Remote Sensing and Climate Diagnostics

Summer semester 2026
Goethe University Frankfurt

Water Cycle

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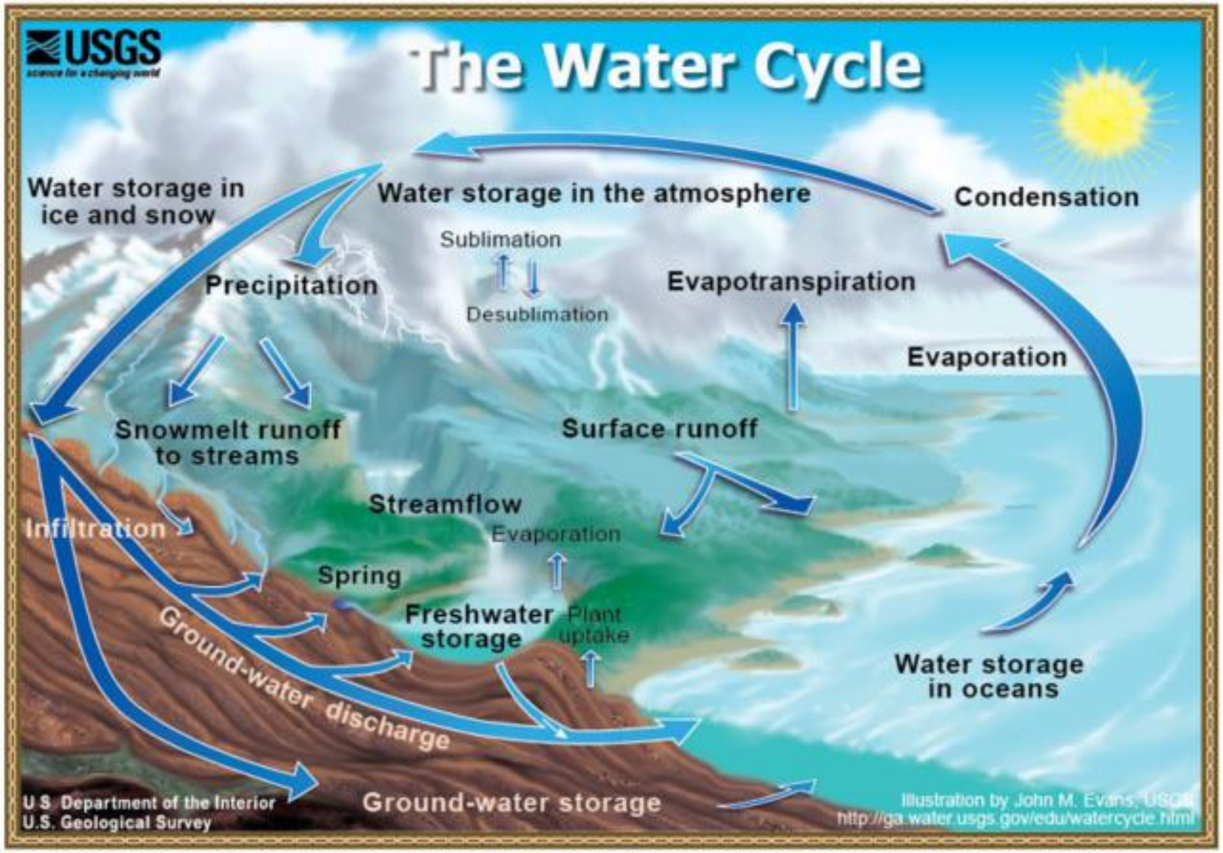
The Water Cycle

Content

- ➔ Motivation
- ➔ Precipitation
- ➔ Evaporation
- ➔ Water vapour
- ➔ The Cycle



Motivation

➔ Within the climate system it is acknowledged that the atmosphere is the most unstable of the five major components of that system (IPCC 2007).

Quelle: blanketearth.blogspot.com

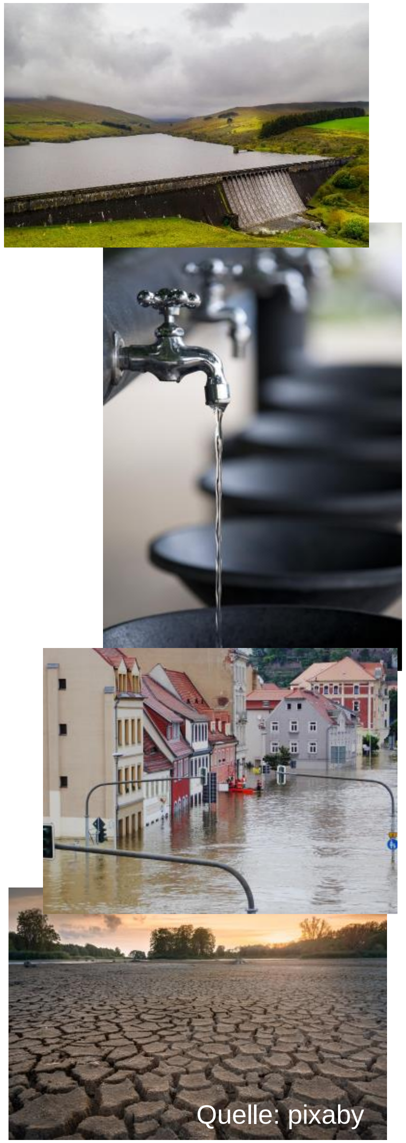
Motivation

- The most variable component within the atmosphere is water, which as water vapour is the strongest greenhouse gas.
- Water in the atmosphere can manifest itself in gas, liquid, and ice phases, each change of phase absorbing or releasing energy.
- Movement of water vapour within the atmosphere transports energy both laterally and vertically, redistributing energy across the globe through the evaporation of water and release of precipitation.
- The net atmospheric moisture transfer from ocean to land is estimated to be $40 \pm 1 \times 10^3$ km^3 $year^{-1}$
  - Spreaded evenly over all land areas, this would form a layer of 27 cm

- Aus: Kidd & Huffman, 2011: Review Global Precipitation Measurement, Meteorol. Appl. 18, 334-353

Motivation

- ➔ The global water cycle..
  - ➔ is a fundamental component of the Earth’s climate system
  - ➔ is linking the atmosphere, oceans, and land through continuous exchanges of water in all phases
  - ➔ strongly influences water availability, weather extremes, and climate conditions worldwide
  - ➔ is highly variable in both space and time
- ➔ observations over the oceans and in remote regions are limited
  - ➔ significant gaps in our understanding of the full system
- ➔ Satellite-based observations help close these gaps
  - ➔ enables us to study the water cycle as an interconnected global system and to better quantify its changes in a warming climate.



Quelle: pixaby

The Water Cycle

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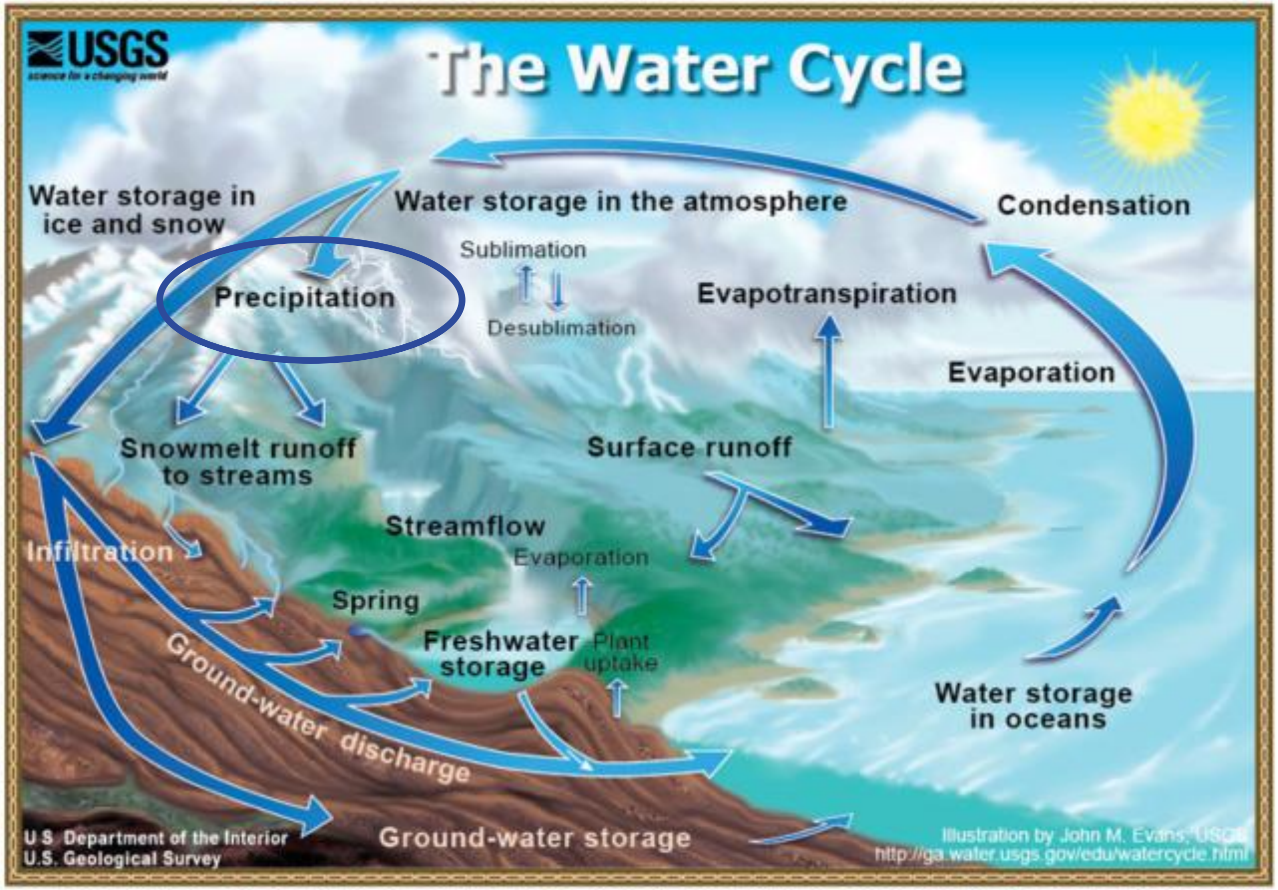


Precipitation: Introduction

- Precipitation is an essential element of the global water cycle
- Crucial role in many aspects of economic and social life
- Great importance in a variety of research areas
  - climate studies
  - management of water resources
  - natural hazards
  - Hydrology …
- precipitation estimation still has many problems to overcome to meet the needs of hydrological and climate research and of operational applications

Precipitation: Introduction

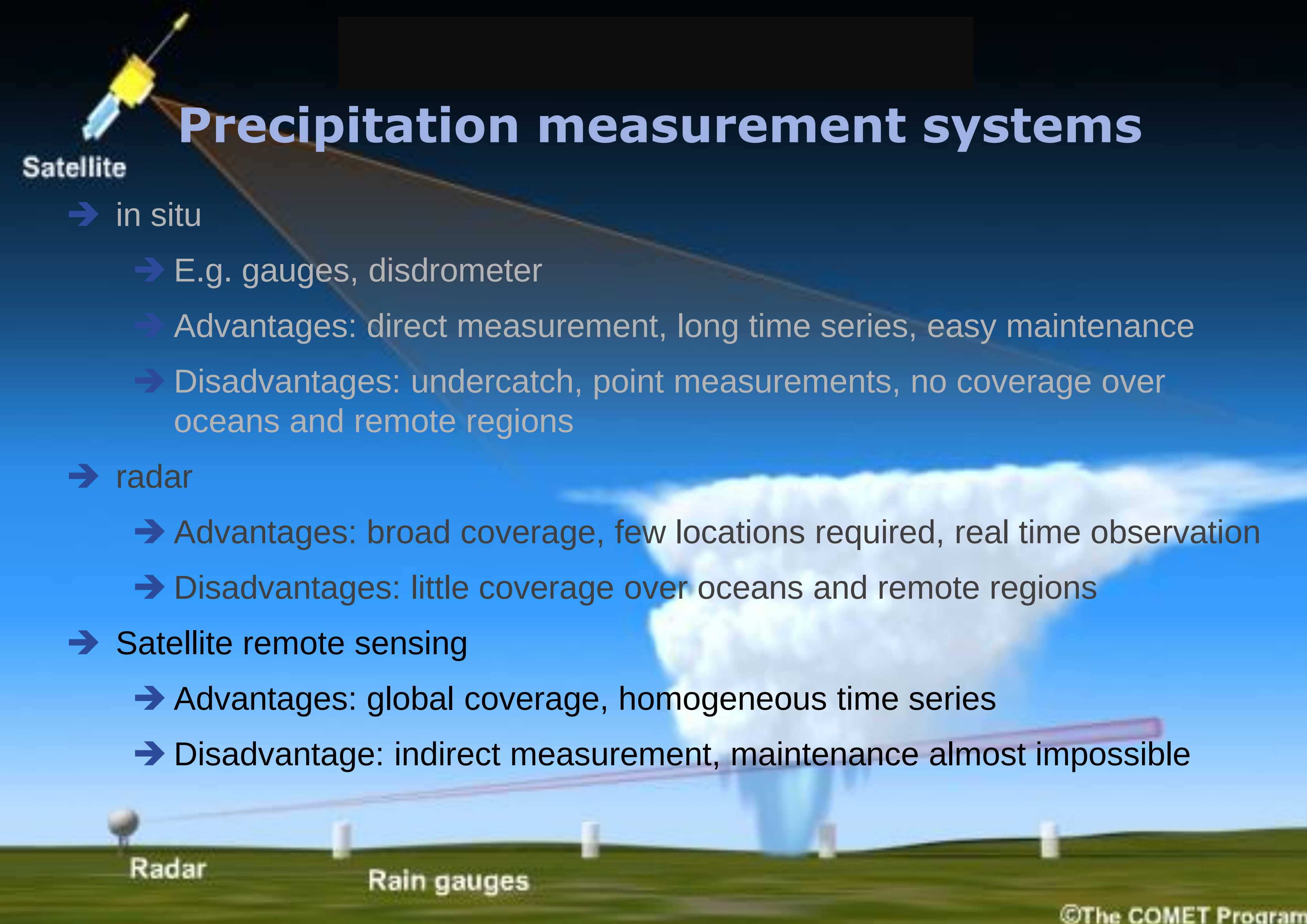
- Precipitation is one of the most difficult atmospheric parameters to measure accurately
- Complicated by several factors:
  - Spatial/temporal variability
  - Phase (liquid, solid, mixed)
  - Hydrometeor types, densities, sizes

Quelle: www.usgs.gov

www.imaging-resource.com

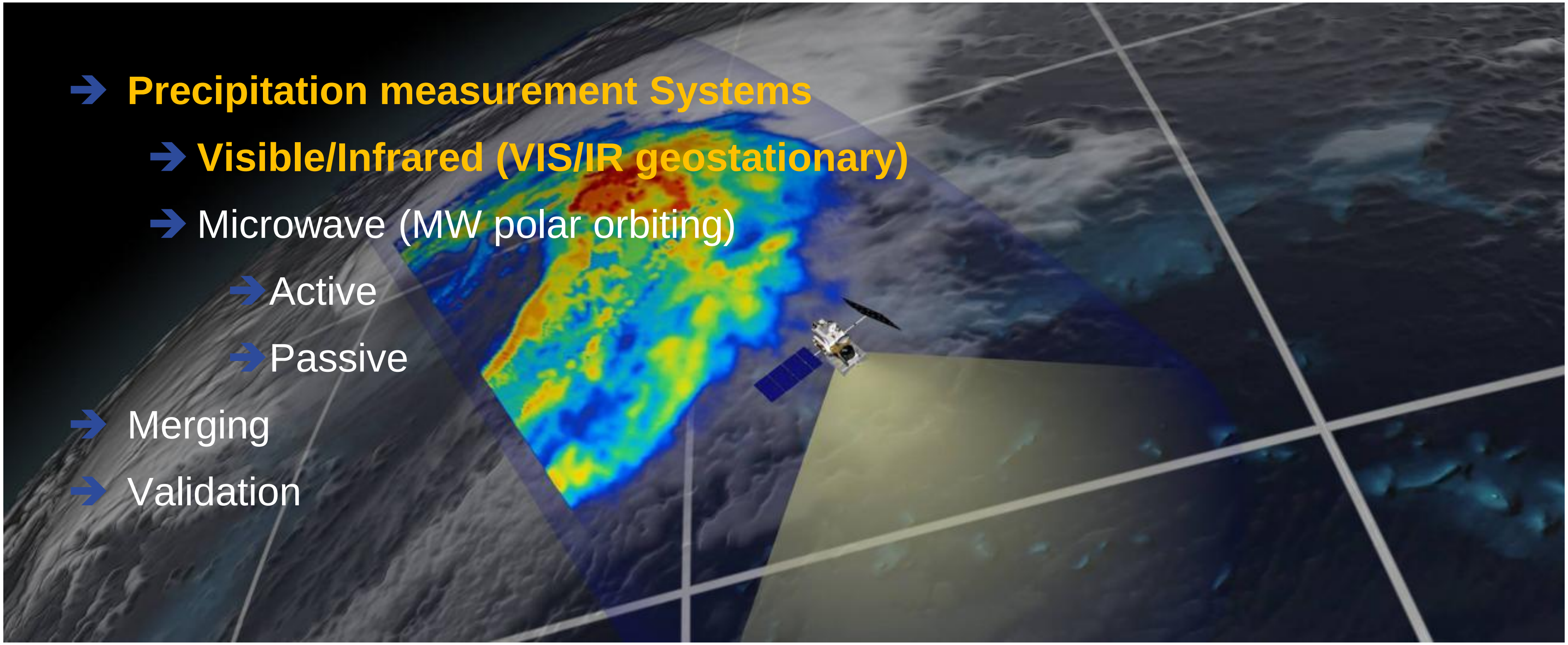
Precipitation measurement systems

- in situ
  - E.g. gauges, disdrometer
  - Advantages: direct measurement, long time series, easy maintenance
  - Disadvantages: undercatch, point measurements, no coverage over oceans and remote regions
- radar
  - Advantages: broad coverage, few locations required, real time observation
  - Disadvantages: little coverage over oceans and remote regions
- Satellite remote sensing
  - Advantages: global coverage, homogeneous time series
  - Disadvantage: indirect measurement, maintenance almost impossible



Remote Sensing of Precipitation

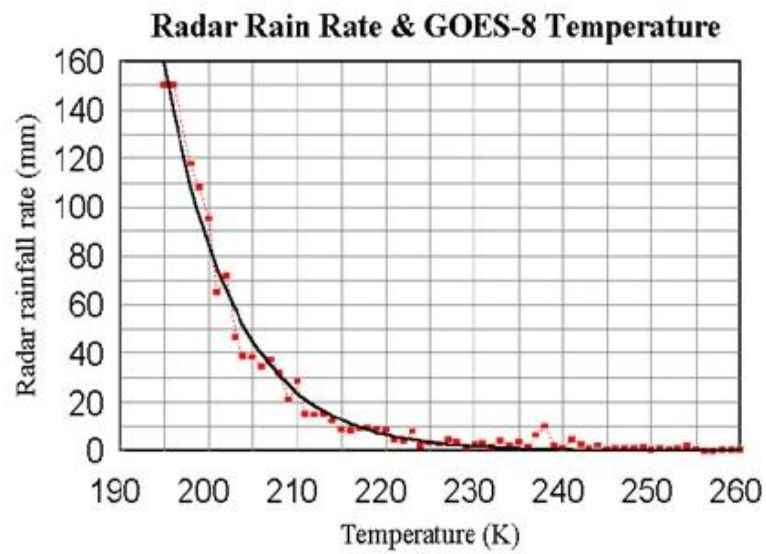
- **Precipitation measurement Systems**
  - **Visible/Infrared (VIS/IR geostationary)**
  - Microwave (MW polar orbiting)
    - Active
    - Passive
- Merging
- Validation



Quelle: https://gpm.nasa.gov/missions/GPM/gpm-core-observatory

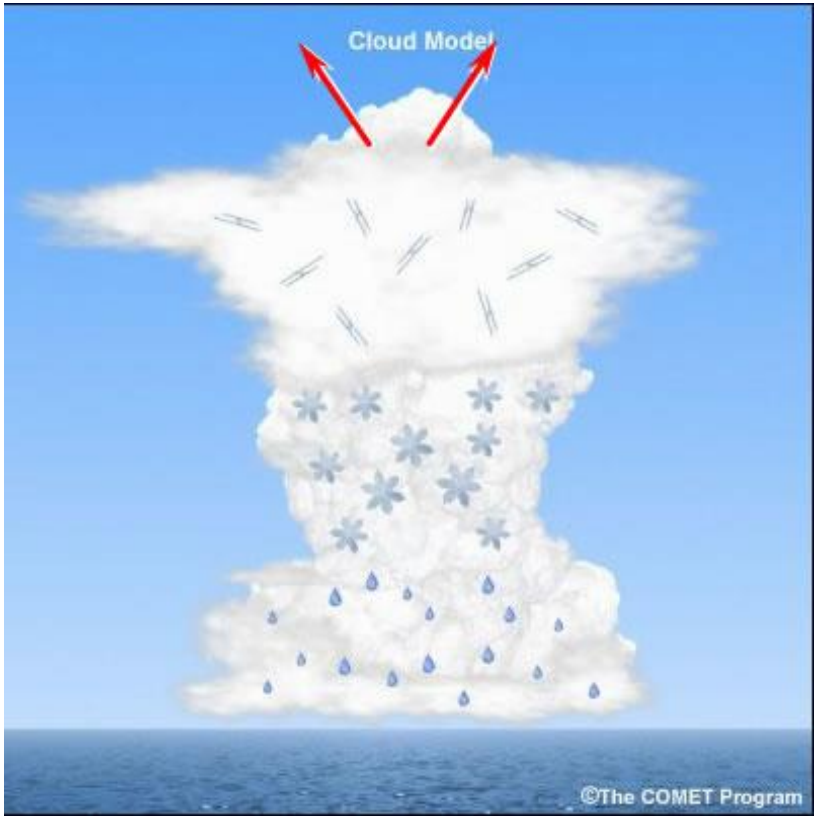
Preciptation measurement Systems
VIS/IR from Geostationary Satellites

- Principle: Rain rate is related to cloud top properties
- The higher the cloud (the lower cloud top temperature CTT), the heavier it rains
- Good approach for convective systems with low horizontal shearing (Arkin und Meisner, 1987)

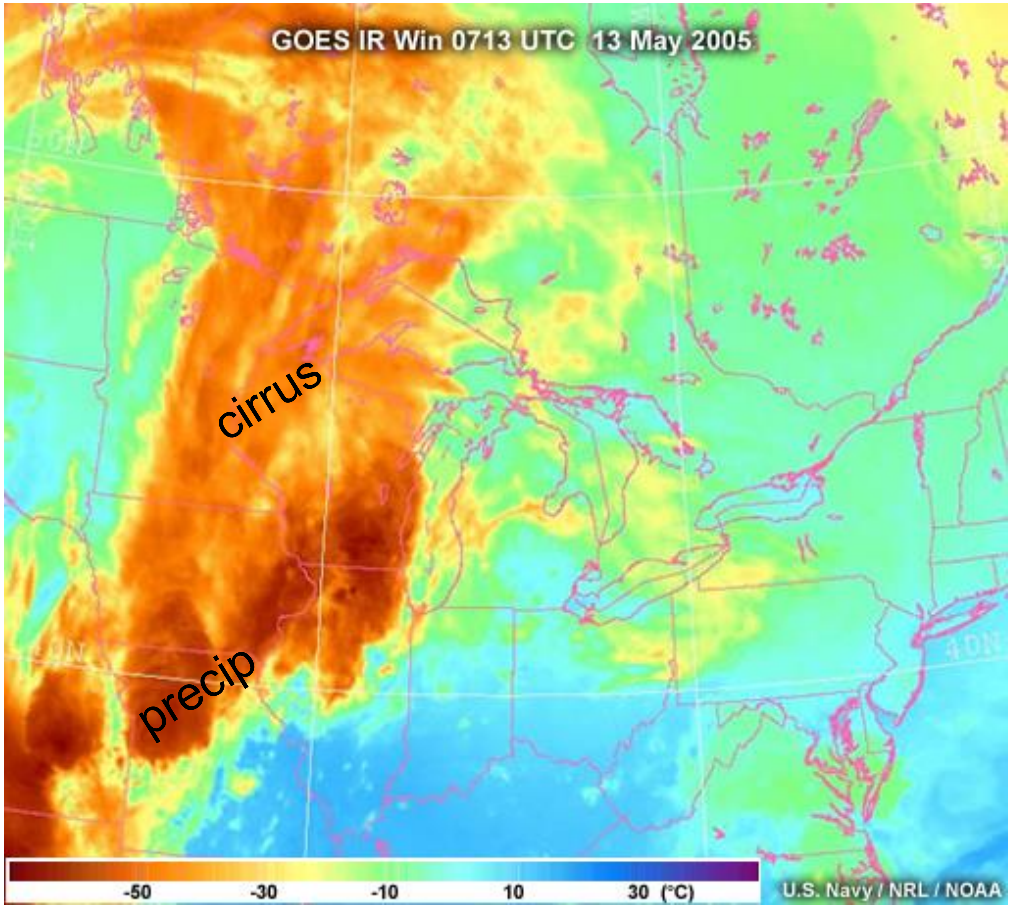


Visible (VIS) reflectivity	Brighter (thicker clouds)	Heavier rain
	Dark	No rain
Infrared (IR) Brightness Temperature	Colder (deeper clouds)	Heavier rain
	Warm	No rain

Preciptation measurement Systems VIS/IR



Quelle: COMET® Website at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)

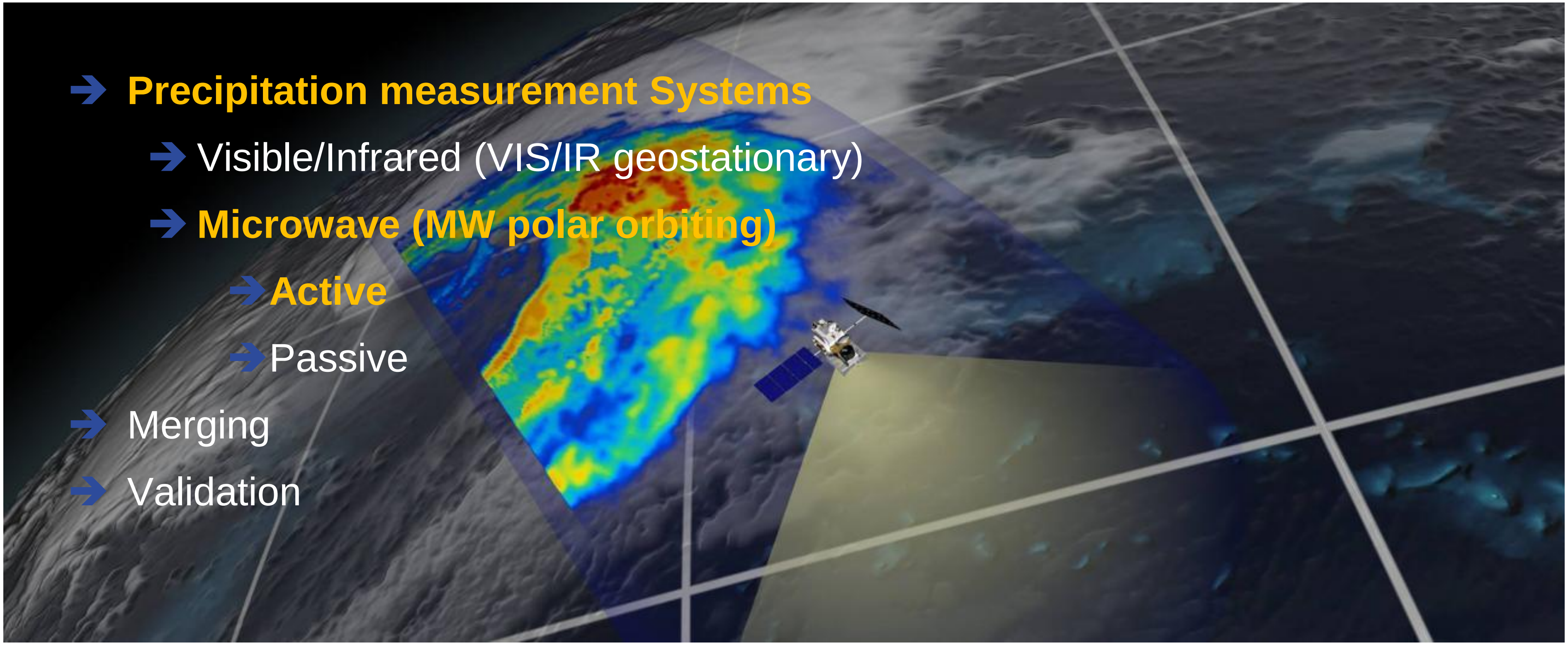


Preciptation measurement Systems VIS/IR

- Advantages:
  - Good space (~3x3 km^2) and time (~ 30 min) resolution

- Disadvantages:
  - poor detection of rain from low warm clouds
  - Only rough idea of the precipitation rate
  - Only empirical dependence of CTT and rain rate
  - Relationship between CTT and rain not simple:
    - not all cold clouds precipitate (might classify cirrus as rain clouds)
    - not all rain comes from cold clouds

Remote Sensing of Precipitation



- **Precipitation measurement Systems**
  - Visible/Infrared (VIS/IR geostationary)
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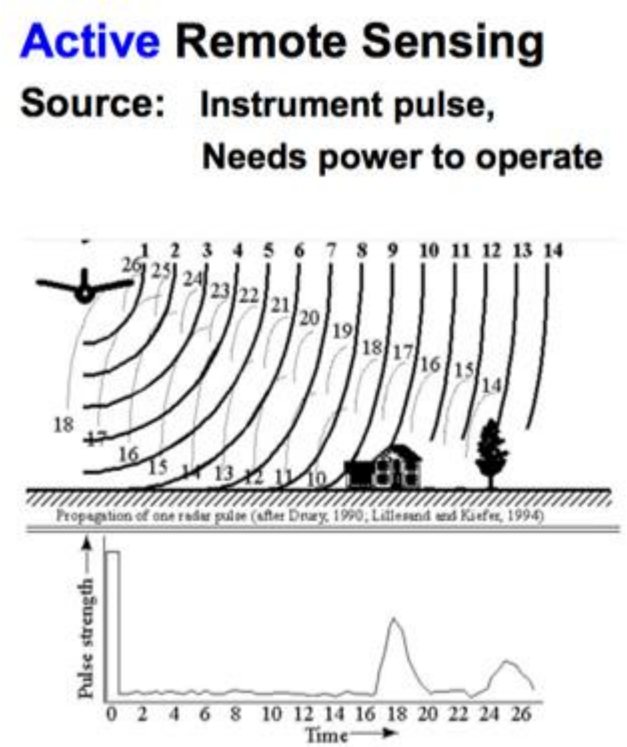
Preciptation measurement Systems
Active Microwave Remote Sensing



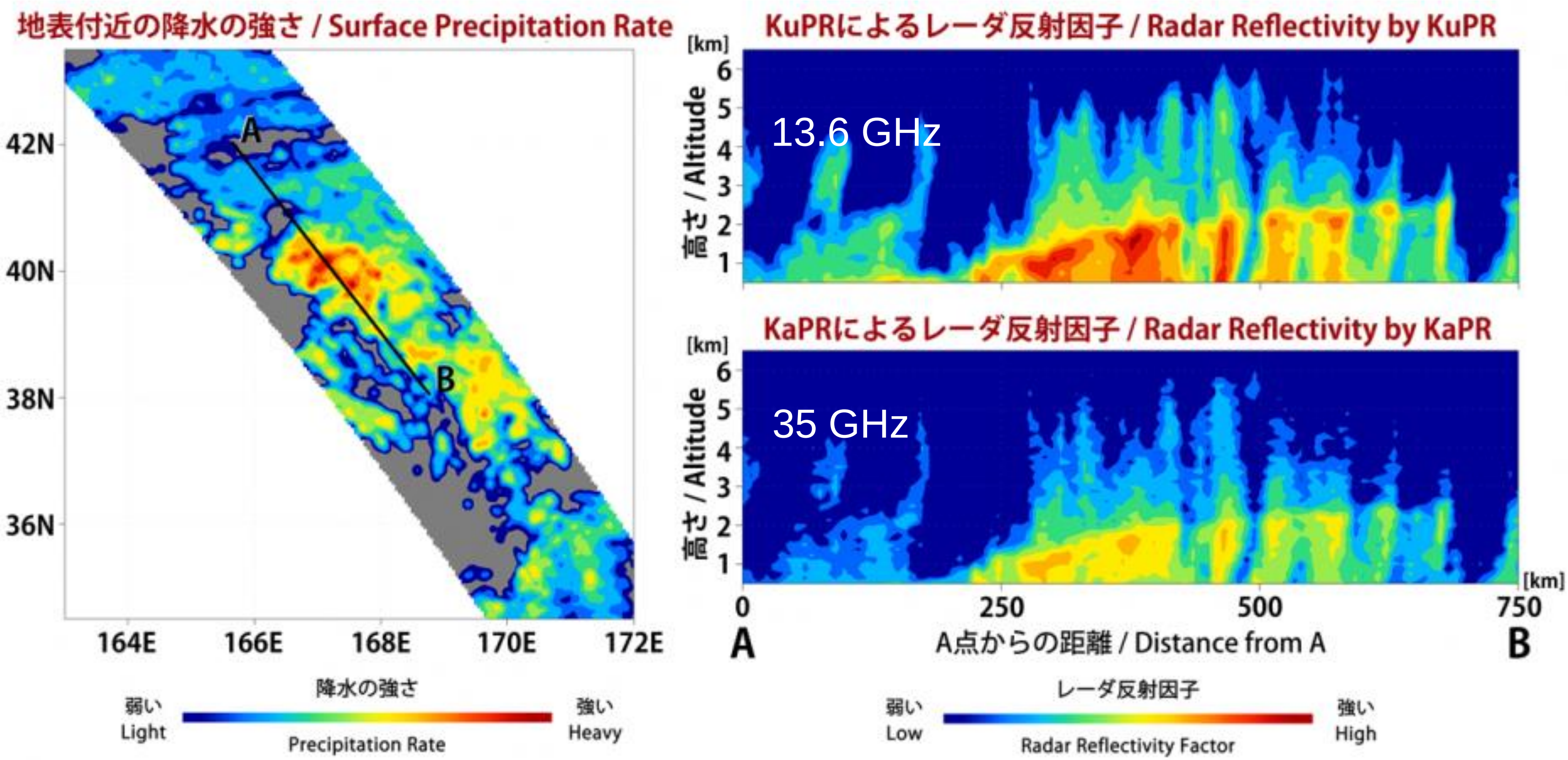
Quelle: NASA Precipitation Measurement Missions

- ➔ Principle: Rain estimated from back-scattered microwave radiation
- ➔ Pulse of microwave energy emitted by satellite interacts with atmosphere and clouds
- ➔ Signal returned is measured by satellite

- ➔ Like weather radar, but located in space and not on the surface

Preciptation measurement Systems
Active Microwave Remote Sensing

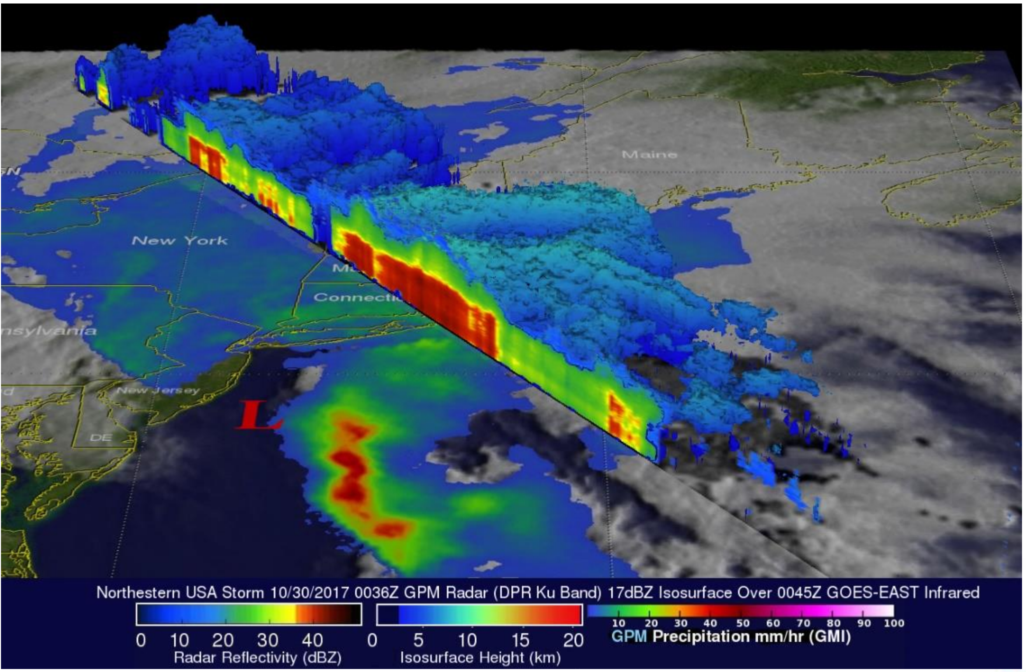
- Measures vertical structure of precipitation
- Global Precipitation Mission – Dual-frequency Precipitation Radar (JAXA/NICT)
- Combination of 13.6 GHz (medium-heavy rain) and 35 GHz (light rain and snow)

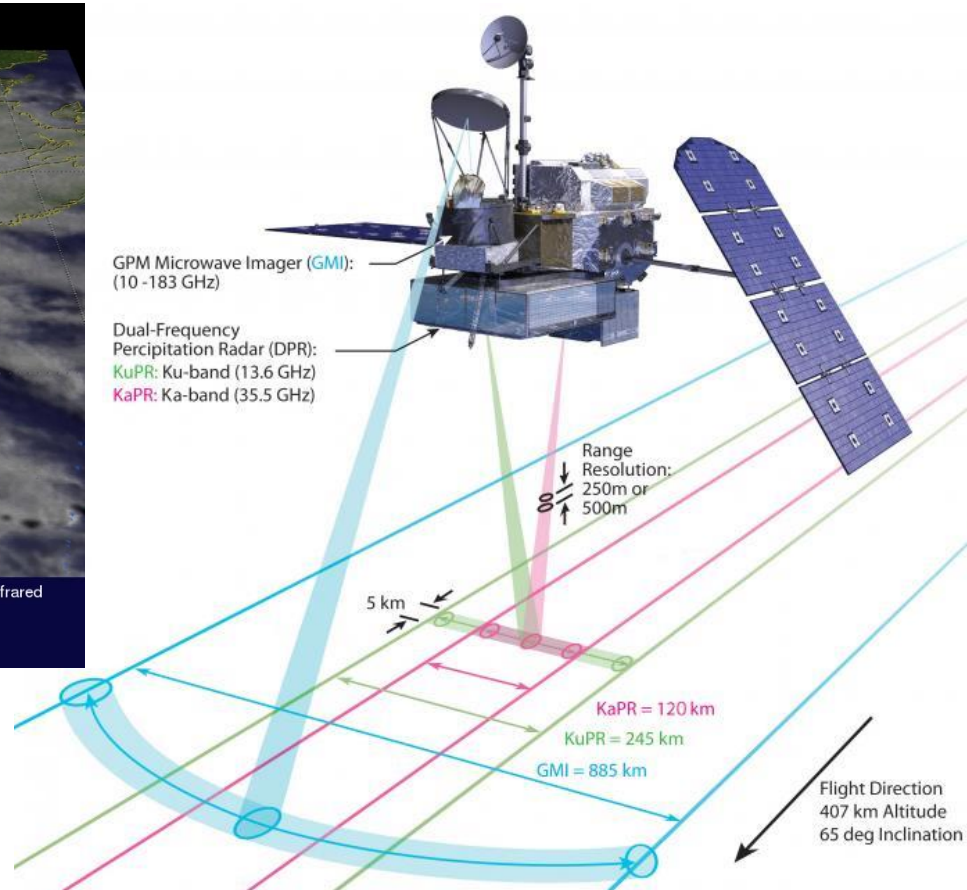


Quelle: https://www.nasa.gov/

Preciptation measurement Systems
Active Microwave Remote Sensing

- ➔ Main disadvantage: low coverage

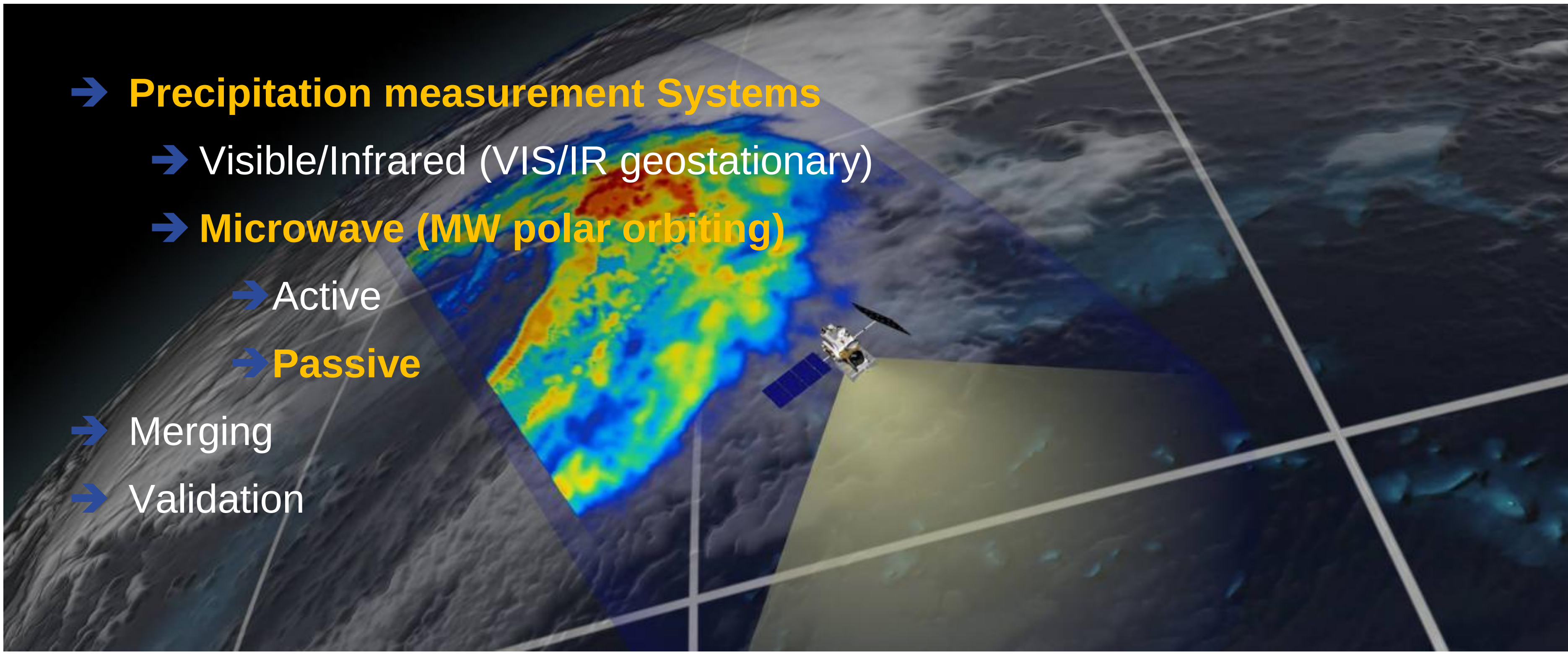




- ➔ combine DPR and PMW
- ➔ TRMM TMI & PR, GPM GMI & DPR
- ➔ 12.1997 – 04.2015 (TRMM), 03.2014 – Present (GPM)
- ➔ 50°S/N (TRMM), 65°S/N (GPM)

Quelle: https://gpm.nasa.gov/missions/GPM

Remote Sensing of Precipitation



- **Precipitation measurement Systems**
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    - **Passive**
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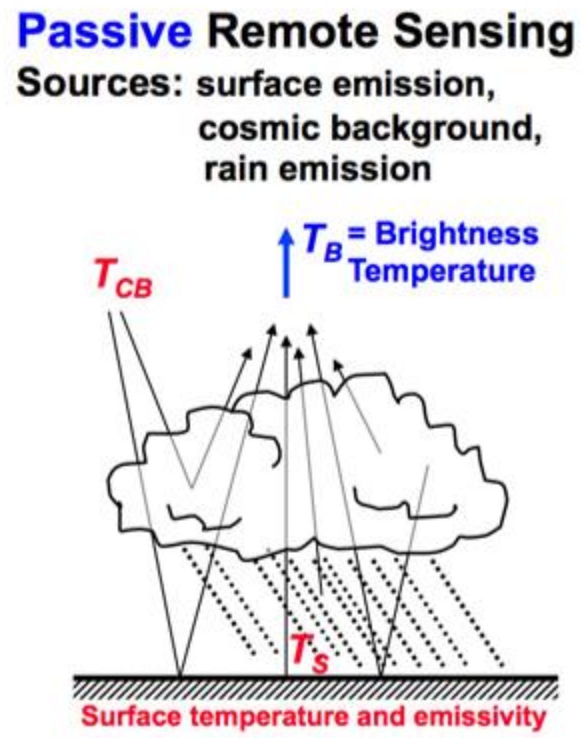
Preciptation measurement Systems
Passive Microwave Remote Sensing



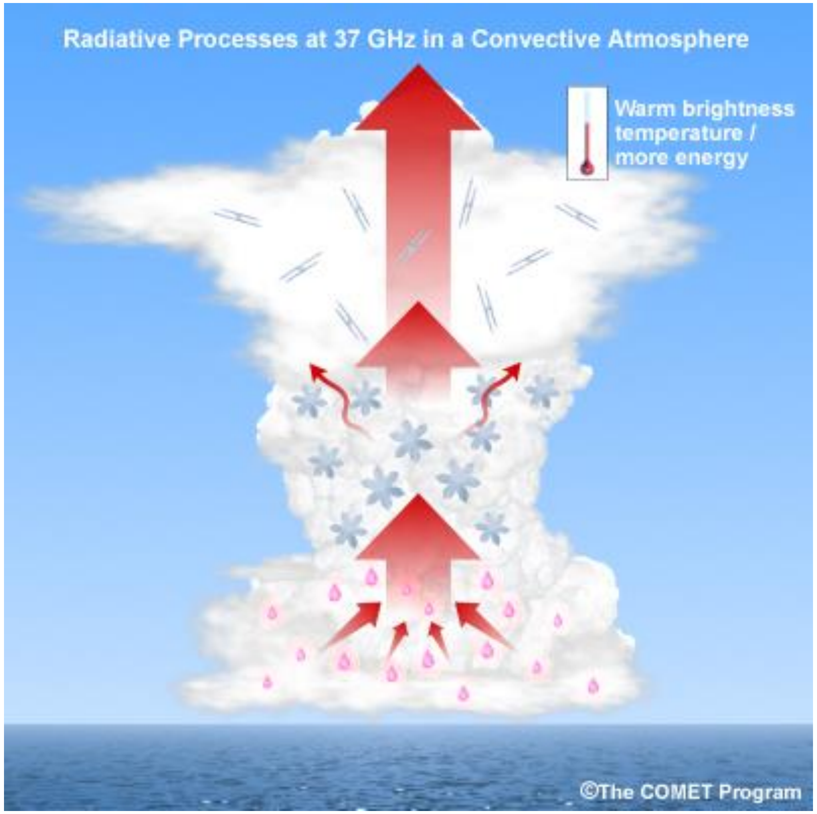
Quelle: NASA Precipitation Measurement Missions

- ➔ Principle: Rainfall related to microwave emissions and scattering
- ➔ Microwave emissions from rain drops (low freq channels (<= 37GHz))
- ➔ and microwave scattering from ice particles (high frequency channels (e.g. 85GHz))

Emission Channels	Warm: many rain drops	Heavy rain
	Cold	No rain
Scattering Channels	Cold: Scattering from ice	Heavy rain
	Warm	No rain

Preciptation measurement Systems
Passive Microwave over ocean

- Emission channels ($f \leq 37$ GHz)
- Emission from surface (ocean) + liquid rain drops + cloud-H_2O
- Emission from rain > Emission from ocean



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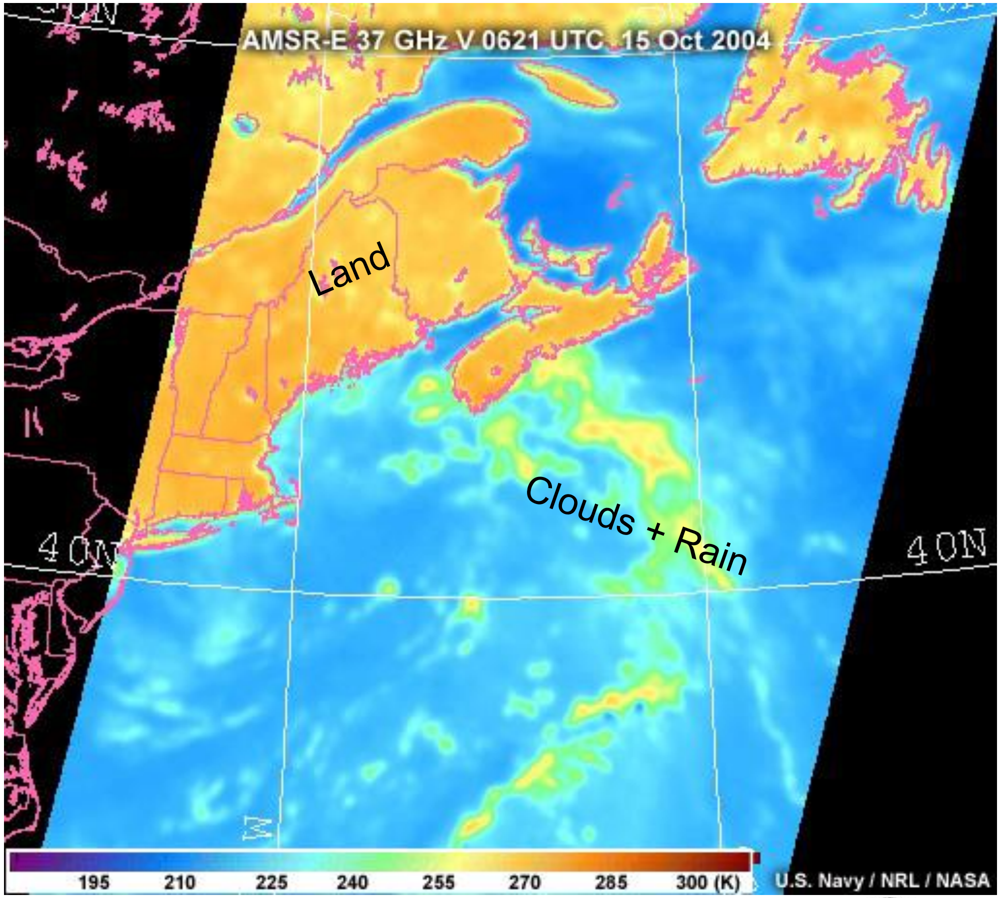
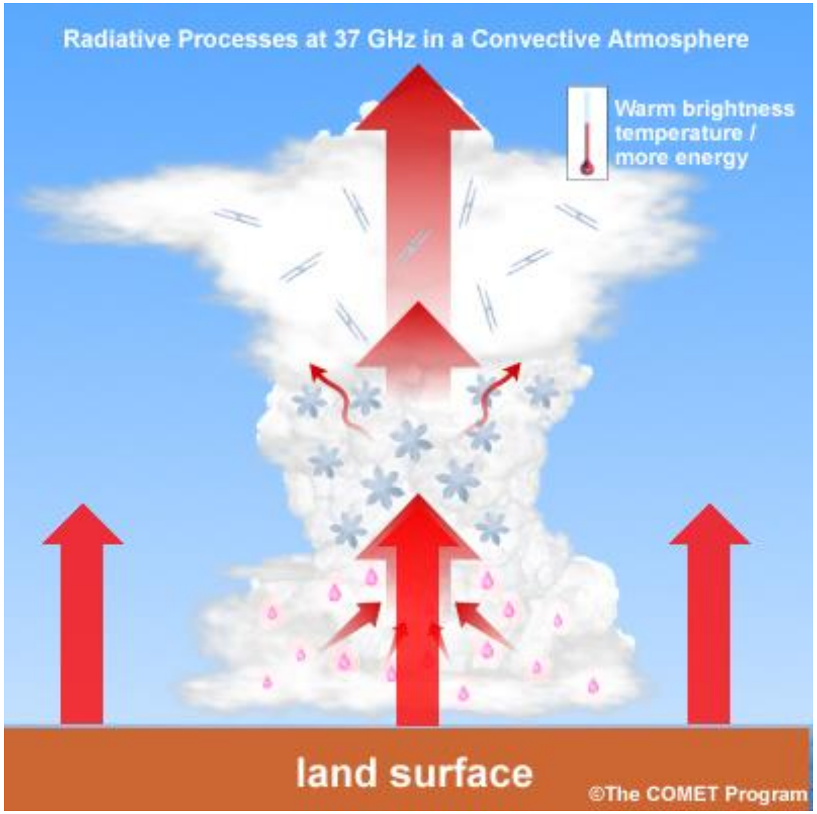


Preciptation measurement Systems
Passive Microwave over land

- ➔ Emission channels ($f \leq 37$ GHz)
- ➔ Emission from surface (land) + liquid rain drops + cloud-H2O
- ➔ Emission from rain ≥ Emission from land



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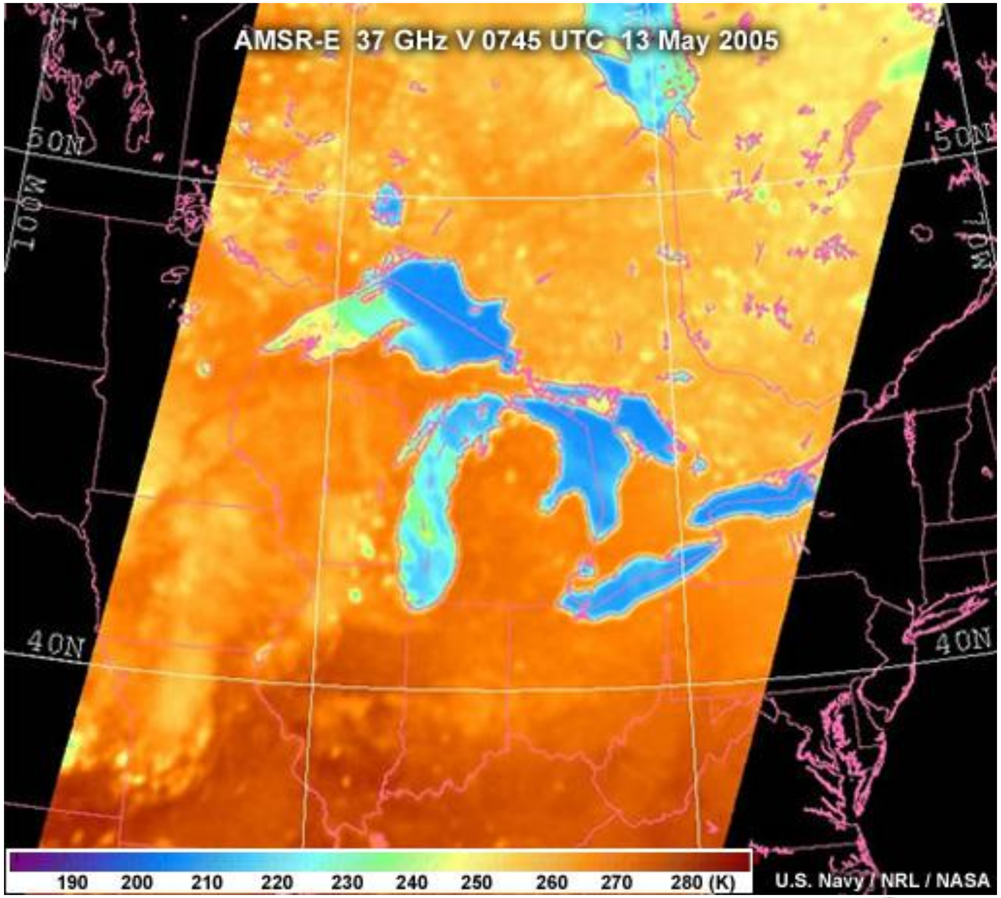
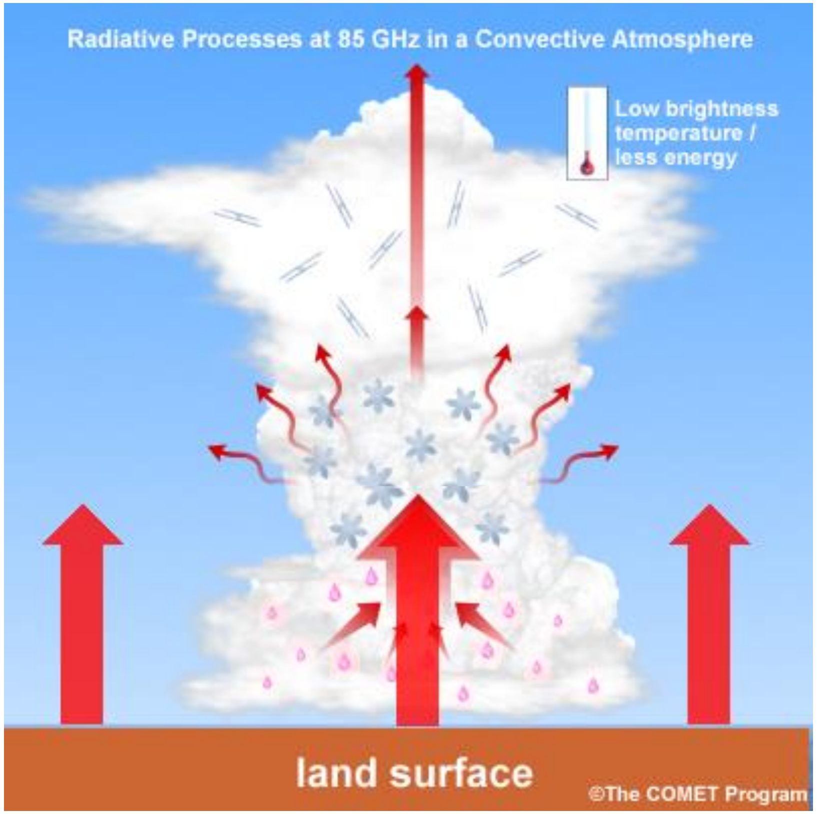


Preciptation measurement Systems
Passive Microwave over land

- ➔ Scattering channels (e.g. 89 GHz)
- ➔ Emission (surface, rain drops, cloud-H_2O) – Scattering (ice particles)



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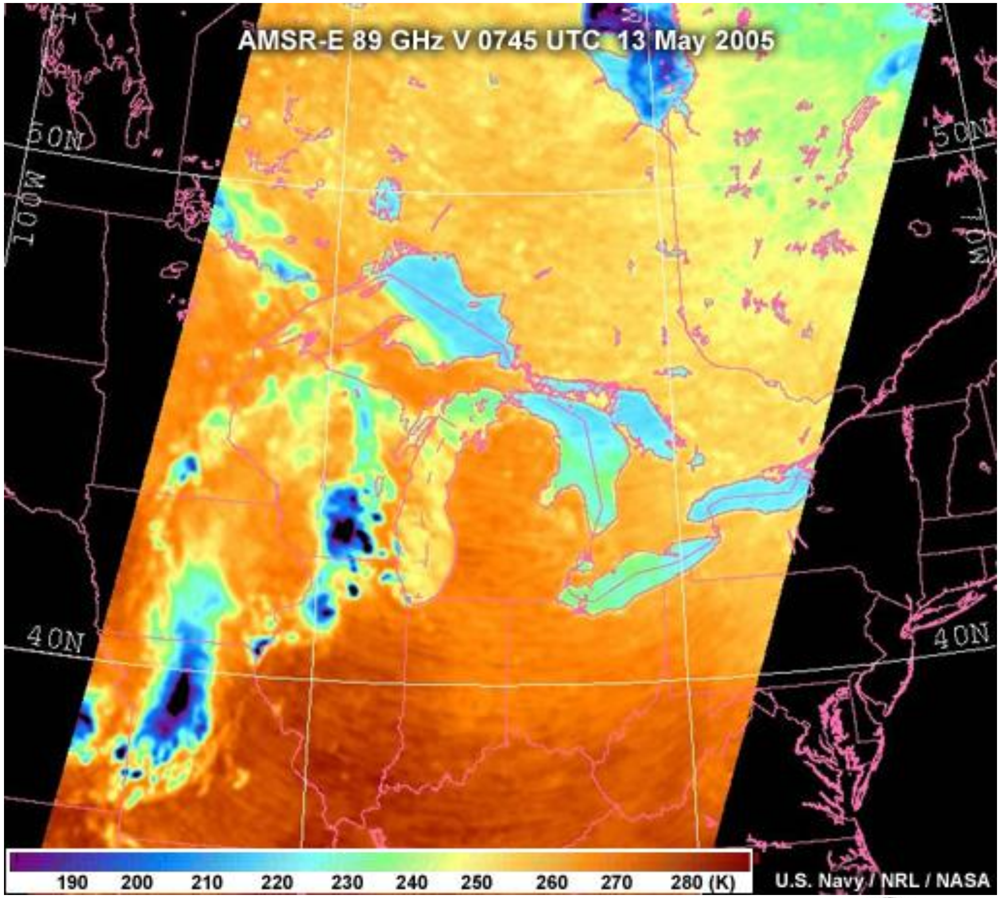
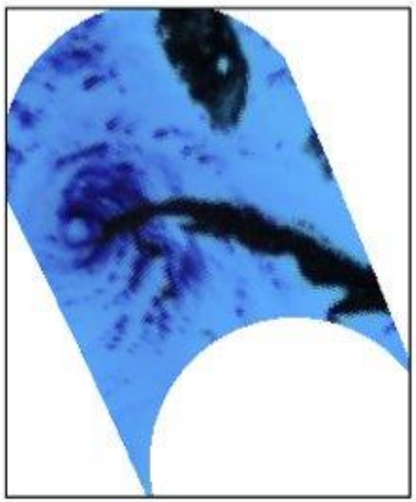


Preciptation measurement Systems
Passive Microwave

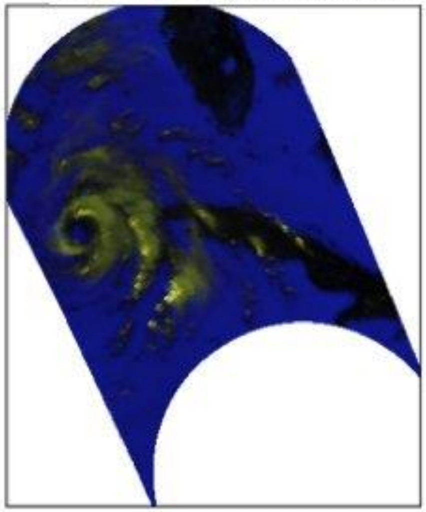
GPM Views Hurricane Michael with multiple channels

10 + 18 GHz Composite



Low frequency channels are sensitive to liquid and surface type. Warmer brightness temperatures indicate rain (or land). In this composite, ocean surfaces are light blue, rain is dark blue, and land is dark gray.

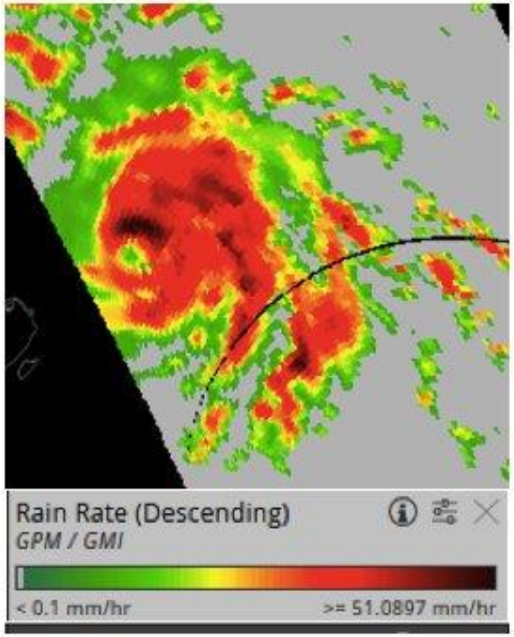
36 + 89 GHz Composite



Mid frequency channels are sensitive to liquid and ice. Ocean surfaces are dark blue, liquid clouds, rain, and land appear dark, and ice-phase precipitation aloft appears gray or white.

183 GHz Composite

High frequency channels are sensitive water vapor and ice. In the composite, darker blue colors indicate a typical clear-sky atmosphere. Lighter red/brown indicate relatively shallow precipitation; bright white is deep convection.

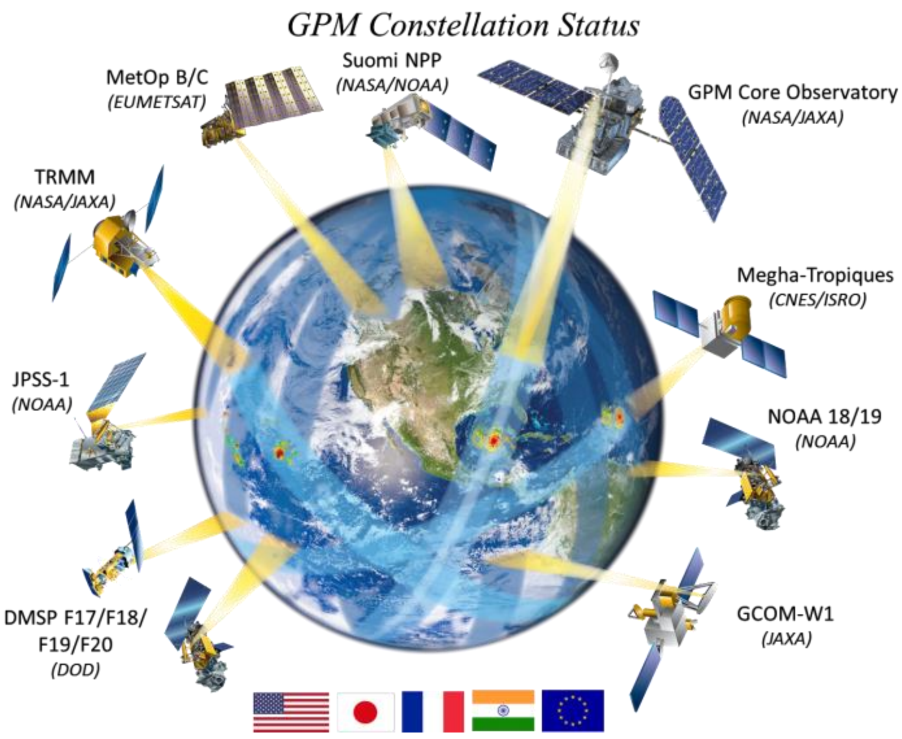


Rain rates from the GPM GMI instrument on October 8th, 2018 as Hurricane Michael was intensifying in the Gulf of Mexico

Quelle: https://disasters.nasa.gov

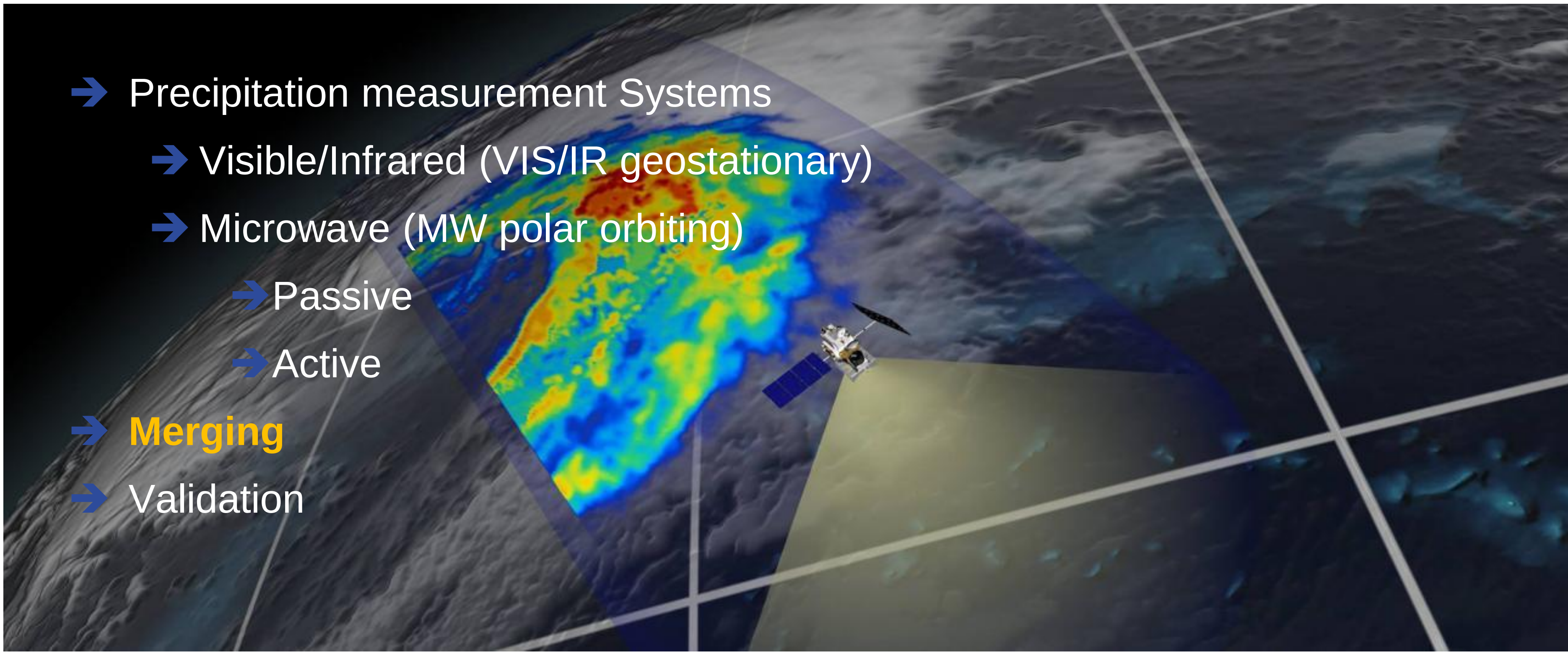
Preciptation measurement Systems
Passive Microwave

- Advantages:
  - Samples remote regions
  - More physically based, more accurate than VIS/IR
- Disadvantages:
  - Poorer time/space resolution
  - Indirect measurement of rain
  - Rain from warm clouds over land not captured (no emission channels!)



Quelle: https://gpm.nasa.gov/image-gallery/gpm-constellation

Remote Sensing of Precipitation



- Precipitation measurement Systems
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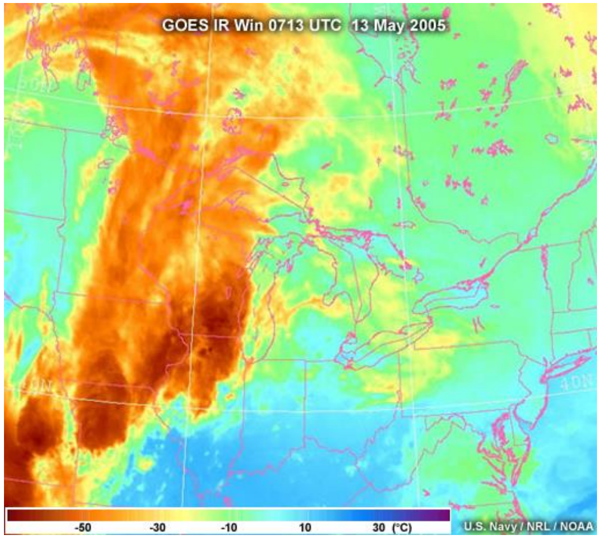
  - Microwave (MW polar orbiting)
    - Passive
    - Active
- **Merging**
- Validation

Quelle: https://gpm.nasa.gov/missions/GPM/gpm-core-observatory

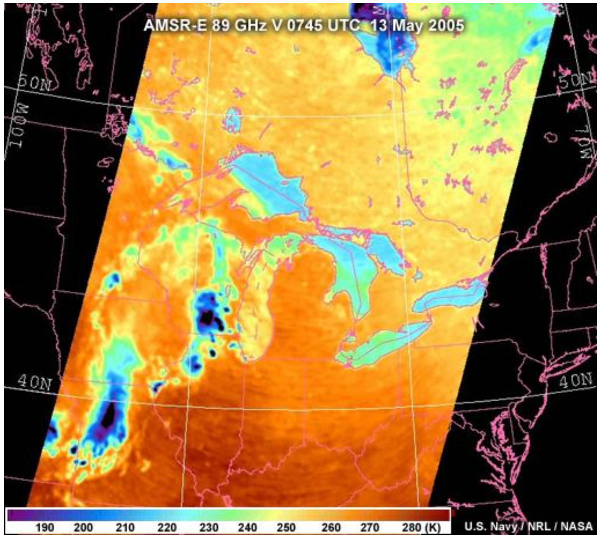
Merging

- Combine strengths of different methods to get most consistent and accurate precipitation estimate

good space/time resolution



good precipitation estimates



- DPR+PMW
- Gauges+PMW: e.g. GPCC land, HOAPS ocean -> DAPAGLOCO
- IR+PMW (e.g. GIRAFE)
- Gauges+IR+PMW (e.g. GPCP)

Quelle: COMET® Website at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)

Merging example: GIRAFE

- Global Interpolated RAinFall Estimation
- Combination of IR TBs and PMW rain rates
- Developed at CM SAF (released April 2024)
- Global Climate Data Record (CDR) 2002-2022
- 1° x 1° x 1 day precipitation amount plus sampling uncertainty
- Accumulated rainfall:

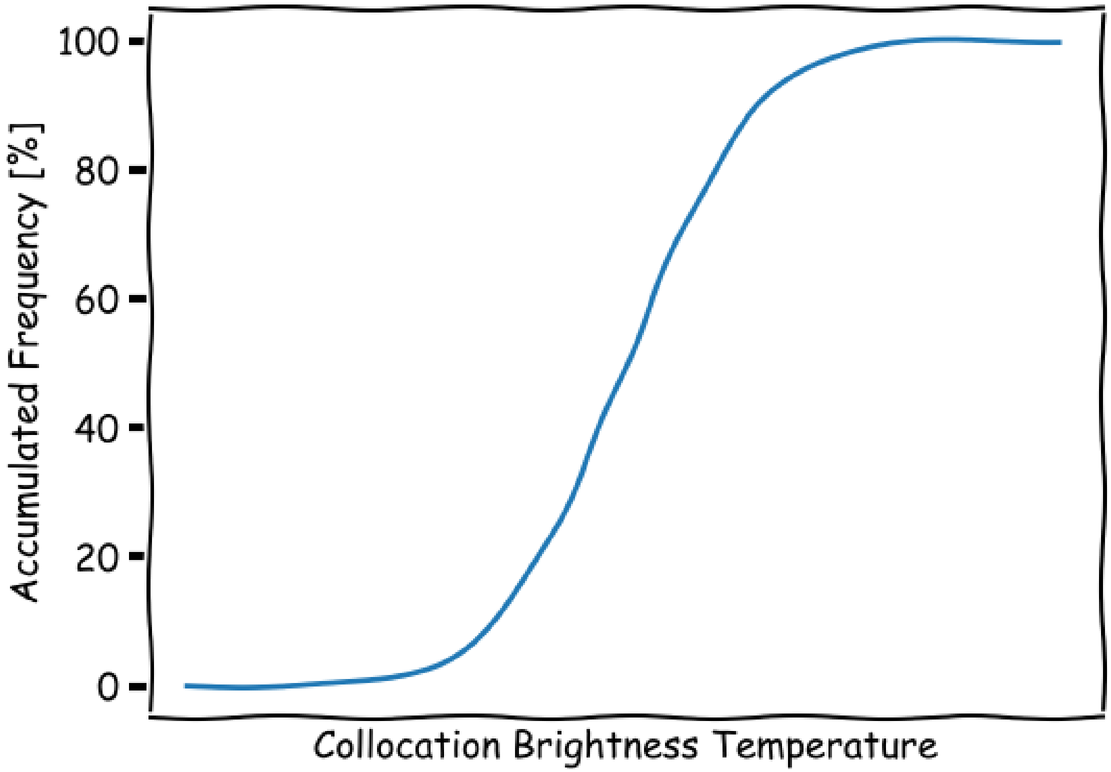
$$R_{acc} = \underbrace{\bar{R}}_{\text{"how much"}} \cdot \underbrace{F_P \cdot t}_{\text{"how long"}}$$

t - Time interval (24h)

$\bar{R}$ - Mean rain rate

$$F_P = \frac{\#\,(T_B < \tau)}{\# T_B}$$ Precipitation Fraction

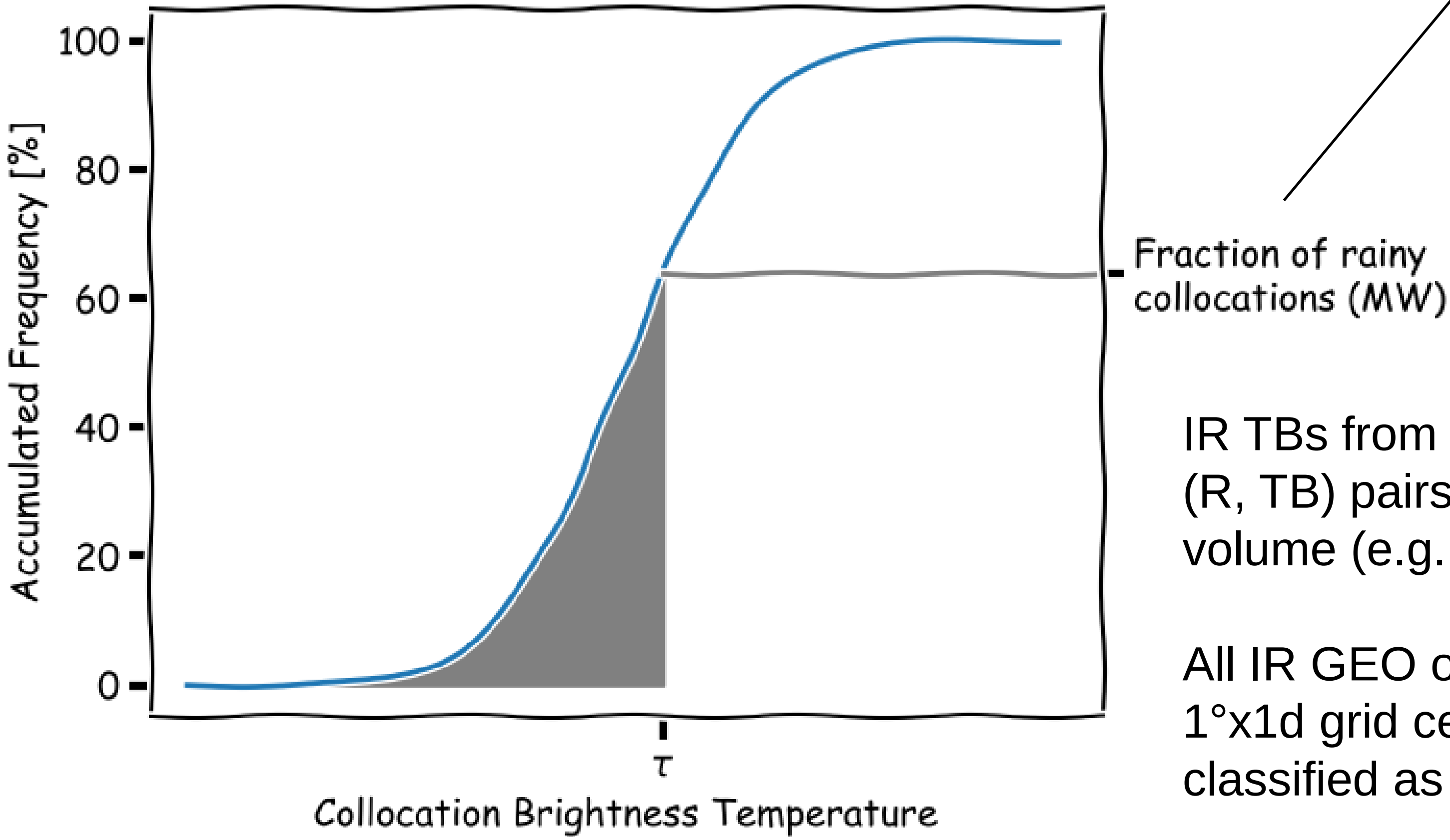
Merging example: GIRAFE derivation of IR TB threshold



IR TBs from all collocated (R, TB) pairs in training volume (e.g. 3°x1d)

Merging example: GIRAFE derivation of IR TB threshold

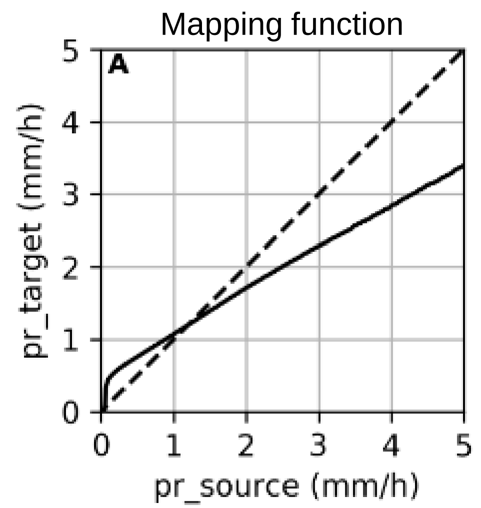
Above threshold of e.g. 0.5 mm/h



IR TBs from all collocated (R, TB) pairs in training volume (e.g. 3°x1d)

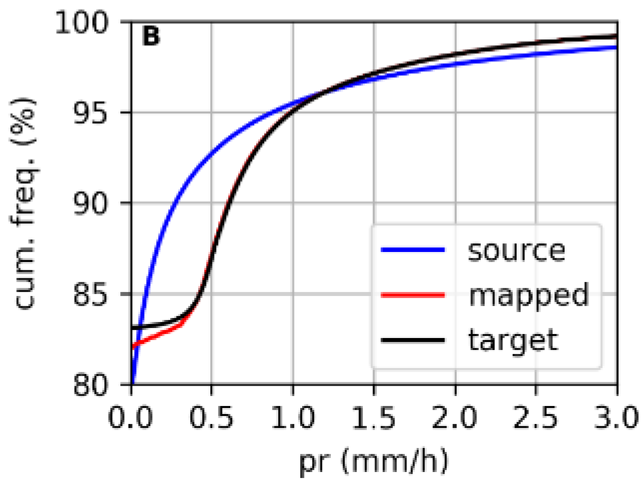
All IR GEO observations in 1°x1d grid cell < τ are classified as precipitation

Merging example: GIRAFE



- ➔ Input data:
  - ➔ IR data from geostationary satellites
  - ➔ Precipitation over land and ocean from different PMW platforms and retrievals

  - ➔ challenge: bring all PMW input data on 1 level to remove instabilities
    - ➔ Quantile mapping
    - ➔ map cumulative distibution of source platform to target platform to remove differences due to retrieval / overpass times



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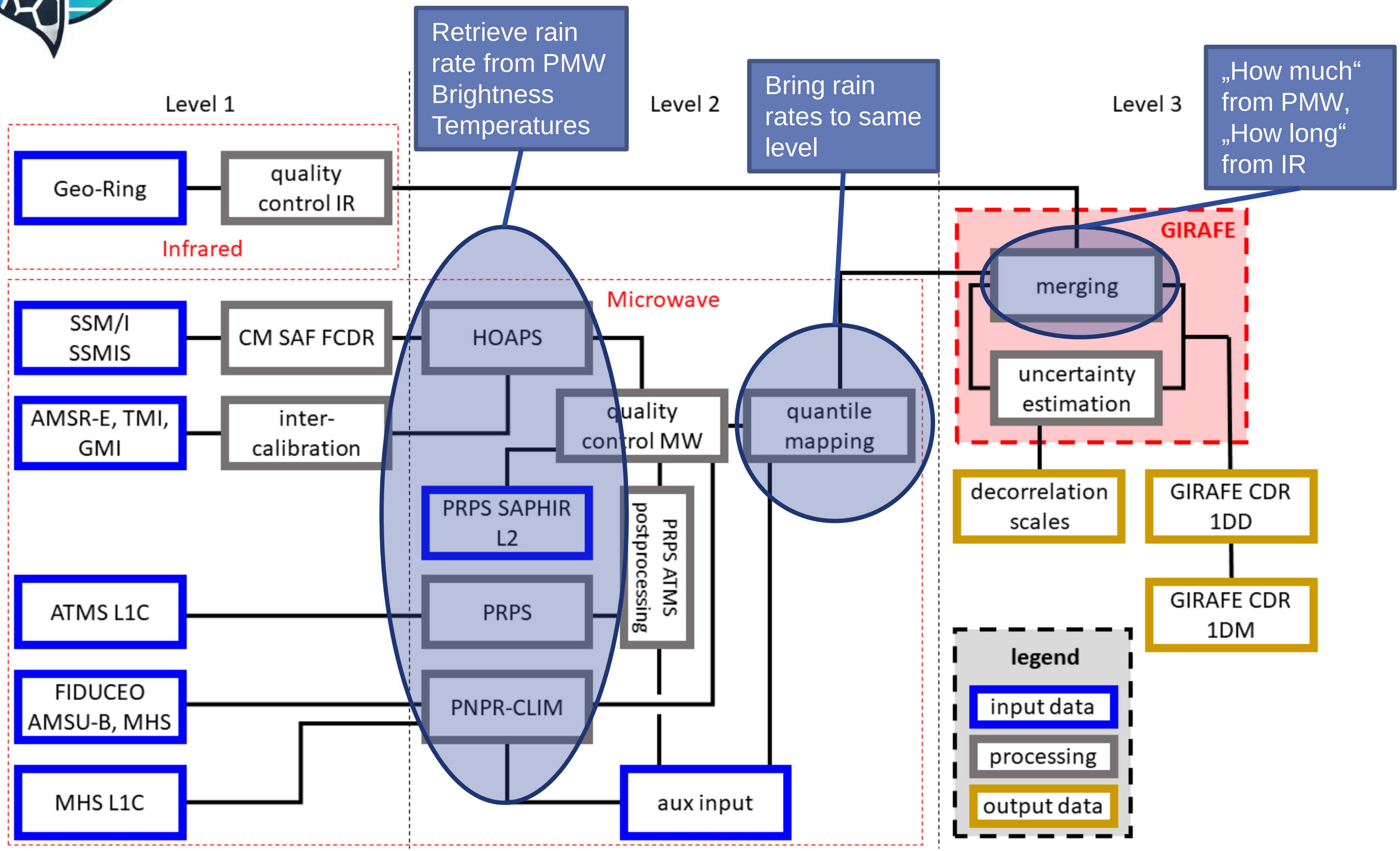

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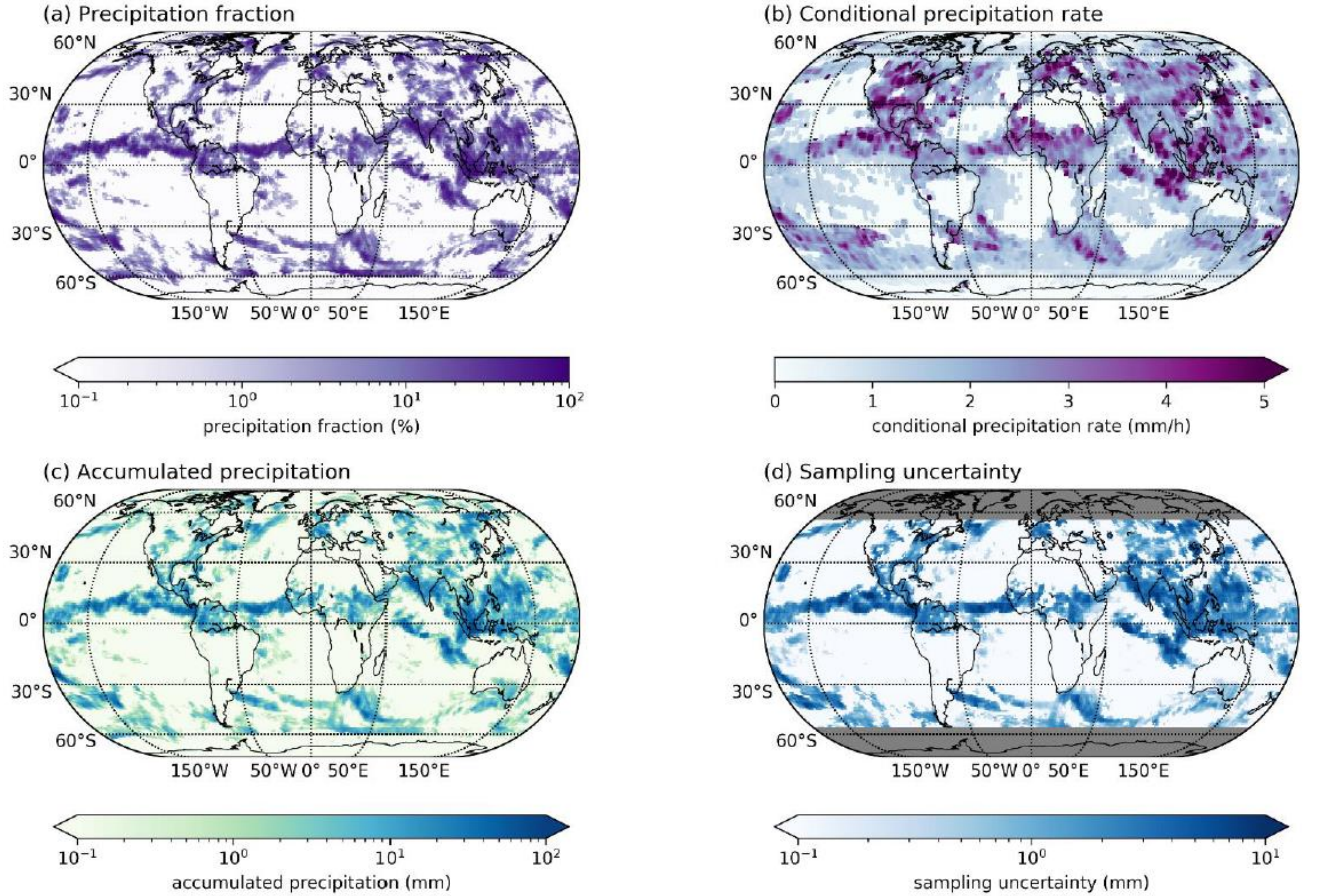
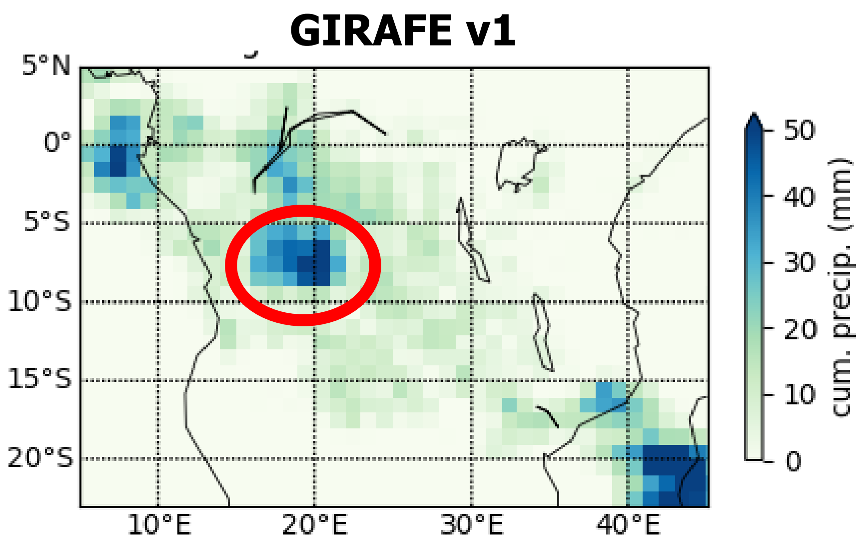
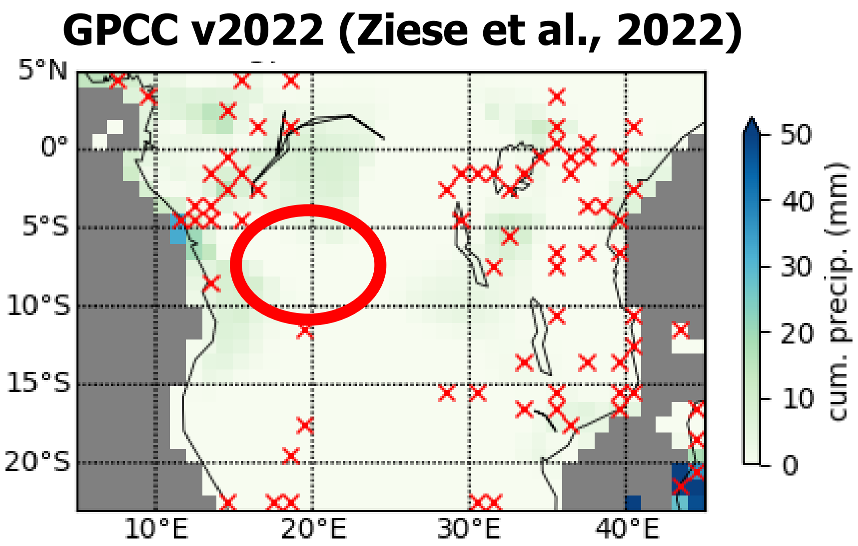


GIRAFE vs GPCC

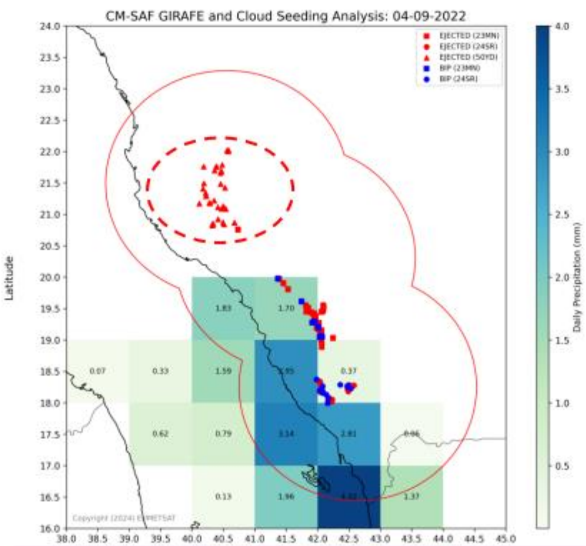
- Rain gauges etc measure precipitation much more directly, but:
- Example: 16 Nov 2019 (contributing to the 2019/20 Congo river floods)
- No ground-based observation (x) in precipitation area, so a station-based dataset like GPCC is „blind“ on this day





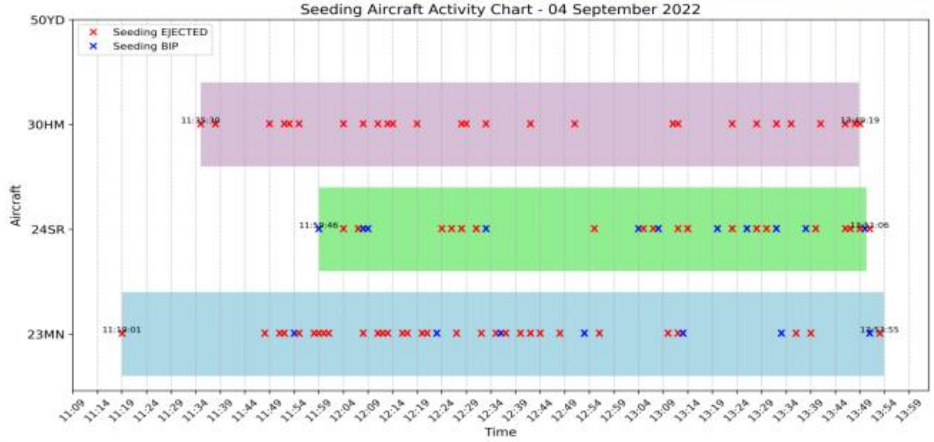
GIRAFE Application: cloud seeding studies

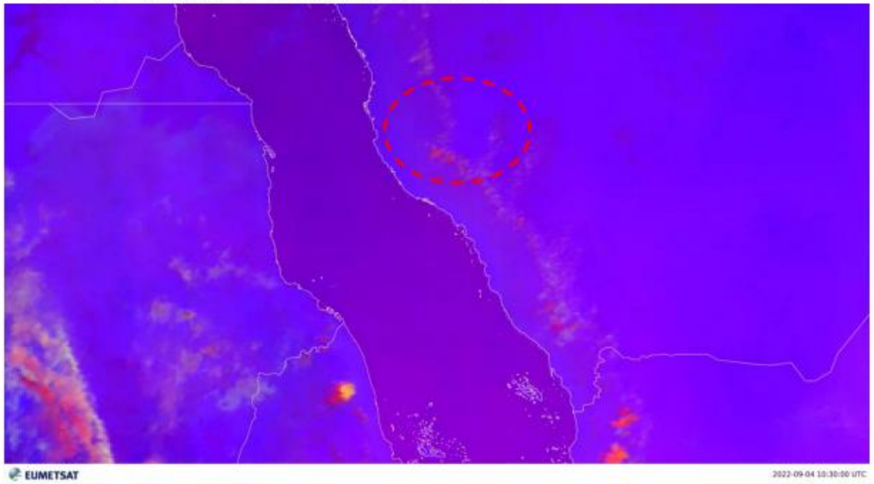
Spatial Analysis of Precipitation Anomalies & Glaciogenic Cloud Seeding Operations Over Saudi Arabia - Ioannis Matsangouras

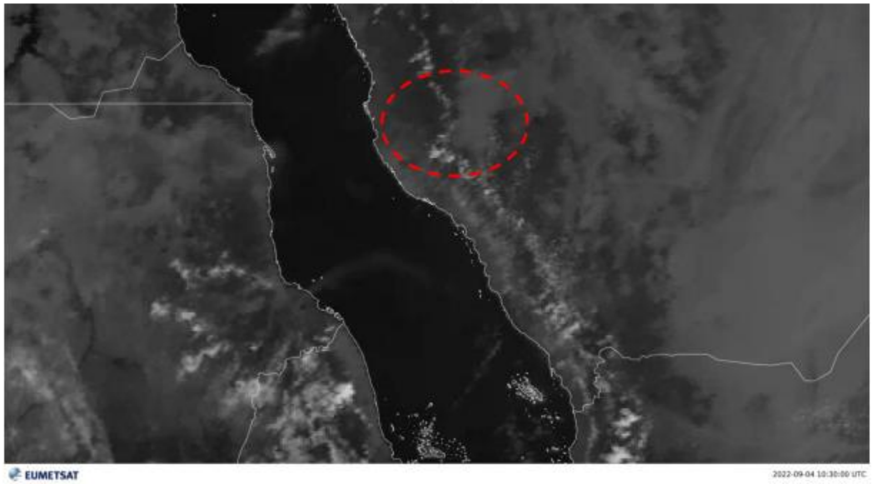


GIRAFE Performance: 4 SEP 2022 2/4

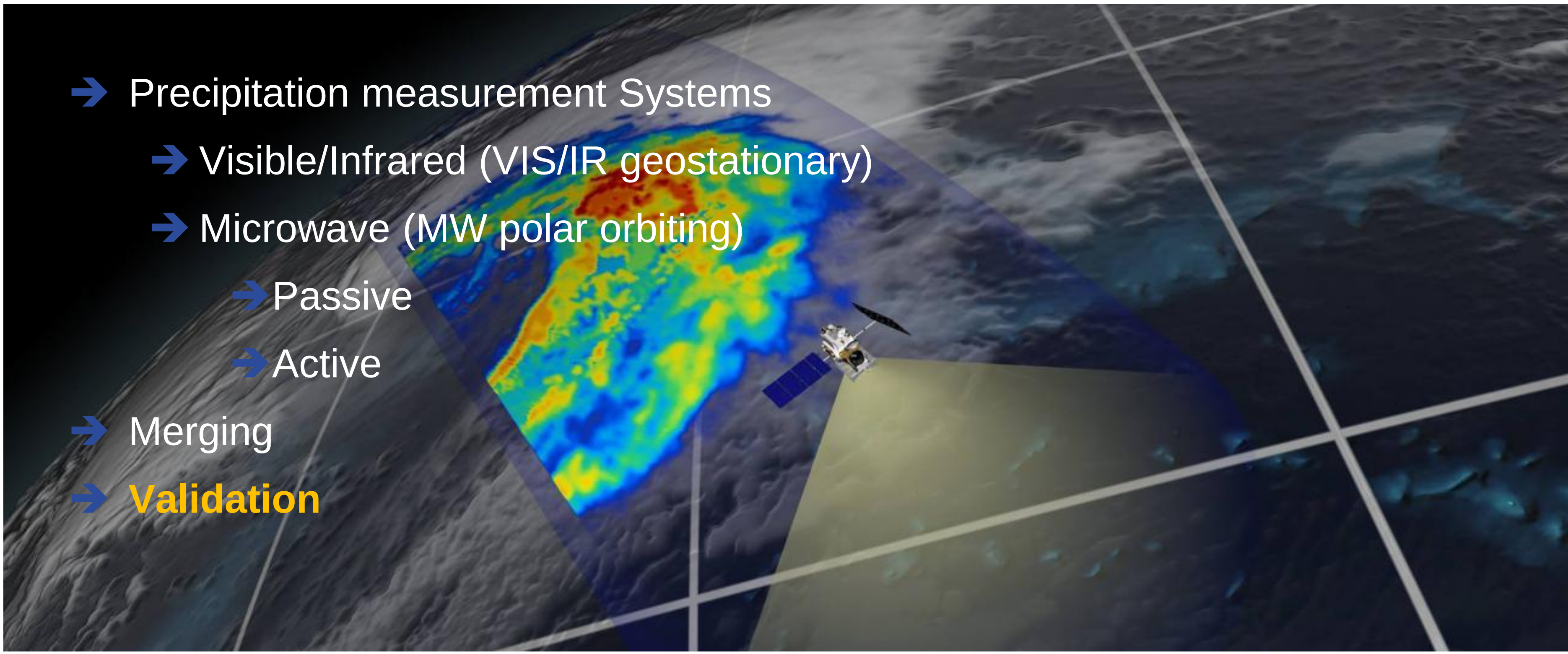
البرنامج الاقليمي لإستمطار السحب
Regional Cloud Seeding Program







Remote Sensing of Precipitation



- Precipitation measurement Systems
  - Visible/Infrared (VIS/IR geostationary)
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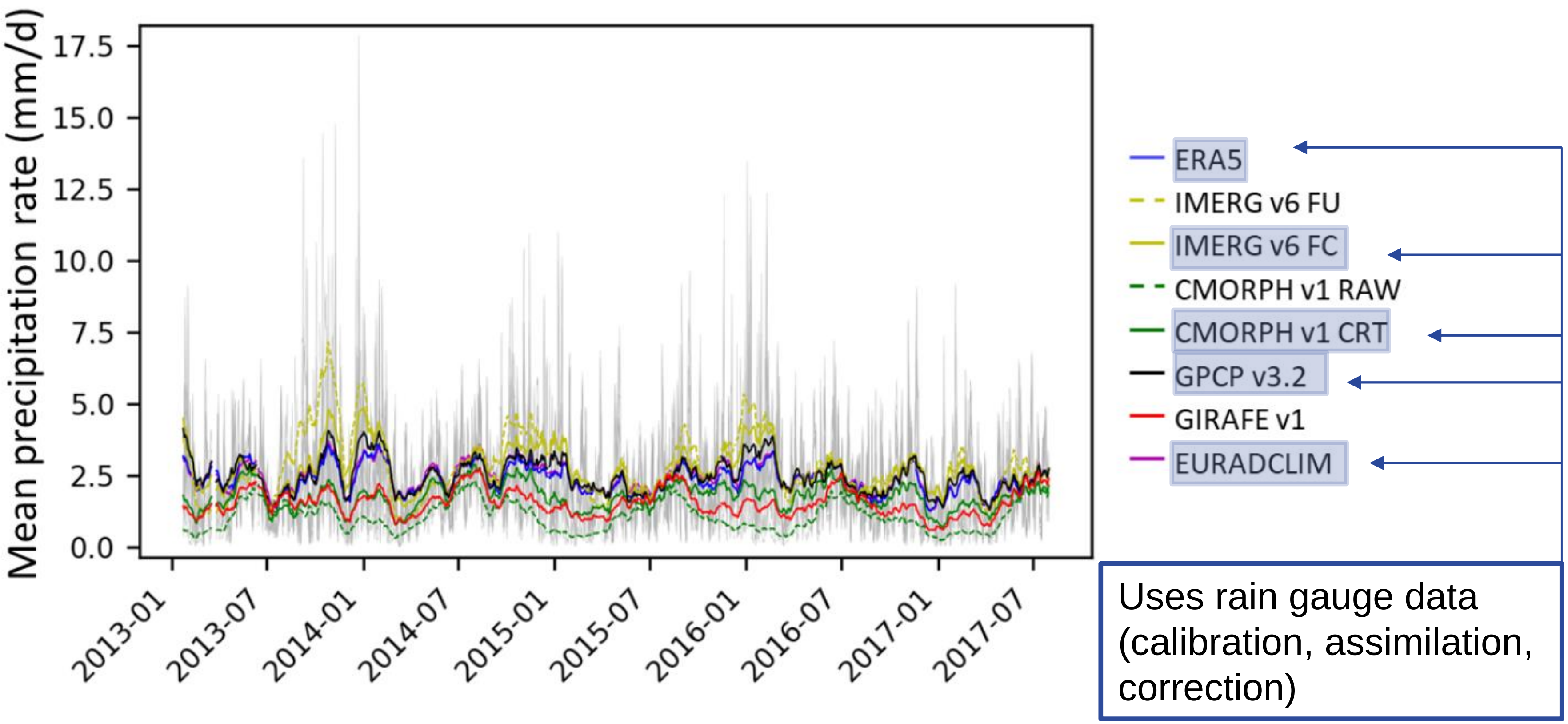
- **Validation**

Quelle: https://gpm.nasa.gov/missions/GPM/gpm-core-observatory

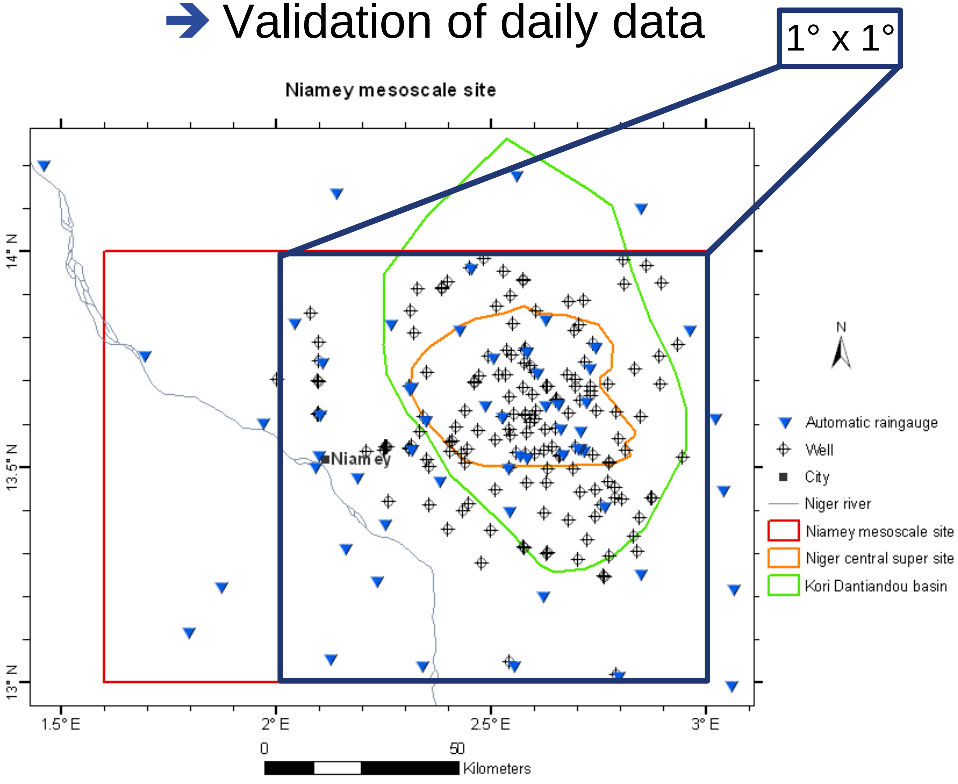
Validation

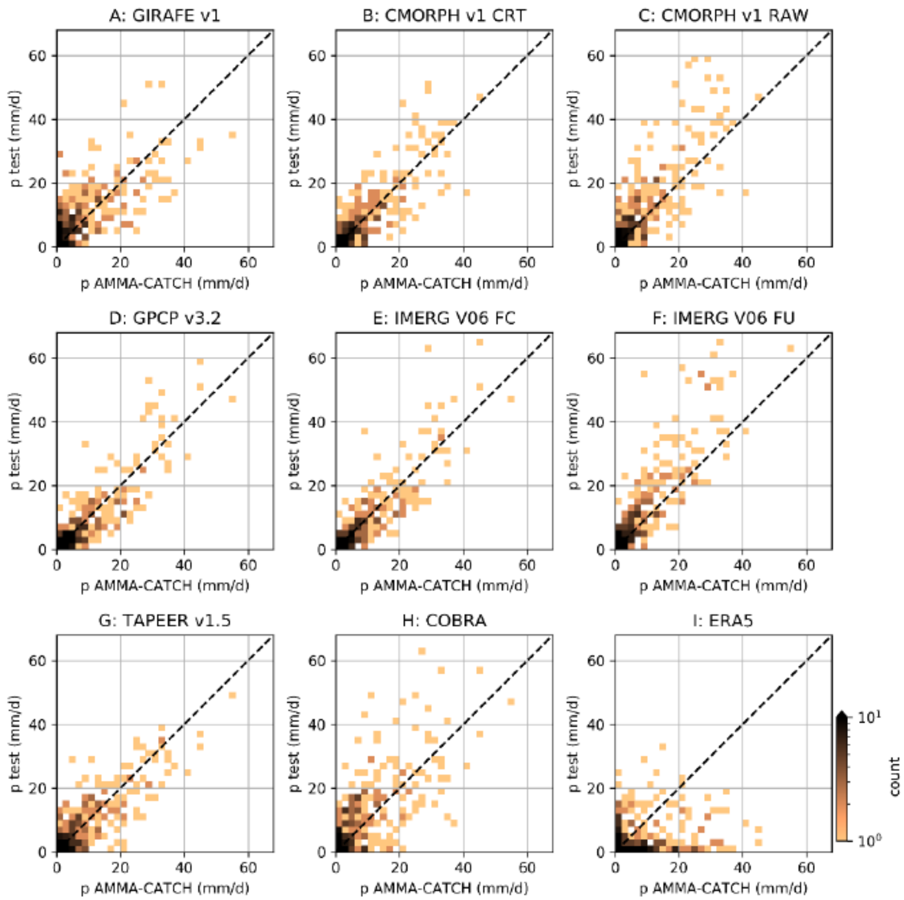
- ➔ if nearly all datasets used for products: nearly no independent dataset left for validation
- ➔ compare available data sets to contextualize our results / precipitation rates



Validation

- ➔ example: validation of precipitation datasets with AMMA-CATCH station data
  - ➔ African Monsoon Multidisciplinary Analysis
  - ➔ high-resolution rain gauge network
  - ➔ Validation of daily data





Validation

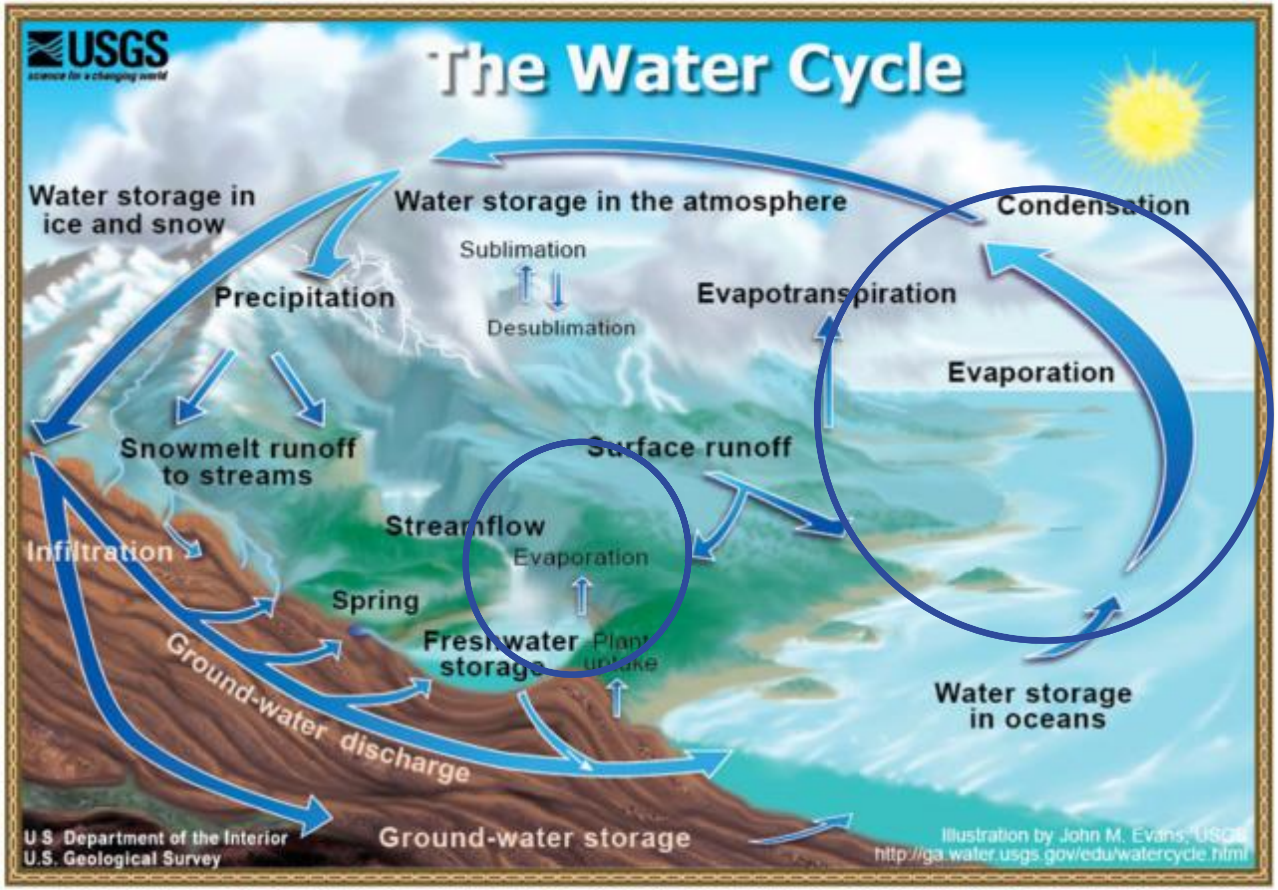
- Be carful what you compare / how to interprete your results:
  - Accumulated or instantaneous rain rate
  - Gridded or single point measurement
  - …

  - Diurnal cycle?
  - Spatial resolution?
  - Collocation distance?
  - Independent datasets?
  - Time of Day definition?
  - …

The Water Cycle

Content

- ➔ Motivation
- ➔ Precipitation
- ➔ Evaporation
- ➔ Water vapour
- ➔ The Cycle

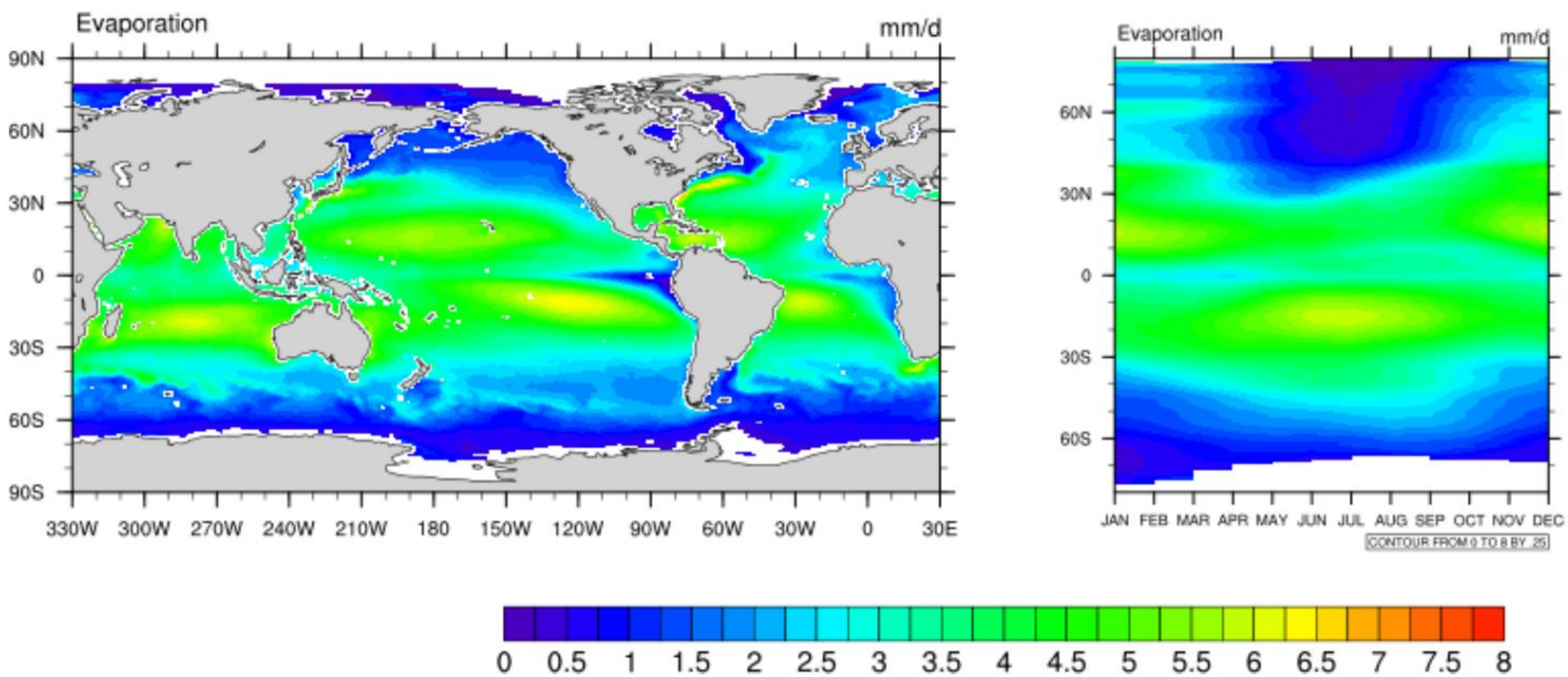


How to measure evaporation?

➔ Derive from latent heat flux Q_l

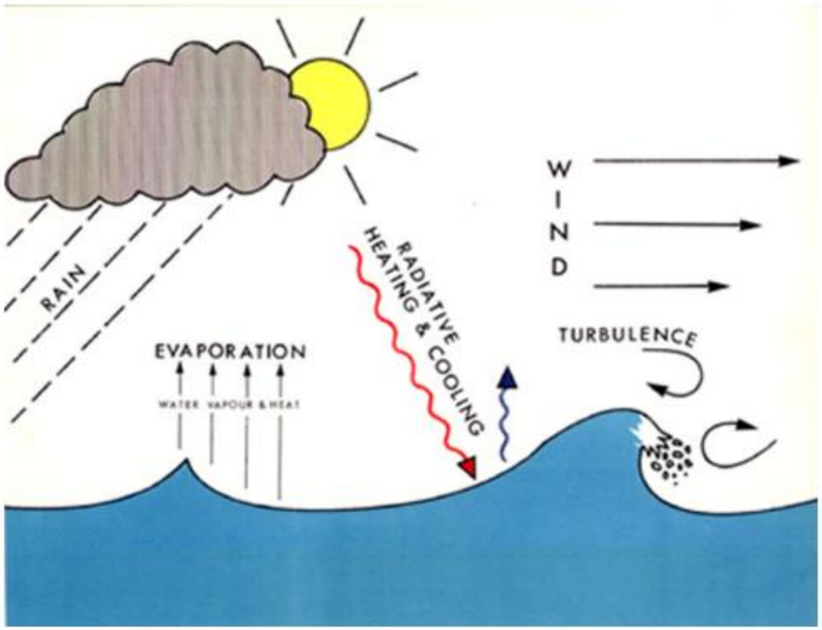
$$E = Q_l/(L_E \rho_0)$$

- ➔ Density of liquid water: ρ_0 = F(T),
- ➔ specific heat of evaporation: L_E = constant



How to measure latent heat fluxes?

- Energy budget of the sea surface is dominated by:
  - Solar (short wave) heating
  - Cooling by emission of long wave radiation
  - Cooling by latent heat flux
- Direct measurement of heat flux:
  - High-frequency measurements onboard research vessels
  - High effort
  - NOC Surface Flux and Meteoro-logical Data Set (NOCS)
- Derive from parameterization
  - Satellites



Schematic showing the different components of the ocean heat fluxes.

How to measure latent heat fluxes from satellites?

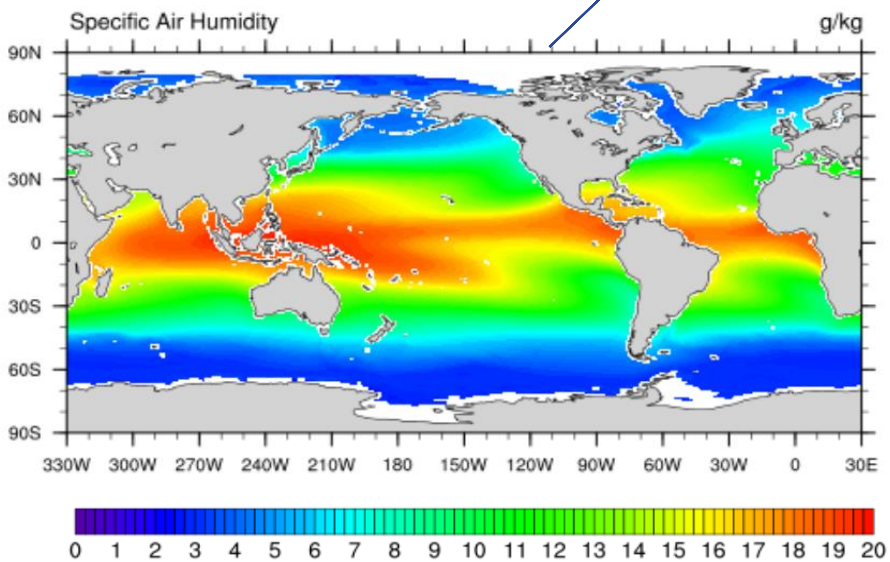
- Parameterisation
- COARE bulk aerodynamic approach: Fairall, JGR 1996:

$$Q_l = \rho L_E C_E u(q_s - q_a)$$

$\rho = F(T_s, p_s, q_a)$

$q_s = F(T_s, p_s)$

ρ = air density	derived
u = wind speed (@10m)	Variable
L_E = specific heat of evaporation	constant
C_E = Dalton number (relating wind speed to latent heat)	
q_s = specific humidity (@sea level)	
q_a = specific humidity (@10m)	



Specific humidity:
Parameterization by
Bentamy et al. (2003):

Directly relates Brightness Temperatures
From MW channels

How to measure ~~latent heat fluxes~~ wind speed from (MW) satellites?

- Parameterisation
- COARE bulk aerodynamic approach: Fairall, JGR 1996:

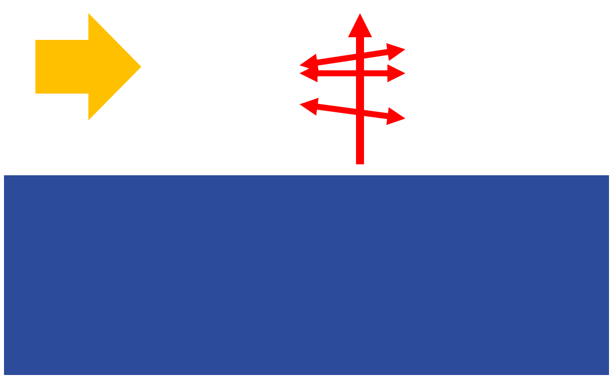
$$Q_l = \rho L_E C_E u(q_s - q_a)$$

$\rho = F(T_s, p_s, q_a)$

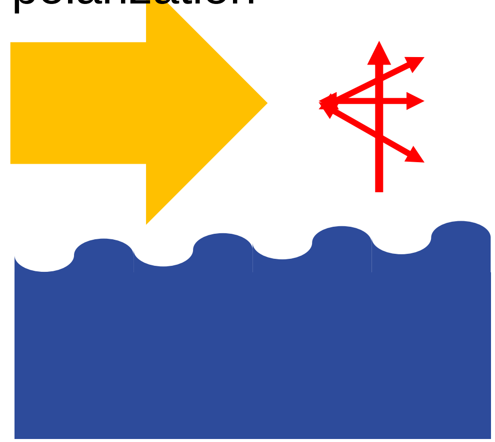
$q_s = F(T_s, p_s)$

ρ = air density	derived
u = wind speed (@10m)	Variable
L_E = specific heat of evaporation	constant
C_E = Dalton number	
q_s = specific humidity (@sea level)	
q_a = specific humidity (@10m)	

Low wind, quiet surface, less vertical polarization



Strong wind, disturbed surface, more vertical polarization



How to measure ~~latent heat fluxes~~ wind speed from (MW) satellites?

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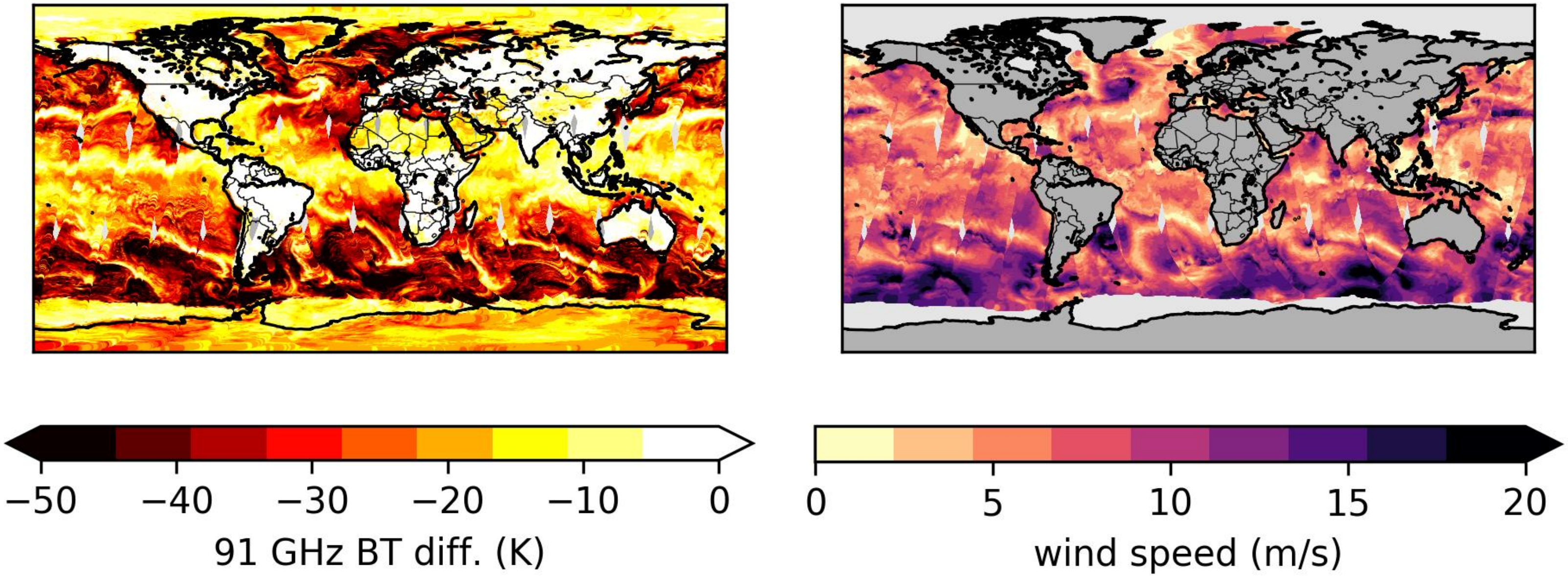
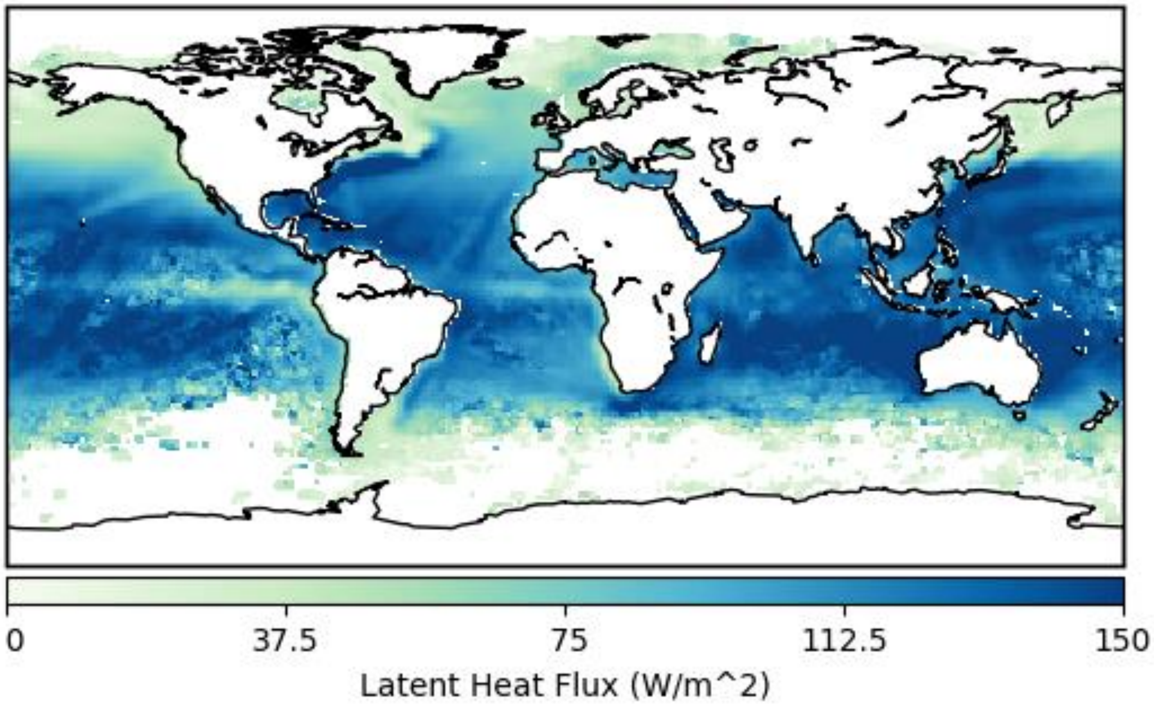


HOAPS SSMIS f18 on 2010/06/05: Horizontally pol. BT minus vertically pol. BT @ 91 GHz and 10 m wind speed

Latent heat from *in situ* observations

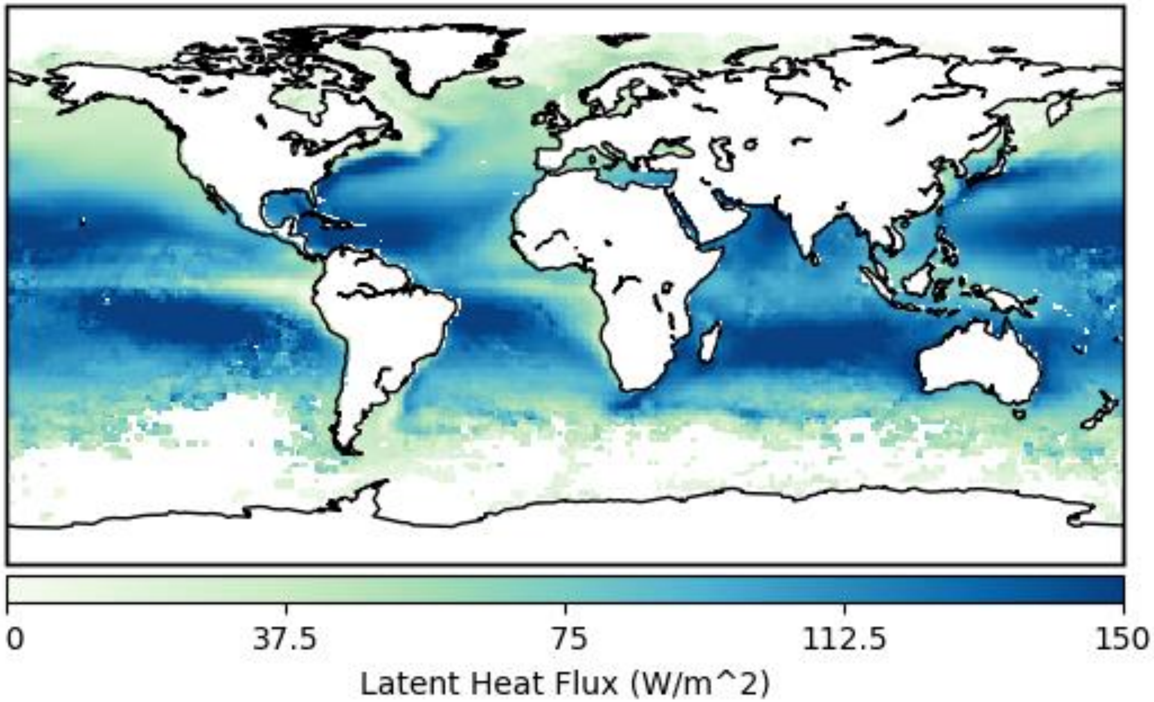
- ➔ E.g. NOC Surface Flux and Meteorological Data Set (NOCS)
  - ➔ Voluntary Observing Ships (VOS), 1973 - ongoing



NOCS mean latent heat flux, 1988-2014

Latent heat from satellite MW observations

➔ HOAPS v4 (1987-2014)

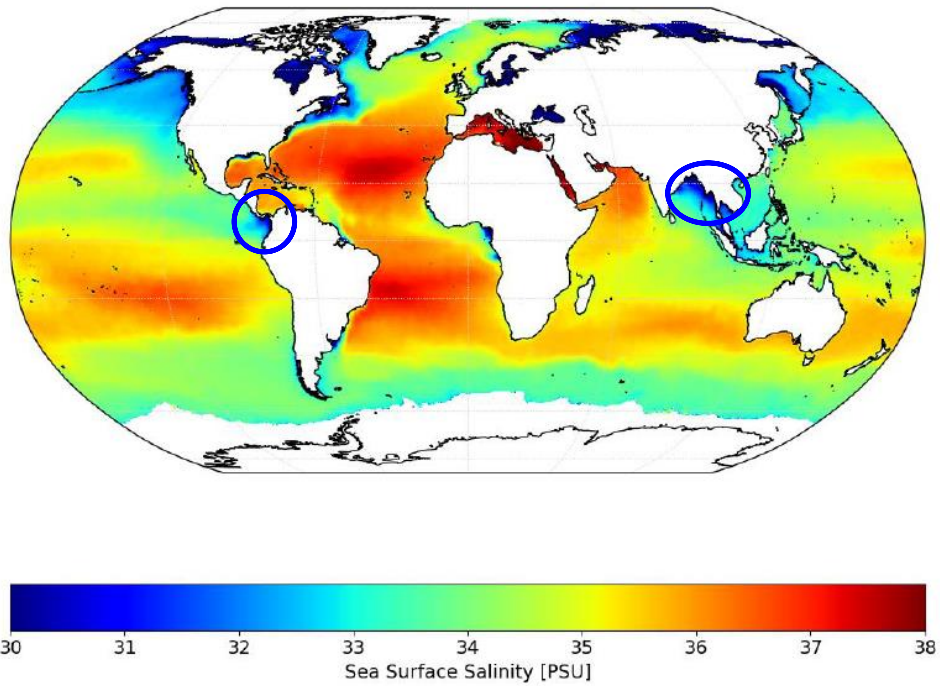


HOAPS mean latent heat flux, 1988-2014

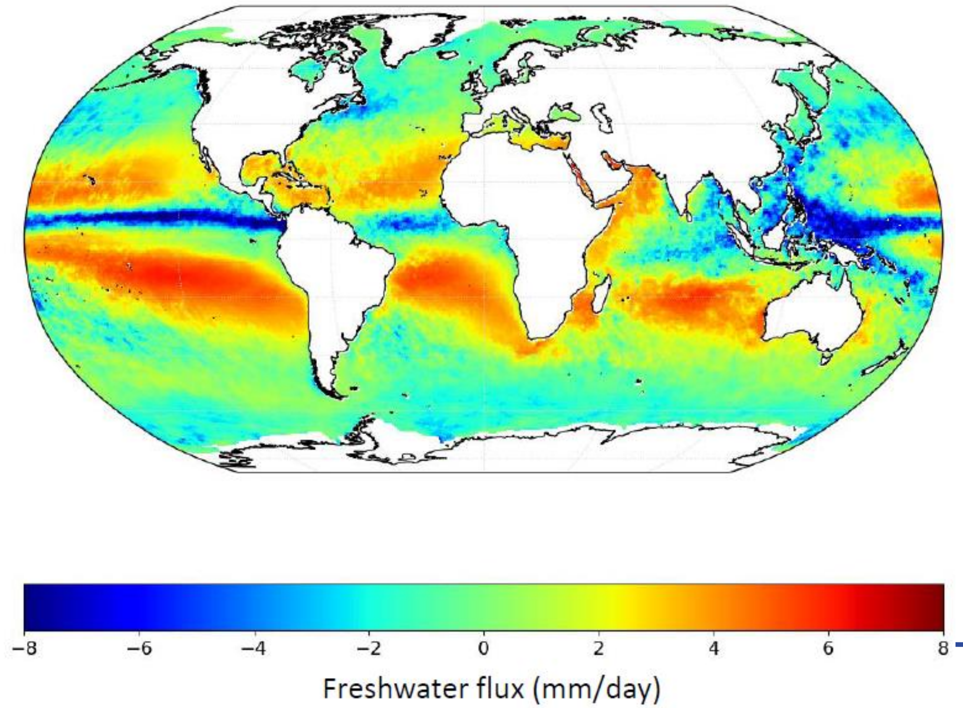
Fresh water flux

- ➔ The net amount of fresh water into the ocean is largely associated with evaporation minus precipitation (E-P)
  - ➔ At least as spatial field where river run-off is limited to specific areas
  - ➔ E-P is positive if E > P
  - ➔ E-P is negative if P > E
- ➔ Sea surface salinity is strongly influenced by E-P (+ run-off)

SMOS Sea surface salinity, 2011



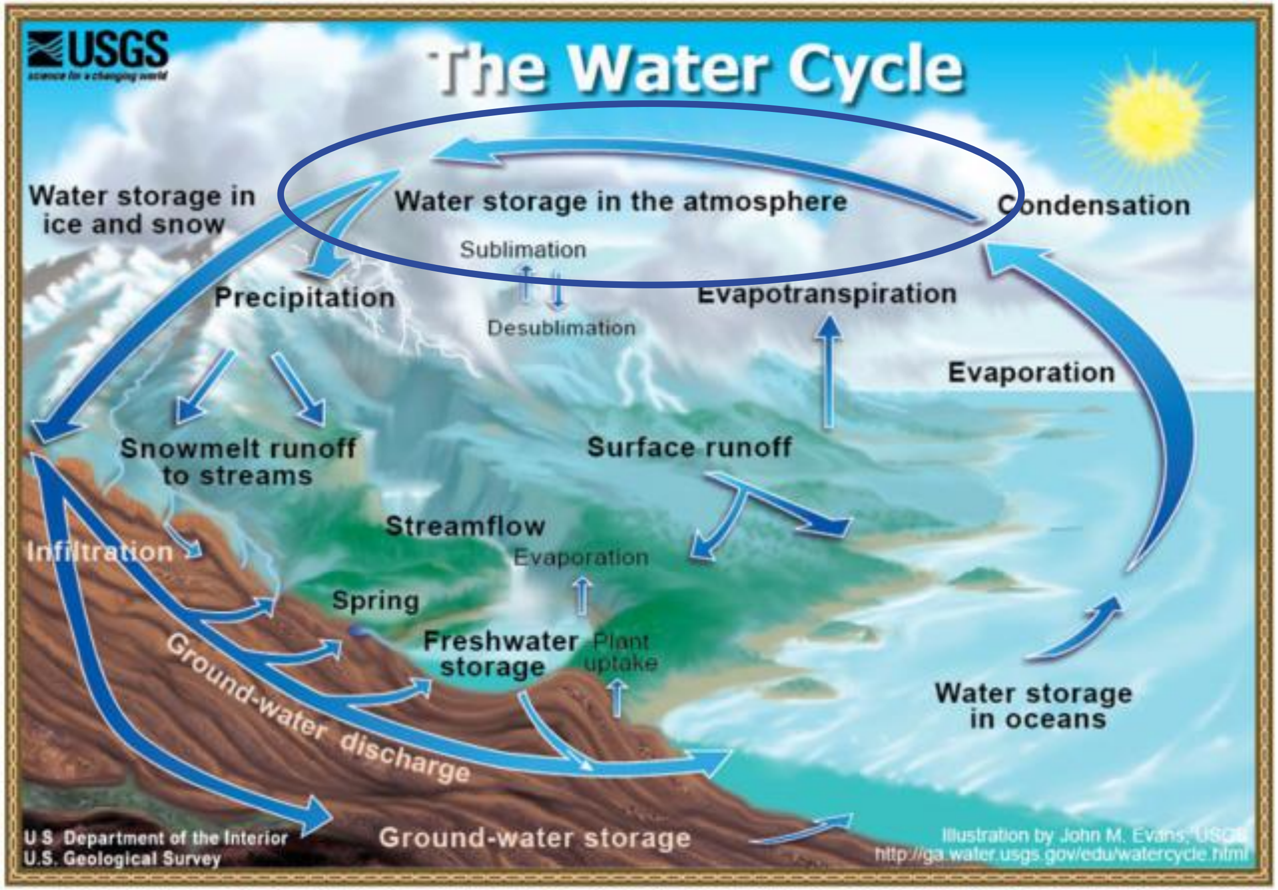
HOAPS freshwater flux (E-P), 2011



The Water Cycle

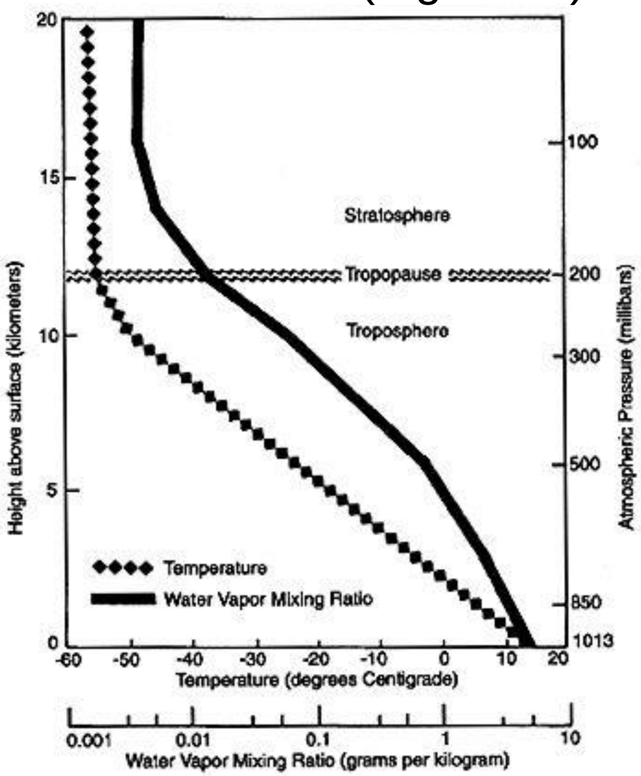
Content

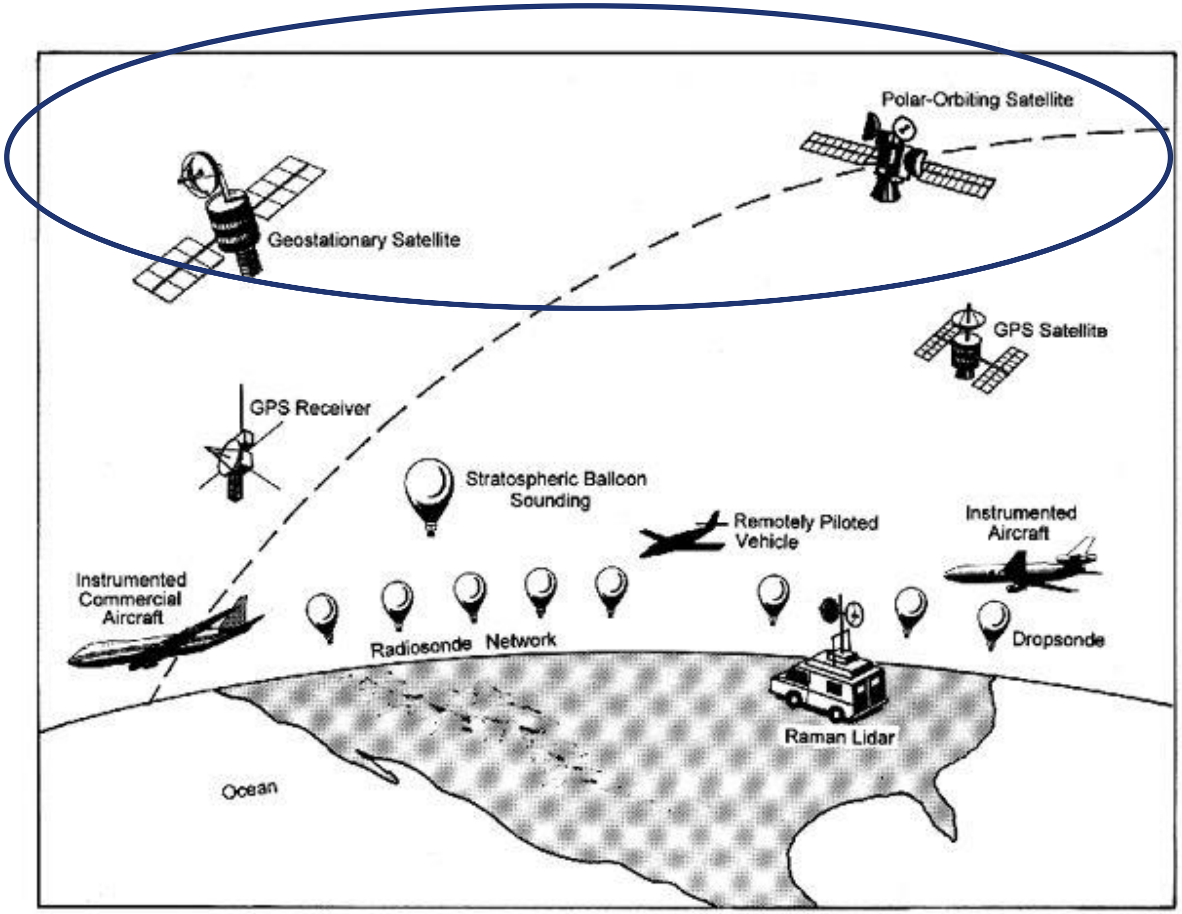
- ➔ Motivation
- ➔ Precipitation
- ➔ Evaporation
- ➔ Water vapour
- ➔ The Cycle



How to observe water vapour content?

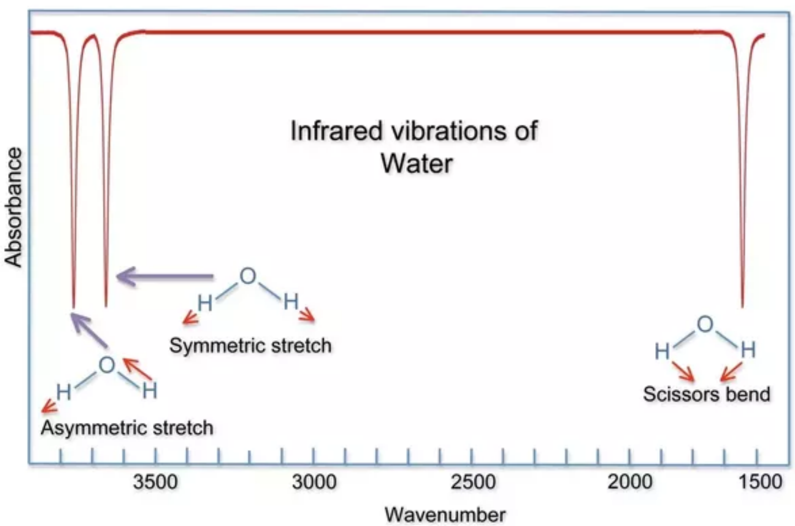
- In situ Radiosonde
- Radar
- Satellite:
  - Absorption
  - GNSS (e.g. GPS)

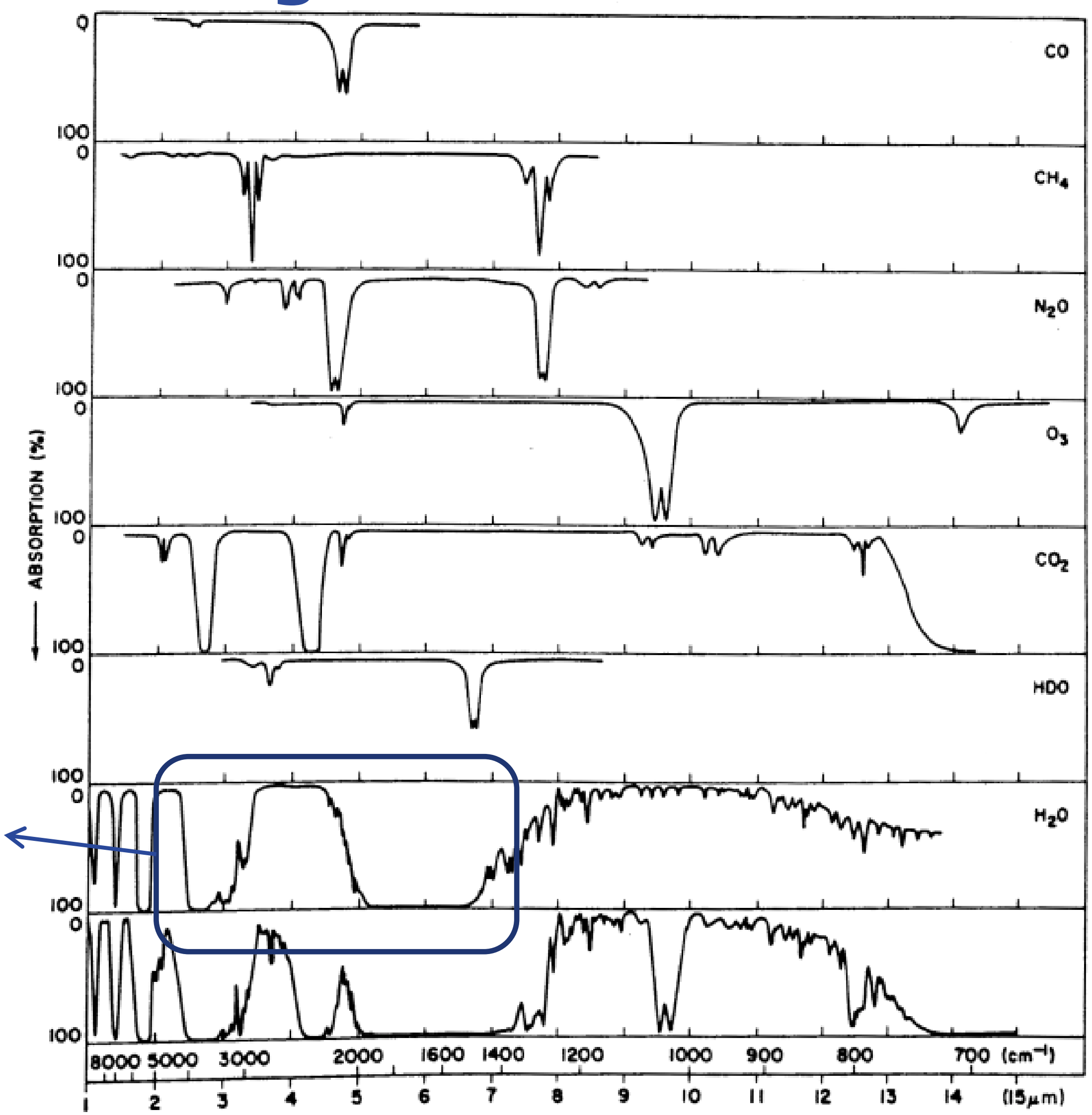




Satellite remote sensing of WV content

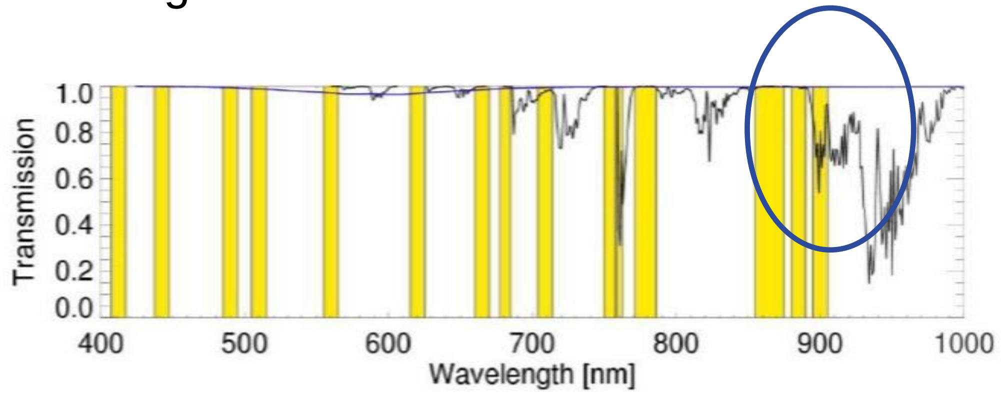
- Absorption / emission at many frequencies/wavelengths
  - Electronic transitions (UV-NIR)
  - Vibrations (IR, key for water vapour)
  - Rotations (MW, all-weather capability)
  - Many combinations (complex spectral signature)

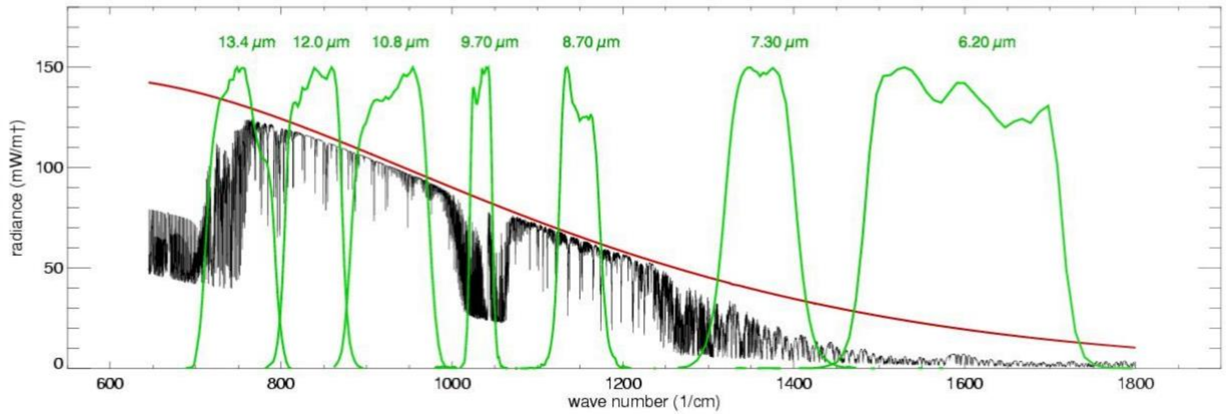


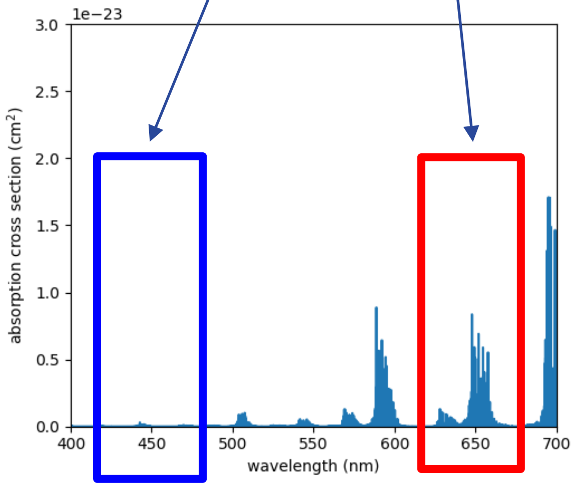


Satellite remote sensing of WV content

- Many instruments at different wavelength
  - Absorption at
    - Red
    - Blue
    - Near infrared
    - Thermal infrared
    - **Microwave**



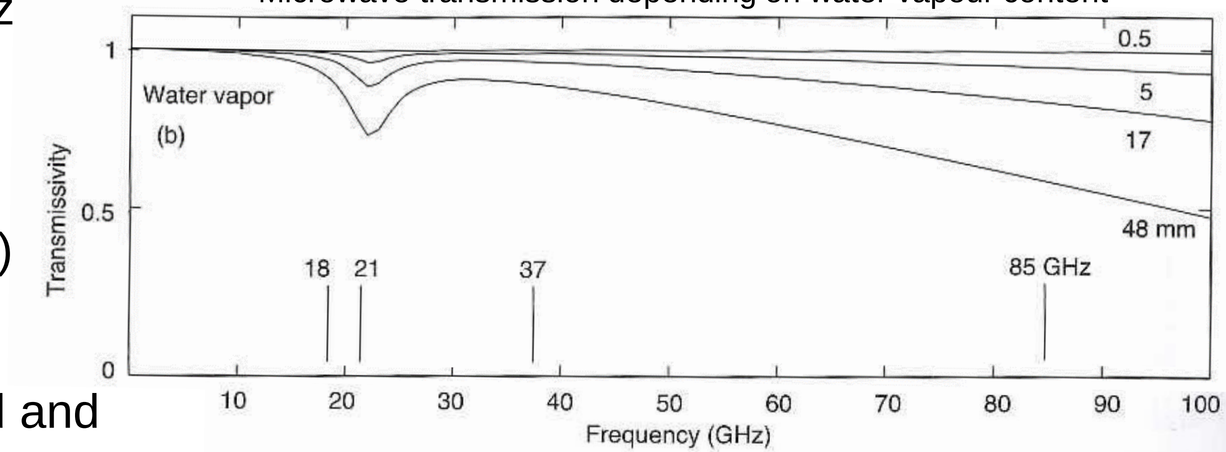




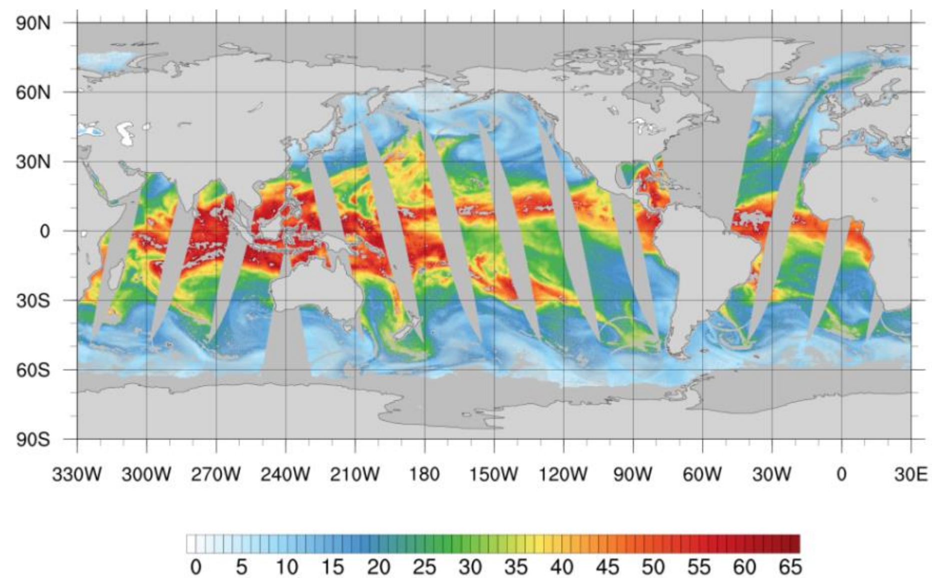
Microwave absorption

- Range: 21 GHz, 85 GHz
- Satellite instruments:
  - PMW
  - (z.B. SSM/I, SSMIS)
- Over ice-free ocean
- Similar spectra for liquid and gaseous H_2O
- Absorption line at 22 GHz is specific for water vapour

Microwave transmission depending on water vapour content



Quelle: S. Martin, An Introduction to Ocean Remote Sensing, 2014



HOAPS-4 water vapour content 15.12.2007

Water vapour content from absorption (satellites)

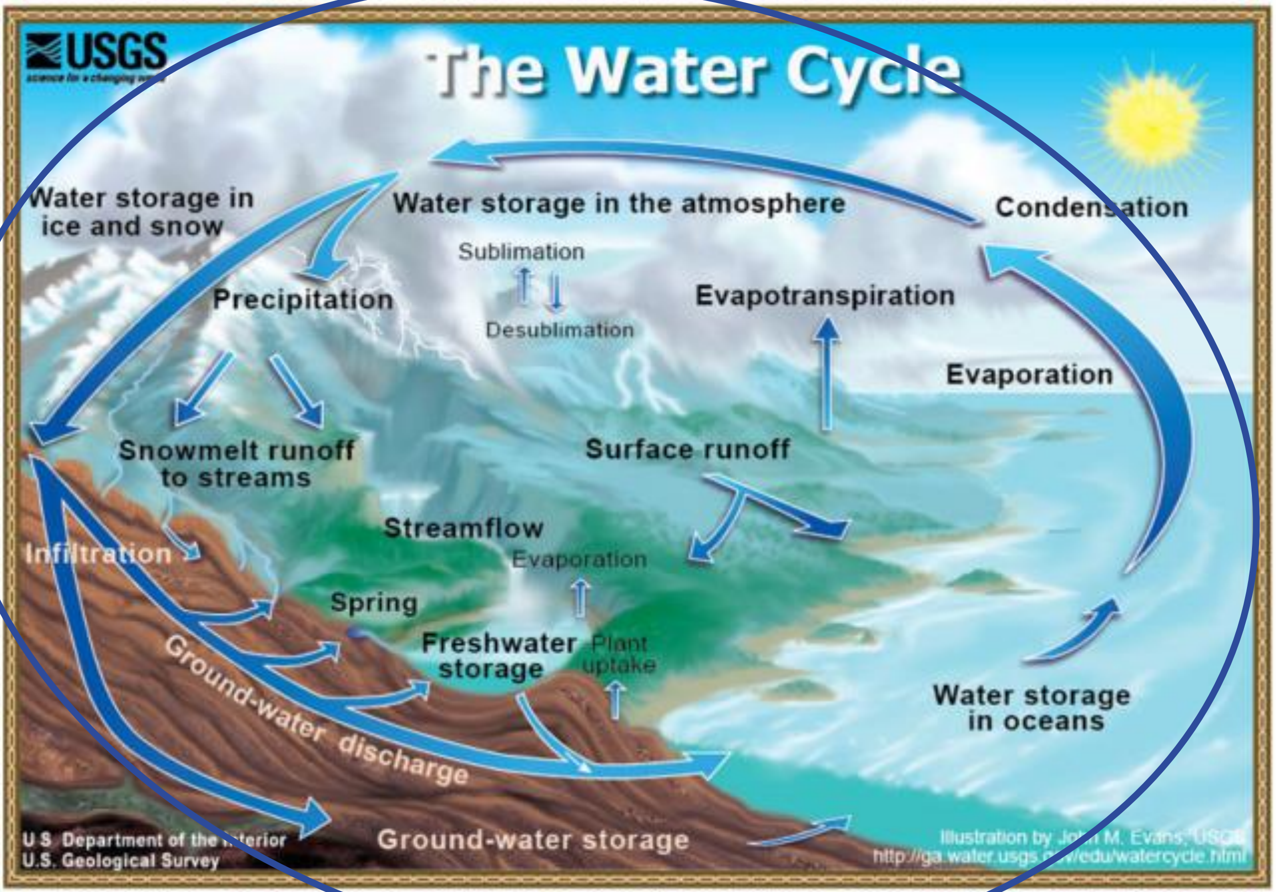
➔ Advantages and Disadvantages of various ranges and instruments

λ-range	UV-Visible	Near infrared	Thermal IR	Microwave
λ (v)	450 or 650 nm (>> THz)	0.9-2 µm (>> THz)	e.g. 6-12 µm (50-25 THz)	e.g. 16, 14, 8, 3 mm (19, 22,37, and 85 GHz)
Diurnal sampling	day	day	day + night	day + night
Cloud situation	clear sky	clear sky	clear sky	Any (except heavy rain)
Surface	Any except snow and ice		Any except snow and ice	Ice-free ocean
Highest sensitivity / vertical resolution	Lower troposphere	Mid-to-high troposphere plus profiles	profiles	Total column
Instruments	GOME(-2), SCIAMACHY, OMI, TROPOMI	MERIS, MODIS	TES, SEVIRI, IASI, AIRS, OCO-2	SSM/I, SSMIS, AMSR-E, TMI, HIRS, TOVS
Coverage and resolution	daily, Low-to-high	daily Very high	Daily to multiple days Low-to-high	Daily to multiple days Low-to-medium

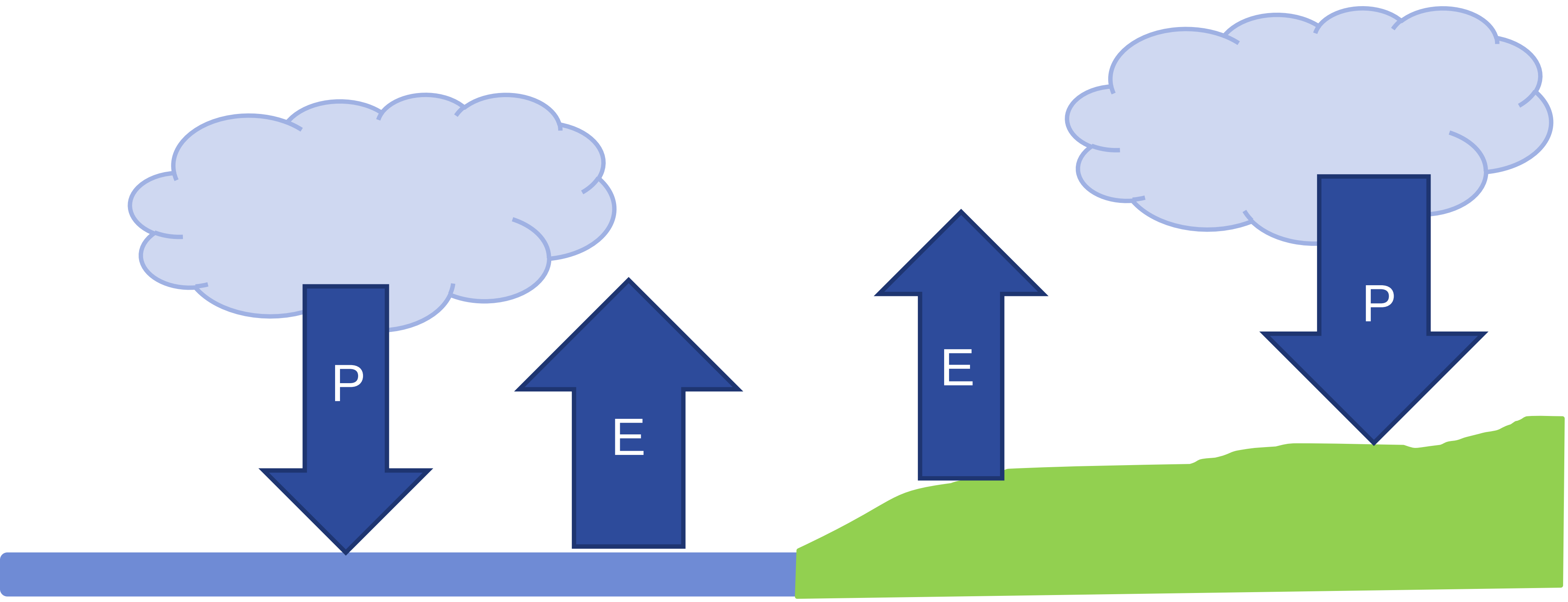
The Water Cycle

Content

- ➔ Motivation
- ➔ Precipitation
- ➔ Evaporation
- ➔ Water vapour
- ➔ The Cycle

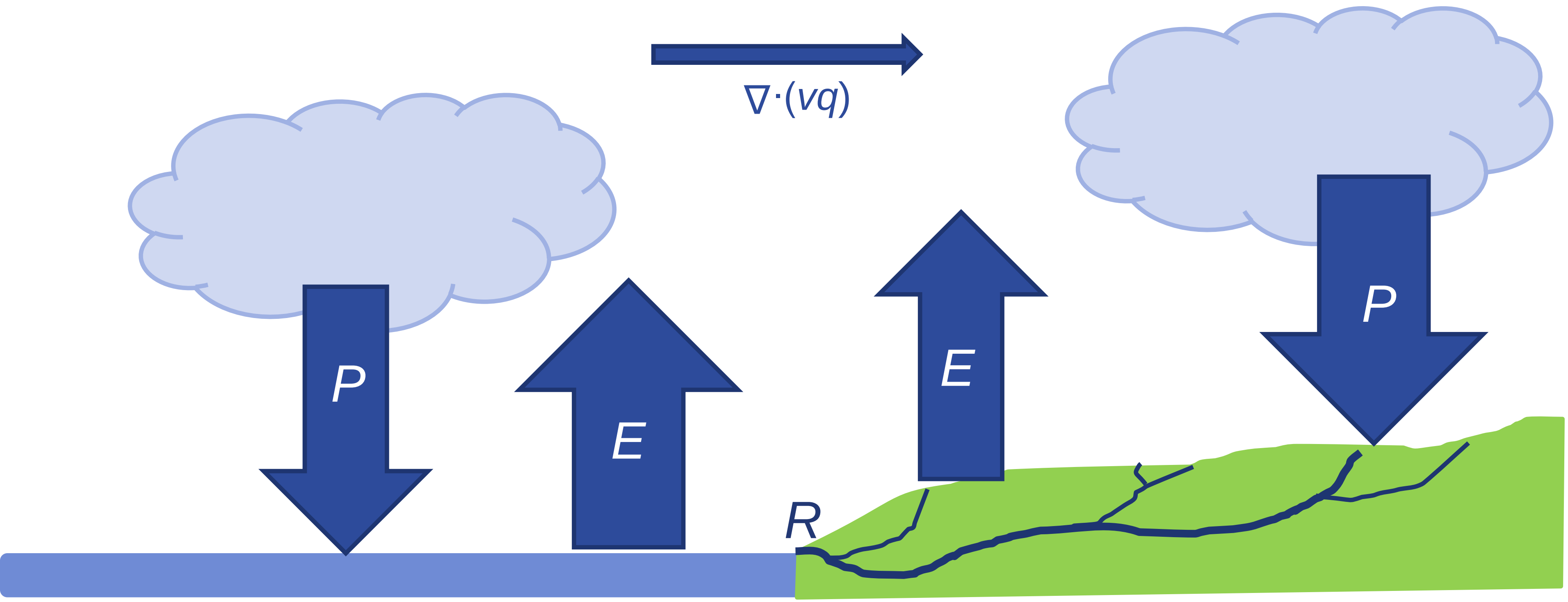


Simplified Water Cycle: Evaporation (E) and Precipitation (P)



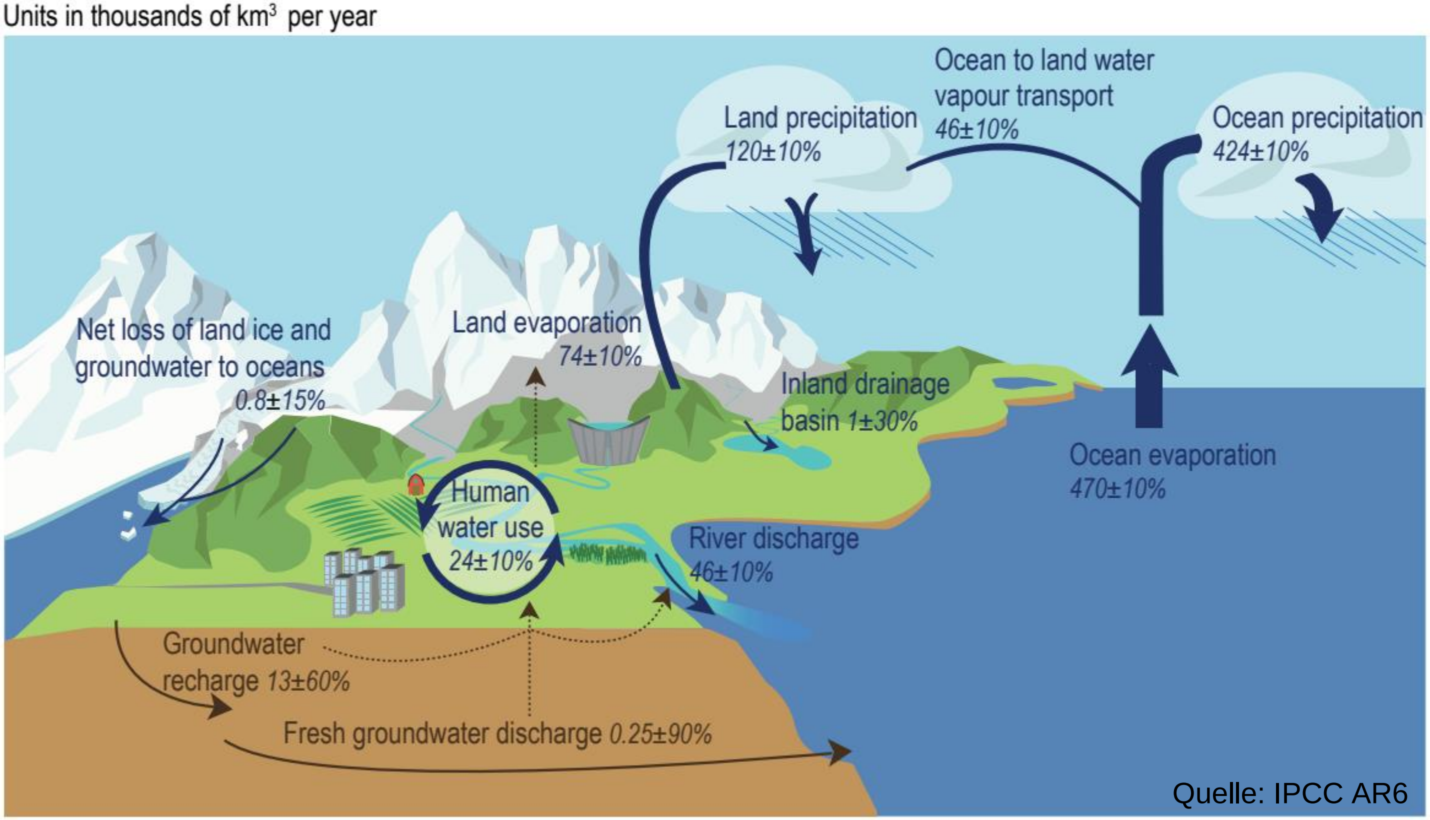
- ➔ $E_{global} = P_{global}$
- ➔ $E_{ocean} - P_{ocean} = -(E_{land} - P_{land})$
- ➔ $E_{ocean} > P_{ocean}$ and $E_{land} < P_{land}$

Simplified Water Cycle: Land-Ocean-Fluxes



- Water(vapor)transport (advection) $\approx \nabla\cdot(vq)$
- Land -> Ocean: Runoff R
- $E_{ocean} > P_{ocean}$ and $E_{land} < P_{land}$ and E, P $\gg \nabla\cdot(vq)$, R
- $E_{ocean} - P_{ocean} \approx -(E_{land} - P_{land})$, $\nabla\cdot(vq) \approx -R$

Simplified Water Cycle in numbers



$E_{land} < P_{land}$

$E_{ocean} > P_{ocean}$

$E, P >> \nabla\cdot(vq), R$

$E_{ocean} - P_{ocean} \approx -(E_{land} - P_{land})$

$(470\text{-}424) = -(74 - 120) = 46$

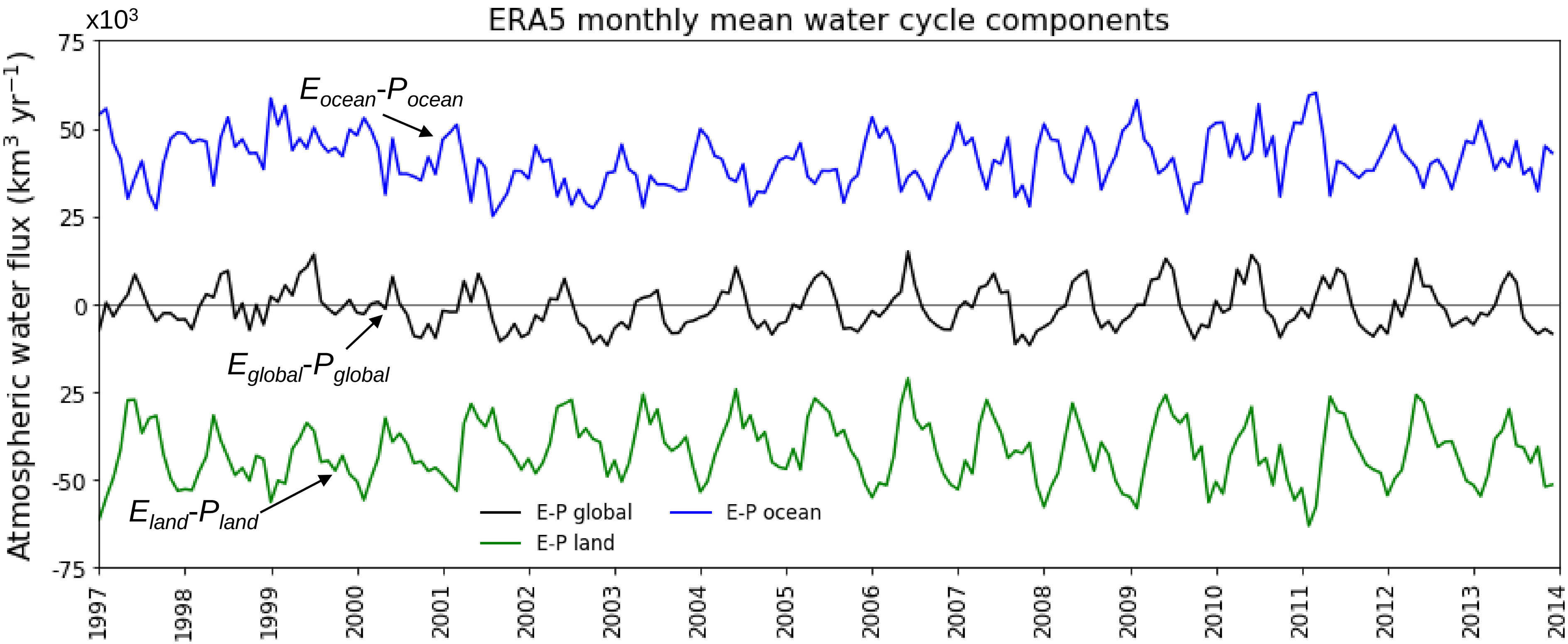
$\nabla\cdot(vq) \approx R$

$46 = 46$

But what about Fresh groundwater discharge etc?
→ note the error bars!

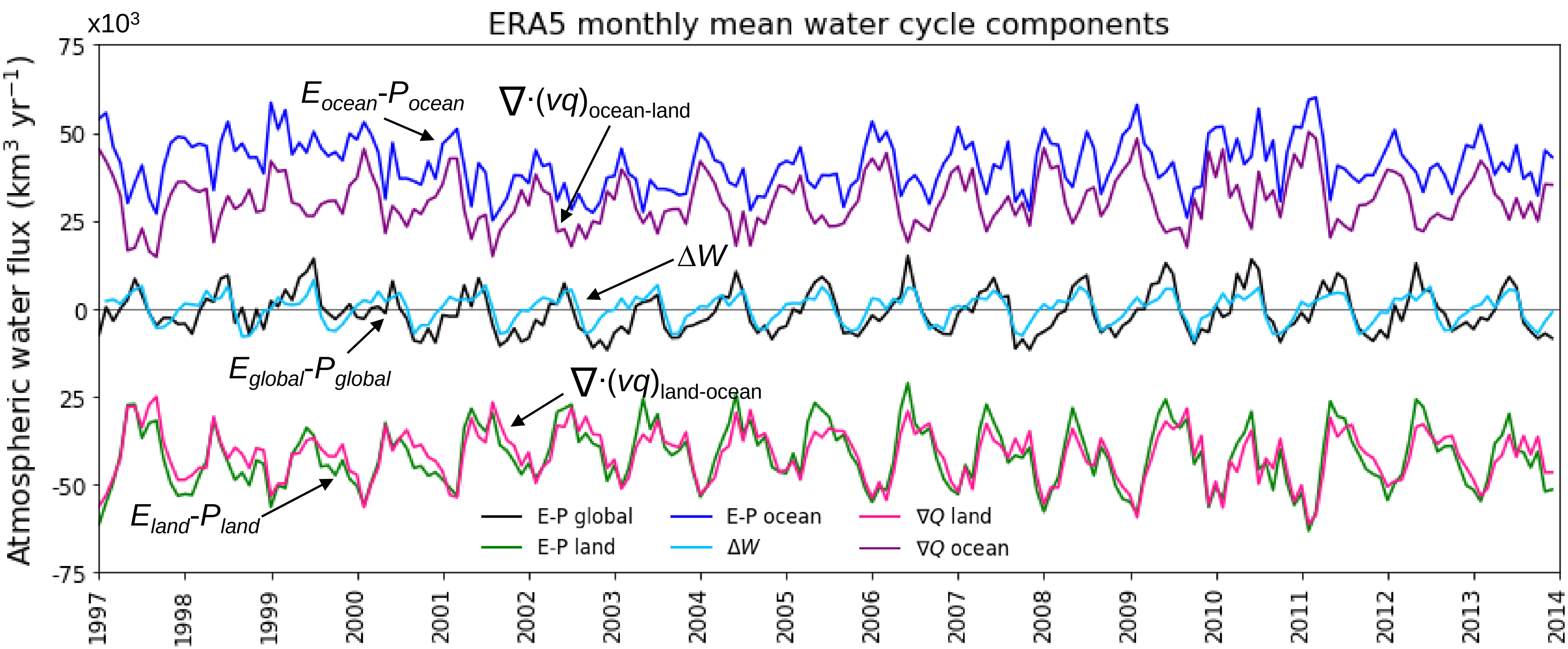
Water Cycle: Seasonal Cycle

➔ $E_{ocean} - P_{ocean} \approx -(E_{land} - P_{land})$



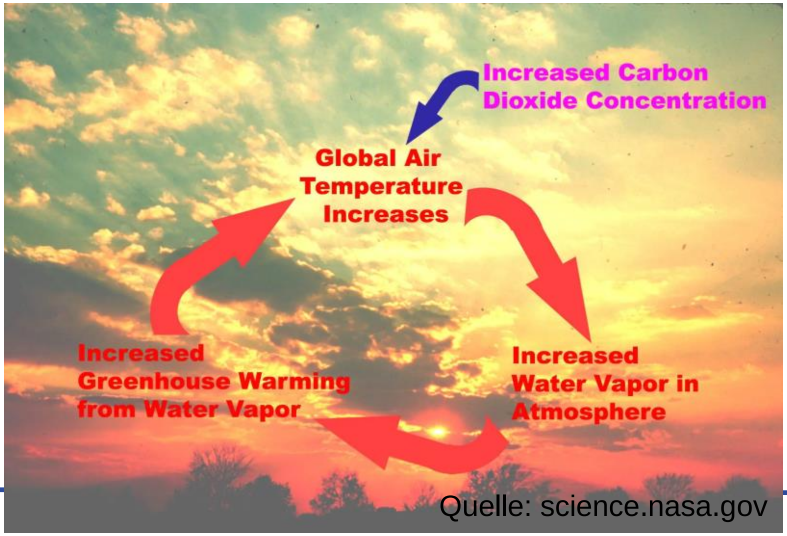
Water Cycle: Seasonal Cycle

- ➔ $E_{ocean} - P_{ocean} \approx -(E_{land} - P_{land})$
  - ➔ What causes the annual cycle of E-P?
  - ➔ Tip: global mean temperature is highest in July
  - ➔ 2. Tip: Clausius-Clapeyron



Water Cycle: Climate Change

- From IPCC, AR6 technical summary:
  - The AR5 assessed that anthropogenic influences have likely affected the global water cycle since 1960. The dedicated chapter in AR6 (…) concludes with *high confidence* that human-caused climate change has driven detectable changes in the global water cycle since the mid-20th century
  - The AR6 further projects with *high confidence* an increase in the variability of the water cycle in most regions of the world and under all emissions scenarios.



Quelle: science.nasa.gov

Positive water vapor feedback loop
→ The cycle reinforces itself

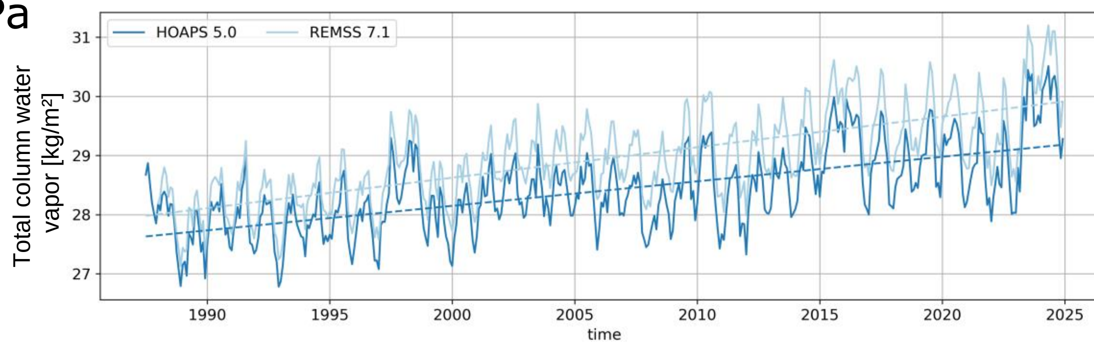
Water Cycle: Global effects of Climate Change

- What happens when it gets warmer, with..
  - Water Vapour (TCWV) ~7% K^{-1}
  - *E and P?* 2-3 % K^{-1}
  - *R* and *E-P*? ?

But: Global average! Large variability of precipitation, regional differences (areas wirth decreasing precip), increase of extreme precipitation events and longer dry periods

- In agreement with Global Climate Models
- Observable?
  - Internal variablility is equal or larger compared to effect of global warming (up to 2014)
  - Consistent across datasets:
    - 4%-5%/K near surface
    - 10%-15%/K at 300hPa

TCWV average over global ice-free oceans



Quelle: z.B. Allan et al., JGR Atmospheres 2022

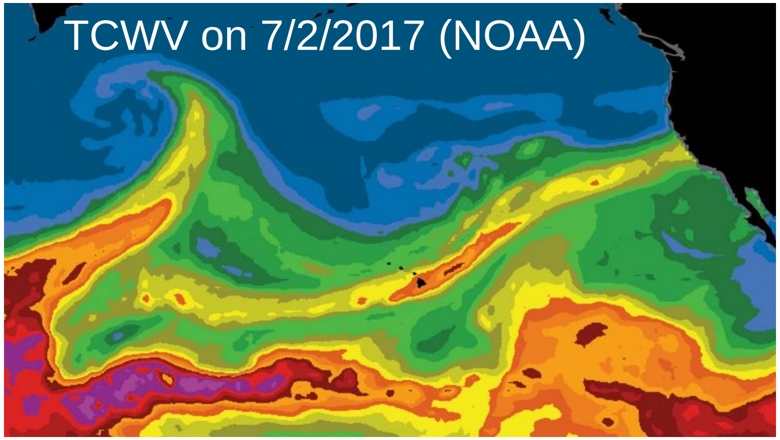
Water Cycle: Regional effects of Climate Change

- The mean global precipitation rate is determined by the earth's energy balance
- But: Regional changes determined by water vapor transport and dynamic processes (weather)

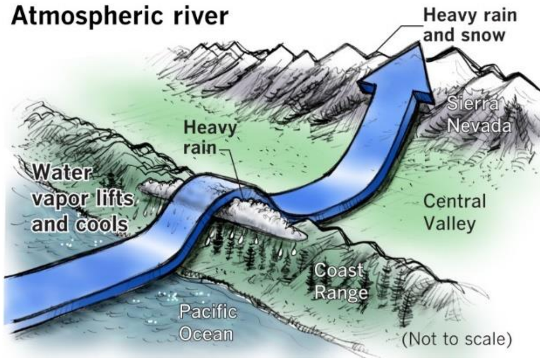
- Regional effects:
  - Increasing frequency of extreme events:
    - Flooding, droughts, stroms
  - Change in precipitation patterns (monsoon, meltwater, atmospheric rivers)
  - Increasing fresh water temperature
- What leads to:
  - Destruction (houses, fields, infrastructure..)
  - Changes in drinking water supply, agricultural production
  - Changes in the spread of diseases
  - biodiversity changes

Atmospheric Rivers

- Atmospheric Rivers (ARs):
  - narrow bands of enhanced water vapor transport
  - Major cause of extreme precipitaton events
  - cause severe flooding in many mid-latitude, westerly coastal regions of the world



- Best-known AR: Pineapple Express
  - Important source of precipitation for California



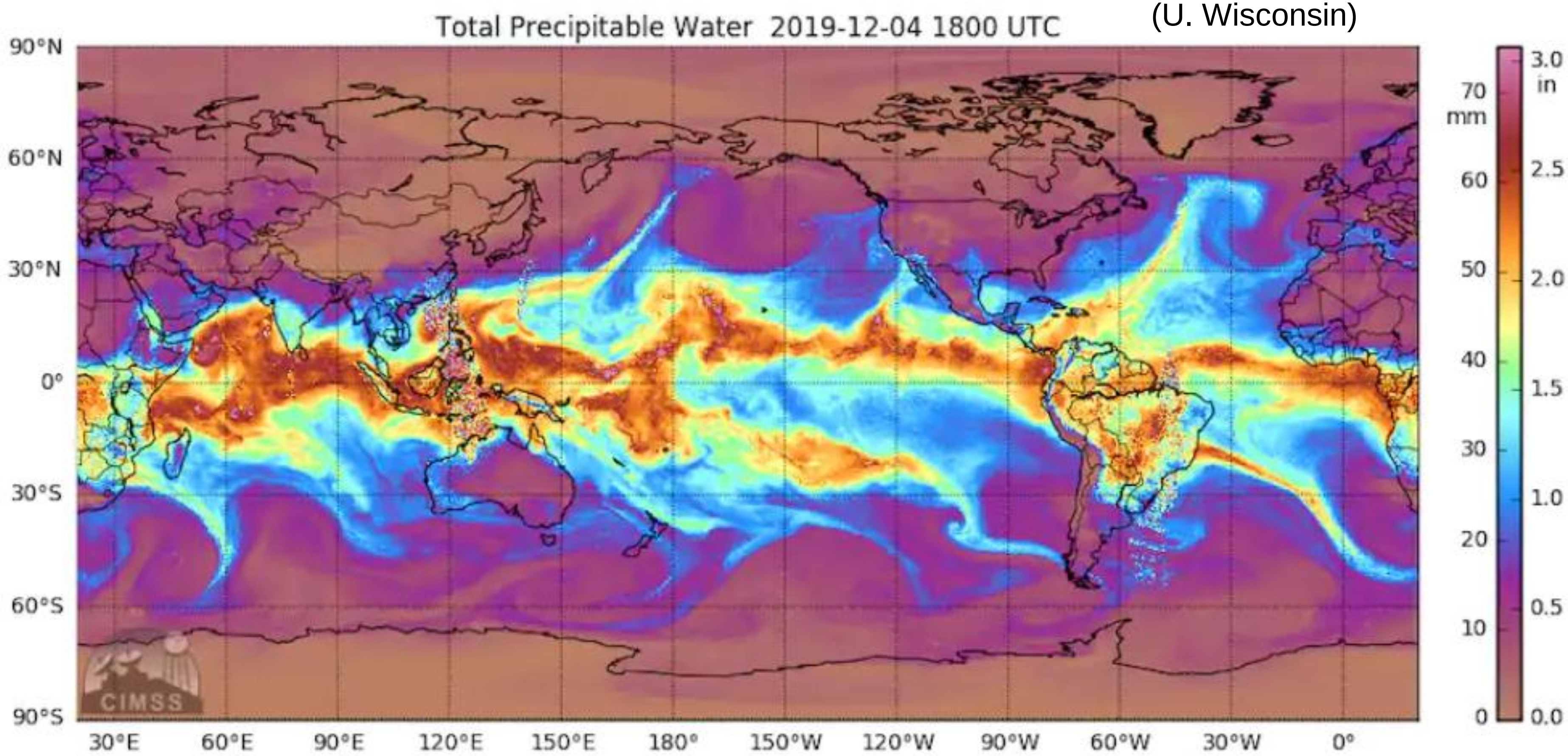
Paul Duginski, LA Times

Just 10 particularly intense atmospheric river events caused nearly half of all flood damage in the U.S. West over the past four decades

Atmospheric Rivers

➔ At least 5-6 ARs

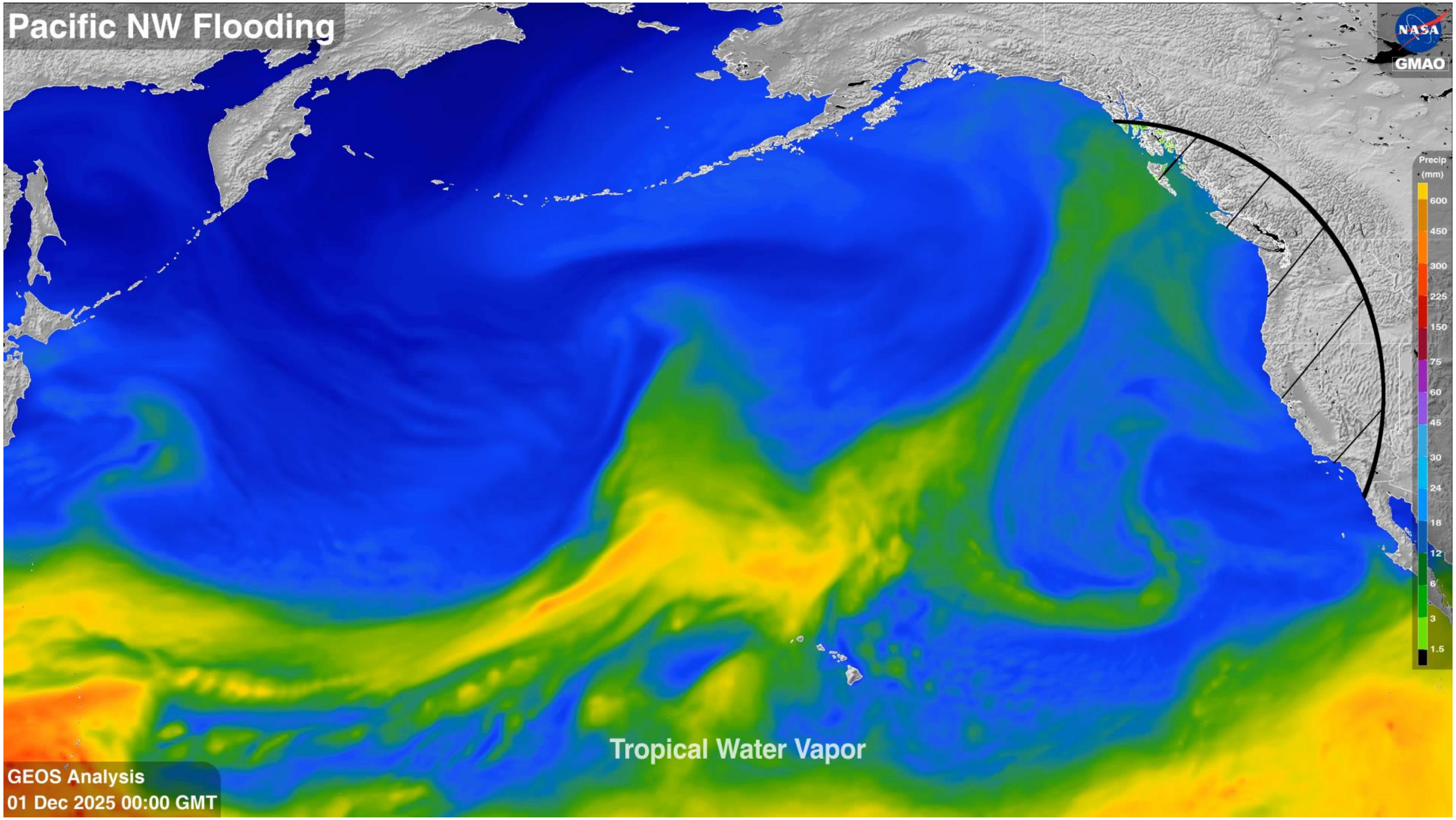
(U. Wisconsin)



Atmospheric Rivers

Pacific Northwest Flooding Dec 2025

(NASA’s Global Modeling and Assimilation Office and NASA's Scientific Visualization Studio.)



Atmospheric Rivers

Notstand ausgerufen

Schwere Überschwemmungen im US-Staat Washington

Stand: 12.12.2025 • 05:23 Uhr tagesschau

Heftige Regenfälle und Überschwemmungen im Nordwesten der USA: Zehntausende Menschen sollen ihre Häuser verlassen. Der Gouverneur hat den Notstand ausgerufen.

Grund für die starken Regenfälle im Nordwesten der USA ist ein Wetterphänomen mit dem Namen "atmosphärischer Fluss". Diese Bänder mit extrem feuchter Luft können mehrere Tage lang heftigen Regen bringen.

Tagesschau 12.12.2025

- among the strongest and longest-lasting AR in this region
- ~96 hours continuous effect in some areas
- Precipitation: ~255 liter/m²
- 19 trillion litres rain within a week (spread across Germany this equals ~5cm)
- Flooding and landslides caused significant damage
- Up to 100 000 people reportedly affected by evacuations.

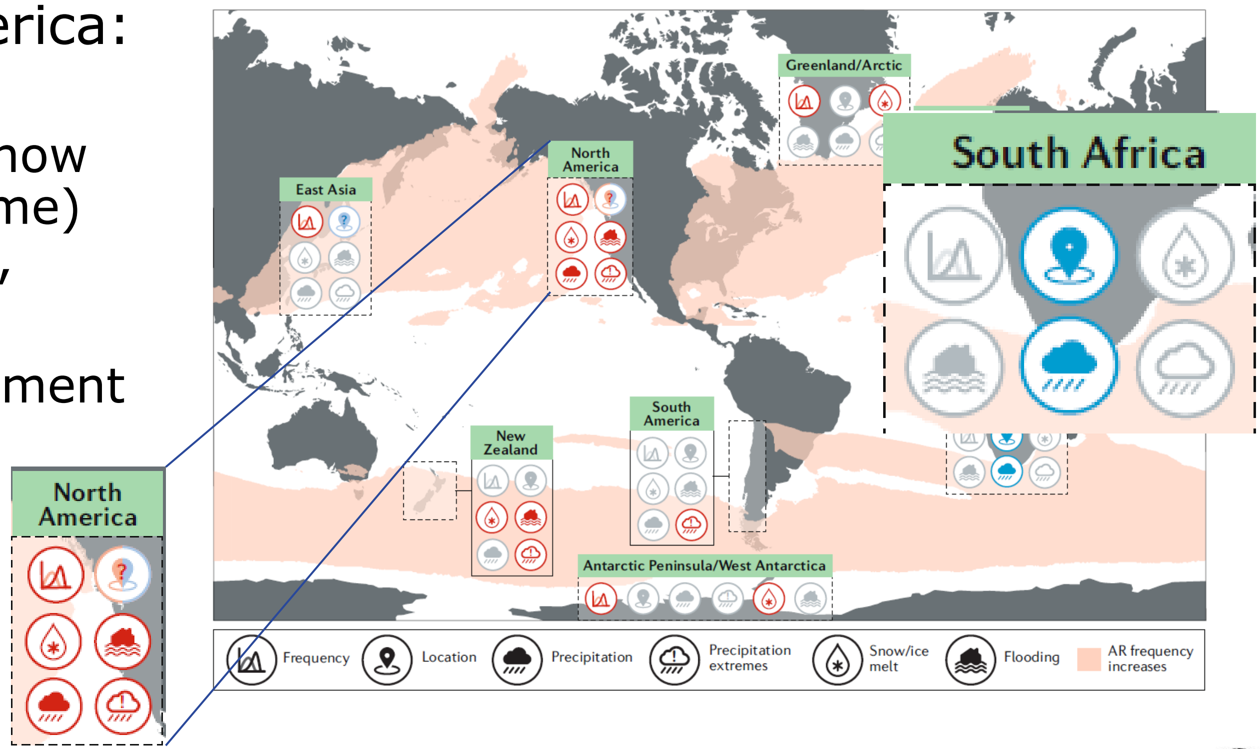
David Ryder/Reuters


David Ryder/Reuters

Atmospheric Rivers and Climate Change

- Global warming leads to:
  - Increase of water vapour in the (warmer) atmosphere: ~7% K^{-1}
  - Change in syonptical patterns: change in frequency and position

- Northern America:
  - increase of frequency, snow melt, (extreme) precipitation, flooding
  - Maybe movement of location



Payne *et al.*, *Nat. Rev. Earth Environ.* 2020

Summary: Measurements

- ➔ Satellite measurements are essential for studying and monitoring the components of the global water cycle
- ➔ Precipitation measurements complicated by
  - ➔ High spatial and temporal variability
  - ➔ Emissions from land surface
- ➔ Heat fluxes can be quantified from satellite data
  - ➔ With indirect methods and uncertainties
- ➔ Water vapor content can be derived very well
  - ➔ Trend: ~7% K^{-1}
  - ➔ Consistent with expectations from Clausius-Clapeyron relationship
- ➔ Water cycle still contains many uncertain components

Summary: Climate Change

- ➔ Changes in global Water Cycle increasingly understood and partially observed
- ➔ Regional changes:
  - ➔ Often much larger than changes on global scale
  - ➔ Increased damages and destructions from extreme events
  - ➔ Changing evaporation and precipitation patterns affect water availability
  - ➔ Significant uncertainties remain, especially at regional scales
- ➔ Further research needed to improve understanding and projections

Literatur

- Allan, R.P. and co-authors, 2020: Advances in understanding large-scale responses of the water cycle to climate change, Ann. NY Acad. Sci., 1472, 49-75, doi: 10.1111/nyas.14337
- Gutenstein, M., Fennig, K., Schröder, M., Trent, T., Bakan, S., Roberts, J. B., and Robertson, F. R.: Intercomparison of freshwater fluxes over ocean and investigations into water budget closure, Hydrol. Earth Syst. Sci., 25, 121–146, https://doi.org/10.5194/hess-25-121-2021, 2021.
- Martin, S., An Introduction to Ocean Remote Sensing, 2nd Edition, Cambridge, 2014
- Levizzani, V., Kidd, C., Kirschbaum, D.B., Kummerow, C.D., Nakamura, K., and Turk, F.J. (Eds.), 2020: Satellite Precipitation Measurement, Vol.1, Advances in Global Change Research 69, Springer International Publishing
- Payne et al, 2020: Responses and impacts of atmospheric Rrivers to climate change, Nature Reviews Earth & Environment, Vol 1., 143-157, doi: 10.1038/s43017-020-0030-5

Literatur

- Bailey, A., P.N. Blossey, D. Noone, J. Nusbaumer, and R. Wood, 2107: Detecting Shifts in Tropical Moisture Imbalances with Satellite-derived Isotope Ratios in Water Vapor, J. Geophys. Res., 122, 5763-5779, doi: 10.1002/2016JD026222
- Fairall, C.W., E.F. Bradley, D.P. Rogers, J.B. Edson, and G.S. Young, 1996: Bulk Parameterization of Air-Sea Fluxes for Tropical Ocean-Global Atmosphere Coupled-Ocean Atmosphere Response Experiment, J. Geophys. Res., 101, 3747-3764
- Guo R., Y. Liu, H. Zhou, Y. Zhu, 2018: Precipitation Downscaling Using a Probability-Matching Approach and Geostationary Infrared Data: An Evaluation over Six Climate Regions, Hydrol. Earth Syst. Sci., 22, 3685-3699, doi: 10.5194/hess-22-3685-2018
- Kidd, C. and G. Huffman, 2011: Review: Global Precipitation Measurement, Meteorol. Appl. 18, 334-353, doi: 10.1002/met.284
- Platt, U., and J. Stutz: Differential Optical Absorption Spectroscopy, Springer, 2008
- Sinreich, R., A. Merten, L. Molina, and R. Volkamer, 2012: Parameterizing Radiative Transfer to Convert MAX-DOAS dSCDs into Near-Surface Box-Averaged Mixing Ratios, Atmos. Meas. Tech., 6, 1521-1532, doi: 10.5194/amt-6-1521-2013
- Worden, J. and the TES team, 2006: Tropospheric Emission Spectrometer Observations of the Tropospheric HDO/H2O Ratio: Estimation Approach and Characterization, J. Geophys. Res., 111, D16, doi 10.1029/2005JD006606