Application of multiplicative random cascades to spatially downscale observed terrestrial water storage anomalies

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Introduction

- ➢ Terrestrial water storage (TWS) is a key component of hydrological cycle
- ➢ TWS exerts important controls on:
  - Water flux
  - Energy flux
  - Biogeochemical flux
- ➢ GRACE-observed TWSA (≥ 160,000 km^2) has been used in regional to global scale hydrological studies:
  - Floods and droughts
  - Groundwater
  - Ecohydrology
- ➢ High resolution TWS will significantly advance hydroclimatic research and applications *i.e.,* downscaling of observed TWSA is required.

Introduction

- Previously GRACE TWSAs has been downscaled:
    - *Zaitchik et al.*, (2008), assimilated TWSA observations into CLSM (1.0^o x 1.25^o) for Mississippi river basin. After assimilation, an increased correlation of TWS estimates with observed river flow for the sub-basins smaller than GRACE observation scale.
    - *Kuss et al.*, (2012), downscaled the aquifer-scale groundwater storage variations derived from GRACE TWSA using statistical regression for Central Valley. They used groundwater storage estimates from C2VSim model to estimate parameters of regression.
    - *Yirdaw et al.*, (2011) and *Sun* (2013), used groundwater level data and artificial neural networks to downscale TWSA to estimate and predict groundwater changes at well level.
    - *Ning et al.*, (2014), used satellite-based precipitation and evapotranspiration, and modeled runoff to downscale 1^o gridded GRACE TWSA at 0.25^o.
- These procedures either require auxiliary information or are based on hydrologic models to downscale TWSA.

Introduction

- Studies have shown that hydroclimatic variables such as precipitation and soil moisture may exhibit the property of scale invariance characterized by following equation:

$$\boldsymbol{R}(\lambda A) \overset{dist}{=} \lambda^{-\tau}\boldsymbol{R}(A)$$

- Multiplicative random cascades have been used to downscale these hydroclimatic variables solely based on their scaling properties *i.e.*, scaling exponent 'τ'
- We hypothesized that, similar to other hydroclimatic variables, GRACE-observed TWSA may exhibit scale-invariant behavior, therefore, providing opportunity to downscale TWSA using random cascades.

Objectives

- To perform the spatial downscaling of observed TWSA, we outlined the following objectives:
  1. Perform fractal analysis to infer scaling behavior and parameters for observed TWSA.
  2. Apply random cascade procedure to downscale large-scale observed TWSA.

Study area and Data

- We used 0.5^{o} TWSA based on GRACE MASCONS produced by CSR.
- Study region: South-west US. The region spans from 115^{o}-123^{o} west and from 35^{o}-43^{o} north (*i.e.*, 16 grids in each direction)
- For purpose of detecting self-similarity, an extended region having 32 grids in each direction is selected.

Methods

- Scaling Analysis

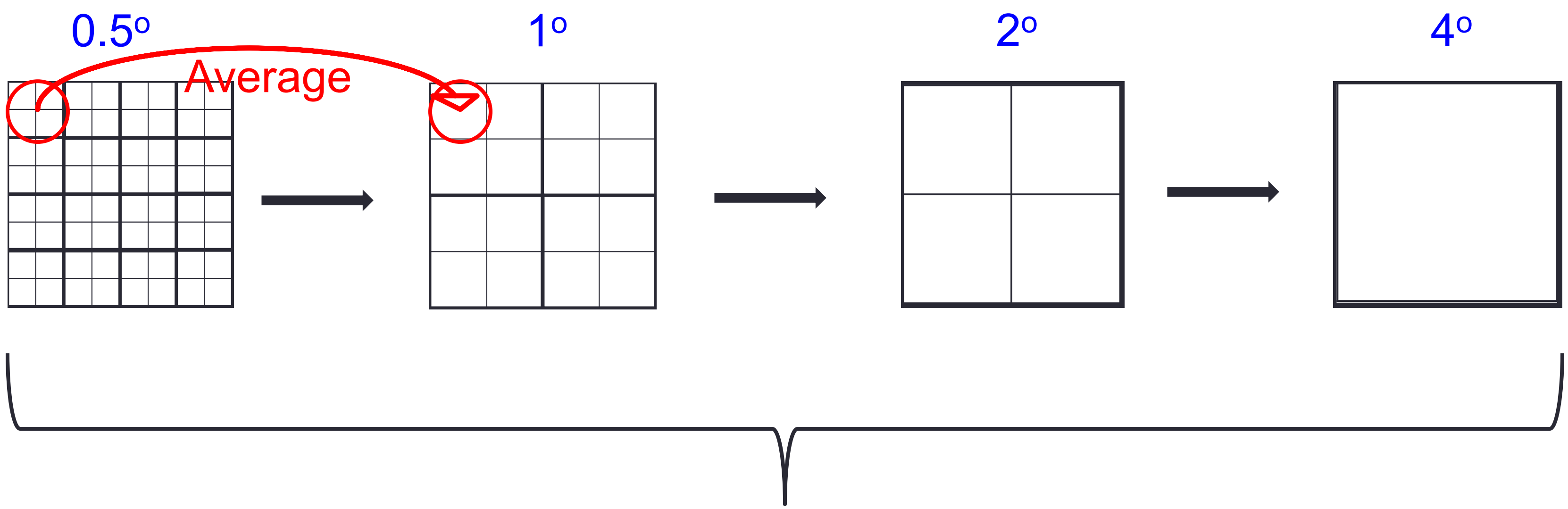
Scale invariance equation can be rewritten as equation below, which means that scale-invariance behavior is characterized by the log-log linearity of statistical moments of order '*q*' and length scale 'λ'

$$\boldsymbol{log}\langle \boldsymbol{R}_{\lambda}^{\boldsymbol{q}}\rangle = -\tau(\boldsymbol{q}).\,\boldsymbol{log}\lambda + \boldsymbol{log}\langle \boldsymbol{R}_{\boldsymbol{0}}^{\boldsymbol{q}}\rangle$$

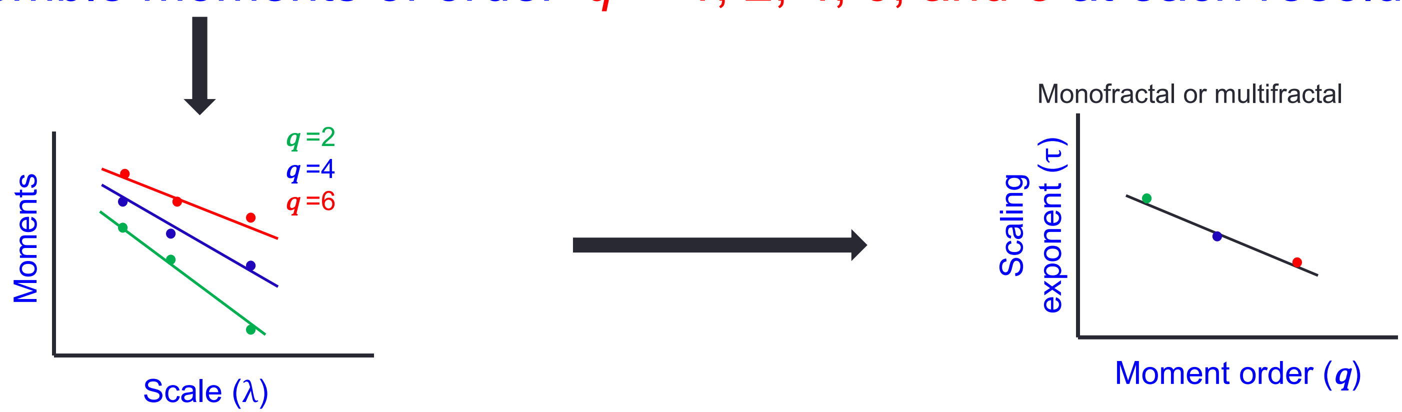
The slope of this log-log relationship is the scaling exponent 'τ' for moment order '*q*'. In the case that scaling exponent varies linearly with moment order, the scaling structure is regarded as monofractal (or simple scaling), otherwise it is multifractal.

Methods

➢ Scaling Analysis



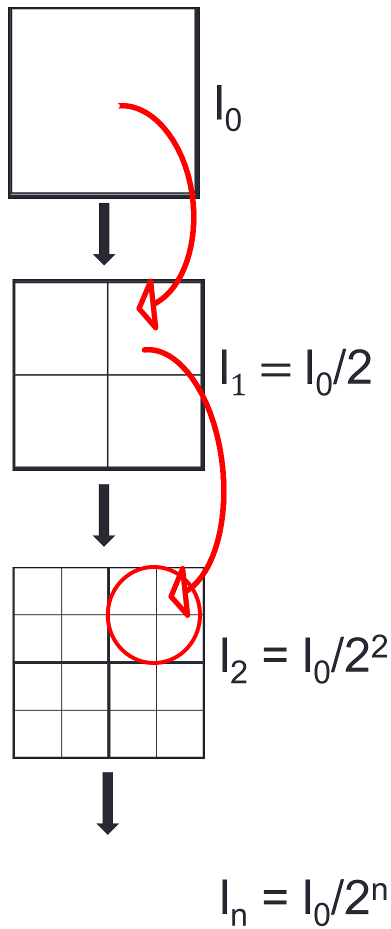
Ensemble moments of order ‘*q*’ = 1, 2, 4, 6, and 8 at each resolution



Methods

- Downscaling TWSA

Random Cascades



Cascade Level 0

r_0 : *large-scale value*

Cascade Level 1

$r_1 = r_0 W_1$

Cascade Level 2

$r_2 = r_1 W_2 = r_0 W_1 W_2$

Cascade Level n

$r(\Delta_n^i) = r_0 \prod_{j=1}^{n} W_j(i)$

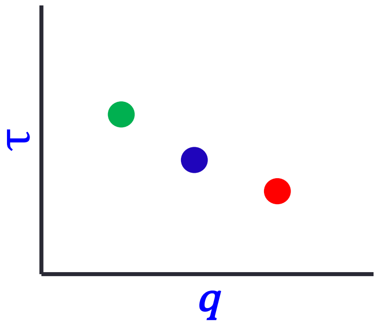
Methods

- Downscaling TWSA

Cascade Generator

1. Uniform (0-1)
2. Beta log-normal

$$W = b^{\beta - \frac{\sigma^2 \ln(b)}{2} + \sigma X}$$



b = branching number = 4

β = spatial intermittency

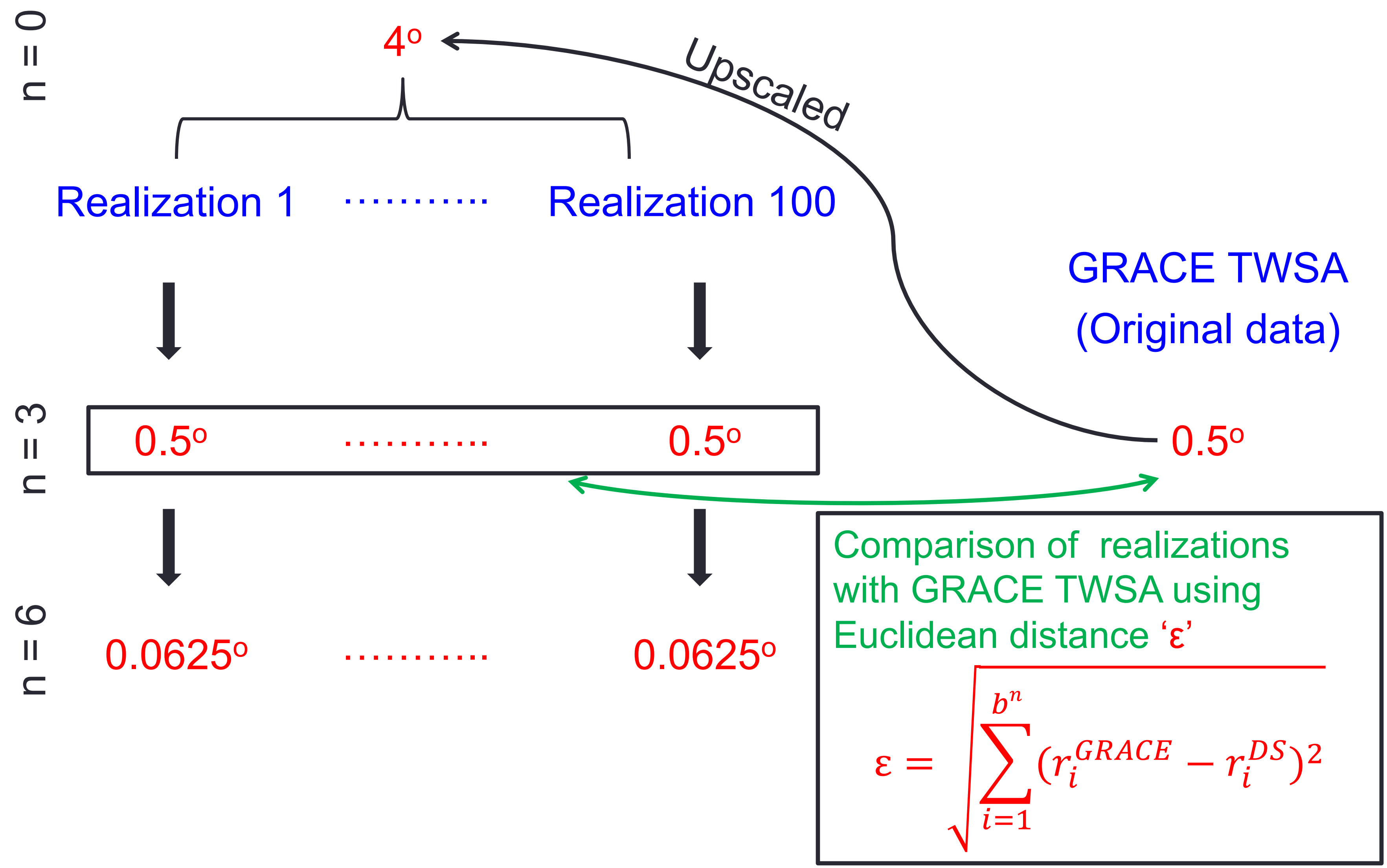
σ = scaling factor

X = standard normal random variable

$$\tau(q) = d(\beta - 1)(q - 1) + \frac{q^2 \sigma^2 d \ln(b)}{2}$$

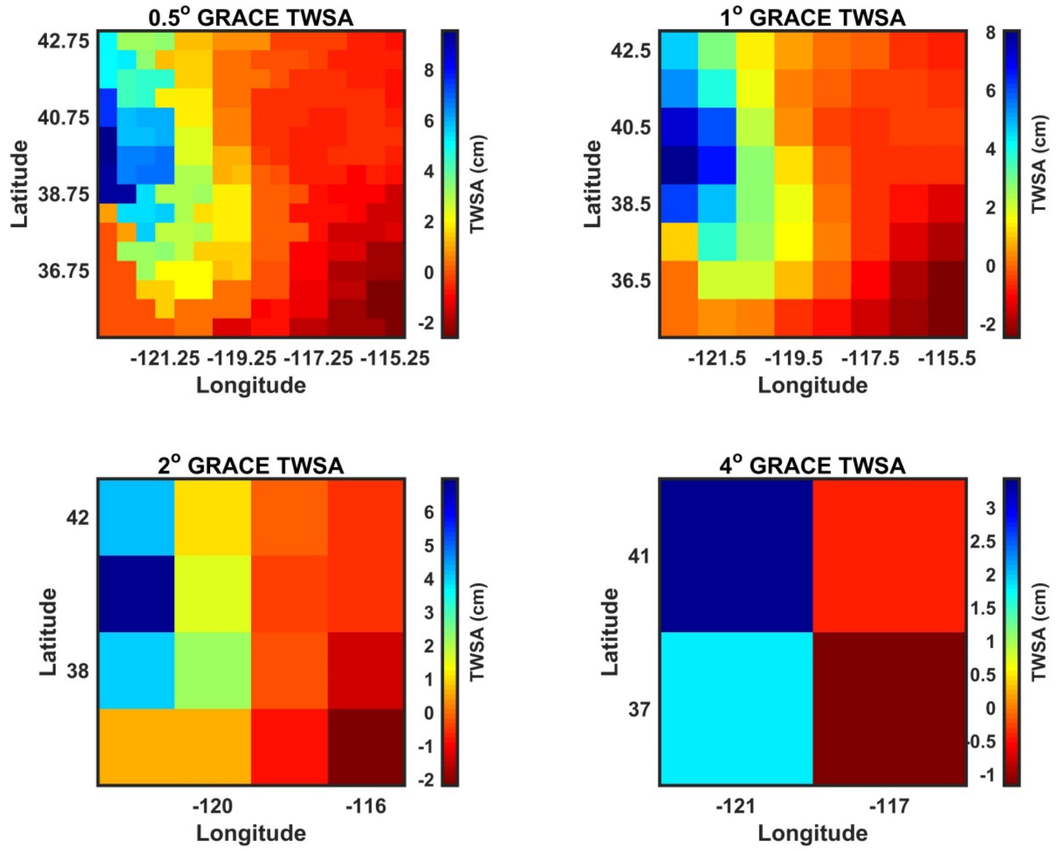
Methods

- Downscaling TWSA

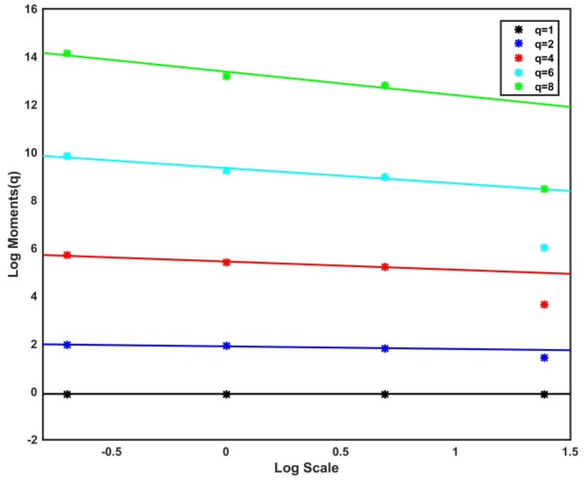


Results

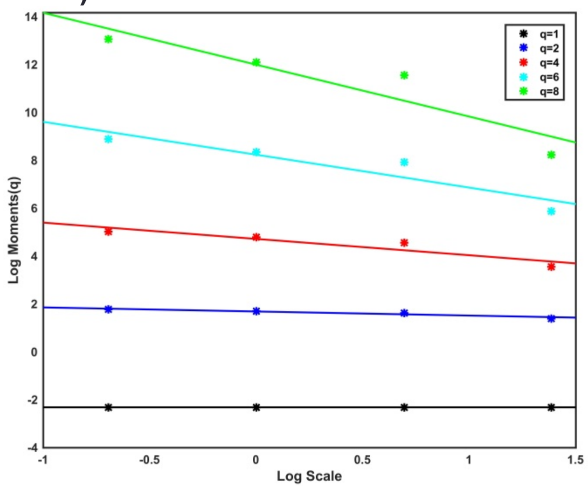
- ➢ Scaling Analysis



a) Study area



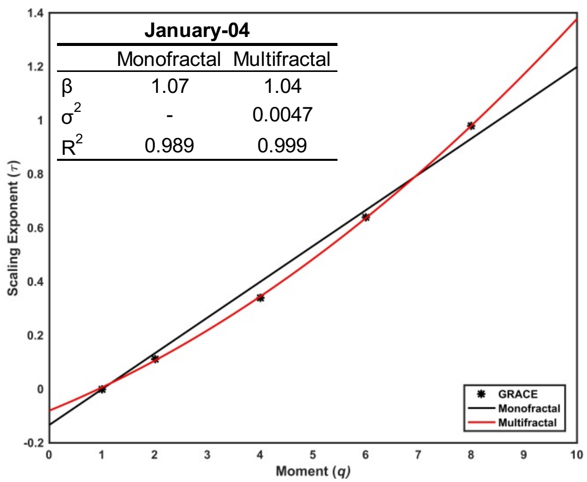
b) Extended area

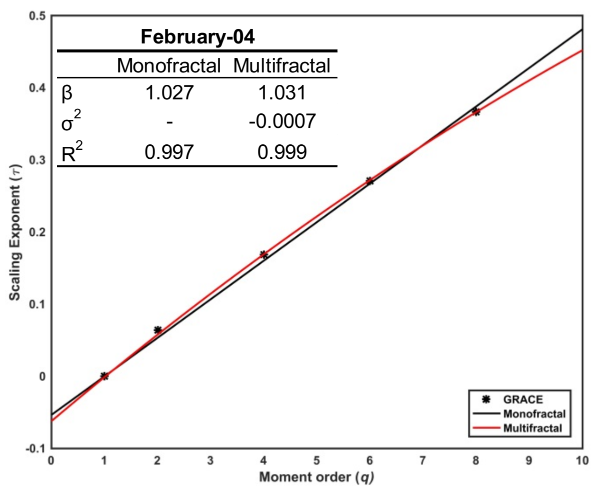


Results

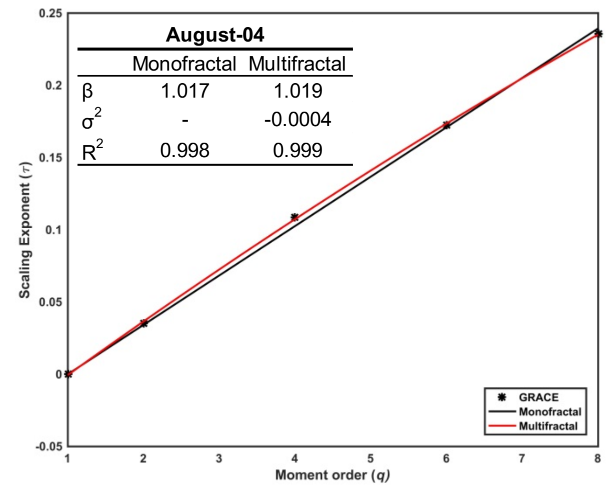
- ➢ Scaling Analysis

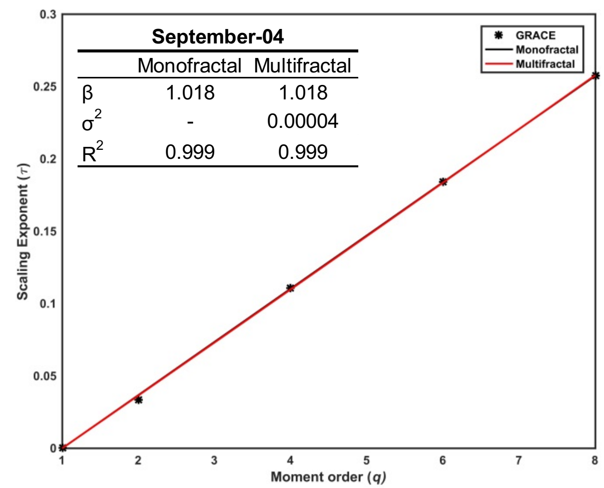
Wet





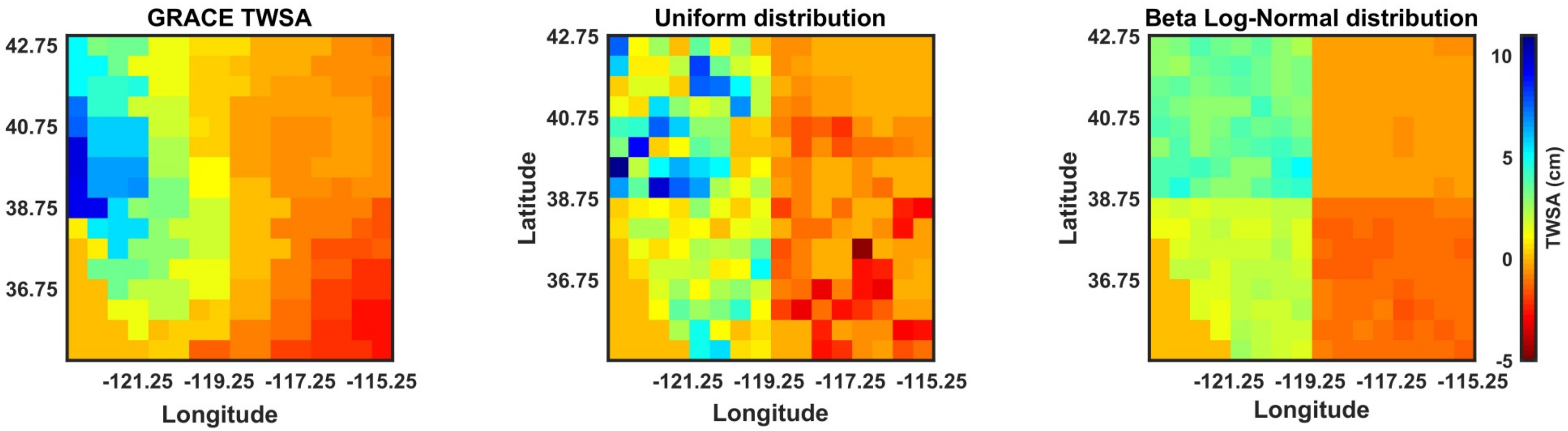
Dry





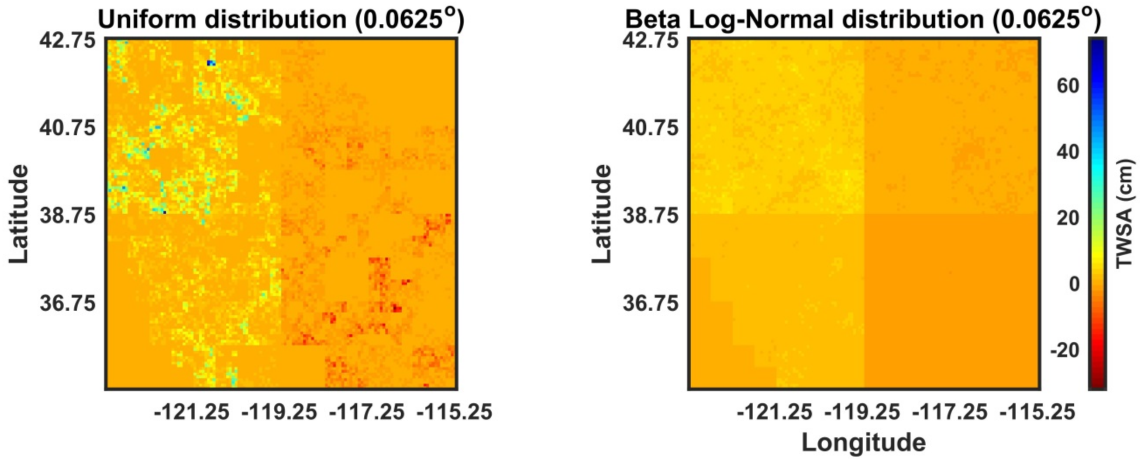
Results

- Downscaling



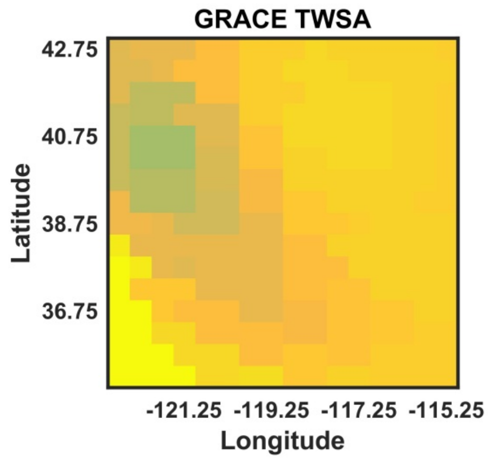
January – 2004

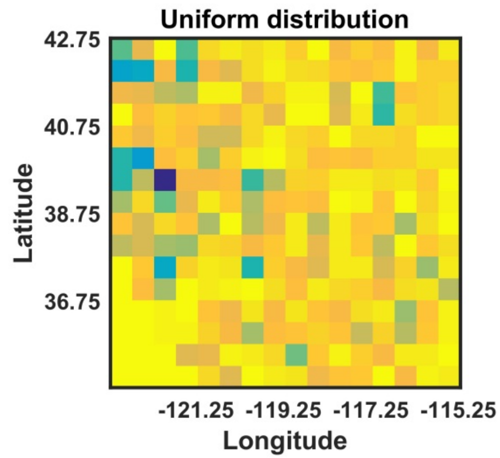
Downscaling Model	Euclidean Distance (cm)
Uniform	33.23
Beta log-normal	27.2

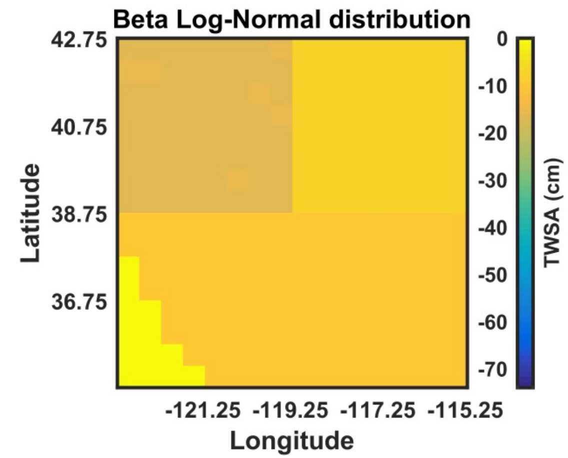


Results

- Downscaling

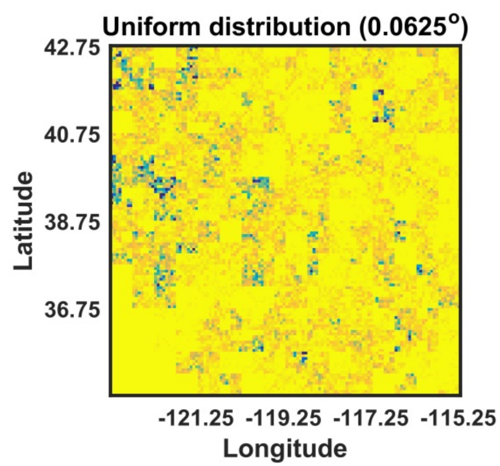


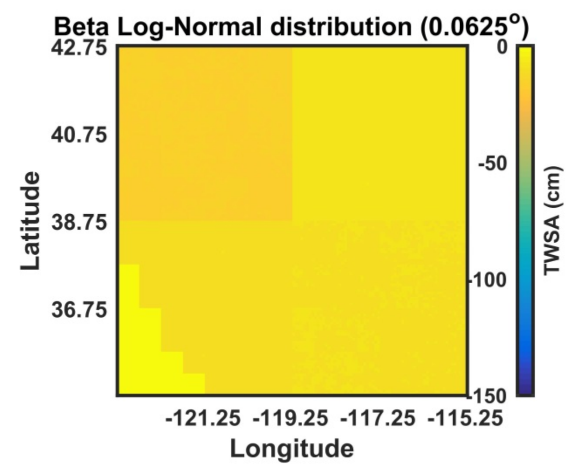




September – 2004

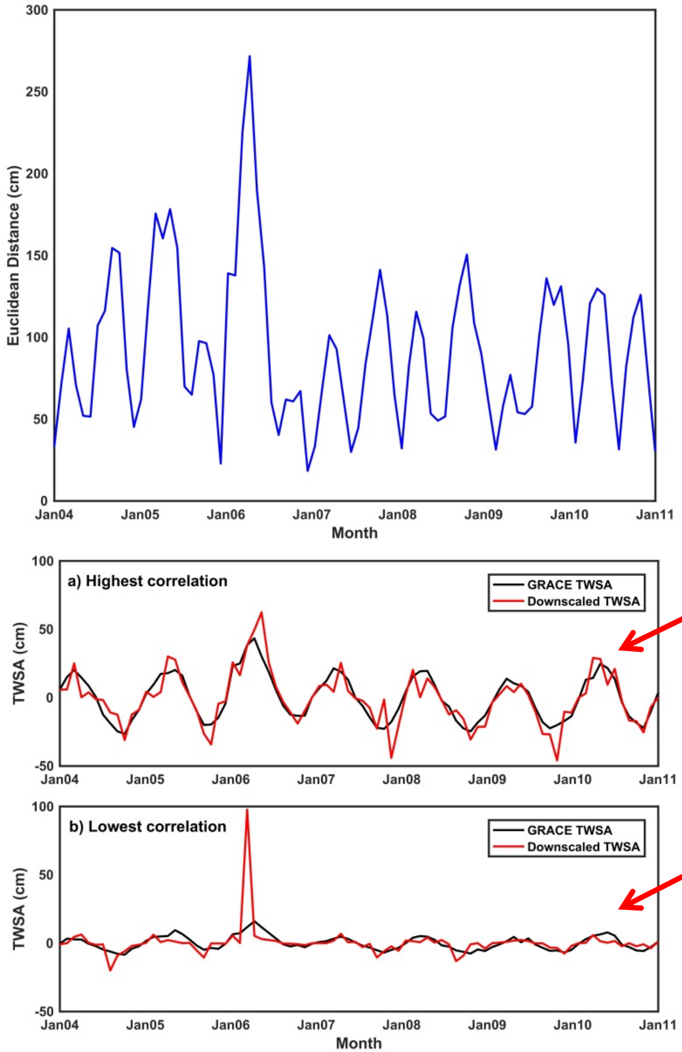
Downscaling Model	Euclidean Distance (cm)
Uniform	154
Beta log-normal	1015





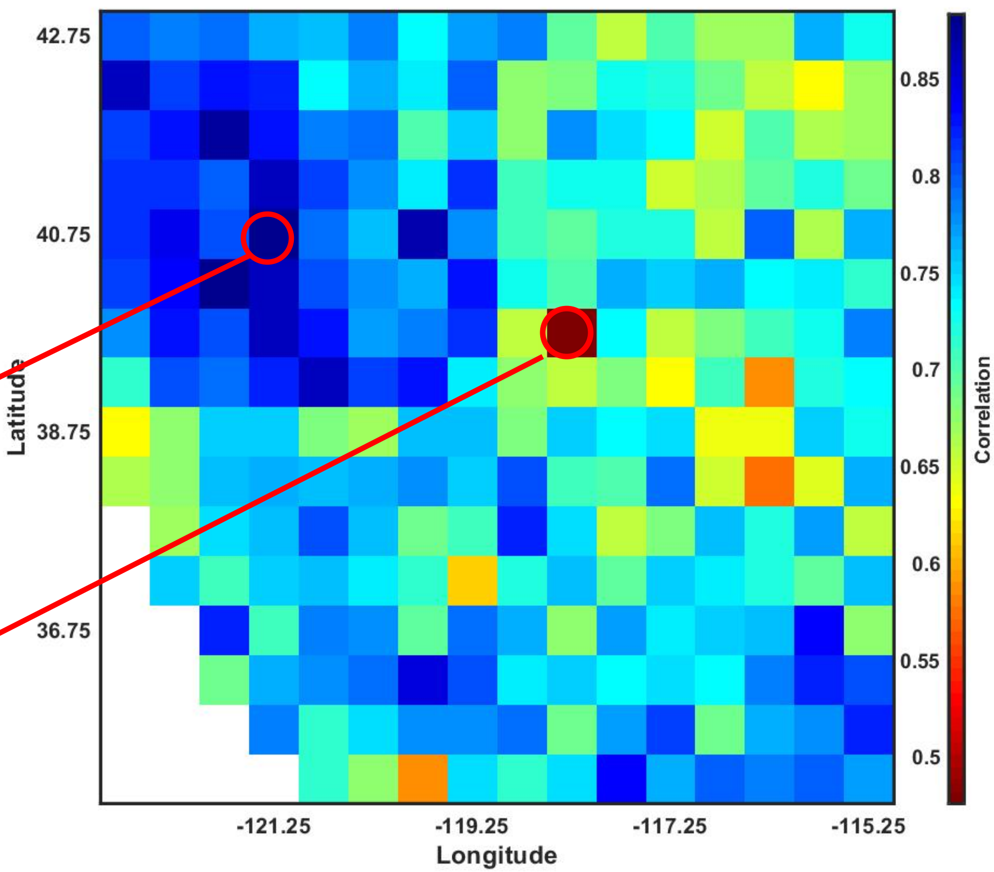
Results

- Downscaling



<u>January, 2004 to December, 2010</u>

Euclidean distance and correlation between GRACE TWSA and downscaled TWSA by uniform distribution.



Conclusions

- Near monofractal behavior in 0.5^{o} GRACE TWSA anomalies is observed.
- Generally, uniformly distributed random cascade model performs better or equally well as compared to beta log-normally distributed cascade model.
- Downscaled TWSA using uniformly distributed model shows more variation than TWSA downscaled using beta log-normal model. This happens due to smaller values of scale factor (σ^2) of beta log-normal model, which refers to near monofractal behavior.

Future work

- Compare downscaled 0.0625^{o} TWSA with observations (e.g., observed groundwater levels)
- Explain the near monofractal behavior of TWSA using physically based reasoning.
- Interpret the physical meaning of parameter (β) beta of beta log-normal model.
- Investigate the possibility of generating and using negative cascade generator.

References

- Zaitchik, B. F., Rodell, M., & Reichle, R. H. (2008). Assimilation of GRACE terrestrial water storage data into a land surface model: Results for the Mississippi River basin. *Journal of Hydrometeorology*, *9*(3), 535-548.
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