The journey towards assimilation of EarthCARE cloud radar and lidar observations

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ECMWF

Frascati, November 2023

Introduction

- Cloud processes are characterized by a wide range of spatial and temporal scales:
  - observing cloud 4D-variability is challenging
  - parametrization of cloud processes in global NWP models is difficult

* Global NWP models describe clouds with a reasonable degree of realism (at least in horizontal structure), however, uncertainties in representation of cloud vertical structure may be substantial.
* Introduction of cloud radar and lidar observations from space provide a large volume of information on the vertical structure of clouds and aerosols *(CloudSat, CALIPSO,* ***EarthCARE****, …):*

⇓

- very important for model evaluation & further model development
- opening new possibilities to explore model improvement through assimilation of data related to clouds

* However, assimilation of vertically resolved cloud information in a global numerical weather system bring a lot of challenges to succeed

Requirements for data assimilation

- To succeed to assimilate new type of observations, especially cloud profiling, requires:
  - reasonable representation of the physical processes related to the observations
  - observation operator being able to provide realistic model equivalents to the observations
  - linearity and regularity of the observation operator used in the variational assimilation framework
  - appropriate screening of observations
  - removal of systematic biases via a bias correction scheme
  - characterizing the components of observation error including representativity issues
  - inclusion of observations into automatic monitoring system

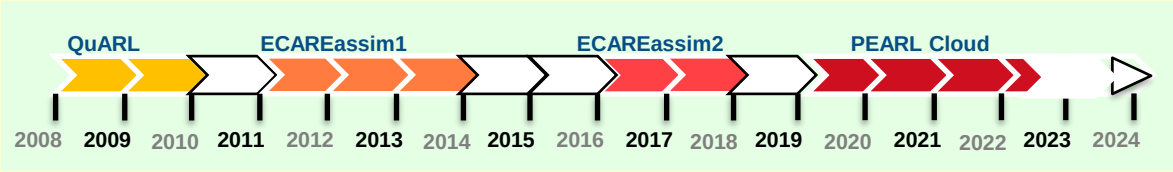
ESA projects at ECMWF

- ERM project (ERM): 1999 – 2001
- Impact of EarthCARE products on NWP (ECAREnwp): 2002 – 2004
- Quantitative assessment of the Operational Value of Space-Borne Radara and Lidar Measurements of Cloud and Aerosol Profiles (QuARL): Sept 2008 – Aug 2010
- STSE Study – EarthCARE Assimilation (ECAREassim1): Sept 2011 – March 2014
- GSP Study – Operational Assimilation of Space-borne Radar and Lidar Cloud Profile Observations for NWP (ECAREassim2): May 2016 – Sept 2018
- ESA-ECMWF Study – Preparations for EarthCARE Assimilation – Radar and Lidar Cloud Observations (PEARL Cloud): October 2019 – …

Model validation

Data assimilation

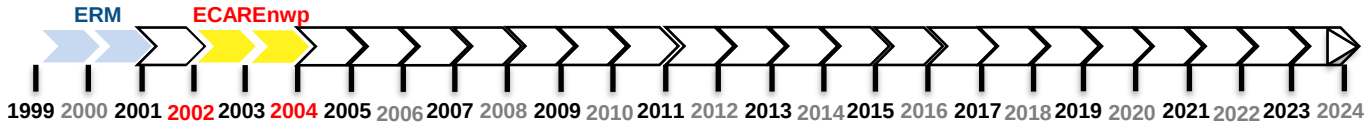
ERA of Tobias Wehr (†) as science officer for the projects:



Tobias' invaluable contributions helped drive all those projects and mission towards data assimilation forward. He is missed greatly.

ECAREnwp project

Impact of EarthCARE products on NWP

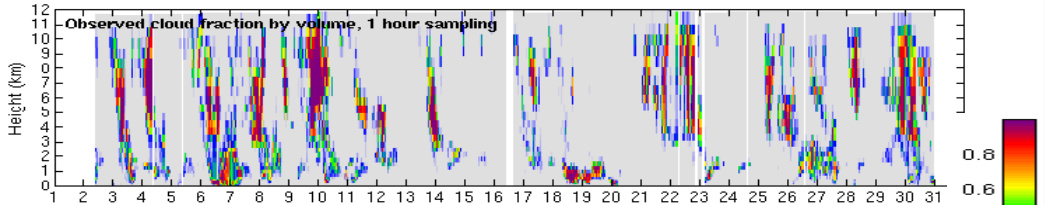


The objectives of the study :

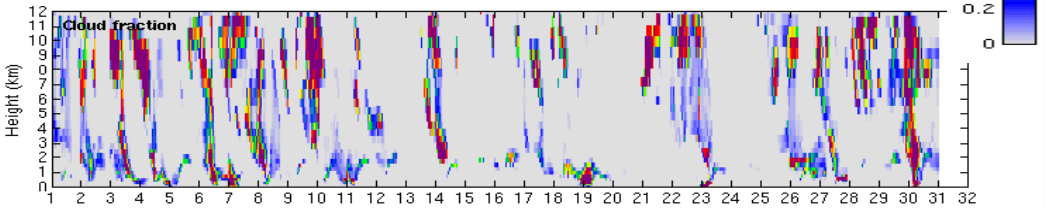
- *Assess the **importance of EarthCARE observations for validation & improvement of physical parametrizations***
- *Perform sensitivity studies to help in defining EarthCARE requirements (e.g. required accuracy of measurements for NWP)*
- *Improve assimilation tools in view of EarthCARE use (introducing the cloud-radiation processes in the assimilating model)*

Model evaluation: Comparison of the model cloudiness profiles against radar estimates at Chilbolton, June 2003

Observed cloud fraction



ECMWF model cloud fraction

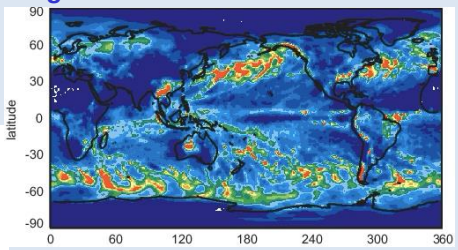


- Model is able to correctly capture the major cloud events although errors in the details are clearly visible.
- Potential of using space-borne radar to derive vertical cloud distributions for model comparison.

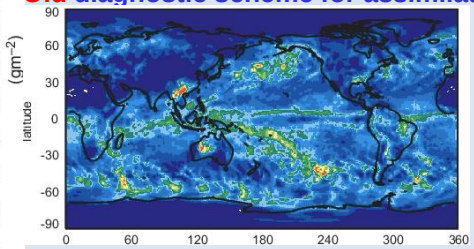
New cloud scheme for assimilation:

12-hour FC of total column cloud water

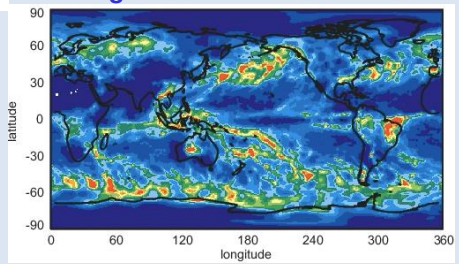
Prognostic scheme of the forecast model

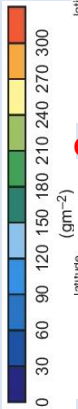


Old diagnostic scheme for assimilating model



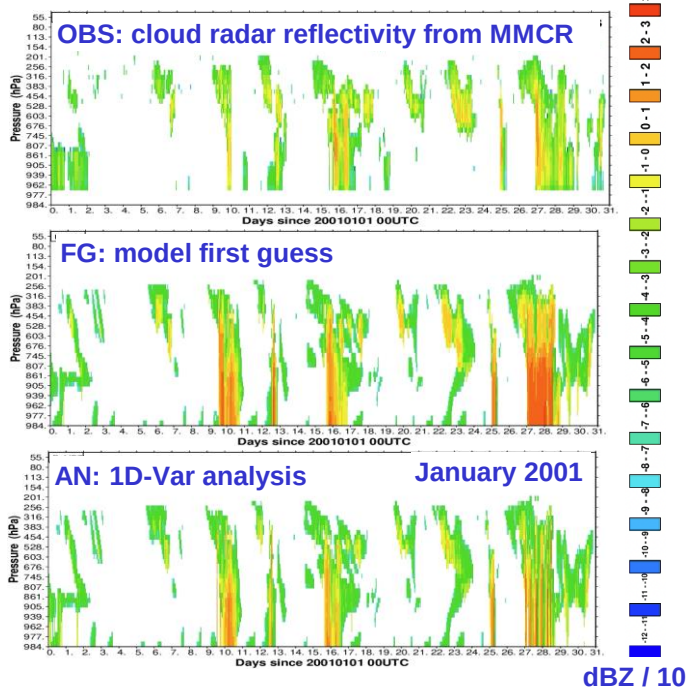
New diagnostic scheme for assimilating model





Feasibility studies for assimilation:

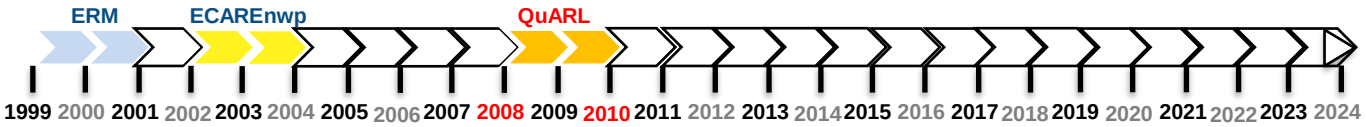
1D-Var using OBS from ARM Program



- 1D-Var AN closer to assimilated obs
- 1D-Var able to modify temperature (T) & humidity (q) ⟶ important for consistency between clouds & dynamics

ECMWF

QuARL project

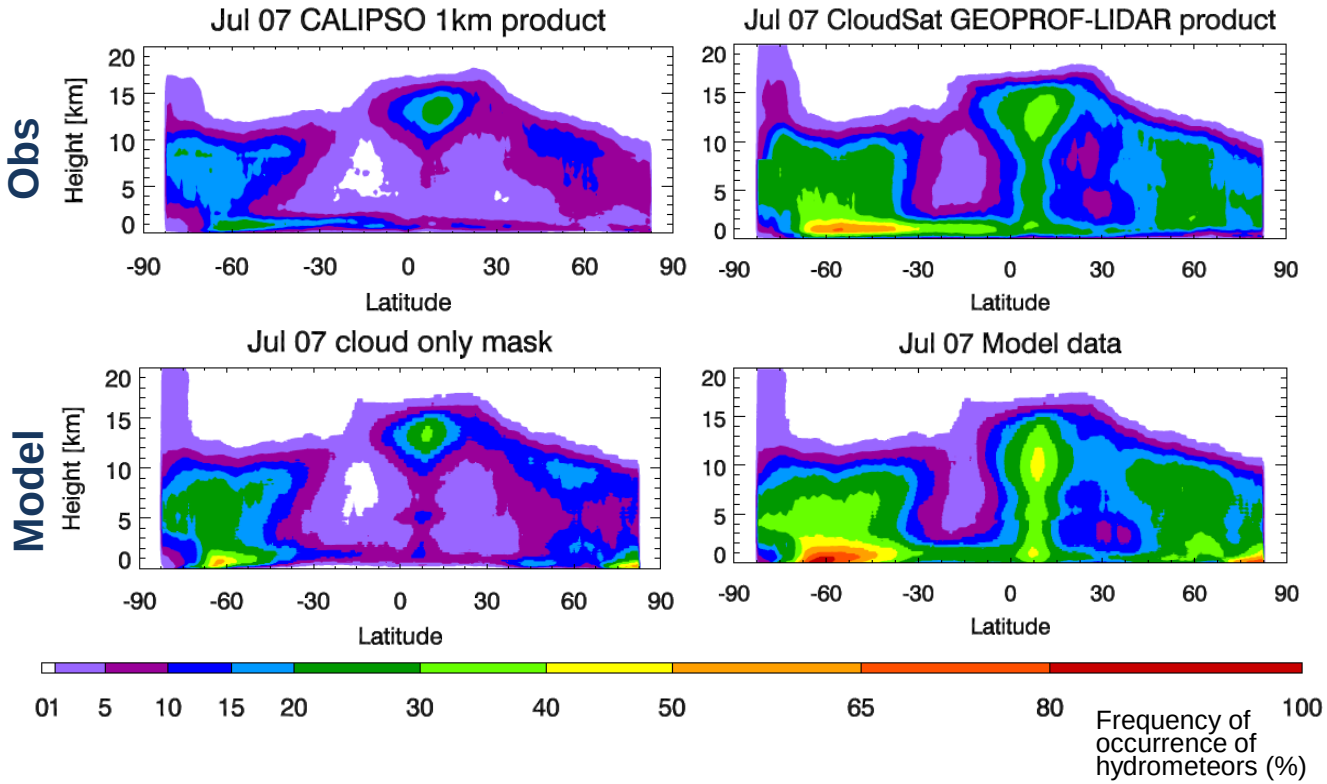


Quantitative Assessment of the Operational Value of Space-Borne Radar and Lidar Measurements of Cloud and Aerosol Profiles

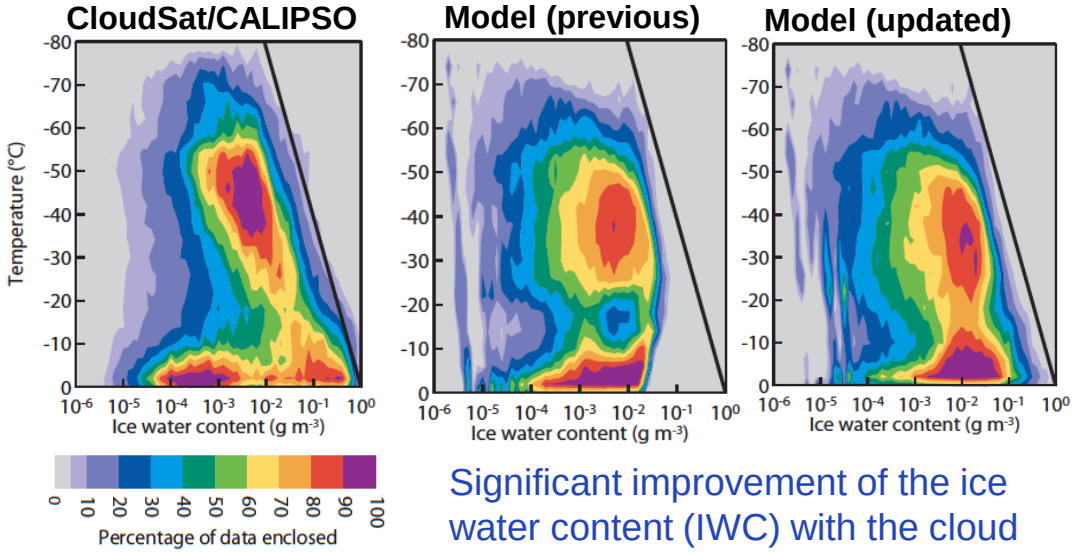
- *<u>The purpose of this project</u> was to make maximum use of the CloudSat/CALIPSO data in the context of the ECMWF atmospheric data assimilation and forecasting system in order to evaluate model errors, to improve the initial conditions and to prepare the utilization of similar observations as will be produced by the EarthCARE mission.*

Global validation with CloudSat/CALIPSO

Frequency of occurrence of hydrometeors [%]



Comparison of IWC vs. temperature – July 2006, NH



Significant improvement of the ice water content (IWC) with the cloud development changing representation of snow & mixed-phase ice cloud.

Validation studies highlight the value of the observations for the model validation and triggering new model developments.

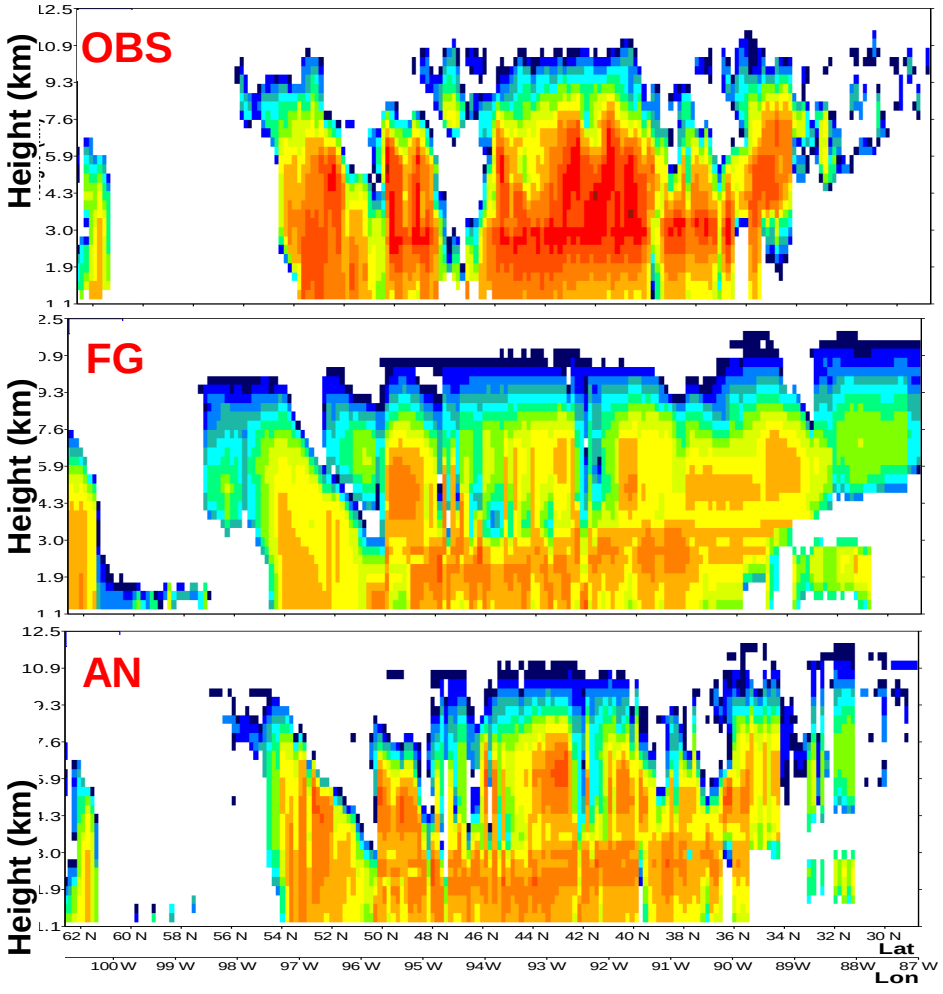
QuARL project

ERM ECAREnwp QuARL

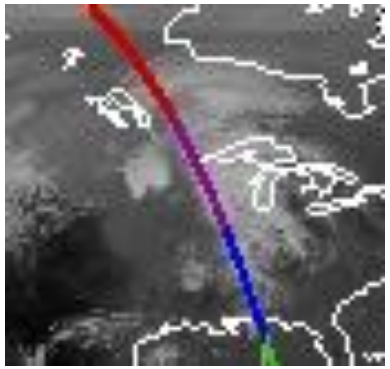
1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024

Quantitative Assessment of the Operational Value of Space-Borne Radar and Lidar Measurements of Cloud and Aerosol Profiles

1D-Var retrievals of cloud information from CloudSat



Cloud reflectivity from 94GHz

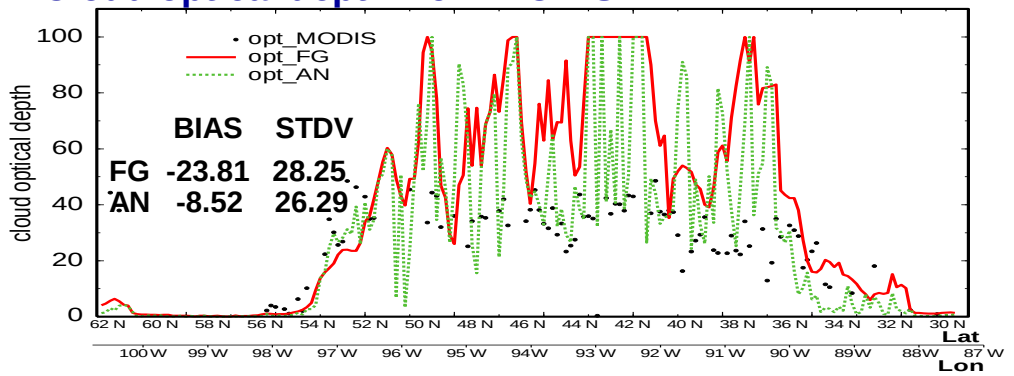


Period: 24 April 2008

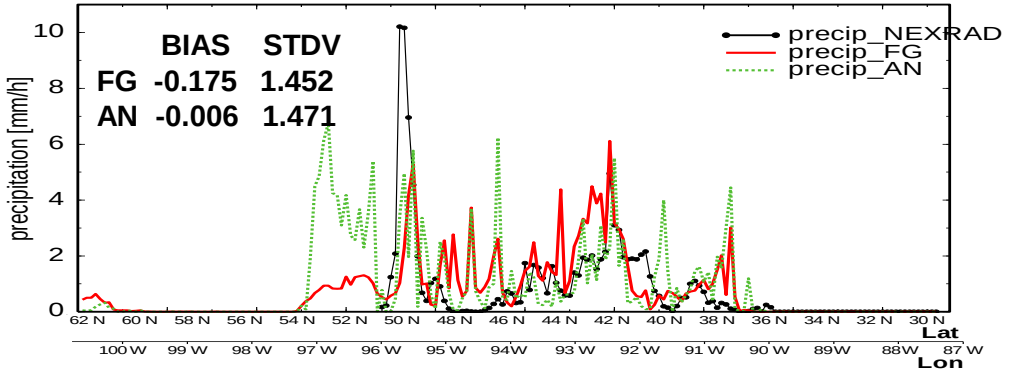
-24 to -21
-21 to -18
-18 to -15
-15 to -12
-12 to -9
-9 to -6
-6 to -3
-3 to 0
0 to 3
3 to 6
6 to 9
9 to 12
12 to 15
15 to 19

Comparison with independent observations

Cloud optical depth from MODIS

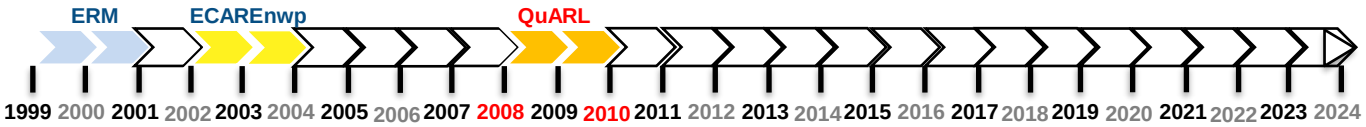


Hourly precipitation rates from NEXRAD



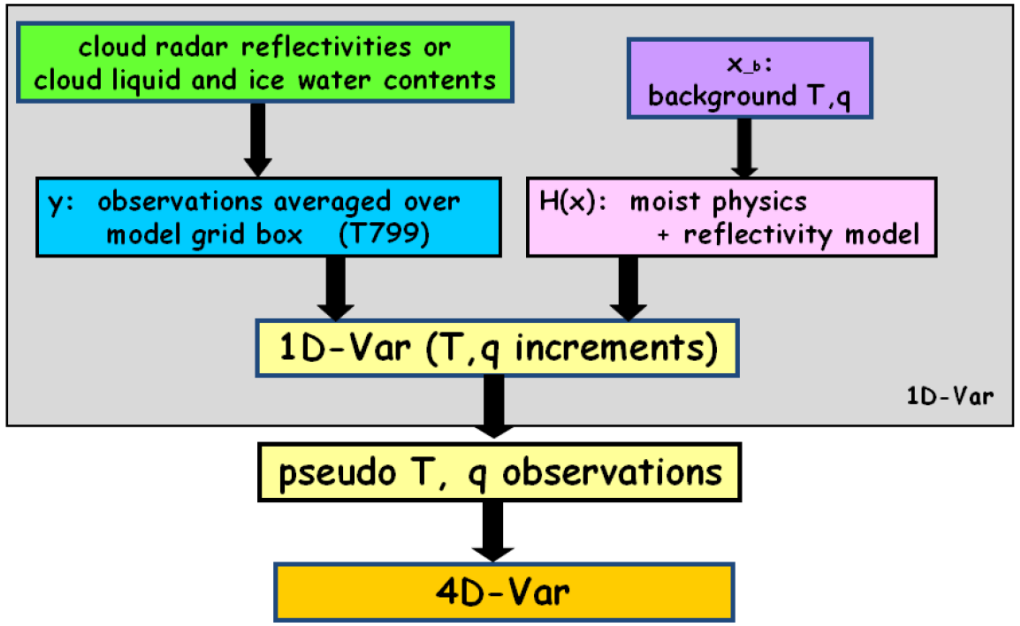
- 1D-Var analysis gets closer not only to the assimilated, but also to the independent observations
- Analysis could benefit from assimilation of spaceborne cloud radar observations ⟶ efforts to be made to further explore their possible use in the assimilation system of NWP

QuARL project

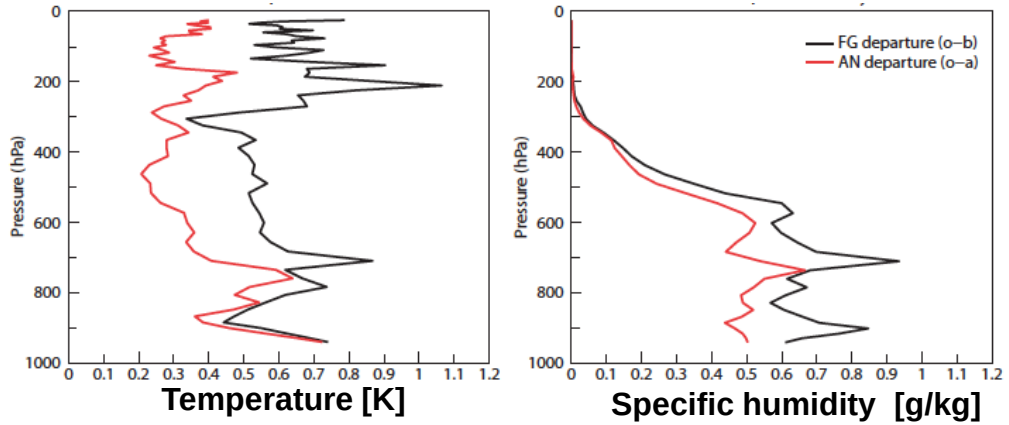


Quantitative Assessment of the Operational Value of Space-Borne Radar and Lidar Measurements of Cloud and Aerosol Profiles

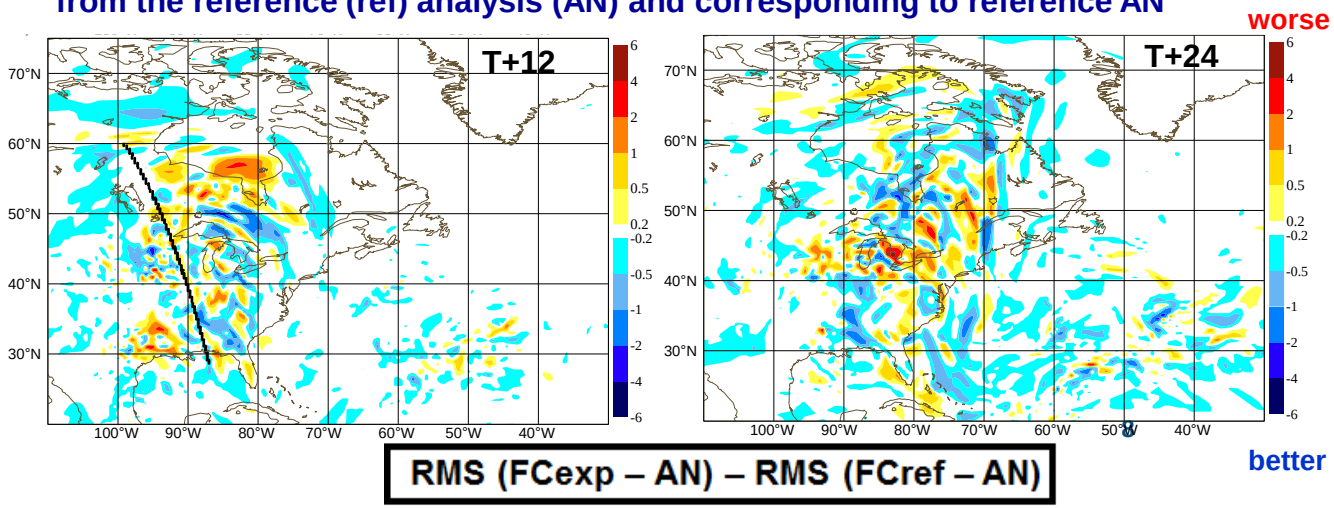
1D+4D-Var technique to study the impact of CloudSat obs on 4D-Var analyses & subsequent forecasts



Impact on analyses: Standard deviation for FG & AN departures from 4D-Var assimilating T & q pseudo-observations from 1D-Var of cloud radar reflectivity



Impact on forecasts: Difference of 200-hPa wind rms errors for the differences between the forecasts (FC) starting from 4D-Var of T & q pseudo-obs (exp) and from the reference (ref) analysis (AN) and corresponding to reference AN



- Information on temperature (T) & humidity (q) retrieved from 1D-Var of cloud radar data & used as pseudo-obs in 4D-Var can improve initial conditions & partly forecast
- Getting more impact from the new data would require to carefully tune their usage in the assimilation system
- *Promising results indicate that it would be highly desirable for NWP to have space-borne radar and lidar observations in near-real time.*

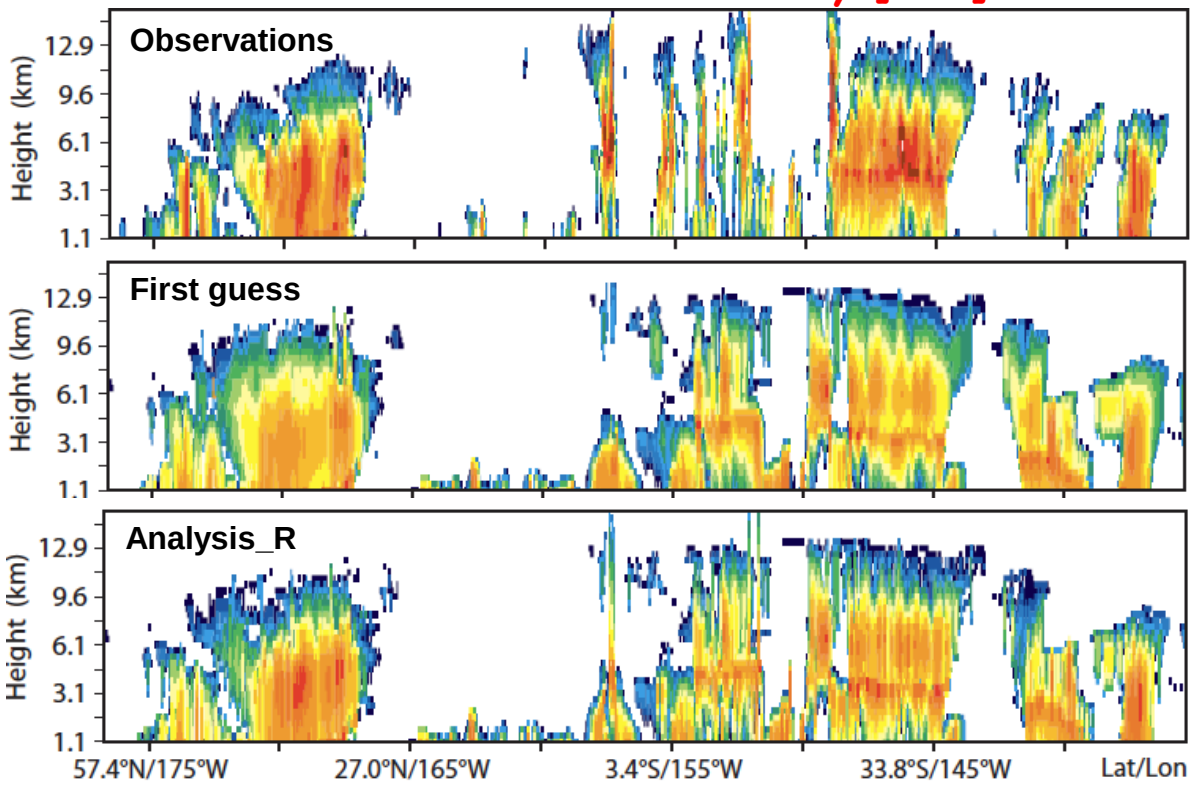
ECAREassim1 project

STSE Study – EarthCARE assimilation

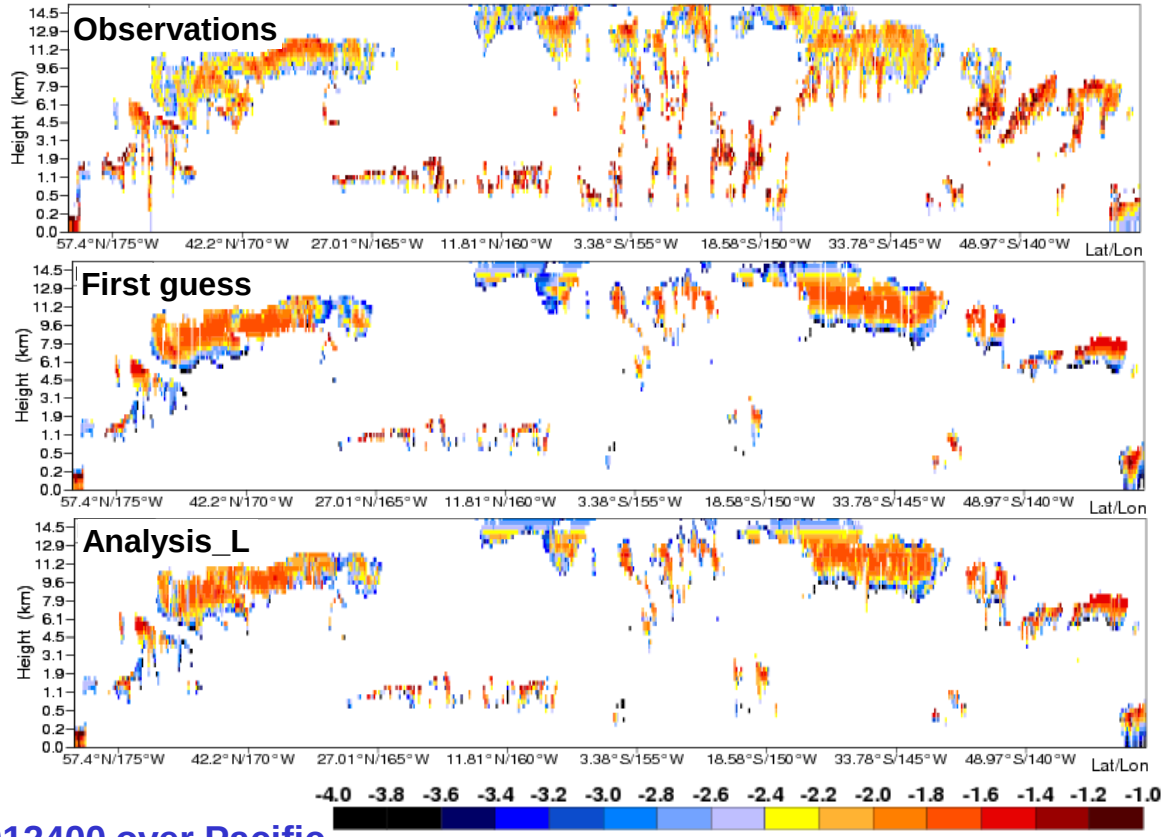
- *The project concentrated on preparing off-line data assimilation and monitoring systems to exploit **combined space-borne lidar and radar cloud observations** for their assimilation in NWP models.*

- The necessary developments for monitoring and assimilation studies have been done:
  - observation operator for cloud radar reflectivity and lidar backscatter
  - quality control and bias corrections schemes & definition of observation errors

1D-Var of cloud radar reflectivity [dBZ]



1D-Var of cloud lidar backscatter [km^{-1} sr $^{-1}$]



ECMWF

2007012400 over Pacific

ECAREassim1 project

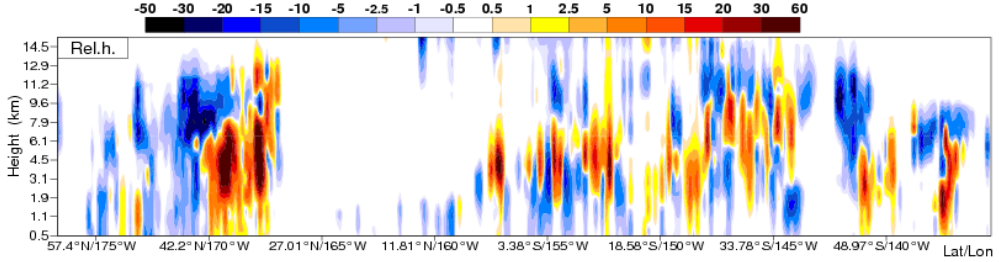
STSE Study – EarthCARE assimilation

1D-Var increments of RH (derived from T & q)

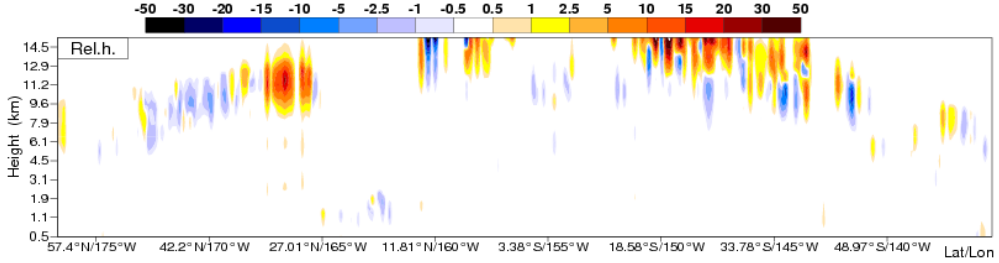
2007012400 over Pacific

1D-Var radar

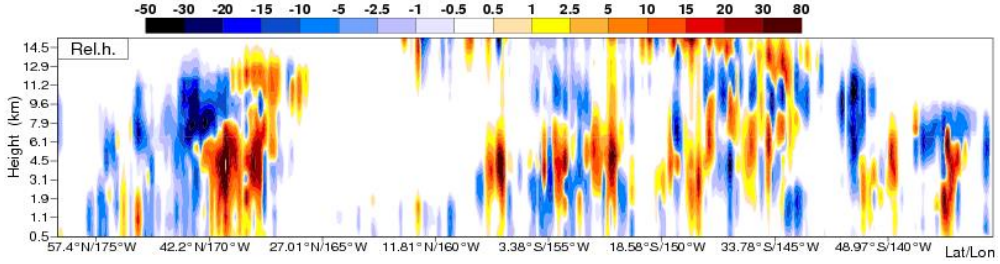
Relative humidity [%]



1D-Var lidar



1D-Var radar+lidar

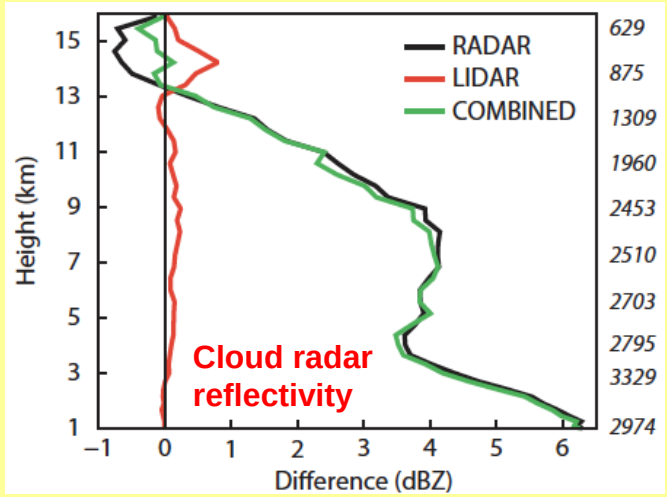


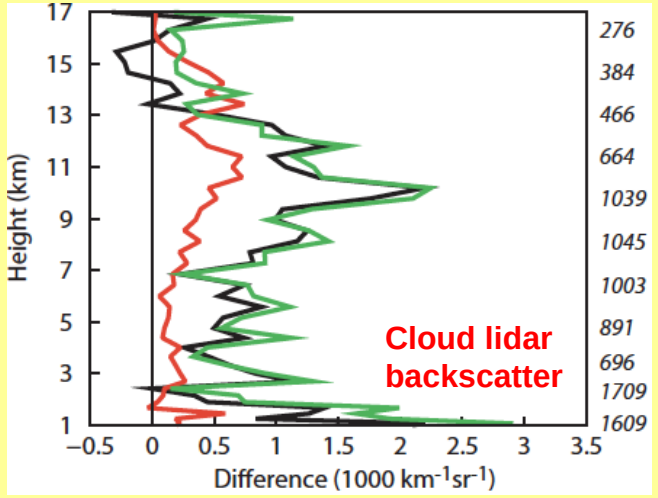
- T & q increments from lidar, smaller than from radar.
- Lidar increments at higher altitudes, i.e. complimentary

1D-Var fit to assimilated observations

Single 12-hour assimilation window: 20070123 21UTC – 20070124 09UTC

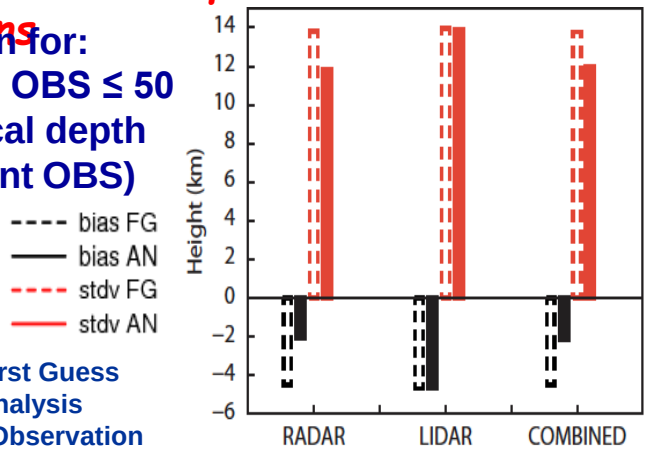
RMS (OBS – FG) – RMS (OBS – AN)





1D-Var fit to independent observations

Comparison for:
FG, AN and OBS ≤ 50
Cloud optical depth
(independent OBS)



FG – First Guess
AN – Analysis
OBS - Observation

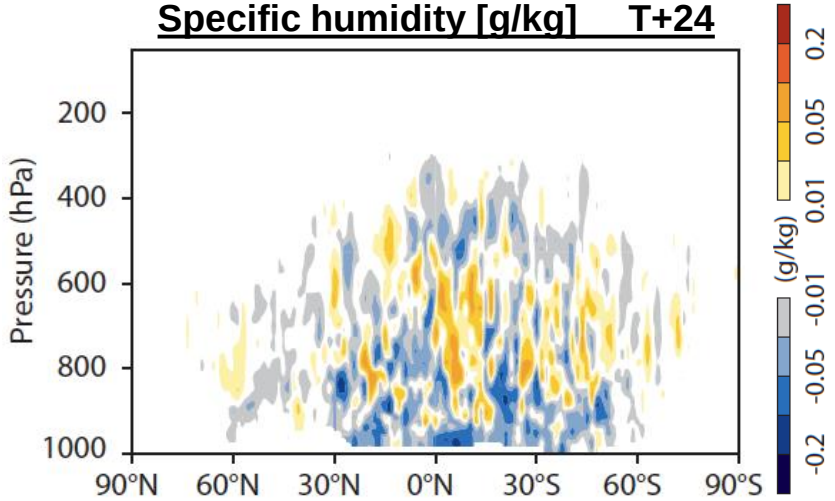
1D-Var analysis gets closer to assimilated & independent obs:

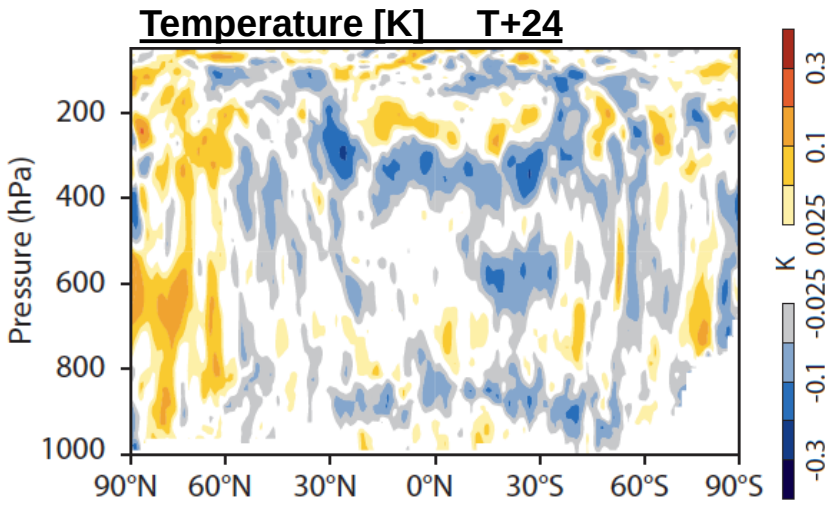
impact of cloud radar reflectivity larger than of lidar backscatter

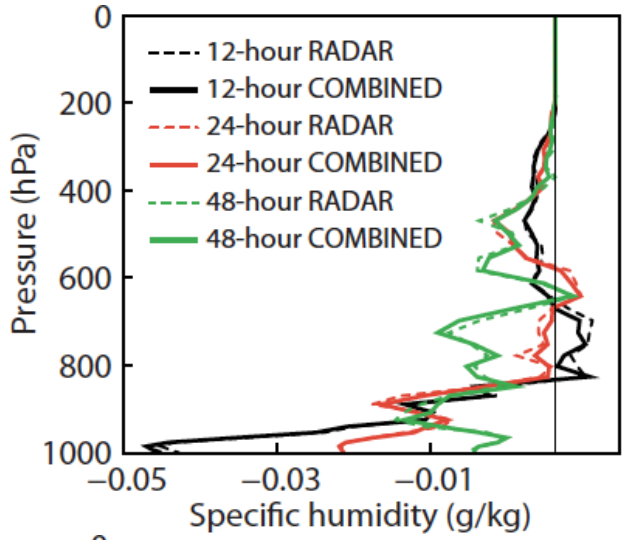
ECAREassim1 project

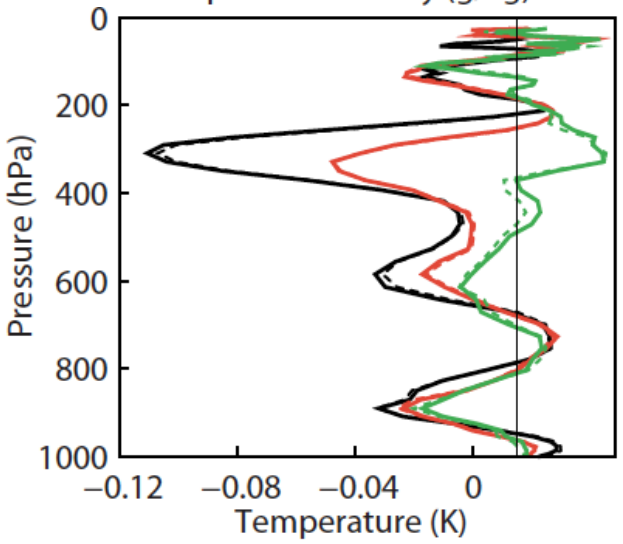
STSE Study – EarthCARE assimilation

1D+4D-Var of T,q pseudo-observations from 1D-Var of radar + lidar: Impact on subsequent forecast









Single 12-hour assimilation window: 20070123 21UTC – 20070124 09UTC

Generally, a positive impact of the new observations on the subsequent forecast:

Even though it decreases in time, it is still noticeable up to 48-hour forecasts

- Information on T & q retrieved from 1D-Var of cloud radar/lidar data and used as pseudo-observations in 4D-Var can lead to improve initial conditions & better forecast
- But direct 4D-Var of cloud radar/lidar observations to be developed:

1D+4D-Var too expensive to be used for operational application

RMS (FCexp – AN) – RMS (FCref – AN)

ECMWF

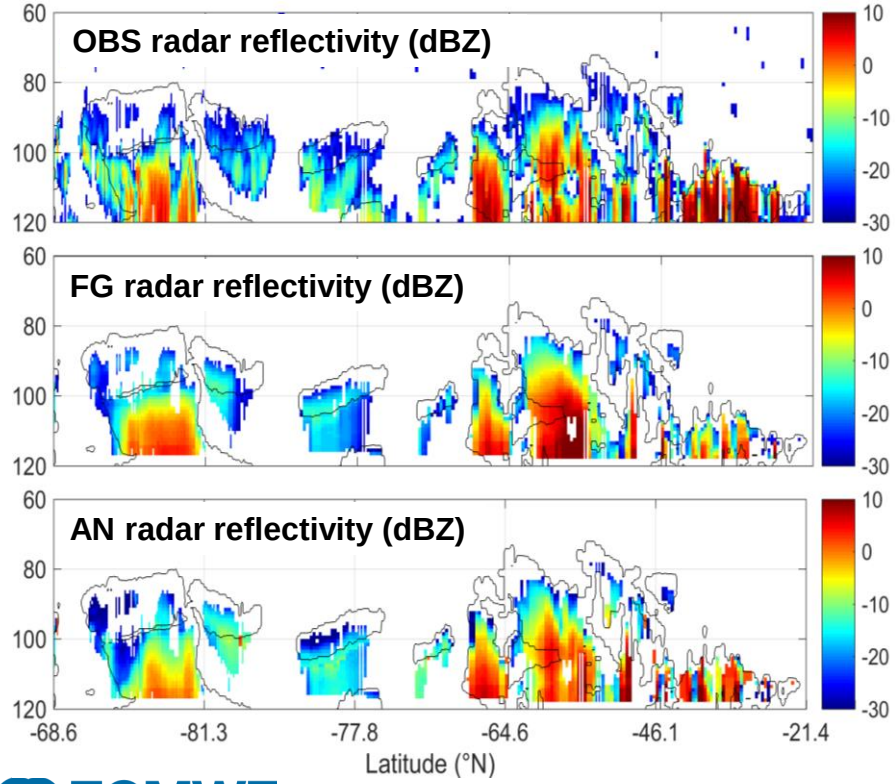
ECAREassim2 project

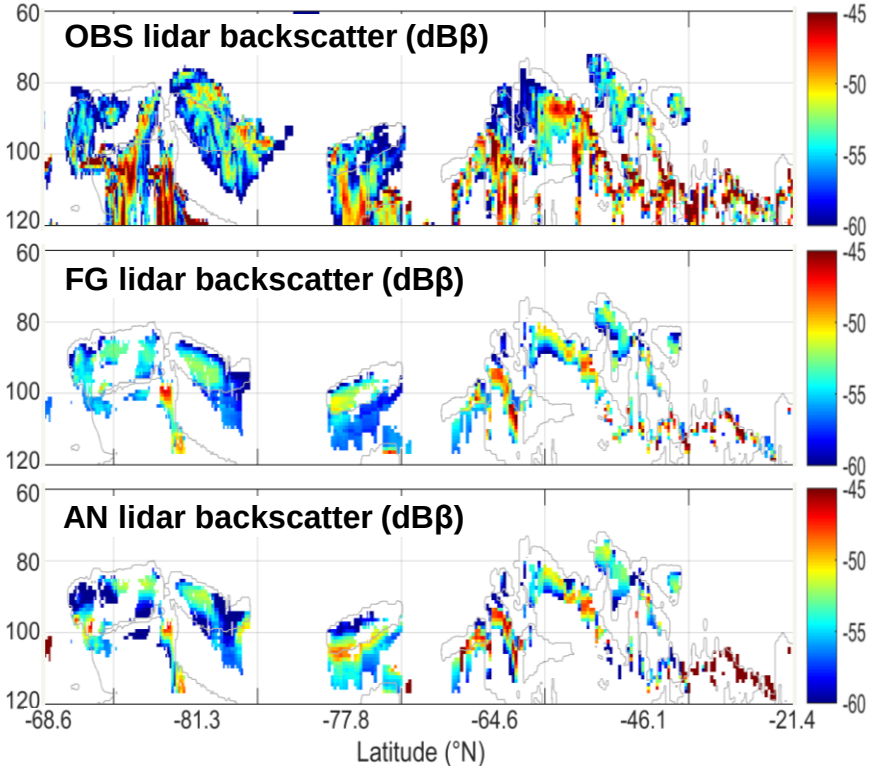
GSP Study – Operational assimilation of Space-borne Radar and Lidar Cloud Profile Observations for NWP

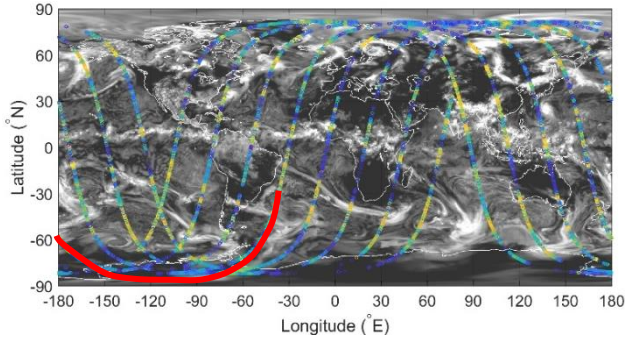
The objectives of the study :

- *Development of an assimilation system that will be able to monitor the data quality of the EarthCARE radar and lidar profiles (limited to cloud observations) and assimilate them into an operational global weather prediction model.*
- ***Direct (in-line) data assimilation and monitoring system** allowing extended research studies beneficial for future applications of EarthCARE.*

Direct 4D-Var assimilation of all observations including cloud radar reflectivity & lidar backscatter







Situation: 20070801 00 UTC

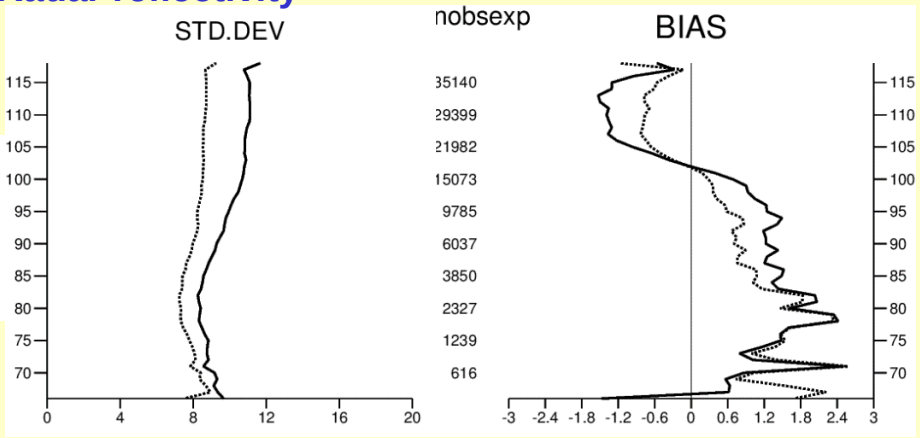
ECAREassim2 project

GSP Study – Operational assimilation of Space-borne Radar and Lidar Cloud Profile Observations for NWP

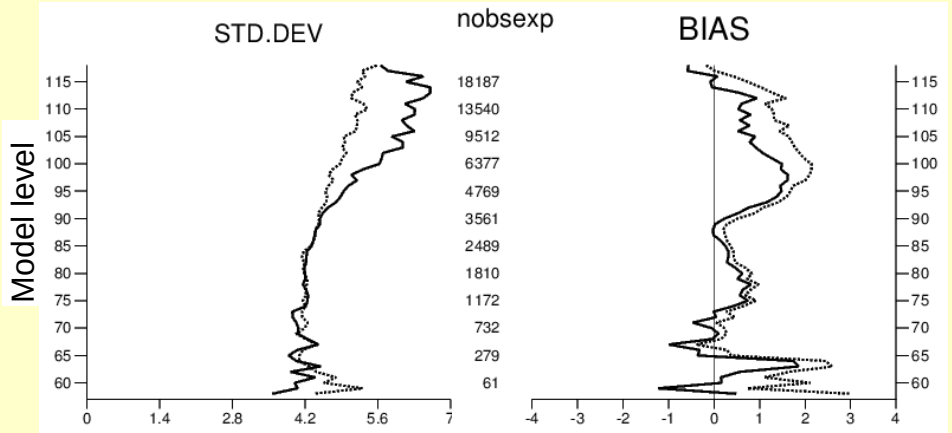
Verification of 4D-Var assimilation runs against assimilated radar & lidar observations

Radar reflectivity

N.Hemis



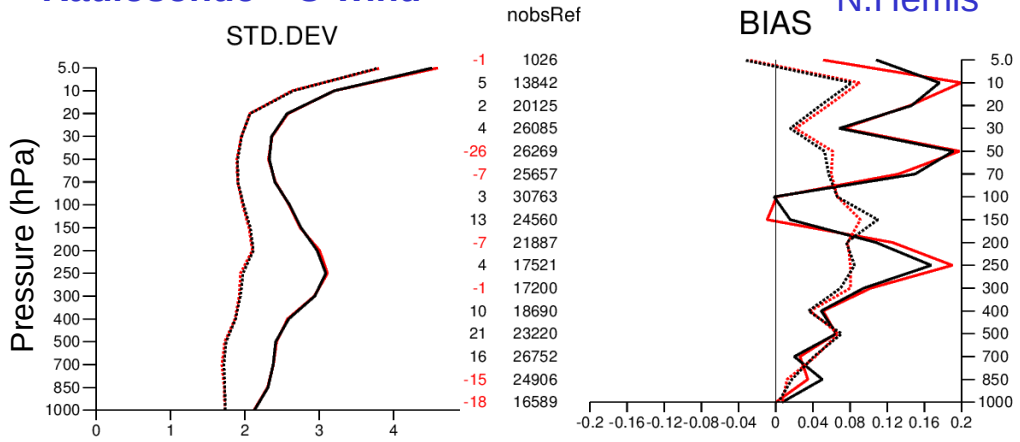
Lidar backscatter



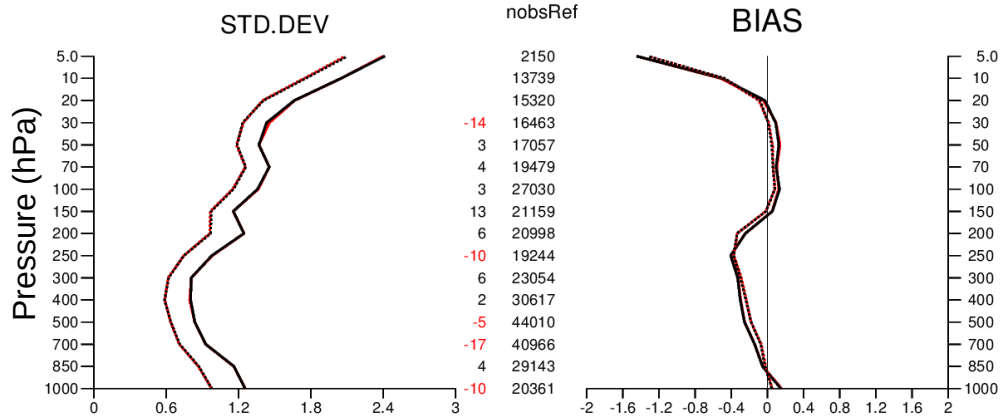
Verification of 4D-Var assimilation runs against other assimilated observations

Radiosonde – U-wind

N.Hemis



Radiosonde – T



CloudSat & CALIPSO assimilation indicated:

- 4D-Var analysis getting closer to assimilated cloud radar reflectivity & lidar backscatter
- a positive impact on analysis fit to other assimilated observations

ECMWF

10-day period – 20 assimilation cycles)

Analysis: 20070801 00:00 UTC – 20070810 12:00 UTC

ECAREassim2 project

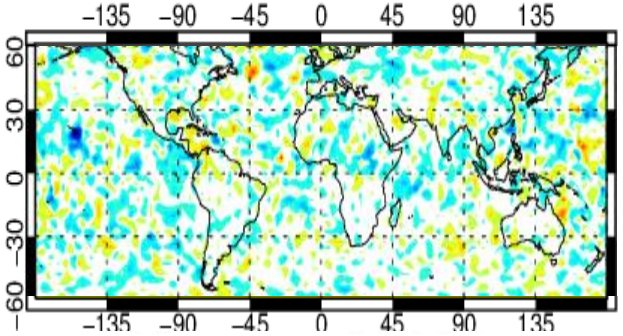
GSP Study – Operational assimilation of Space-borne Radar and Lidar Cloud Profile Observations for NWP

4D-Var using new observations – impact on subsequent forecast (FC)

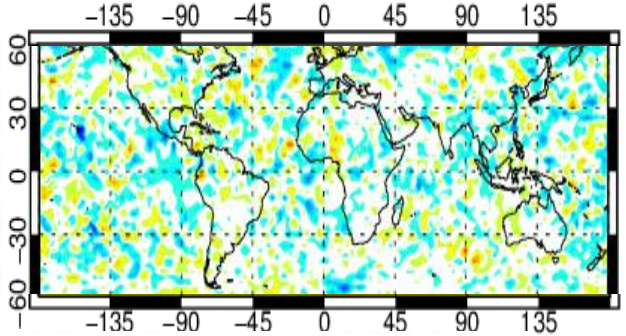
CHANGE IN ERROR: EXP – CONTROL

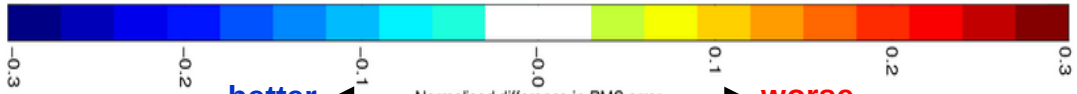
31-day period: 20070801 00 UTC – 20070831 12 UTC

VW – 850 hPa T + 12

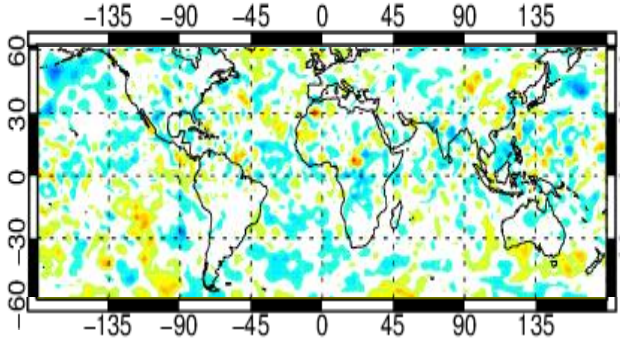


VW – 850 hPa T + 24

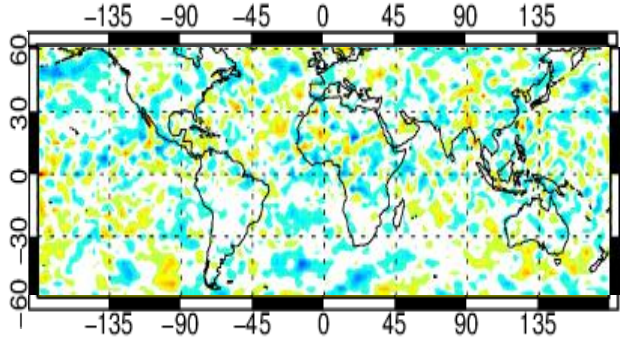


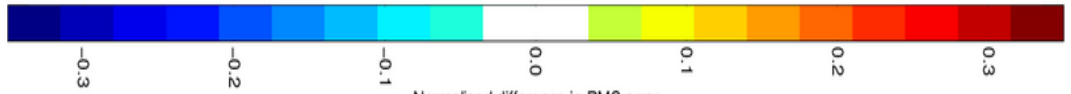


T – 1000 hPa T + 12

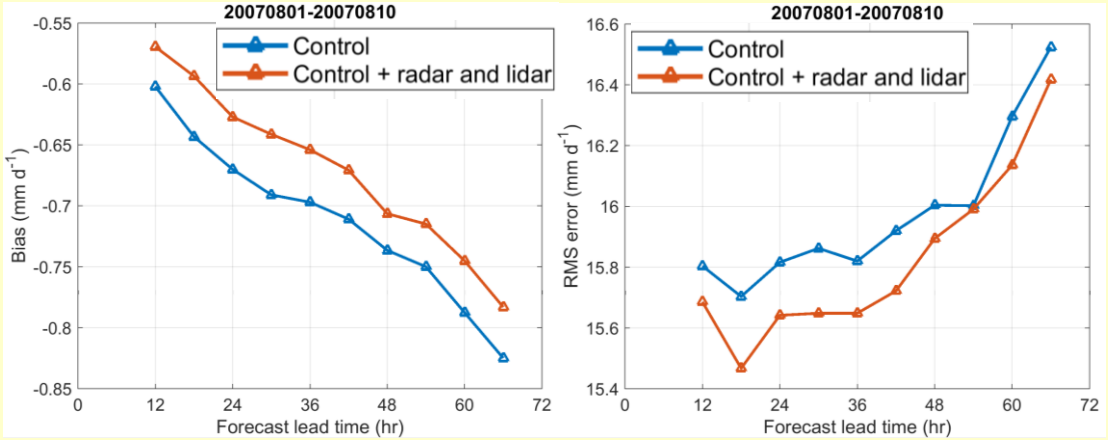


T – 1000 hPa T + 24





Verification of FC against TRMM data
for 10 days of 4D-Var cycling (20070801 – 20070810)



Assimilation of CloudSat & CALIPSO observations:

- a positive impact on the subsequent short-term FC
- improving forecasts of rain rates in Tropics

- The direct assimilation of space-borne cloud radar & lidar into a global NWP model demonstrated for the first time.
- Further gains in forecast skill could be achieved by refining obs.error, bias correction & tuning of superobbing.
- *Encouraging results pave the way for potential operational assimilation of EarthCARE observations in the future.*

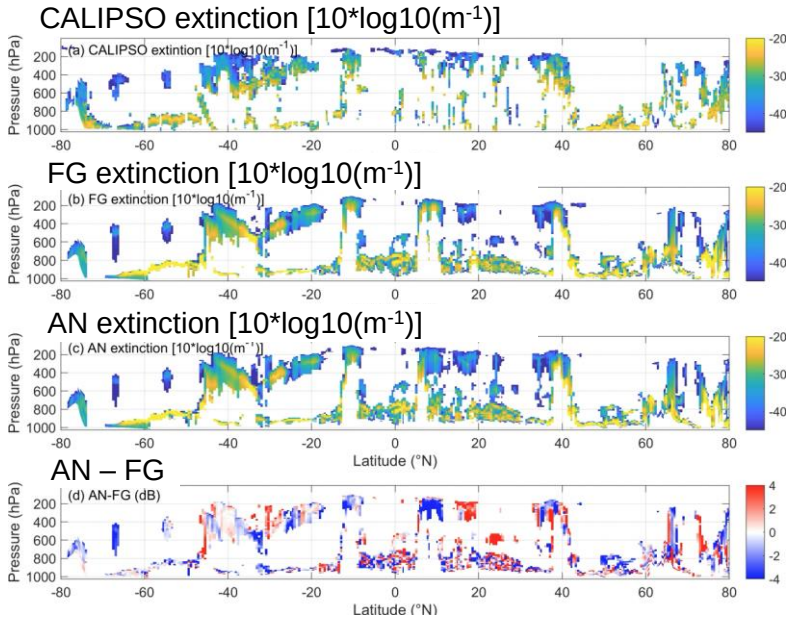
PEARL Cloud project

Preparations for EarthCARE assimilation - Radar and Lidar Cloud (Observations)

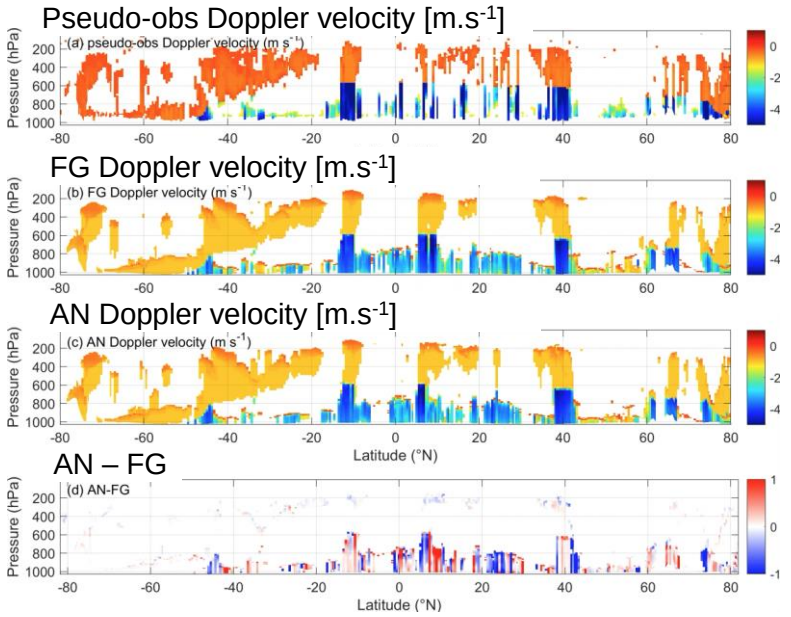
- *Joint ECMWF-ESA project to maintain & improve **developments for monitoring & potential assimilation of EarthCARE cloud radar & lidar observations in preparation for its launch**:*
  - Port assimilation developments to the latest model cycle and maintain
  - Optimise observation impact through improvements of: observation operator, bias correction, observation error, screening, …
  - Explore synergies with other on-board sensors
  - Prepare observation processing so monitoring can begin as soon as possible after satellite launch

Developments for additional EarthCARE products: observation operators & monitoring system

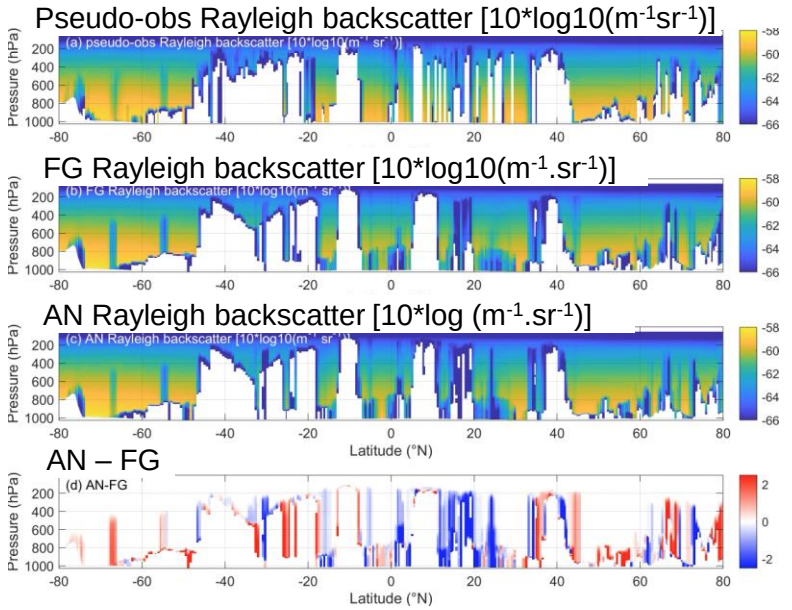
Lidar cloud extinction



Radar Doppler velocity



Rayleigh backscatter



Transect on 20070801 00 UTC

PEARL Cloud project

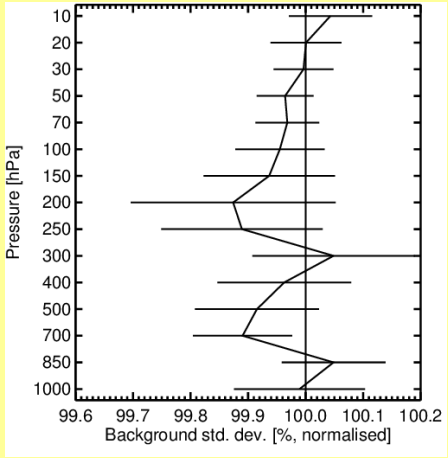
Preparations for EarthCARE assimilation - Radar and Lidar Cloud (Observations)

4D-Var experiments using CloudSat radar reflectivity & CALIPSO lidar backscatter

Improved fit to other assimilated obs

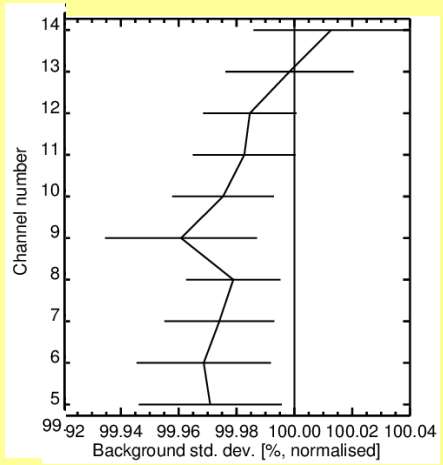
Wind

In-situ wind - Global

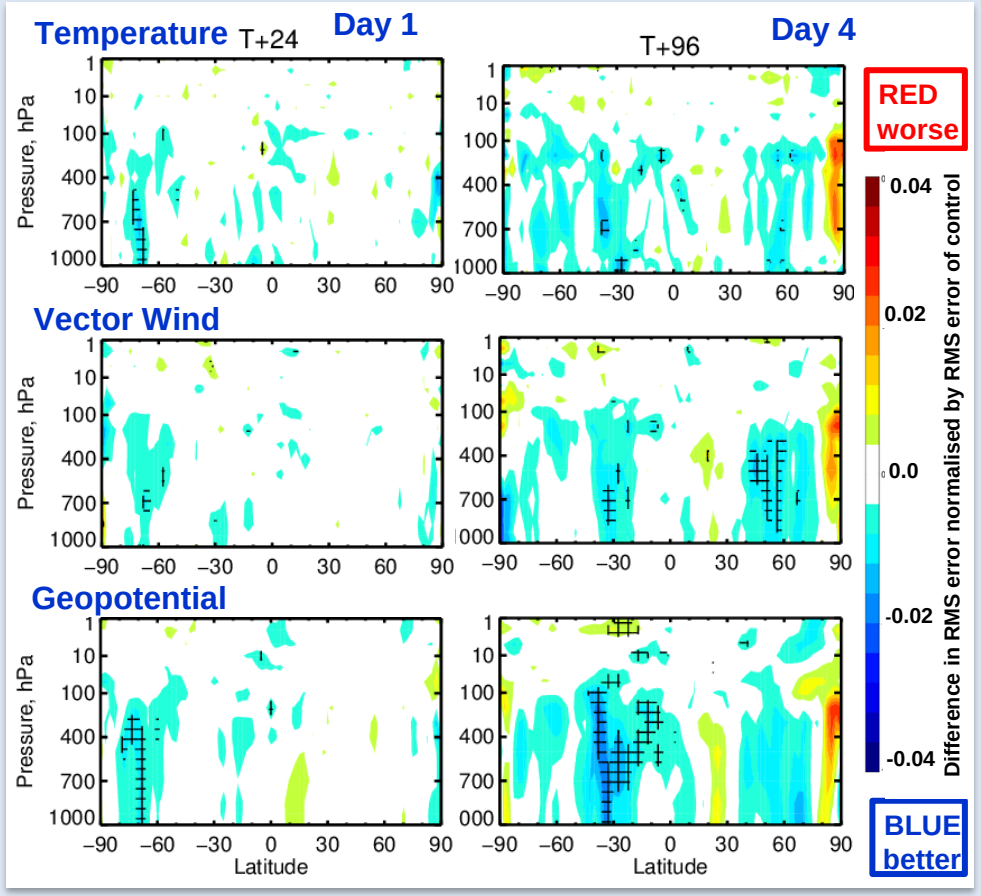


Temperature

AMSUA - Global

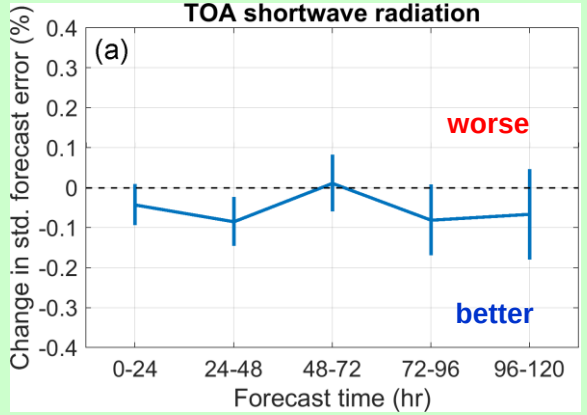


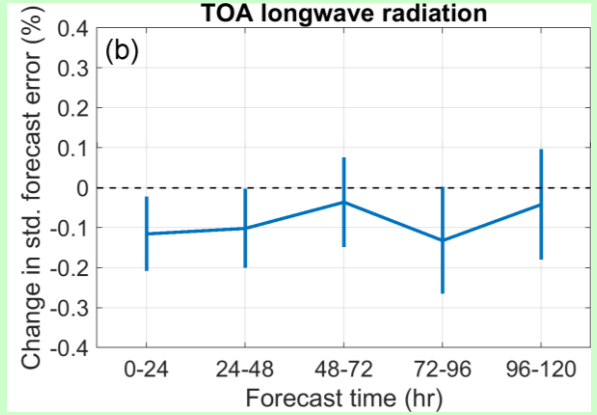
Improvements to medium-range FC skills



Forecast error reduction grows with forecast lead time

significant 0.5 - 1% improvements in global upper tropospheric temperature & winds at day 4-7!





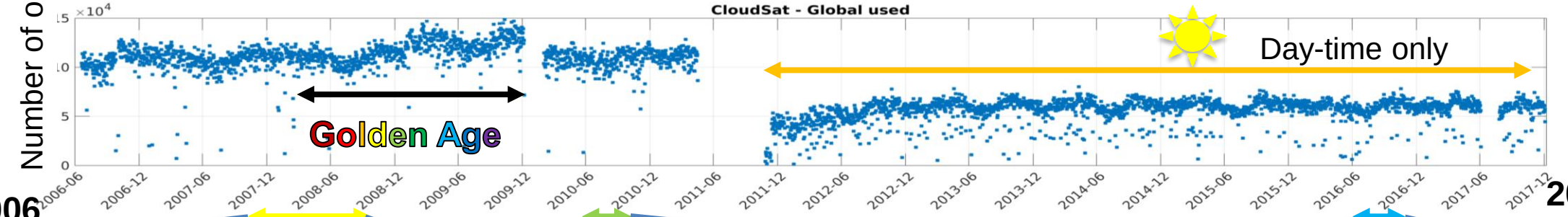
Improvements to forecast of TOA radiation based on verification against independent CERES observations

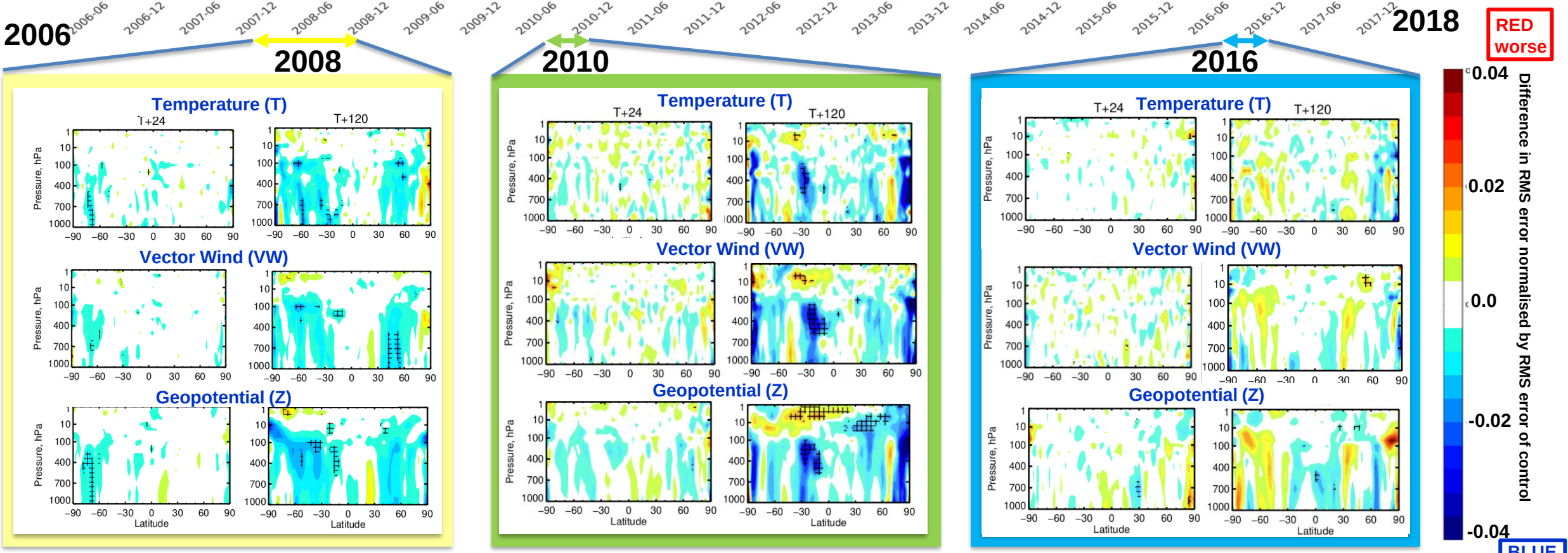
11-month combined period:
1 August 2007 – 31 August 2008

PEARL Cloud project

Preparations for EarthCARE assimilation - Radar and Lidar Cloud (Observations)

How does the impact of assimilating CloudSat and CALIPSO change over time?





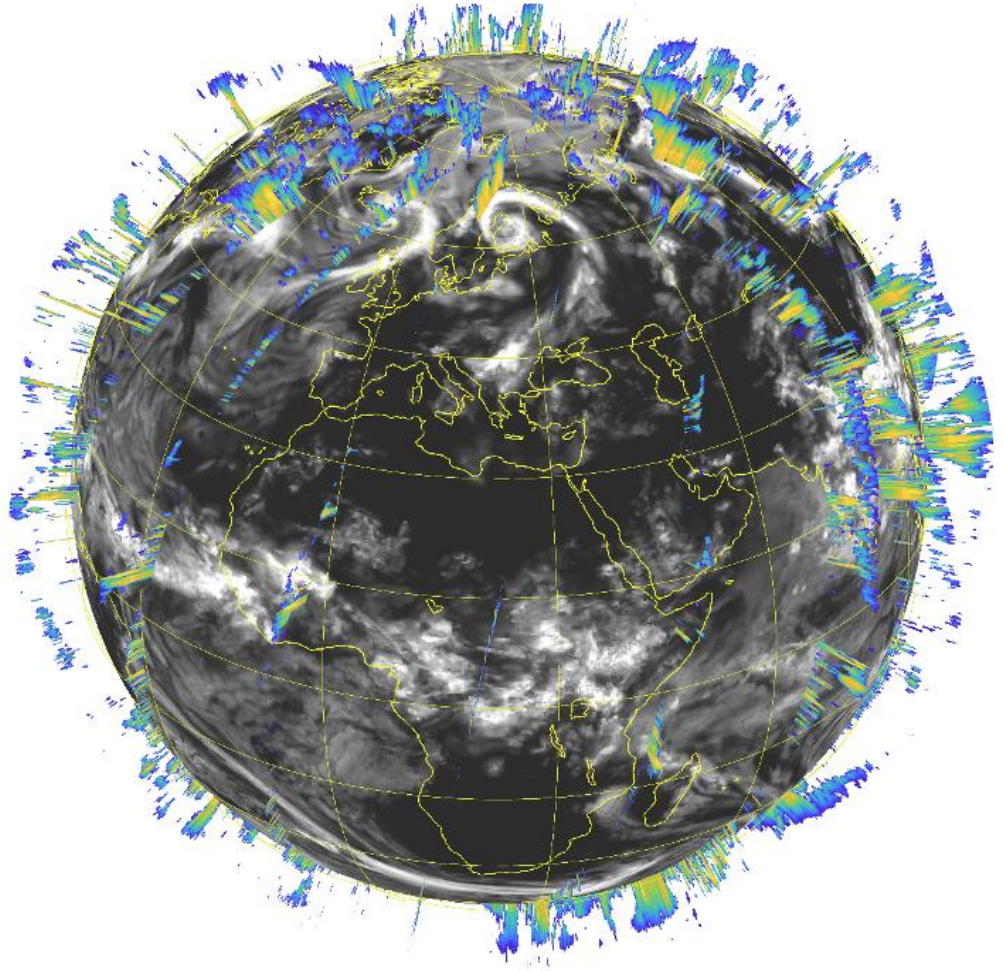
11-month period

3-month period

3-month period

Summary

- ECMWF is preparing for the near real-time monitoring and assimilation of EarthCARE cloud radar and lidar observations as part of a joint ESA-ECMWF project.
- If assimilated, EarthCARE cloud radar and lidar data is expected to have a significant positive impact on medium-range weather forecasts (*Janisková and Fielding, 2020*).
- Instrument simulators (*Fielding and Janisková, 2020*) built within ECMWF model provide support for the scientific exploitation of EarthCARE data, for example to improve the realism of digital twins within the DestinE framework.
- Observation quality monitoring against NWP data is an invaluable tool for validation of meteorological satellite data, including from EarthCARE.



Fielding, M. D. and M. Janisková, 2020: Direct 4D-Var assimilation of space-borne cloud radar reflectivity and lidar backscatter. Part I: Observation operator and implementation. Quarterly Journal of the Royal Meteorological Society, 146(733), 3877–3899.

Janisková, M. and M.D. Fielding, 2020: Direct 4D-Var assimilation of space-borne cloud radar reflectivity and lidar backscatter. Part II: Impact on analysis and subsequent forecast. Quarterly Journal of the Royal Meteorological Society, 146(733), 3900–3916.