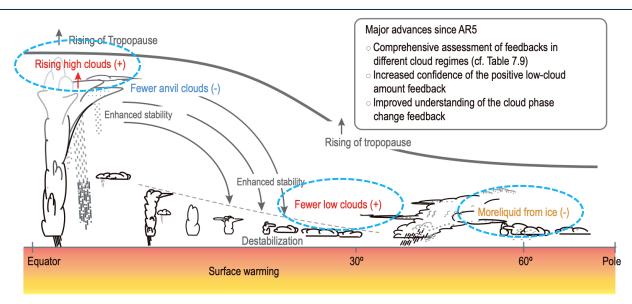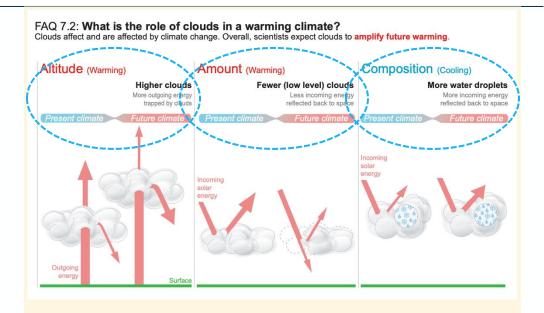Surface warming

Figure 7.9 | Schematic cross section of diverse cloud responses to surface warming from the tropics to polar regions. Thick solid and dashed curves indicate the tropopause and the subtropical inversion layer in the current climate, respectively. Thin grey text and arrows represent robust responses in the thermodynamic structure to greenhouse warming, of relevance to cloud changes. Text and arrows in red, orange and green show the major cloud responses assessed with *high*, *medium* and *low confidence*, respectively, and the sign of their feedbacks to the surface warming is indicated in the parenthesis. Major advances since AR5 are listed in the box. Figure adapted from Boucher et al. (2013).

Cloud feedback A *climate feedback* involving changes in any of the properties of clouds as a response to a change in the local or global surface temperature. Understanding cloud feedbacks and determining their magnitude and sign requires an understanding of how a change in *climate* may affect the spectrum of cloud types, the cloud fraction and height, the radiative properties of clouds, and finally the Earth's radiation budget.

Box SPM.1.3: The CMIP6 models considered in this Report have a wider range of climate sensitivity than in CMIP5 models and the AR6 assessed *very likely* range, which is based on multiple lines of evidence. These CMIP6 models also show a higher average climate sensitivity than CMIP5 and the AR6 assessed best estimate. The higher CMIP6 climate sensitivity values compared to CMIP5 can be traced to an amplifying cloud feedback that is larger in CMIP6 by about 20%. {Box 7.1, 7.3, 7.4, 7.5, TS.3.2}

FAQ 7.2: What is the role of clouds in a warming climate?
Clouds affect and are affected by climate change. Overall, scientists expect clouds to **amplify future warming**.

Altitude (Warming)
Higher clouds
More outgoing energy trapped by clouds
Present climate — Future climate

Amount (Warming)
Fewer (low level) clouds
Less incoming energy reflected back to space
Present climate — Future climate

Composition (Cooling)
More water droplets
More incoming energy reflected back to space
Present climate — Future climate

Incoming solar energy
Outgoing energy
Surface

FAQ 7.2, Figure 1 | Interactions between clouds and the climate, today and in a warmer future. Global warming is expected to alter the altitude **(left)** and the amount **(centre)** of clouds, which will amplify warming. On the other hand, cloud composition will change **(right)**, offsetting some of the warming. Overall, clouds are expected to amplify future warming.

FAQ 7.2 | What Is the Role of Clouds in a Warming Climate?

One of the biggest challenges in climate science has been to predict how clouds will change in a warming world and whether those changes will amplify or partially offset the warming caused by increasing concentrations of greenhouse gases and other human activities. Scientists have made significant progress over the past decade and are now more confident that changes in clouds will amplify, rather than offset, global warming in the future.

Clouds cover roughly two-thirds of the Earth's surface. They consist of small droplets and/or ice crystals, which form when water vapour condenses or deposits around tiny particles called *aerosols* (such as salt, dust, or smoke). Clouds play a critical role in the Earth's *energy budget* at the top of our atmosphere and therefore influence Earth's surface temperature (see FAQ 7.1). The interactions between clouds and the climate are complex and varied. Clouds at low altitudes tend to reflect incoming solar energy back to space, creating a cooling effect by preventing this energy from reaching and warming the Earth. On the other hand, higher clouds tend to trap (i.e., absorb and then emit at a lower temperature) some of the energy leaving the Earth, leading to a warming effect. On average, clouds reflect back more incoming energy than the amount of outgoing energy they trap, resulting in an overall net cooling effect on the present climate. Human activities since the pre-industrial era have altered this climate effect of clouds in two different ways: by changing the abundance of the aerosol particles in the atmosphere and by warming the Earth's surface, primarily as a result of increases in greenhouse gas emissions.

CLOUDS AND CLIMATE

HIGHER CLOUD

LOWER CLOUD

High thin clouds **trap outgoing heat** more than they reflect incoming solar energy, warming the atmosphere

More high thin clouds mean more **outgoing heat** is trapped
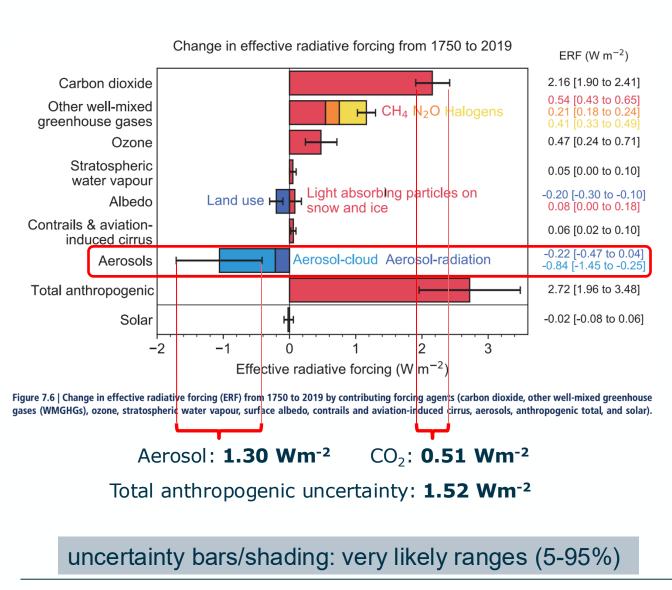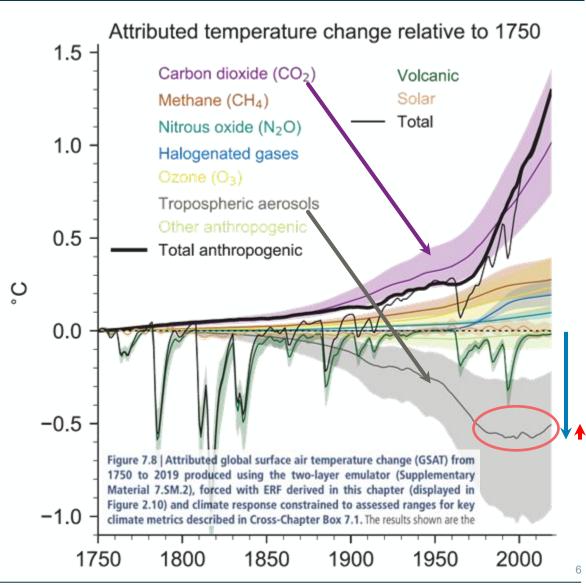
Low thick clouds reflect **incoming solar energy** more than they trap outgoing heat, cooling the atmosphere

Fewer low thick clouds mean **less solar energy** is reflected back to space

Overall, clouds currently cool the climate system

Cloud distribution is expected to change in the future and amplify climate warming

CLOUDS

CLIMATE

Clouds affect and are affected by climate

ESA | JAXA
earthcare

esa

ERF and aerosol-cloud-radiation interactions

Change in effective radiative forcing from 1750 to 2019

Forcing agent	ERF (W m^{-2})
Carbon dioxide	2.16 [1.90 to 2.41]
Other well-mixed greenhouse gases — CH_4	0.54 [0.43 to 0.65]
N_2O	0.21 [0.18 to 0.24]
Halogens	0.41 [0.33 to 0.49]
Ozone	0.47 [0.24 to 0.71]
Stratospheric water vapour	0.05 [0.00 to 0.10]
Albedo — Land use	-0.20 [-0.30 to -0.10]
Light absorbing particles on snow and ice	0.08 [0.00 to 0.18]
Contrails & aviation-induced cirrus	0.06 [0.02 to 0.10]
Aerosols — Aerosol-cloud	-0.22 [-0.47 to 0.04]
Aerosol-radiation	-0.84 [-1.45 to -0.25]
Total anthropogenic	2.72 [1.96 to 3.48]
Solar	-0.02 [-0.08 to 0.06]

Effective radiative forcing (W m^{-2})

Figure 7.6 | Change in effective radiative forcing (ERF) from 1750 to 2019 by contributing forcing agents (carbon dioxide, other well-mixed greenhouse gases (WMGHGs), ozone, stratospheric water vapour, surface albedo, contrails and aviation-induced cirrus, aerosols, anthropogenic total, and solar).

Aerosol: **1.30 Wm^{-2}**   CO$_2$: **0.51 Wm^{-2}**

Total anthropogenic uncertainty: **1.52 Wm^{-2}**

Attributed temperature change relative to 1750

Carbon dioxide (CO$_2$)   Volcanic
Methane (CH$_4$)   Solar
Nitrous oxide (N$_2$O)   Total
Halogenated gases
Ozone (O$_3$)
Tropospheric aerosols
Other anthropogenic
Total anthropogenic

Figure 7.8 | Attributed global surface air temperature change (GSAT) from 1750 to 2019 produced using the two-layer emulator (Supplementary Material 7.SM.2), forced with ERF derived in this chapter (displayed in Figure 2.10) and climate response constrained to assessed ranges for key climate metrics described in Cross-Chapter Box 7.1. The results shown are the

uncertainty bars/shading: very likely ranges (5-95%)

Effective radiative forcing of aerosols and clouds

aerosol type dependence

Figure 6.12 | Contribution to effective radiative forcing (ERF) (a) and

Figure 7.5 | Net aerosol effective radiative forcing (ERF) from different lines of evidence. The headline AR6 assessment of −1.3 [−2.0 to −0.6] W m⁻²

7.3.3.4. In AR5, the overall assessment of total aerosol ERF (ari+aci) used the median of all ESM estimates (…) but placed more confidence in a subset of models that were deemed more complete in their representation of aerosol-cloud interactions. These models, which include aerosol effects on mixed-phase, ice, and/or convective clouds, (…)
Likewise, studies that constrained models with satellite observations (…) were given extra weight. (…)
Finally, based on higher resolution models, doubt was raised regarding the ability of ESMs to represent the cloud-adjustment component of ERFaci with fidelity.

[In AR6], the best estimate and range is revised relative to AR5, partly based on updates to the above lines of argument. (…) As in AR5, there is still reason to question the ability of ESMs to simulate adjustments in LWP and cloud cover in response to aerosol perturbation, (…)
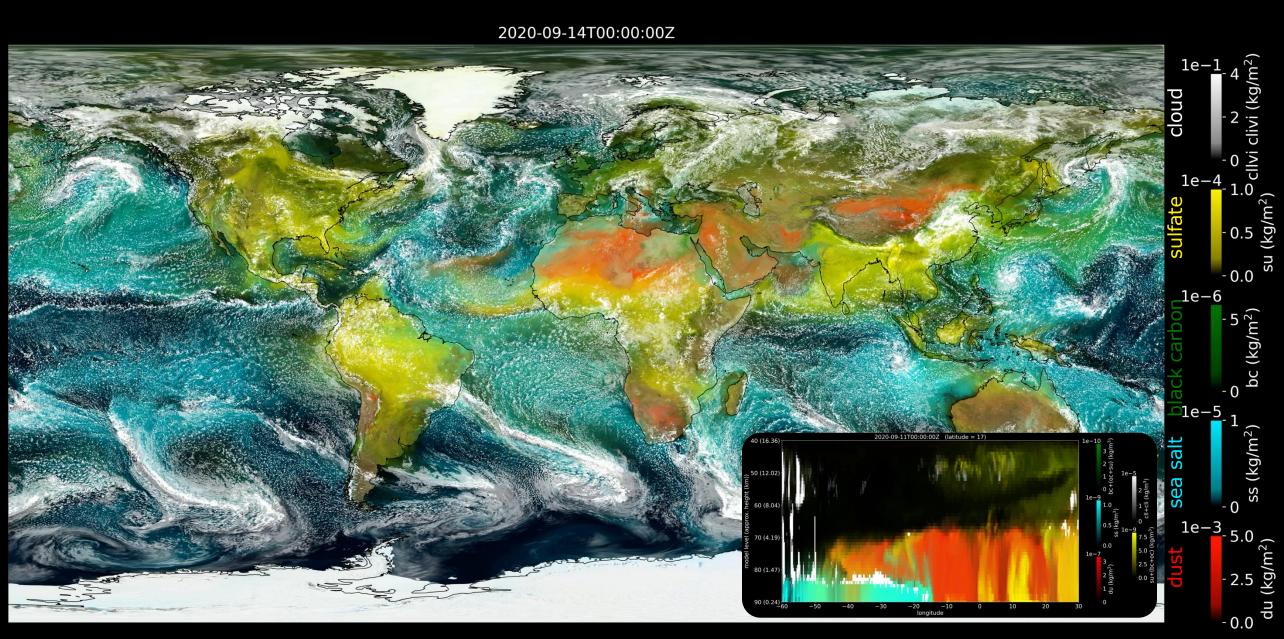
There is thus strong evidence for a substantive negative total aerosol ERF, which is supported by the broad agreement between observation-based and model-based lines of evidence for both ERFari and ERFaci that has emerged since AR5.
However, considerable uncertainty remains, particularly with regards to the adjustment contribution to ERFaci, as well as missing processes in current ESMs, notably aerosol effects on mixed-phase, ice, and convective clouds. This leads to a medium confidence in the estimate of ERFari+aci and a slight narrowing of the uncertainty range.
(…)
There is high confidence that ERFaci contributes most (75-80%) to the total aerosol effect.

Next-gen climate models with interactive aerosols (ICON-HAM-lite)

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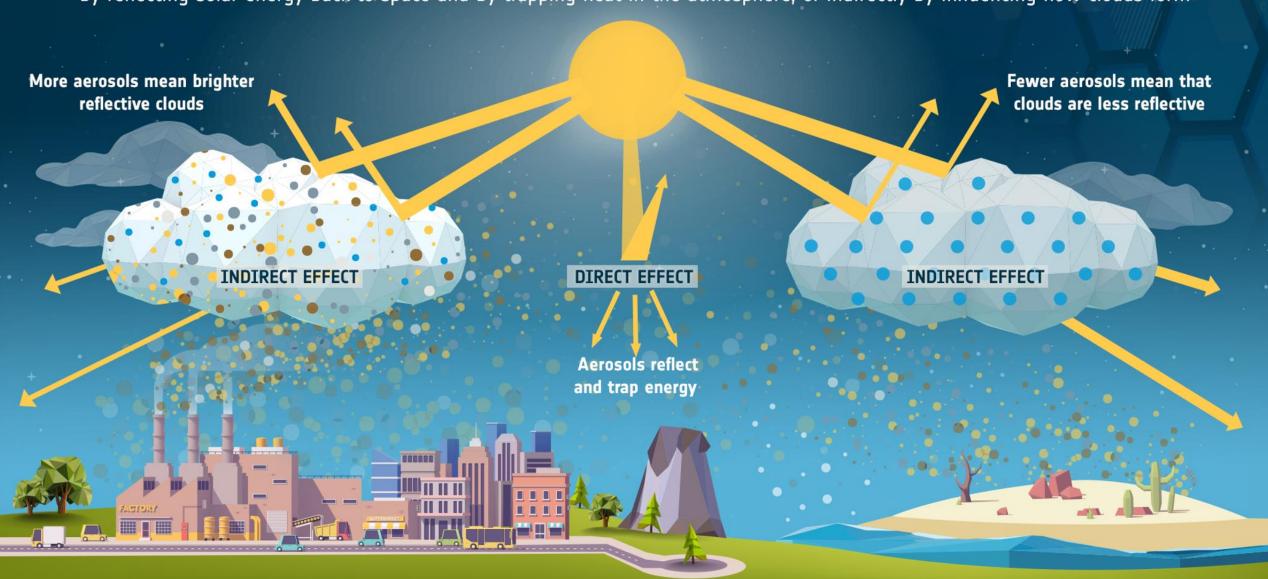
AEROSOLS AND CLIMATE

Aerosols – tiny particles such as dust suspended in the air – affect the climate, either directly by reflecting solar energy back to space and by trapping heat in the atmosphere, or indirectly by influencing how clouds form

More aerosols mean brighter reflective clouds

Fewer aerosols mean that clouds are less reflective

INDIRECT EFFECT

DIRECT EFFECT

INDIRECT EFFECT

Aerosols reflect and trap energy

esa

EarthCARE: an Earth Explorer satellite mission for cloud, aerosol, and Earth radiation budget research
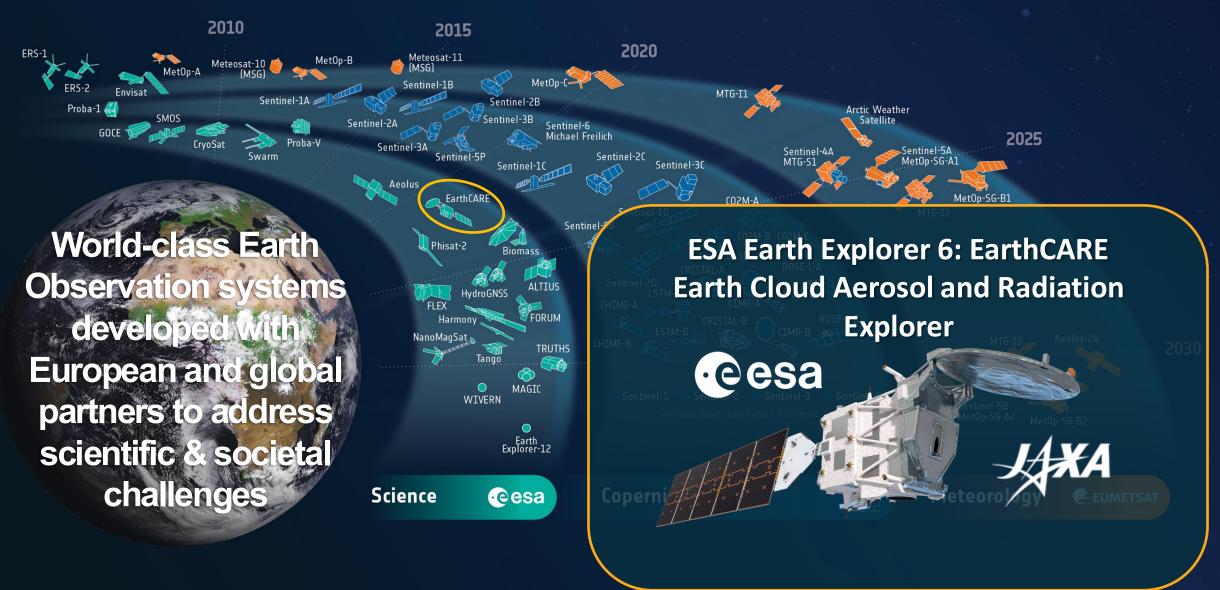
09/10/2025

Alex Hoffmann on behalf of the joint ESA and JAXA EarthCARE Team

Joint Training in Atmospheric Composition

Online Webinar

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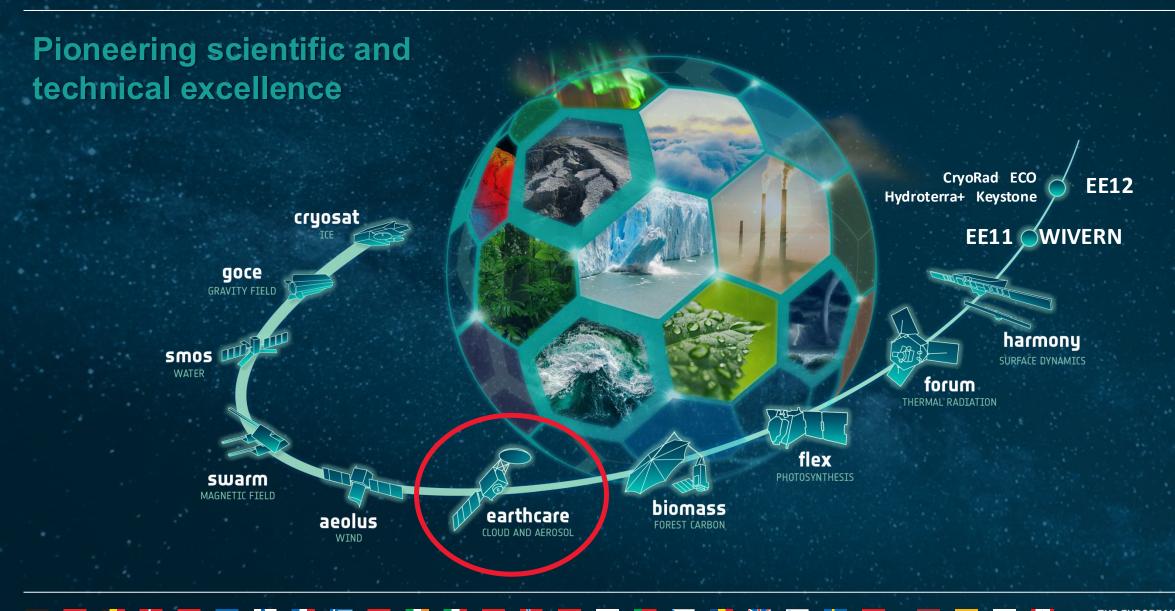
ESA's Earth Observation fleet

World-class Earth Observation systems developed with European and global partners to address scientific & societal challenges

ESA Earth Explorer 6: EarthCARE
Earth Cloud Aerosol and Radiation Explorer

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Earth Explorers:

Pioneering scientific and technical excellence

cryosat
ICE

goce
GRAVITY FIELD

smos
WATER

swarm
MAGNETIC FIELD

aeolus
WIND

earthcare
CLOUD AND AEROSOL

biomass
FOREST CARBON

flex
PHOTOSYNTHESIS

forum
THERMAL RADIATION

harmony
SURFACE DYNAMICS

CryoRad   ECO
Hydroterra+   Keystone

EE12

EE11   WIVERN

From early ideas to implementation…

| 1998 | 2001 | 2004 | 2015 | 2023 |

Earth Radiation Mission Candidate
https://doi.org/10.1117/12.332702

EarthCARE Candidate (Ph 0)
Report for Assessment

EarthCARE Candidate (Ph A)
Report for Mission Selection

Illingworth et al, BAMS
Mission description publication
https://doi.org/10.1175/BAMS-D-12-00227.1

Wehr et al, AMT
Science and system overview publication
https://doi.org/10.5194/amt-16-3581-2023

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… to launch in May 2024

Vandenburg (USA), 28 May 2024, 22:20 UTC
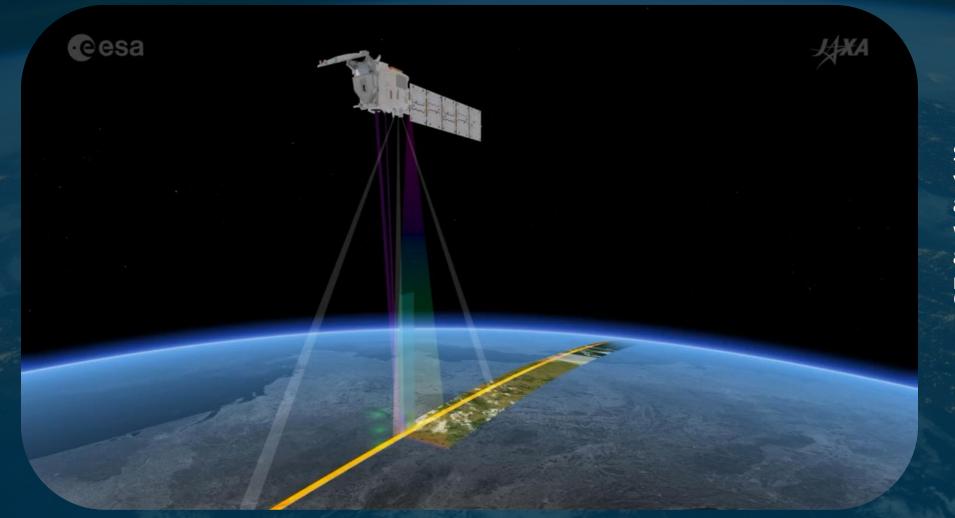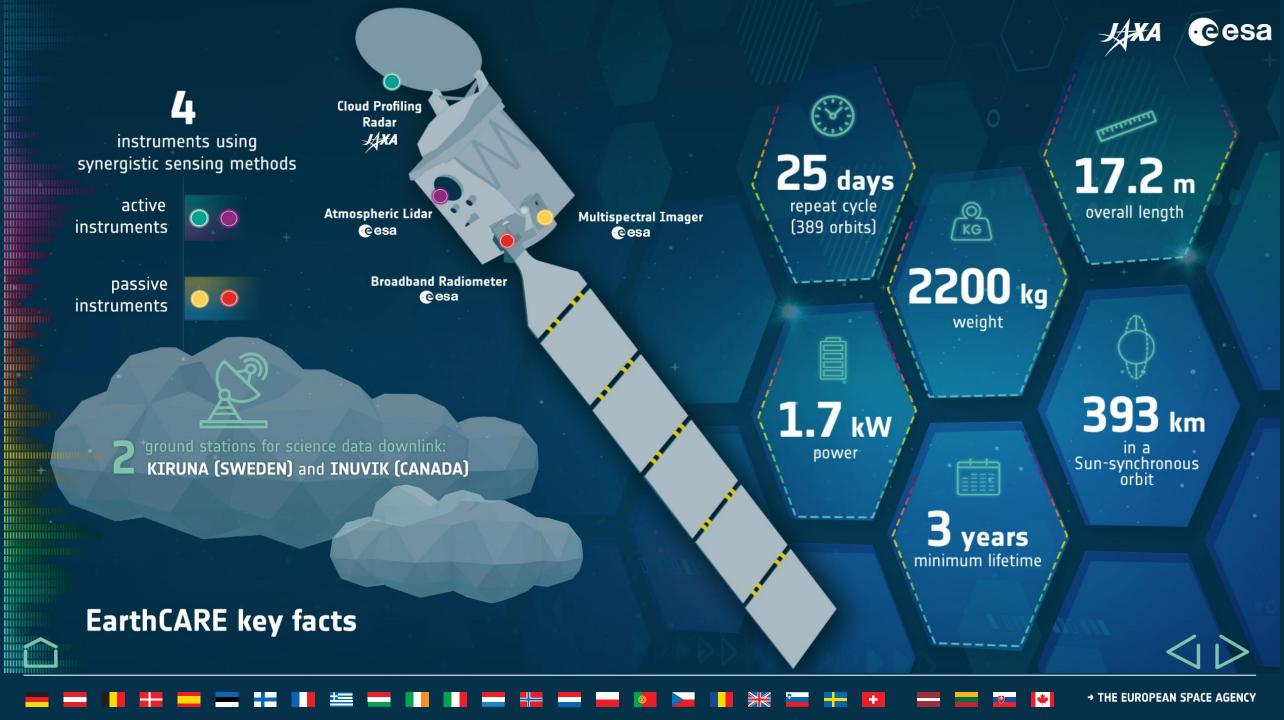
EarthCARE: Scientific objectives

Systematic provision of vertical profiles of clouds and aerosols, collocated with measurements of solar and emitted thermal radiation.

How do aerosols and clouds heat or cool the Earth?

Direct verification of impact of clouds and aerosols on atmospheric heating rates and radiative fluxes.
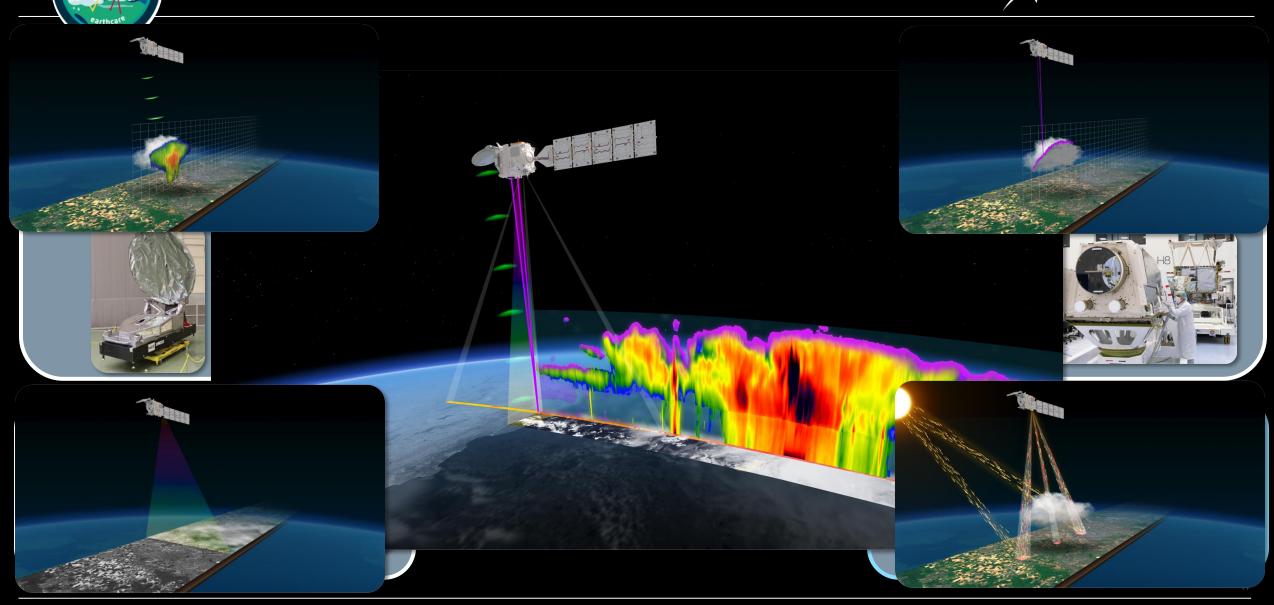
See EarthCARE Mission Requirements Document (MRD) for more details on mission objectives and requirements.

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EarthCARE key facts

4 instruments using synergistic sensing methods

active instruments

passive instruments

Cloud Profiling Radar
JAXA

Atmospheric Lidar
eesa

Broadband Radiometer
eesa

Multispectral Imager
eesa

2 ground stations for science data downlink:
KIRUNA (SWEDEN) and **INUVIK (CANADA)**

25 days repeat cycle (389 orbits)

17.2 m overall length

2200 kg weight

1.7 kW power

3 years minimum lifetime

393 km in a Sun-synchronous orbit

JAXA eesa

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EarthCARE: key measurement specs
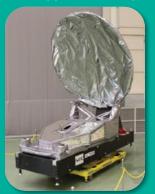
Cloud Profiling Radar CPR
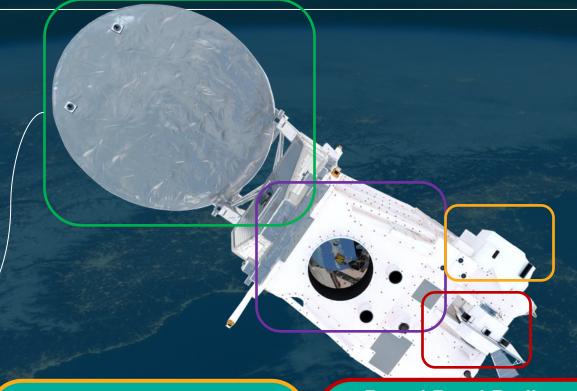
High power 94GHz cloud radar with Doppler

- *2.5 m antenna*
- *Resolution 800m (hor) x 500m (ver)*
- *Range -1 km to 20 km*
- *Doppler velocity range ±10ms^{-1}*
- *Doppler velocity accuracy 1ms^{-1} @10km integration, -19dBZ*

L1: radar reflectivity & vertical Doppler velocity

Atmospheric LIDAR ATLID

High spectral resolution, UV LIDAR

- 355 nm source
- Vertical profiles 0-40km, 100-500m resolution
- Horizontal sampling 280m
- Rayleigh co-pol
- Mie co-pol
- Mie cross-pol

L1: attenuated backscatter profiles

Multi Spectral Imager MSI

- *150km swath (-35 km to +115 km)*
- *500m Ground Sampling Distance*
- *VIS, Near IR, SWIR Camera (VNS)*
- *Thermal IR Camera (TIR)*

L1: radiances (VNS), brightness temperature (TIR)

Broad Band Radiometer BBR

- *TOA fluxes with accuracy better than 10Wm^{-2}*
- *3 telescopes, Total Wave and Short Wave radiances at same location, different angles*
- *SW 0.25 to 4 µm, LW 4 µm to >50 µm*
- *Angular sampling 0, +/- 55 °*
- *Spatial resolution 10kmx10km*
- *Spatial sampling 1 km*

L1: Solar and Thermal TOA rad.

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CPR instrument

- 94 GHz cloud radar with Doppler capability
  - 2.5 m transmit/receive antenna (800 m footprint)

- Transmitter
  - Emits 3.3 µs pulses, peak power 1500 W

- Receiver
  - Vertical resolution 500 m oversampled at 100 m
  - 500 m horizontal integration
  - 3 Pulse Repetition Frequencies, dependant on latitude, 6100 to 7500 Hz
  - Minimum sensitivity better than -35 dBZ for 10km integration and uniform clouds
  - Doppler velocity measurement range ± 10 ms^{-1}
  - Doppler velocity measurement accuracy 1 ms^{-1} @10km integration, -19 dBZ
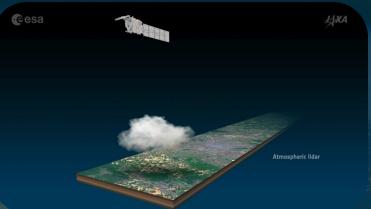
→ Profiles of radar reflectivity, vertical velocities of cloud and precipitation particles.

→ Radar signal allows penetration much deeper into clouds, compared to lidar.

→ Synergistic use with the atmospheric lidar and multispectral imager used to classify atmospheric targets and derive atmospheric profiles, important for making radiative transfer calculations.
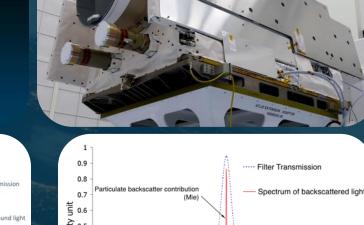
ATLID instrument
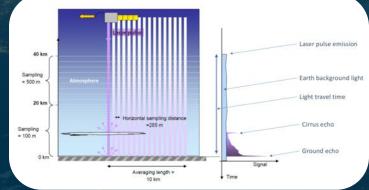
- Bi-static, 355 nm UV lidar
  - Actively controlled co-alignment loop

- Transmitter
  - Power laser head emits **37 mJ** pulses of 26 ns at a repetition rate of 51 Hz
  - Linear polarised output
  - 15 m ground footprint points 3° backwards to minimise specular reflection

- 3-channel receiver
  - Cross-polar channel
  - Co-polar, spectrally broadened molecular backscatter ("Rayleigh") channel
  - Co-polar, particulate backscatter channel ("Mie")
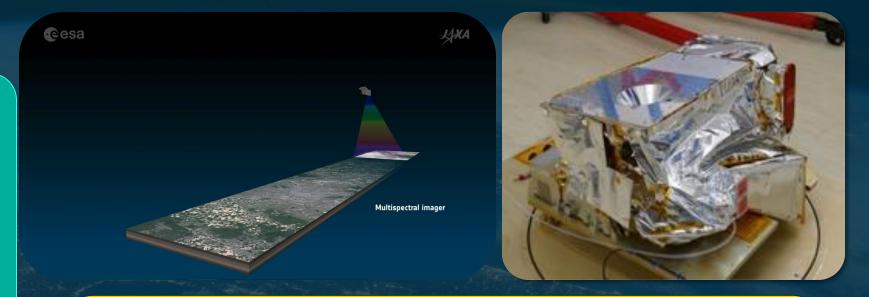
→ Profiles of aerosols, thin clouds and the top of thick clouds.
→ Aerosol properties including altitude, thickness, detailed optical properties and aerosol type.
→ High-spectral resolution receiver and depolarisation channel.

Multispectral imager

- 7 channel imager

- Visible, Near-IR and Shortwave IR camera
  - 4 separate optic trains
  - Pushbroom, linear detectors

- Thermal IR camera
  - Three channels share defined by dichroics
  - Common 2-D detector uses Time Delay Integration to increase SNR
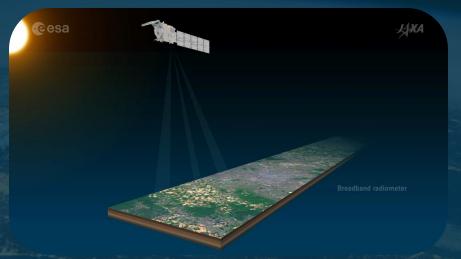
→ Provision of scene context information.

→ Derivation of "MSI-only" cloud and aerosol data products.

→ Nadir pixel used in retrieval of synergistic products with the ATLID and CPR.

→ Across-track data (selected channels) used for creation of 3D scenes, for 1D and 3D radiative transfer calculations to calculate radiative properties.

→ Used to improve the unfiltering of BBR measured radiances.

BBR instrument

- Broadband Radiometer

  - 3 views: forewards, aft and nadir

  - 2 channels per view: short-wave and total-wave, from which is derived a long-wave

  - Pushbroom onto microbolometer arrays

  - Unfiltering for the spectral response of the scene is improved using data from the MSI

Broadband radiometer

→ Unfiltered, top-of-atmosphere radiances, short-wave and long-wave fluxes

Data processing chain

CPR Level 1b (JAXA)
- Radar reflectivity
- Doppler velocity profiles

ATLID Level 1b (ESA)
Attenuated backscatter in
- Rayleigh channel
- Co-polar Mie channel
- Cross-polar Mie channel

MSI Level 1b/c (ESA)
TOA radiances for four solar channels, TOA brightness temperatures for three thermal channels

BBR Level 1b (ESA)
Filtered TOA short-wave and total-wave radiances

CPR Level 2a
Radar echo product, feature mask, cloud type, liquid and ice cloud properties, vertical motion, rain and snow estimates, ...

ATLID Level 2a
Feature mask and target classification, extinction, backscatter & depol. profiles, aerosol properties, ice cloud properties, ...

MSI Level 2a
Cloud mask, cloud micro-physical parameters, cloud top height, aerosol parameters, ...

BBR Level 2b
Unfiltered top-of-atmosphere radiances, short-wave and long-wave fluxes
Products are enhanced by using MSI

Synergistic Level 2b
Target classification, cloud & aerosol prof. at x-sectn, ...

3D Scenes Construction
Expand syn. retrievals across-track using MSI; ≈40km wide
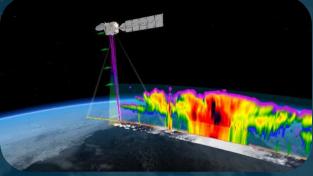
Radiative Transfer Products
calculated radiances, fluxes, heating rate profiles

microphsyical observations + theory

Assessment
Comparison of calculated fluxes and radiances to BBR observations

direct observations

Operational software developed directly by science teams

EarthCARE data production model (ESA)

ESA Chain: 24 Data Processors

Cloud-top, vertically integrated, layerwise

Aerosol
Aerosol layer height, classification
Optical thickness,
Layer-mean extinction-to-backscatter ratio
Layer-mean particle linear depolarization ratio
Angstrom exponent

Cloud and precipitation
Cloud-top height, phase, type
Optical thickness
Effective radius
Liquid, ice, rain water path
Surface snow rate
Surface rain rate

Radiation
Radiative fluxes at TOA
Broadband radiances at TOA

Vertical profiles

Aerosol
Aerosol fraction
Aerosol species
Extinction
Extinction-to-backscatter ratio
Particle linear depolarization ratio

Cloud and precipitation
Extinction
Effective radius
Liquid, ice, rain water content
Snow rate, median diameter
Rain rate, drop size
Cloud/precipitation fraction
Cloud/precipitation classification

Radiation
Broadband radiances
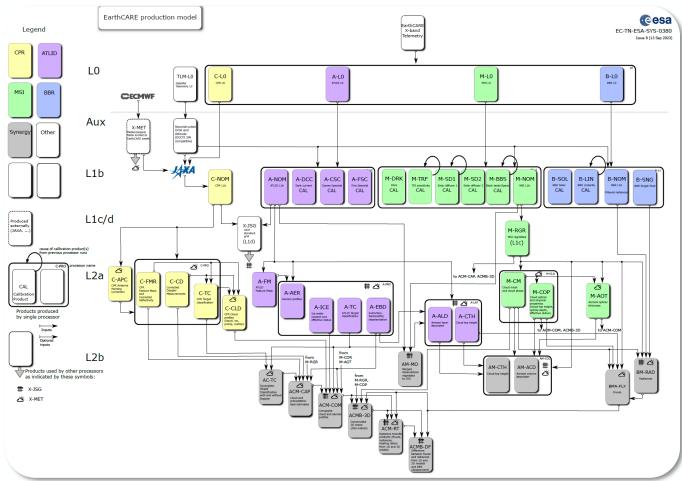Radiative fluxes

AMT special issue: *EarthCARE Level 2 algorithms and data products*
https://amt.copernicus.org/articles/special_issue1156.html

Preface to the special issue "EarthCARE Level 2 algorithms and data products": Editorial in memory of Tobias Wehr

Robin J. Hogan[1,2], Anthony J. Illingworth[2], Pavlos Kollias[3], Hajime Okamoto[4], and Ulla Wandinger[5]

[1]European Centre for Medium-Range Weather Forecasts, Reading, UK
[2]Department of Meteorology, University of Reading, Reading, UK
[3]School of Marine and Atmospheric Sciences, Stony Brook University, New York, USA
[4]Research Institute for Applied Mechanics, Kyushu University, Fukuoka, Japan
[5]Leibniz Institute for Tropospheric Research, Leipzig, Germany

Correspondence: Robin J. Hogan (r.j.hogan@ecmwf.int)

EarthCARE data products

esa

JAXA

ATLID	BBR	MSI	CPR
L1	L1	L1	L1
L2A		L2A	L2A
L2B			

ATLID	BBR	MSI	CPR
L1	L1	L1	L1
L2A		L2A	L2A
L2B			

Aux Proc

X-JSG **X-MET**
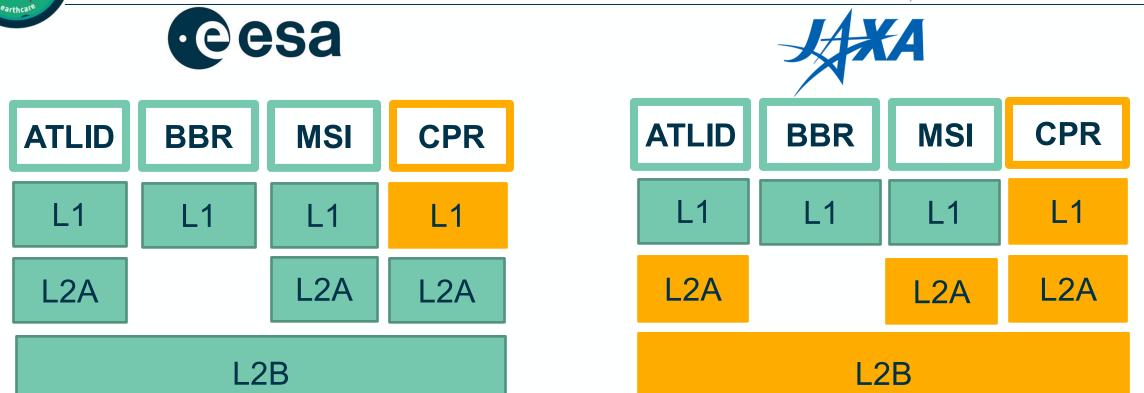
- Mutual dependency at Level 1 requiring for strong coordination between Agencies
- Separate Level 2 chains provide opportunity for collaboration and comparison
- Each agency coordinates the validation of its own products

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Jan 2025 — Level 1b Single Sensor Products
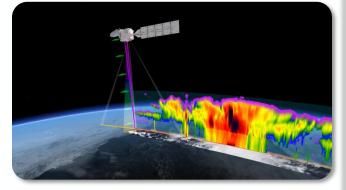
March 2025 — Level 2a Single Sensor Products
Level 2b Two Sensor Products

Dec 2025 — Level 2b Synergistic Products

Free and Open Data Policy

https://earth.esa.int/eogateway/missions/earthcare/data

https://www.esa.int/Applications/Observing_the_Earth/FutureEO/EarthCARE/EarthCARE_goes_live_with_data_now_available_to_all
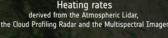
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https://www.esa.int/Applications/Observing_the_Earth/FutureEO/EarthCARE/EarthCARE_synergy_reveals_power_of_clouds_and_aerosols
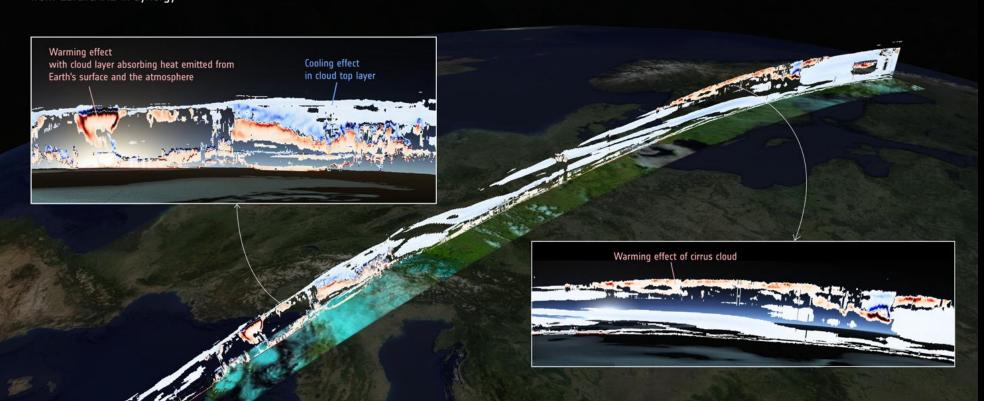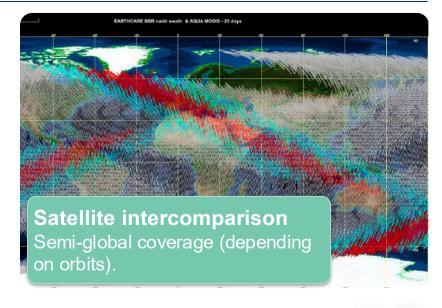
EarthCARE validation sources

Networks
Continuous surface-based data acquisition
Slower collection of collocations but broader coverage of geophysical and meteorological conditions.

KA
DLR HALO
Safire F20
FAAM-BAE
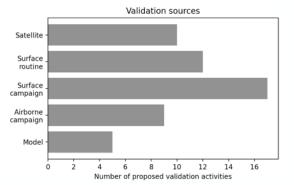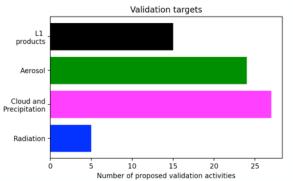
Airborne campaigns
Under-flights for product validation:
Rapidly collect numerous, precise collocations.

EARTHCARE BBR nadir swath & AQUA MODIS - 25 days

Satellite intercomparison
Semi-global coverage (depending on orbits).

ECMWF

Assimilation
Systematic monitoring (incl. calibration drift detection) with NWP model.

Validation sources

Satellite
Surface routine
Surface campaign
Airborne campaign
Model

Number of proposed validation activities

Validation targets

L1 products
Aerosol
Cloud and Precipitation
Radiation

Number of proposed validation activities

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EarthCARE data with aircraft tracks

Two aircraft seen in CPR data

Cloud top measured by Atmospheric Lidar (ATLID)

PERCUSION flight track

MAESTRO flight track

Cloud structure measured by Cloud Profiling Radar (CPR)

Atlantic Ocean

https://www.esa.int/Applications/Observing_the_Earth/FutureEO/EarthCARE/Taking_to_the_skies_for_EarthCARE

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ATLID: atmospheric lidar fundamentals

Telescope
Main plate
Radiator
M1
M2
Struts

Power Laser Head (PLH)
Beam-Expander (E-BEX)
Telescope support baseplate (TSB)
Emission baffle

ATLID Stable Structure Assembly (SSA) and equipments

Atmospheric LIDAR ATLID

High spectral resolution, UV LIDAR

- *355 nm source*
- *Vertical profiles 0-40km, 100-500m resolution*
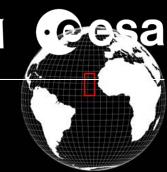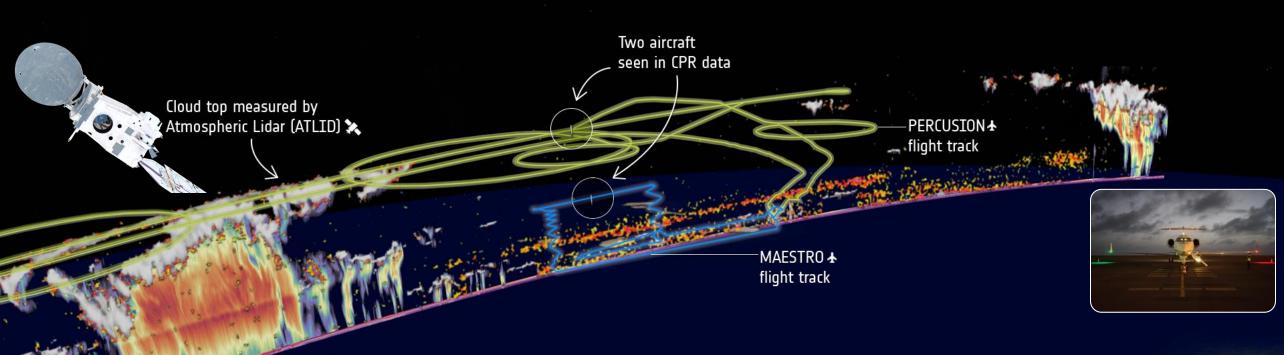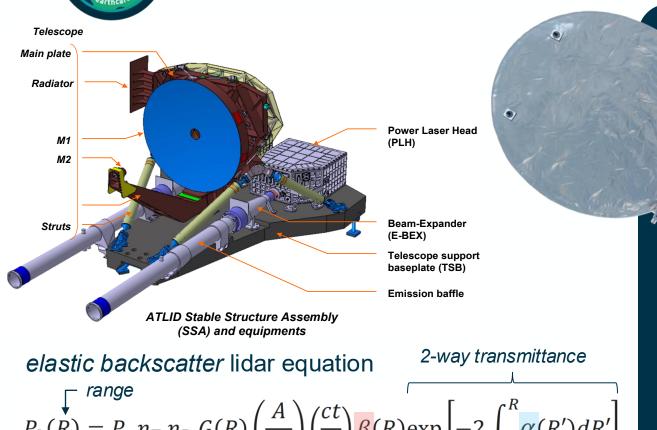- *Horizontal sampling 280m*
- *Rayleigh co-pol*
- *Mie co-pol*
- *Mie cross-pol*

L1: attenuated backscatter profiles

elastic backscatter lidar equation

range

2-way transmittance

$$P_L(R) = P_o\, \eta_T\, \eta_R\, G(R) \left(\frac{A}{R^2}\right)\left(\frac{ct}{2}\right)\beta(R)\exp\left[-2\int_0^R \alpha(R')dR'\right]$$

Laser power per pulse

system variables   *atmospheric variables*

β: volume **backscatter** coefficient
α: **extinction** coefficient: **absorption** + **scattering** by molecules + aerosols

molecules   aerosols

Rayleigh Scattering   Mie Scattering   Mie Scattering, larger particles

→ Direction of incident light

ATLID: High Spectral Resolution Lidar

Aerosol or cloud particles

Scattered light **is not** thermally broadened

Fast moving gas molecules

Scattered light **is** thermally broadened

Air density profile | Elastic "Mie" signal | Rayleigh signal

Aerosol or cloud layer

$$S = \frac{\alpha_{Part}}{\beta_{Part}}$$
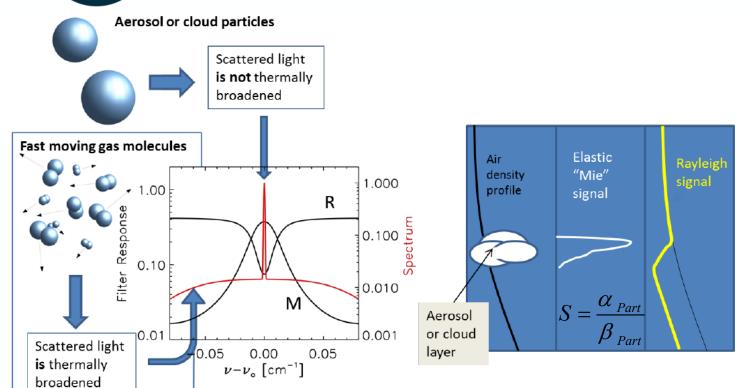
Compared to e.g. CALIPSO where total (Mie+Ray) signals are not separated:
- Direct measurement of aerosol extinction
- Measurement of extinction-to-backscatter ratio
- Improved daylight performance

Non-HSRL lidar

One measurement but two unknowns

$$P(z) = \frac{1}{z^2}\left(\beta_{Part}(z) + \beta_{Mol}(z)\right)e^{-2\int_0^z \alpha(z')dz'}$$

Must assume $S = \dfrac{\alpha_{Part}}{\beta_{Part}}$ in order to recover backscatter and extinction.

HSRL lidar

Two measurement and two unknowns

$$P_{Part}(z) = \frac{1}{z^2}\beta_{Part}(z)e^{-2\int_0^z \alpha(z')dz'}$$

$$P_{Mol}(z) = \frac{1}{z^2}\beta_{Mol}(z)e^{-2\int_0^z \alpha(z')dz'}$$

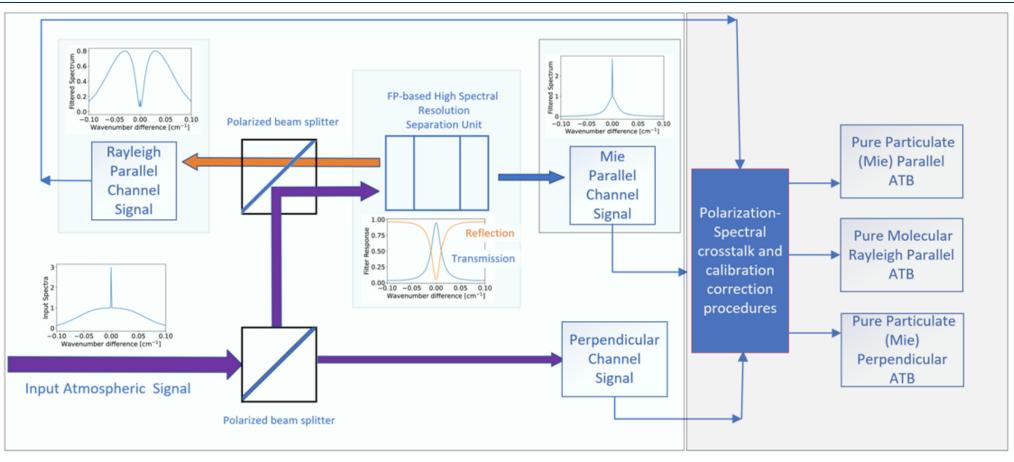$$= \sigma_{Ray}\frac{1}{z^2}N(z)e^{-2\int_0^z \alpha(z')dz'}$$

→ Can determine S !

ATLID: HSRL and polarization receiver
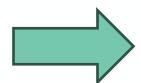

ATLID has three channels:
1. A perpendicular channel
2. A parallel (mainly-) particulate scattering channel
3. A parallel (mainly-) molecular scattering channel
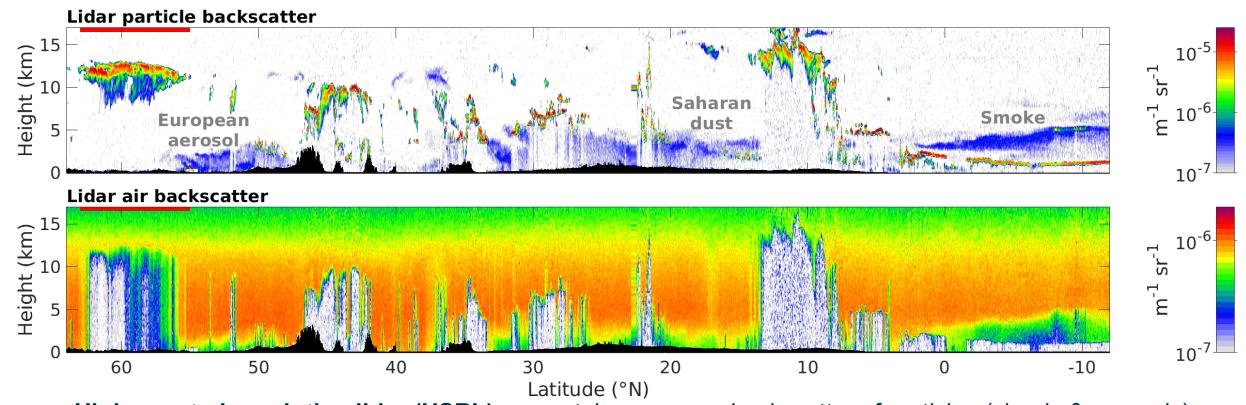
After spectral/polarization cross-talk correction and calibration
1. Perpendicular particulate channel (cross-polar Mie)
2. Parallel particulate scattering channel (co-polar Mie)
3. Molecular scattering channel (Rayleigh)

Lidar particle backscatter

European aerosol · Saharan dust · Smoke

Lidar air backscatter
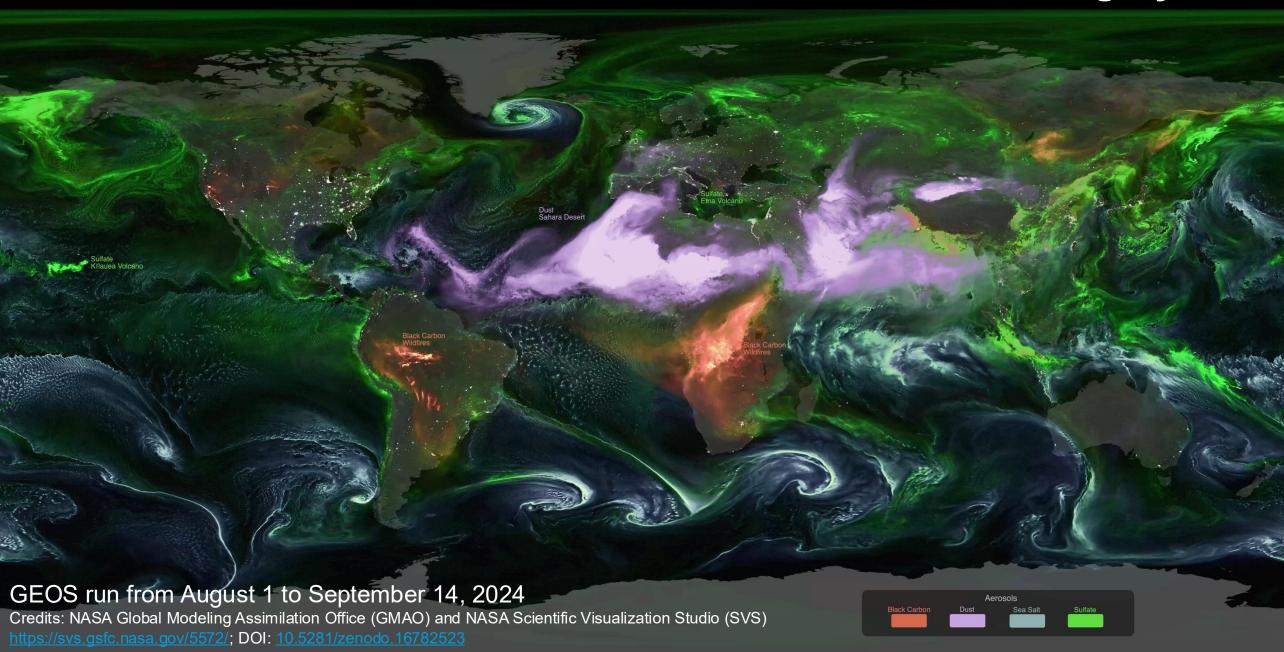
- **High spectral resolution lidar (HSRL)** separately measures backscatter of particles (clouds & aerosols) and air (Rayleigh scattering)

- Can unambiguously calculate the important profile of extinction coefficient from how much the air backscatter is attenuated

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Aerosols modelled with NASA's Goddard Earth Observing System

Sulfate
Kīlauea Volcano

Dust
Sahara Desert

Sulfate
Etna Volcano

Black Carbon
Wildfires

Black Carbon
Wildfires

GEOS run from August 1 to September 14, 2024

Aerosols

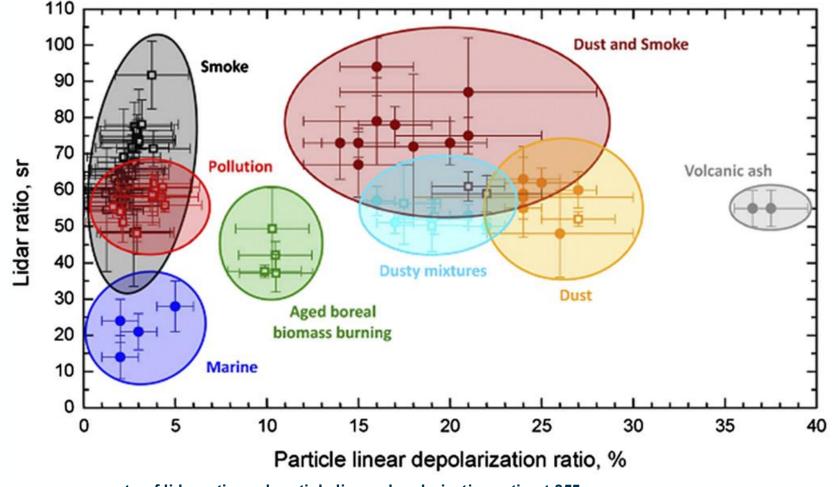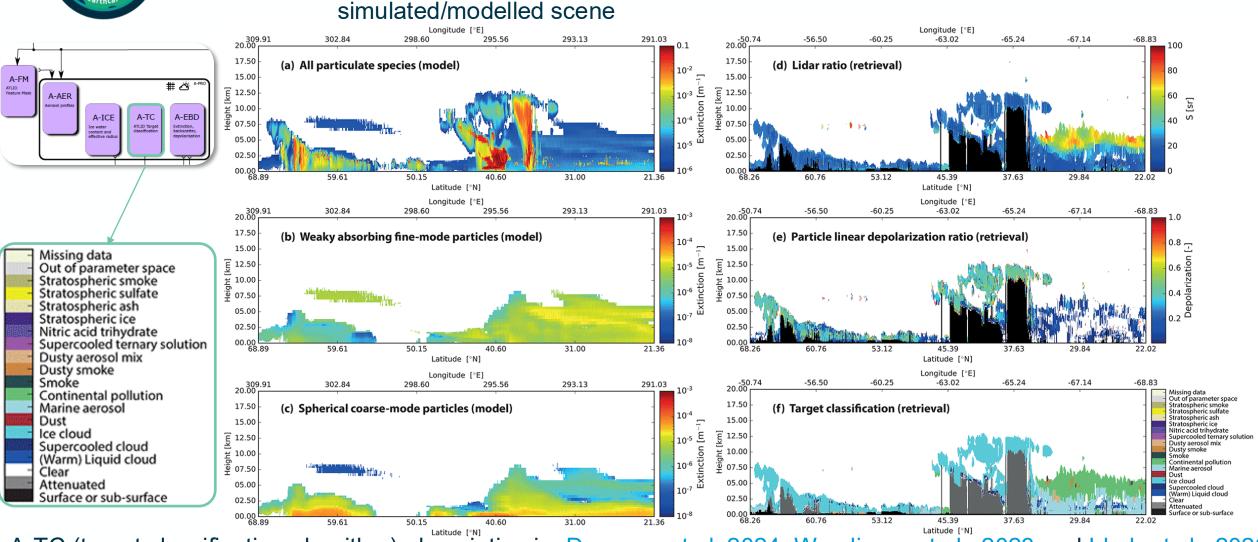| Black Carbon | Dust | Sea Salt | Sulfate |

ATLID: aerosol type classification

Aerosol classification from measurements of lidar ratio and particle linear depolarization ratio at 355 nm.
Ground-based observations were performed with the Raman-polarization lidars (POLIS) (University of Munich, dots) and Polly XT (Leibniz Institute for Tropospheric Research, open squares) at Cape Verde (dust, marine, dust and smoke, dusty mixtures; dots; Groß et al. 2011); Leipzig, Germany (pollution, aged boreal biomassburning aerosol, dusty mixtures; open squares); Munich, Germany (volcanic ash; dots; Groß et al. 2012); in the Amazon basin (smoke; open squares; Baars et al. 2012); and over the North Atlantic (dust, dust and smoke; open squares; Kanitz et al. 2013). *Source: Figure 8, Illingworth et al, 2015*

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simulated/modelled scene

A-TC (target classification algorithm), description in: Donovan et al, 2024, Wandinger et al., 2023 and Irbah et al., 2023

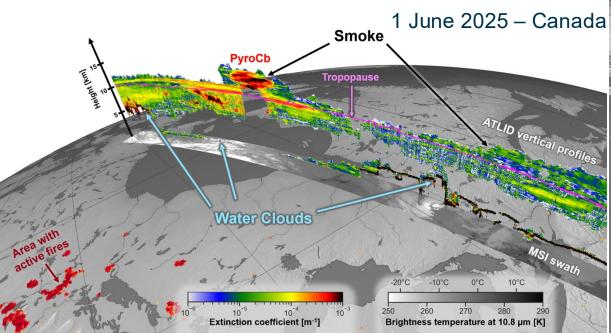# ATLID: smoke from wildfires into UTLS

2025 was second only to 2023 in the intensity of the Canadian wildfires, and just ahead of 2024.
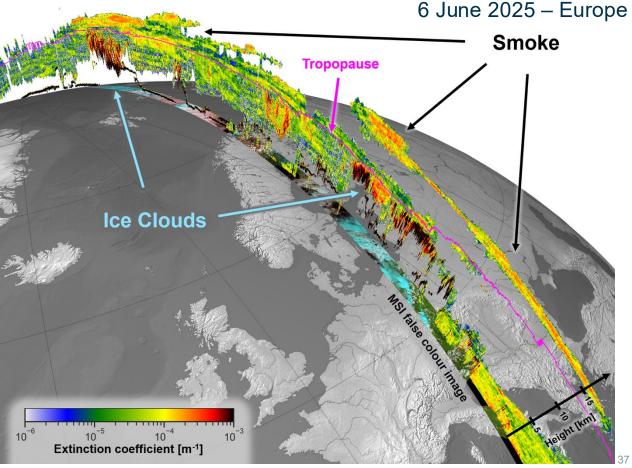
Injection of dense smoke plumes into the upper atmosphere.

EarthCARE can tracked smoke layers over vast distances.

What's the impact on long-term climate, ozone,

cloud formation and radiative forcing?

Towards scientific exploitation
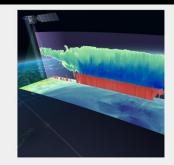
https://earth.esa.int/eogateway/missions/earthcare

EarthCARE Product Data Handbook:
https://earthcarehandbook.earth.esa.int/

https://www.earthcarescience.net/home

New measurements
What can we learn from the Doppler radar and the high spectral resolution lidar?
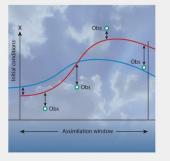
Radiative closure
Radiation calculations check that retrieved clouds are consistent with broadband radiation measurements.

Model evaluation
How can we use the data to evaluate and improve weather and climate models?

Data assimilation
How will the data be ingested into weather forecast and air-quality models?

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Radiative closure

- EarthCARE continually compares **computed fluxes from ACM-RT** to **measurements by the broadband radiometer** (processed by BMA-FLX)

- If they agree, it gives us confidence in the retrieved cloud properties; if they disagree then we have something to improve in our algorithms or something to learn about the atmosphere!

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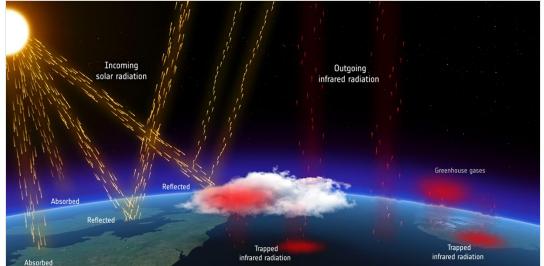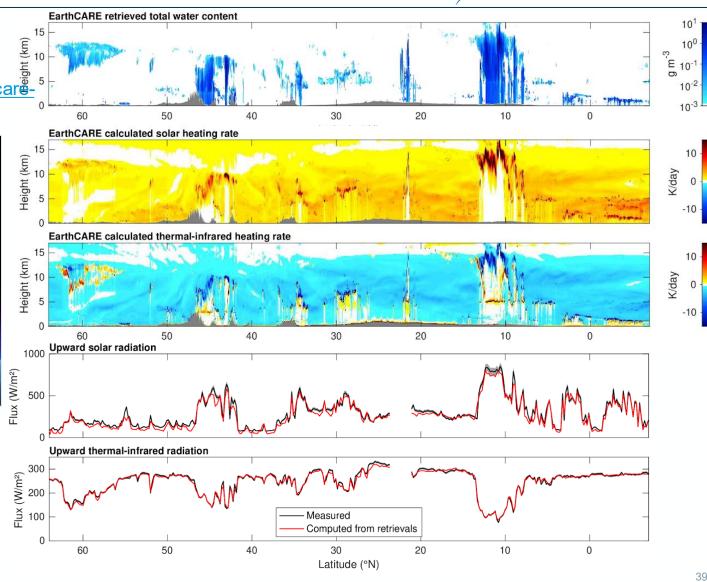
https://www.earthcarescience.net/science/model-evaluation
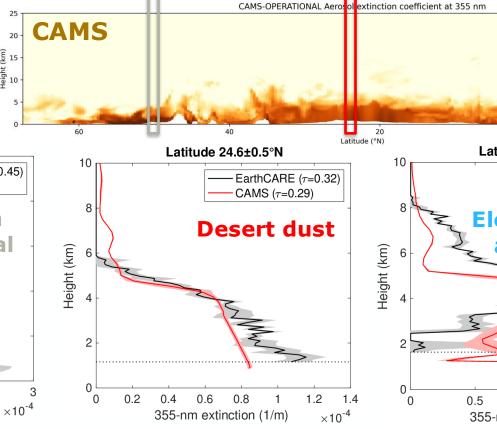
CAMS: ECMWF's air quality forecast including 15 prognostic aerosol variables
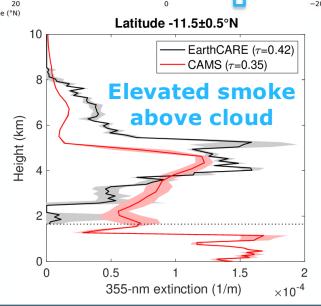
Outputs 355-nm extinction coefficient

Have never before been able to evaluate aerosol profiles globally with such resolution & accuracy, nor above clouds!

ATL-EBD particle_extinction_coefficient_355nm_low_resolution; aerosol only

ATLID A-EBD

CAMS-OPERATIONAL Aerosol extinction coefficient at 355 nm

CAMS

Latitude 52.7±0.5°N

European continental aerosol

- EarthCARE (τ=0.45)
- CAMS (τ=0.23)

Latitude 24.6±0.5°N

Desert dust

- EarthCARE (τ=0.32)
- CAMS (τ=0.29)

Latitude -11.5±0.5°N

Elevated smoke above cloud

- EarthCARE (τ=0.42)
- CAMS (τ=0.35)

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Model eval: CAMS aerosols in India

Peter Hill,
Robin Hogan,
David Donovan

Unprecedented quantitative, global evaluation of aerosol profiles in CAMS air-quality forecasts!

CAMS 355-nm optical depth   08 Apr 2025, 09 UTC

EarthCARE natural colour image (M-RGR)   08 Apr 2025, 08:58-09:11 UTC

EarthCARE aerosol 355-nm extinction coefficient (A-EBD)

CAMS aerosol 355-nm extinction coefficient

Aerosol 355-nm optical depth
- EarthCARE
- AERONET
- CAMS

CAMS underestimates high optical depth in south-west India

Good agreement between **EarthCARE** and **AERONET**

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Improving ice/snow fall speed in ECMWF model

CPR mean fall speed
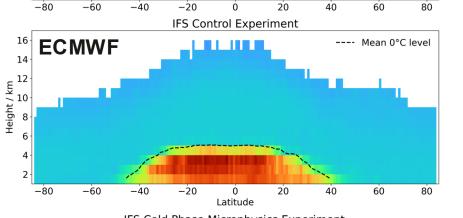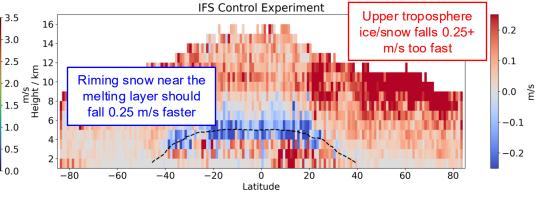
Rebecca Murray-Watson, Mark Fielding, Richard Forbes

Ice & snow fall speeds affect model climate and forecast skill: this is first time we have been able to evaluate it globally!
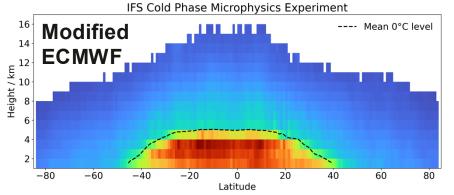
ECMWF model is very simple! ice falls at 0.13 m/s, snow at 1 m/s
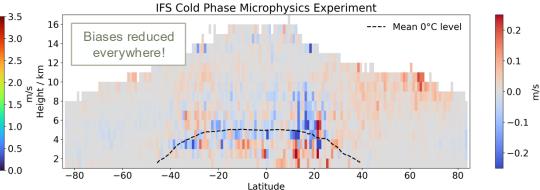
Modifications: use a *mass-weighted* fall speed; add *rimed snow*, temperature-dependent size & air-density effect

EarthCARE

ECMWF

Modified ECMWF

IFS Control Experiment — Upper troposphere ice/snow falls 0.25+ m/s too fast

Riming snow near the melting layer should fall 0.25 m/s faster

IFS Cold Phase Microphysics Experiment — Biases reduced everywhere!
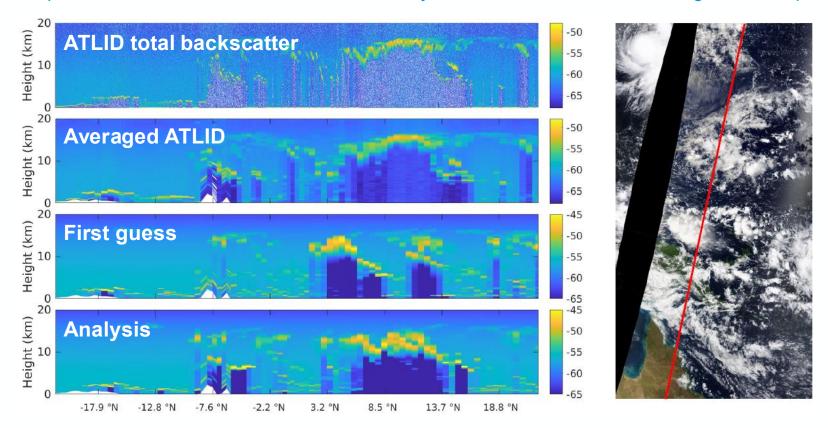
Data assimilation and NWP impact

Mark Fielding,
Marta Janiskova
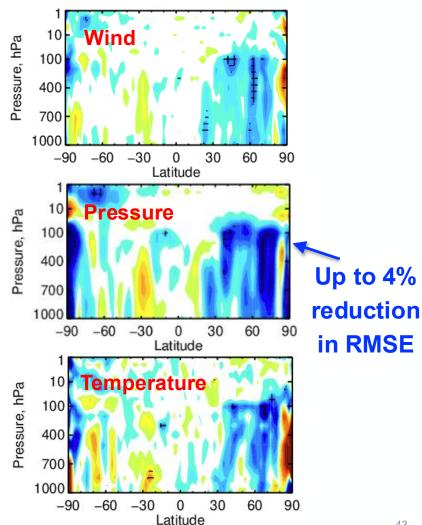
https://www.ecmwf.int/en/newsletter/183/earth-system-science/earthcare-data-begin-make-impact

Impact on 5-day forecast skill

ATLID total backscatter

Averaged ATLID

First guess

Analysis

Wind

Pressure

Temperature

Up to 4% reduction in RMSE

Assimilation of CPR reflectivity and ATLID backscatter into ECMWF model improves skill: *will go operational in Cycle 50r1 (autumn 2025)*

ECMWF is working on assimilation of ATLID into aerosol forecasts

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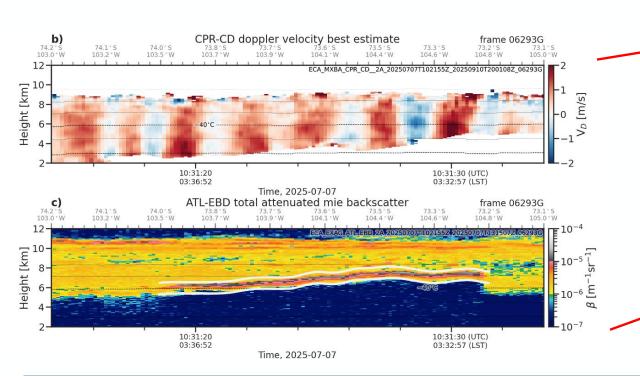
Gravity waves in Antarctic cloud

Shannon Mason
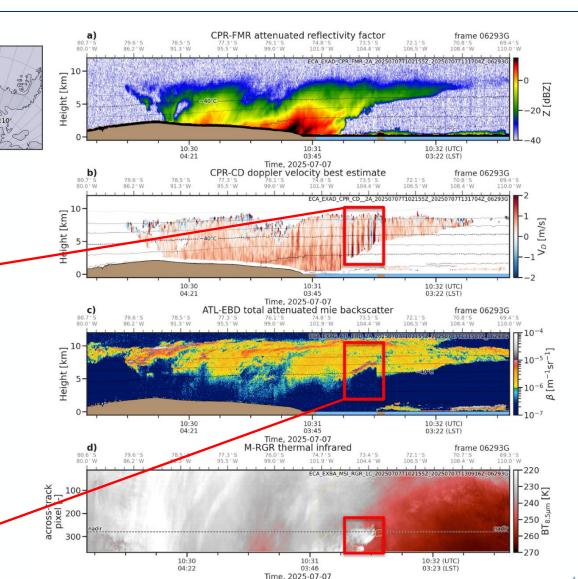
https://earth.esa.int/eogateway/success-story/earthcare-reveals-how-atmospheric-ripples-boost-cloud-formation-over-antarctica

Gravity waves are common in the atmosphere, particularly in the vicinity of orography, and can lead to cloud formation.
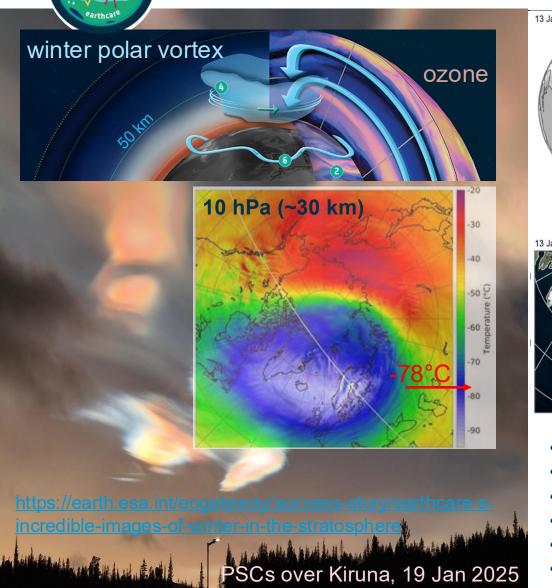
In this example over Antarctica, gravity waves were detected by the CPR with a wavelength of 18 km and an amplitude up to 2 m/s.

Polar Stratospheric Clouds

winter polar vortex

50 km

ozone

10 hPa (~30 km)

-78°C

https://earth.esa.int/eogateway/success-story/earthcare-s-incredible-images-of-winter-in-the-stratosphere

PSCs over Kiruna, 19 Jan 2025

13 Jan 2025, 23:25-23:36 UTC 03579B-C

ATLID co-polar channel

Type II PSC

Type I PSC

13 Jan 2025, 23:25-23:36 UTC 03579B-C

EUROPE

ATLID cross-polar channel

Type II PSC

Type I PSC

tropopause

- Polar Stratospheric Clouds (PSCs) over the Arctic (and Antarctica)
- Form inside the polar vortex, at heights of ~20-30 km
- PSC Type I: supercooled nitric acid (and sulfuric acid) and water (T < -78°C)
- Contribute to polar ozone depletion (see Tritscher et al., 2021)
- PSC Type II: ice crystals (nacreous clouds) (T ~< -83 to -85 °C)
- Mountain leewaves (gravity waves) can form lenticular PSCs

45

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A direct look into the eye of a hurricane
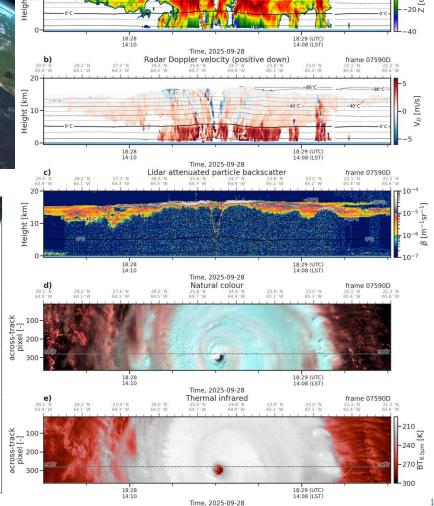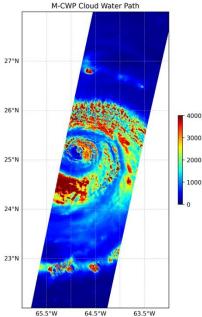
https://www.earthcarescience.net/gallery/tropical-cyclones

See also:
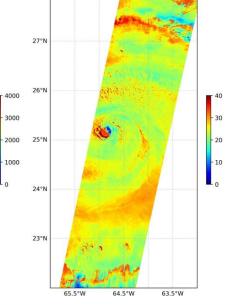
https://earth.esa.int/eogateway/success-story/earthcare-stares-into-the-eye-of-tropical-cyclone-vince

18:27:30

18:29:30

MSI 20250928 07590D

credits: JAXA

Hurricane Humberto
28 September 2025

M-CWP Cloud Water Path
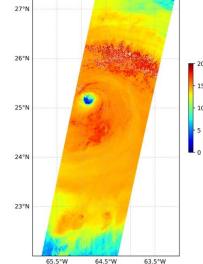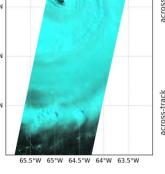
M-REFF Cloud Effective Radius

M-CTH Cloud Top Height [km]

RGB

a) Radar reflectivity — frame 07590D

b) Radar Doppler velocity (positive down) — frame 07590D

c) Lidar attenuated particle backscatter — frame 07590D

d) Natural colour — frame 07590D

e) Thermal infrared — frame 07590D

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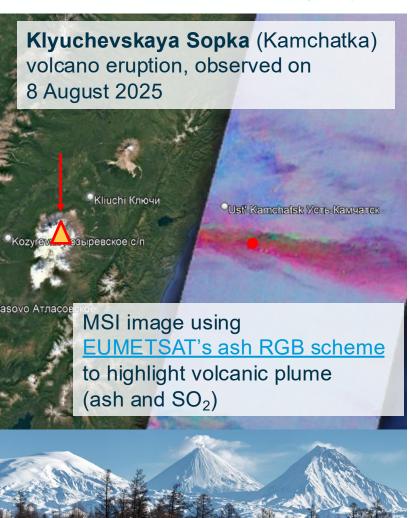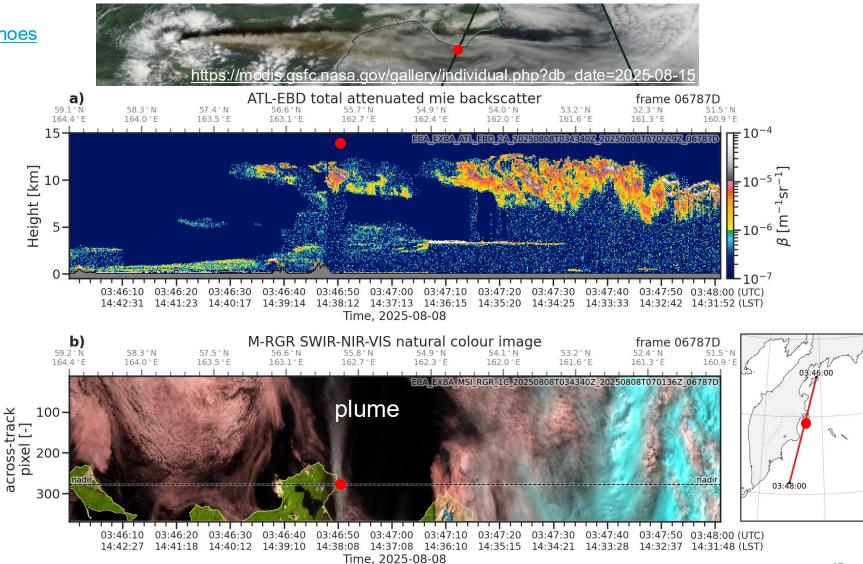
Observing volcanic plumes

https://www.earthcarescience.net/gallery/volcanoes

Klyuchevskaya Sopka (Kamchatka) volcano eruption, observed on 8 August 2025

MSI image using EUMETSAT's ash RGB scheme to highlight volcanic plume (ash and SO_2)

https://modis.gsfc.nasa.gov/gallery/individual.php?db_date=2025-08-15

a) ATL-EBD total attenuated mie backscatter — frame 06787D

ECA_EXBA_ATL_EBD_2A_20250808T034340Z_20250808T070229Z_06787D

b) M-RGR SWIR-NIR-VIS natural colour image — frame 06787D

ECA_EXBA_MSI_RGR_1C_20250808T034340Z_20250808T070136Z_06787D

plume

THE EUROPEAN SPACE AGENCY

In a nutshell:

- EarthCARE **explores the scientific basis of the** interactions between cloud, aerosol, and radiation, and will **improve satellite algorithms, numerical weather predictions, and climate model projections**, with **new features** such as synergetic observations by four sensors

- EarthCARE hosts two unique remote sensing instruments, CPR (**Doppler Radar**) and ATLID (**High Spectral Resolution Lidar**)

- The EarthCARE satellite was successfully launched on **28 May 2024**
  - Level 1 products were released to the public on **14th January 2025**
  - Level 2 single-sensor products and 2-sensor synergy products were released on **17th March 2025**
  - 3-sensor and 4-sensor synergy products are scheduled to be released in **December 2025**

- Validation results show **very promising early product quality and offering significant scientific opportunities.**

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HAKURYU EarthCARE "White Dragon"

Nickname "HAKURYU" ("White Dragon") proposed by JAXA:

"The nickname embodies the distinctive appearance of the EarthCARE satellite. In Japan, dragons are revered as divine creatures governing water, aligning with the EarthCARE mission of elucidating the radiation balance mechanism of the Earth's atmosphere through the interaction of water and ice cloud formations with aerosols.

Among dragons, HAKURYU is believed to fly faster than others, resonating with the image of satellites orbiting the Earth at high speeds.

Furthermore, in the Five Elements philosophy, white represents the west, symbolizing good cooperation with Europe, located in the western direction from Japan."

BACK-UP SLIDES

Timeline: 1998 — 2001 — 2004 — 2015 — 2023

Anthropogenic and natural forcing of the climate for the year 2000, relative to 1750

Figure 2-2: The influence of external factors on climate can be broadly compared using the concept of
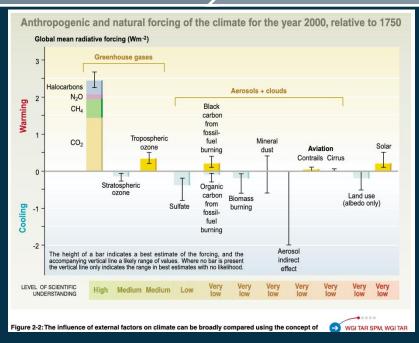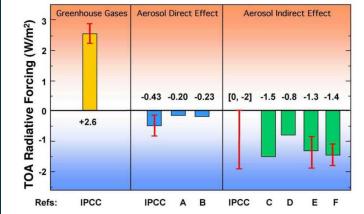

Figure 2.1: Global annual mean radiative forcing at the top of atmosphere corresponding to changes from 1750 to 2000 following IPCC (2001) together with some more recent assessments of aerosol direct and indirect effects (modelling and satellite studies). The IPCC values show smaller direct forcings than recently derived by Bellouin et al. (up to -1.9 Wm⁻², see text). Note that although direct radiative forcing is fairly well known, indirect forcing of aerosols is extremely uncertain. (A: Takemura et al., 2002, B: Kaufman et al., 2003, C: Takemura, 2003a, D: Takemura, 2003b, E: Nakajima et al., 2001, F: Sekiguchi et al., 2003) Estimates of the SW, LWS and NET cloud feedbacks are much larger than the other values in the graph..
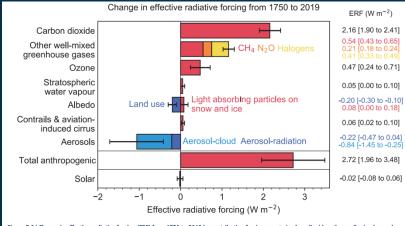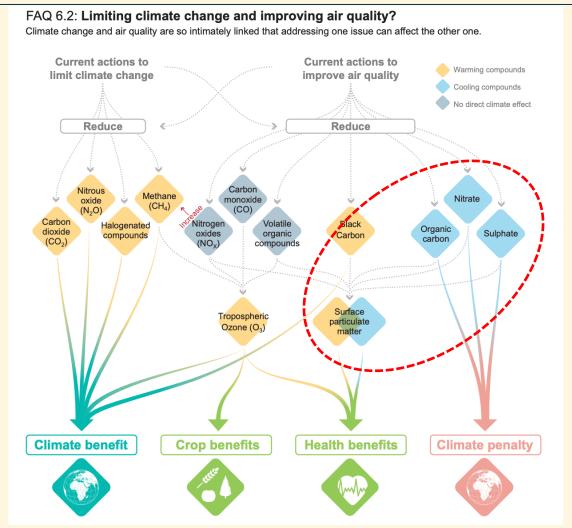

Figure 7.6 | Change in effective radiative forcing (ERF) from 1750 to 2019 by contributing forcing agents (carbon dioxide, other well-mixed greenhouse gases (WMGHGs), ozone, stratospheric water vapour, surface albedo, contrails and aviation-induced cirrus, aerosols, anthropogenic total, and solar).

Aerosols, climate change and air quality

FAQ 6.2: Limiting climate change and improving air quality?

Climate change and air quality are so intimately linked that addressing one issue can affect the other one.

FAQ 6.2, Figure 1 | Links between actions aiming to limit climate change and actions to improve air quality. Greenhouse gases (GHGs) and aerosols (orange and blue) can affect climate directly. Air pollutants (bottom) can affect human health, ecosystems and climate. All these compounds have common sources and sometimes interact with each other in the atmosphere which makes it impossible to consider them separately (dotted grey arrows).
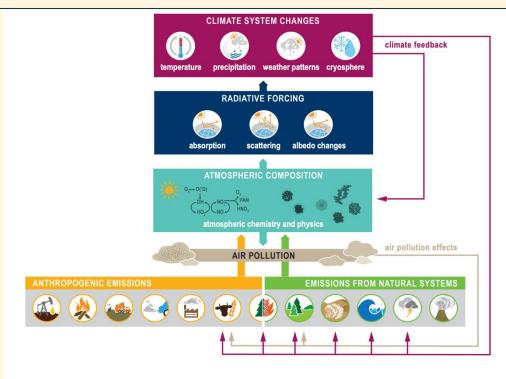
Figure 6.1 | Sources and processes leading to atmospheric short-lived climate forcer (SLCF) burden and their interactions with the climate system.

FAQ 6.2 | What Are the Links Between Limiting Climate Change and Improving Air Quality?

[…]

There are, however, also 'win-lose' actions. For example, wood burning is defined as carbon neutral because a tree accumulates the same amount of carbon dioxide throughout its lifetime as is released when wood from that tree is burned. However, burning wood can also result in significant emissions of air pollutants, including carbon monoxide, nitrogen oxides, volatile organic compounds, and particulate matter, that locally or regionally affect the climate, human health and ecosystems (FAQ 6.2, Figure 1). Alternatively, decreasing the amount of sulphate aerosols produced by power and industrial plants, and from maritime transport, improves air quality but results in a warming influence on the climate, because those sulphate aerosols contribute to cooling the atmosphere by blocking incoming sunlight.

Air quality and climate change represent two sides of the same coin, and addressing both issues together could lead to significant synergies and economic benefits while avoiding policy actions that mitigate one of the two issues but worsen the other.
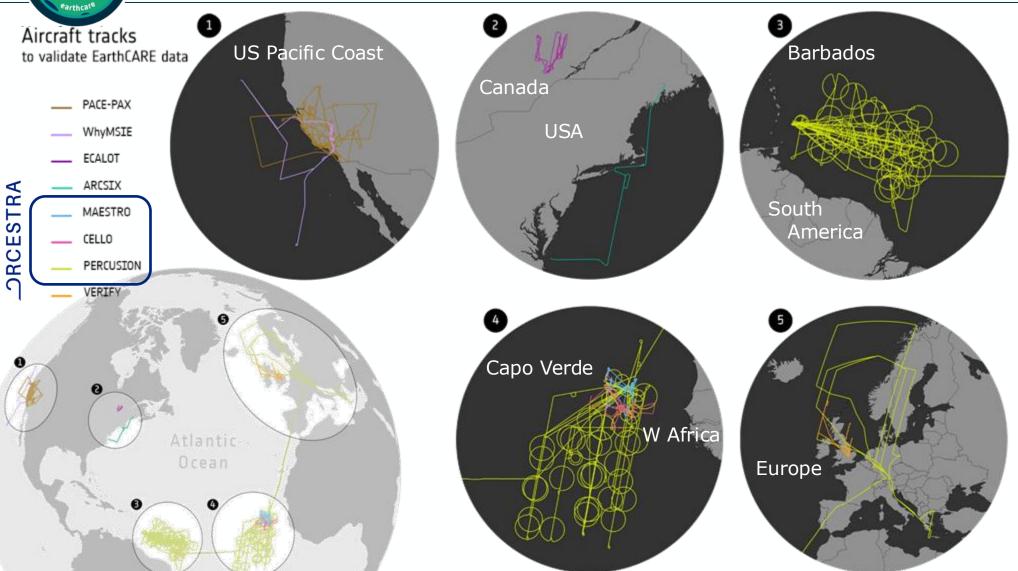
from MAAP to ASCEND

Airborne validation campaigns

Aircraft tracks to validate EarthCARE data

Legend:
- PACE-PAX
- WhyMSIE
- ECALOT
- ARCSIX
- MAESTRO
- CELLO
- PERCUSION
- VERIFY

ORCESTRA

1. US Pacific Coast
2. Canada / USA
3. Barbados / South America
4. Capo Verde / W Africa
5. Europe

More than 100 flights (… and counting)!

International effort involving complex cooperation between more than 60 research organisations, space agencies and aircraft teams

Legacy, Future and Internat'l Collaboration

CloudSat
2006-2023
94 GHz Radar

CALIPSO
2006-2023
532/1064 nm Lidar

Aeolus
2018-2023
355 nm HSRL Lidar

EarthCARE 2024-

ACDL/DQ-1, 2022-
532nm(HSR)/1064nm/
1572nm Lidar
ACDL/DQ-2, 2025-

CHINA NATIONAL SPACE ADMINISTRATION

AOS-Sky [US led]
Single-frequency Doppler Radar
Microwave Radiometer
Backscatter Lidar
Polarimeter
FIR Imaging Radiometer

AOS-Storm
[US led, pre-decisional]
Backscatter Lidar
Microwave Radiometer

PMM [Japan led]
Ku Wide-Swath Doppler Radar
Microwave Radiometer

HAWCsat [Canada led]
Aerosol & Water Vapor Limb Imager

AOS will fly in two orbits: Polar & Inclined

**AOS-Storm/
PMM**
2029-
**AOS-Sky/
HAWCsat**
2031-

eps-Aeolus/-2
2034-
355nm   HSRL Lidar

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