Validation of reservoir operation using satellite remote sensing for global hydrological models under ISIMIP

Cross-sectoral ISIMIP and PROCLIAS Workshop: 6th June 2023

Sector meeting: Water global (1)

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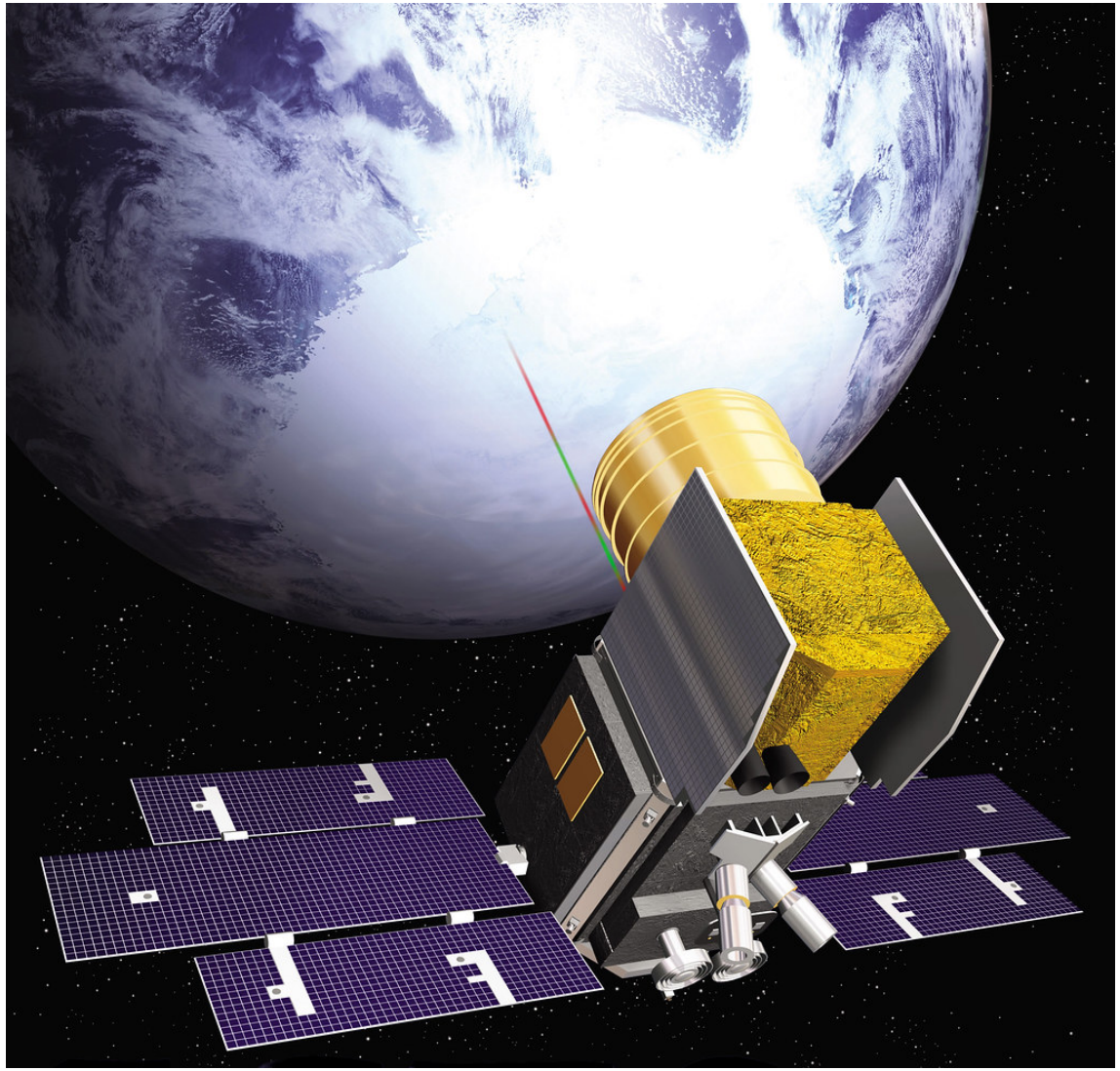
Introduction

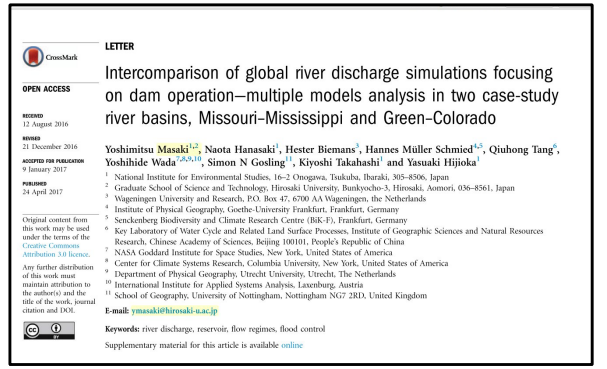
Background:

Validation and intercomparison of reservoir operation outputs in global hydrological simulations have not been done using space-borne remote-sensing data



Introduction (continued)

- Review
  - Model intercomparison
    - Masaki et al. 2017: intercompared six global hydrological models, but hampered by the lack of ground observation of reservoir operation
  - Estimating storage change from space
    - Gao et al. 2012: combined altimetry data and surface area from MODIS to get storage variation of 34 reservoirs in the world
    - Busker et al. 2019: Combined Landsat based surface area and DAHITI altimetry for 137 global lakes and reservoirs; decreased dependency on reservoir parameters
- Research Question:
  - **How well do the global hydrological models perform when compared to satellite data?**
  - Develop a systematic methodology for comparing reservoir storage in model output against satellite remote sensing data



LETTER

Intercomparison of global river discharge simulations focusing on dam operation—multiple models analysis in two case-study river basins, Missouri–Mississippi and Green–Colorado

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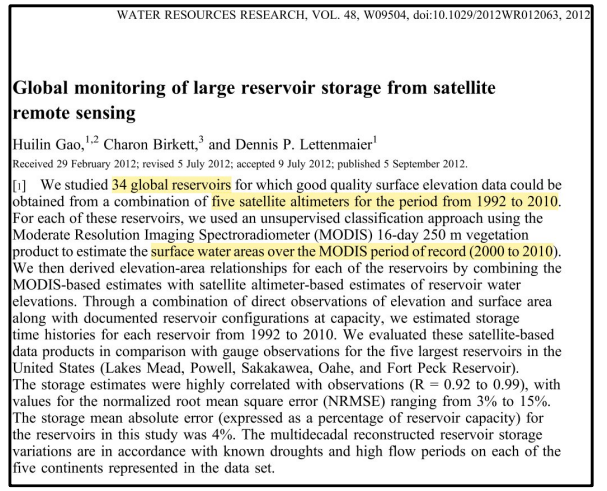
Keywords: river discharge, reservoir, flow regimes, flood control

Supplementary material for this article is available online



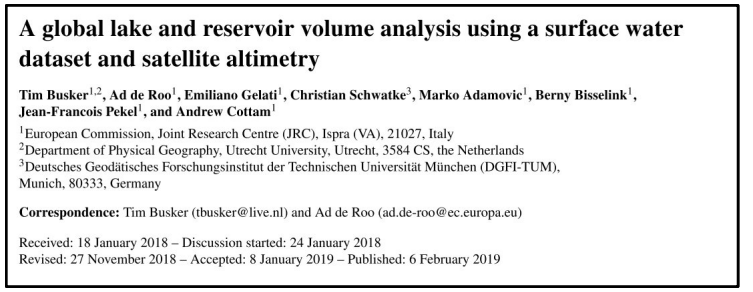
WATER RESOURCES RESEARCH, VOL. 48, W09504, doi:10.1029/2012WR012063, 2012

Global monitoring of large reservoir storage from satellite remote sensing

Huilin Gao,[1,2] Charon Birkett,[3] and Dennis P. Lettenmaier[1]

Received 29 February 2012; revised 5 July 2012; accepted 9 July 2012; published 5 September 2012.

[1] We studied 34 global reservoirs for which good quality surface elevation data could be obtained from a combination of five satellite altimeters for the period from 1992 to 2010. For each of these reservoirs, we used an unsupervised classification approach using the Moderate Resolution Imaging Spectroradiometer (MODIS) 16-day 250 m vegetation product to estimate the surface water areas over the MODIS period of record (2000 to 2010). We then derived elevation-area relationships for each of the reservoirs by combining the MODIS-based estimates with satellite altimeter-based estimates of reservoir water elevations. Through a combination of direct observations of elevation and surface area along with documented reservoir configurations at capacity, we estimated storage time histories for each reservoir from 1992 to 2010. We evaluated these satellite-based data products in comparison with gauge observations for the five largest reservoirs in the United States (Lakes Mead, Powell, Sakakawea, Oahe, and Fort Peck Reservoir). The storage estimates were highly correlated with observations (R = 0.92 to 0.99), with values for the normalized root mean square error (NRMSE) ranging from 3% to 15%. The storage mean absolute error (expressed as a percentage of reservoir capacity) for the reservoirs in this study was 4%. The multidecadal reconstructed reservoir storage variations are in accordance with known droughts and high flow periods on each of the five continents represented in the data set.



A global lake and reservoir volume analysis using a surface water dataset and satellite altimetry

Tim Busker[1,2], Ad de Roo[1], Emiliano Gelati[1], Christian Schwatke[3], Marko Adamovic[1], Berny Bisselink[1], Jean-Francois Pekel[1], and Andrew Cottam[1]

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Correspondence: Tim Busker (tbusker@live.nl) and Ad de Roo (ad.de-roo@ec.europa.eu)

Received: 18 January 2018 – Discussion started: 24 January 2018
Revised: 27 November 2018 – Accepted: 8 January 2019 – Published: 6 February 2019

Methods

- **Data**
  - Ground observation (truth)
    - Storage (V): ResOpsUS (Steyaert et al, 2022; CONUS only)
  - Reservoir specification
    - Dam height (hc), Lake area (Ac), etc: GranD for ISIMIP (Lehner et al. 2011)
  - Satellite products
    - Area (A): GRSAD (Gao et al, 2019) and DAHITI (Schwatke et al. 2015)
  - Simulation products
    - Storage (V): ISIMIP3a (H08 and WaterGAP2)

- **Pre-process**
  - Derive satellite based V from A.
  - Assume linear A-h relationship

Linear A-h relationship: h= a × A + b

Change in Volume= $\Delta V = \frac{(h_2 - h_1) \cdot (A_1 + A_2)}{2}$

- Gao's Method

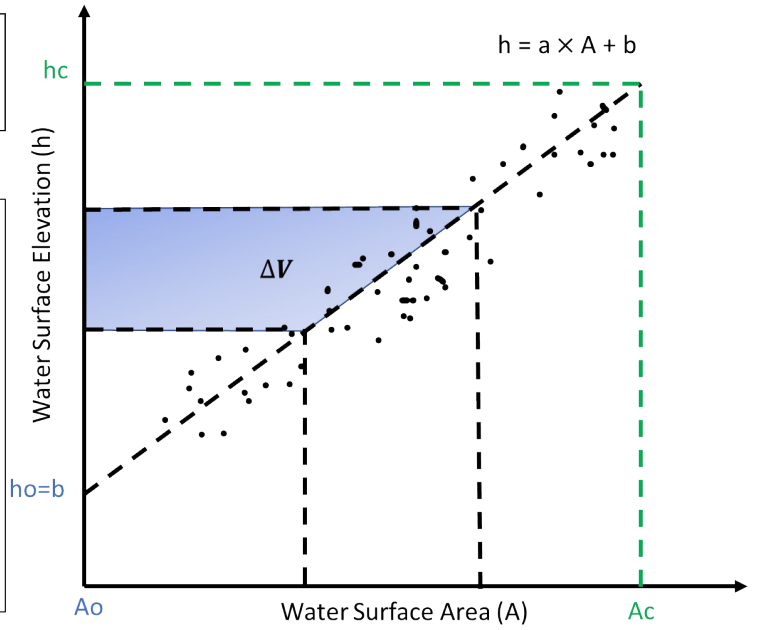
$$Vi = Vc - \frac{(hc - hi) \cdot (Ac + Ai)}{2}$$

- Busker's Method

$$Storage\ Volume = Vi = \frac{(hi - b) \cdot Ai}{2}$$

Water volume can be calculated using h or A only

$$Vi = \frac{(hi - b)^2}{2a} = \frac{a \cdot (Ai)^2}{2}$$



Methods (continued)

Simulation: ISIMIP3a-histsoc (water global)

- Model:
  - H08
  - WaterGAP (WGP)
- Meteorological forcing:
  - G5 : GSWP3+W5E5
  - CW : CR20v3+W5E5
  - CE : CR20v3 +ERA5
- e.g., H08_G5, WGP_CE

Nomenclature

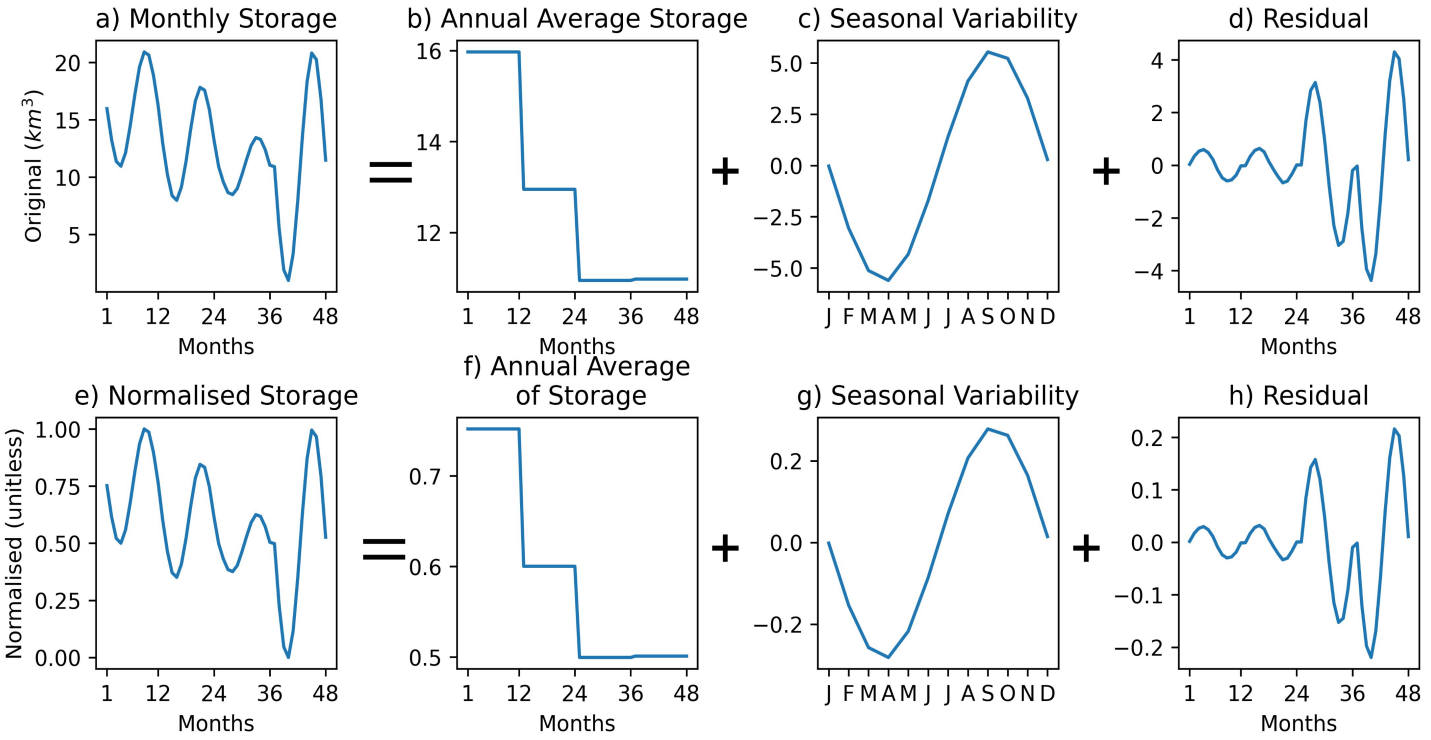
Ground Observation:

- Grd_obs

Satellite:

- GRSAD_Gao = GRSAD + Gao's capacity data + Gao's Method
- GRSAD_ISIMIP= GRSAD + ISIMIP's capacity Data + Gao's Method
- GRSAD_Busker= Gao data + Busker's Method [No capacity data needed]
- DAHITI = Dahiti data + Busker's method [No capacity data needed]

Analysis in brief

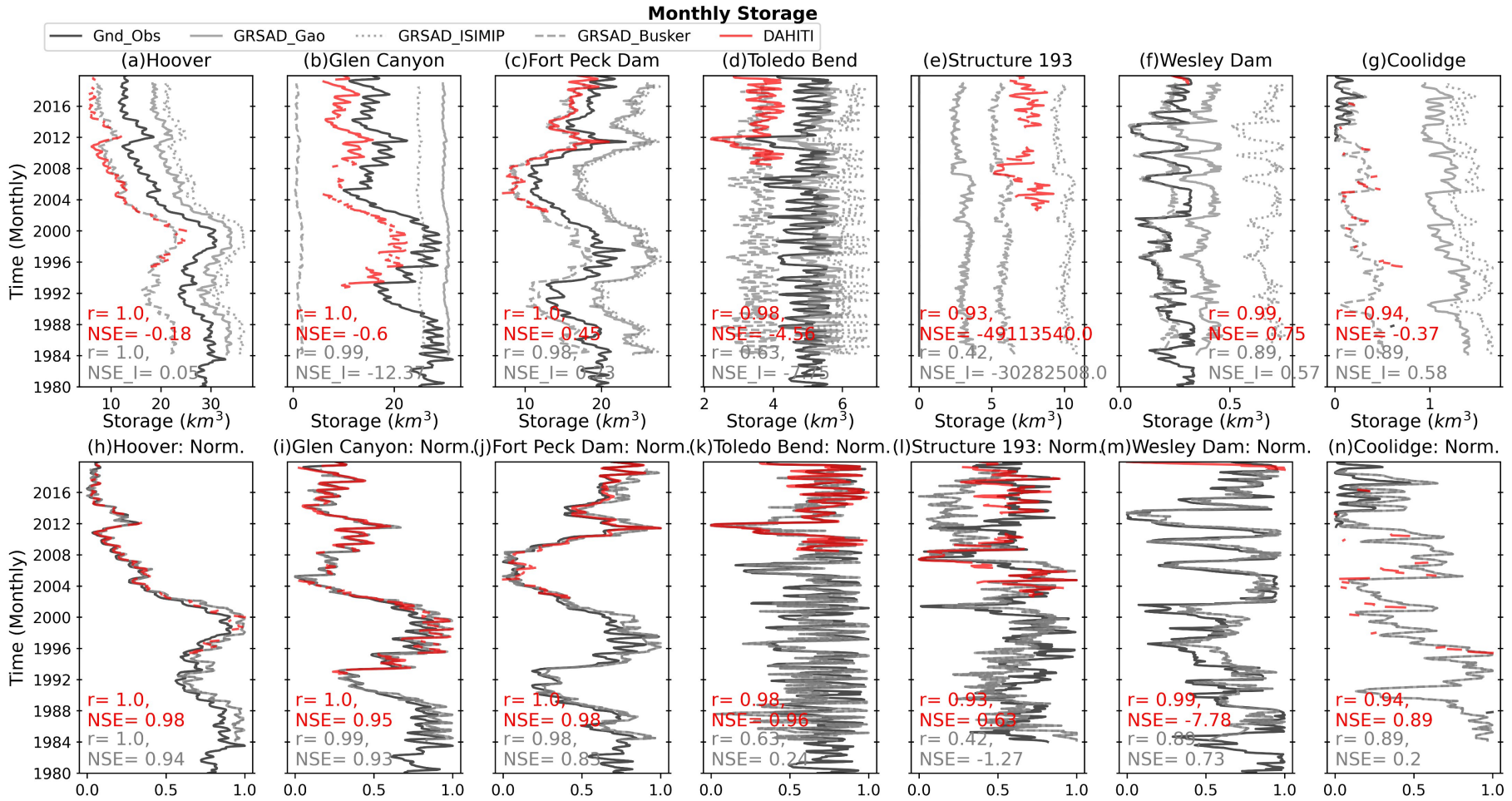


- Raw data (monthly)
- Normalized (monthly)
  - min=0, max=1
  - Timing information (only), long-term trend preserves.
  - Bias and amplitude information lost.
- Decomposition:
  - Monthly Storage=annual average storage + Seasonal variability + residual
- Validation of:
  - Monthly Reservoir Storage
  - Decomposed values (annual average, Seasonal variability, residual)
- Metrics: Correlation coefficient (must be same for both raw and normalized data)

Results: Timeseries of reservoir storage from satellite-based data and ground observation

Do satellite-based storage agree well with ground observation?

- Raw data
  - Sometimes good (g) but generally bad
    - Reason: Large parameter dependency
- Normalized
  - Quite well agreed each other.
    - Reason: parameter dependencies eliminated
    - Surface area considerations wither off
- DAHITI better than GRSAD, but poor in temporal coverage
  - Basis: correlation and NSE

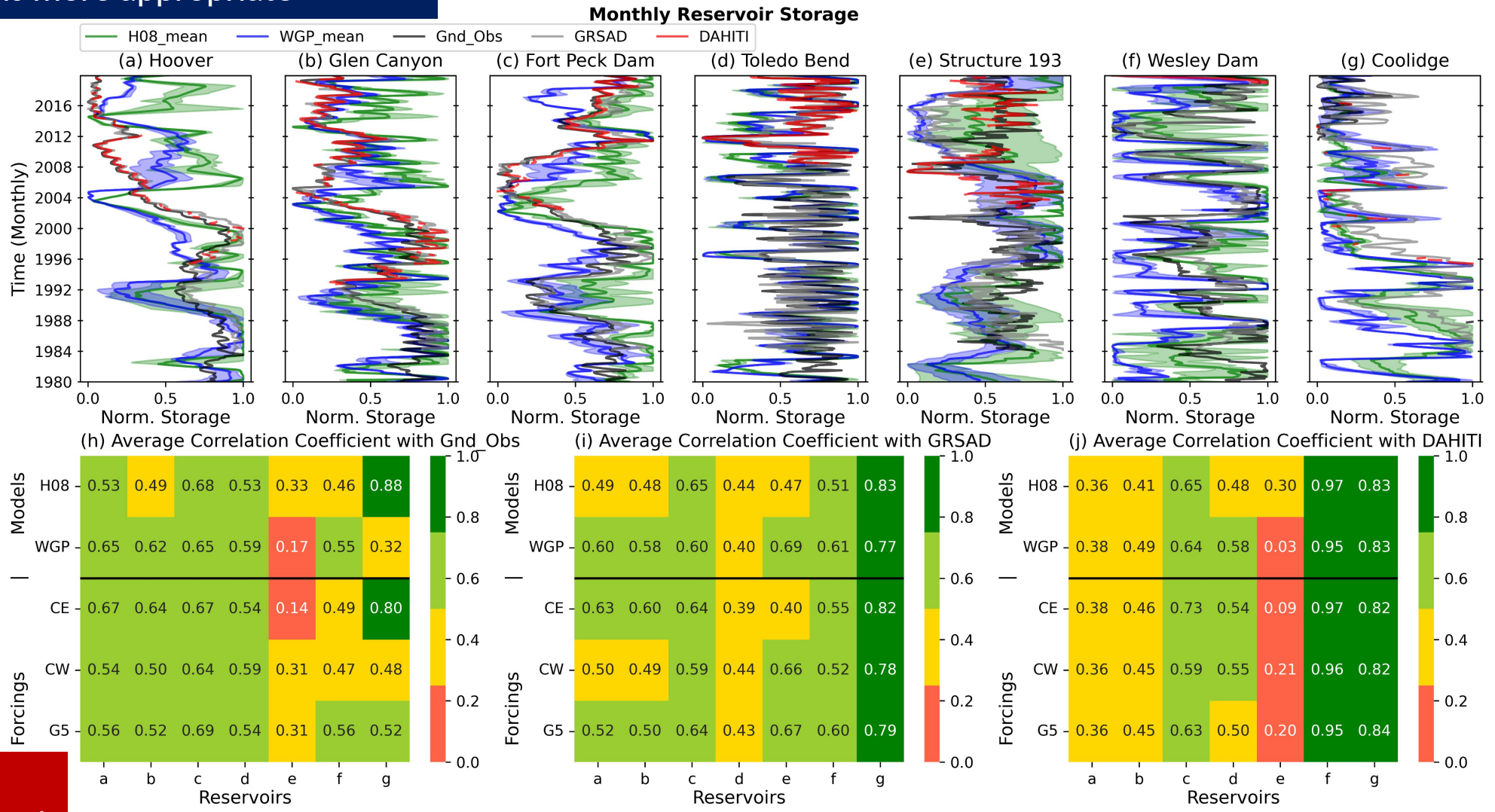


Satellite-based storage raw timeseries is parameter dependent, but normalized one seems much robust.

Results: Model simulations compared against ground truth and satellite data

How good do the models simulate the reservoir storage?
Are the findings consistent with ground observation?
Which satellite product seems more appropriate

- Generally, the model performance is good
  - Issues Post 2005
  - H08 more sensitive to climate forcings
- WGP performs relatively better than H08 (almost similar)
- Forcings performances are similar, but
  - G5>CW~CE
- GRSAD has better consistency, owing to its longer temporal coverage



WGP>H08; G5>CW~CE
Satellite consistent with ground
GRSAD is better

Summary and Conclusions:

How well do the satellite data derived match with the ground observation?

- Readily available satellite data is reliable with normalization
- DAHITI can well but it lacks good temporal coverage
- GRSAD is better due to temporal coverage
  - **Take away message:** Satellite data can be used after normalization. DAHITI is good but lacks temporal coverage while GRSAD has good temporal coverage.

How well do the global hydrological models simulate reservoir storage?

- Simulations generally match both satellite and ground observation.
- Overall, WaterGAP2 simulations are relatively better than H08
- G5 forcings produce the best results compared to CW and CE
- Findings are consistent with ground observation for
  - GRSAD more consistent
  - DAHITI: not very consistent, mostly due to lack of temporal coverage.
  - Validation must be done using multiple satellite data
- **Take away message**: In general, the simulation results match the satellite and ground observation, but further improvement in modelling is needed

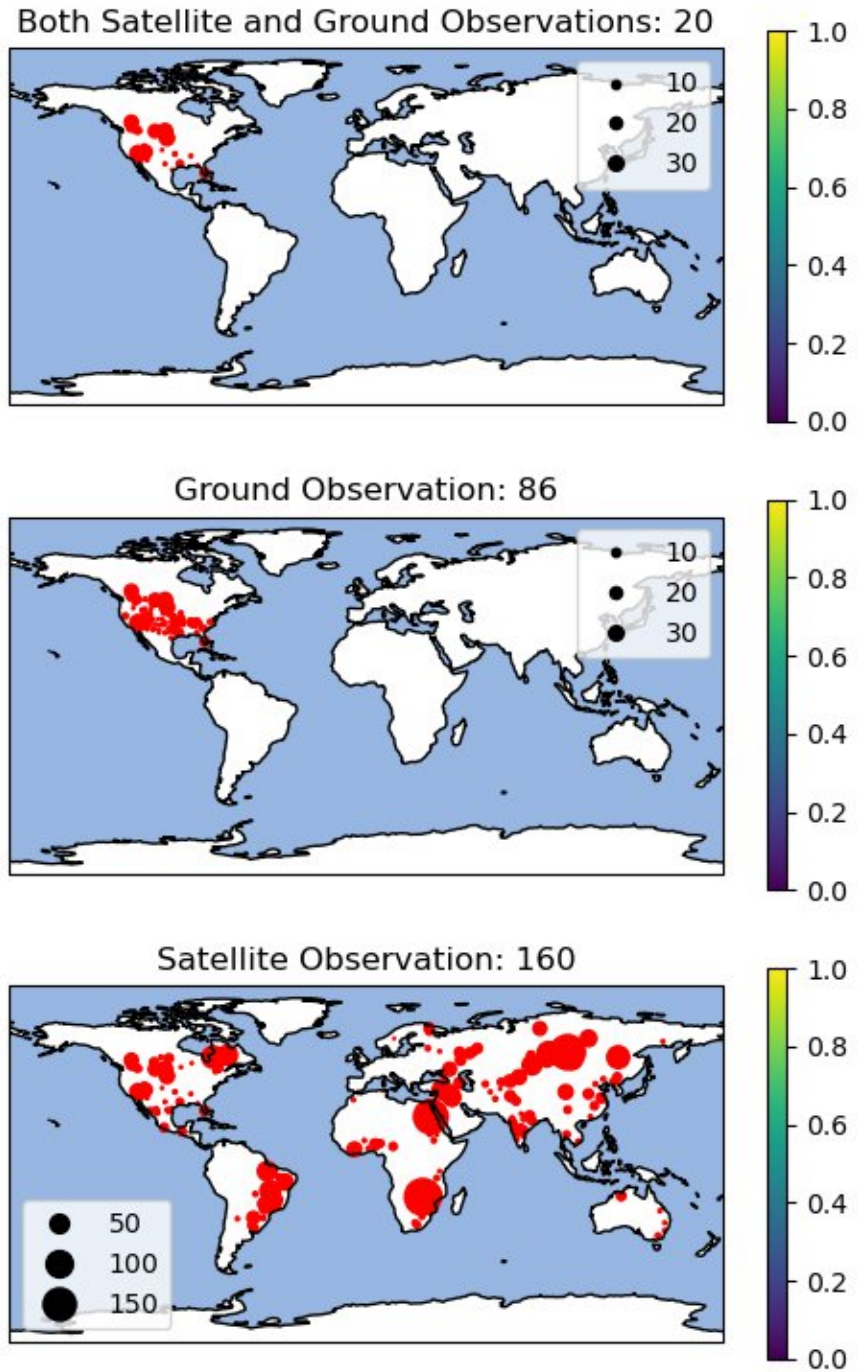
The satellite data is a good source for evaluating ungauged reservoirs, at least the temporal aspects of storage. However, a single source of satellite data should not be relied on.

What we want to do?

- Global scale Validation
- Better Model and forcings Intercomparison
- Pathway to data assimilation

What we need?

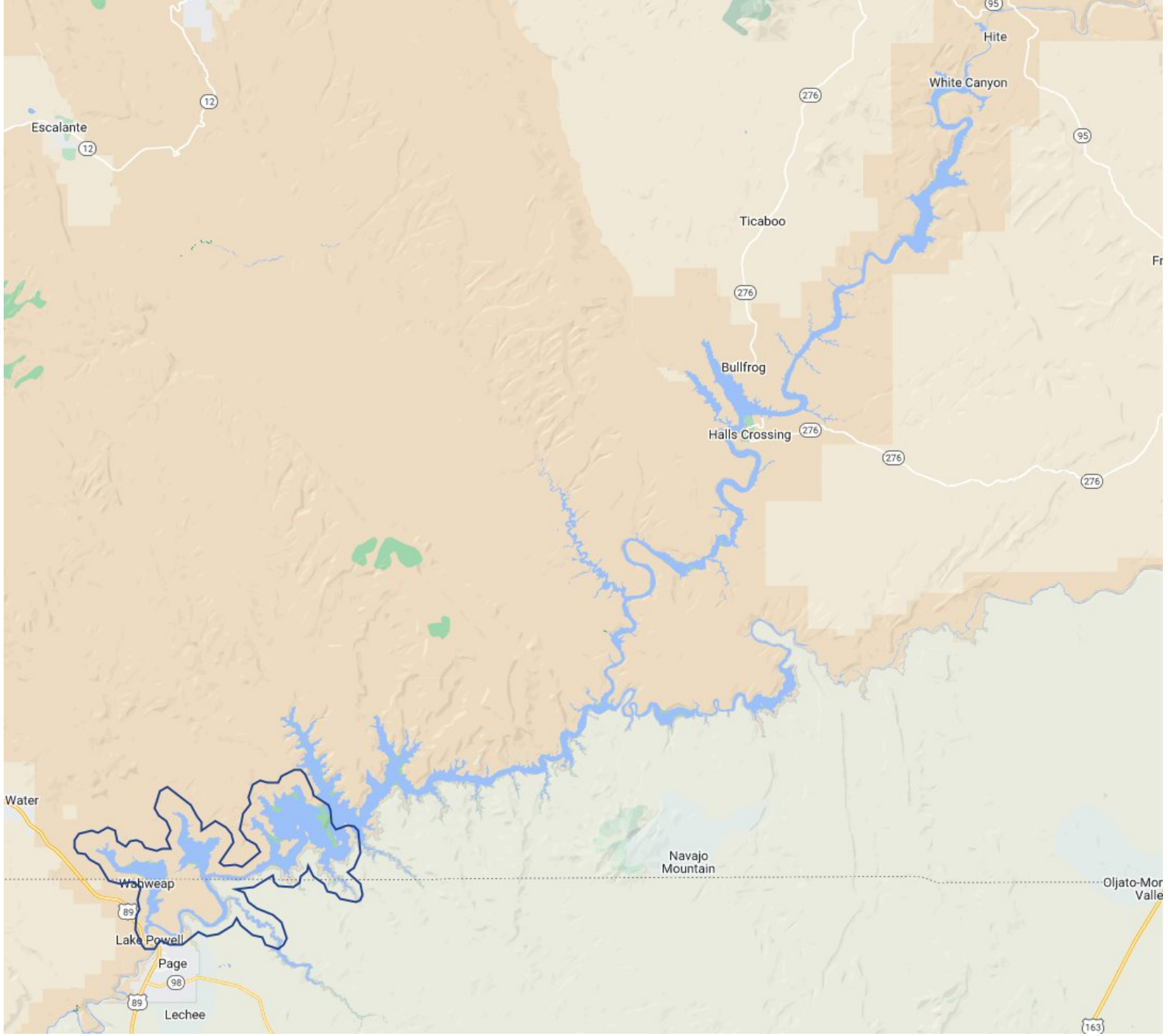
- More model simulations: currently only WaterGAP and H08 and MIROC-INTEG-LAND provided reservoir storage data across all forcings, still waiting for others (CWatM has only G5)
- Single referenced satellite data products: DAHITI, Hydroweb have no reference with GRanD or hydrolakes
- Temporally consistent satellite data
- Organized global reservoir ground observations



Thank You

Questions?

Lake Powell: GRSAD area



Results: Annual average storage and seasonal variability from ground observation and satellite data

Which component of satellite-based volume is more reliable?

Annual storage

•Quite well represented by satellite data: High R and NSE

•DAHITI better than GRSAD

- •Exceptions:
  - Structure 193_GRSAD: unknown
  - Wesley_ DAHITI: short satellite data
  - Coolidge_ DAHITI: short ground obs

Seasonal Variability

•Well agreed each other in most cases: High R and NSE

•DAHITI is better than GRSAD

- •Exceptions:
  - Wesley_ DAHITI: short satellite data
  - Coolidge_ DAHITI: short ground obs

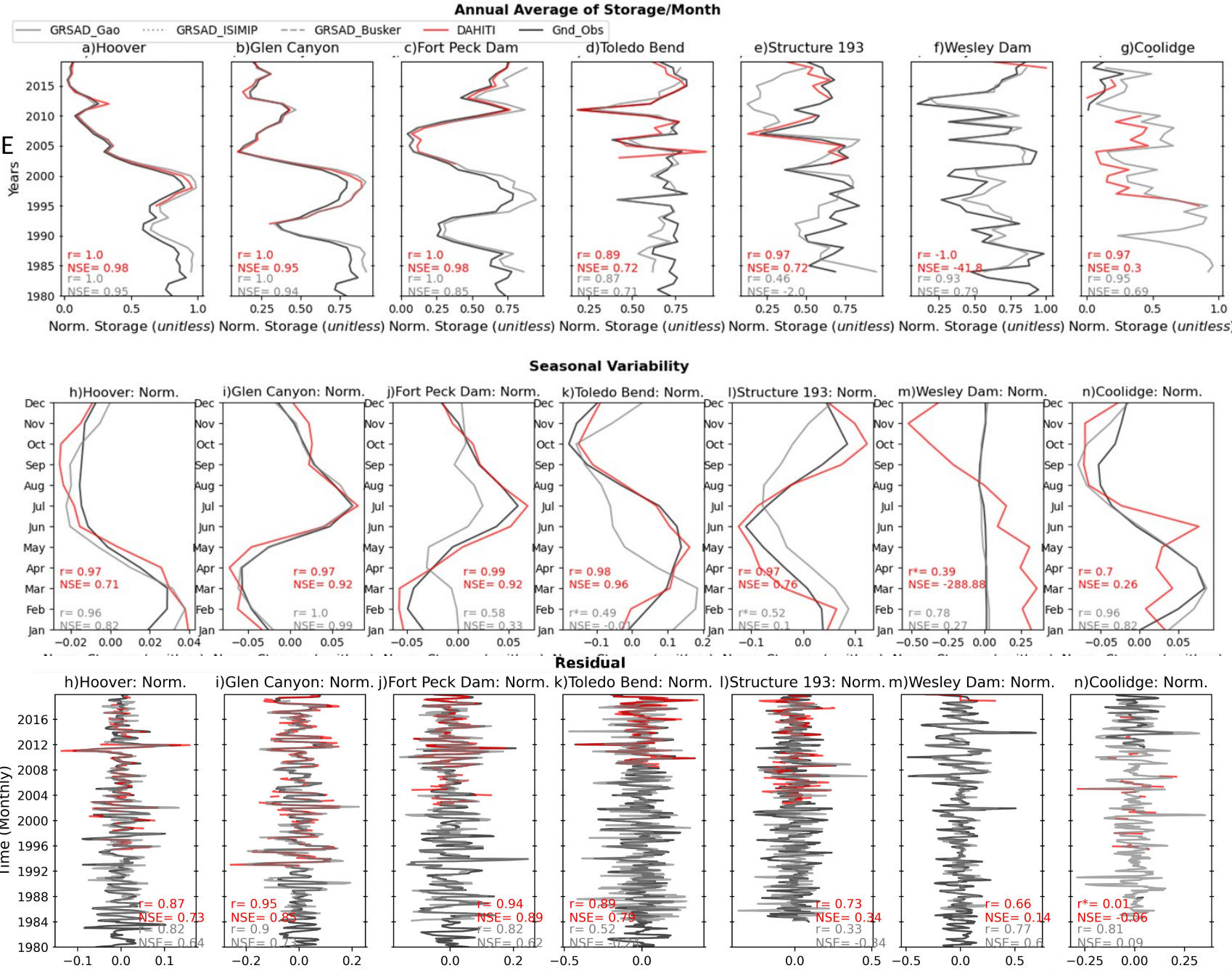
Residual

- Quite well agreed each other.
- DAHITI is better than GRSAD

•Glen Canyon is in the upstream of Hoover, and expected to hav seasonal variabity. But it's completely opposite.

Annual storage has better R and NSE than seasonal variability, particularly for GRSAD: can be used for ungauged reservoirs

Both annual storage and seasonal variability are reliable for DAHITI if sufficient data is available.



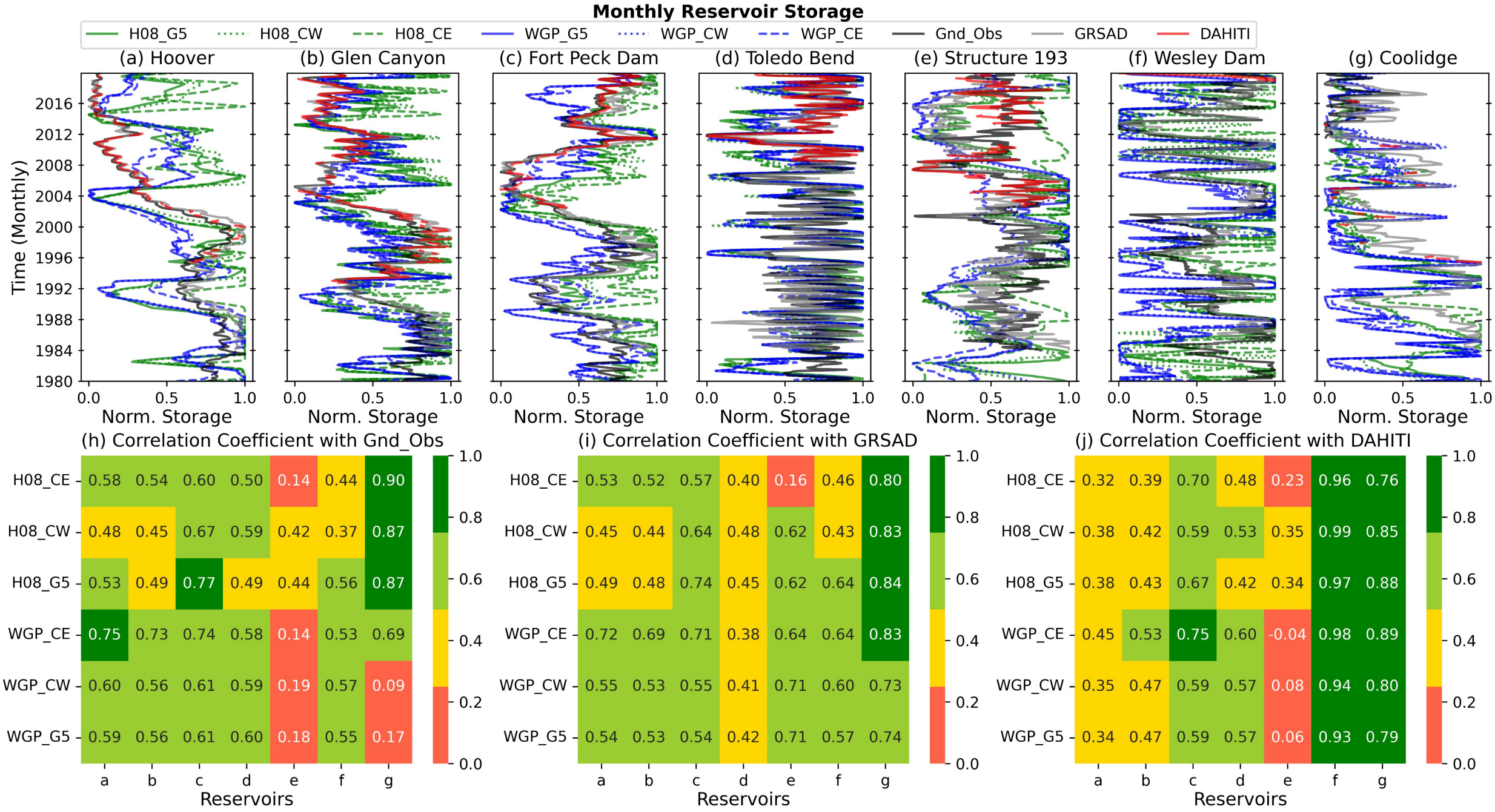
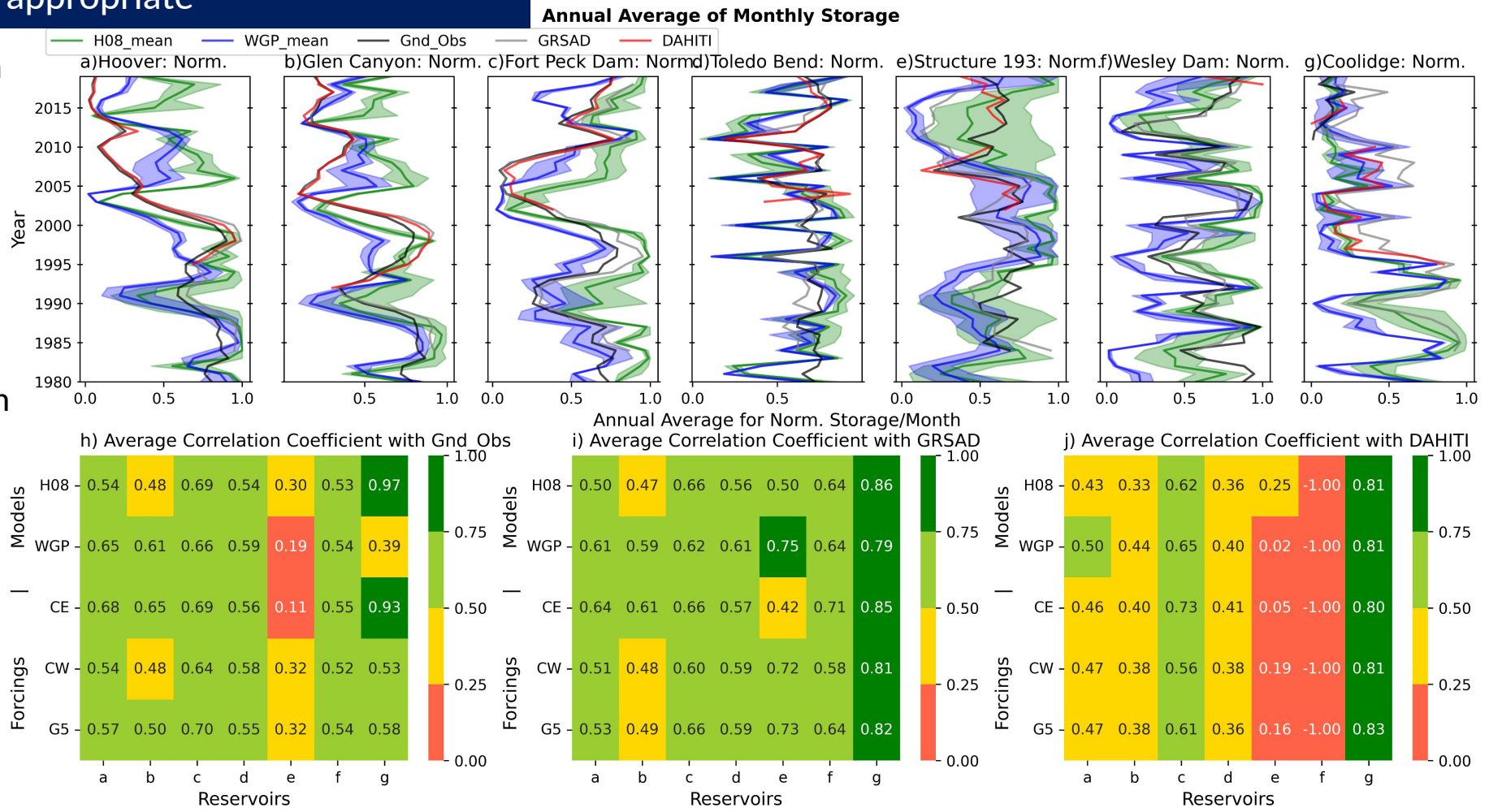

Monthly Reservoir Storage
H08_G5
H08_CW
H08_CE
WGP_G5
WGP_CW
WGP_CE
Gnd_Obs
GRSAD
DAHITI
(a) Hoover
(b) Glen Canyon
(c) Fort Peck Dam
(d) Toledo Bend
(e) Structure 193
(f) Wesley Dam
(g) Coolidge
Time (Monthly)
2016
2012
2008
2004
2000
1996
1992
1988
1984
1980
0.0
0.5
1.0
Norm. Storage
(h) Correlation Coefficient with Gnd_Obs
H08_CE 0.58 0.54 0.60 0.50 0.14 0.44 0.90
H08_CW 0.48 0.45 0.67 0.59 0.42 0.37 0.87
H08_G5 0.53 0.49 0.77 0.49 0.44 0.56 0.87
WGP_CE 0.75 0.73 0.74 0.58 0.14 0.53 0.69
WGP_CW 0.60 0.56 0.61 0.59 0.19 0.57 0.09
WGP_G5 0.59 0.56 0.61 0.60 0.18 0.55 0.17
a b c d e f g
Reservoirs
1.0
0.8
0.6
0.4
0.2
0.0
(i) Correlation Coefficient with GRSAD
H08_CE 0.53 0.52 0.57 0.40 0.16 0.46 0.80
H08_CW 0.45 0.44 0.64 0.48 0.62 0.43 0.83
H08_G5 0.49 0.48 0.74 0.45 0.62 0.64 0.84
WGP_CE 0.72 0.69 0.71 0.38 0.64 0.64 0.83
WGP_CW 0.55 0.53 0.55 0.41 0.71 0.60 0.73
WGP_G5 0.54 0.53 0.54 0.42 0.71 0.57 0.74
a b c d e f g
Reservoirs
(j) Correlation Coefficient with DAHITI
H08_CE 0.32 0.39 0.70 0.48 0.23 0.96 0.76
H08_CW 0.38 0.42 0.59 0.53 0.35 0.99 0.85
H08_G5 0.38 0.43 0.67 0.42 0.34 0.97 0.88
WGP_CE 0.45 0.53 0.75 0.60 -0.04 0.98 0.89
WGP_CW 0.35 0.47 0.59 0.57 0.08 0.94 0.80
WGP_G5 0.34 0.47 0.59 0.57 0.06 0.93 0.79
a b c d e f g
Reservoirs

Figure 3: Model simulations compared against ground truth and satellite data for annual average

How good do the models simulate the simulate the annual average?
Is the finding consistent with ground observation?
Which satellite product seems more appropriate

- Simulations match the observations in most cases
  - Performance of reservoirs depletes after 2005
- GRSAD results are similar to ground observations but not DAHITI
  - Exceptions:
    - Structure 193 sims follow GRSAD and not ground observation or DAHITI
    - Fort Peck and Coolidge simulations are also quite good when compared with DAHITI along with ground observations and GRSAD
- H08 vs WGP
  - WGP>H08
  - H08 has more variability with input forcings
- CE performance is better than CW and G5
  - CE>G5>CW



WGP>H08; CE>G5>CW
Yes
GRSAD

supplementary

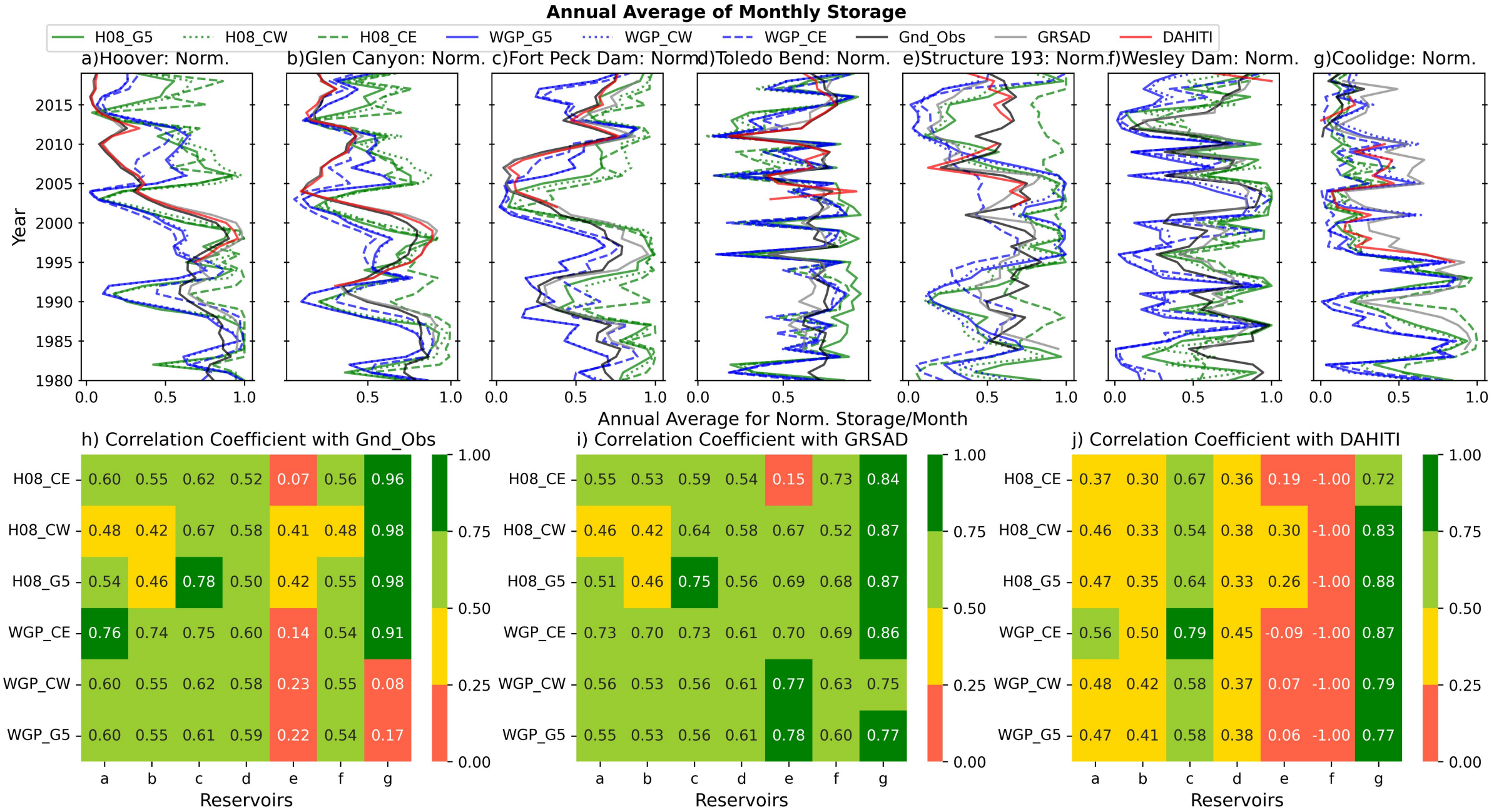
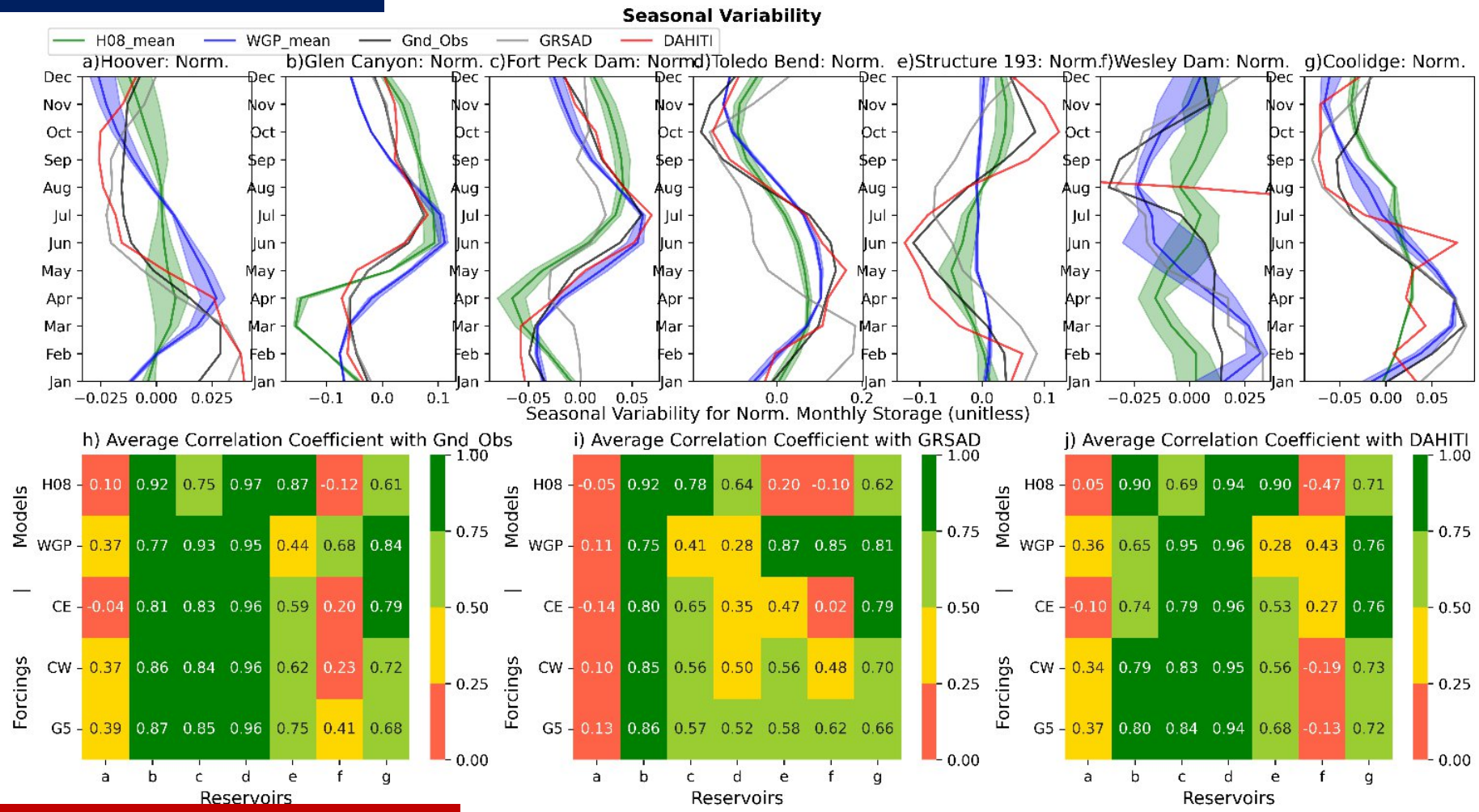


Figure 4: Model simulations compared against ground truth and satellite data for seasonal variability

How good do the models simulate the seasonal variability?
Is the finding consistent with ground observation?
Which satellite product seems more appropriate?

- Simulations capture the seasonal cycle in most cases
- DAHITI results are more similar to ground observations compared to GRSAD
- Structure 193 WGP: No variability still correlation is good for GRSAD
- H08 vs WGP
  - WGP(11/21)>H08
  - H08 has more variability with input forcings (std?)
  - Structure 193: H08 better in gnd_obs and DAHITI, WGP better for GRSAD
- Forcings:
  - G5 performance is better than CW and CE (bold/box the best)
    - G5>CW>CE



WGP>H08; G5>CW>CE
Yes
DAHITI, even with missing values

Supplementary

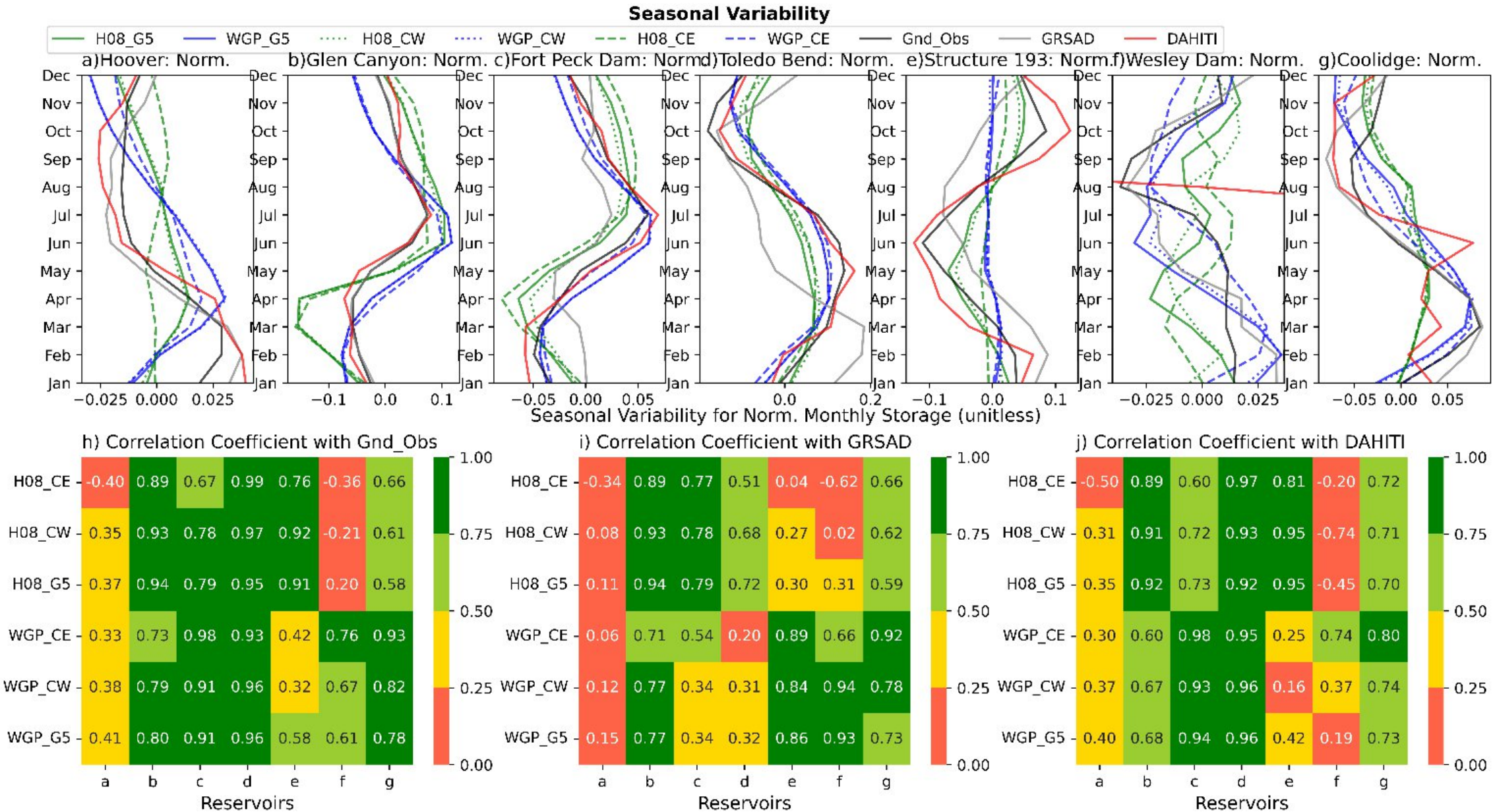
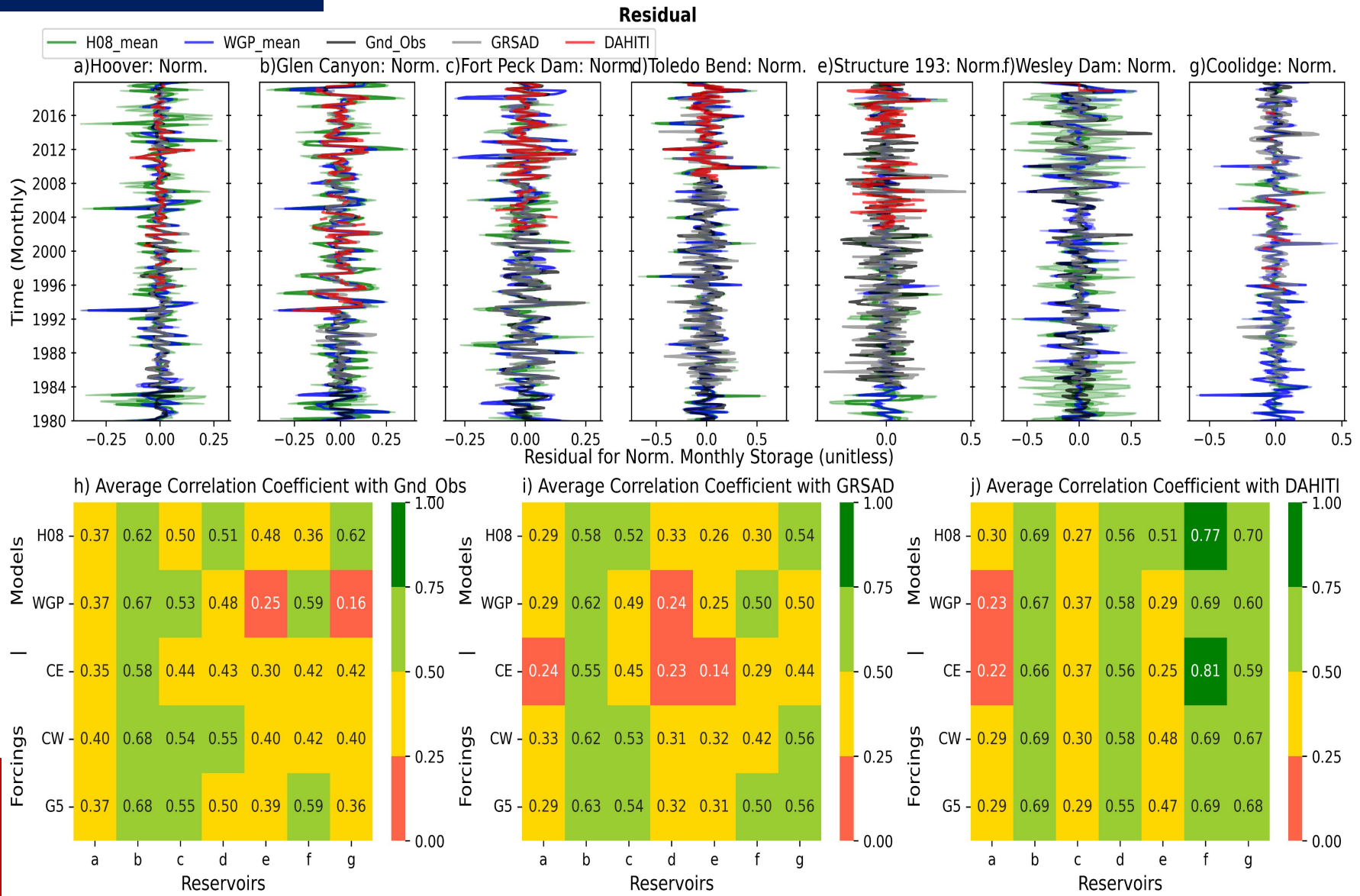


Figure 5: Model simulations compared against ground truth and satellite data for residuals

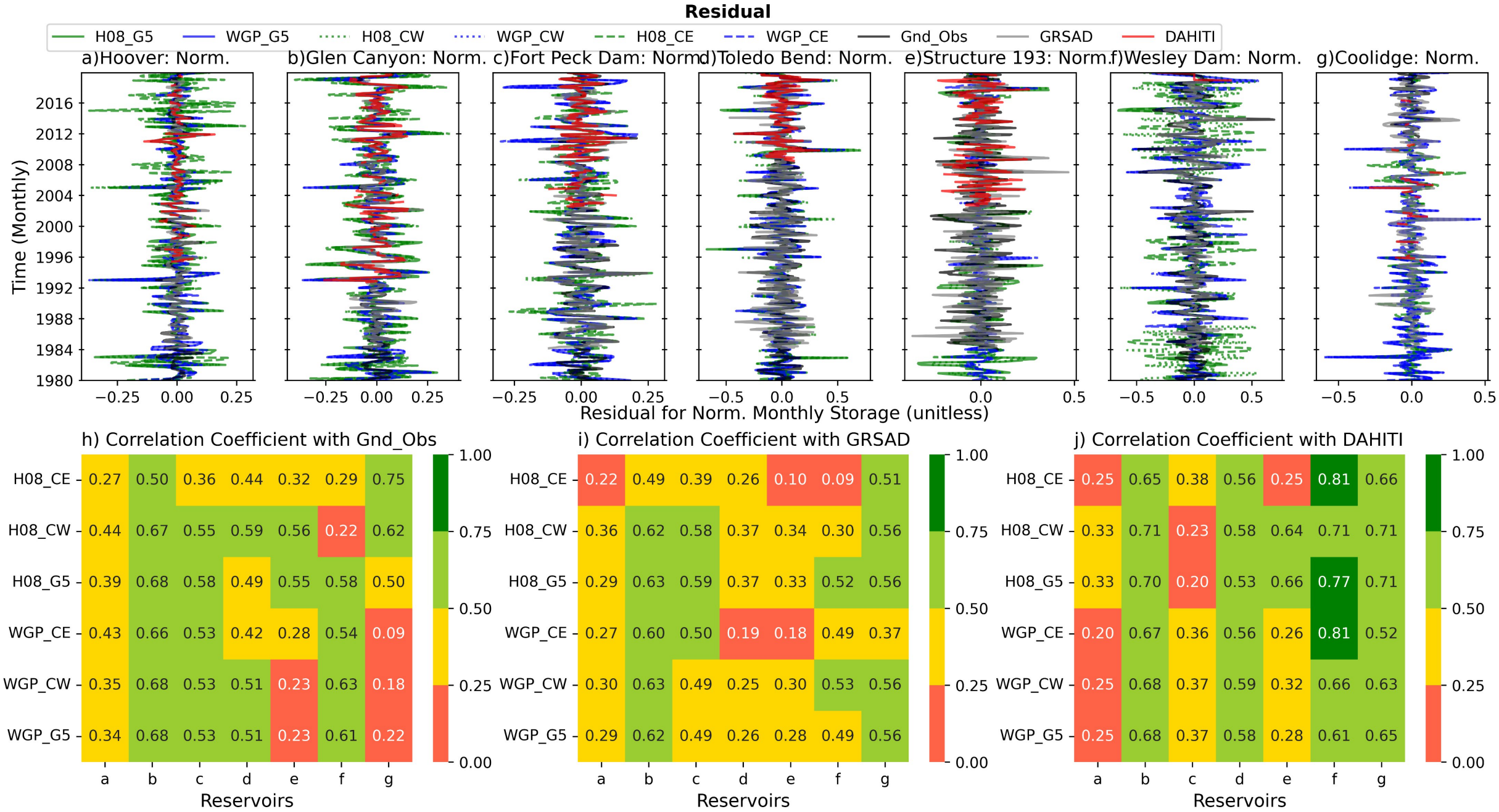
How good do the models simulate the seasonal variability?
Is the finding consistent with ground observation?
Which satellite product seems more appropriate?

- Simulations capture the rise and fall of residual in most cases
- GRSAD results are more similar to ground observations compared to GRSAD
- H08 vs WGP
  - H08>WGP
  - H08 has more variability with input forcings
  - CW performance is better than G5 and CE (bold/box the best)
  - CW>G5>CE

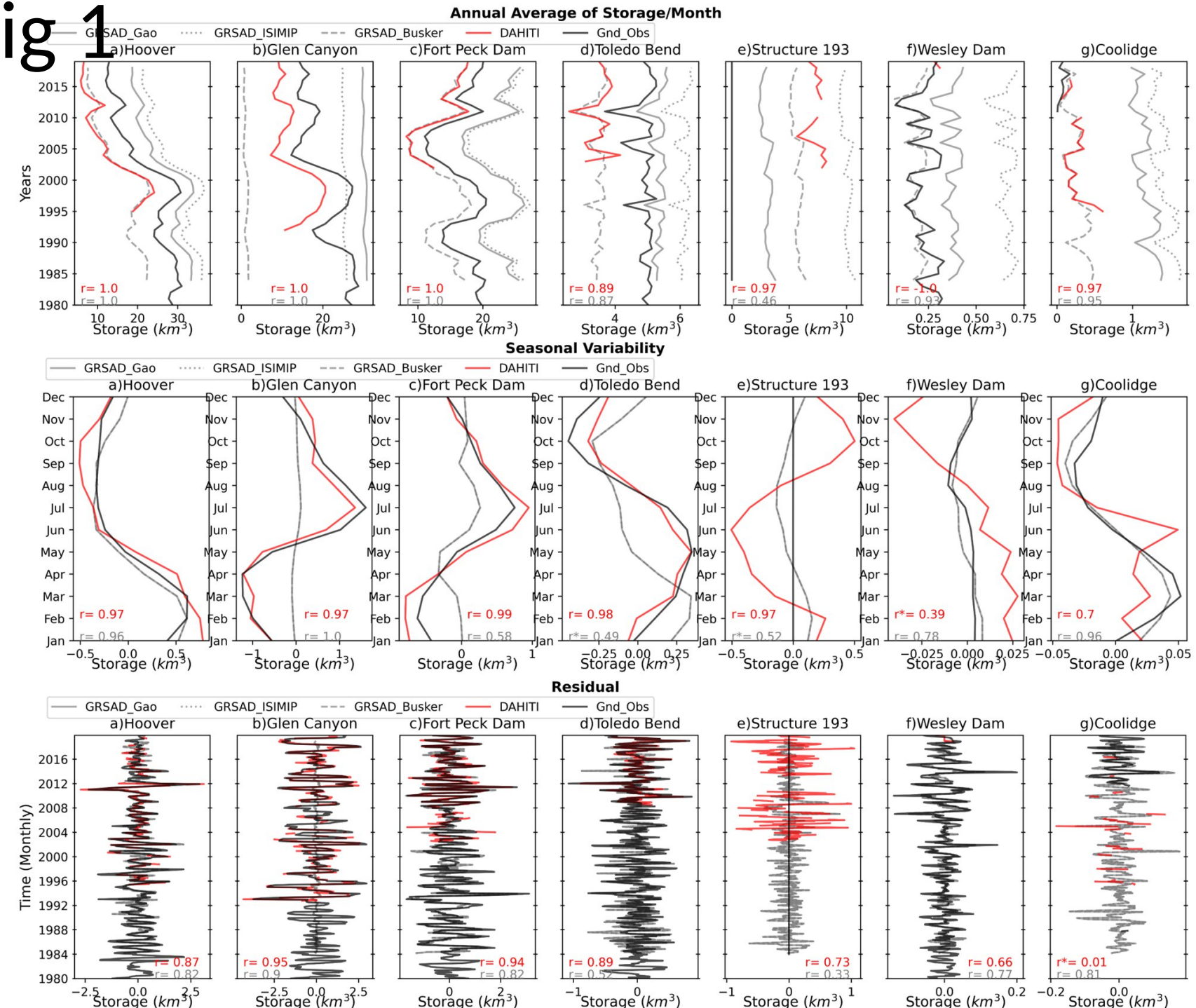
H08>WGP; CW>G5>CE
Yes
GRSAD but difficult to say



supplementary



Supplementary Fig 1



Conclusions:

How well do the global hydrological models perform when compared to satellite data?

- **How well do the satellite data derived match with the ground observation?**
- Readily available satellite data is reliable with normalization
- DAHITI can well replicate both annual storage and seasonal variability, but it lacks good temporal coverage
- GRSAD is good for annual storage and not for seasonal variability.
  - **Take away message:** Satellite data can be used after normalization. DAHITI is better but lacks temporal coverage while GRSAD has good temporal coverage but not reliable for components other than annual storage

- **How well do the global hydrological models simulate reservoir storage?**
- Simulations generally match both satellite and ground observation.
- Overall, WaterGAP2 simulations are relatively better than H08
- CW forcings produce the best results compared to G5 and CE
- Findings are consistent with ground observation for
  - GRSAD: both annual average storage and seasonal variability.
  - DAHITI: consistent only for seasonal variability but not for annual storage, mostly due to lack of temporal coverage.
  - Validation must be done using multiple satellite data
  - **Take away message**: In general, the simulation results match the satellite and ground observation, but further improvement in modelling is needed to improve the mimic

The satellite data is a good source for evaluating ungauged reservoirs, at least the temporal aspects of storage. However, a single source of satellite data should not be relied on

Methods

Linear A-h relationship: h = a × A + b

Change in Volume $= \Delta V = \frac{(h2 - h1) \cdot (A1 + A2)}{2}$

- Gao's Method

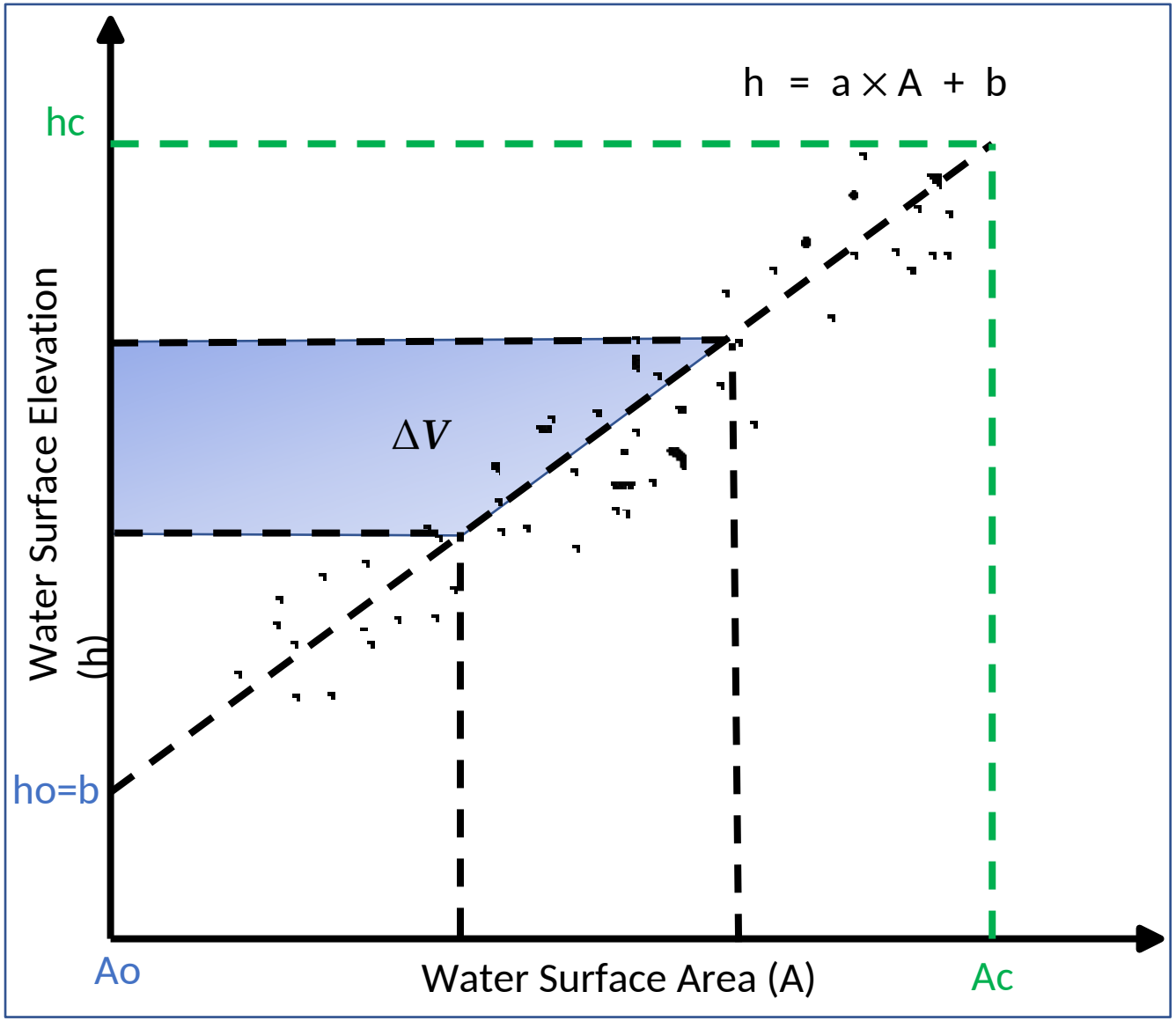
$$Vi = Vc - \frac{(hc - hi) \cdot (Ac + Ai)}{2}$$

- Busker's Method

$$Storage\ Volume = Vi = \frac{(hi - b) \cdot Ai}{2}$$

Water volume can be calculated using h or A only

$$E[Vi] = \frac{(hi - b)2}{2a} = \frac{a \cdot (Ai)2}{2}$$



Observed Data used in this study(ground and satellite)

Name	Publication	Data	Details	Period	Advantages/Remarks
ISIMIP reservoirs data	Lehner et al, 2011	**storage volume, hc, Ac**	Global inventory of reservoir data	-	**Reservoir specification**
ResOpsUS	Steyaert et al, 2022	Reservoir volume	Integrated observed reservoir volume in CONUS	Variable	Ground Observation
GRSAD (Gao et al, 2019)	Zhao, G. and H. Gao,2018	Monthly Water surface area **(A)**	time series of area values for 6817 global reservoirs based on the dataset by Pekel et al. (2016)	1984 to 2018	contaminations from clouds, cloud shadows, and terrain shadows adjusted automatically; consistent
GRBD: Global Reservoir Bathymetry Dataset	Li, Y., H. Gao, G. Zhao, and K. Tseng, 2020.	Hypsometric Parameters: a **and b** and **storage volume**	high resolution 3D bathymetry of 347 global reservoirs, which represents 50% of the overall global storage capacity.	-	provides the Area-Elevation (A-E) and Elevation-Volume (E-V) relationships
DAHITI	Schwatke et al., 2015	Water surface **(A)** & elevation **(h)**	hydrological information on lakes, reservoirs, rivers, derived from satellite data	1984 to 2020 (Variable)	Long available period; has discontinuities; Needs individual data requests;