Atmospheric observations - satellite: overview, recent developments and gap analysis

Christina Köpken-Watts
Deutscher Wetterdienst (DWD), Germany

Thanks to: *N. Bormann (ECMWF), H. Anlauf (DWD), A. Cress (DWD), R. Faulwetter (DWD), V. Maurer (DWD), L. Scheck (DWD), R. Borde (EUMETSAT), M. Dahoui (ECMWF), S. Healy (ECMWF), M. Janiskova (ECMWF), T. McNally (ECMWF), E. Pavelin (MetOffice), S. English (ECMWF)*

What do we need atmospheric observations for ?

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Observations required to describe
all physically relevant parameters
for a considered process
- as completely as possible

Model dynamics and physics help
to bridge gaps by linking the variables
→ maturity of model and DA algorithm are
key to optimally exploit available data

Model development

- Understanding of processes
- Evaluation of parameterizations
- Verification of forecasts

Data Assimilation

- Operational real-time forecasts
- Reanalyses

Climate analysis

Applications determine the requirements - and what constitutes a gap, e.g.

- Horizontal scale global / regional
- Time scale short-range or medium-range NWP / long timeseries (climate)
- Required quantities e.g. NWP: prognostic variables, parameters in parameterisations

→ Focus here: operational NWP, esp. global data assimilation

Christina.Koepken-Watts@dwd.de

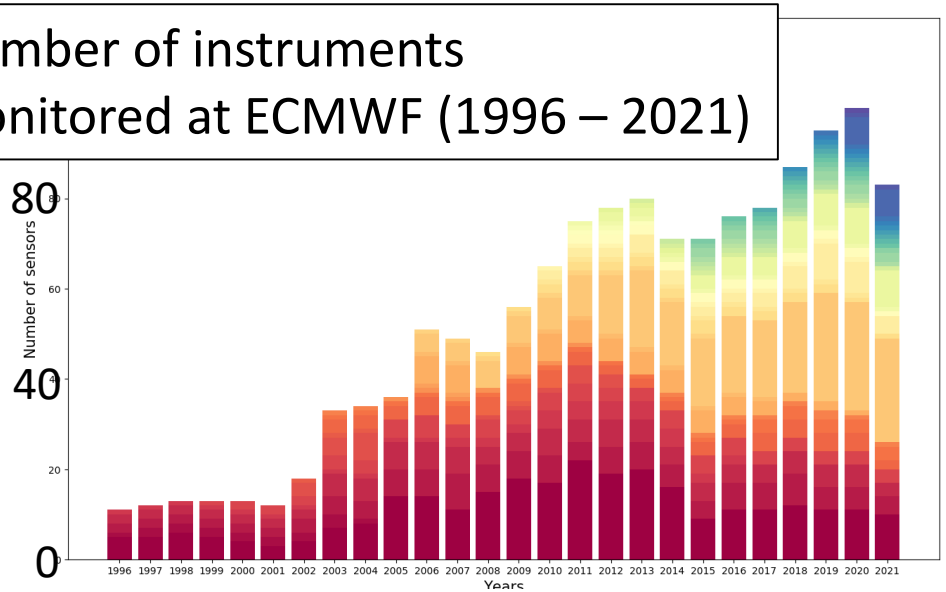
Which role do atmospheric satellites play?

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Atmospheric satellite observations

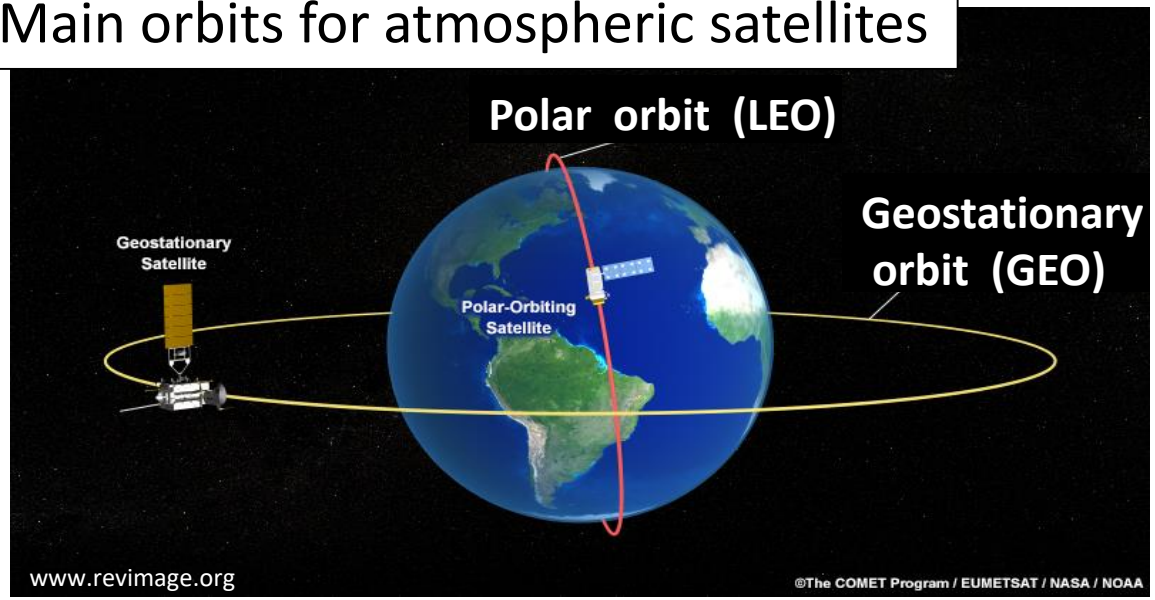
- contribute largest number of observations
- are the key component to forecast quality
- operational & research platforms: LEO and GEO

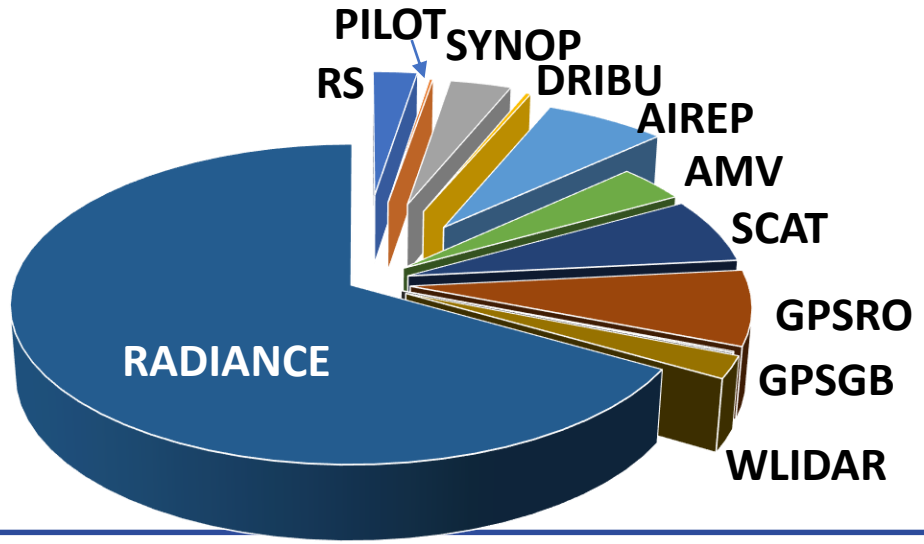
Number of instruments monitored at ECMWF (1996 – 2021)



(Mohamed Dahoui, ECMWF)

Main orbits for atmospheric satellites





85% of used obs from satellites

(DWD, 2021)

Christina.Koepken-Watts@dwd.de

What do satellites measure ?

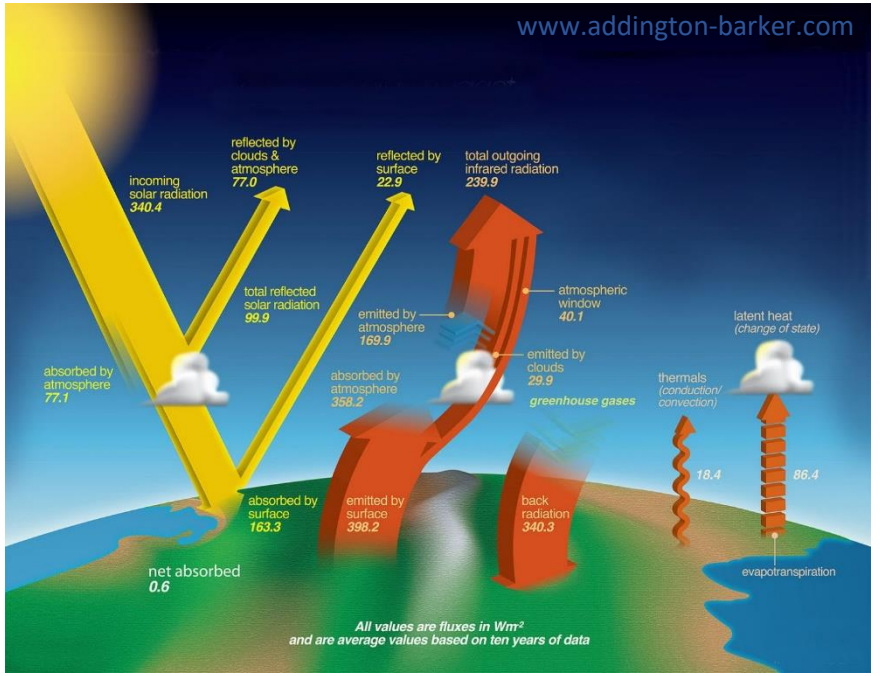
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

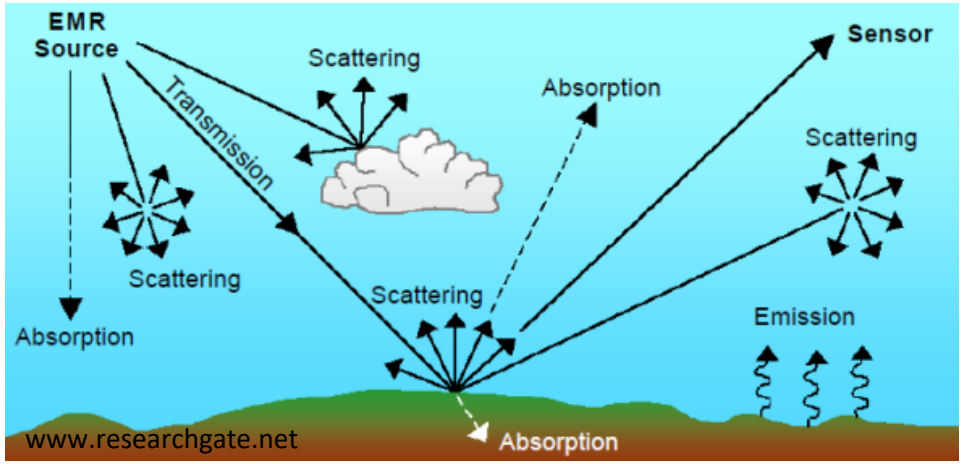
I) Passive radiometers:

- measure emitted or reflected radiation
- from earth-atmosphere system
- visible (VIS), infrared (IR), microwave (MW)

II) Active instruments:

- measure backscattered radiation (radar, lidar)



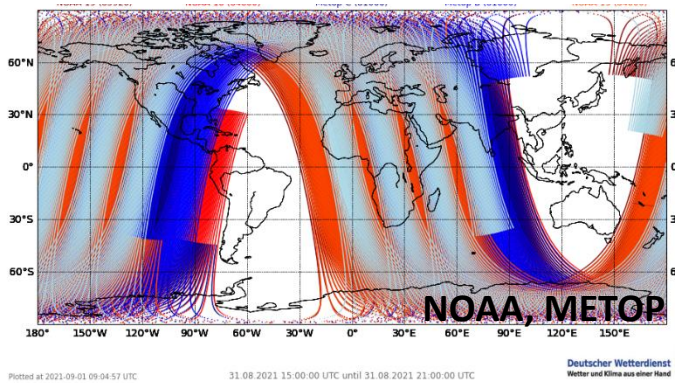


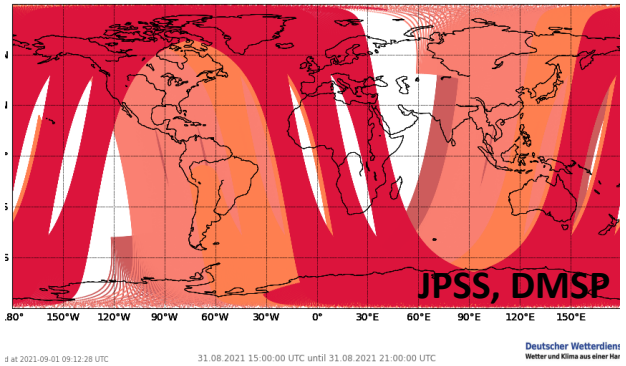
- Satellites measure the targeted quantities indirectly
- Knowledge of other influencing parameters needed
- Forward models needed to compute observation equivalents of the NWP model state

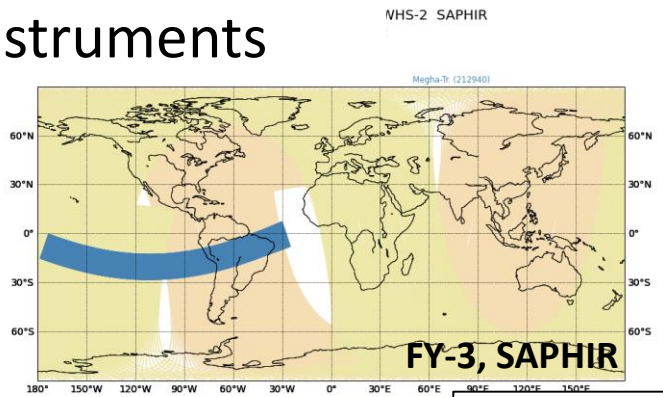
Observations of T and q profile from LEO

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Coverage for selected satellites with IR & MW sounding instruments







+ METEOR-M series

Horizontal coverage:

- Global, operational and stable
- Footprint sizes: typically ~ 12 – 50 km (nadir)

Temporal coverage:

- Gaps – fixed local solar time passage
- Partly filled through complementary orbits
  - Metop (EUMETSAT, morning)
  - NOAA, JPSS (NOAA, afternoon)
- Improving in the future:
  - FY-3E, … (CMA China, early morning)
  - Upcoming fleets of small satellites e.g. TROPICS, AWS …

Christina.Koepken-Watts@dwd.de

Observations of T and q profile from LEO

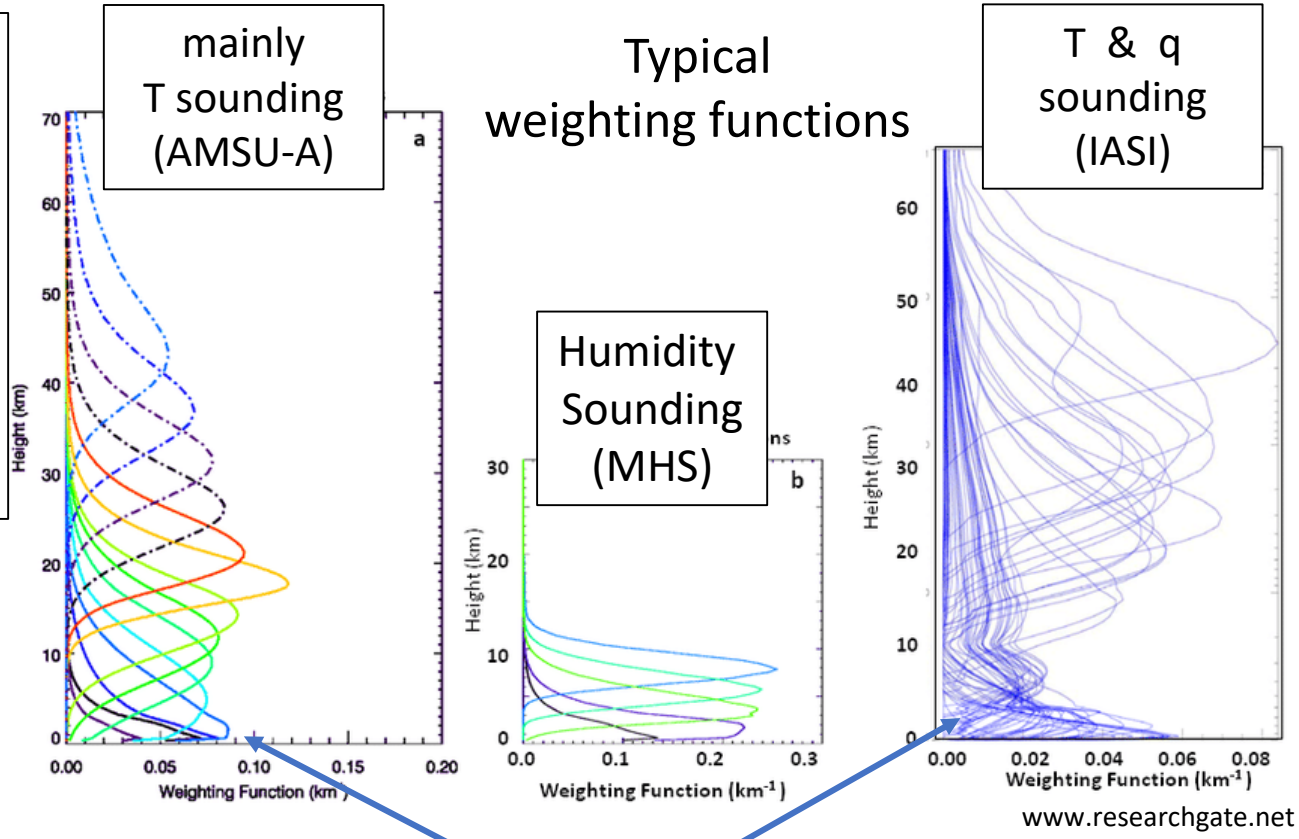
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

MW sounders:

- Profile information (also cloudy situations)
- AMSU-A, MHS, ATMS, MWHS, ...

Hyperspectral IR sounders

- More vertical detail (only above clouds)
- IASI, CrIS, HIRAS, …



Gap: Limited vertical resolution

→ Limb sounders can complement

- Key area: upper troposphere to mesopause
- High vertical – low horizontal resolution
- but: few research satellites only
  e.g. AURA MLS (MW limb sounding)

Low peaking channels:

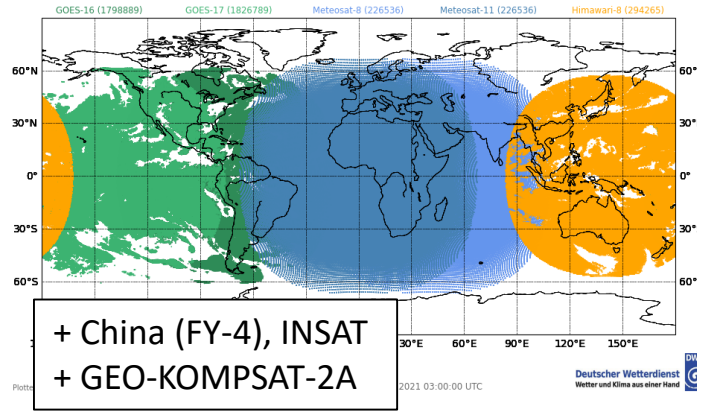
→ knowledge of surface influence critical

GEO observations of T and q

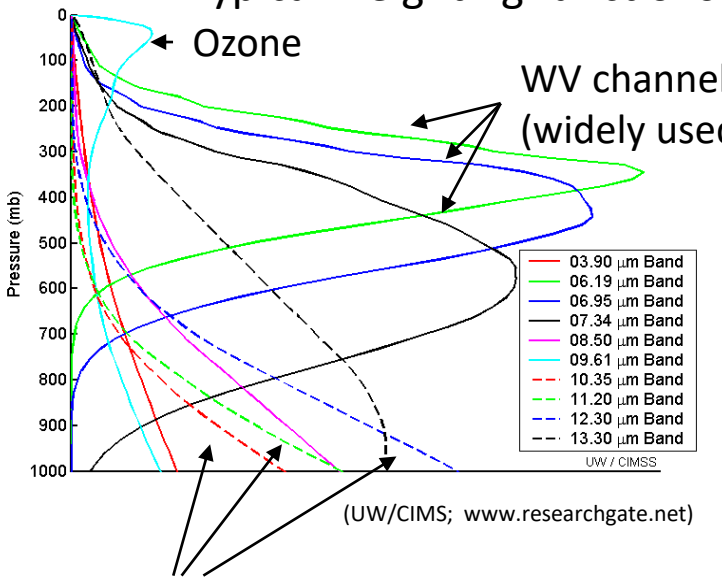
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

- VIS and IR imagers
- Complementary to LEO:
  - Continuous coverage in disc
  - High temporal resolution
    5 – 15 min.
  - Limited vertical resolution

Coverage by GOES, METEOSAT, Himawari



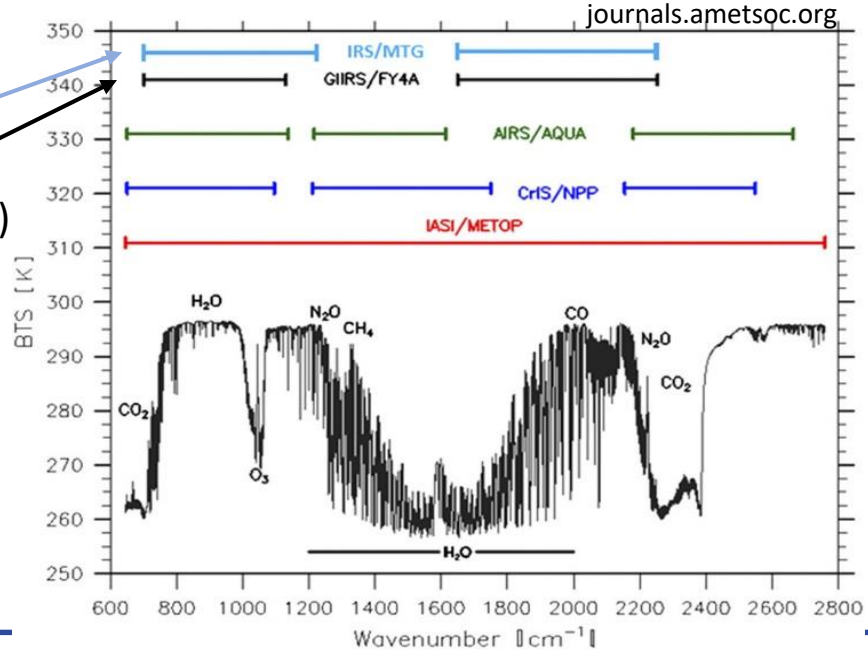
Typical weighting functions



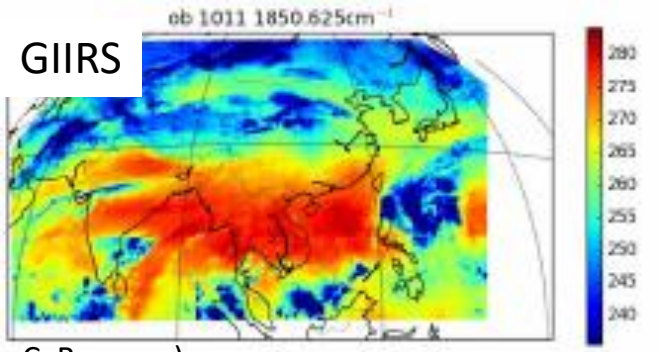
(UW/CIMS; www.researchgate.net)

- New technology:
  - GEO hyperspectral IR
  - MTG IRS (~ 2024)
  - GIIRS (FY-4A 2016, FY-4B 2021)

journals.ametsoc.org



GIIRS



C, Burrows)

Window channels:

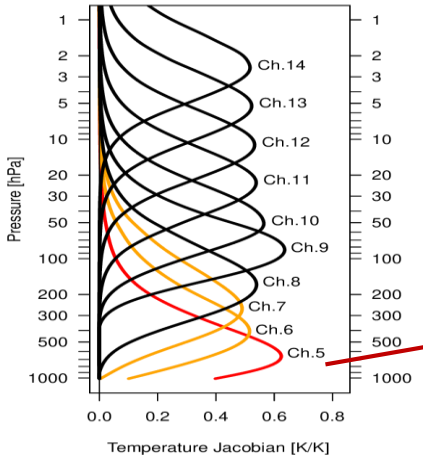
- Low troposphere signal (+surface)
- Knowledge of surface emission needed
- Underexploited, but
  → potential also for diurnal cycle, high-resolution, short-range NWP

Christina.Koepken-Watts@dwd.de

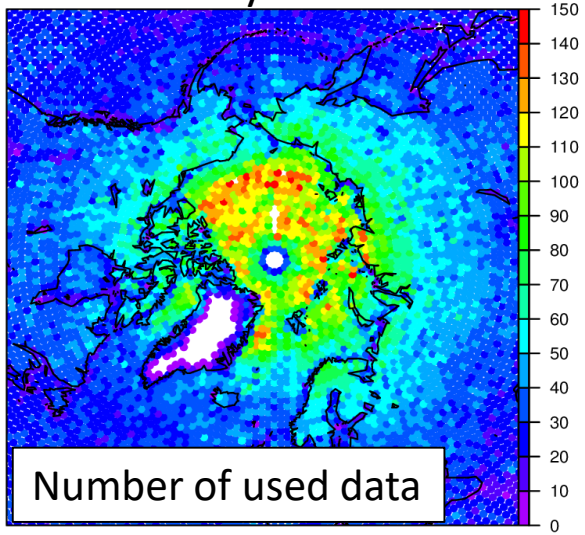
Usage gaps for satellite sounding data T and q

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

1) AMSU-A low channels:

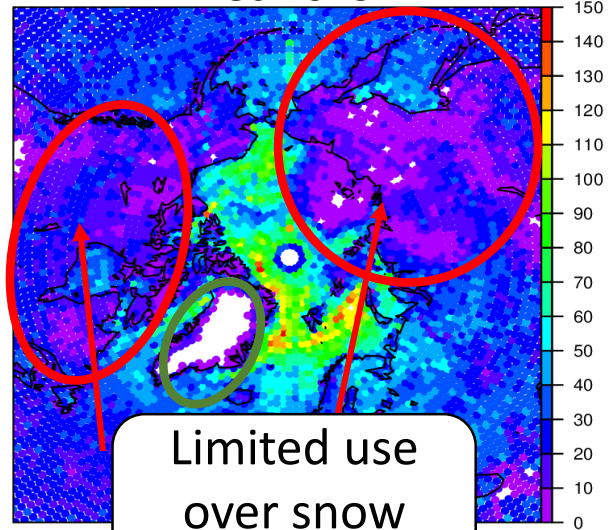


July 2019



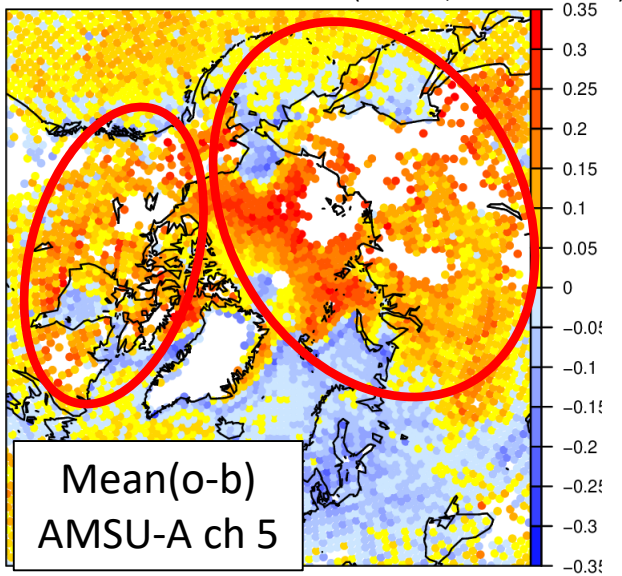
Number of used data

Dec 2019



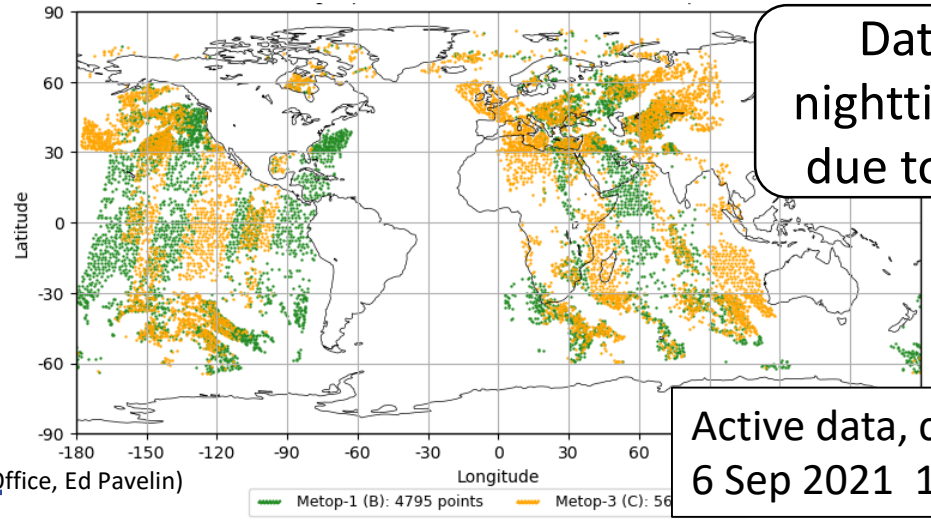
Limited use over snow covered land

(ECMWF, Niels Bormann)



Mean(o-b) AMSU-A ch 5

2) IASI low peaking channels



(MetOffice, Ed Pavelin)

Data assimilated nighttime only (mainly due to Ts inccuracies)

Active data, ch. 1408 cm^{-1}
6 Sep 2021 18 UTC

Data gaps in usage often linked to model quality, esp. at earth surface
→ improvements needed
- land modelling (→ ESMs)
- forward models (e.g. snow, ice)

Christina.Koepken-Watts@dwd.de

Radiooccultation observations: GNSS-RO

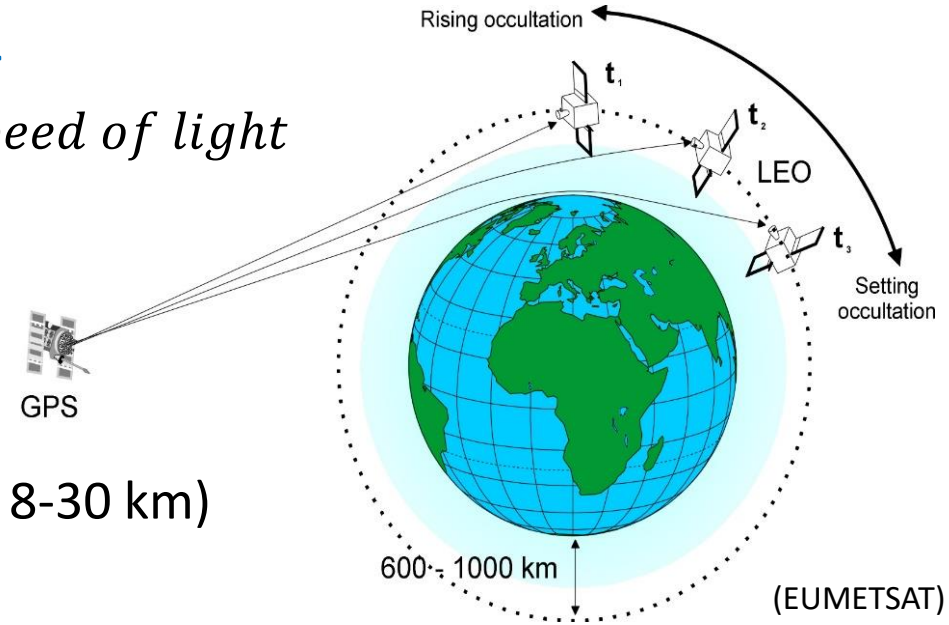
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Measurement of travel time from GNSS satellite to LEO receiver

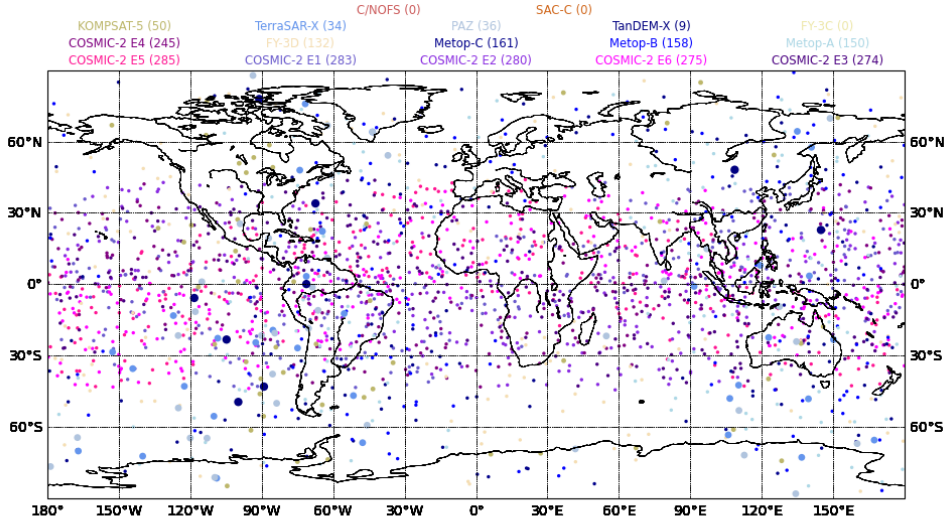
- $T = L / c \;,\; L = \int n(s)\, ds \;,\; n = refractive\ index, c = speed\ of\ light$
  $n = f(T, q, p) \rightarrow$ information about T, q - profile
- Small sensitivity to p_s
- Height range for profiles: ≈ 3 km – 30 km (60 km)

✓ Essentially bias free observations

→ Anchor for bias corrections of radiance data in DA (esp. ~ 8-30 km)



(EUMETSAT)



Coverage : 9 – 15 UTC, 28 Aug 2021

Operational:

- COSMIC-2 (tropics), METOP-A/B/C, FY-3, …

Research:

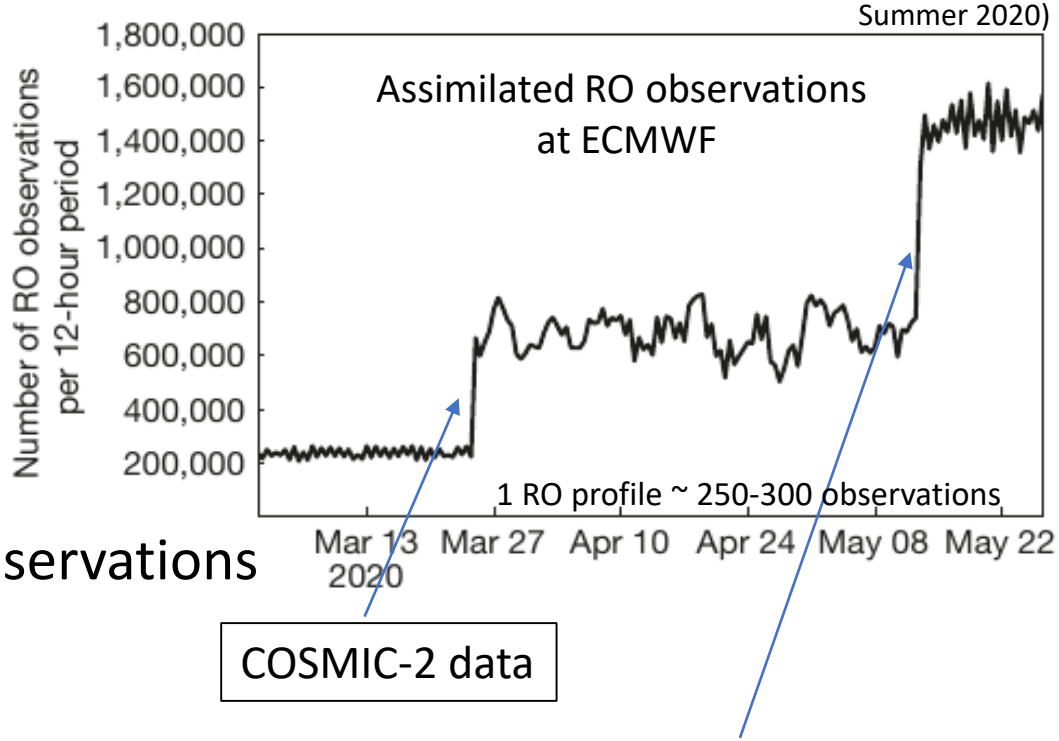
- KOMPSAT-5, PAZ, TerraSAR-X, TanDEM-X, GRACE-FO

More receivers in space, but not all provide near-real time data

Recent developments for GNSS-RO

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

(Sean Healy, ECMWF Newsletter, Summer 2020)



✓ Good prospects for increasing data coverage

- Recent addition of COSMIC-2 satellites (tropics)
- Additional data from commercial providers
  - e.g. SPIRE, GeoOptics, …
  - large fleets of (often) nano-satellites for RO observations
  - Issue: free exchange of data
- New instruments will receive signals of several GPS systems:
  GPS, GLONASS, Galileo, BeiDou …
  e.g. Sentinel-6 (Tri-G receiver)

SPIRE data provided to selected NWP centres during drop in aircraft OBS (spring 2020)

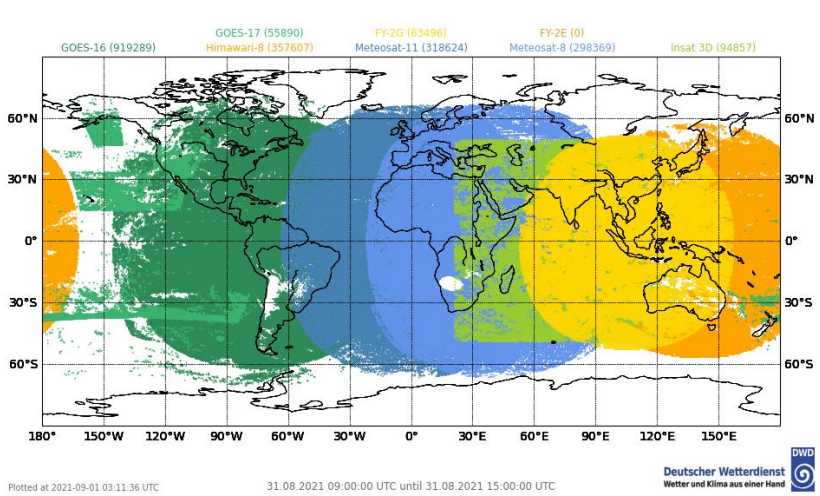
Christina.Koepken-Watts@dwd.de

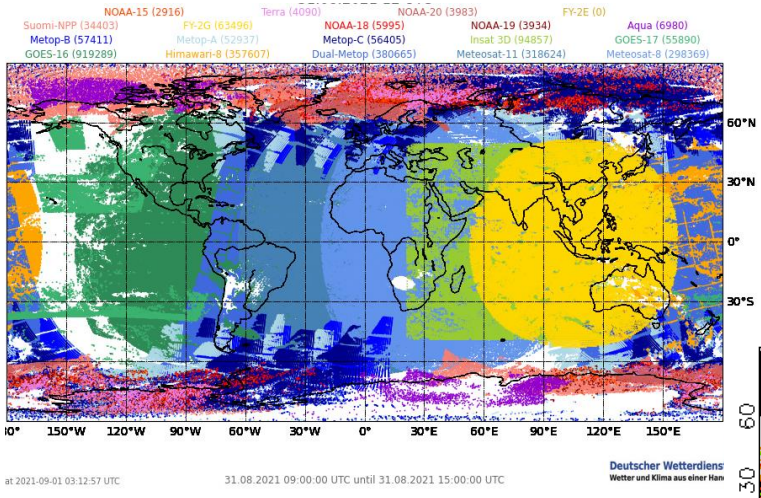
Wind observations from satellites

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

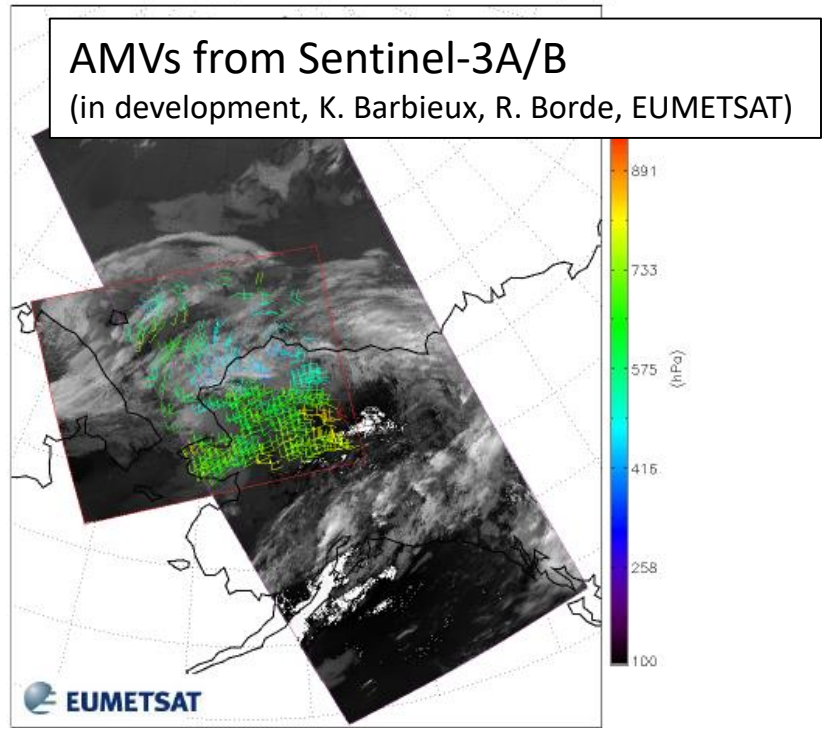
Atmospheric motion vectors - AMVs

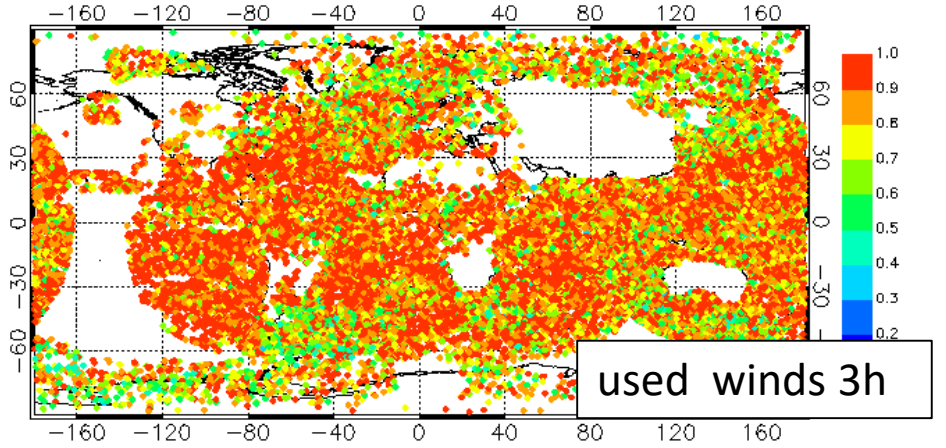
- derived from consecutive images – GEO or LEO orbit pairs
- VIS, IR and WV channels
- (u,v) : tracking of cloud objects and water vapour structures
- Height assignment: cloud top and T-profile (from NWP)





AMVs from Sentinel-3A/B
(in development, K. Barbieux, R. Borde, EUMETSAT)





used winds 3h

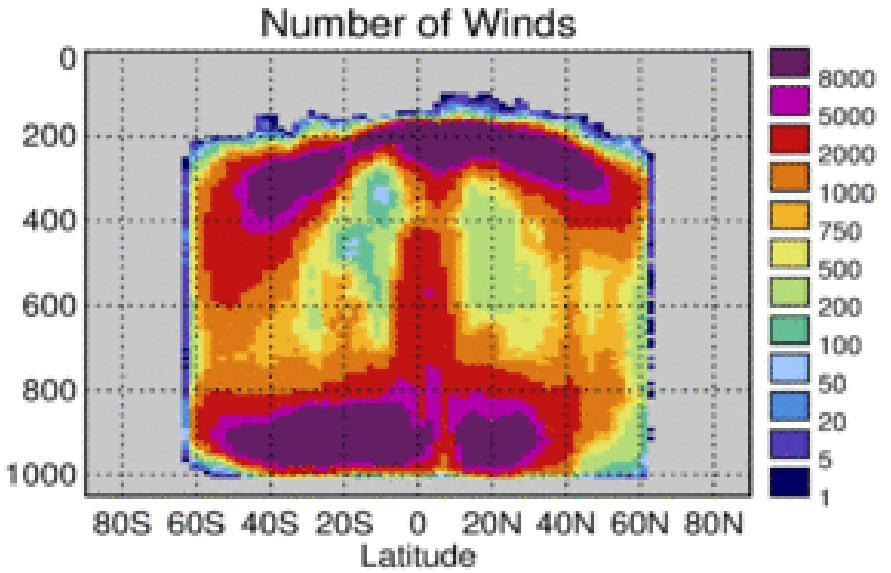
➢ Good horizontal coverage, some gaps remain 55-70 N/S

➢ Not all AMVs are of the same quality – usage gaps

Wind observations from satellites

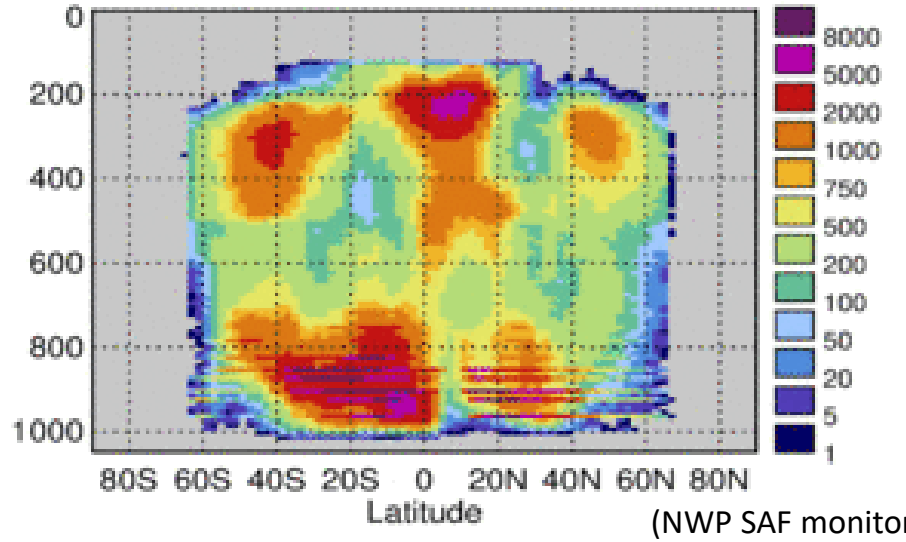
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

- Vertical coverage by AMVs
  - Distribution mostly linked to cloud cover
  - Best coverage at high and low levels
  - Few winds at mid levels, in subtropical subsidence zone
  - Clear-sky WV channel winds more complicated to use (broad vertical signal)
  - No profile information



IR winds
GOES-16

Jul 2021



IR winds
MET-11

Jul 2021

(NWP SAF monitoring, MetOffice)

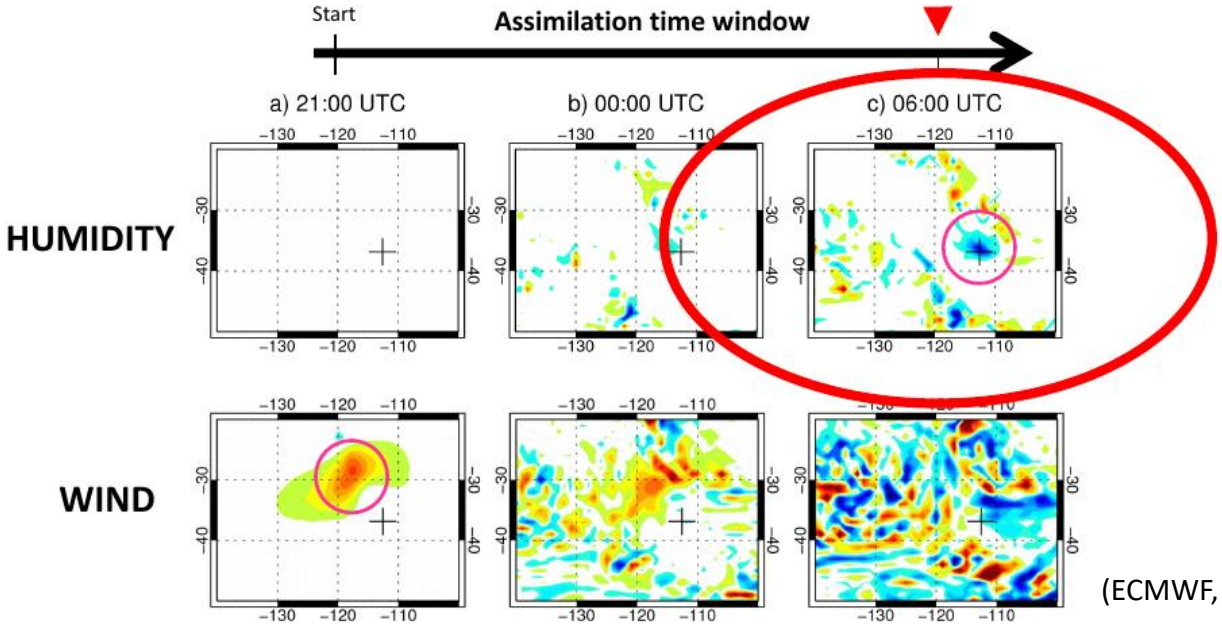
Christina.Koepken-Watts@dwd.de

Indirect wind `observations` from satellites

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

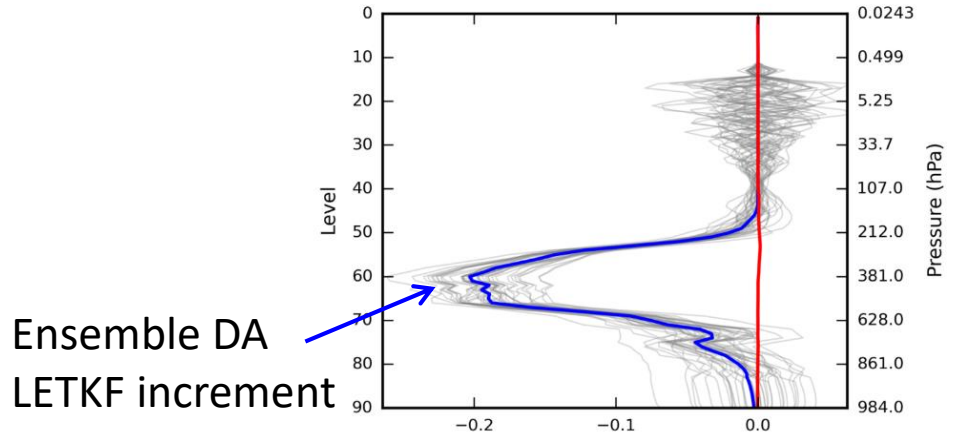
DA can exploit relationship between wind and other fields (e.g. q, trace gases, cloud, …)

4Dvar: Adjustment of model trajectory over time window
Model integration and adjoint link e.g. v ↔ q



(ECMWF, T. McNally)

Ensemble-DA:
Ensemble covariances
link variables, e.g. v ↔ q



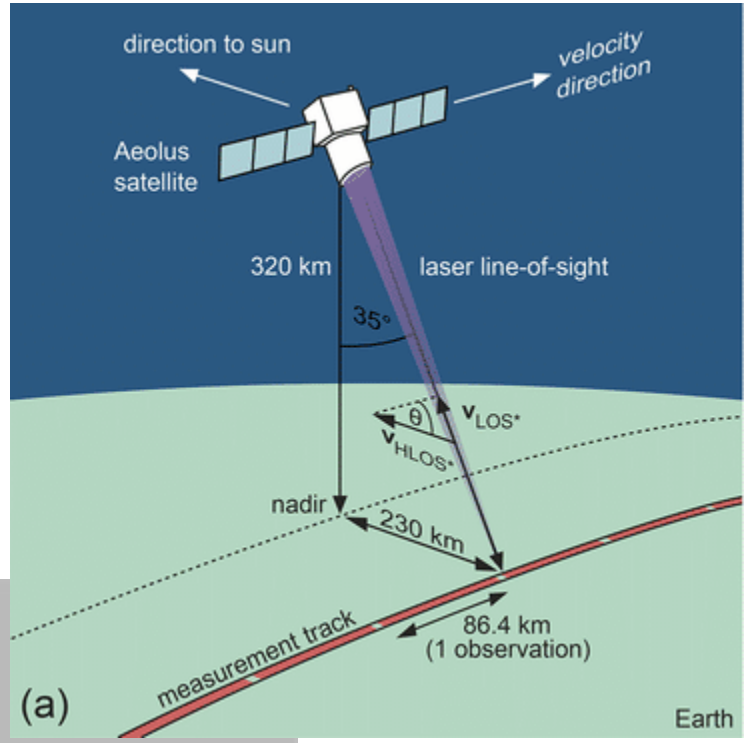
Ensemble DA
LETKF increment

Wind increment from
single WV radiance OBS

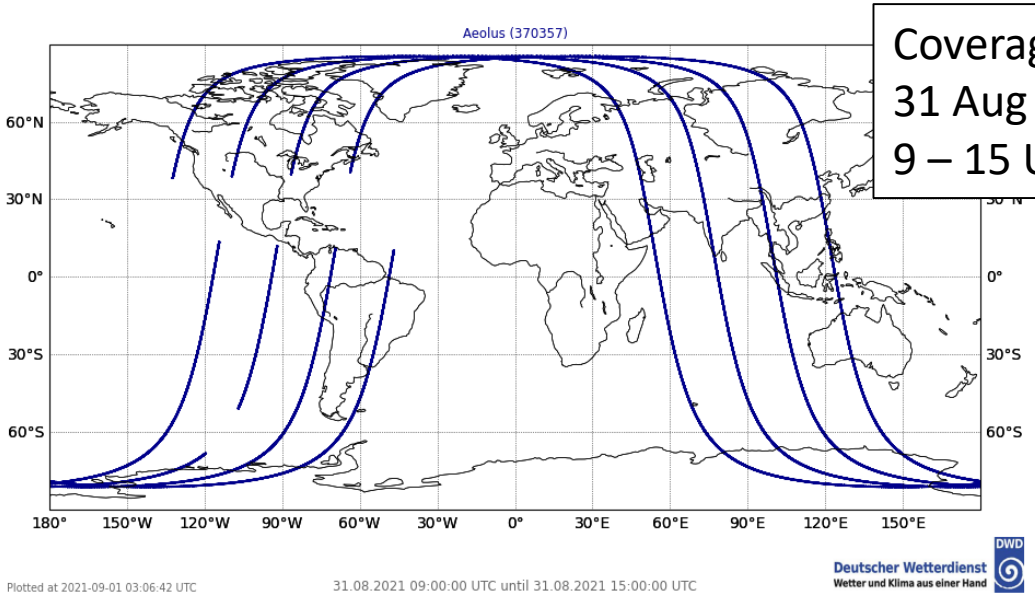
Wind from - WV channels, current sounders&imagers, future GIIRS-FY4, MTG-IRS, …
- Ozone, trace gases … (more potential in complex models, ESMs)
- Cloud and precipitation structures (e.g. MW radiances, lightning MTG-LI)

New winds from ALADIN/Aeolus

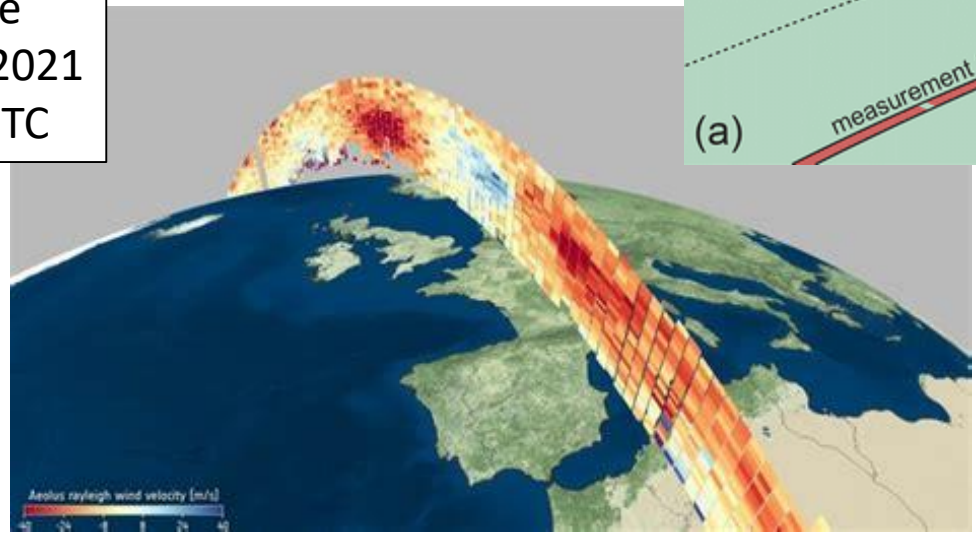
- First Doppler Laser operated in space (since 2018 to ~ 2022)
- Measures Doppler phase shift of backscattered pulse
  - Movement of air molecules and aerosols & clouds
    →horizontal line-of-sight winds
  - Profiles: 0 km – 30 km height, 24 layers (Δz≈250m-2km)
  - Operational: May 2020



www.researchgate.net



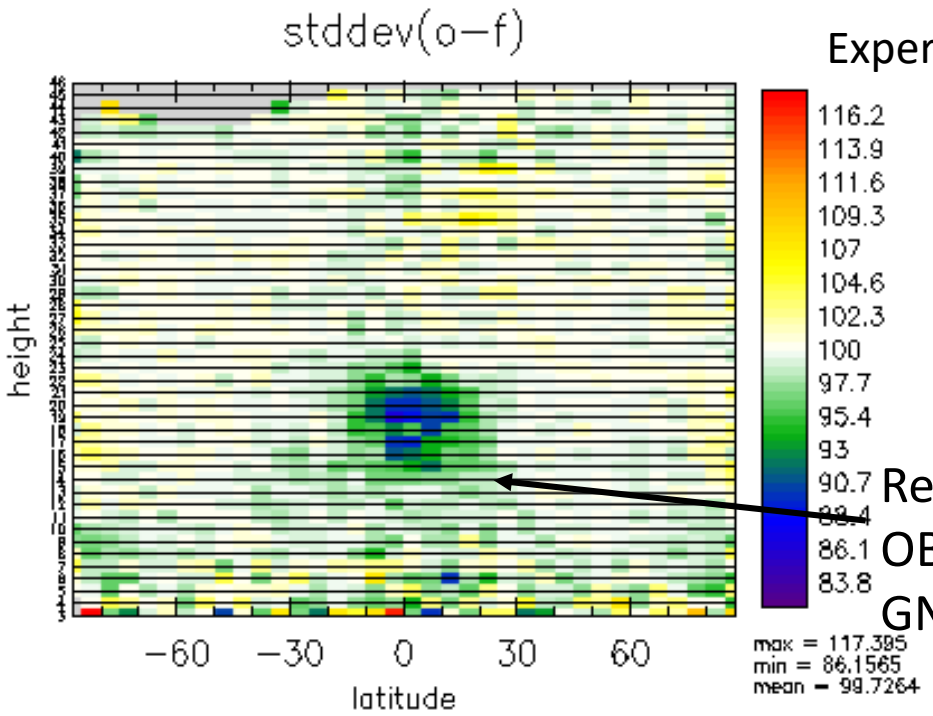
Coverage
31 Aug 2021
9 – 15 UTC



www.geoawesomeness.com

New winds from ALADIN/Aeolus

- Only ~2% of used data
- Consistent very large positive forecast impact
- Pronounced in tropics, mid tropo- to stratosphere
- Illustrates need for direct wind profile measurments



Experiment 1 Jan – 28 Feb 2020

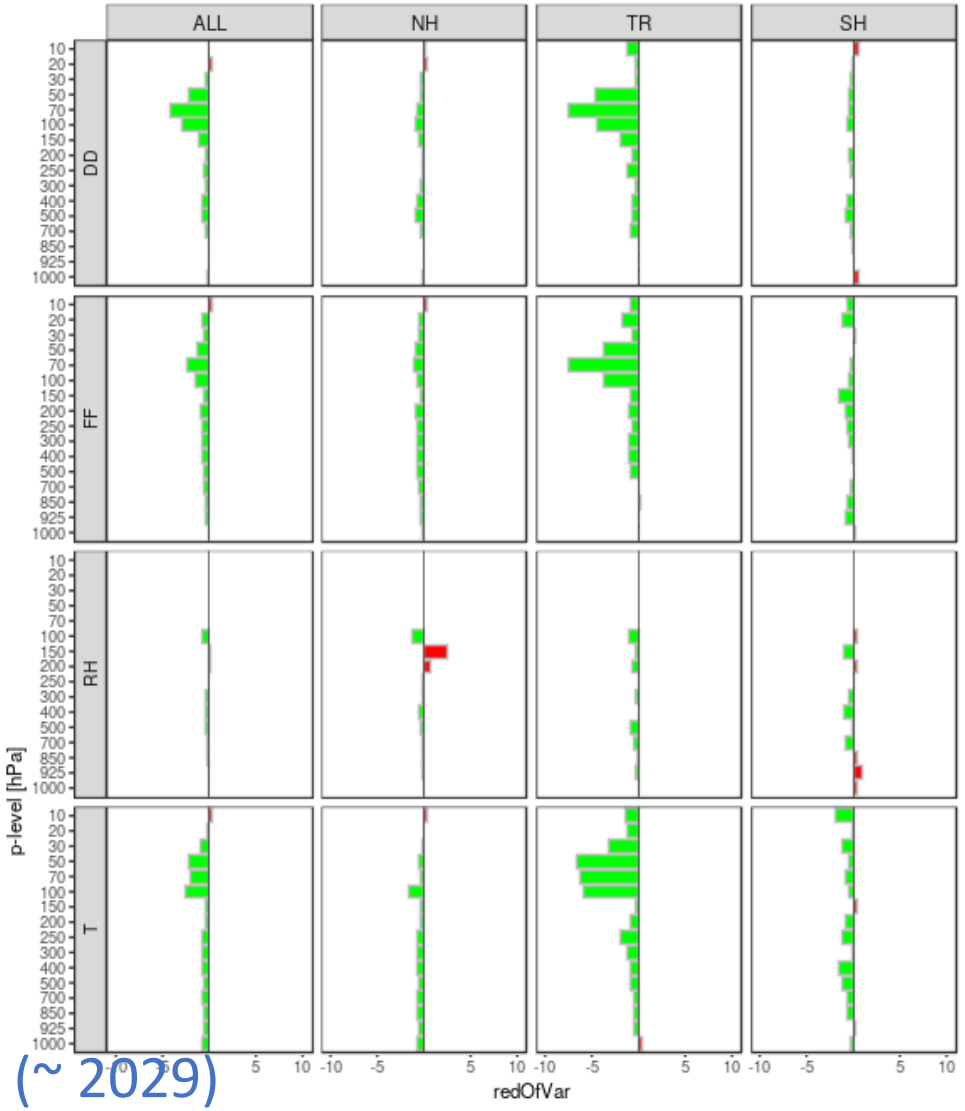
Large 2-8% reduction of forecast RMSE vs radiosondes

Reduction in OBS-FG of GNSS-RO

Aeolus EXP better then Control run

Forecast verification vs RS

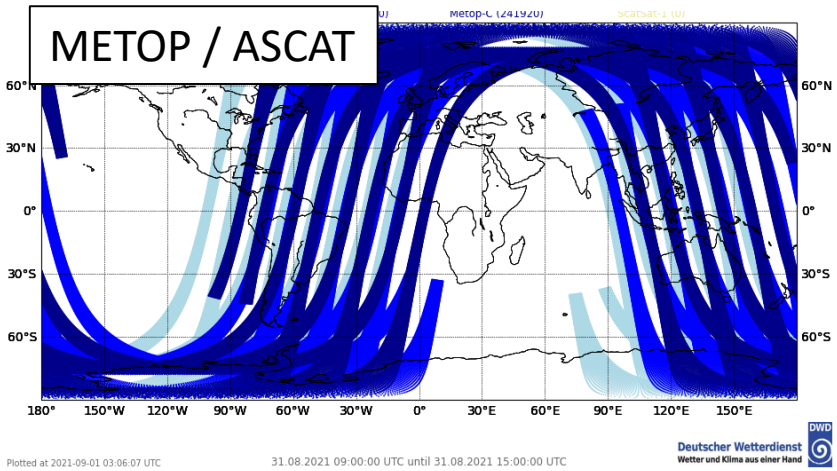
(DWD, A. Cress)

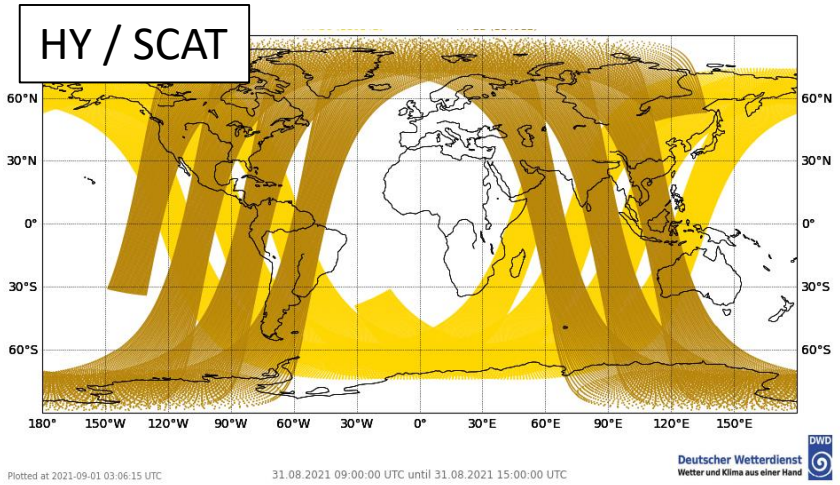


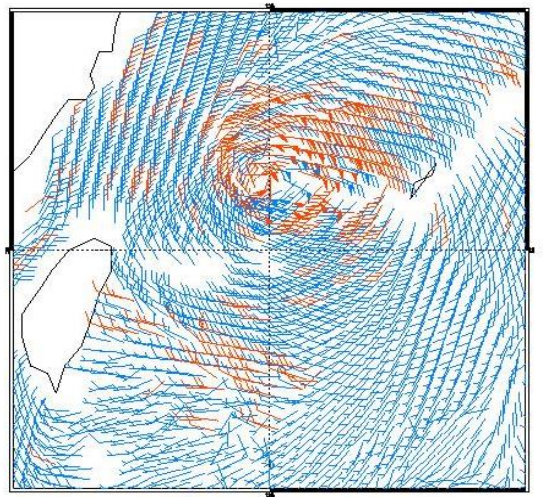
➢ Follow-on mission DWL initiated by EUMETSAT/ESA (~ 2029)

Near-surface satellite winds over ocean

Deutscher Wetterdienst
Wetter und Klima aus einer Hand







Active instruments - backscatter signal = f (surface roughness)

- Scatterometer: wind vectors @ 10m height
- Altimeters: wind speed

Passive radiances:

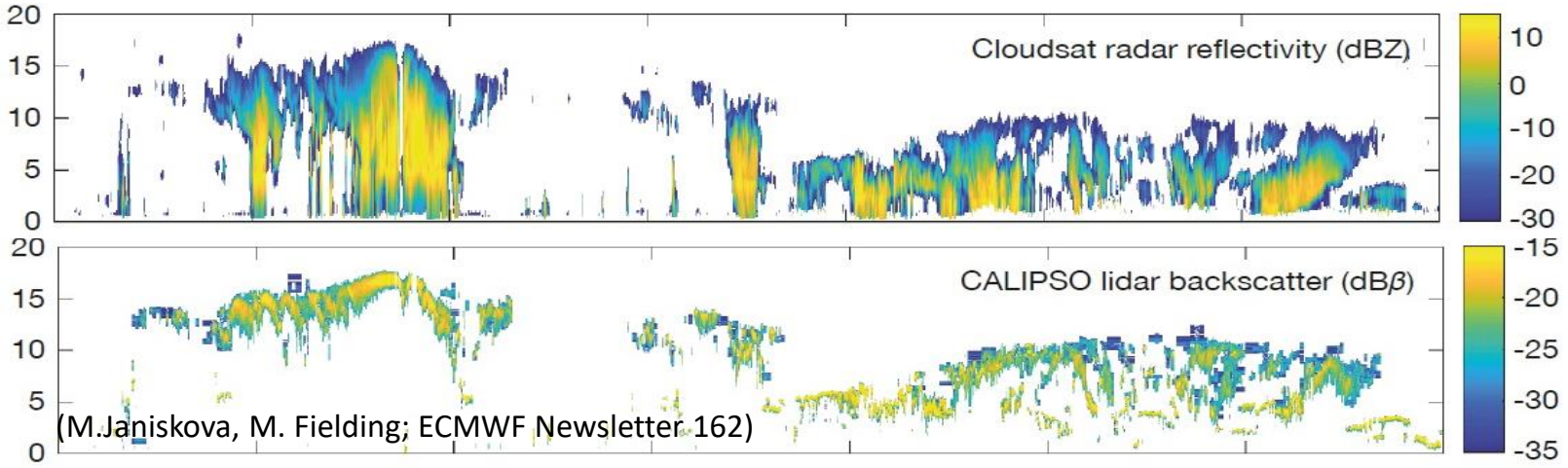
- MW imagers - wind speed information
  (through emissivity changes with roughness, polarization signal)

➢ ‚Boundary' observations between ocean and atmosphere

➢ Research into more direct use of measurements → coupled assimilation development

Satellite observations of clouds

- Model evaluation & data assimilation:
  - Liquid and ice water path
  - Vertical distribution
  - Microphysics (phase, particle size)



(M.Janiskova, M. Fielding; ECMWF Newsletter 162)

- Current observations:
  - MW sounders/imagers: cloud liquid / ice water contents, microphysics – little vertical resolution
  - IR: mostly cloud top information
  - VIS / NIR: cloud liquid water, cloud ice, cloud top microphysics
  - Active radar, lidar: vertical profile, but sparse coverage (e.g. Cloudsat, CALIPSO)

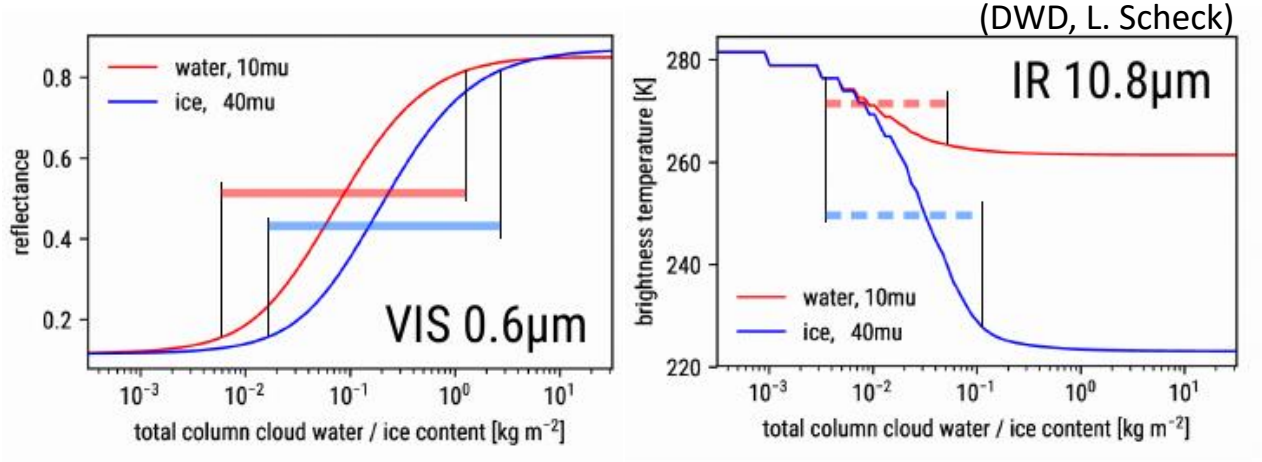
- Future observations – will provide relevant addition to cloud obs:
  - Active instruments: e.g. EarthCare (~2023) → research satellite: radar & lidar
  - Extended MW range: e.g. EPS-SG / ICI → some vertical information, esp. also ice clouds
  - Multi-angle & polarization: e.g. EPS-SG / 3MI → enhanced capability (phase, vertical structure, …)

Cloud observations for model evaluation

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

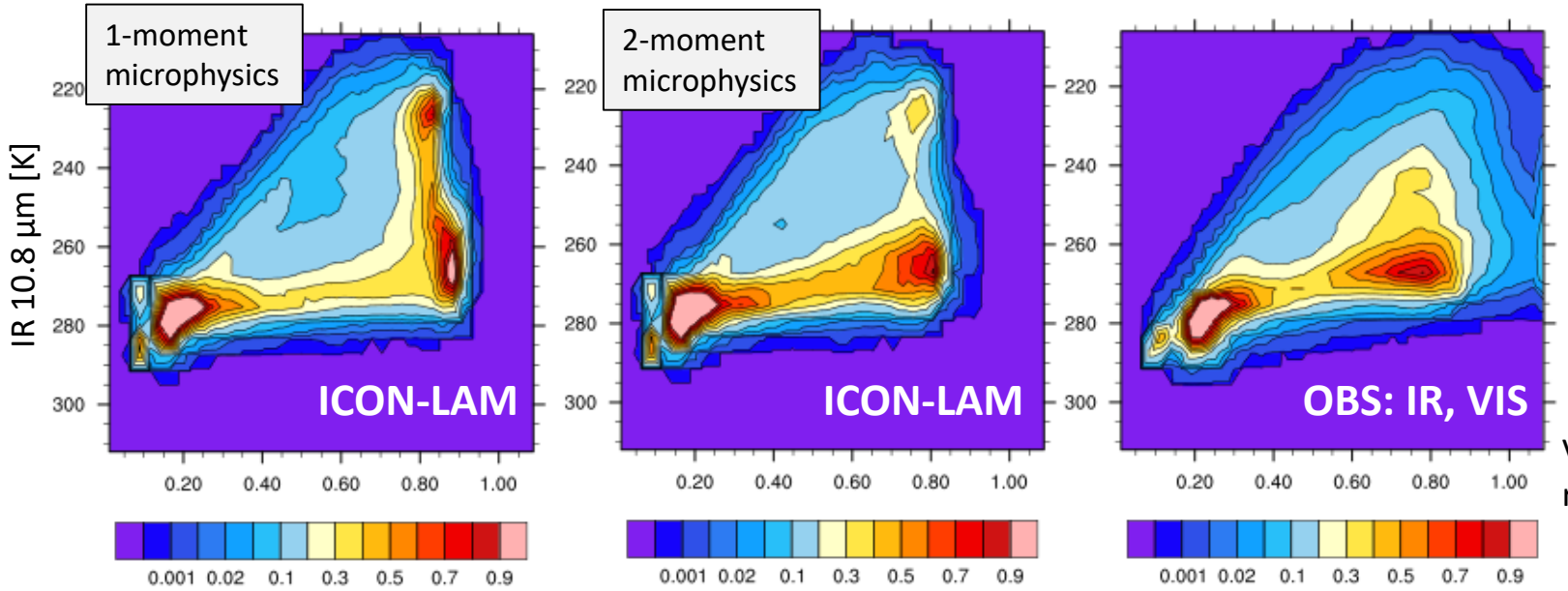
- Model cloud evaluation classically uses retrievals
- Increasingly also done in radiance space
  → forward operators
- Recent developments:
  - Forward operators for active radar, lidar (CloudSat / CALIPSO)
  - Fast visible forward operator MFASIS/RTTOV

(DWD, L. Scheck)



Example:

- Use of VIS forward operator MFASIS with ICON-LAM
- Model microphysics: 1-moment vs 2-moment
- Data: SEVIRI, Jan 2019



(DWD, V. Maurer, A. de Lozar)

VIS reflectance

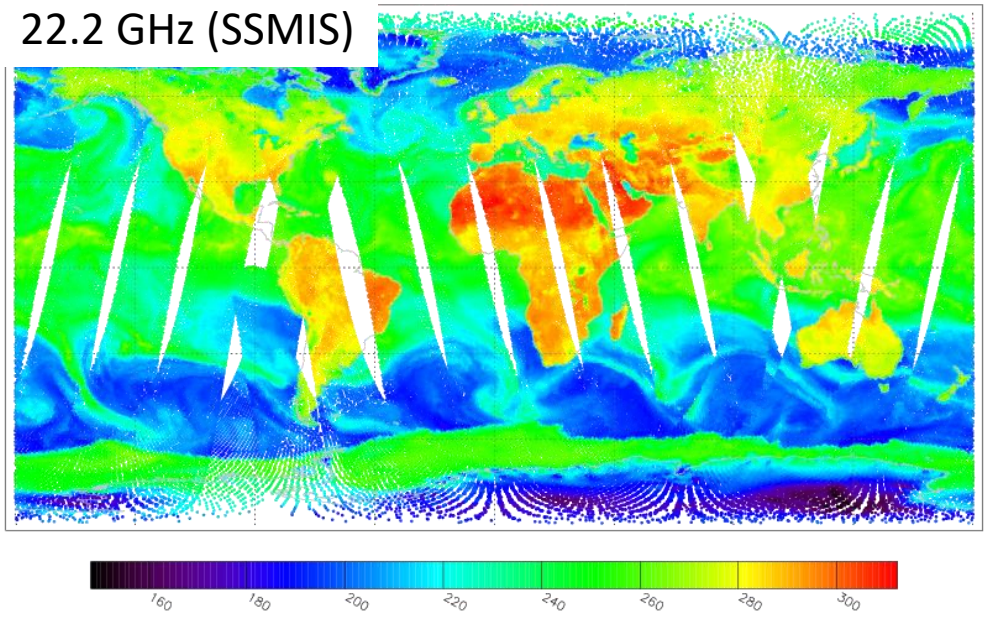
Christina.Koepken-Watts@dwd.de

Additional complementary data

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

MW – imagers (LEO)

- Column water vapour
  Low level winds, cloud & precipitation signals
- Indirect winds through 4D-tracing (all-sky)
- Many current and future instruments
  e.g. SSMIS, AMSR-2, GMI, MWRI, CIMR, ...



Water vapour from VIS (0.9 µm)

- Over land, good horizontal resolution
- Day time only
- Current and future, both LEO and GEO , e.g. OLCI, FCI, MetImage …

Lightning observations

- GEO imagers, e.g. GOES/GLM, MTG/LI , FY4/LMI…
- Convective information

Requirements and existent gaps

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Observed parameters

- Wind profile
- Clouds, ice
- P_s

Coverage+resolution: space & time

- Polar areas (‚geo-like observations')

→ Molniya orbit (ARCTICA-M)

Coverage+resolution: vertical

- Limb sounding
- PBL → ground-based remote sensing

Data availability: timeliness, exchange

- NRT availability
- Open data exchange (e.g. commercial data)

Satellite agency developments

Measurement accuracy and stability

→ NWP & climate applications

- T, and q reference instruments needed
- Bias correction methods and bias aware DA
- Error characterization

Use of full resolution data

→ esp. high-resolution NWP

- Treatment of horizontal error correlations

Use of data all–sky & all-surface

- Forward models (e.g. surface, scattering, for all observed fequencies)
- NWP model complexity and accuracy

Application & science developments

Summary

- Satellite data provide wealth of information on most atmospheric parameters for NWP
- Number of data, usage and their impact is steadily increasing

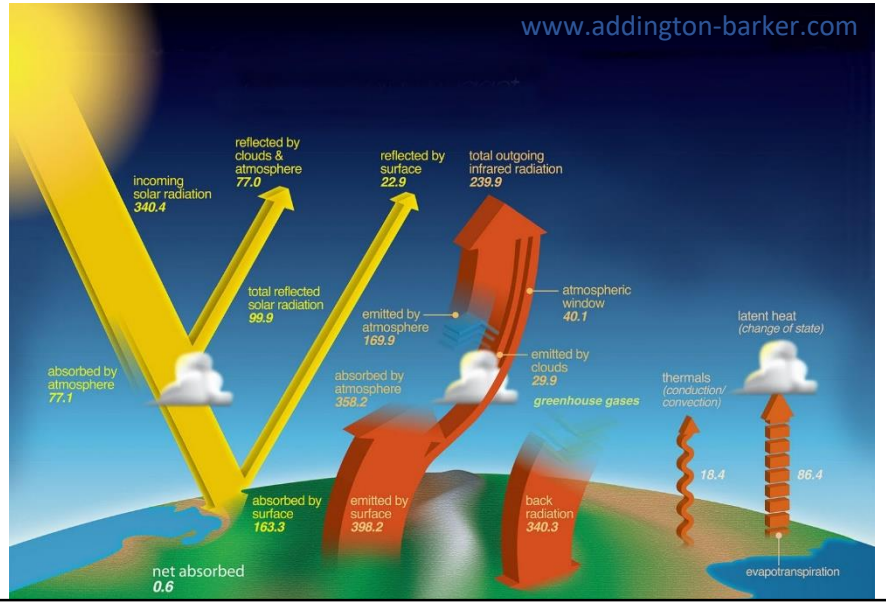
- Important new data sources in near future:
  - GEO hyperspectral IR, DWL wind lidar, mini-Sats increasing MW temporal coverage
  - New data on clouds ICI, more active observation systems
  - See also OSCAR: https://space.oscar.wmo.int/spacecapabilities
- Gaps
  - depend on the system considered (e.g. global or high-resolution)
  - can be reduced through new data sources → satellite agencies
  - … but also through improved modelling (NWP & forward operators) and improved DA methods

What do satellites measure ?

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

I) Passive radiometers:

- measure emitted or reflected radiation
- from earth-atmosphere system
- visible (VIS), infrared (IR), microwave (MW)



skin temperature

T – profile

$$L_\nu = B_\nu(Ts)\ \epsilon_\nu\ \Gamma_{\nu s} + \int_0^\infty B_\nu\left(T(z)\right)\frac{d\Gamma_\nu}{dz}\,dz + \left(\begin{array}{c} surface\ reflected \\ radiation \end{array}\right) + \left(\begin{array}{c} cloud/rain \\ contribution \end{array}\right)$$

emissivity

Absorption in atmosphere
= f (**water vapour profile,** trace gases, …)

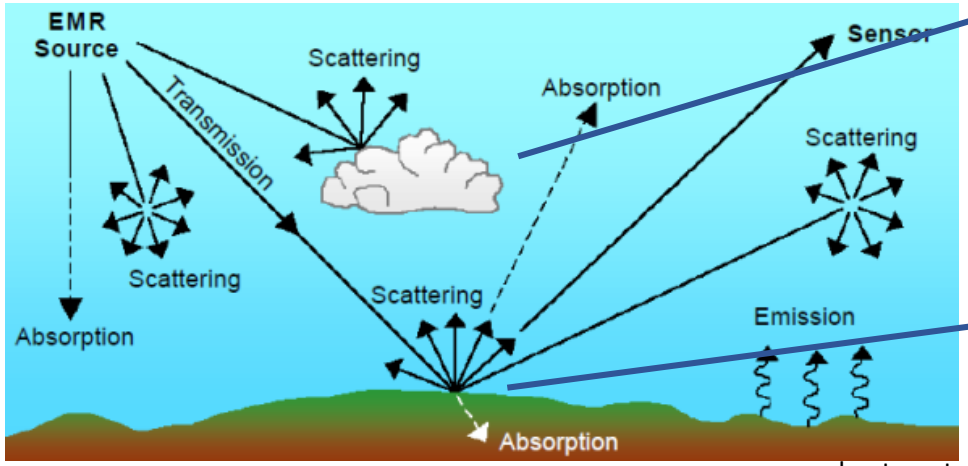
= f (**water and ice particles)**

Emissivity $_s$ / reflectance $_s$ = f (soil type, vegetation, soil moisture, snow, ice, ocean wind, salinity, ...)

Christina.Koepken-Watts@dwd.de

What do satellites measure ?

II) Active instruments: measure backscattered radiation (radar, lidar)



www.researchgate.net

Clouds:

scattering = f (water and ice particles)

→ information on cloud particles, vertical structure

Ocean surface:

scattering = f (roughness, emissivity)

→ information on near-surface wind

- Satellite observations measure the targeted quantities indirectly
- Good knowledge on other influencing parameters needed to fully exploit data
  - Provided e.g. by NWP model
- Forward models needed to compute observation equivalents of the NWP model state