A decade-long record of temporal gravity observed by the Swarm satellites

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Swarm 10 Year Anniversary & Science Conference 2024
08 – 12 April 2024 | Copenhagen, Denmark

Context and objectives

- ESA/DISC funded project (since 9/2017)
- Provide highest-quality monthly-independent GNSS-based gravity field models from Swarm
- Combine individual gravity solutions, computed with:
  - different kinematic orbit solutions
  - different inversion approaches
- Monthly combined Swarm gravity field models:
  - period length set by the calendar month (first to last day)
  - from 2013-12-01 to 2023-12-31
  - available from:
    - ICGEM https://icgem.gfz-potsdam.de/sp/02_COST-G_/Swarm
    - ESA swarm-diss.eo.esa.int > *Level2longterm* > *EGF_*

Kinematic Orbits

Institute	Software	Reference
AIUB	Bernese v5.3	Jäggi et al. (2016)[1]
IfG	Gravity Recovery Object Oriented Programming System (GROOPS)	Suesser-Rechberger et al. (2022)[2]
TUD	GPS High precision Orbit determination Software Tool (GHOST)	IJssel et al. (2015)[3]

[1] ftp://ftp.aiub.unibe.ch/leo_orbits/swarm
[2] ftp://ftp.tugraz.at/outgoing/ITSG/tvgogo/orbits/Swarm
[3] http://earth.esa.int/web/guest/swarm/data-access

Individual Gravity field models

Inst.	Approach	Reference
AIUB	Celestial Mechanics Approach	Jäggi et al. (2016)
ASU	Decorrelated Acceleration Approach	Bezděk et al. (2016)
IfG	Short-Arcs Approach Improved	Suesser-Rechberger et al. (2022)
OSU	Energy Balance Approach	Guo et al. (2015)

Combined Gravity field models

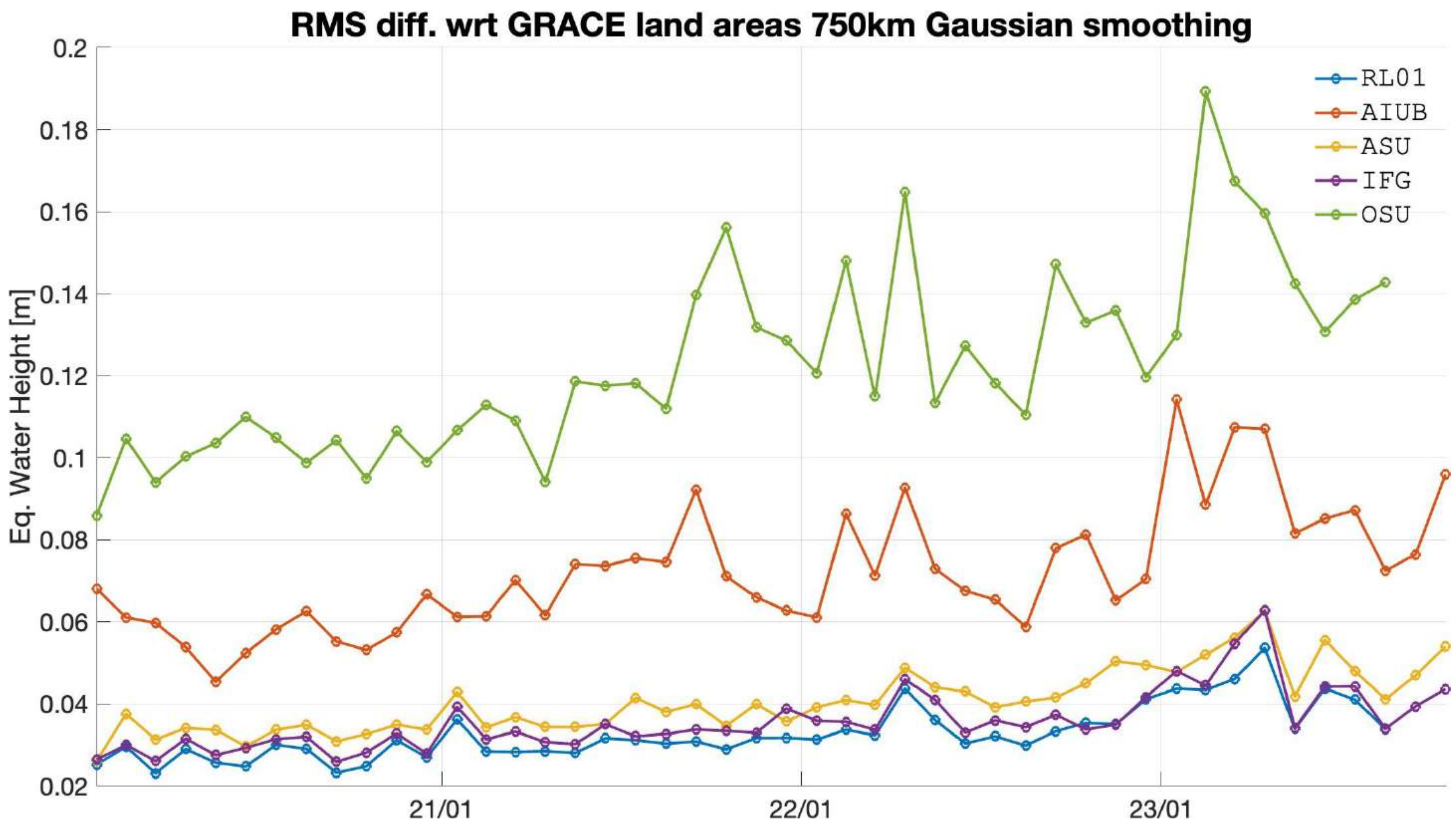
- Combination at the level of solutions, up to degree 40
- Weights applied to individual solutions derived from Variance Component Estimation (VCE)
- Degrees 2-20 considered in VCE
- João Teixeira da Encarnação and Pieter Visser (2019). *TN-03: Swarm models validation*. Tech. rep. TU Delft. doi: 10.13140/RG.2.2.33313.76640

Gravity field model pre-processing

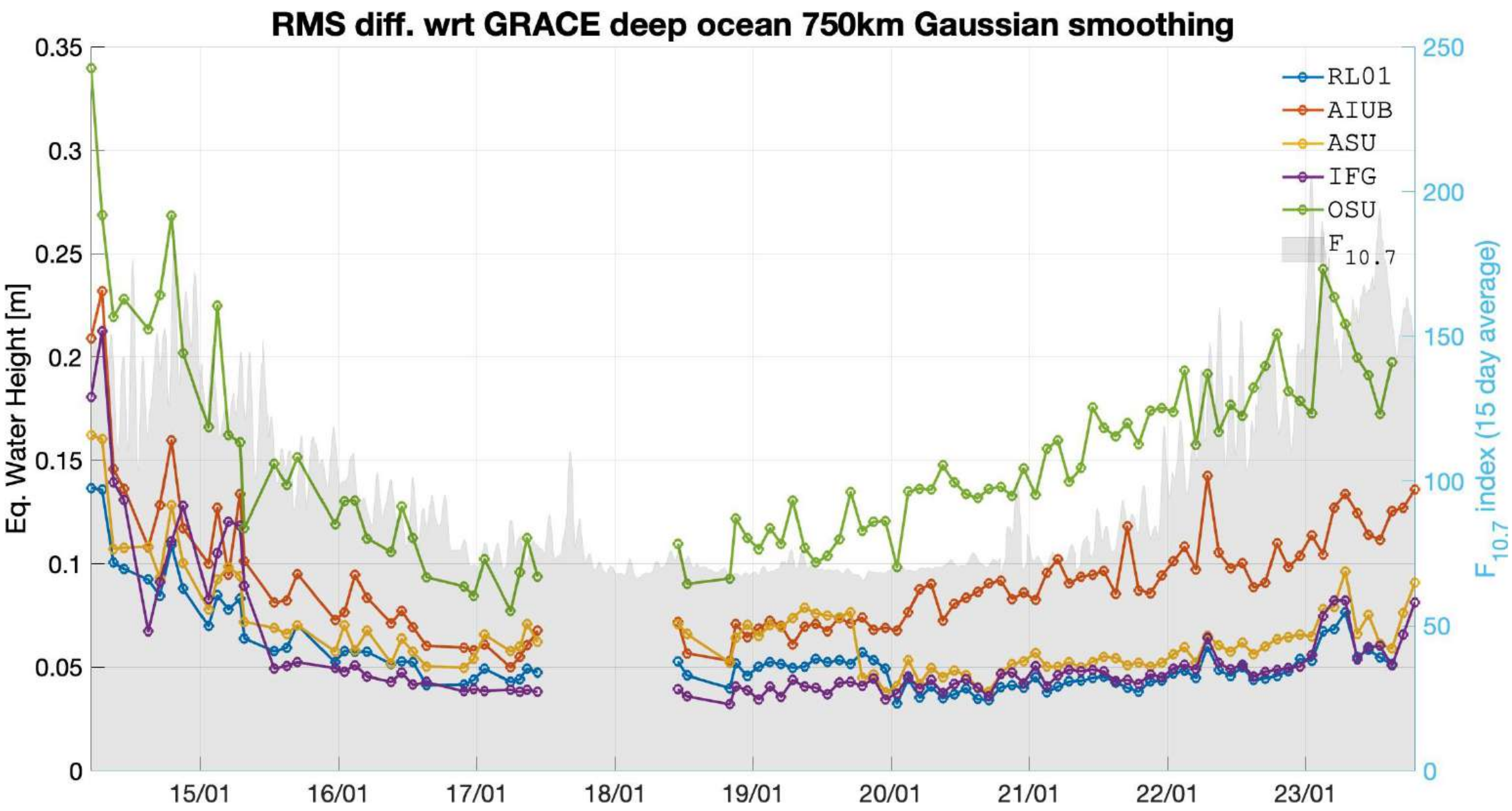
- Analysis spans 2016-01-01 until 2023-12-31
- Temporal variations relative to static GGM05G (Ries et al., 2016)
- Gaussian smoothing with 750-km radius
- C_{20} replaced with values from weekly GRACE/GRACE-FO TN-14 time series
- Swarm ACC data not used

Analyses setup

- GRACE/GRACE-FO CSR RL06 considered (with same pre-processing)
- GRACE/GRACE-FO solutions interpolated at Swarm model epochs (except over gaps longer than 120 days)
- Ocean signal, with no buffer zone, removed for land analyses
- Ocean analyses exclude coastal areas ≈ 1000 km or less from coast lines
- IfG KO solutions:
  - Considered for ASU solutions for Oct - Dec 2019 (and later)
  - Not considered for RL01 solutions prior to Jan 2020

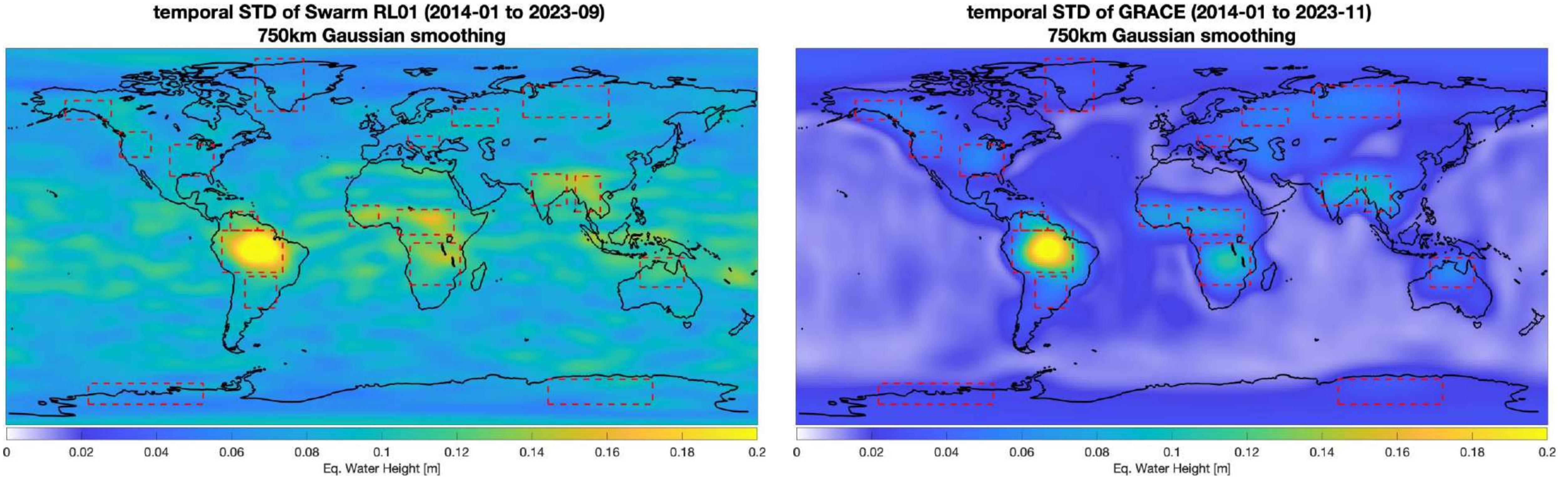


RMS diff. wrt GRACE land areas 750km Gaussian smoothing
Eq. Water Height [m]
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
21/01
22/01
23/01
RL01
AIUB
ASU
IFG
OSU



RMS diff. wrt GRACE deep ocean 750km Gaussian smoothing
Eq. Water Height [m]
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
15/01
16/01
17/01
18/01
19/01
20/01
21/01
22/01
23/01
RL01
AIUB
ASU
IFG
OSU
$F_{10.7}$
$F_{10.7}$ index (15 day average)
250
200
150
100
50
0

Signal variability: 18 selected basins



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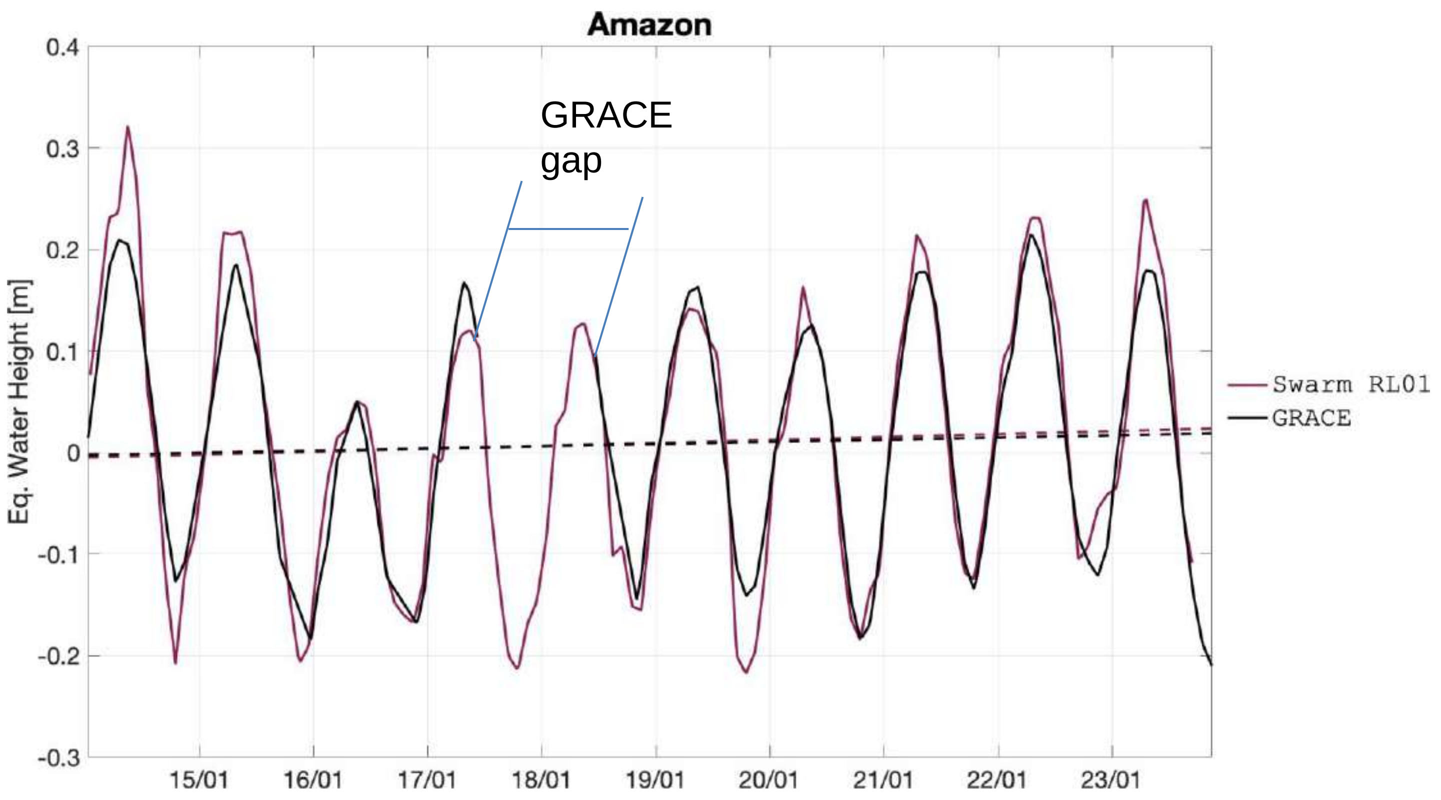

solution	constant term [cm]	constant term Δ [cm]	linear term [cm/year]	linear term Δ [cm/year]	corr. coeff. [ ]
Swarm RL01	1.32	-0.46	0.29	0.07	0.96
GRACE	1.78	0.00	0.21	0.00	1.00

latitude -17 to 3 degrees, longitude -76 to -47 degrees

Statistics from all 18 analysed basins

solution	constant term Δ RMS [cm]	linear term Δ RMS [cm/year]	corr. coeff. mean [ ]
Swarm RL01	1.05	0.35	0.75
GRACE	0.00	0.00	1.00

Conclusions

- Combined model better than individual models under any metric
- Swarm signal useful below degree 15 (750 km radius smoothing)
- Swarm gravity field model quality stable since 2016,
  - but increase in solar activity slowly degrading disagreement with GRACE/GRACE-FO
- IfG KO orbit processing changes result in a visible improvement since 2020
- Ocean areas are ≈ 30-50% noisier than land areas
- Seasonal land signal clearly resolvable by Swarm (compared to GRACE/GRACE-FO):
  - Temporal correlations dip under 0.5 over degree 14
  - Global spatial agreement at ≈ 3-4 cm RMS EqWH
  - Over 18 analysed basins (of various sizes), considering **all Swarm data**:
    - trends agree under 0.36 cm/year EqWH
    - correlation is at 0.75

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Please cite

João Teixeira da Encarnação et al. (2020). “Description of the multi-approach gravity field models from Swarm GPS data”. In: *Earth System Science Data* 12.2, pp. 1385–1417. doi: 10.5194/essd-12-1385-2020. url: https://essd.copernicus.org/articles/12/1385/2020/

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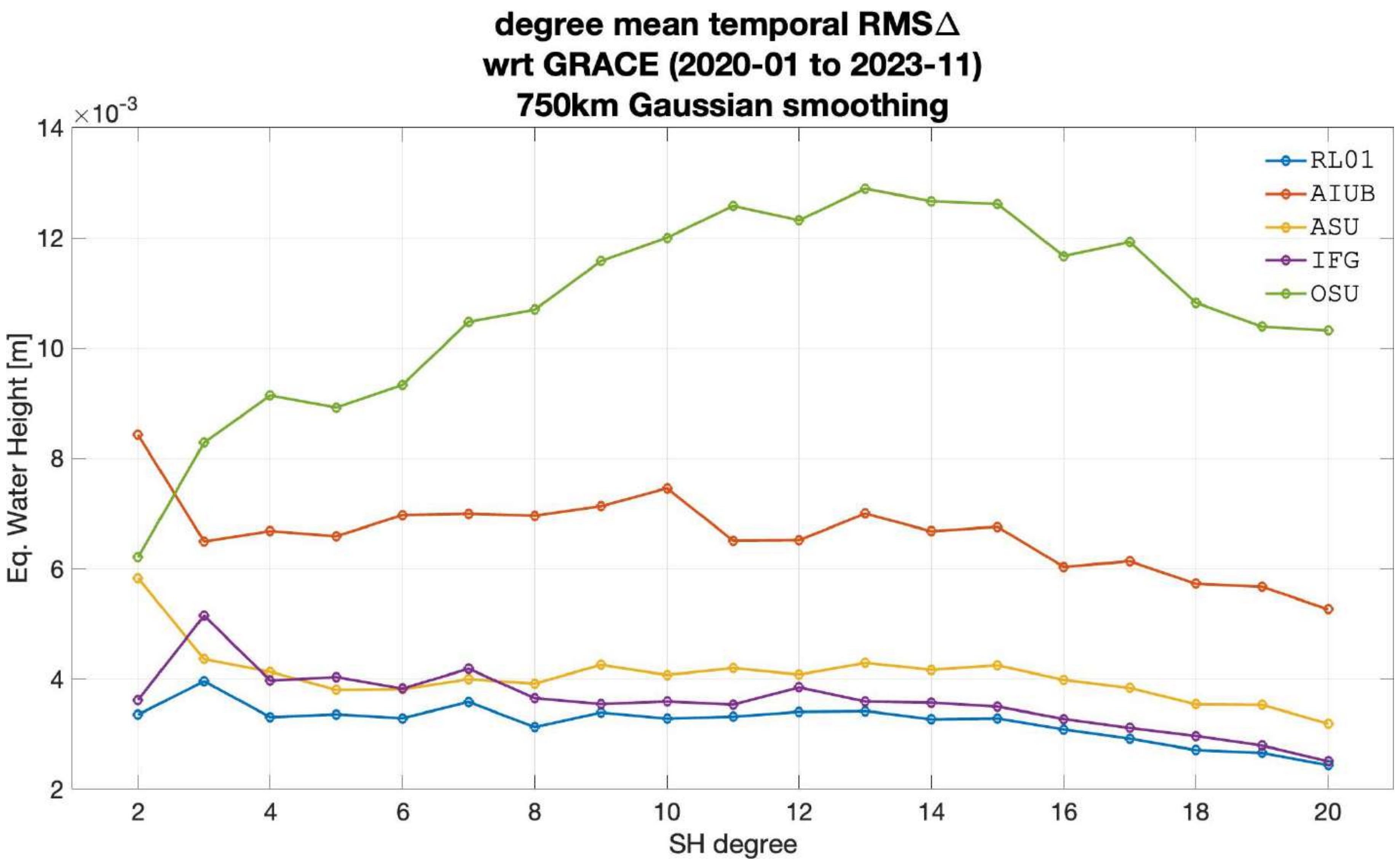
Extra slides



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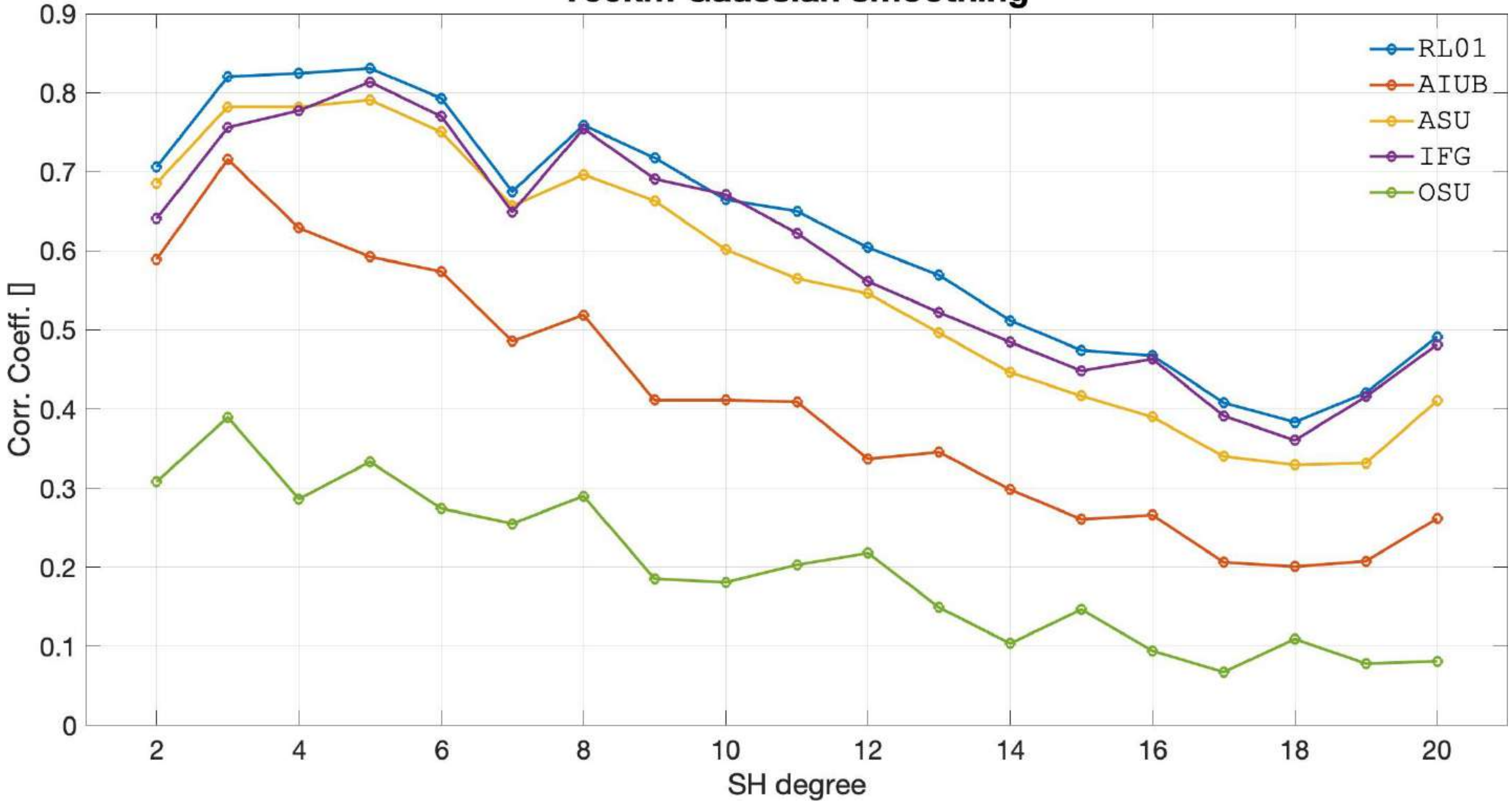
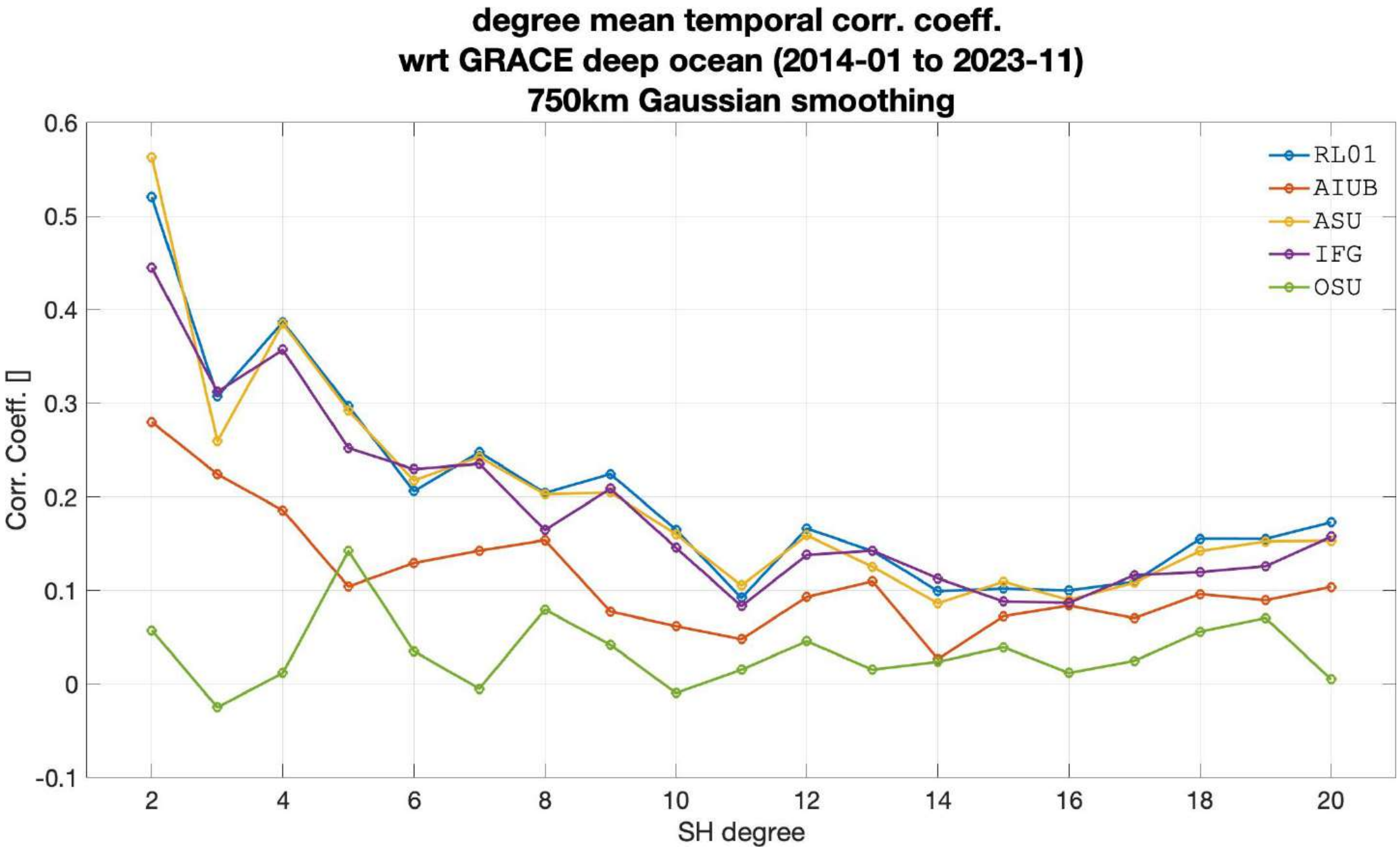
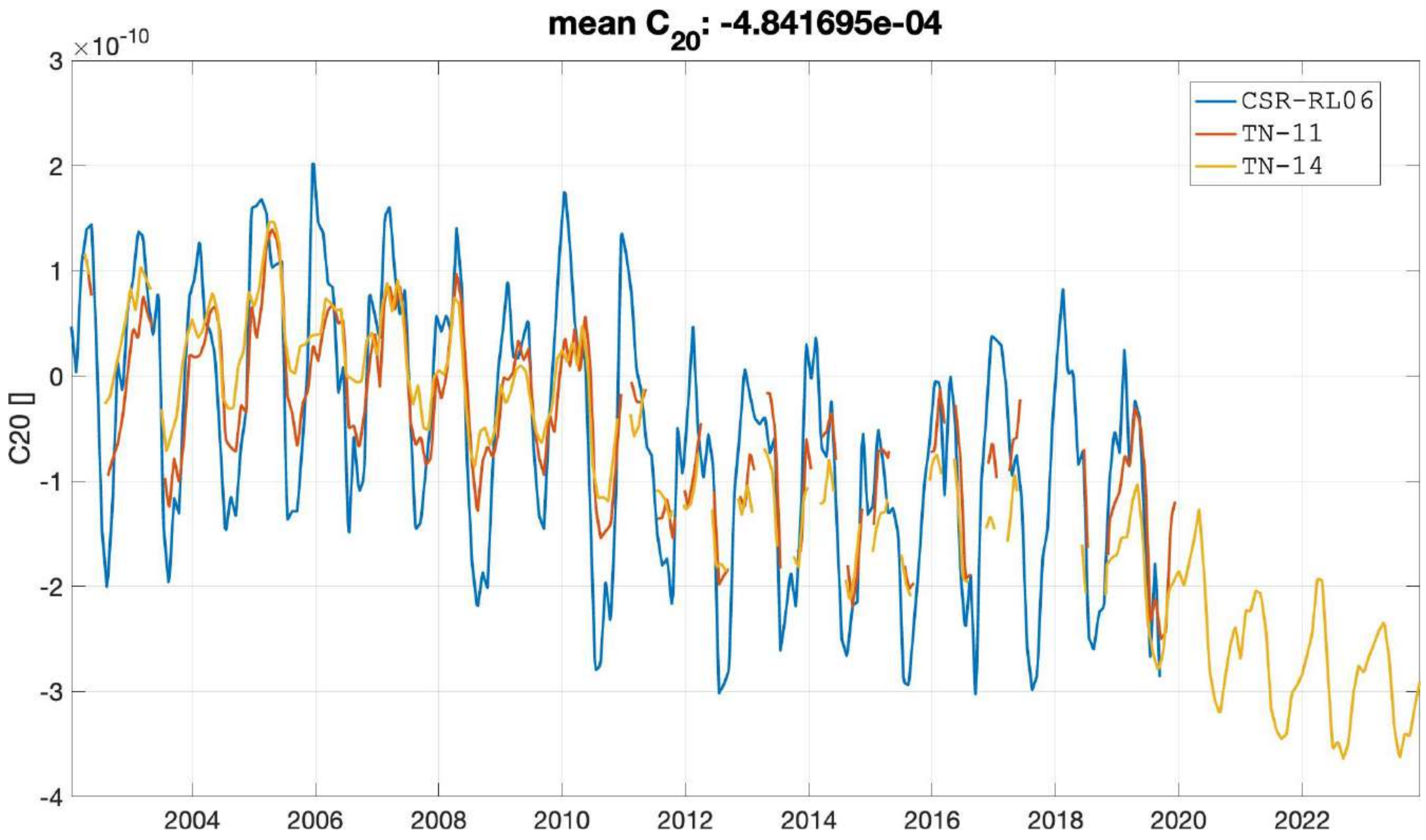
degree mean temporal corr. coeff. wrt GRACE land areas (2020-01 to 2023-11) 750km Gaussian smoothing




degree mean temporal corr. coeff.
wrt GRACE deep ocean (2014-01 to 2023-11)
750km Gaussian smoothing
Corr. Coeff. []
SH degree
RL01
AIUB
ASU
IFG
OSU
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
2
4
6
8
10
12
14
16
18
20

C_{20}



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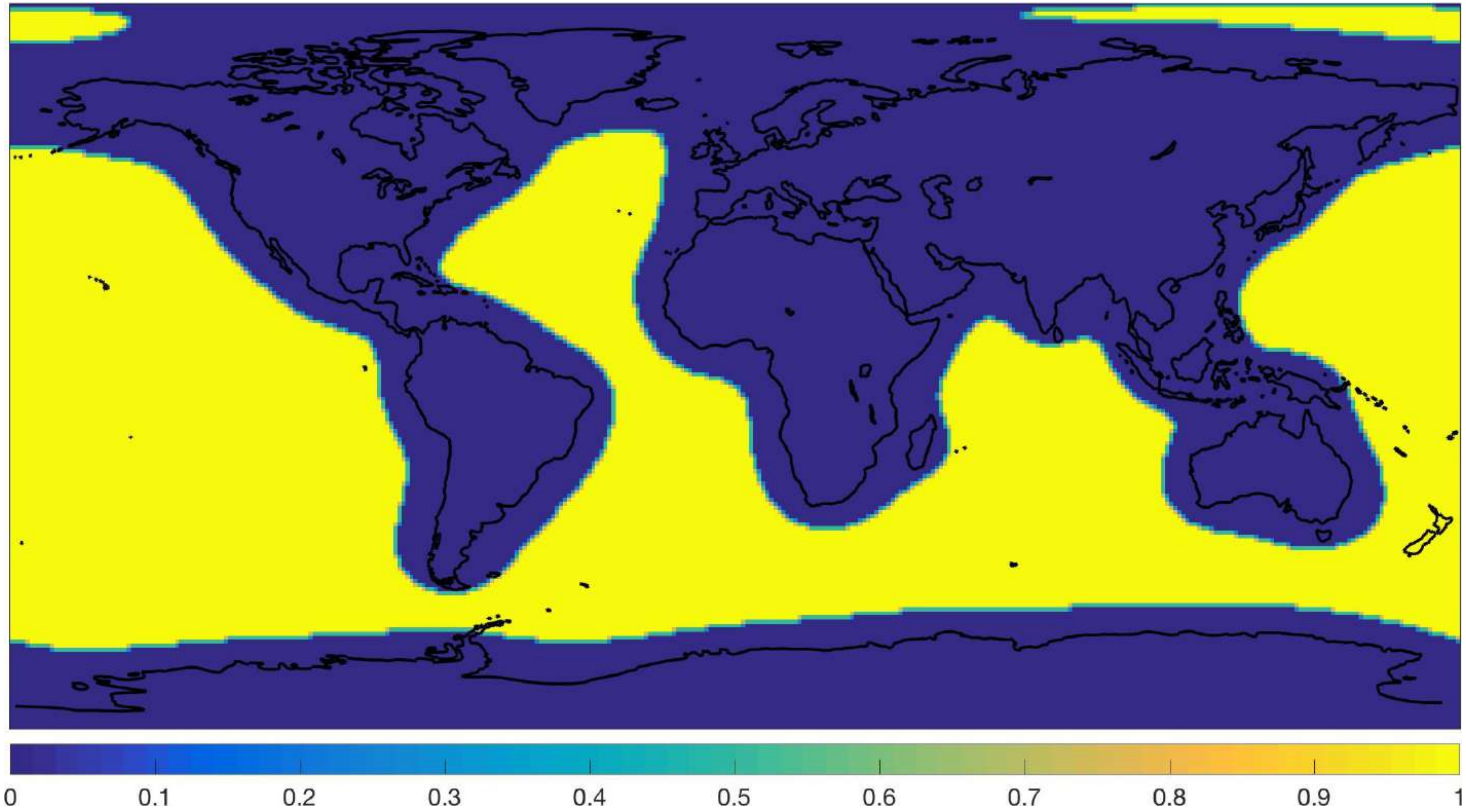
Ocean mask



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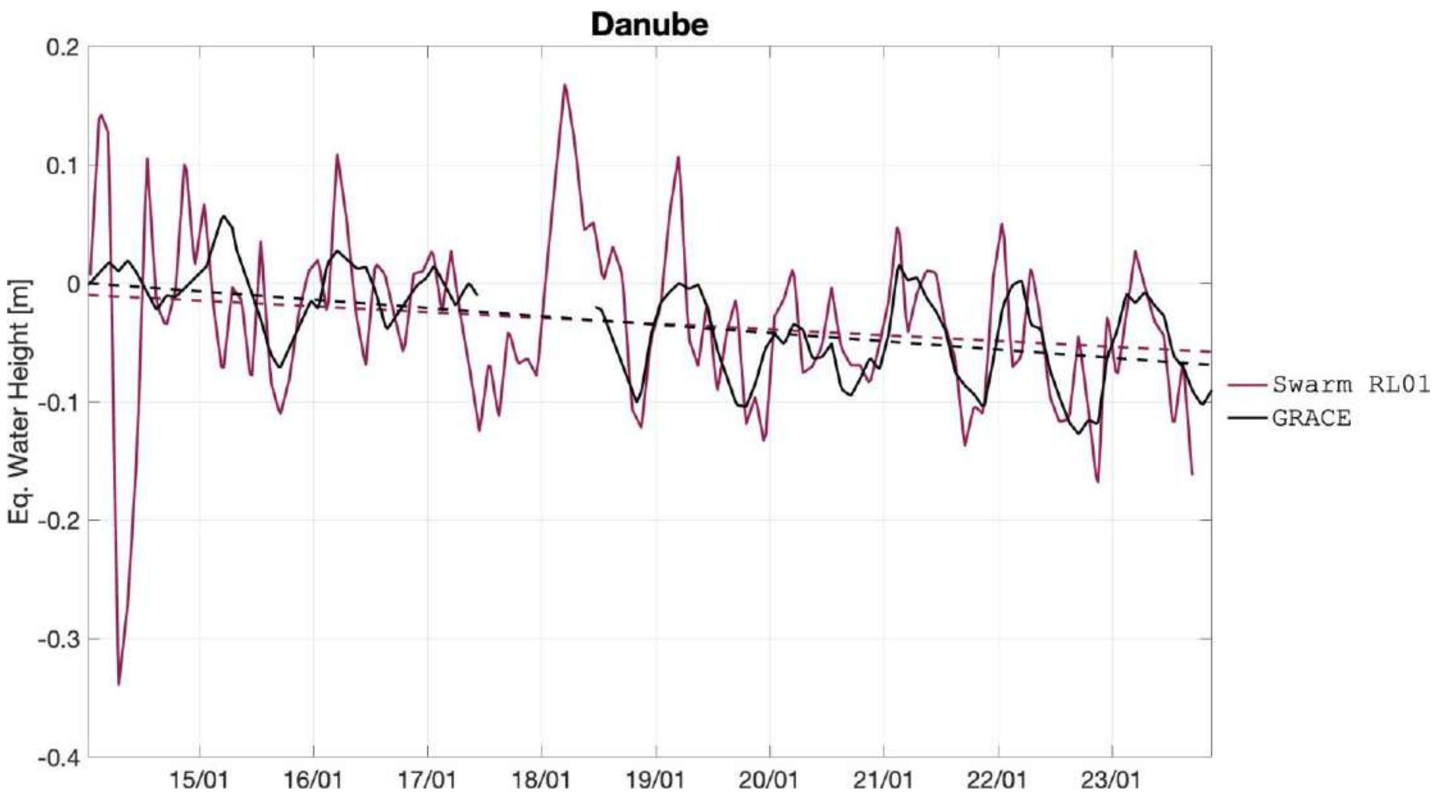
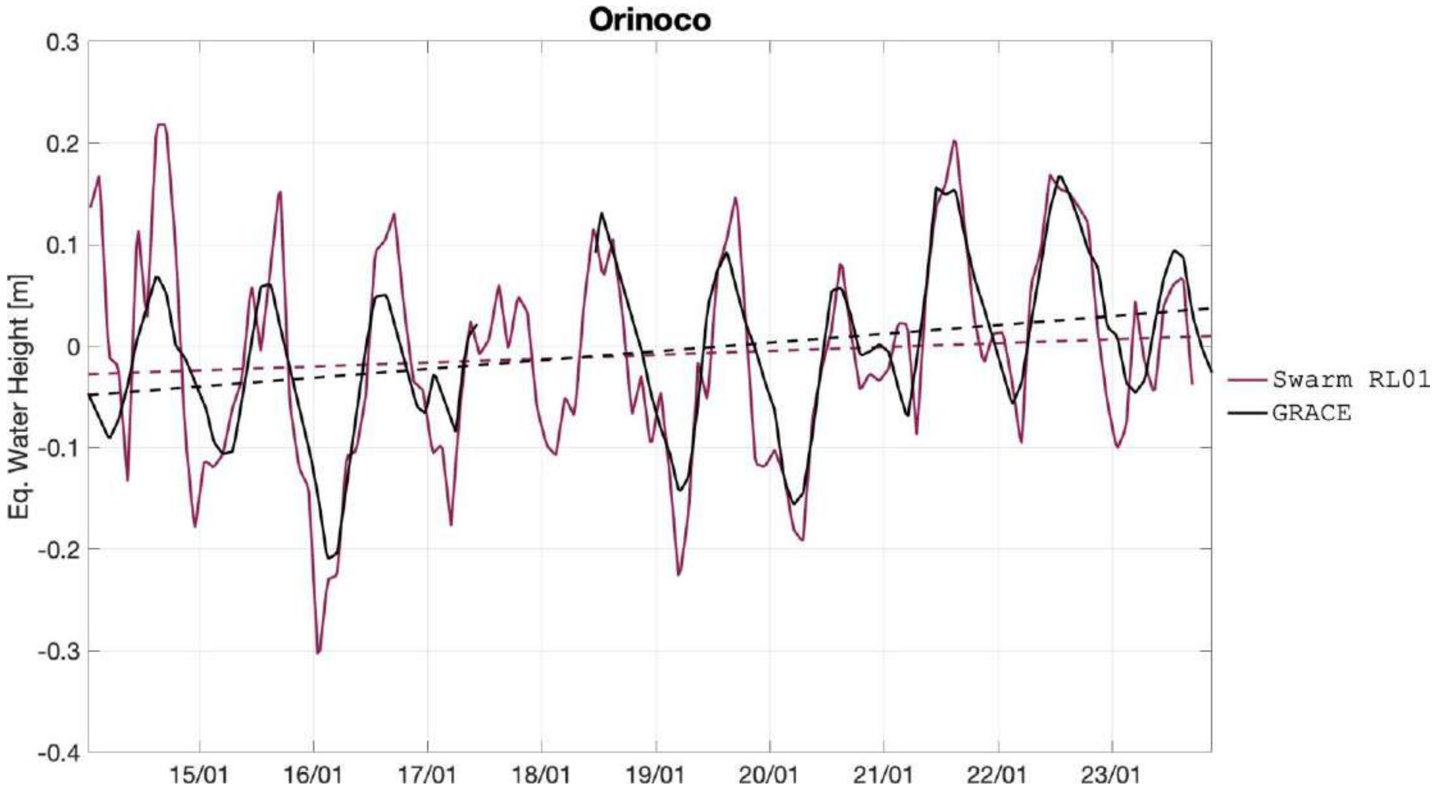


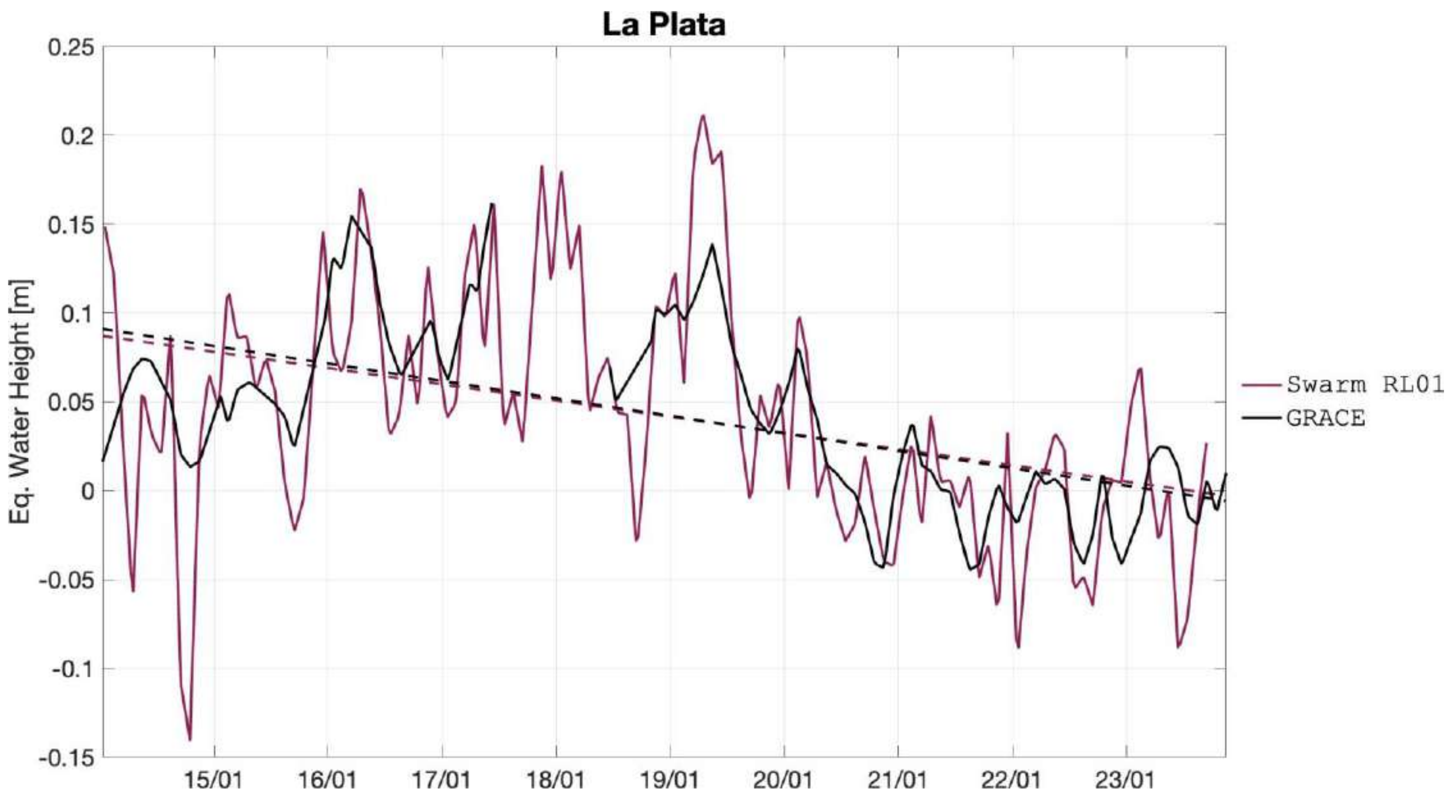
solution	constant term [cm]	constant term Δ [cm]	linear term [cm/year]	linear term Δ [cm/year]	corr. coeff. [ ]
Swarm RL01	-3.24	0.31	-0.49	0.21	0.37
GRACE	-3.55	0.00	-0.70	0.00	1.00

latitude 43 to 48 degrees, longitude 13 to 28 degrees



solution	constant term [cm]	constant term Δ [cm]	linear term [cm/year]	linear term Δ [cm/year]	corr. coeff. [ ]
Swarm RL01	-0.90	-0.54	0.38	-0.48	0.85
GRACE	-0.35	0.00	0.87	0.00	1.00

latitude -3 to 12 degrees, longitude -72 to -59 degrees



solution	constant term [cm]	constant term Δ [cm]	linear term [cm/year]	linear term Δ [cm/year]	corr. coeff. [ ]
Swarm RL01	4.31	0.35	-0.91	0.07	0.76
GRACE	3.95	0.00	-0.98	0.00	1.00

latitude -34 to -19 degrees, longitude -65 to -50 degrees

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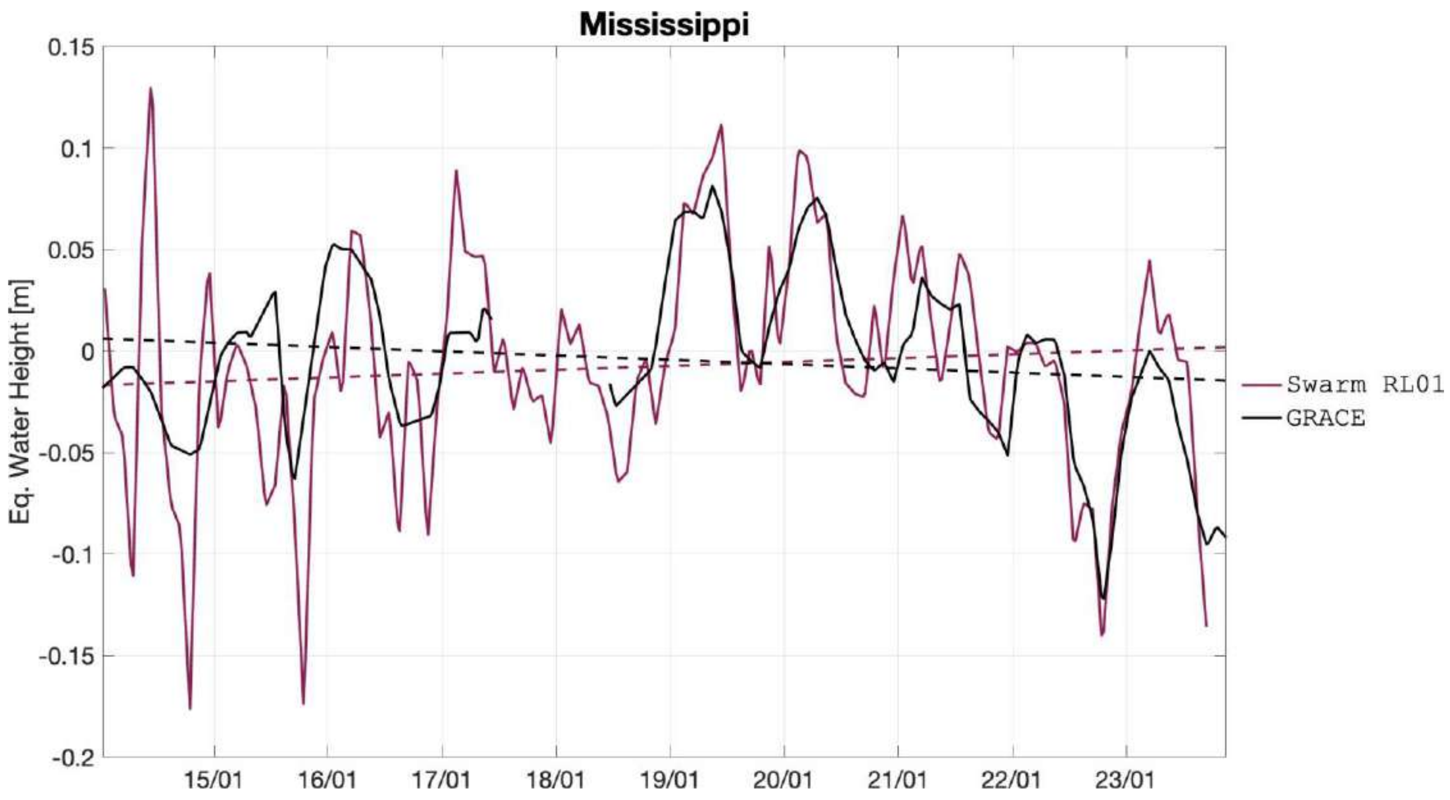
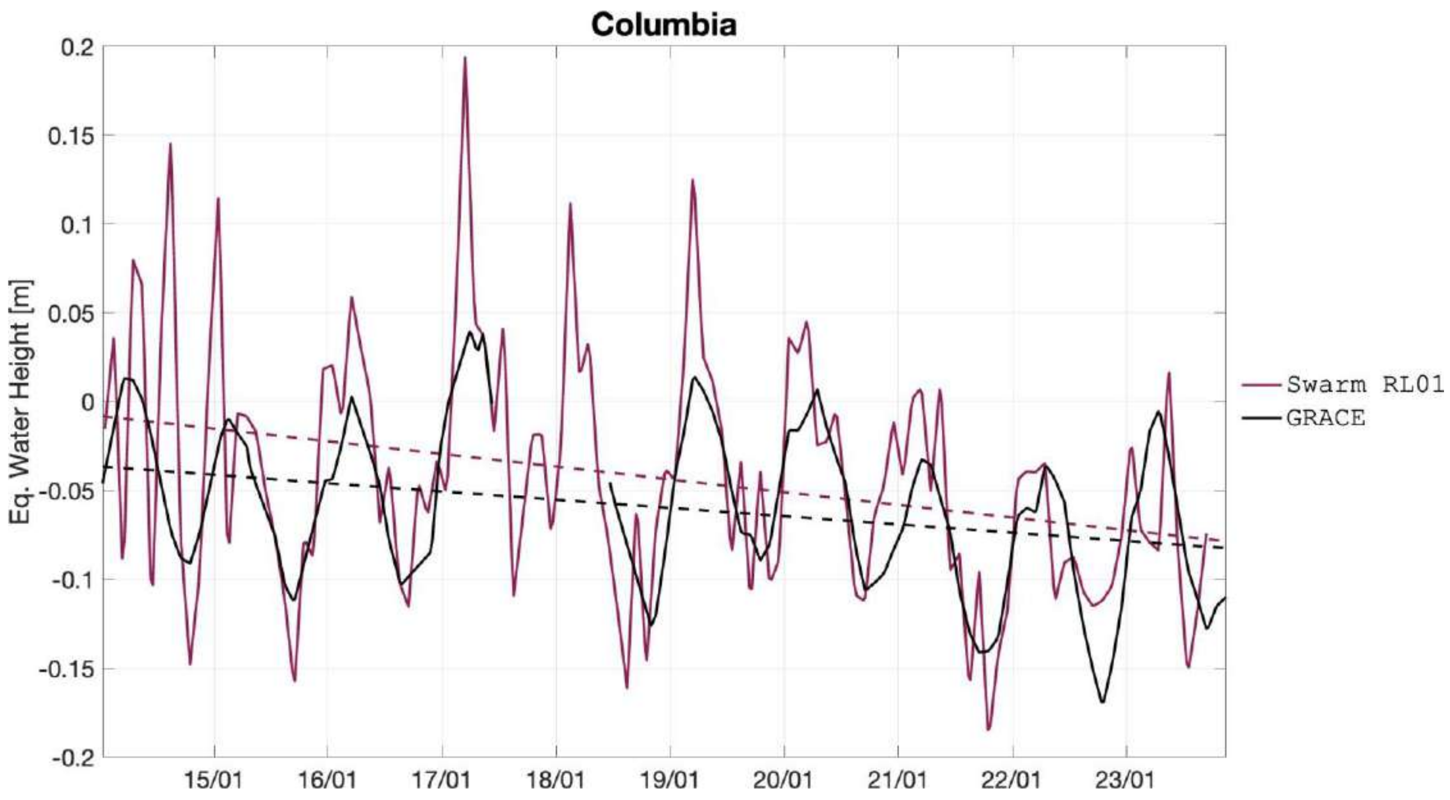


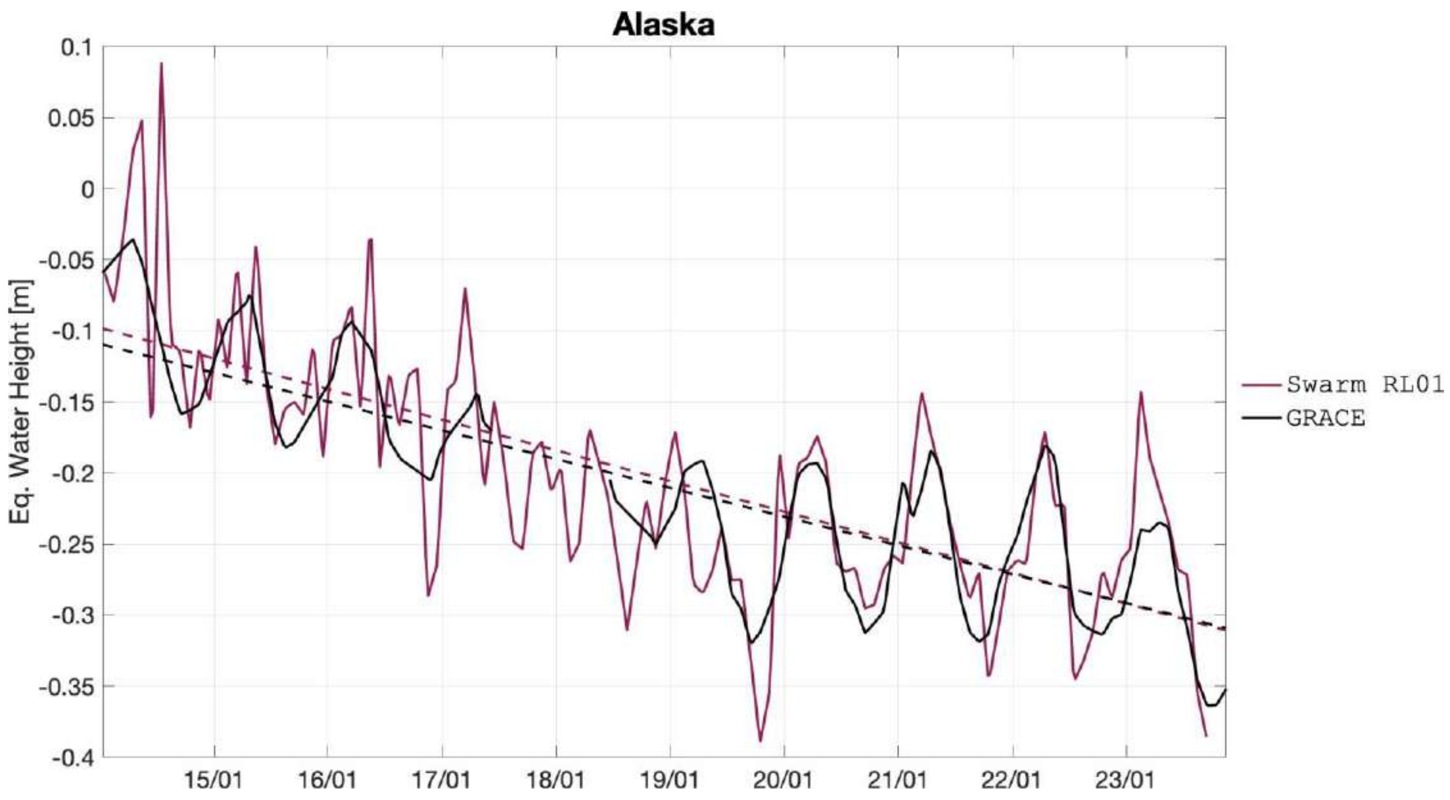
solution	constant term [cm]	constant term Δ [cm]	linear term [cm/year]	linear term Δ [cm/year]	corr. coeff. [ ]
Swarm RL01	-0.68	-0.37	0.19	0.40	0.70
GRACE	-0.31	0.00	-0.21	0.00	1.00

latitude 29 to 44 degrees, longitude -101 to -80 degrees



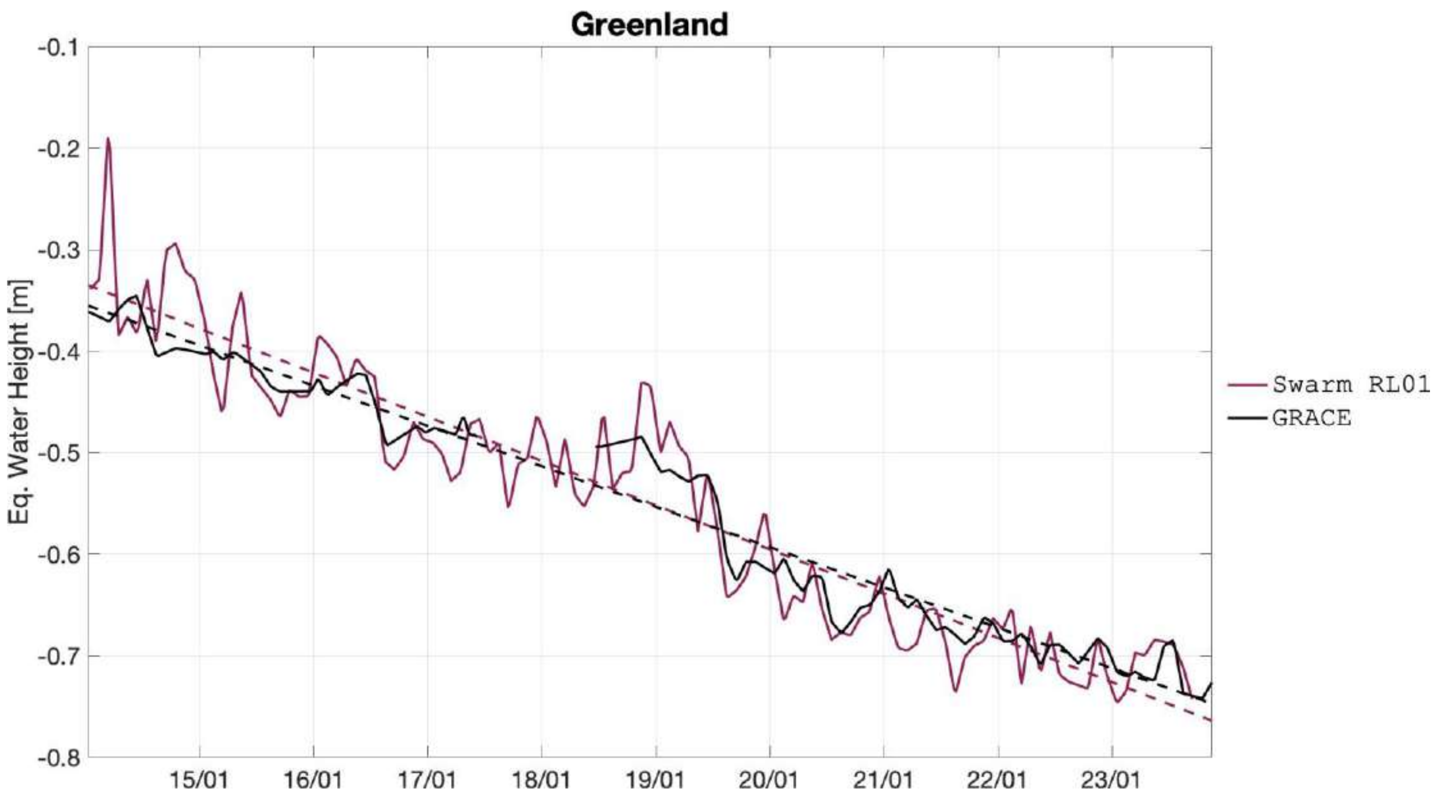
solution	constant term [cm]	constant term Δ [cm]	linear term [cm/year]	linear term Δ [cm/year]	corr. coeff. [ ]
Swarm RL01	-4.16	1.70	-0.71	-0.25	0.69
GRACE	-5.86	0.00	-0.46	0.00	1.00

latitude 38 to 50 degrees, longitude -125 to -110 degrees



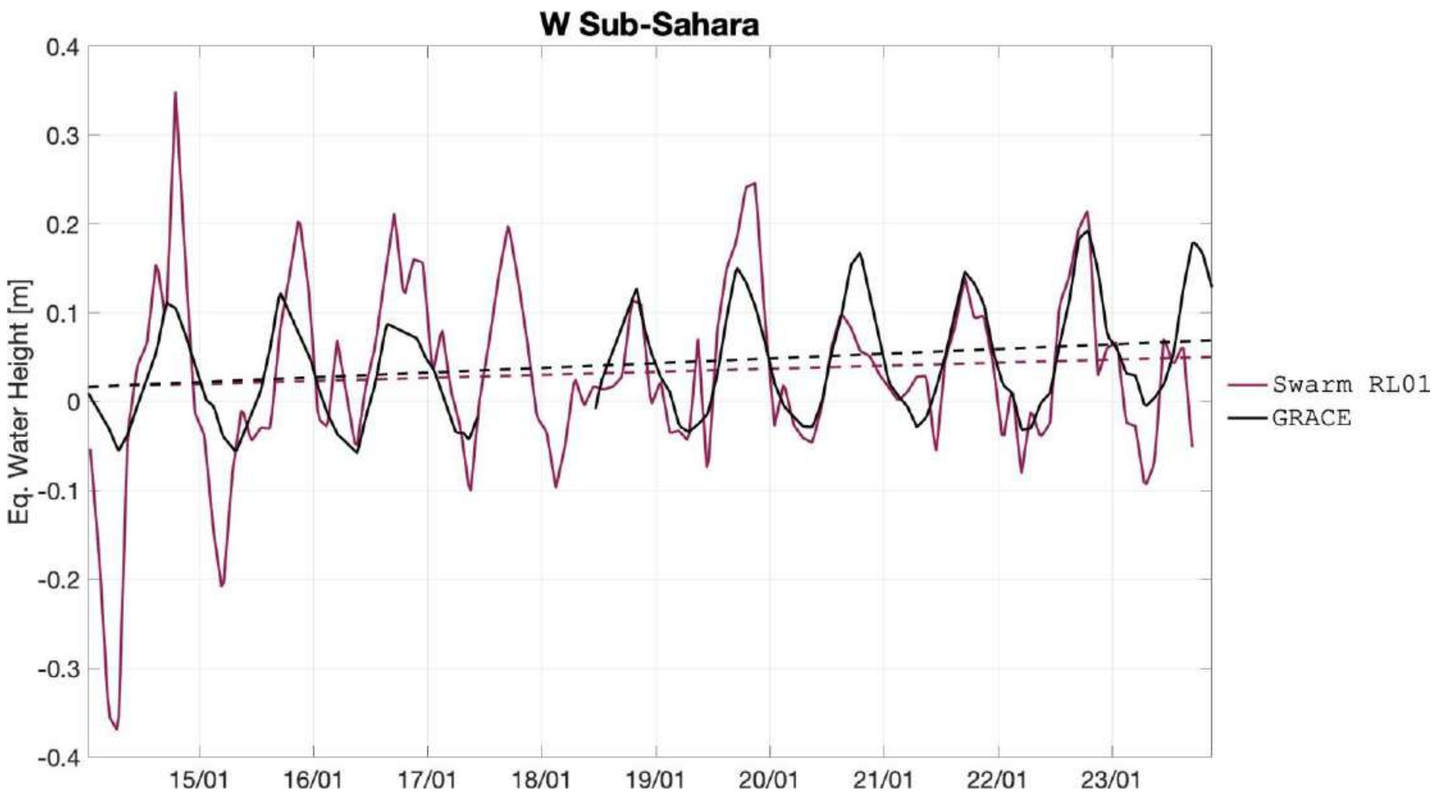
solution	constant term [cm]	constant term Δ [cm]	linear term [cm/year]	linear term Δ [cm/year]	corr. coeff. [ ]
Swarm RL01	-20.20	1.40	-2.16	-0.13	0.88
GRACE	-21.60	0.00	-2.02	0.00	1.00

latitude 56 to 65 degrees, longitude -151 to -129 degrees



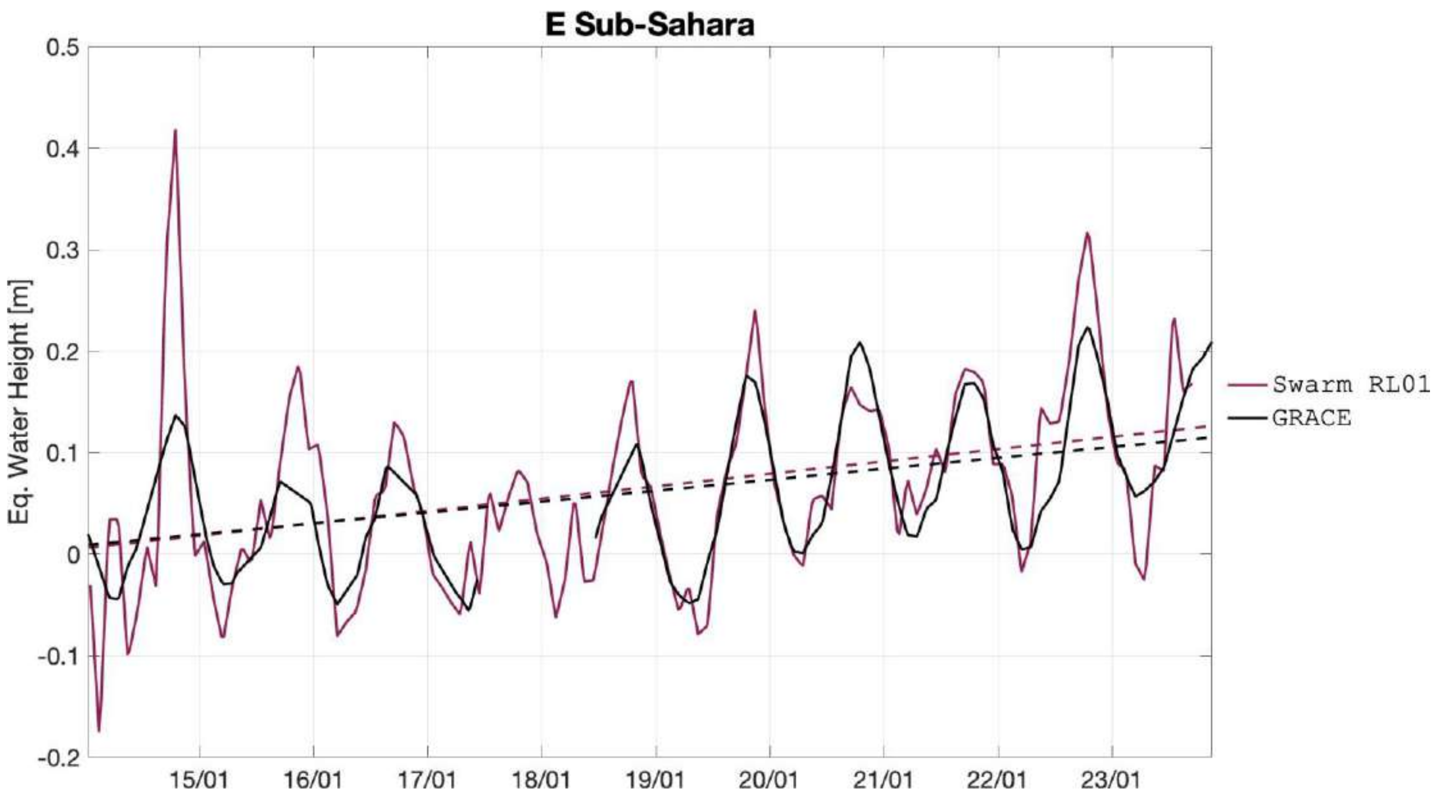
solution	constant term [cm]	constant term Δ [cm]	linear term [cm/year]	linear term Δ [cm/year]	corr. coeff. [ ]
Swarm RL01	-54.64	2.24	-4.35	-0.38	0.96
GRACE	-56.89	0.00	-3.97	0.00	1.00

latitude 60 to 85 degrees, longitude -60 to -37 degrees



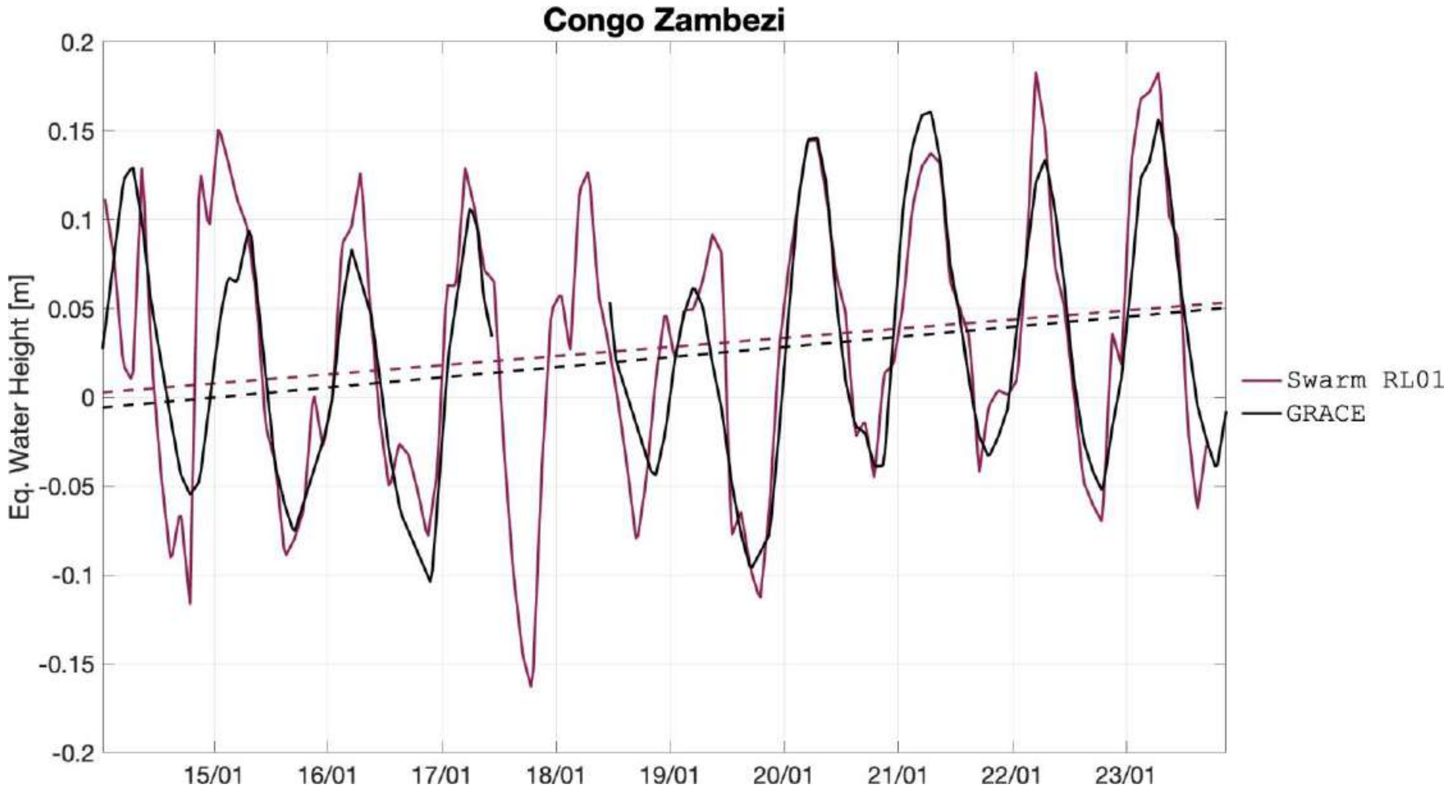
solution	constant term [cm]	constant term ∆ [cm]	linear term [cm/year]	linear term ∆ [cm/year]	corr. coeff. [ ]
Swarm RL01	3.11	-0.98	0.34	-0.19	0.71
GRACE	4.09	0.00	0.53	0.00	1.00

latitude 5 to 15 degrees, longitude -15 to -1 degrees



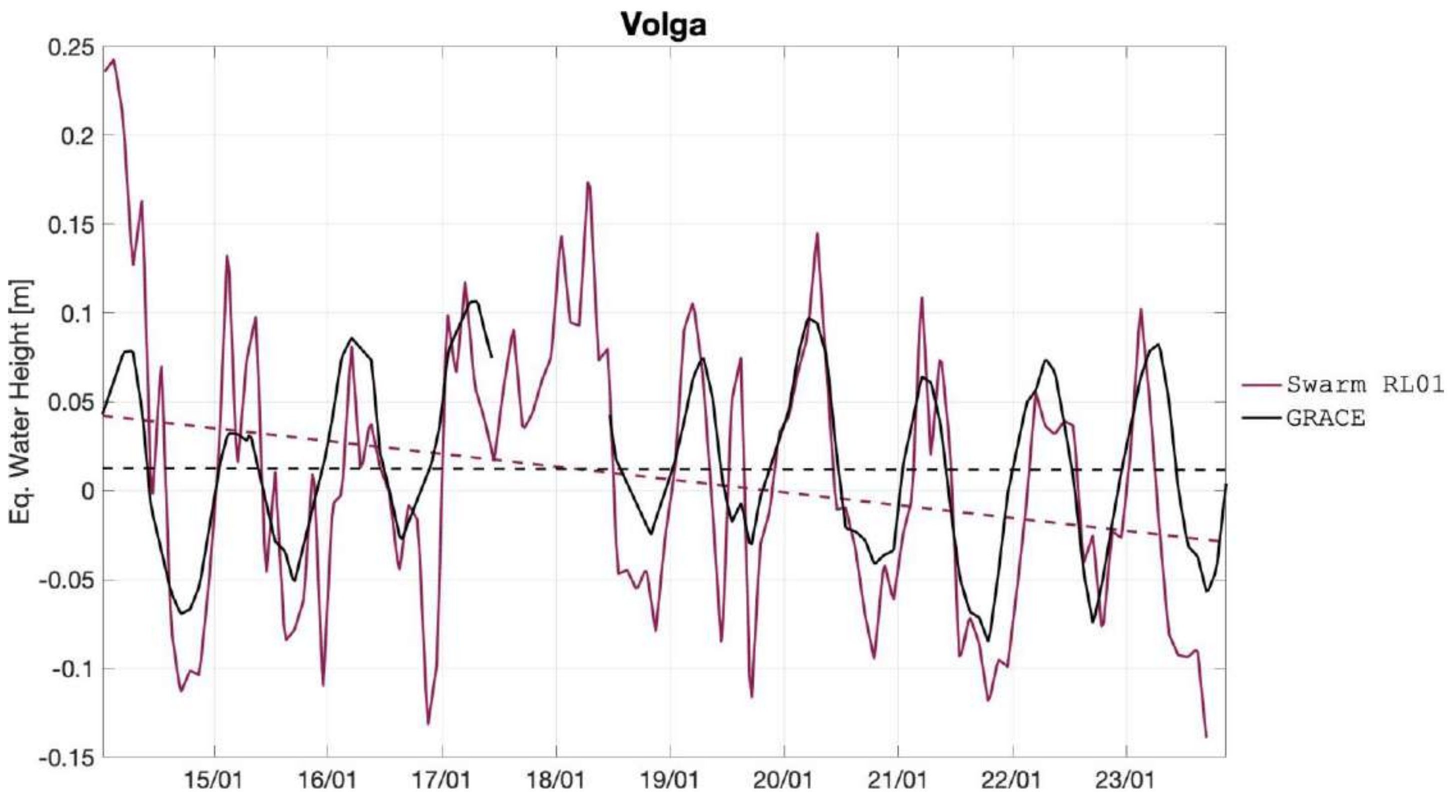
solution	constant term [cm]	constant term Δ [cm]	linear term [cm/year]	linear term Δ [cm/year]	corr. coeff. [ ]
Swarm RL01	6.30	0.06	1.22	0.14	0.83
GRACE	6.24	0.00	1.07	0.00	1.00

latitude 1 to 13 degrees, longitude -8 to 35 degrees



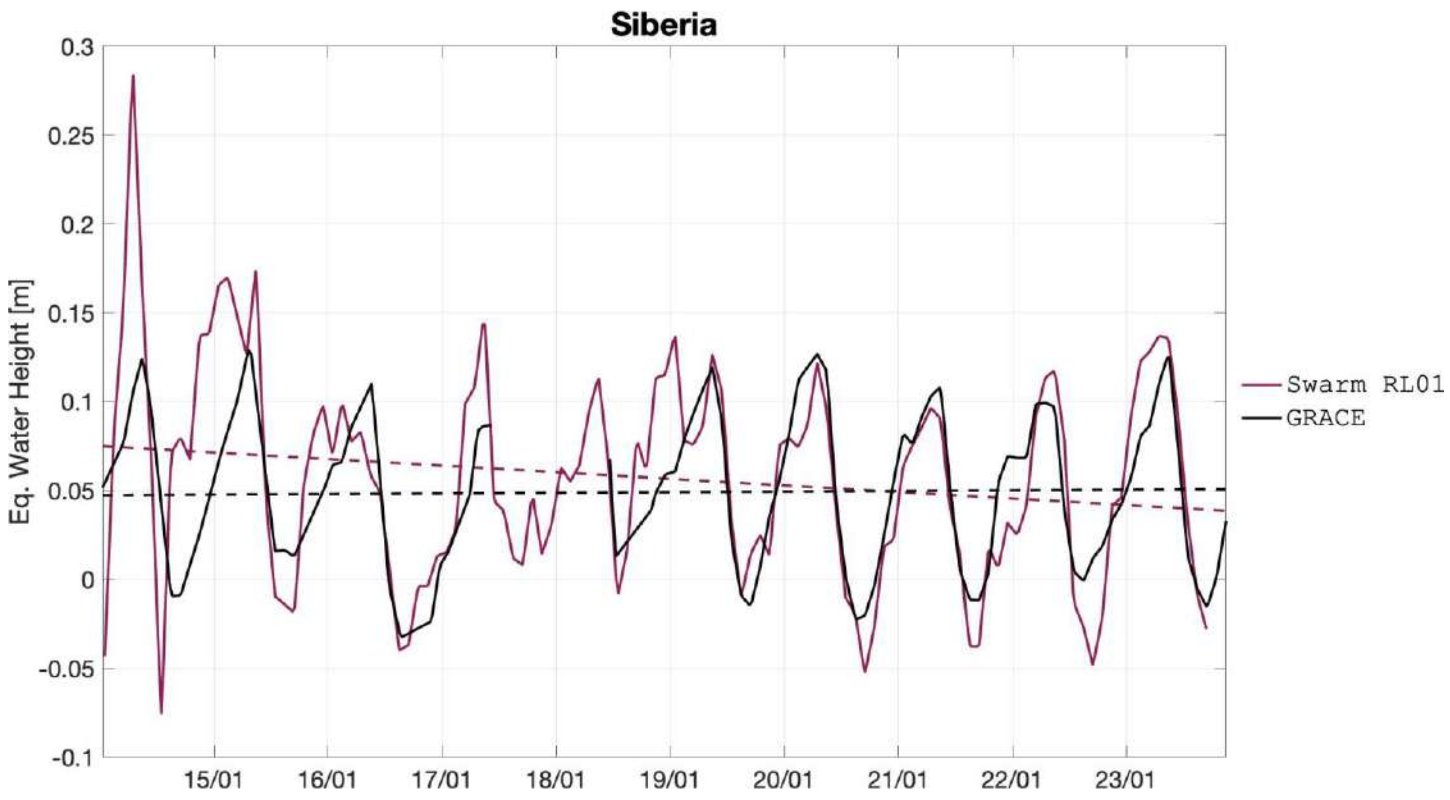
solution	constant term [cm]	constant term Δ [cm]	linear term [cm/year]	linear term Δ [cm/year]	corr. coeff. [ ]
Swarm RL01	2.92	-0.04	0.51	-0.06	0.84
GRACE	2.96	0.00	0.57	0.00	1.00

latitude -23 to -3 degrees, longitude 14 to 38 degrees



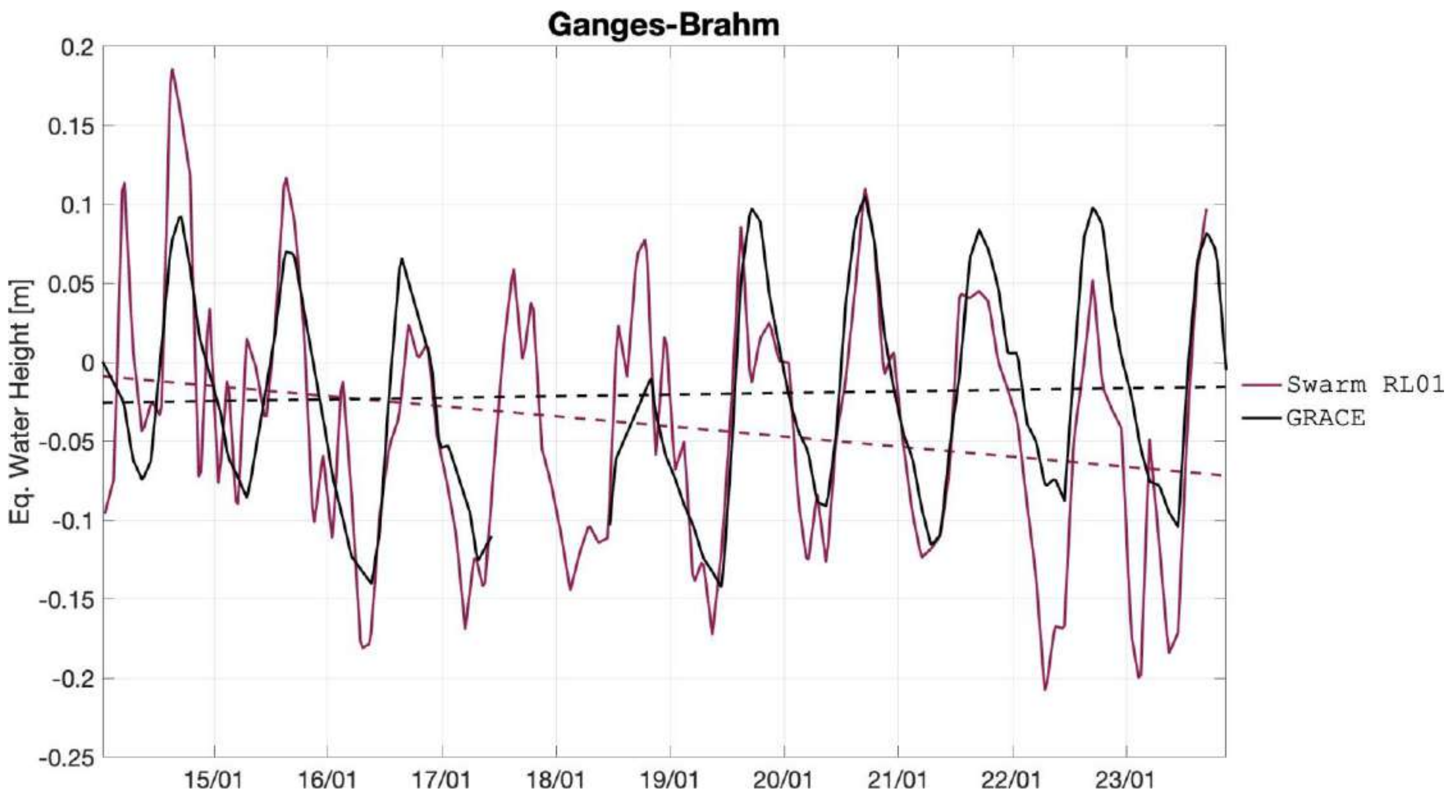
solution	constant term [cm]	constant term Δ [cm]	linear term [cm/year]	linear term Δ [cm/year]	corr. coeff. [ ]
Swarm RL01	0.90	-0.64	-0.72	-0.71	0.74
GRACE	1.54	0.00	-0.01	0.00	1.00

latitude 53 to 61 degrees, longitude 34 to 56 degrees



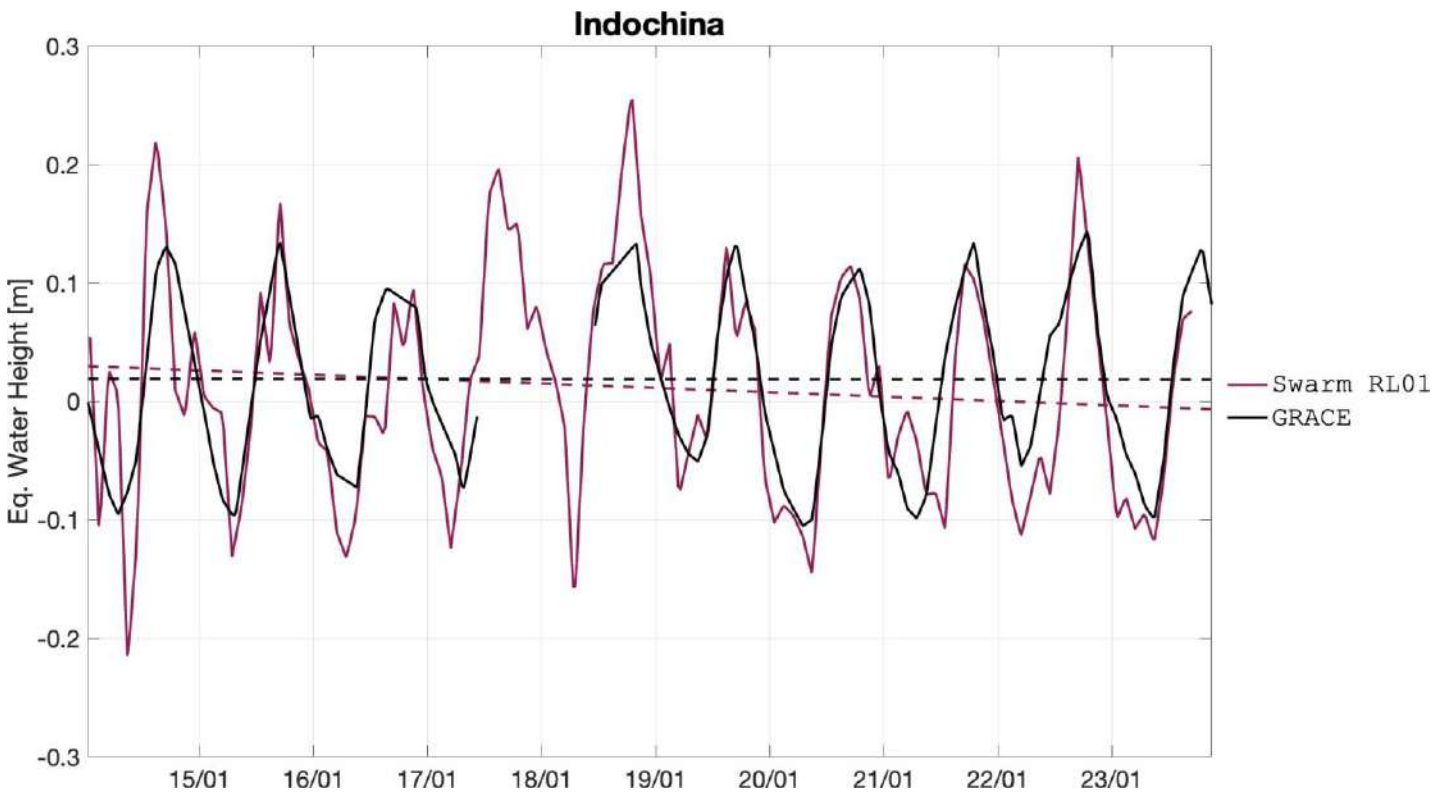
solution	constant term [cm]	constant term ∆ [cm]	linear term [cm/year]	linear term ∆ [cm/year]	corr. coeff. [ ]
Swarm RL01	5.77	0.53	-0.37	-0.40	0.76
GRACE	5.24	0.00	0.03	0.00	1.00

latitude 57 to 72 degrees, longitude 68 to 109 degrees



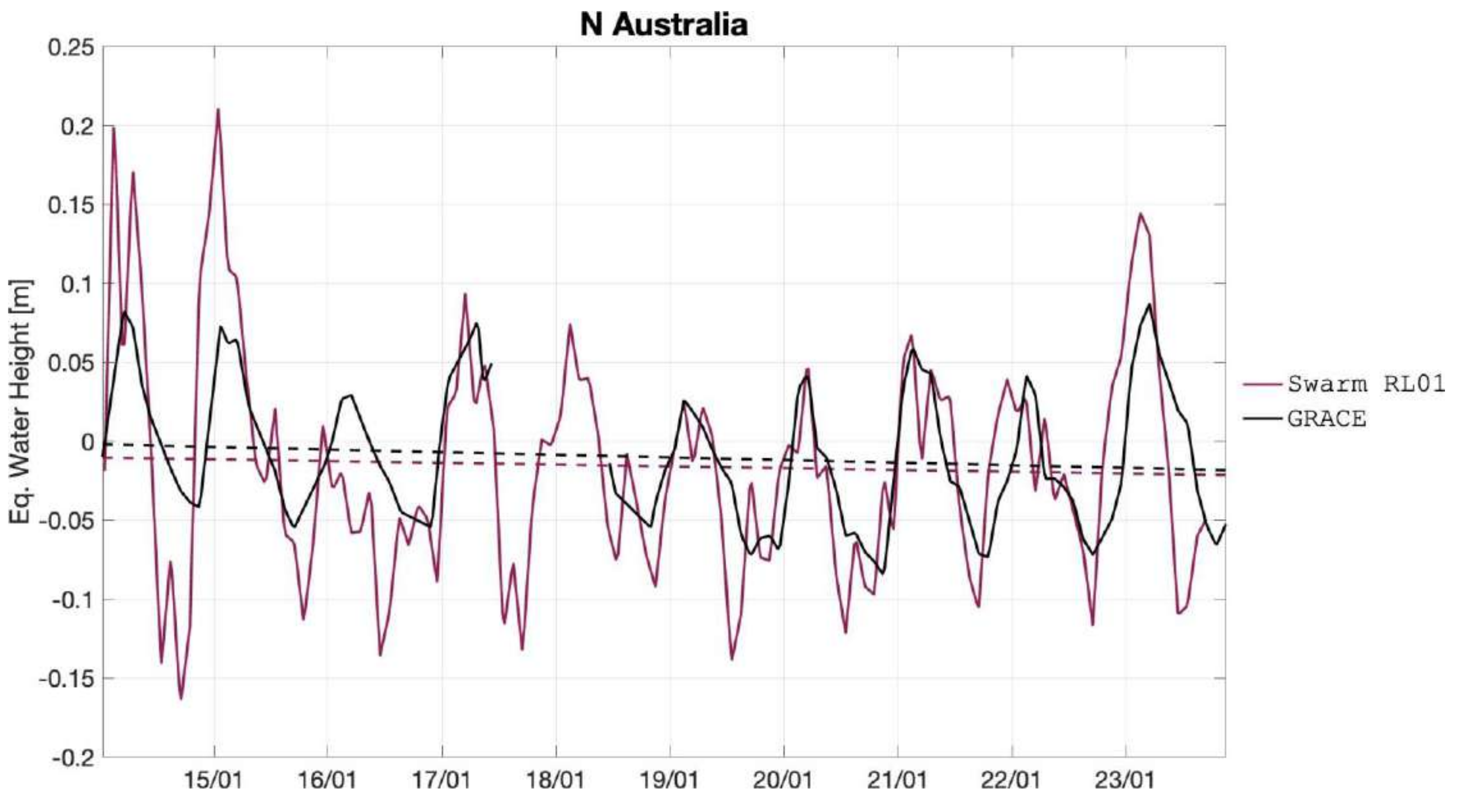
solution	constant term [cm]	constant term Δ [cm]	linear term [cm/year]	linear term Δ [cm/year]	corr. coeff. [ ]
Swarm RL01	-4.08	-1.56	-0.64	-0.74	0.75
GRACE	-2.52	0.00	0.10	0.00	1.00

latitude 15 to 30 degrees, longitude 72 to 89 degrees



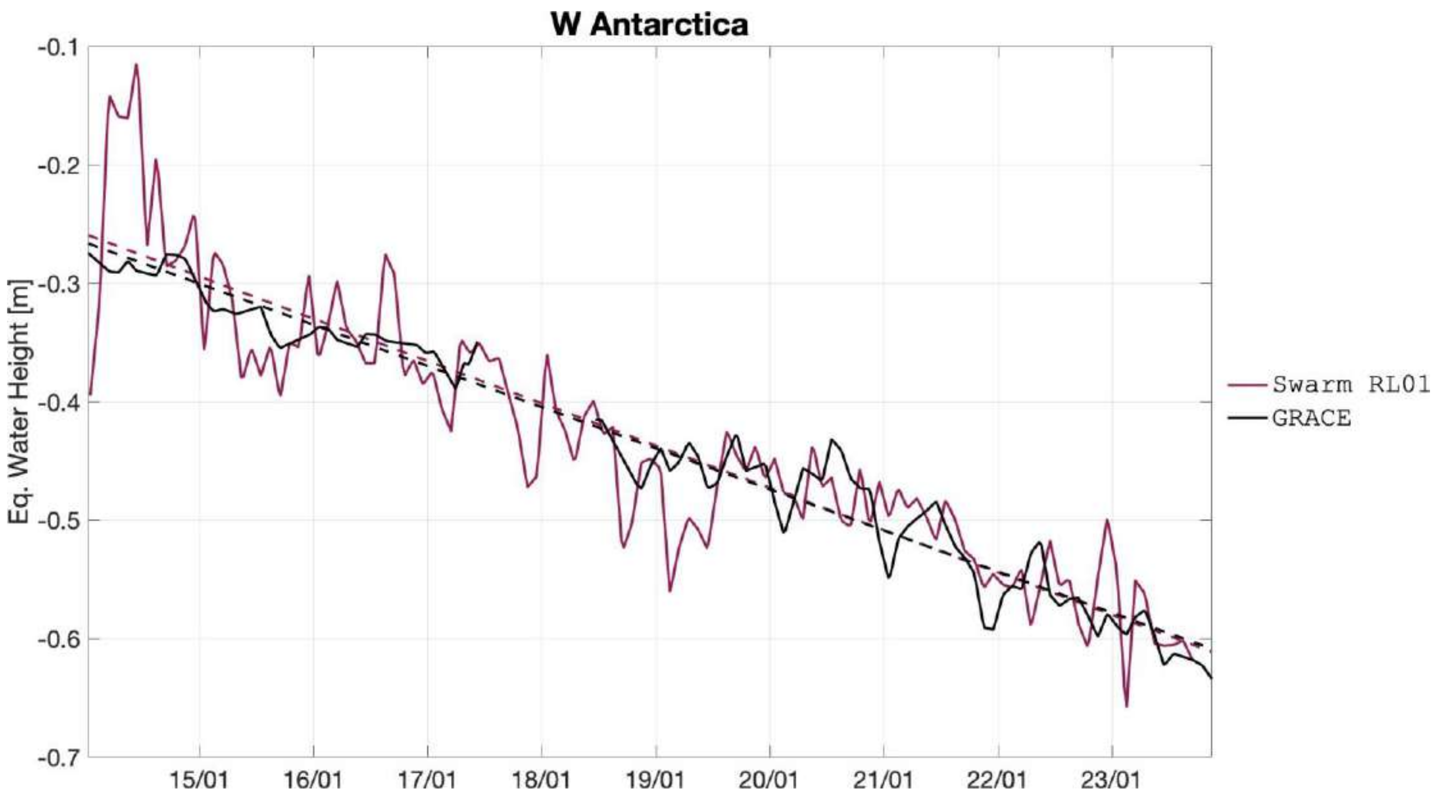
solution	constant term [cm]	constant term Δ [cm]	linear term [cm/year]	linear term Δ [cm/year]	corr. coeff. [ ]
Swarm RL01	1.04	-0.31	-0.37	-0.36	0.80
GRACE	1.35	0.00	-0.01	0.00	1.00

latitude 12 to 29 degrees, longitude 93 to 105 degrees



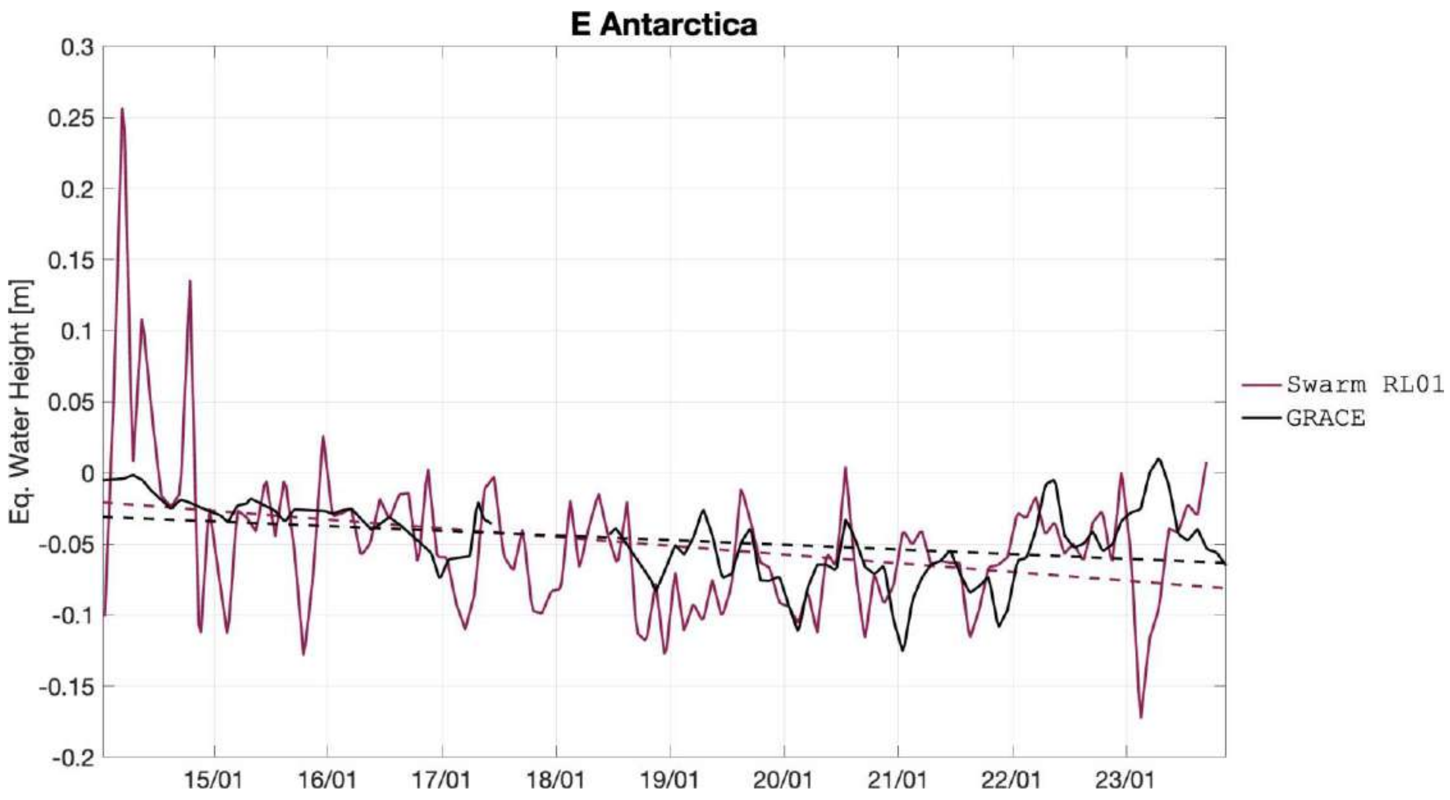
solution	constant term [cm]	constant term Δ [cm]	linear term [cm/year]	linear term Δ [cm/year]	corr. coeff. [ ]
Swarm RL01	-1.51	-0.68	-0.11	0.05	0.68
GRACE	-0.83	0.00	-0.17	0.00	1.00

latitude -24 to -10 degrees, longitude 124 to 145 degrees



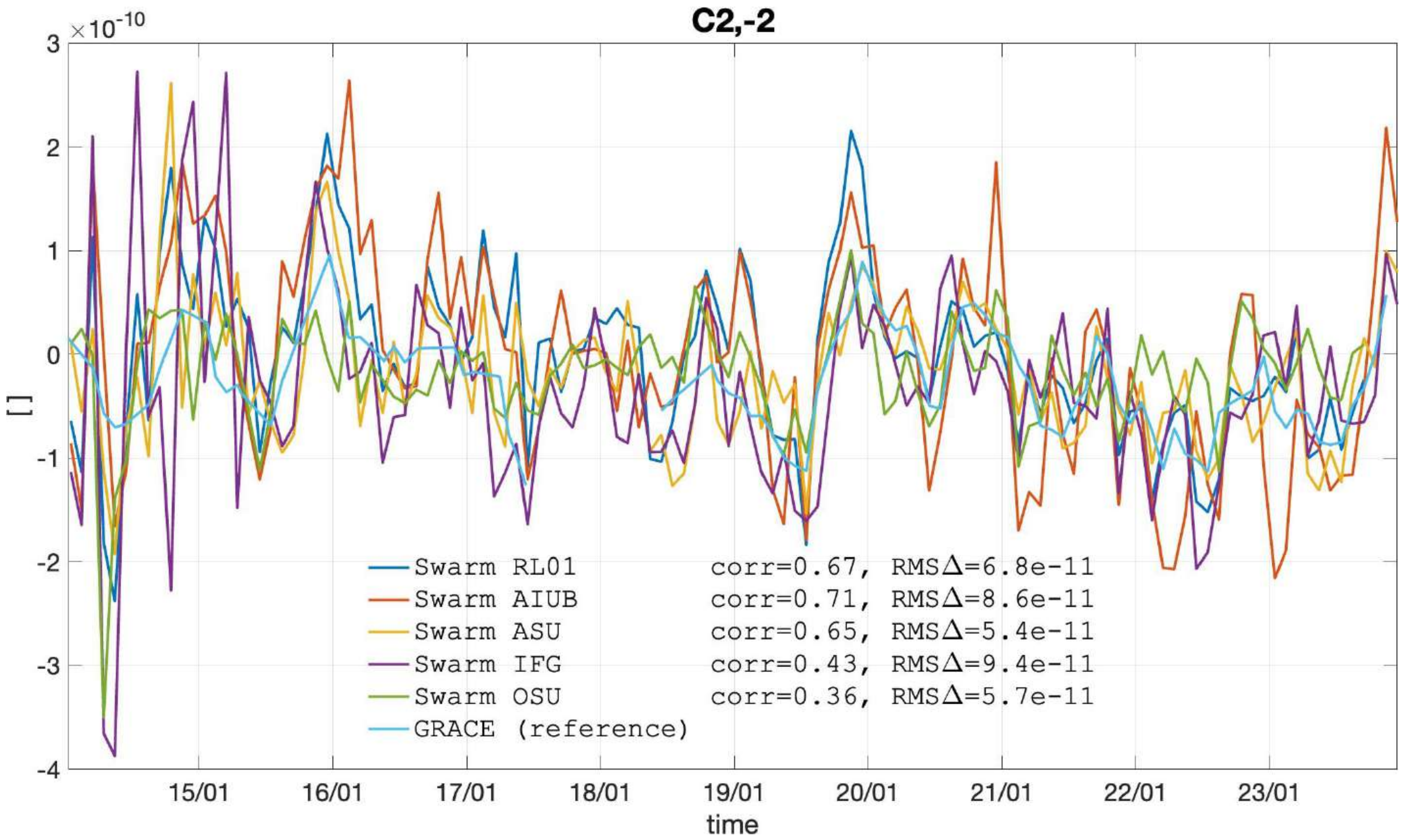
solution	constant term [cm]	constant term Δ [cm]	linear term [cm/year]	linear term Δ [cm/year]	corr. coeff. [ ]
Swarm RL01	-43.23	2.10	-3.57	-0.10	0.92
GRACE	-45.33	0.00	-3.47	0.00	1.00

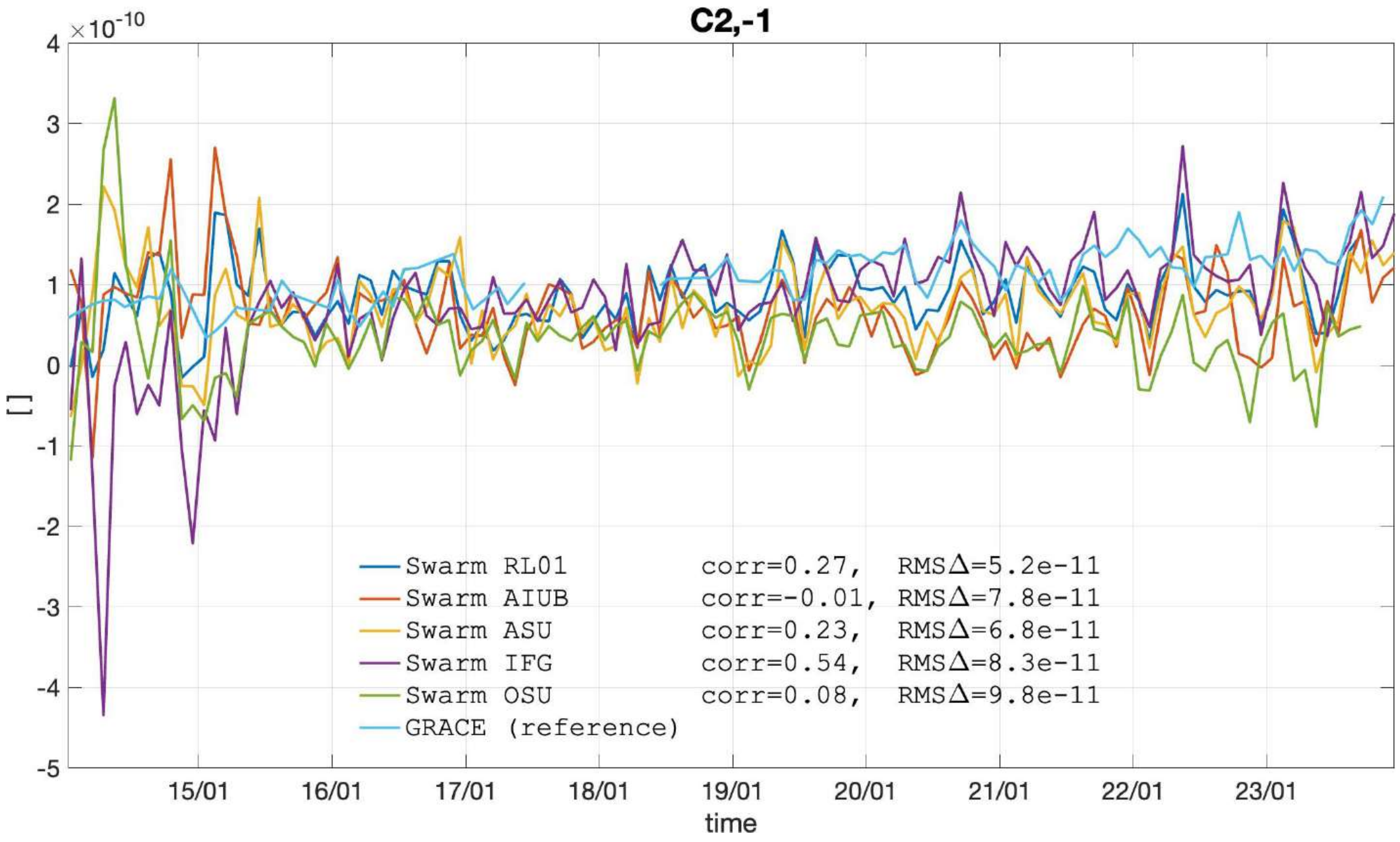
latitude -80 to -70 degrees, longitude -140 to -85 degrees



solution	constant term [cm]	constant term Δ [cm]	linear term [cm/year]	linear term Δ [cm/year]	corr. coeff. [ ]
Swarm RL01	-5.02	-0.21	-0.61	-0.29	0.40
GRACE	-4.81	0.00	-0.33	0.00	1.00

latitude -80 to -68 degrees, longitude 80 to 130 degrees


C2,-2
×10^-10
3
2
1
0
-1
-2
-3
-4
[]
Swarm RL01 corr=0.67, RMSΔ=6.8e-11
Swarm AIUB corr=0.71, RMSΔ=8.6e-11
Swarm ASU corr=0.65, RMSΔ=5.4e-11
Swarm IFG corr=0.43, RMSΔ=9.4e-11
Swarm OSU corr=0.36, RMSΔ=5.7e-11
GRACE (reference)
15/01
16/01
17/01
18/01
19/01
20/01
21/01
22/01
23/01
time



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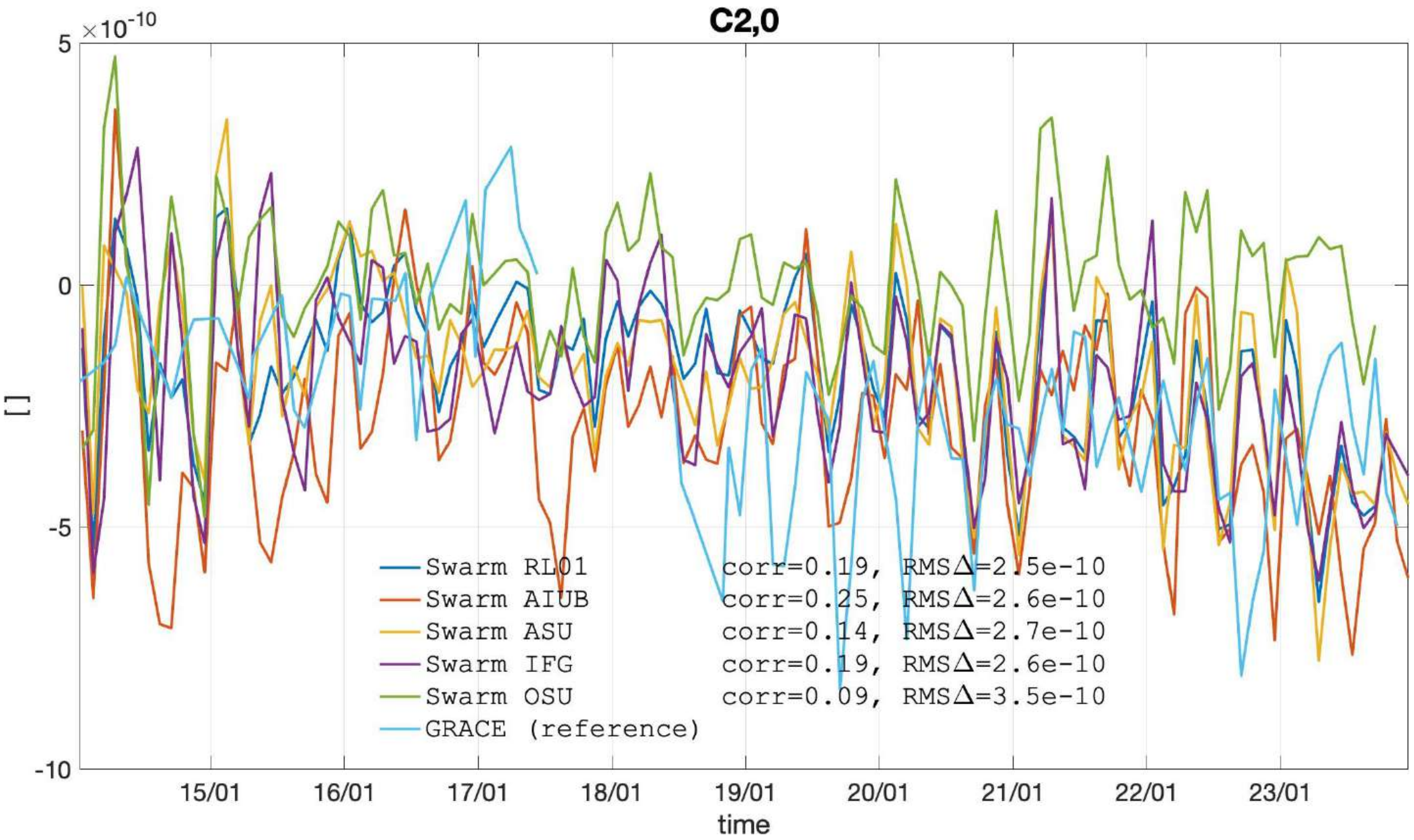

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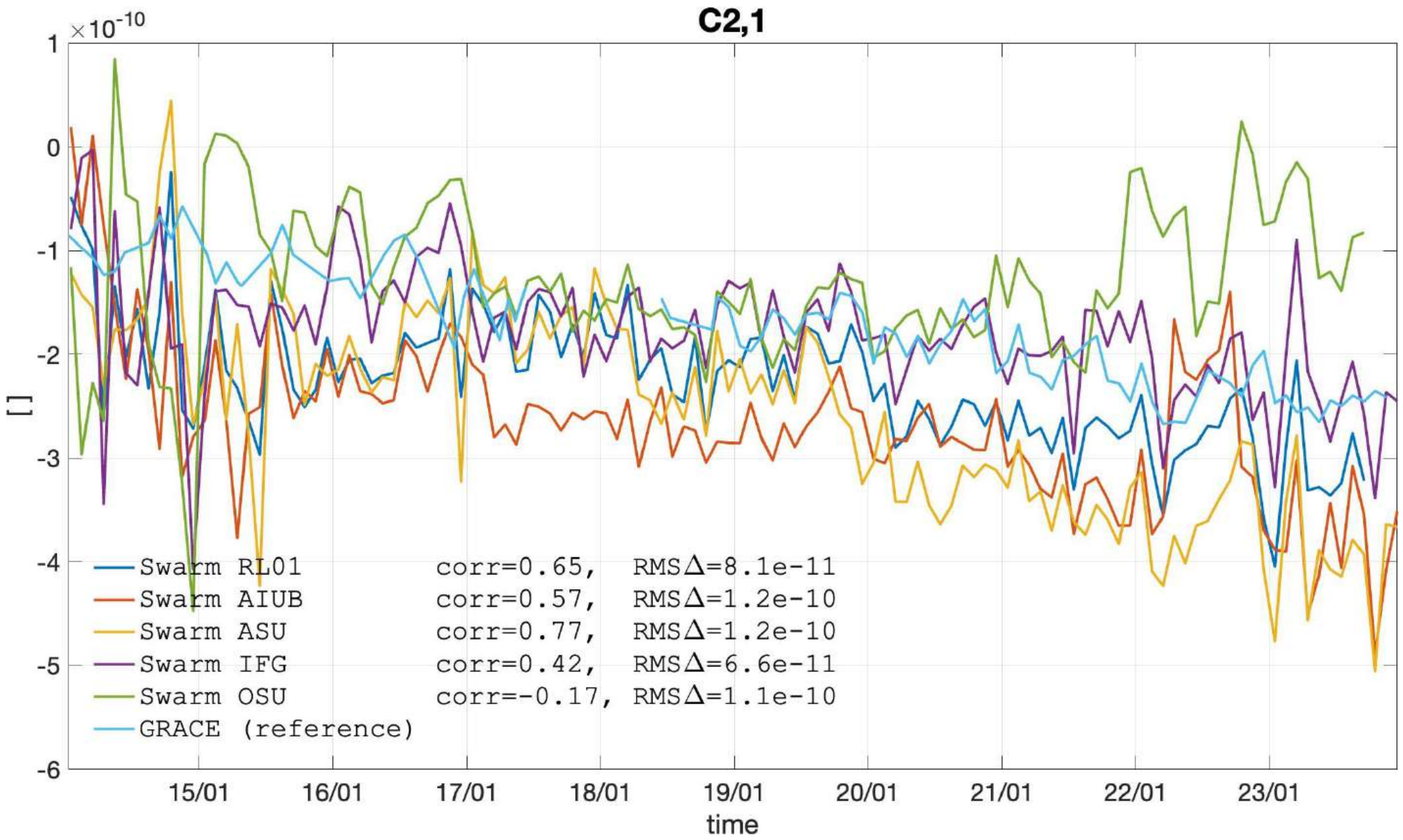
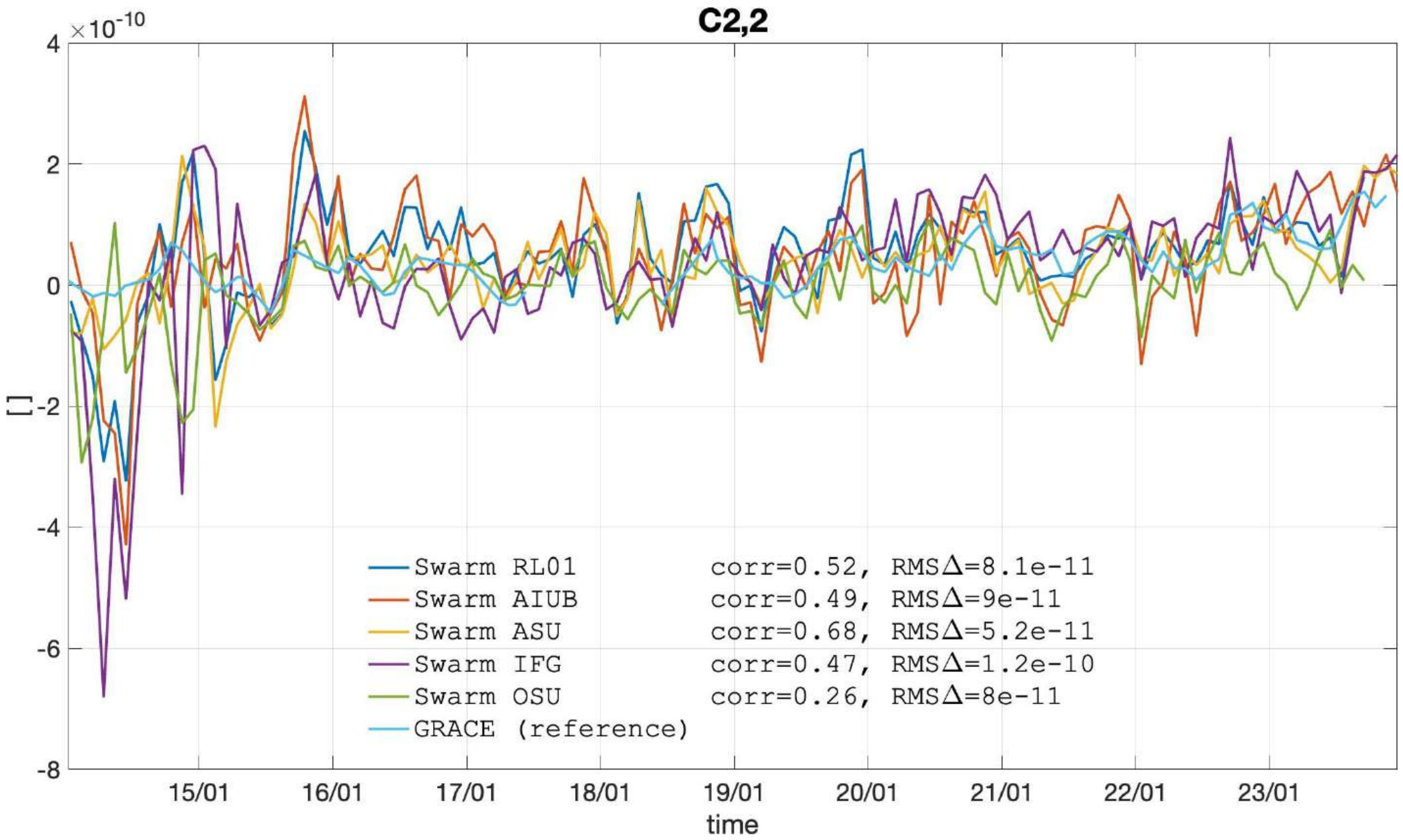
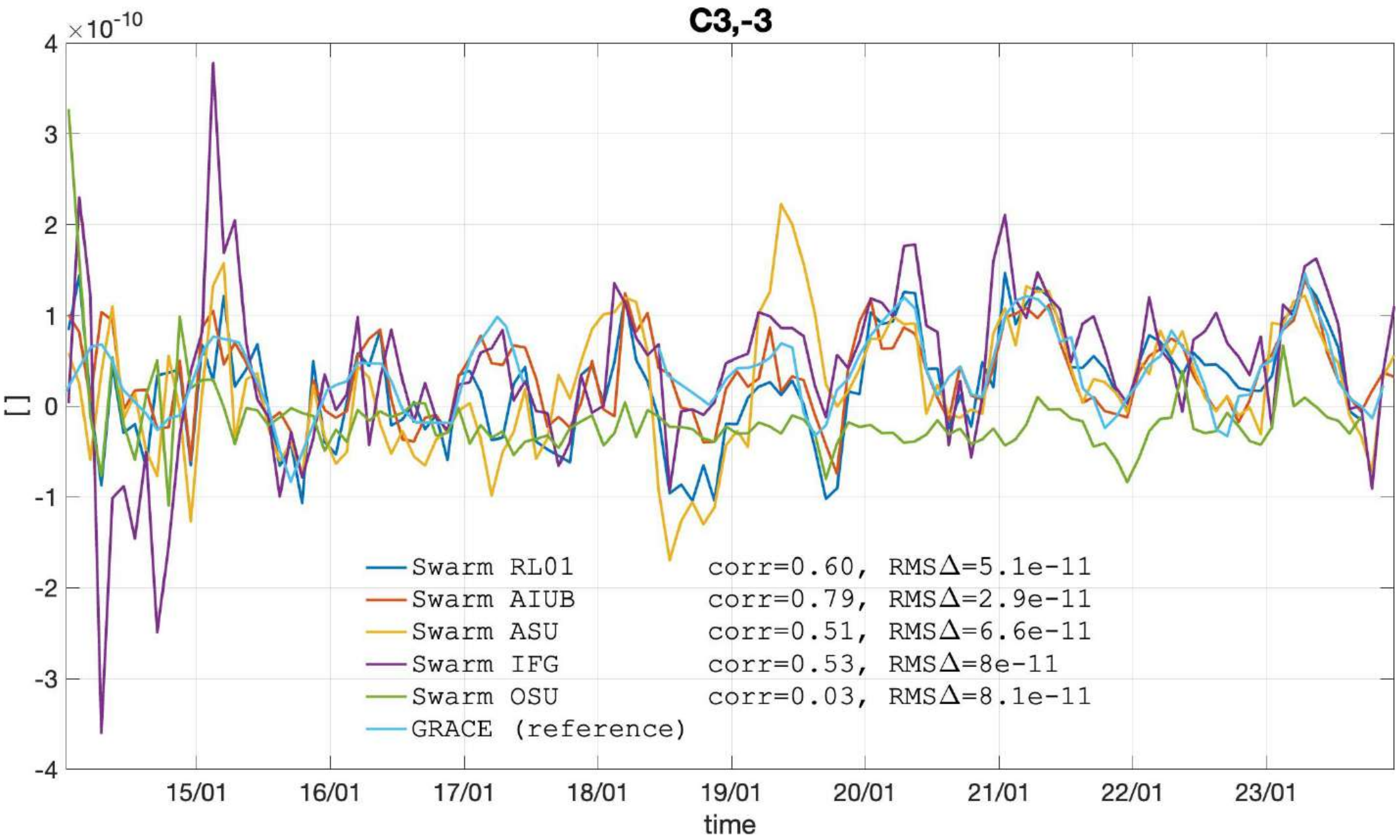
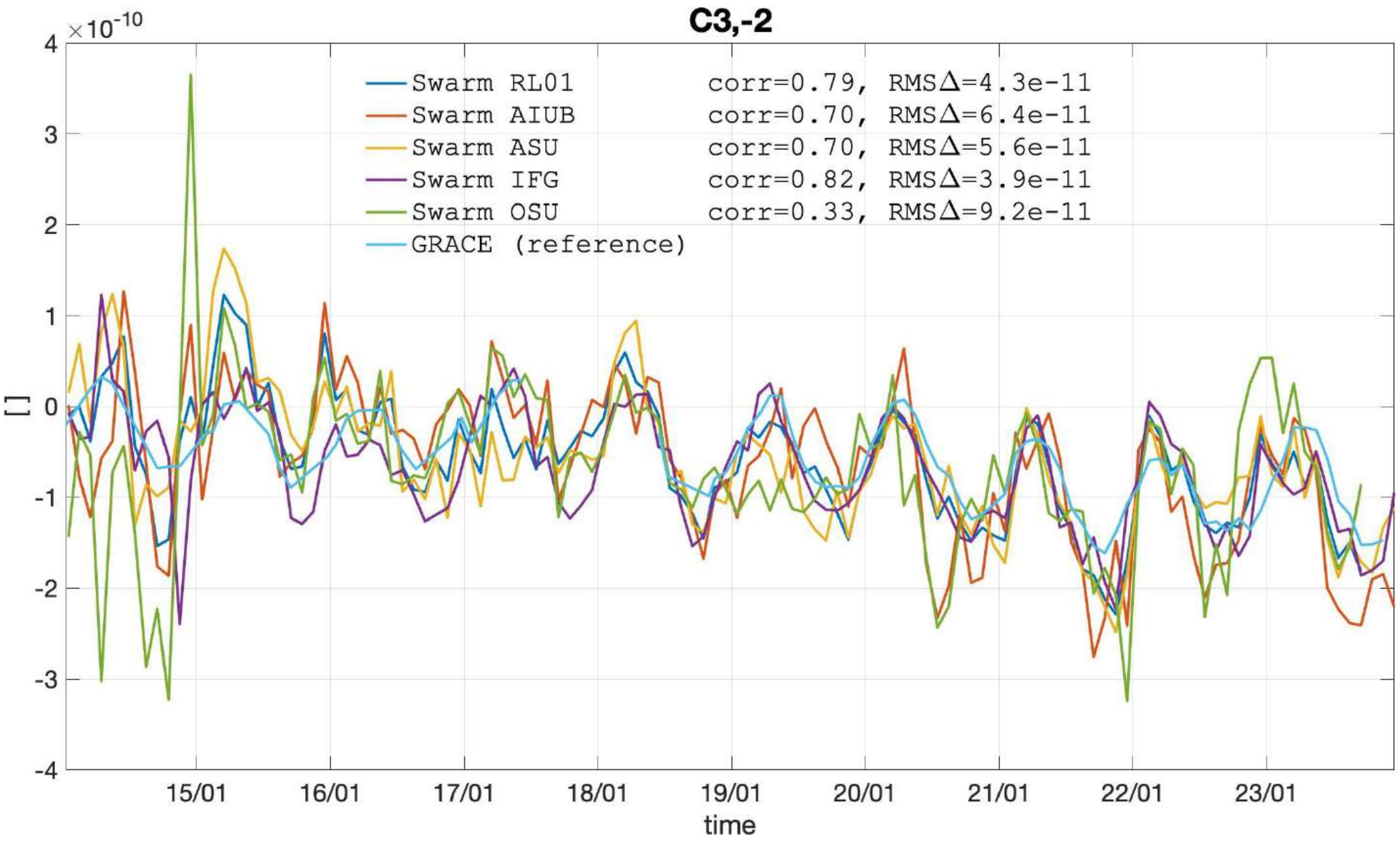

C2,1
×10^-10
1
0
-1
-2
-3
-4
-5
-6
[]
15/01
16/01
17/01
18/01
19/01
20/01
21/01
22/01
23/01
time
Swarm RL01 corr=0.65, RMSΔ=8.1e-11
Swarm AIUB corr=0.57, RMSΔ=1.2e-10
Swarm ASU corr=0.77, RMSΔ=1.2e-10
Swarm IFG corr=0.42, RMSΔ=6.6e-11
Swarm OSU corr=-0.17, RMSΔ=1.1e-10
GRACE (reference)



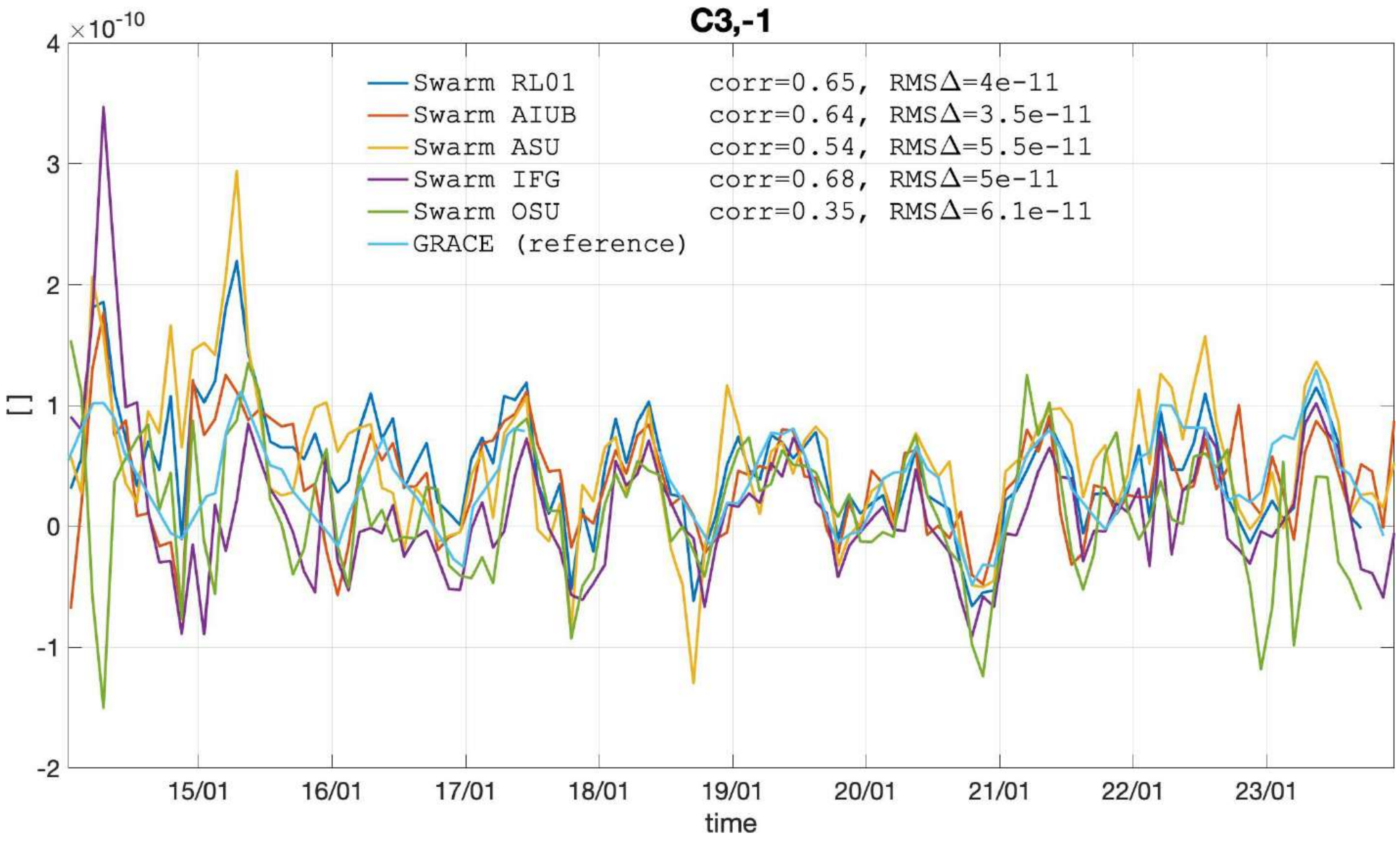
C2,2
×10^-10
4
2
0
-2
-4
-6
-8
[ ]
15/01
16/01
17/01
18/01
19/01
20/01
21/01
22/01
23/01
time
Swarm RL01 corr=0.52, RMSΔ=8.1e-11
Swarm AIUB corr=0.49, RMSΔ=9e-11
Swarm ASU corr=0.68, RMSΔ=5.2e-11
Swarm IFG corr=0.47, RMSΔ=1.2e-10
Swarm OSU corr=0.26, RMSΔ=8e-11
GRACE (reference)



swarm SWARM DISC COST-G UNIVERSITÄT BERN Astronomical Institute of the Czech Academy of Sciences GFZ Helmholtz Centre Potsdam The Ohio State University TU Delft TU Graz TEXAS The University of Texas at Austin



swarm SWARM DISC COST-G UNIVERSITÄT BERN Astronomical Institute of the Czech Academy of Sciences GFZ Helmholtz Centre Potsdam The Ohio State University TU Delft TU Graz TEXAS The University of Texas at Austin



C3,-1
×10^-10
Swarm RL01 corr=0.65, RMSΔ=4e-11
Swarm AIUB corr=0.64, RMSΔ=3.5e-11
Swarm ASU corr=0.54, RMSΔ=5.5e-11
Swarm IFG corr=0.68, RMSΔ=5e-11
Swarm OSU corr=0.35, RMSΔ=6.1e-11
GRACE (reference)
[]
4
3
2
1
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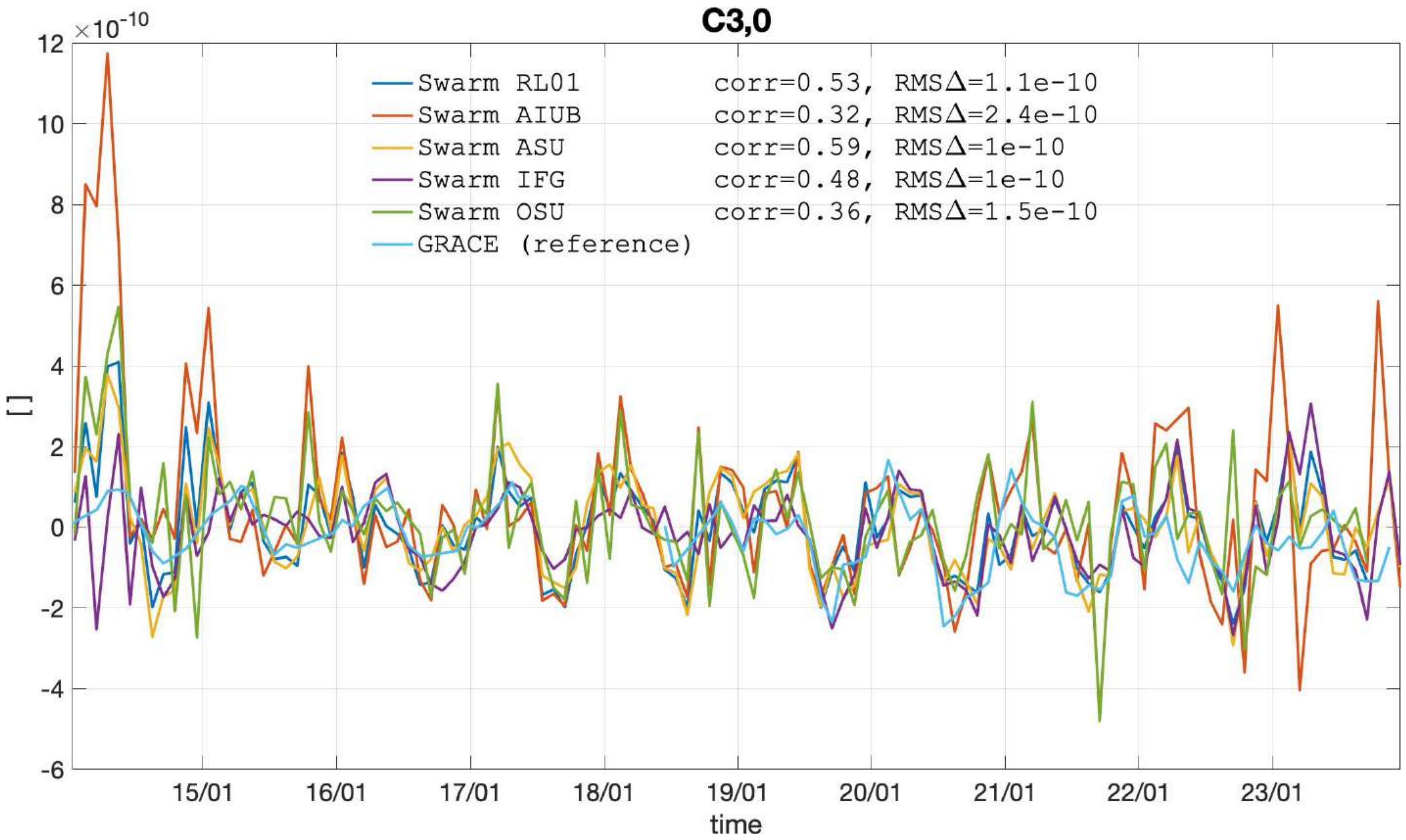
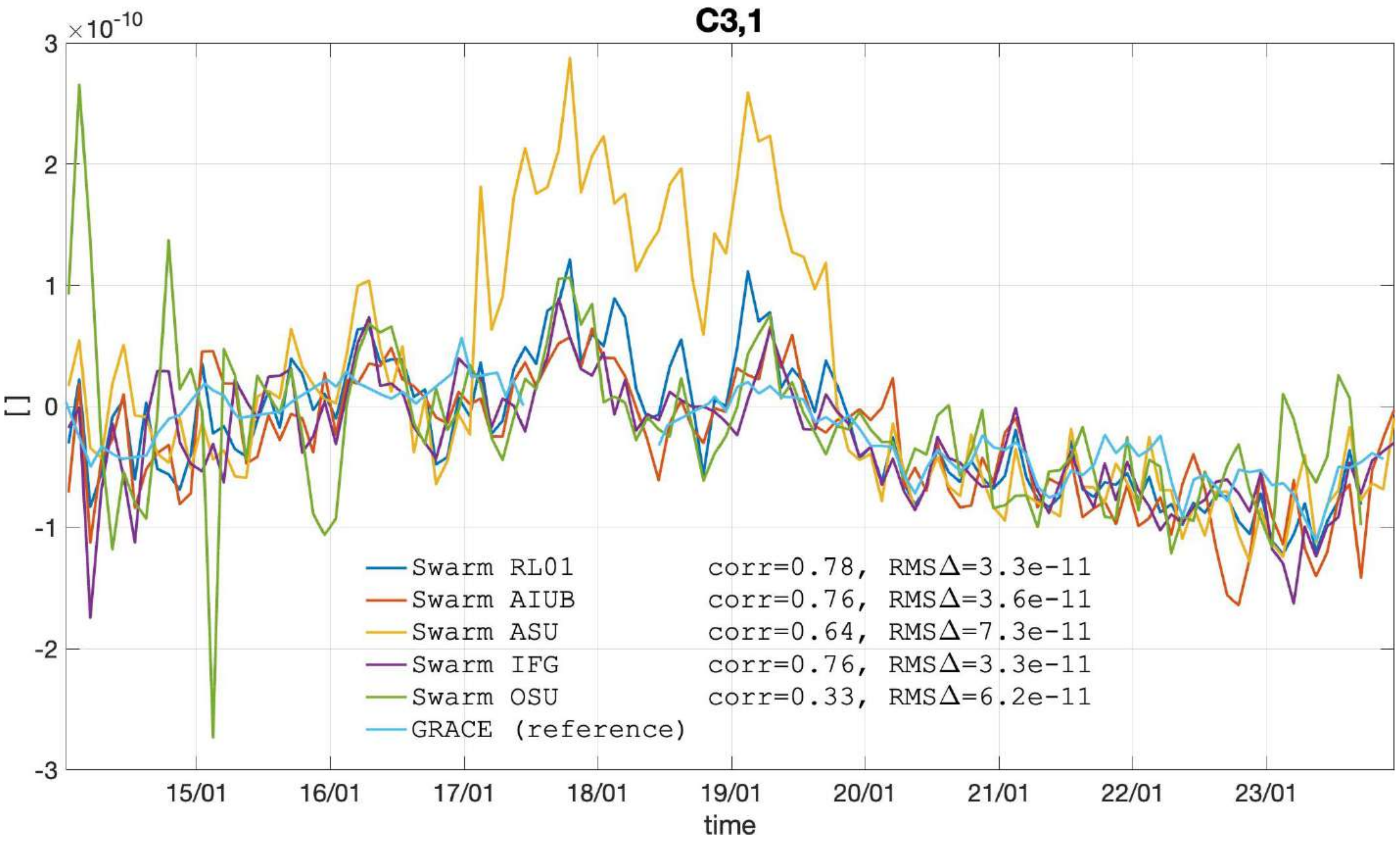
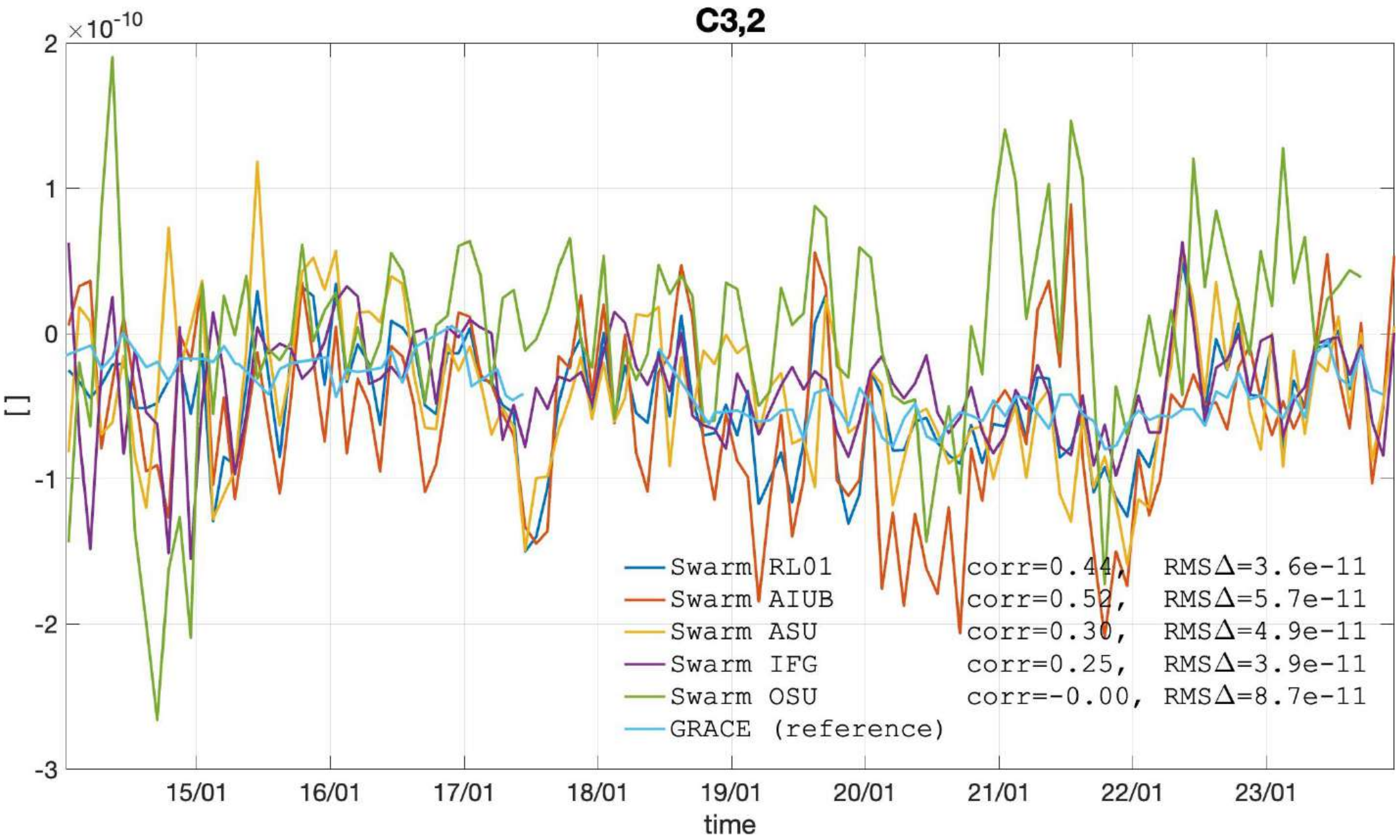
-1
-2
15/01
16/01
17/01
18/01
19/01
20/01
21/01
22/01
23/01
time

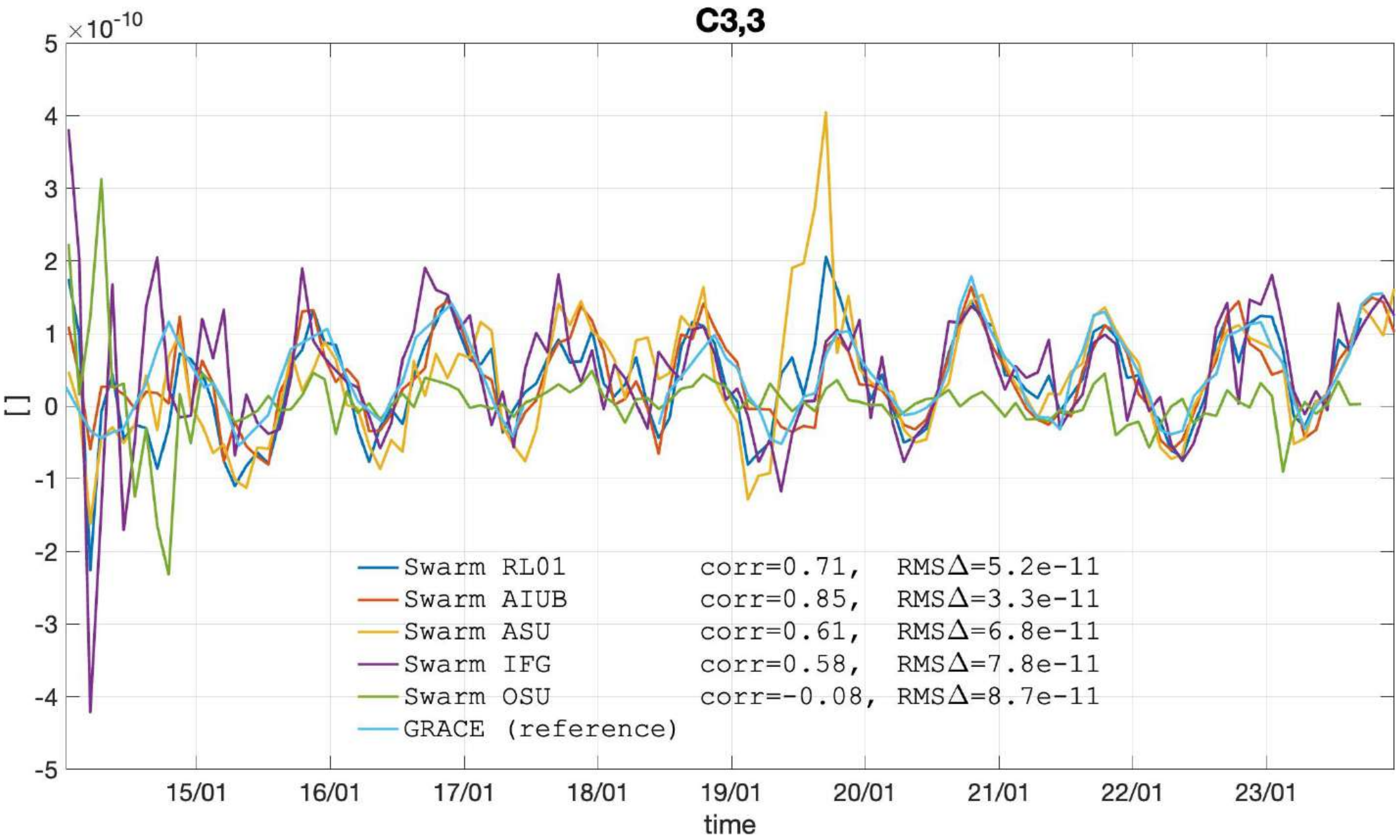


swarm SWARM DISC COST-G Universität Bern Astronomical Institute of the Czech Academy of Sciences GFZ Helmholtz Centre Potsdam The Ohio State University TU Delft TU Graz TEXAS The University of Texas at Austin



swarm SWARM DISC COST-G
UNIVERSITÄT BERN
Astronomical Institute of the Czech Academy of Sciences
GFZ Helmholtz Centre Potsdam
The Ohio State University
TU Delft
TU Graz
TEXAS The University of Texas at Austin


C3,2
×10^-10
2
1
0
-1
-2
-3
[]
15/01
16/01
17/01
18/01
19/01
20/01
21/01
22/01
23/01
time
Swarm RL01 corr=0.44, RMSΔ=3.6e-11
Swarm AIUB corr=0.52, RMSΔ=5.7e-11
Swarm ASU corr=0.30, RMSΔ=4.9e-11
Swarm IFG corr=0.25, RMSΔ=3.9e-11
Swarm OSU corr=-0.00, RMSΔ=8.7e-11
GRACE (reference)



swarm SWARM DISC COST-G u^b UNIVERSITÄT BERN Astronomical Institute of the Czech Academy of Sciences GFZ Helmholtz Centre Potsdam The Ohio State University TU Delft TU Graz TEXAS The University of Texas at Austin

AIUB Processing strategy

Software: Bernese v5.5 (Dach et al., 2015)

Approach: Celestial Mechanics Approach (Beutler et al., 2010)

Reference GFM: AIUB-GRACE03S (Jäggi et al., 2011)

Empirical Parameters: Daily and 15 minutes, both piecewise-constant (constrained)

Single Sat. Combination: NEQ equal weights

Temporal correlations: None

Drag Model: None

EARP and EIRP Models: None

Non-tidal Model: **Unti Nov 2017:** Atmosphere and Ocean De-aliasing Level 1B (Flechtner, 2011)

After Nov 2017: Atmosphere and Ocean De-aliasing Level 1B RL06 (Dobslaw et al., 2017)

Ocean Tidal Model: 2011 Empirical Ocean Tide model (Savcenko and Bosch, 2012)

Permanent Tide System: tide free

ASU Processing strategy

Software: (developed in-house)

Approach: Decorrelated Acceleration Approach (Bezděk et al., 2014)

Reference GFM: ITG GRACE-only static model, 2010 (Mayer-Gürr et al., 2010)

Empirical Parameters: Daily constant-piecewise

Coord. Axis Combination: TBD

Single Sat. Combination: NEQ, equal weights

Temporal correlations: Empirical decorrelation filter

Drag Model: Naval Research Laboratory Mass Spectrometer and Incoherent Scatter radar (Picone et al., 2002)

EARP and EIRP Models: Knocke, Ries, and Tapley (1988)

Non-tidal Model: Atmosphere and Ocean De-aliasing Level 1B RL06 (Dobslaw et al., 2017)

Ocean Tidal Model: 2004 Finite Element Solution (Lyard et al., 2006)

Permanent Tide System: tide-free

IfG Processing strategy

Software: GROOPS

Approach: Short-Arcs Approach (Mayer-Gürr, 2006)

Reference GFM: GOCO release 05 satellite-only gravity field model (Mayer-Gürr, 2015)

Empirical Parameters: Piecewise linear for each arc (ranging from 15 to 45 minutes)

Single Sat. Combination: NEQ, relative weighting from VCE

Temporal correlations: Empirical covariance function

Drag Model: Jacchia-Bowman 2008 (Bowman et al., 2008)

EARP and EIRP Models: Rodriguez-Solano et al. (2012)

Non-tidal Model: AOD1B-RL06 (Dobslaw et al., 2017)

Ocean Tidal Model: 2014 Finite Element Solution (Carrere et al., 2015)

Permanent Tide System: zero tide

OSU Processing strategy

Software: (developed in-house)
Approach: Improved Energy Balance Approach (Shang et al., 2015)
Reference GFM: GRACE Intermediate Field 48 (Ries et al., 2011) up to Degree and Order (D/O) 200
Empirical Parameters: 2nd order polynomial every 3 hours, 1-Cycle Per Revolution (CPR) sinusoidal every 24 hours
Single Sat. Combination: NEQ, equal weights
Temporal correlations: None
Drag Model: Naval Research Laboratory Mass Spectrometer and Incoherent Scatter radar (Picone et al., 2002)
EARP and EIRP Models: Knocke, Ries, and Tapley (1988)
Non-tidal Model: **AODB1B** Flechtner (2011)
Ocean Tidal Model: 2011 Empirical Ocean Tide model (Savcenko and Bosch, 2012)
Permanent Tide System: tide-free

Common assumptions

Atmospheric Tidal Model: Biancale and Bode (2006)

Regularization: none

Solid Earth Tidal Model: IERS2010

Pole Tidal Model: IERS2010

Ocean Pole Tidal Model: IERS2010

Third body perturbations: Sun, Moon, Mercury, Venus, Mars, Jupiter and Saturn, following the JPL Planetary and Lunar Ephemerides (Folkner et al., 2014)

$C_{2,0}$ **coefficient:** estimated alongside other coefficients

Acronyms I

AA	Acceleration Approach, Rummel (1979)
AIUB	Astronomical Institute of the University of Bern, Switzerland, www.aiub.unibe.ch
AOD1B	Atmosphere and Ocean De-aliasing Level 1B product, Flechtner, Schmidt, and Meyer (2006), Flechtner (2007) and Flechtner (2011)
AOD1B-RL06	Atmosphere and Ocean De-aliasing Level 1B RL06 product, Dobslaw et al. (2017)
ASU	Astronomical Institute (Astronomický ústav), AVCR, Ondřejov, www.asu.cas.cz/en
AVCR	Czech Academy of Sciences (Akademie věd České Republiky), Czech Republic, www.avcr.cz/en/
CMA	Celestial Mechanics Approach, Beutler et al. (2010)
CPR	Cycle Per Revolution
D/O	Degree and Order
DAA	Decorrelated Acceleration Approach, Bezděk et al. (2014) and Bezděk et al. (2016)
EARP	Earth Albedo Radiation Pressure
EIRP	Earth Infrared Radiation Pressure

Acronyms II

EBA	Energy Balance Approach, O'Keefe (1957) and Jekeli (1999)
EOT	Empirical Ocean Tide model
EOT11a	2011 Empirical Ocean Tide model, Savcenko and Bosch (2012)
FES	Finite Element Solution global tide model
FES2004	2004 Finite Element Solution global tide model, Lyard et al. (2006)
FES2014	2014 Finite Element Solution global tide model, Carrere et al. (2015)
GFM	Gravity Field Model
GHOST	GPS High precision Orbit determination Software Tool, Helleputte (2004) and Wermuth, Montenbruck, and Helleputte (2010)
GIF48	GRACE Intermediate Field 48, Ries et al. (2011)
GOCO	Gravity Observation COmbination
GOCO05S	GOCO release 05 satellite-only gravity field model, Mayer-Gürr (2015)
GPS	Global Positioning System
GRACE	Gravity Recovery And Climate Experiment, Tapley, Reigber, and Melbourne (1996) and Tapley (2004)
GRACE-FO	GRACE Follow On, **Kornfeld2019**

Acronyms III

GROOPS	Gravity Recovery Object Oriented Programming Systeem, Mayer-Gürr et al., (2020)
IEBA	Improved Energy Balance Approach, Shang et al. (2015)
IERS	International Earth Rotation Service
IERS2010	IERS Conventions 2010, Petit and Luzum (2010) Institute
IfG	of Geodesy, TUG, Graz, www.ifg.tugraz.at
ITG	Institut für Geodäsie und Geoinformation, Germany
ITG-GRACE2010s	ITG GRACE-only static model, 2010, Mayer-Gürr et al. (2010)
JB2008	Jacchia-Bowman 2008, Bowman et al. (2008)
JPL	Jet Propulsion Laboratory, USA, www.jpl.nasa.gov
JPL-PLE	JPL Planetary and Lunar Ephemerides, Folkner et al. (2014)
KO	Kinematic Orbit
L1B	Level 1B data
NEQ	Normal Equation
NRLMSISE	US Naval Research Laboratory Mass Spectrometer and Incoherent Scatter radar atmospheric model, Picone et al. (2002)
OSU	Ohio State University, www.osu.edu

Acronyms IV

RL06	Release 6
RMS	Root Mean Squared
SAA	Short-Arcs Approach, Mayer-Gürr (2006)
TUG	Graz University of Technology, Austria, www.tugraz.at
USA	United States of America
VCE	Variance Component Estimation

Symbols

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