Remote Sensing and Climate Diagnostics
SoSe 2026

Wolken

Dr. Martin Stengel (DWD),

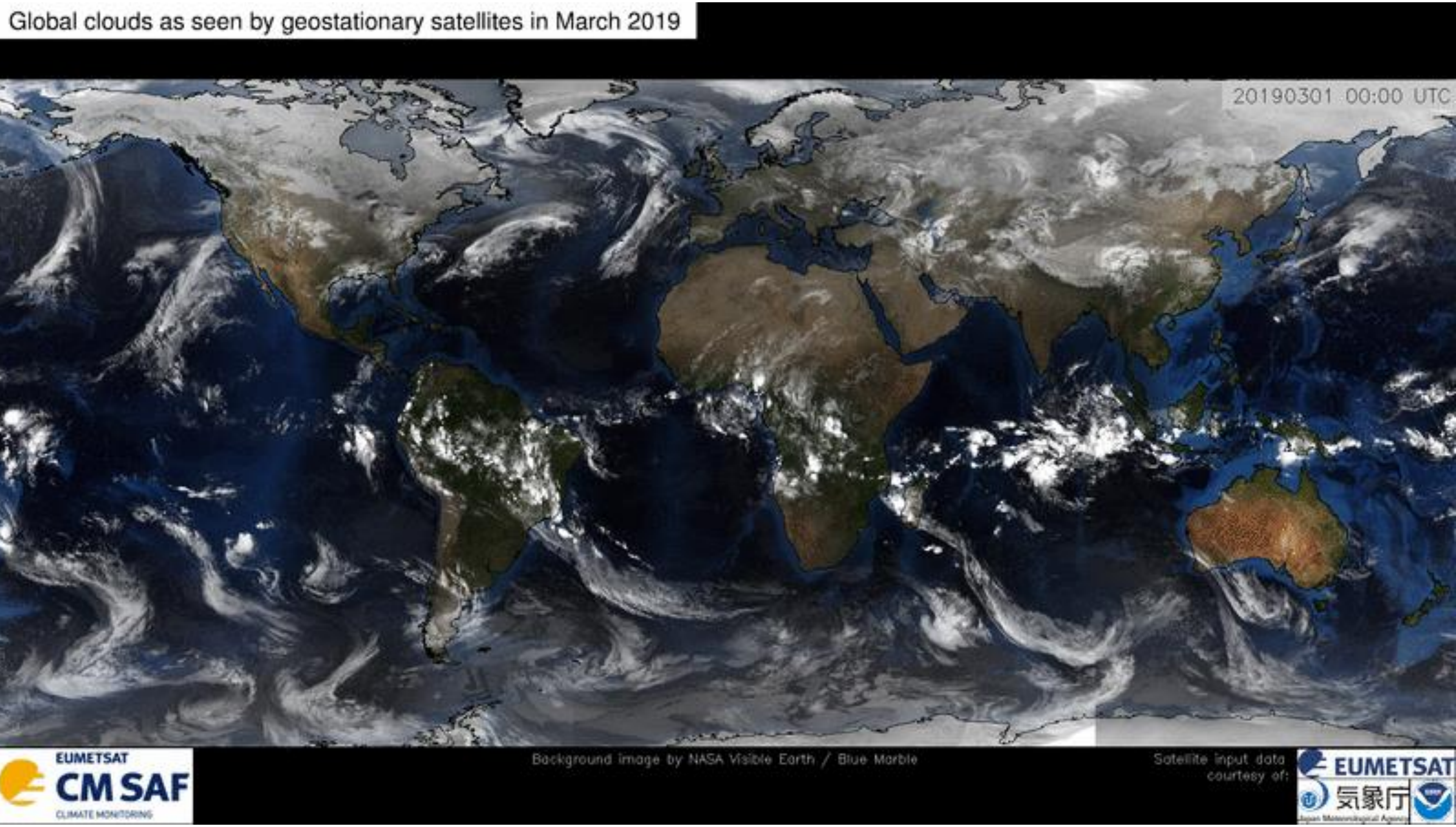
martin.stengel@dwd.de

20.04.2026

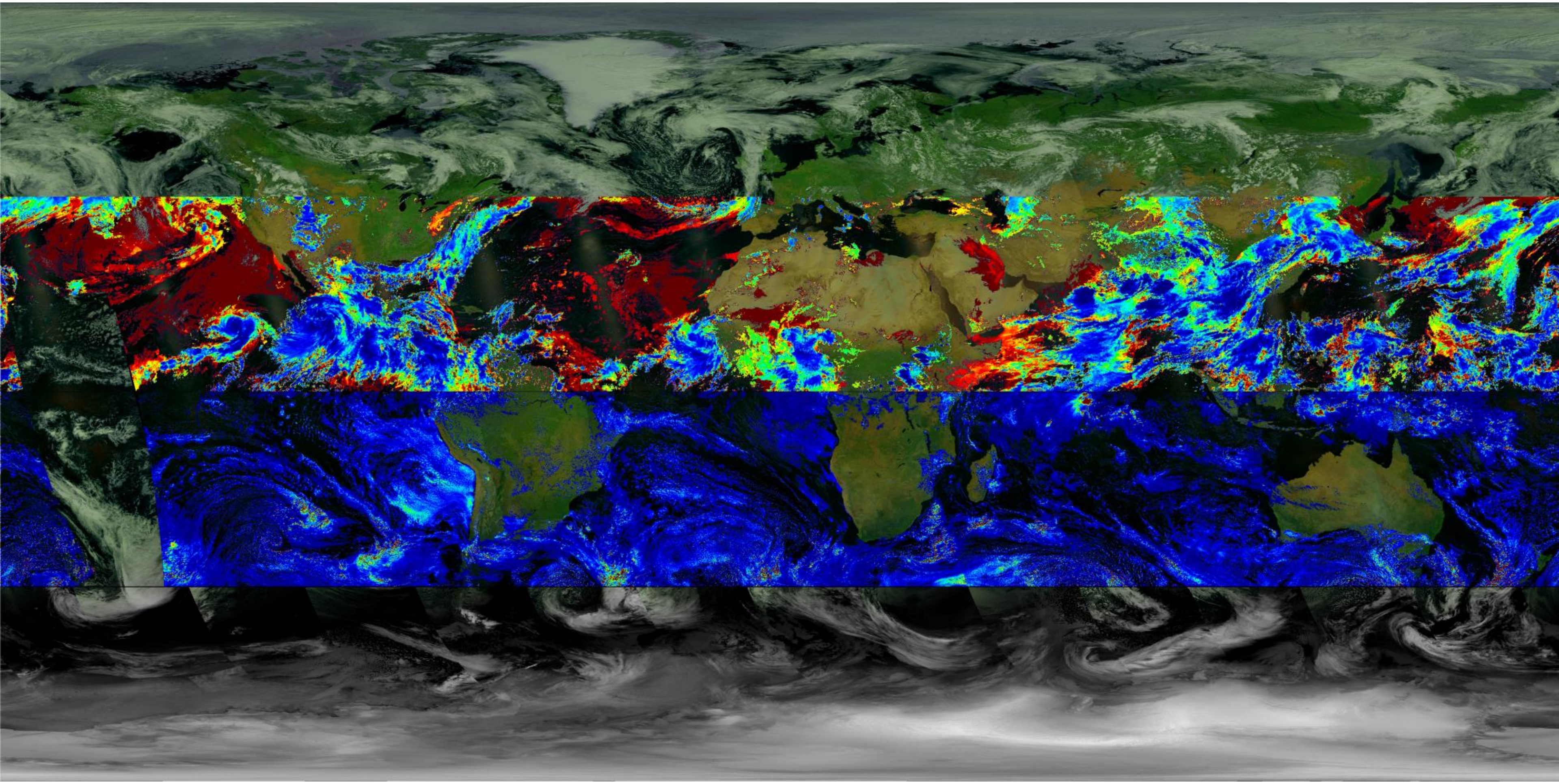
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Kyrill Loop

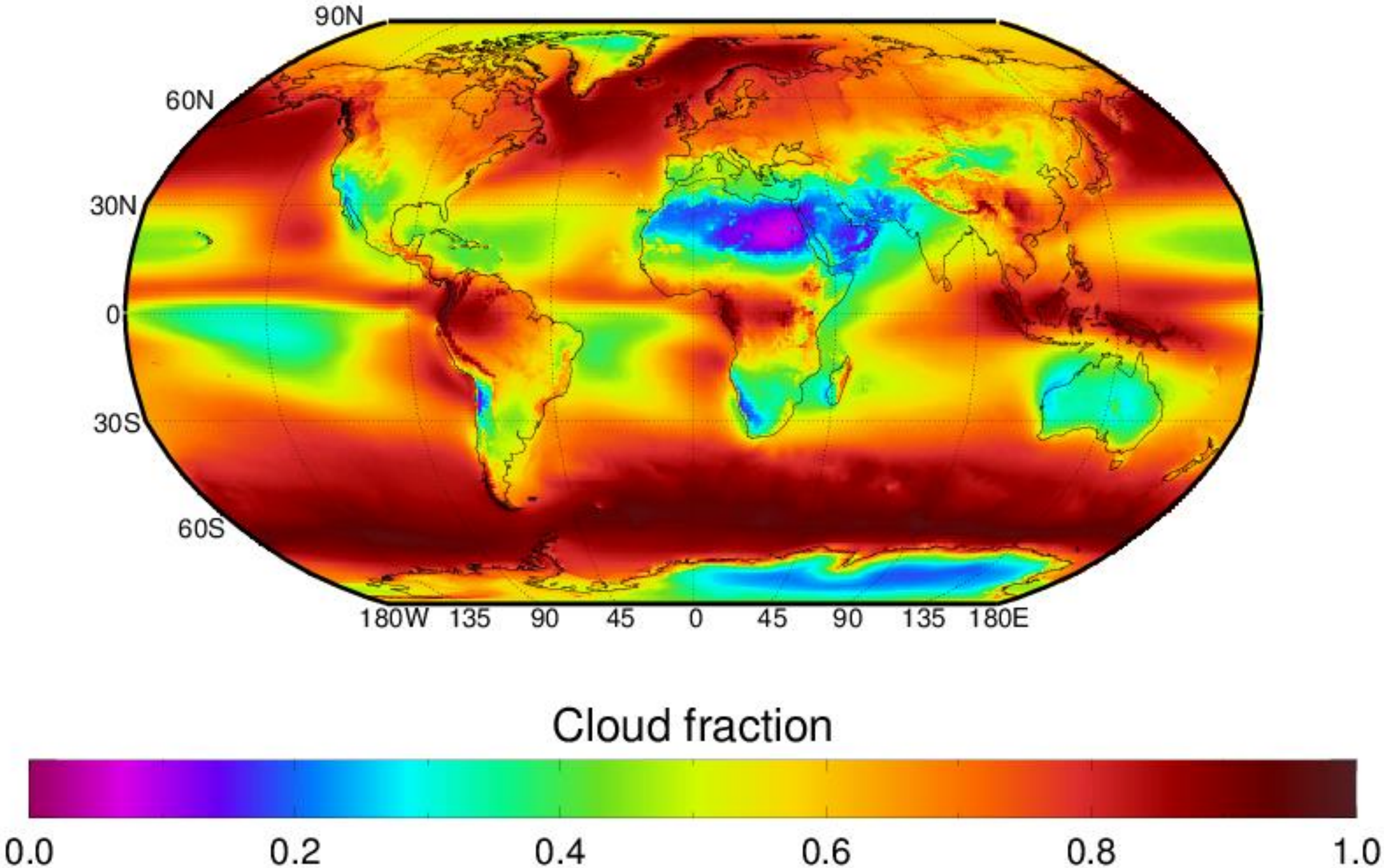
Global cloudiness



Global cloudiness



Global cloudiness



Outline

- Role of clouds in the climate system
- Detecting clouds using satellite sensors
- (Some) cloud properties that can be (are) inferred from satellite measurements
- Validation
- Cloud property datasets
- Application examples
- Summary
- *Projects*

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The importance of clouds for the climate

Clouds affect the climate but changes in the climate, in turn, affect the clouds. This relationship creates a complicated system of climate feedbacks, in which clouds modulate Earth's radiation and water balances.

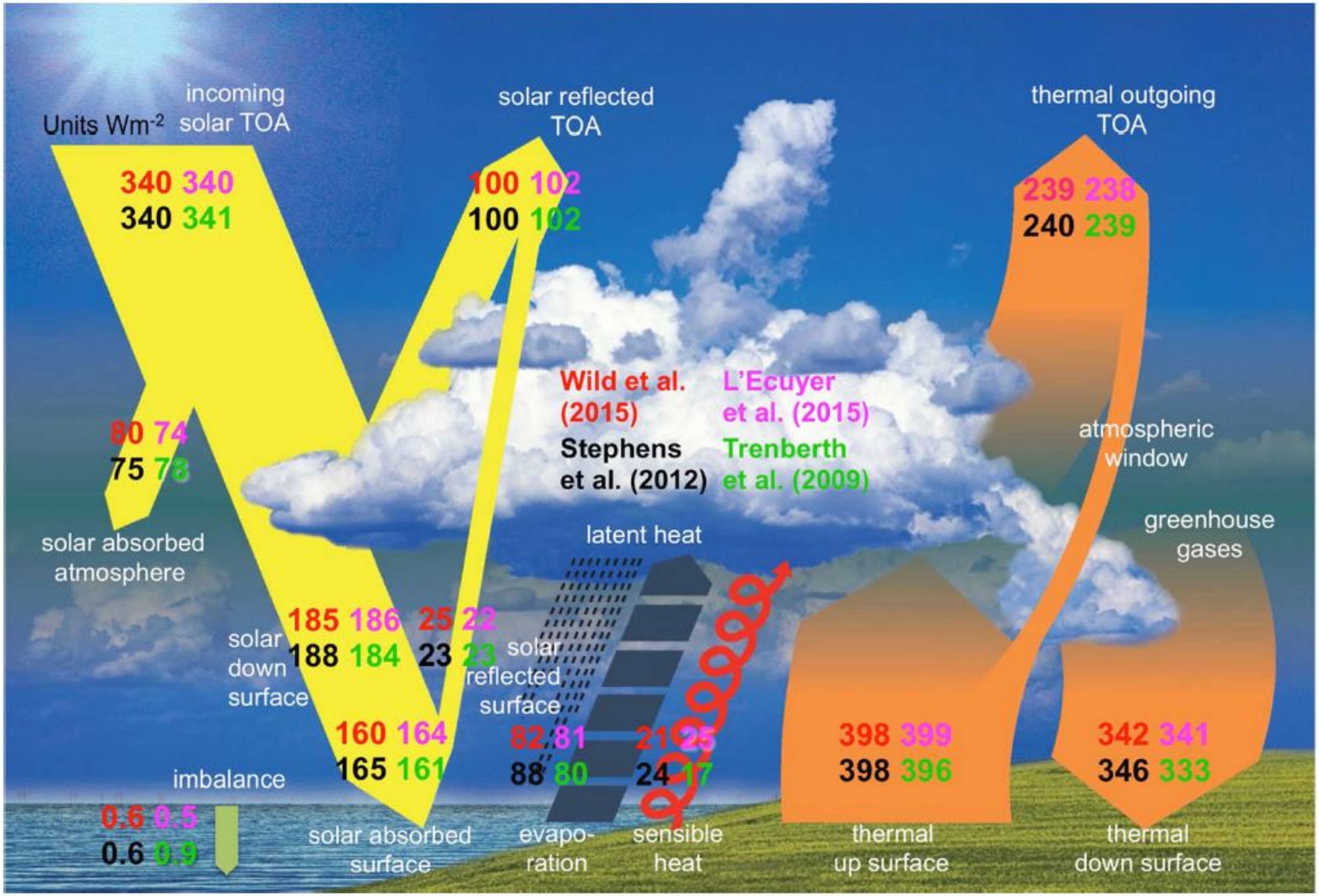
- Clouds cool Earth's surface by reflecting incoming sunlight.
- Clouds warm Earth's surface by absorbing heat emitted from the surface and re-radiating it back down toward the surface.
- Clouds warm or cool Earth's atmosphere by absorbing heat emitted from the surface and radiating it to space.
- Clouds warm and dry Earth's atmosphere and supply water to the surface by forming precipitation.
- …

from http://isccp.giss.nasa.gov/role.html

=> The global net radiative effect of clouds is about -20 Wm-2

To understand how clouds and their radiative effect (can) change in a changing climate (e.g. due to anthropogenic impact), we must observe the state and changes of cloud properties (e.g. cloud cover, height, thermodynamic phase, optical thickness, effective radius). In addition we need atmospheric models that explain the link.

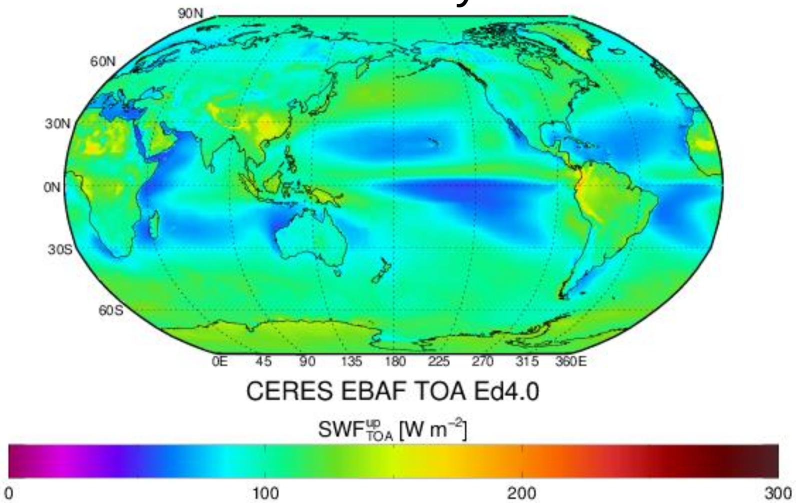
The importance of clouds for the climate



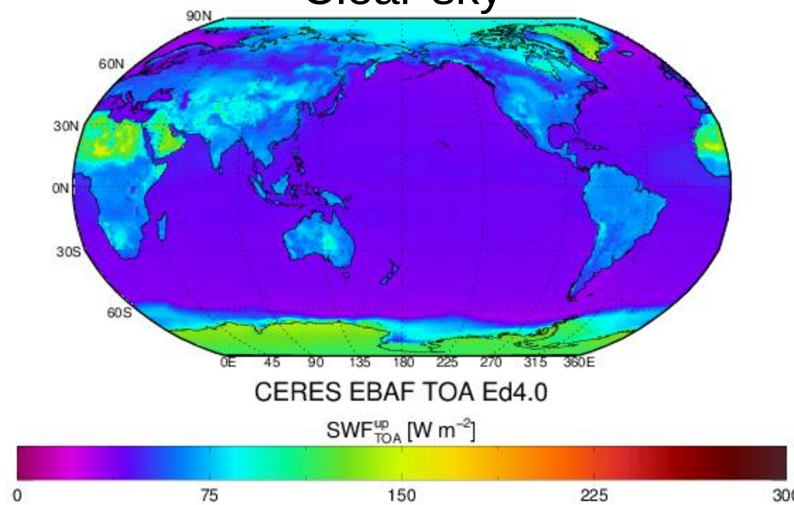
The importance of clouds for the climate

The top-of-the-atmosphere (TOA) radiative effect of clouds – shortwave (SW):

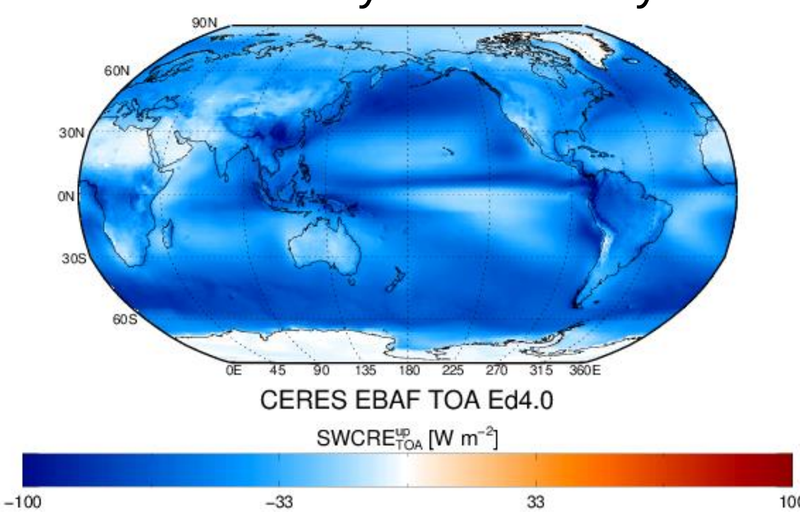
Allsky



Clear-sky



Clear-sky minus Allsky

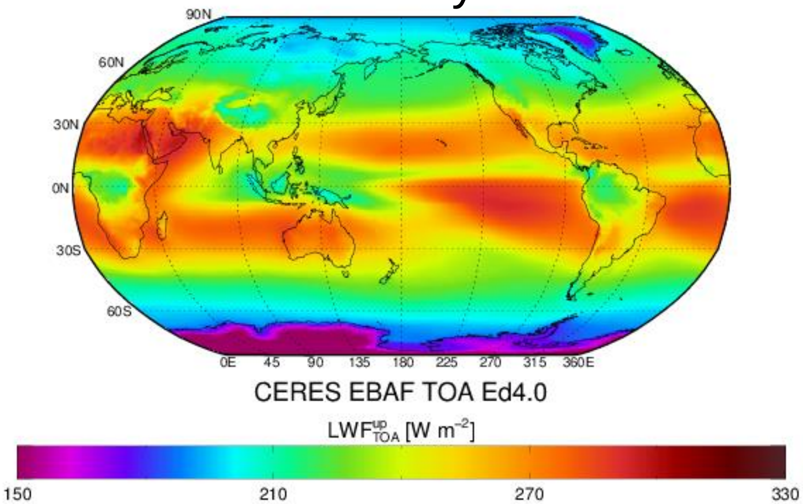


	CERES
SW CRE [W/m^2]	-46.9

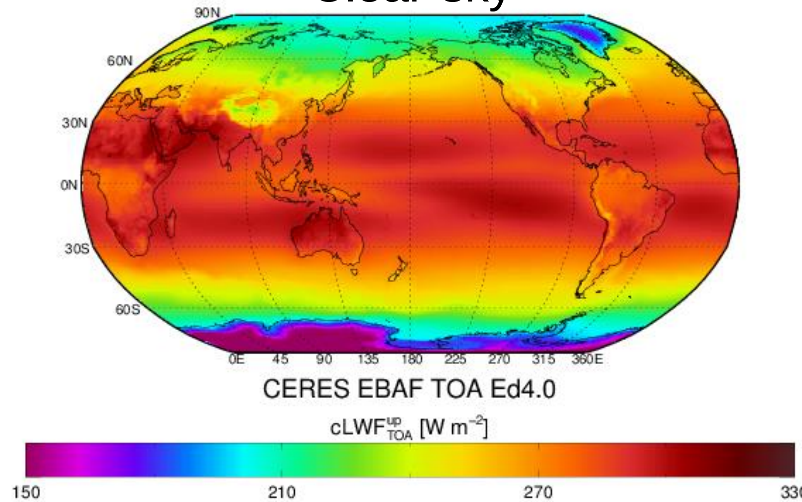
The importance of clouds for the climate

The top-of-the-atmosphere (TOA) radiative effect of clouds – longwave (LW):

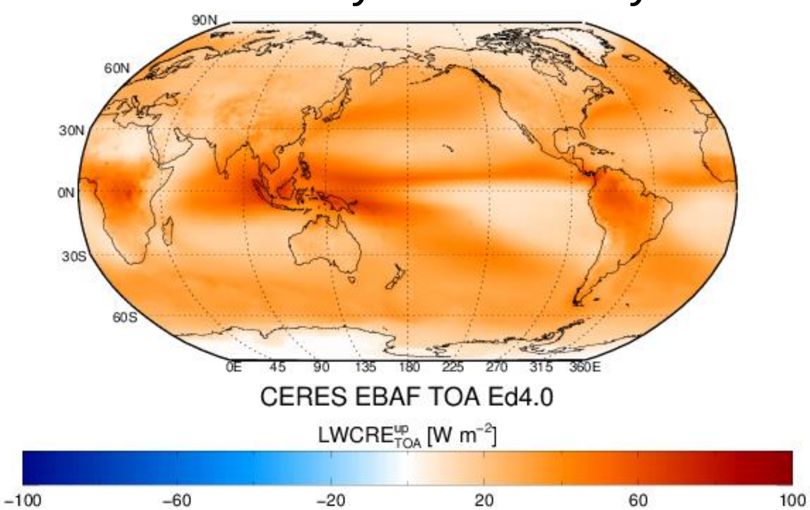
Allsky



Clear-sky



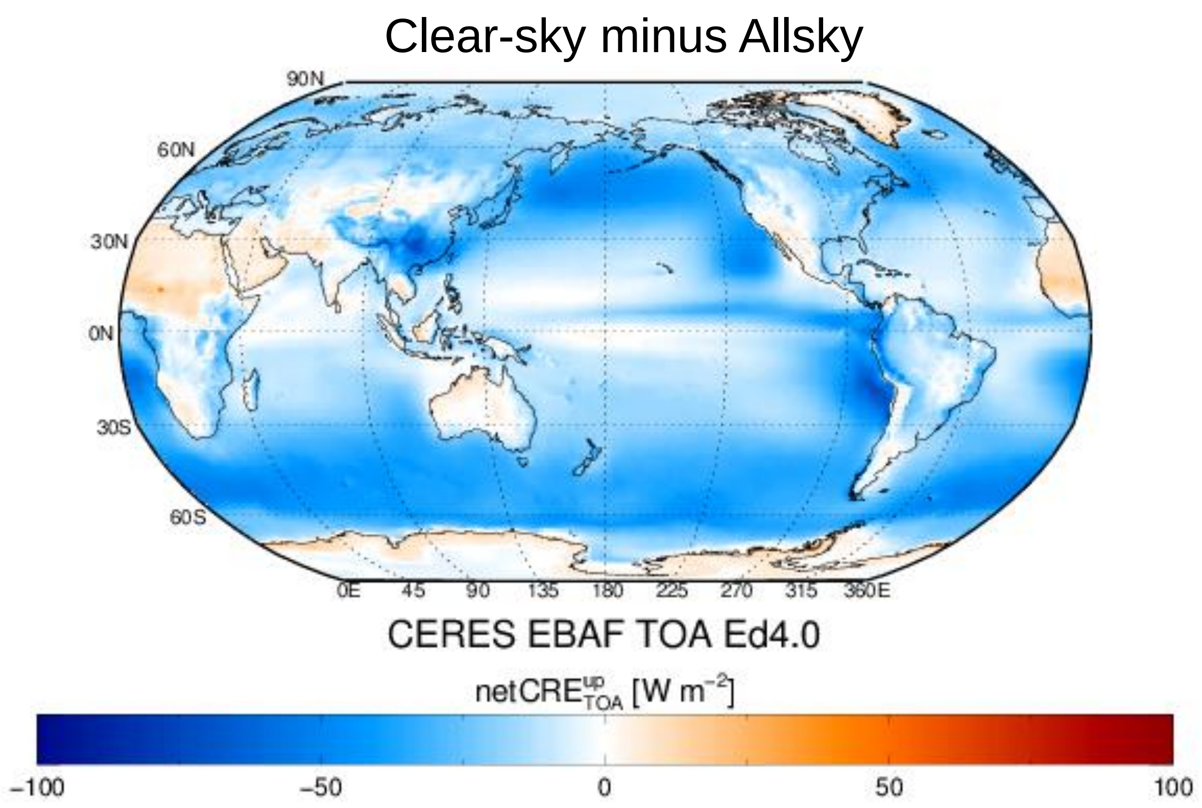
Clear-sky minus Allsky



	CERES
LW CRE [W/m^2]	25.9

The importance of clouds for the climate

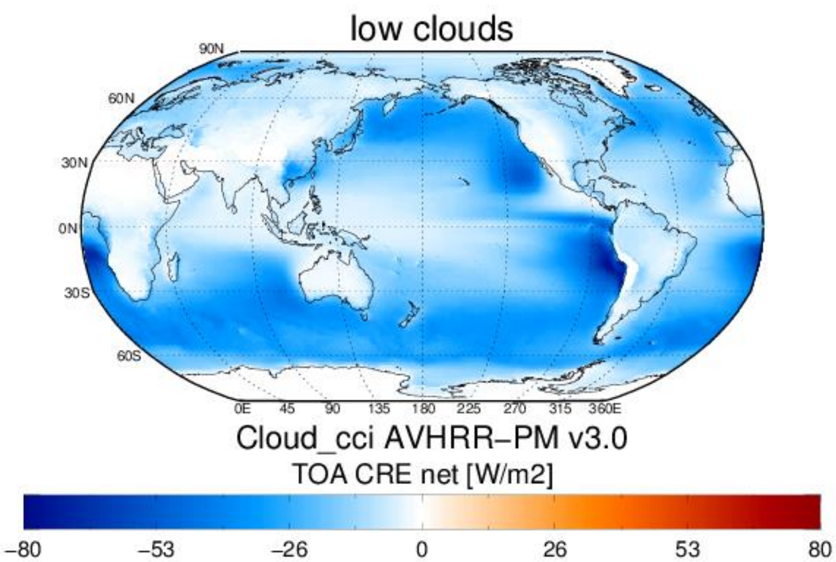
The top-of-the-atmosphere (TOA) radiative effect of clouds – net (SW+LW):

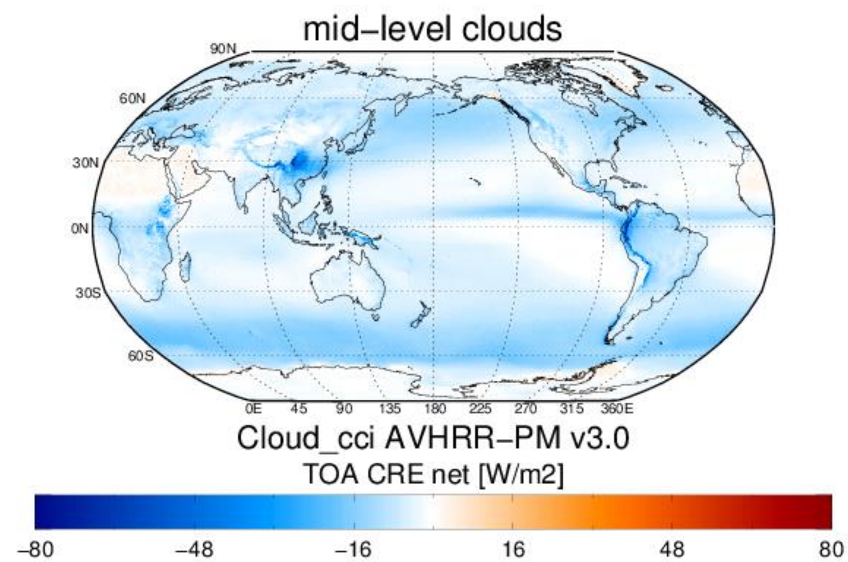


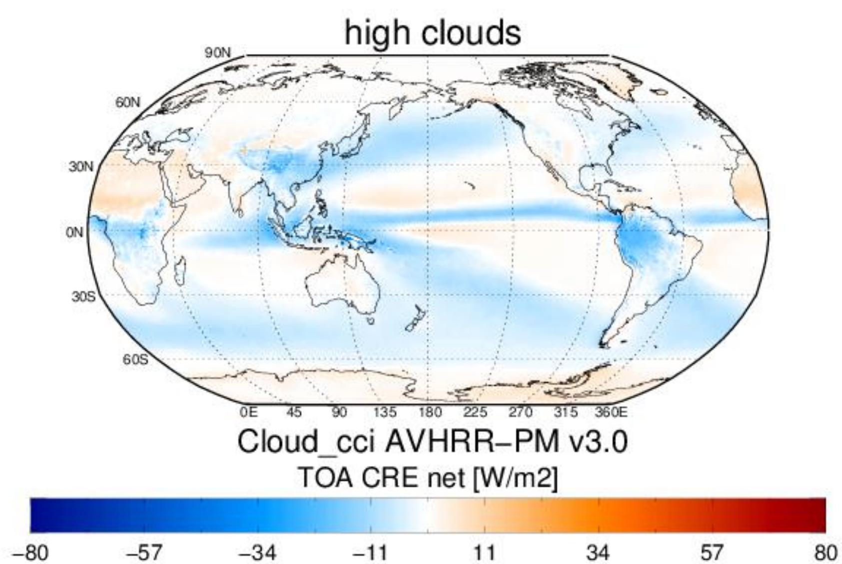
	CERES
SW CRE [W/m^2]	-46.9
LW CRE [W/m^2]	25.9
Net CRE [W/m^2]	-20.9

The importance of clouds for the climate

The top-of-the-atmosphere (TOA) radiative effect of clouds – net (SW+LW):







Motivation for generating satellite cloud datasets

- The climatological characterization of clouds, their properties and associated processes require both atmospheric models and observational datasets.
- For atmospheric models, observations can for example serve as
  - Reference for model tuning
  - Contributor to the analysis of the initial atmospheric state
  - Boundary constraints during the modelled evolution of the atmosphere
  - Constraints for developments of model physics.
  - They can further be used to analyse the long-term state of clouds and their spatial and temporal variability.
- On global scales, satellites observations with their spatial and temporal coverage are uniquely suited for such applications
- However, the satellite observations, both radiances and retrieved geophysical parameters, are desired with high accuracy in this context.

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Detecting clouds

What is a cloud?

A collection of liquid or frozen particles floating in the atmosphere and sustained by vertical motion (updrafts)

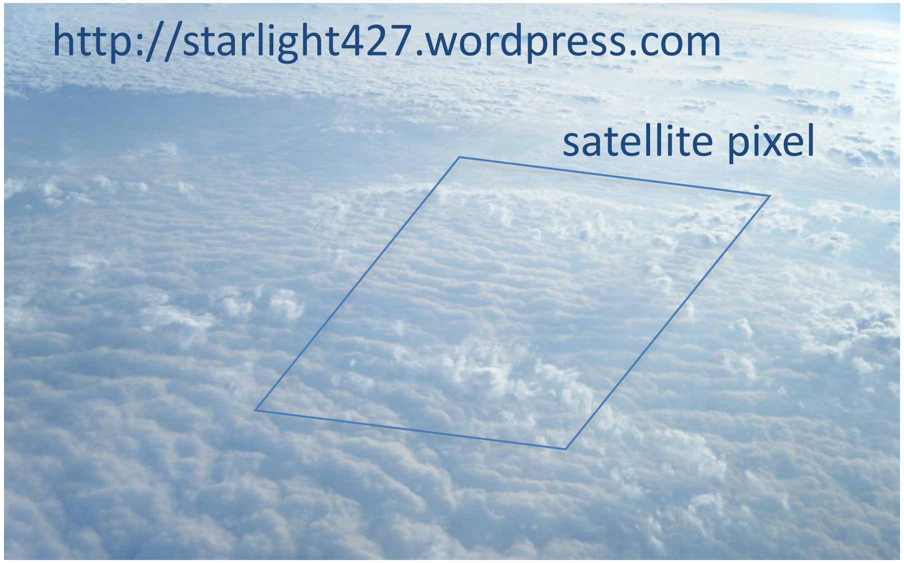
How can we identify them with satellite measurements in VIS/IR?

We identify clouds by their ability to reflect sunlight and by the temperature of their cloud tops, i.e., their brightness in visible and thermal imagery!

What conditions need to be fulfilled for successful cloud detection from space?

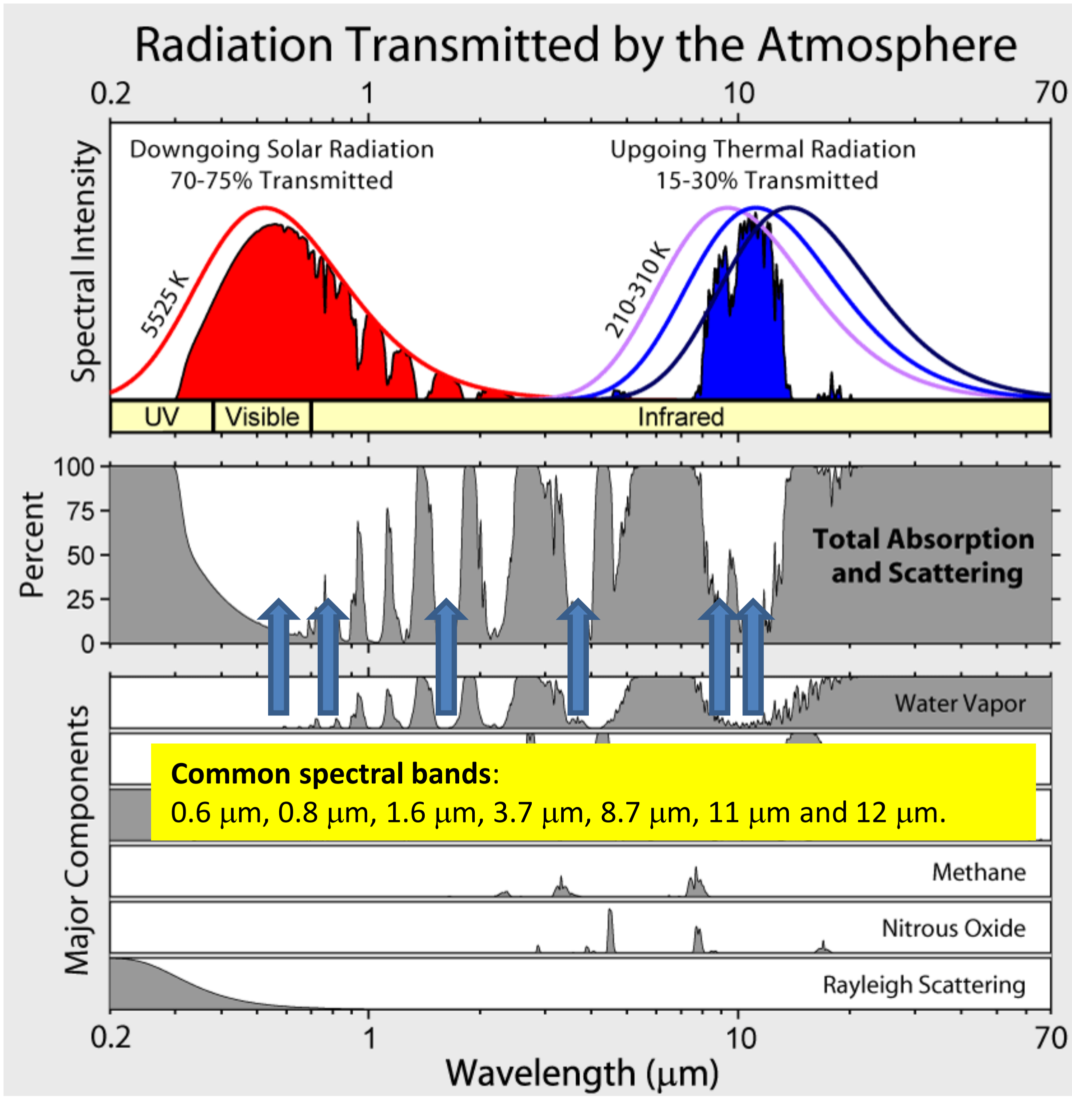
- The atmosphere itself must be transparent
- Clouds must appear brighter than the Earth surface, or
- Cloud tops must be colder than the Earth surface

Detecting clouds



Detecting clouds

We need a transparent atmosphere to be able to observe clouds in imagery!



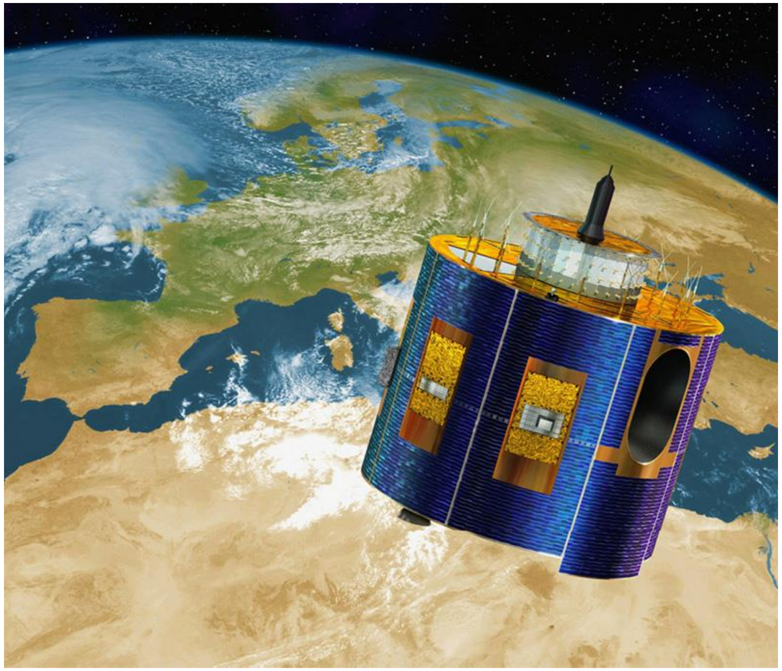
Detecting clouds

Examples of suitable satellite sensors for cloud detection – here passive VIS/IR imagers

The Metop-A satellite carrying AVHRR imager with 6 spectral bands

Polar-orbiter, global coverage

The METEOSAT satellite carrying SEVIRI imager with 12 spectral bands

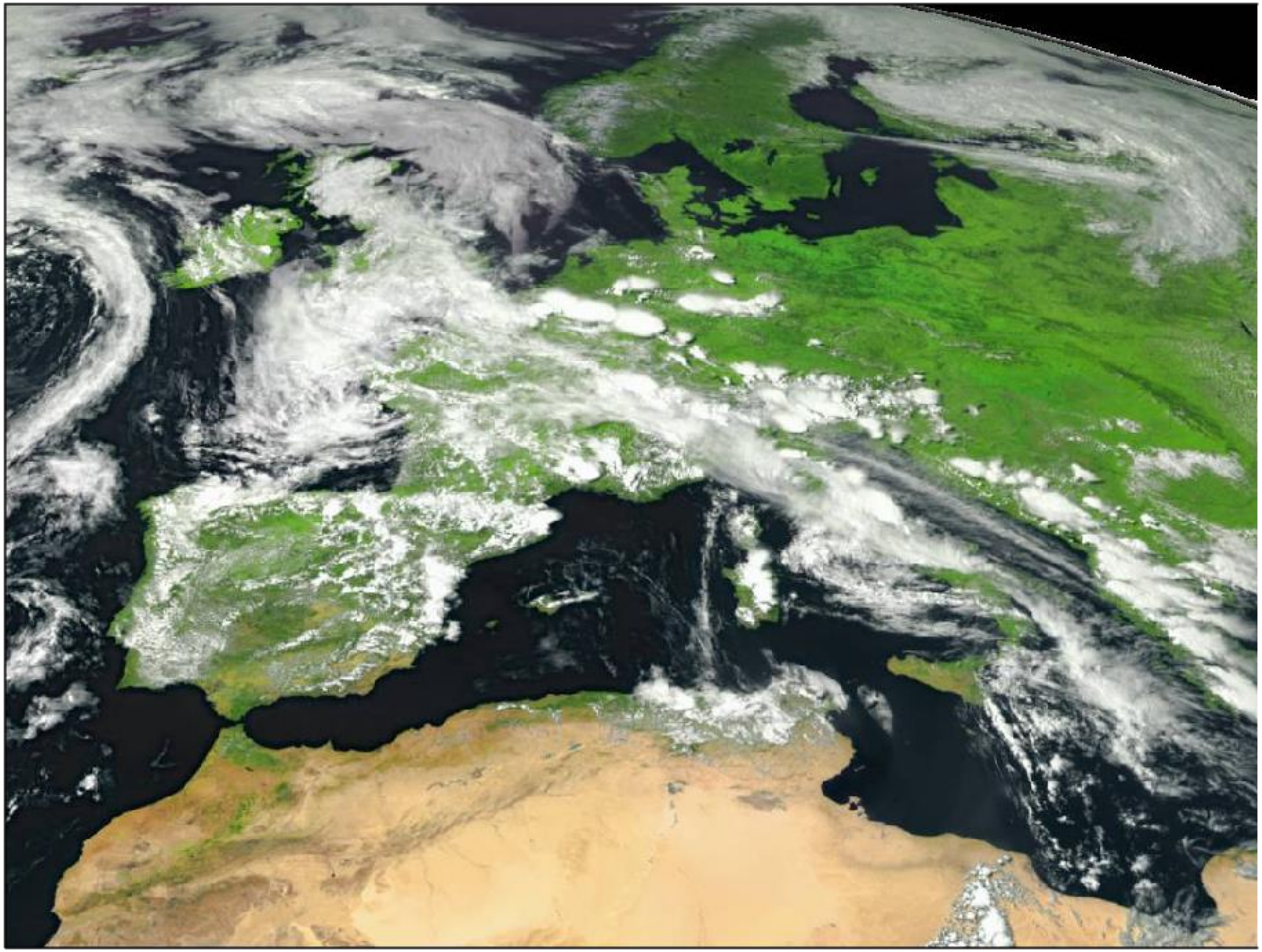


Geostationary, high temporal sampling

Detecting clouds

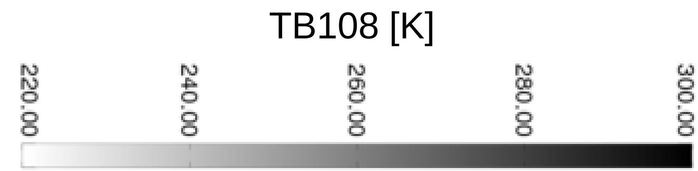
We need contrast between clouds and other objects to be able to detect clouds in imagery!

CM SAF / FU Berlin SEVIRI RGB image – 20080602 1345 UTC

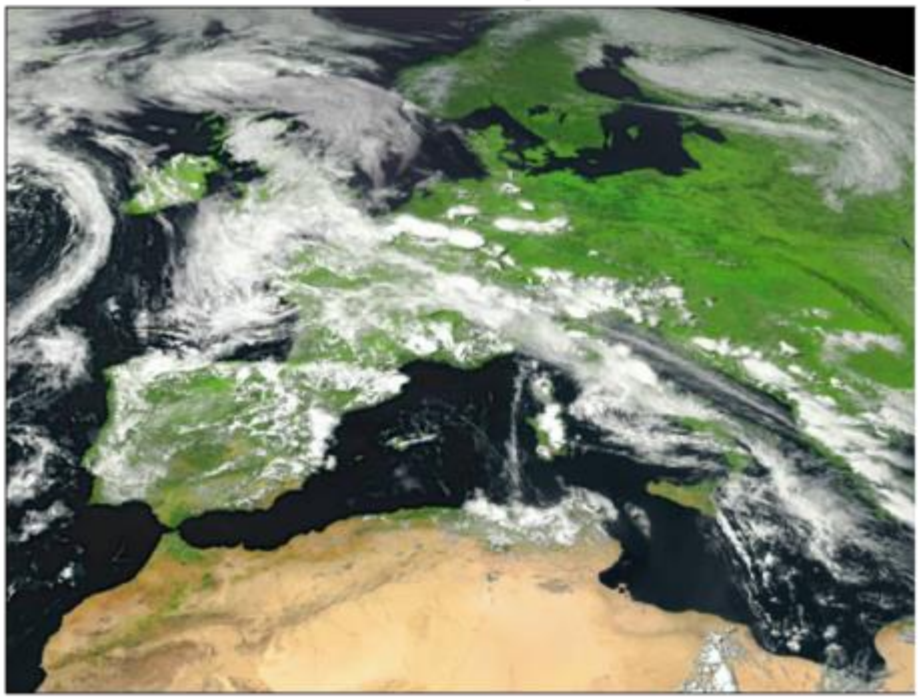


Detecting clouds

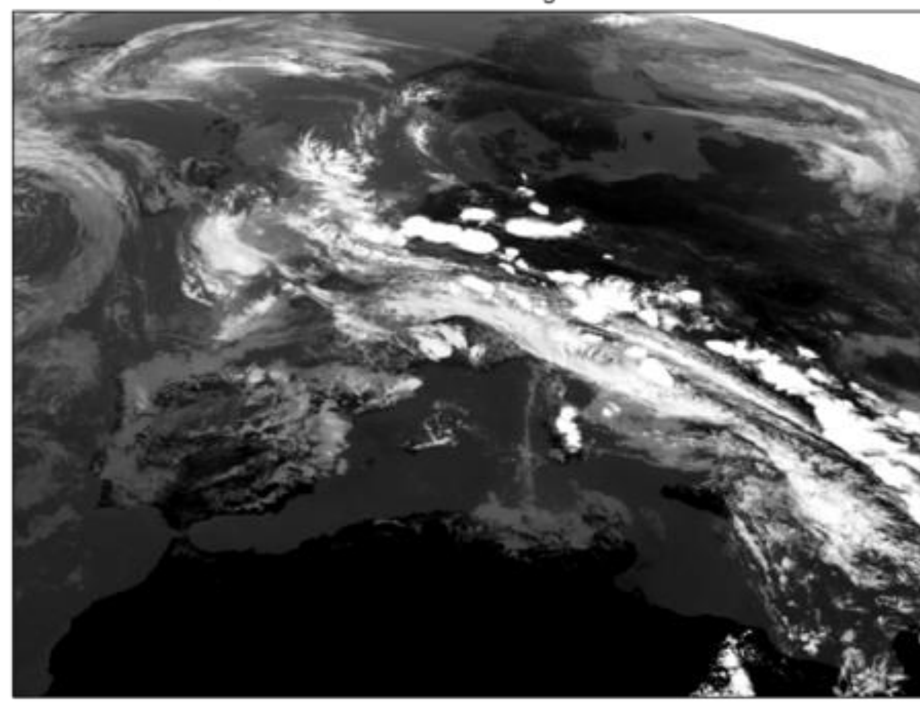
- We identify clouds by their ability to reflect sunlight and by the temperature of their cloud tops, i.e., their brightness in visible and thermal imagery!
- We need contrast between clouds and other objects to be able to detect clouds in imagery!



CM SAF / FU Berlin SEVIRI RGB image – 20080602 1345 UTC



CM SAF / FU Berlin SEVIRI IR108 image – 20080602 1345 UTC



Detecting clouds

Cloud features potentially used in cloud screening procedure:

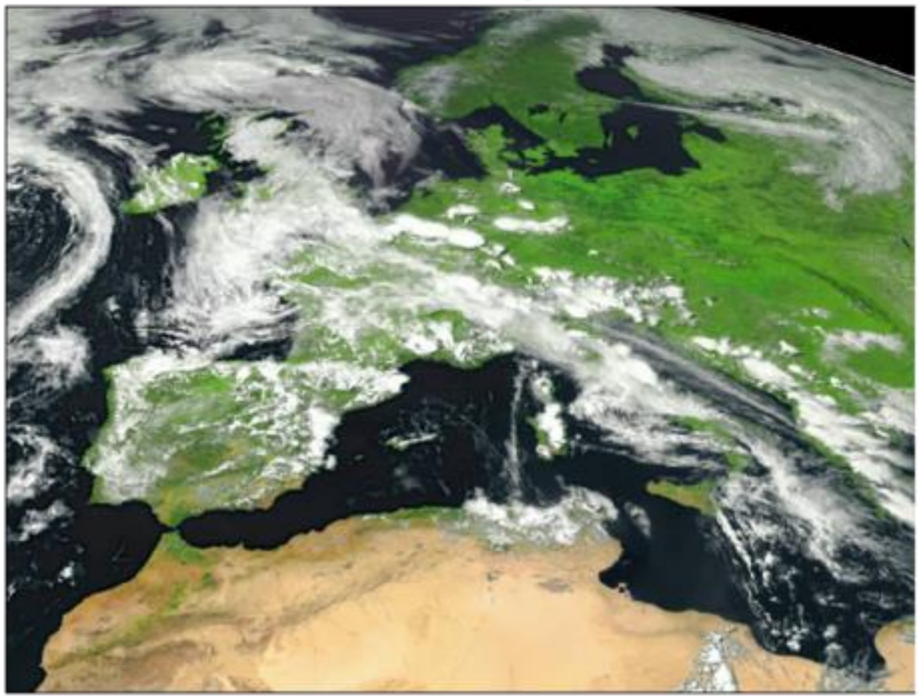
- Clouds are brighter than Earth surfaces in visible channels
- Clouds are colder than Earth surfaces in infrared channels
- Water clouds reflect radiation at short-wave infrared channels (1.6 micron and 3.7 micron) while Earth surfaces do not reflect
- Thin ice clouds are less transparent at longer infrared wavelengths, i.e., cirrus can be detected using difference between 11 and 12 micron channels
- Water clouds at night are not black-bodies in 3.7 micron channel, i.e., can be detected using difference between 3.7 and 11 micron

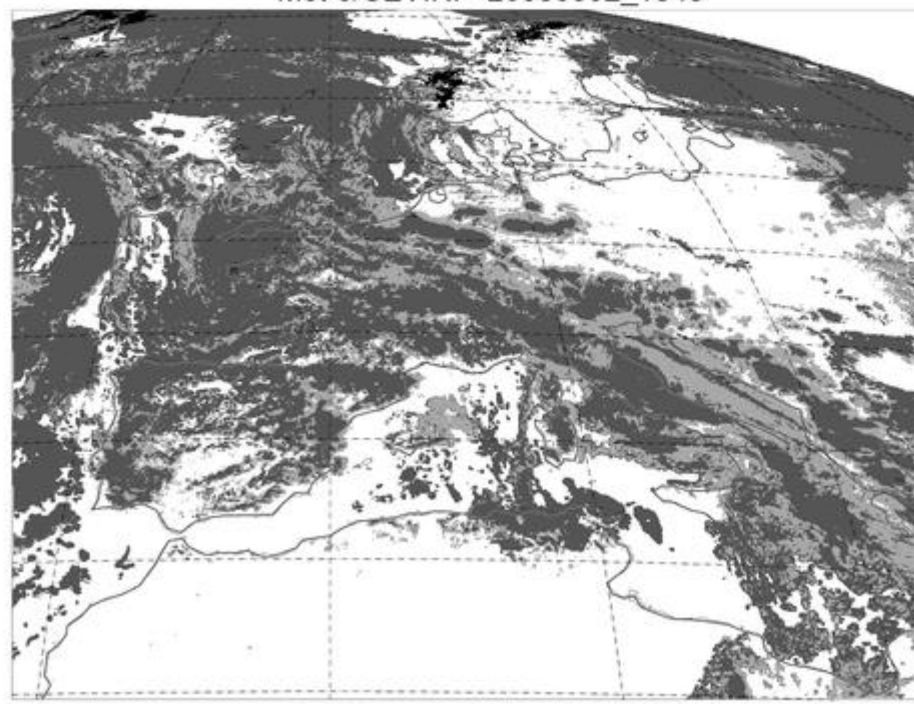
Potential methodology (threshold procedure) to implemented detection:

- Multispectral thresholding, i.e., a pixel is labeled cloudy if radiances exceed thresholds in a number spectral channels or channel combinations (e.g. radiance differences)
- Thresholds depend on illumination conditions, viewing angles and the atmospheric background state (taken from NWP)
- For several tests, thresholds are based on simulations of radiances from cloud-free surfaces (needs NWP data)

Detecting clouds

- Cloud mask example for SEVIRI





More information can be found:

- NWC-MSGv2010-ATBD (2010)

Detecting clouds

Which clouds might potentially be undetected?

1. Bright clouds over bright surfaces, e.g., over snow-covered or desert surfaces

2. Cold clouds over cold surfaces, e.g. over almost all polar surfaces in the polar winter + thin cirrus clouds over snow-covered surfaces

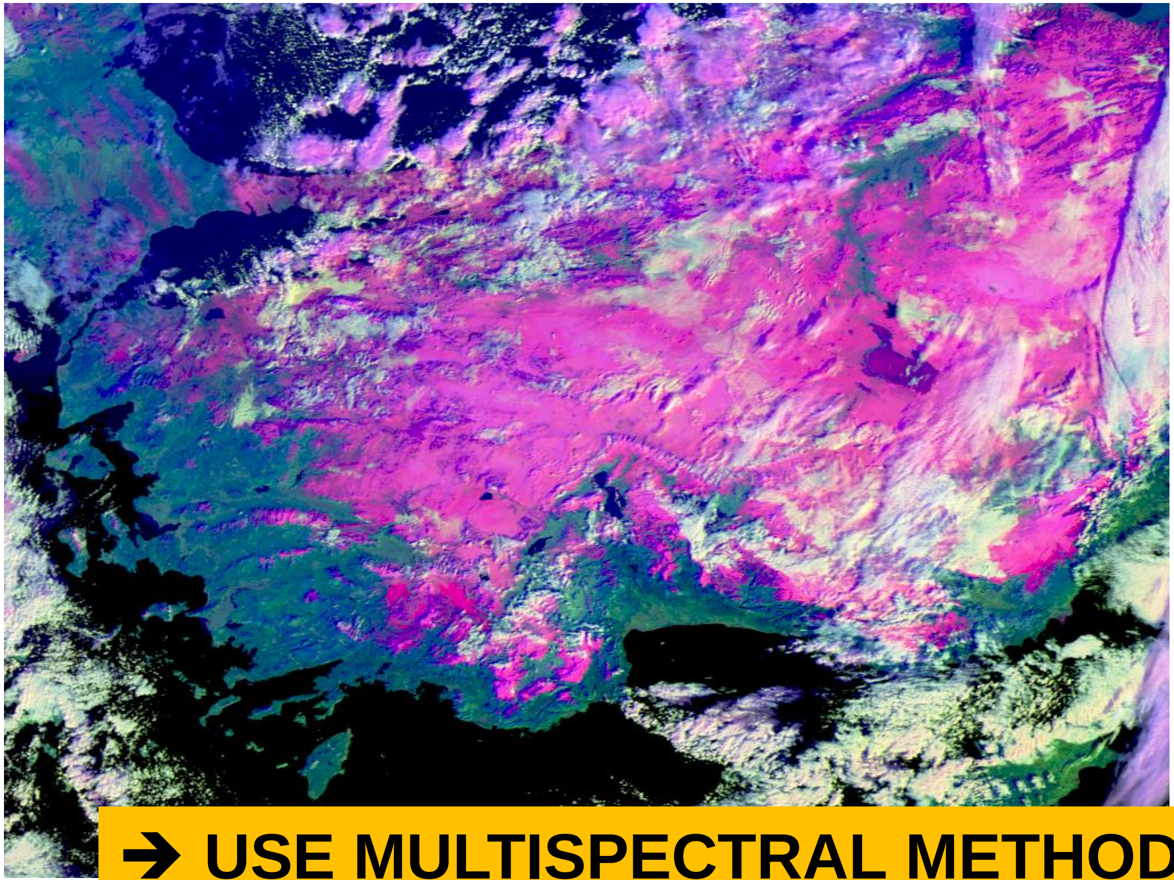
3. Extreme cases: Low clouds are warmer than the surface (e.g., stratus clouds over the Arctic ocean in polar summer)

…

Detecting clouds

Use differences in the appearance of clouds in different spectral channels!

Example below over Turkey: Clouds over snow-cover (magenta) can 'easily' be detected if utilising that they reflect in the 1.6 micron channel while snow is not!!!



Metop-A RGB Composite

17 January 2012
VIS0.6, NIR1.6, IR11.0
07:49:00 UTC

➔ USE MULTISPECTRAL METHODS!!!

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Cloud properties – cloud top height/pressure

Cloud height retrievals from passive imagers in space are difficult. Why?

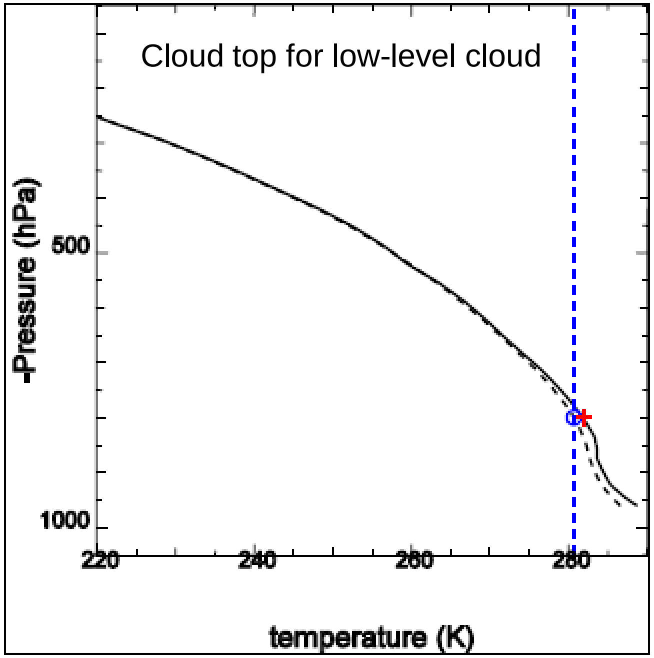
We measure the vertically integrated (i.e., along the line of sight) radiation that enters the sensor detector in space

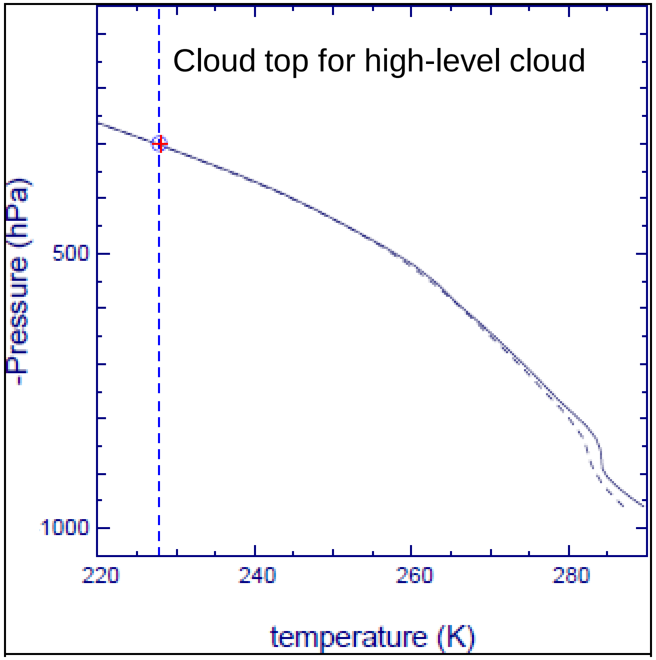
➔ If we observe a thin transparent cloud, radiation contributions come in various proportions from the cloud itself and all underlying clouds/surfaces! Even if the cloud is opaque (thus, we are able to estimate the true cloud top temperature), this temperature can often be found at several altitudes in the atmosphere (due to inversions)

Cloud properties – cloud top height/pressure

For opaque clouds
(negligible brightness temperature difference between 11 and 12 micron channels):

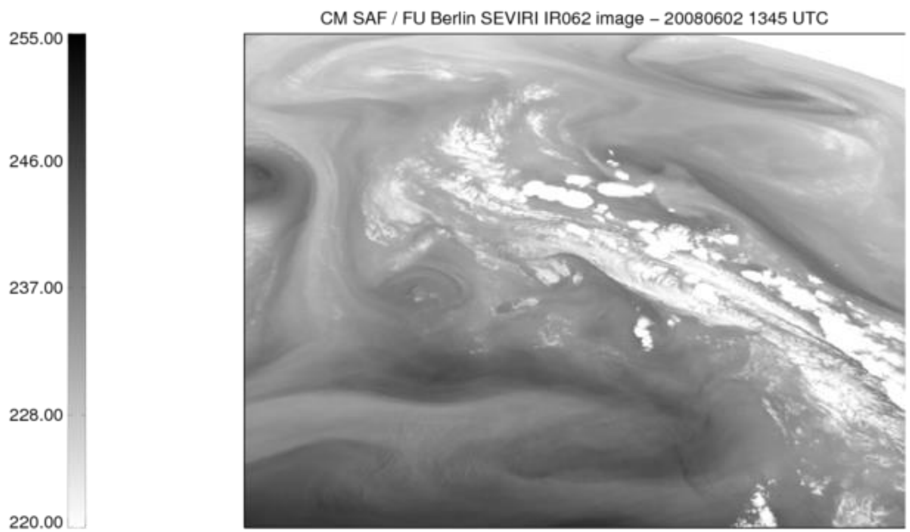
Common procedure: Matching of measured brightness temperatures (vertical dashed line) with simulated ones (dashed curve, using radiative transfer methods like RTTOV) and reference profiles from NWP (solid curve)





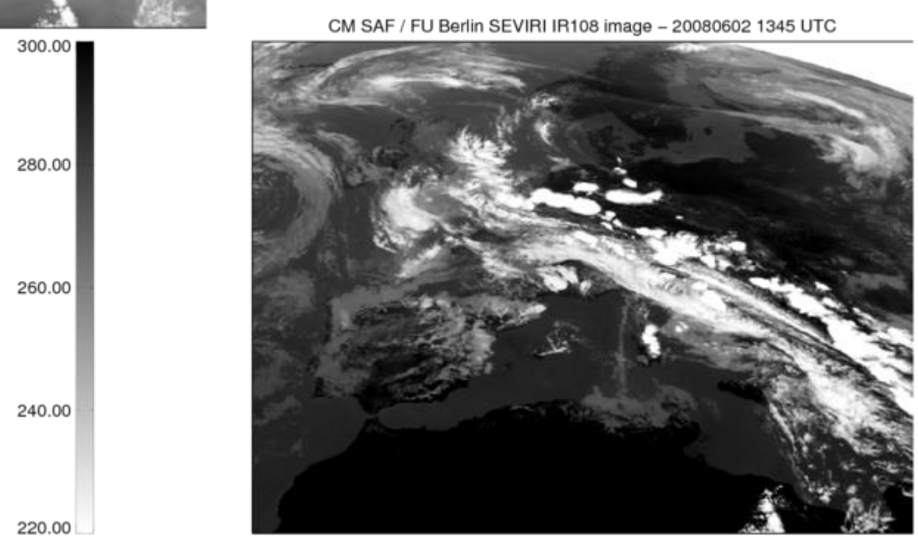
Cloud properties – cloud top height/pressure

For semi-transparent clouds: Form quotas of radiances in two channels with different transmissivities – the quota is a function of pressure in an atmosphere without temperature inversions (called Radiance Ratioing or CO_2 slicing– only applicable to instruments with sounding channel(s))



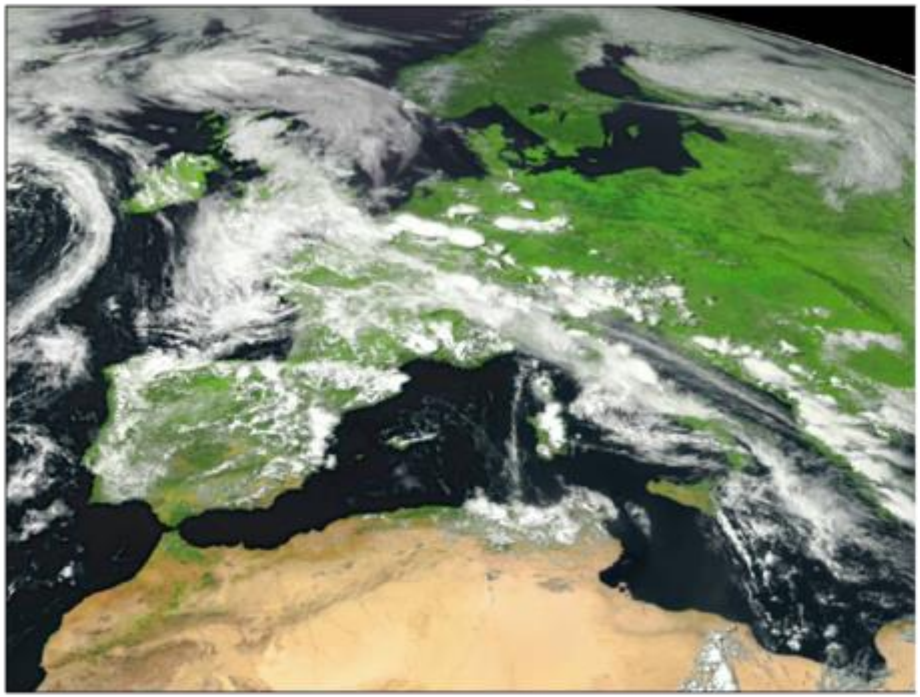
Sounding channel
(only high clouds visible)

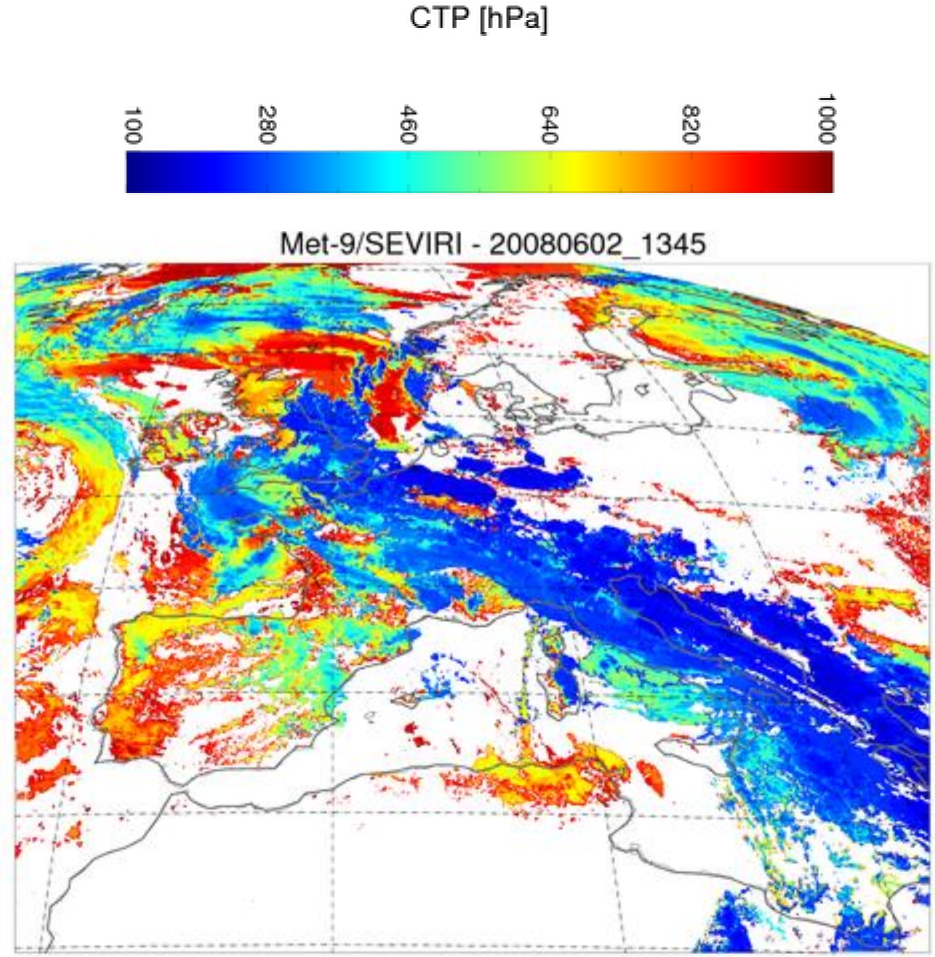
Window channel
('All' clouds visible)



Cloud properties – cloud top height/pressure

CM SAF / FU Berlin SEVIRI RGB image – 20080602 1345 UTC





More information can be found:

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Cloud microphysical/optical properties

What can we say about cloud properties on the cloud particle scale?

Some of these properties are

- Cloud Optical Thickness *= Integrated dimensionless extinction coefficient*
- Cloud Effective Radius *= Area-weighted particle size*
- Cloud Phase *= Liquid, frozen, mixed*
- Liquid Water Path *= Integrated liquid cloud condensate in* kgm^{-2}
- Ice Water Path *= Integrated frozen cloud condensate in* kgm^{-2}

Cloud microphysical/optical properties

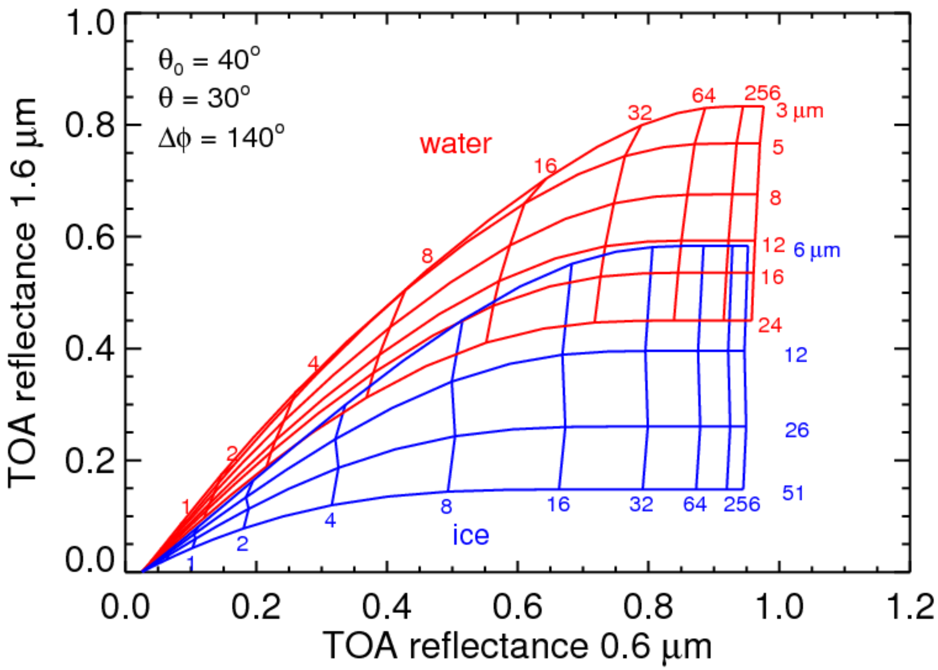
Basic principle of COT-REF retrievals:

- Reflectance of clouds at a non-absorbing wavelength in the visible region (VIS: 0.6 or 0.8 micron) is strongly related to the optical thickness
- Reflectance of clouds at an absorbing wavelength in the near-infrared region (NIR: 1.6 or 3.7 micron) is primarily related to particle effective radius
- Ice clouds absorb more (reflects less) radiation at NIR wavelengths

Radiance transfer simulations made with DAK (Doubling-Adding KNMI model)

Nakajima & King (1990)

Curves show iso optical thickness values vertically and iso effective radii horizontally

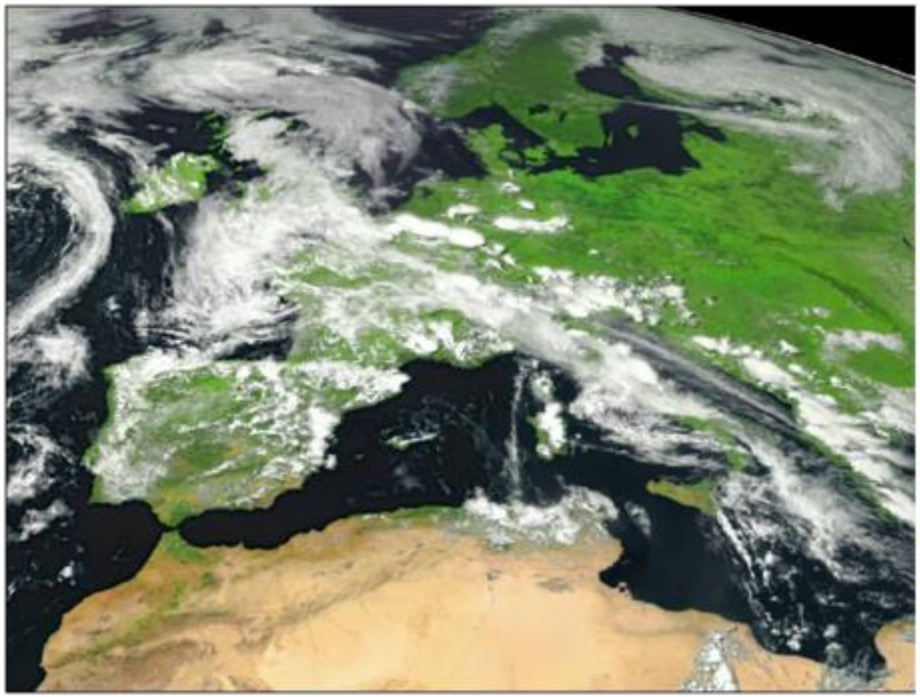


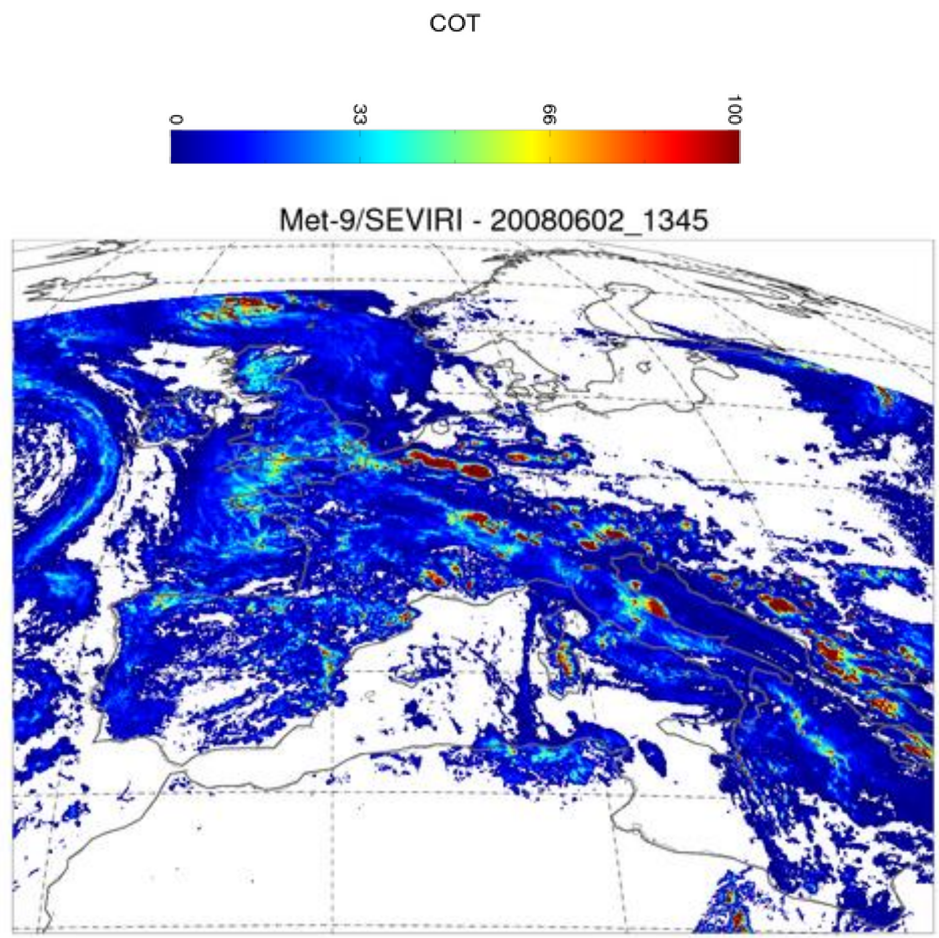
Practical implementation: Search in lookup tables (LUT) with simulated radiances for water clouds (red) and ice clouds (blue)

(Roebeling et al., 2006; CMSAF-KNMI-ATBD-SEVIRI-CPP, 2012)

Cloud microphysical properties – optical thickness

CM SAF / FU Berlin SEVIRI RGB image – 20080602 1345 UTC





More information can be found:

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Retrievals of effective radius and cloud optical thickness are only possible during daytime!

Cloud microphysical/optical properties

Computation of liquid (LWP) or ice water (IWP) paths:

Products derived from optical thickness τ and effective radius re using the following parameterisation

$$LWP = A\,\tau r_e\,\rho_l$$

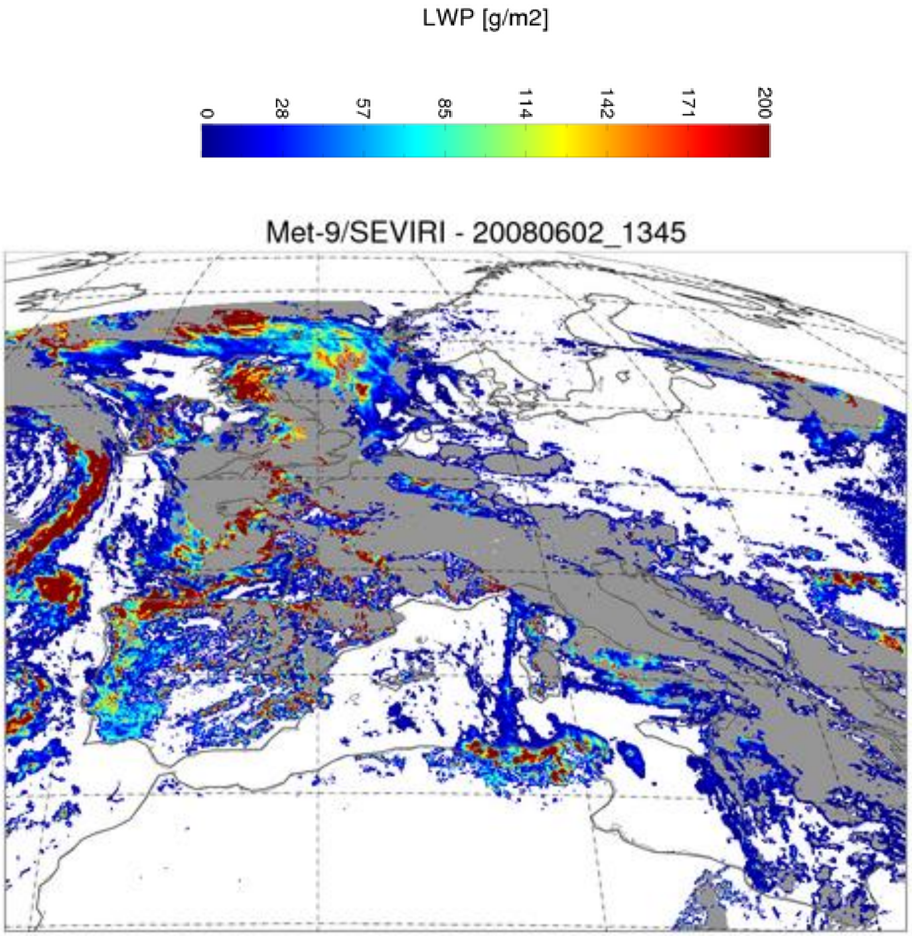
$$IWP = A\,\tau r_e\,\rho_i$$

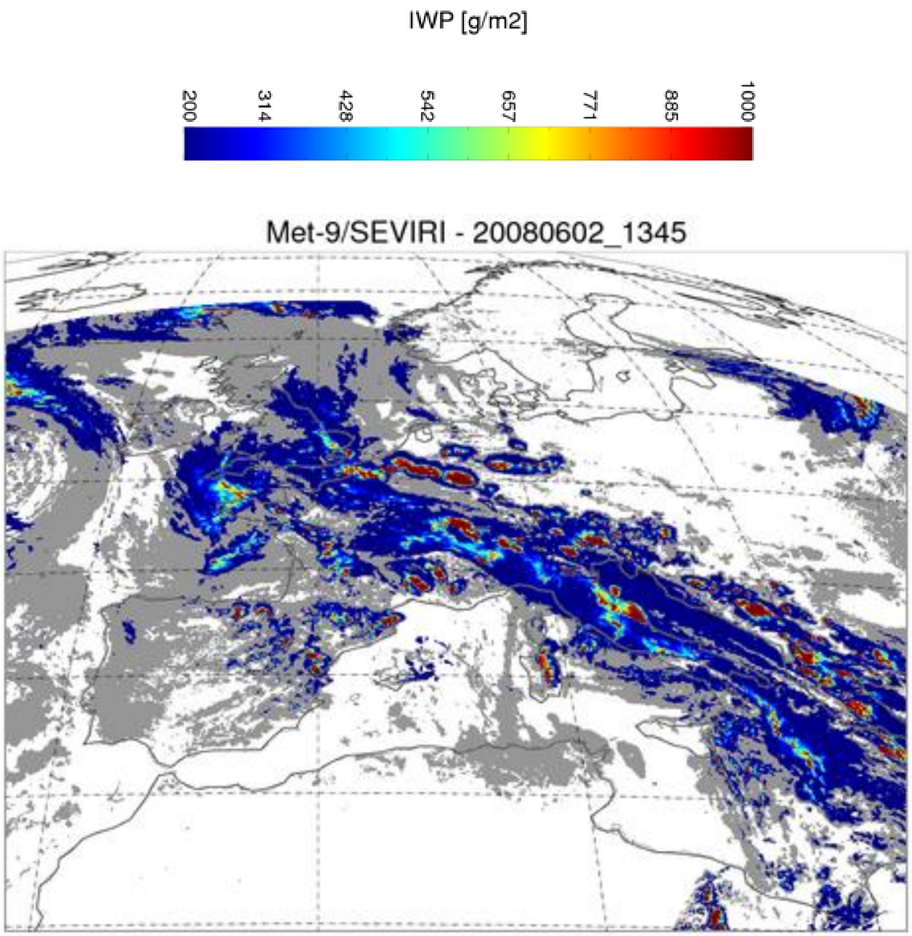
where ρ is density of water/ice (Stephens, 1978) and A = 2/3 (vertically homogeneous) or 5/9 (adiabatically stratified).

Alternative formula for IWP (Heymsfeld, 2003):

$$IWP = \frac{1}{0.065}\,\tau^{\frac{1}{0.84}}$$

Cloud microphysical/optical properties





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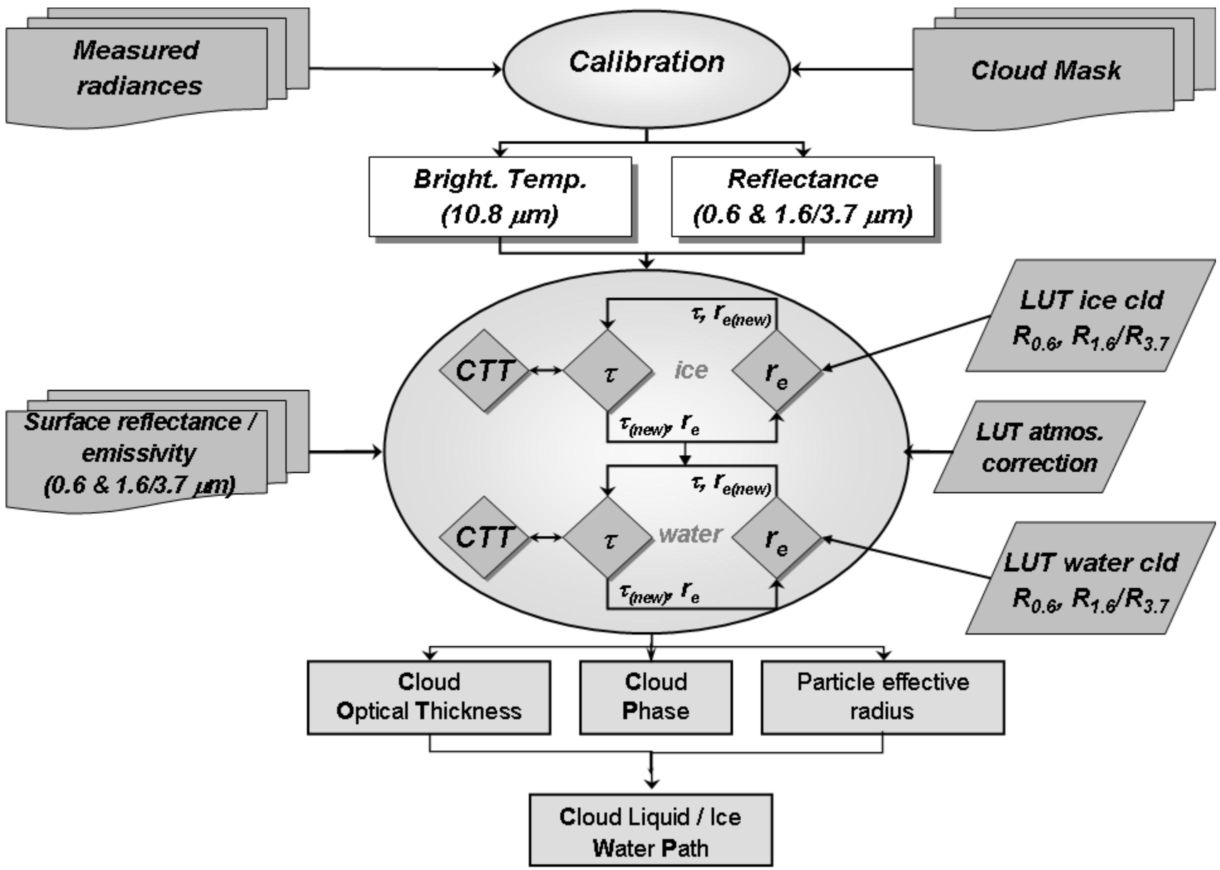
Cloud microphysical/optical properties

Flow chart for Cloud Physical Products (CPP) algorithm (Roebeling, 2006)



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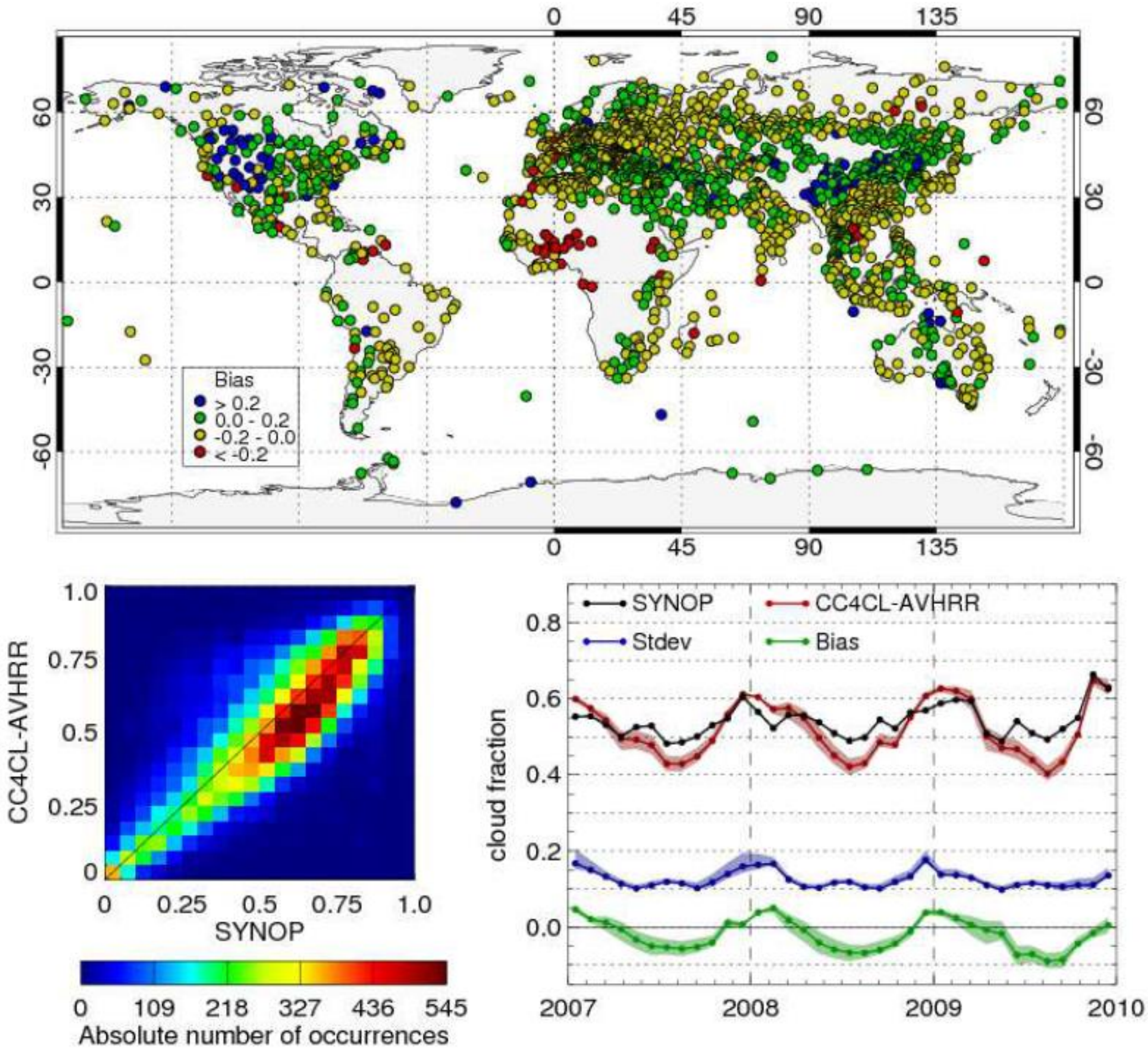
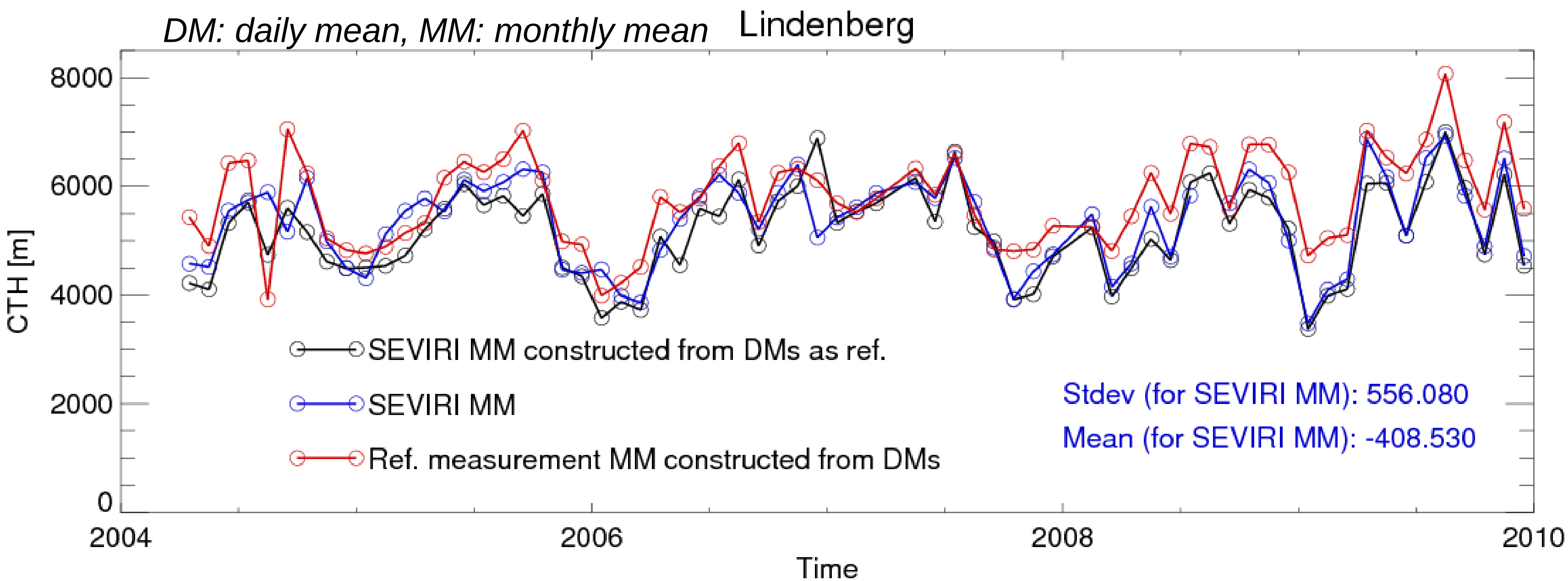
Validation (ground-based reference)

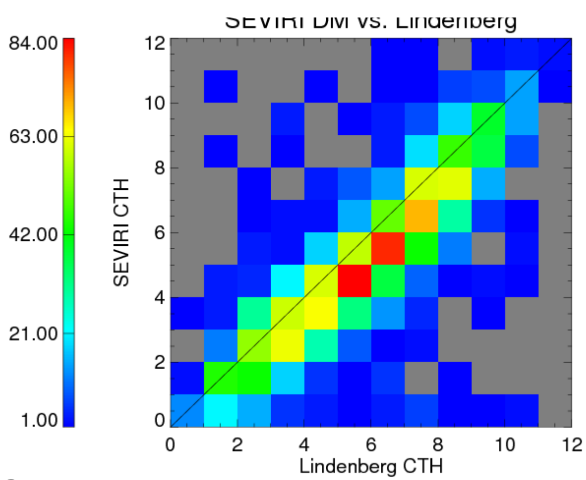
- Validation of CFC vs. SYNOP

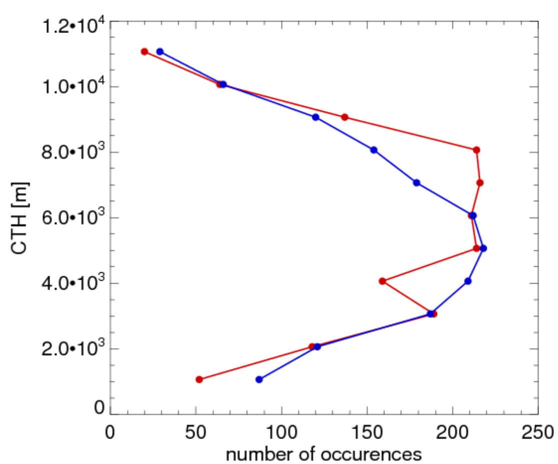


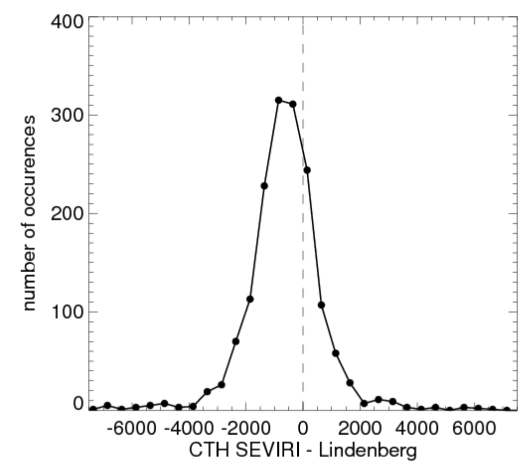
Validation (ground-based reference)

- Validation of CTH vs. 35.5 GHz cloud radar (MIRA 36)

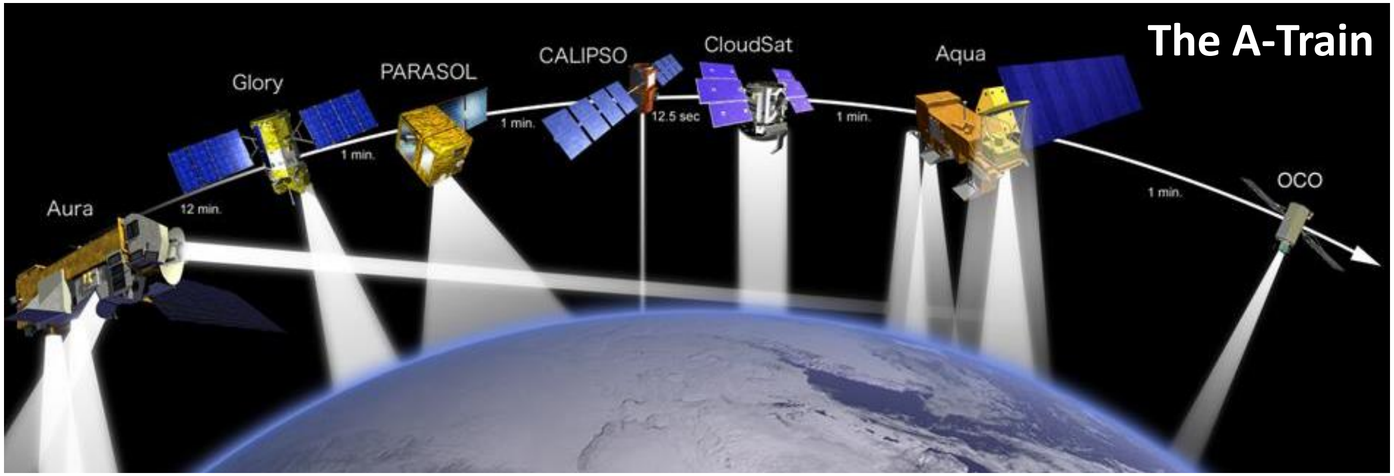








Validation (e.g. using active A-Train instruments)



Here, difficulties often occur wrt. representativness and spatial and temporal matching of different observations (types

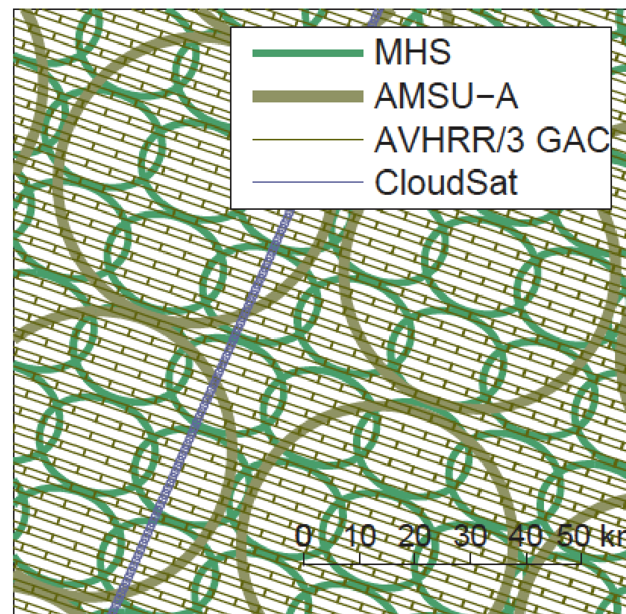
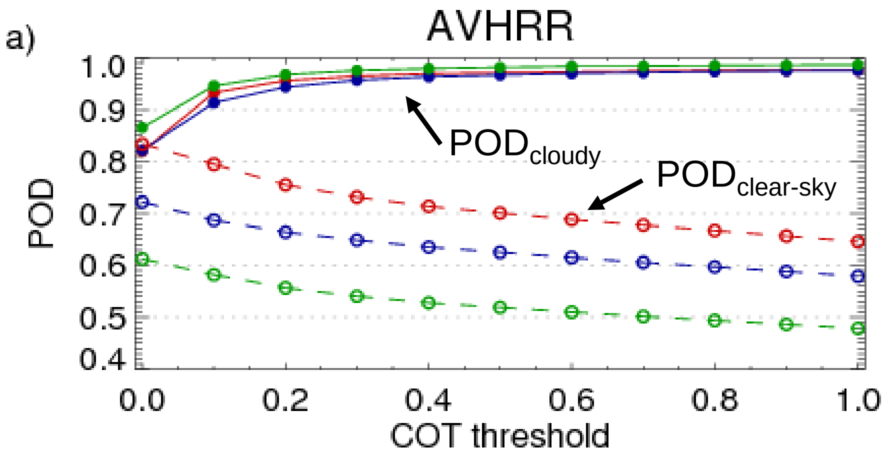
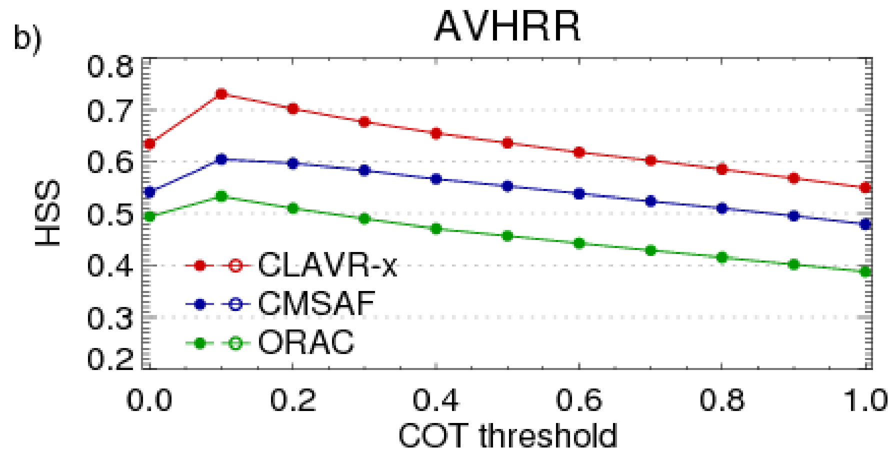


Figure 1. Illustration of footprint sizes for a selection of instruments.

Validation (e.g. using active A-Train instruments)

- Reference data:
  CALIPSO CAL_LID_L2_05kmCLay-Prov-V3-01 (Feature Classification Flag as **cloud mask**; Feature Optical Depth for 532 nm for **optical depth**)
- Assessing the sensitivity of cloud mask agreement wrt. COT





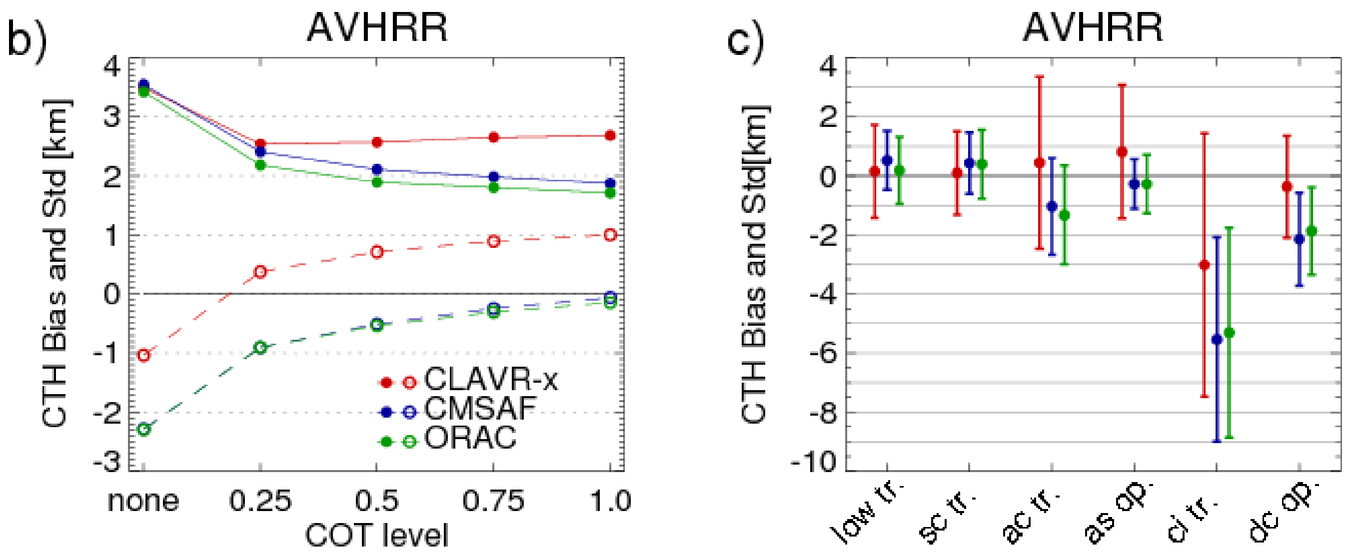
Stengel et al. (2013)

	AVHRR		
	CLAVR-x	CM SAF	ORAC
POD-cloudy	0.82	0.82	0.87
POD-clear	0.83	0.72	0.61
HSS	0.63	0.54	0.49
HSS (COT > 0.1)	0.73	0.60	0.53

Table: Cloud mask evaluation scores (given as probability of detection, POD, and Heidke Skill Score, HSS) for clear-sky and cloudy scenes using CALIPSO as reference for AVHRR (38,112 samples).

Validation (e.g. using active A-Train instruments)

- Reference data:
  CALIPSO CAL_LID_L2_05kmCLay-Prov-V3-01 (Feature Classification Flag for **height**; Feature Optical Depth for 532 nm for **optical depth**)
- Assessing the sensitivity of CTH agreement wrt. COT and cloud type



low tr.: low overcast transparent, sc tr: transition stratocumulus
ac. tr.: altocumulus transparent, as. op.: altostratus opaque
ci. tr.: cirrus transparent, dc. op.: deep convective opaque

Stengel et al. (2013)

Validation (e.g. using active A-Train instruments)

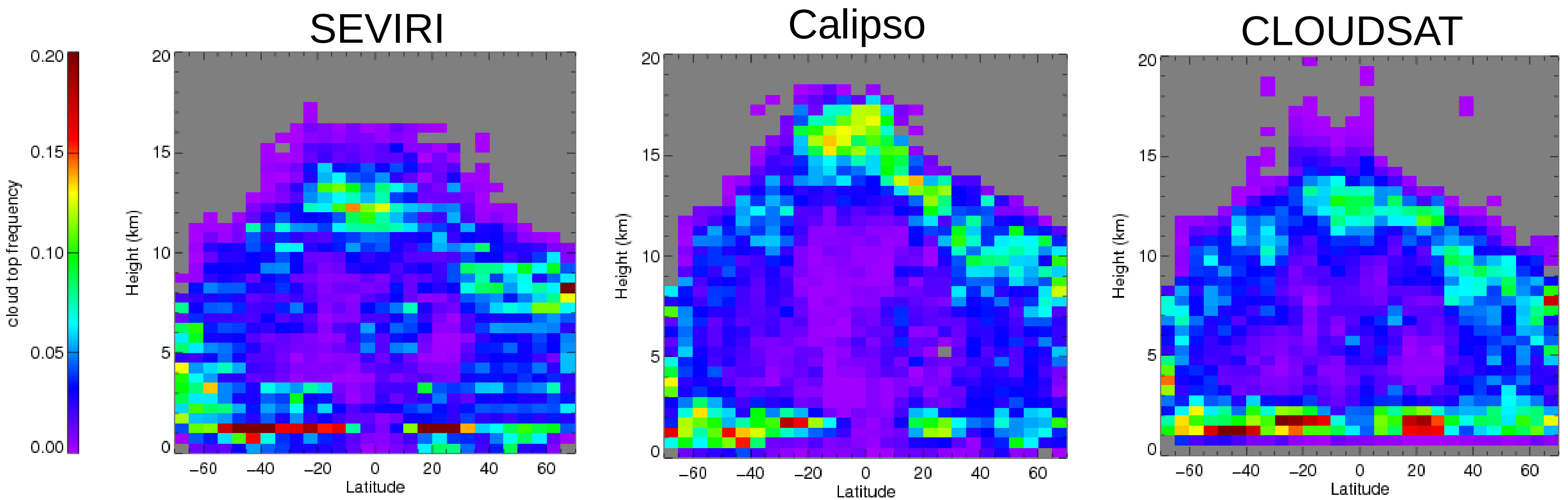


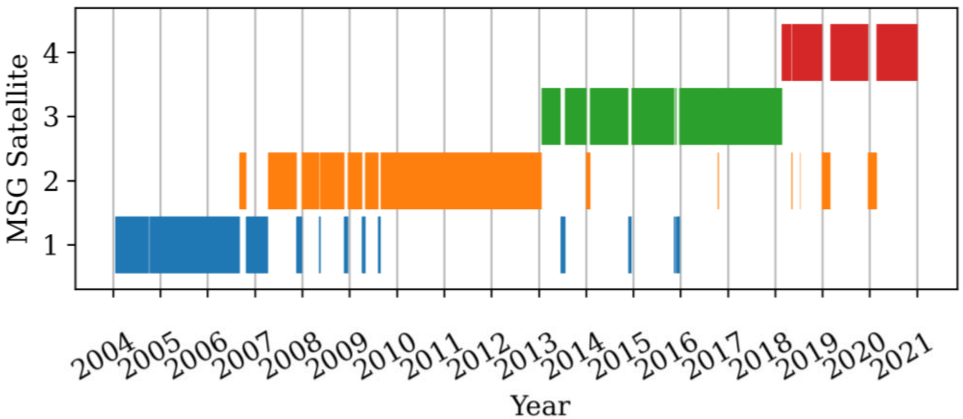
Fig 15: *Comparison of SEVIRI's CTH with Cloudsat and Calipso, based on level 2 data, original SEVIRI resolution, results for 01/2009. Upper 2 panels: Calipso, lower 2 panels: SEVIRI and Cloudsat (average over longitudes covered by SEVIRI).*

Outline

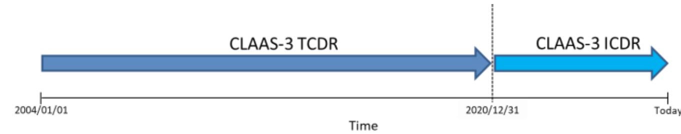
- Role of clouds in the climate system
- Detecting clouds using satellite sensors
- (Some) cloud properties that can be (are) inferred from satellite measurements
- Validation
- Cloud property datasets
- Application examples
- Summary
- *Projects*

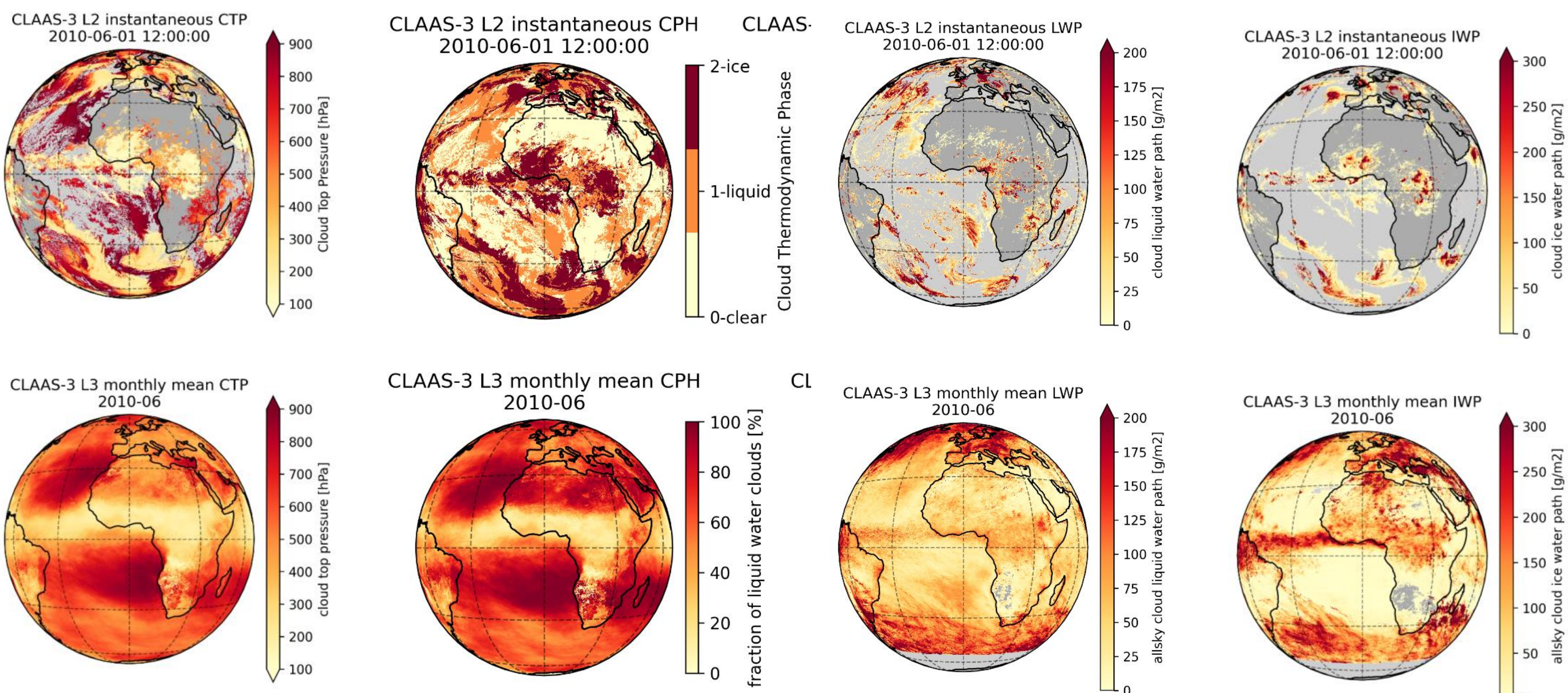
CM SAF cloud data records – CLAAS-3

CLAAS-3 (Benas et al., ESSD, 2023)



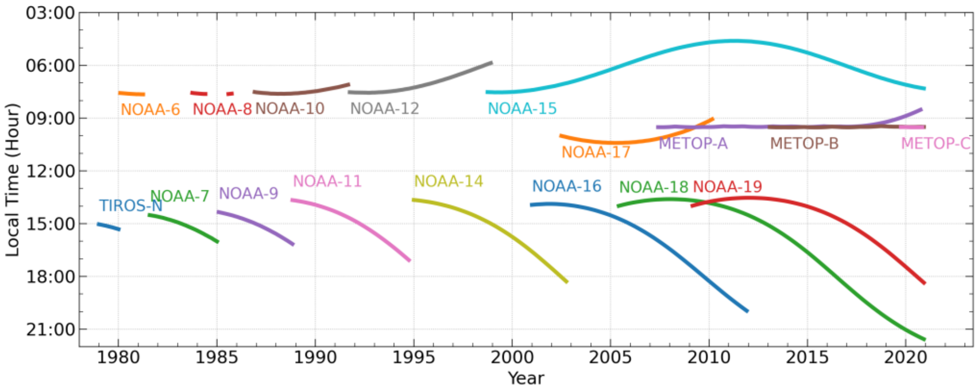
15min, Daily & monthly means: CFC (all/day/night), COT (liquid/ice), CPH, LWP, IWP, JCH



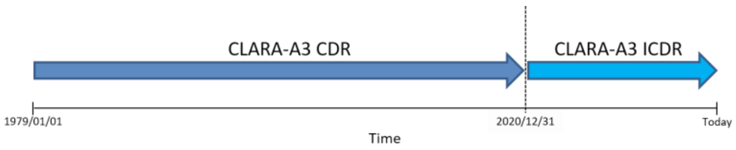


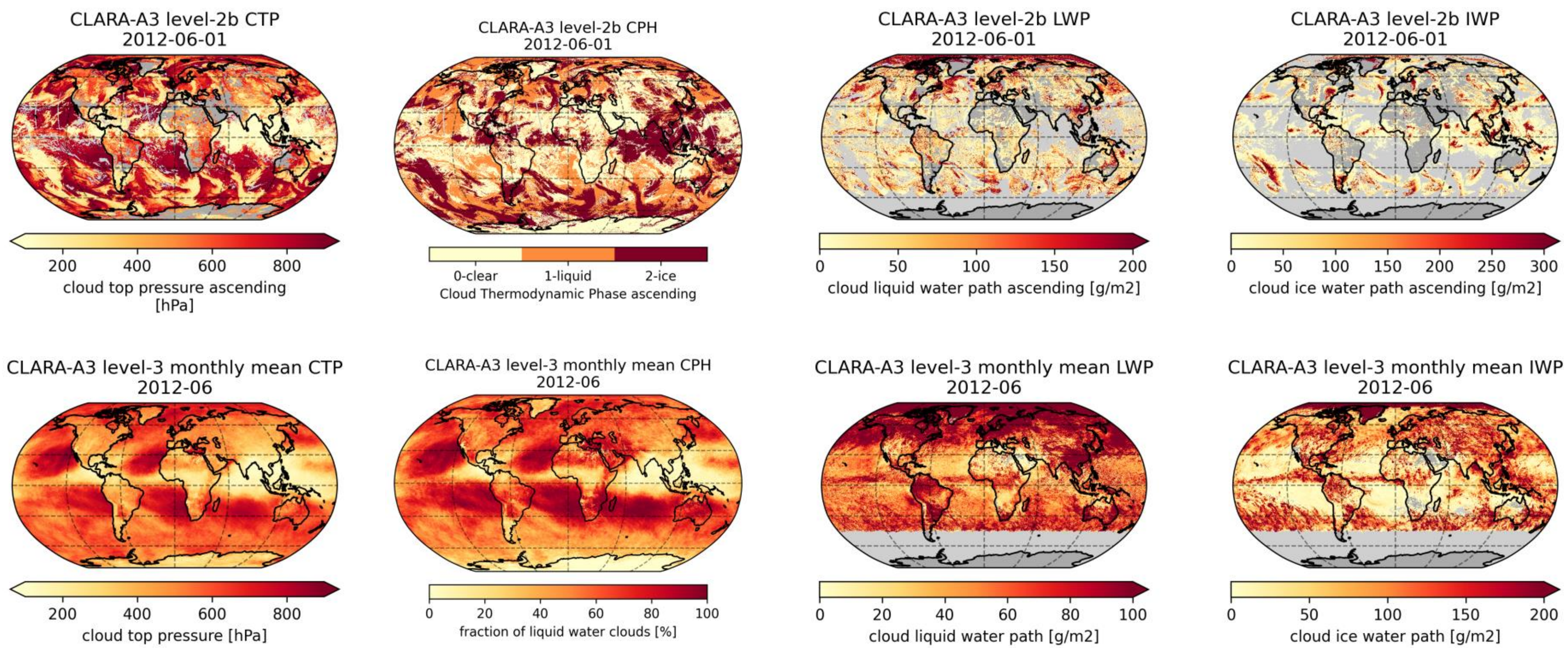
CM SAF cloud data records – CLARA-A3

(Karlsson et al., ACP, 2023)

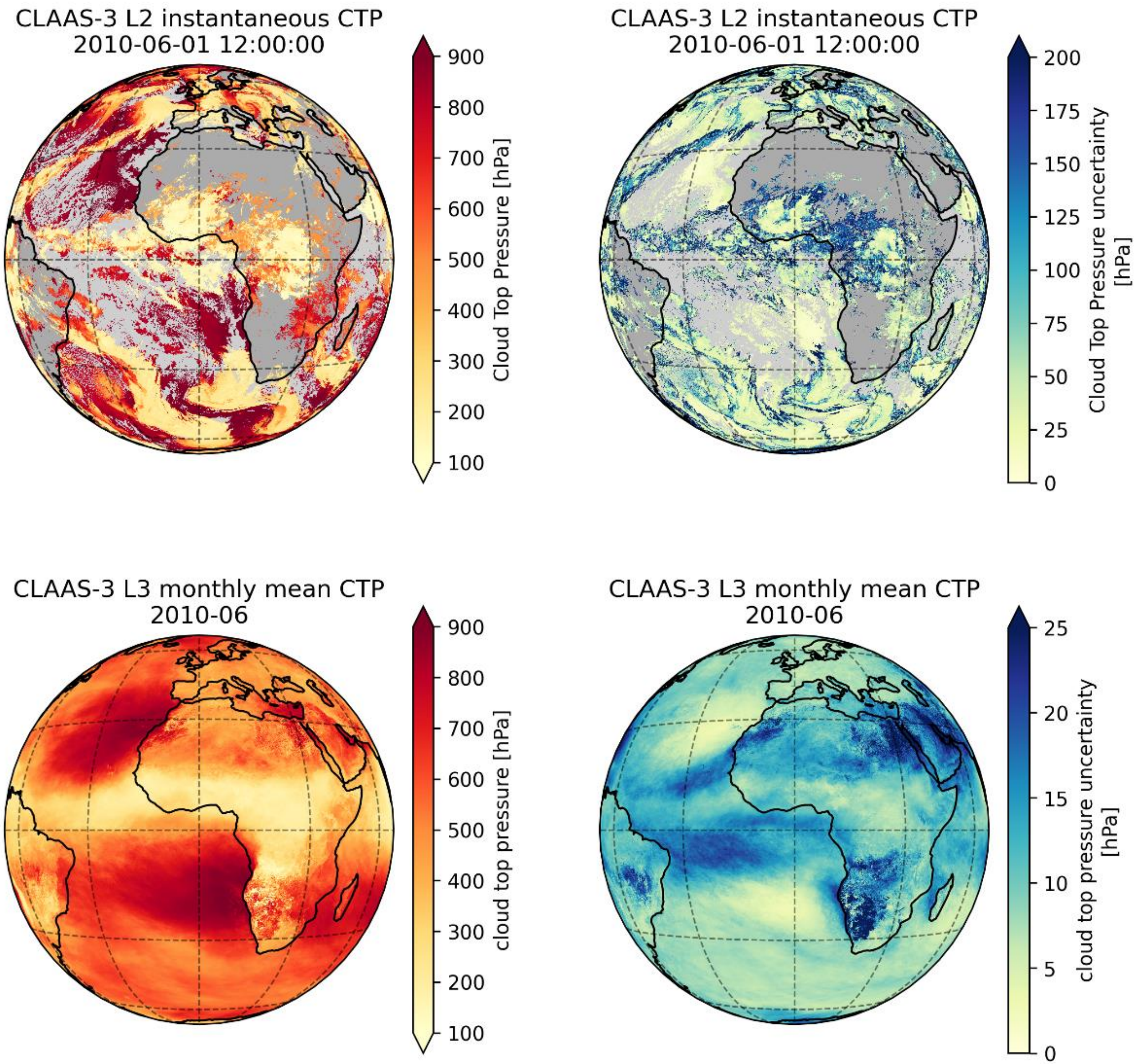


Level2b, Daily & monthly means: CFC (all/day/night), COT (liquid/ice), CPH, LWP, IWP, JCH

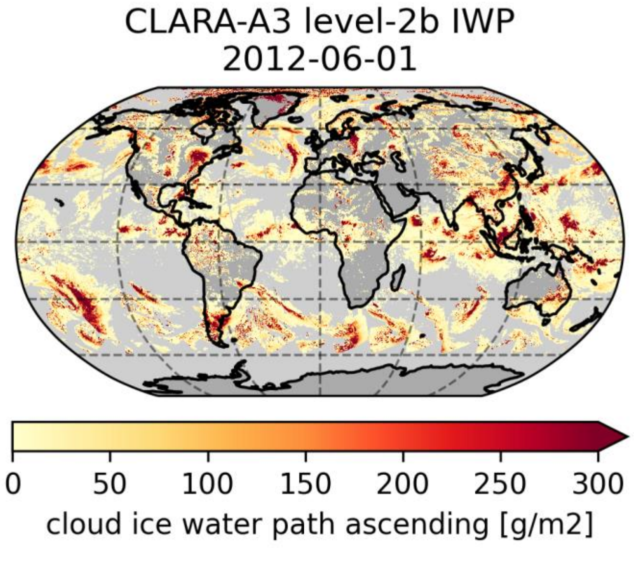


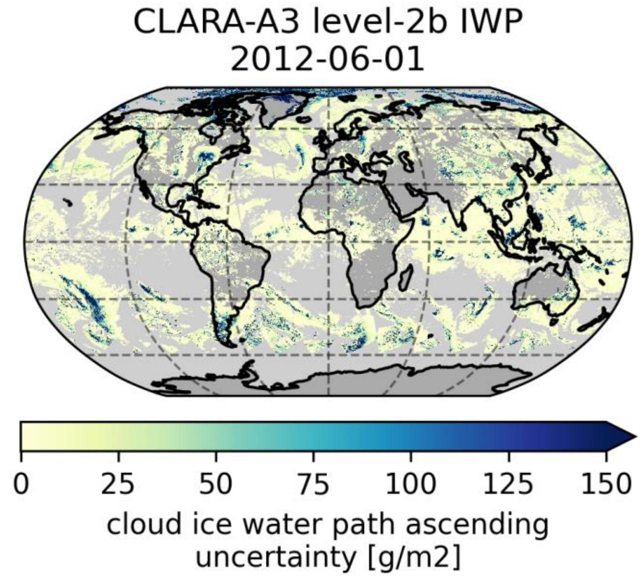


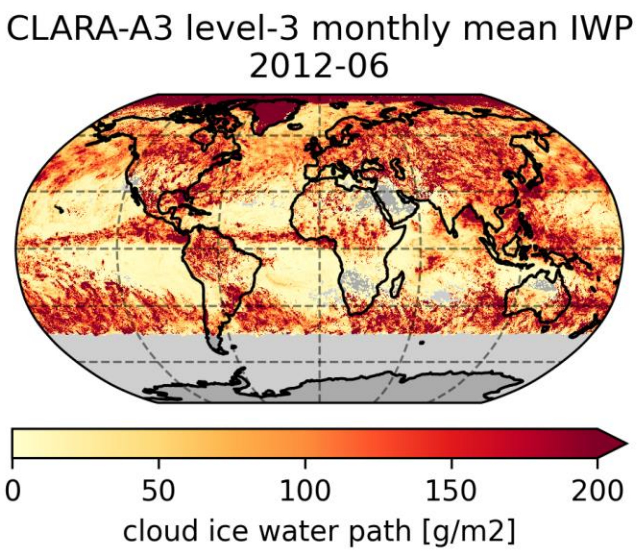
Datasets – uncertainties I

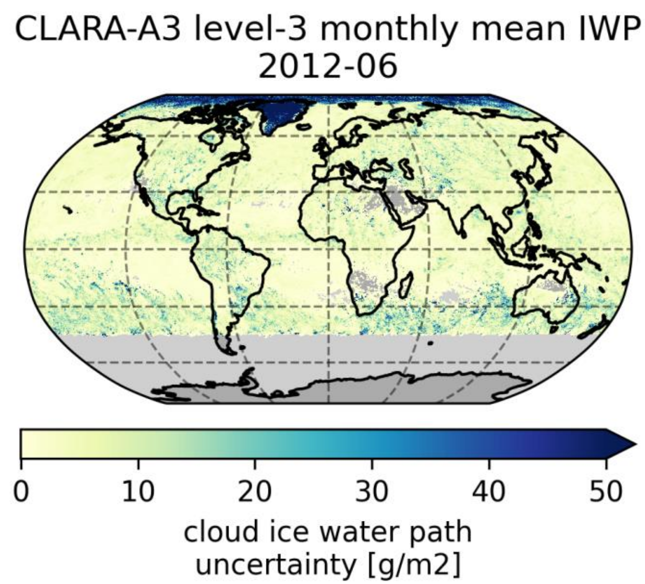


Datasets – uncertainties II

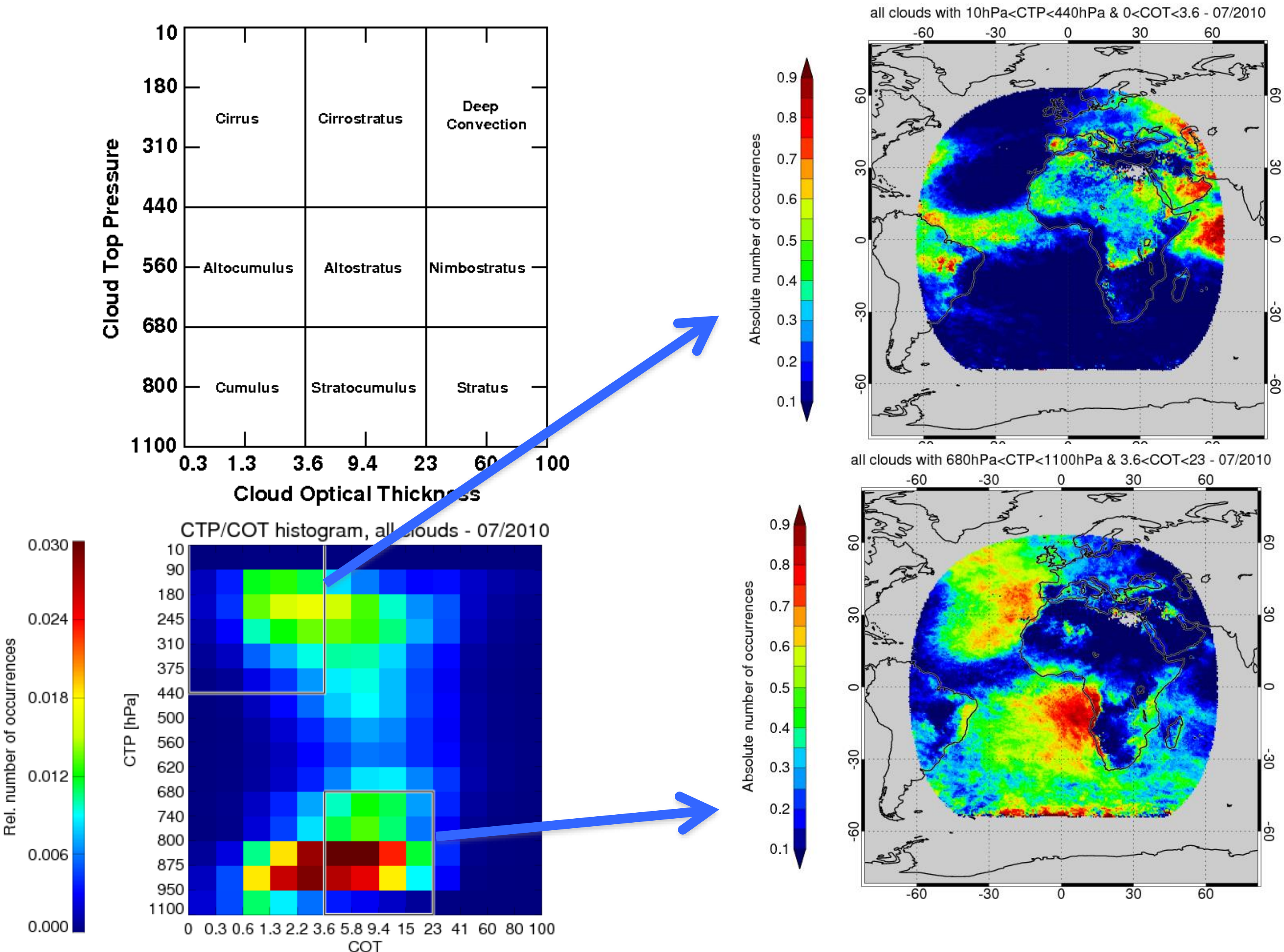








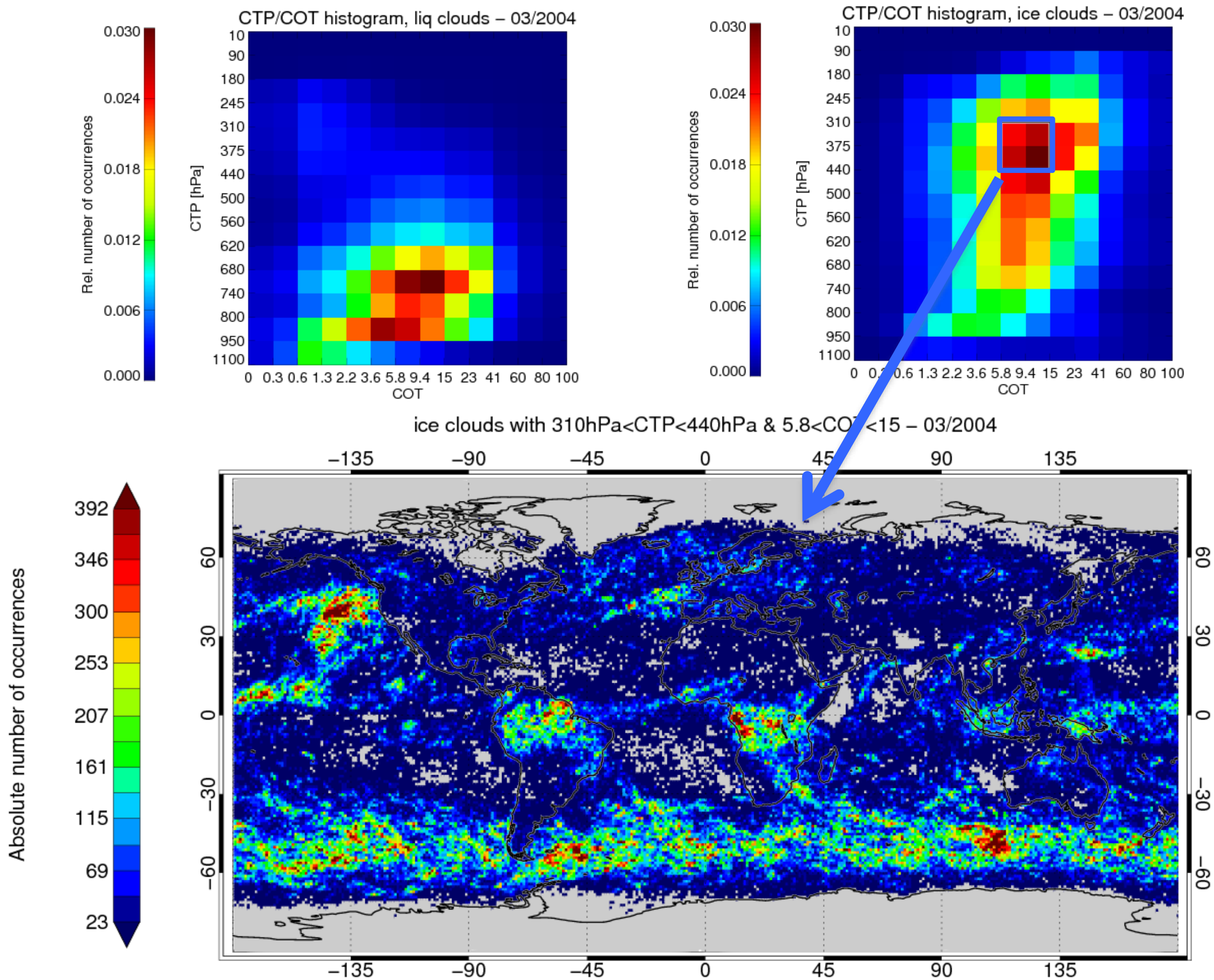
Datasets – CLAAS 2dim. COT/CTP histograms



Stengel et al. (ACP, 2014)

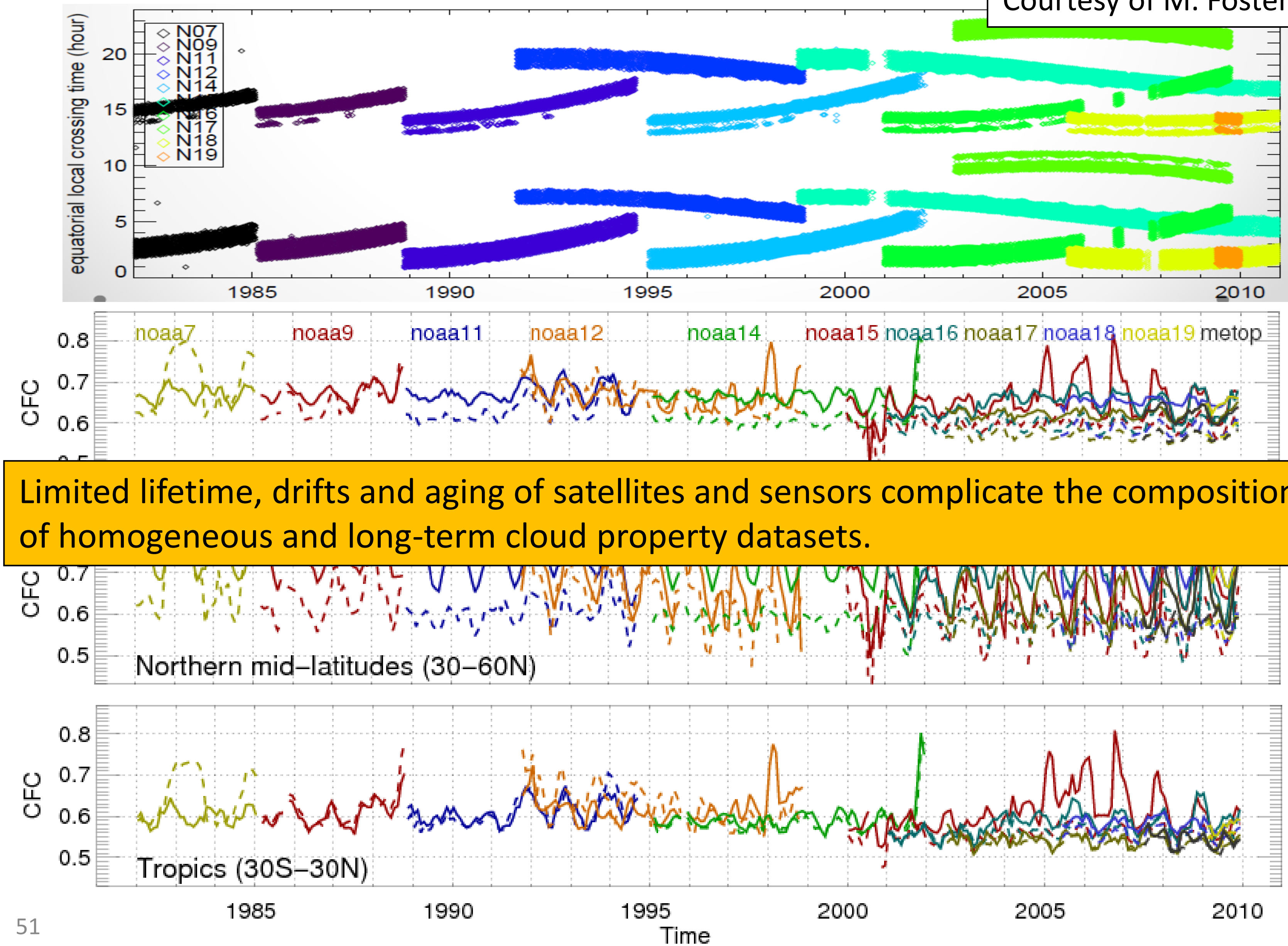
Datasets – CLARA-A1 2dim. histograms

- Joint Cloud property Histograms



Datasets - Long-term stability/homogeneity

Courtesy of M. Foster

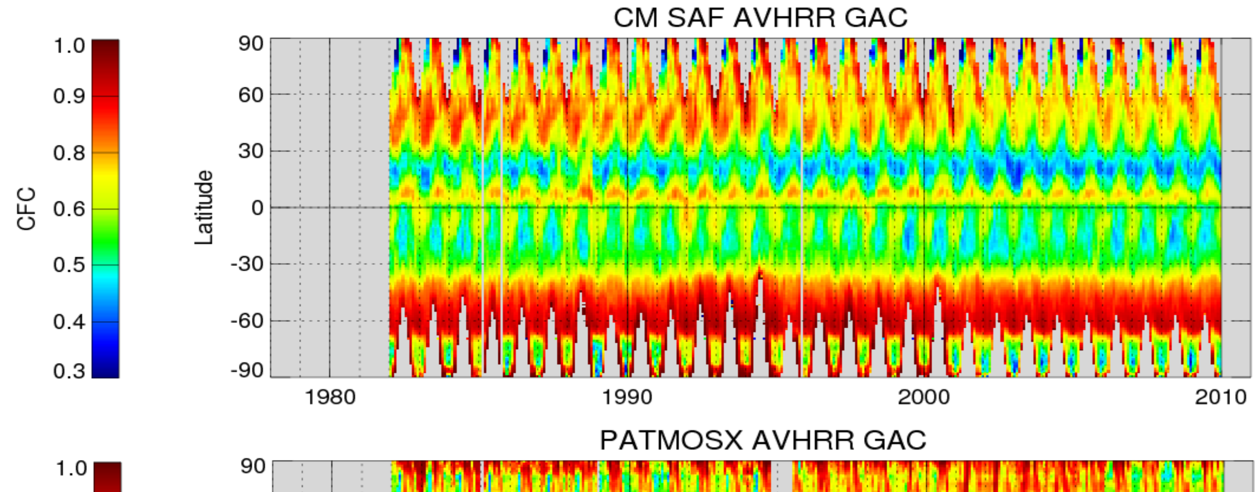


Limited lifetime, drifts and aging of satellites and sensors complicate the composition of homogeneous and long-term cloud property datasets.

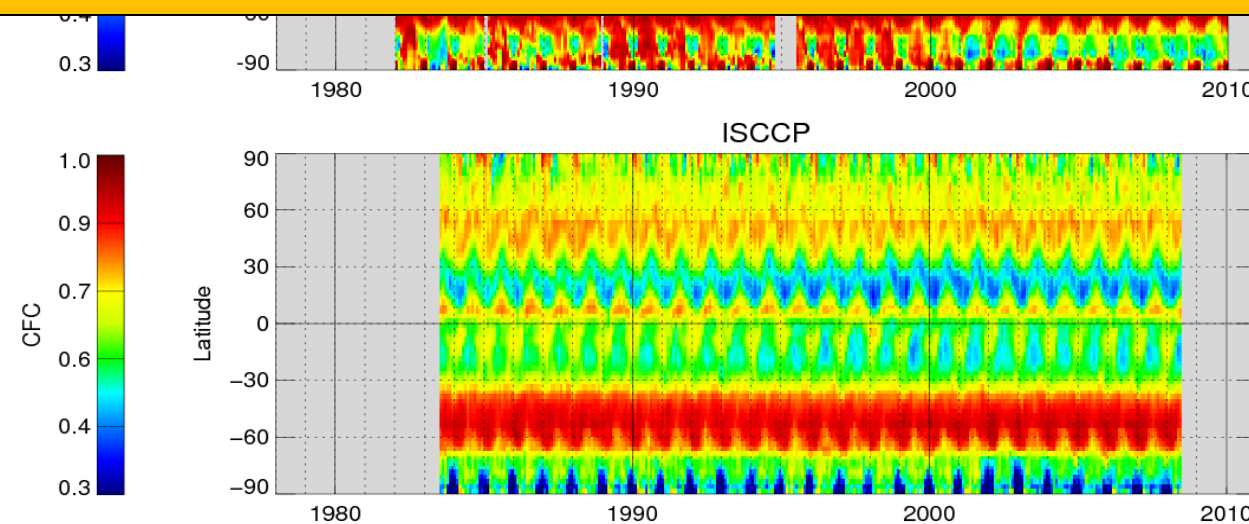
Datasets - AVHRR using cloud climatologies

- **CLARA-A1** (CMSAF cLoud, Albedo and Radiation – AVHRR based version 1), covering 1982-2009; Karlsson et al. (2013)
- **CLARA-A2** (CMSAF cLoud, Albedo and Radiation – AVHRR based version 2), covering 1982-2015; Karlsson et al. (2016)
- **Cloud_cci AVHRR-PMv3**, covering 1982-2016, Stengel et al. (2020)
- **Patmos-X v6** (AVHRR Pathfinder Atmospheres - Extended version 6), covering 1982-2012; (Heidinger et al., 2009; Heidinger et al., 2012)
- **ISCCP** (International Satellite Cloud Climatology Project), covering 1982-2008 , Rossow, W. B., & Schiffer, R. A. (1999). Note, ISCCP also uses geostationary instruments.
- …

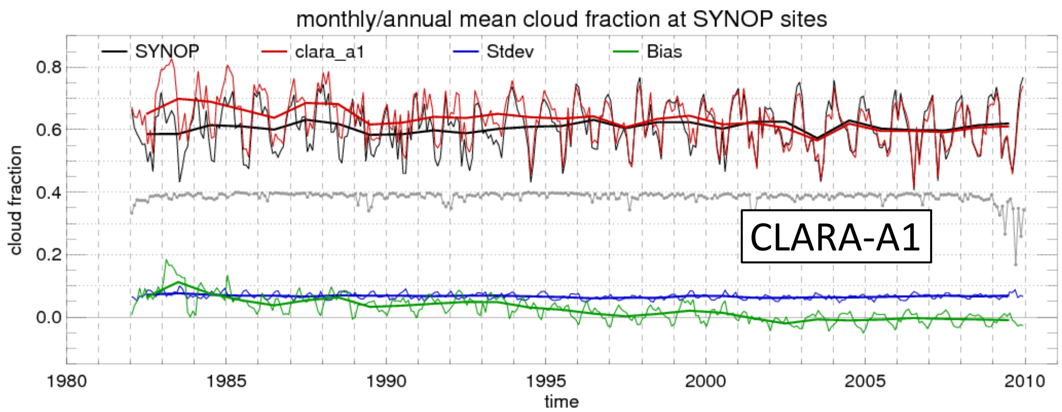
Datasets - AVHRR using cloud climatologies

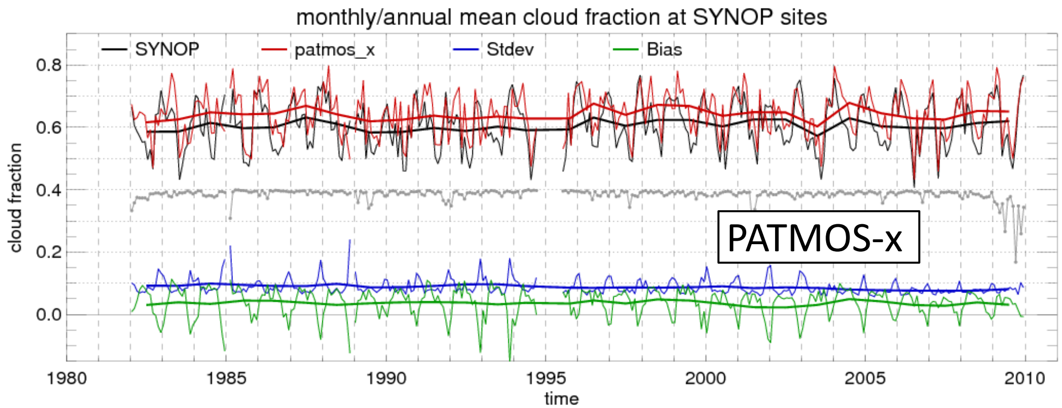


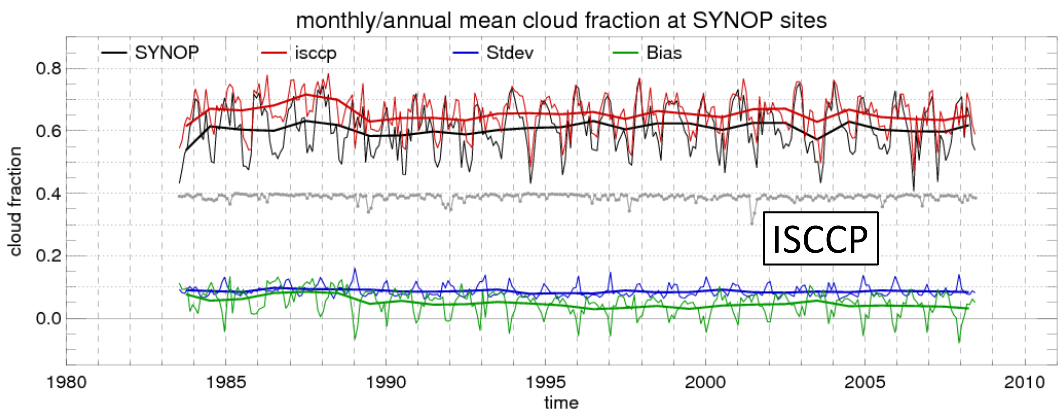
Difference in datasets, which use the same satellite sensor, are sometimes significant. These differences can among others be caused by different (inter-)calibration of the measurements, different retrieval schemes, different auxiliary data and different aggregation approaches.

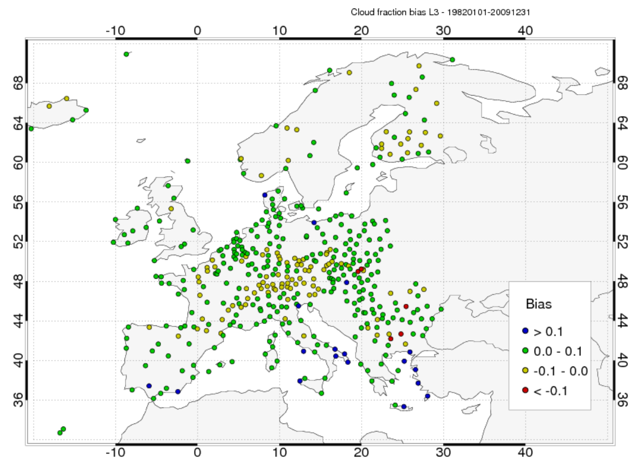


Datasets - AVHRR using cloud climatologies









Comparing cloud fraction at European SYNOP sites

Outline

- Role of clouds in the climate system
- Detecting clouds using satellite sensors
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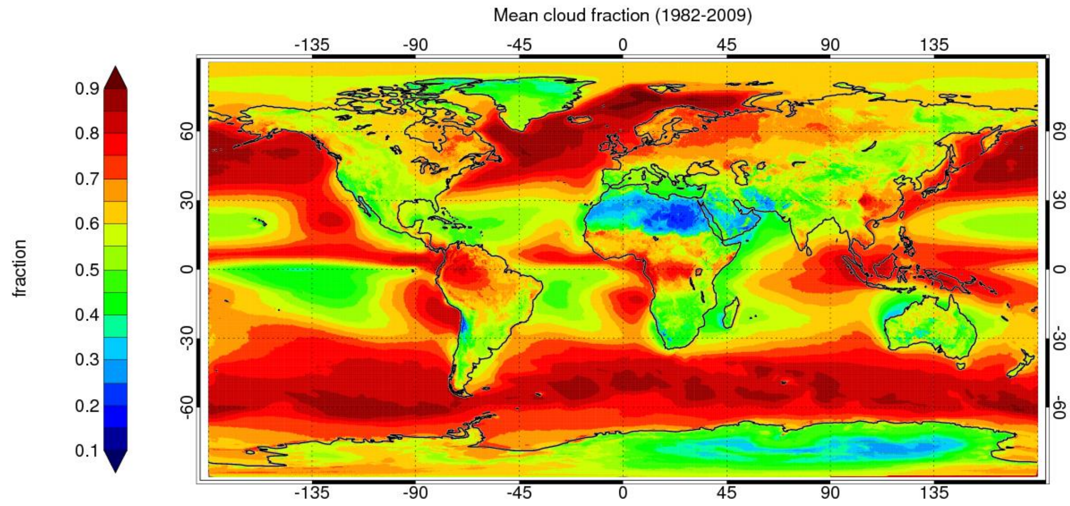
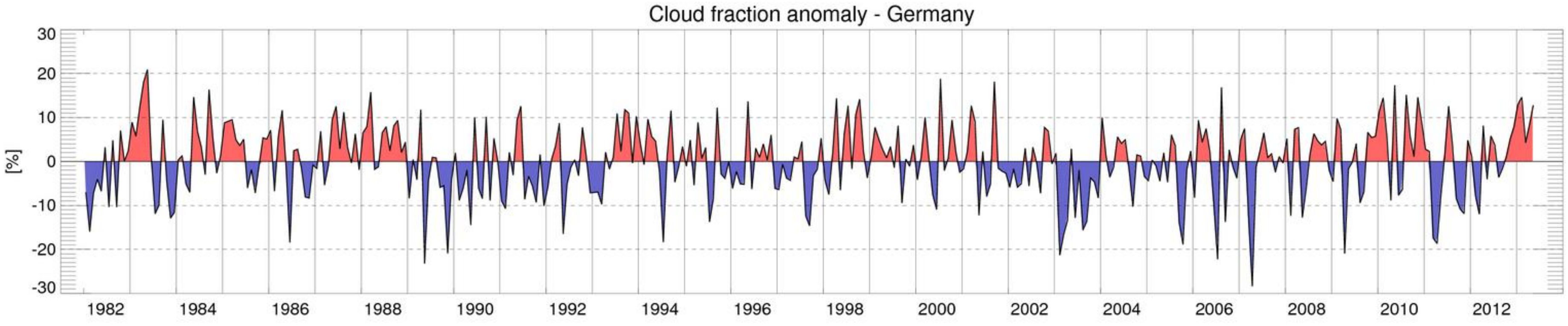
- Validation
- Cloud property datasets
- Application examples
- Summary
- *Projects*

Application (1/9): Climatological analysis

- Trend and anomaly studies

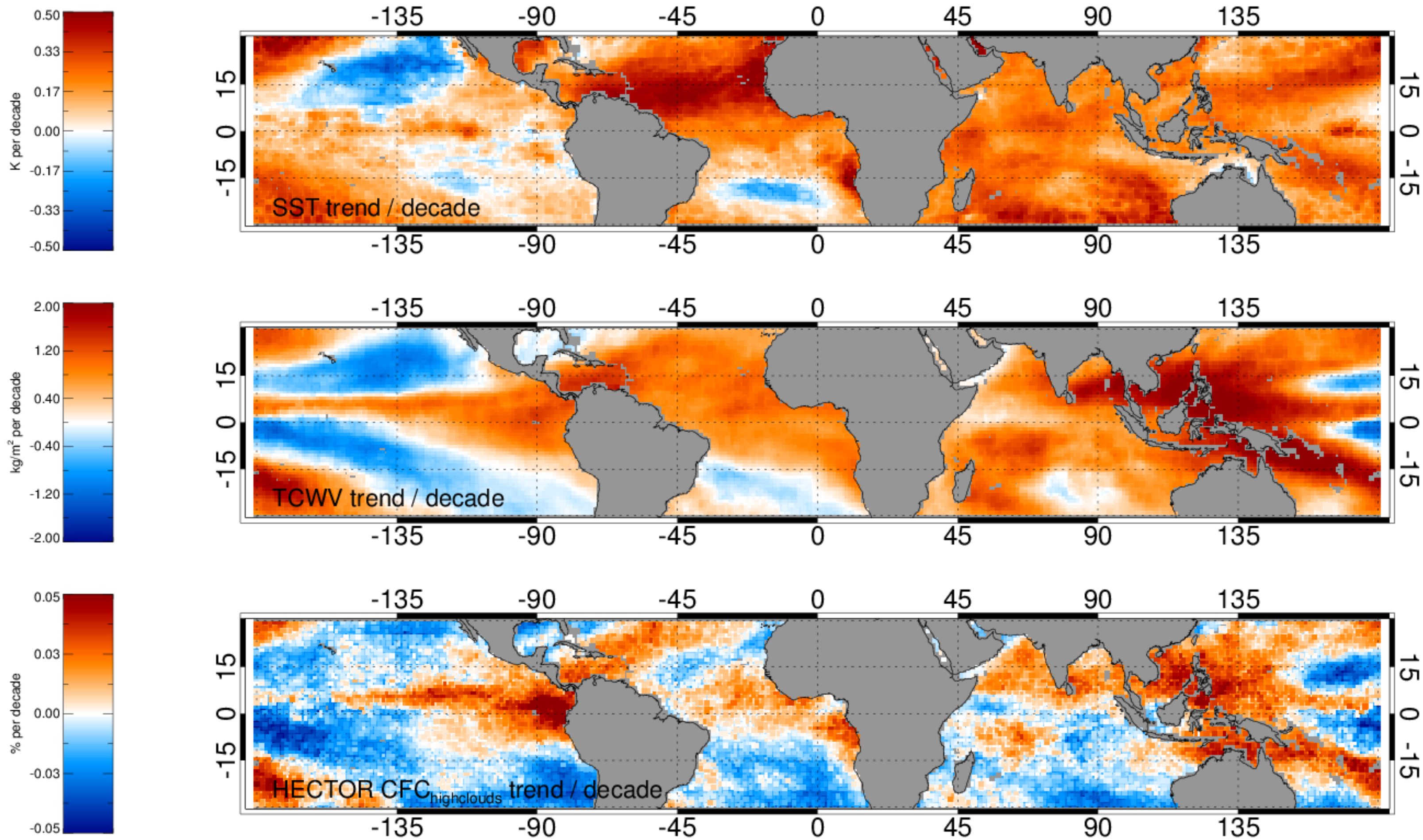




Application (2/9): Climatological analysis, jointly with other geophysical properties

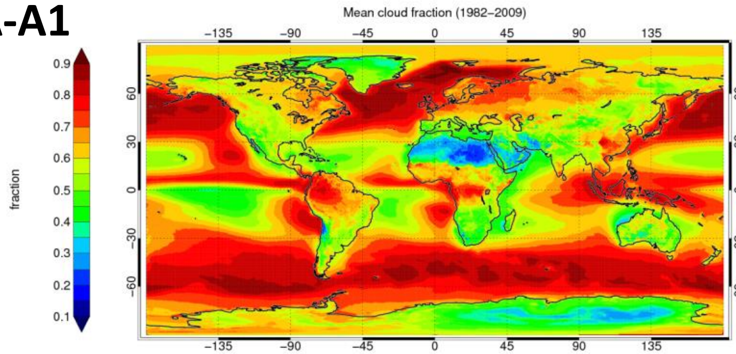
- Trend and anomaly studies

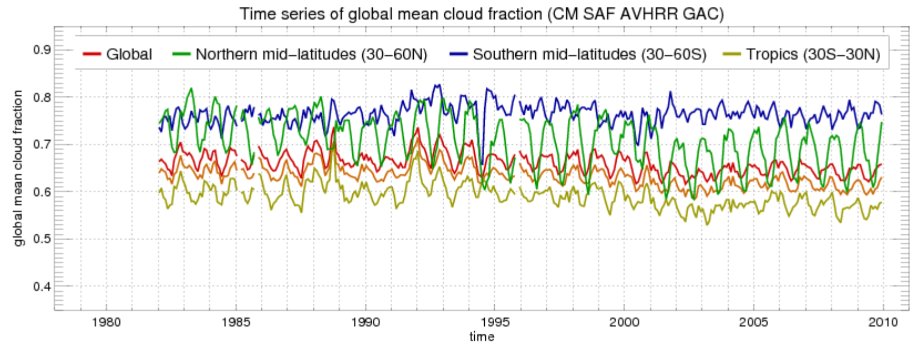
SST: AVHRR Pathfinder Version 5.2; Casey et al. (2010)
TCWV: HOAPS-3.3; Kinzel et al. (2017)
$HECTOR_{beta}$: CM SAF HIRS-based cloud properties



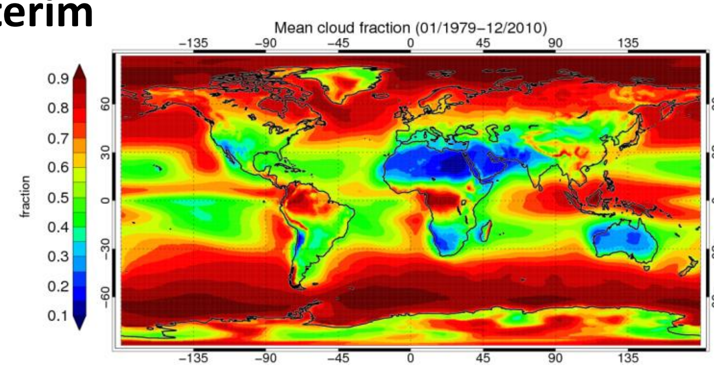
Applications (3/9): Model evaluation

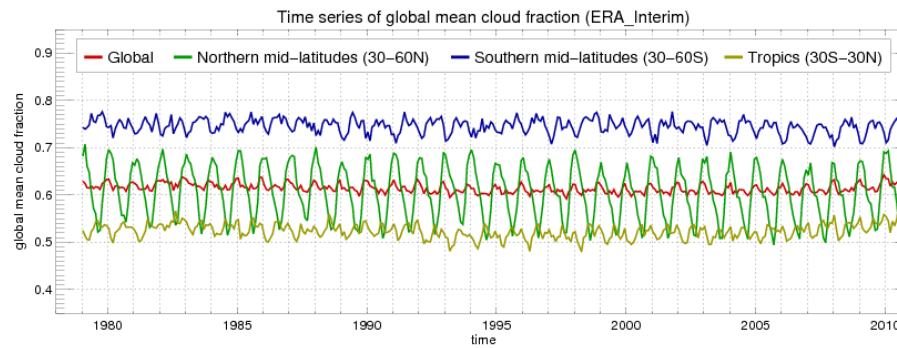
CLARA-A1



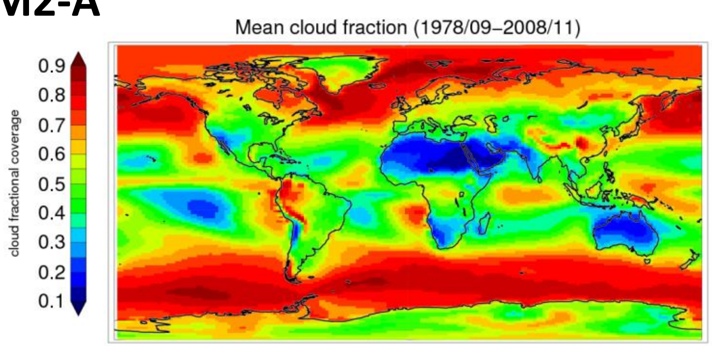


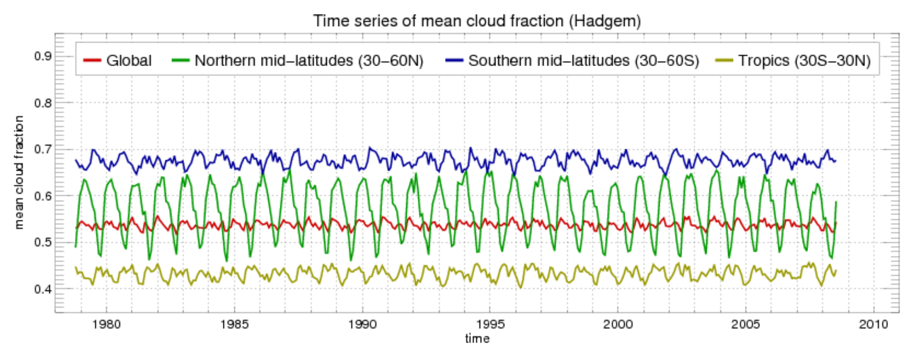
ERA-Interim





HadGEM2-A

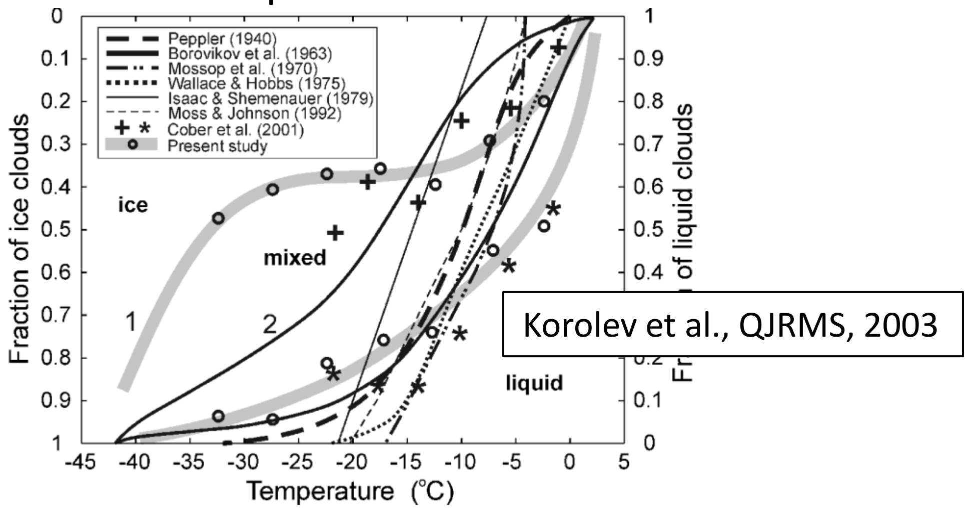




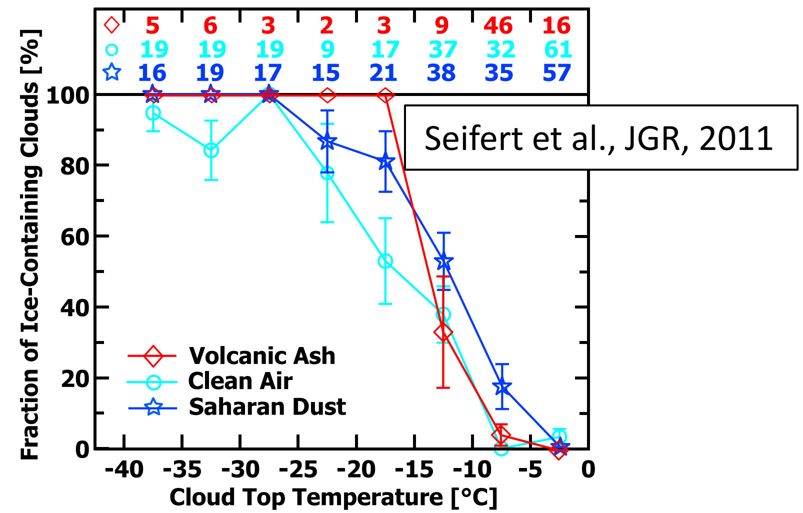
Application (4/9): Process studies

- Temperature dependent transition of thermodynamic phase

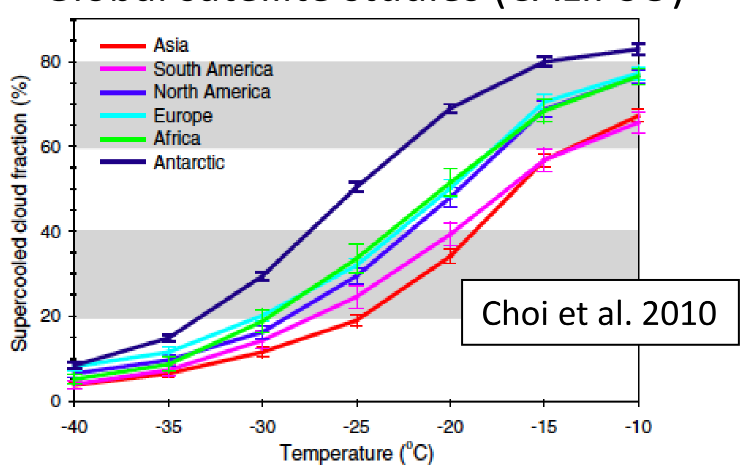
Airplane studies



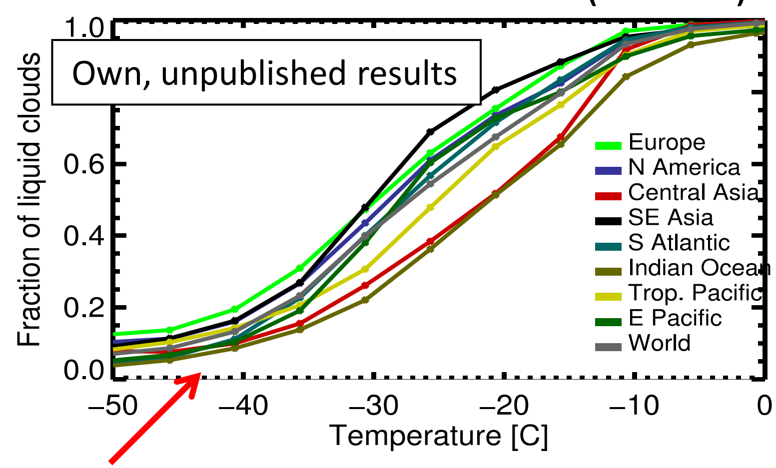
Ground studies



Global satellite studies (CALIPSO)



Global satellite studies (MODIS)

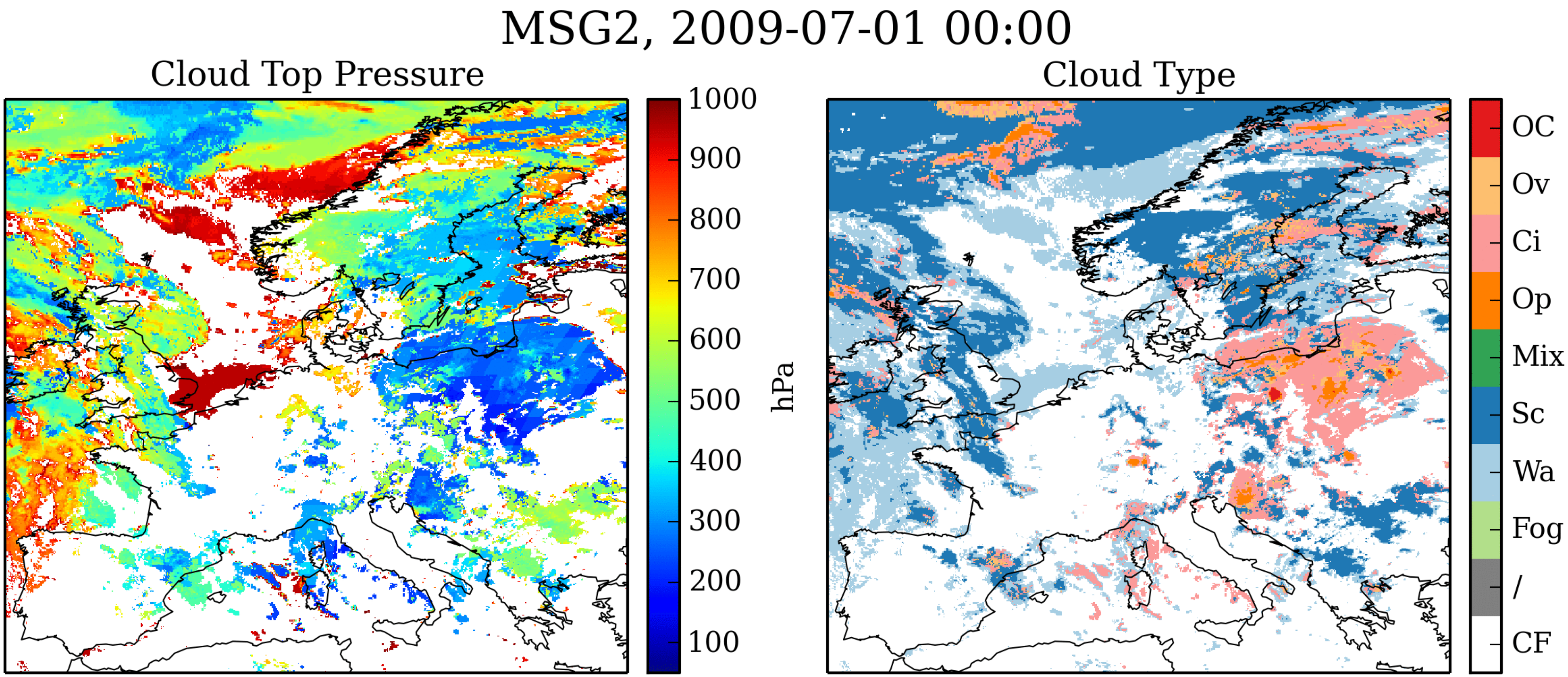


cloud-top only

Application (4/9): Process studies

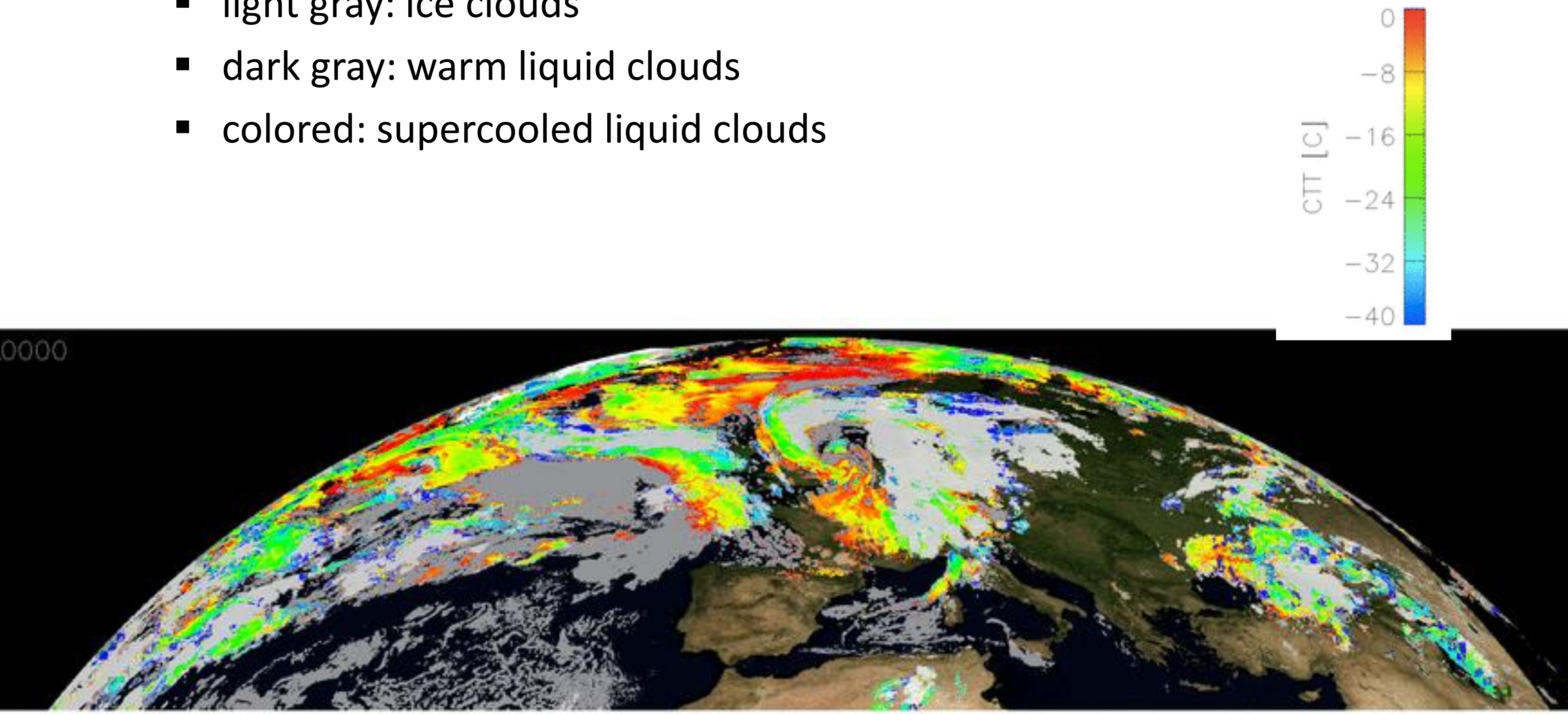
- Temperature dependent transition of thermodynamic phase

Cloud top temperature (CTT) | Cloud top phase (CPh)



Application (4/9): Process studies

- Temperature dependent transition of thermodynamic phase
  - light gray: ice clouds
  - dark gray: warm liquid clouds
  - colored: supercooled liquid clouds



Application (5/9): Process studies

- Temporal characteristics of clouds

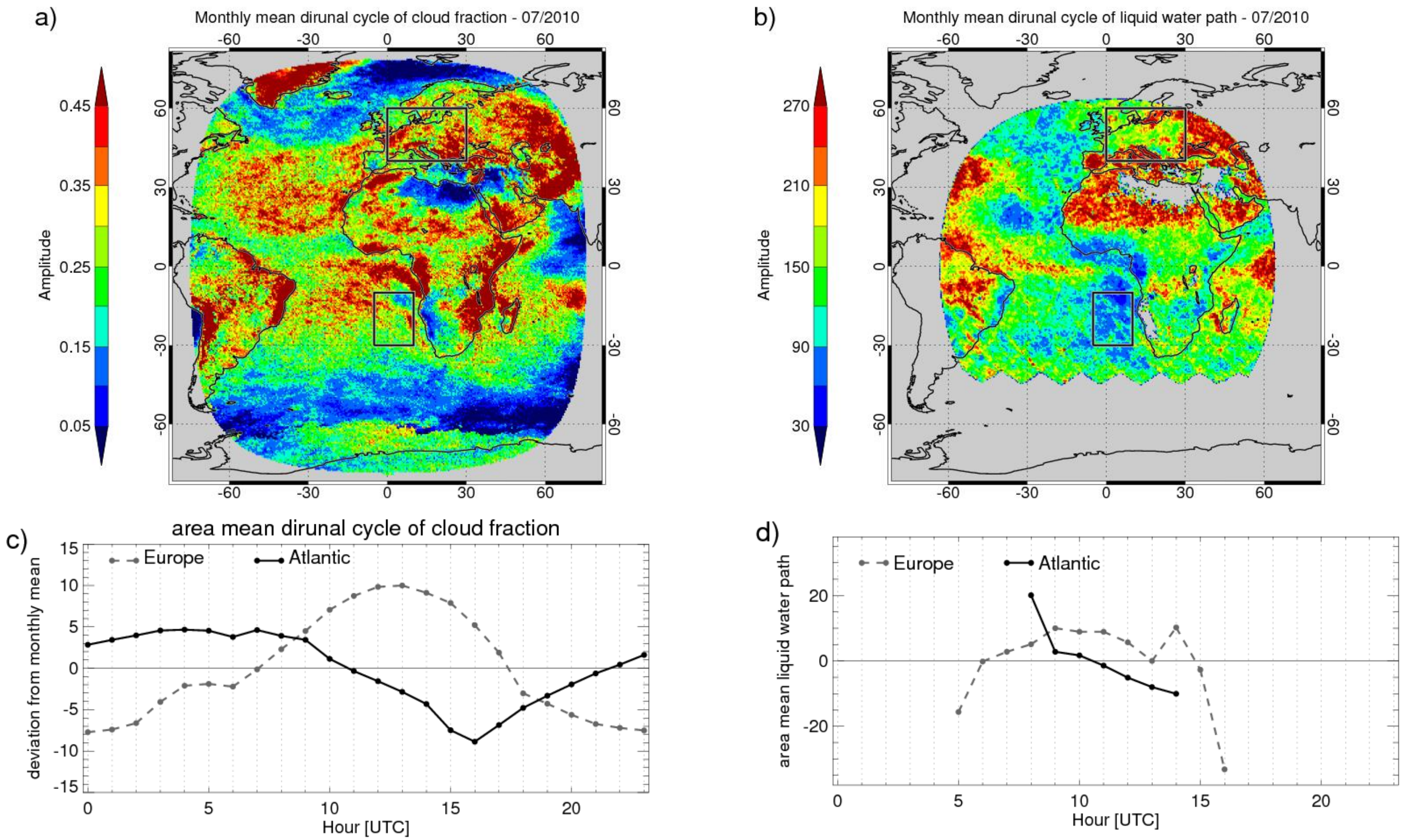
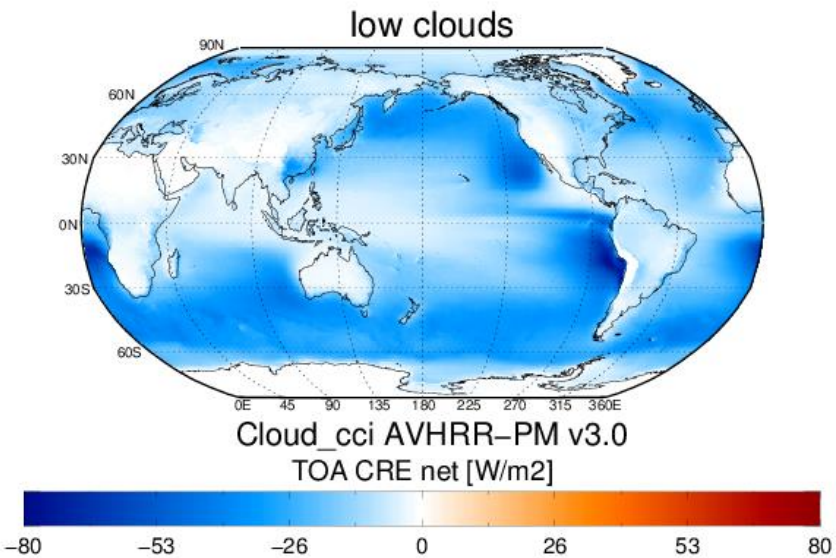
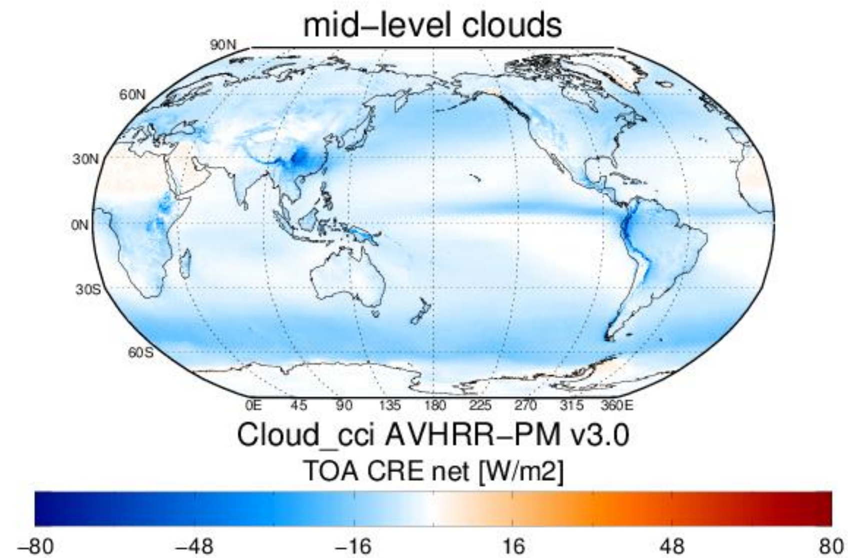


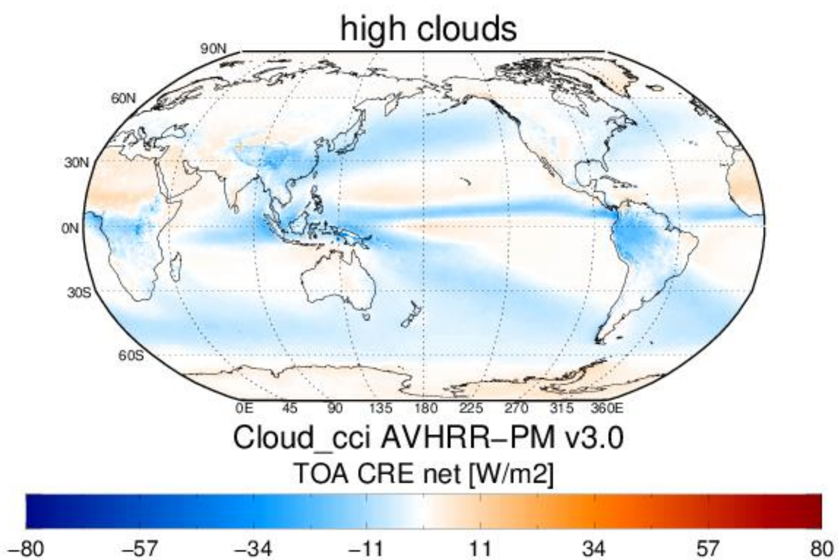
Fig.: Exemplary maps of monthly mean diurnal cycle of cloud fraction (panel (a)) and liquid water path (panel (b), this data was smoothed over 3 neighbouring pixels to better visualize large scale features.). Shown are the respective amplitude (may minus min) for each grid box. In the bottom panels, the average values as function of the time of day for selected regions are shown. The locations of the regions are indicated in the maps. Figure taken from Stengel et al. (2014)

Application (6/9): Quantification of radiative effect

The top-of-the-atmosphere (TOA) radiative effect of clouds – net (SW+LW):

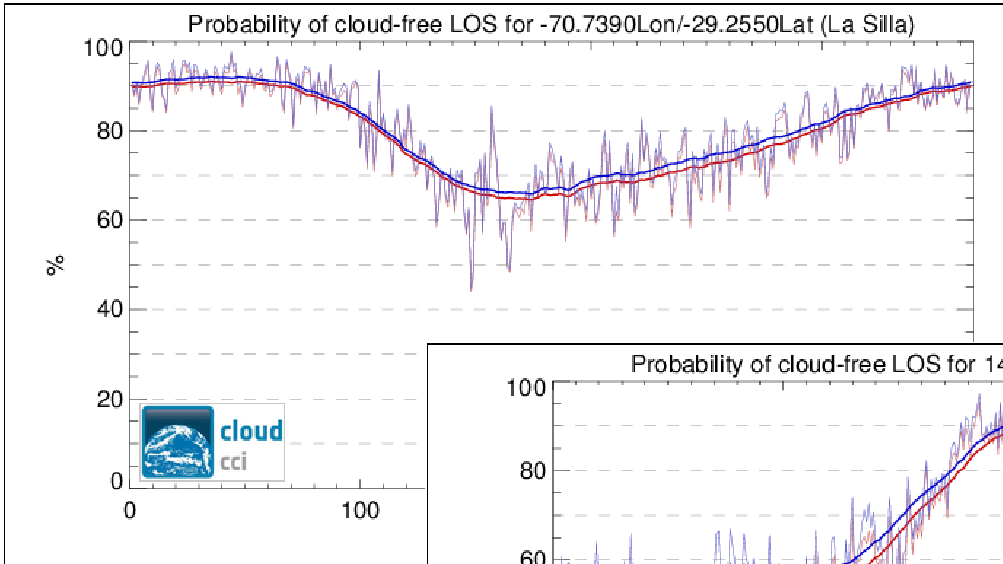


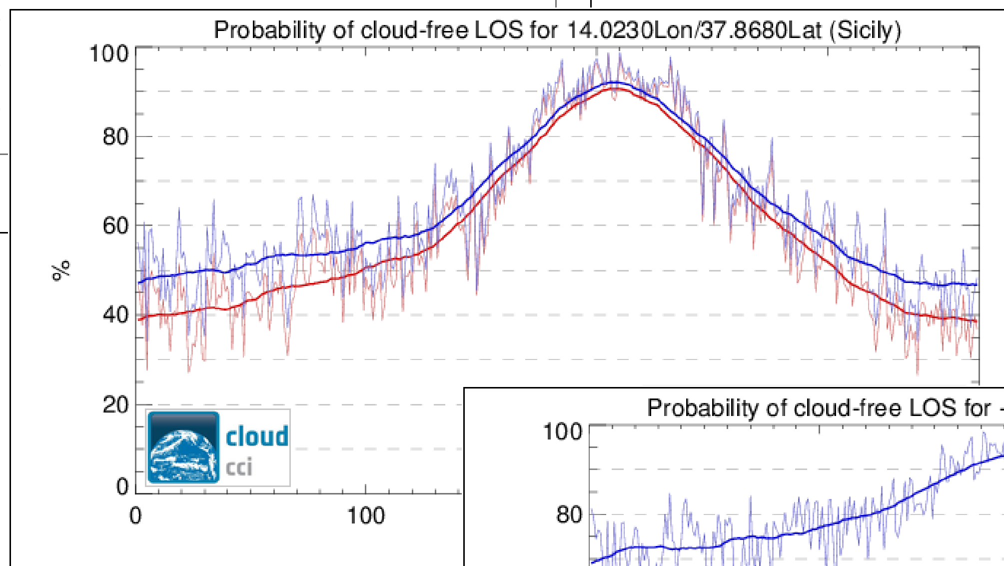


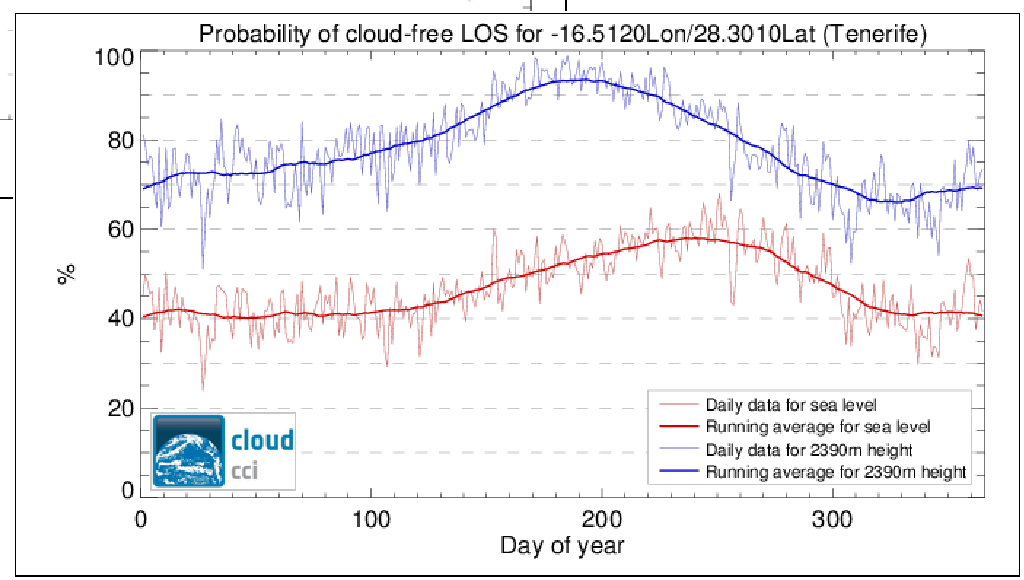


Application (7/9):

Probabilty of clear sky



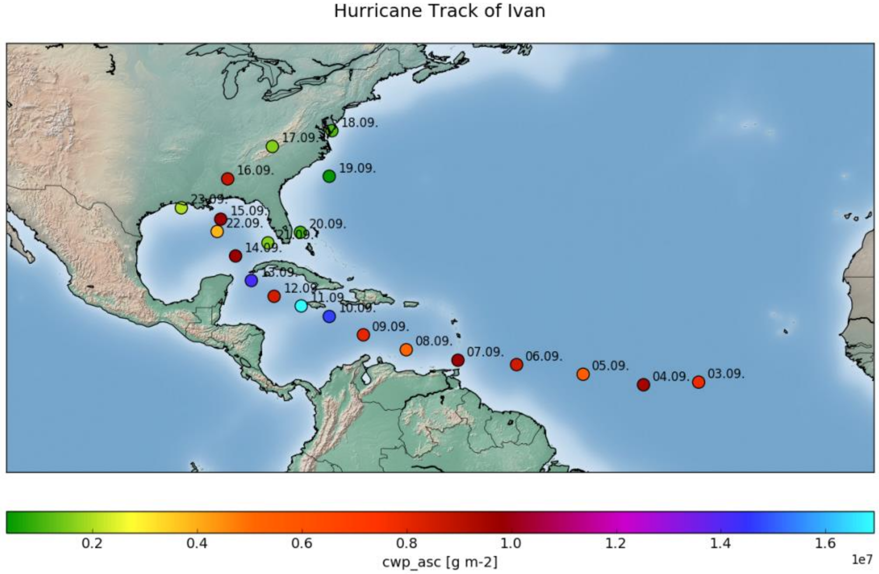


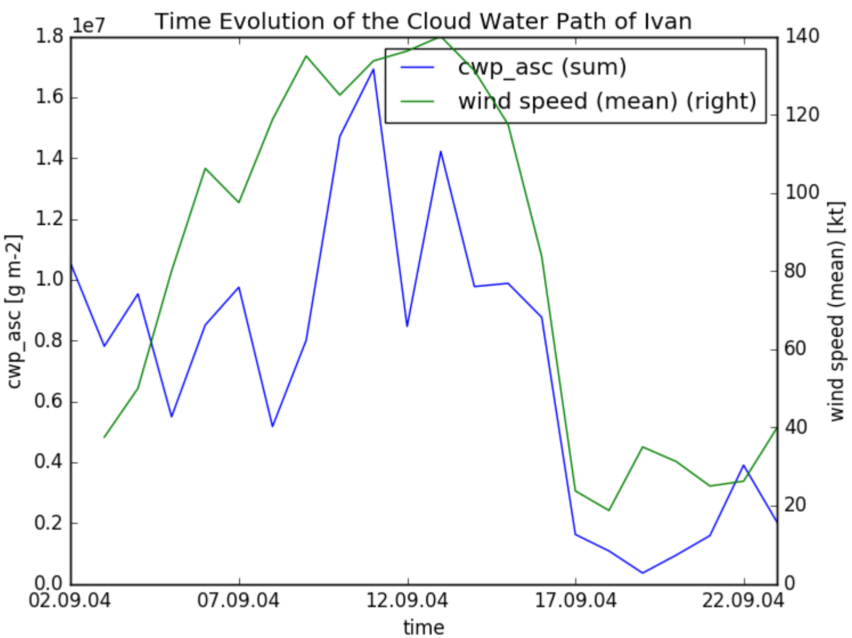


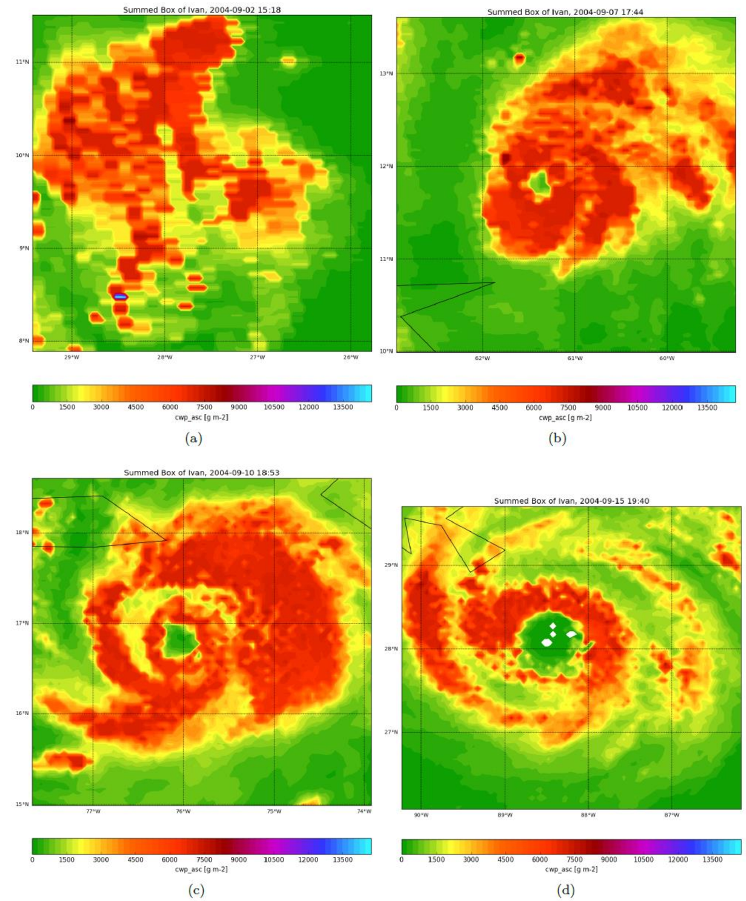
Prepared for ESA, Darmstadt, ESA / ESOC / OPS-GSY

Application (8/9):

Hurricane cloud properties



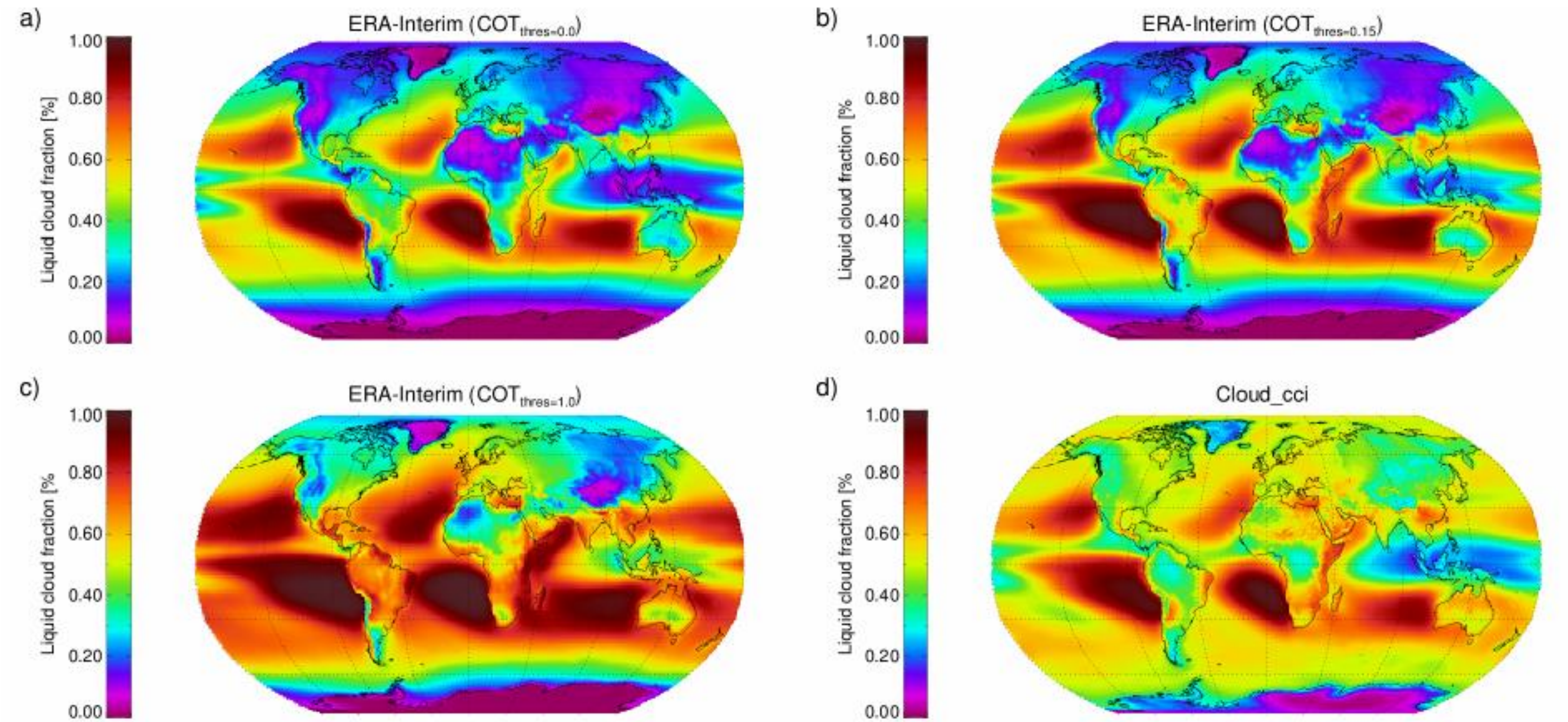


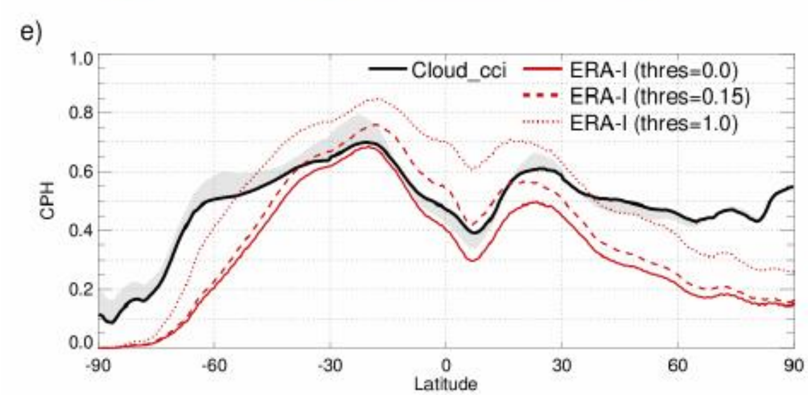


Student‘s project, University of Frankfurt

Application (9/9):

Evaluation of ERA-Interim using a simplifed simulator

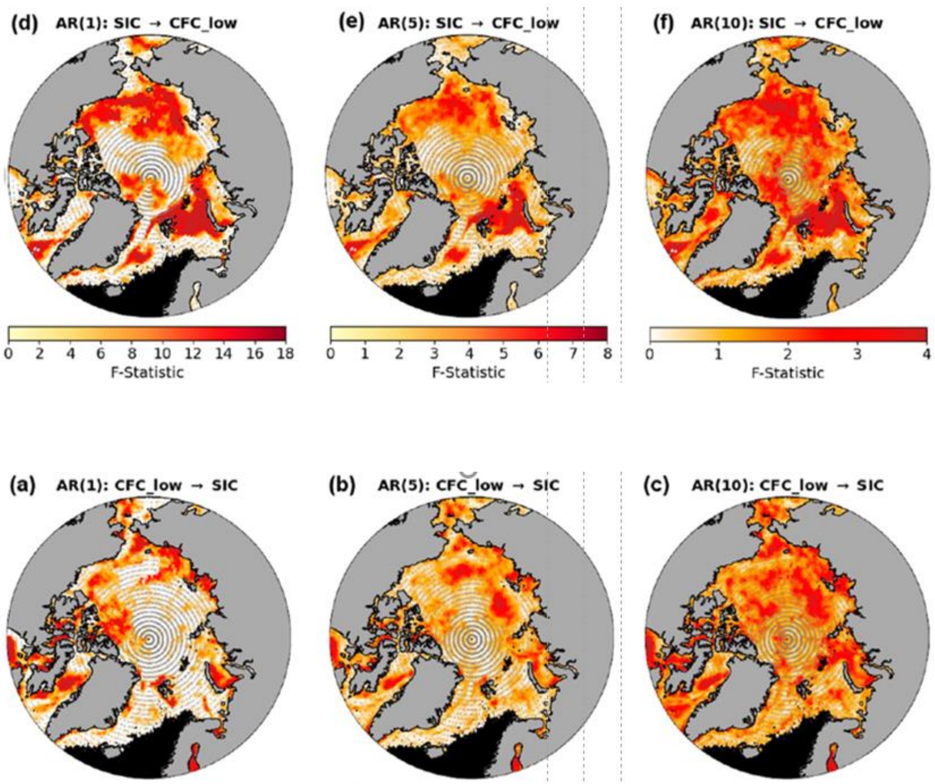




DWD, study is part of Cloud_cci project

Application (10/9):

Interaction (feedback) between arctic sea ice concentration and the occurrence of low-level clouds



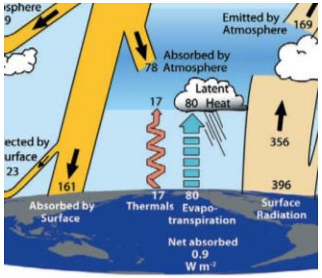
Less Arctic sea-ice
→ More low-level clouds

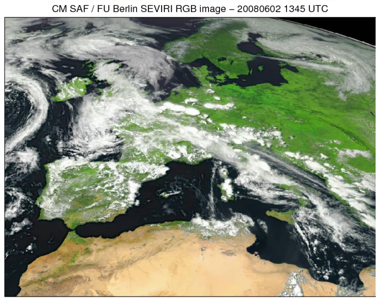
More low-level clouds
→ Less Arctic sea-ice

…. to reveal **strong evidence** for a **positive cloud – sea-ice feedback** in the **Arctic** with the capability to contribute to autumnal Arctic amplification.
(Philipp et al., J. Climate, 2020, https://doi.org/10.1175/JCLI-D-19-0895.1)

Summary I

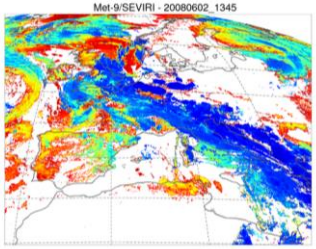
- Clouds are very important for the climate because they interact with radiation in many aspects

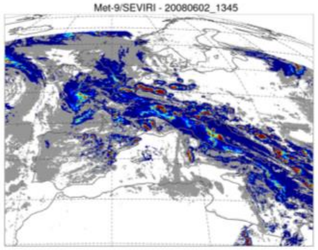




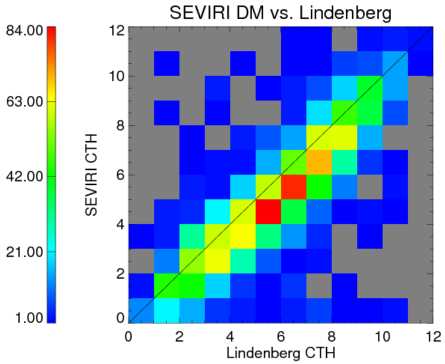
- Deviating radiative properties of clouds (compared to surface and other atmospheric components must exist (and are used) for cloud detecting

- Multiple cloud properties can be (are) inferred from satellite sensors (examples of AVHRR and SEVIRI were shown)



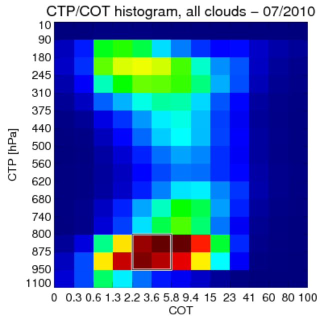


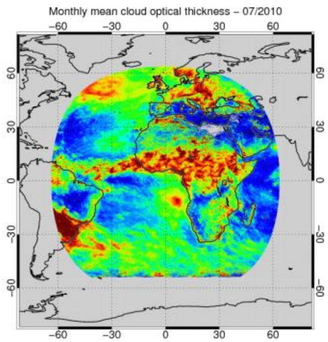
- Validation studies to be carried out to ensure/quantify quality of derived cloud properties (uncertainty estimates)



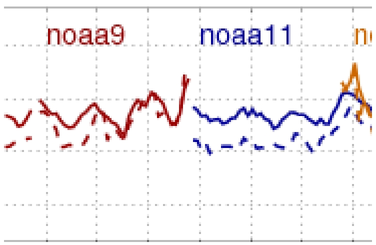
Summary II

- Generating datasets requires are careful preparation of the input data, the application of long-term stable retrievals, proper summary/representation of the data; also wrt. the needs of the user community

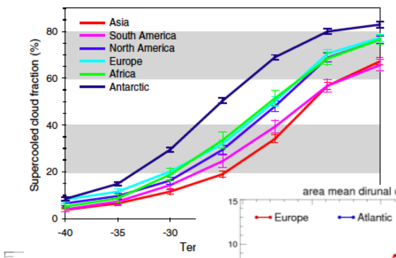




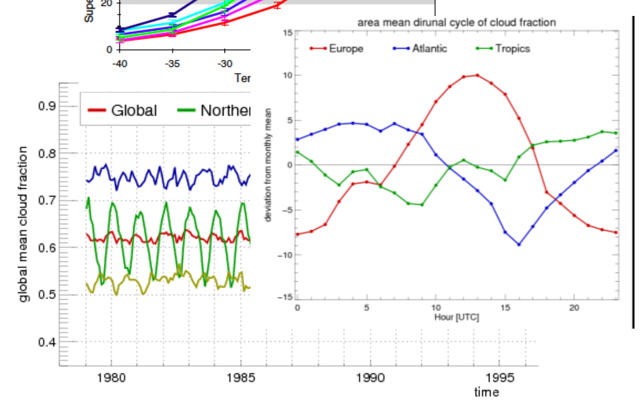
- Careful analysis of stability and homogeneity



- Proper documentation of datasets: data, approaches,.., also document strengths AND weaknesses of the dataset



- Cloud property datasets facilitate various climatological applications, e.g. glaciation processes and diurnal cycle of cloud properties; and in general the analysis of the state of global cloudiness and corresponding changes



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