

# Bridging the Gap via EOFs

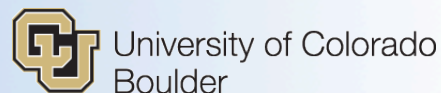
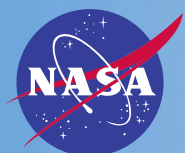
M. Talpe<sup>1</sup>, R. S. Nerem<sup>1</sup>, F. Lemoine<sup>2</sup>, R. E. Riva<sup>3</sup>, E. Pilinski<sup>1</sup>, and D. Chinn<sup>2</sup>

<sup>1</sup> University of Colorado at Boulder, CIRES, CCAR

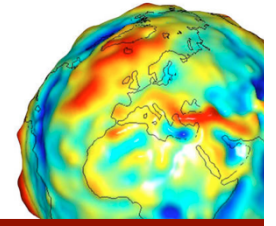
<sup>2</sup> Goddard Space Flight Center, NASA

<sup>3</sup> Delft University of Technology

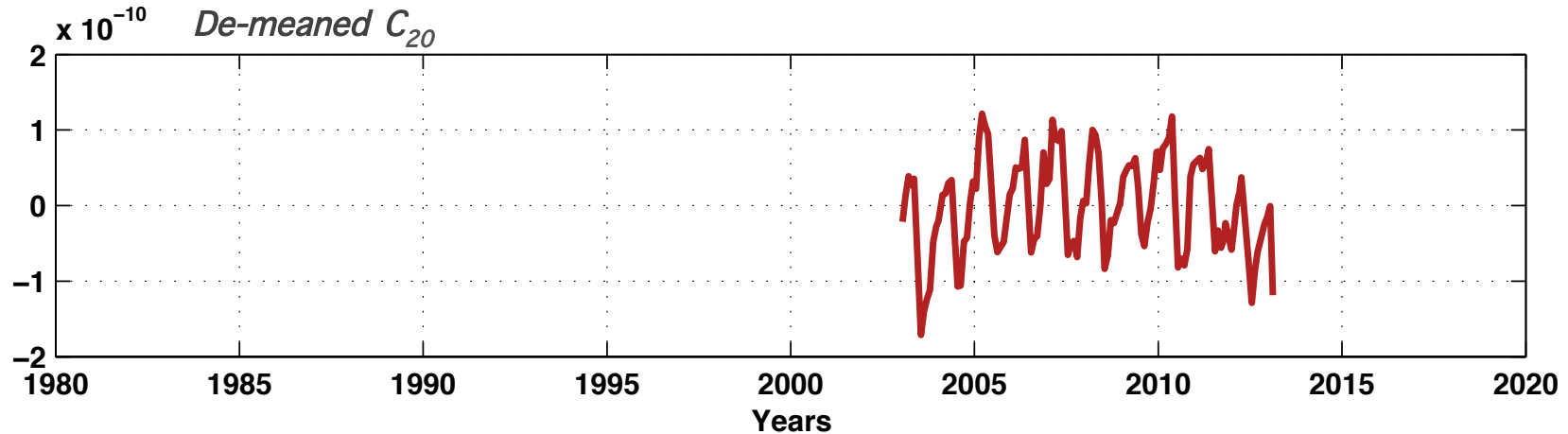
GRACE Science Team Meeting  
Austin, TX  
23 October 2013



# GRACE and beyond

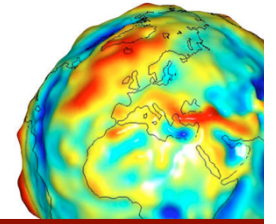


- Unprecedented impact in measuring time-varying gravity

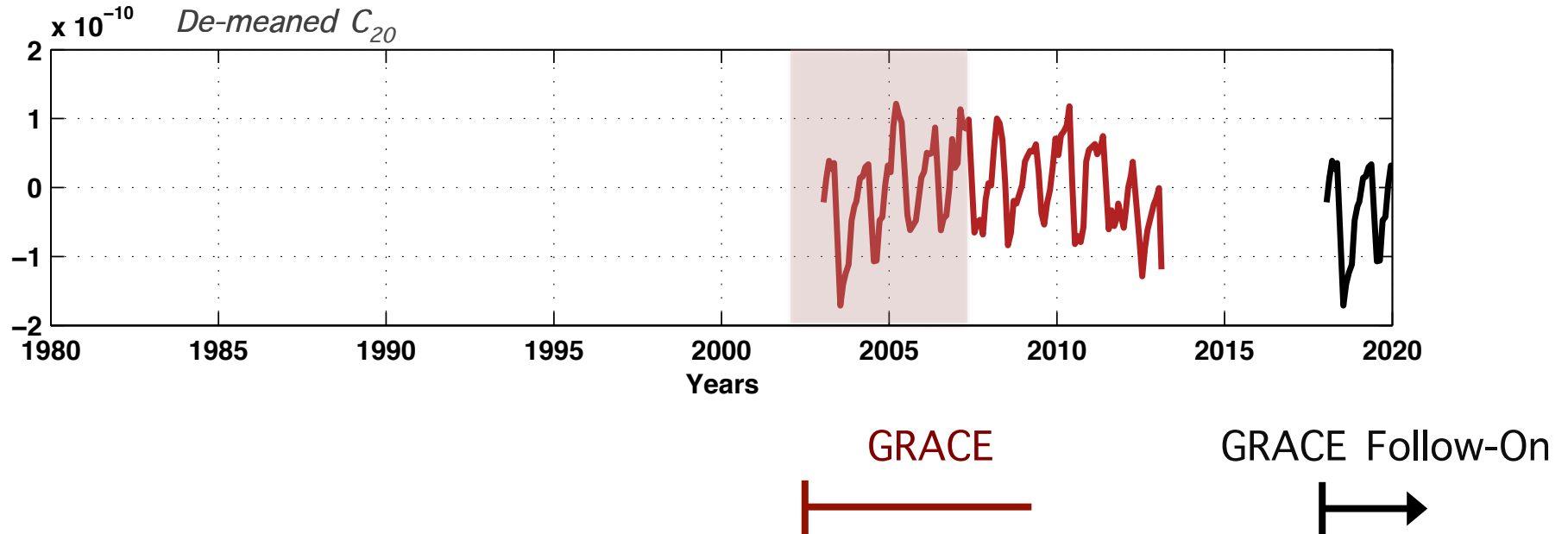


GRACE

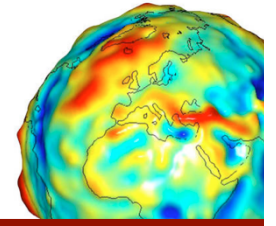
# GRACE and beyond



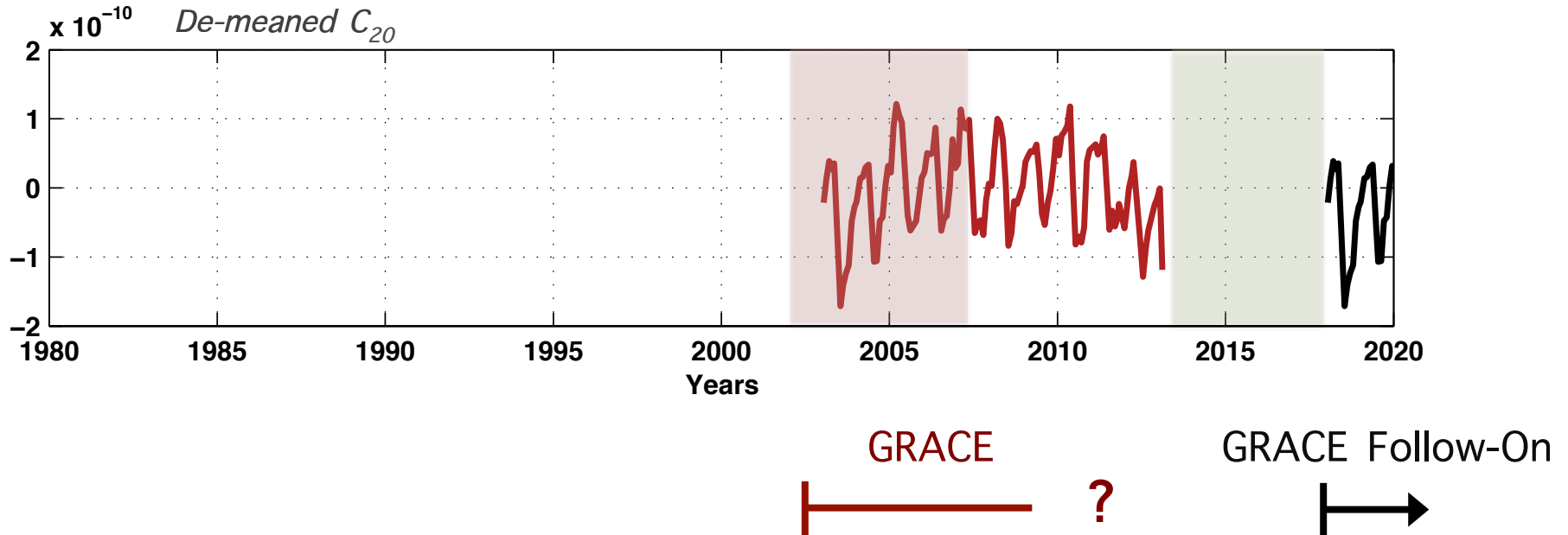
- Unprecedented impact in measuring time-varying gravity
- Mission lifetime of 5 years + GFO launch slated for 2017



# GRACE and beyond

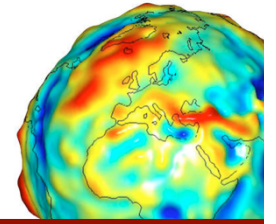


- Unprecedented impact in measuring time-varying gravity
- Mission lifetime of 5 years + GFO launch slated for 2017
- Gap → Discontinuous global gravity science products



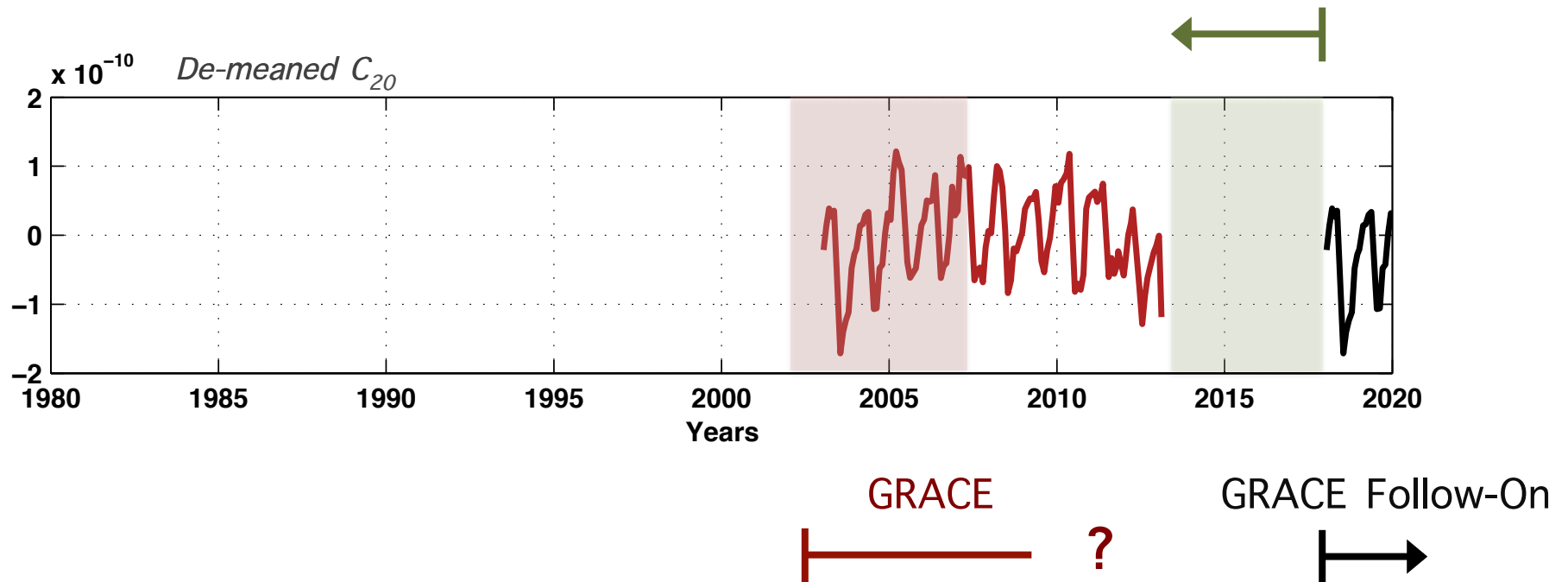


# Bridging the gap

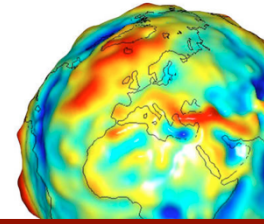


Seek to produce global fields that will:

- I. Cover the GRACE-GFO gap

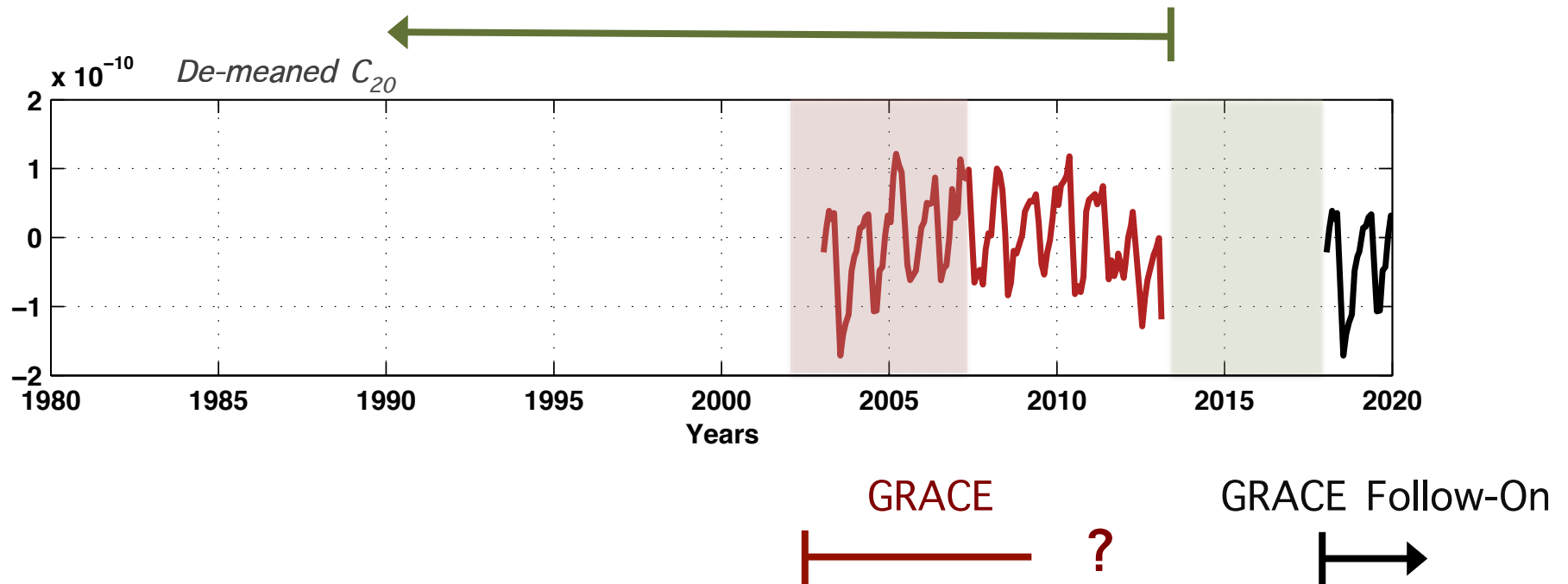


# Bridging the gap

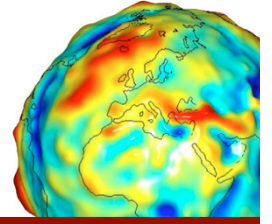


Seek to produce global fields that will:

1. Cover the GRACE-GFO gap
2. Extend the times series pre-2002



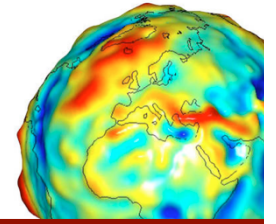
# How to bridge the gap?



Underlying questions... (Exploring and lots of TBD)

1. What tool?
2. Validation?
3. Improvements?

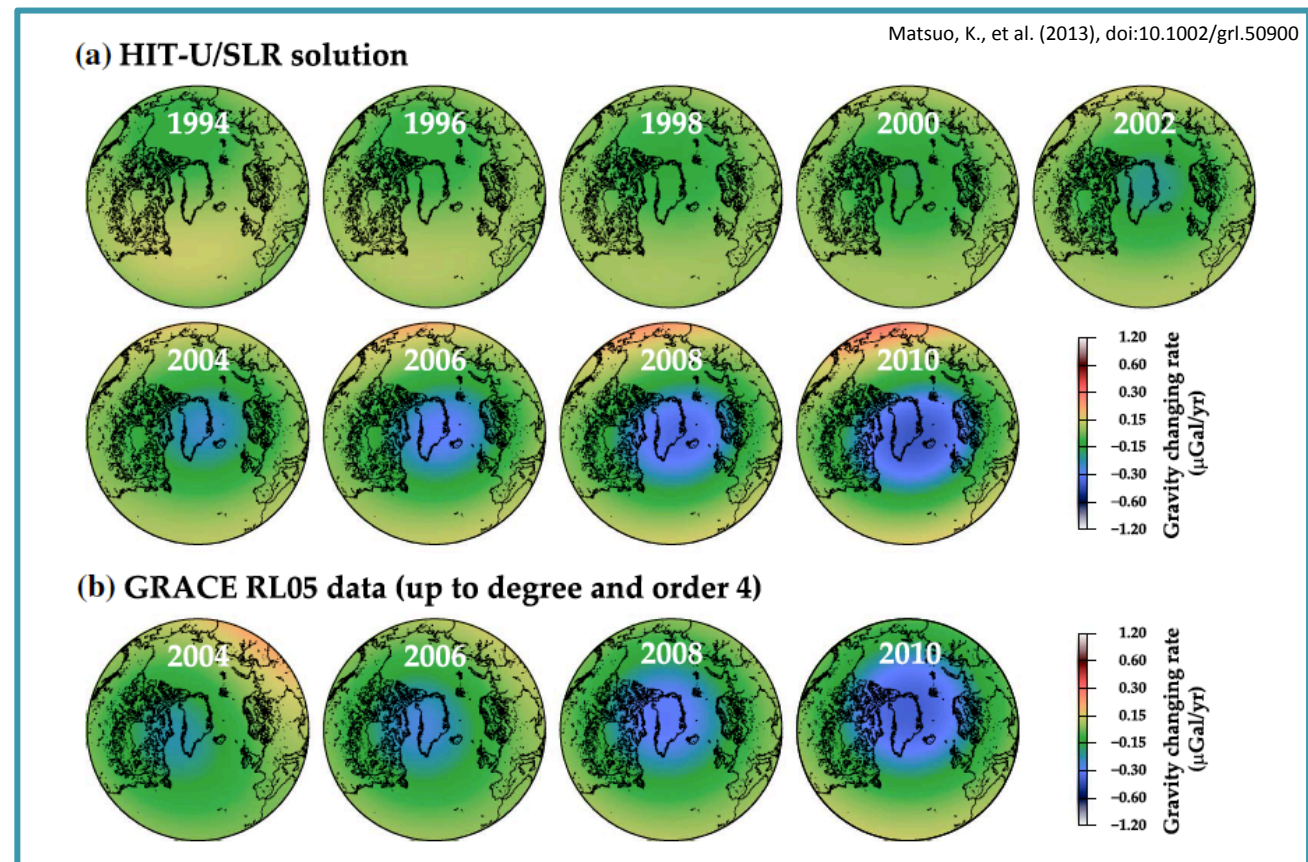
# How to bridge the gap?



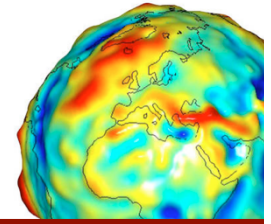
Matsuo, K., et al. (2013)

HIT-U/SLR

GPS to corroborate



# How to bridge the gap?



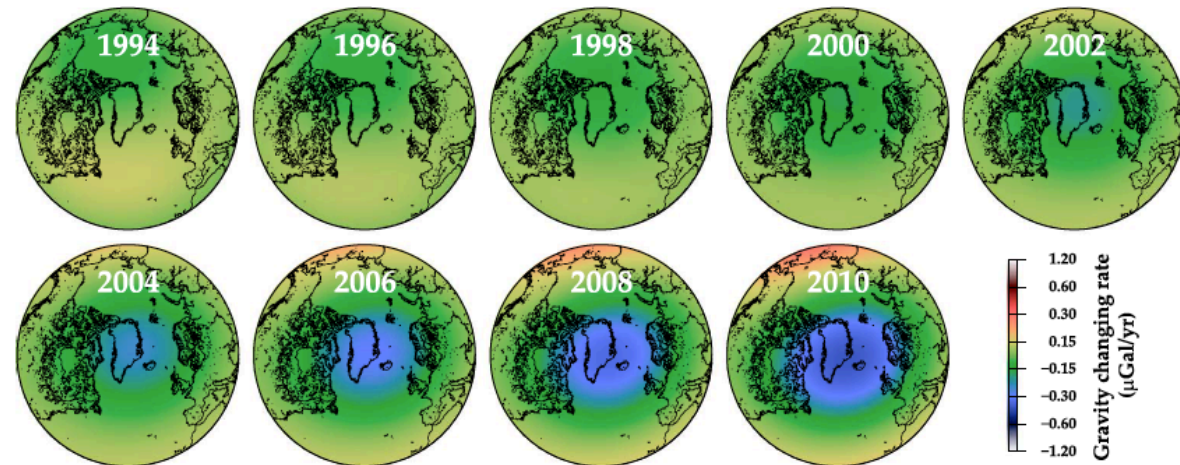
Matsuo, K., et al. (2013)

HIT-U/SLR

GPS to corroborate

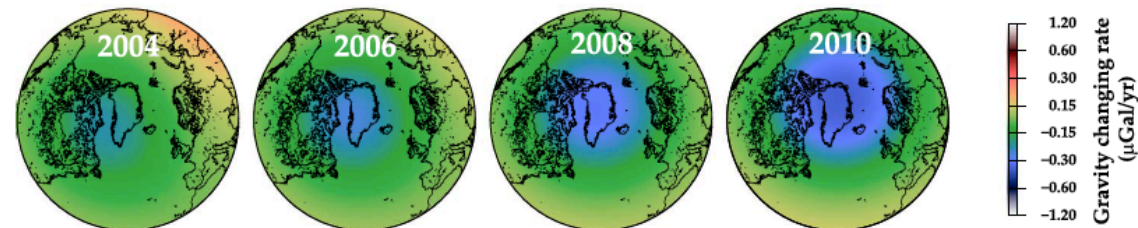
“[...] the SLR data series constitutes a continuous benchmark for time history of the Greenland ice mass changes for over two decades.”  
[Matsuo et al., 2013]

(a) HIT-U/SLR solution



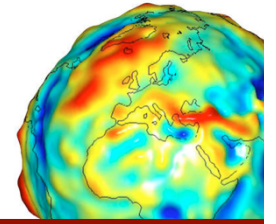
Matsuo, K., et al. (2013), doi:10.1002/grl.50900

(b) GRACE RL05 data (up to degree and order 4)





# How to bridge the gap?



Baur, O. (2013)

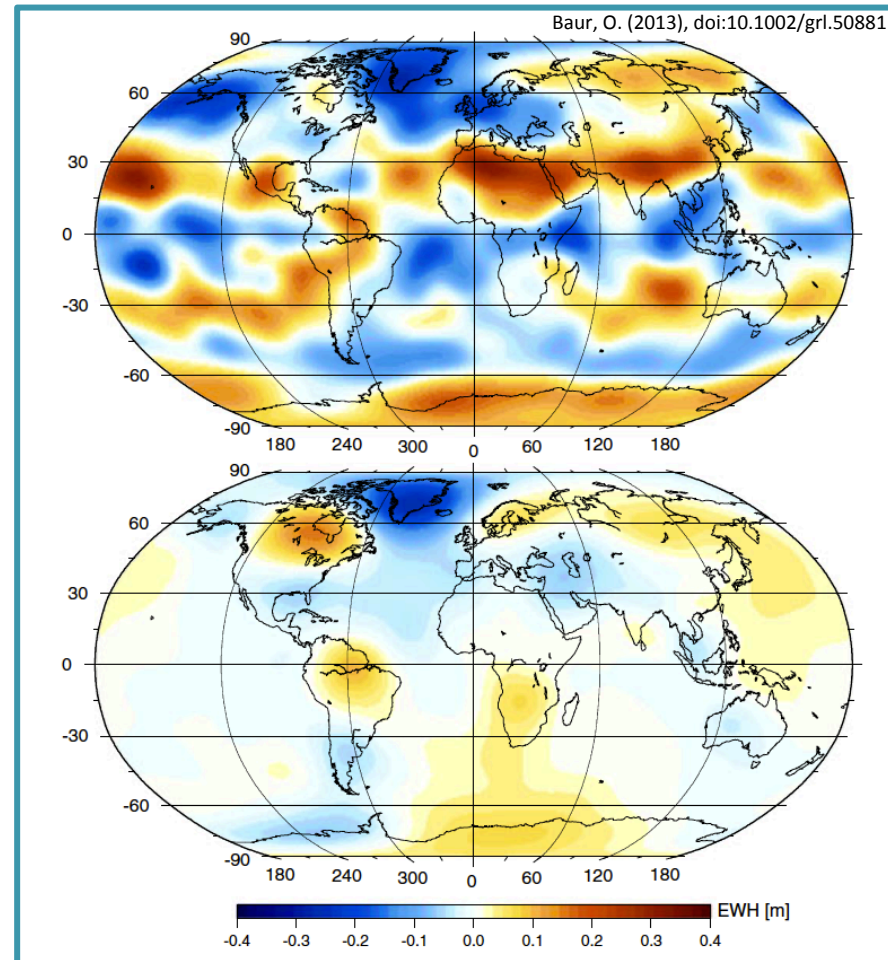
CHAMP

GPS to corroborate

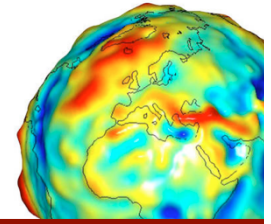
Weigelt, M., et al. (2013)

CHAMP

hl-SST



# How to bridge the gap?



Baur, O. (2013)

CHAMP

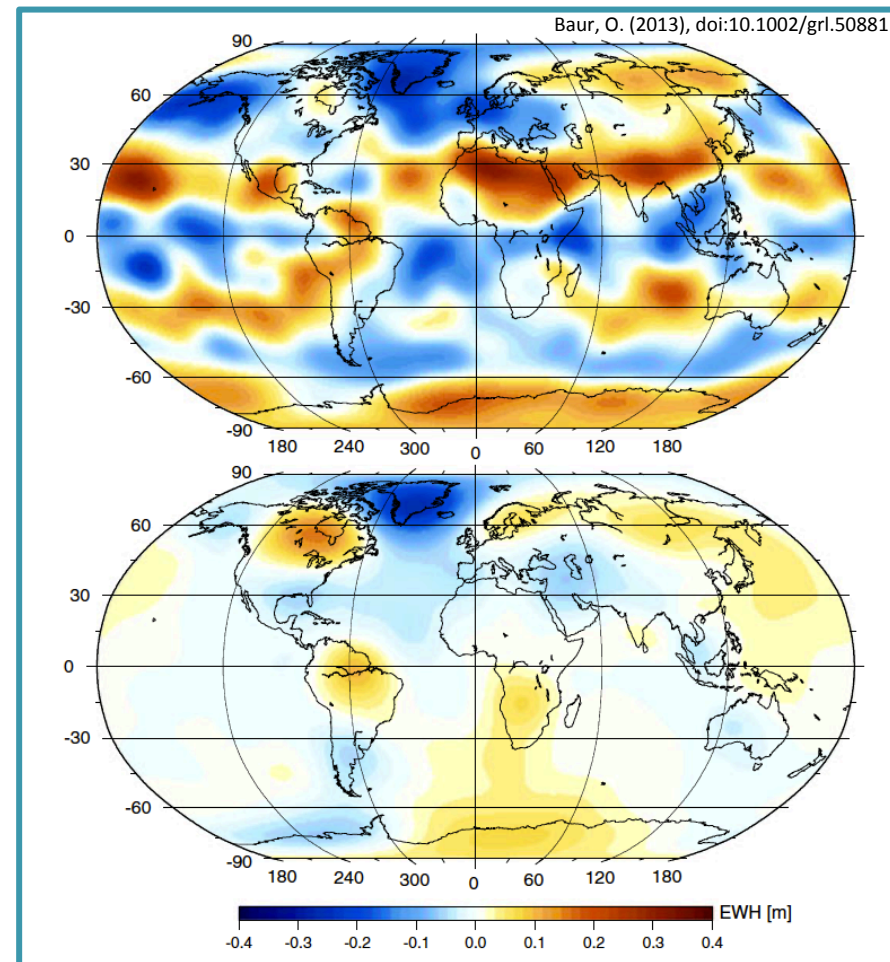
GPS to corroborate

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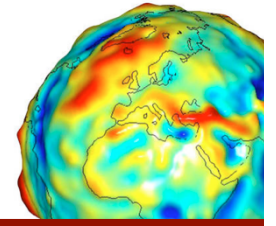
CHAMP

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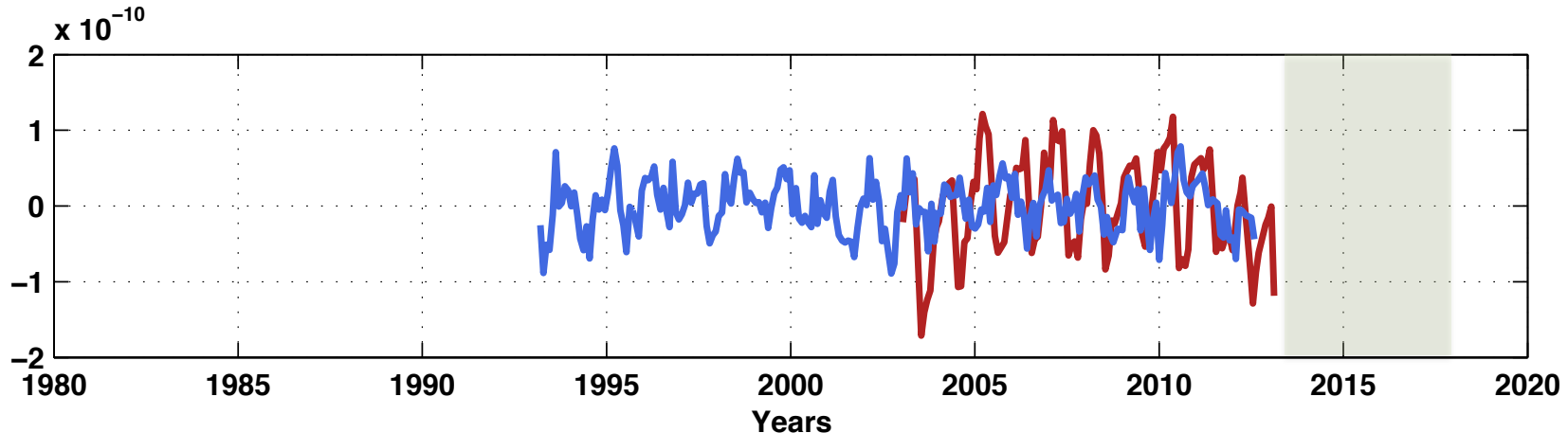
“[...] orbit analysis of low-Earth orbiting spacecrafts is suitable to asses Greenland mass balance in the absence of the GRACE satellites”  
[Baur, 2013]



# Method?



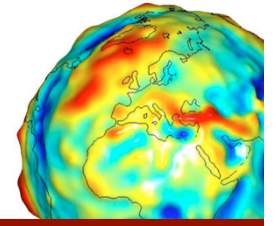
- Other datasets available?
- Conventional tracking data (CTD): SLR, DORIS
  - Continuous tracking and long time-series



BRIDGING THE GAP: What tool?

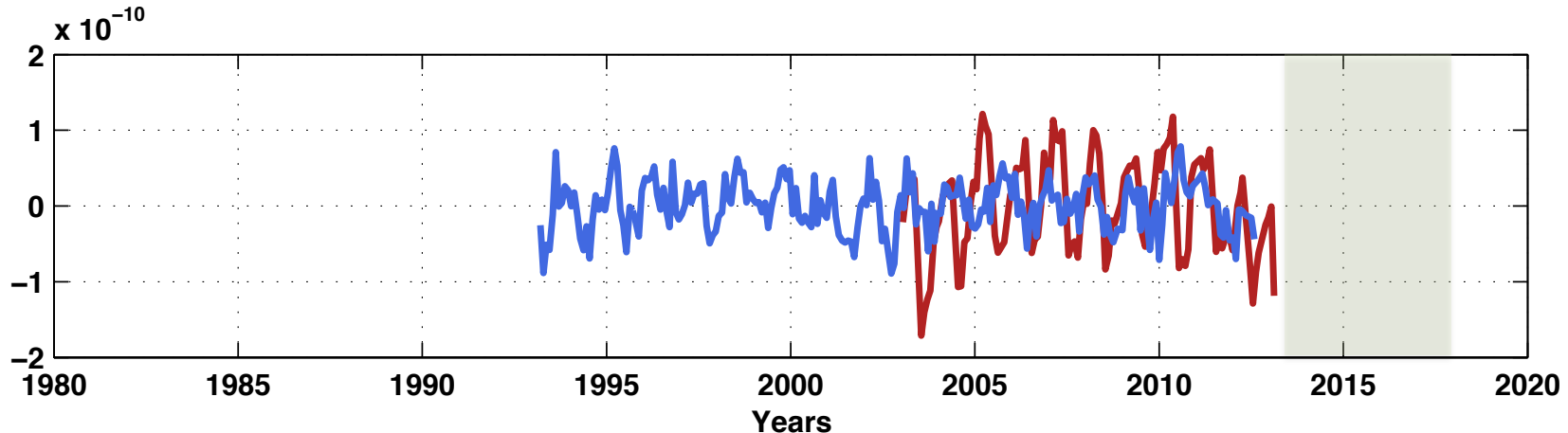


# Method?



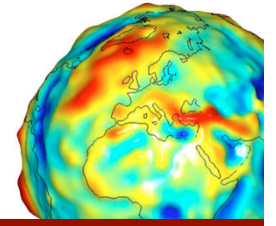
- Other datasets available?
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→ Combine CTD and GRACE via EOFs



BRIDGING THE GAP: What tool?

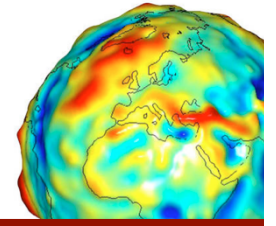
# Data – Global gravity fields



## I. GRACE fields

- Obtained from GRACE, processed by CSR RL05
- High(est) spatial resolution (60x60), short time series
- $C_{20}$  replaced, GIA removed, de-stripped, de-measured, de-seasoned

# Data – Global gravity fields



## 1. GRACE fields

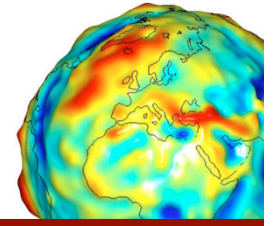
- Obtained from GRACE, processed by CSR RL05
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## 2. Conventional tracking data (CTD) fields

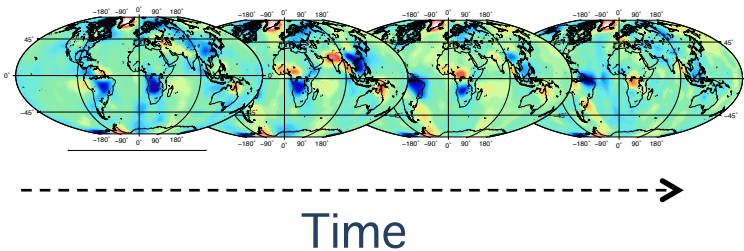
- Collected from 11 satellites – SLR, DORIS
- Low spatial resolution (4x4), long time series (since 1993)
- Pre-processing to make CTD match GRACE



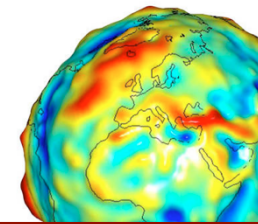
# Method – EOF Decomposition



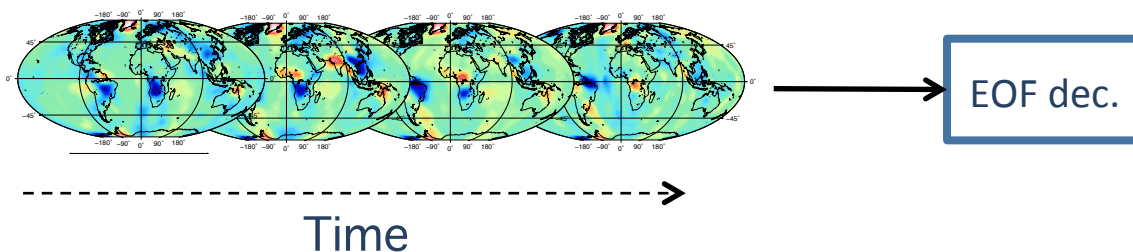
- ① EOF (Empirical Orthogonal Functions): describe large, multi-dimensional dataset using minimal information



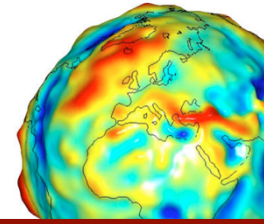
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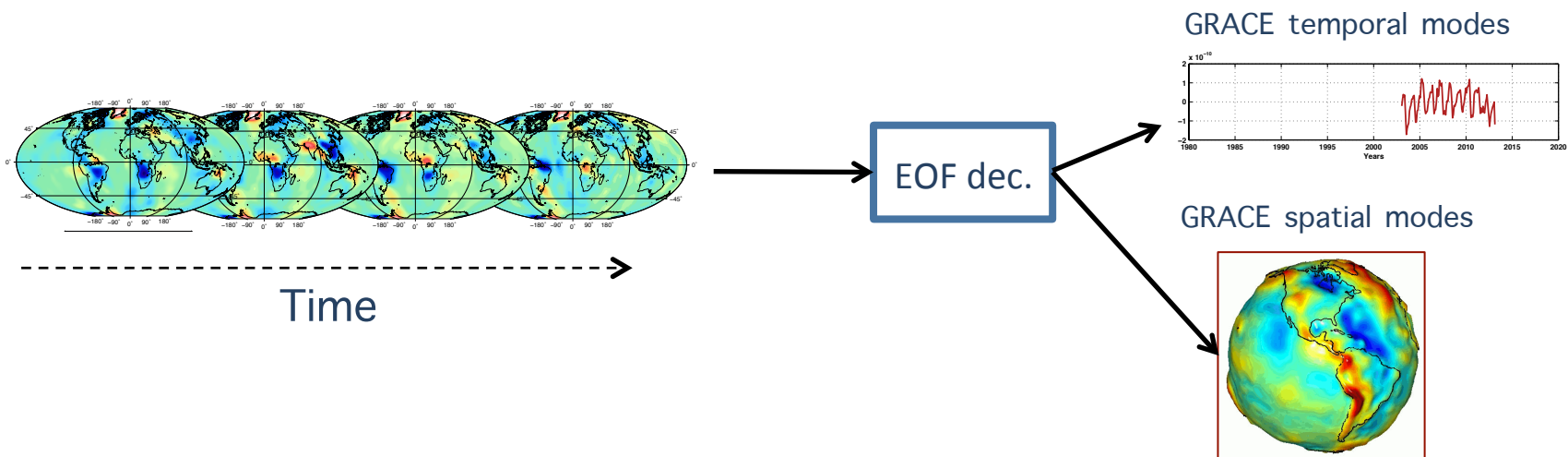
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- ②  $[U, S, V] = \text{SVD}(C_{lm})$



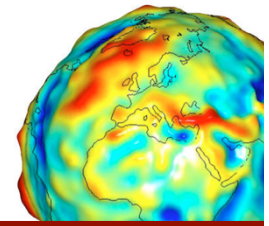
# Method – EOF Decomposition



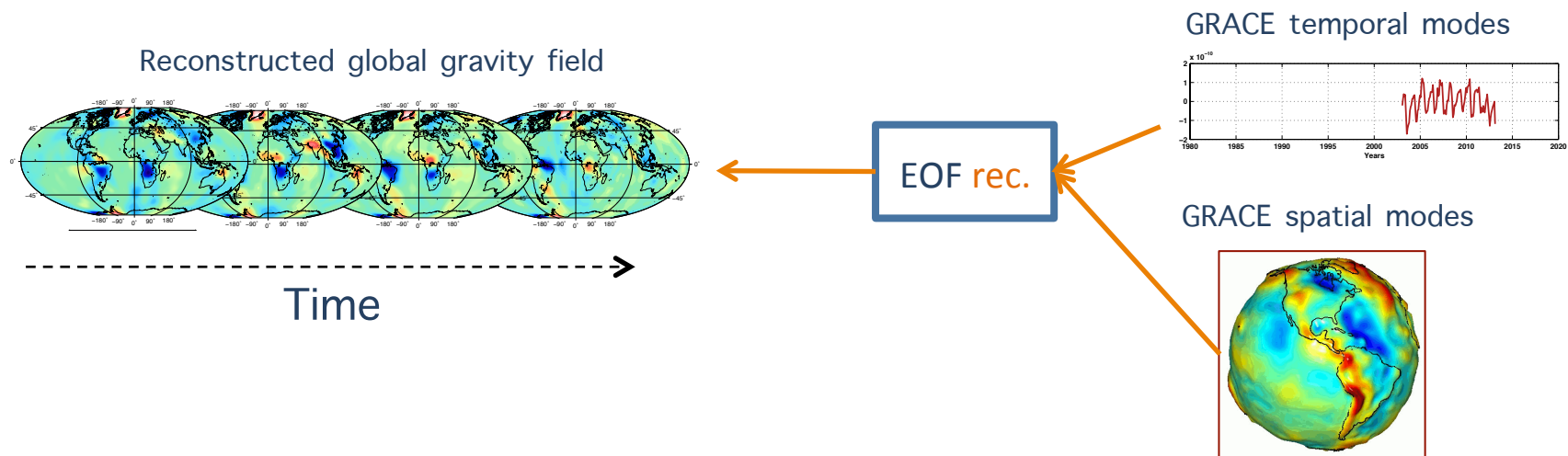
- ① EOF (Empirical Orthogonal Functions): describe large, multi-dimensional dataset using minimal information
- ②  $[U, S, V] = \text{SVD}(C_{lm})$
- ③ **Temporal modes:**  $T(t) = U * S$   
**Spatial modes:**  $S(\theta, \lambda) = V$



# Method – EOF Reconstruction

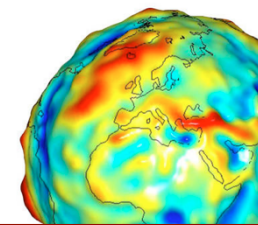


Reconstruction = Spatial x Temporal



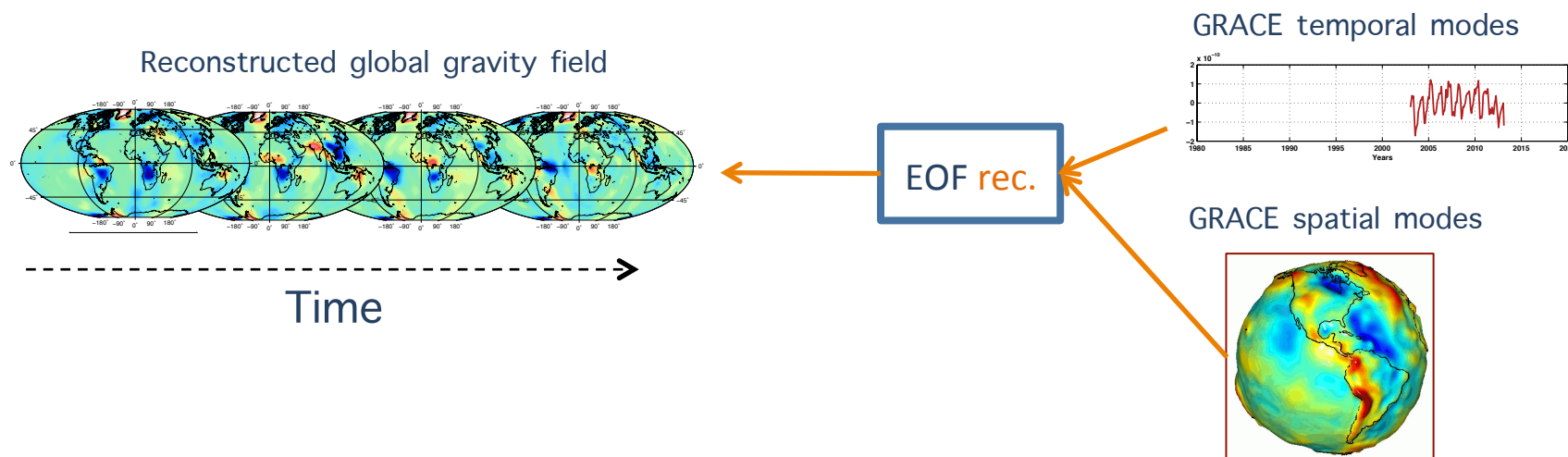
BRIDGING THE GAP: What tool?

# Method – EOF Reconstruction



$$\text{Reconstruction} = \sum \text{Spatial} \times \text{Temporal}$$

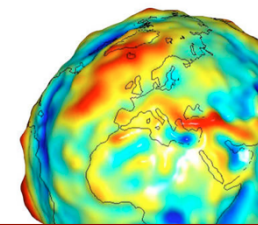
– Summed over number of modes desired



BRIDGING THE GAP: What tool?

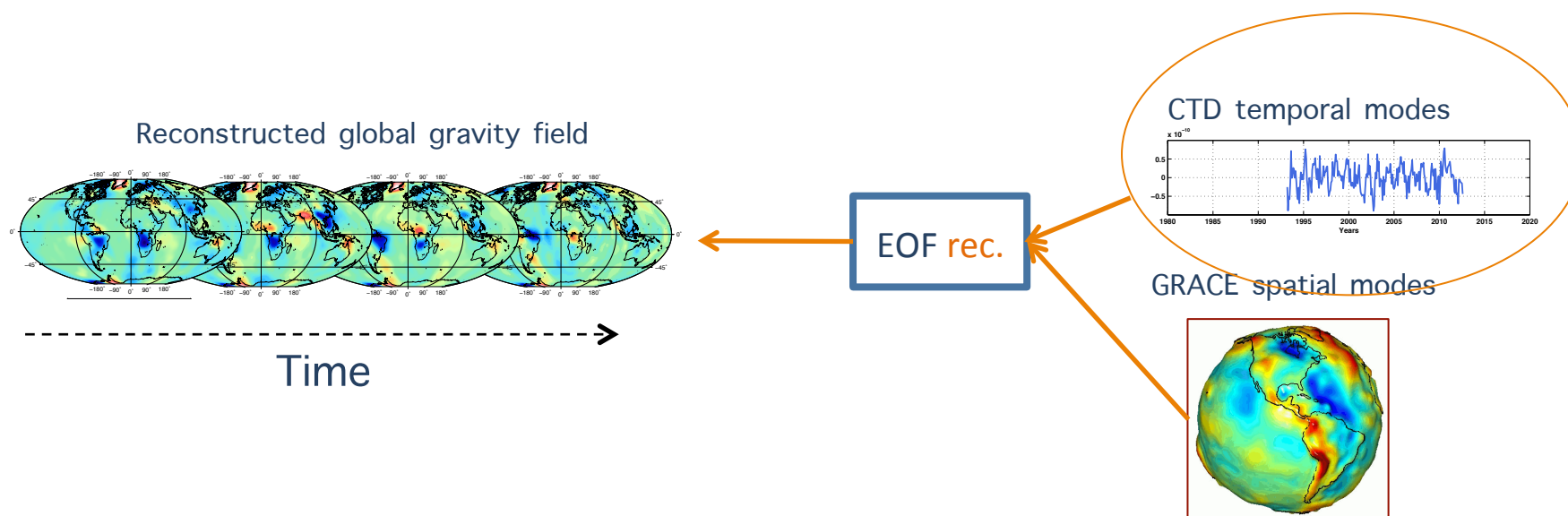


# Method – EOF Reconstruction

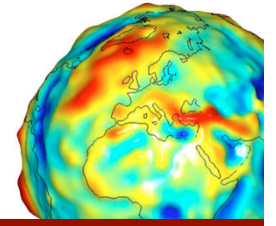


$$\text{Reconstruction} = \sum \text{Spatial} \times \text{Temporal}$$

- Summed over number of modes desired
- Temporal modes from Conventional Tracking Data (GSFC)



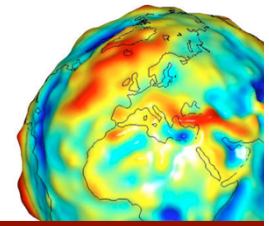
# How to bridge the gap?



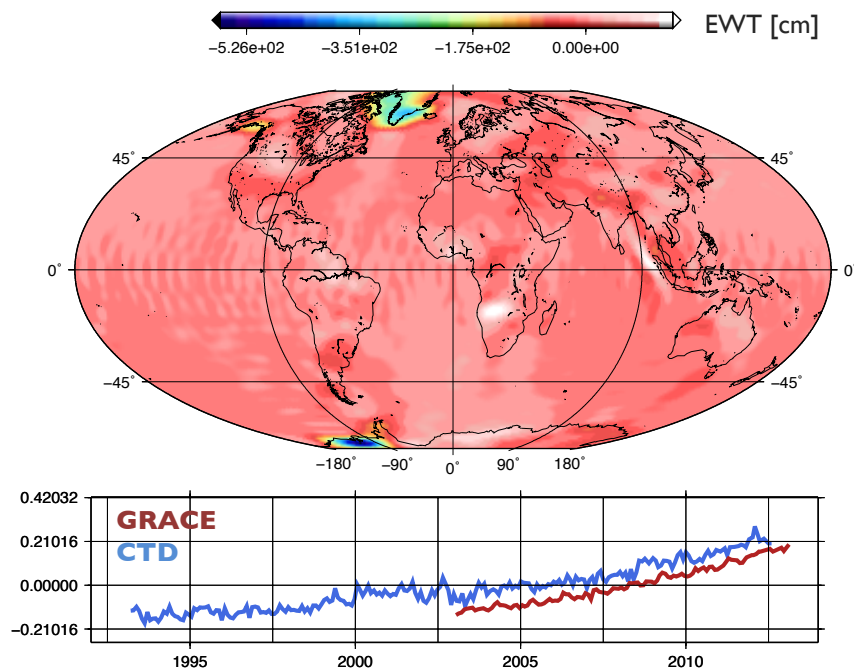
Underlying questions... (Exploring and lots of TBD)

1. What tool? EOFs with GRACE and SLR
2. Validation?
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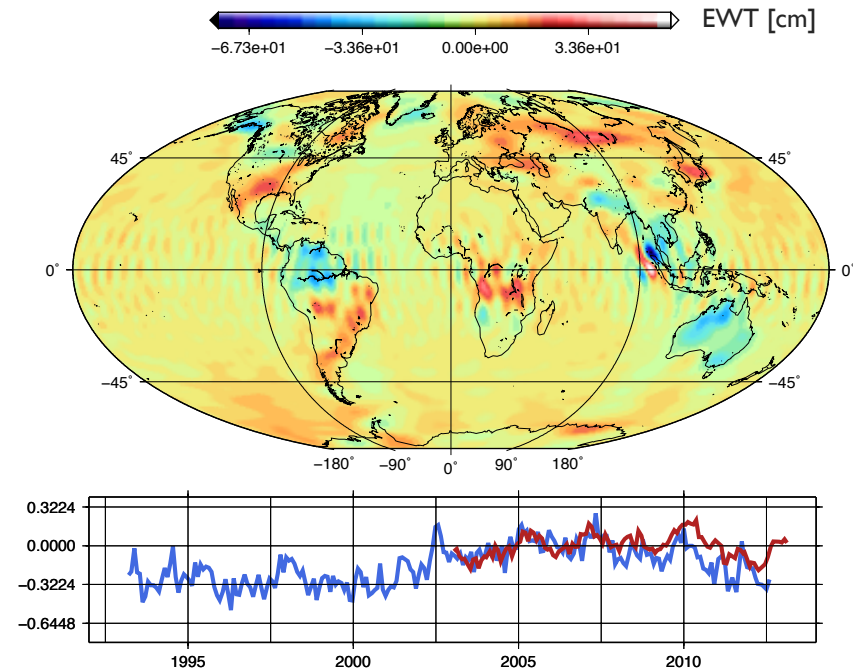
# Results – Spatial & temporal modes



**Mode 1**

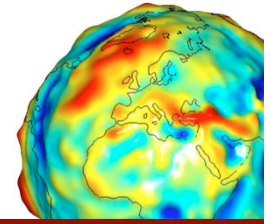


**Mode 2**

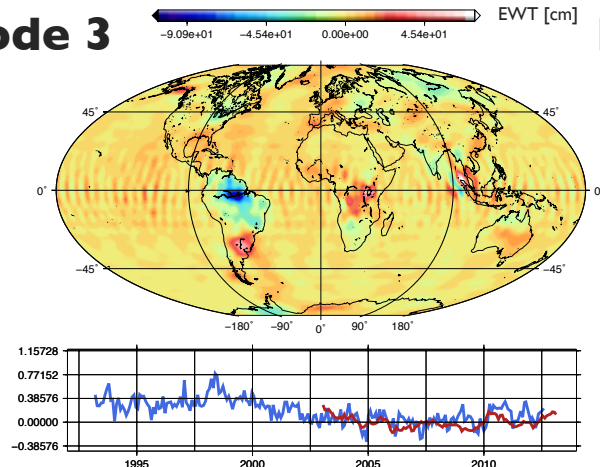


First mode is “trend” mode

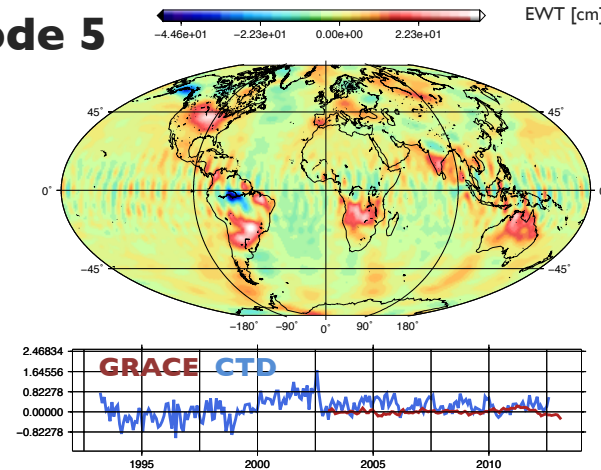
# Results – Spatial & temporal modes



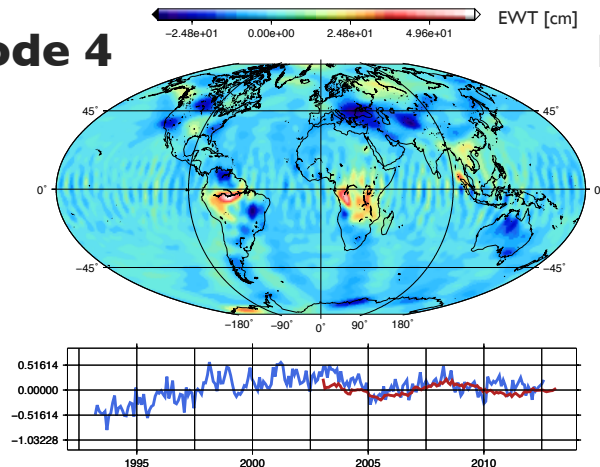
**Mode 3**



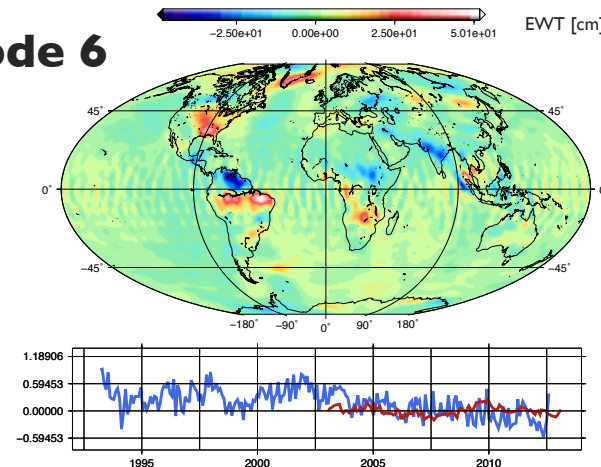
**Mode 5**



**Mode 4**

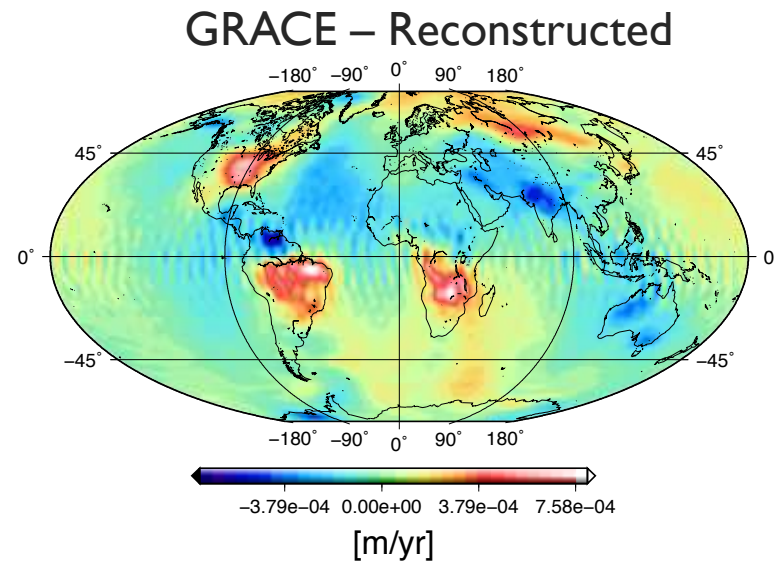
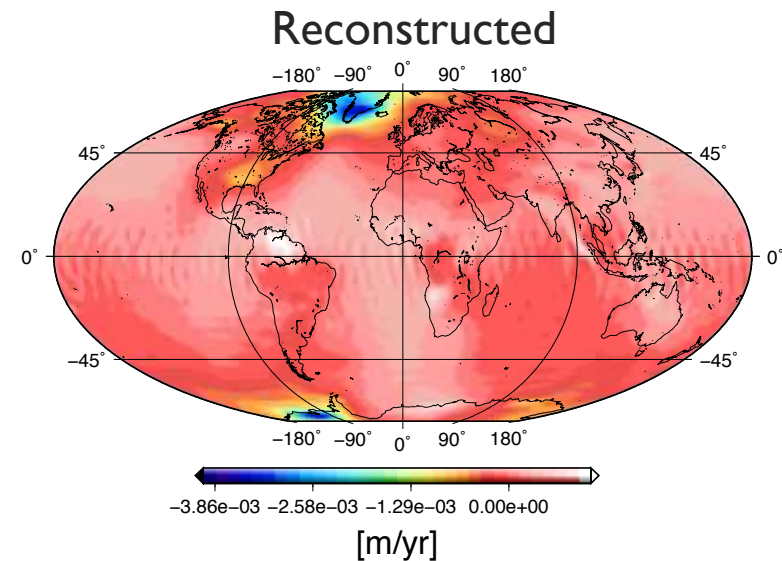
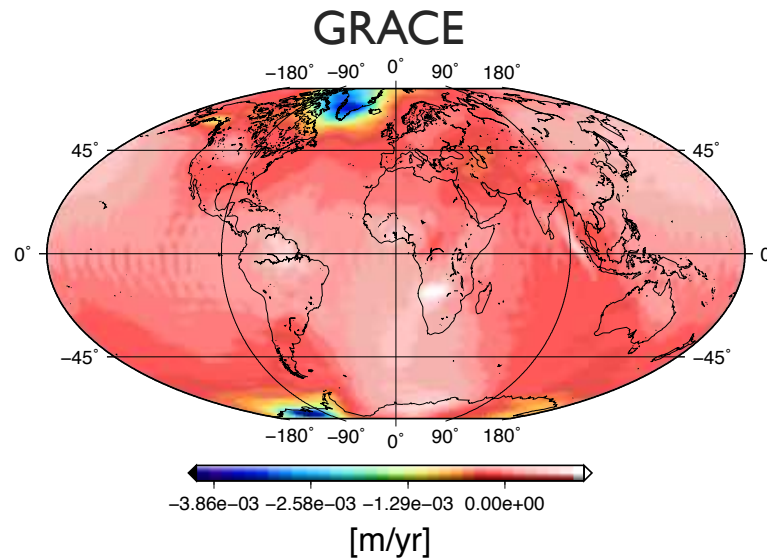
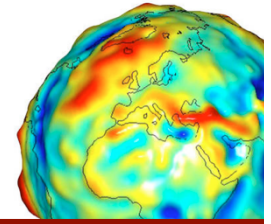


**Mode 6**



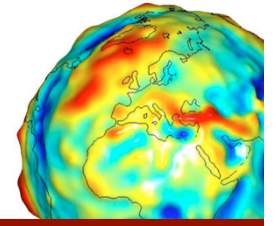
Other modes likely reflect hydrologic variations

# Results – Geoid trend [2003-2013]

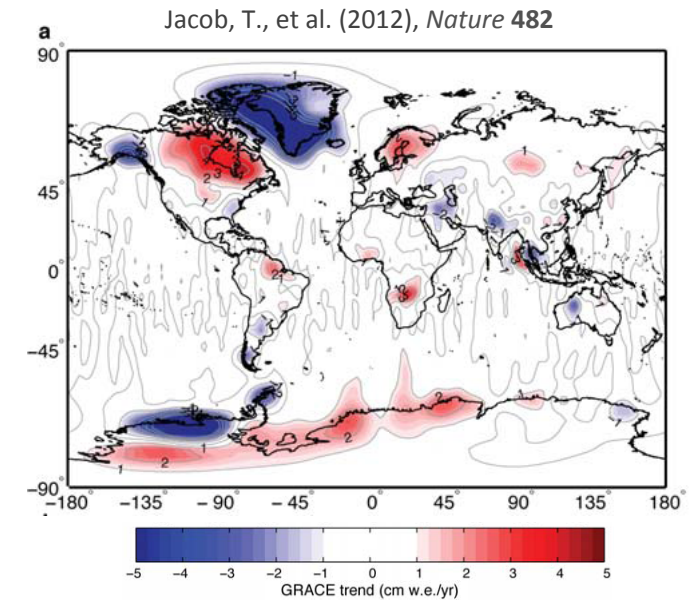




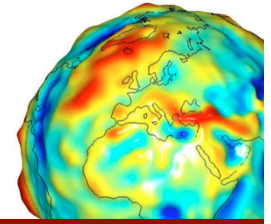
# Validation – Cryosphere



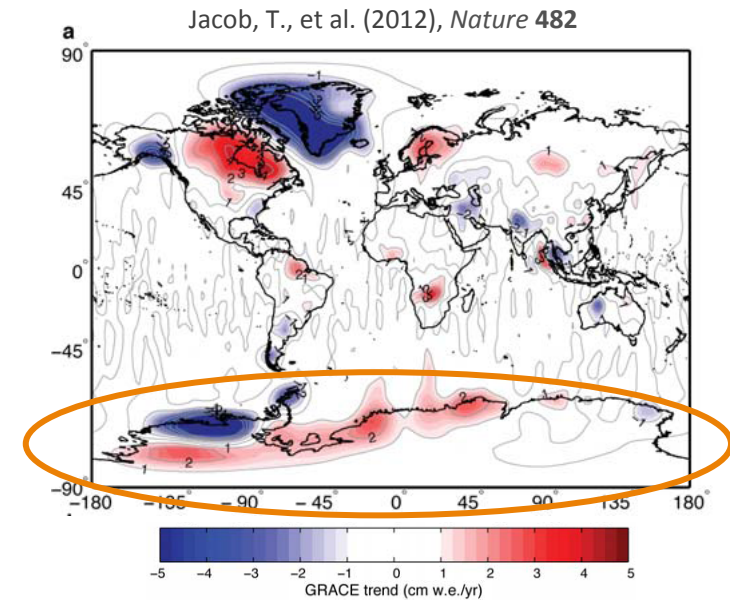
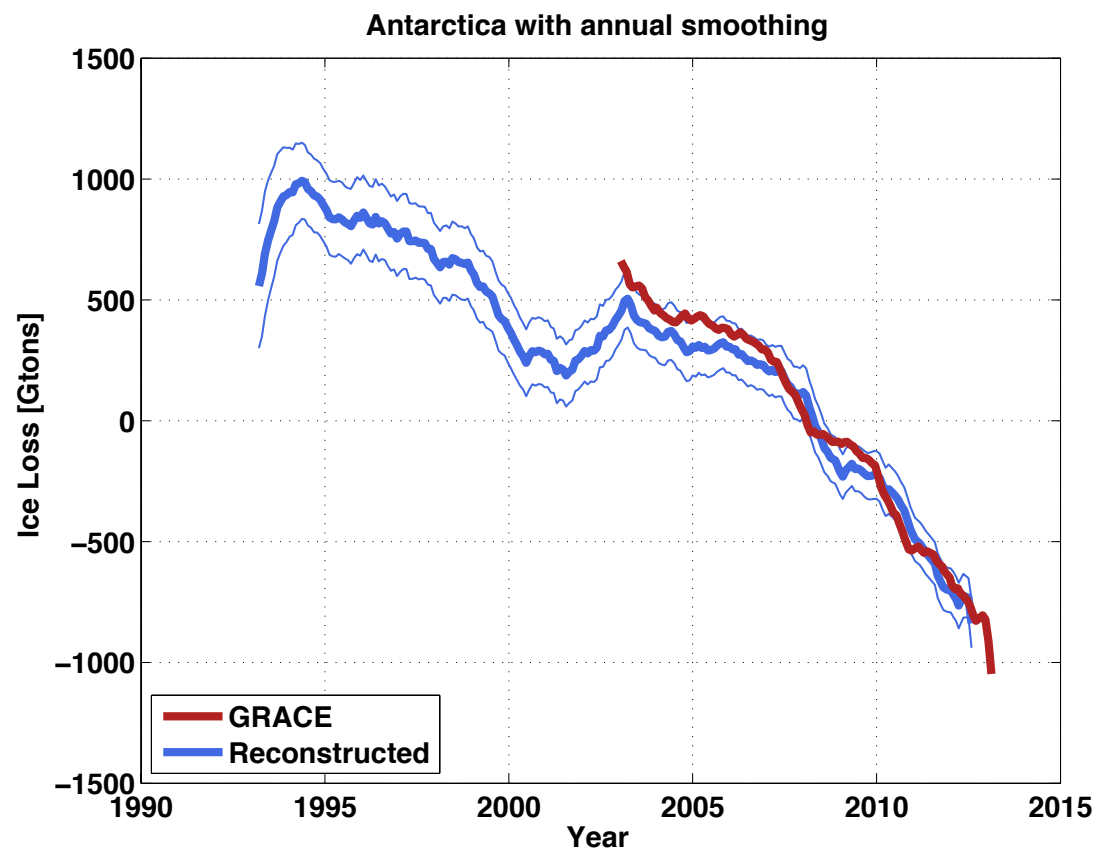
Ice sheet melt via averaging kernel



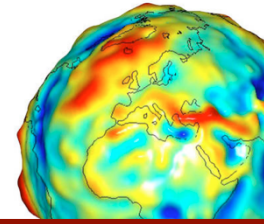
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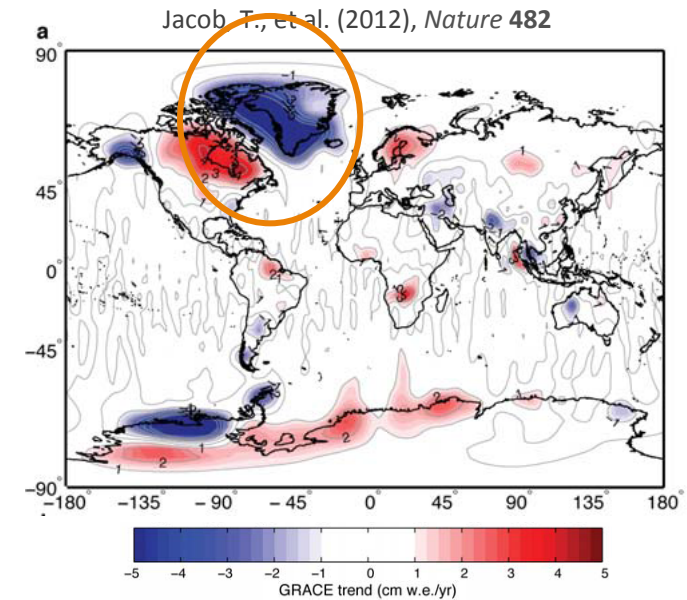
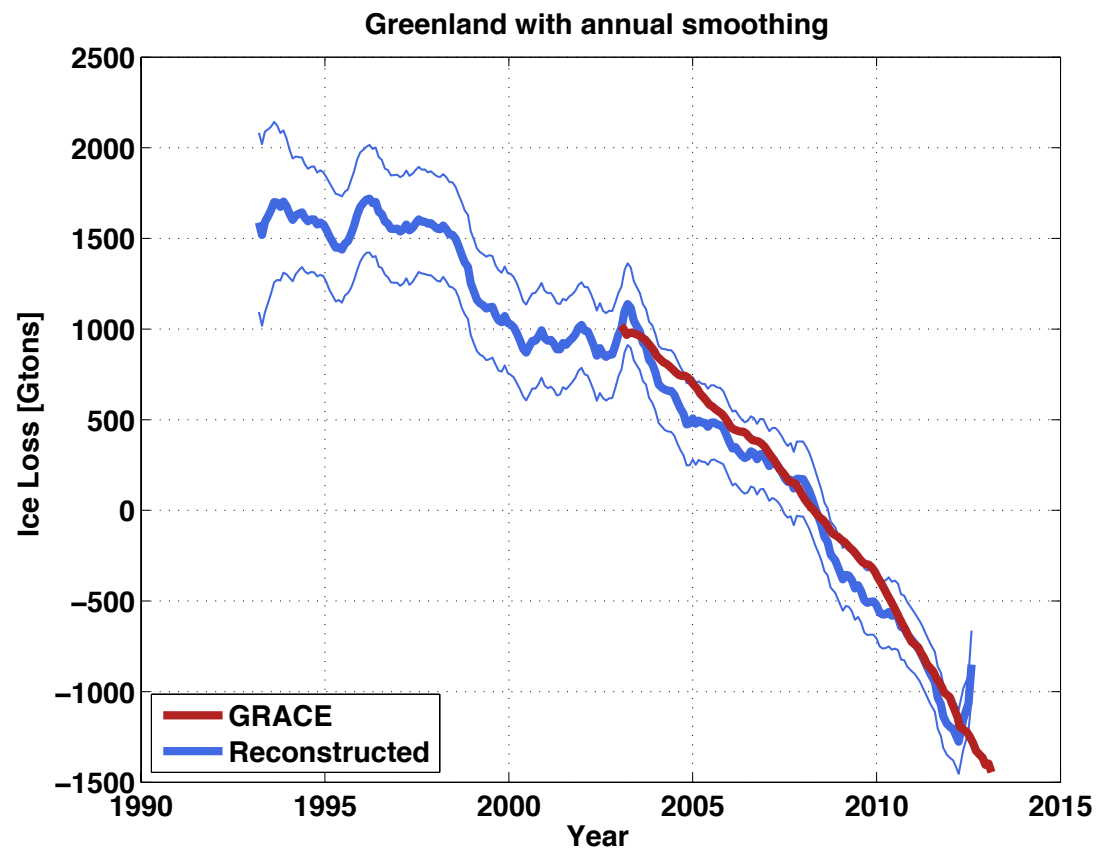
## Ice sheet melt via averaging kernel



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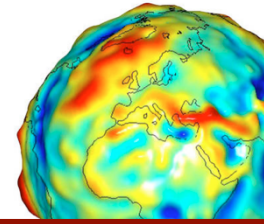


## Ice sheet melt via averaging kernel





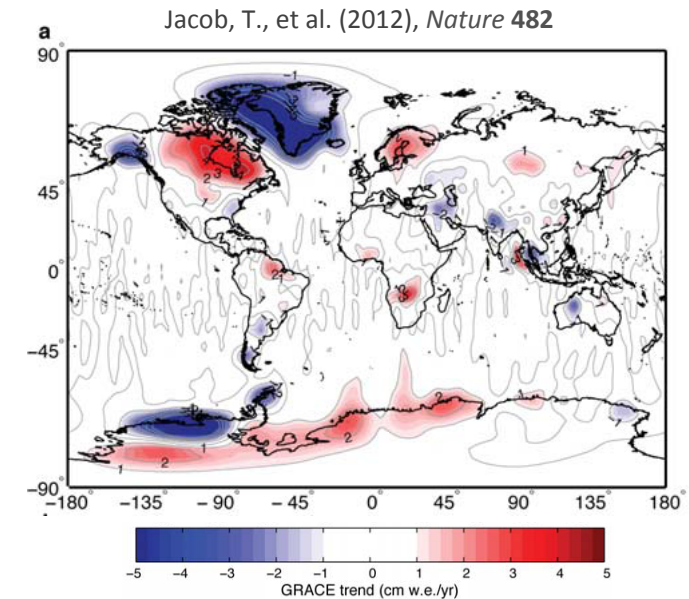
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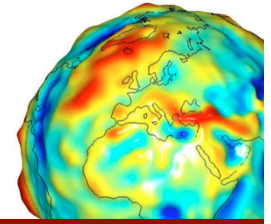
## Ice sheet melt via averaging kernel

### 2003-2013: GRACE vs. Reconstructed

		Reference	Reconstructed
Greenland	CHANGE [Gton]	$2230 \pm 140$	$2090 \pm 500$
	TREND [Gton/yr]	$-239 \pm 6$	$-234 \pm 6$
	ACC. [Gton/yr <sup>2</sup> ]	$-11 \pm 1$	$-8 \pm 6$
Antarctica	CHANGE [Gton]	$1370 \pm 120$	$1130 \pm 230$
	TREND [Gton/yr]	$-150 \pm 6$	$-130 \pm 10$
	ACC. [Gton/yr <sup>2</sup> ]	$-10 \pm 1$	$-12 \pm 3$

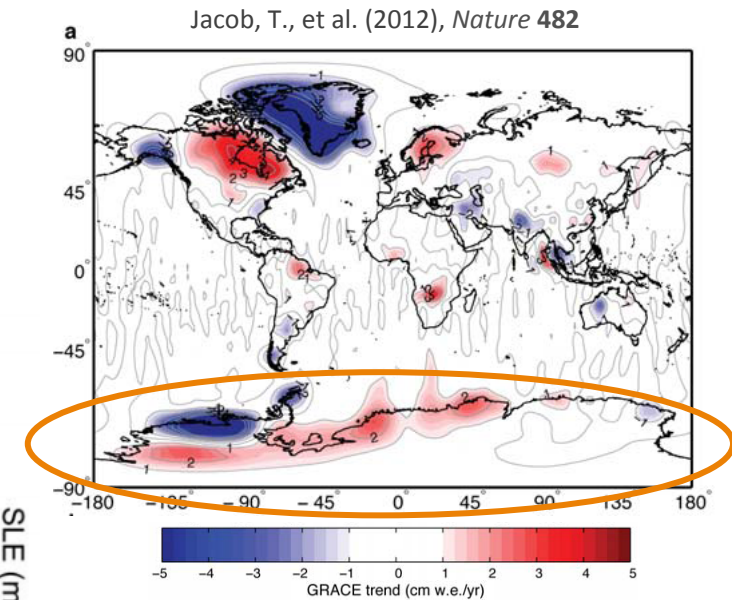
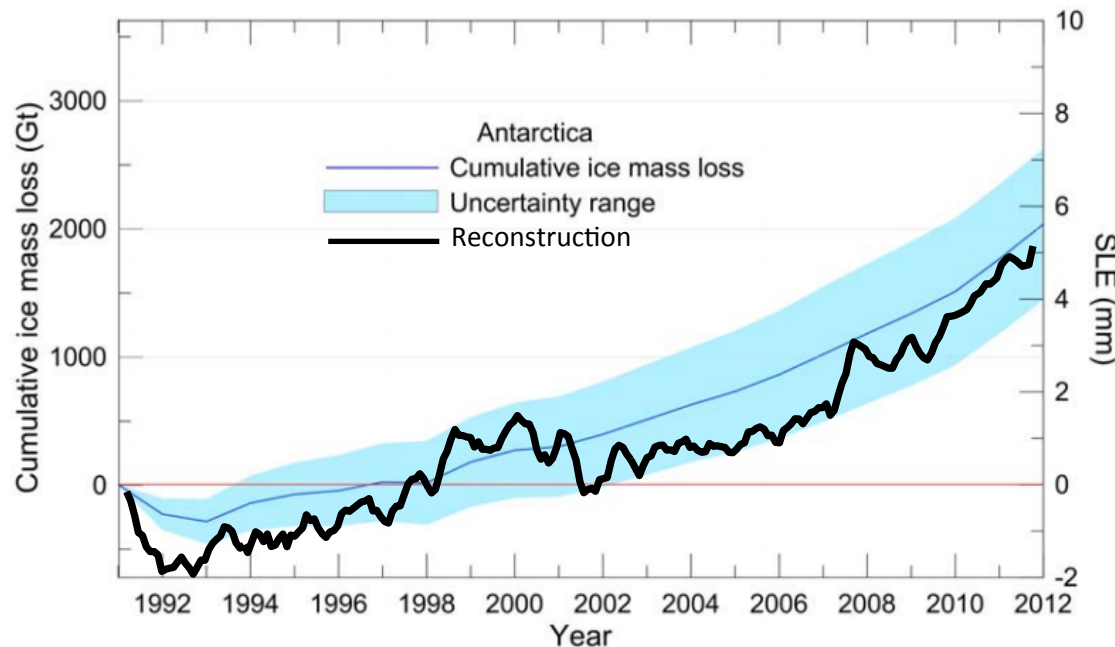


# Validation – Cryosphere

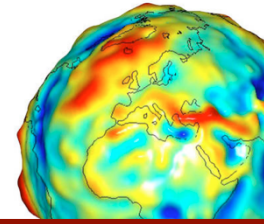


## Ice sheet melt via averaging kernel

1993-2013: IPCC, Chap 4, Fig 4.16

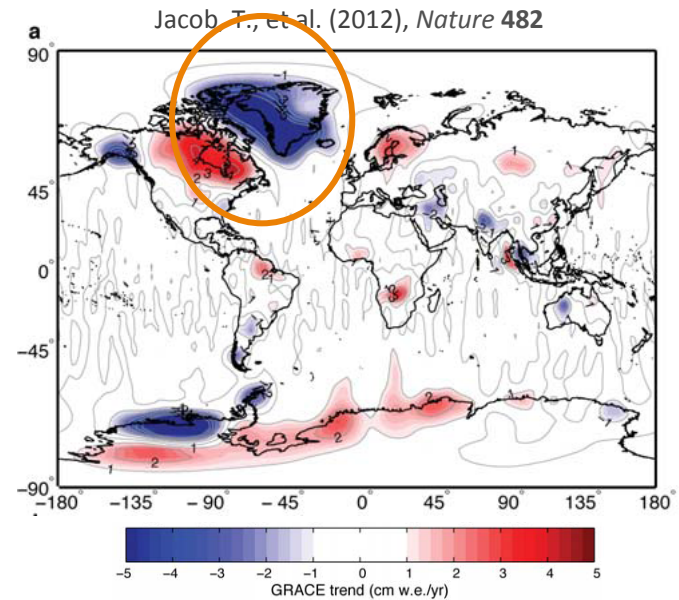
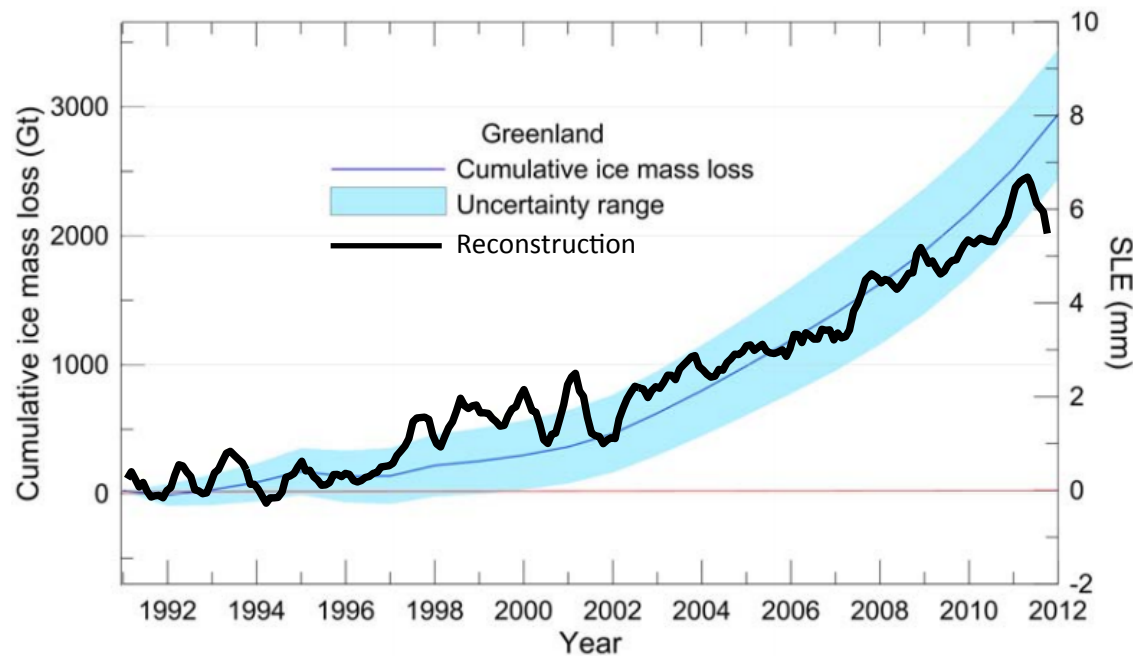


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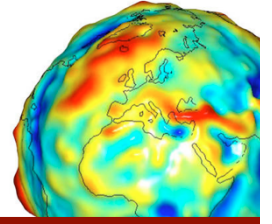


## Ice sheet melt via averaging kernel

1993-2013: IPCC, Chap 4, Fig 4.15



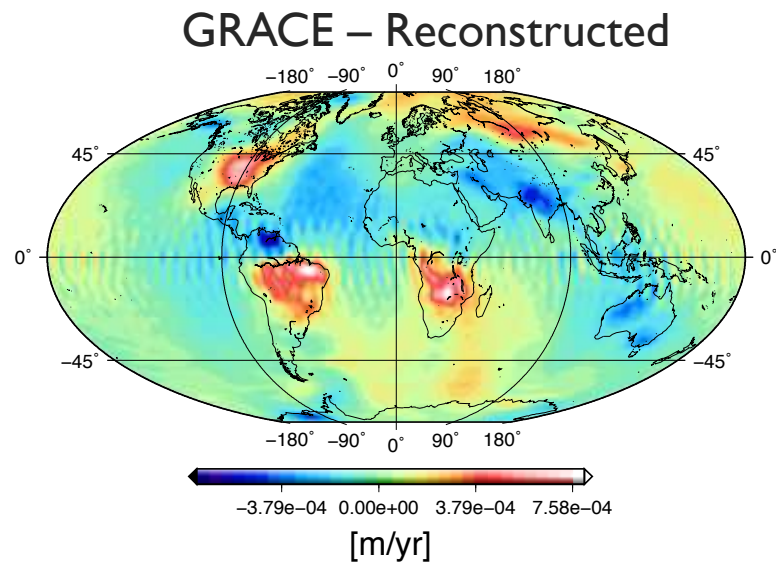
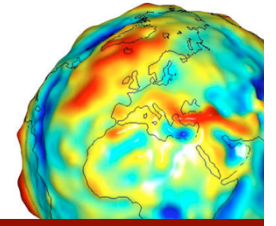
# How to bridge the gap?



Underlying questions... (Exploring and lots of TBD)

1. What tool? EOFs with GRACE and SLR
2. Validation? Agreement in trend and ice sheet melt
3. Improvements?

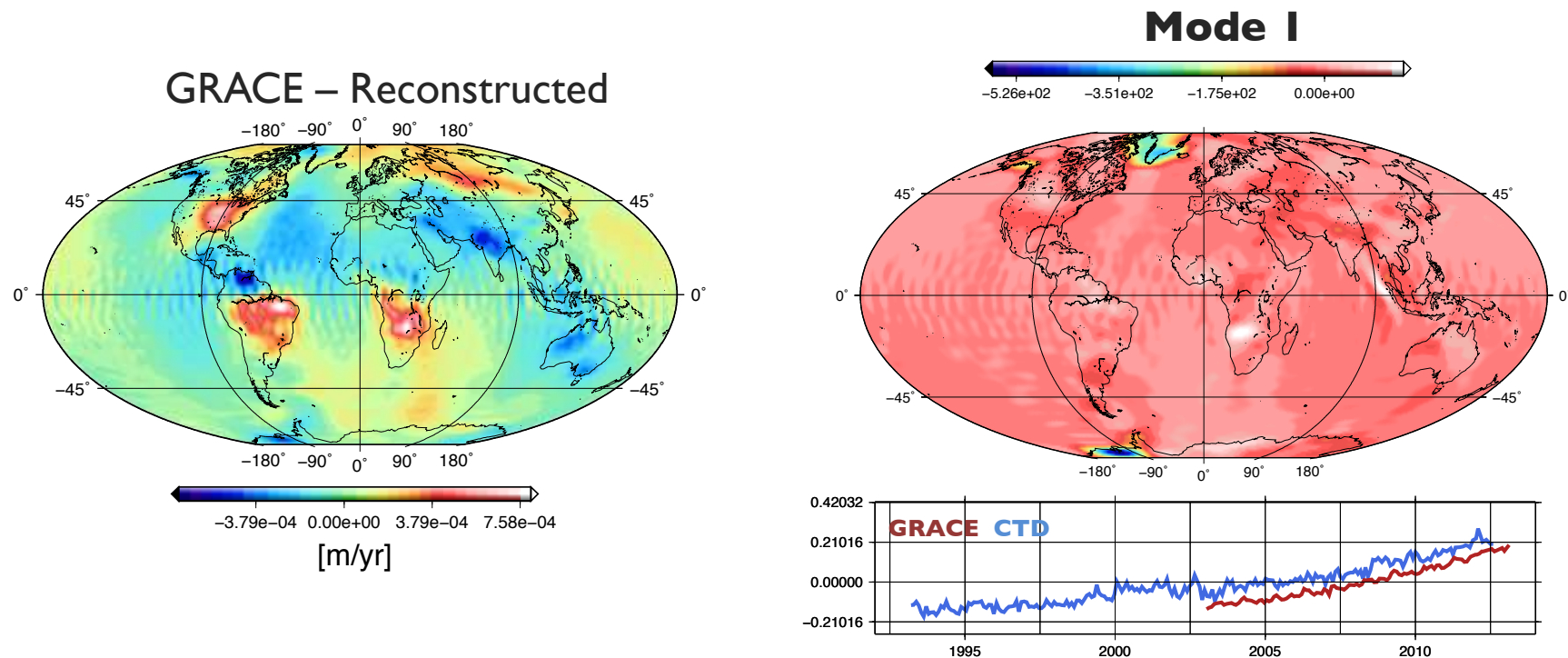
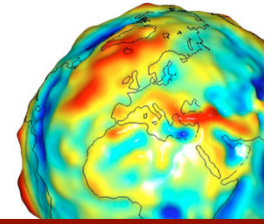
# EOF Improvement – Motivation



- Extra signals + poor month-to-month comparison

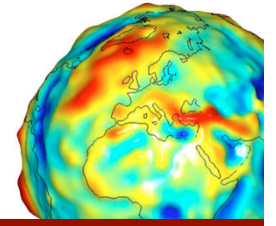


# EOF Improvement – Motivation

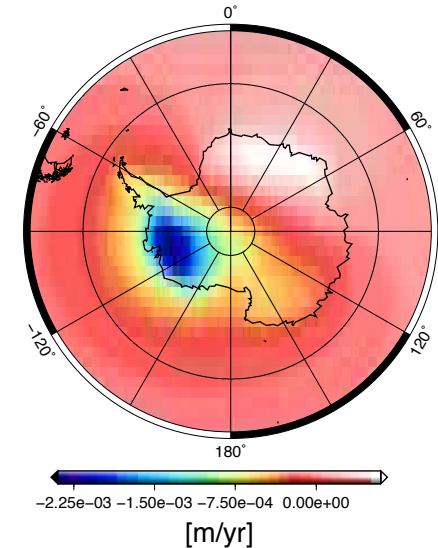
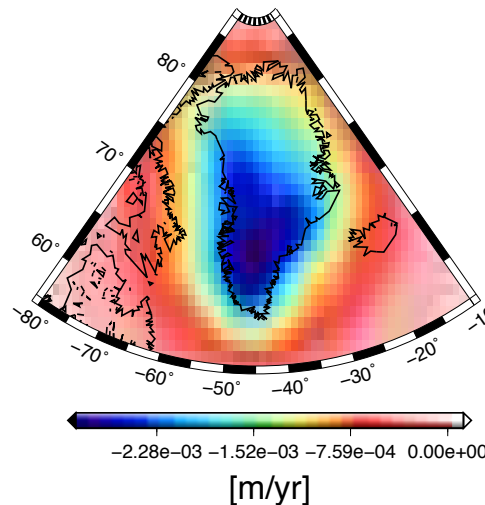
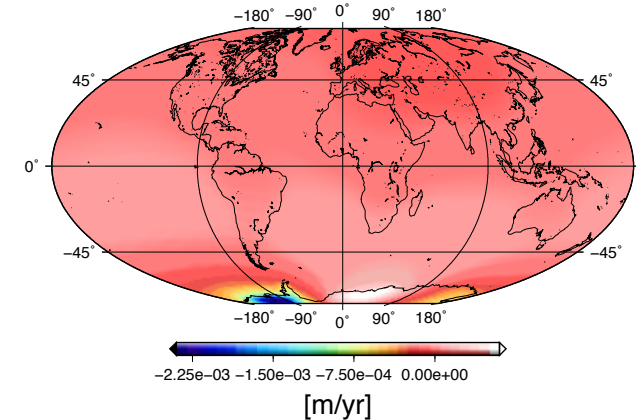
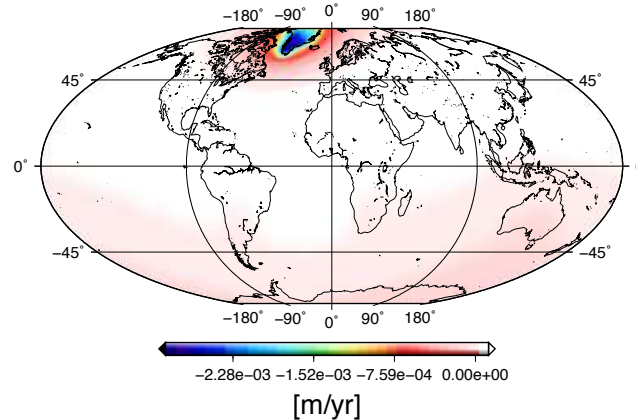


- Extra signals + poor month-to-month comparison
- Seek to deconstruct the first linear trend mode

# Fingerprints

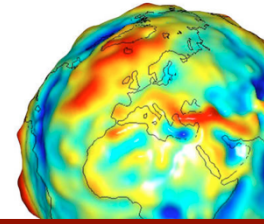


- In first mode, spatial modes are not properly separated.
- Subtract fitted fingerprints from GRACE fields

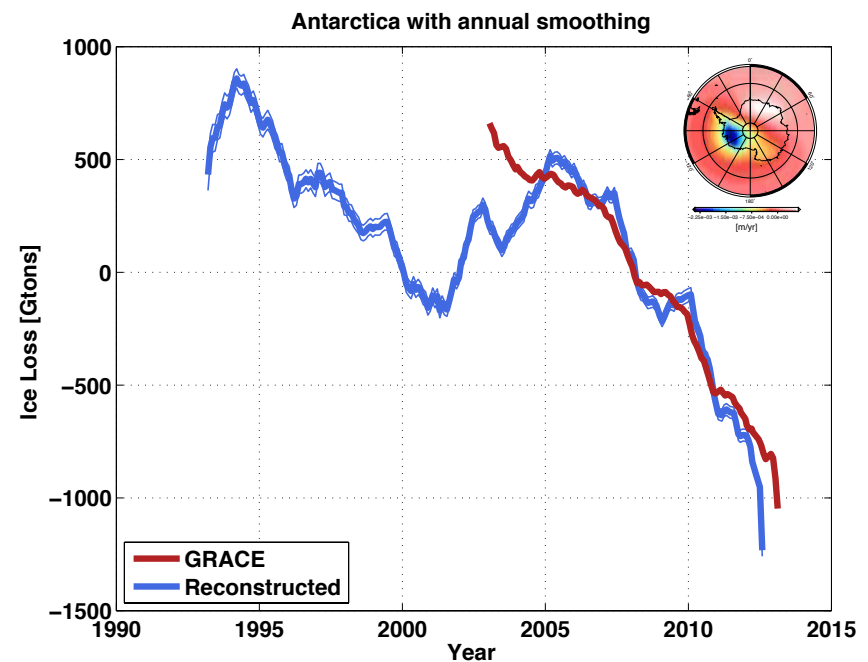
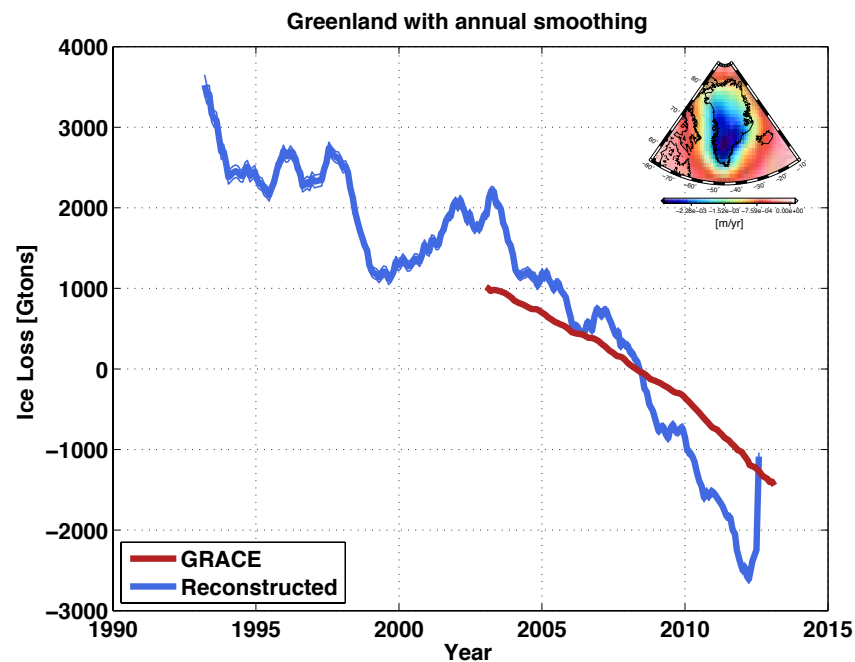


Riva, R. E. M., et al. (2010), *GRL* **37**

# Fingerprints – Influence of SLR

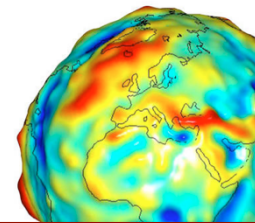


Fingerprints of regions as spatial modes  
SLR captures behavior of mass loss



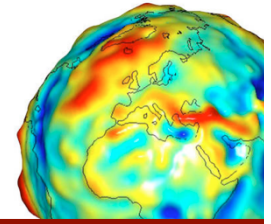


# Fingerprints – Influence of SLR

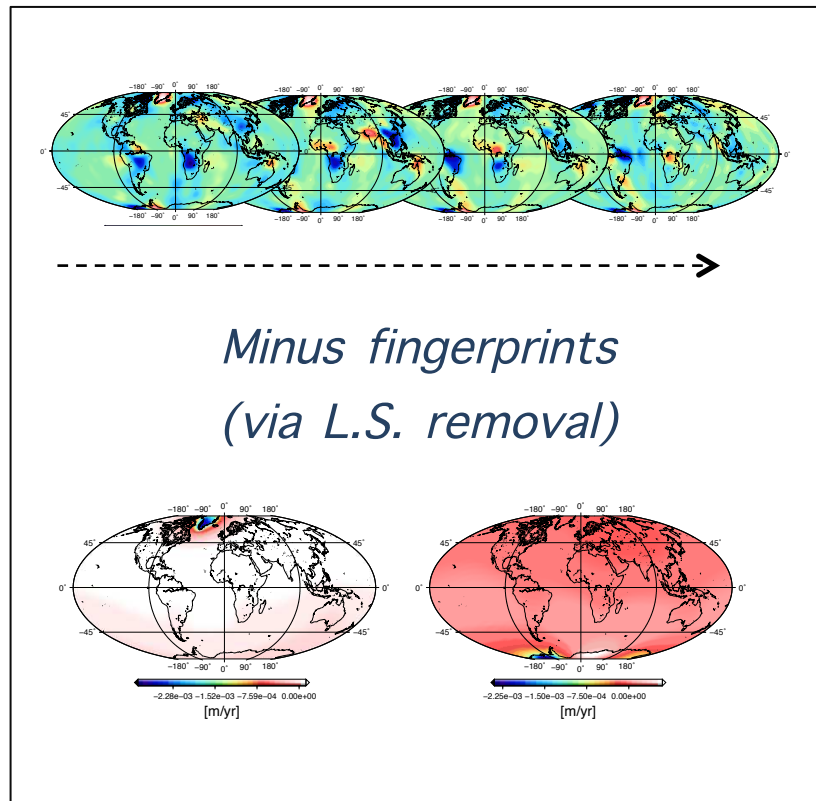


SLR-GSFC vs. SLR-CSR (Tellus)

# EOF Decomposition w/ Fingerprints

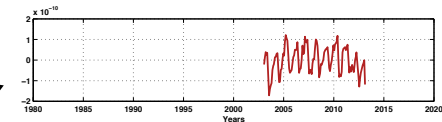


## GRACE-Fingerprint-Free fields

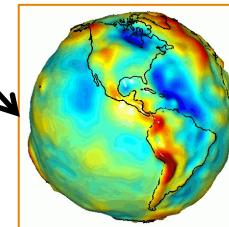


EOF dec.

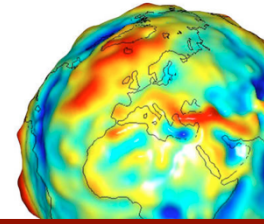
## GRACE-Fingerprint-Free temporal modes



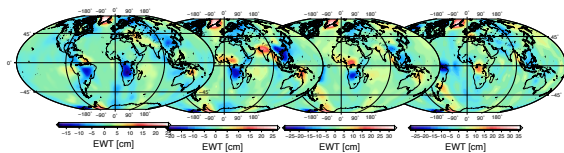
## GRACE-Fingerprint-Free spatial modes



# EOF Reconstruction w/ Fingerprints

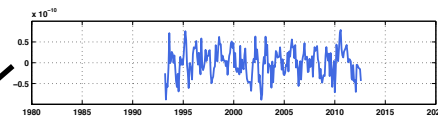


Reconstructed Fields



EOF rec.

Temporal Modes

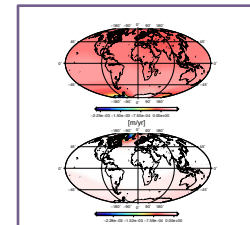
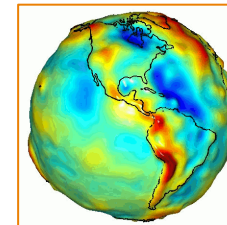


*Fitting to SLR via  
Normal equations*

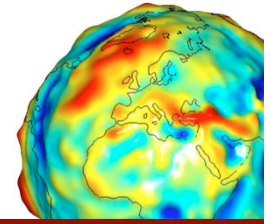
Spatial Modes

GRACE-Fingerprint-  
Free spatial modes

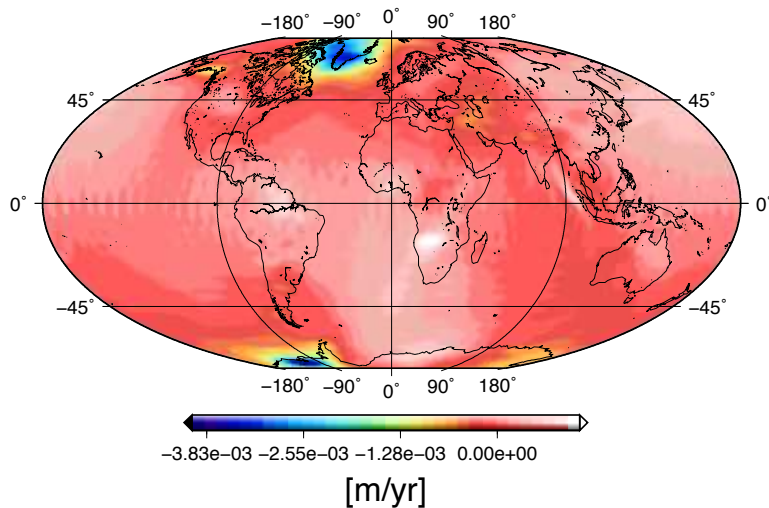
Fingerprints



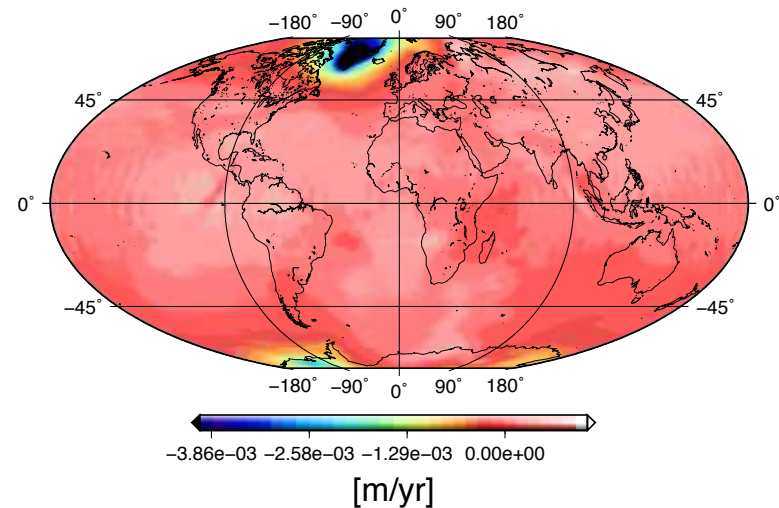
# Fingerprints – Trends



Truth trend

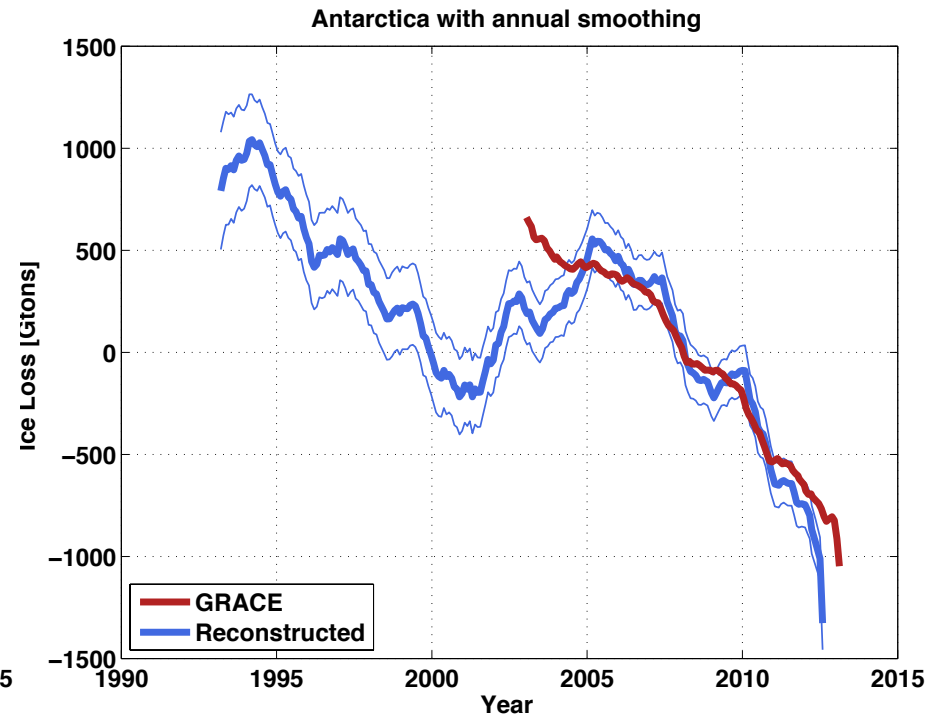
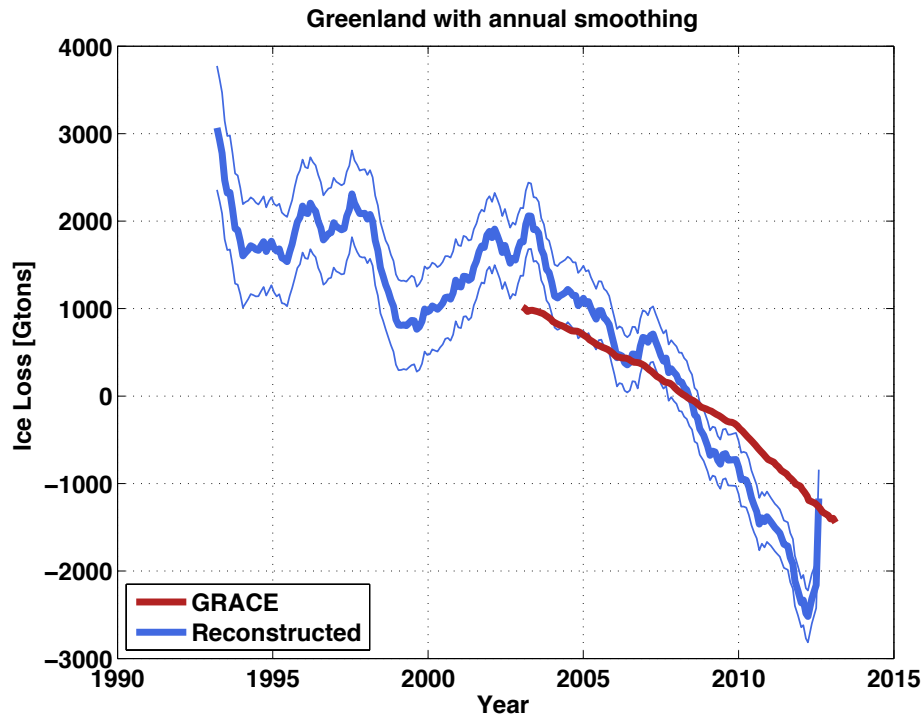
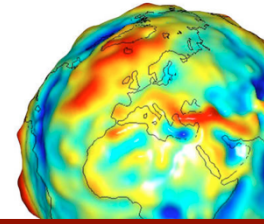


Reconstructed trend [2003-2013]



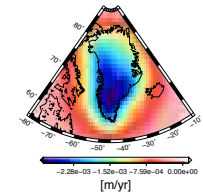
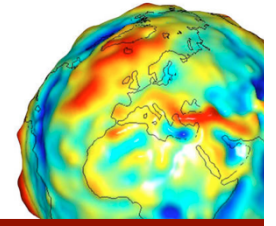
Larger signal over Greenland

# Fingerprints – Cryosphere



Behavior is captured—a little steep for Greenland

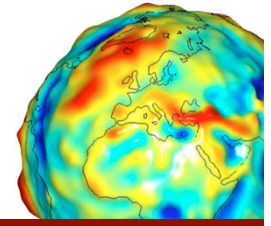
# Future work



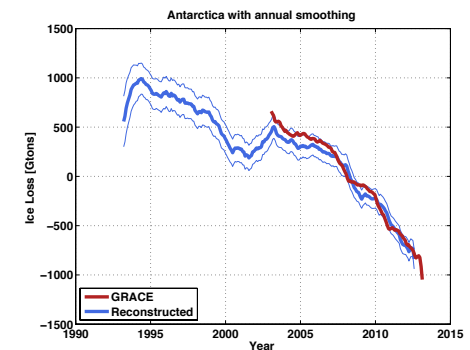
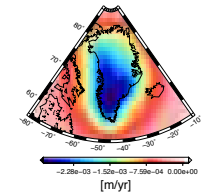
- Fingerprints
  - Tweak shape of fingerprints to reflect changing melt patterns
  - Revisit GIA model over Antarctica
- Reconstruction
  - Expand validation process to pre-GRACE with in-situ observations
  - Test smaller spatial modes (basins)
  - Define errors of GRACE spatial modes
- Data
  - Add CTD data to extend back time-series to 1970s
  - Examine influence of other SLR solutions



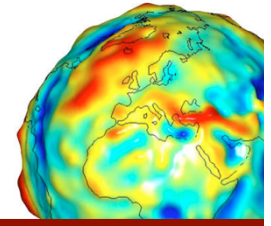
# Future work



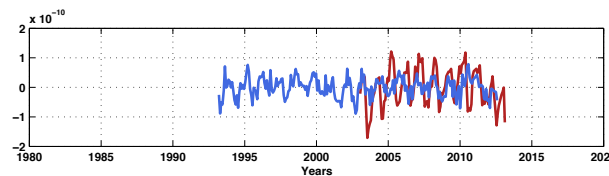
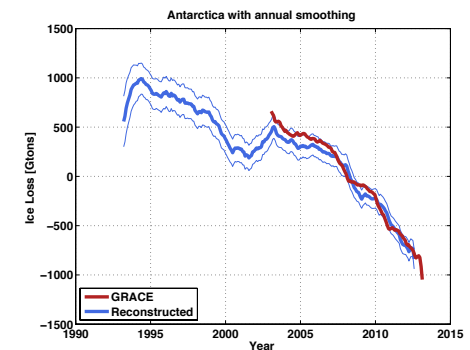
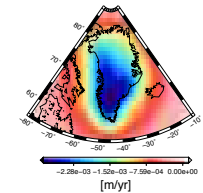
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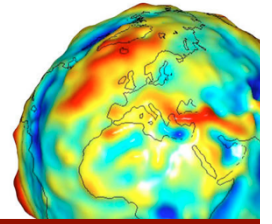
# Future work



- Fingerprints
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# Conclusion – How to bridge the gap?



Underlying questions... (Exploring and lots of TBD)

1. What tool? EOFs with GRACE and SLR
2. Validation? Agreement in trend and ice sheet melt
3. Improvements? Fingerprints + residuals reduce dependence on first mode but further specification of fingerprints is needed