Spaceborne radar & lidar: from model evaluation to data assimilation

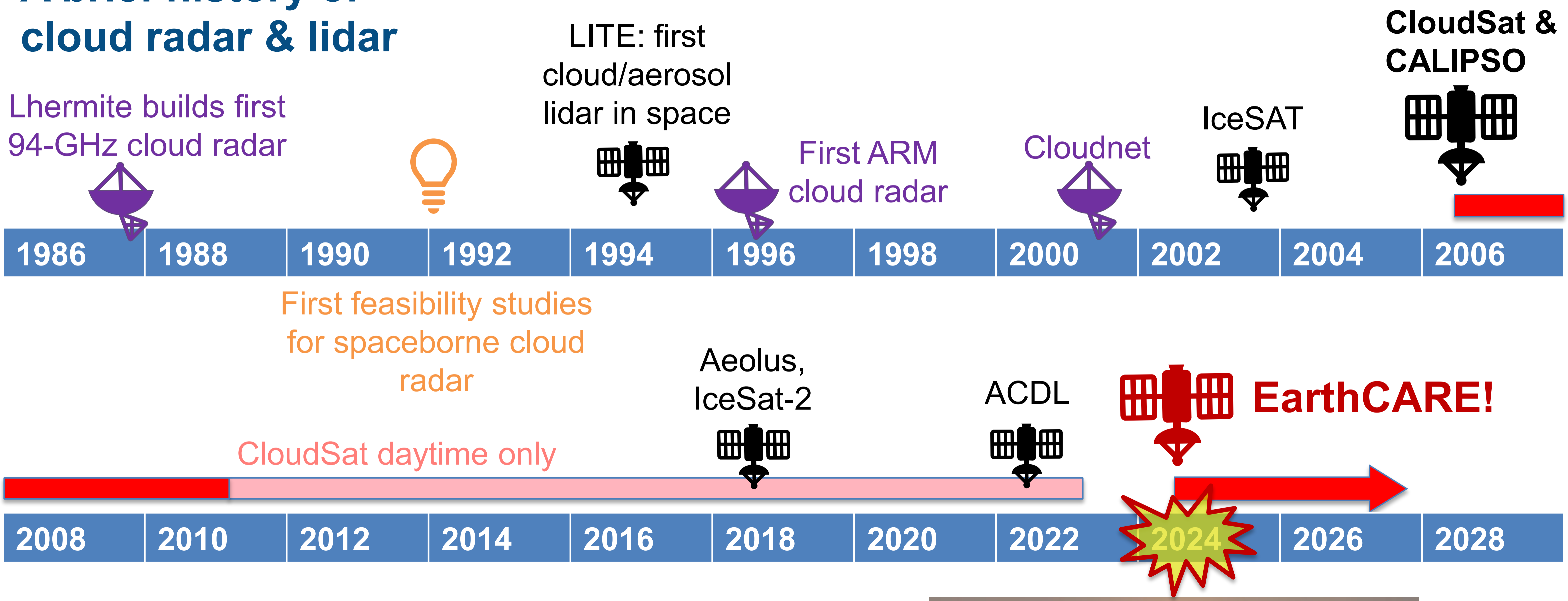
Robin Hogan (ECMWF)
Mark Fielding
Shannon Mason
Richard Forbes
Rebecca Murray-Watson
Peter Hill
Marta Janisková
Kamil Mroz
Bernat Puigdomenech-Treserras
Jason Cole and many others

robin.hogan@ecmwf.int

Overview

- Brief history of cloud radar and lidar
- How spaceborne lidar improved mixed-phase clouds in weather and climate models
- What can the EarthCARE satellite measure?
- Evaluating aerosol extinction in CAMS forecasts
- Using aircraft campaigns underflying EarthCARE to validate retrievals and test radar ice scattering models
- Using EarthCARE to improve ice and snow fallspeed in the IFS
- Using EarthCARE to improve tropical cirrus
- First assimilation of the EarthCARE radar

A brief history of cloud radar & lidar



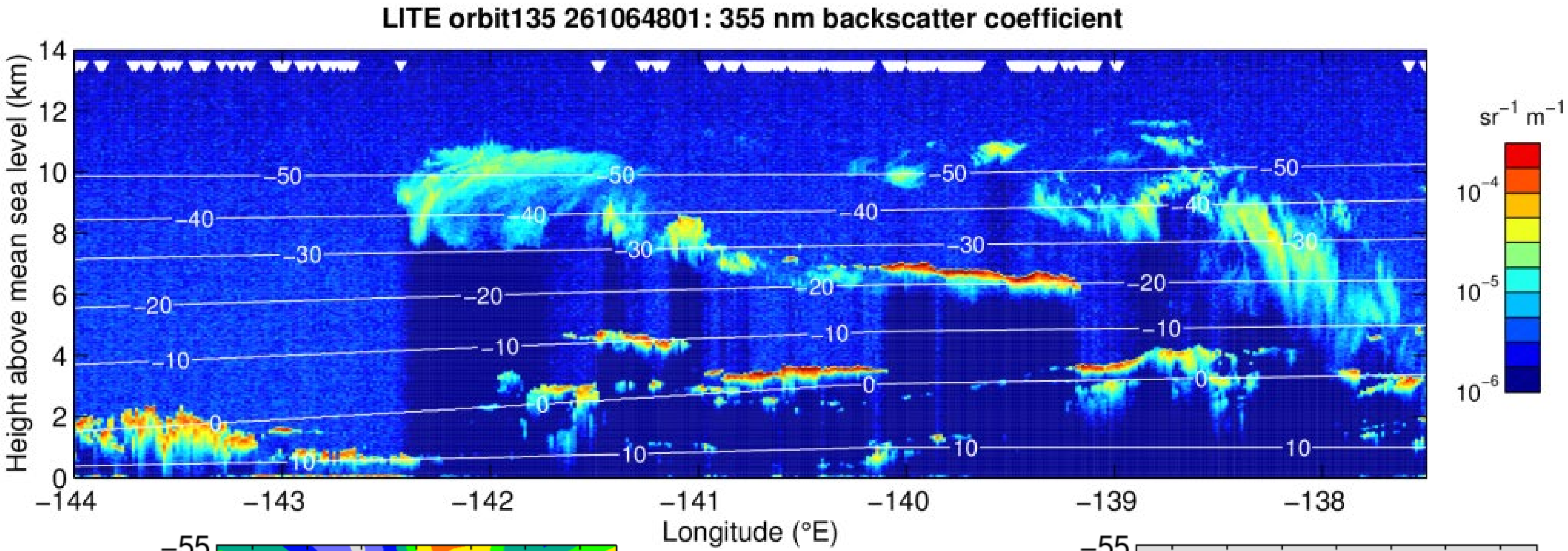
EarthCARE: the ESA-JAXA Earth Cloud, Aerosol and Radiation Explorer

Launched 28 May 2024

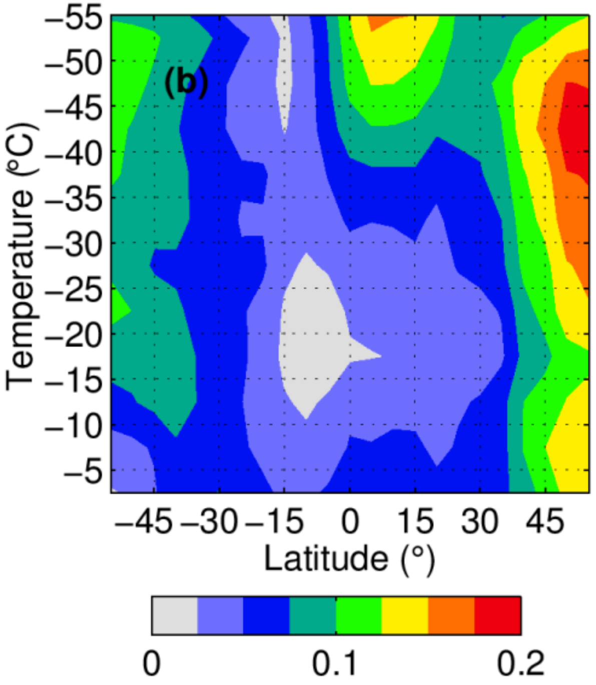
ECMWF

Spaceborne lidar "LITE" provided a new perspective on mixed-phase clouds

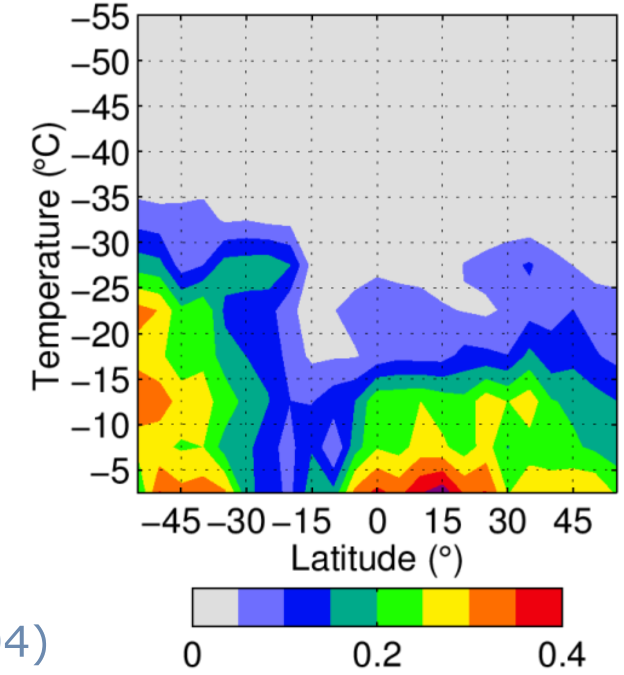
- Liquid clouds have a much higher lidar backscatter than ice



- Global cloud occurrence from LITE, 9-20 September 1994



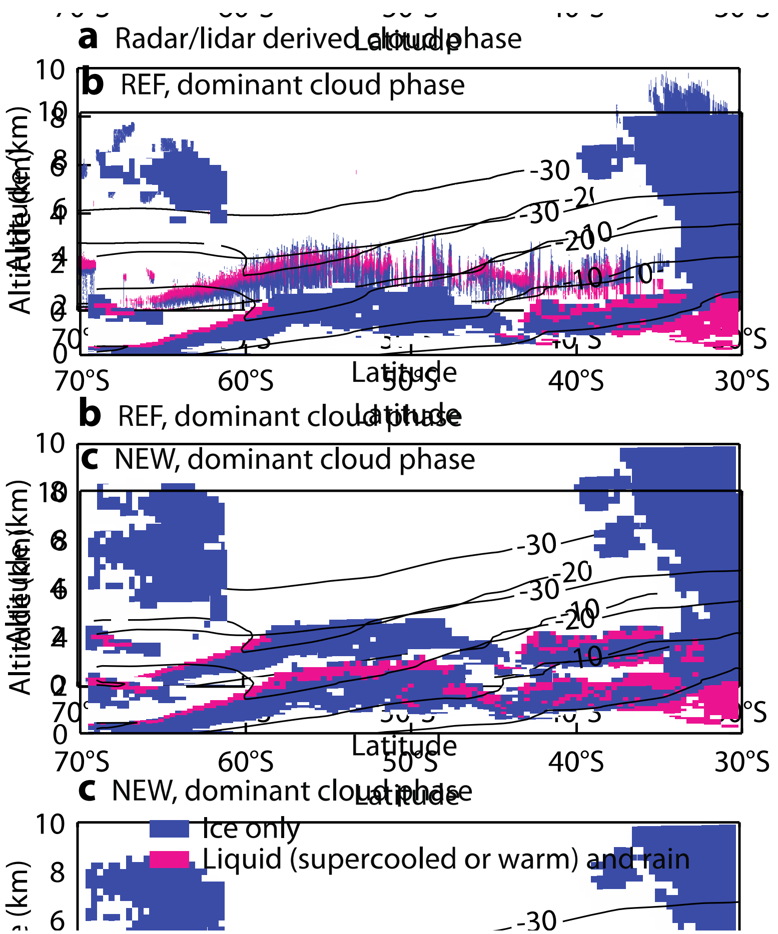
- Fraction of clouds containing supercooled water



Hogan et al. (2004)

CloudSat/CALIPSO helped improve mixed-phase clouds in the ECMWF model

- **New mixed-phase cloud treatment** informed by CALIPSO cloud top phase (Forbes & Ahlgrimm 2014)
- **Convective detrainment of supercooled water** in cold air outbreaks greatly improves shortwave radiation in Southern Ocean (Forbes et al. 2016)



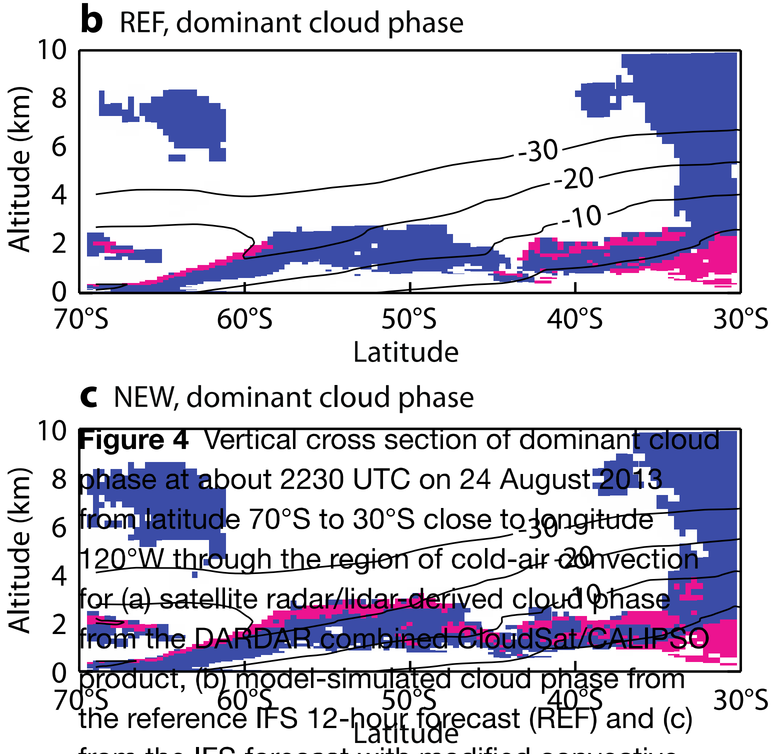
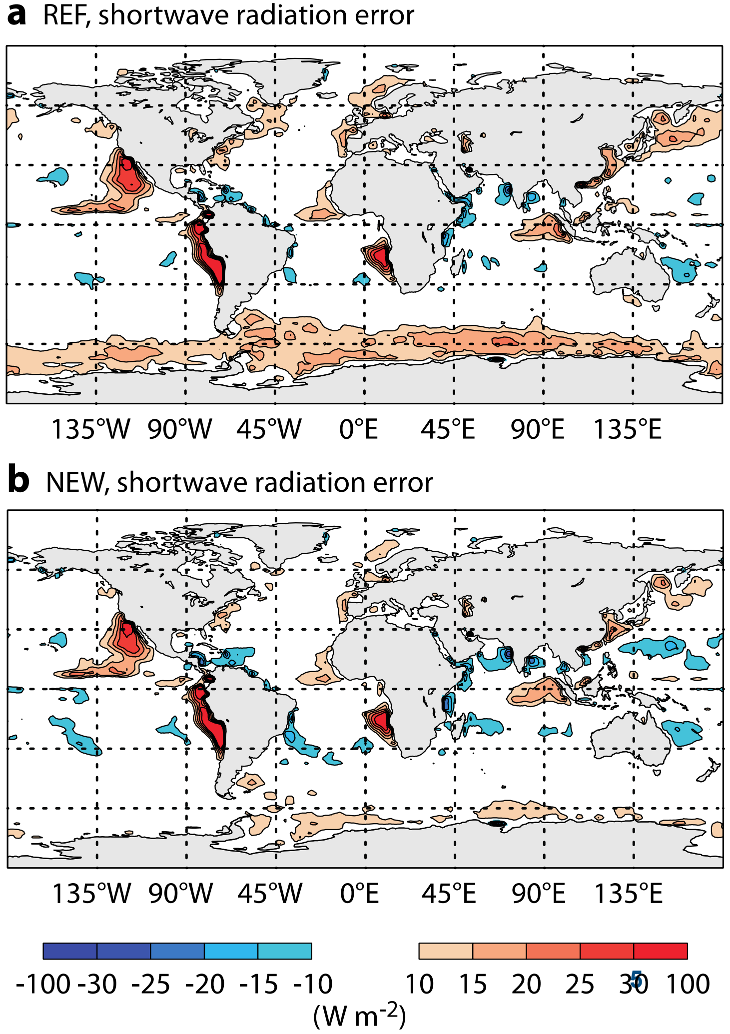
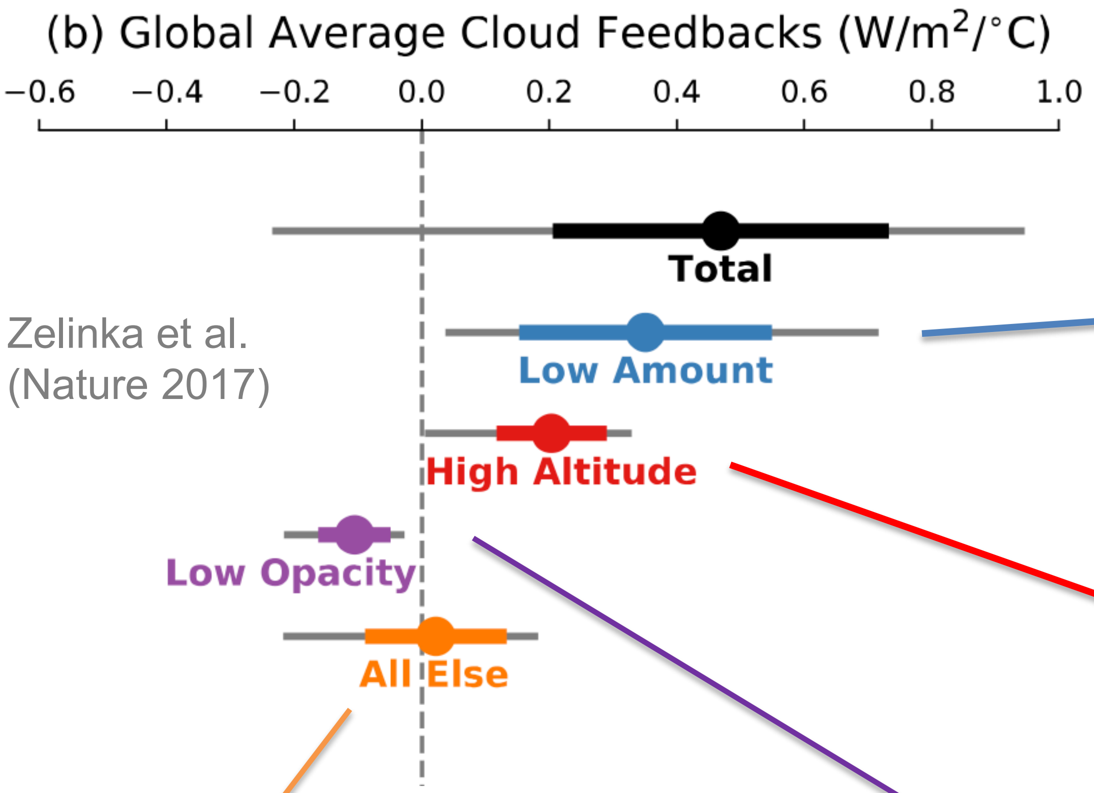


Figure 4 Vertical cross section of dominant cloud phase at about 2230 UTC on 24 August 2013 from latitude 70°S to 30°S close to longitude 120°W through the region of cold-air convection for (a) satellite radar/lidar-derived cloud phase from the DARDAR combined CloudSat/CALIPSO product, (b) model-simulated cloud phase from the reference IFS 12-hour forecast (REF) and (c) from the IFS forecast with modified convective supercooled liquid water detrainment (NEW). Temperature contours are shown every 10°C from 0° to -30°C.



CloudSat/CALIPSO helped us better understand cloud feedbacks



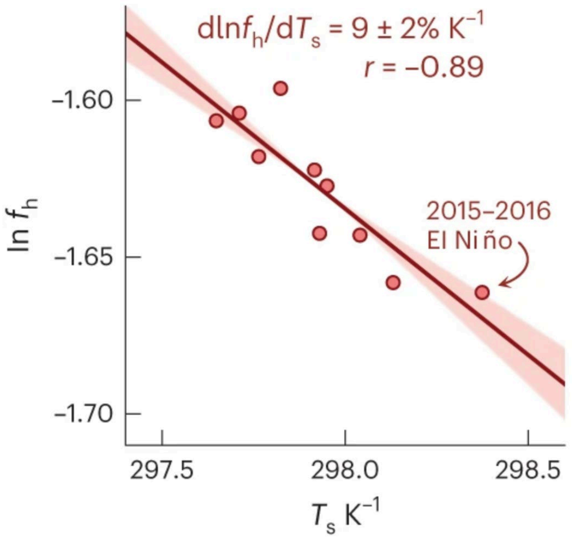
Zelinka et al. (Nature 2017)

Future changes to low clouds (including their response to changing aerosols) are hugely important but very uncertain

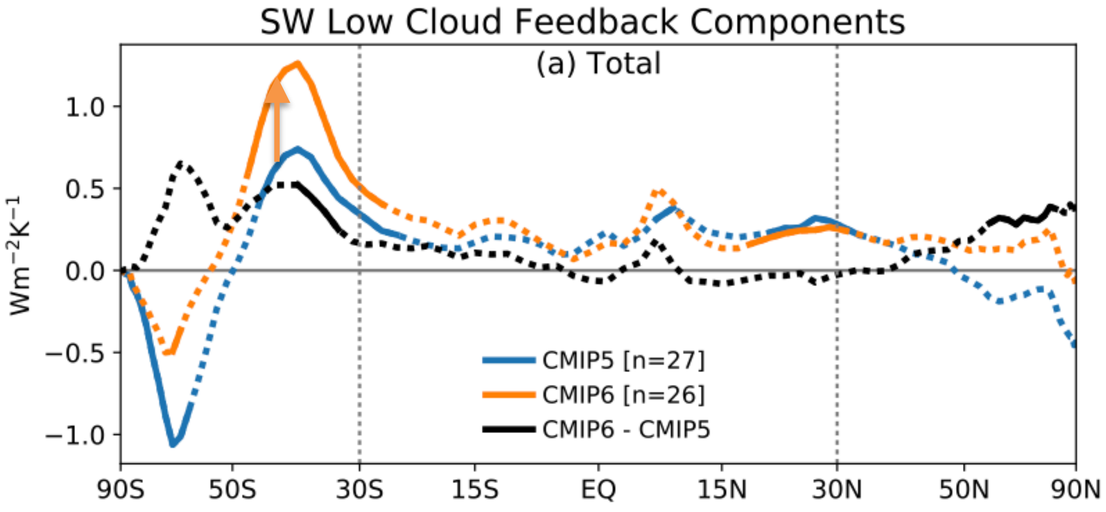
Plenty more work required!

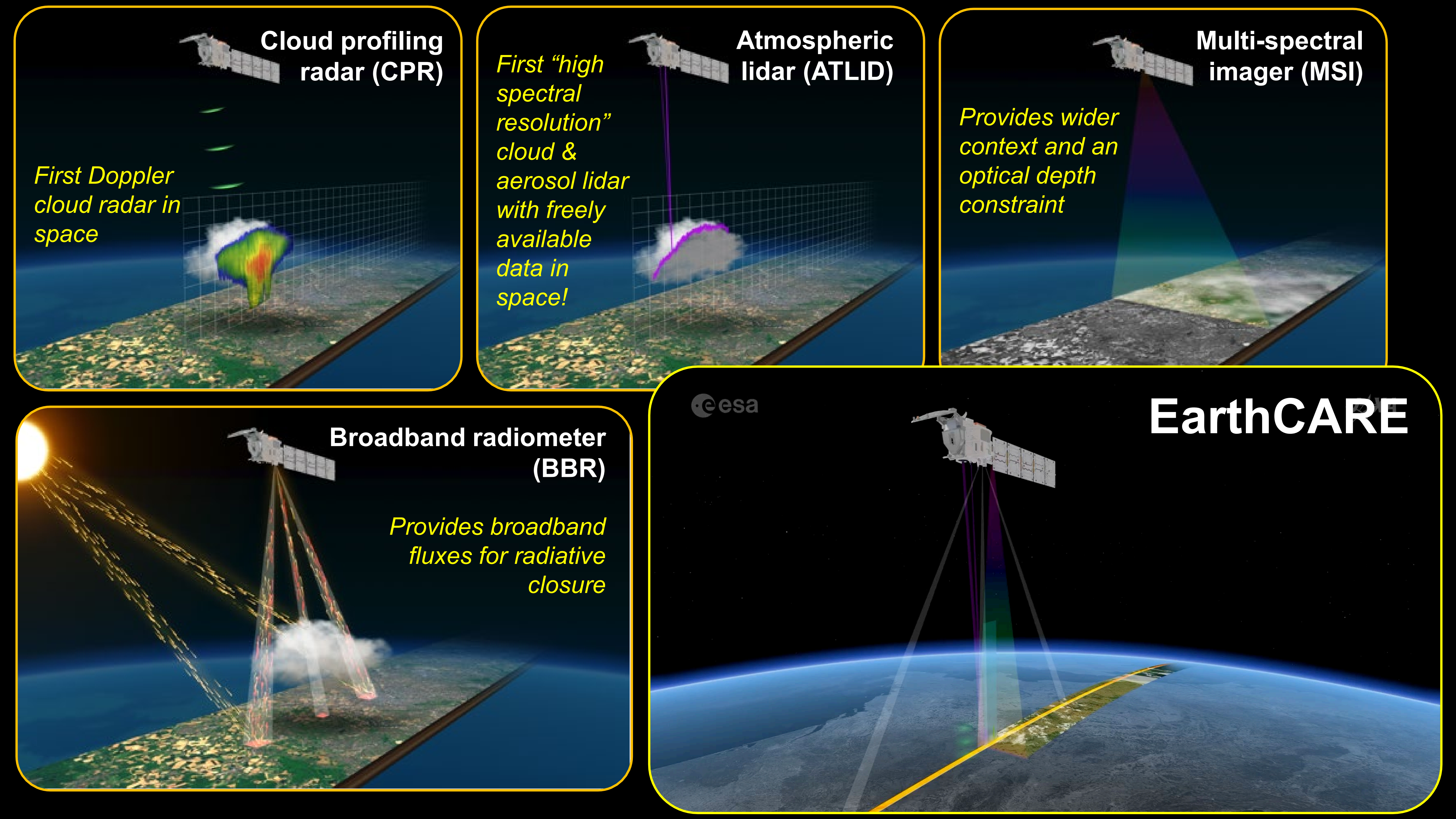
High cloud tops rise and cool, now detectable in CloudSat observations (Richardson et al)

e.g. CALIPSO anvil cloud area weakly dependent on temperature (McKim et al. 2024)

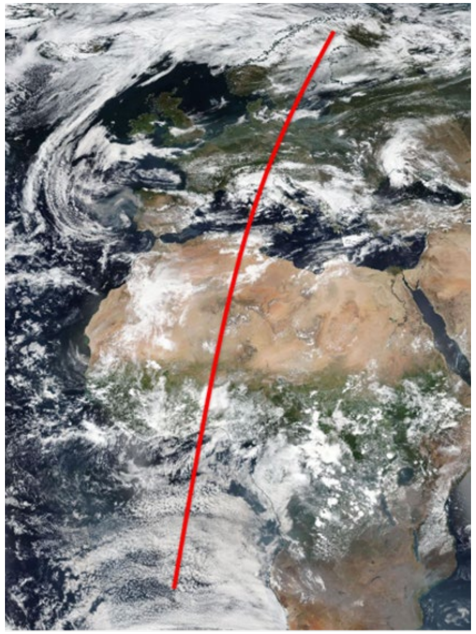


CALIPSO cloud phase observations improved models, reducing negative feedback & uncertainty (Zelinka et al. 2020)



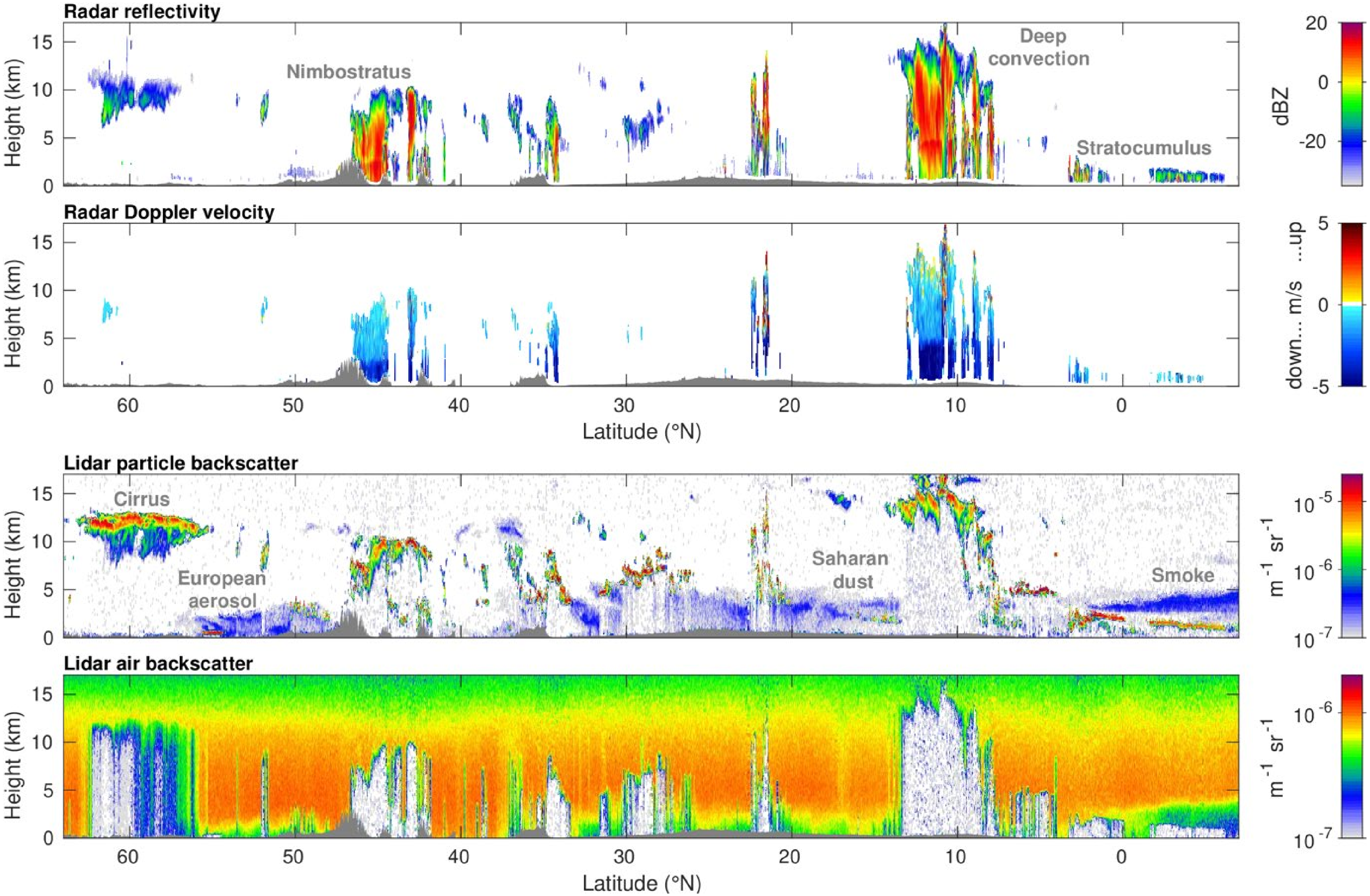

Cloud profiling radar (CPR)
First Doppler cloud radar in space
Atmospheric lidar (ATLID)
First "high spectral resolution" cloud & aerosol lidar with freely available data in space!
Multi-spectral imager (MSI)
Provides wider context and an optical depth constraint
Broadband radiometer (BBR)
Provides broadband fluxes for radiative closure
esa
EarthCARE

EarthCARE observations



Rate of decrease of air backscatter with range provides *unambiguous* extinction coefficient of cloud & aerosol particles

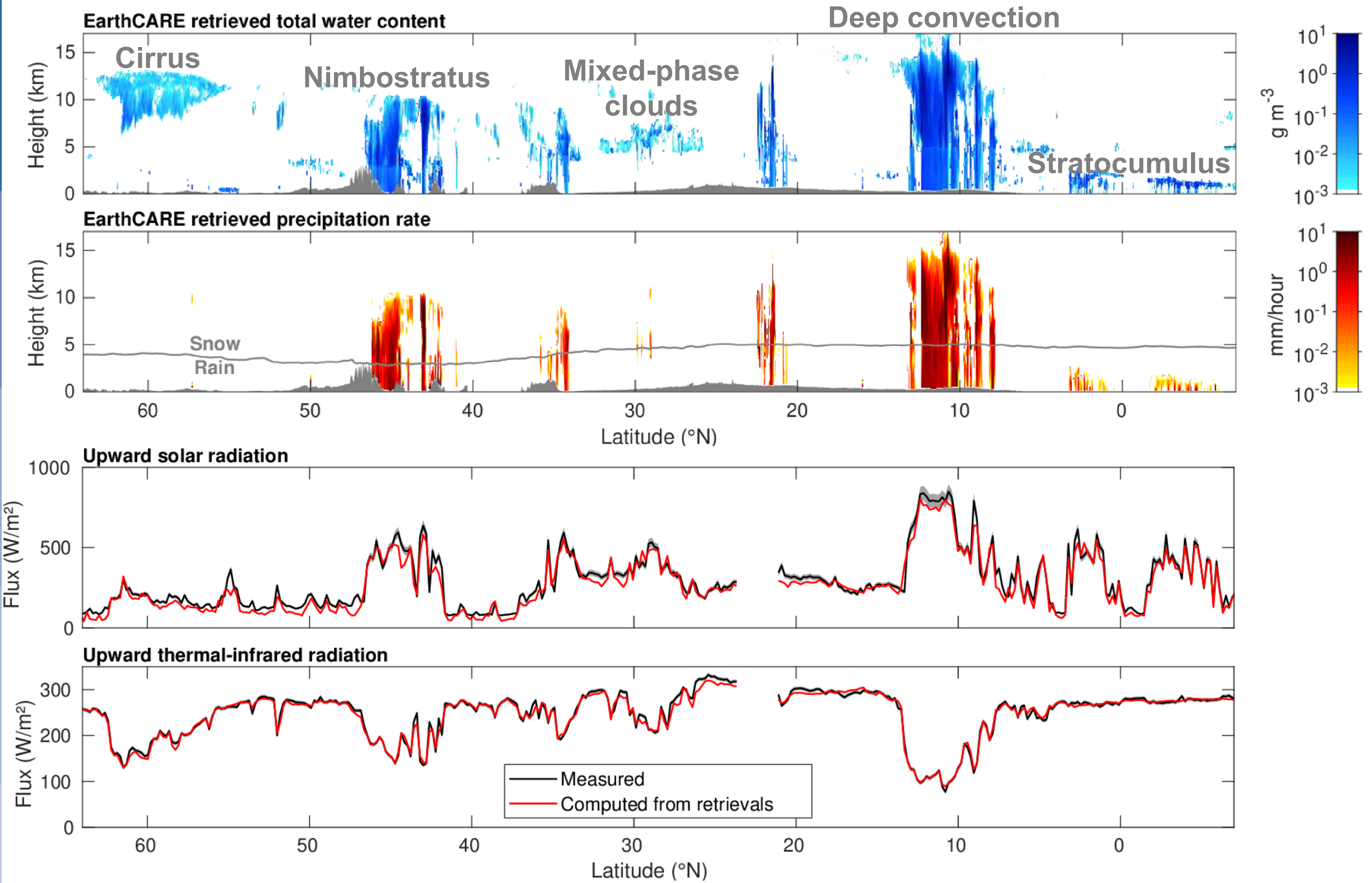
ECMWF

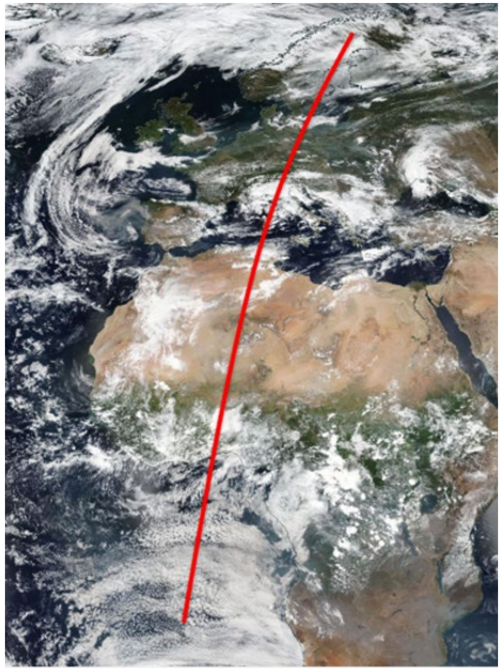


8000 km sample, 18 Sept 2024

Retrieved cloud & precipitation

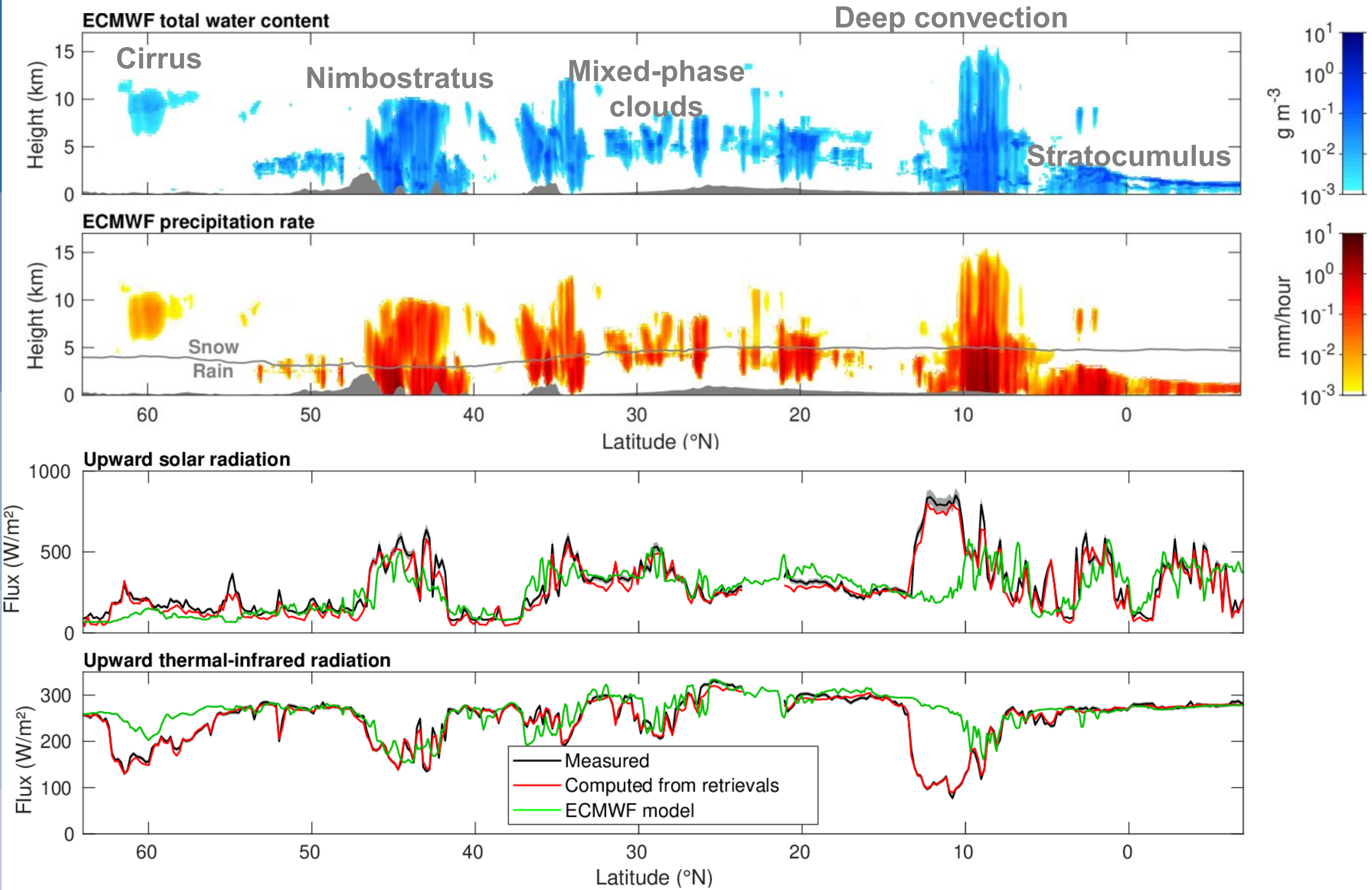
- Synergy retrievals (ACM-CAP)…
- …fed into radiative transfer calculations (ACM-RT)





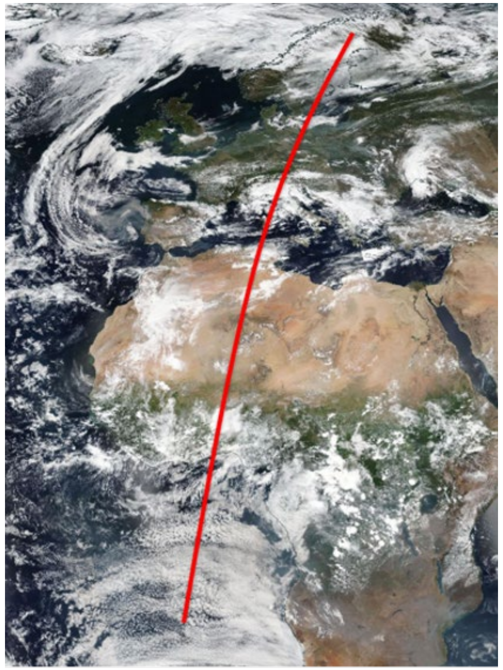
ECMWF

Robin Hogan, Shannon Mason, Bernat Puigdomenech-Treserras, Jason Cole, Zhipeng Qu, Howard Barker



Equivalent ECMWF forecast

- Cloud too "diffuse"
- Deep convection misplaced

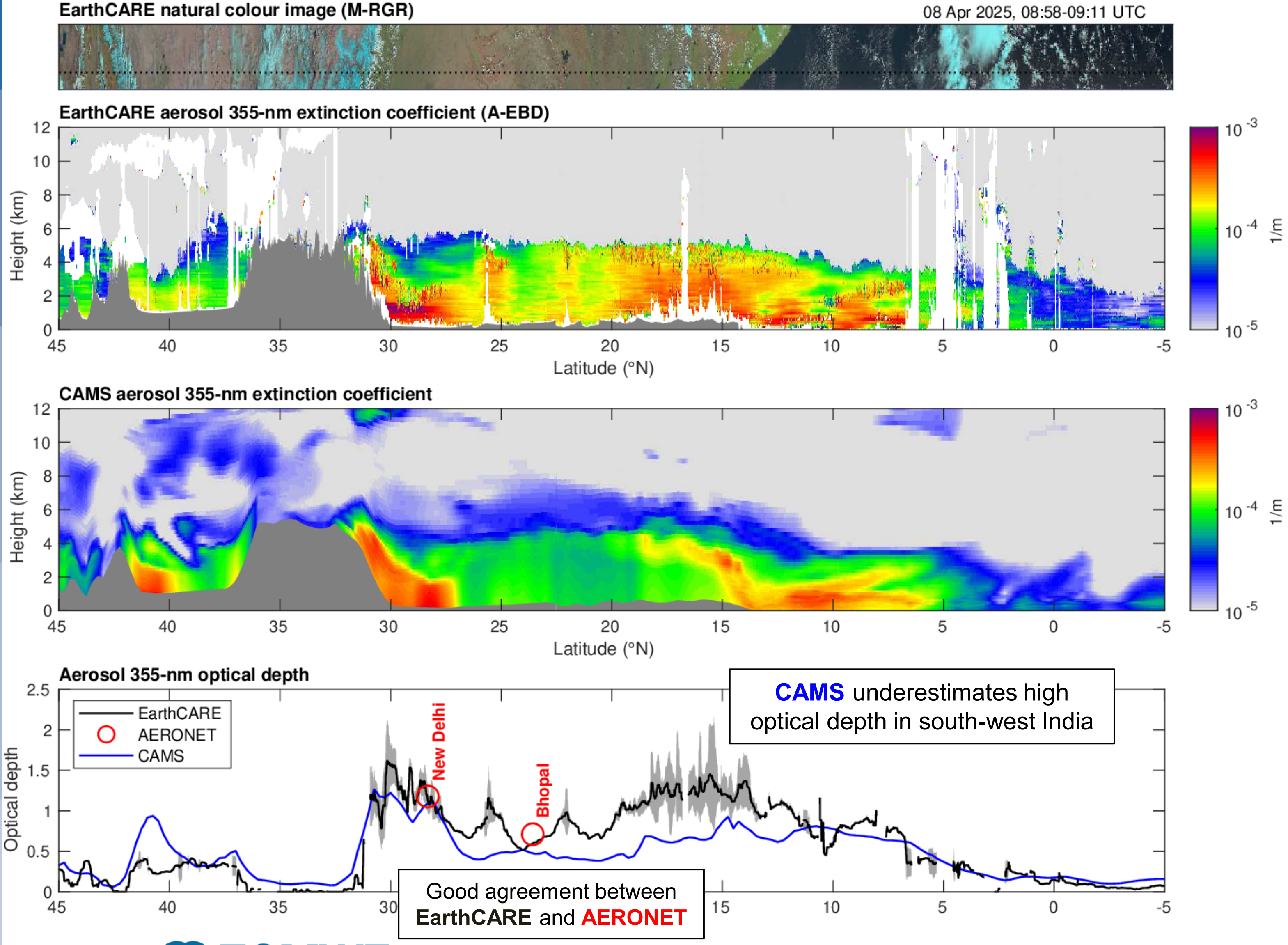


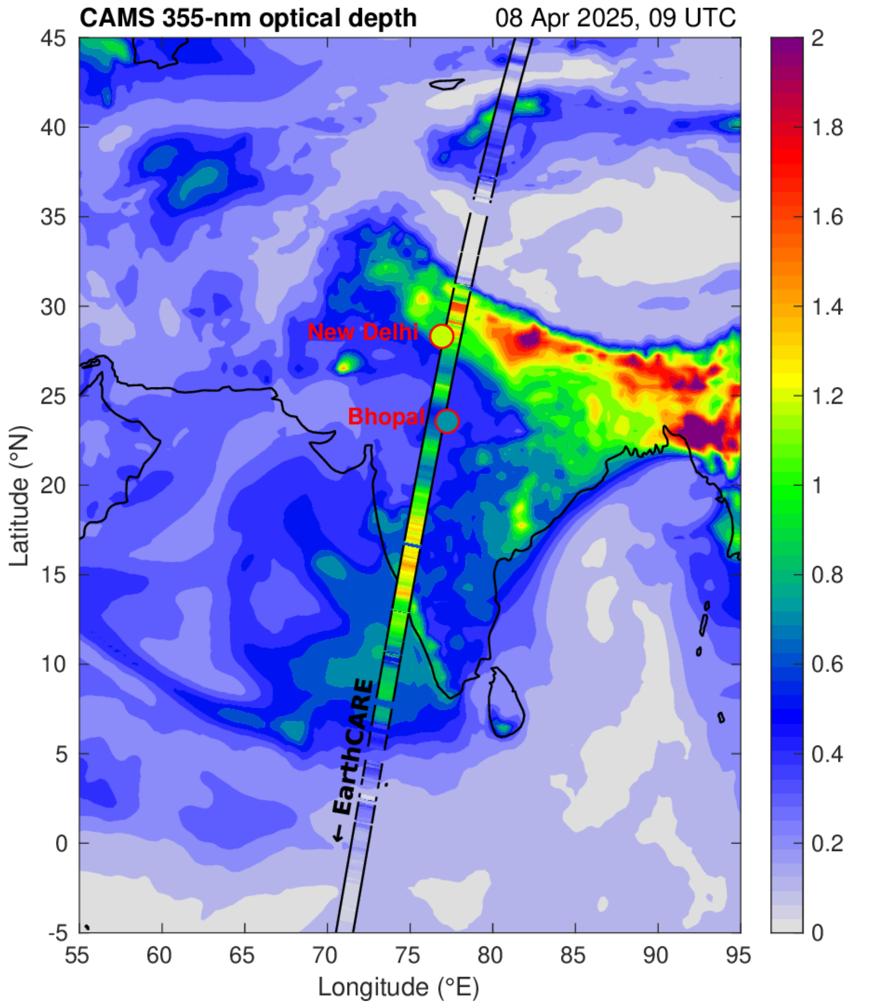
ECMWF

Robin Hogan, Shannon Mason, Bernat Puigdomenech-Treserras, Jason Cole, Zhipeng Qu, Howard Barker

Evaluating CAMS aerosols in India, 8 April 2025

Robin Hogan, Peter Hill, David Donovan





- *We have never before been able to evaluate aerosol profiles globally with such resolution and accuracy!*

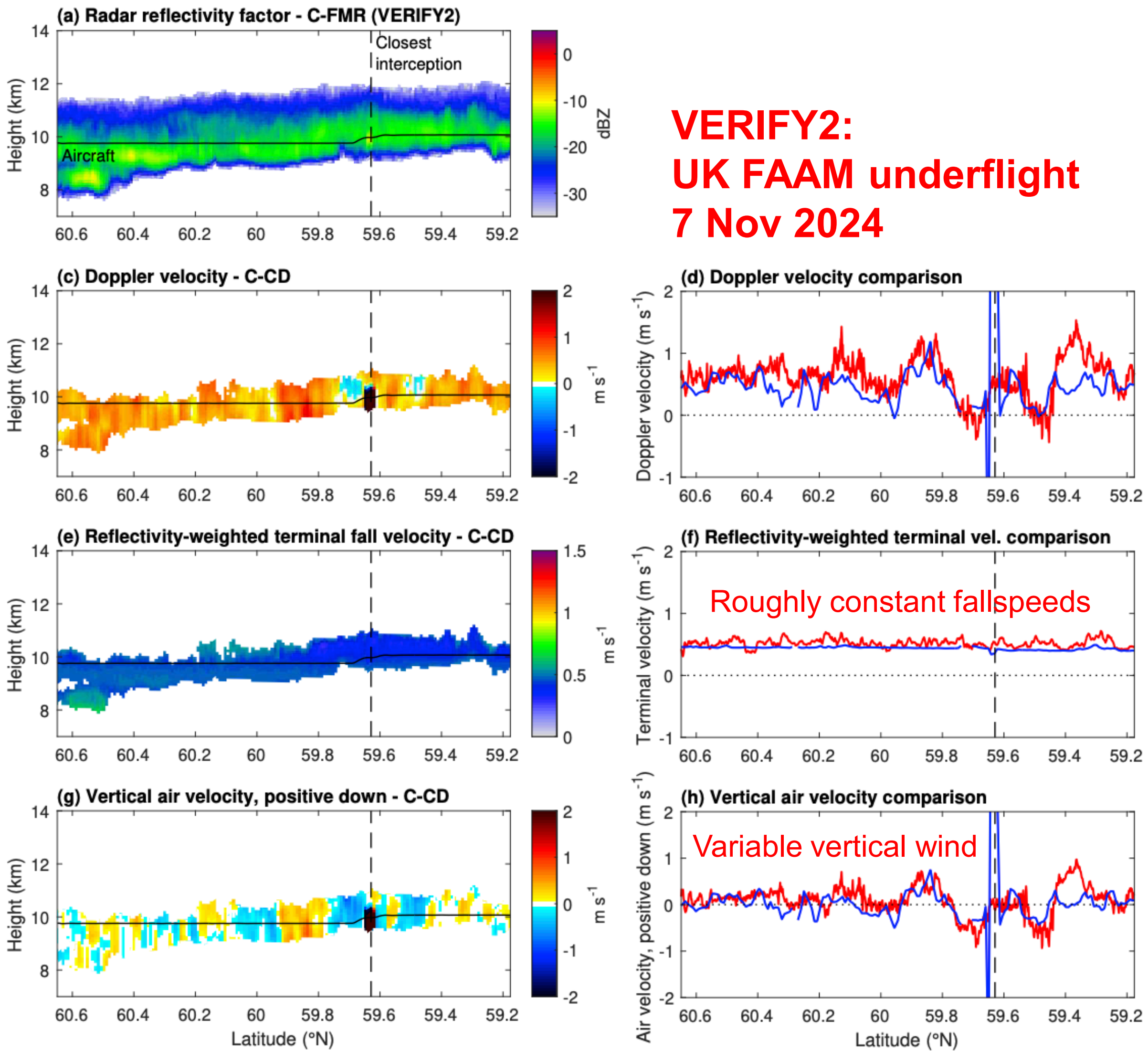
ECMWF

Using aircraft campaigns to validate EarthCARE's fall-speeds and vertical wind

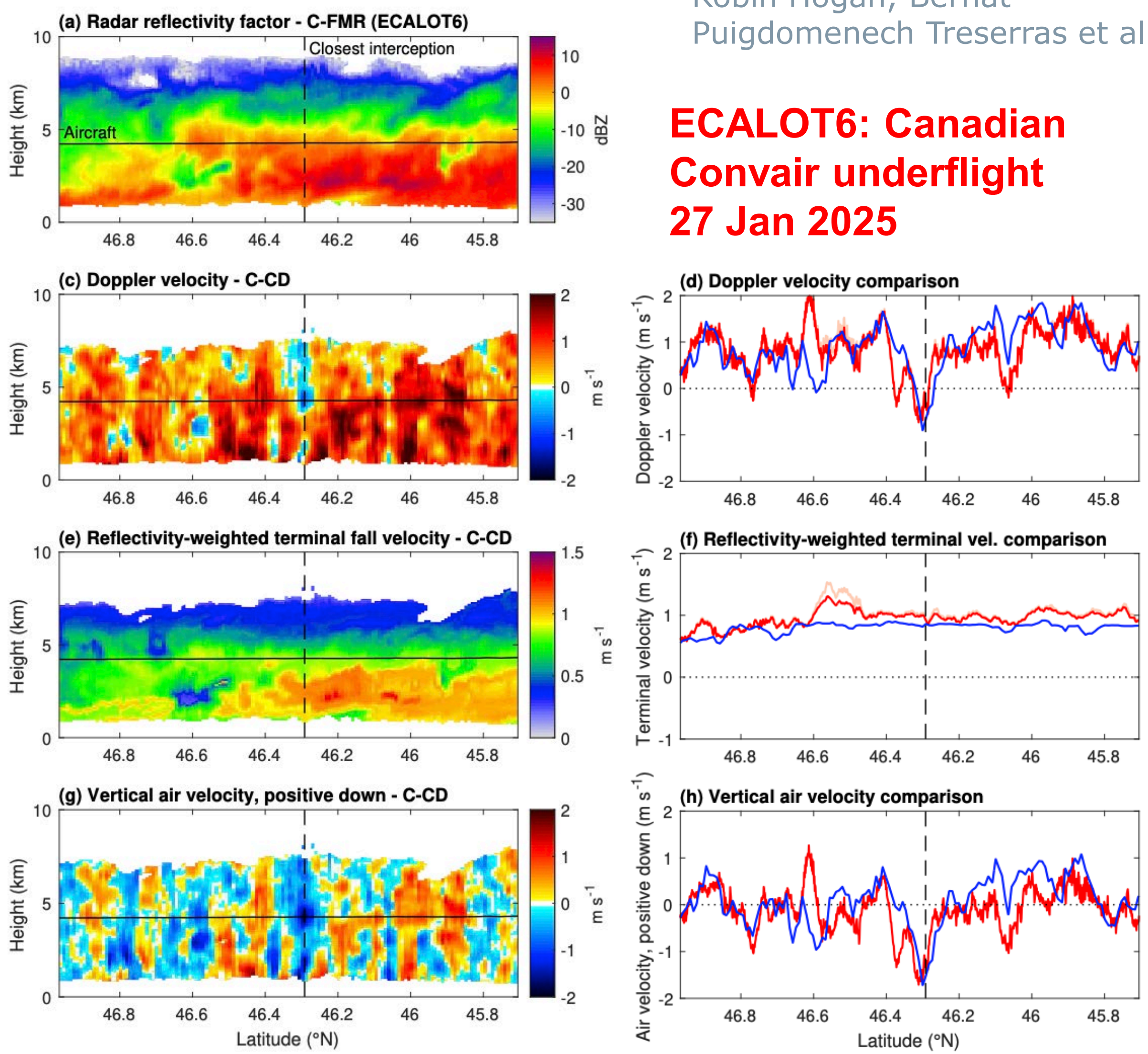
- **EarthCARE** assumes rapid variations in Doppler velocity due to air motion, slow variations to terminal fall-speed
- **Aircraft** measurements confirm this, giving confidence in fall-speeds for evaluating models

Robin Hogan, Bernat Puigdomenech Treserras et al.

VERIFY2: UK FAAM underflight 7 Nov 2024



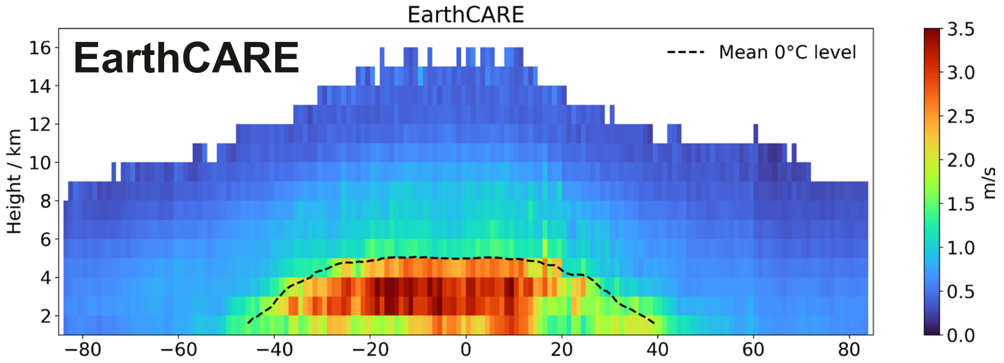
ECALOT6: Canadian Convair underflight 27 Jan 2025



Improving ice/snow fall speed in the ECMWF model

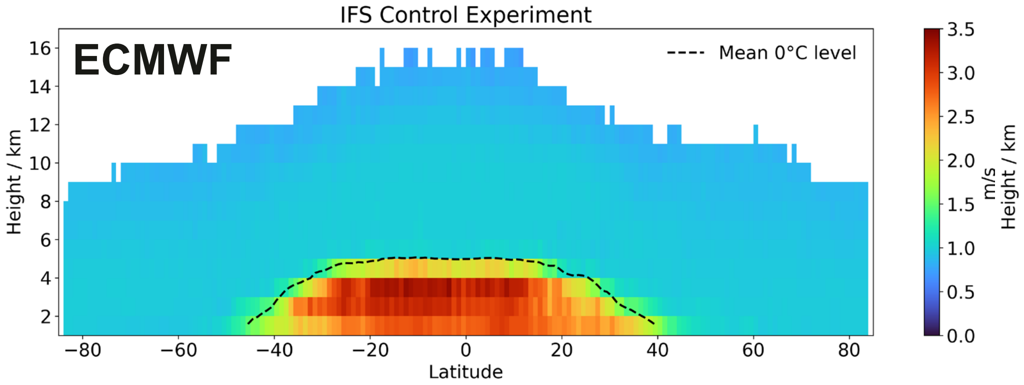
Rebecca Murray-Watson,
Mark Fielding, Richard Forbes

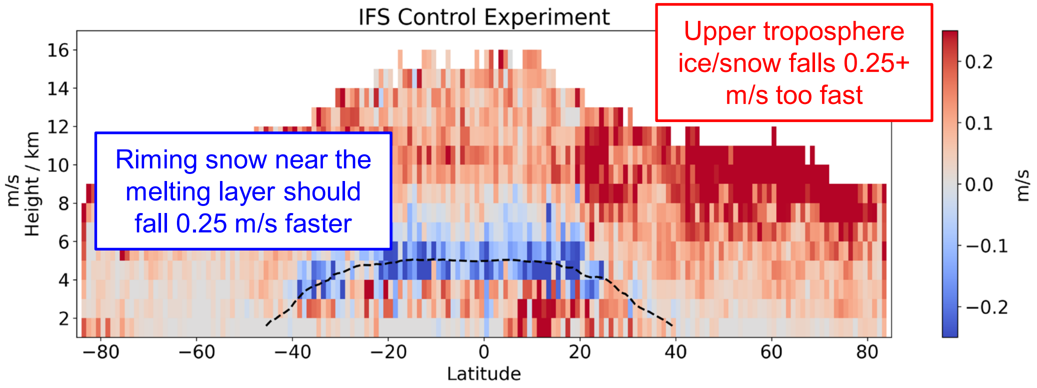
CPR mean fall speed



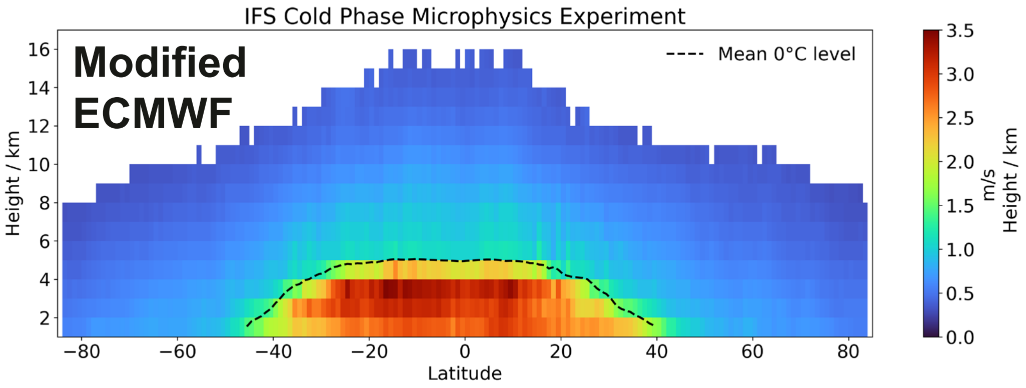
Ice & snow fall speeds affect model climate and forecast skill: this is first time we have been able to evaluate it globally!

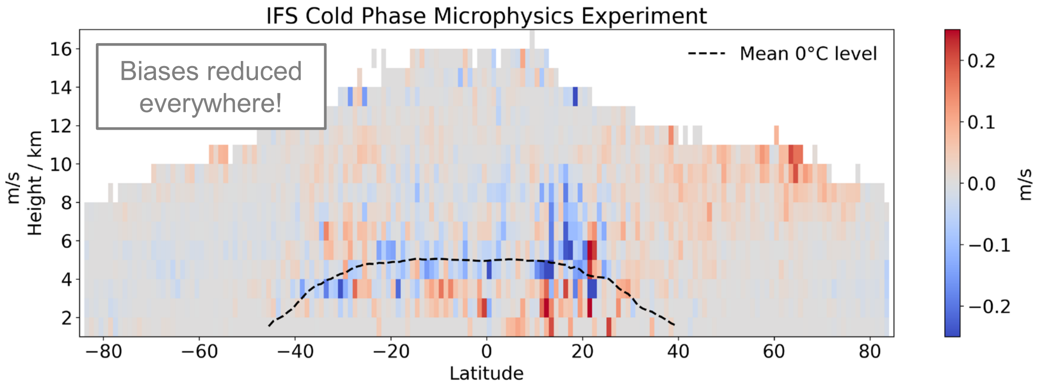
ECMWF model is very simple! ice falls at 0.13 m/s, snow at 1 m/s





Modifications: use a *mass-weighted* fall speed; add *rimed snow*, temperature-dependent size & air-density effect



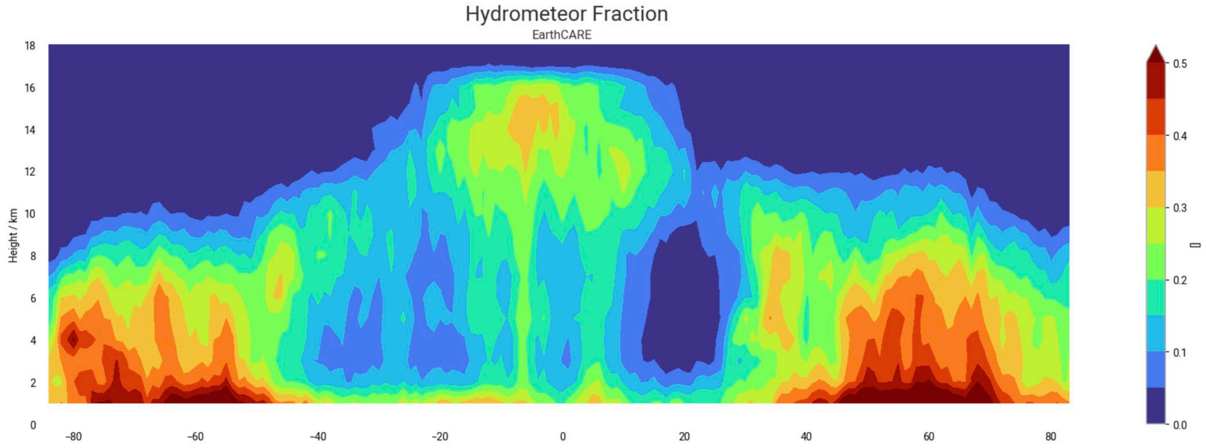


ECMWF

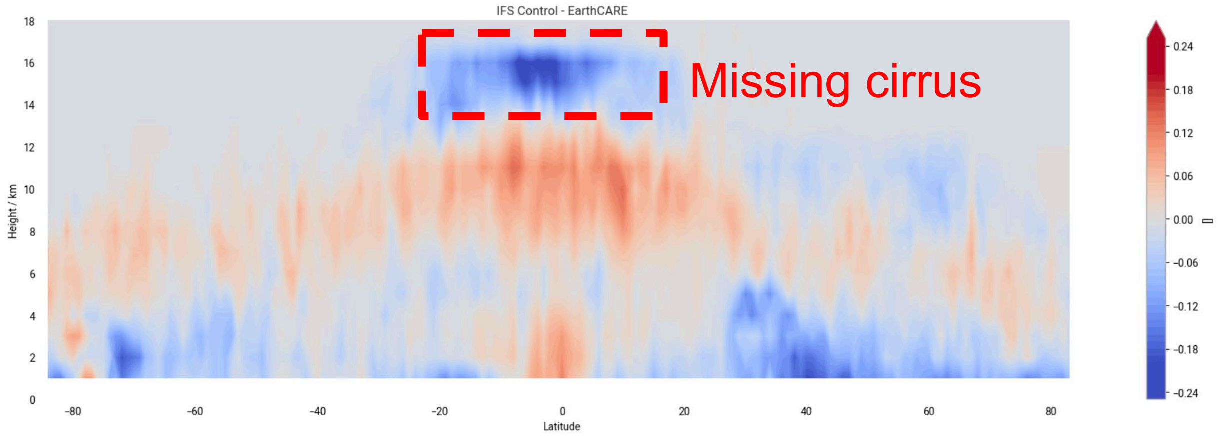
Diagnosing and fixing an underestimate of tropical cirrus

Mark Fielding, Rebecca Murray-Watson, Richard Forbes

- **EarthCARE radar and lidar hydrometeor fraction**



- **Current IFS minus EarthCARE**



Current treatment of ice clouds:

1. Cloudy part of gridbox always at ice saturation: cloud growth governed by saturation adjustment

2. Colder than -40°C, ice forms only if air reaches ice supersaturation (homogeneous nucleation)

New treatment of ice clouds:

1. Clear and cloudy parts of gridbox both have gridbox-mean humidity: cloud growth governed more realistically by ice deposition and sublimation

2. Colder than -40°C, ice can also form at lower supersaturations by heterogeneous nucleation using the Gasparini et al. (2025) parameterization

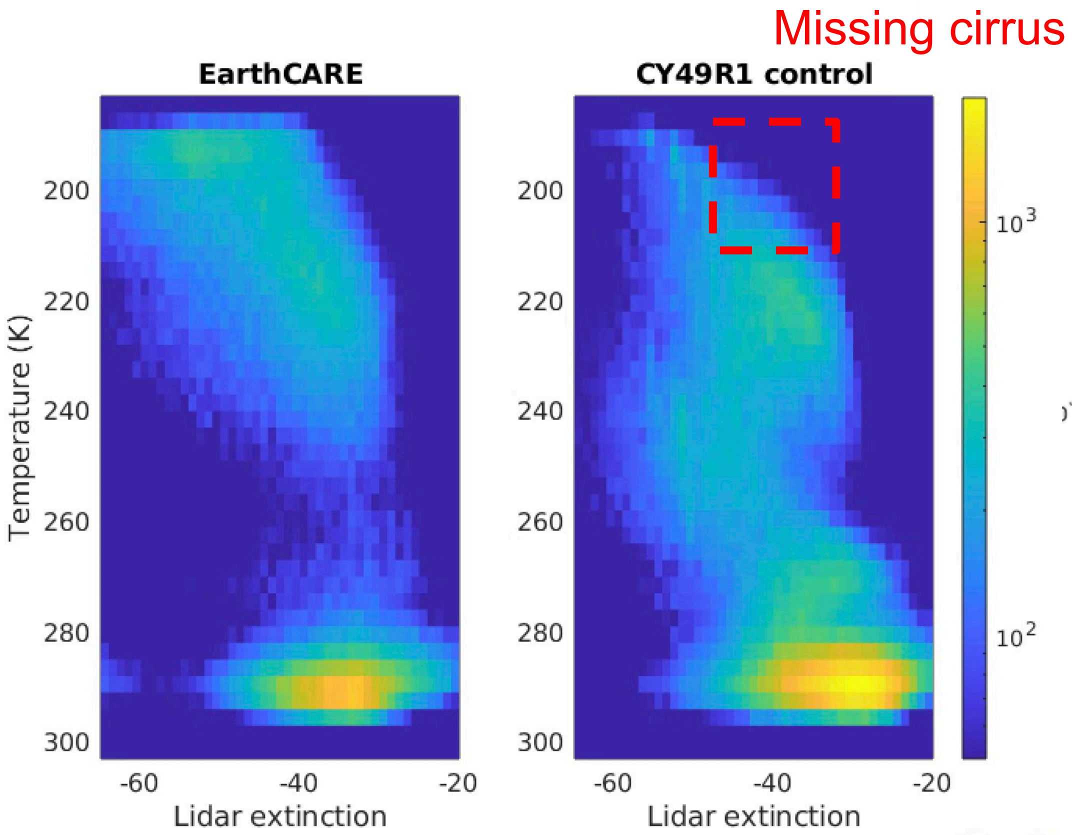
ECMWF

Current scheme…

Mark Fielding, Rebecca Murray-Watson, Richard Forbes

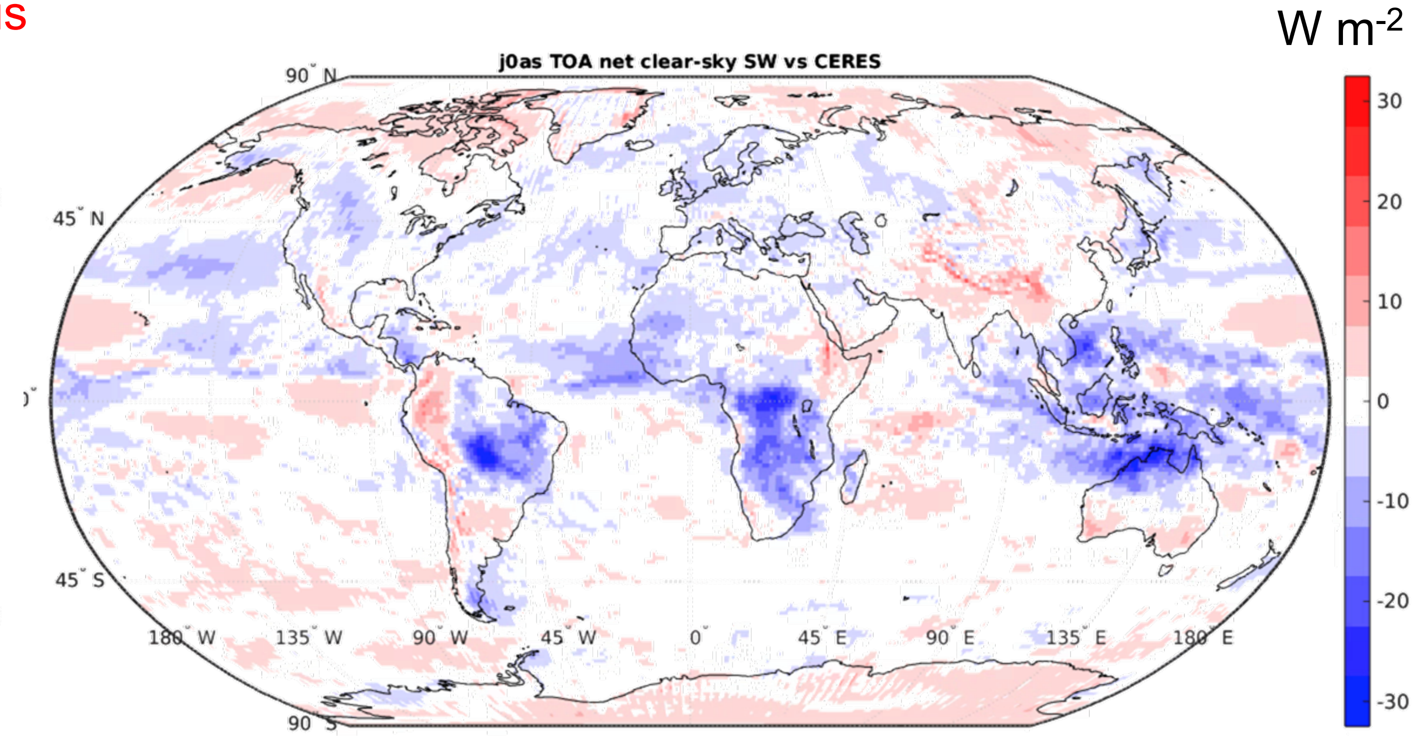
Ice extinction coefficient

- Distribution of clearly misses high cirrus compared to EarthCARE's high spectral resolution lidar



Top-of-atmosphere net longwave minus CERES

- Too low in many areas, i.e. outgoing longwave radiation too high

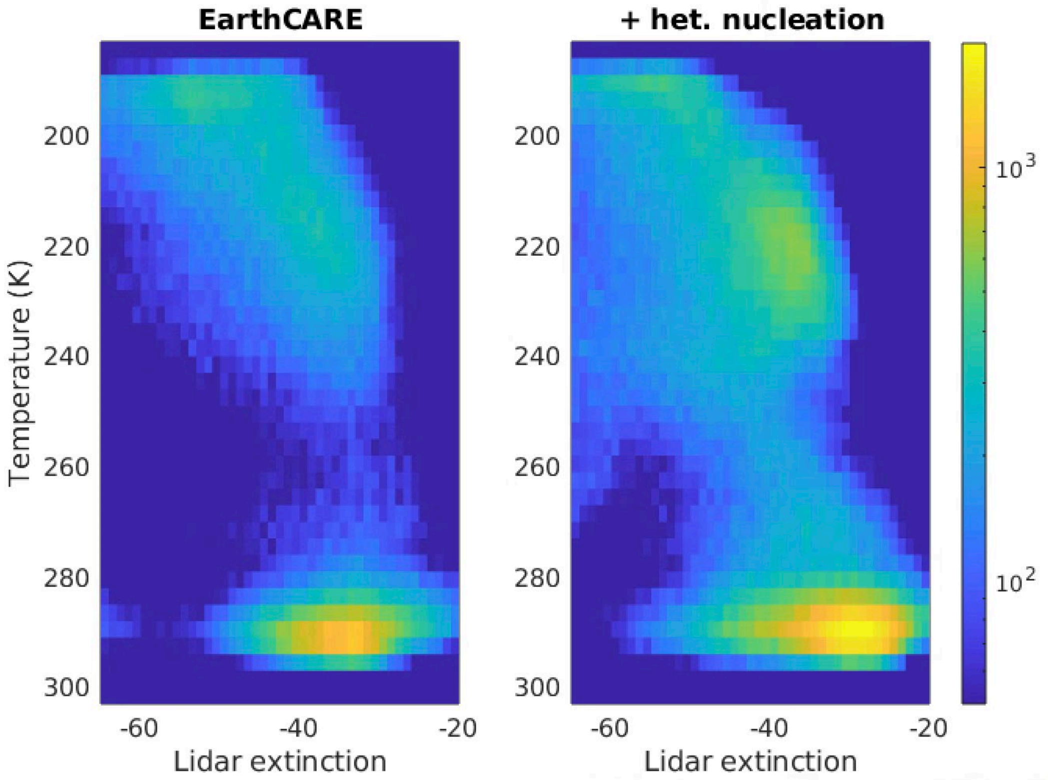


…new scheme

Mark Fielding, Rebecca Murray-Watson, Richard Forbes

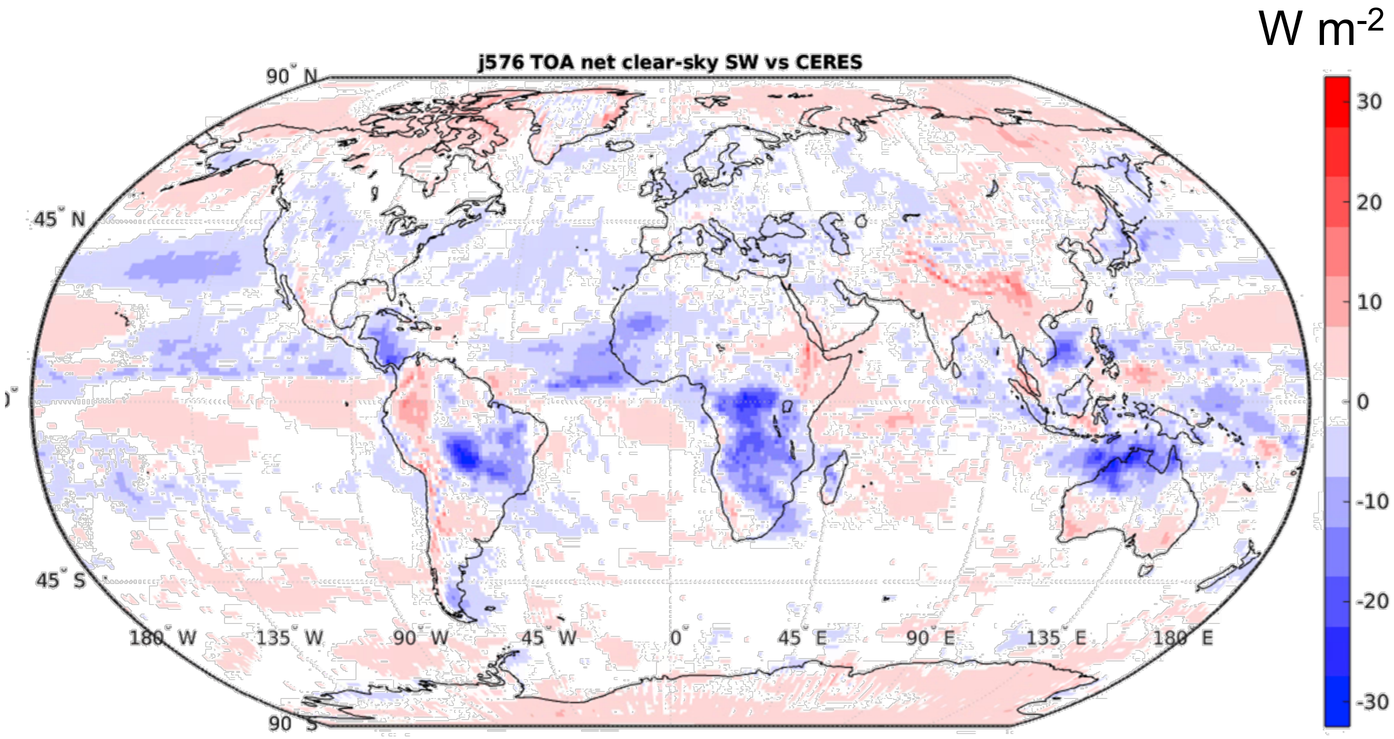
Ice extinction coefficient

- Much more realistic!



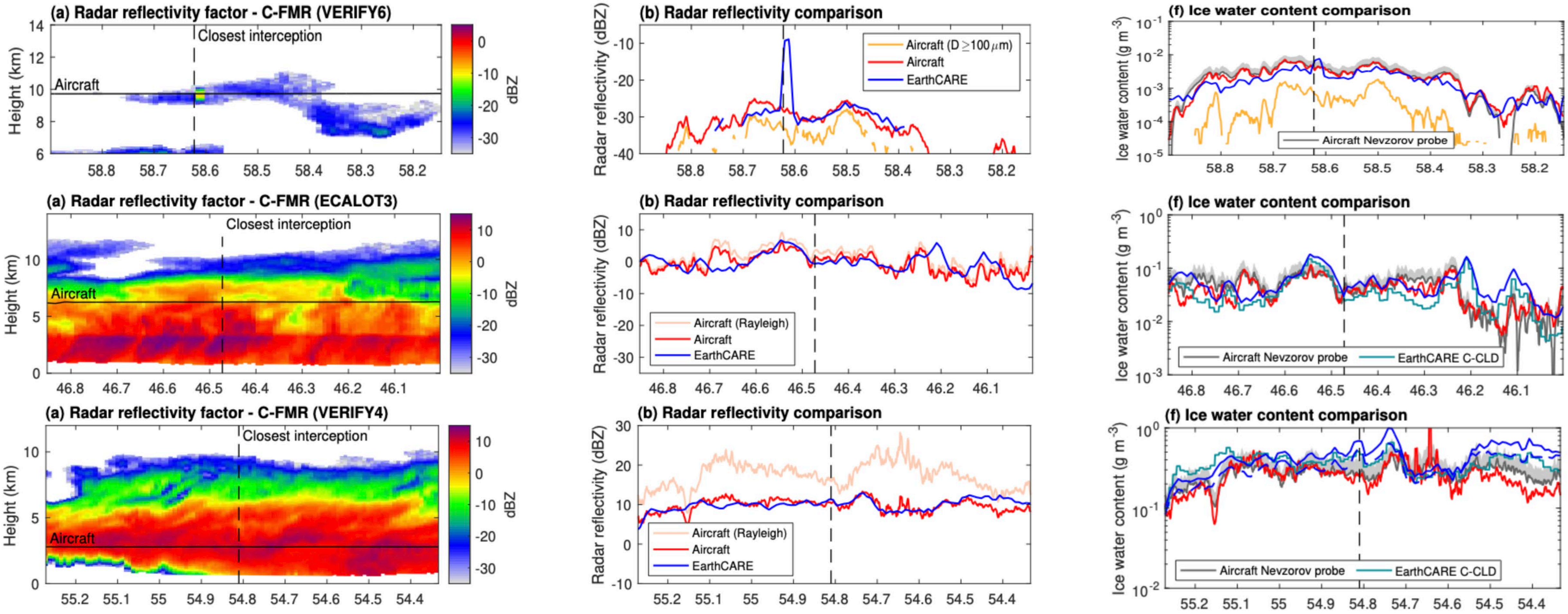
Top-of-atmosphere net longwave minus CERES

- Distribution not perfect but much better balance between positive and negative errors



Using aircraft campaigns to validate ice scattering and ice water content retrieval

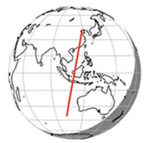
- Simulate radar reflectivity of ice particles from aircraft size spectra using **SSRGA** model (Hogan & Westbrook 2014): *fits well between -30 and +10 dBZ, even when 15 dB deviation from Rayleigh scattering!*
- Evaluate IWC retrievals from radar & lidar (ACM-CAP; Mason et al. 2023): *good agreement for first two cases (Brown & Francis mass-size relationship applicable) but somewhat overestimated for denser snow case*

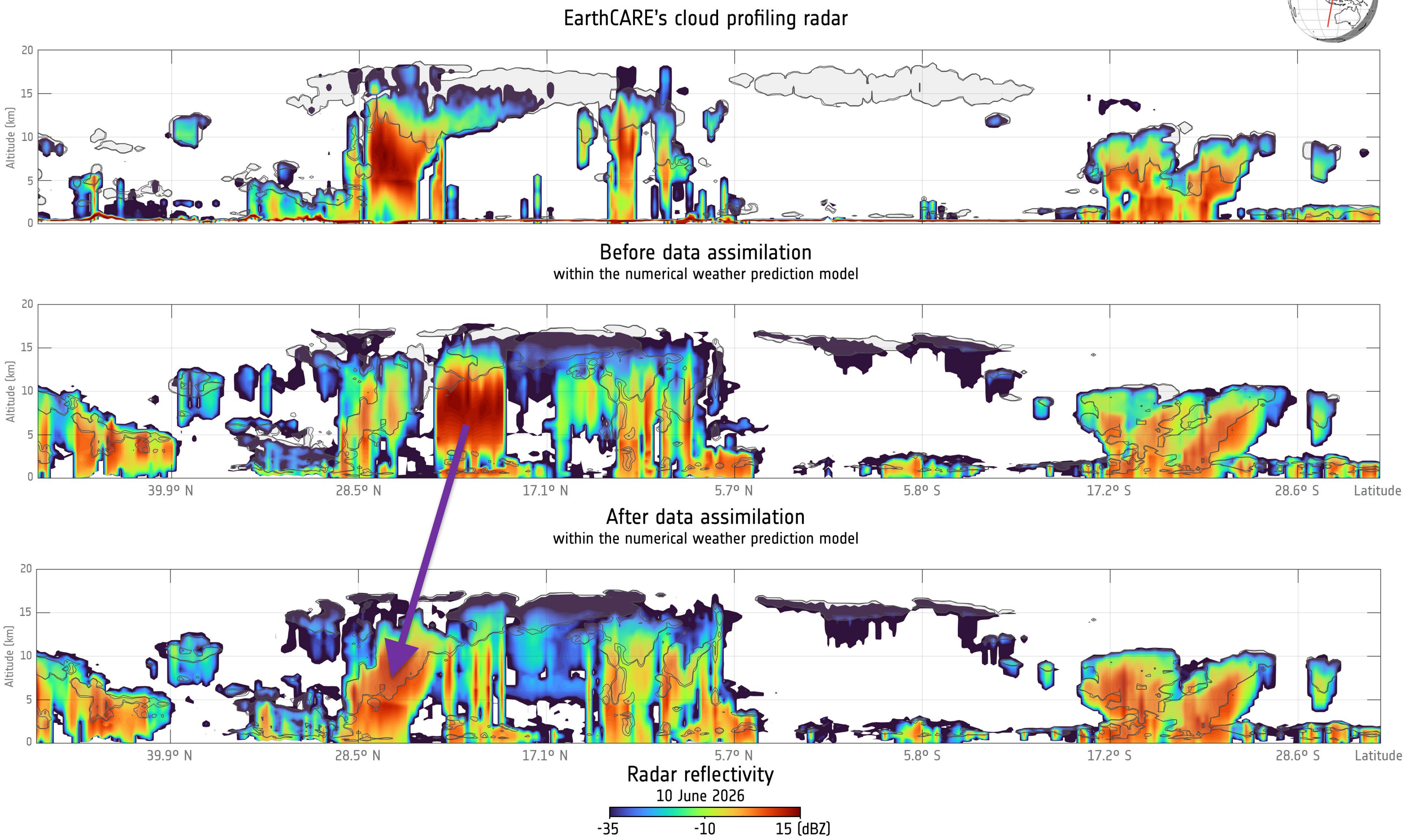


EarthCARE radar assimilation turned on 10 June 2026

Mark Fielding
Marta Janiskova
Kamil Mroz

- First ever operational assimilation of spaceborne cloud radar observations!

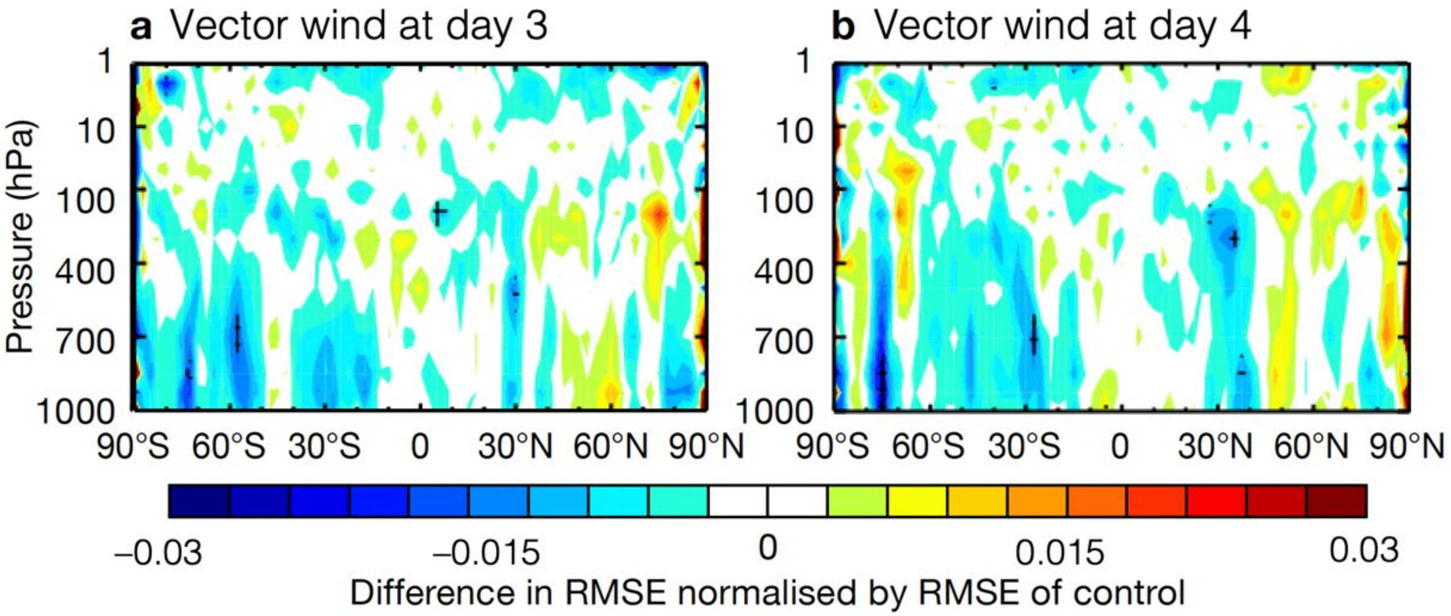




- Example in the west Pacific on the first day of assimilation
- Radar forward model makes use of SSRGA ice scattering model
- Assimilation improves the position of a large convective system in the initial conditions

Forecast impact

- Earlier research experiments suggest a modest reduction in root-mean-squared errors in wind and temperature
- We expect greater impact in future when we turn on lidar assimilation and possibly assimilation of radar Doppler velocity and path-integrated attenuation over the sea

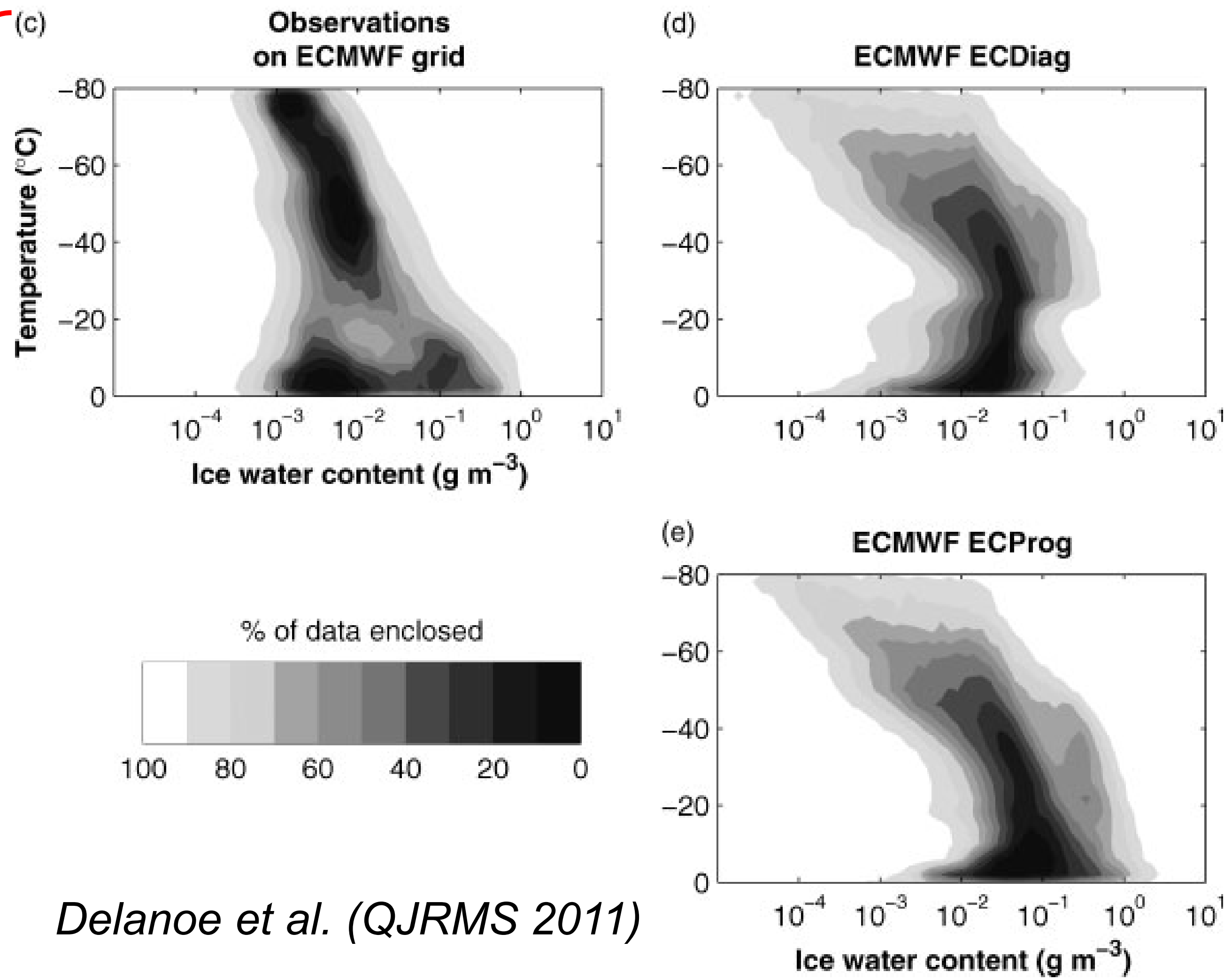


Summary

- EarthCARE's 10+ year mission presents a huge opportunity to make substantial improvements in the representation of clouds, aerosols, precipitation and radiation in weather and climate models
- In-situ aircraft campaign data are invaluable for evaluating EarthCARE retrievals and radar scattering models, which in turn gives confidence in the use of EarthCARE for model evaluation and assimilation
- Further information at www.earthcarescience.net and earth.esa.int/eogateway/missions/earthcare

Further impact of CloudSat & CALIPSO on ECMWF model developments

- CloudSat vs ECMWF ice water path clearly showed **need to include snow in radiation scheme**: ~10 W m^{-2} in convective regions (Li et al. 2014)
- Dreary paper: **rain occurs twice as often as it should** with on average half the intensity it should (Stephens et al. JGR 2010)
- **Prognostic ice water content** agrees much better with radar-lidar retrievals than diagnostic (Delanoe et al. QJRMS 2011)
- **Understand cloud/precip occurrence biases** from forward modelling reflectivity (DiMichele et al. QJRMS 2012)
- **Evaluation of CAMS dust profiles** using CALIPSO (Georgoulias et al. 2018, Ryder et al. 2023)



Delanoe et al. (QJRMS 2011)