Optimized signal denoising and mass balance estimates of GRACE-like mass change time series

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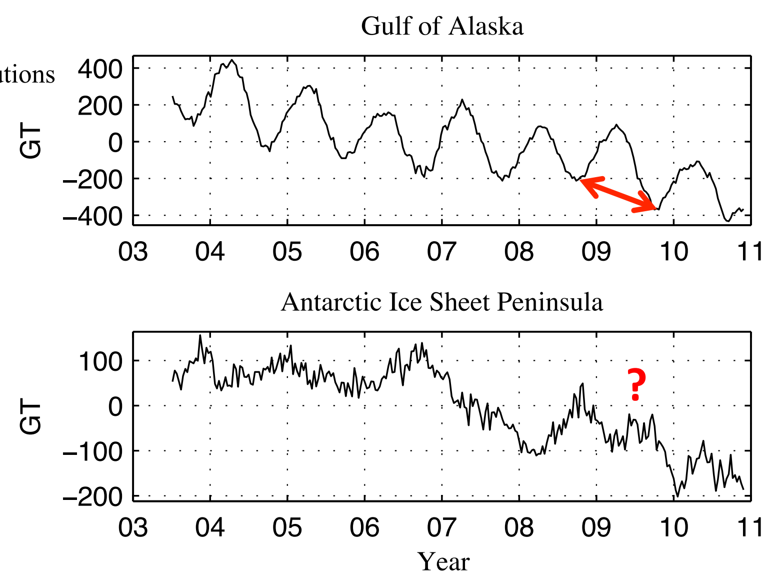
Optimized denoising and mass balance estimation

Motivation

- Apply optimal signal denoising algorithm to regional and individual mascon time series for regional analysis and global mascon product
- Compute seasonal timing and corresponding net mass balances for improved understanding of cryospheric regions
  - Annual mass balance: Mass change between same dates (e.g. Oct 1)
  - Net mass balance: Mass change between seasonal minima

10-day regional mascon solutions from [Luthcke et al., 2013]



Low noise and high-frequency signal:
--> Net mass balance is easily found

Strong noise and high-frequency signal:
--> Net mass balance is difficult

Optimized denoising and mass balance estimation

<u>Procedure to estimate mass balances</u>

1. Denoise the signal
2. Isolate the seasonal signal to determine seasonal timing
3. Compute the seasonal mass values by applying times in Step 2 to the denoised signal of Step 1
4. Compute the mass balances by differencing the extrema of Step 3 (min-min=net balance; max-min=summer; min-max=winter)
5. Compare seasonal timing and mass balances to truth (for simulation)

Input: Time series of regional mass change
Output: Seasonal timing and seasonal/net mass balances

Ideally we would also like to be able to compute uncertainties for both the seasonal timing and mass balance estimates.

Optimized denoising and mass balance estimation

Summary of work

1. Simulation of GRACE-like time series of mass change with noise
2. Search for optimal denoising algorithm
   - Gaussian smoothing
   - Wavelet thresholding
   - Ensemble Empirical Mode Decomposition (EEMD)
   - Complete EEMD with Adaptive Noise (CEEMDAN)
   - Weiner filtering
3. Search for optimal method to isolate seasonal timing
   - Wavelet multiresolution analysis
   - EEMD and CEEMDAN
   - Cluster analysis of EEMD and CEEMDAN (new method)
4. Results and analysis: Apply signal denoising (#2) and isolation of seasonal signal (#3) to simulated signals (#1) to compute mass balances estimates

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Optimized denoising and mass balance estimation

1. Simulation of GRACE-like time series of mass change

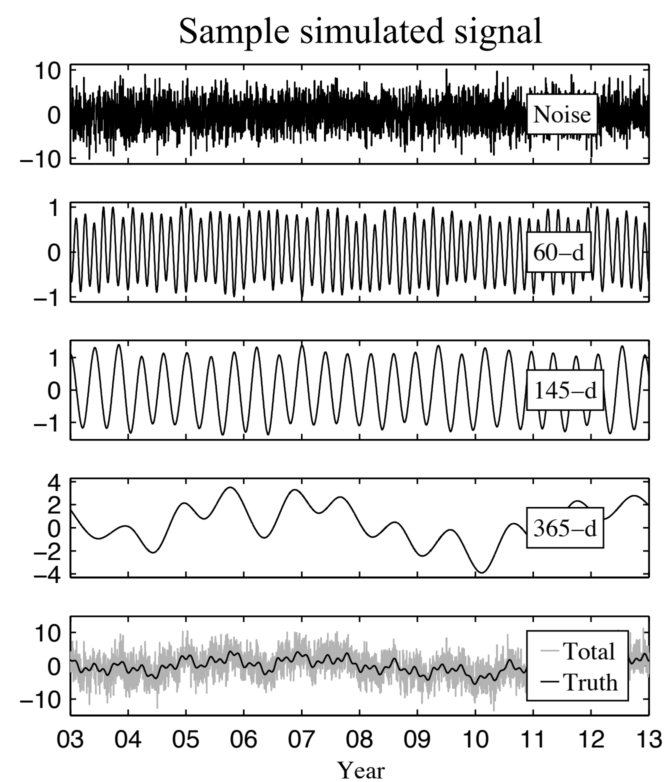
- Simulated data is sum of ~365-d, ~145-d, ~60-d, and Gaussian white noise with 1-day sample rate. The 365d/145d/60d signals vary in amplitude and frequency.
- This signal is averaged with 10-day and 30-day windows to match GRACE sampling
- We define the following ratios for analyzing the effects of noise and the high-frequency signal:

  RMS($365d_{osc}$) is defined to be equal to 1

  $\boldsymbol{R_n}$ = RMS(noise)/RMS($365d_{osc}$) = RMS(noise)

  $\boldsymbol{R_{hf}}$ = RMS(145+60d)/RMS($365d_{osc}$) = RMS(145+60d)

- Due to the wide range of trend magnitudes for different regions, any selected value would be arbitrary and would skew the results, so trends are not included in simulated data: <u>Results will be pessimistic for regions with large trends.</u>



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2. Search for optimal denoising algorithm

- **Gaussian smoothing:** Convolve signal with normal distribution with smoothing window of 10-days.
- **Wavelet denoising:** 1.) Wavelet transform decomposes the input signal for a selected wavelet type; 2.) soft or hard thresholding is applied to the "noise" wavelet coefficients; 3.) the signal is reconstructed with the inverse wavelet transform.
- **EEMD and CEEMDAN:** Variations of the Empirical Mode Decomposition (EMD), first proposed by [Huang et al. 1998]. This is an adaptive data analysis method that does not rely on any *a priori* constraints and is unique in that it is not dependent on assumptions of stationarity or linearity.
- **Weiner filter:** In the Fourier domain, uses the signal and noise spectra to form an ideal low-pass filter. We analyze the optimal case (signal and noise are known), and a modified case where the signal is the FFT of the Gaussian smoothed signal and the noise is found from the highest frequency wavelet coefficients.

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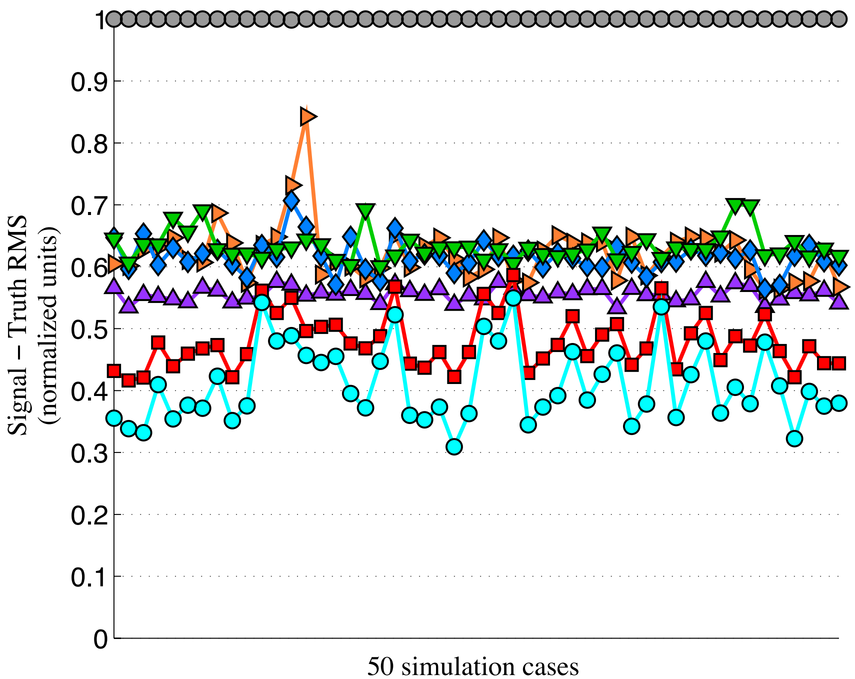
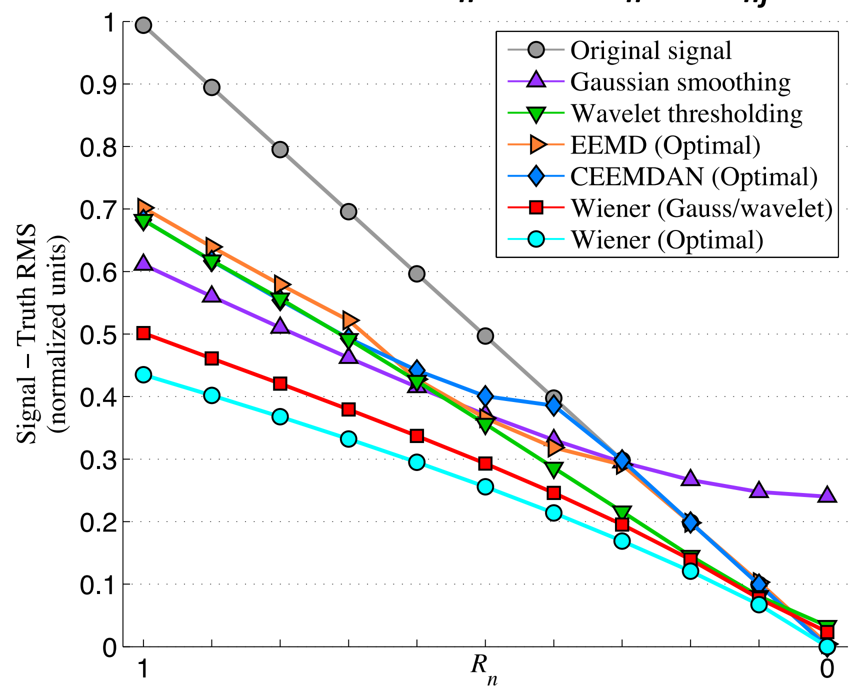
2. Search for optimal denoising algorithm: RESULTS

Technique comparison for 50 different randomized signals with R_n=1 and R_{hf}=1



Technique comparison for different levels of noise: R_n=1 --> R_n=0 (R_{hf}=1)



Conclusion: Wiener (Gauss/wavelet) filter provides the best performance.

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3. Search for optimal method to isolate seasonal timing

The goal is to isolate the seasonal variations from the high-frequency signal and noise.

- **Wavelet multiresolution analysis:** Execute the discrete wavelet transform, zero out all frequency bands except that which contains the seasonal frequency, then apply inverse wavelet transform.
- **EEMD and CEEMDAN:** Identify the intrinsic mode function (IMF) that defines the seasonal variations.
- **EEMD and CEEMDAN cluster analysis:** This newly developed method stores the individual seasonal IMFs from the standard EEMD/CEEMDAN execution, and only considers the seasonal extrema for cases where the correct number of extrema are found (one minima/maxima per year). The spread of seasonal extrema provides a useful approach for quantifying uncertainties in the seasonal timing.

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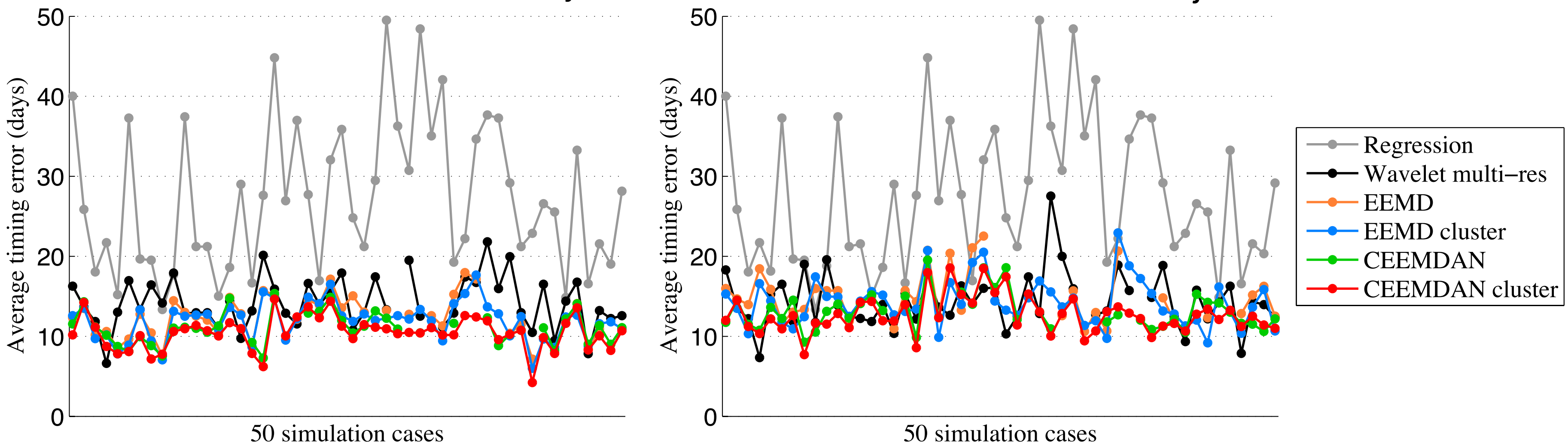
3. Search for optimal method to isolate seasonal timing: RESULTS

Comparison for 50 different signals with no noise: $\boldsymbol{R_n}$=0, $\boldsymbol{R_{hf}}$=1

Comparison for 50 different signals with noise: $\boldsymbol{R_n}$=1, $\boldsymbol{R_{hf}}$=1



Conclusion: CEEMDAN cluster provides the most consistent performance. This approach also provides an effective way to compute uncertainties in the seasonal timing, containing the truth for 98% (no noise) and 94% (with noise) of extrema.

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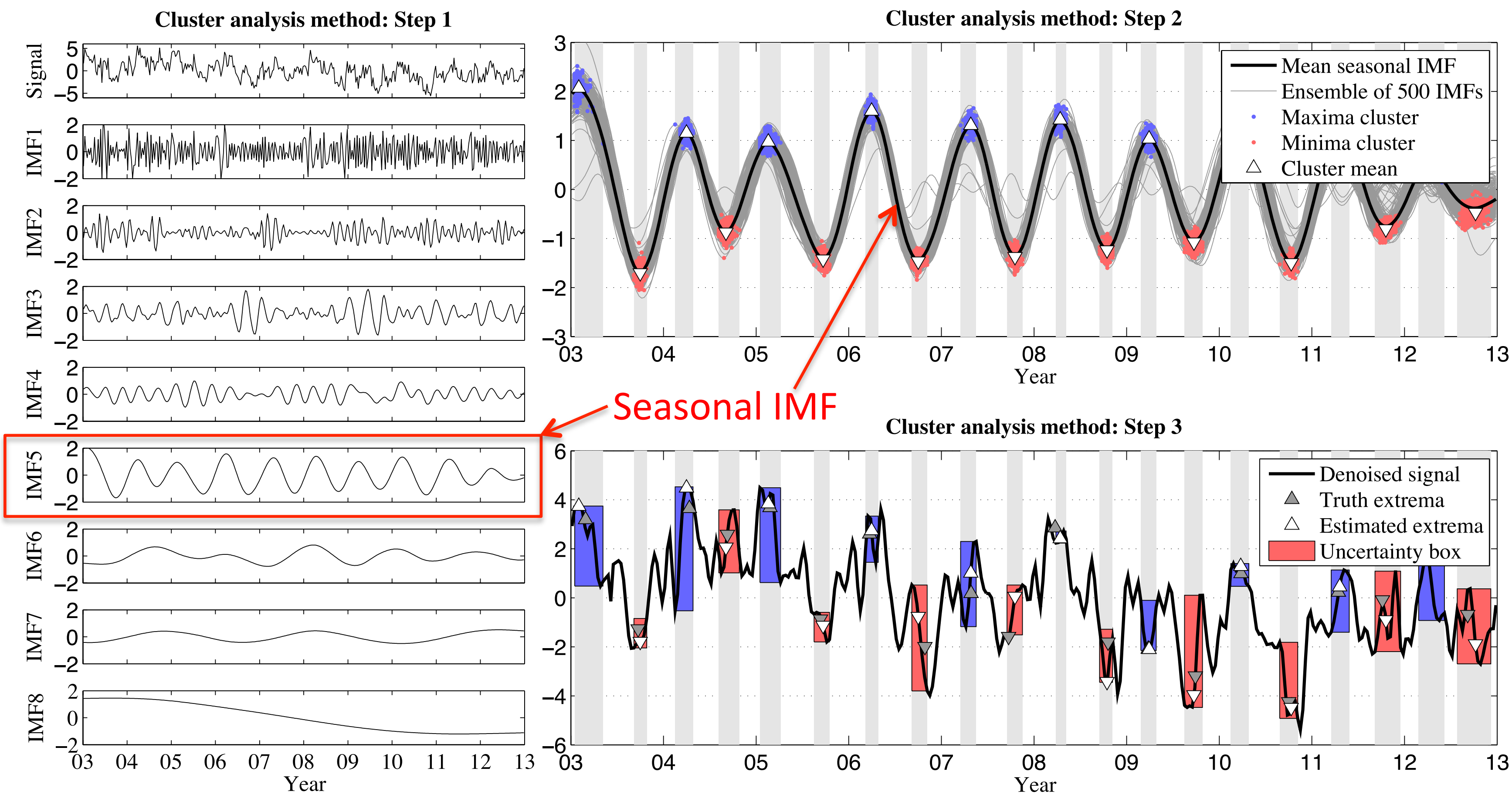
4. Results and analysis

Summary of CEEMDAN cluster analysis method for mass balance estimation



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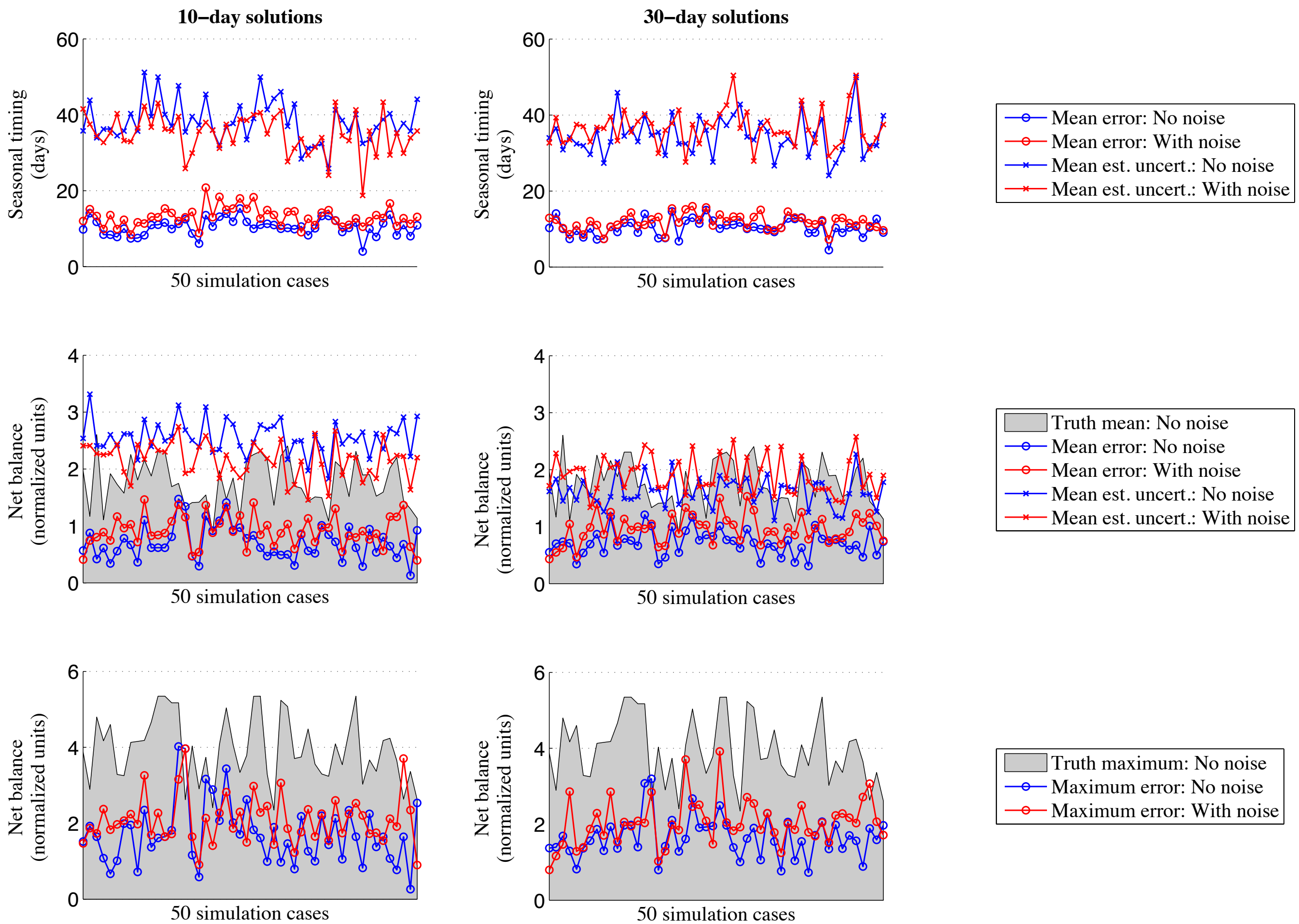
4. Results and analysis: Effect of noise



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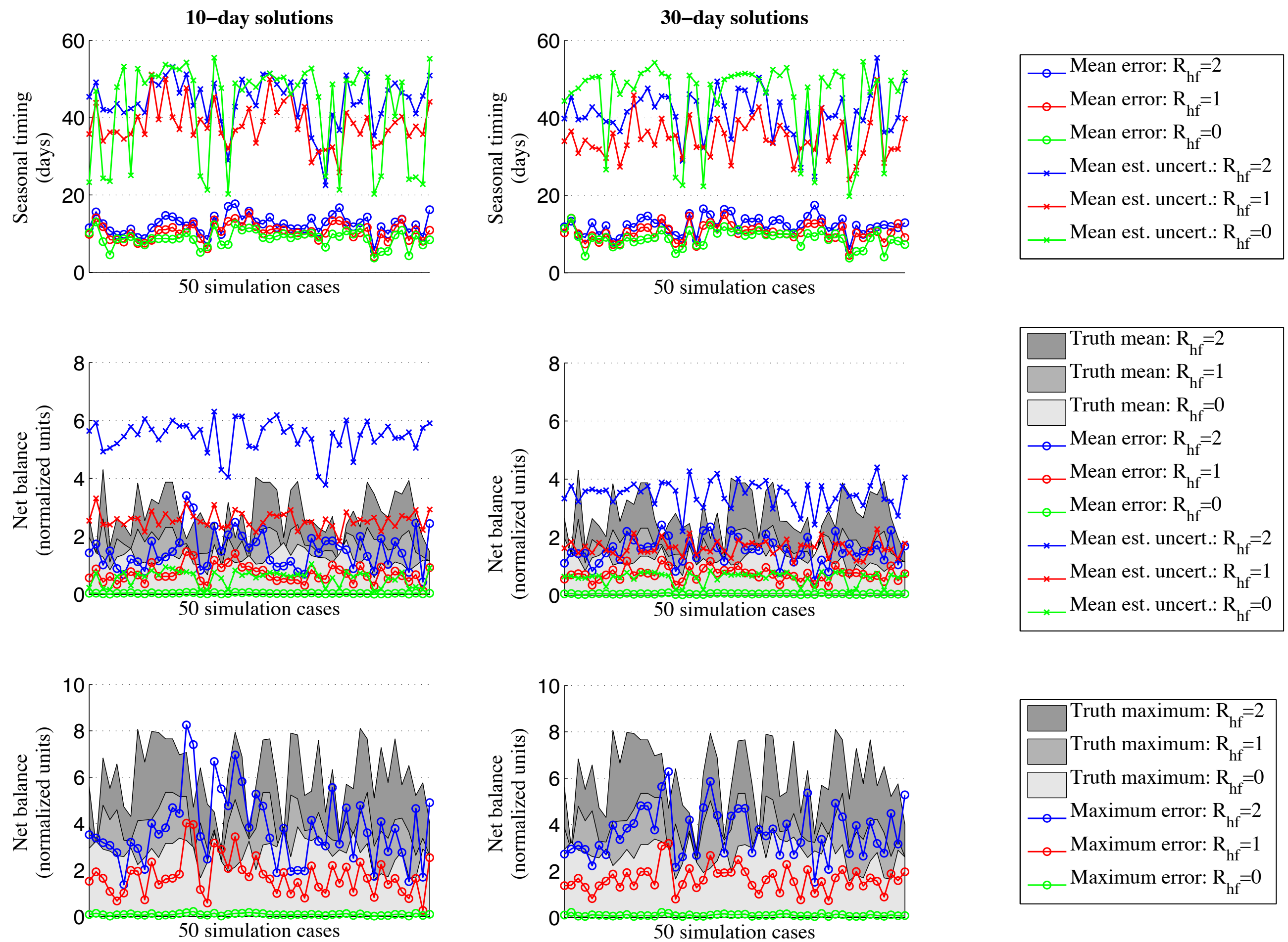
4. Results and analysis: Effect of high-frequency signal power



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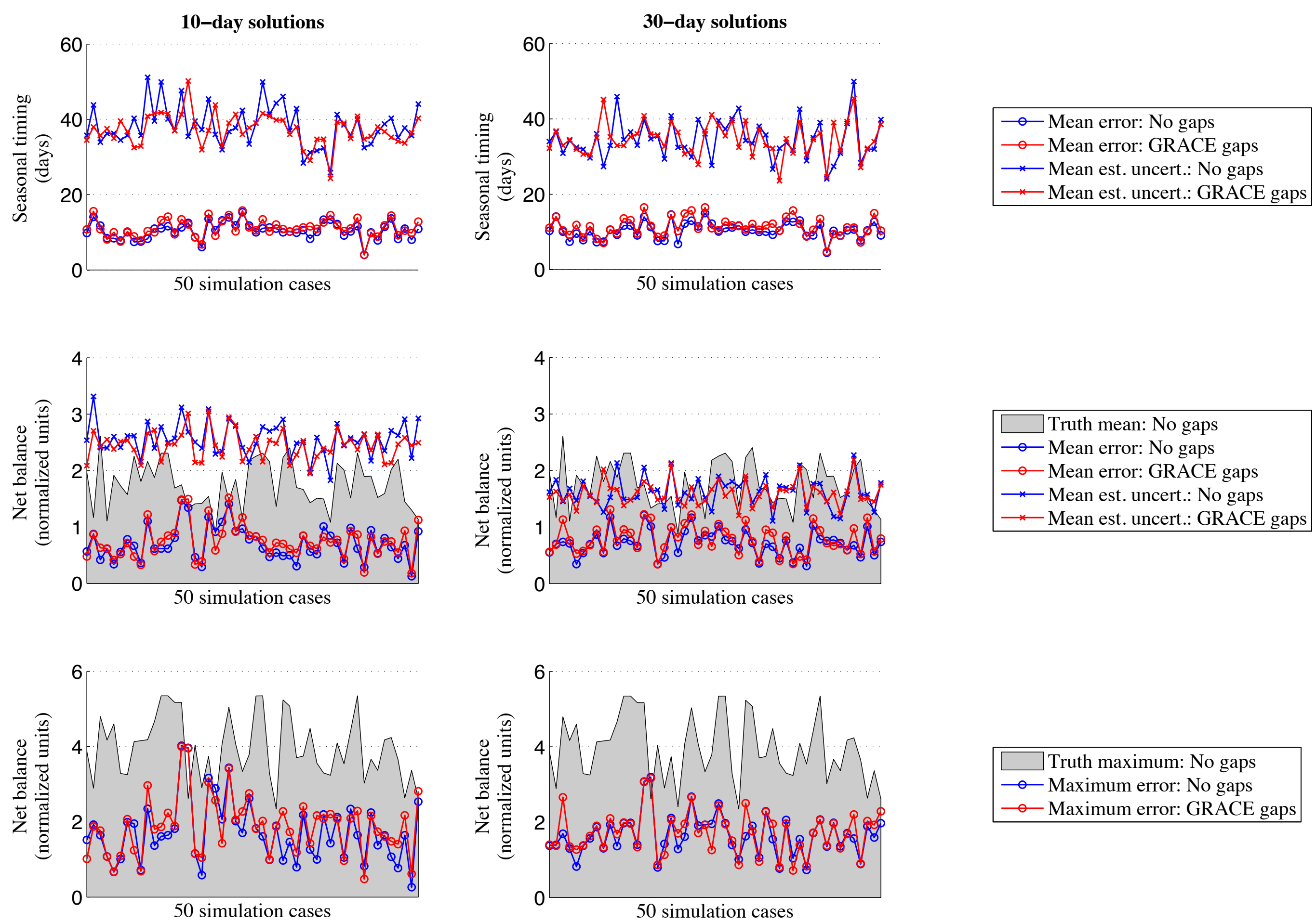
4. Results and analysis: Effect of GRACE mission data gaps (Jan 1, 2003 – Jan 1, 2013)



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Summary and Conclusions

- Gauss/wavelet Wiener filter shows excellent performance at denoising GRACE-like signals with 10-day averaging. The Gaussian smoothing and highest wavelet coefficients define the signal and noise spectra respectively.
- The newly-developed cluster analysis application of the CEEMDAN algorithm consistently performs well in isolating the seasonal signal and provides a reliable way to quantify uncertainties. Mean seasonal timing errors ≈10-15 days.
- Even high levels of noise do not significantly affect determination of seasonal timing and mass balances.
- Strong high-frequency signals do not affect seasonal timing estimates but have large effects on mass balances.
- The effect of GRACE data gaps is small.
- Very little difference in performance between 10-day and 30-day averages. One observable disadvantage of the 30-day averages is a tendency to underestimate the mass balance errors when the high-frequency signal power is strong.

This work is currently in review with Advances in Adaptive Data Analysis.