**Supplementary information**

**Using GRACE/GRACE-FO, Data-Driven, and Modeling to Assess the Twentieth and Twenty-first Century Water Storage Changes in the Nile River Basin**

Emad Hasan1,6\*, Aondover Tarhule2, Pierre-Emmanuel Kirstetter3,4,5

*1Department of Geological Sciences and Environmental Studies, State University of New York, SUNY at Binghamton, NY, USA.*

*2 Department of Geography, Geology, and the Environment, Illinois State University, Normal, IL, USA.*

*3School of Meteorology, University of Oklahoma, Norman, OK*

*4School of Civil Engineering and Environmental Science, University of Oklahoma, Norman, OK*

*5NOAA/National Severe Storms Laboratory, Norman, OK*

*6Geology Department, Faculty of Science, Damietta University, New Damietta, Egypt.*

To be submitted to the Remote Sensing Journal

**\*Corresponding Author**

Emad Hasan, Ph.D.

Email: [emad.hasan@binghamton.edu](mailto:emad.hasan@binghamton.edu)

**Contents of this file**

Tables S1 to S5

Figures S1 to S3

****

**Figure S1.** NRB year-to-year TWSA changes (A) between 2002 to 2020, and the yearly changes (compared to the overall average) in the TWSA (B).



**Figure S2.** GRACE-TWSA-based net storage between 2002 to 2020 across BNB (A), WNB (B) and Atbara sub-basins.

**Figure S3.** Coevolution between monthly GPCC and CRU precipitation data (A), and GAMLSS-based TWSA and CLMS TWSA (B). Plot C shows the monthly projected TWSA.

****

**Figure S4.** Simulated ARIMA TWS (A), the dark below of the plot is the one-year gap, and the residual plot of the model (B).



**Figure S5.** NRB storage figures from TWS (A), GWS (B), SMS (C), and runoff (D) between 1948 to 2014 of CLSM-F2.5 LSM. The storage-based figures are relatively high relative to the runoff in the basin.

**Table S1.** Source information for datasets and drought indicators utilized in this research.

|  |  |  |  |
| --- | --- | --- | --- |
| **Data** | **Link** | **Resolution** | **Reference** |
| TWS | <https://grace.jpl.nasa.gov/data/get-data/> | 1.0° (SH06)  0.25° (M06 CSR)  0.5° (M06 JPL) | (Landerer, 2019)  (Save, 2019)  (Wiese et al., 2019 ) |
| Precip. | GPCC, <http://gpcc.dwd.de>.  CRU, <http://www.cru.uea.ac.uk/data> | 0.5°  0.5° | (Schneider et al., 2011)  (Jones and Harris, 2013) |
| Temp. | CRU, <http://www.cru.uea.ac.uk/data> | 0.5° | (Jones and Harris, 2013) |
| PET | CRU, <http://www.cru.uea.ac.uk/data> | 0.5° | (Jones and Harris, 2013) |
| GPCC\_DI | <https://www.dwd.de/EN/ourservices/gpcc/gpcc.html> | 1.0° | (Finger et al., 2015) |
| ScPDSI | <https://www.rdocumentation.org/packages/scPDSI/versions/0.1.3> | 0.5° | (Zhong et al., 2018) |
| SPI | <https://digital.csic.es/handle/10261/10006> | 0.5° | (Beguería and Vicente, 2009) |
| SPIE | <https://digital.csic.es/handle/10261/202305> | 0.5° | (Beguería and Vicente, 2020) |
| ClimGen | <https://crudata.uea.ac.uk/~timo/climgen/#data> | --- | (Osborn, 2009) |

**Table S2.** Standard thresholds used to identify the drought severity levels.

|  |  |  |
| --- | --- | --- |
| Category | Description | GRACE-DSI & PDSI |
| W4 | Exceptionally Wet | 2.0 or greater |
| W3 | Extremely Wet | 1.60 to 1.99 |
| W2 | Very Wet | 1.30 to 1.59 |
| W1 | Moderately Wet | 0.80 to 1.29 |
| W0 | Slightly Wet | 0.50 to 0.79 |
| WD | Near Normal | 0.49 to -0.49 |
| D0 | Abnormally dry | -0.50 to -0.79 |
| D1 | Moderate drought | -0.80 to -1.29 |
| D2 | Severe drought | -1.30 to -1.59 |
| D3 | Extreme drought | -1.60 to -1.99 |
| D4 | Exceptional drought | -2.0 or less |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| TWS (Mean) | Uncert | Length (Month) | Date | |
| Begin | End |
| 33.33 | ±4.68 | 22 | 04/2002 | 01/2004 |
| -58.27 | ±4.16 | 30 | 2/2004 | 01/2009 |
| 58.55 | ±3.76 | 30 | 02/2009 | 06/2012 |
| -24.76 | ±4.55 | 41 | 12/2008 | 06/2012 |
| 86.20 | ±5.03 | 85 | 07/2012 | 07/2019 |
| 280.82 | ±5.56 | 9 | 08/2019 | 04/2020 |

**Table S3.** Summary of the regime-shift analysis of the NRB mean TWS between 2002 to 2020.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| TWS (Cycle) | Uncert | Length (Month) | Date | |
| Begin | End |
| 45.28 | ±2.81 | 24 | 04/2002 | 03/2004 |
| -41.38 | ±2.74 | 31 | 4/2004 | 10/2006 |
| 36.31 | ±3.04 | 25 | 11/2006 | 11/2008 |
| -42.77 | ±2.56 | 43 | 12/2008 | 06/2012 |
| 5.83 | ±3.21 | 18 | 07/2012 | 12/2013 |
| 49.31 | ±2.89 | 33 | 01/2014 | 09/2016 |
| -35.57 | ±3.45 | 9 | 10/2016 | 06/2017 |
| 68.65 | ±3.36 | 23 | 07/2017 | 05/2019 |
| 251.46 | ±4.24 | 11 | 06/2019 | 04/2020 |

**Table S4.** Summary of the regime-shift analysis of the NRB in the TWS cyclic component between 2002 to 2020.

**Table S5.** GAMLESS (A) and ARIMA (B) models’ goodness-of-fit criteria.

|  |  |
| --- | --- |
| Observations | 170 |
| DF | 166 |
| SSE | 278.44 |
| MSE | 1.64 |
| RMSE | 1.28 |
| WN Variance | 1.92 |
| MAPE(Diff) | 90.31 |
| MAPE | 661.75 |
| -2Log (Like.) | 599.03 |
| FPE | 1.64 |
| AIC | 607.02 |
| AICC | 607.27 |
| BIC | 619.57 |
| Iterations | 31 |

|  |  |  |  |
| --- | --- | --- | --- |
| **Paras** | **AIC** | **LRT** | **Pr(Chi)** |
| Precipitation | 794.36 | 50.12 | 3.4e-10 \*\*\* |
| Temperature | 873.46 | 129.22 | < 2.2e-16 \*\*\* |

(A) (B)

R2 = 0.86

NSC: 0.86

**Models’ metrics**

Residual Sum Squares (RSS) or Sum Squared Error (SSE),

where, is the observed, and ( is the modeled parameter using a general linear regression formulation, .

Mean Squared Error (MSE),

where, the mean of the squares of errors between the observed and the modeled (.

Classic Akaike information criterion (Classic AIC),

where, is the number of model parameters, is the maximum likelihood.

Akaike information criterion corrected (AICc),

Bayesian Information Criterion (BIC),

Likelihood Ratio test (LRT), White Noise Variance (WN Variance), Mean Absolute Percentage Error (MAPE), Fit Percentage estimation (FPE).

Reference

Beguería, S. and Vicente, S., 2009. SPI Calculator.

Beguería, S. and Vicente, S., 2020. SPEIbase v.2.6 [Dataset].

Finger, P., Ziese, M., Meyer-Christoffer, A., Schneider, U. and Becker, A., 2015. GPCC Interpolation Test Dataset at 1.0°. Global Precipitation Climatology Centre (GPCC) at Deutscher Wetterdienst.

Jones, P.D. and Harris, I.C., 2013. CRU TS3.21: Climatic Research Unit (CRU) Time-Series (TS) Version 3.21 of High Resolution Gridded Data of Month-by-month Variation in Climate (Jan. 1901- Dec. 2012). University of East Anglia Climatic Research Unit, NCAS British Atmospheric Data Centre, 24 September 2013.

Osborn, T.J., 2009. A user guide for ClimGen: a flexible tool for generating monthly climate data sets and scenarios, Climatic Research Unit (CRU), School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK.

Save, H., 2019. CSR GRACE RL06 Mascon Solutions. Dataset accessed [2019-09-8]. In: H. Save (Editor). Texas Data Repository Dataverse.

Schneider, U., Becker, A., Meyer-Christoffer, A., Ziese, M. and Rudolf, B., 2011. Global Precipitation Analysis Products of the GPCC, Deutscher Wetterdienst, Offenbach a. M., Germany.

Wiese, D.N., Yuan, D.-N., Boening, C., Landerer, F.W. and Watkins, M.M., 2019 JPL GRACE and GRACE-FO Mascon Ocean, Ice, and Hydrology Equivalent Water Height Coastal Resolution Improvement (CRI) Filtered Release 06 Version 02. Ver. 02. PO.DAAC, CA, USA. Dataset accessed [2019-03-11] at <https://doi.org/10.5067/TEMSC-3JC62>.

Zhong, R., Chen, X., Wang, Z., Lai, C., Goddard, S., Wells, N. and Hayes, M., 2018. scPDSI: Calculation of the Conventional and Self-Calibrating Palmer Drought Severity Index.