Statistical investigation of sensitivity of continental water storage with respect to ENSO

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Introduction

Climate change has a strong impact on hydrologic variables. To investigate the impact of the El Niño phenomenon on terrestrial water storage variation, El Niño / Southern Oscillation (ENSO) index is used to estimate water storage variation through two linear models. The prediction by ENSO is validated against monthly observations from GRACE.

ENSO Index

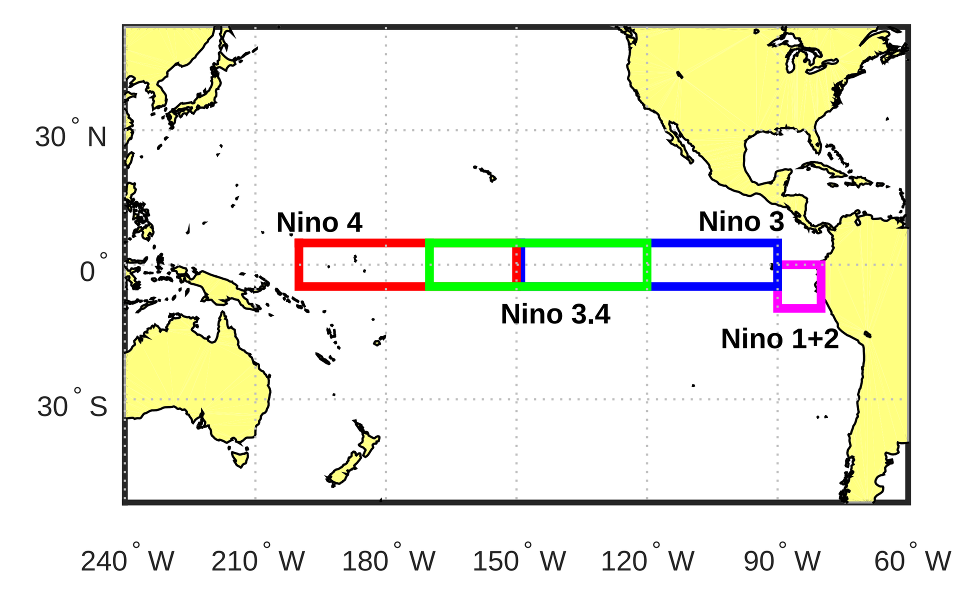

Figure 1: Regions which ENSO index represents in Pacific Ocean

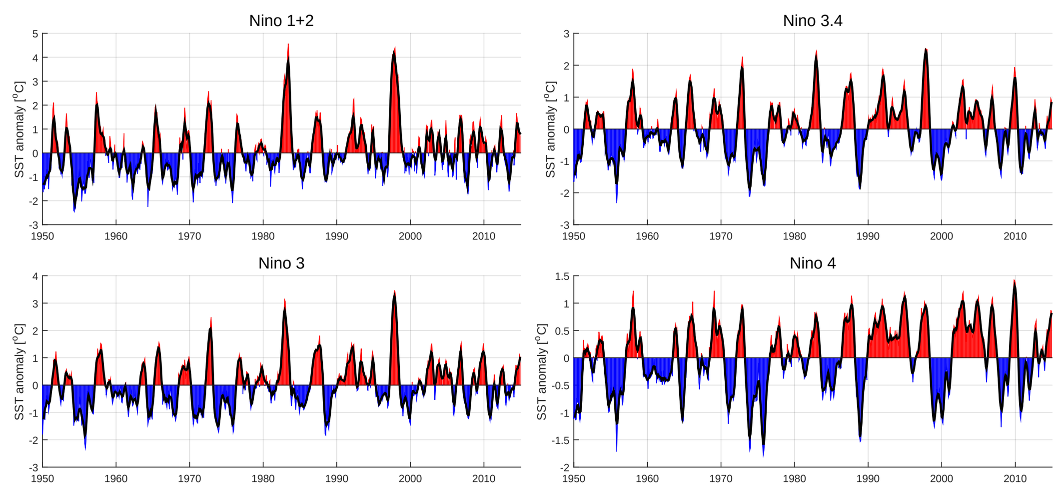

Figure 2: 4 ENSO indices

The ENSO indices show quasi-periodic climate patterns that occurs across the tropical Pacific Ocean.

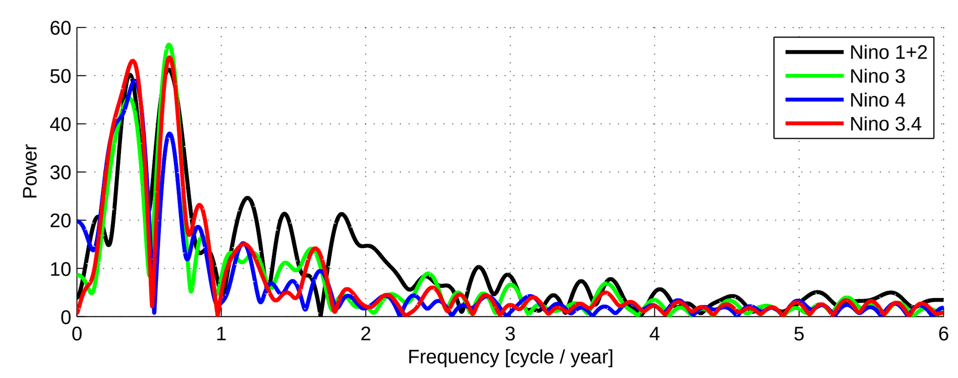

Figure 3: Power spectrum of 4 ENSO indices time series. All of them show strong frequency at or close to 0.34 and 0.65, which presents 3-year and 1.5-year cycle.

Methods

Model I

- Considering the different dominant frequency of GRACE and ENSO signals, we build up a linear model which takes the phase delay into account. It describes the relationship between GRACE and ENSO observations at different epochs. In this model, we assume that ENSO signals are always forward to GRACE signals.

$$\Delta M_t = dM_t - \widetilde{dM}_t = a_1 \cdot dS_{t-1} + a_2 \cdot dS_{t-2} + \ldots + a_p \cdot dS_{t-p}$$

- dM_t is monthly water storage anomaly at epoch t, $\widetilde{dM}_t$ is the mean for every month, ΔM_t is residual after removing the monthly mean, dS_t is monthly sea surface temperature anomaly from ENSO, and a_p are model parameters for different epochs with prediction step p.

$$\begin{bmatrix} \Delta M_{t_1} \\ \Delta M_{t_2} \\ \vdots \\ \Delta M_{t_n} \end{bmatrix} = \begin{bmatrix} dM_{t_1} - \widetilde{dM}_{t_1} \\ dM_{t_2} - \widetilde{dM}_{t_2} \\ \vdots \\ dM_{t_n} - \widetilde{dM}_{t_n} \end{bmatrix} = \begin{bmatrix} dS_{t_1-1} & dS_{t_1-2} & \cdots & dS_{t_1-p} \\ dS_{t_2-1} & dS_{t_2-2} & \cdots & dS_{t_2-p} \\ \vdots & \vdots & \ddots & \vdots \\ dS_{t_n-1} & dS_{t_n-2} & \cdots & dS_{t_n-p} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_p \end{bmatrix}$$

Model II

- The target of building this auto-regressive model is trying to combine 4 ENSO indices together, so as to see how they influence the water storage variation.

$$\Delta M_t = dM_t - \widetilde{dM}_t = a \cdot dM_{t-\tau} + b_1 \cdot dS_{1,t-\tau} + \ldots + b_m \cdot dS_{m,t-\tau}$$

- dM_t, $\widetilde{dM}_t$, ΔM_t represent respectively monthly water storage anomaly, monthly mean and monthly residual at time t. $dS_{m,t}$ are observations from m different ENSO indices, a and b_m are model parameters with various lead time τ in months.

$$\begin{bmatrix} \Delta M_{t_1} \\ \Delta M_{t_2} \\ \vdots \\ \Delta M_{t_n} \end{bmatrix} = \begin{bmatrix} dM_{t_1} - \widetilde{dM}_{t_1} \\ dM_{t_2} - \widetilde{dM}_{t_2} \\ \vdots \\ dM_{t_n} - \widetilde{dM}_{t_n} \end{bmatrix} = \begin{bmatrix} dM_{t_1-\tau} & dS_{1,t_1-\tau} & \cdots & dS_{m,t_1-\tau} \\ dM_{t_2-\tau} & dS_{1,t_2-\tau} & \cdots & dS_{m,t_2-\tau} \\ \vdots & \vdots & \ddots & \vdots \\ dM_{t_n-\tau} & dS_{1,t_n-\tau} & \cdots & dS_{m,t_n-\tau} \end{bmatrix} \begin{bmatrix} a \\ b_1 \\ \vdots \\ b_m \end{bmatrix}$$

- Different from Model I, this model contains more information in spatial domain and less information in time domain.

Metrics for performance analysis

- **N**ash-**S**utcliffe **E**fficiency (**NSE**)

$$\mathrm{NSE} = 1 - \frac{\sum_{n=1}^{N}(X_n - Y_n)^2}{\sum_{n=1}^{N}(X_n - \overline{Y})^2},$$

  - X_n is the modeled data, Y_n is the observed data, and $\overline{Y}$ is the mean of observations.

- NSE with respect to monthly mean ($\widetilde{\mathrm{NSE}}$)

$$\widetilde{\mathrm{NSE}} = 1 - \frac{\sum_{n=1}^{N}(X_n - Y_n)^2}{\sum_{n=1}^{N}(X_n - \widetilde{Y})^2},$$

  - X_n is the modeled data, Y_n is the observed data, and $\widetilde{Y}$ is the monthly mean of observations.

Datasets

The GRACE data are then filtered by a Gaussian smoothing filter with 350 km radius and a destriping filter. The ENSO indices are provided by NOAA Climate Prediction Center (CPC). The time series of both GRACE and ENSO are divided into a 60-month training period (2004 - 2008) and 60-month forcast and validation period (2009 - 2013).

Results: Model I

Model parameters are solved by using a least-squares regression with data in training period, and Nino 3.4 was used here to predict water storage variation.

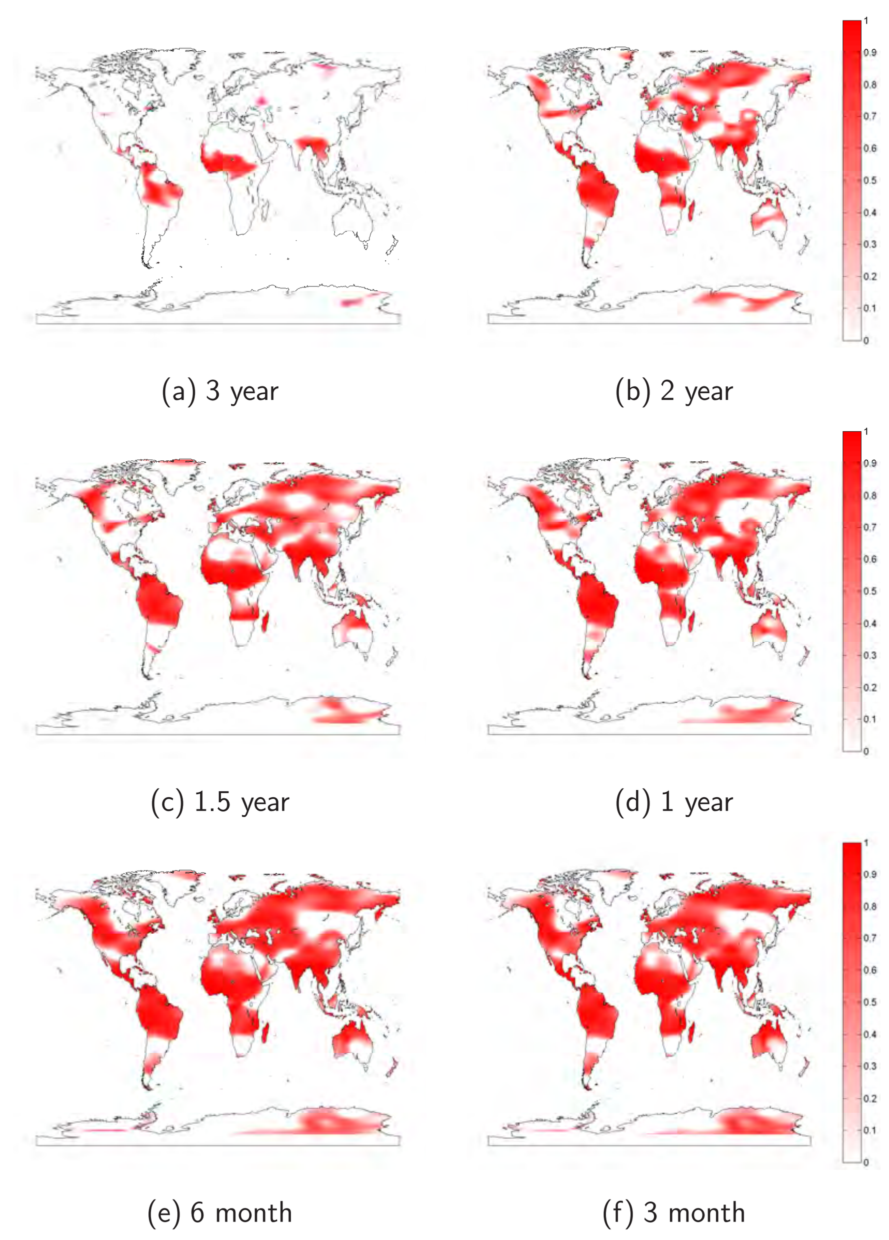

Figure 4: NSE for each grid cell between observations from GRACE and estimation by ENSO with different lead time.

To see how the ENSO influence the catchments on the globe, we do prediction at catchment scale and evaluate the prediction by $\widetilde{\mathrm{NSE}}$.

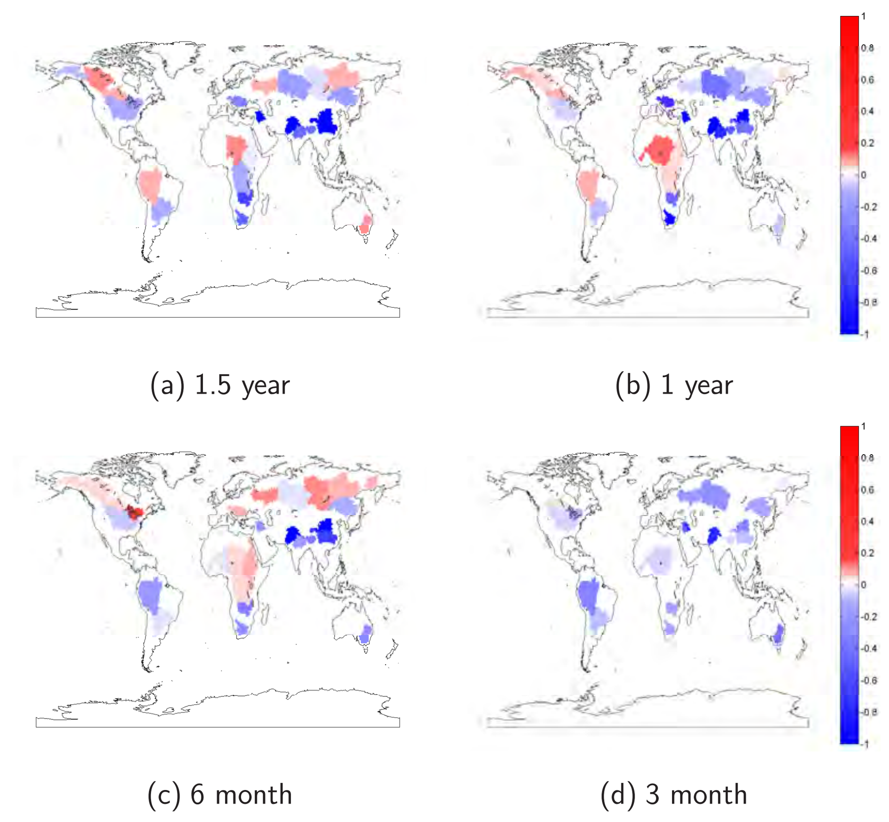

Figure 5: $\widetilde{\mathrm{NSE}}$ for 28 catchments in different continents with different lead time. The catchments with $\widetilde{\mathrm{NSE}}$ above 0 are influenced greatly by ENSO.

Here are prediction time series shown as examples from four catchments (Niger in Africa, Yangtze in Asia, Danube in Europe, and Amazon in South America), which are influenced by ENSO.

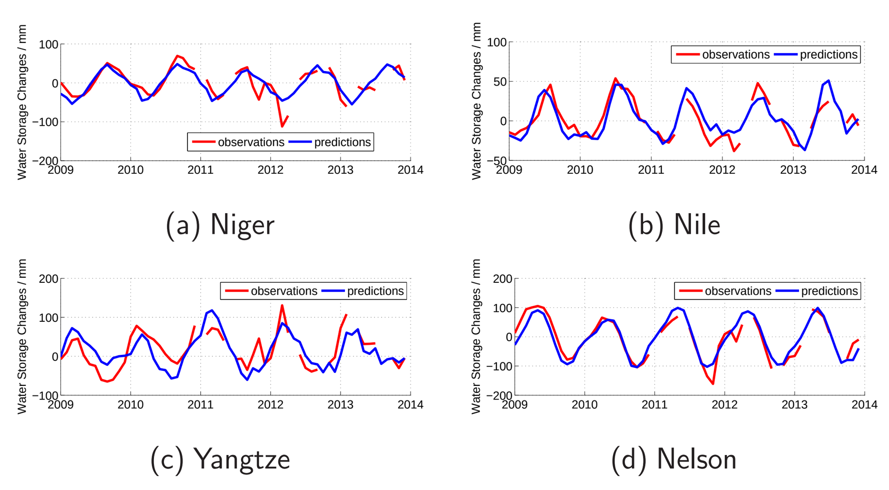

Figure 6: Water storage variation in different basins from GRACE and prediction by ENSO. The time seris are predicted by one-year lead time.

Results: Model II

Four ENSO indices are used here to estimated water storage variation through model. Because of the time lag between GRACE and ENSO after El Niño happened, we test the sensitivity of prediction to different lead time τ.

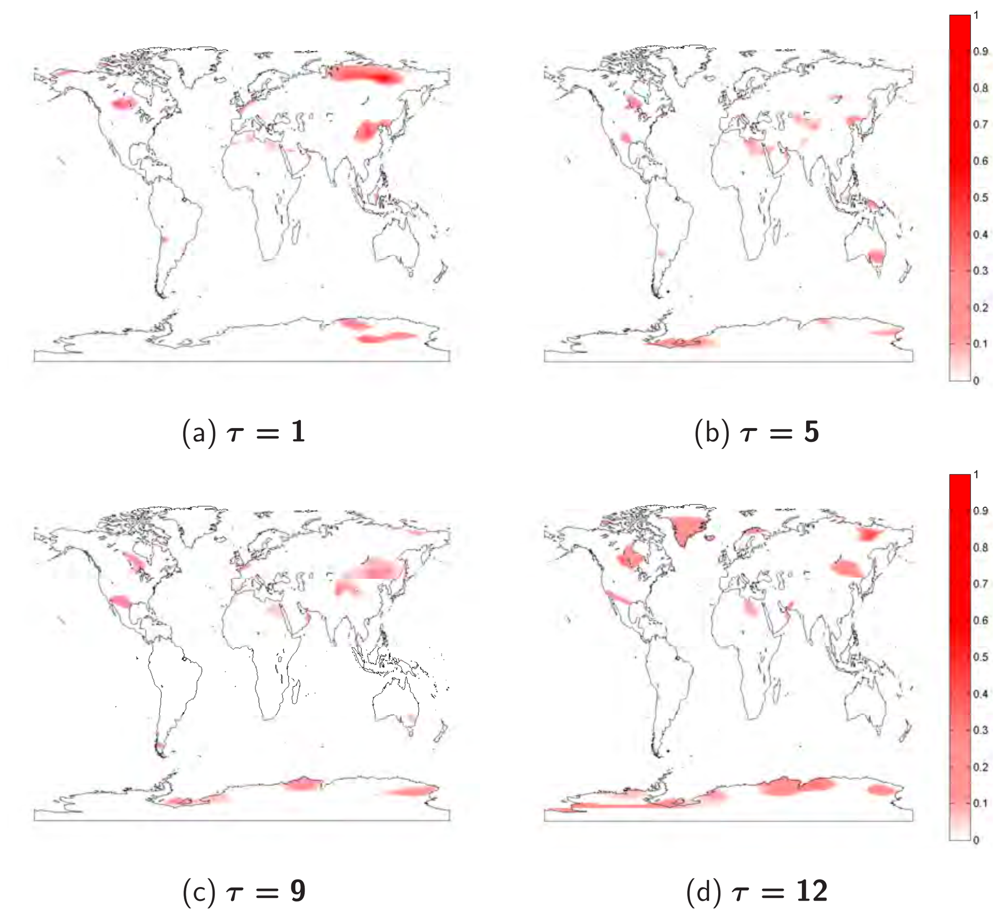

Figure 7: $\widetilde{\mathrm{NSE}}$ for each grid cell between GRACE and prediction by ENSO with different lead time. The region with $\widetilde{\mathrm{NSE}}$ above 0 are influenced greatly by ENSO at time lag τ.

Here is an example of Amazon basin in South America to show the performance of the model.

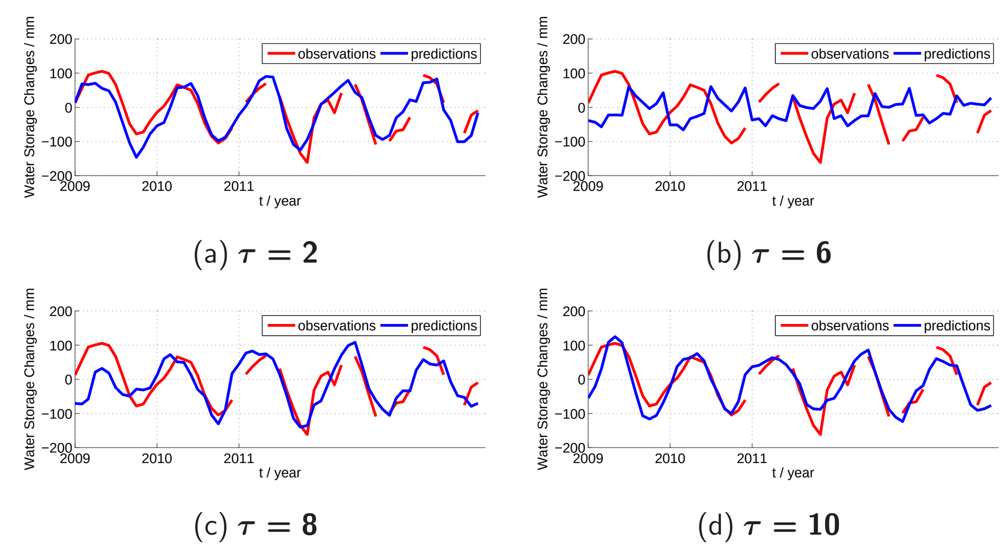

Figure 8: Water storage variation in Amazon basin from GRACE and prediction by ENSO with different lead time τ.

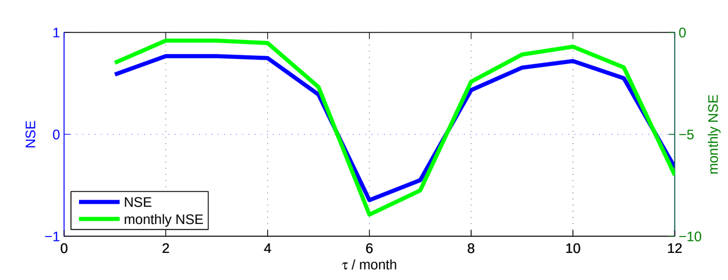

Figure 9: **NSE** and $\widetilde{\mathrm{NSE}}$ for predictions in Amazon basin by ENSO compared with GRACE

To evaluate the time lag between ENSO and total water storage change observed by GRACE, we apply Hilbert transform ENSO index and water storage anomalies. It provides us a proper reference to choose optimal τ for different regions.

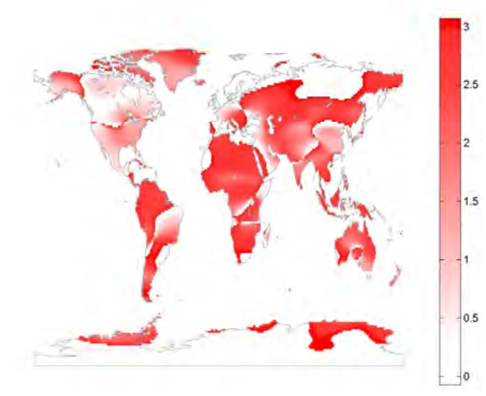

Figure 10: Time lag (in months) between ENSO and the water storage changes observed by GRACE

Conclusion

- Model I has better performance than Model II on predicting water storage at catchment scale.
- Model I can be applied to predict the water storage variation in catchments, and for different catchments, we need to choose an optimal lead time.
- Model II has potential to combine more different climate indices together to predict water storage variation.
- ENSO index has influence on water storage variation in catchments, which might help to analyze the hydrological cycle, and also to fill the potential GRACE gaps in the future.

References

[1] J.T.Reager, *River basin flood potential inferred using GRACE gravity observations at several months lead time*, Nature Geoscience, 2014

[2] T.Phillips, *The influence of ENSO on global terrestrial water storage using GRACE*, Geophysical Research Letters, Vol.39, L16705, 2012

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