Training event “Climate change and air quality: challenges and objectives for the atmospheric research.”

Long term archiving and harmonization: CCI

Thomas Popp –

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Ministero dell'Università e della Ricerca

Italiadomani

German Aerospace Center - DLR
German Remote Sensing Data Center – DFD
Department Atmosphere / Group „Aerosol and Radiation“

Thomas Popp

ESA Climate Change Initiative (CCI) Science Leader Aerosol_cci

Copernicus Climate Change Initiative (C3S): PI Atmospheric Composition

climate change initiative

→ AEROSOL

Algorithm development, benchmarking, user case studies

aerosol cci

Atmospheric Composition ECVs

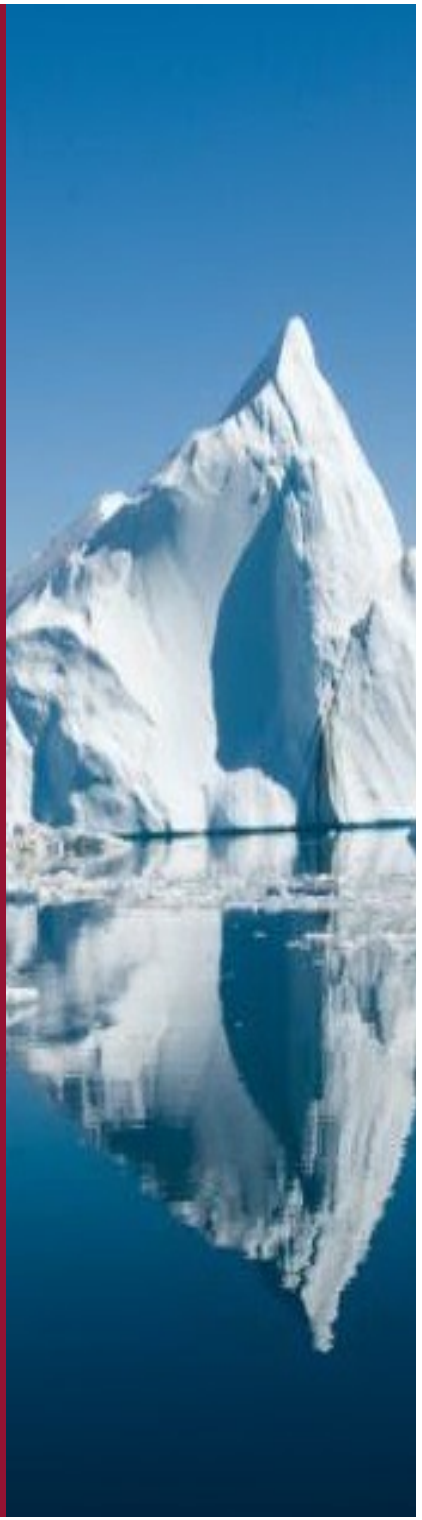
Greenhouse gases

Ozone

Aerosol properties

An operational service

Climate Change



PROGRAMME OF THE EUROPEAN UNION

Copernicus Europe's eyes on Earth

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A question to start with …

To monitor climate change:

Which measurements do we need?

Essential Climate Variables

An **Essential Climate Variable (ECV)** is a physical, chemical or biological variable or a group of linked variables that critically contributes to the **characterization of Earth's climate**. GCOS currently specifies 55 ECVs.

ECV datasets provide the **empirical evidence** needed to **understand** and **predict** the evolution of climate, to guide **mitigation** and **adaptation** measures, to assess **risks** and enable **attribution** of climate events to underlying causes, and to underpin climate services. They are required to support the work of the **UNFCCC** and the **IPCC**.

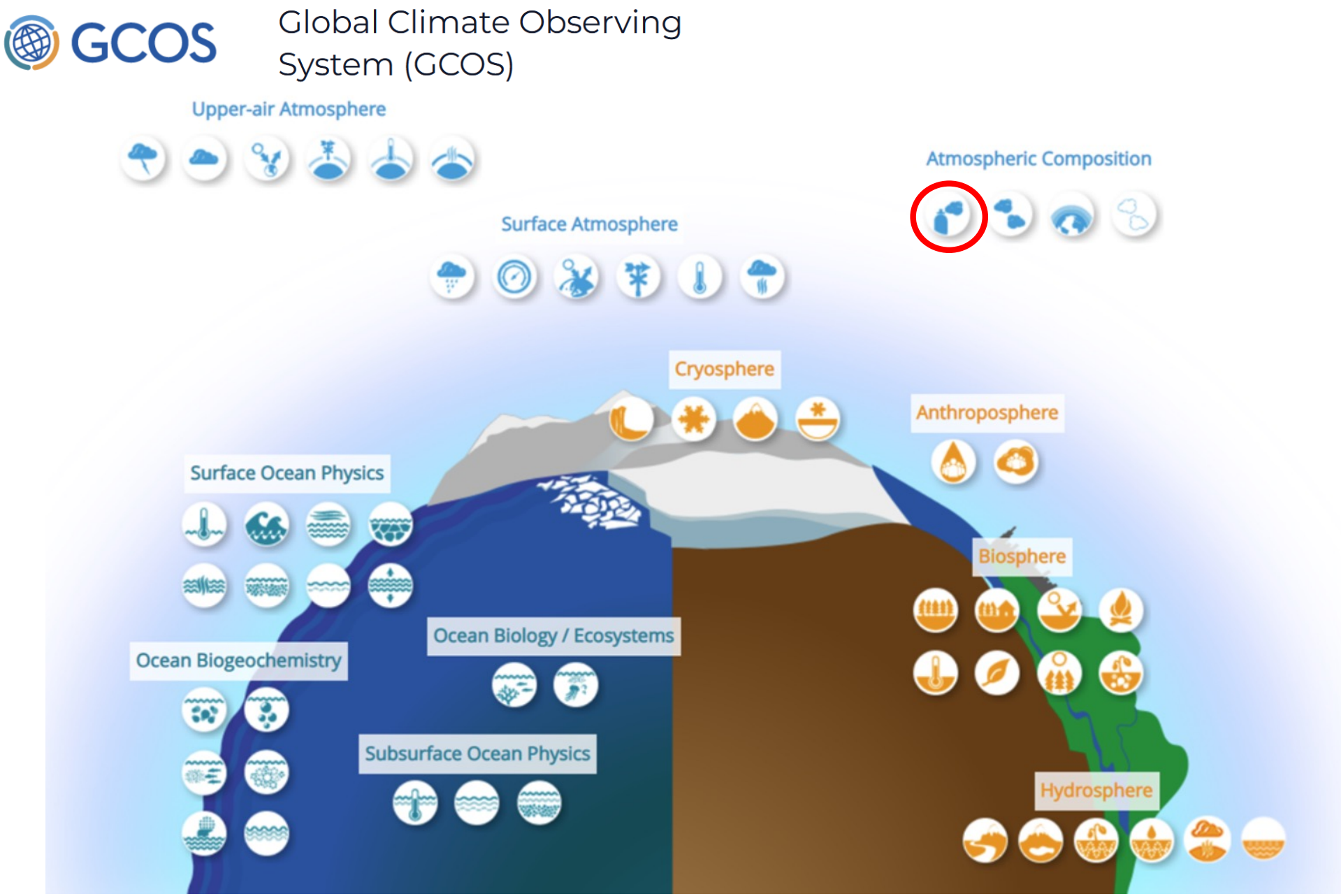
ECV are identified based on the following criteria:

- **Relevance:** The variable is critical for characterizing the climate system and its changes.
- **Feasibility:** Observing or deriving the variable on a global scale is technically feasible using proven, scientifically understood methods.
- **Cost effectiveness:** Generating and archiving data on the variable is affordable, mainly relying on coordinated observing systems using proven technology, taking advantage where possible of historical datasets.

ECV Observation Requirements

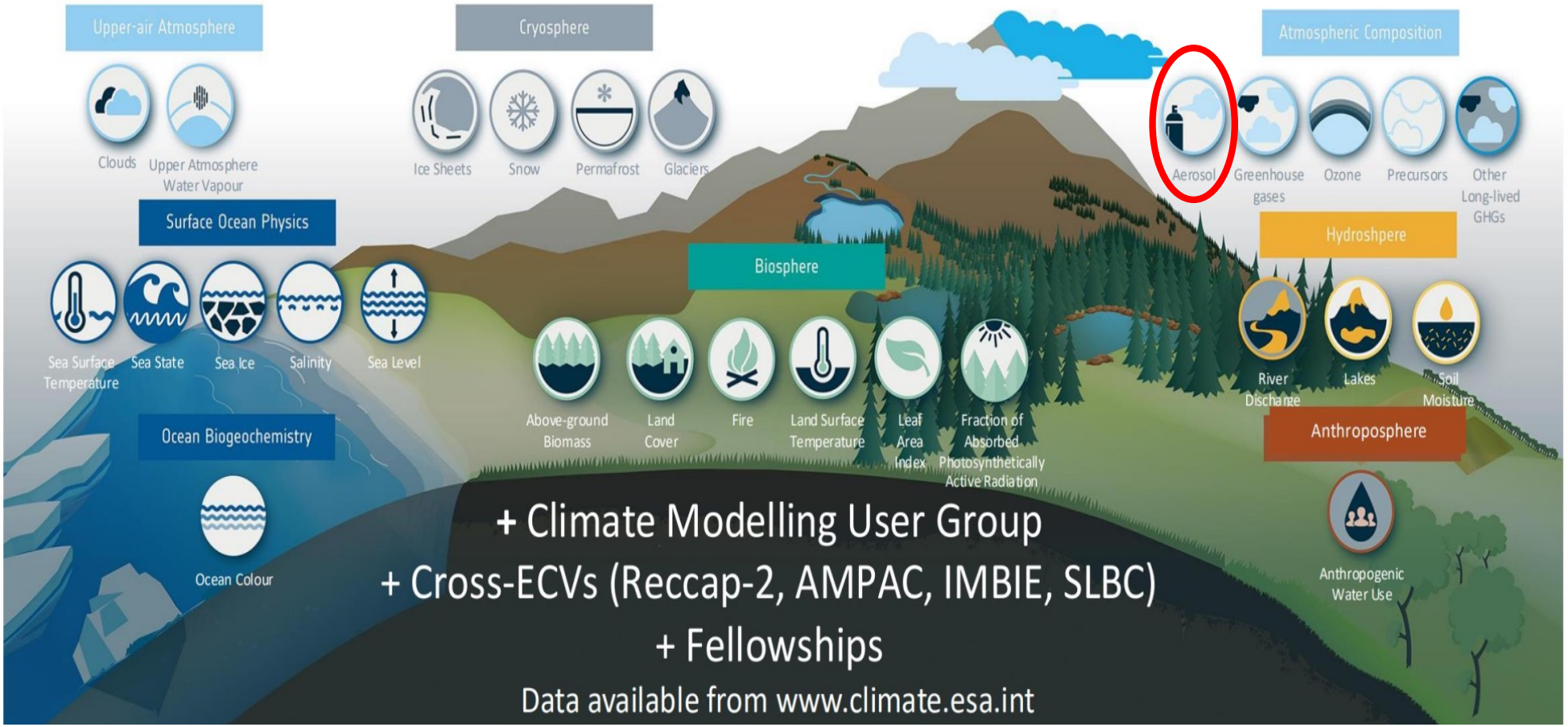
- … are defined **by application and** are **independent from measurements**
- Different measurement types offer **complementary capabilities**

GCOS Global Climate Observing System



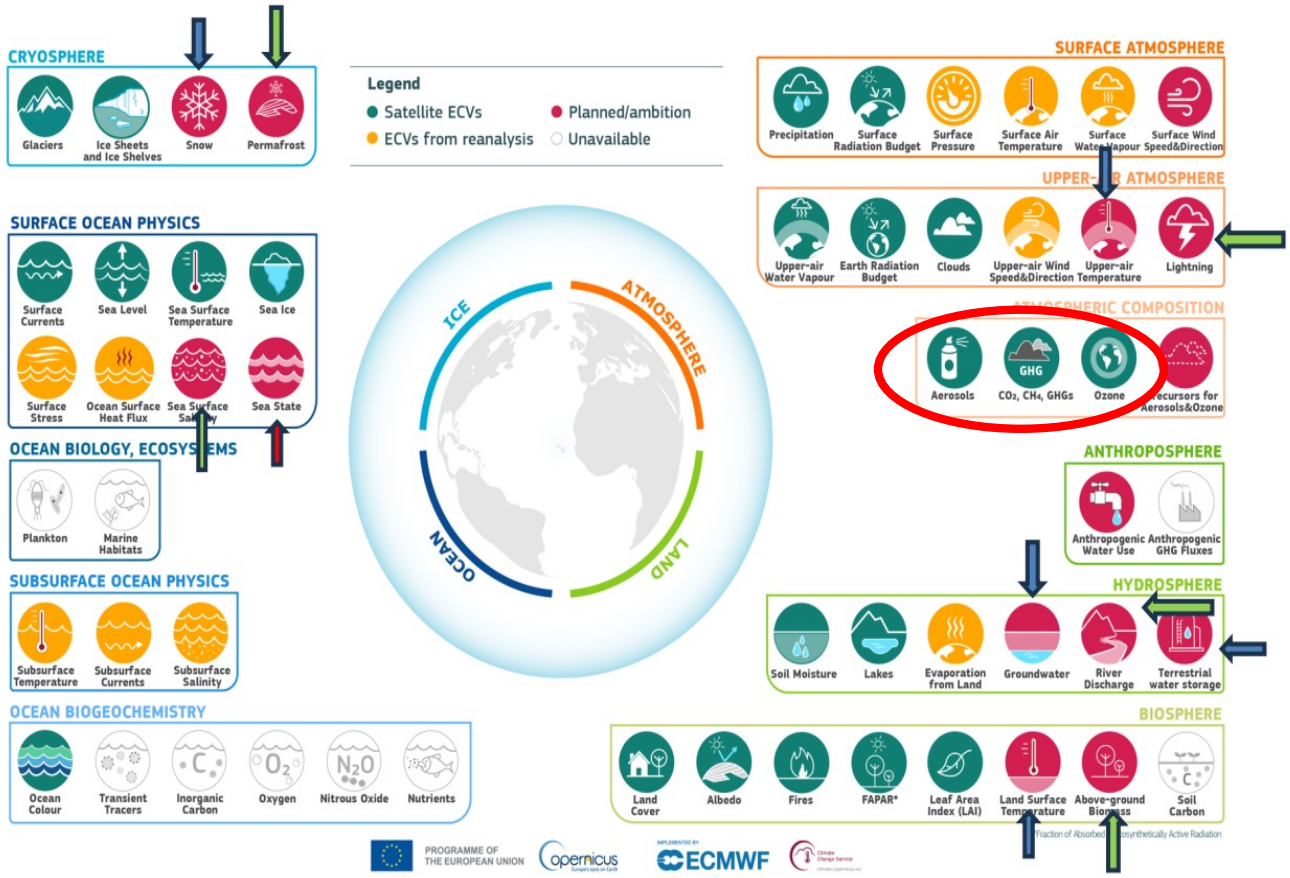
ESA's CLIMATE CHANGE INITIATIVE

GCOS defined **55** Essential Climate Variables | **36** benefit from space observations | **27** generated by ESA Climate Change Initiative



Copernicus Climate Change Service C3S

ECV programme – status & evolution



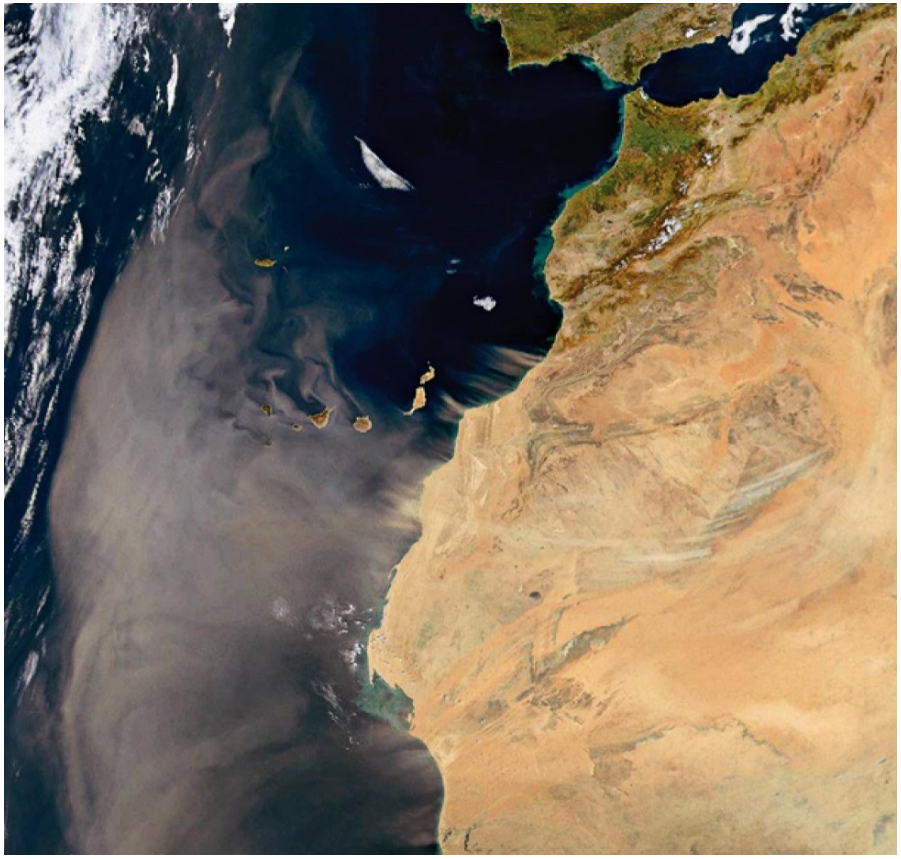
New ECVs in C3S2-phase II

Requested ECVs in C3S2-phase II

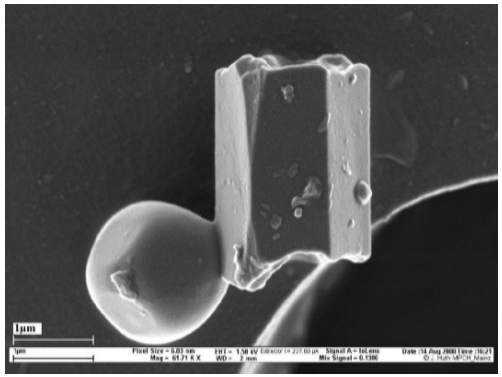
Potential additional ECVs from 2025

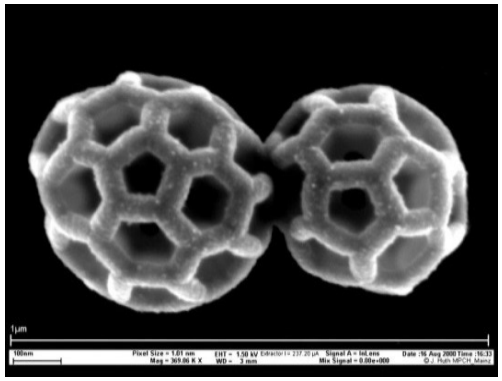
Atmospheric aerosols: A zoo of tiny particles

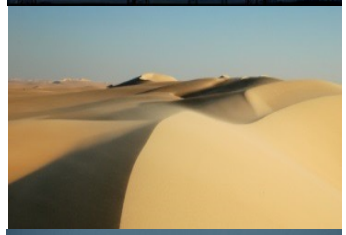
… visible from space

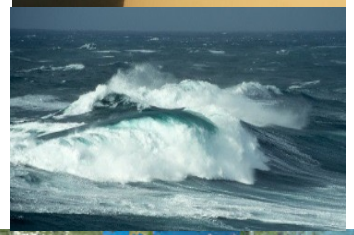


… example images





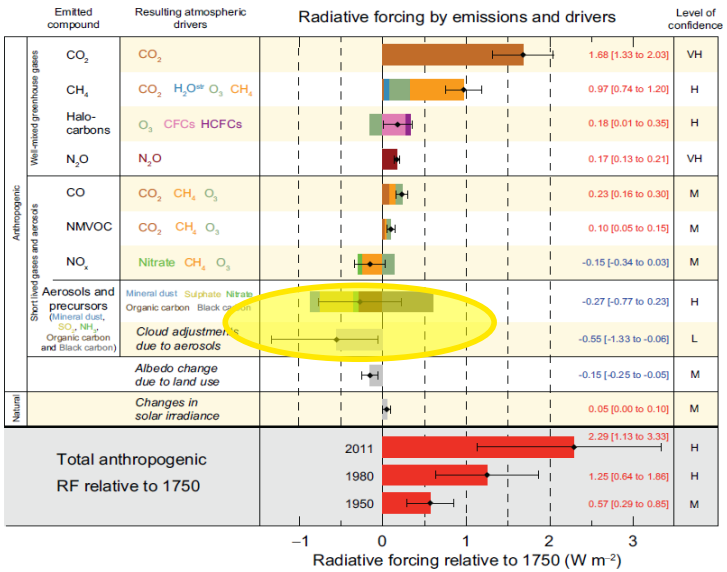




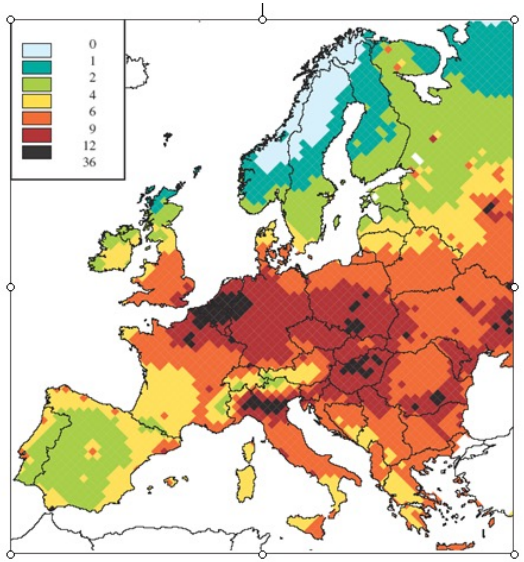
… different sources

Tiny particles in the atmosphere are relevant

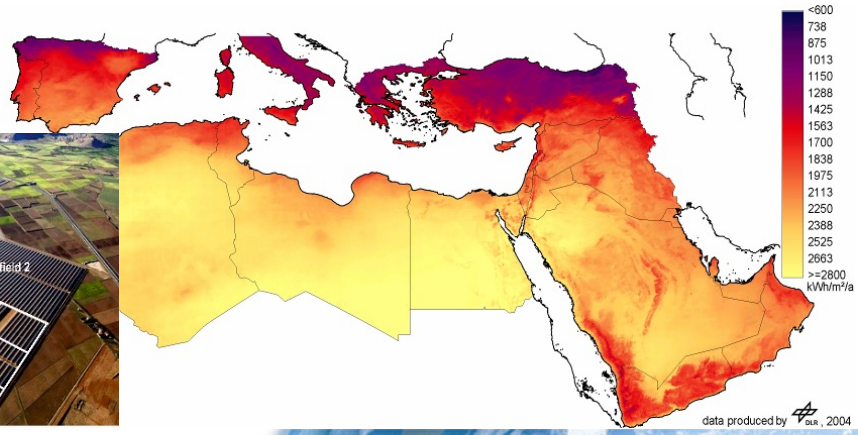
… IPCC forcing



… air quality



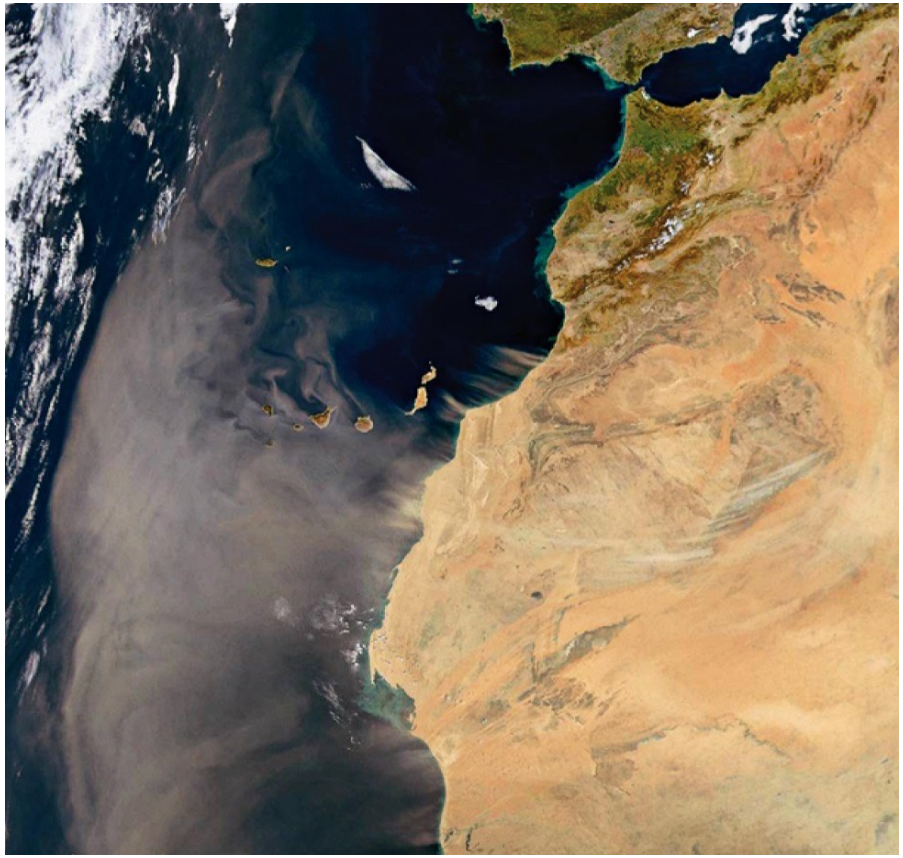
… solar energy

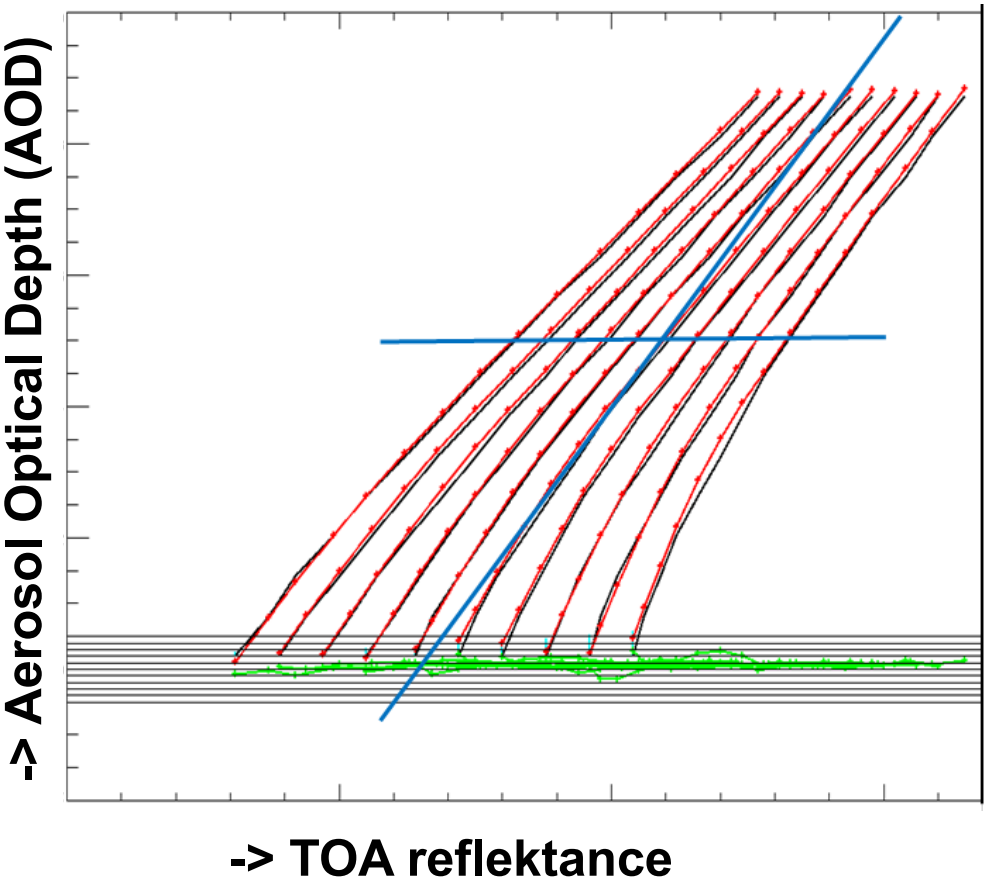


… atmospheric correction

DLR

Aerosol inversion – principle





DLR

A question on data portals …

To access climate data:

Which user wishes do you have?

Long-term archiving

- ESA CCI
  - Algorithm development, benchmarking, initial CDR processing
  - started 2010 with initial 10 ECV projects
  - analysis of de-central vs central archiving conept
  - CCI portal as common platform (+ toolbox)
    - https://climate.esa.int/en/data/#/dashboard

- Copernicus Climate Change Service
  - started in 2016 (proof of concept phase)
  - transfer of operational tasks for mature CCI ECVs from 2018
  - Climate Data Store + jupyter notebooks
    - https://cds.climate.copernicus.eu/#!/home
    - Observations (Satellite ECVs, in-situ)
    - Reanalysis
    - Predictions and projections

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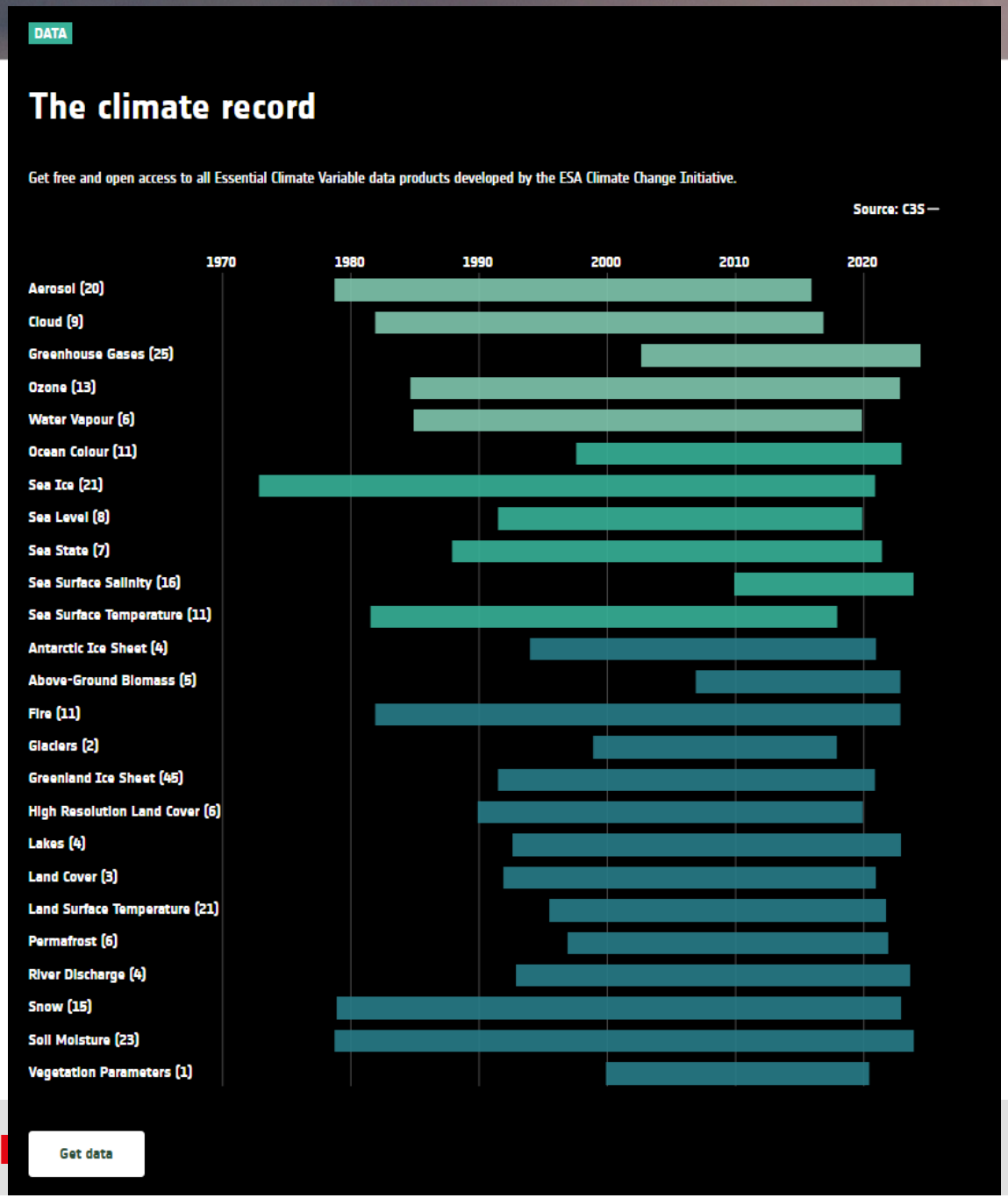
CCI portal



Climate Data Store

Aerosol properties gridded data from 1995 to present derived from satellite observations

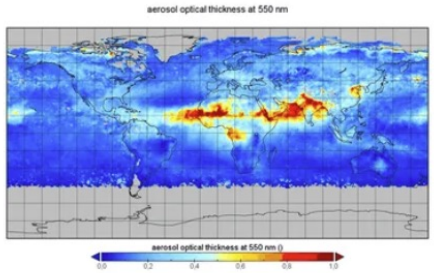
Overview | Download | Quality | Documentation

Info

1 Apr 2022

GOMOS on ENVISAT version 5.00 data have been deprecated. Consult Known Issues in the Documentation tab.

This data set provides observational records of aerosol properties obtained from observations collected by various satellite instruments. Aerosols are minor constituents of the atmosphere by mass, but critical components in terms of impact on climate. Aerosols influence the global radiation balance directly by scattering and absorbing radiation, and indirectly through influencing cloud reflectivity, cloud cover and cloud lifetime.



The main variables provided by this dataset are: aerosol optical depth, fine mode aerosol optical depth, dust aerosol optical depth, single scattering albedo, aerosol layer height and aerosol extinction coefficient. These variables are derived from observations from several sensors using a set of different processing techniques. This provides the possibility to derive a large set of complementary aerosol properties needed to describe the complex nature of atmospheric aerosols. Furthermore, different algorithms have their specific strengths and weaknesses, meaning that datasets originating from the same sensor but processed by different algorithms provide a way to evaluate uncertainties (e.g. areas of good or bad agreement between them). Altogether, the aerosol properties dataset is very extensive and offers a choice of complementary options – which is appropriate depends on the intended application.

Quality Assurance

Data Management

Data records

Metadata

Documentation

References

Citation and attribution

DOI: 10.24381/cds.239d815c

Licence

Licence to use Copernicus Products

Publication date

2019-12-11

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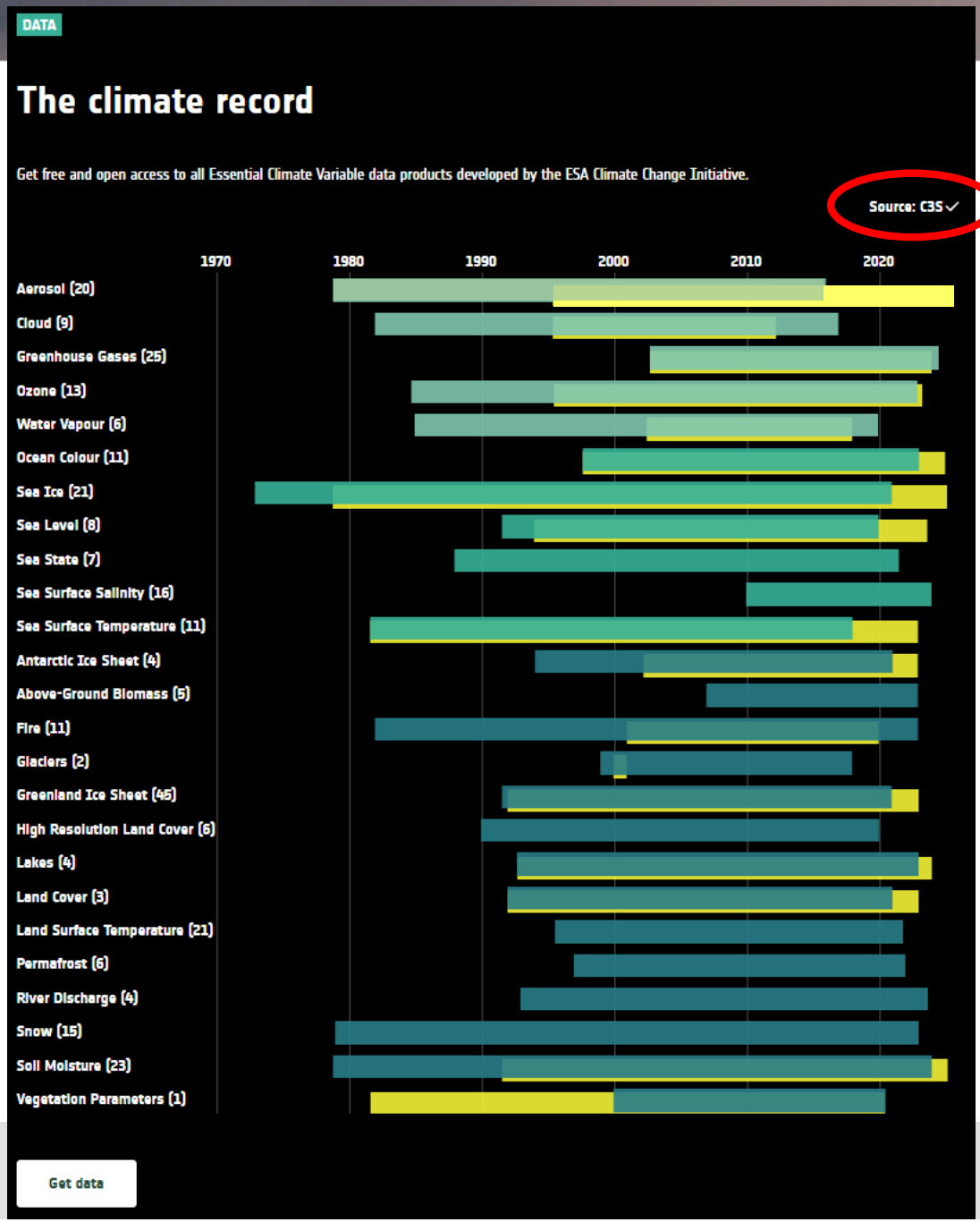
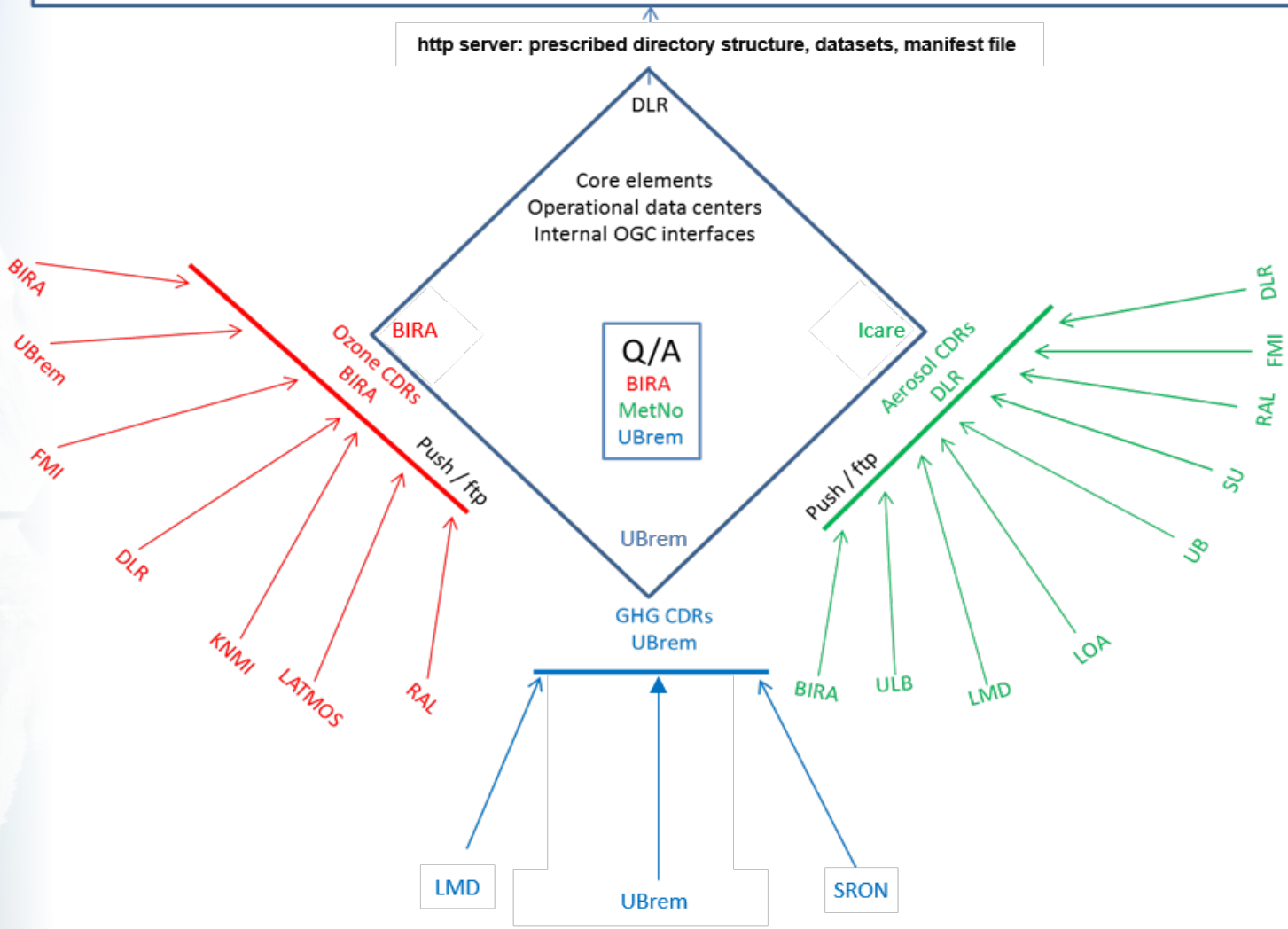
CCI portal - connect to C3S



Climate Change

Climate Data Store



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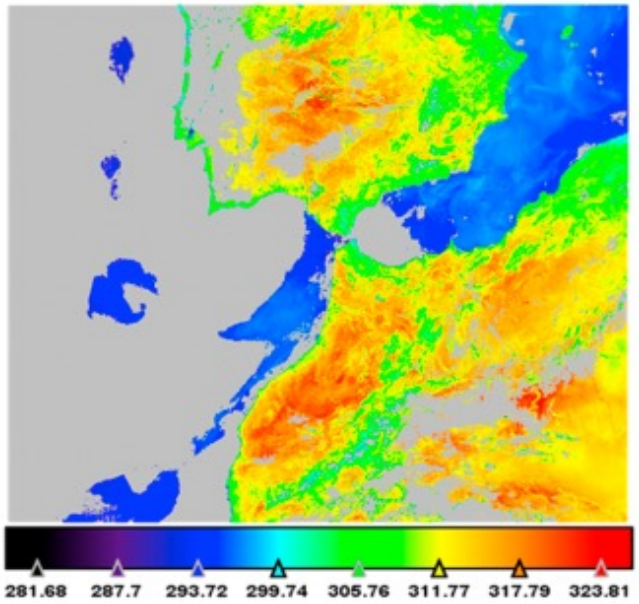
A question on satellite data for climate …

To create
a long record
of an Essential Climate Variable
for Atmospheric Aerosol
from satellite data

Which challenges can you imagine?

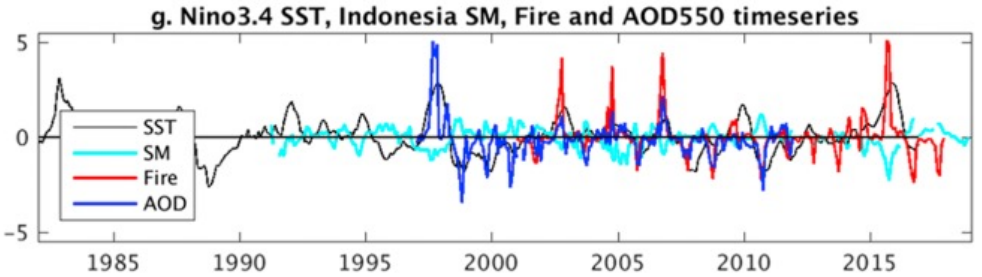
Harmonization: Consistency

- “**independent measurements compatible within their individual uncertainties**”
- 3-level definition applicable to single and multiple variables
  - Technical: harmonized format, metadata, access
  - Retrieval: use the same auxiliary datasets
  - Scientific: compatible ECVs and reference



- Concept for testing consistency

Consistency type	Required background knowledge	Assessment method
Retrieval level		
Categorical auxiliary data (masks)	Incompatible mask classes	Visual: Combined images
		Contingency matrix
		Class combination maps
Continuous auxiliary data	Target variable sensitivity to auxiliary variable	Visual: Homogeneity
		Difference maps
		Statistical comparison
Scientific level		
Self-consistency (single quantity)	Behavior of one quantity	Visual: Features as expected
	Known record features	Quantitative variability
	Known map features	Trend analysis
	Physical equation	
Mutual consistency (multiple quantities)	Linkage between quantities	Difference maps
	Physical model	Trend comparisons
	Understood Earth system phenomena	Correlations and other measures of covariability



Popp Thomas, Michaela I. Hegglin, Rainer Hollmann, Fabrice Ardhuin, Annett Bartsch, Ana Bastos, Victoria Bennett, Jacqueline Boutin, Michael Buchwitz, Emilio Chuvieco, Philippe Ciais, Wouter Dorigo, Darren Ghent, Richard Jones, Thomas Lavergne, Christopher Merchant, Benoit Meyssignac, Frank Paul, Shaun Quegan, Tracy Scanlon, Marc Schröder, Stefan Simis, Ulrika Willén, Consistency of satellite climate data records for Earth system monitoring, Bull. Am. Met. Soc., 101, E1948–E1971, DOI10.1175/BAMS-D-19-0127.1, 2020

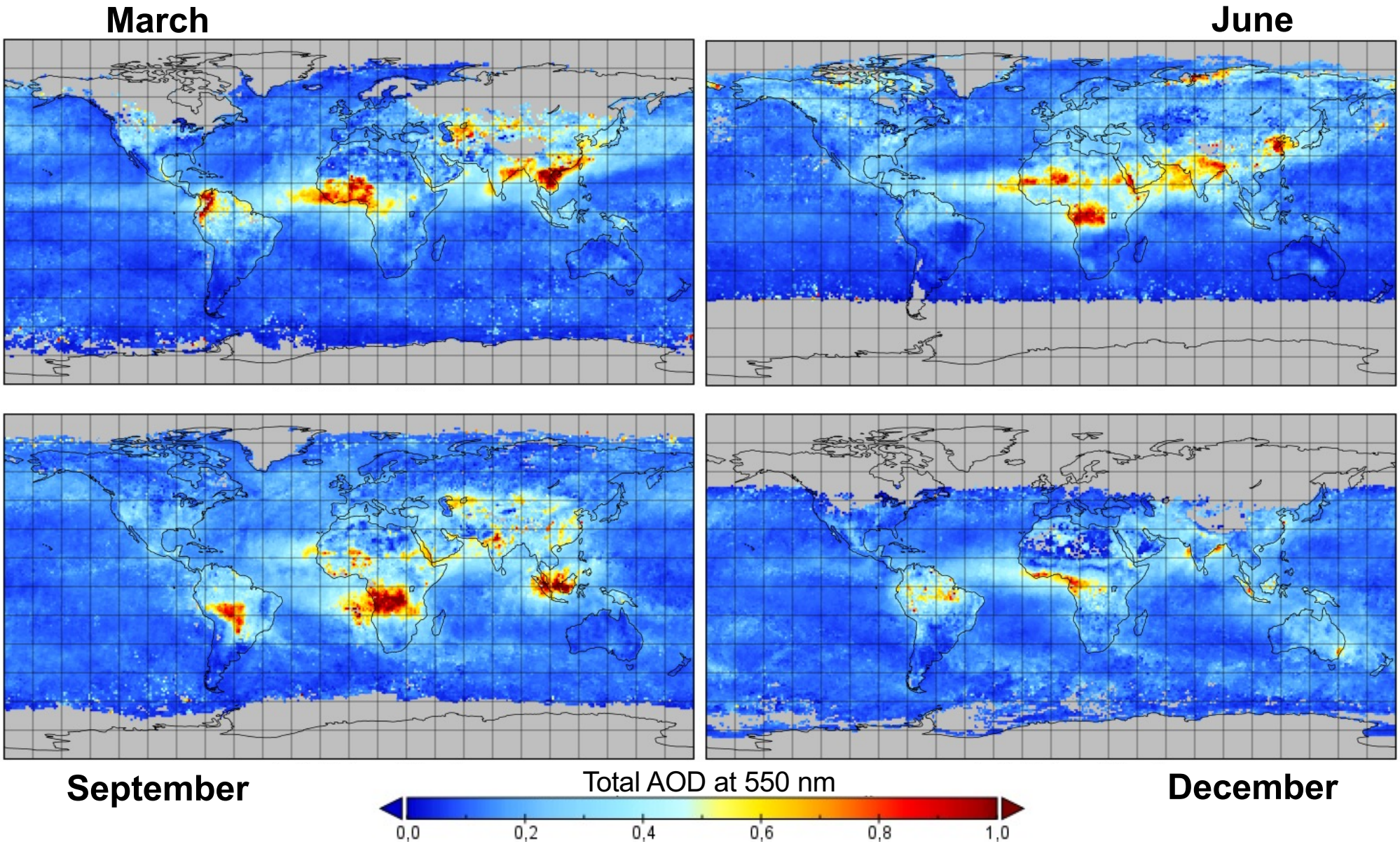
Consistency and CDR best practices

- **CDR best practices**
  - Aerosol_cci experiences + AEROCOM / AEROSAT community dialogue

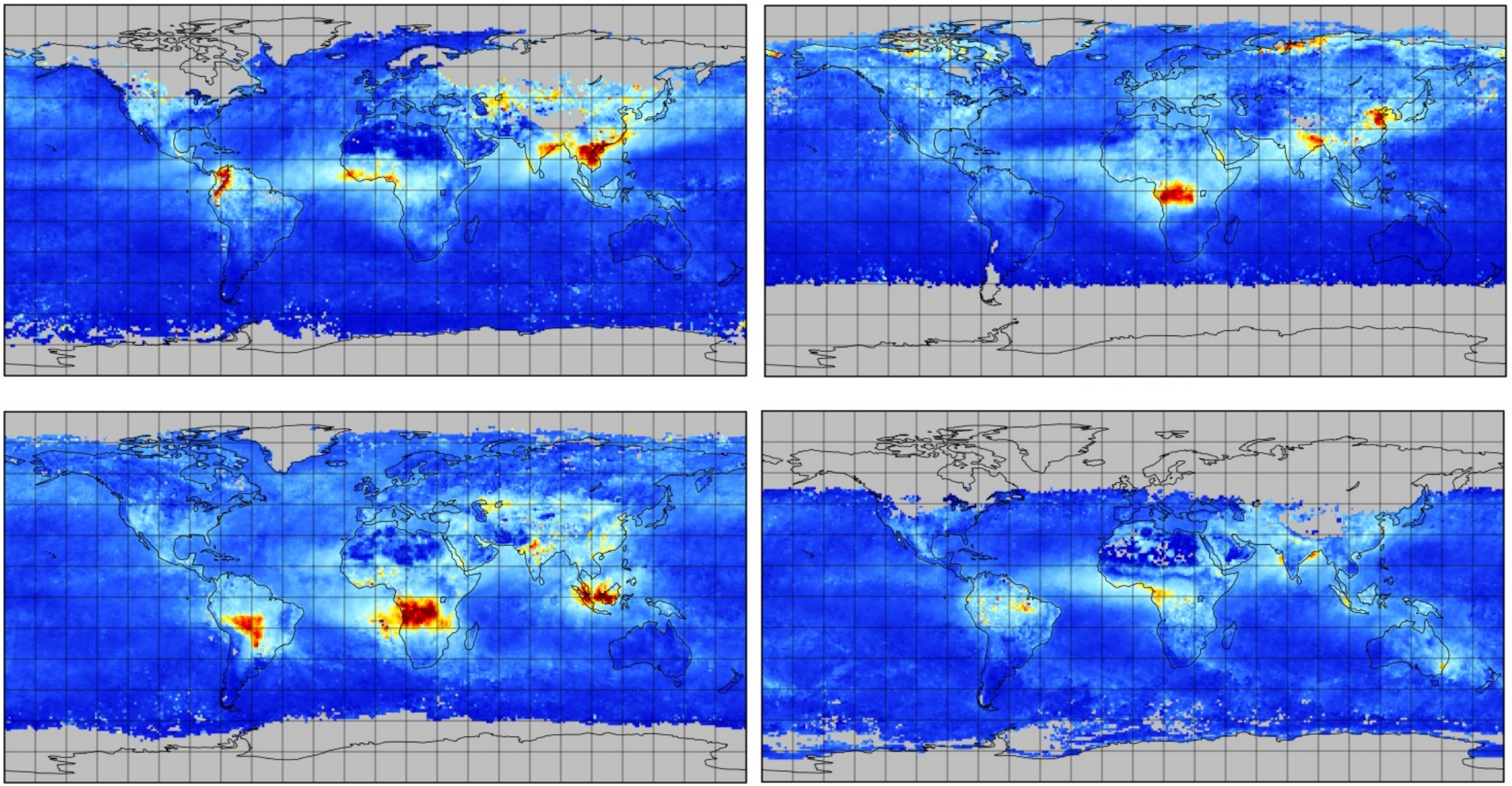
  - Practical implementation of the GCOS principles
    - Full validation: global + regional, stratified by AOD
    - Comparing algorithms: coverage + statistics + correlations
    - Long time series: stability + consistency
    - Open development approach to co-benefit in the community
    - Involvement of users to meet their needs
    - Reference data: AERONET + more capable satellite retrievals
    - Uncertainties in the products - need to be validated
    - Ensembles enable combining strengths of different algorithms

Thomas Popp, Gerrit de Leeuw, Christine Bingen, Christoph Brühl, Virginie Capelle, Alain Chedin, Lieven Clarisse, Oleg Dubovik, Roy Grainger, Jan Griesfeller, Andreas Heckel, Stefan Kinne, Lars Klüser, Miriam Kosmale, Pekka Kolmonen, Luca Lelli, Pavel Litvinov, Linlu Mei, Peter North, Simon Pinnock, Adam Povey, Charles Robert, Michael Schulz, Larisa Sogacheva, Kerstin Stebel, Deborah Stein Zweers, Gareth Thomas, Lieuwe Gijsbert Tilstra, Sophie Vandenbussche, Pepijn Veefkind, Marco Vountas and Yong Xue, Development, Production and Evaluation of Aerosol Climate Data Records from European Satellite Observations (Aerosol_cci), Remote Sensing, 8, 421; doi:10.3390/rs8050421, 2016

SLSTR: Monthly Aerosol Optical Depth (2019)

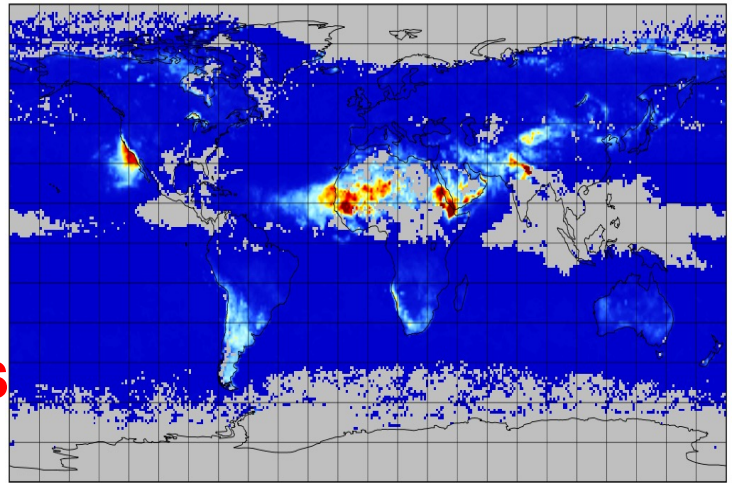


SLSTR Fine Mode AOD (2019)

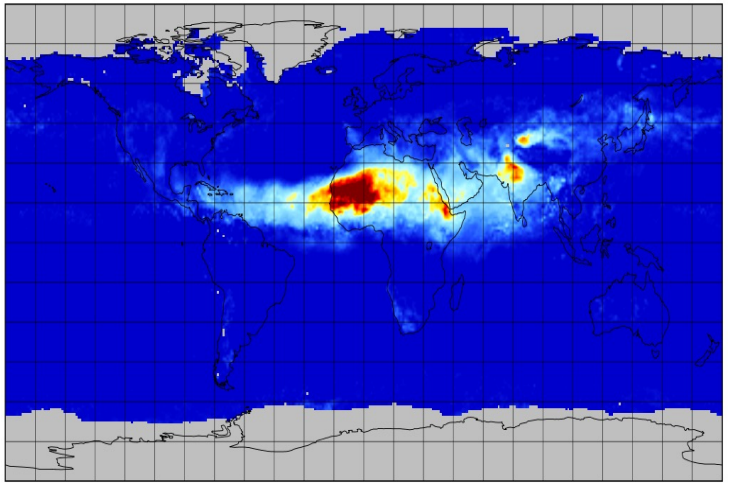


IASI Dust AOD ensemble (June 2018)

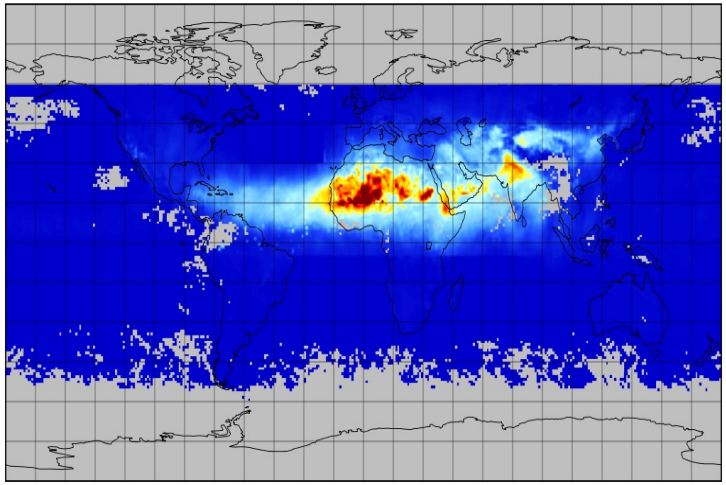
DLR IMARS



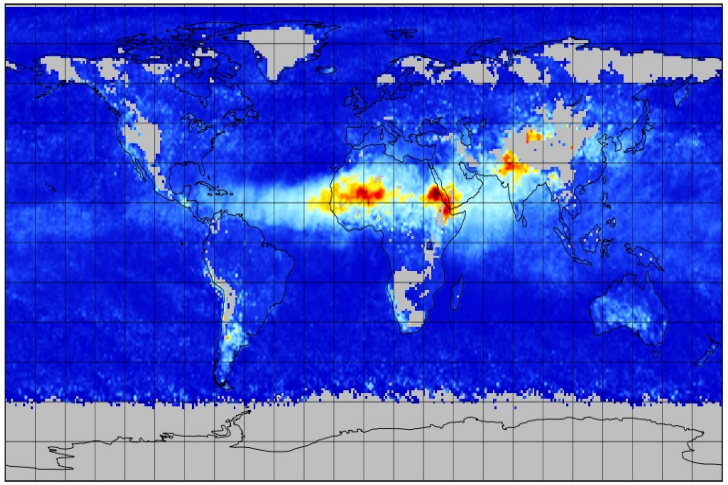
ULB



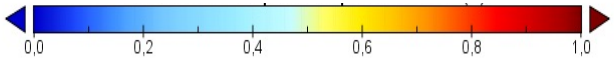
BIRA



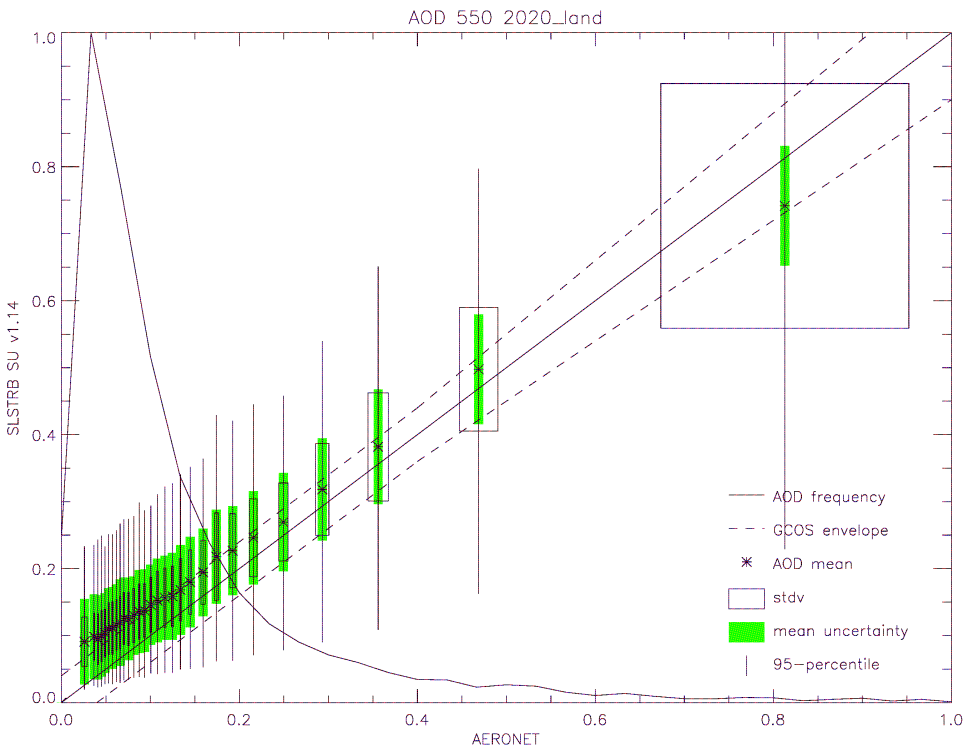
LMD

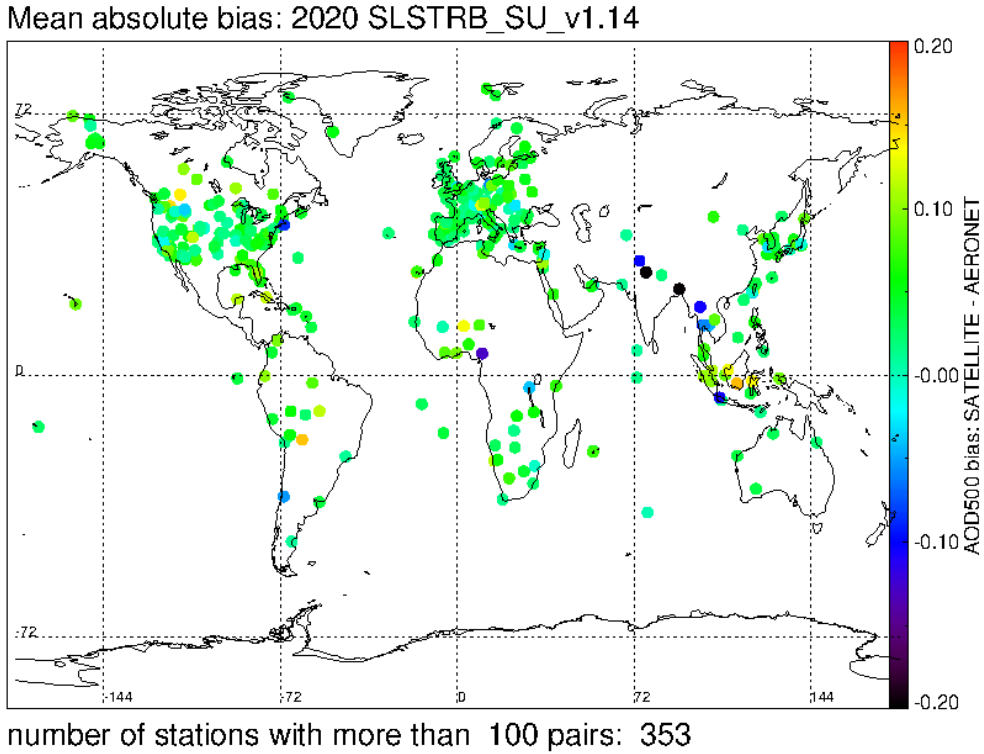


Dust AOD at 550 nm

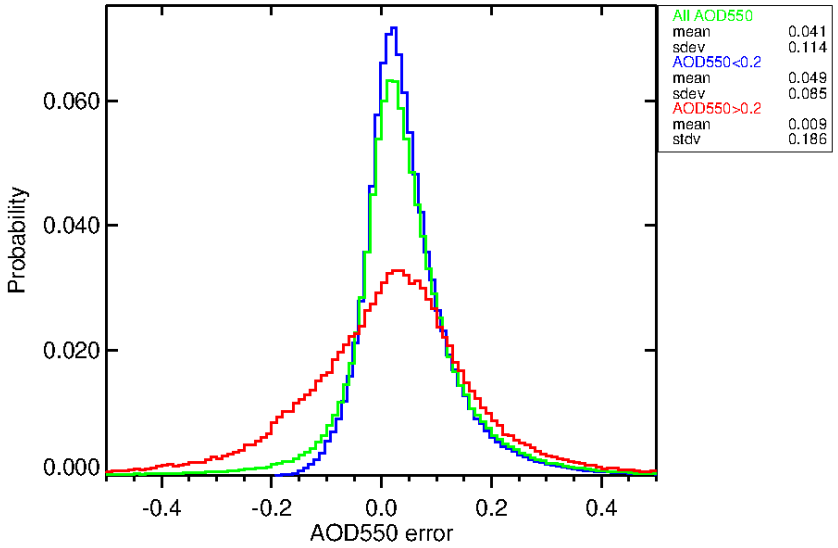


Benchmarking Swansea SLSTR algorithm





number of stations with more than 100 pairs: 353

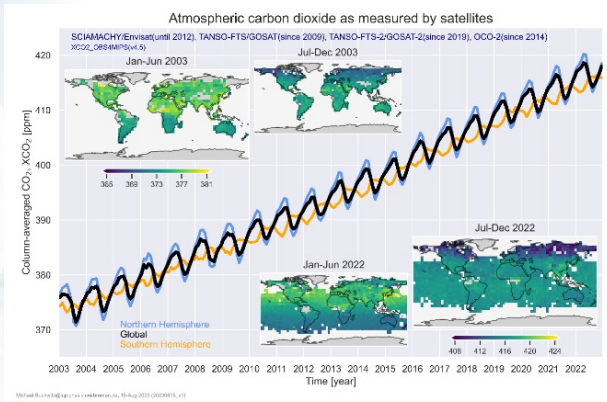


A question on operational user support …

Which support as a user would you need?

Climate Change

Atmospheric composition ECVs: Motivation



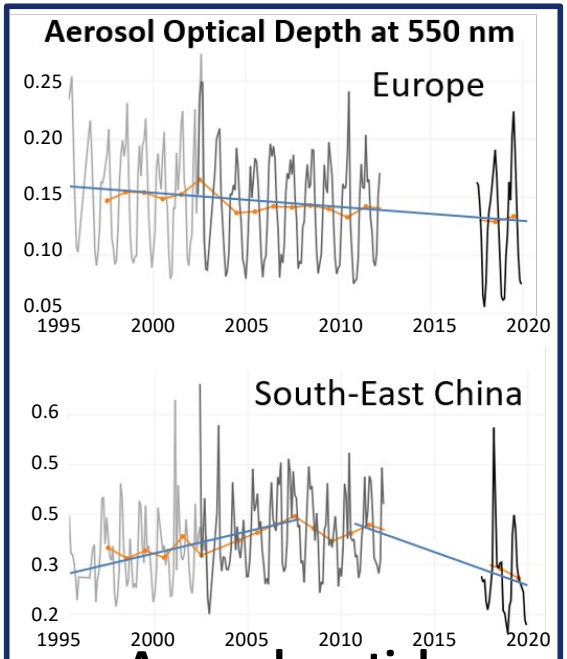
Greenhouse gases

Global

Continuous increase

Warming

CO_2, CH_4

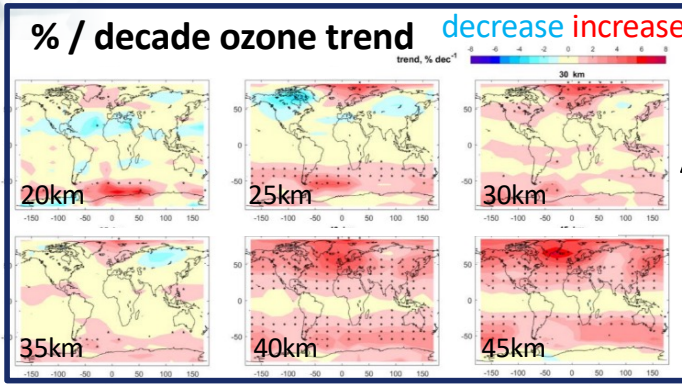


Aerosol particles

Type-dependent

Regionally varying

Mostly Cooling



Ozone

Altitude-dependent

Varying trends

Mostly Warming

Other relevance: ozone hole, air quality, renewable energy, …

Main achievements: Aerosol Climate Data Records

Climate Change

sensor	satellite	period	algorithms	mode	variables
Nadir radiometer line					
MERIS	ENVISAT	2002 - 2012	XBAER S4M Ensemble	ICDR, CDR	AOD
OLCI	Sentinel-3A	2016 -	XBAER S4O Ensemble	ICDR, CDR	
Dual-view radiometer line					
ATSR-2	ERS-2	1995 - 2003	ADV ORAC SU Ensemble	ICDR, CDR	AOD, Fine Mode AOD
AATSR	ENVISAT	2002 - 2012	ADV ORAC SU Ensemble	ICDR, CDR	
SLSTR	Sentinel-3A	2016 -	SDV ORAC SU Ensemble	ICDR, CDR	
Thermal infrared spectrometer line					
IASI	METOP-A	2007-2021	IMARS MAPIR LMD ULB Ensemble	ICDR, CDR	Dust AOD, Dust Layer Height
IASI	METOP-C	2019 -	IMARS MAPIR LMD ULB Ensemble	ICDR, CDR	
Multi-angle polarimeter line					
POLDER	PARASOL	2005 - 2013	GRASP	CDR	AOD, Fine Mode AOD, Single Scattering Albedo, Aerosol Layer Height
Star occultation spectrometer line					
GOMOS	ENVISAT	2002 - 2012	AERGOM	CDR	Aerosol extinction profiles (stratosphere)

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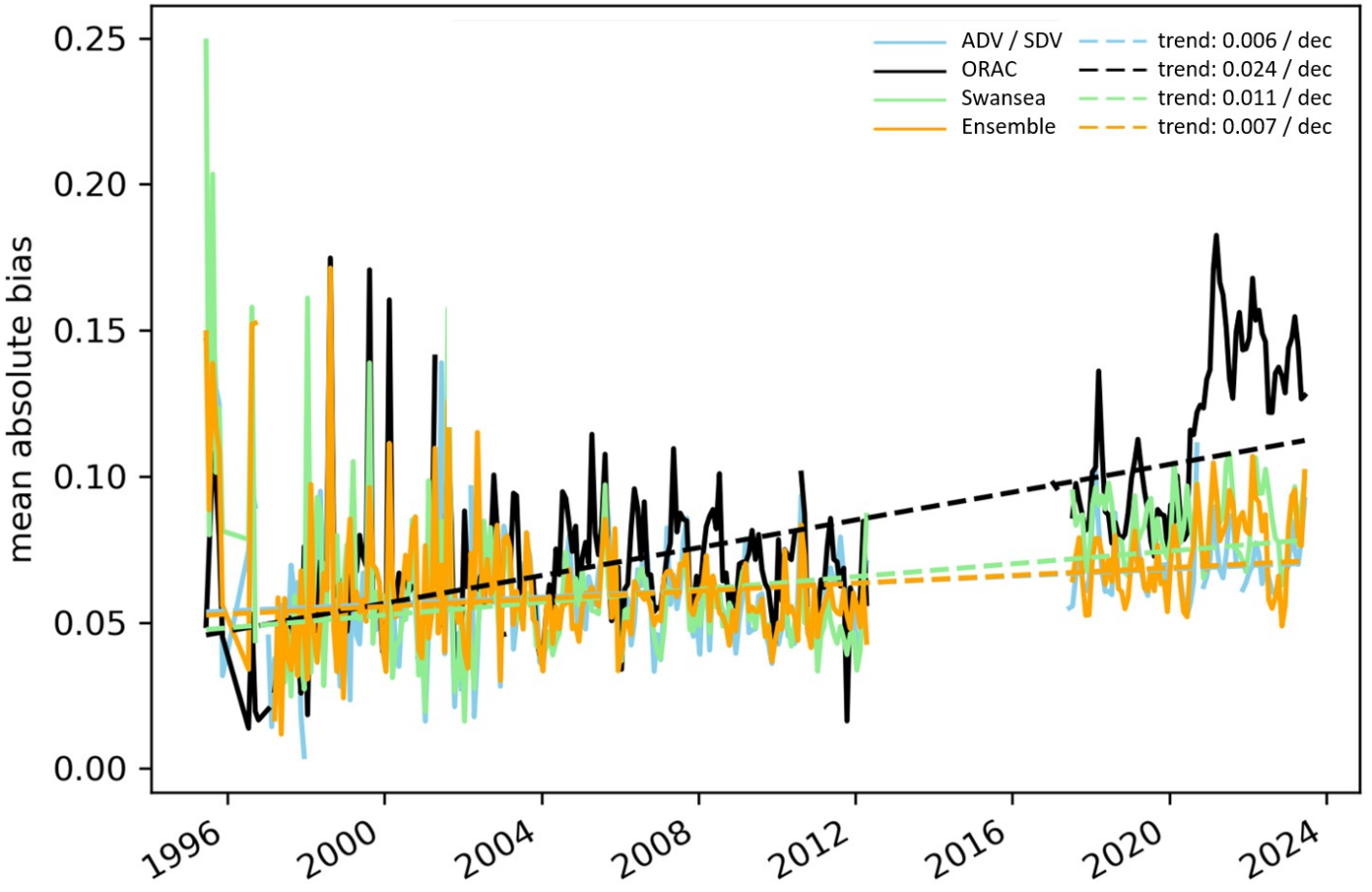
Climate Change

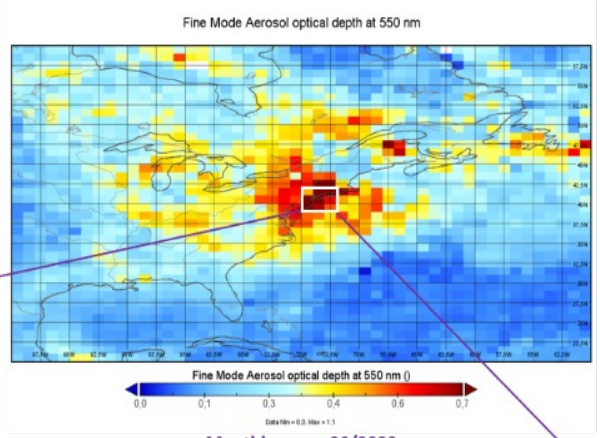
Main achievements: Aerosol record stability

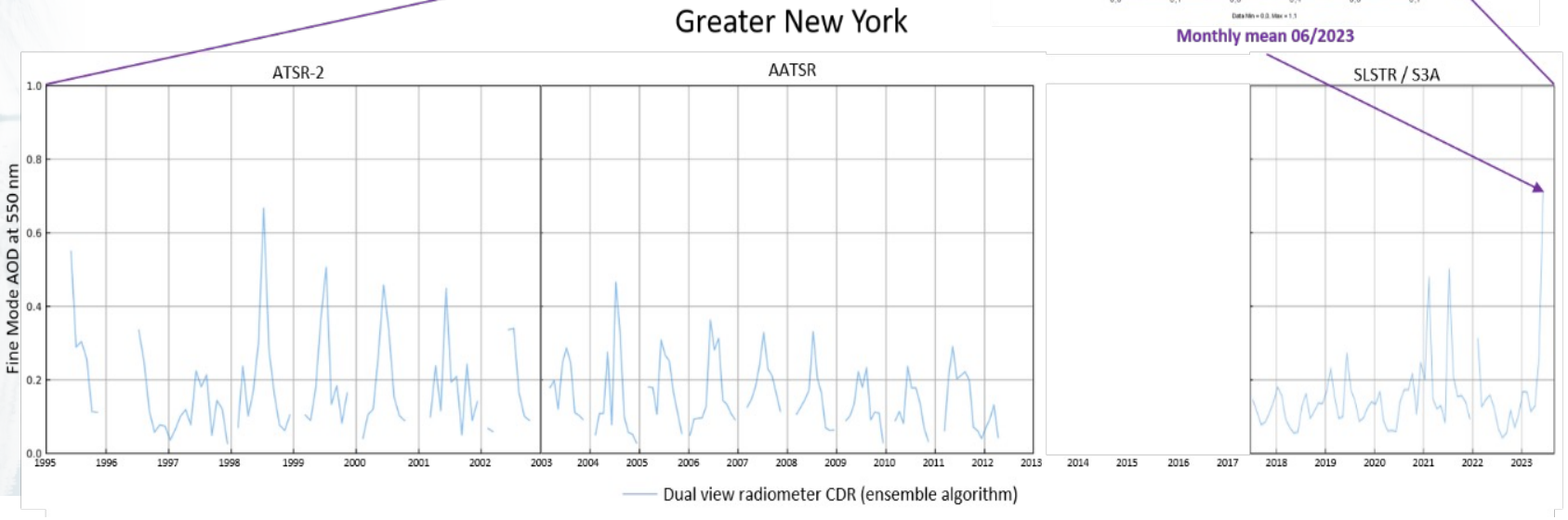
- FM-AOD multi-sensor records from the dual view instrument series ATSR-2, AATSR, SLSTR vs AERONET
- All 4 CDRs pass the GCOS threshold criterion (0.04 / decade); ADV and ensemble pass the goal criterion (0.01 / decade); pvalues confirm the significance of all 4 trends



Main achievements: Aerosol extreme event

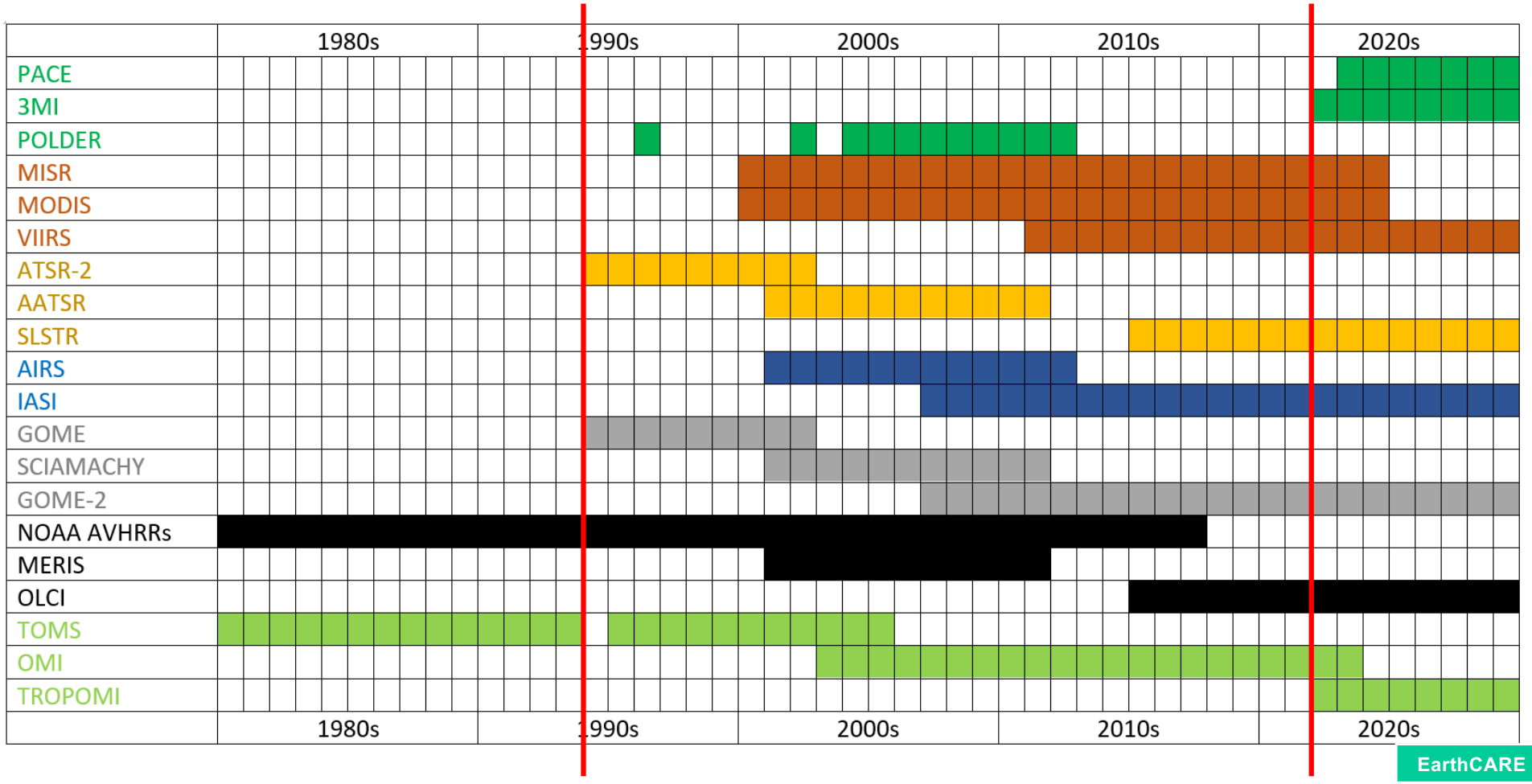
Climate Change





Aerosol CDRs: suitable instruments

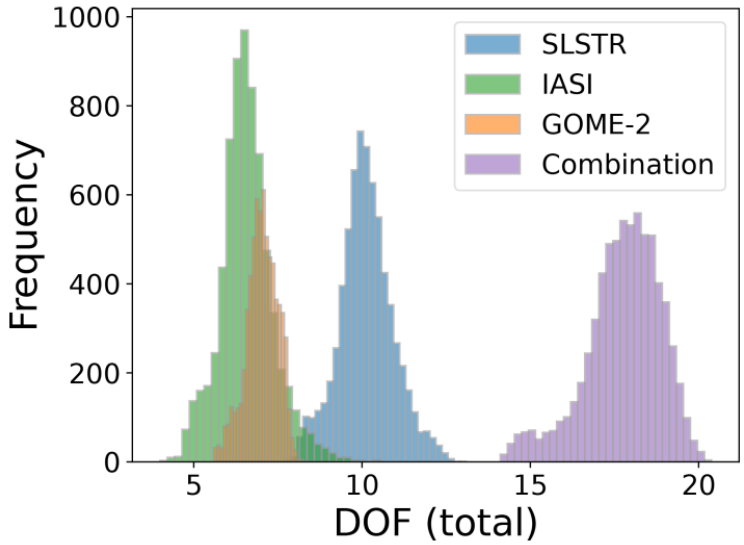
Satellite sensor line(s) for long aerosol records

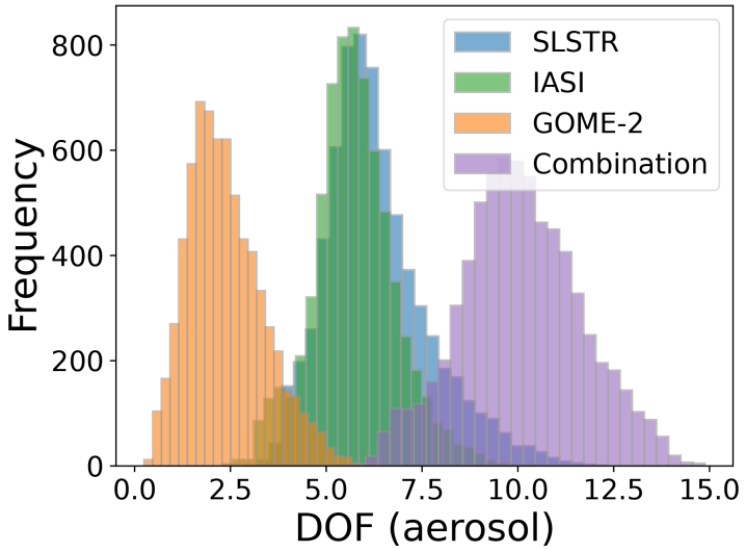


DLR

Higher information content of synergetic retrieval

- **Multi-sensor algorithm**
  - Optimal estimation approach SLSTR + IASI + GOME-2
  - AOD + aerosol properties
  - Exploit comprehensive information content of UV + VIS + TIR + dual view



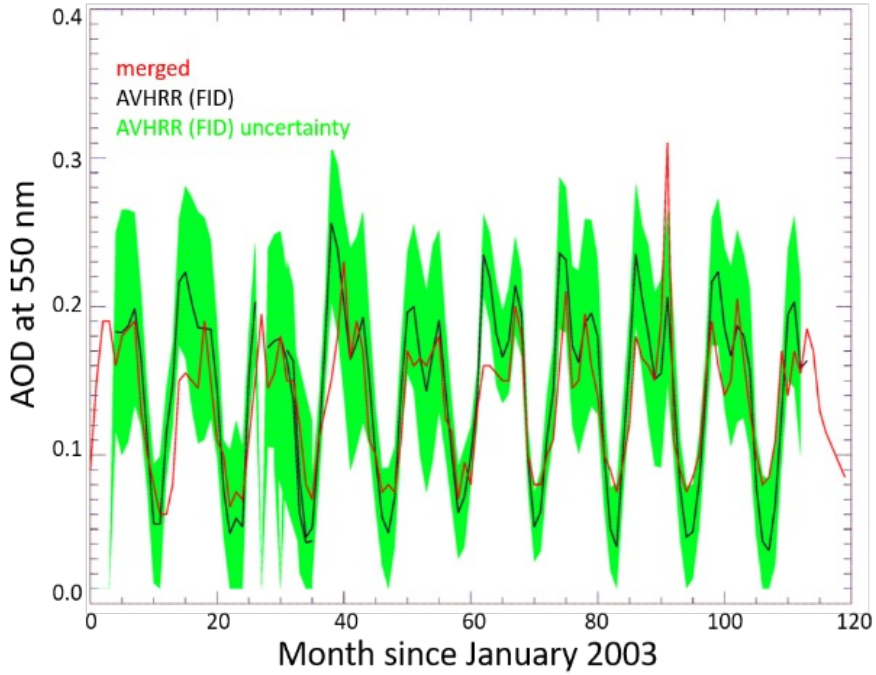


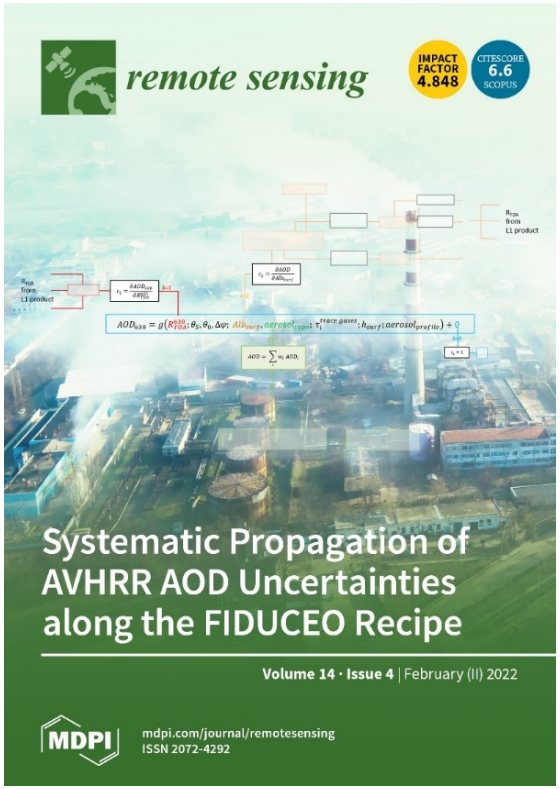
Ulrike Stöffelmair, Thomas Popp, Marco Vountas, and Hartmut Bösch, Satellite Aerosol Retrieval from a combination of three different Instruments: Information content analysis, accepted for publication, AMT, 2025

DLR

Systematic error propagation L2 –L3

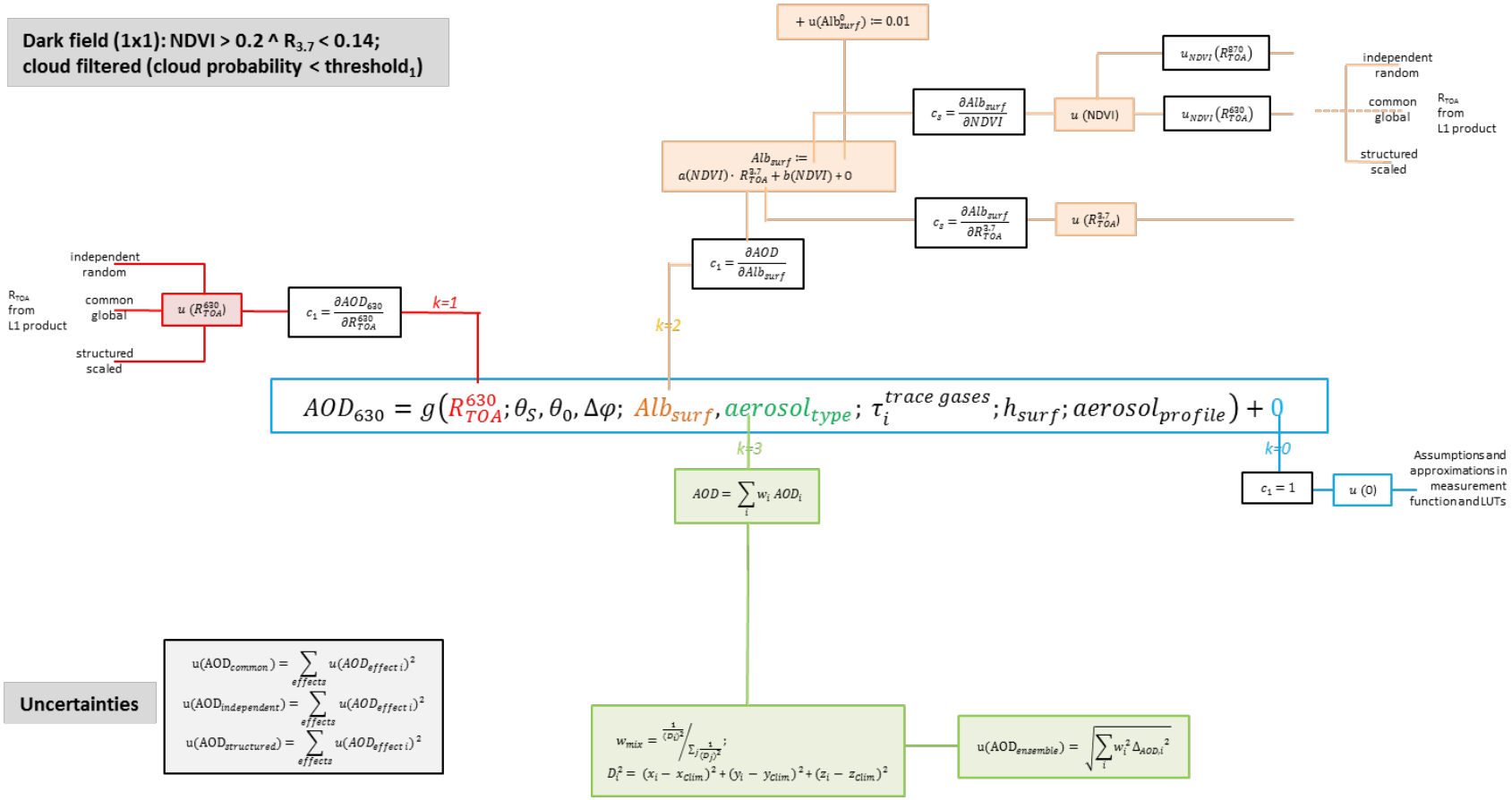
- Standards, demonstration
- Utilization for uncertainty-weighted ensemble
- Input: Level1 error characterization, AERONET





Popp T., Mittaz J., Systematic propagation of AVHRR AOD uncertainties - a case study to demonstrate the FIDUCEO approach, Rem. Sens., 2022, 14, 875, https://doi.org/10.3390/rs14040875

Analysis tree L2A



DLR

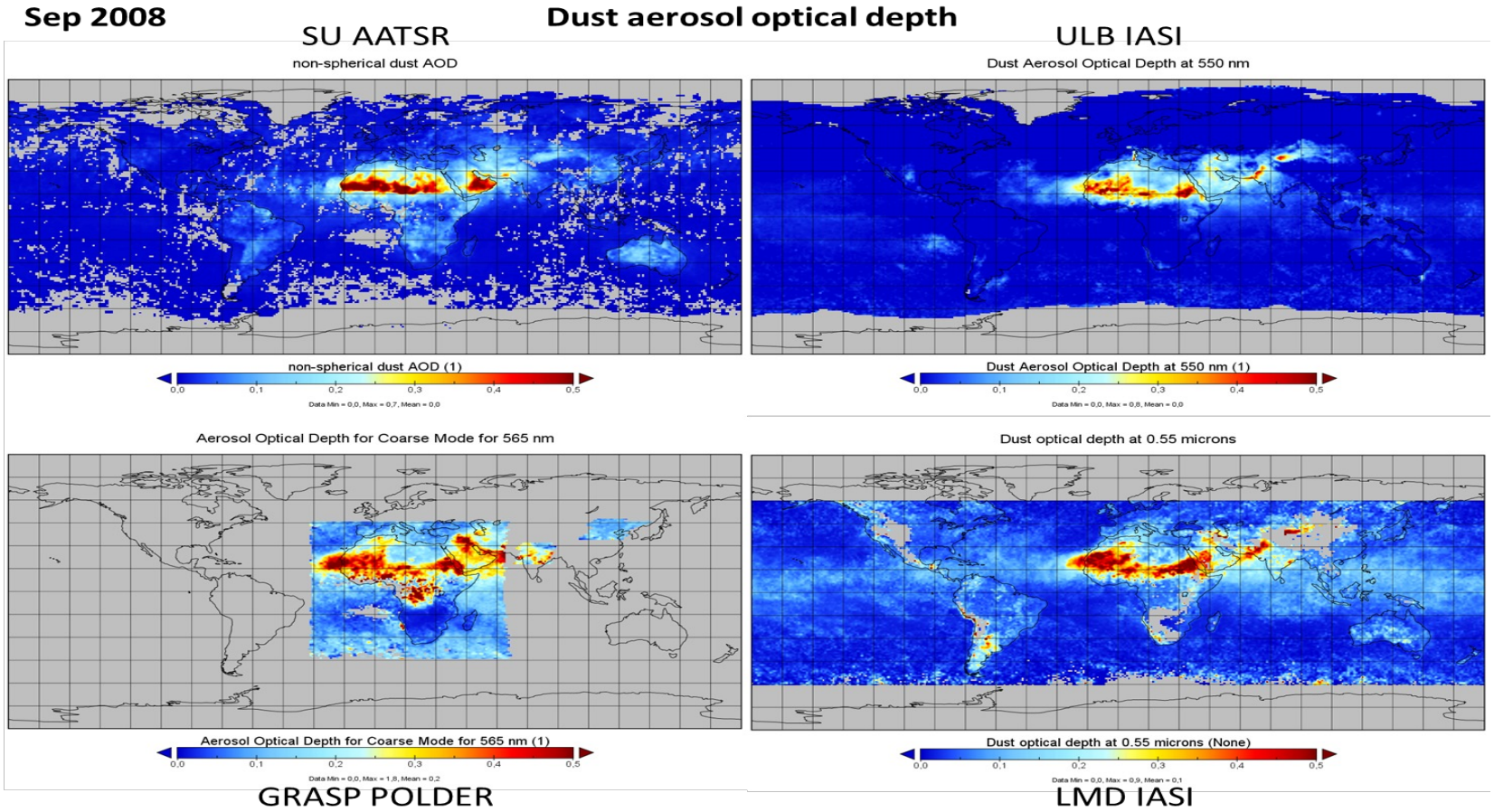
Fiduceo

A question on consistency …

Which types of inconsistency in satellite records can you imagine?

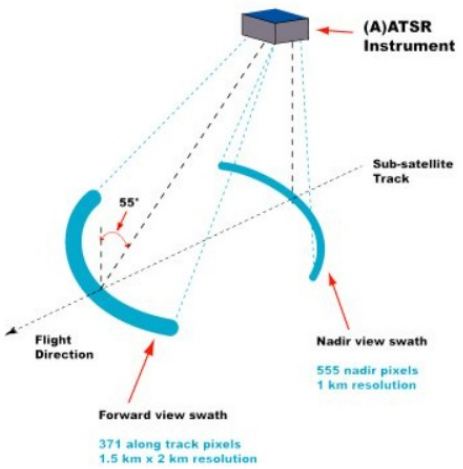
(In)consistencies of single sensor aerosol properties

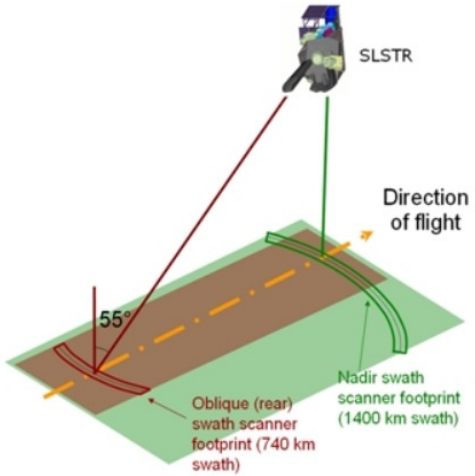
- **Possible inconsistencies**
  - Different sensors have different **sensitivities and sampling**
  - Different retrievals use different **pre-defined aerosol components + cloud masking**
  - CDR composed from **separate pieces from subsequent similar sensors**
    - Possibly with larger uncertainties in earlier pieces
  - **Different aerosol parameters** are obtained from different sensors



Dual view record – opposing viewing directions

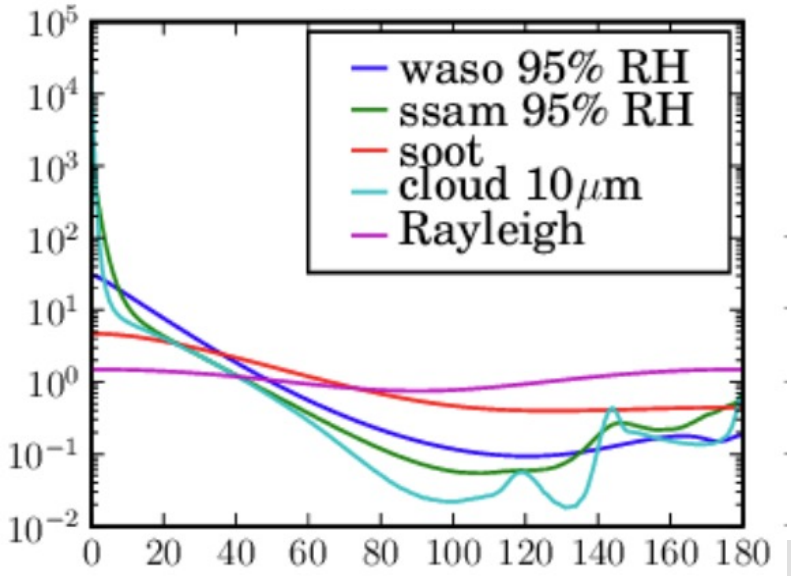
- Dual view sensor line
- ATSR instruments / SLSTR instruments
- Have opposing oblique viewing directions





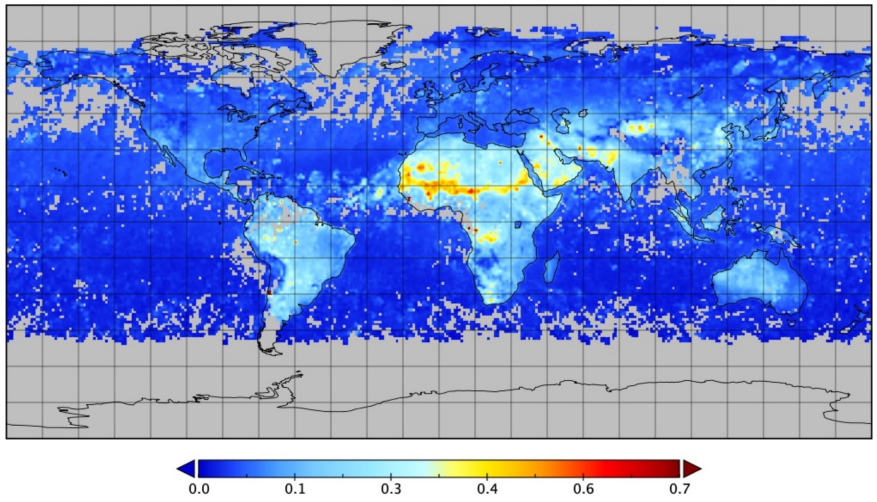
- Aerosol / Mie scattering anisotropy
  - Larger with larger particle size
  - Very large forward peak

- Consequences: Swansea algorithm open issues
  - SLSTR bias
    - despite major efforts for consistency
  - Fine Mode fraction bias
    - adaptation of dust properties?

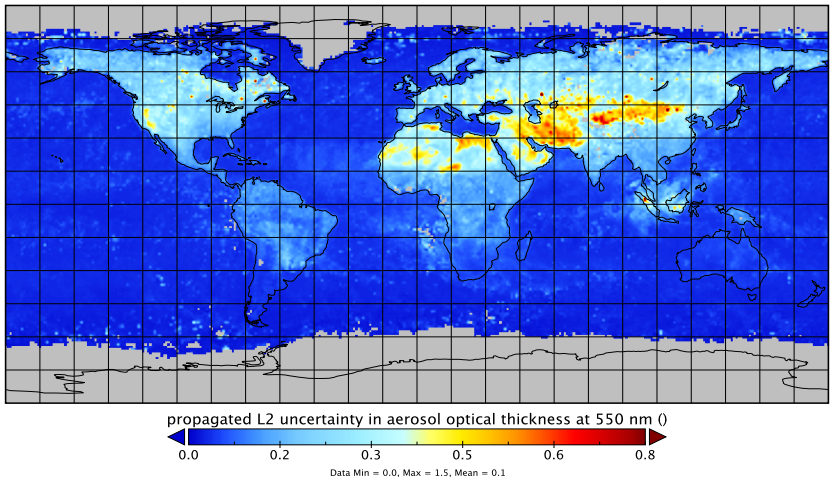


SU CCI: AATSR vs SLSTR Uncertainty

AATSR



SLSTR



- Propagated L2 Uncertainty in retrieval
- High in ‘backscatter’ direction
- Opposite hemispheric pattern (A)ATSR vs SLSTR
- Recommended for S3NGO ASLSTR revert to original geometry, additional channels for aerosol

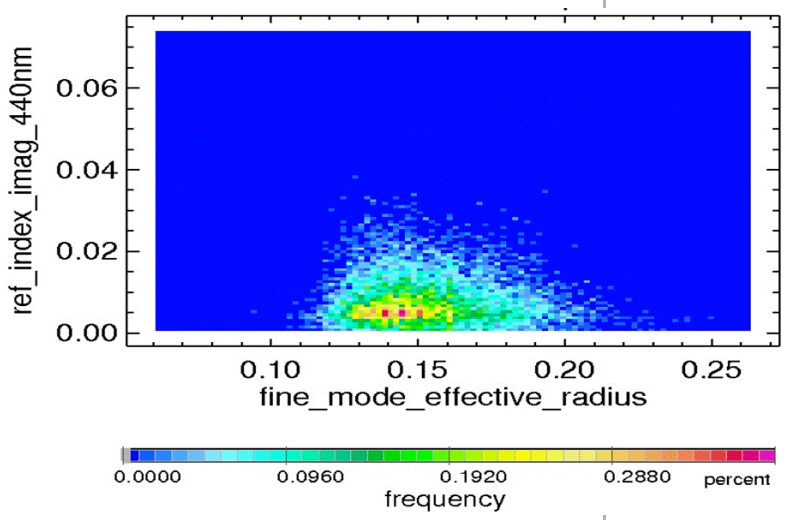
Aerosol_cci: Aerosol components

Simple

natural variability – information content

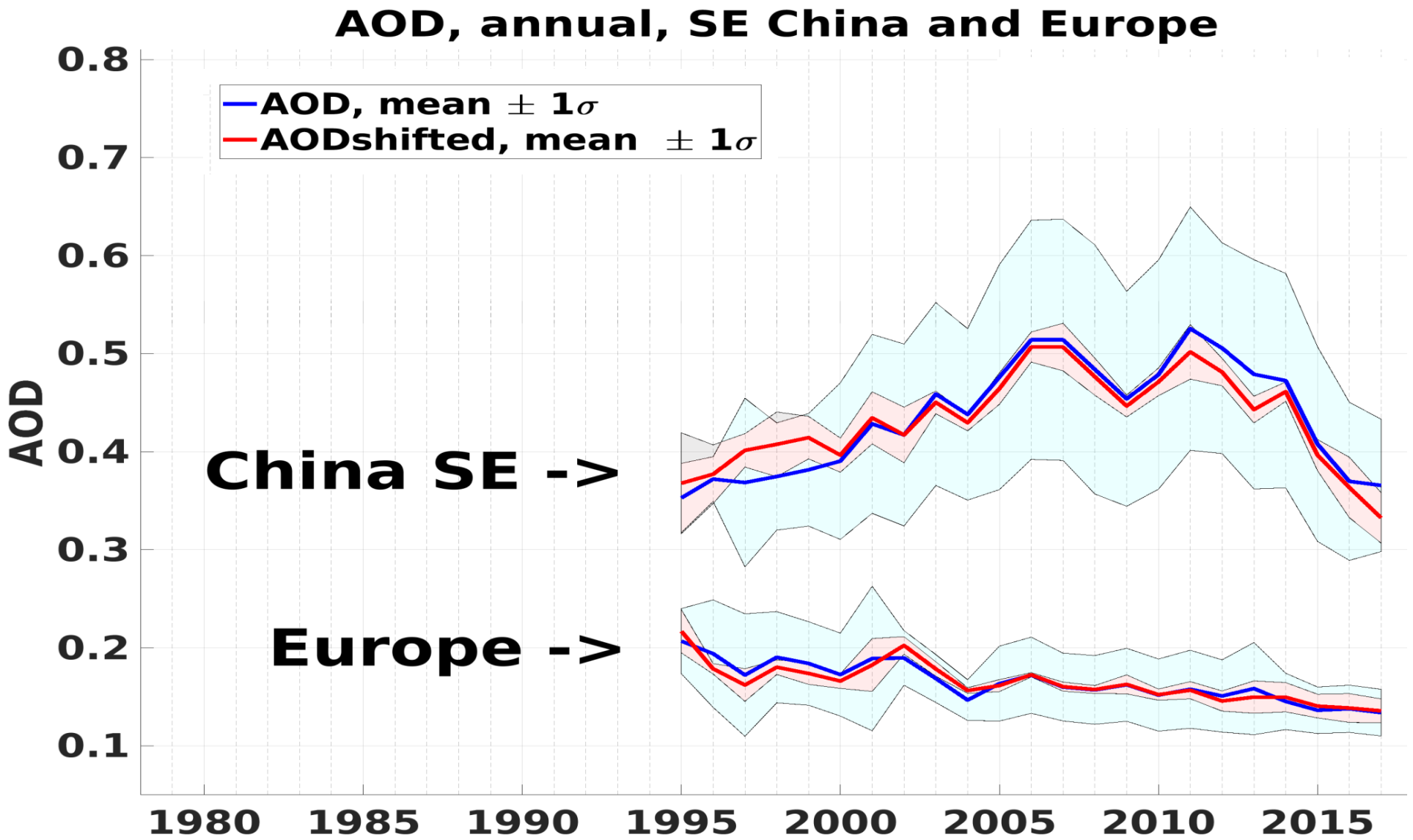
Mean Aeronet

global statistics



aerosol component	Refr. index, real part (55µm)	Refr. Index, imag part (.55µm)	reff (µm)	geom. st dev (σ_i)	variance (ln σ_i)	mode. radius (µm)	comments	aerosol layer height
Dust	1.56	0.0018	1.94	1.822	0.6	0.788	non-spherical	2-4km
	1.4	0	1.94	1.822	0.6	0.788	AOD threshold constraint	0-1 km
	1.4	0.003	0.140	1.7	0.53	0.07	(ss-albedo at 0.55 µm: 0.98)	0-2 km
	1.5	0.040	0.140	1.7	0.53	0.07	(ss-albedo at 0.55 µm: 0.802)	0-2 km

Multi-satellite time series
experiment about consistency

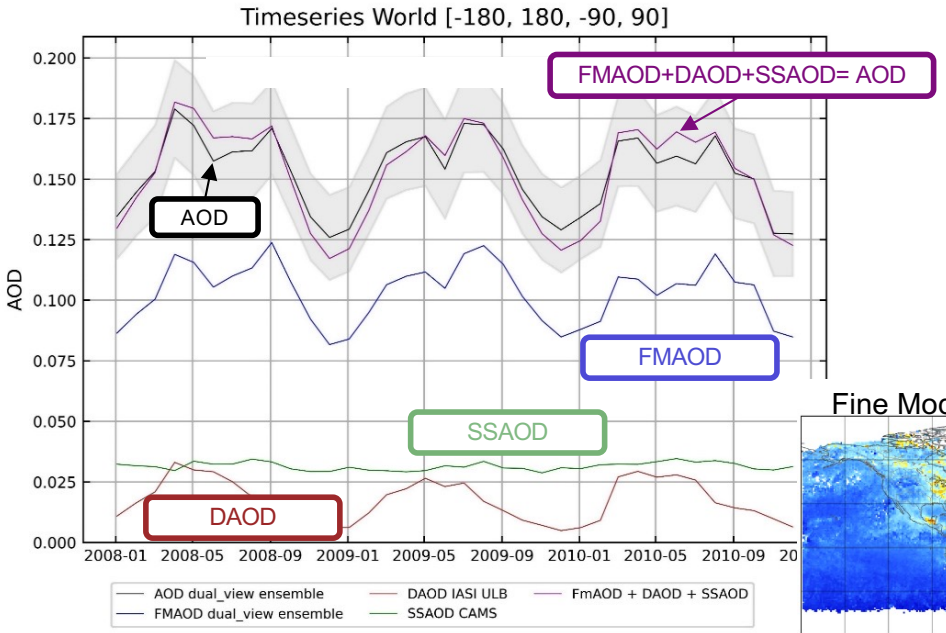


Sogacheva Larisa, Thomas Popp, Andrew M. Sayer, Oleg Dubovik, Michael J. Garay, Andreas Heckel, N. Christina Hsu, Hiren Jethva, Ralph A. Kahn, Pekka Kolmonen, Miriam Kosmale, Gerrit de Leeuw, Robert C. Levy, Pavel Litvinov, Alexei Lyapustin, Peter North, Omar Torres and Antti Arola, Merging regional and global aerosol optical depth records from major available satellite products, **Atmospheric Chemistry and Physics**, 20, 2031 – 2056, https://doi.org/10.5194/acp-20-2031-2020, 2020

Aerosol satellite dataset consistency
Copernicus Climate Change Service

Consistency: AOD = FMAOD+DAOD+SS

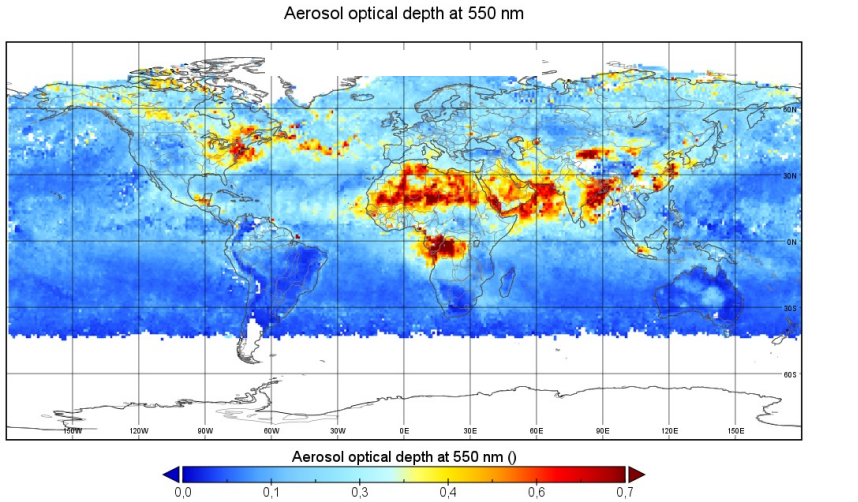
Global mean



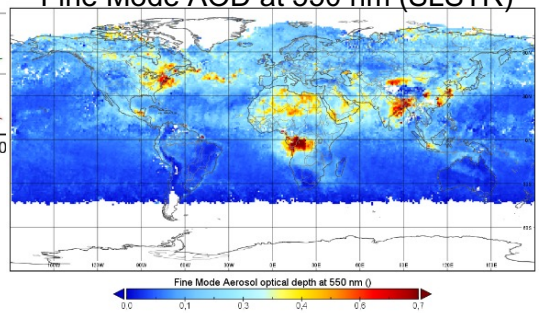
Courtesy: U. Stöffelmair, Master's Thesis

June 2023 (3 ensemble algorithms)

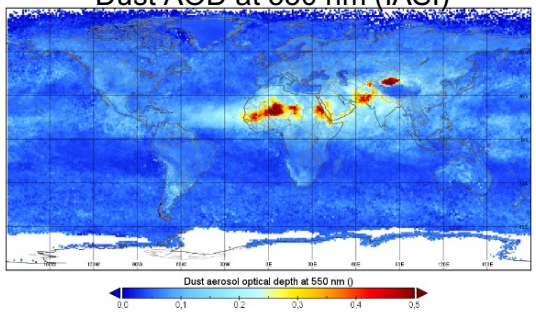
Total AOD at 550 nm (SLSTR)



Fine Mode AOD at 550 nm (SLSTR)



Dust AOD at 550 nm (IASI)



Wrap-up

- Long-term archiving
  - CCI and C3S provide operational capabilities
  - Together they guide users between their portals

- Harmonization
  - Large efforts in both programs to assure consistency
  - This is a challenging task – shown with example aerosol
    - Technical aspects (e.g. dual view instrument inconsistency)
    - Algorithm limitations: mathematically ill-posed problem
    - Validation challenges – gaps in reference data:
      - open clean ocean areas
      - Changing number of stations over long term
  - CDR best practices to implement GCOS principles
    - Have been defined to safeguard CDR quality

DLR

A final question …

What was new for you / what surprised you?