NEROGRAV

New Refined Observations of Climate Change from Spaceborne Gravity Missions

International Spring School
Neustadt an der Weinstraße, Germany, March 10-14, 2025

Water cycle and climate applications of GRACE/-FO

Annette Eicker (HafenCity University Hamburg)

Not enough water?

River Rhine, Summer 2022

© Federico Gambarini/dpa

Too much water?

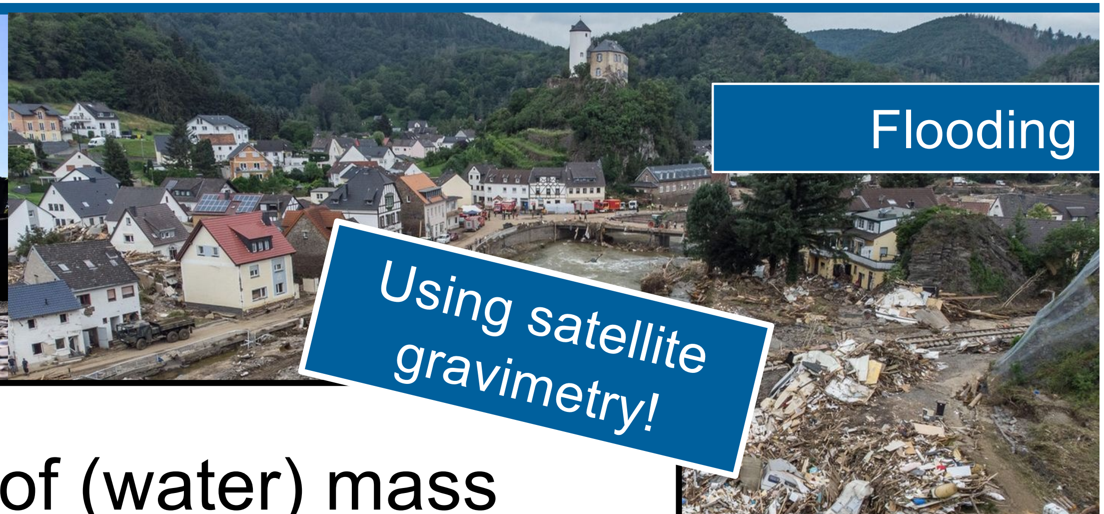
Male, Malediven

Water melting?

Stefan Winkler (distributed via imaggeo.egu.eu)


Water at the wrong location?
Ahr Valley, July 2021
dpa Bildfunk Picture Alliance/dpa | Boris Roessler

Climate change



redistributions of (water) mass

(on and underneath the Earth‘s surface)

Outline

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long

short

temporal scales

climate trends (centuries)
- climate model evaluation

3

present-day trends (decades)
- sea level, ice mass, ...

inter-annual variations
- ENSO, droughts, ...

seasonal changes (months)

weeks to month
- floods, ...

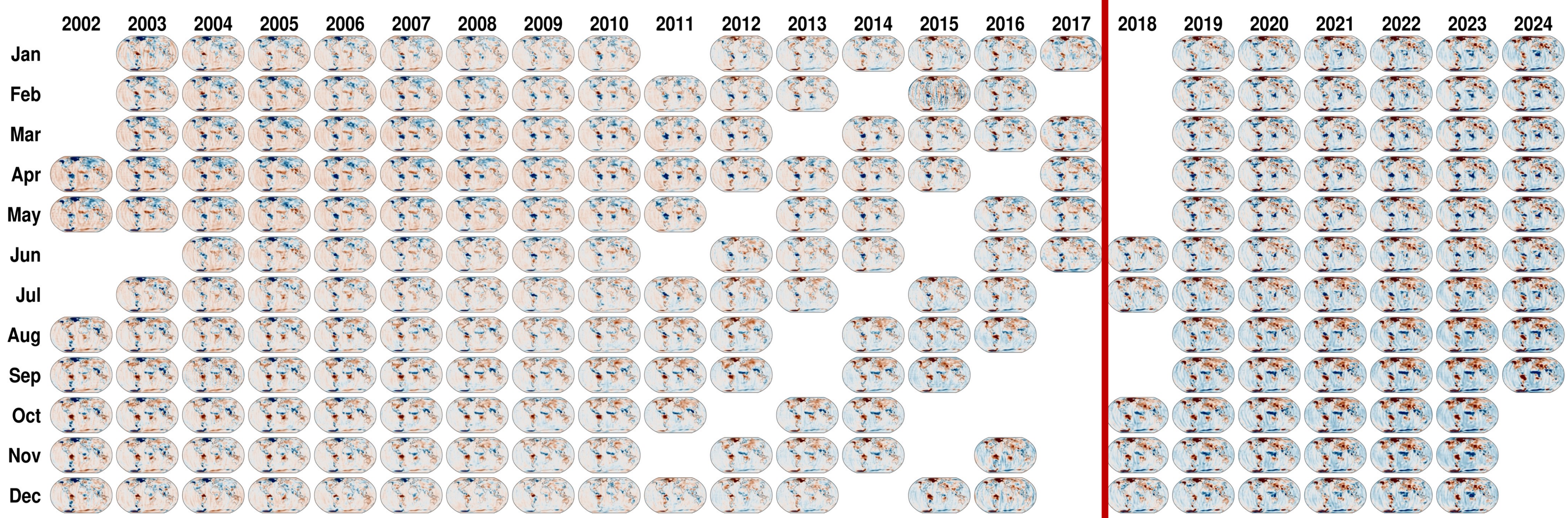
Recap of some highlights
+
Hydrological applications of GRACE/-FO

1

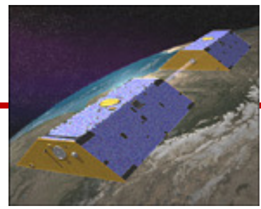
short-term changes (days)
- hydro-meteorological fluxes

2

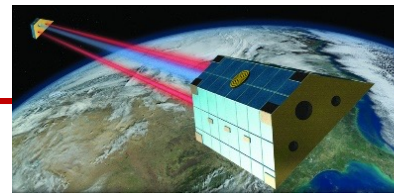
GRACE monthly gravity field models



GRACE



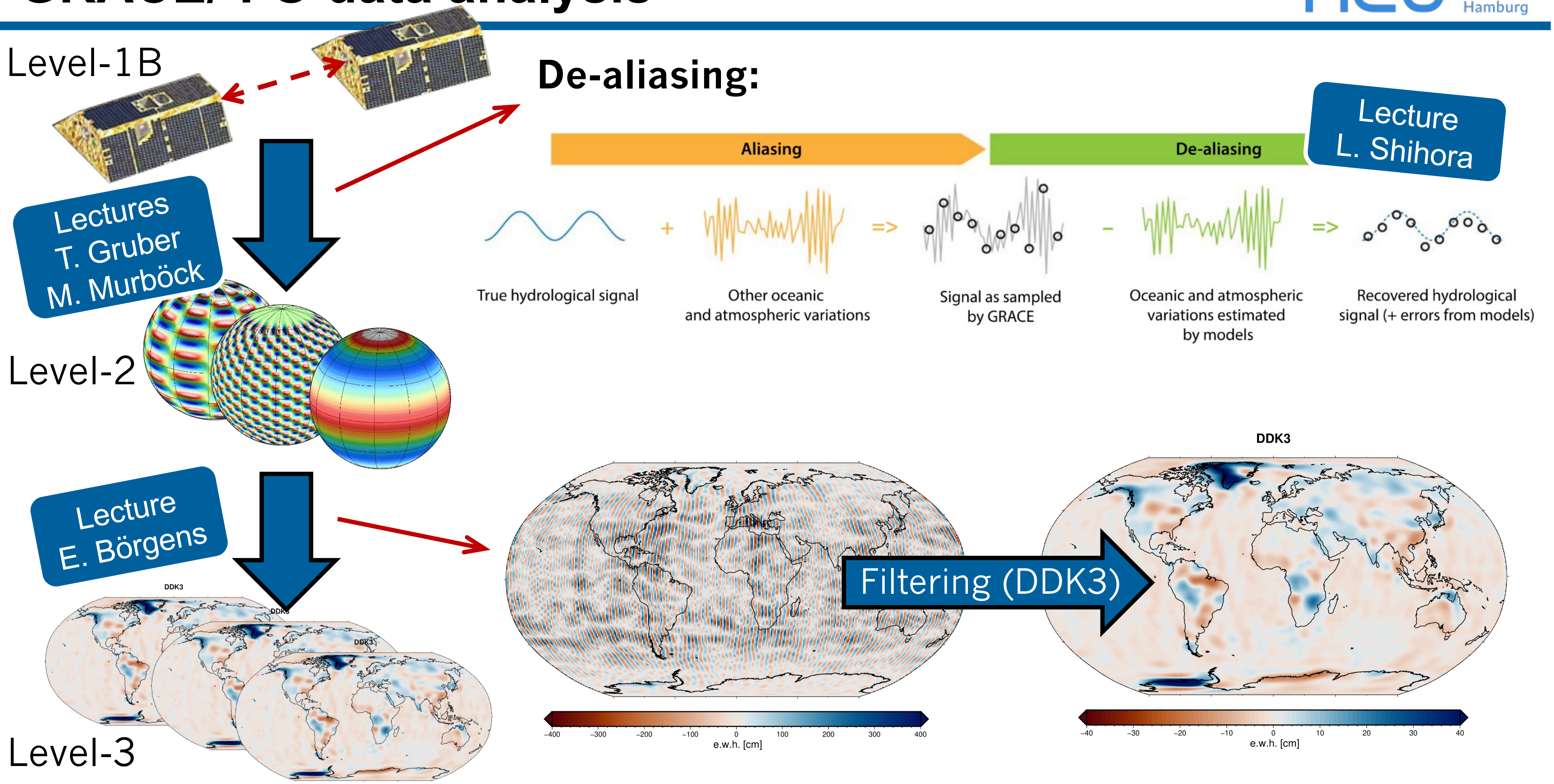
GRACE-FO



Thank you, Eva (and ChatGPT)!

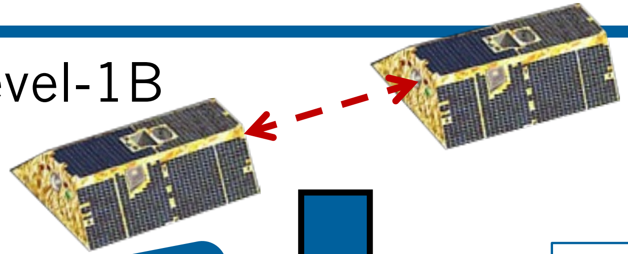
Which signals are (not) included in these gravity field solutions?

GRACE/-FO data analysis



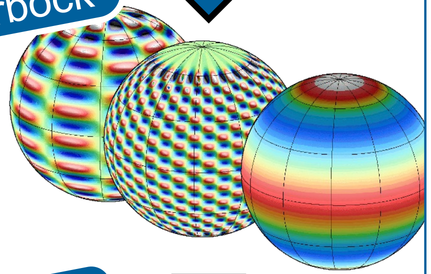
GRACE/-FO data analysis

Level-1B

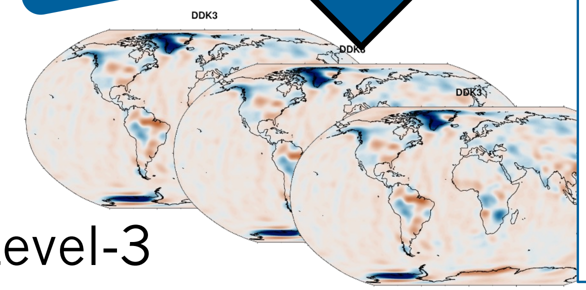


Lectures
T. Gruber
M. Murböck

Level-2



Lecture
E. Börgens



Level-3

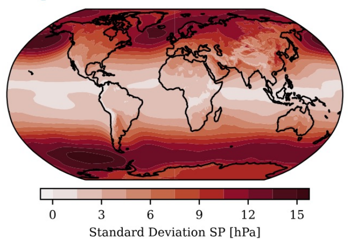
Background models:

- **Atmosphere and ocean (AOD1B)**

Lecture
L. Shihora

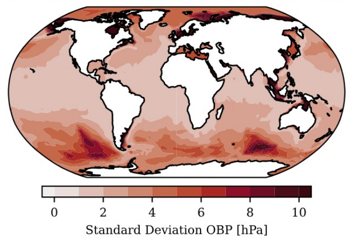
AOD1B Components

Atmospheric Surface Pressure:



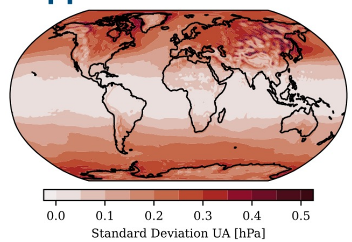
+

Ocean Bottom Pressure:



+

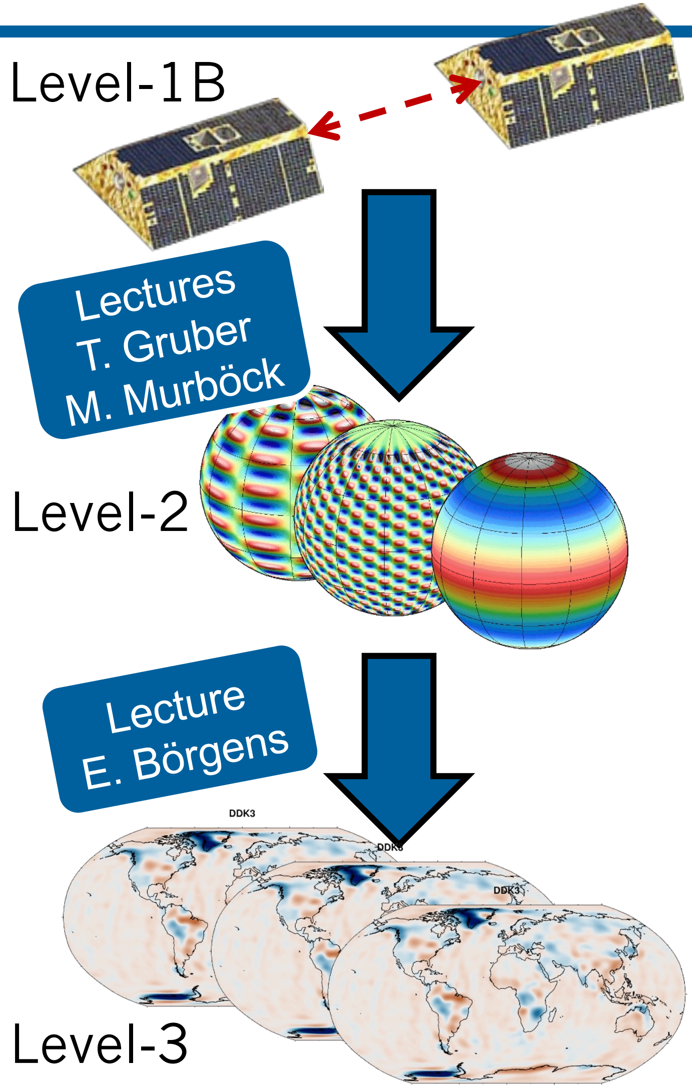
Upper Air Variations:



GFZ Helmholtz Centre for Geosciences

HELMHOLTZ

GRACE/-FO data analysis



Background models:

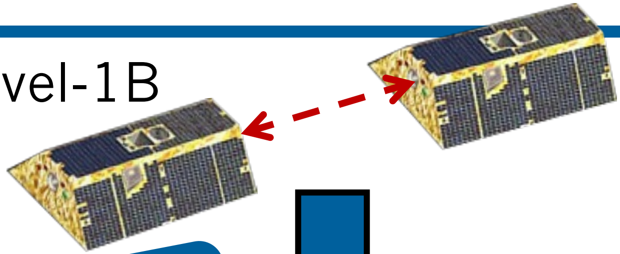
- **Atmosphere and ocean (AOD1B)**
- **Ocean tides**

(+ Solid Earth tides, etc.)

Lecture
L. Shihora

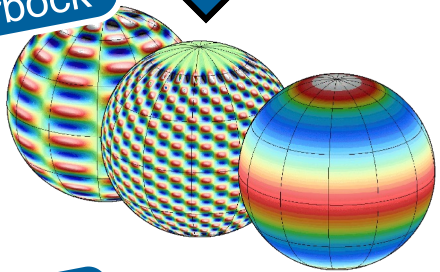
GRACE/-FO data analysis

Level-1B

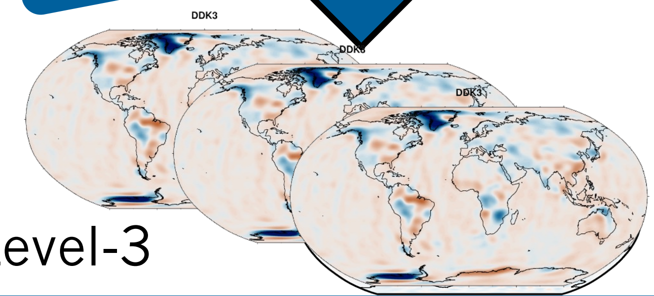


Lectures
T. Gruber
M. Murböck

Level-2



Lecture
E. Börgens



Level-3

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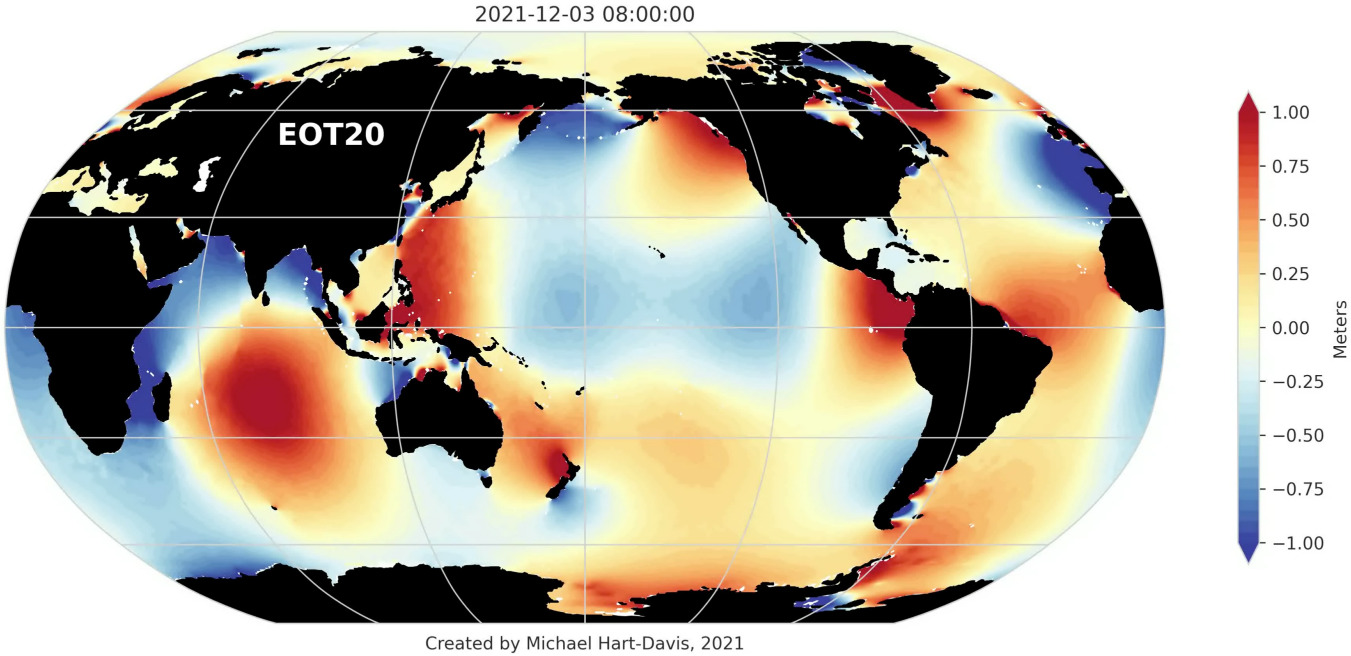
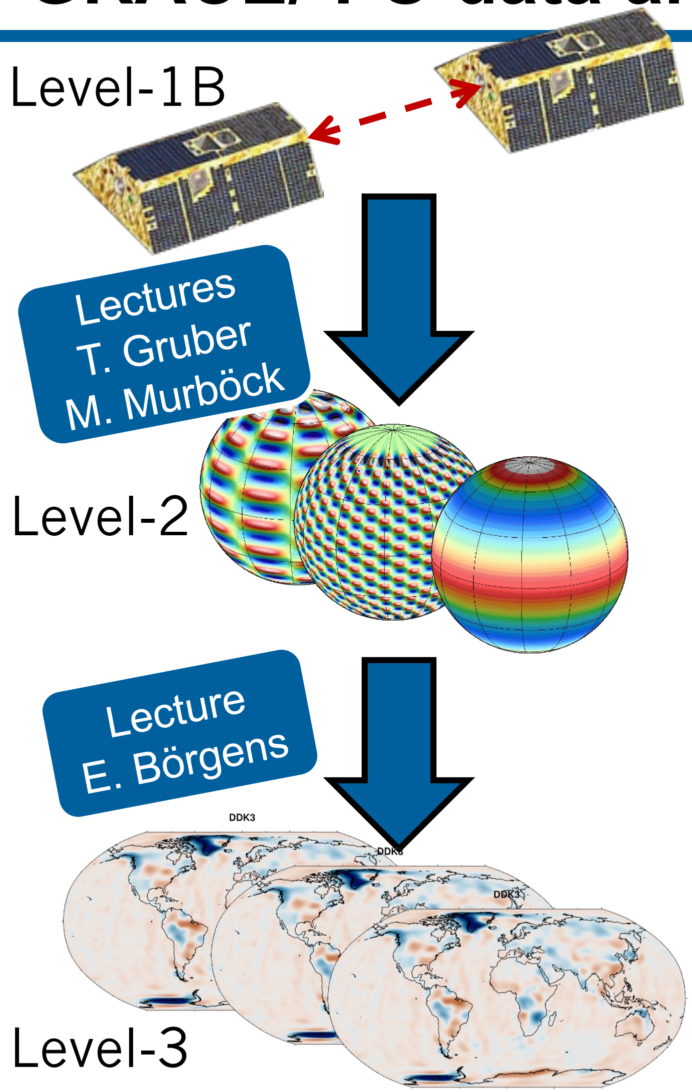
Lecture
L. Shihora

Lecture
M. Hart Davis



GRACE/-FO data analysis



Background models:

- **Atmosphere and ocean (AOD1B)**
- **Ocean tides**

(+ Solid Earth tides, etc.)

Lecture
L. Shihora

Lecture
M. Hart Davis

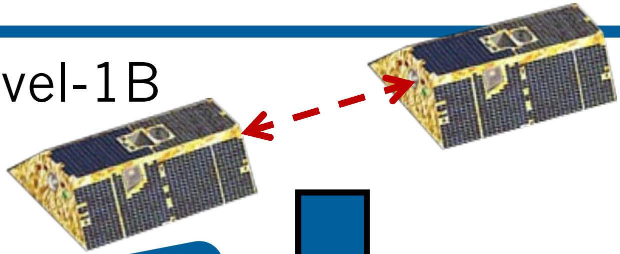
Two consequences of subtracting background models:

1) de-aliasing
2) signal separation!

GRACE/-FO data analysis

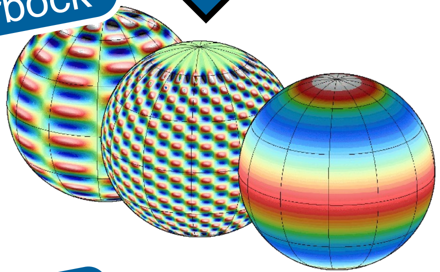
HafenCity Universität Hamburg

Level-1B



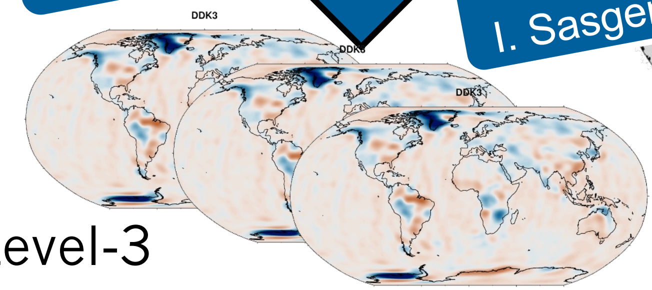
Lectures T. Gruber M. Murböck

Level-2



Lecture E. Börgens

Level-3



Background models:

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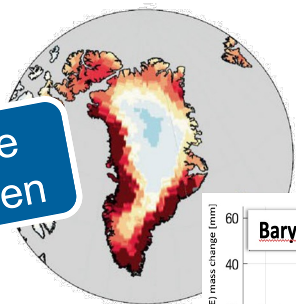
Lecture L. Shihora

Lecture M. Hart Davis

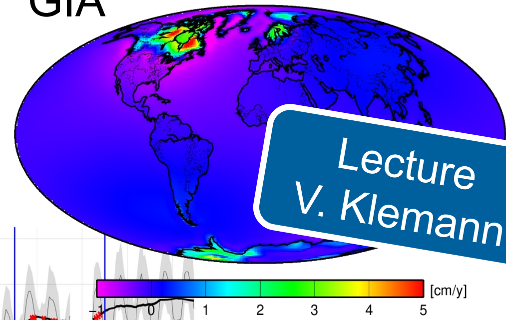
Included in gravity field models:

Ice mass



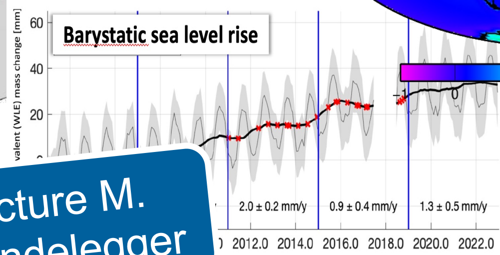
Lecture I. Sasgen

GIA



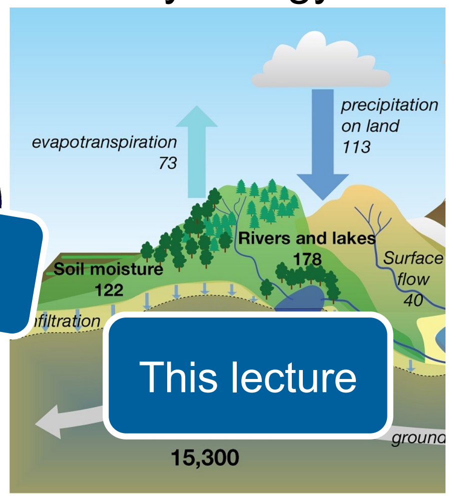
Lecture V. Klemann

Sea level



Lecture M. Schindelegger

Hydrology



This lecture

+ others (e.g. Earthquakes)

GRACE/-FO data analysis

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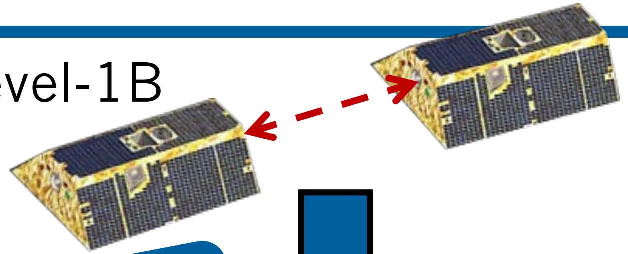
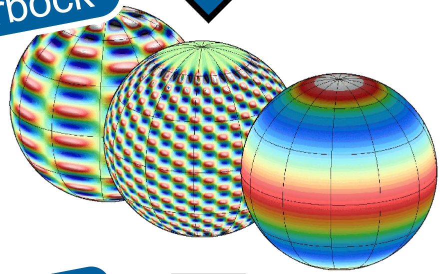
Level-1B



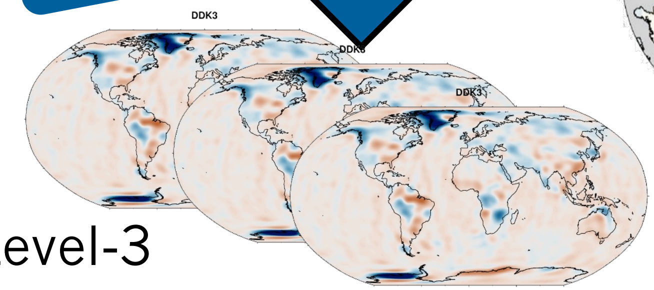
Lectures
T. Gruber
M. Murböck

Level-2



Lecture
E. Börgens

Level-3



Background models:

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- **Ocean tides**

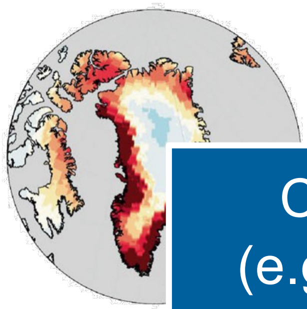
(+ Solid Earth tides, etc.)

Lecture
L. Shihora

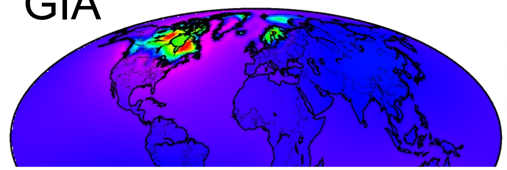
Lecture
M. Hart Davis

Included in gravity field models:

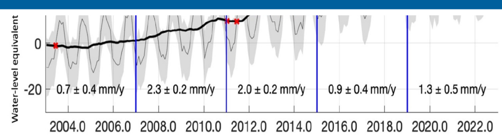
Ice mass



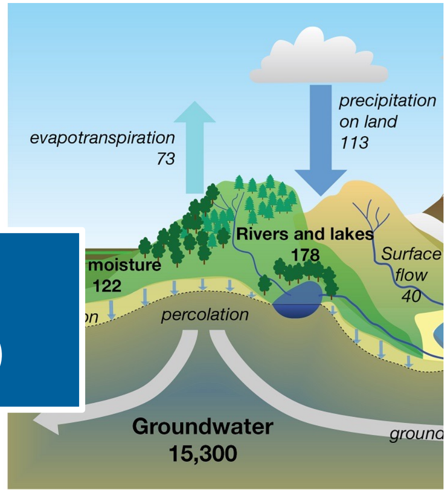
GIA



Challenge: Signal separation
(e.g. using geophysical models)

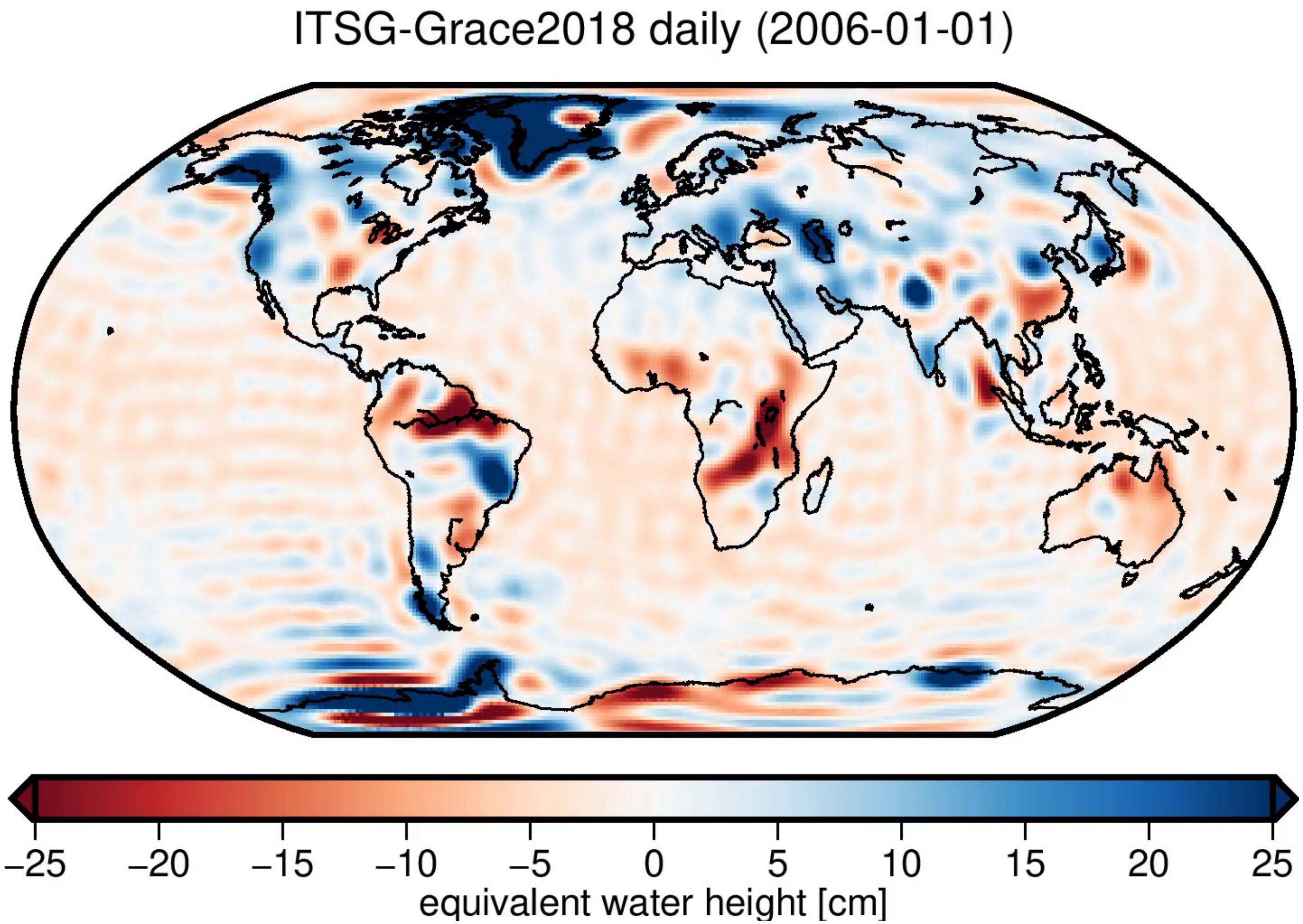


Hydrology

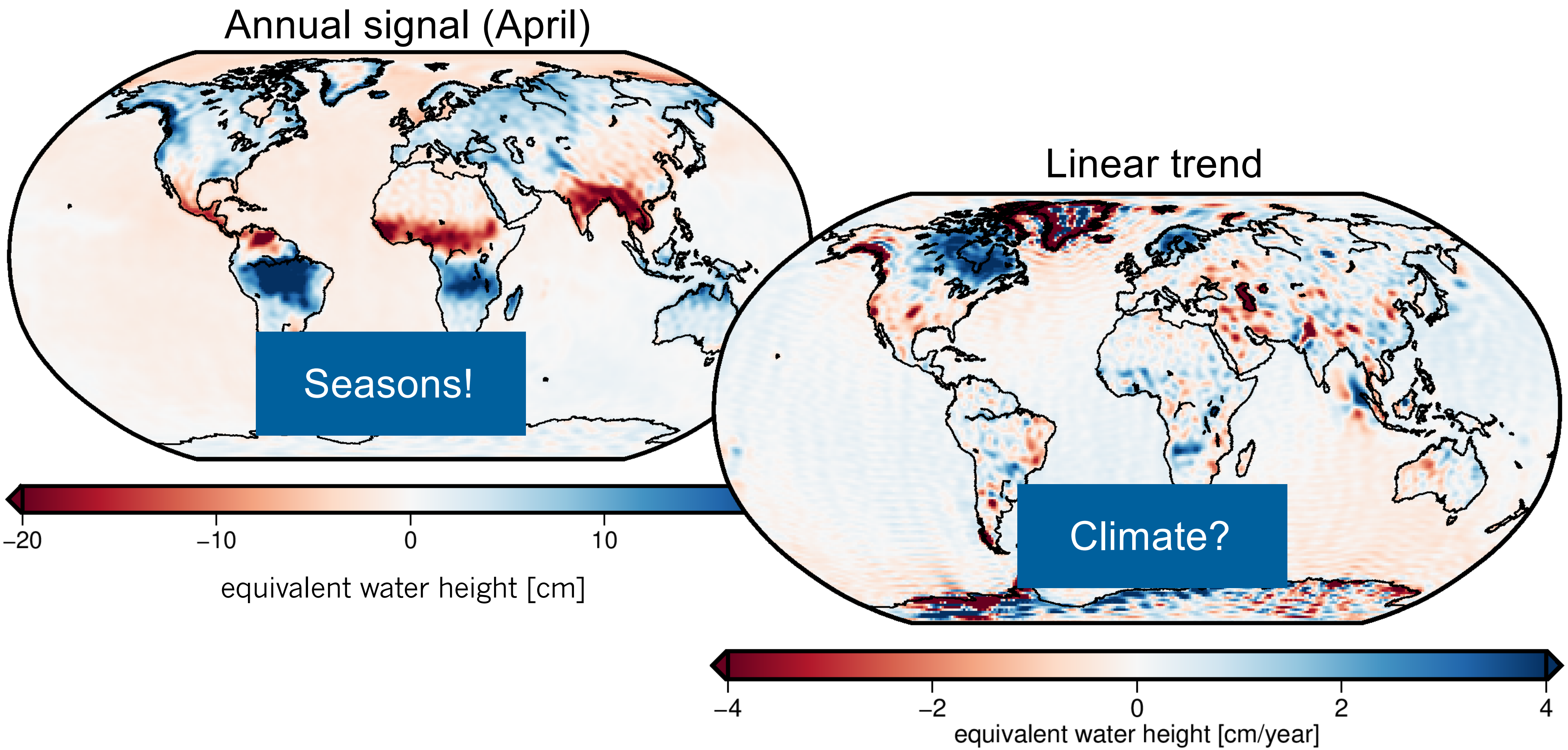


+ others (e.g. Earthquakes)

Mass variations from GRACE/-FO



Mass variations from GRACE/-FO

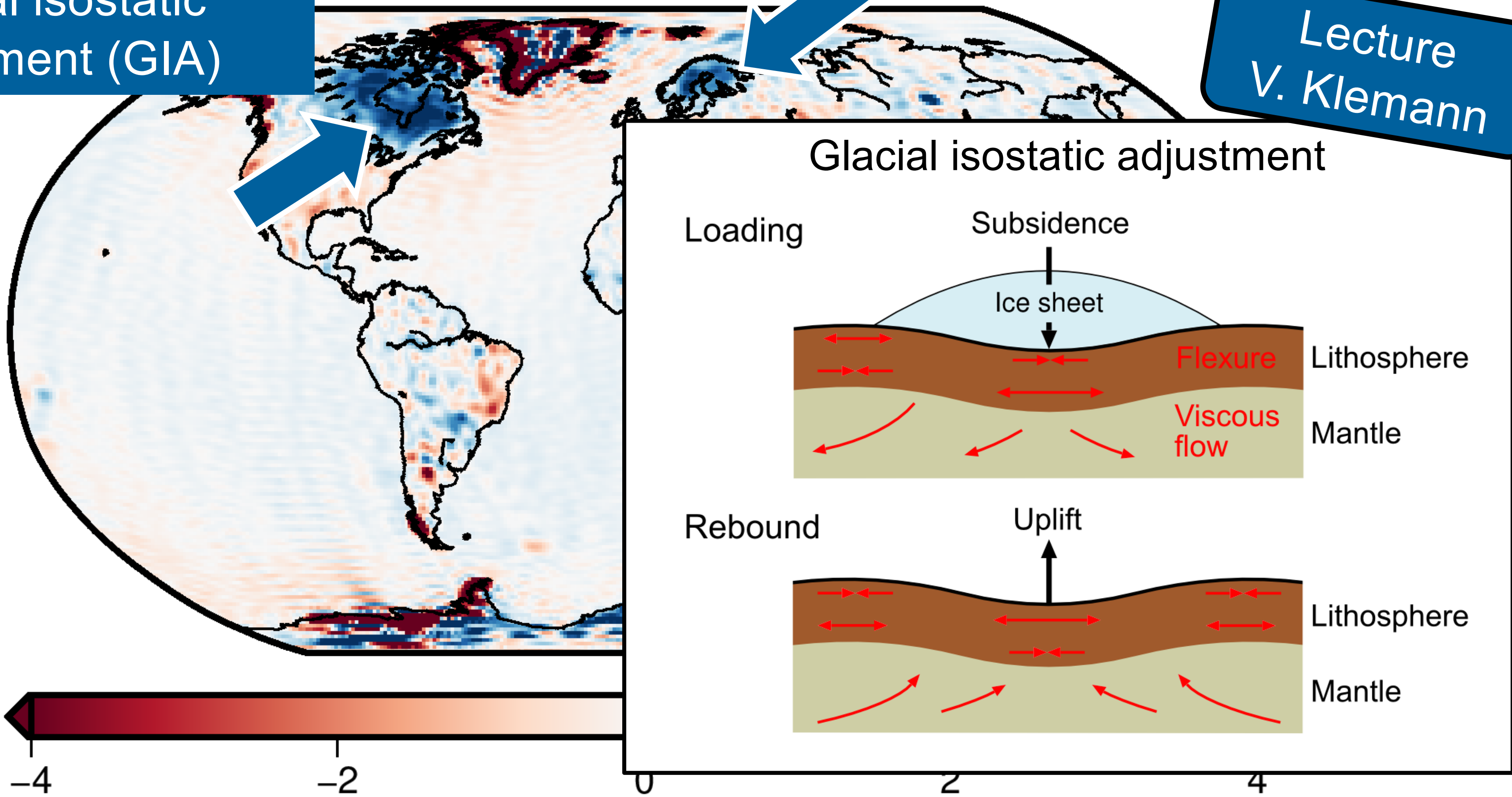


Long-term trend

Glacial isostatic adjustment (GIA)

Linear trend

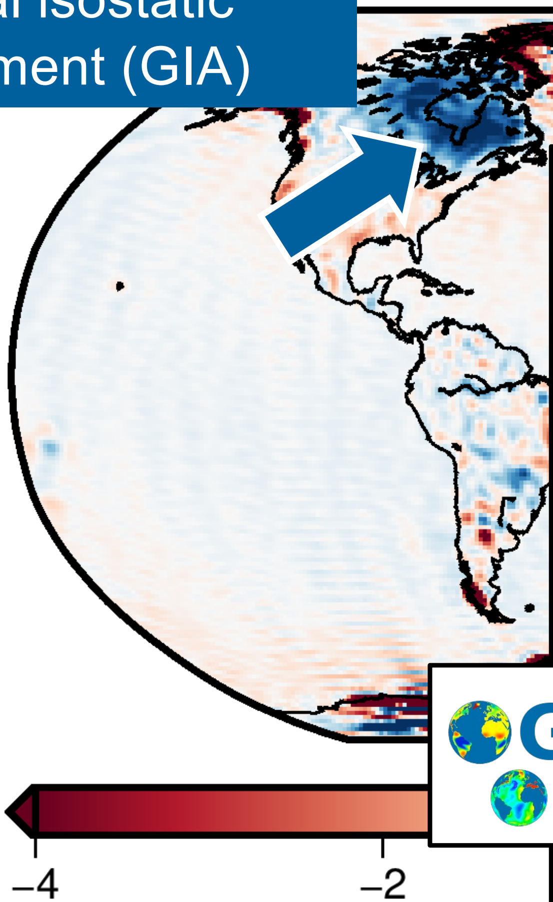
Lecture V. Klemann

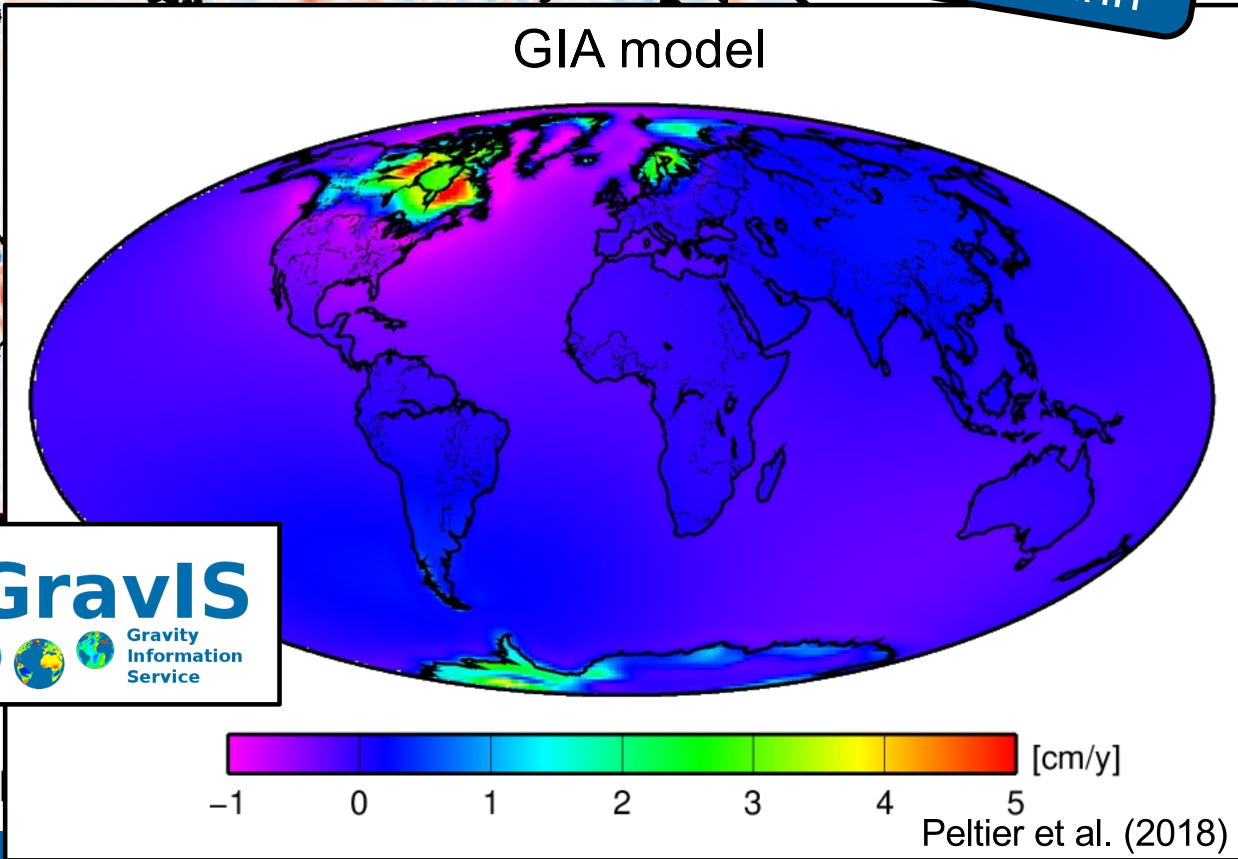


Long-term trend

Glacial isostatic adjustment (GIA)

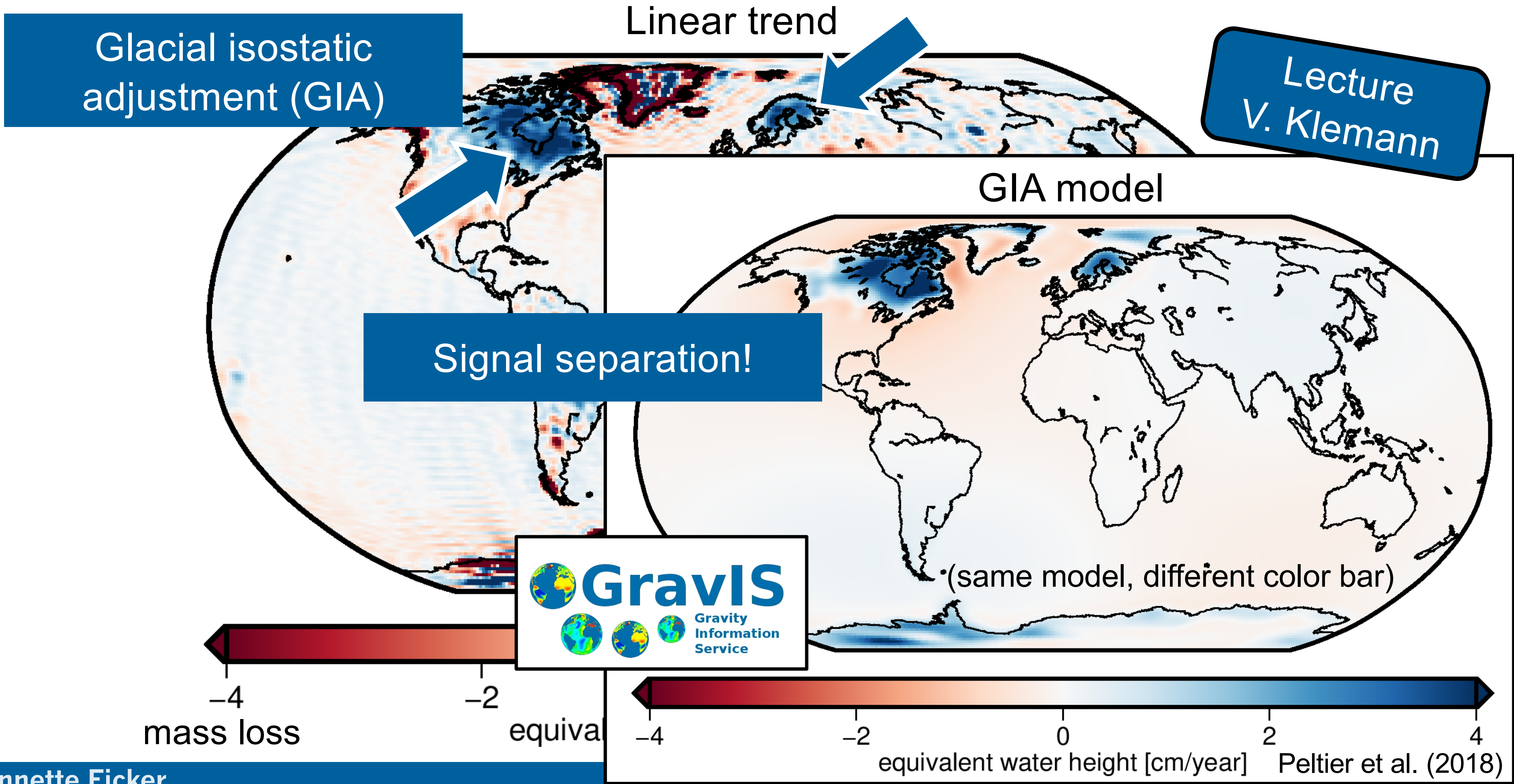
Lecture V. Klemann



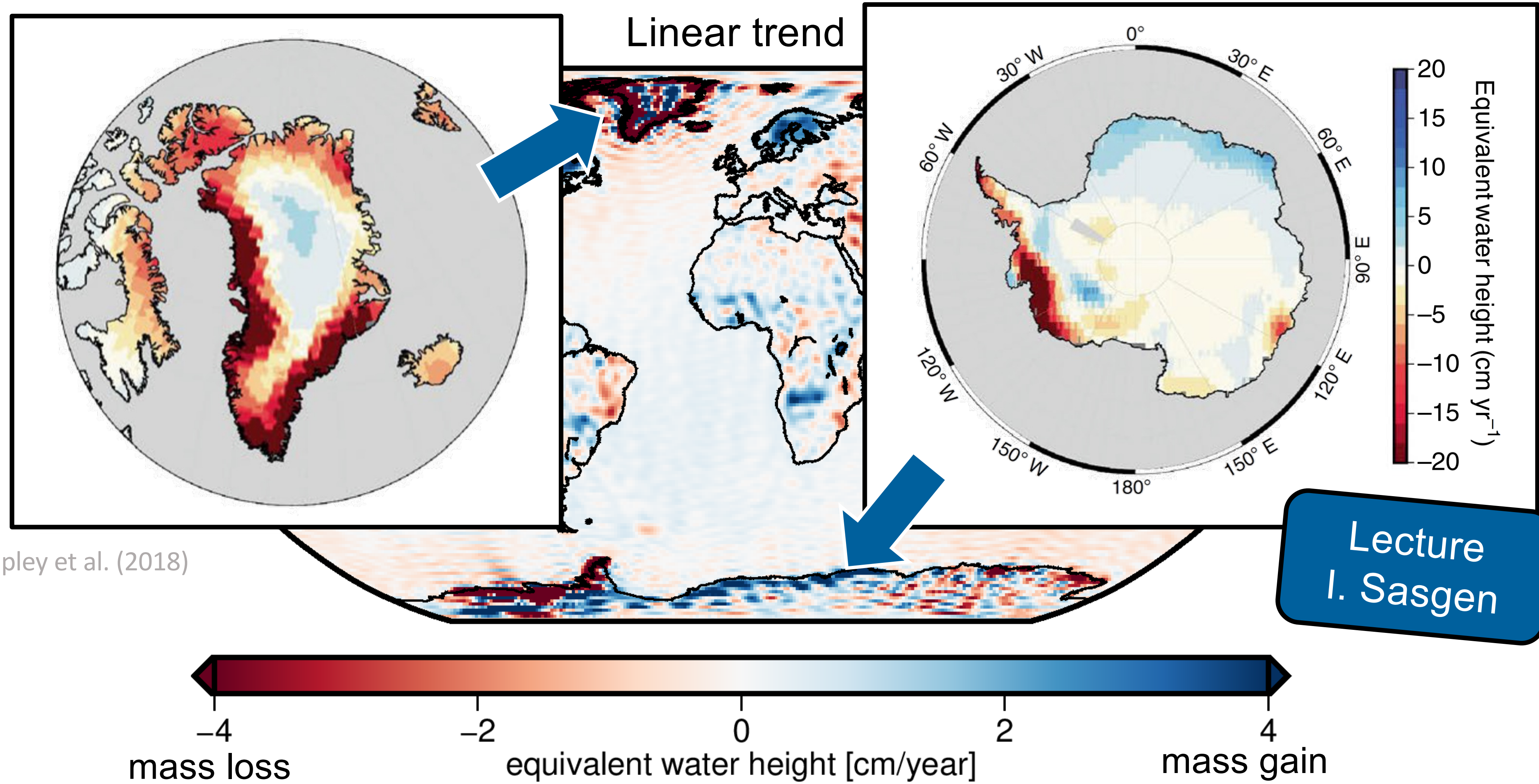


GravIS Gravity Information Service

Long-term trend



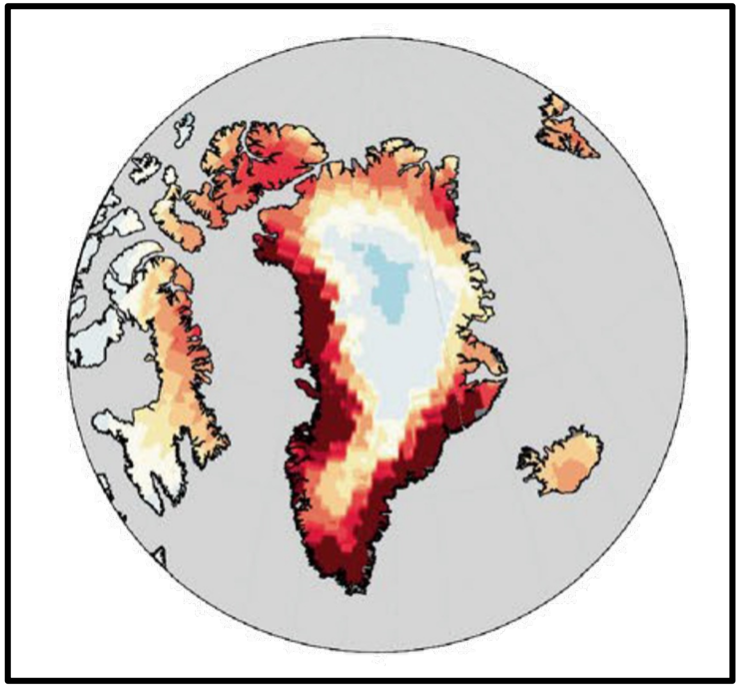
Ice mass loss



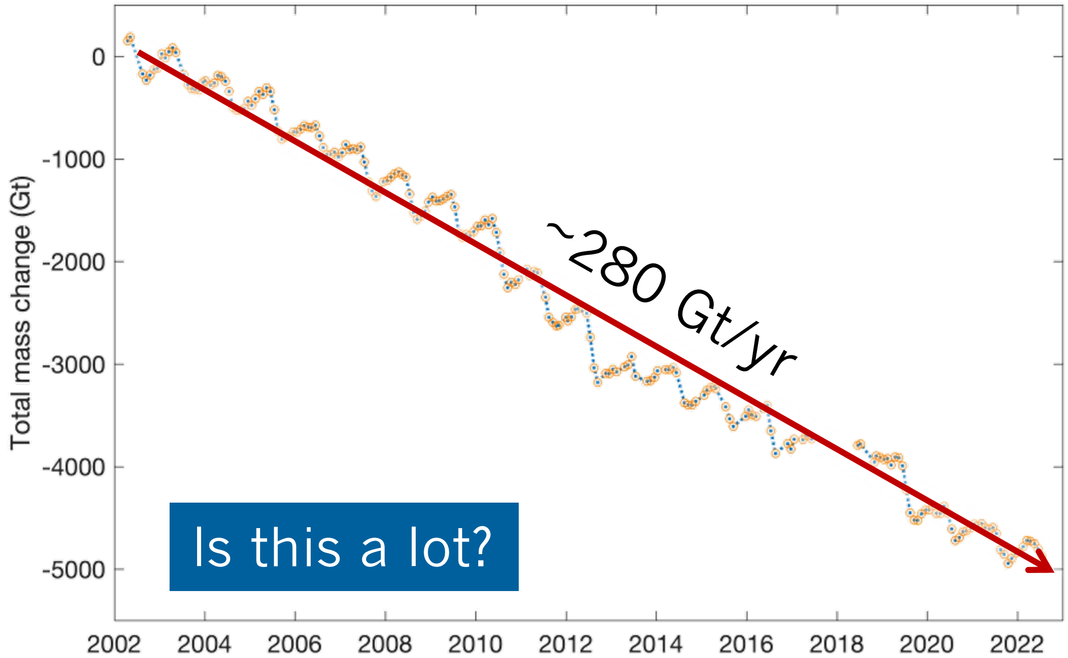
Tapley et al. (2018)

Lecture
I. Sasgen

Ice mass loss



Tapley et al. (2018)



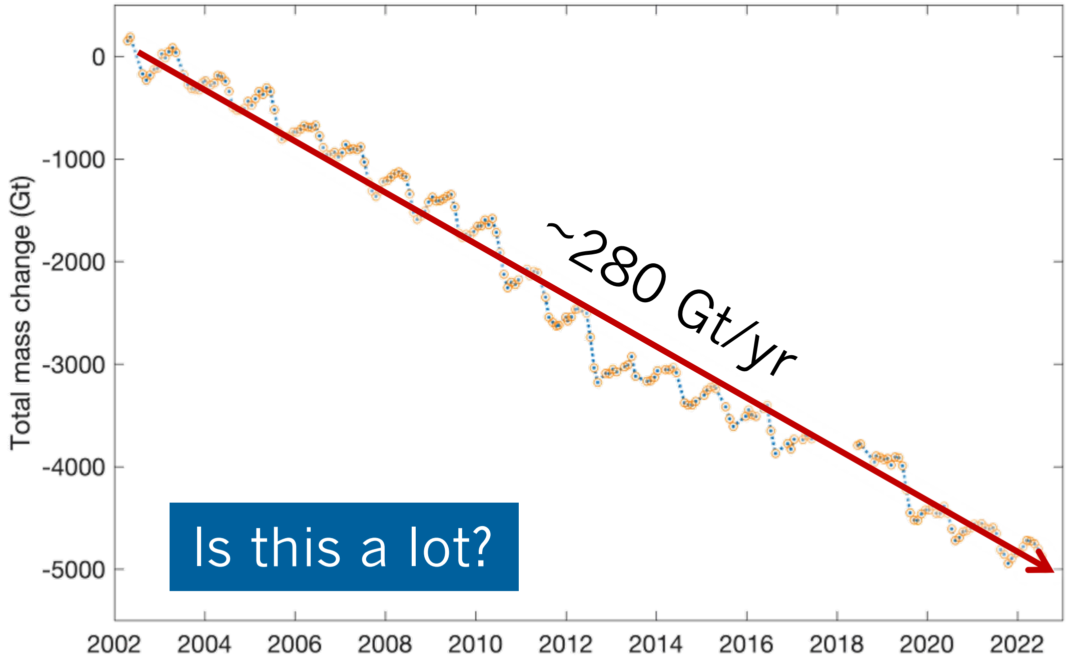
NOAA, Moon et al. 2022, doi:10.25923/c430-hb50

Ice mass loss

150.000

of these ice blocks are melting in Greenland

every second.



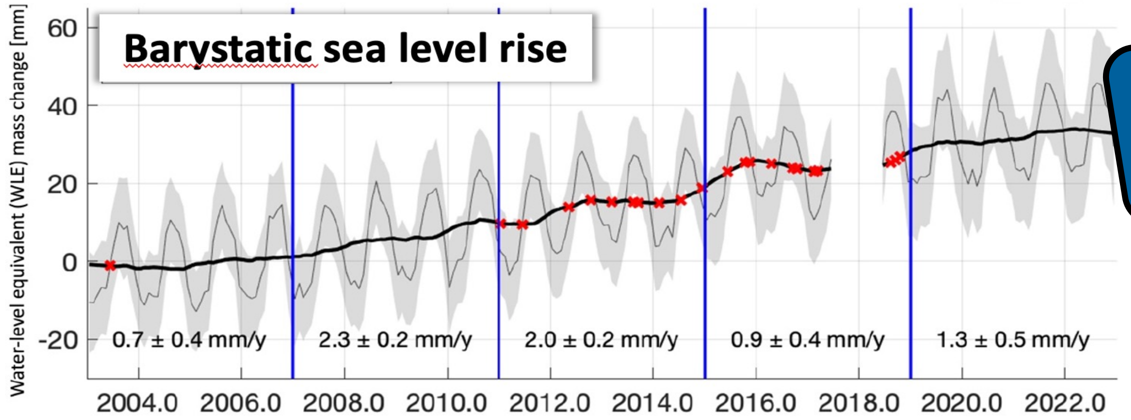
NOAA, Moon et al. 2022, doi:10.25923/c430-hb50

What happens to sea level?

Sea level

What does GRACE/-FO tell us?

Ocean mass increase ⇔ Imbalance of fluxes



Ludwigsen et al. (2024, Nat. Commun.)

Lecture M. Schindelegger

What happens to sea level?

What does GRACE/-FO tell us?

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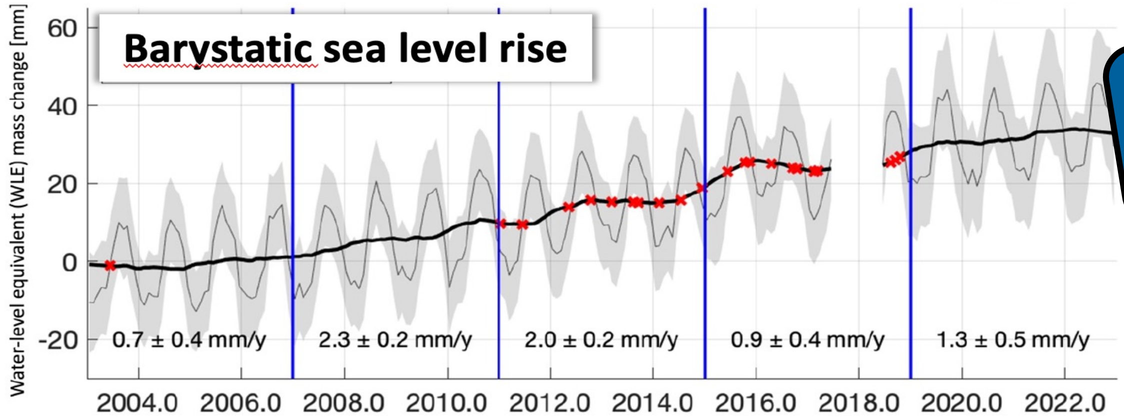

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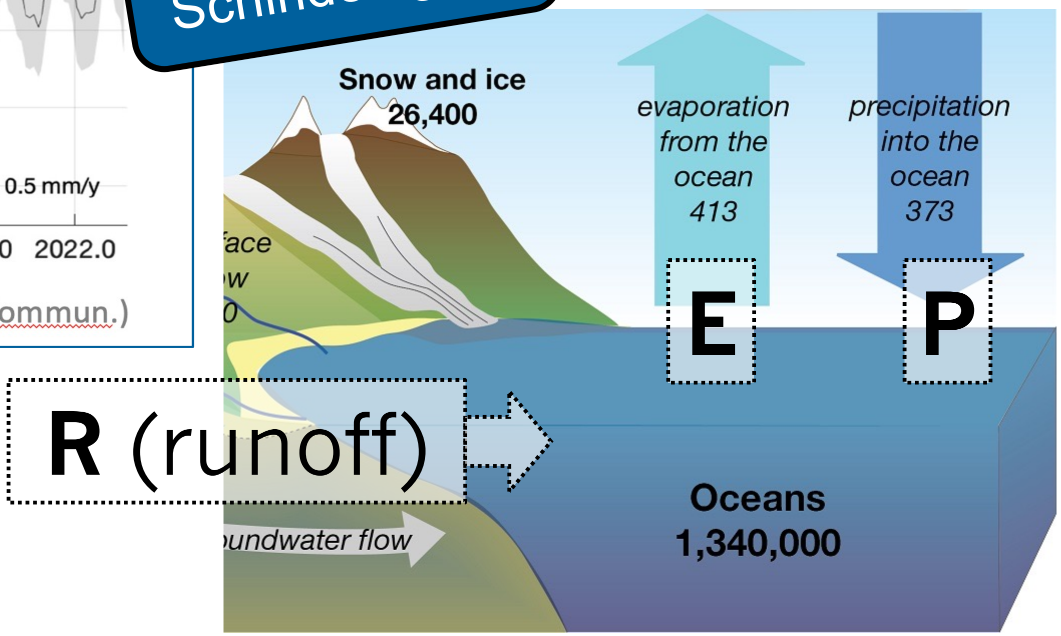
Lecture M. Schindelegger



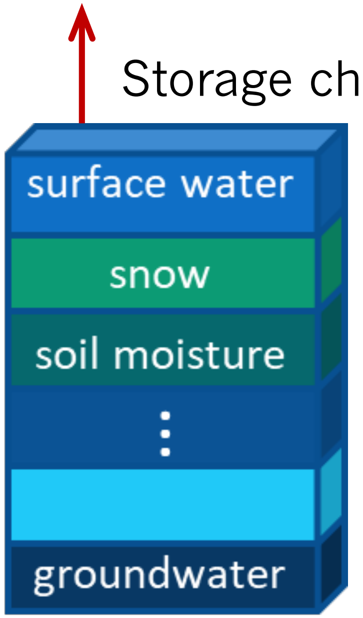
www.visionlearning.com/en/library/Earth-Science/6/The-Hydrologic-Cycle/99

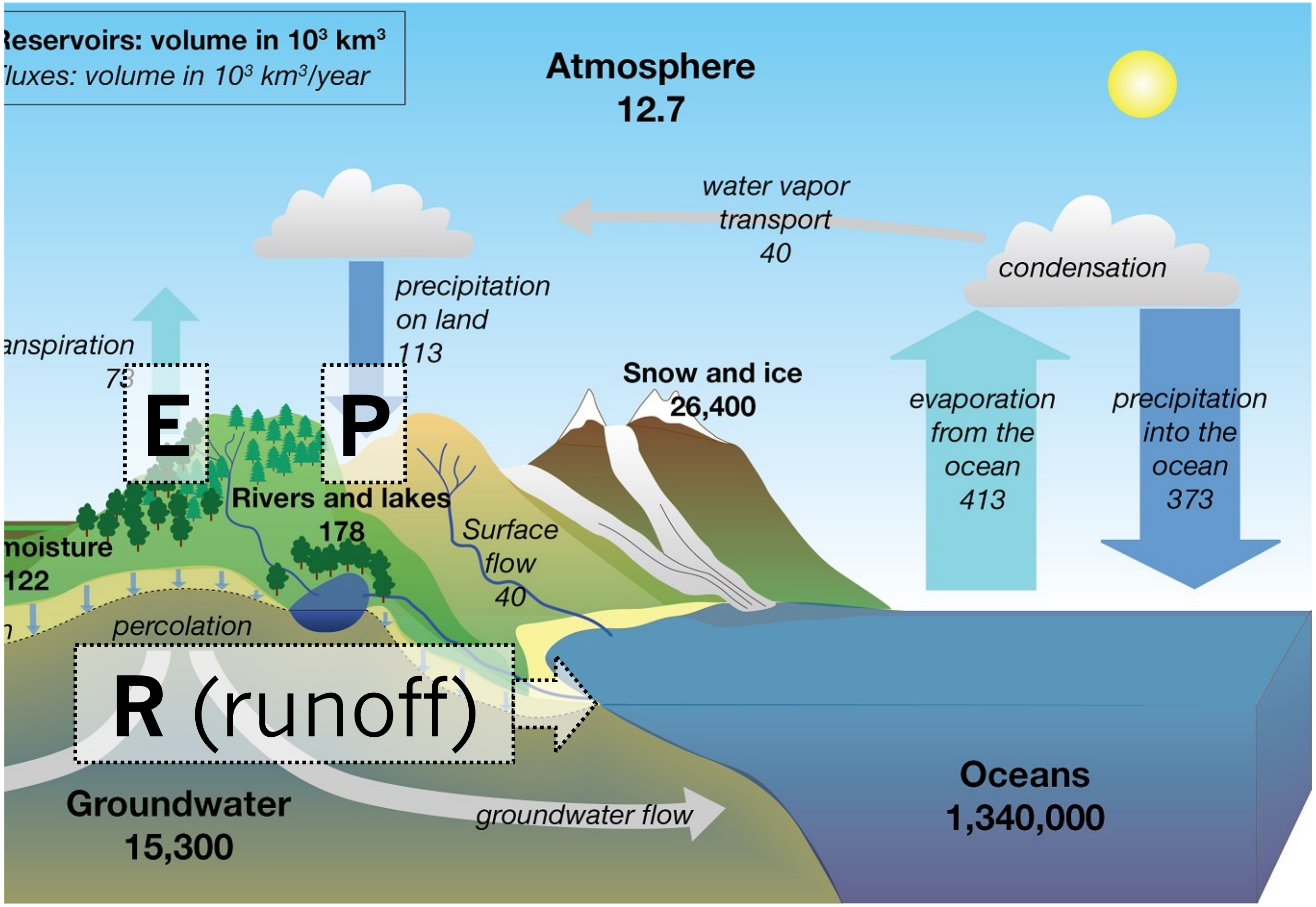
Terrestrial water storage

Terrestrial water balance

$$\frac{dS}{dt} = P - E - R$$

Storage change

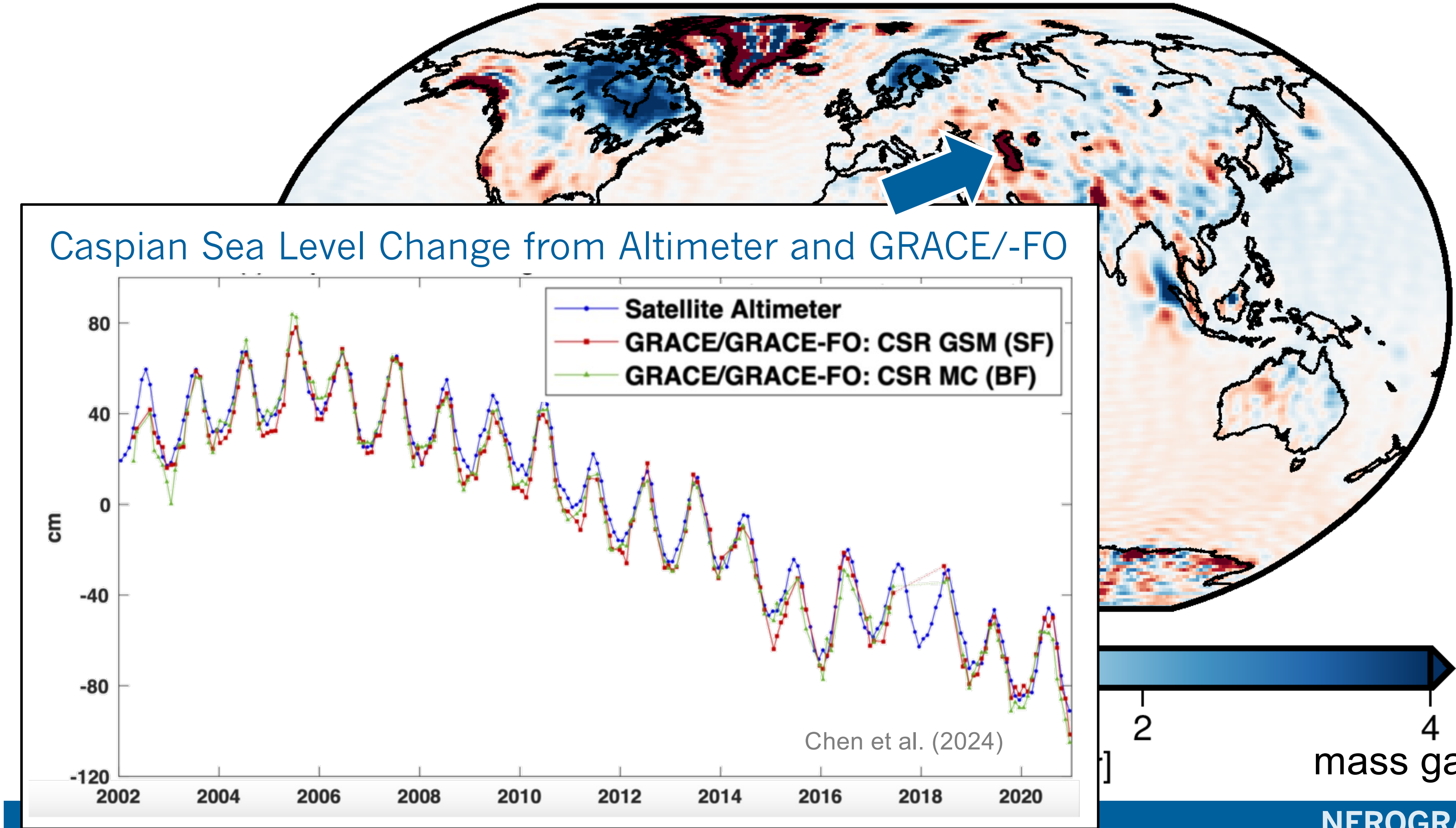




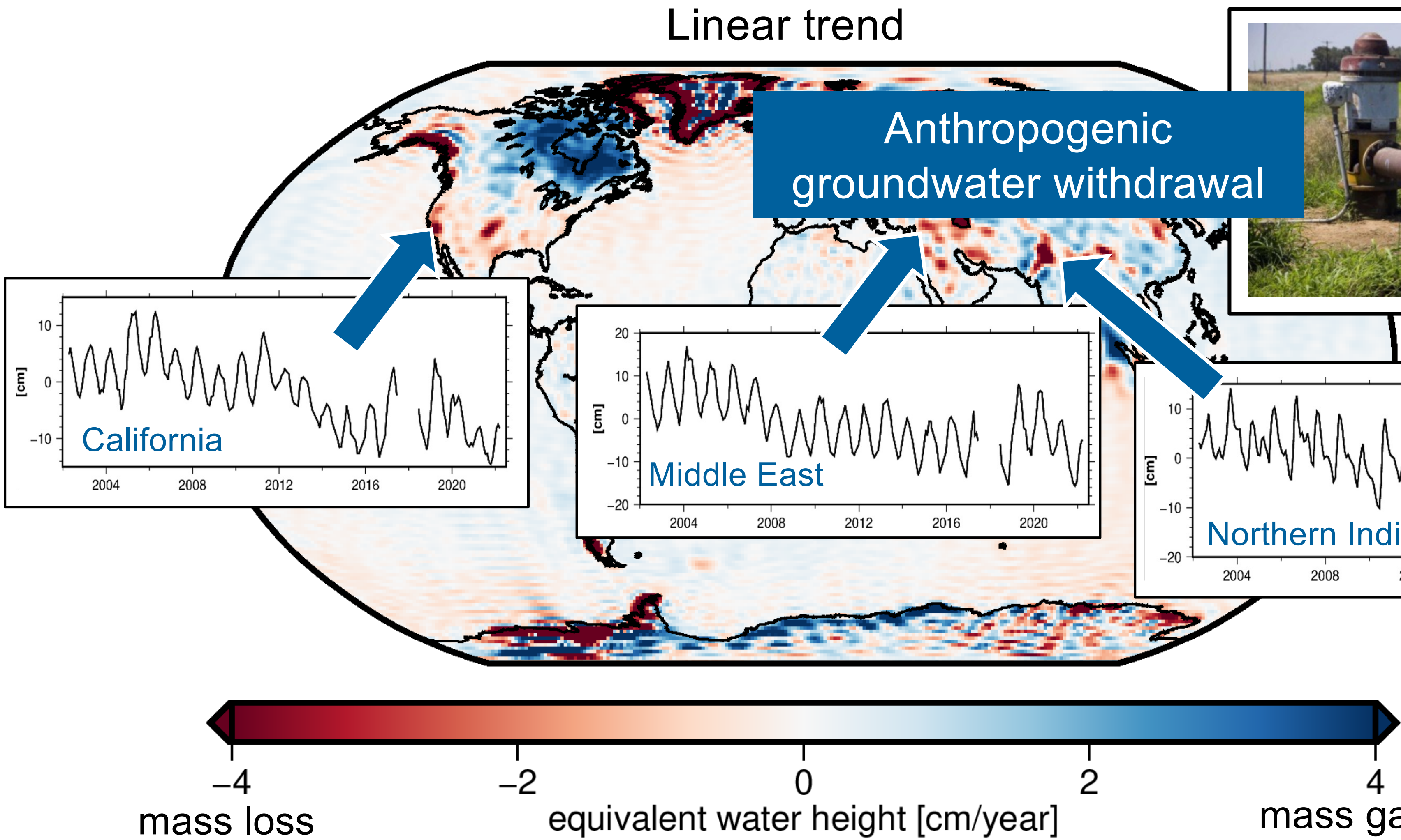
www.visionlearning.com/en/library/Earth-Science/6/The-Hydrologic-Cycle/99

Long-term trend

Linear trend



Long-term trend



Groundwater

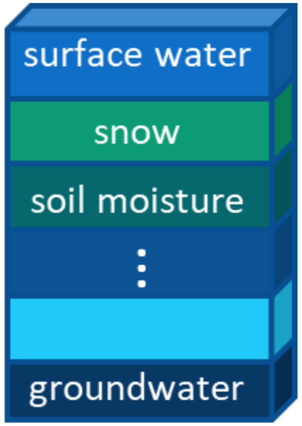
Irrigation

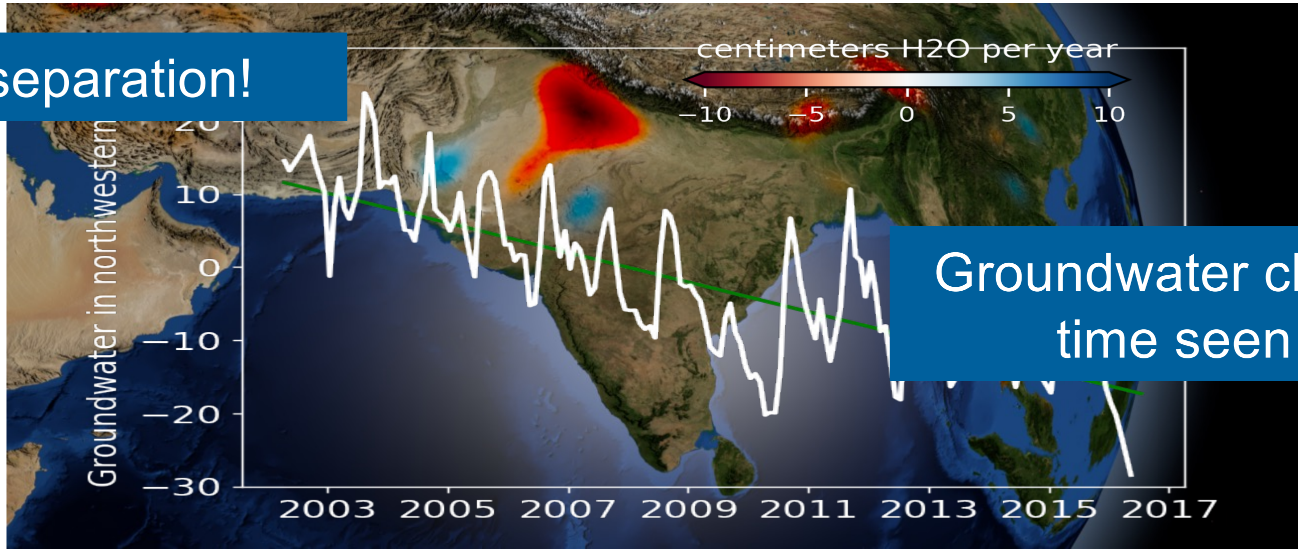
+

Anthropogenic groundwater withdrawal

Over-exploitation of groundwater resources

Signal separation!





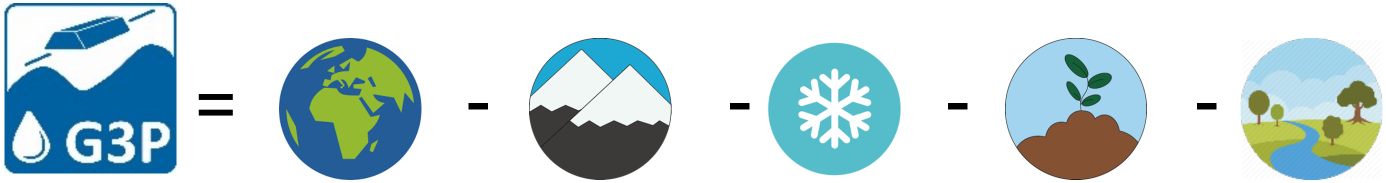
Groundwater change for the first time seen from space!

Fig.: A. Kvas (TU Graz)

Groundwater: G3P Project

HafenCity Universität Hamburg

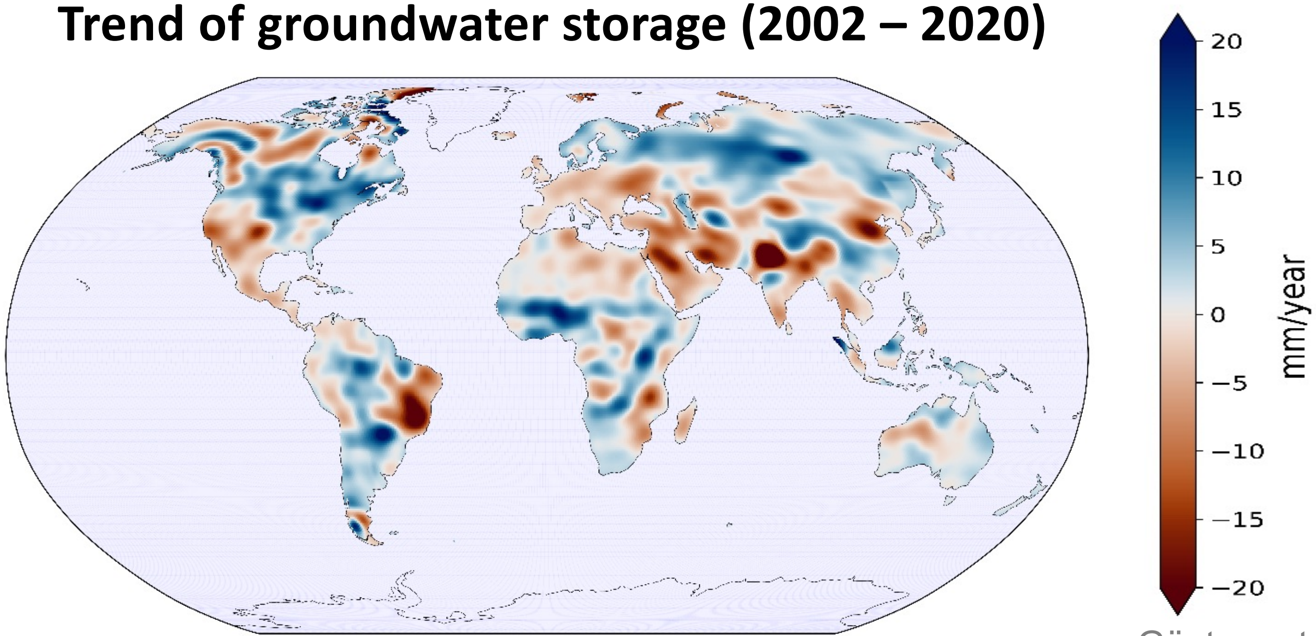
Groundwater: G3P Project



Ground-water = TWS - Glaciers - Snow - Soil moisture - Surface water

New Copernicus Service

Trend of groundwater storage (2002 – 2020)



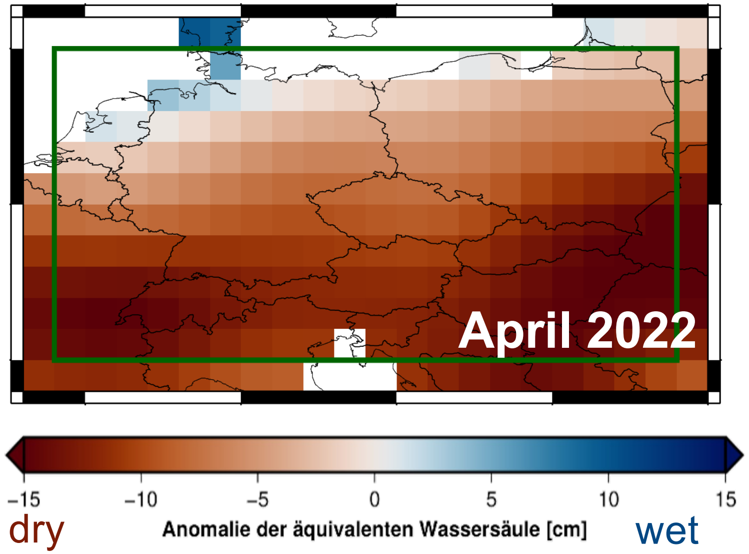
Güntner et al. (2022)

Gravity for monitoring of droughts and floods?

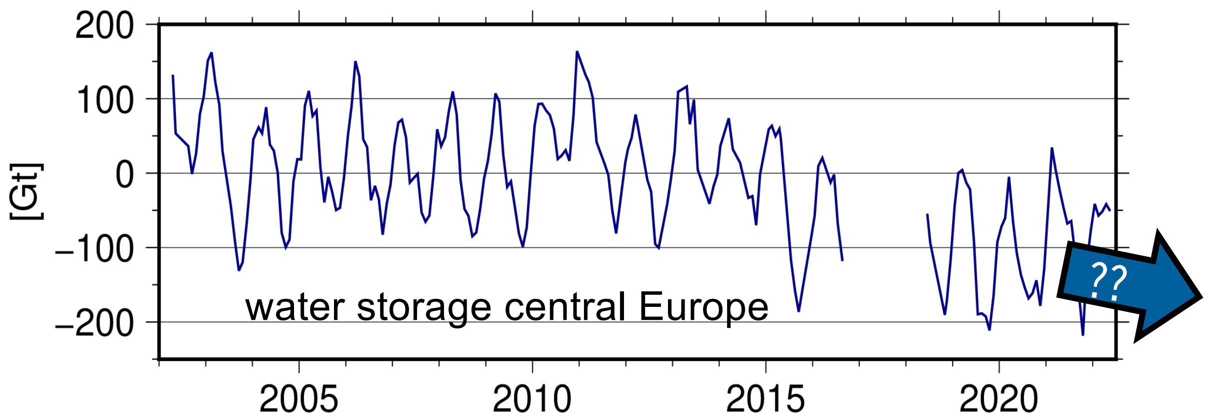

Drought in Europe
Rhine river, Summer 2022
© Federico Gambarini/dpa

Drought in central Europe

Long-term water deficit



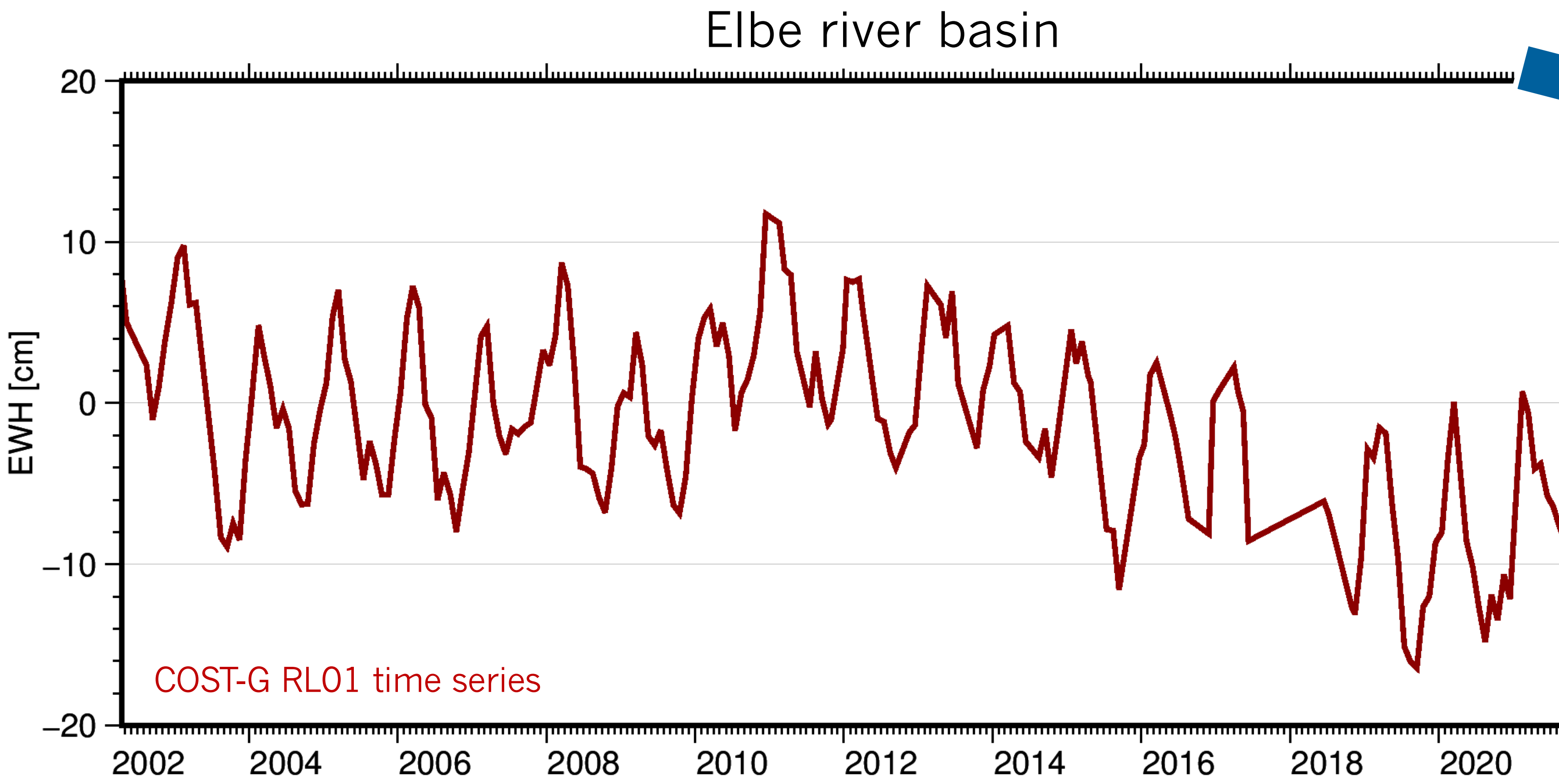
Water deficit:
200 Gigatons



(c) E. Börgens, GFZ

Drought in central Europe

HafenCity Universität Hamburg



by GravIS Gravity Information Service

Drought in central Europe

Gravity as early-warning system?

by GravIS Gravity Information Service

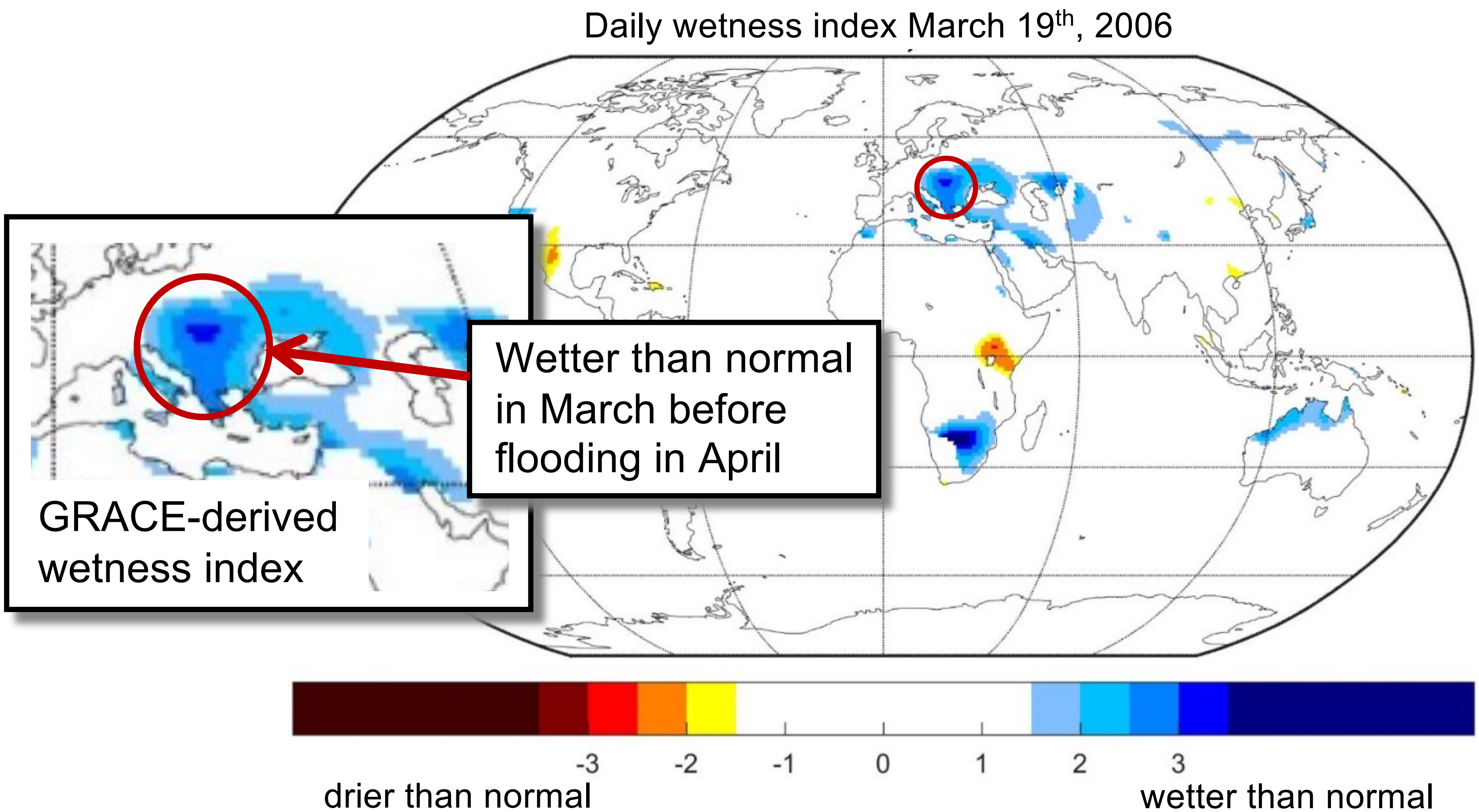
Gravity as early-warning system?

Gravity as early-warning system?

saturated soils

danger of flooding

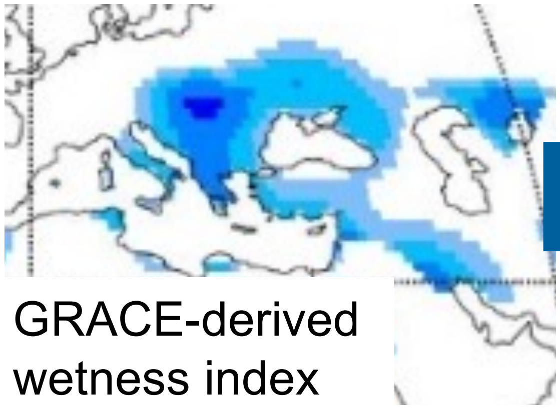
Gravity as early-warning system?



Jäggi et al. (2019)

Gravity as early-warning system?

Ideally: Daily GRACE solutions
in (near) real time

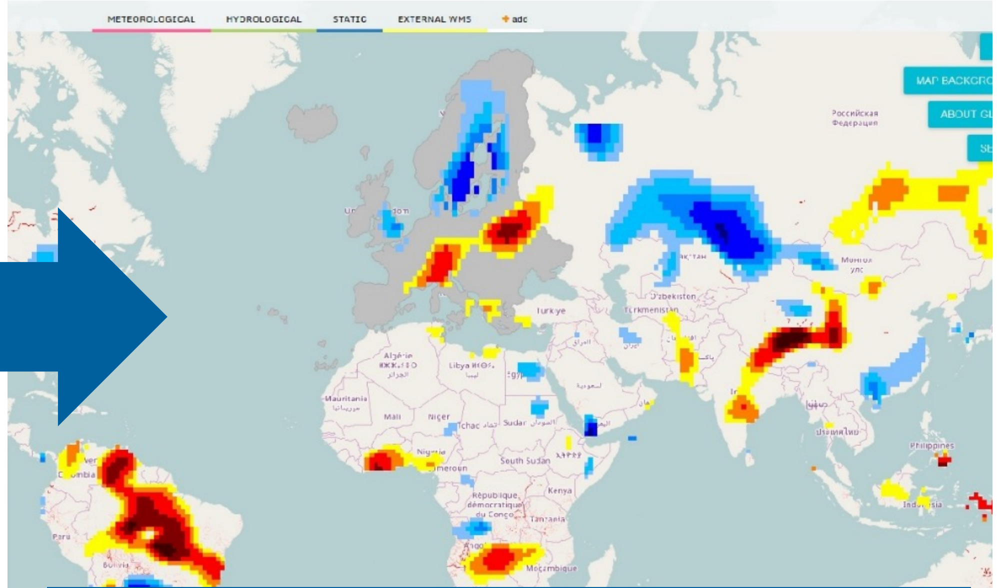


GRACE-derived
wetness index

Goal: include in operational flood (or drought) early warning systems

European Commission

GLOFAS
Global Flood Awareness System

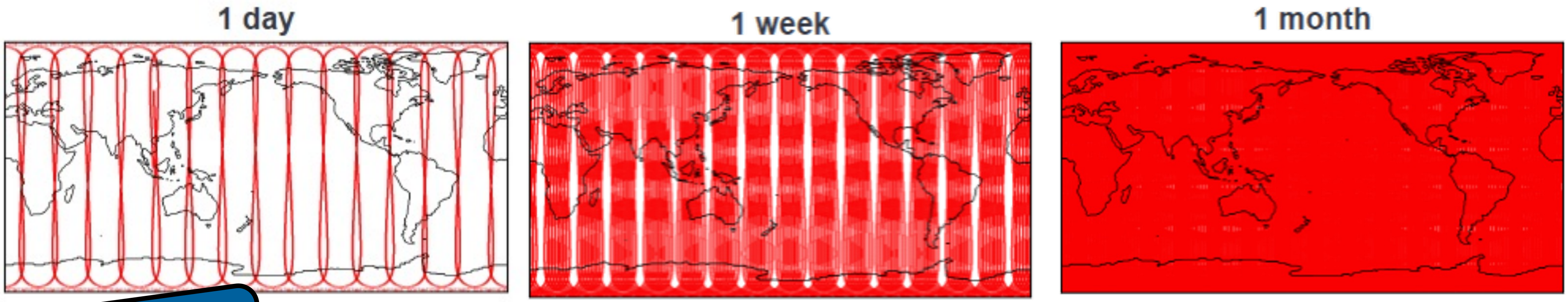


Wetness index (prototype) included
in GloFAS Forecast Viewer

Jäggi et al. (2019)

Short time scale (days)?

Ideally: Daily GRACE solutions in (near) real time



Lecture L. Shihora

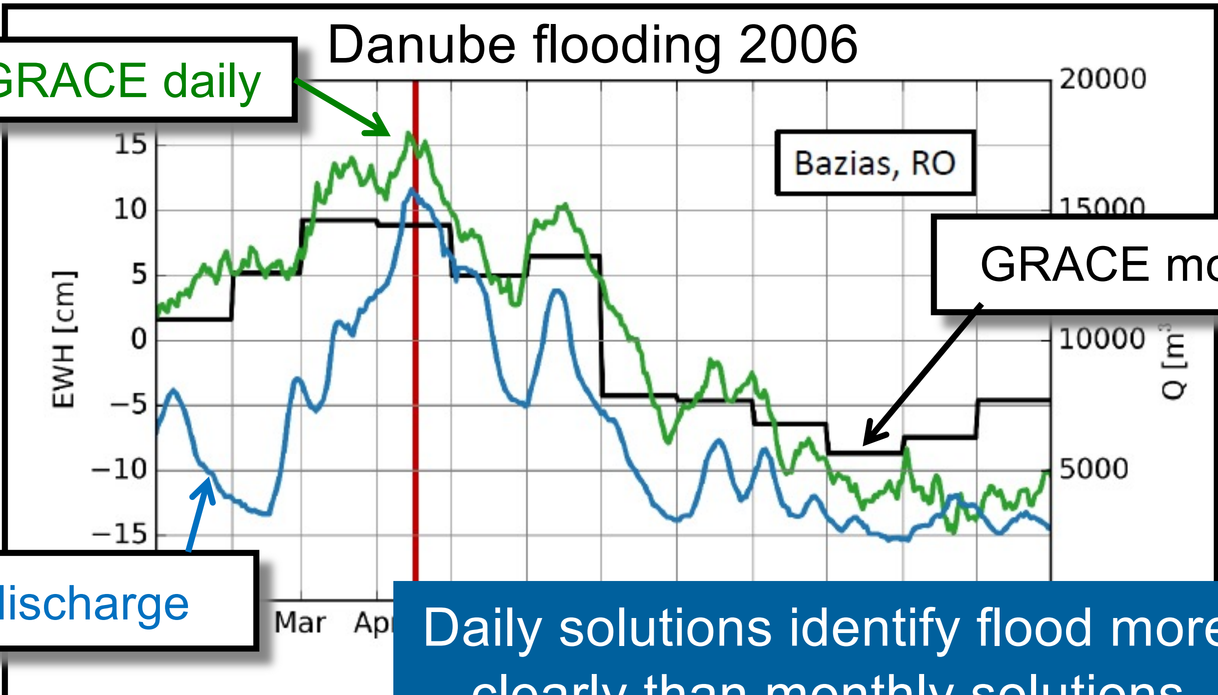
GRACE ground tracks

Additional information needed, daily solutions not independent (e.g. Kalman filter)

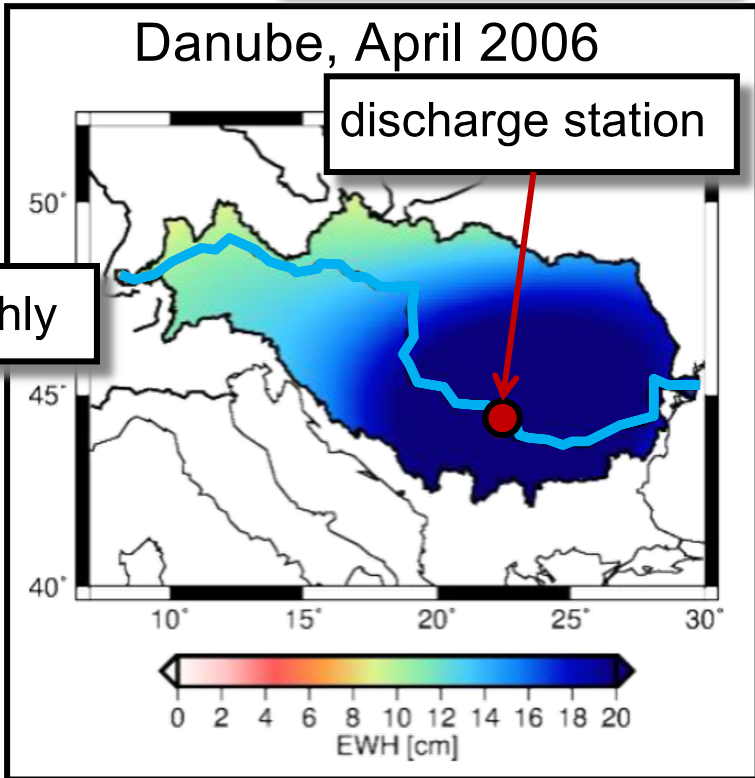
ITSG-Grace2018 daily

Flooding

Ideally: Daily GRACE solutions in (near) real time



Daily solutions identify flood more clearly than monthly solutions



Kvas et al. (TU Graz)

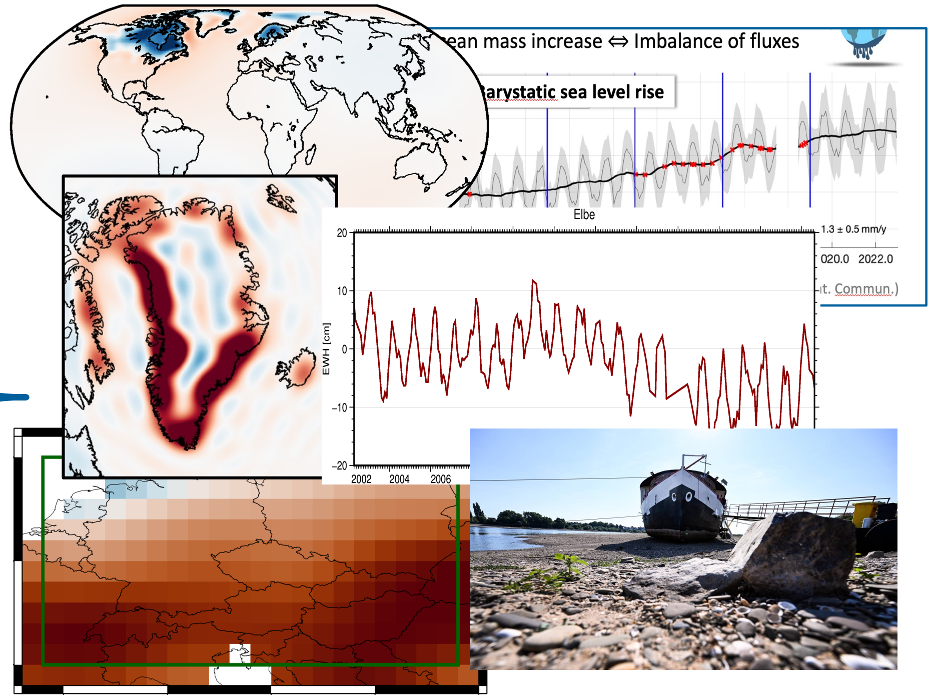
Outline

long

temporal scales

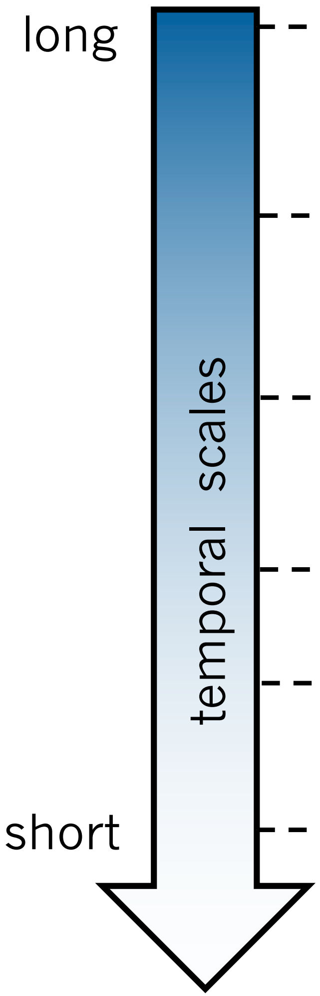
short

- **climate trends (centuries)**
  - climate model evaluation
- **present-day trends (decades)**
  - sea level, ice mass, ...
- **inter-annual variations**
  - ENSO, droughts, ...
- **seasonal changes (months)**
- **weeks to month**
  - floods, ...
- **short-term changes (days)**
  - hydro-meteorological fluxes



Pushing the limits!

Outline



climate trends (centuries)
- climate model evaluation

present-day trends (decades)
- sea level, ice mass, ...

inter-annual variations
- ENSO, droughts, ...

seasonal changes (months)

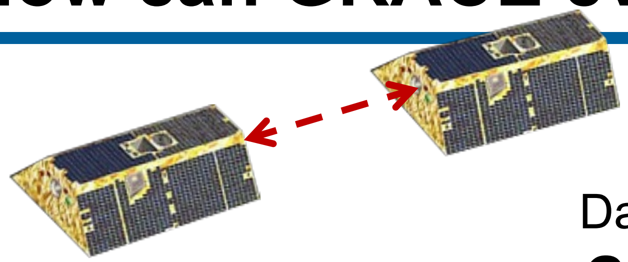
weeks to month
- floods, ...

short-term changes (days)
- hydro-meteorological fluxes

Can GRACE data evaluate atmosphere models (on daily time scales?)

Pushing the limits!

How can GRACE evaluate reanalyses?



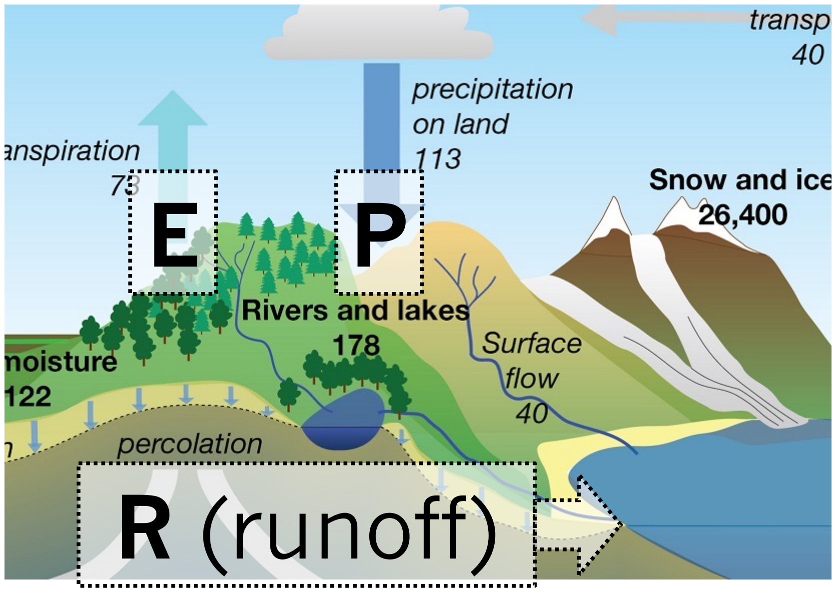
Daily data!
GRACE
(first derivative)

Terrestrial water balance

precipitation — runoff

$$\frac{dS}{dt} = P - E - R$$

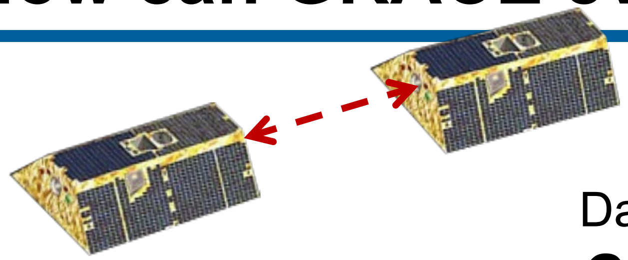
evapo-
transpiration



Can GRACE data evaluate atmosphere models (on daily time scales?)

Update of:
Eicker, A., Jensen, L., Wöhnke, V., Dobslaw, H., Kvas, A., Mayer-Gürr,. T., Dill, R. (2020): Evaluating short-term hydro-meteorological fluxes with daily satellite data from the GRACE mission, *Scientific reports, 10, 4505,* https://doi.org/10.1038/s41598-020-61166-0

How can GRACE evaluate reanalyses?

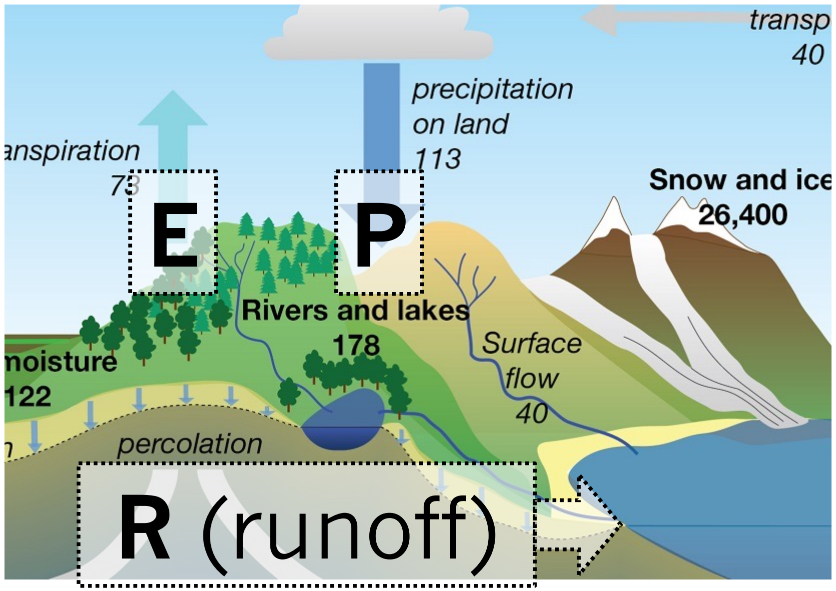


Daily data!
GRACE
(first derivative)

Terrestrial water balance

$$\frac{dS}{dt} = P - E - R$$

precipitation, runoff, evapo-transpiration



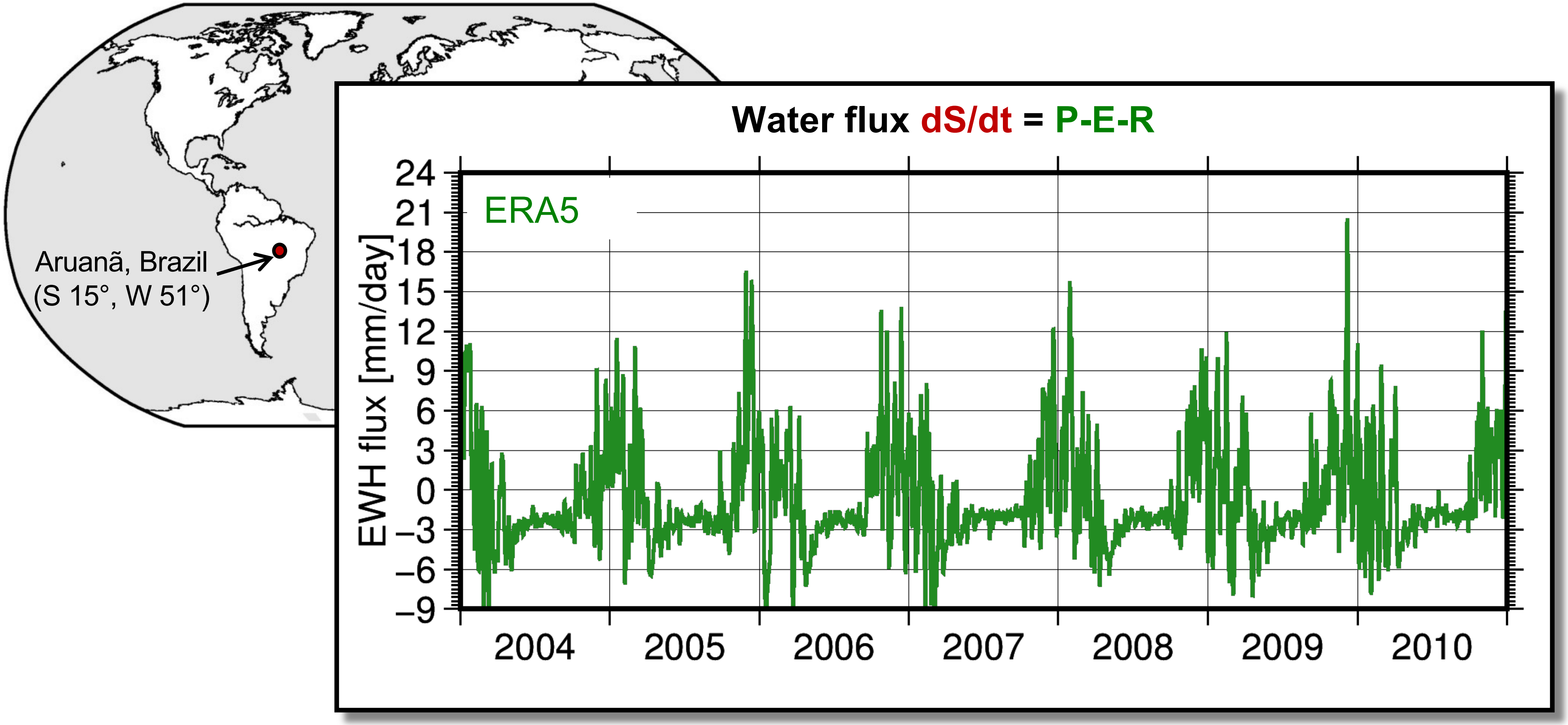
Reanalyses

ERA-Interim
ERA5 NEW

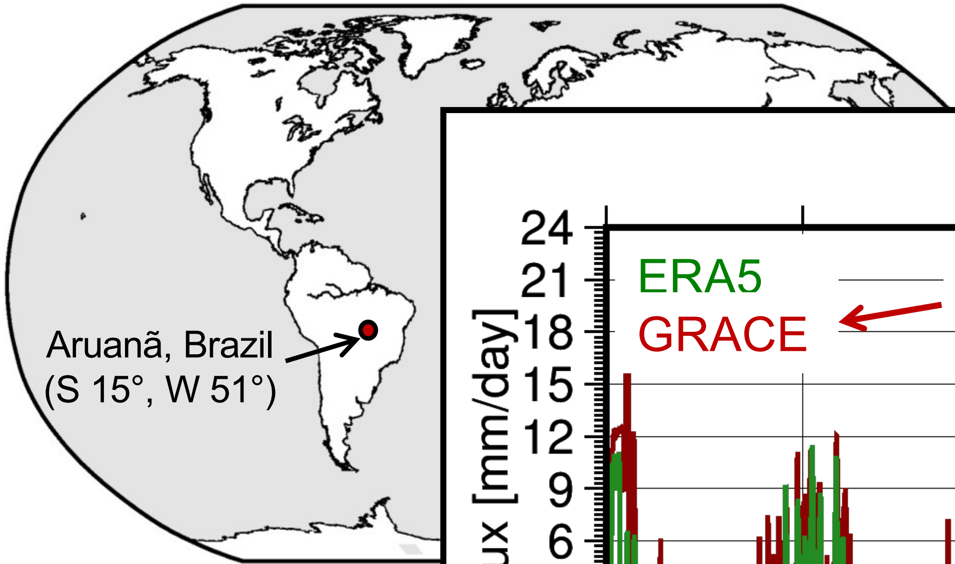
ECMWF

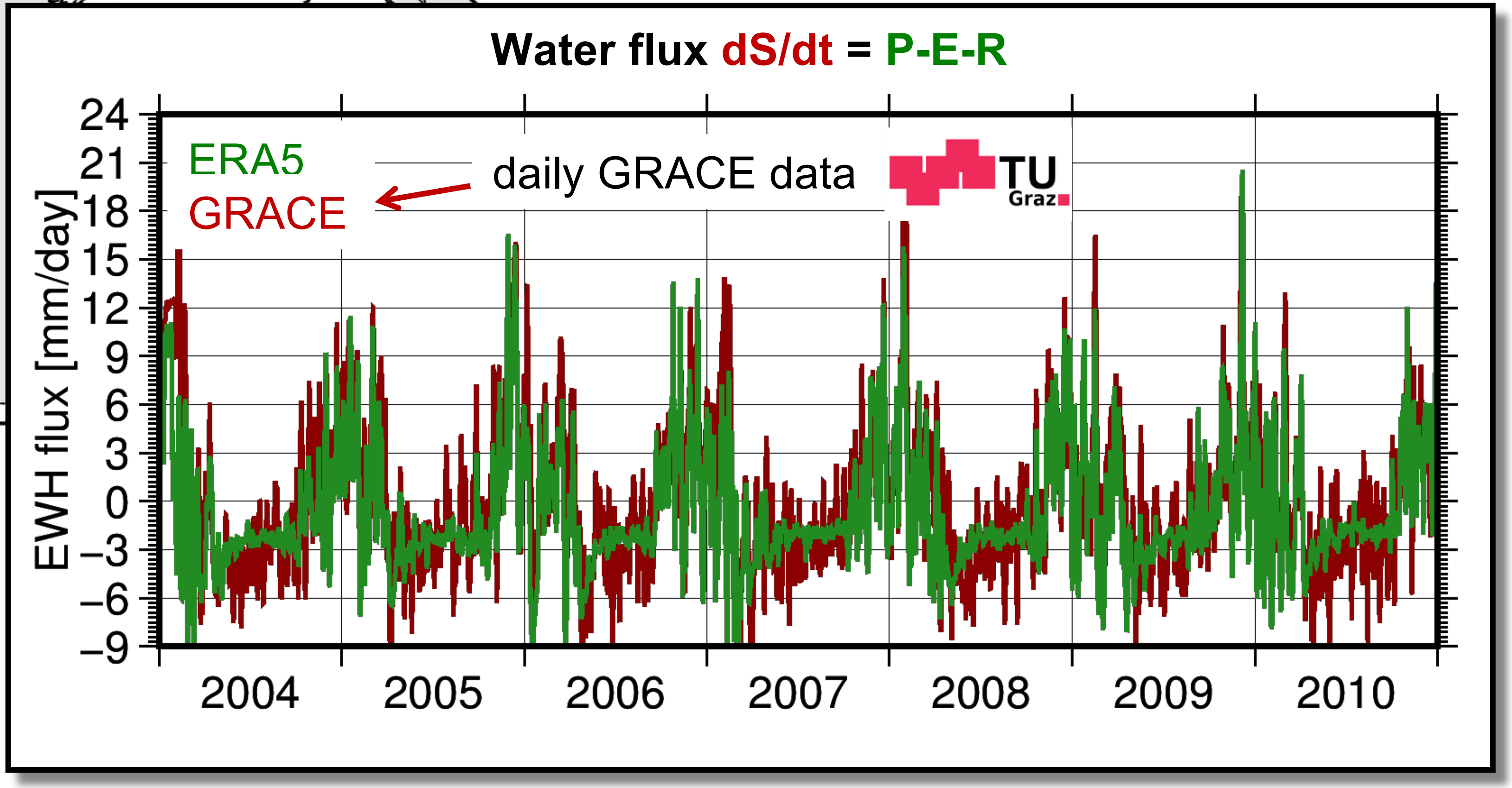
Update of:
Eicker, A., Jensen, L., Wöhnke, V., Dobslaw, H., Kvas, A., Mayer-Gürr,. T., Dill, R. (2020): Evaluating short-term hydro-meteorological fluxes with daily satellite data from the GRACE mission, *Scientific reports, 10, 4505,* https://doi.org/10.1038/s41598-020-61166-0

Daily fluxes



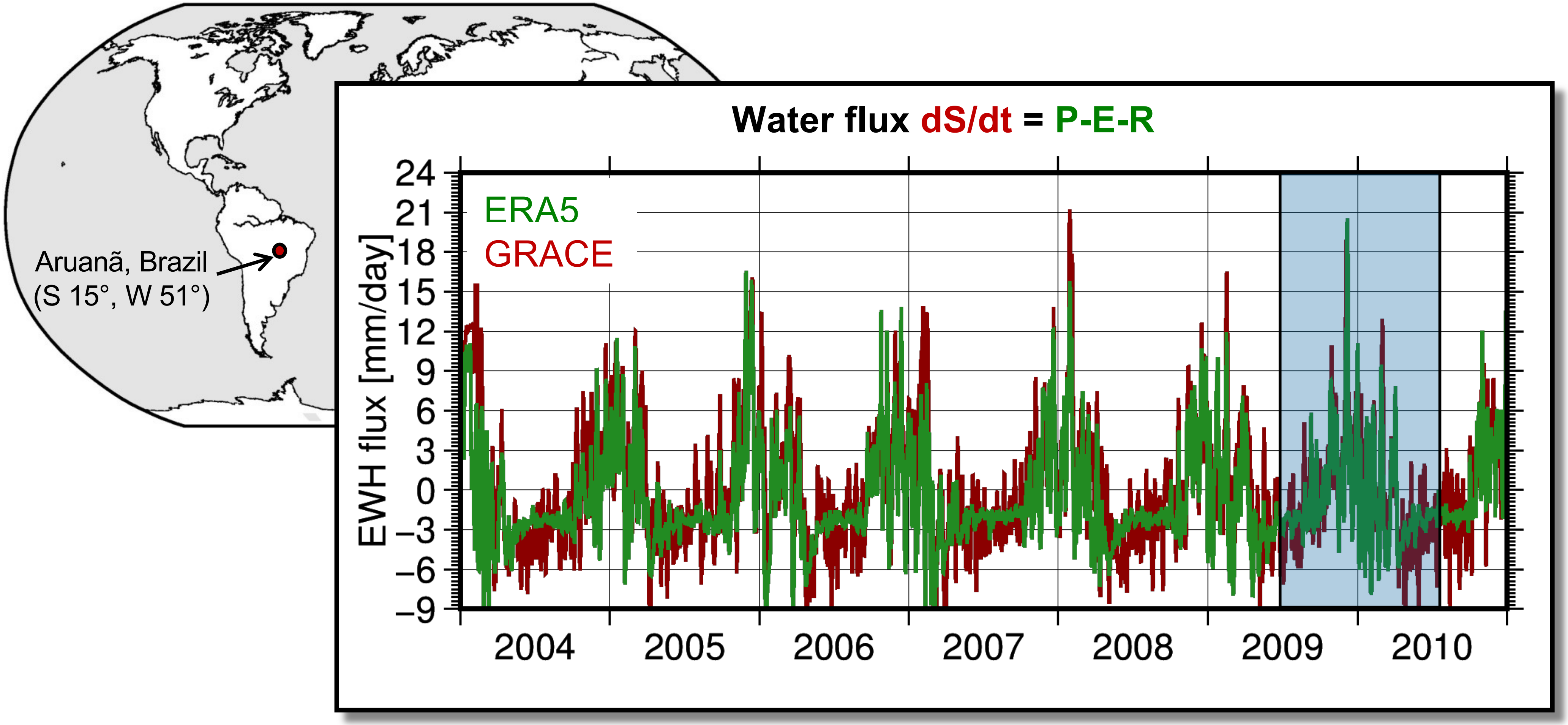
Daily fluxes



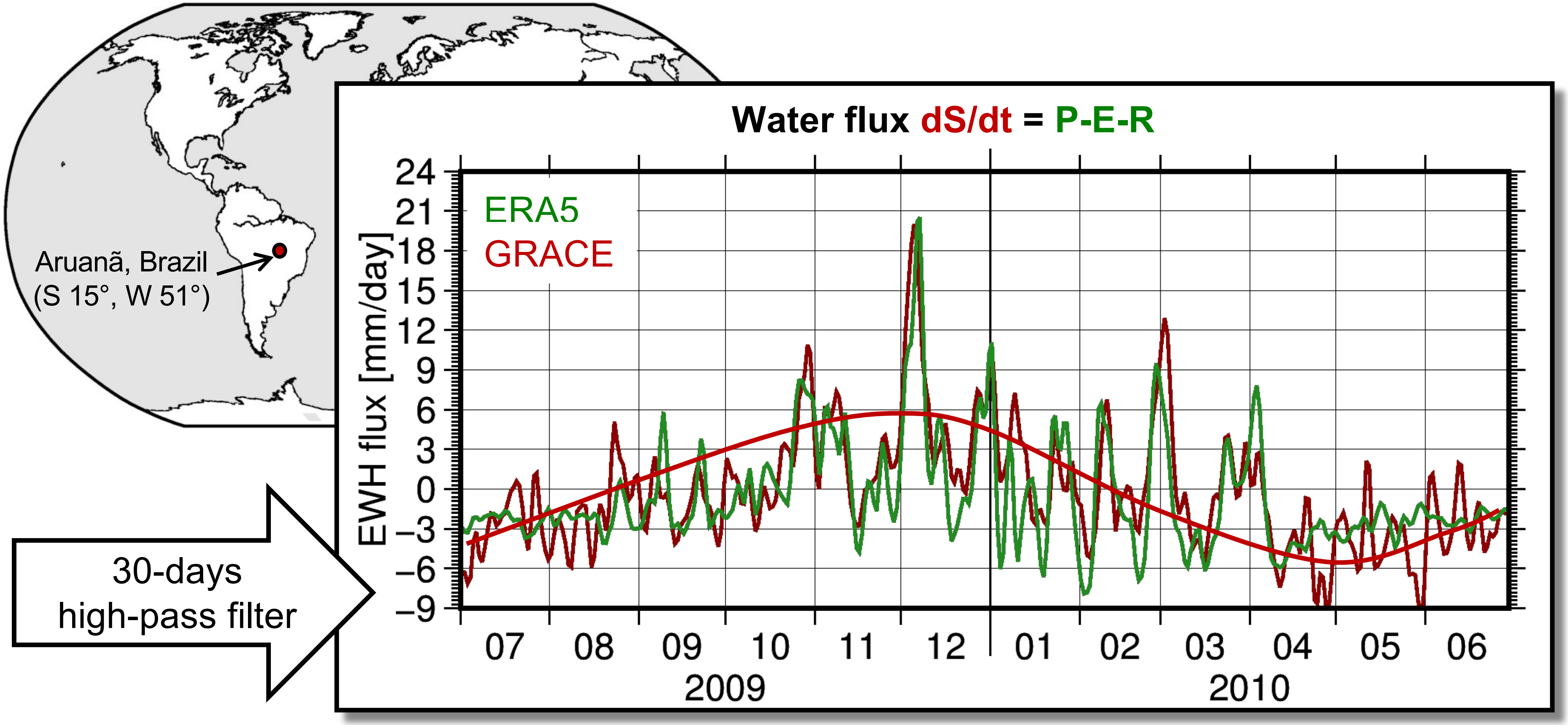


Nominal temporal resolution of GRACE: 1 month

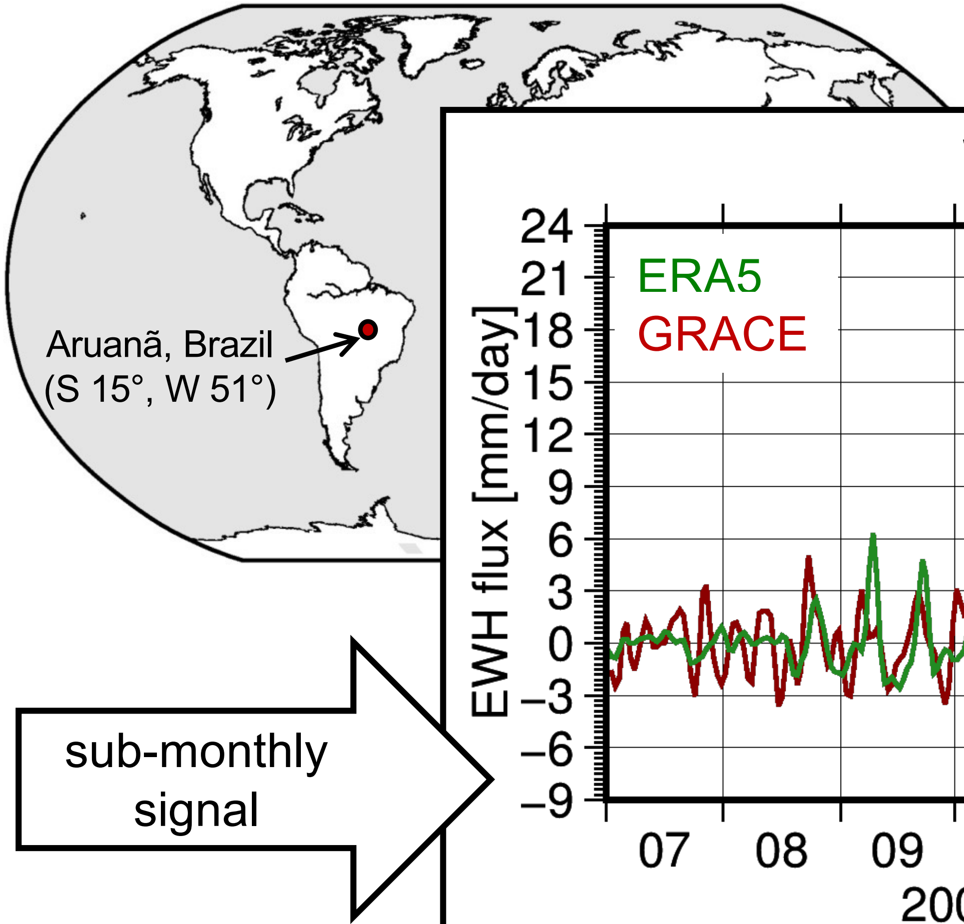
Daily fluxes

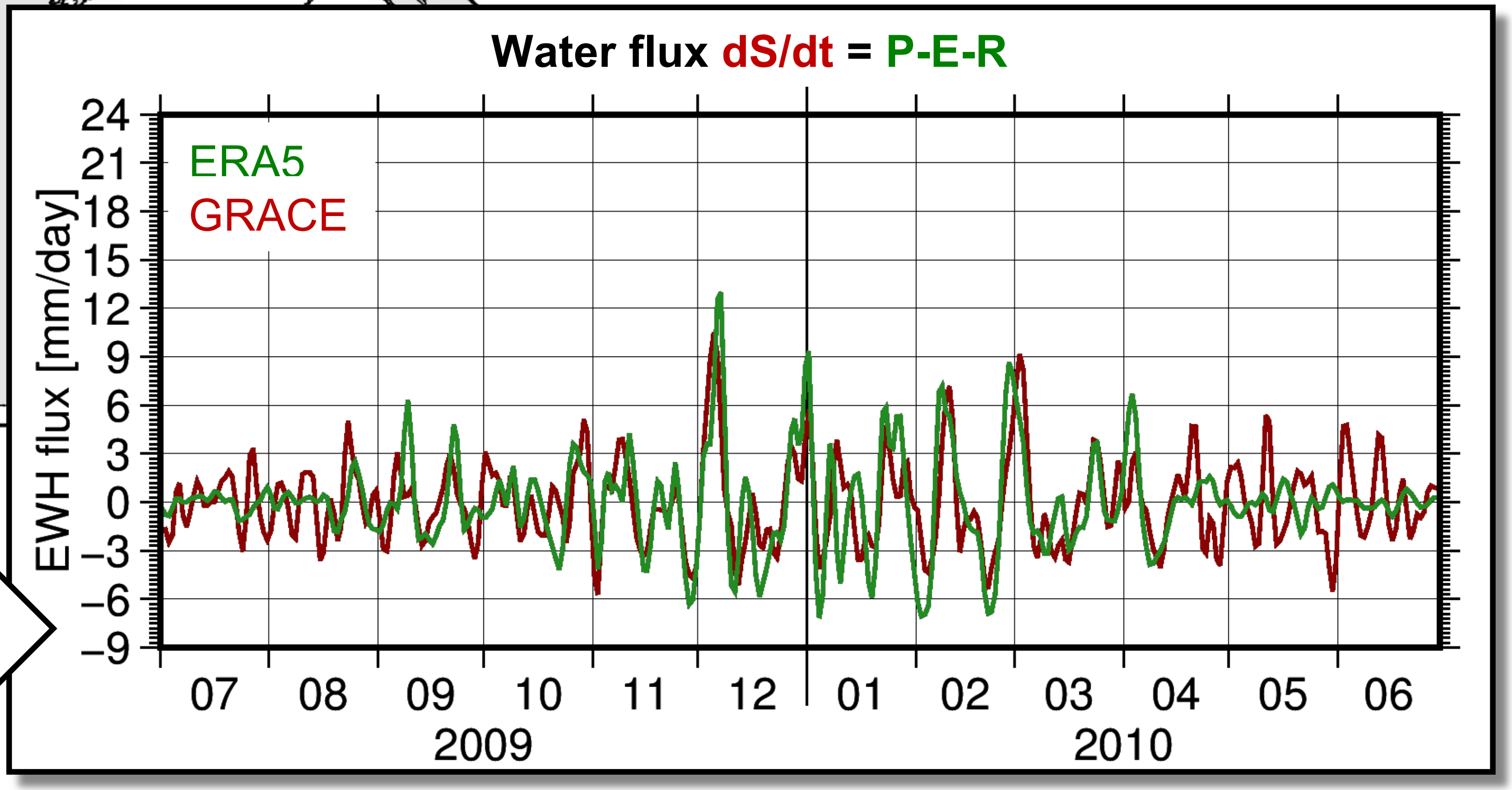


Daily fluxes

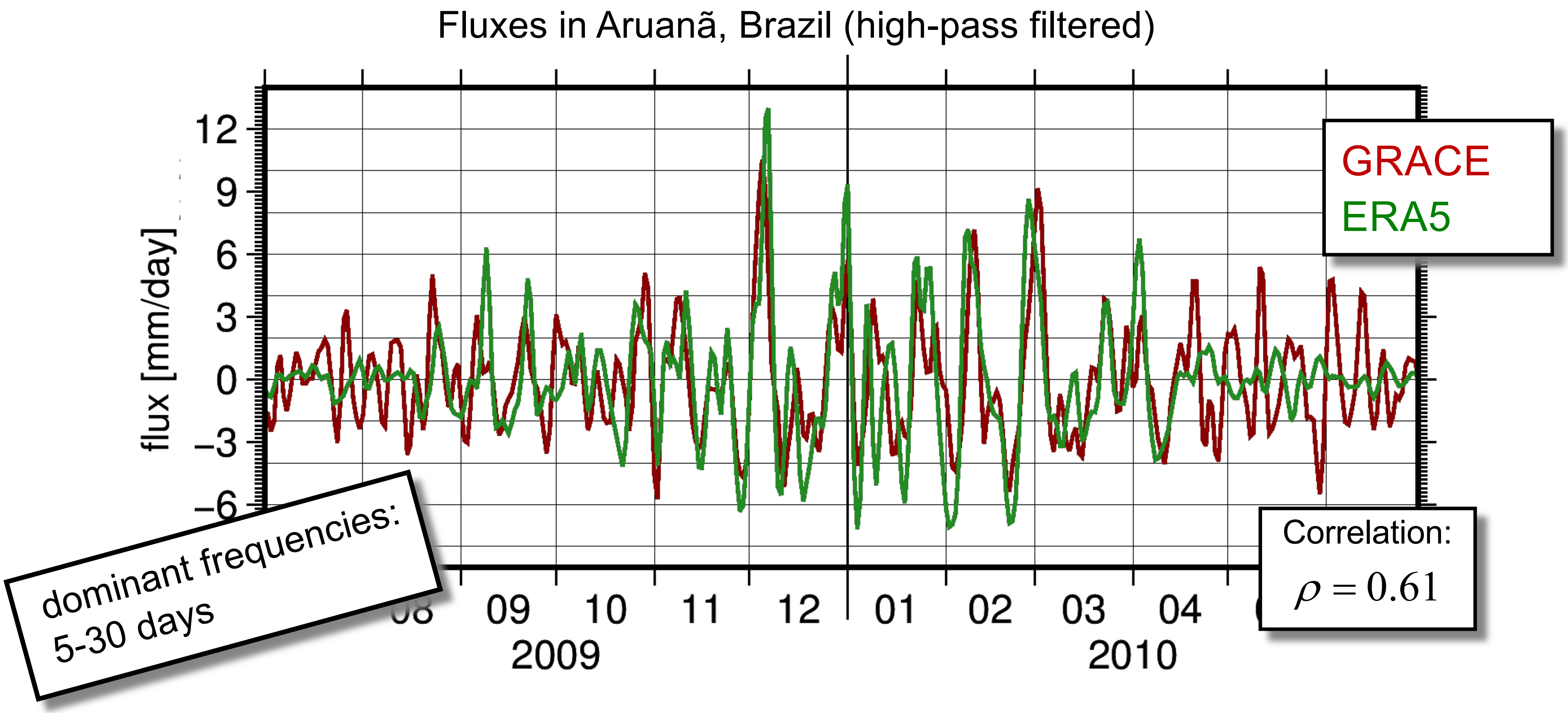


Daily fluxes

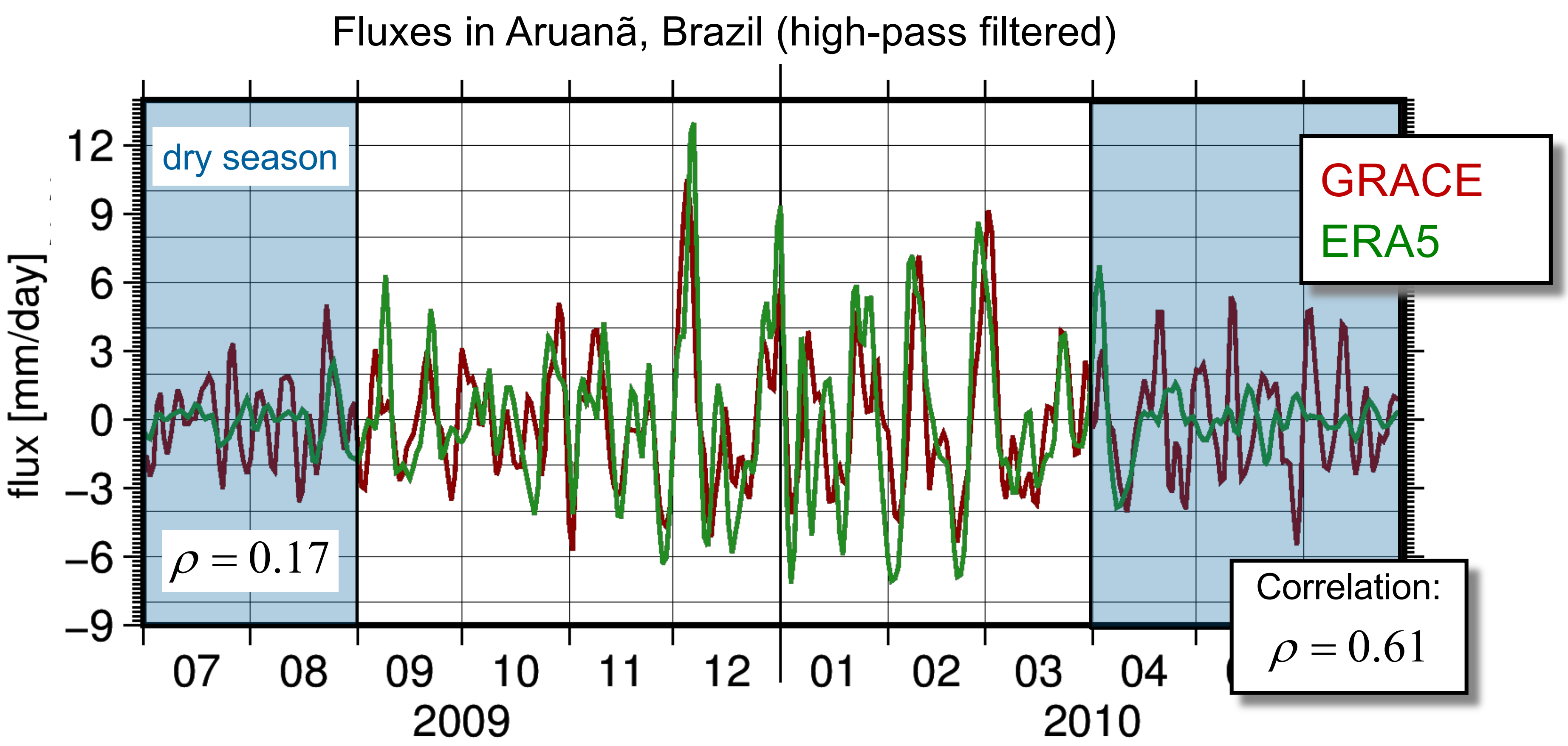




Comparison GRACE vs. ERA5



Comparison GRACE vs. ERA5



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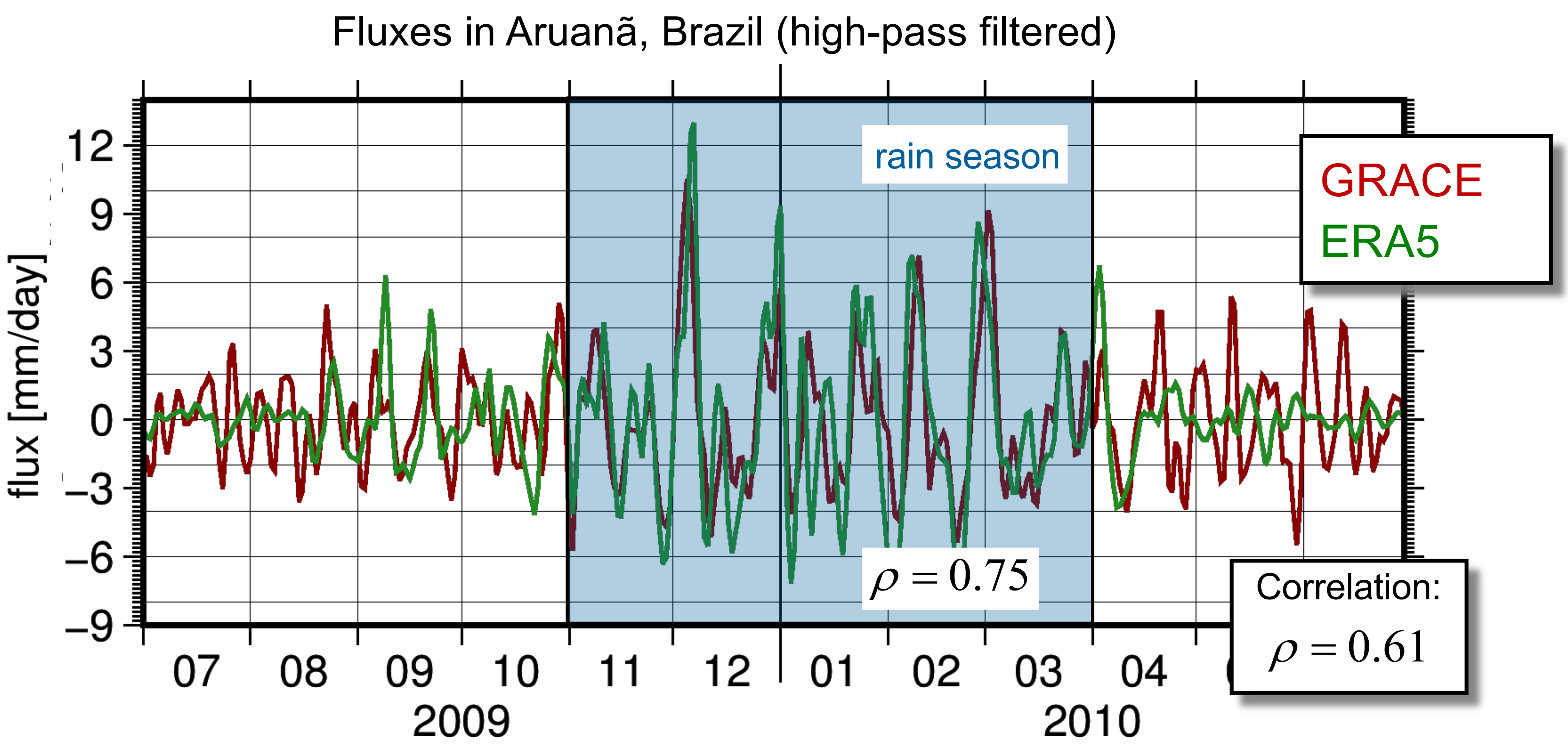
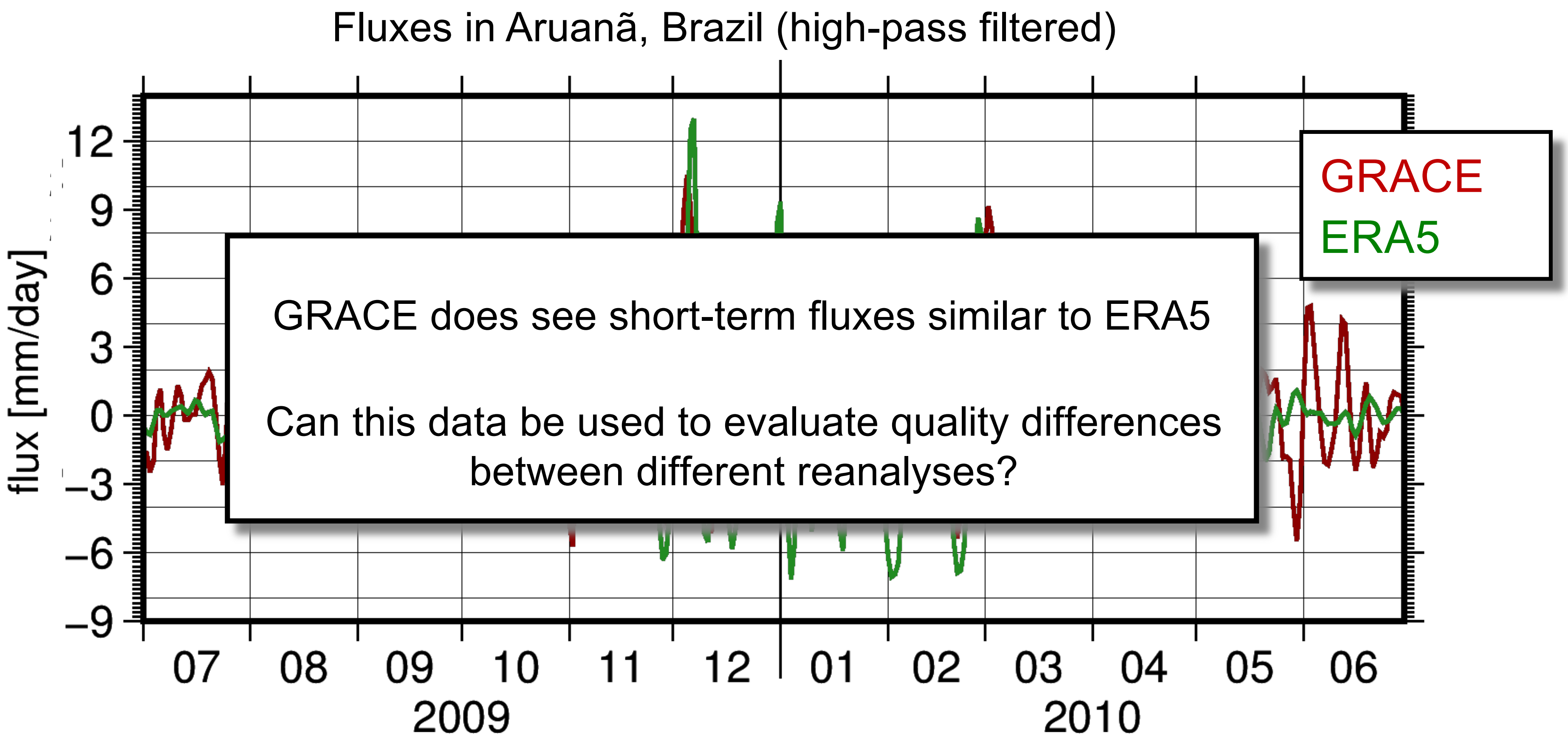


Comparison GRACE vs. ERA5

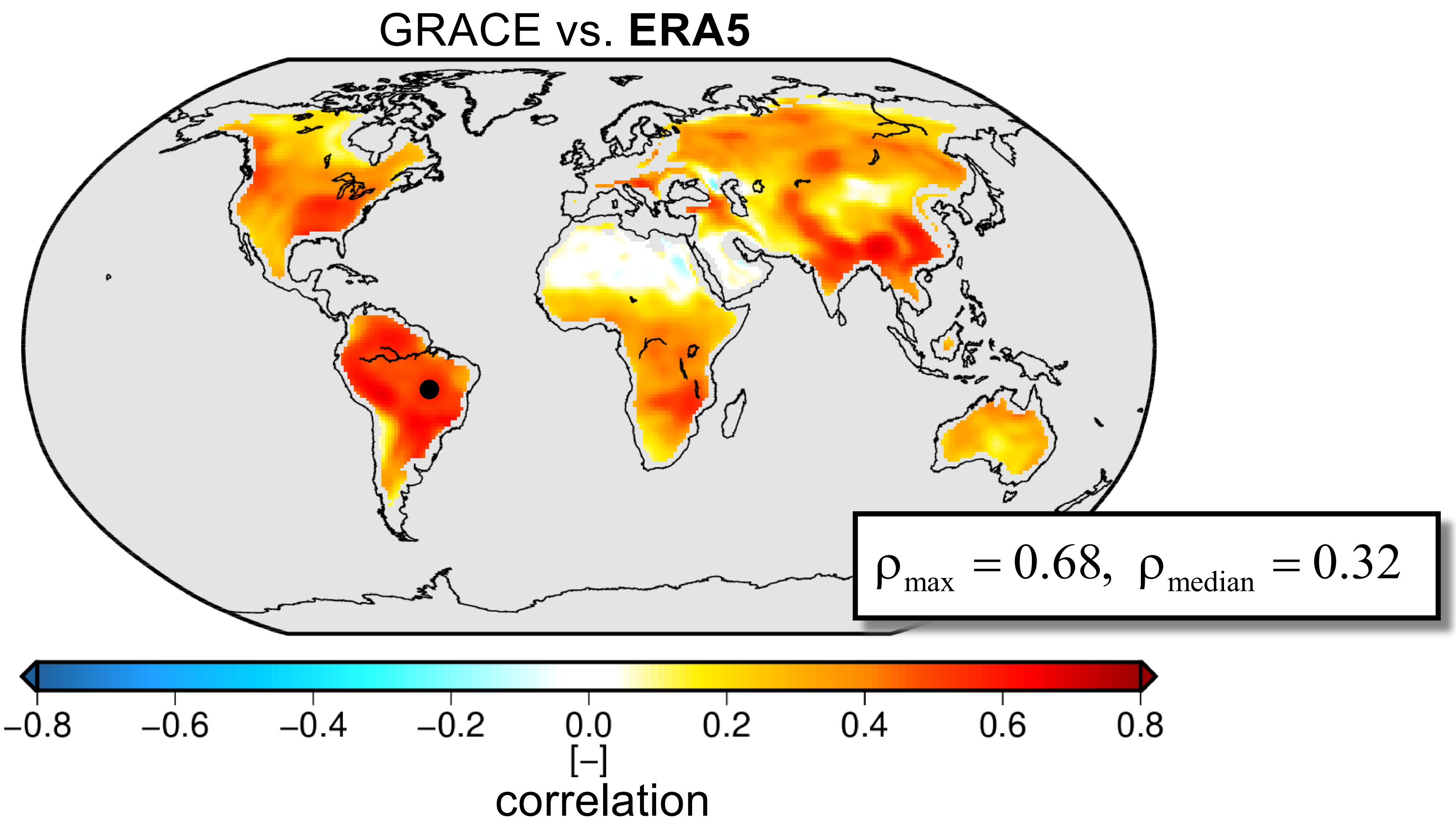


GRACE does see short-term fluxes similar to ERA5

Can this data be used to evaluate quality differences between different reanalyses?

Correlation (2003-2015)

NEW!



Correlation (2003-2015)

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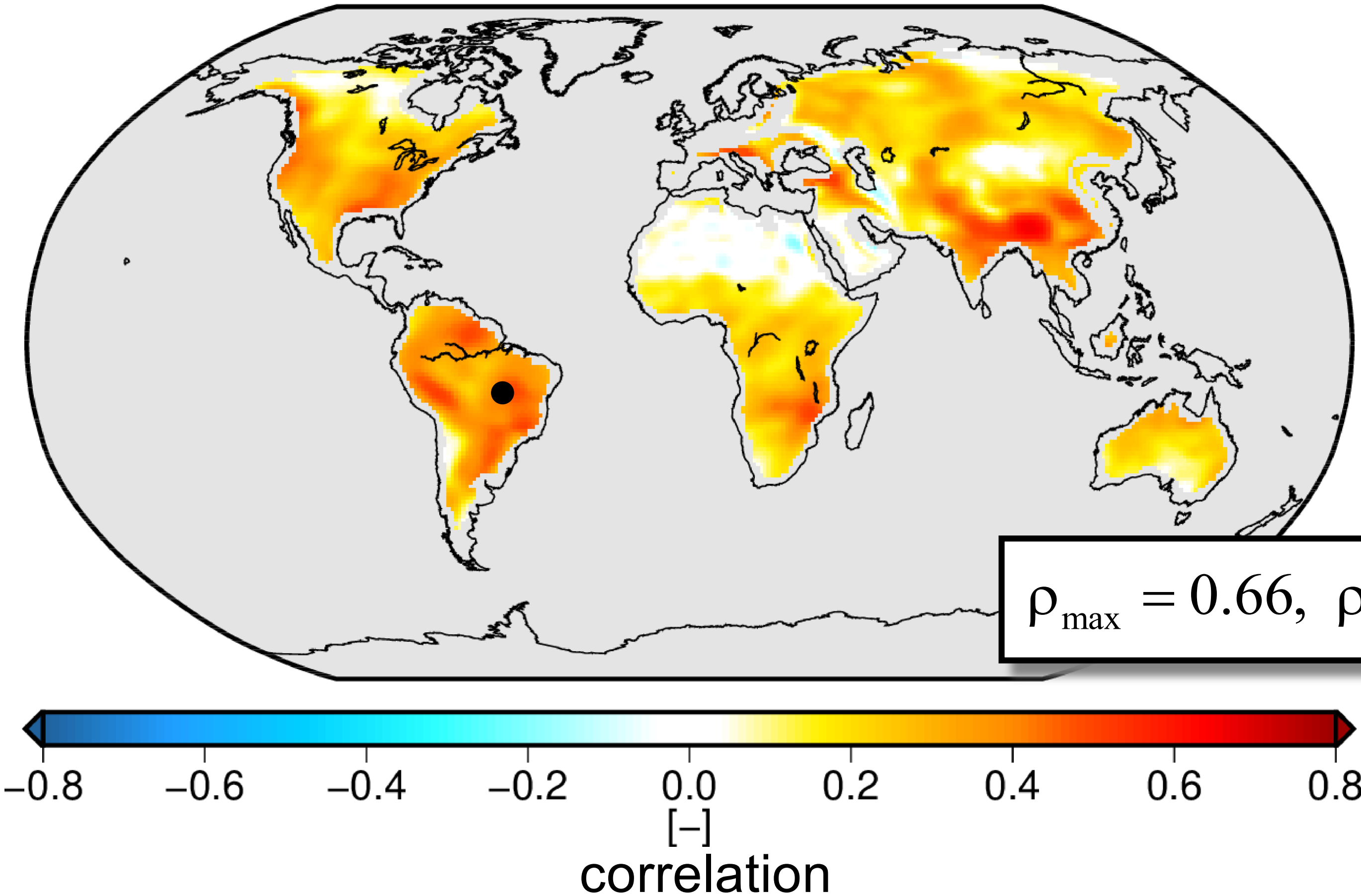
OLD!

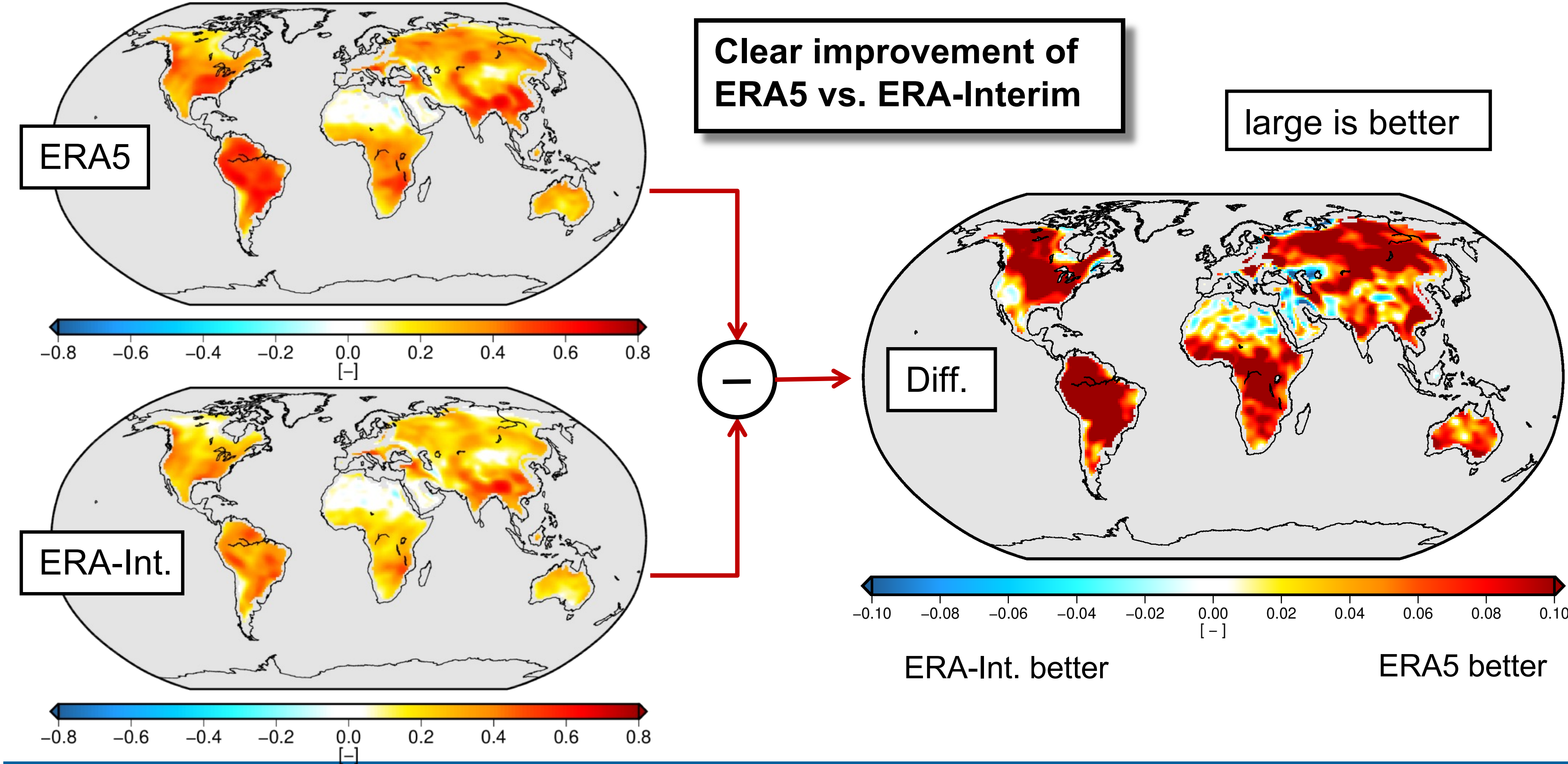
GRACE vs. **ERA-Interim**



Correlation

Clear improvement of ERA5 vs. ERA-Interim

large is better



Root means squared deviation (RMSD)

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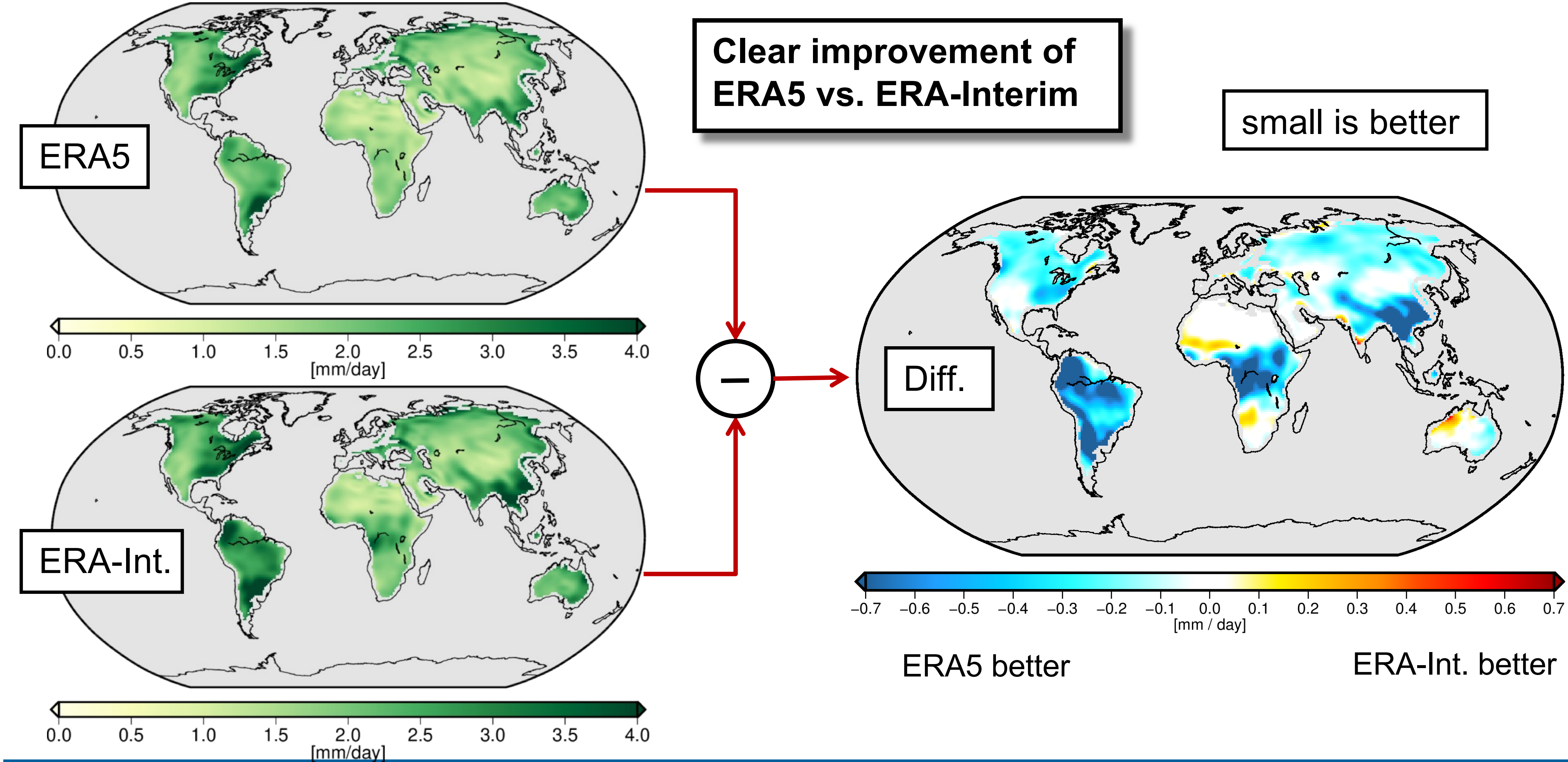
Clear improvement of ERA5 vs. ERA-Interim

small is better



Root means squared deviation (RMSD)

Clear improvement of ERA5 vs. ERA-Interim

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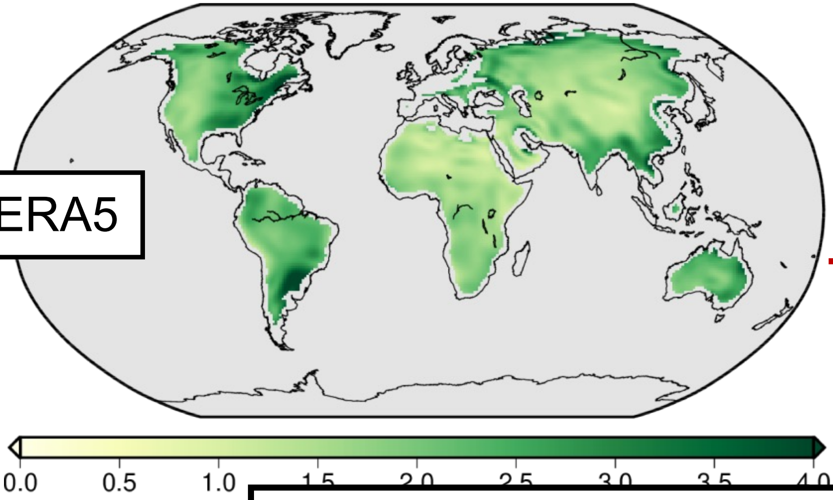
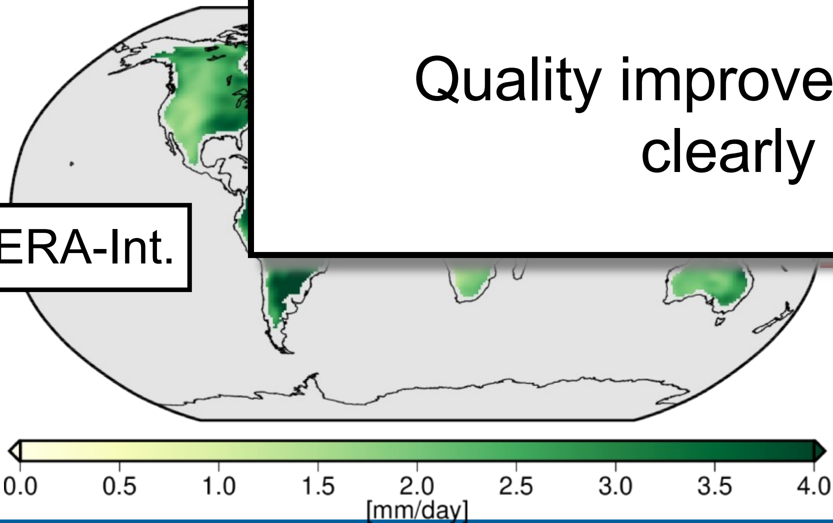
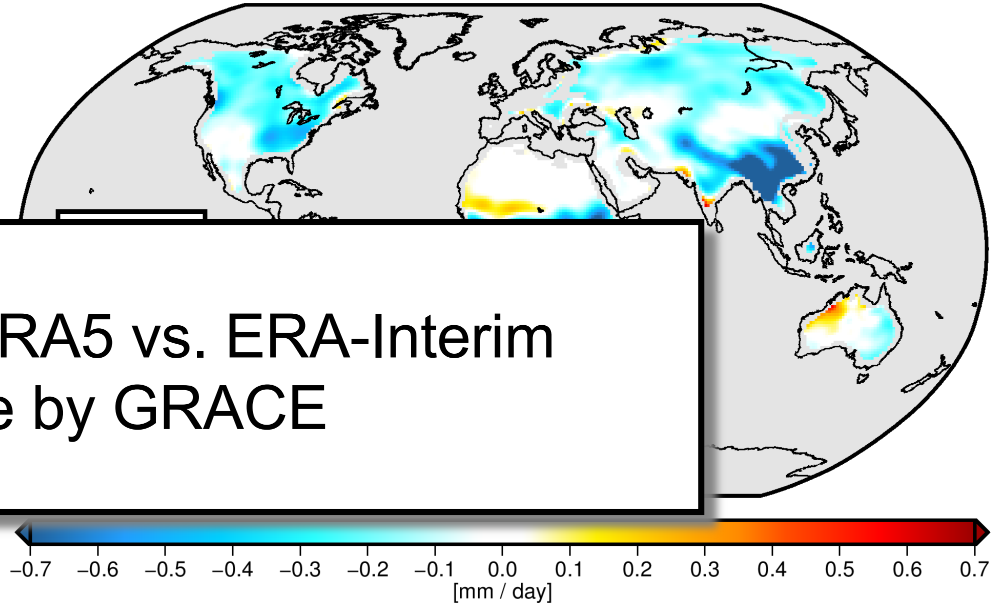
ERA5



ERA-Int.





ERA5 better

ERA-Int. better

Quality improvement of ERA5 vs. ERA-Interim clearly detectable by GRACE

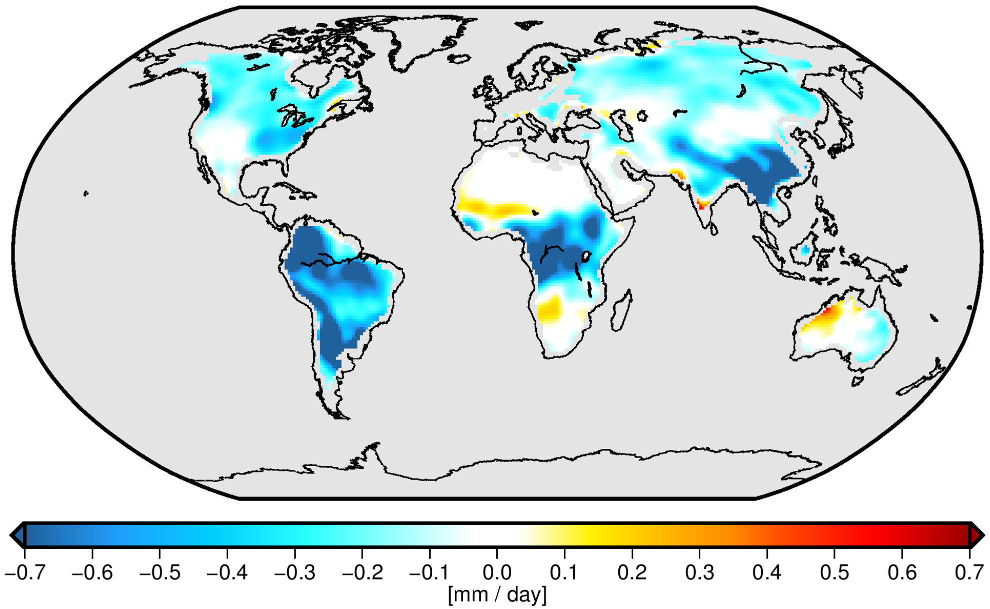
GRACE vs. GPCC

Improvement (RMSD) ERA5 vs. ERA-Interim

Are identified improvements reliable?

=> Compare to **GPCC rain gauge** evaluation of precipitation

GRACE



ERA5 better

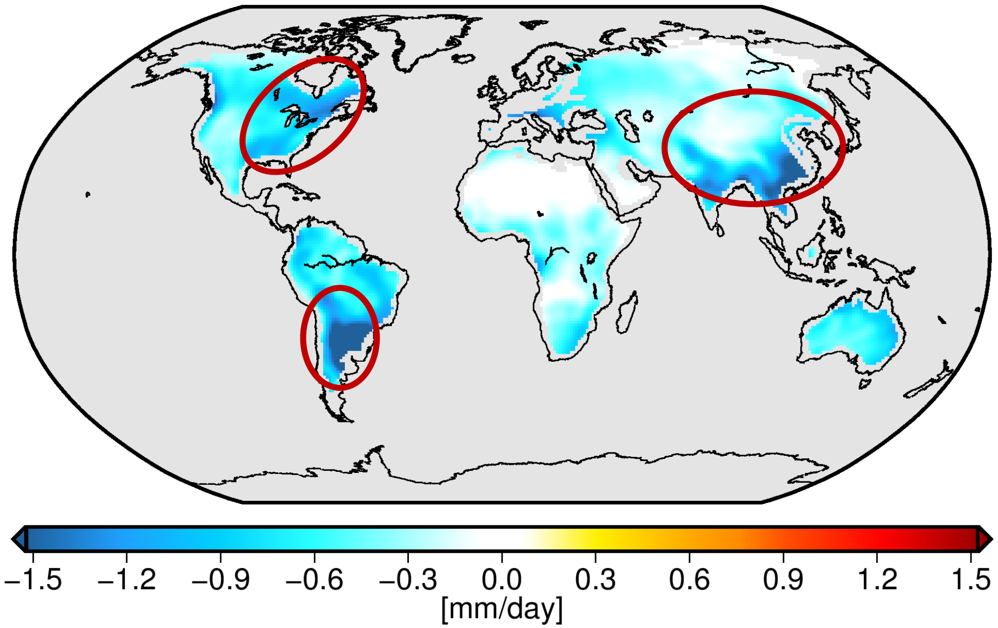
ERA-Int. better

dS/dt vs. P-E-R

GRACE vs. GPCC

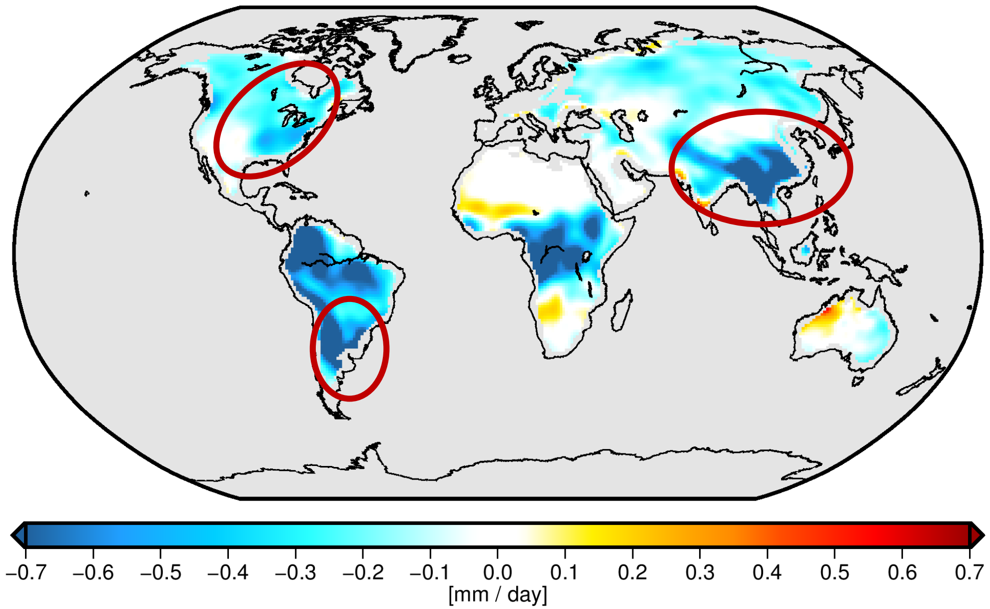
Improvement (RMSD) ERA5 vs. ERA-Interim

GPCC



precipitation only

GRACE



ERA5 better

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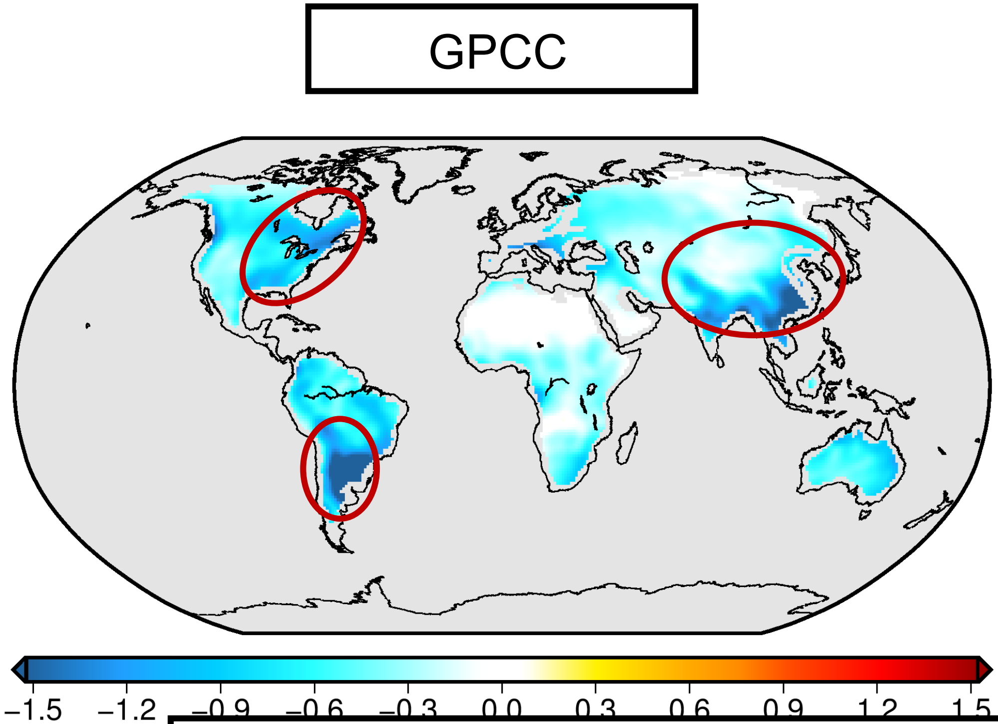
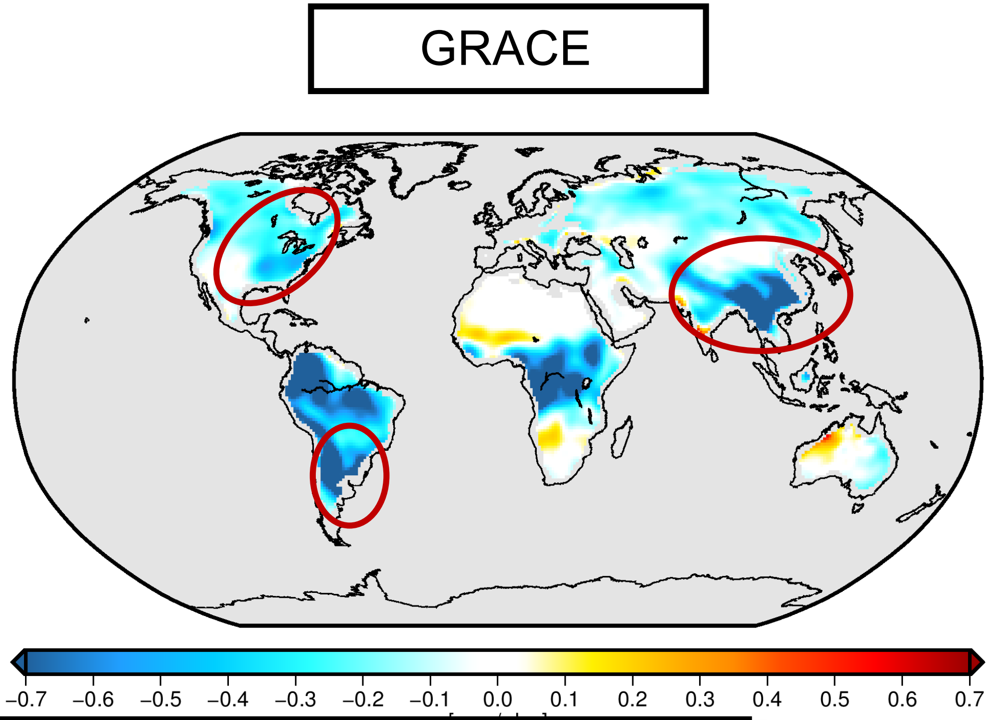
dS/dt vs. P-E-R

GRACE vs. GPCC

Improvement (RMSD) ERA5 vs. ERA-Interim



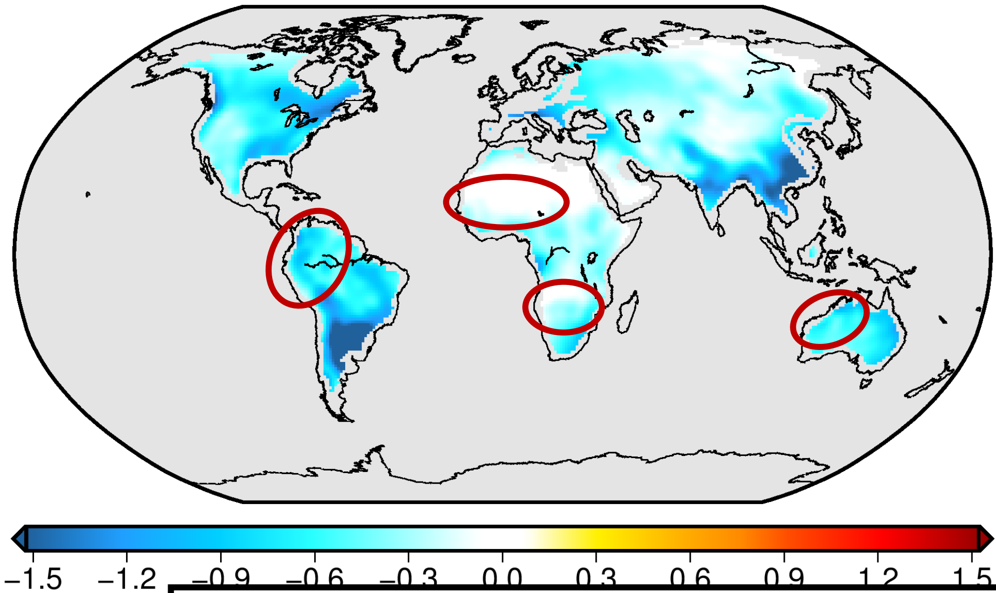


GRACE largely confirms regions of improvement identified by GPCC…

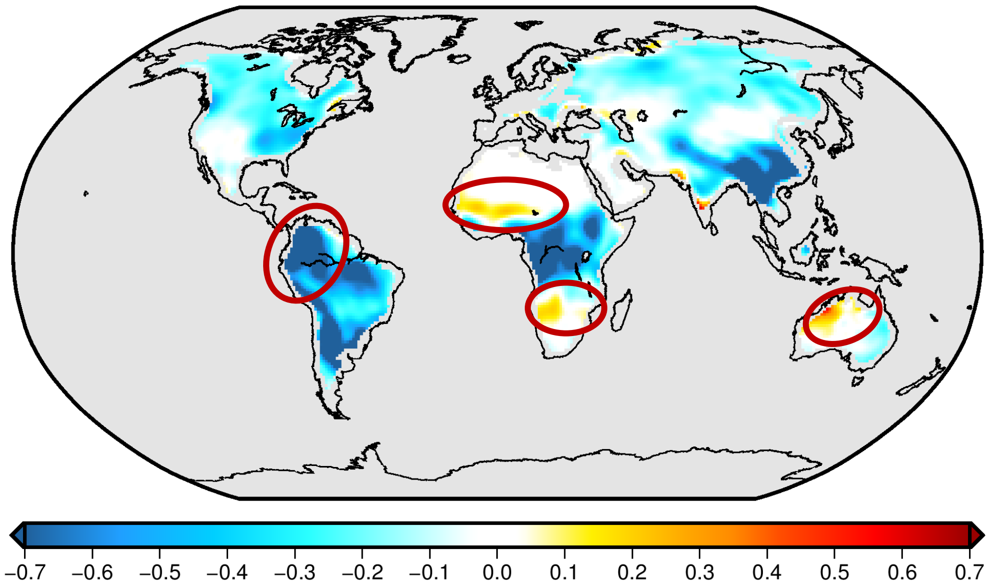
GRACE vs. GPCC

Improvement (RMSD) ERA5 vs. ERA-Interim

GPCC



GRACE



A-Int. better

GRACE largely confirms regions of improvement identified by GPCC…

… but also identifies a few differences => info about other fluxes?

Time scales

long

temporal scales

short

climate trends (centuries)
- climate model evaluation

present-day trends (decades)
- sea level, ice mass, ...

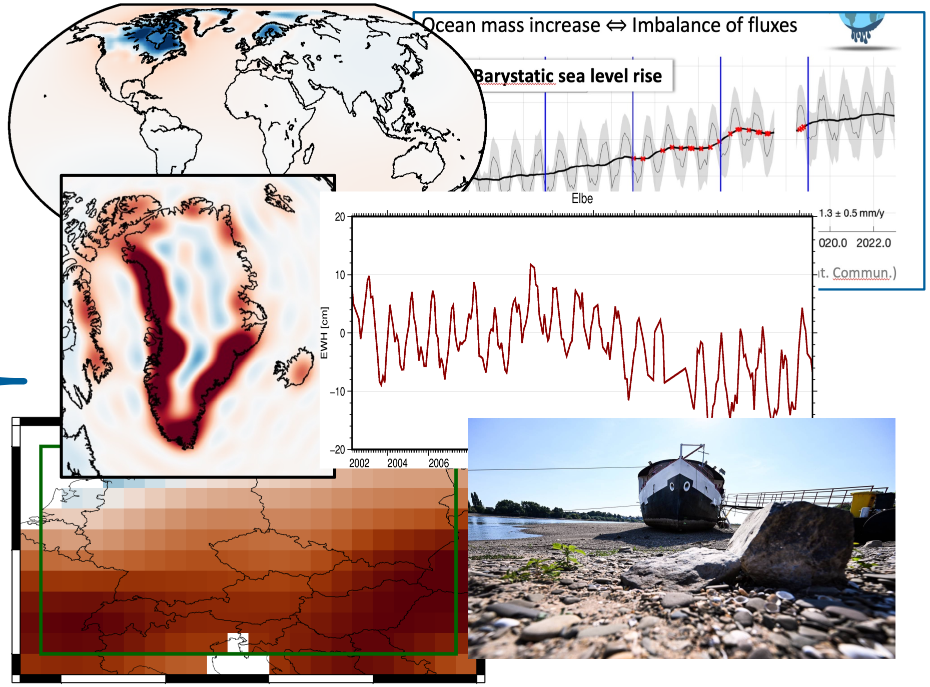
inter-annual variations
- ENSO, droughts, ...

seasonal changes (months)

weeks to month
- floods, ...

short-term changes (days)
- hydro-meteorological fluxes

A crazy idea?



Pushing the limits!

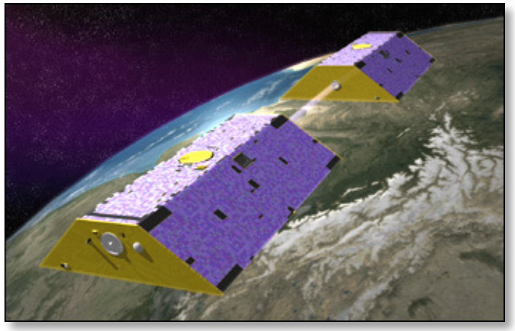
Introduction

hcu HafenCity Universität Hamburg

Global couple climate models

Coupled Model Intercomparison Project

Satellite gravimetry

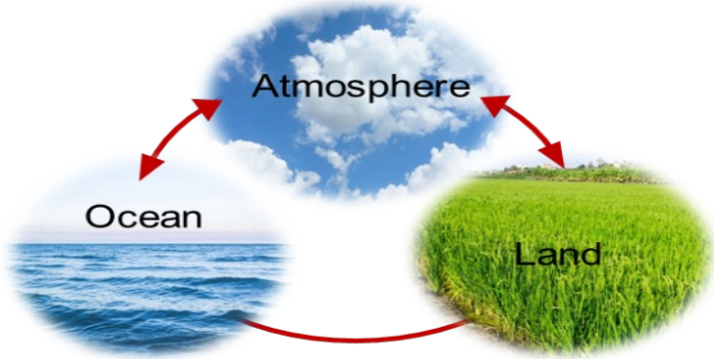


GRACE
GRACE-FO
…

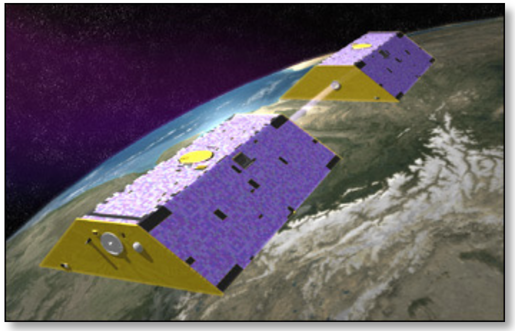
=> Use satellite gravimetry to evaluate climate models*

* regarding **land water-storage** related variables

Global couple climate models



Satellite gravimetry

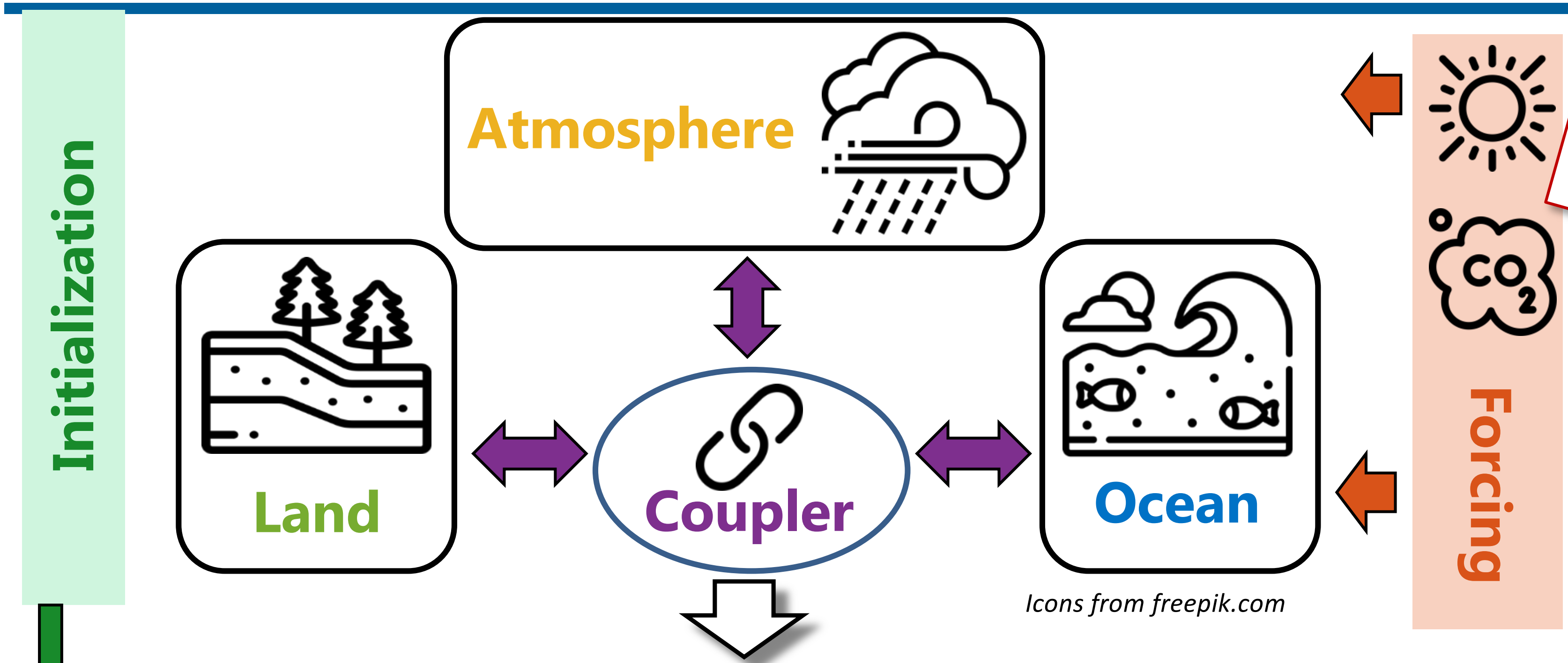


GRACE
GRACE-FO
…

=> Use satellite gravimetry to evaluate climate models*

* regarding **land water-storage** related variables

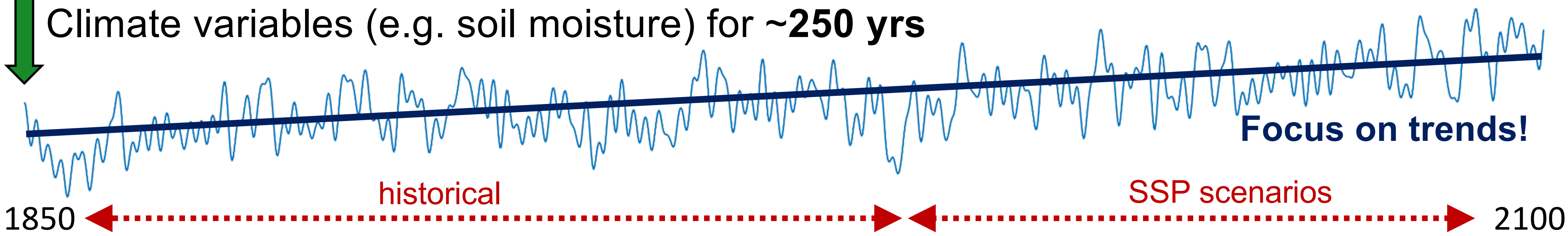
Coupled climate models



No other observations (precipitation, temperature,...)!

- sun’s energy
- greenhouse gas (GHG) concentrations
- aerosols
- land use change

Climate variables (e.g. soil moisture) for **~250 yrs**

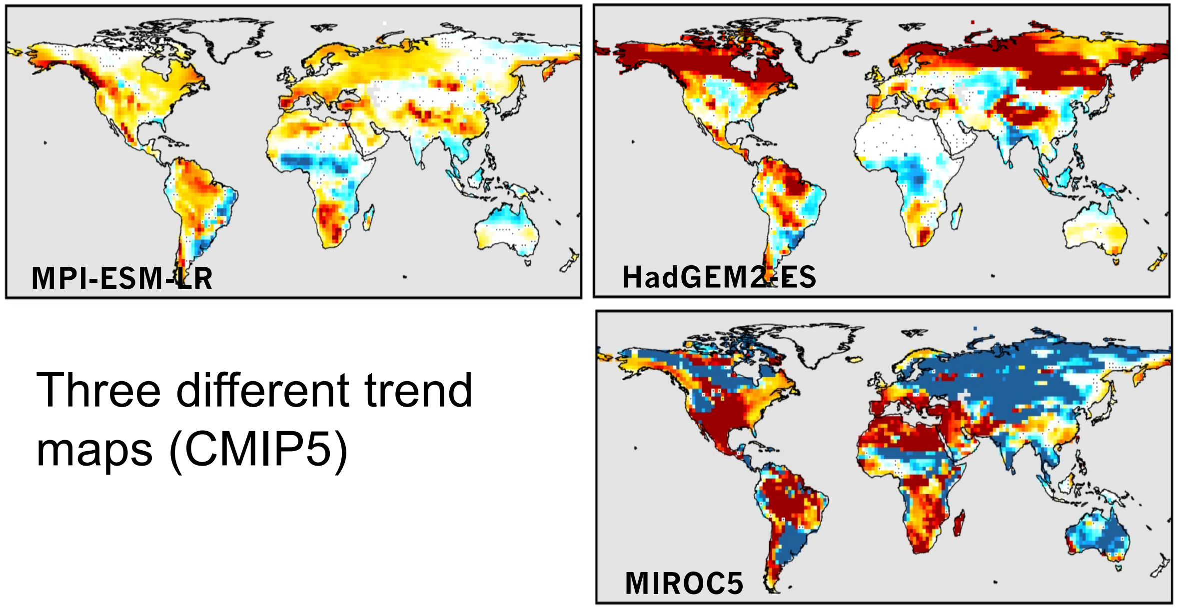


Assessment of trends

Initialization

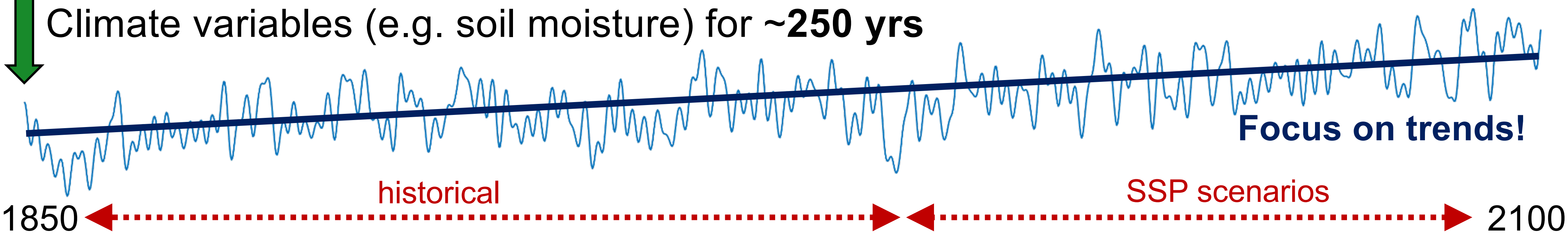
Challenges:

- Large uncertainty among models



Three different trend maps (CMIP5)

Climate variables (e.g. soil moisture) for **~250 yrs**



Assessment of trends

Initialization

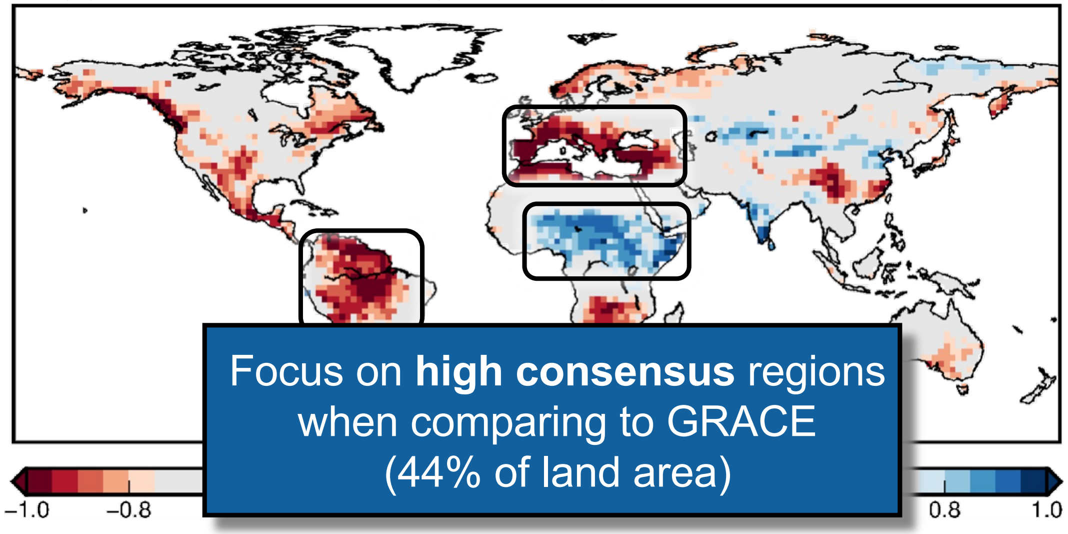
Challenges:

- Large uncertainty among models

Where do models agree on the (sign of) the trend?

=> „model consensus“

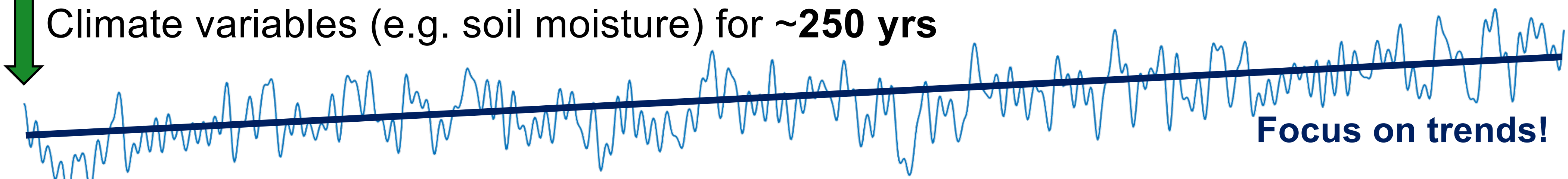
CMIP6 (17 models)



Focus on **high consensus** regions when comparing to GRACE (44% of land area)

fraction of models agreeing on sign of trend

Climate variables (e.g. soil moisture) for **~250 yrs**



historical | SSP scenarios

1850 ← → 2100

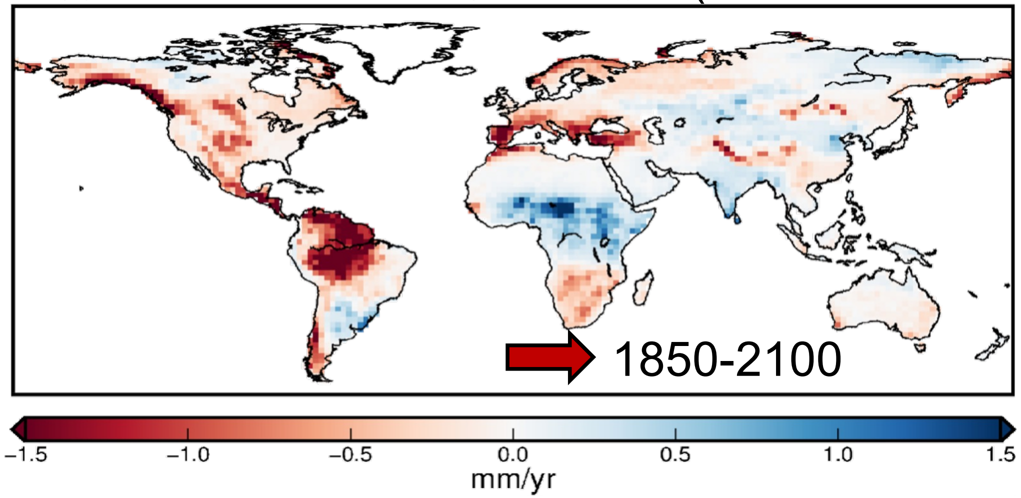
Assessment of trends

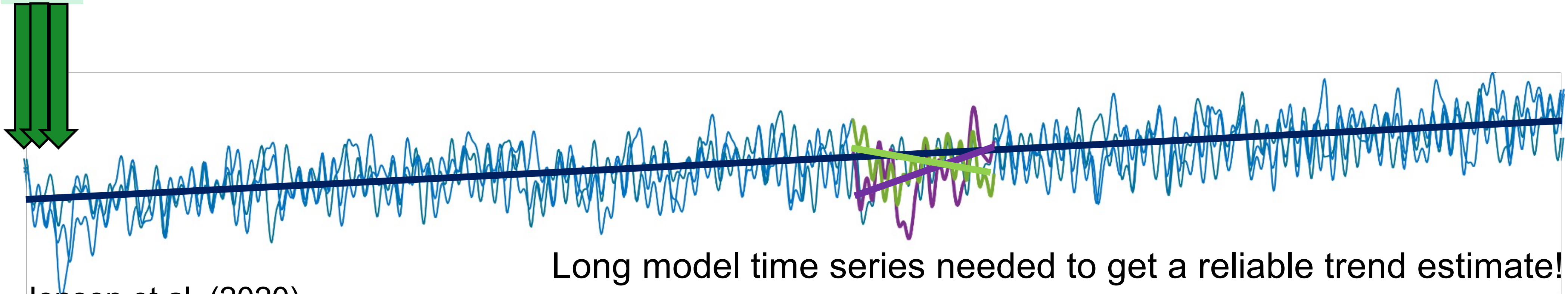
Initialization

Challenges:

- Large uncertainty among models
- Inter-annual variations are stochastic

CMIP6 trend (model median)





Long model time series needed to get a reliable trend estimate!

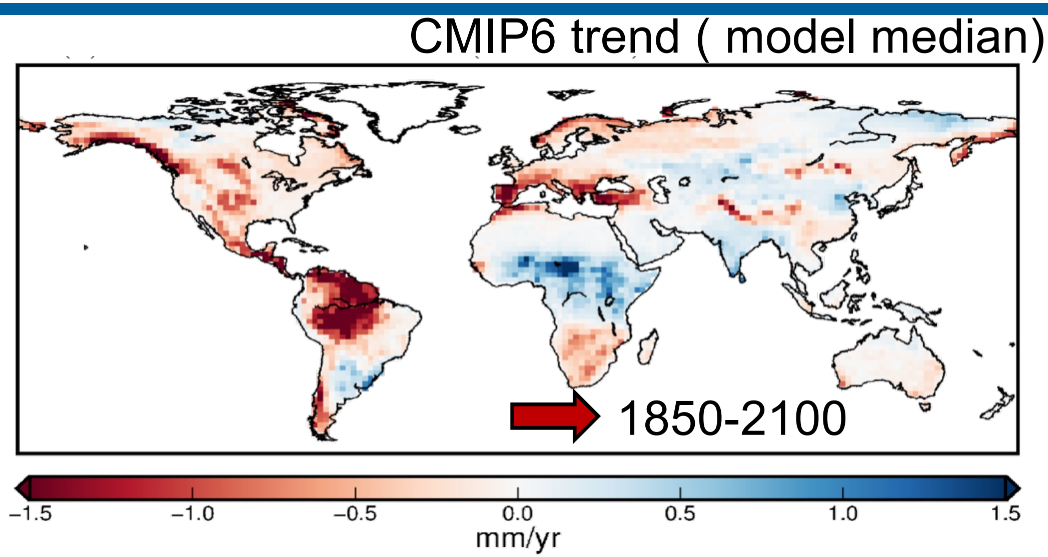
Jensen et al. (2020)

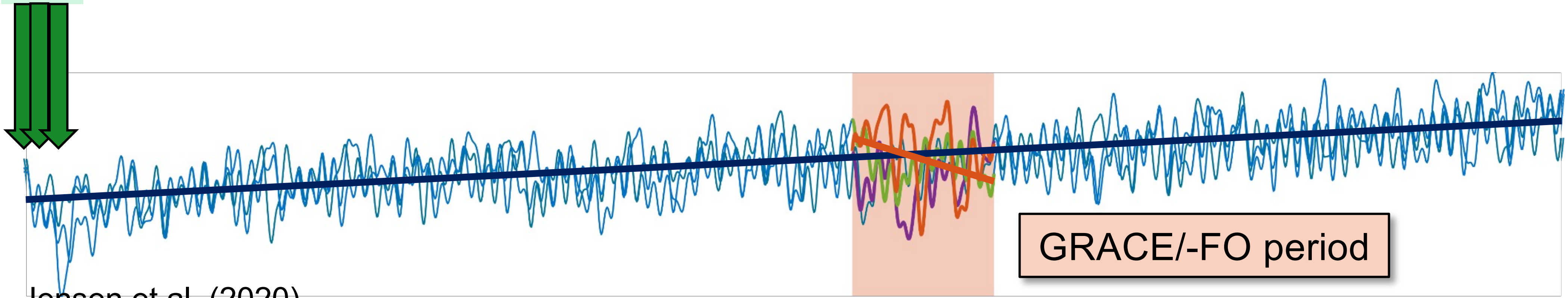
Assessment of trends

Initialization

Challenges:

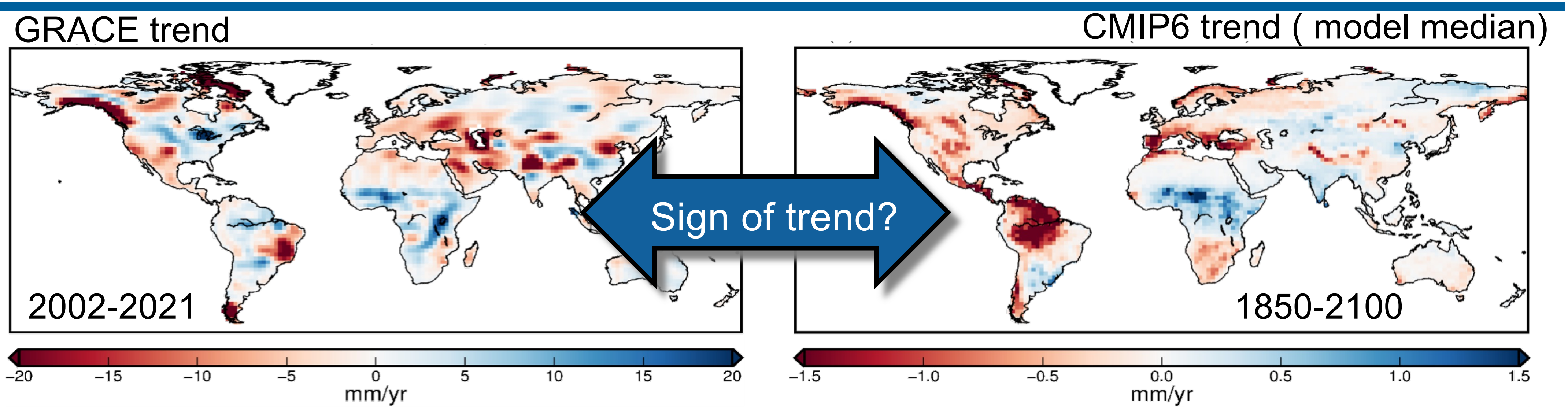
- Large uncertainty among models
- Inter-annual variations are stochastic

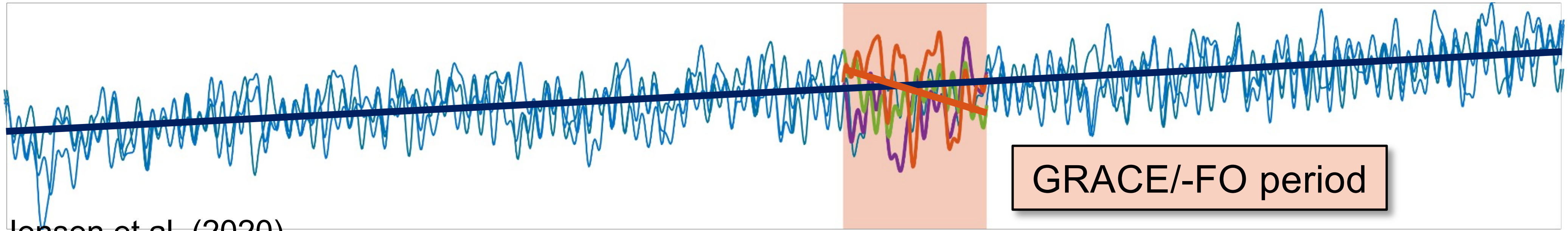




Jensen et al. (2020)

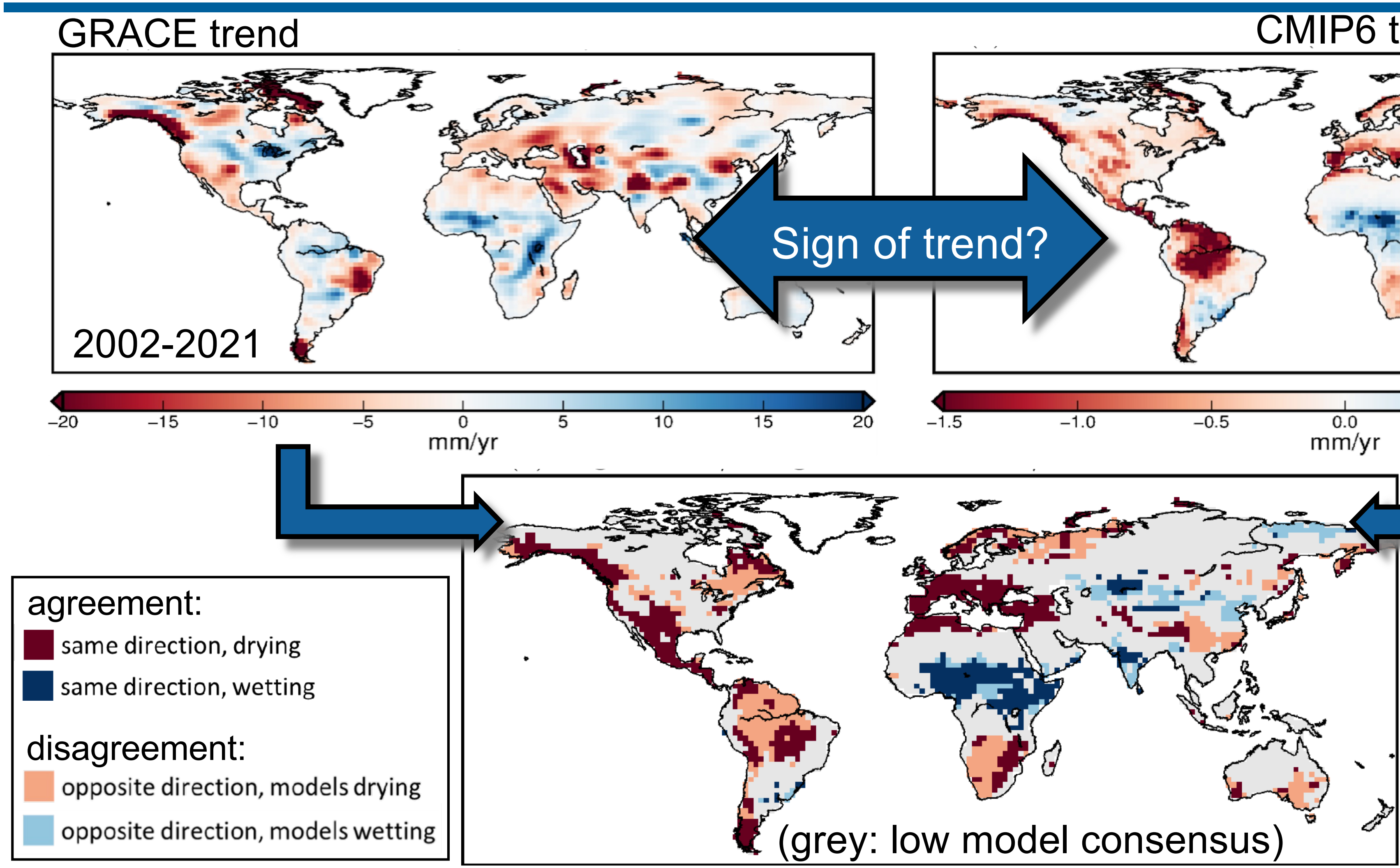
Assessment of trends: CMIP vs. GRACE





Jensen et al. (2020)

Assessment of trends: CMIP vs. GRACE

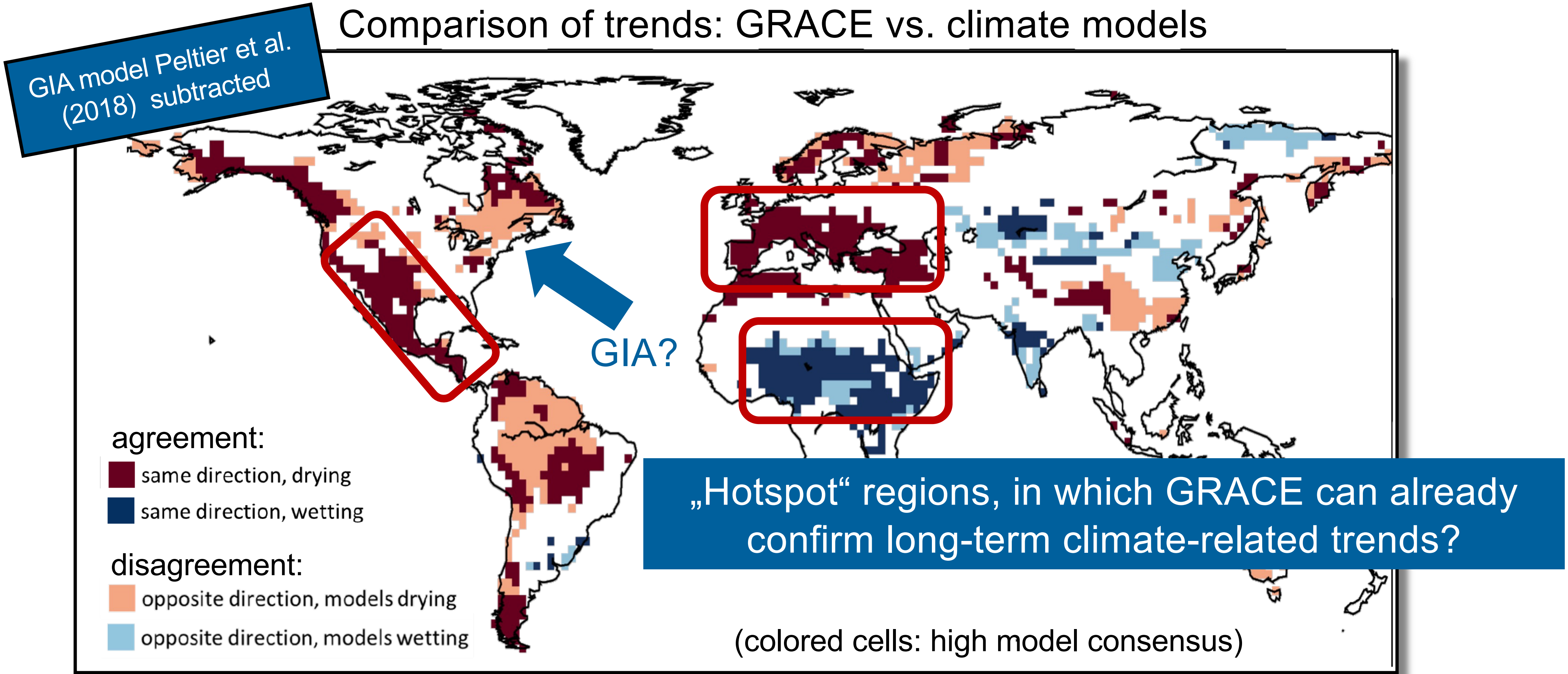


(Only regions of high model consensus!)

(Dis-)Agreement CMIP6/GravIS

Assessment of trends

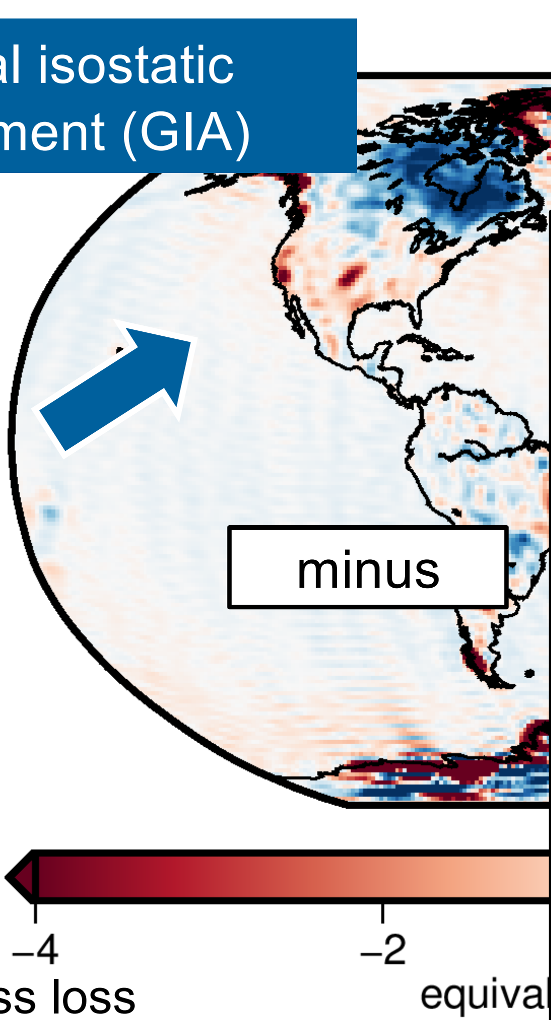
Comparison of trends: GRACE vs. climate models



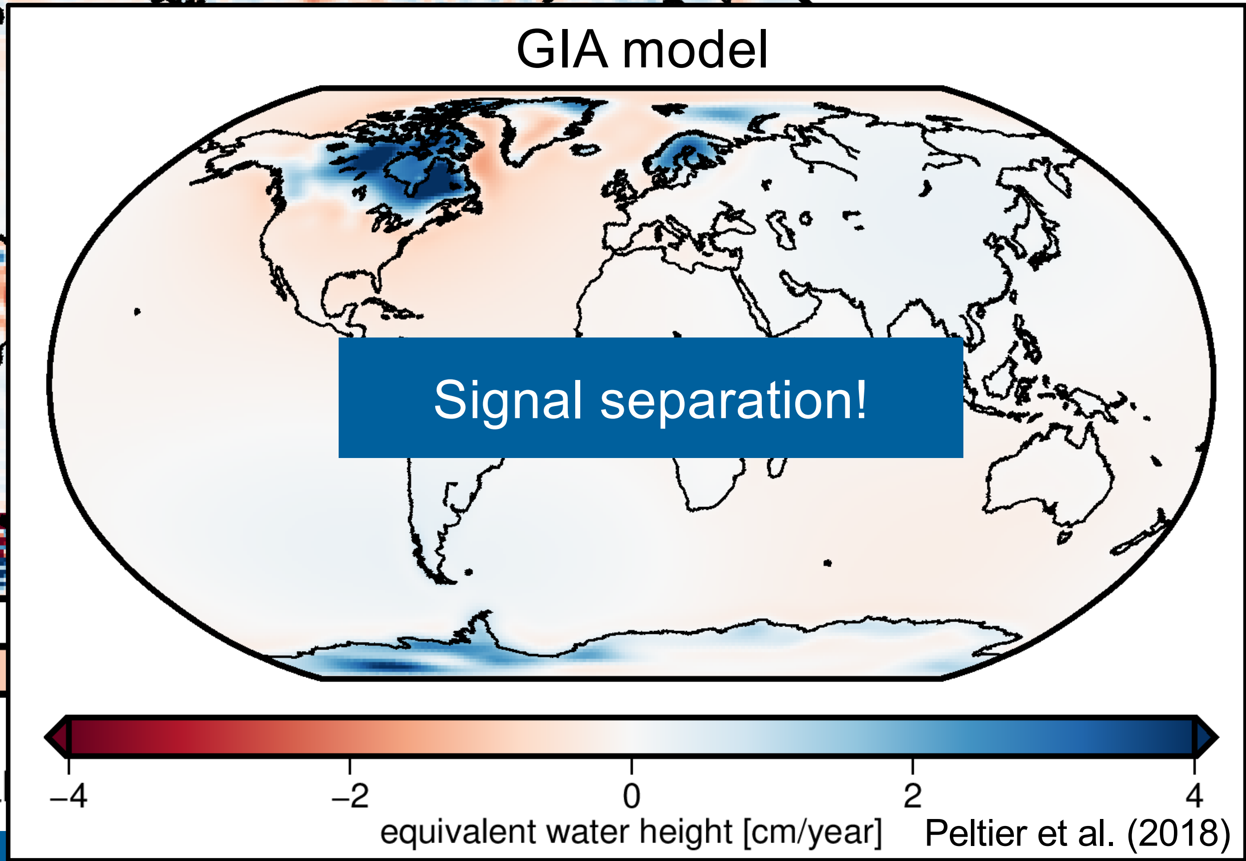
(Eicker et al. in preparation)

Long-term trend

Glacial isostatic adjustment (GIA)



minus

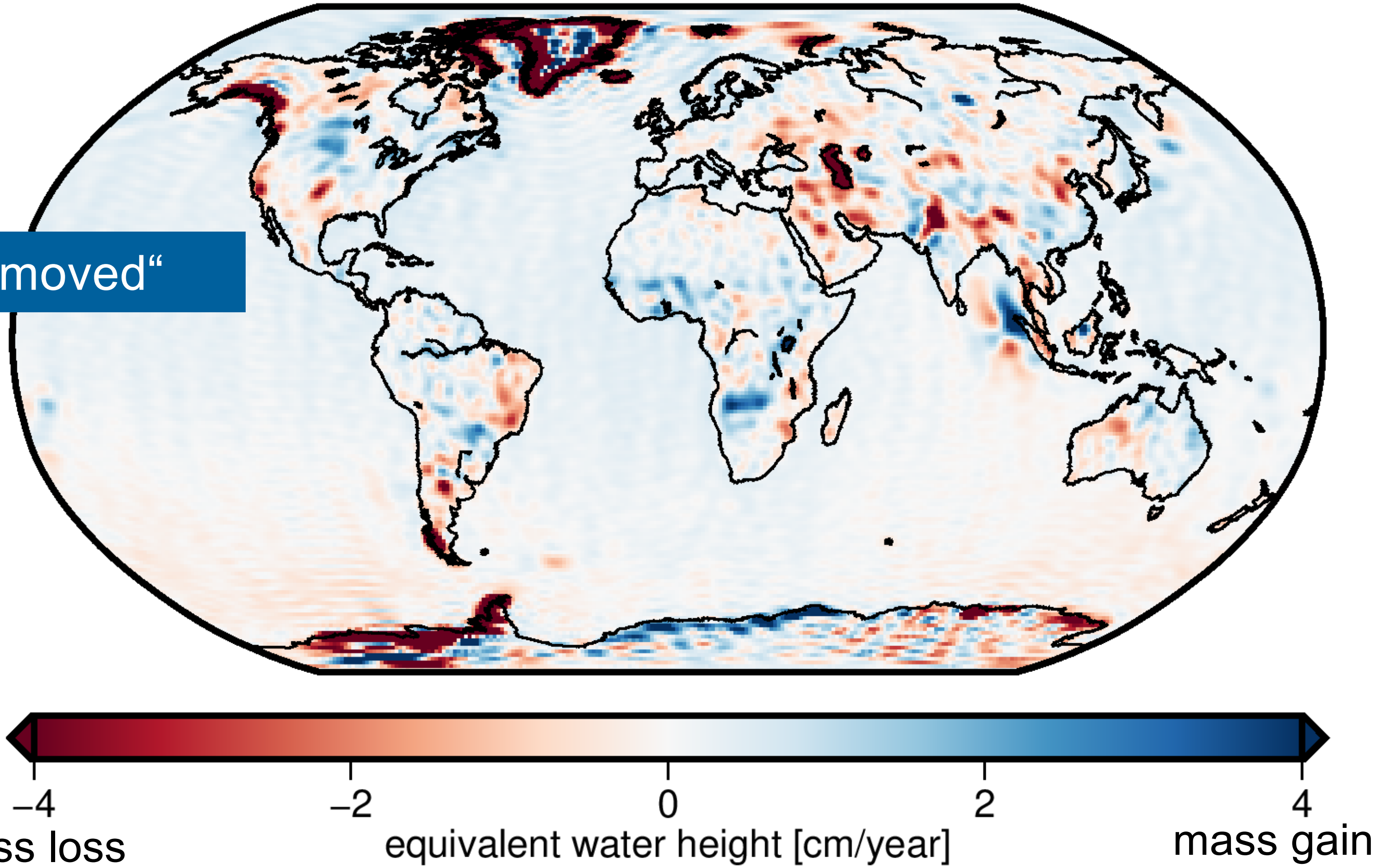


Signal separation!

Long-term trend

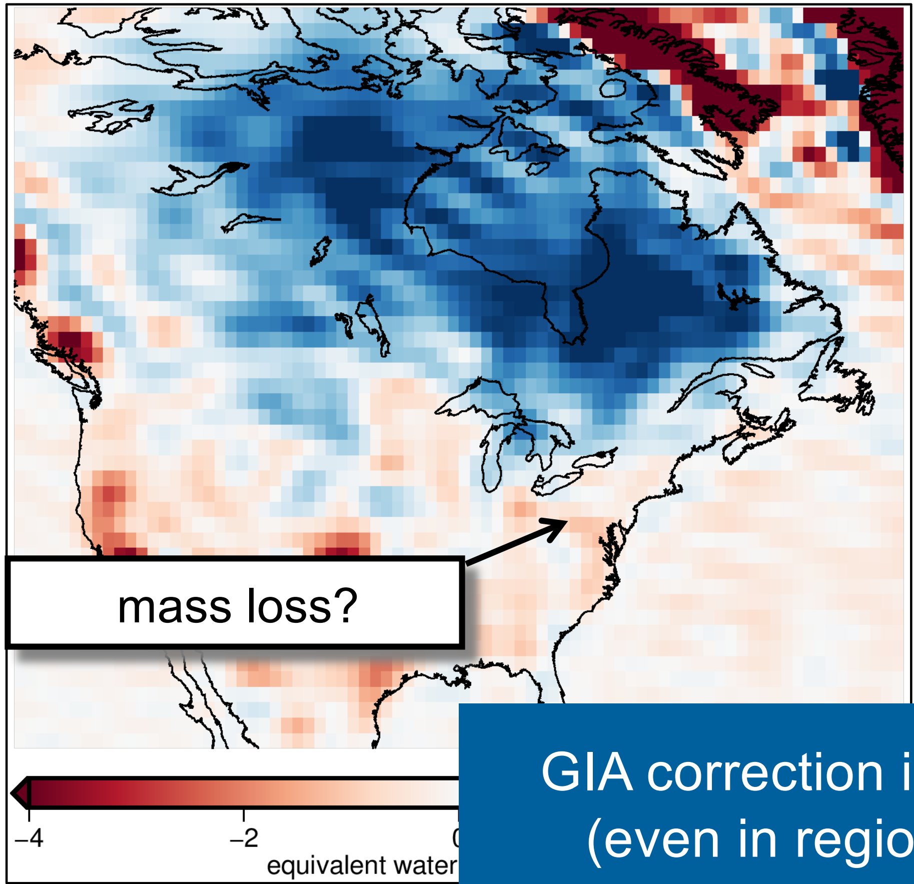
Linear trend

GIA „removed“

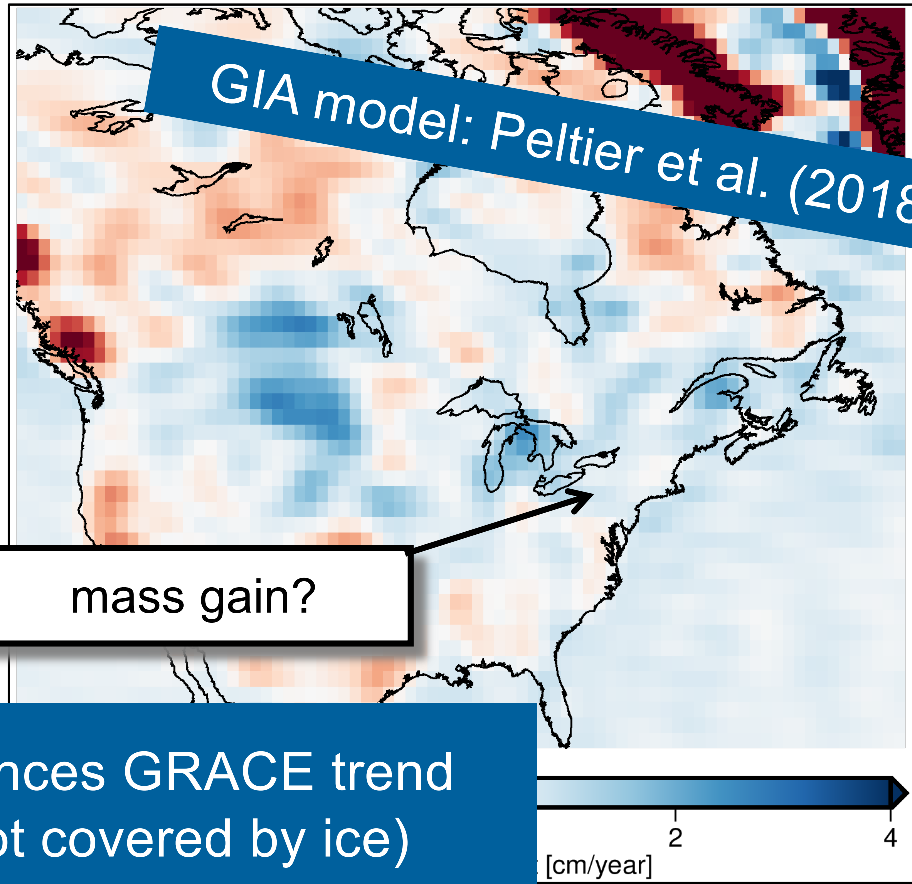


Long-term trend

with GIA



without GIA



GIA correction influences GRACE trend
(even in regions not covered by ice)

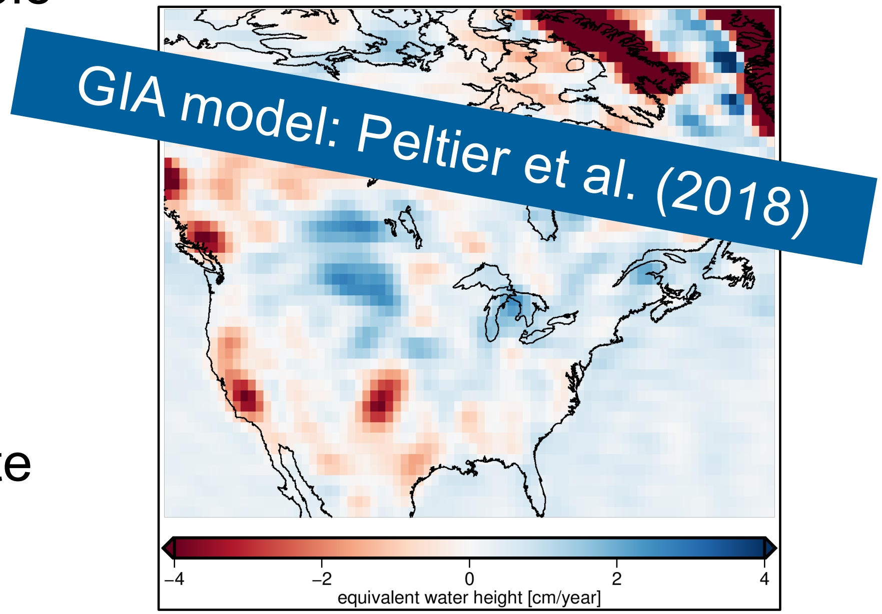
Long-term trend

1. Simulate **GIA uncertainty** using an ensemble of 52 GIA models (Bagge et al. 2021)
   - different ice histories
   - different mantle viscosity profiles

2. Investigate influence on **GRACE trend**

=> Importance for, e.g. using GRACE for climate model evaluation.

without GIA



GIA correction influences GRACE trend
(even in regions not covered by ice)

(Eicker et al. 2024)

Influence of GIA ensemble on TWS trend

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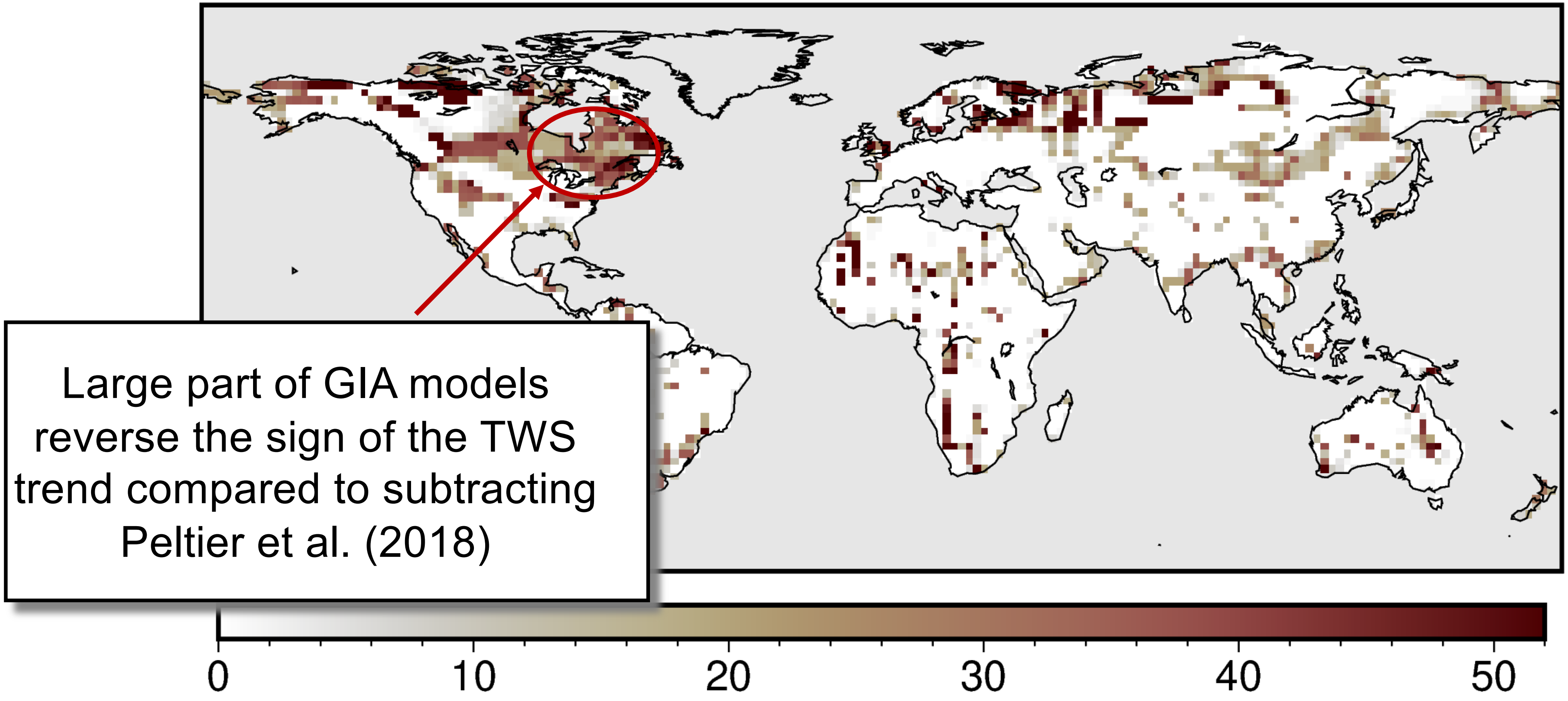

(Eicker et al. 2024)

Assessment of trends

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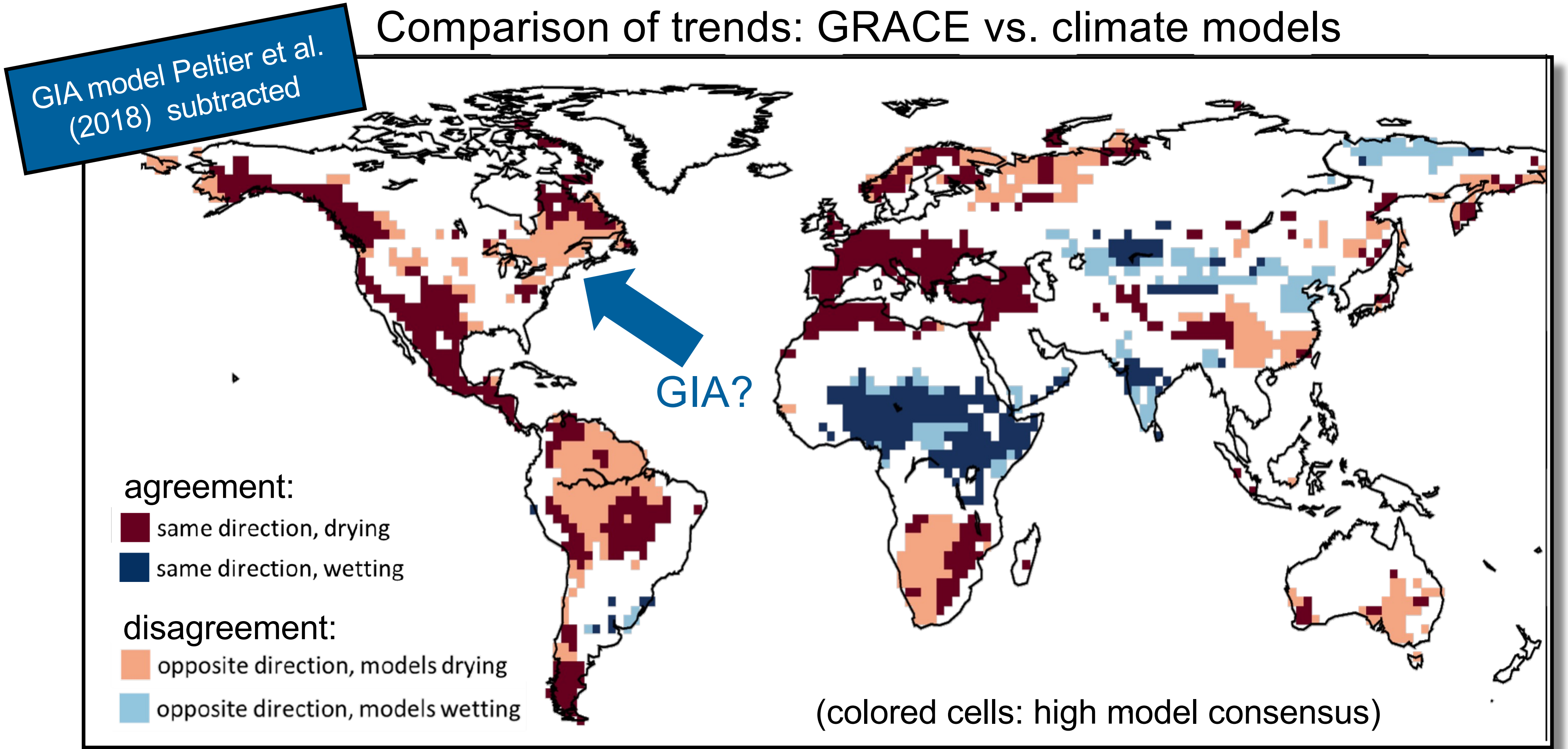
Comparison of trends: GRACE vs. climate models

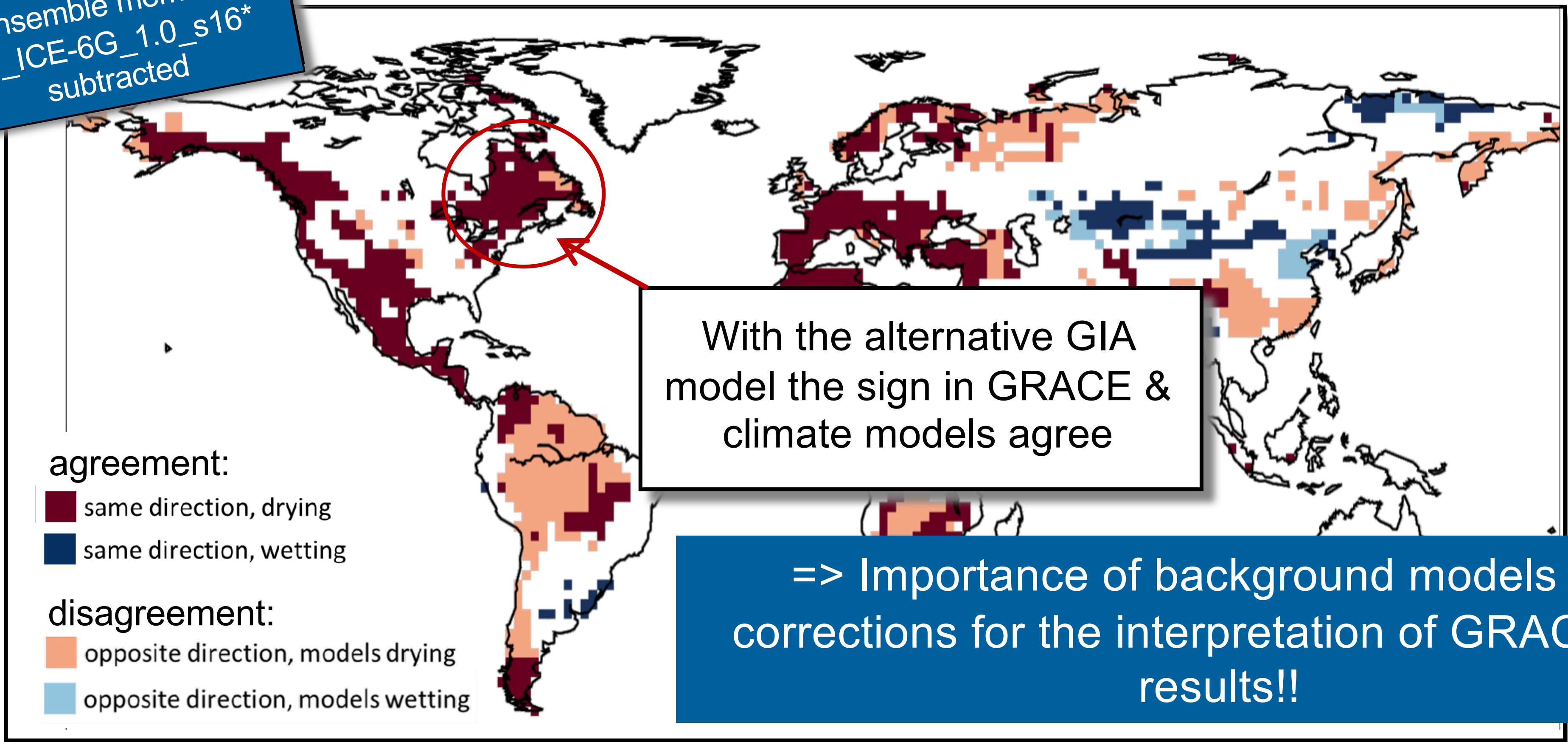


(Eicker et al. in preparation)

Assessment of trends

Ensemble member 3D_ICE-6G_1.0_s16* subtracted

Comparison of trends: GRACE vs. climate models



With the alternative GIA model the sign in GRACE & climate models agree

=> Importance of background models and corrections for the interpretation of GRACE/-FO results!!

* GIA model 3D_ICE-6G_1.0_s16 showed very good agreement with observed uplift rates

(Eicker et al. 2024)

Climate change

Satellite gravimetry: an excellent tool for water cycle and climate monitoring.

- sensitive to water storage change under the Earth's surface
  - groundwater monitoring
  - potential for flood and drought early warning
- directly measures mass change
  - no ice density required, seperation of sea level components,…

Challenges:

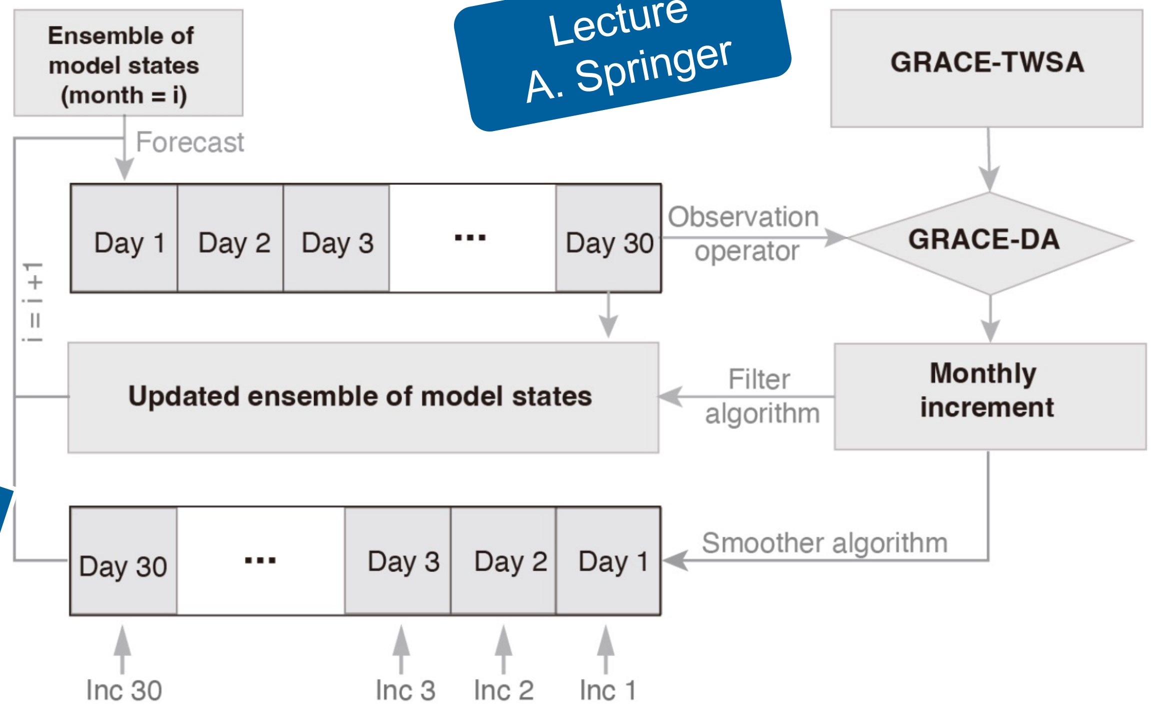
- signal separation
- spatial resolution, leakage
- time series still rather short for climate studies

Looking forward to GRACE-C

Climate change

Data assimilation

Lecture A. Springer



Challenges:

- signal separation
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Climate change

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Interested in more climate applications from GRACE/-FO (and other data)?

3. ICCC Workshop

Geodesy for Climate Research

March 24-25, 2025, online

https://iccc.iag-aig.org/iccc-workshops/ws25