Assessing Spatial and Temporal Variations in the Ocean Heat Content and Earth Energy Imbalance from Space Geodetic Data

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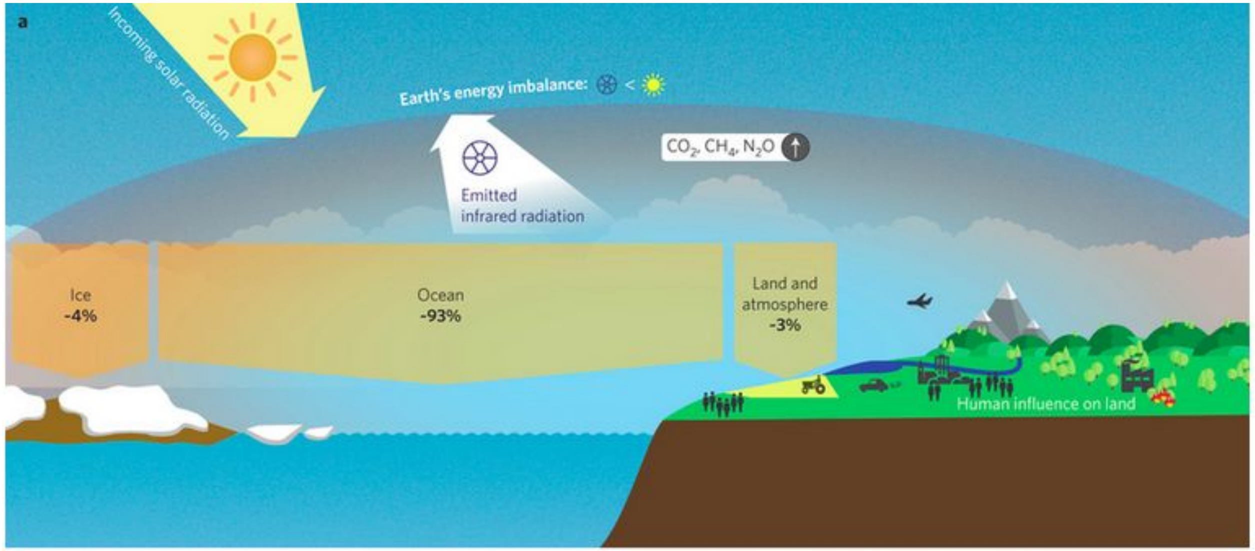
Earth energy imbalance

- ➔ The **Earth's energy imbalance (EEI)** is the difference between the amount of energy arriving from the sun at the top of the atmosphere and the amount of energy returned to space.
- ➔ Because of greenhouse gases emissions, there is a net positive EEI leading to the accumulation of heat in the climate system, mostly the ocean.
- ➔ Monitoring the EEI is essential to assess how our climate is changing in response to greenhouse emissions.
- ➔ Measuring the EEI is a challenge:
  - ◆ ~ 0.5-1 W/m^2 versus 340 W/m^2 of energy entering and leaving the top of the atmosphere



From von Schuckmann et al. 2016 NCLIM

Overview

→ 1) EEI estimates from the space geodetic approach

→ 2) Propagation of space geodetic uncertainties in the EEI estimate

→ 3) EEI uncertainties and contribution of barystatic sea level uncertainties

→ 4) Take home messages and recommendations

1) EEI estimates from the space geodetic approach

➔ Measuring the EEI is a **challenge**:

Climate science question	Accuracy in EEI measure at decadal scale (90% CL)	Accuracy in EEI trend (90% CL)
Assessing EEI variations and trend	**± 0.3 W/m²**	**± 0.1 W/m²/decade**
Enable the effect of Green House Gases reduction policies	**± 0.1 W/m²**	**-**

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➔ **Space geodetic approach** provides an indirect estimate of the **Earth Energy Imbalance (EEI)** by estimating changes in the **Ocean Heat Content (OHC)** based on the combination of space altimetry and gravimetry data, and in-situ T/S profiles (Meyssignac et al, 2019; Marti et al., 2022):

- Good spatial and temporal coverage of space geodetic data
- OHC estimates over full ocean depth
- Well-characterised uncertainties on the space geodetic data and propagation to the OHC and EEI

1) EEI estimates from the space geodetic approach

➔ Method is based on the **sea level budget equation:**

- $\Delta SL_{total} = \Delta SL_{mass} + \Delta SL_{thermosteric} + \Delta SL_{halosteric}$
- OHC change is derived from the thermosteric sea level change : $\Delta OHC = \frac{\Delta SL_{thermosteric}}{IEEH}$
- Global OHC change is the sum of local OHC change
- EEI is the time derivative of GOHC multiplied by the capacity of the ocean to absorb the excess of energy stored by the Earth system: $EEI \approx \frac{1}{\alpha} \frac{d\,GOHC}{dt}$

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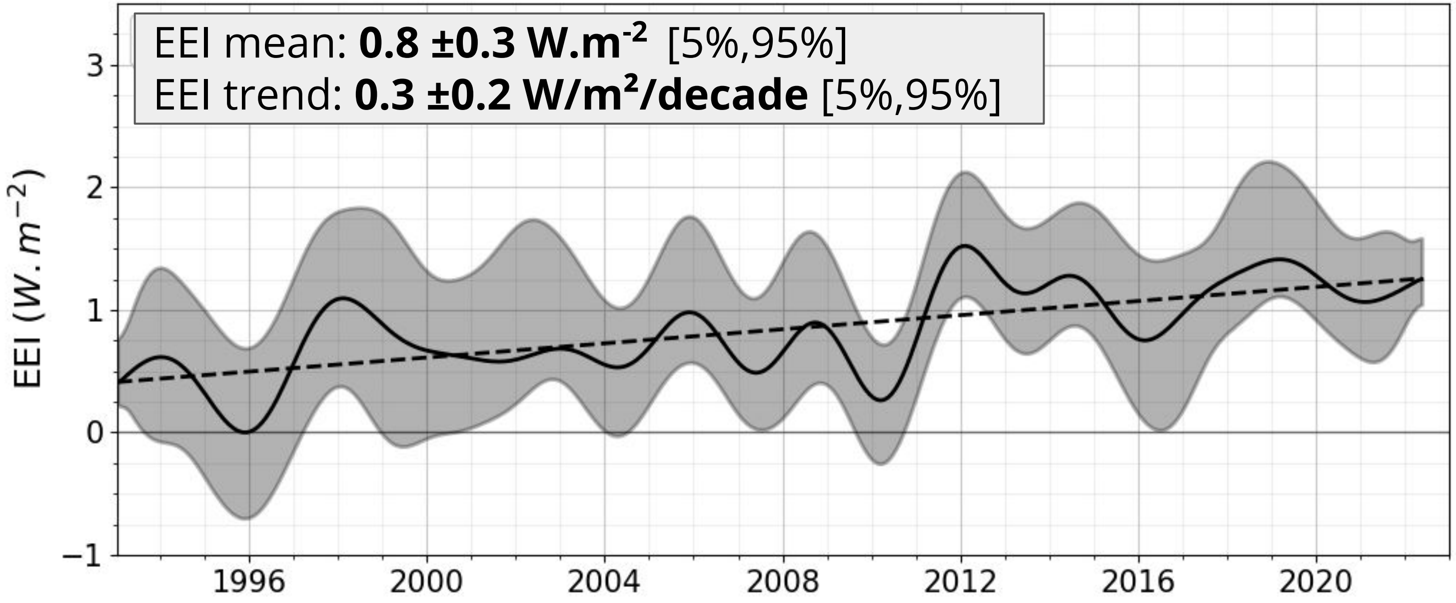
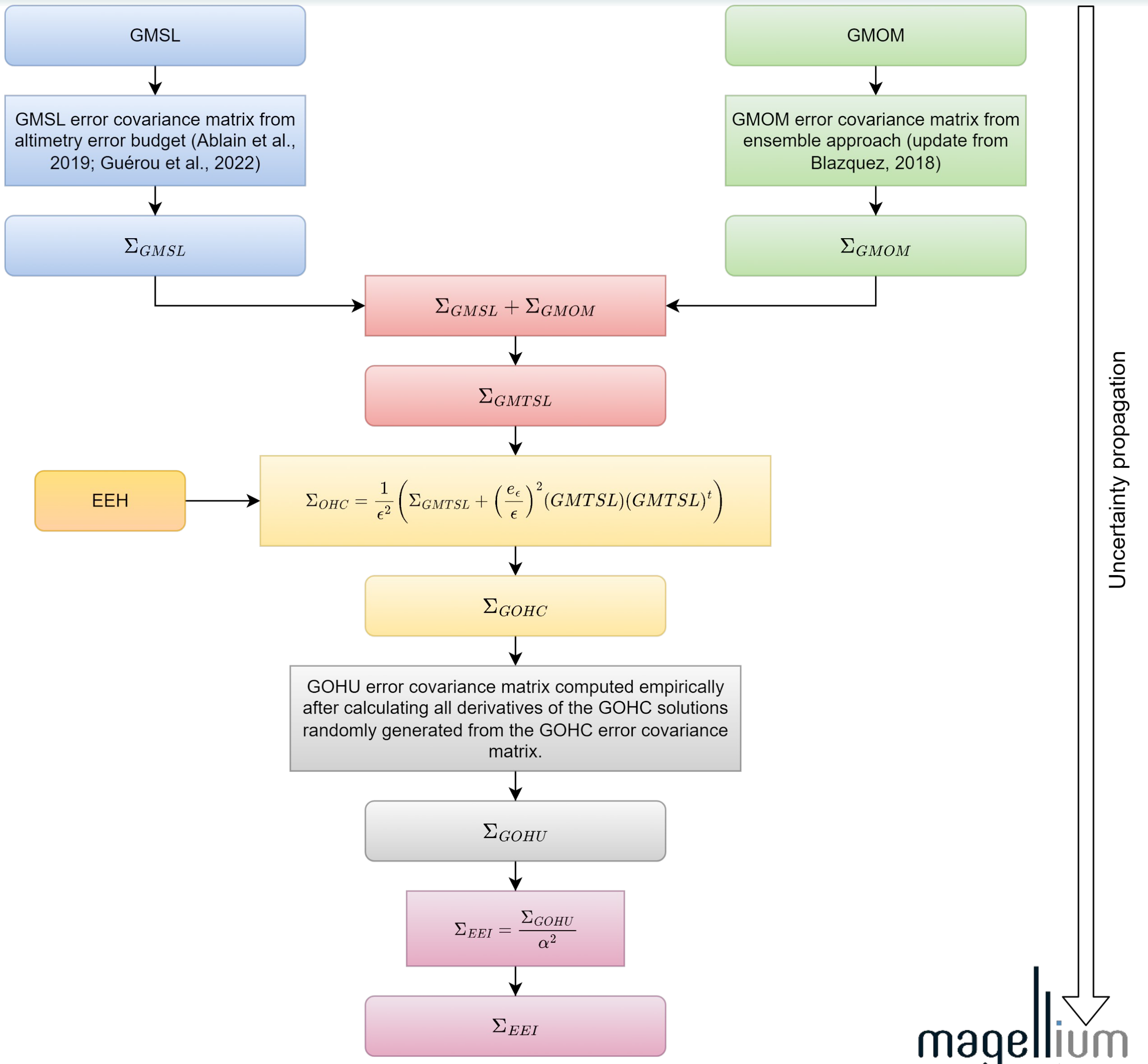


From Marti et al., 2024

2) Propagation of uncertainties in the EEI estimates

➔ Uncertainties are propagated from input data (space geodetic data, IEEH) until the GOHC change and EEI estimate by calculating and propagating error covariance matrices (∑)

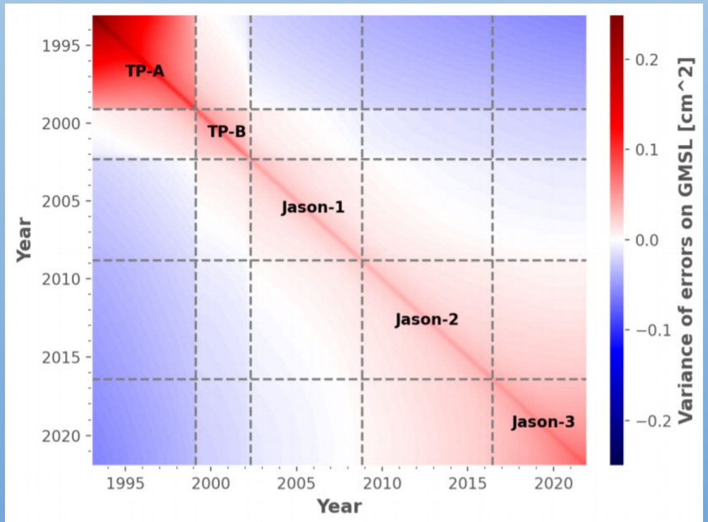


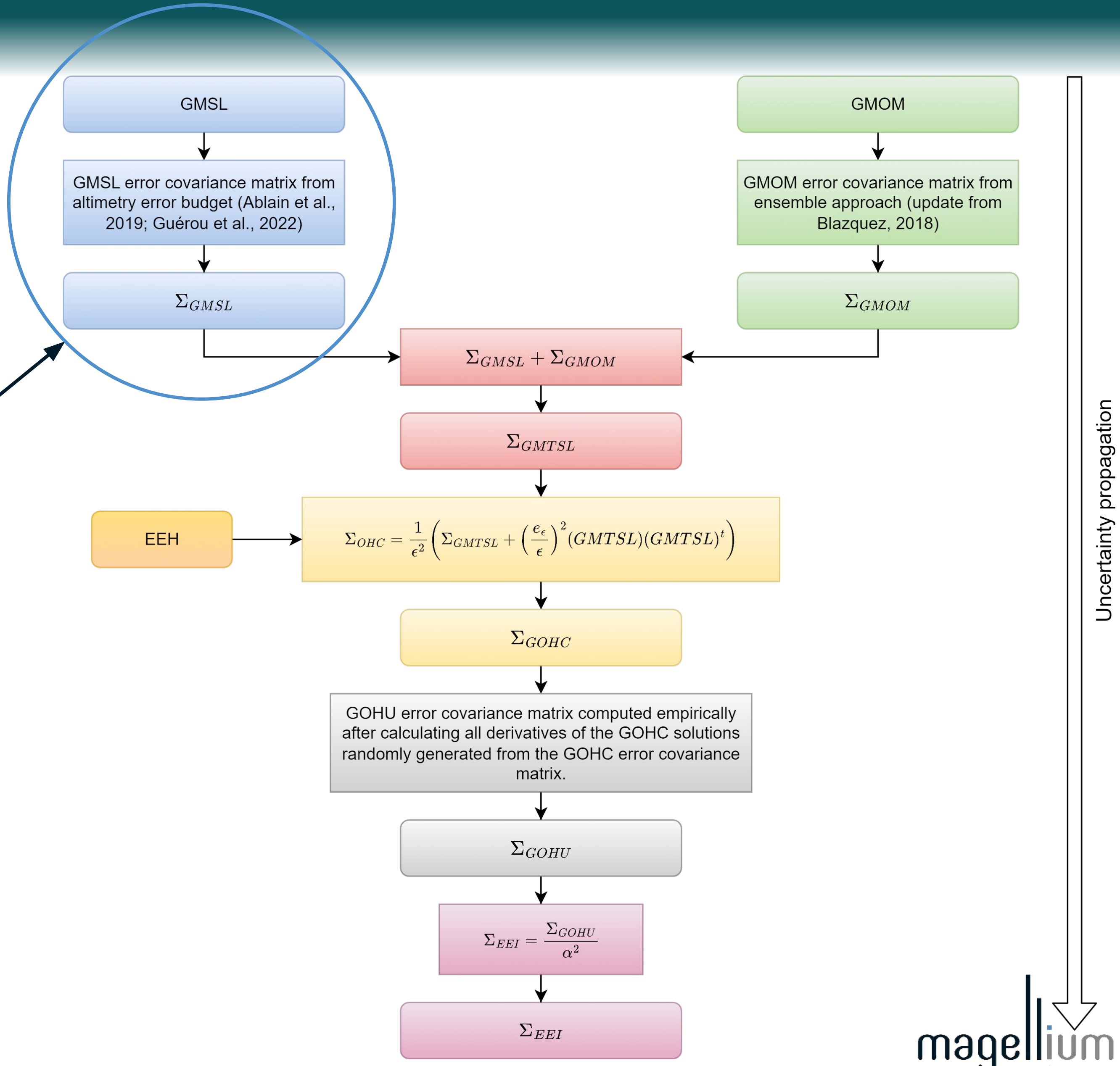
2) Propagation of uncertainties in the EEI estimates

Source of uncertainties		Type of uncertainties	uncertainties (1-sigma)
Short time-correlated errors due to POD, altimeter parameter, geophysical corrections		short time-correlated effects ($\lambda < 2$ months)	u_σ = 1.7 mm for T/P u_σ = 1.2 mm for T/P u_σ = 1.1 mm for JA2 u_σ = 1.0 mm for JA3
		short time-correlated effects (2 months $< \lambda <$ 1 months)	u_σ = 1.4 mm for T/P u_σ = 1.2 mm for JA1 u_σ = 1.1 mm for JA2 u_σ = 1.1 mm for JA3
Wet tropospheric correction stability		large time-correlated effects (λ=5 years)	u_σ = 1.1 mm (1.7 mm for JA3)
Precise orbit determination stability	ITRF	linear time-correlated effect	u_δ= 0.1 mm/yr
	gravity fields	with large time-correlated effects (λ=10 years)	u_σ = 0.5 mm ≥ 2002 (JAs) u_σ = 1.1 mm < 2002 (T/P)
Mean sea level offset estimate		jump	u_Δ =2.0 mm for TPA-TPB u_Δ < 0.3 mm for TPA-JA1, JA1-JA2, JA2-JA3
GIA correction		linear time-correlated effect	u_δ = 0.05 mm/yr
Altimeter parameters stability		linear time-correlated effect	u_δ = 0.7 mm/yr over TP-A u_δ = 0.1 mm/yr over TP-B

Ablain et al. (2019), Guérou et al. (2022) 4

Σ_{GMSL} =





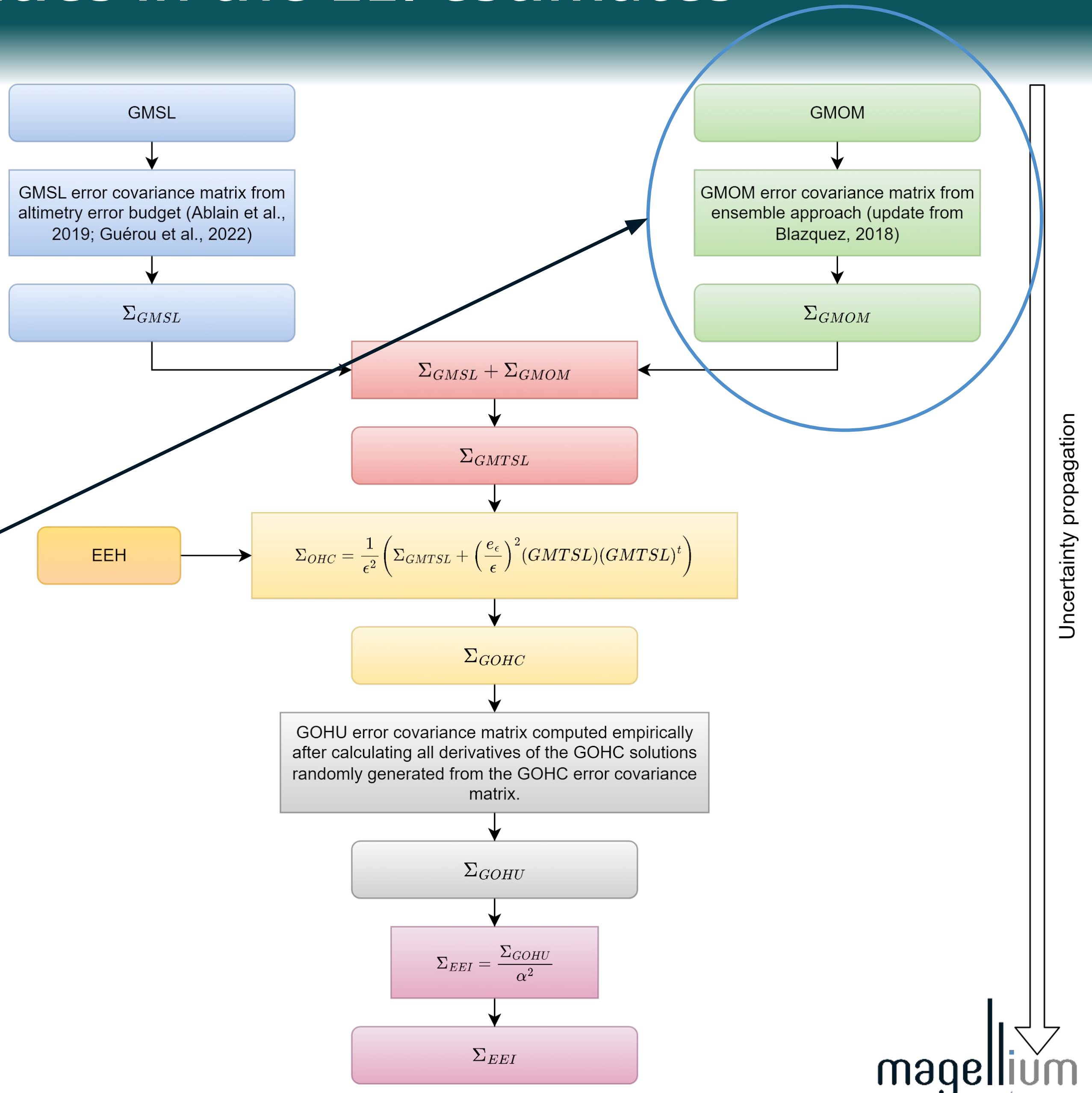
magellium artal group

2) Propagation of uncertainties in the EEI estimates

➔ For the barystatic sea level changes, the covariance matrix is calculated from an ensemble of solutions, including 5 processing centers and various post-processing corrections, based on Blazquez et al. (2018)

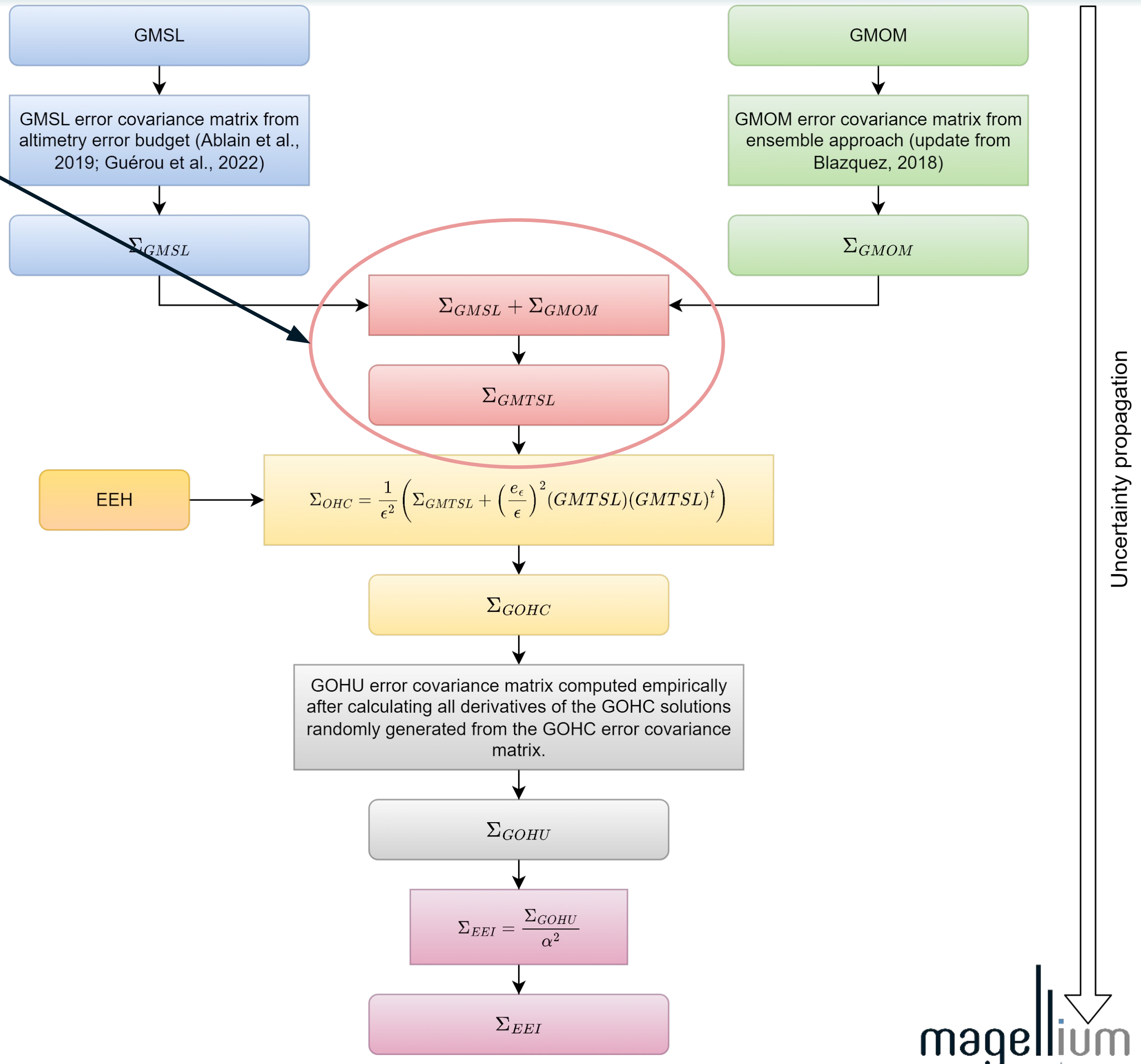
Error sources	mm/yr
Processing centers	0.02
geocenter motion	0.43
C20	0.01
filtering	0.01
GIA	0.15
Total	**0.45**

Barystatic uncertainty budget (Blazquez et al., 2018)



2) Propagation of uncertainties in the EEI estimates

→ Covariance matrix of global mean thermostric is the sum of GMSL and GMOM covariance matrices : errors are assumed independent.



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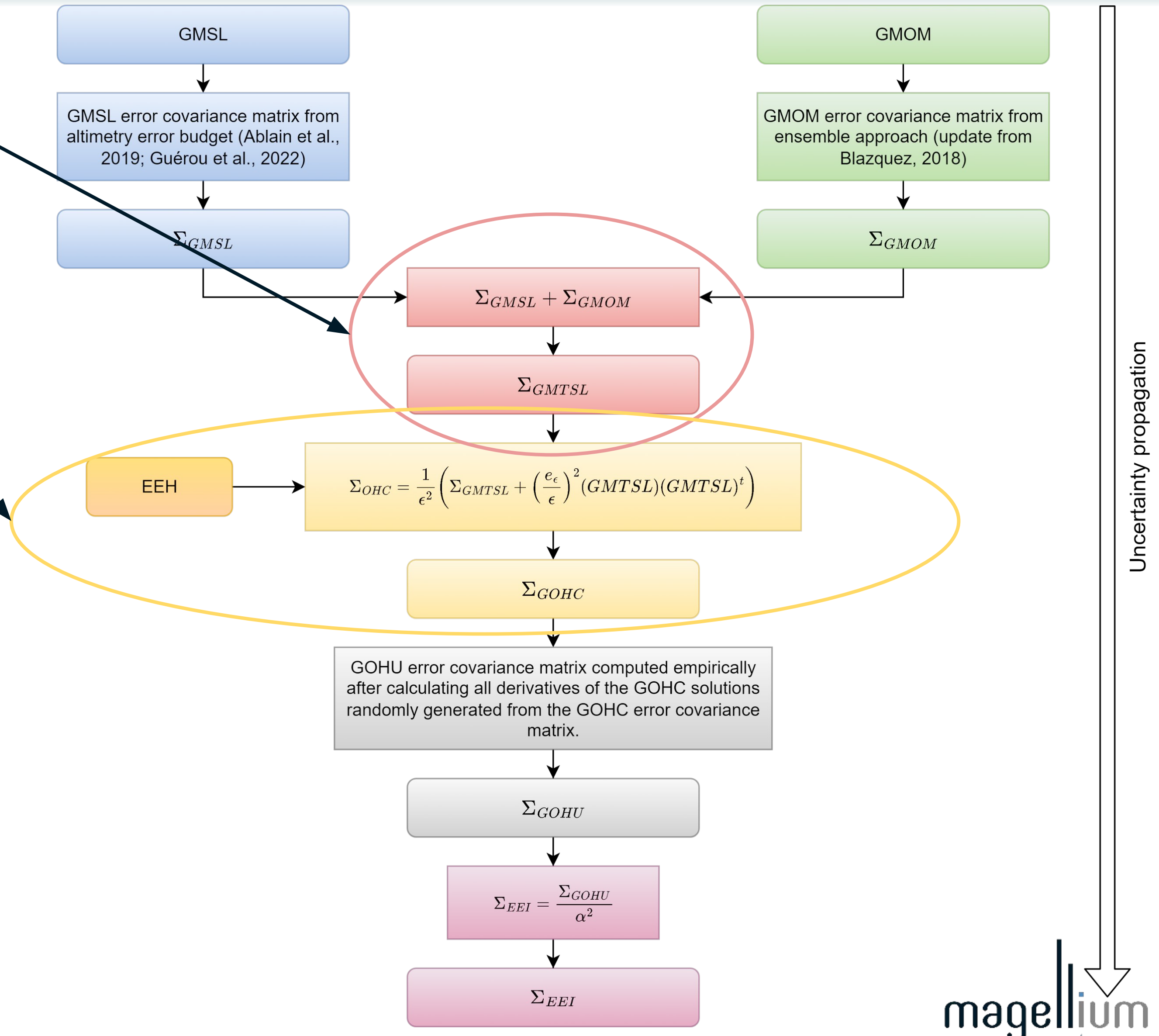
➔ Covariance matrix of global mean thermostric is the sum of GMSL and GMOM covariance matrices : errors are assumed independent.

➔ Covariance matrix of global OHC takes into account additional uncertainty of the IEEH coefficient



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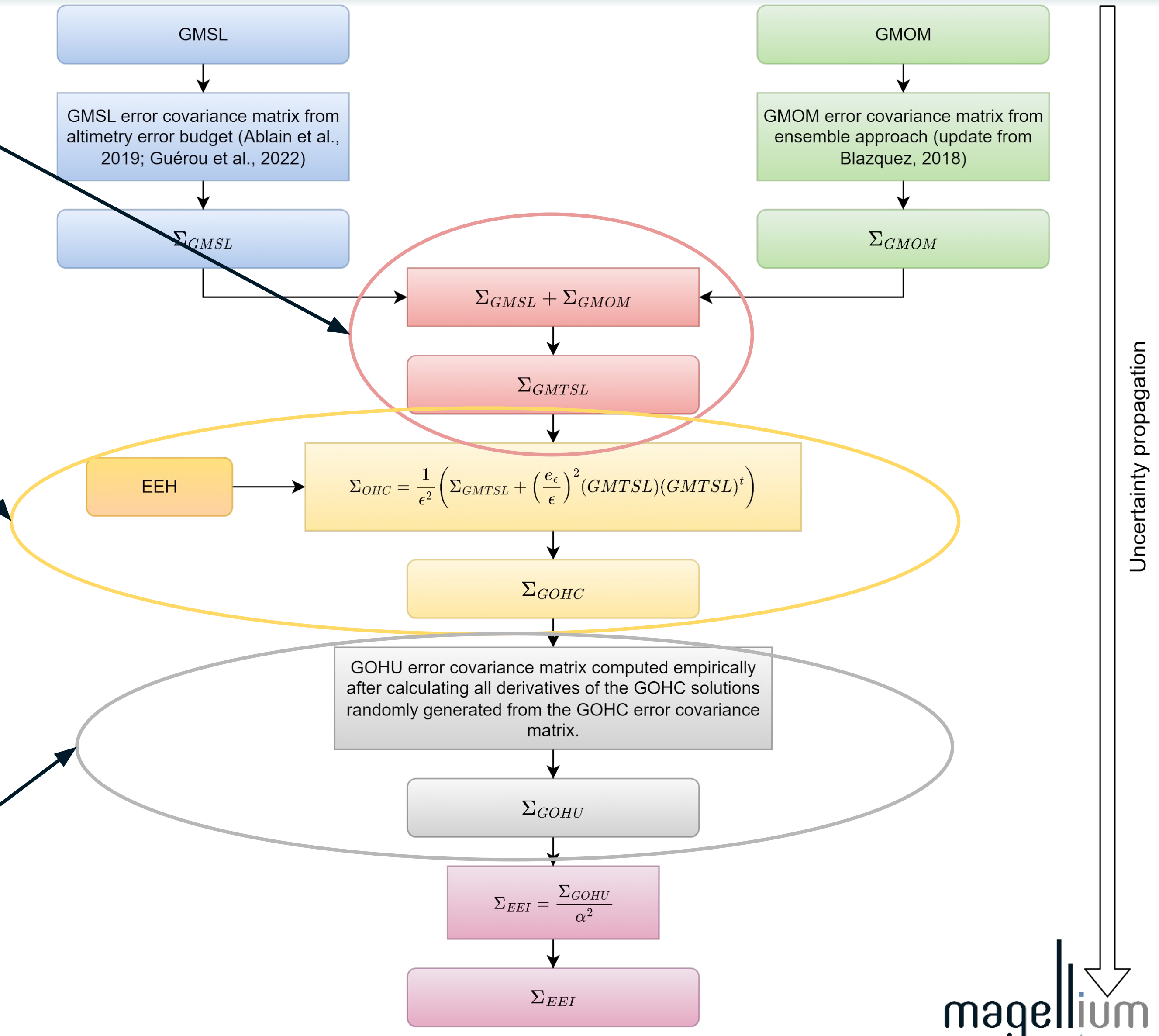
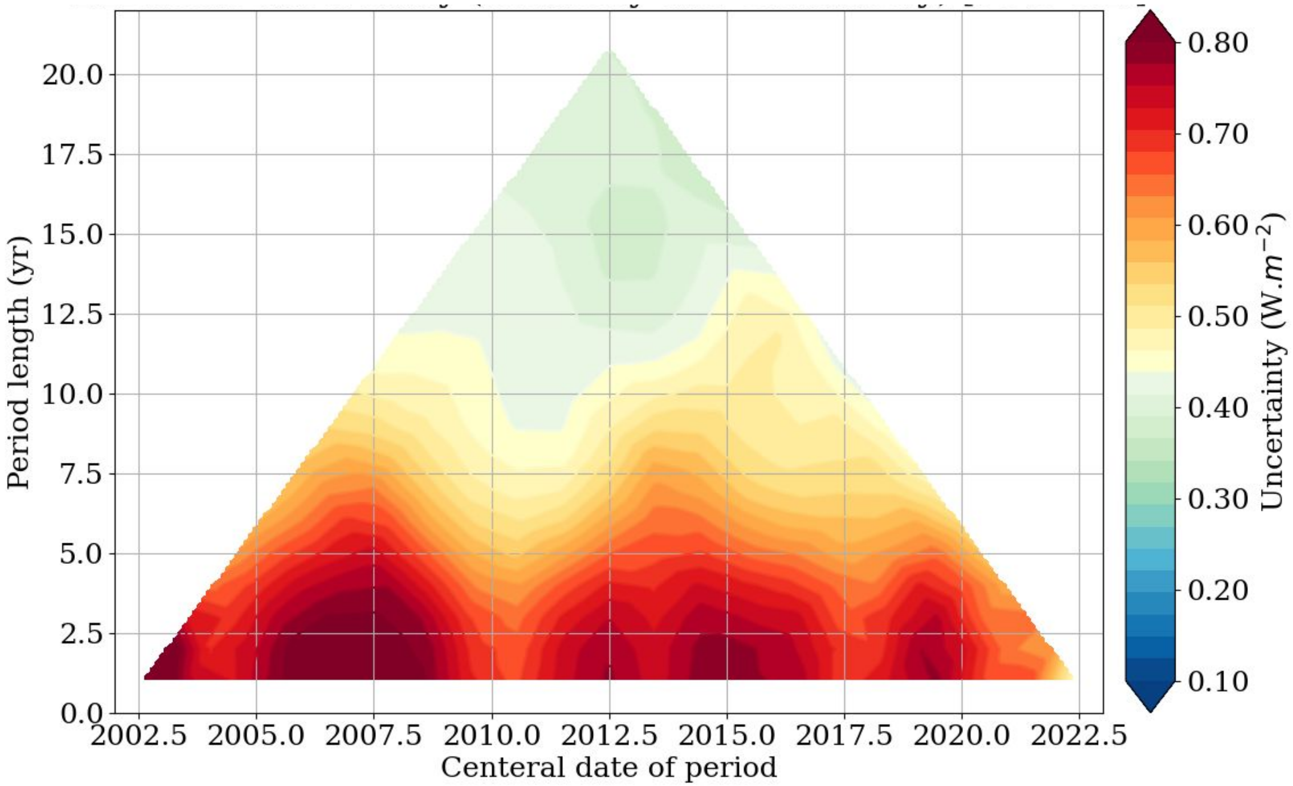
➔ Covariance matrix of global OHC takes into account additional uncertainty of the IEEH coefficient

➔ As the global ocean heat uptake (OHU) is the time derivative of the GOHC after applying a low-pass filter (2-3 years), the covariance matrix is calculated empirically



3) Uncertainties in the EEI and gravimetry contribution

➔ Trend/acceleration uncertainties derived from an OLS method where ∑ is taken into account (Ablain et al, 2009, 2019) : $\hat{\beta} = N(\beta, (X^tX)^{-1}(X^t\Sigma X)(X^tX)^{-1})$



EEI mean uncertainties ([5-95%] CL)

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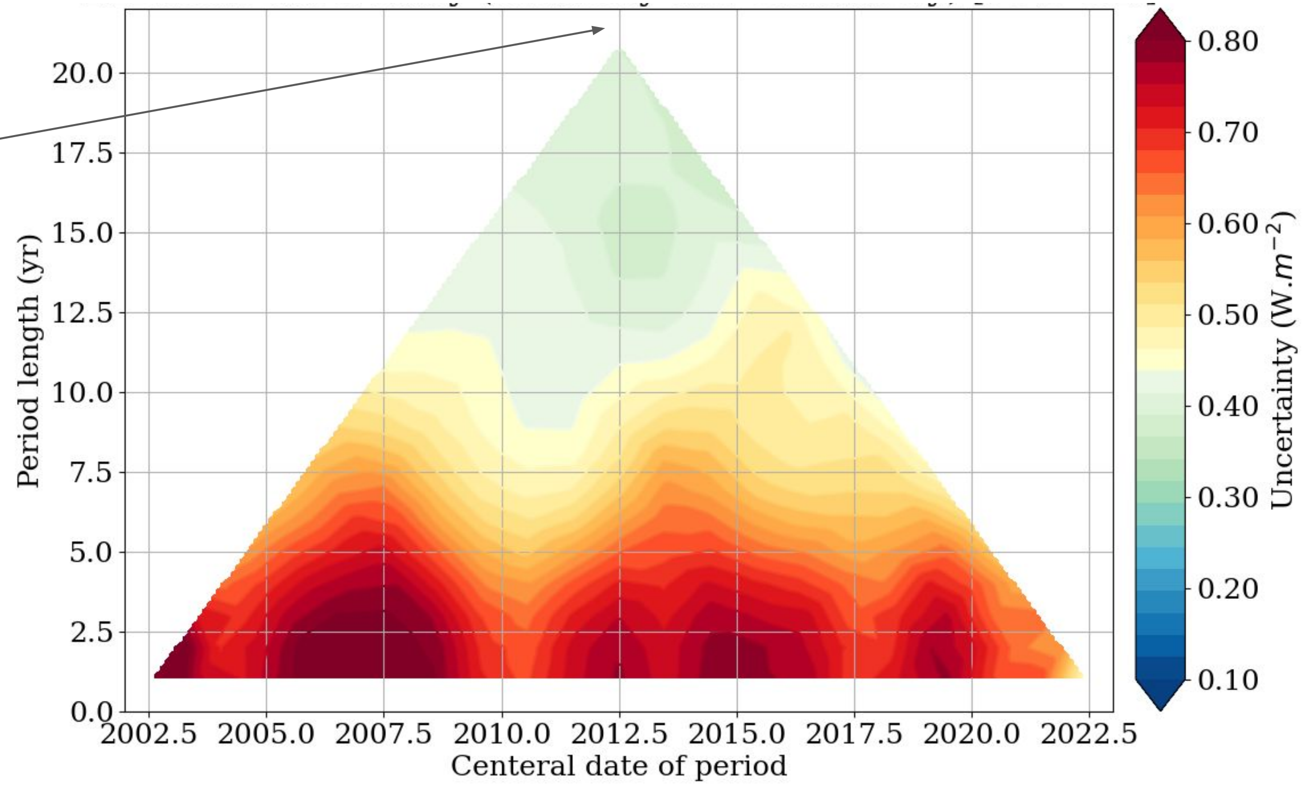
± 0.4 W.m^{-2}
over 20 years



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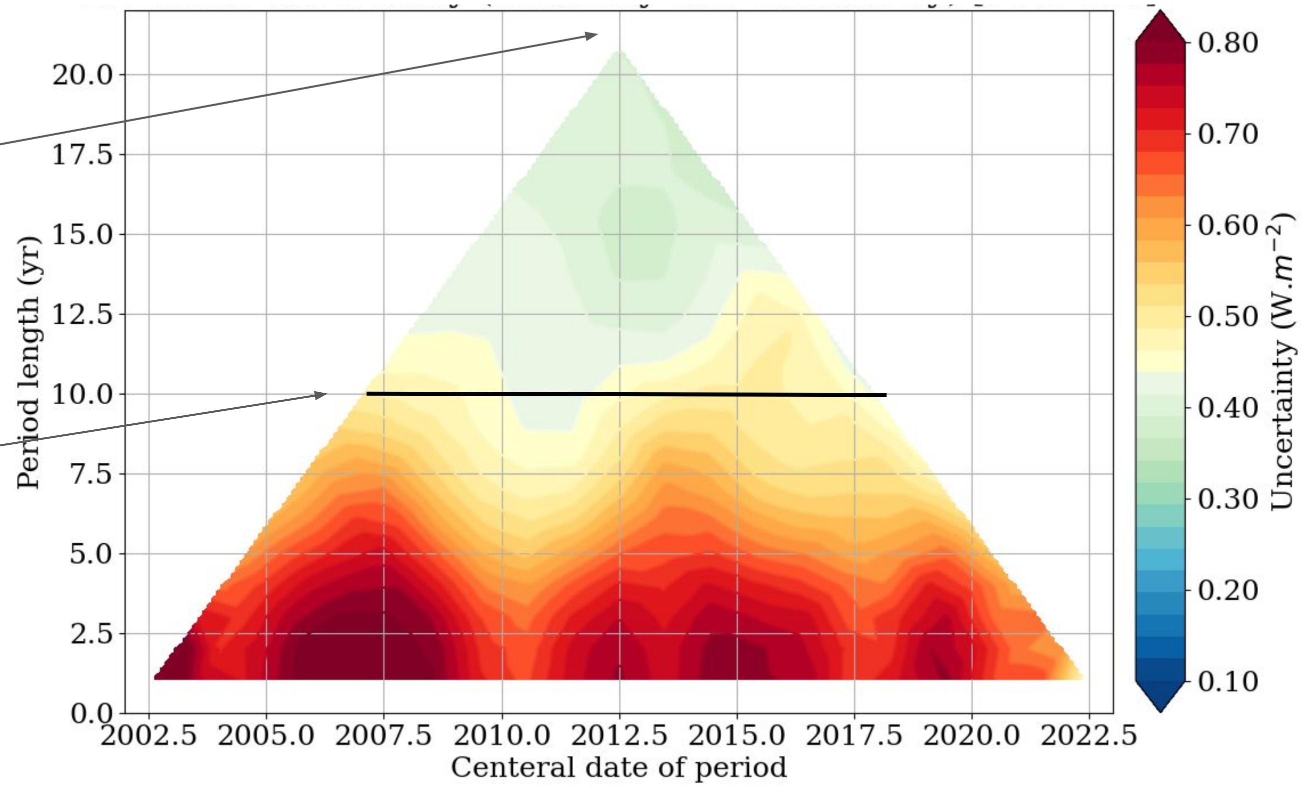
between ±0.4 and ±0.6 W.m^{-2} over 10 years



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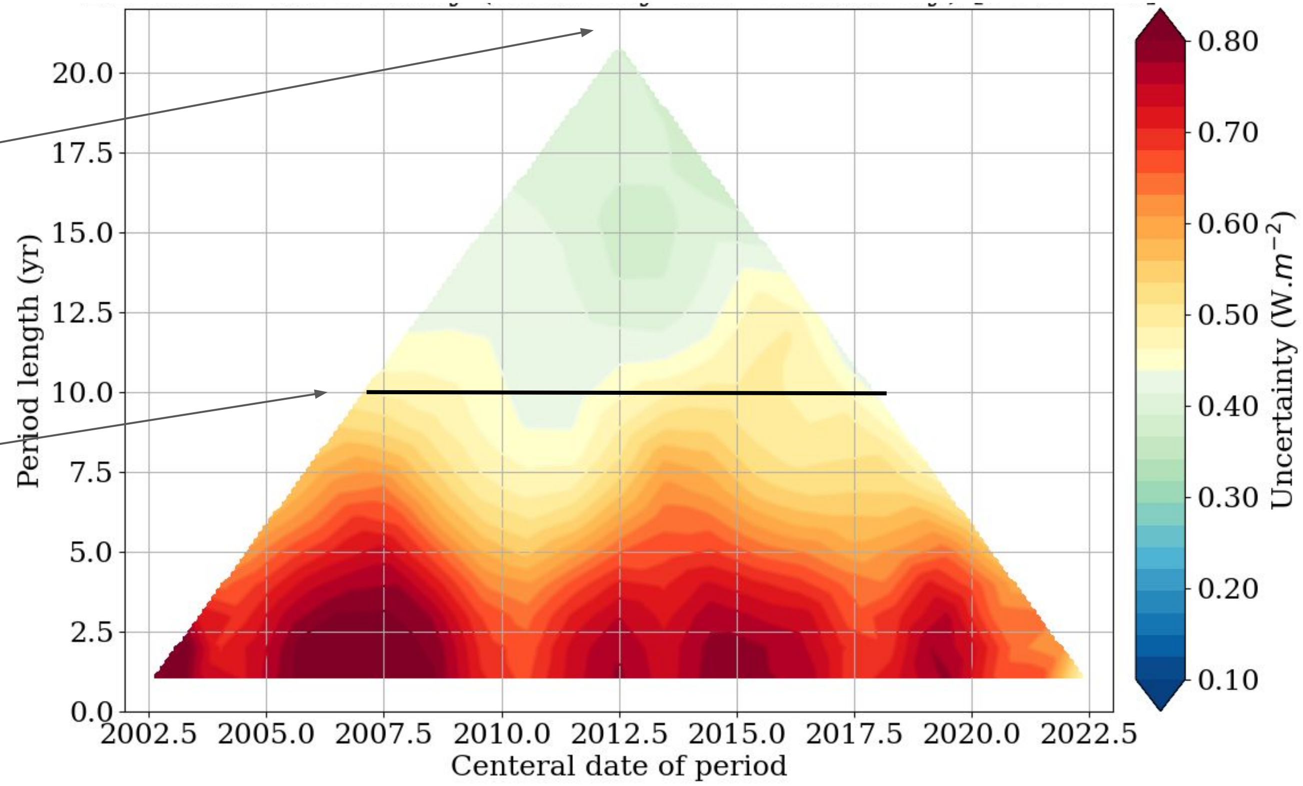
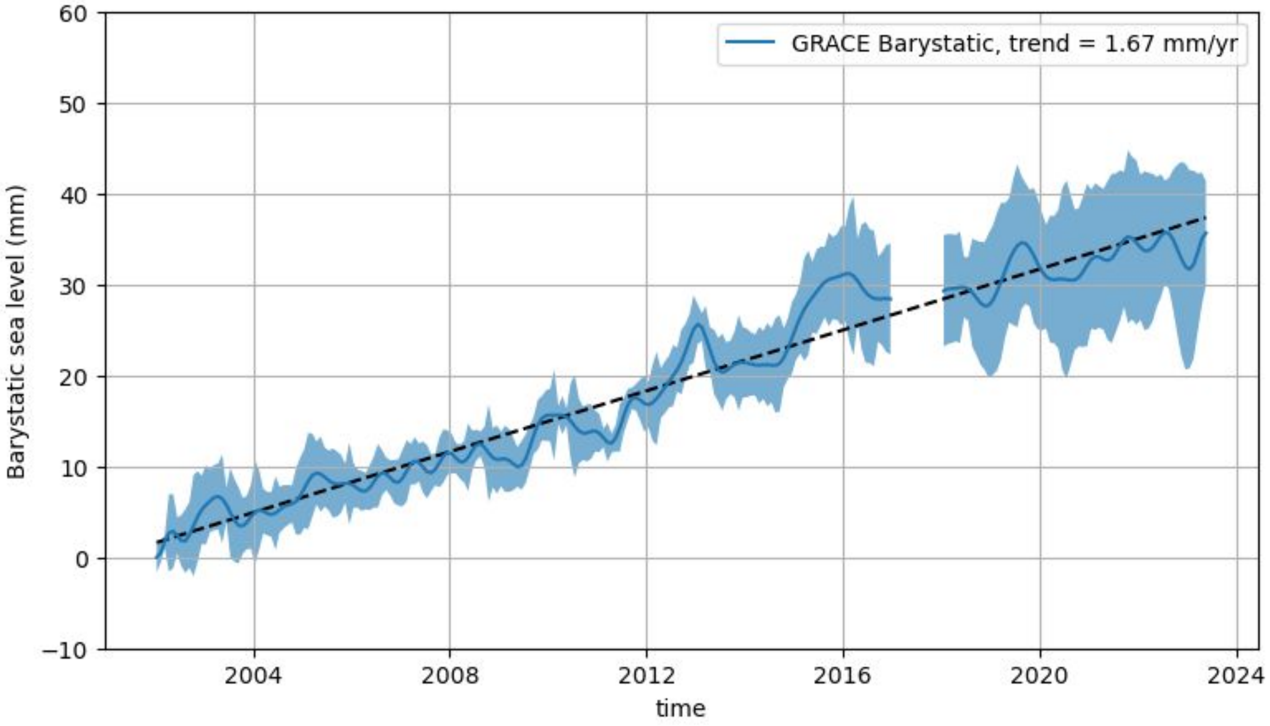


EEI mean uncertainties ([5-95%] CL)

Scientific requirements not yet reached:
0.1 *$W.m^{-2}$* over 10 years

3) Contribution of gravimetry to EEI errors

- ➔ Barystatic sea level anomalies are estimated with an **ensemble approach**:
  - 5 processing centers (CSR, JPL, GFZ, ITSG, CNES)
  - 2 geocenter models (Lemoine & Reinquin, 2017; Sun et al., 2016)
  - 3 SLR products estimating low degree coefficients (C20, C30) of the gravitational potential
  - 2 GIA models (ICE6G_D, Caron et al., 2018)
  - 2 filters (DDK3, DDK6)



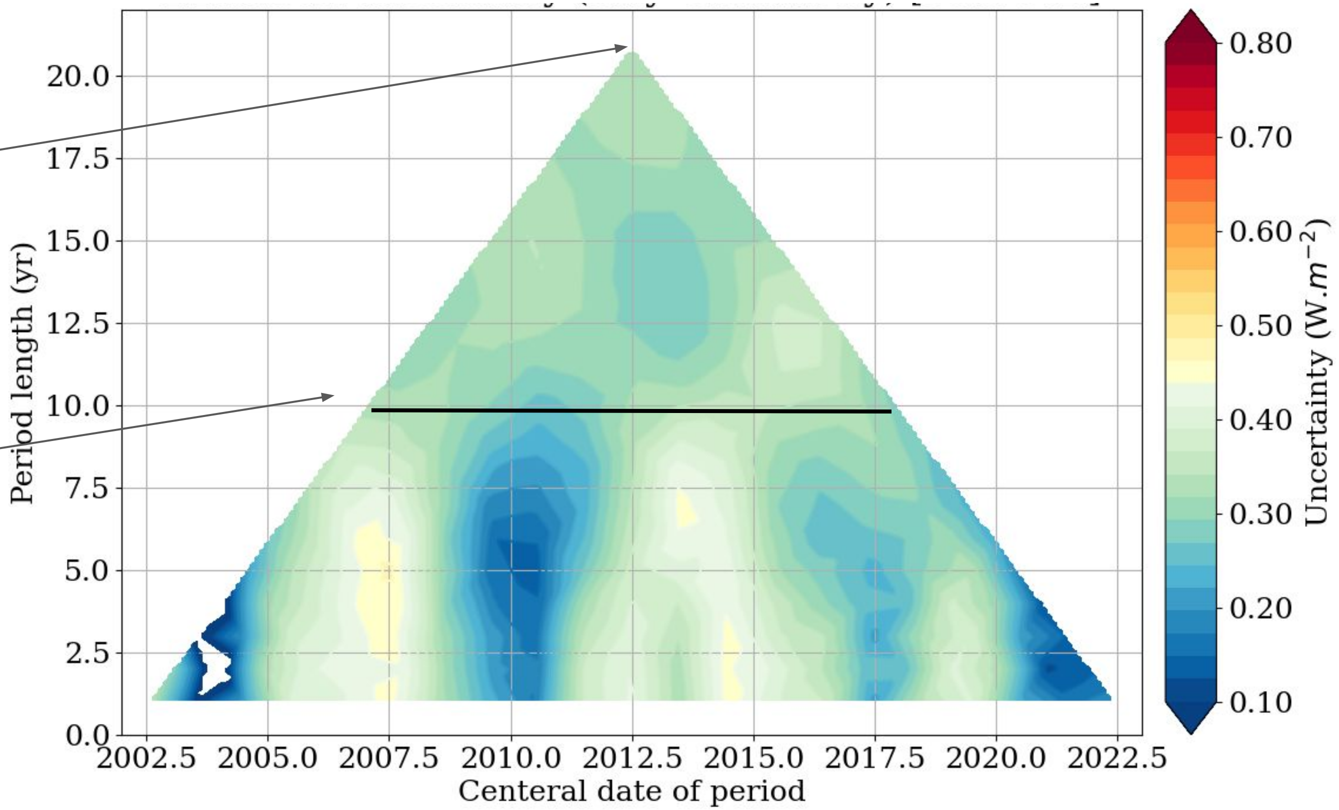
- ➔ **Over the 2002-2023 period:**
  - Barystatic trend is : +1.7 mm/yr ±0.4 mm/yr
  - Within a **[5%,95%] confidence interval**

3) Uncertainties in the EEI and gravimetry contribution

➔ Contribution of **sea level barystatic uncertainties alone** to the EEI mean :

± 0.3 W.m^{-2} over 20 years

between ±0.2 and ±0.4 W.m^{-2} over 10 years



EEI mean uncertainties ([5-95%] CL)

4) Take home messages and recommendations

➔ **Gravimetry missions** provide a precise, accurate and stable data record over than 20 years:

- Barystatic trend is : +1.7 mm/yr ±0.4 mm/yr [5%,95%]

➔ **Better accuracy needed** in barystatic estimates to answer scientific questions as the closure of the sea level budget, the monitoring of EEI:

- **±0.1 mm/yr [5%,95%]** for the barystatic trend over 10 years (Meyssignac et al 2023)

➔ Using space geodetic data (altimetry and gravimetry) provide accurate EEI estimates:

- EEI mean: **0.8 ±0.3 W.m^{-2}** [5%,95%]
- EEI trend: **0.3 ±0.2 W/m^2/decade** [5%,95%]

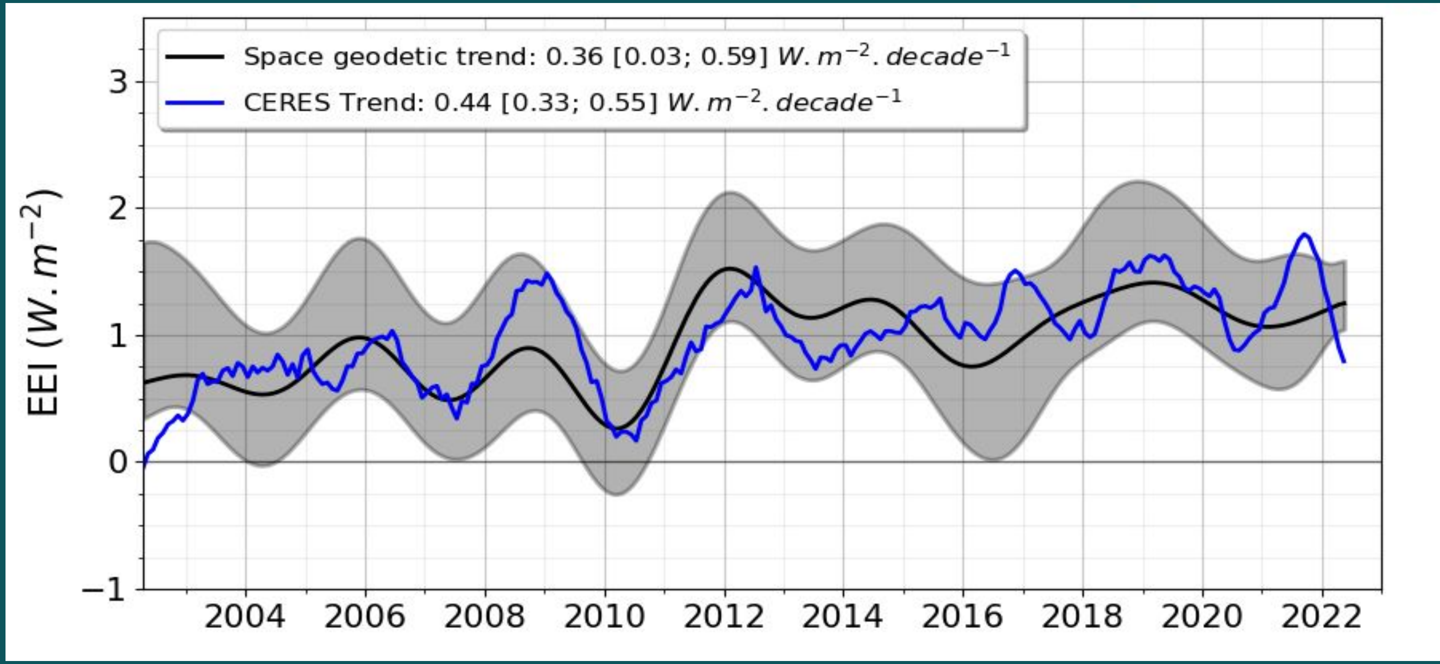
➔ To date, requirements on the EEI mean (**0.1 W.m^{-2} [5%,95%] over 10 years**) are not yet reached:

- Gravimetry uncertainty contribute at 10 years for **0.2 W/m^2** over the last decade

➔ **Further improvements needed:**

- Improve uncertainty characterisation from geocenter, leakage correction

Thank you for your attention.



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