DDK-filter Reassessment using Time Variable Error Covariance Information

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GRACE - Why time variable filtering?

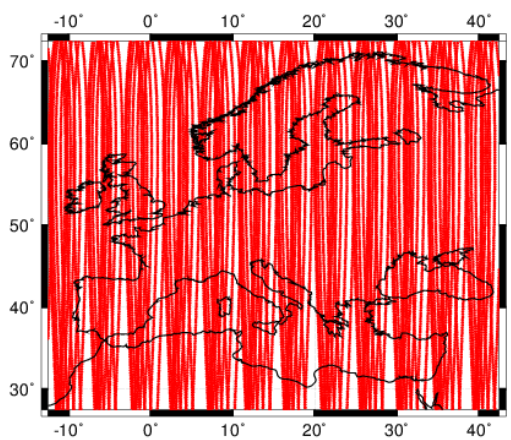
- Decreasing altitude → increasing sensitivity
- Changing ground track pattern → changing correlations within parameters more …
- Varying instrument performance

Upward continuation

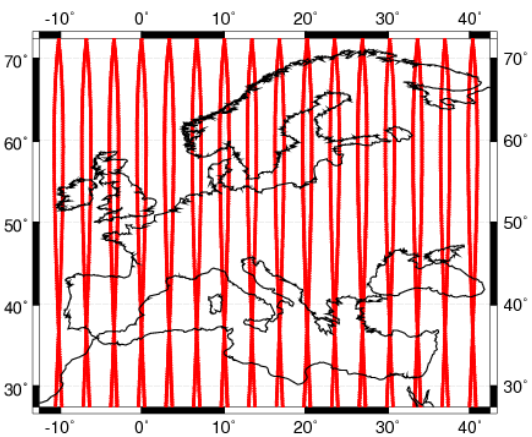
$$u = \left(\frac{r_e}{r_e + h_{GRACE}}\right)^{l+1}$$

SH degree l	$u_{500\,km}/u_{350\,km}$
30	2.0
60	3.8
90	7.4
120	14.4

Jan. 2016



Dec. 2009

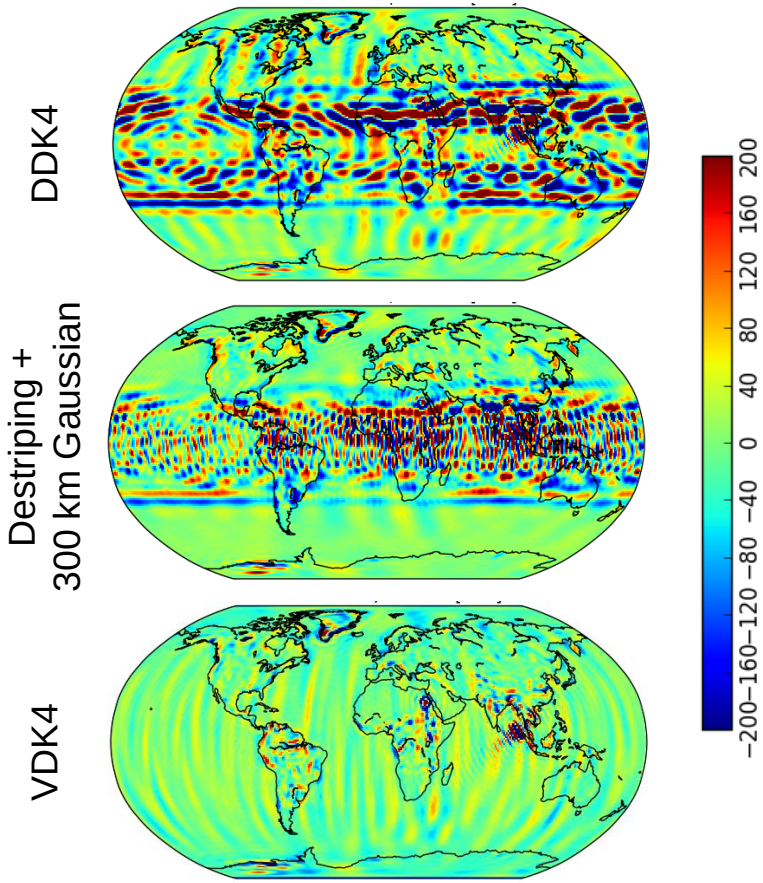


Reassassing DDK

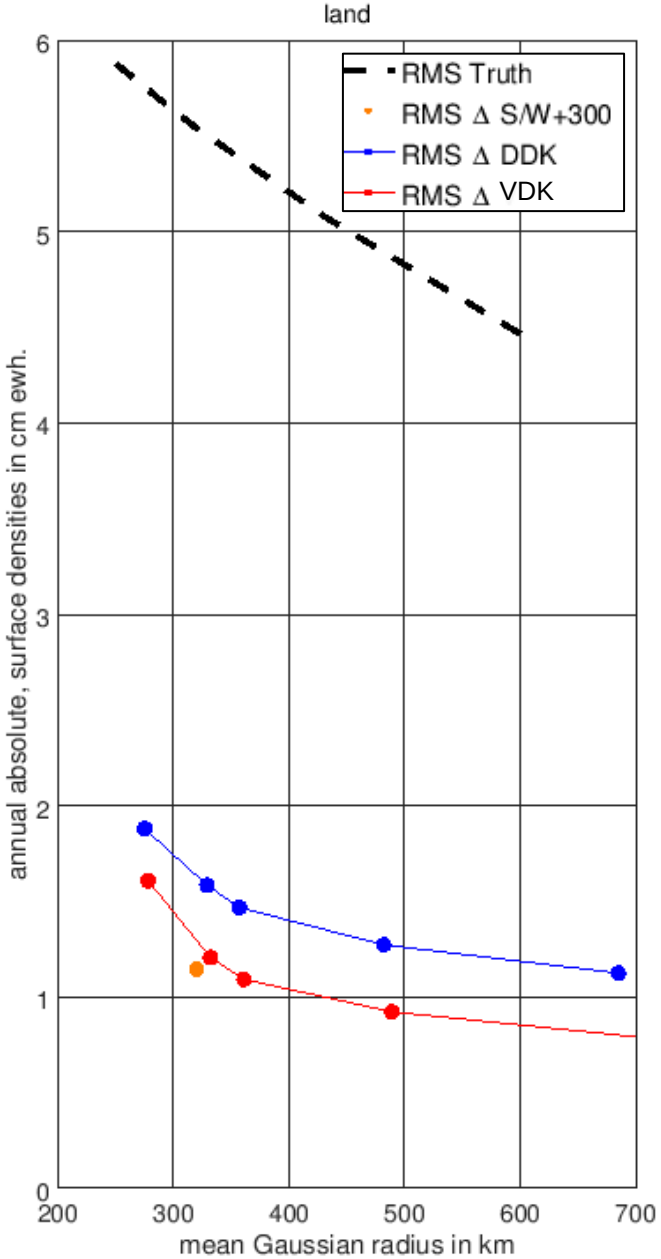
	DDK [Kusche, 2007; Kusche et al. 2009]	**VDK** DDK reassessment (cf. Horvath, 2017)
Error VCM	Constant (based on older VCM; block diagonal)	Time variable (based on actual RL05a VCM; full)
Signal VCM	Constant (based on Hydrological model; SH degree dependent)	
Filter parameter	$\alpha_{DDK1} / \alpha_{DDK5} = 1000$	$\alpha_{VDK1} / \alpha_{VDK5} = 1000$

Closed-loop validation

Monthly (bad coverage) residuals in terms of surf. mass dens. in mm ewh.



Global absolute annual amplitude RMS of truth and residuals with different filters and filter strengths



Conclusions

- Time variable decorrelation filter using the most accurate error (and signal) VCM proposed for GRACE (and GRACE-Follow-On) data in order to account for changing sensitivity
- Candidate filter method for GFZ Level 3 processing (cf. Dahle et al., EGU2018-17878, Poster on the new GFZ Level 3 web portal GravIS)
- Closed-loop simulation results show
  - smallest global residuals for bad coverage months
  - better global retrieval of linear and annual terms than static DDK
  - smaller basin residuals compared to DDK and Destriping+Gaussian
- Real data analyses show a reduction of the total RMS over the oceans for the GFZ RL05a time series around 16% (VDK5 vs. DDK5) and 18% (4)

Content – Navigation

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Which filter to be applied?

	Isotropic	Anisotropic	
Homo-geneous	Gaussian		
Inhomo-geneous		Destriping [Swenson and Wahr, 2006]	Regularization [Kusche, 2007]

[Devaraju, 2015]

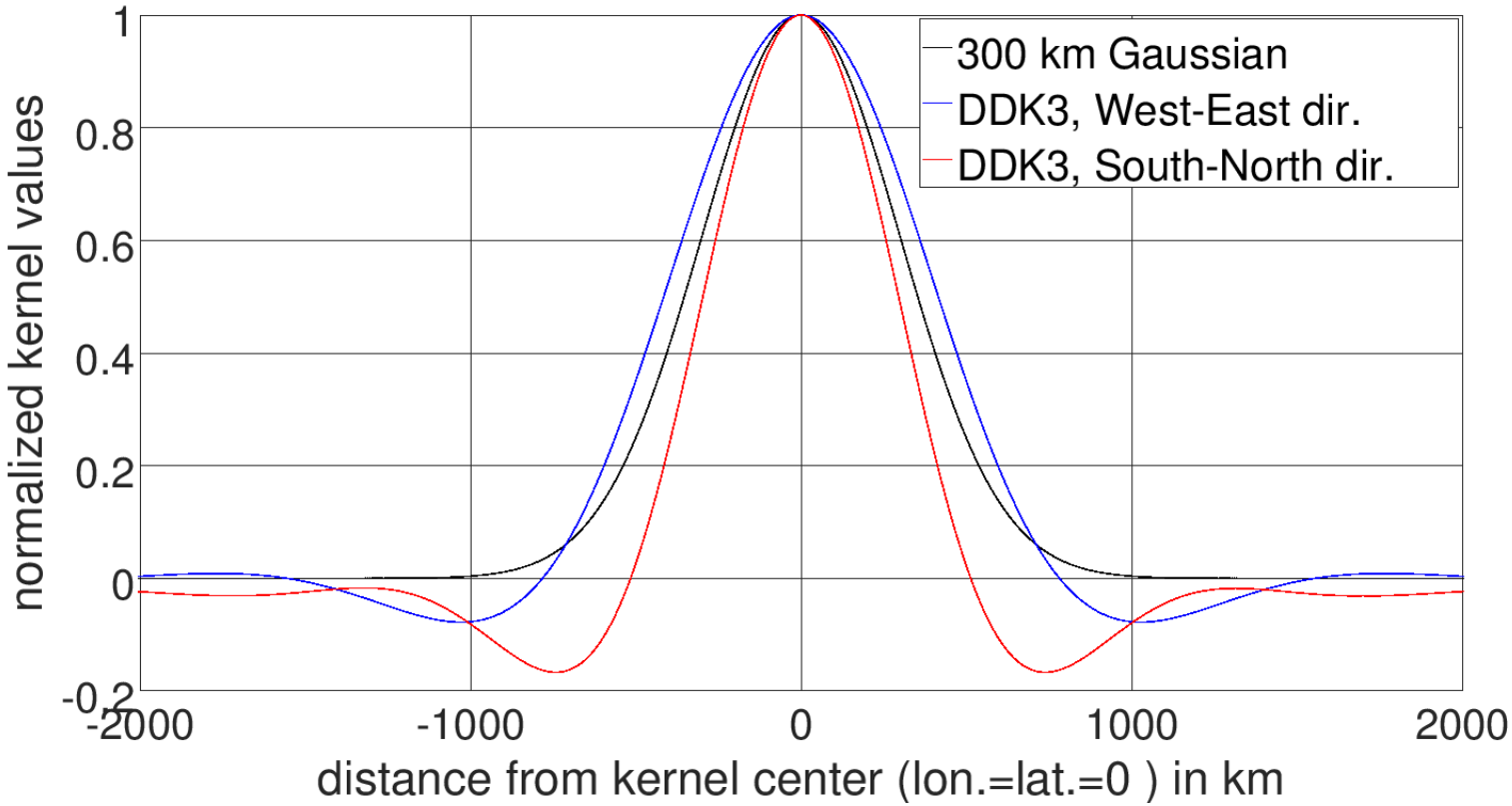
Which filter to be applied?

Isotropic

Anisotropic

Homo-geneous

Inhomo-geneous



Reassassing DDK

Inverse error variance-covariance matrix (VCM)

Regularization/ Filter parameter

Inverse signal VCM

filtered spherical harmonic (SH) coefficients

raw SH coefficients

$$\mathbf{x}_\alpha = \underbrace{(\mathbf{N} + \alpha\,\mathbf{M})^{-1}\,\mathbf{N}}_{\mathbf{W}_\alpha}\,\mathbf{x}$$

Filter matrix → $\mathbf{W}_\alpha$

[Kusche, 2007; Kusche et al. 2009]

Reassassing DDK

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Filter parameter	$\alpha_{DDK1} / \alpha_{DDK5} = 1000$	$\alpha_{VDK1} / \alpha_{VDK5} = 1000$

Filter characteristics

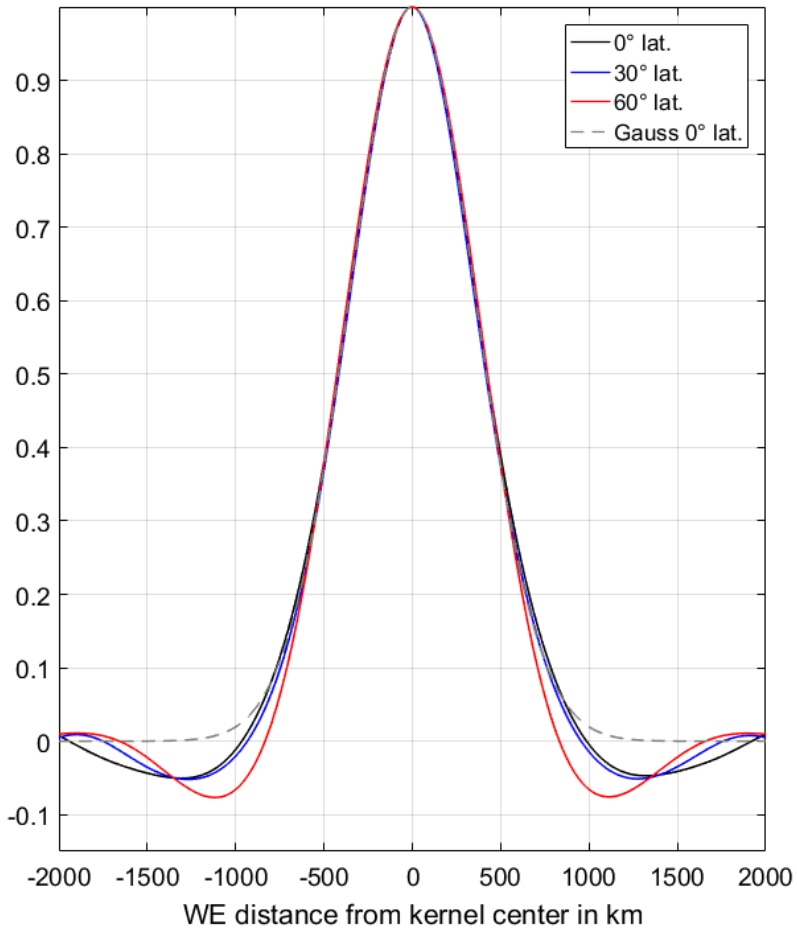
Simulated error VCM (cf. Flechtner et al., 2016):

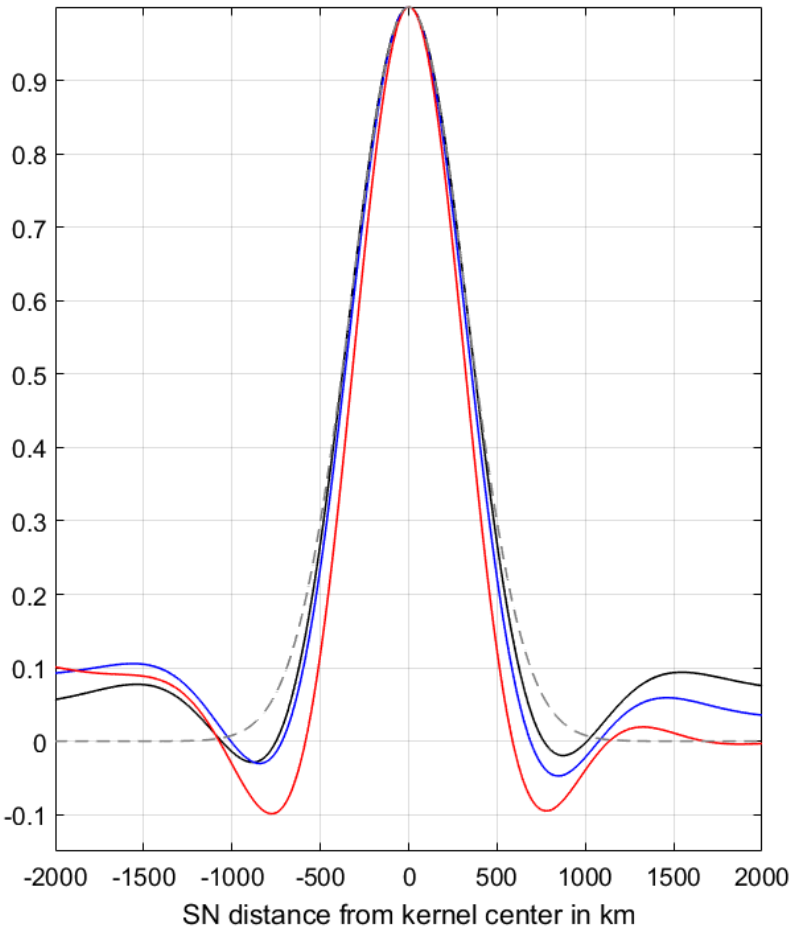
- 5 years GRACE-like simulation with decreasing altitudes from 490 to 450 km and realistic instrument errors
- Software: GFZ´s Earth Parameters and Orbits System (EPOS)
- Maximum spherical harmonic (SH) degree and order 100

Real data VCM:

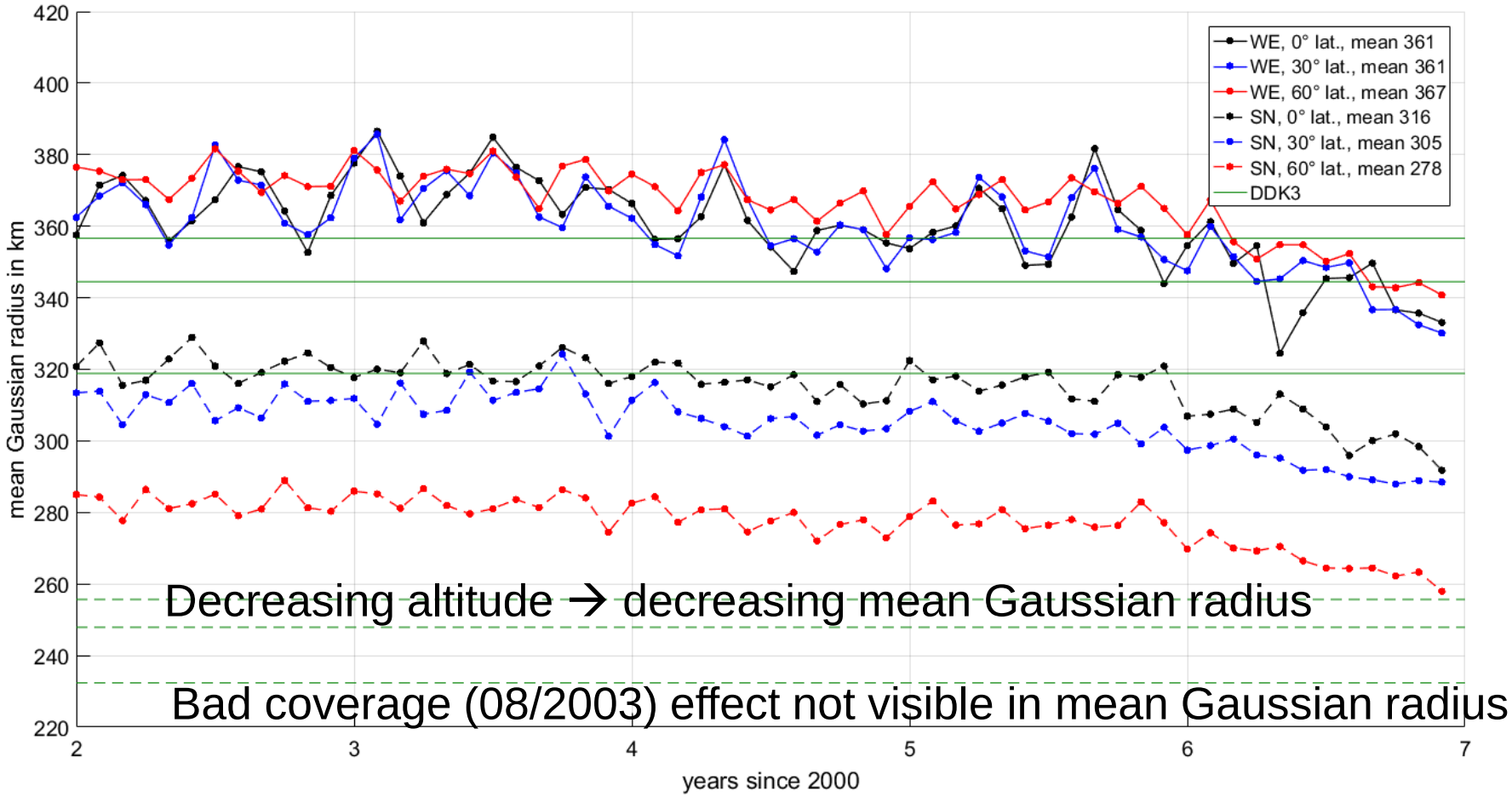
- GRACE GFZ RL05a (processed with EPOS)
- Maximum spherical harmonic degree and order 90

Filter kernel of VDK3 (03/2004)



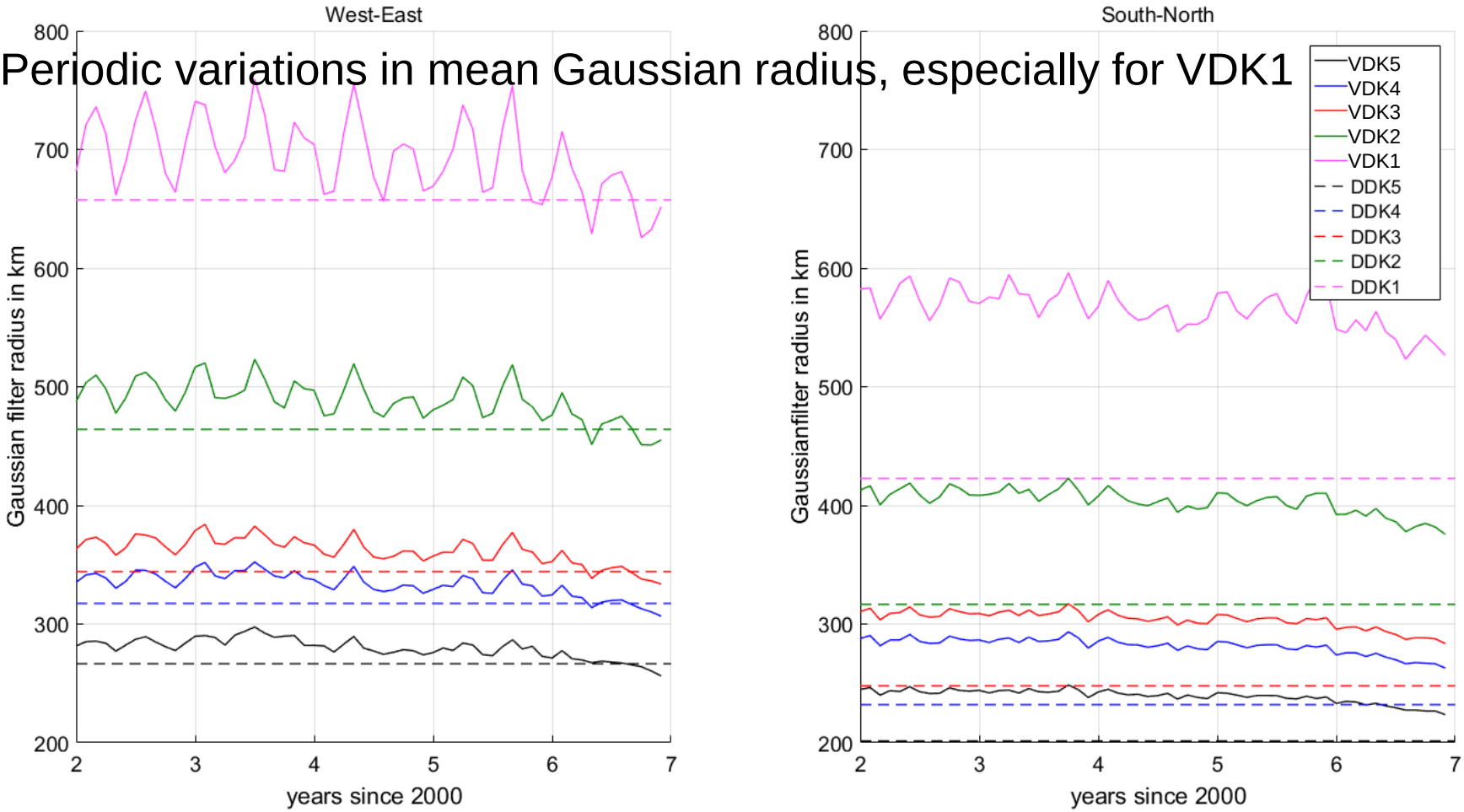


Mean Gaussian radius: VDK3 vs. DDK3



Mean Gaussian radius: DDK vs. VDK

Periodic variations in mean Gaussian radius, especially for VDK1



Mean Gaussian radius: DDK vs. VDK

DDK	1	2	3	4	5
WE	685	482	357	329	275
SN	439	328	256	239	207
mean	562	405	307	284	241
VDK	**1**	**2**	**3**	**4**	**5**
mean WE	701	489	361	332	278
mean SN	588	420	316	292	248
mean	645	455	339	312	263

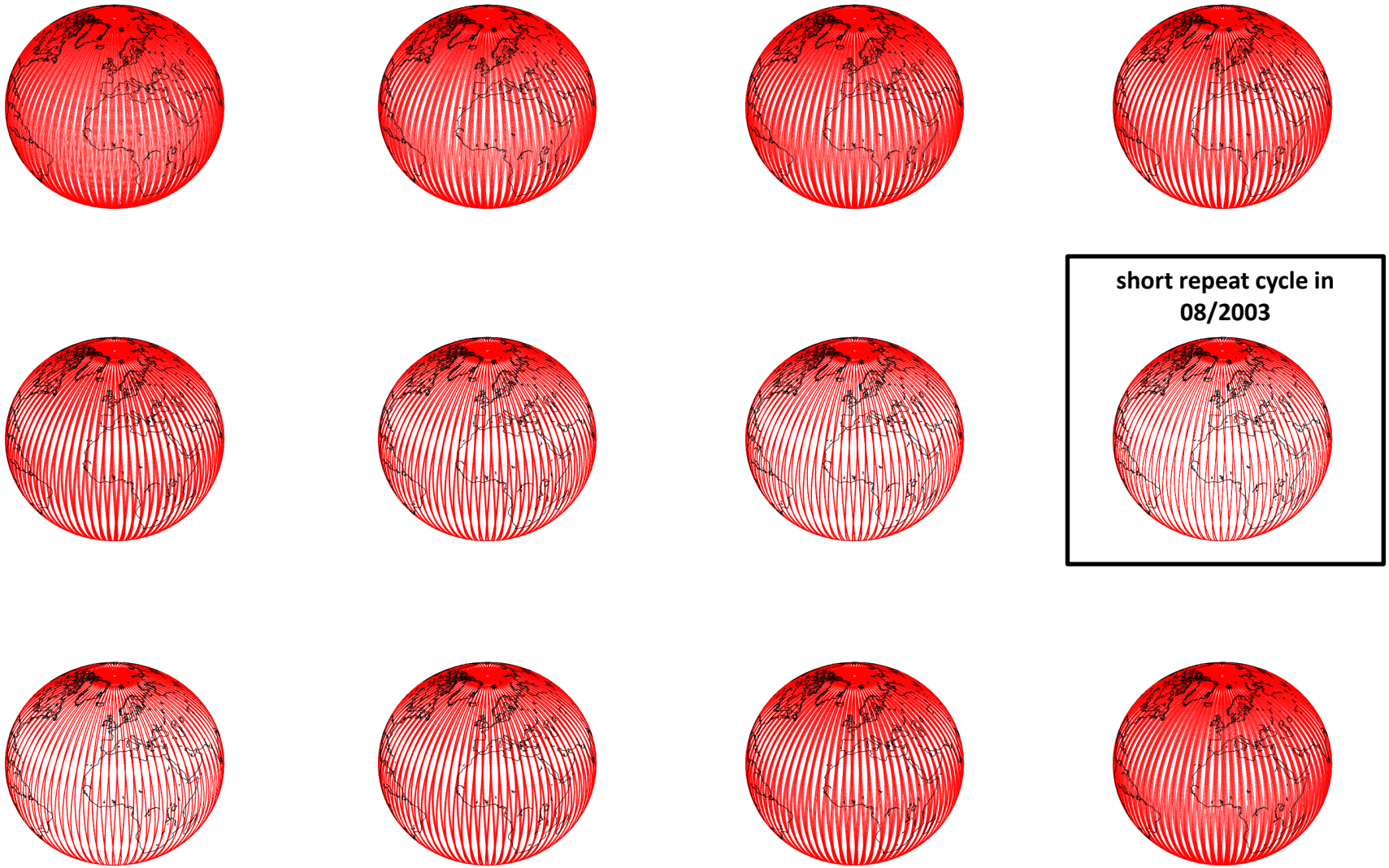
Significant larger VDK SN radii compared to DDK

Closed-loop simulation

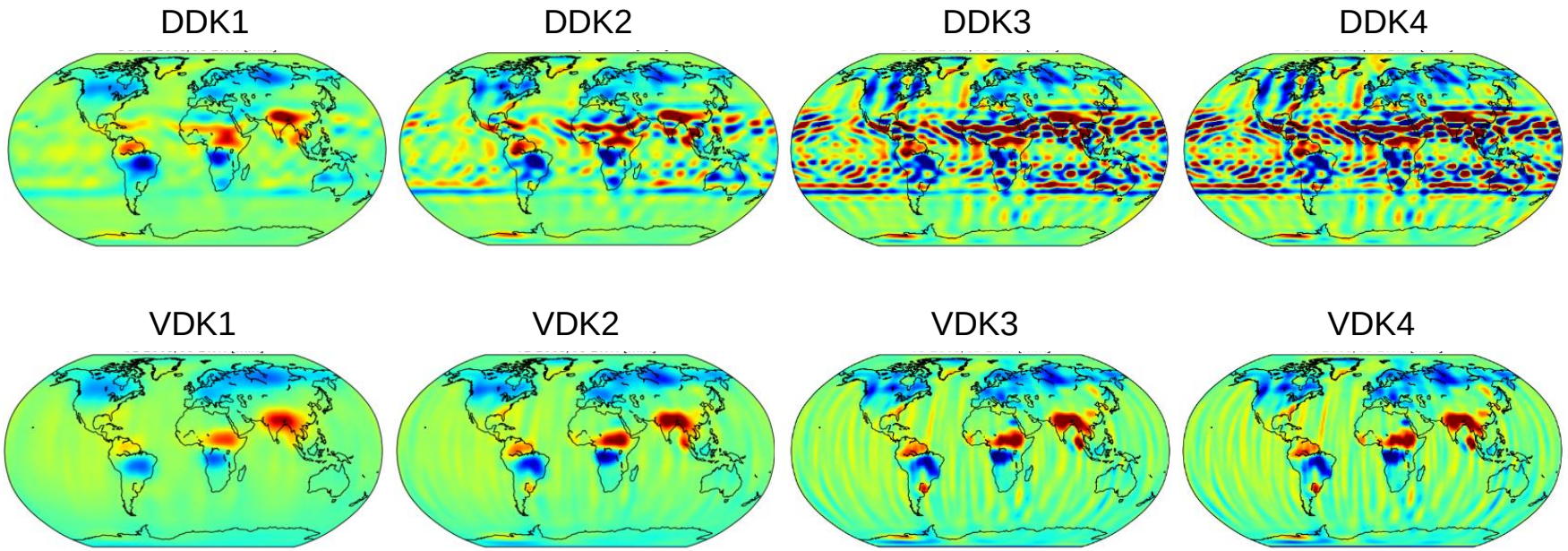
- Five years 01/2002-12/2006 based on GRACE-like mission design
- Initial altitude 490 km, final altitude 450 km
- Realistic instrument and background model errors applied
- Ground truth: ESA Earth system model AOHIS (Dobslaw et al. 2015)
- Software: GFZ´s Earth Parameters and Orbits System (EPOS)
- Maximum SH degree and order 100

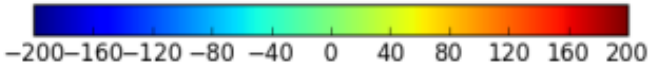
Further details in Flechtner et al. (2016): *What Can be Expected from the GRACE-FO Laser Ranging Interferometer for Earth Science Applications?*

Simulated orbit coverage in 2003



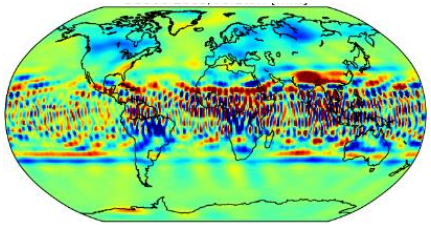
Filtered residuals wrt. static reference in 08/2003





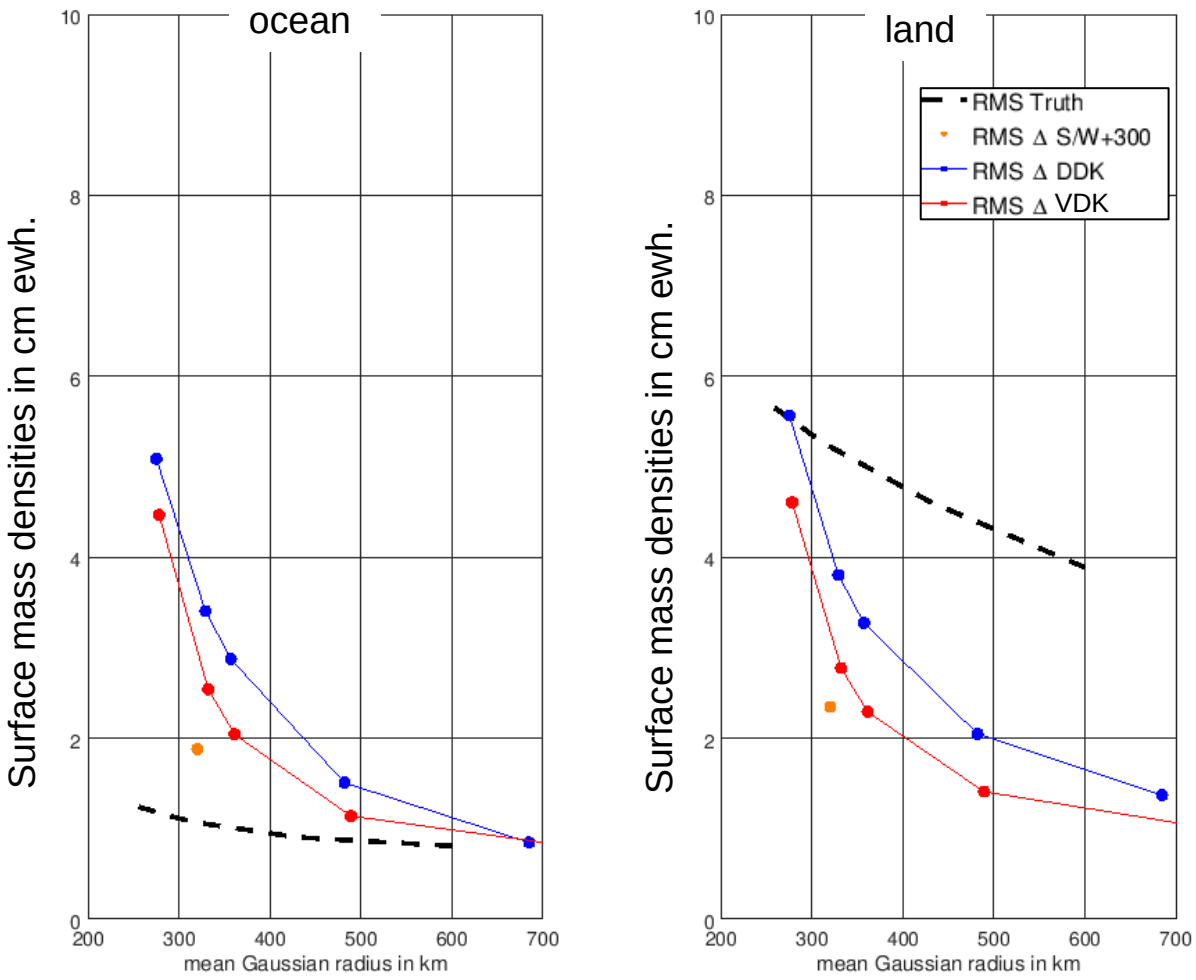
Surface mass densities in mm ewh.

Destriping + 300 km Gaussian



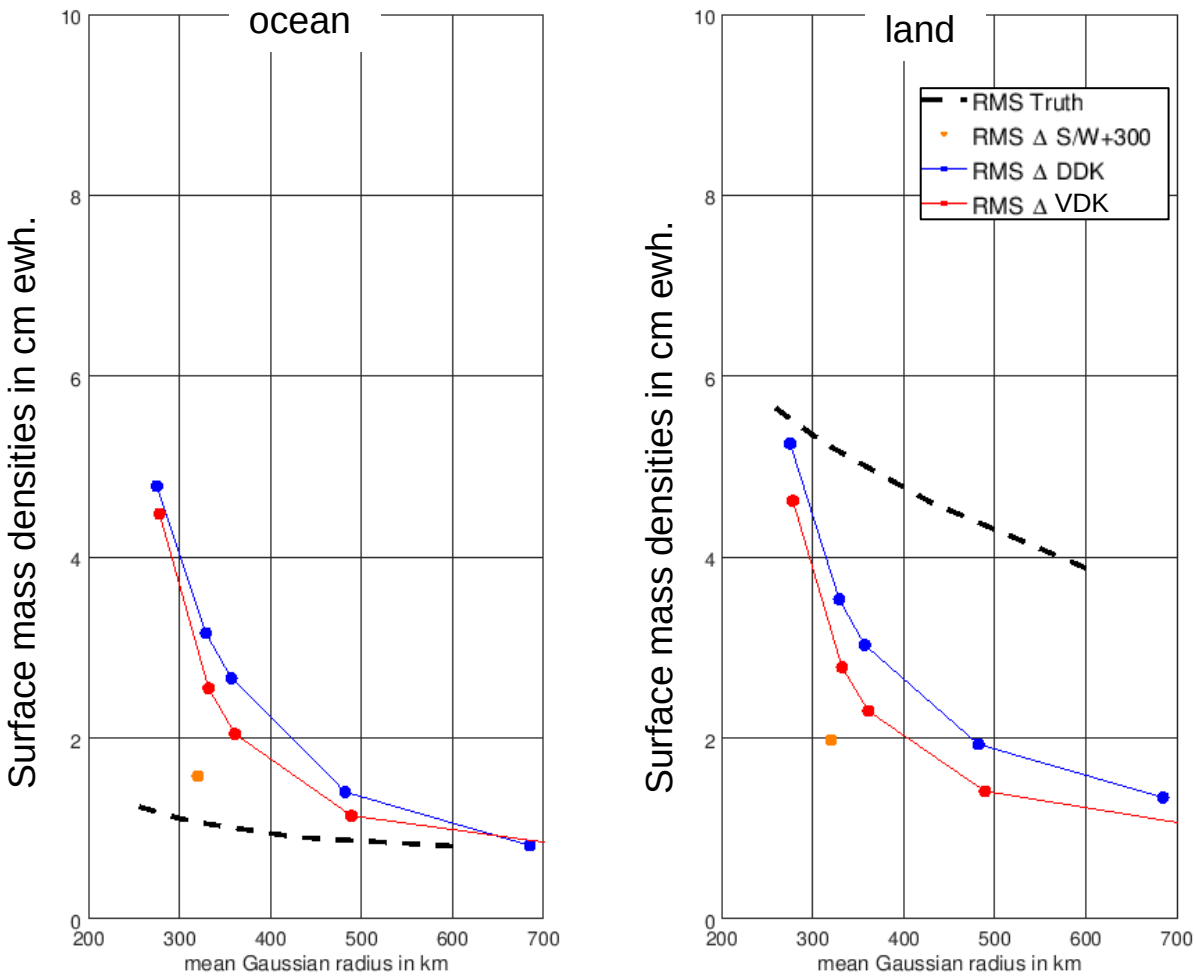
Ocean/Land total RMS of the truth and the residuals for Destriping, DDK and VDK filters

- C_{20} neglected
- Reference Gaussian filtered → ommision error reduction
- 500 km land area extension
- RMS weighted by cos(latitude)
- All months



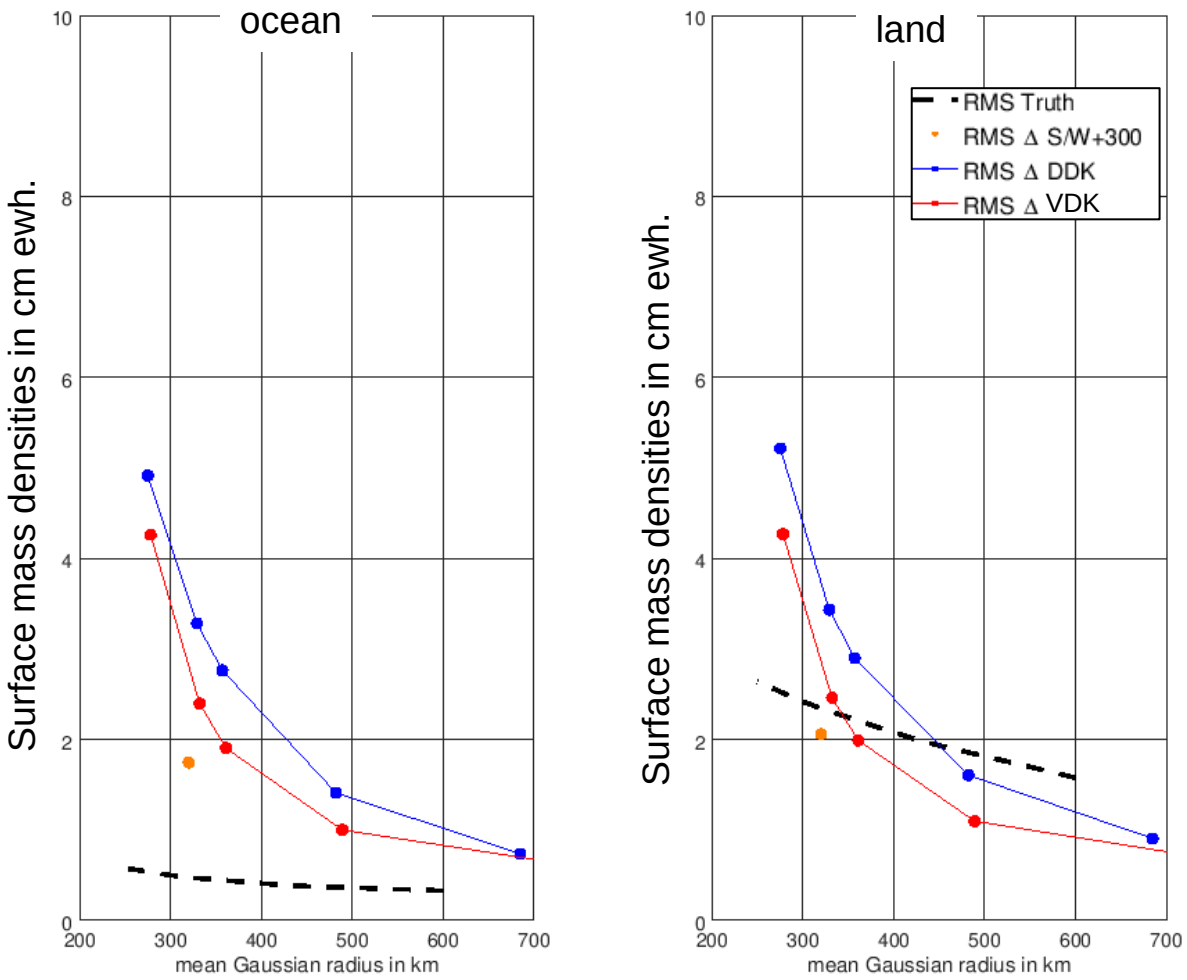
Ocean/Land total RMS of the truth and the residuals for the different filters

- C_{20} neglected
- Reference Gaussian filtered → ommision error reduction
- 500 km land area extension
- RMS weighted by cos(latitude)
- 2 bad months neglected



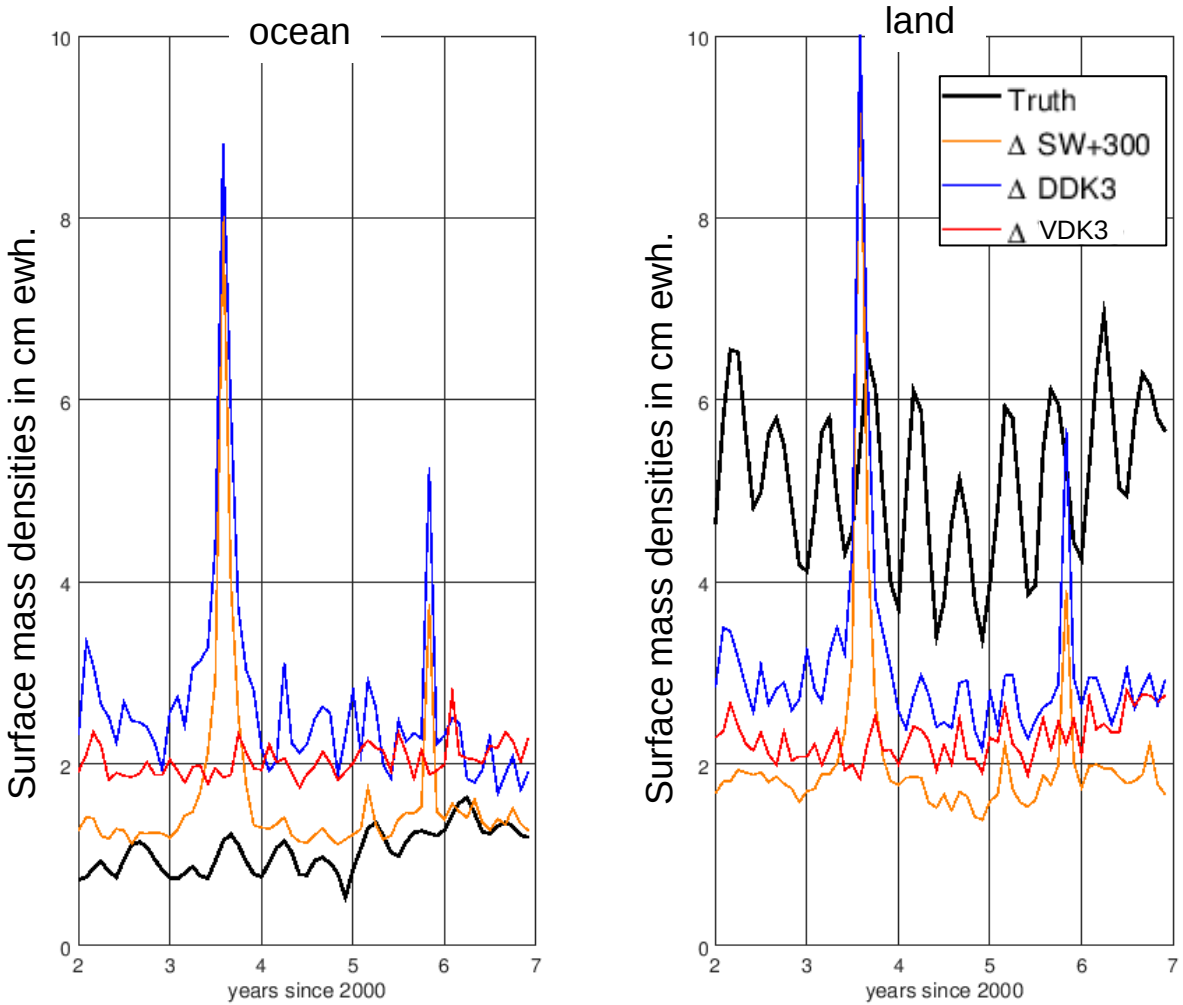
Ocean/Land total RMS of the truth and the residuals for the different filters

- C_{20} neglected
- Reference Gaussian filtered → ommision error reduction
- 500 km land area extension
- RMS weighted by cos(latitude)
- Linear and annual terms subtracted



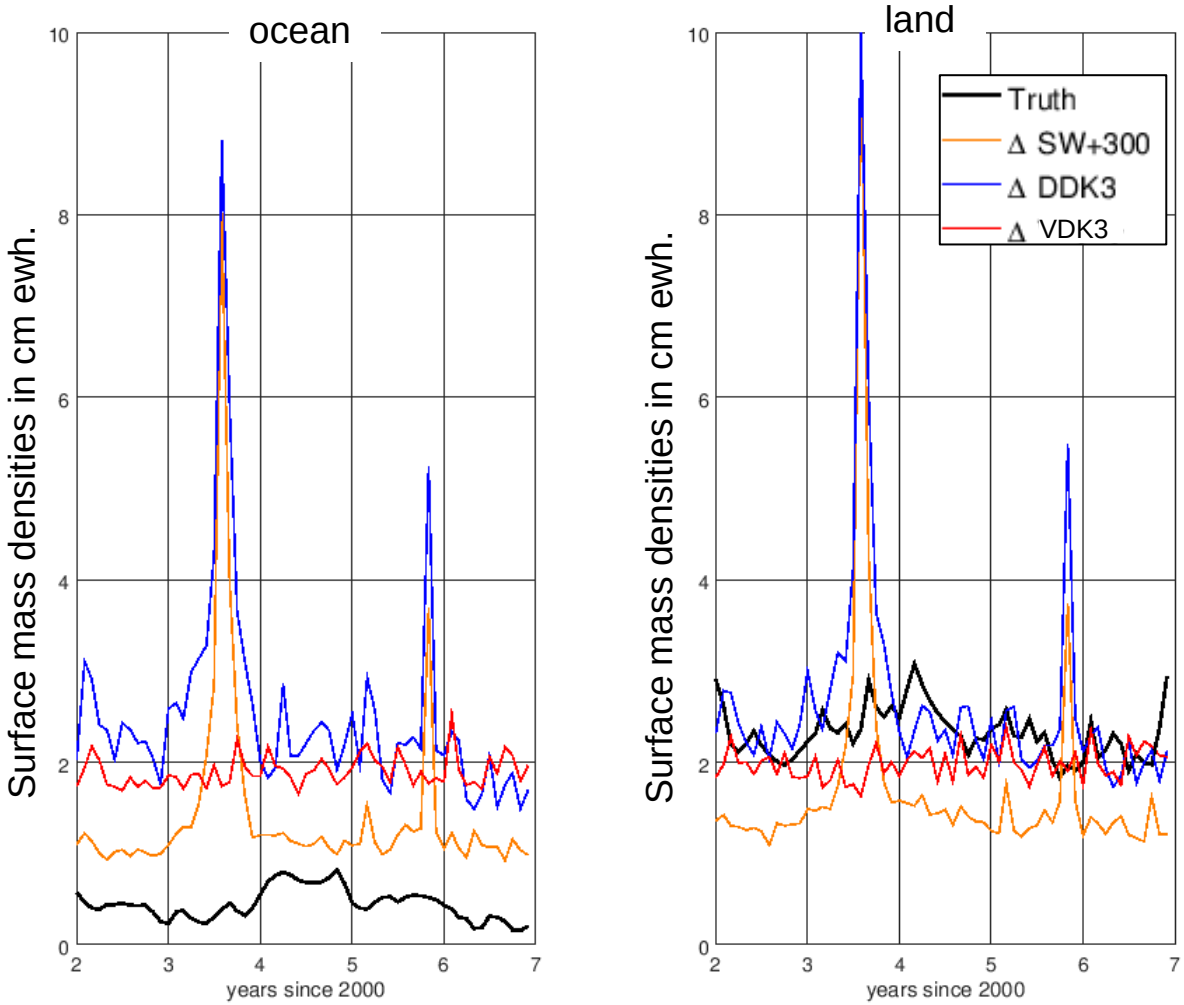
Ocean/Land monthly RMS of the truth and the residuals for Destriping, DDK3 and VDK3 filters

- Reference 340 km Gaussian filtered → ommision error reduction
- 500 km land area extension
- RMS weighted by cos(latitude)



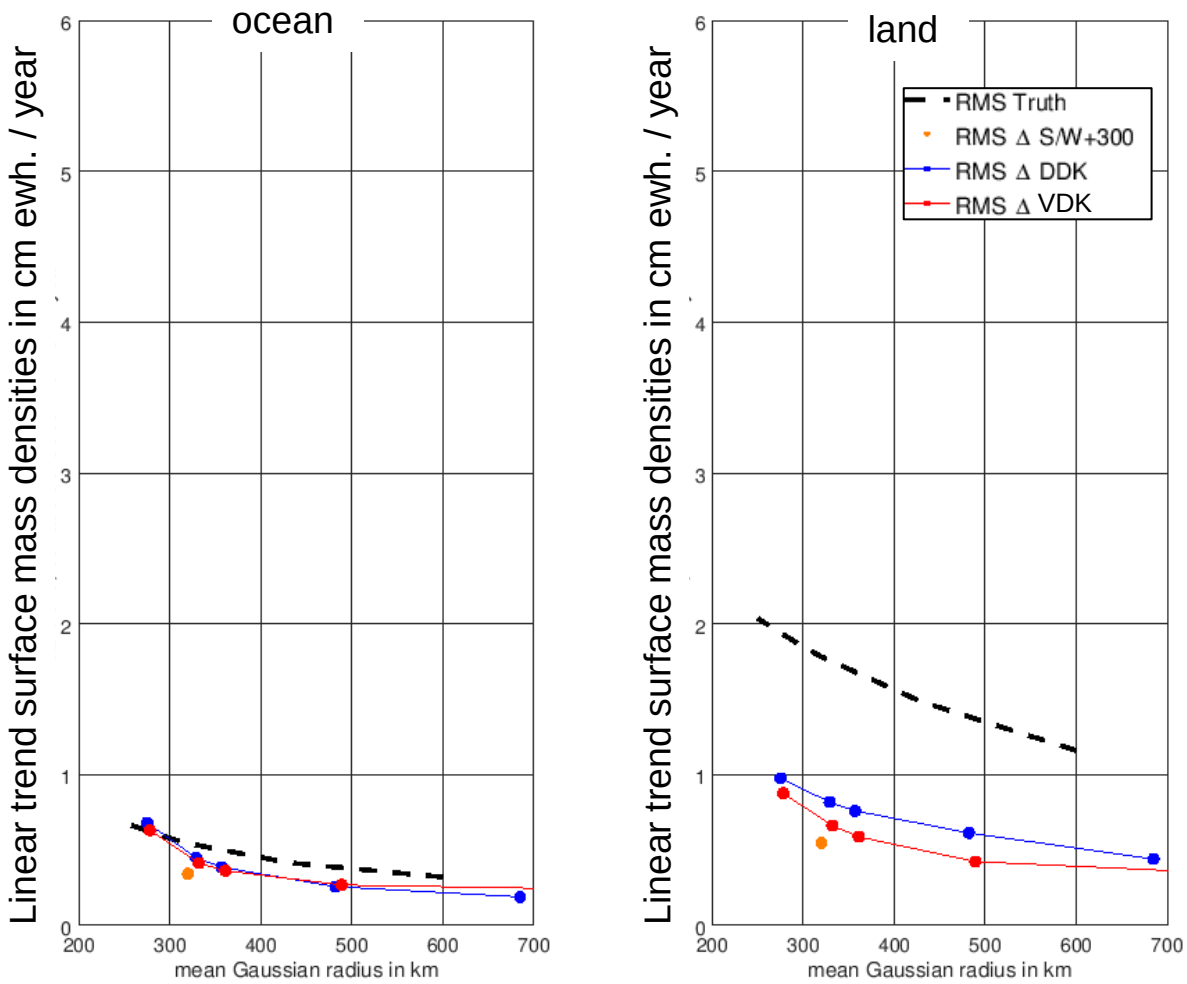
Ocean/Land monthly RMS of the truth and the residuals for Destriping, DDK3 and VDK3 filters

- Reference 340 km Gaussian filtered → ommision error reduction
- 500 km land area extension
- RMS weighted by cos(latitude)
- Linear and annual terms subtracted



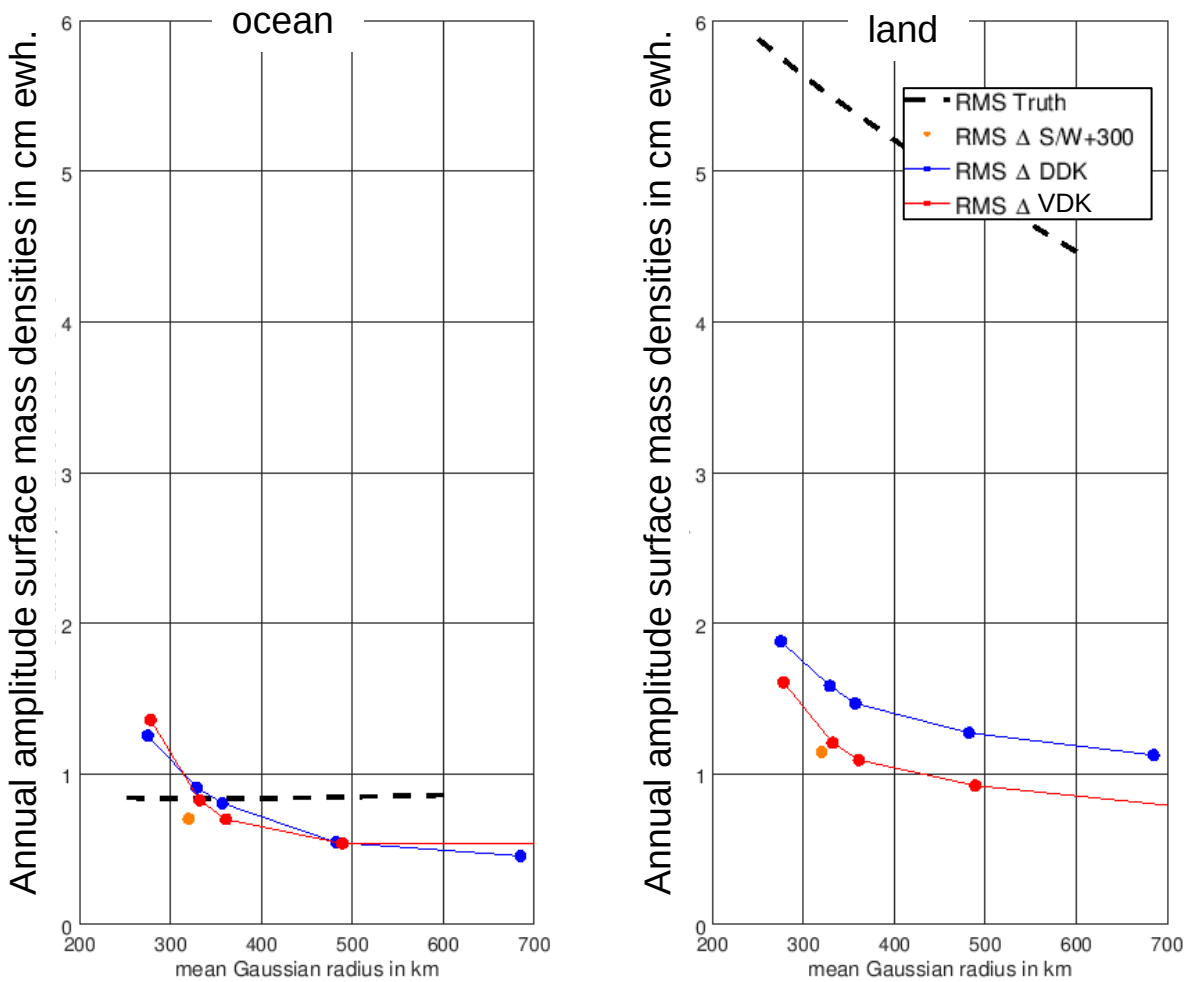
Ocean/Land total RMS of linear trend for the truth and the residuals for the different filters

- C_{20} neglected
- Reference Gaussian filtered → ommision error reduction
- 500 km land area extension
- RMS weighted by cos(latitude)



Ocean/Land total RMS of annual amplitude for the truth and the residuals for the different filters

- C_{20} neglected
- Reference Gaussian filtered → ommision error reduction
- 500 km land area extension
- RMS weighted by cos(latitude)



Basin analysis

- 13 basins for large and smaller rivers
- Simple integration mask
- Reference 300 km Gaussian filtered → ommission error reduction
- Performance criteria:
  - Raw RMS of the difference wrt. the truth
  - Comparison of linear and annual parameters
  - RMS of linear and annual reduced residuals

Raw residual RMS in mm ewh.

Basin #grid points	Basin Name	DDK1	DDK2	DDK3	DDK4	DDK5	V1	V2	V3	V4	V5	SG300
497	**Amazon**	7.6	6.7	6.5	6.6	7.0	7.6	6.6	**6.2**	6.3	6.5	6.9
450	**Ob**	9.5	6.8	**6.5**	7.3	10.0	12.7	9.7	8.6	8.6	9.2	7.0
358	**Mississipi-Missouri**	9.2	7.4	7.2	7.2	7.2	10.7	8.2	7.2	**7.1**	7.2	8.6
311	**Congo**	18.2	11.0	9.9	**9.8**	10.2	27.2	14.1	11.2	10.9	11.0	13.6
263	**Nile**	27.4	23.1	21.5	20.9	19.5	29.1	19.1	16.5	**16.4**	17.1	26.6
188	**Niger**	14.3	11.7	10.8	10.8	12.1	17.8	13.1	**10.5**	10.6	11.8	13.0
158	**Ganges-Bramap.**	28.1	15.3	13.7	13.8	14.7	42.2	17.6	7.4	**6.7**	7.1	19.4
94	**Danube**	14.8	10.3	9.3	9.2	9.1	17.8	13.8	9.1	8.8	8.6	**8.5**
89	**Indus**	24.5	14.2	14.0	14.8	17.0	36.8	20.2	12.8	**12.4**	13.1	18.2
81	**Orinoco**	58.0	30.0	23.8	22.0	20.0	87.0	45.0	26.0	23.2	**19.6**	40.4
74	**Mekong**	36.5	23.2	20.5	21.0	23.6	45.7	28.8	18.8	**17.3**	17.4	29.7
30	**Parnaiba**	46.3	32.3	29.2	28.8	28.6	55.7	43.3	28.8	27.7	27.1	**26.8**
25	**Rhine**	20.8	18.5	29.1	33.8	49.0	31.0	16.4	24.3	27.6	35.6	**16.0**
	MEAN	24.2	16.1	15.8	15.8	17.5	31.0	19.7	14.4	**13.6**	14.7	18.1

Smallest residuals

Linear and annual terms and residual RMS in mm ewh.

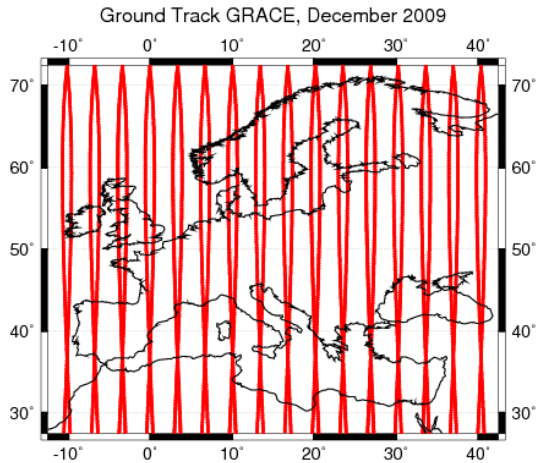
		Linear trend / year			Annual amplitude			Annual phase in day of max.			Residual RMS	
Basin #grid points	Basin Name	Truth	DDK4	VDK4	Truth	DDK4	VDK4	Truth	DDK4	VDK4	DDK4	VDK4
497	**Amazon**	2.2	1.7	0.3	22.4	24.6	**21.8**	69	71	**70**	6.5	**5.8**
450	**Ob**	39.2	**42.3**	42.6	21.9	24.6	**24.5**	58	**63**	64	**5.7**	8.6
358	**Mississipi-Missouri**	-7.1	**-6.5**	-6.4	13.2	**14.6**	16.2	141	**118**	117	5.8	**4.8**
311	**Congo**	-1.2	-0.7	-1.4	4.0	6.1	6.2	278	**282**	273	**9.4**	9.9
263	**Nile**	-1.4	0.0	-1.5	7.1	9.8	11.4	264	244	**247**	11.9	**11.0**
188	**Niger**	-0.9	-1.8	-1.8	3.4	5.3	5.7	262	220	**240**	13.7	**9.9**
158	**Ganges-Bramap.**	-5.6	-4.7	-5.3	20.8	**20.4**	20.5	284	274	**276**	12.1	**5.8**
94	**Danube**	-1.9	-1.3	-1.0	10.3	18.2	**13.8**	251	248	248	17.2	**8.7**
89	**Indus**	2.4	2.7	1.7	12.9	**9.2**	7.2	304	317	**314**	17.0	**9.2**
81	**Orinoco**	4.2	5.4	6.0	13.7	17.6	**15.4**	58	79	**67**	17.2	**9.1**
74	**Mekong**	0.2	-1.3	-2.8	22.4	21.9	**22.2**	262	**264**	267	13.3	**10.3**
30	**Parnaiba**	-0.7	4.0	0.3	18.1	17.2	13.0	77	81	**74**	20.7	**17.9**
25	**Rhine**	-1.1	0.8	2.1	9.6	13.4	18.5	248	293	**272**	37.3	**18.8**
	MEAN										14.4	**10.0**

Smallest residuals Not significant

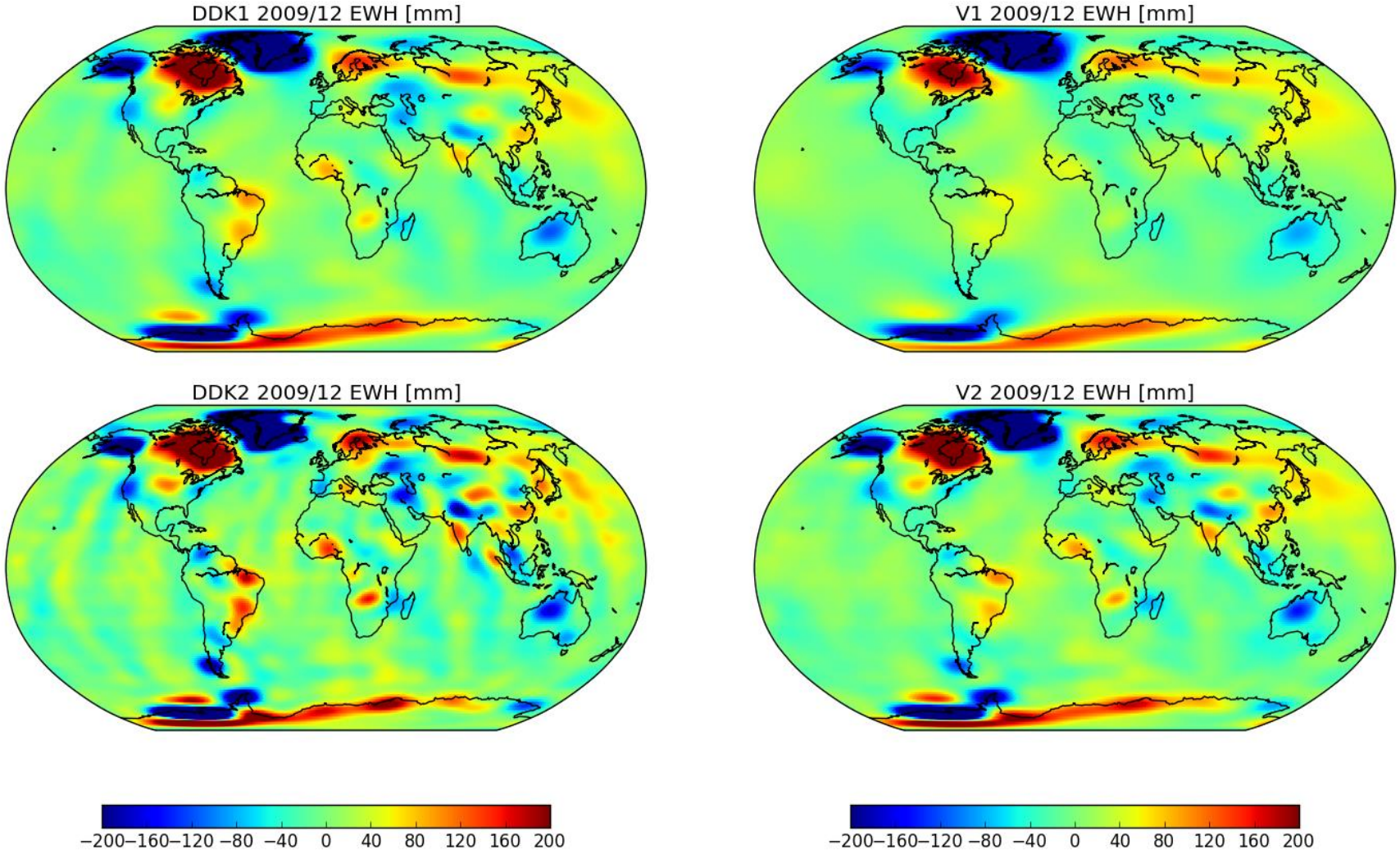
Real data analysis

GRACE GFZ RL05a solutions 2002 – 2017

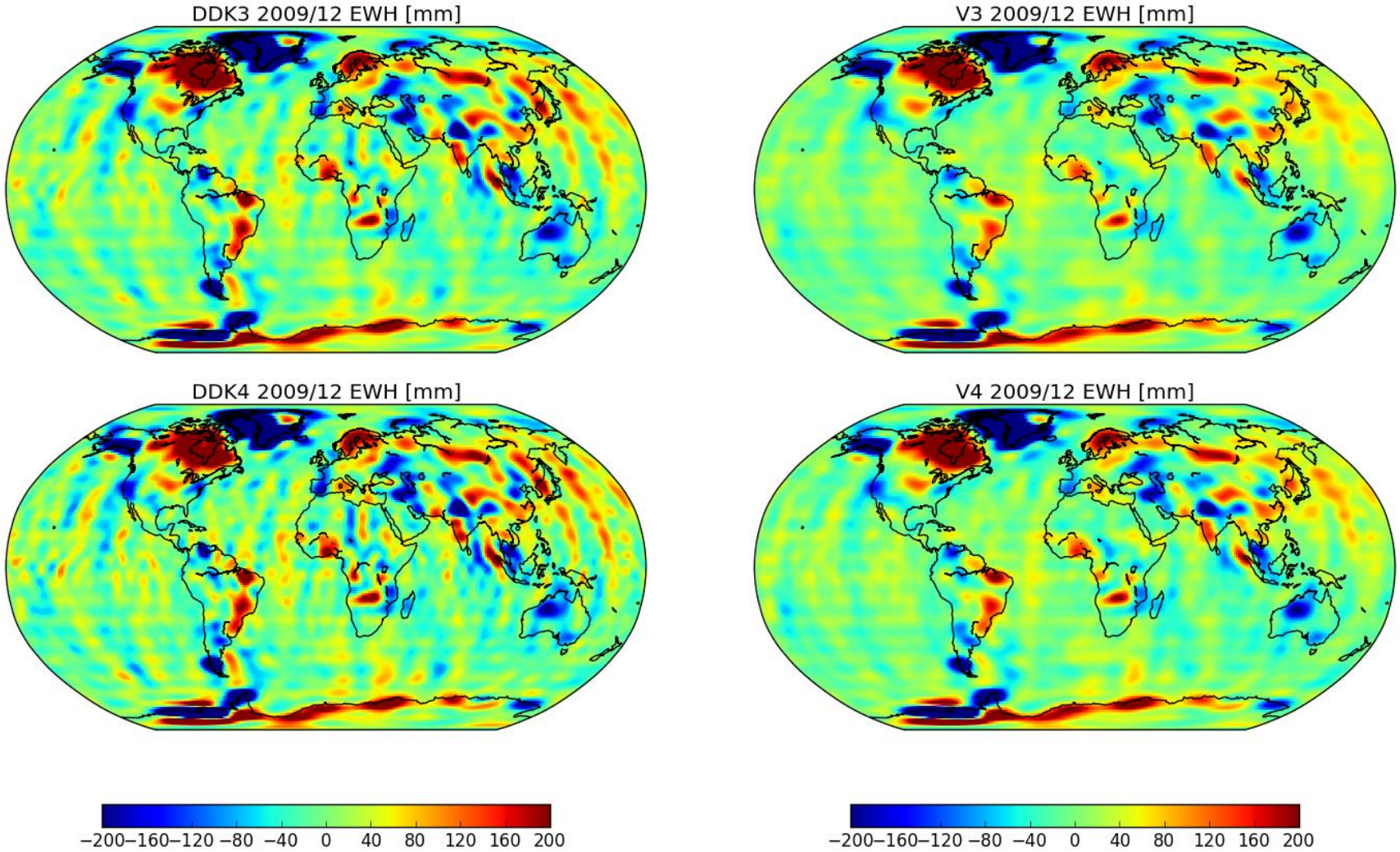
7 day repeat cycle in 12/2009



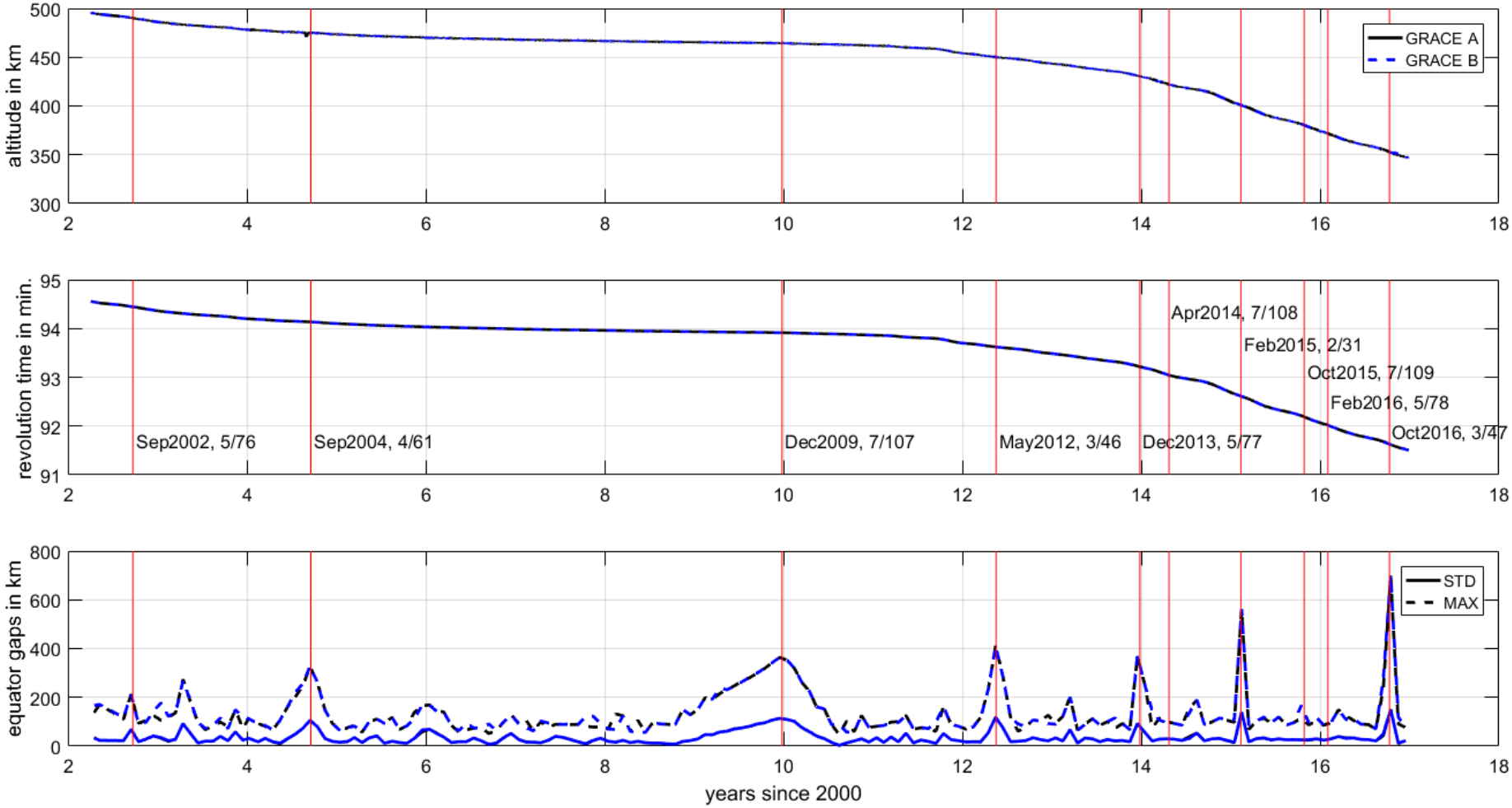
Surface mass densities for 12/2009: DDK1/2, VDK1/2



Surface mass densities for 12/2009: DDK3/4, VDK3/4

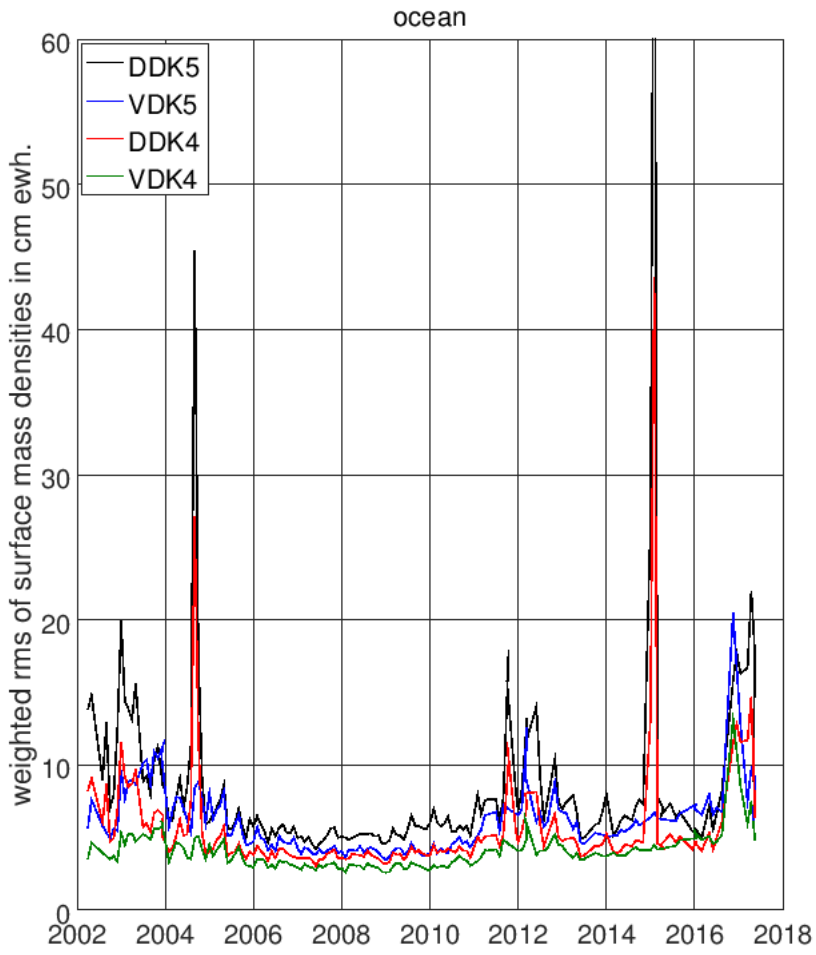


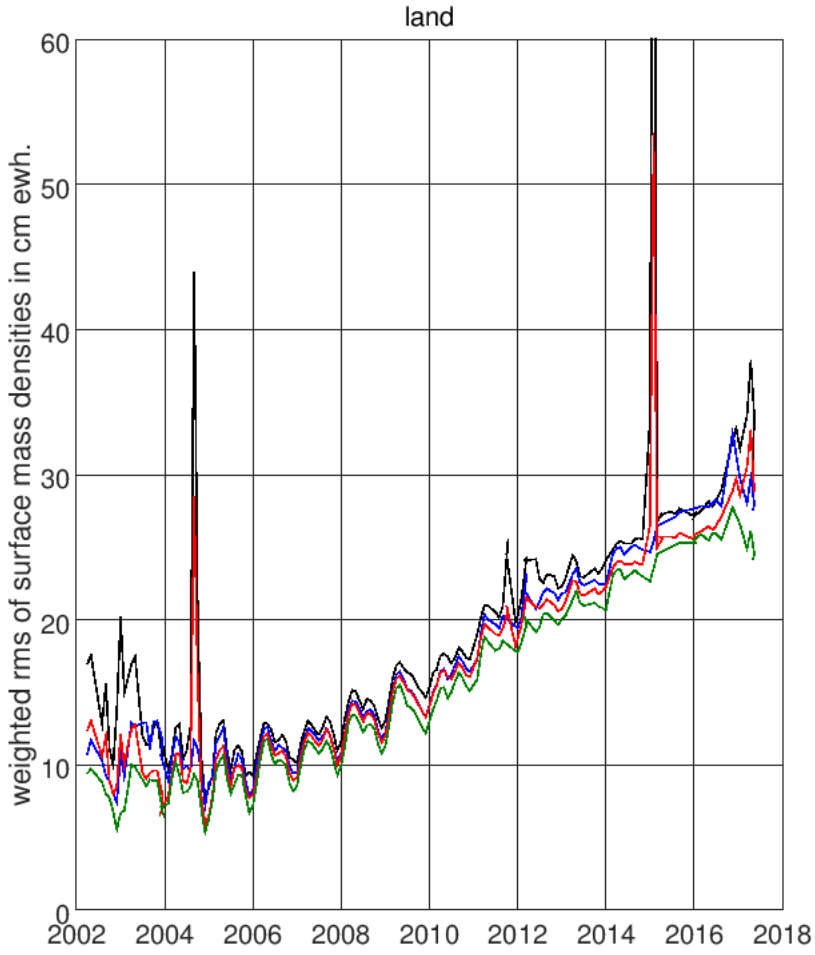
GRACE short repeat cycles



RMS over ocean/land

Ocean RMS improvement VDK vs. DDK median: VDK5 (16%), VDK4 (18%)





Conclusions

- Time variable decorrelation filter using the most accurate error (and signal) VCM proposed for GRACE (and GRACE-Follow-On) data in order to account for changing sensitivity
- Candidate filter method for GFZ Level 3 processing (cf. Dahle et al., EGU2018-17878, Poster on the new GFZ Level 3 web portal GravIS)
- Closed-loop simulation results show
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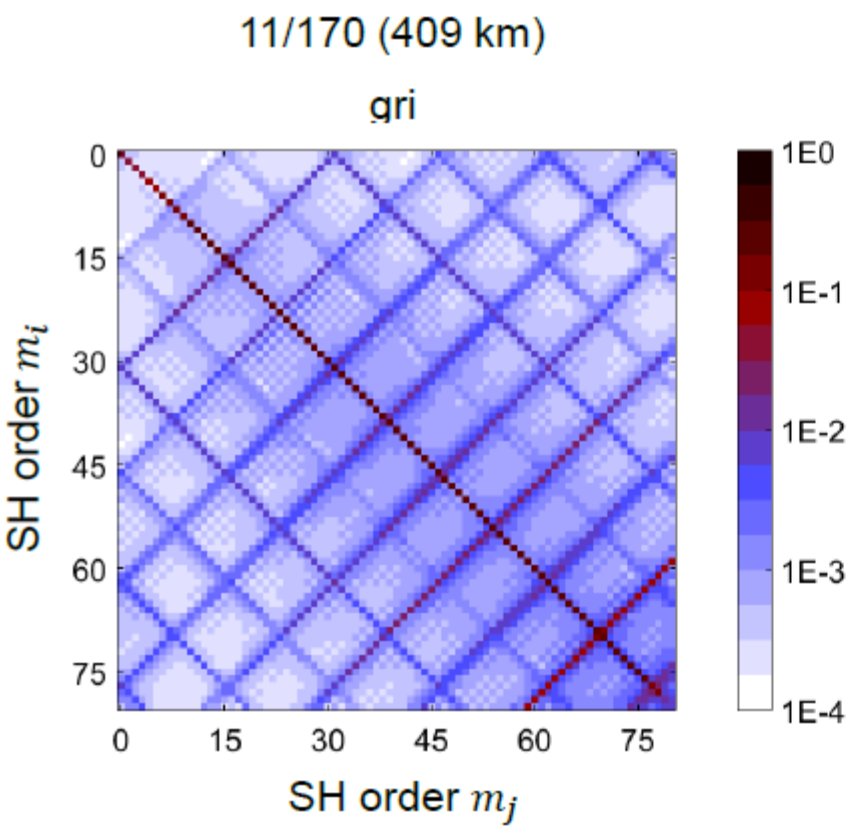
GRACE-like correlation RMS per SH order



Off diagonal correlations

- Parallel to main diagonal
  $m_i - m_j = \text{const.}$
- Perpendicular to main diag.
  $m_i + m_j = \text{const.}$

[Murböck et al., 2016, GSTM]

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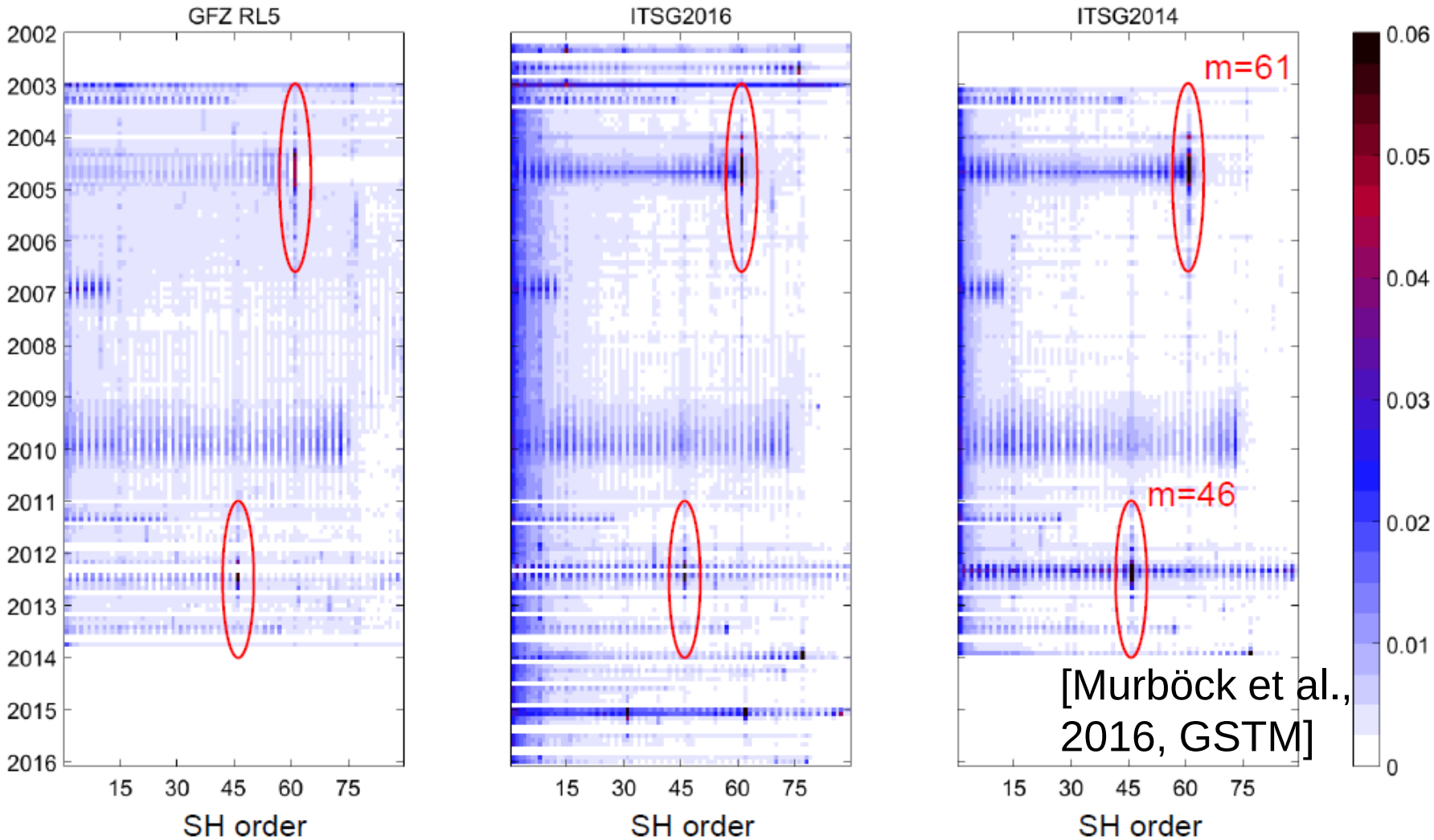
GRACE correlations, $m_i - m_j$ = const.



[Murböck et al., 2016, GSTM]

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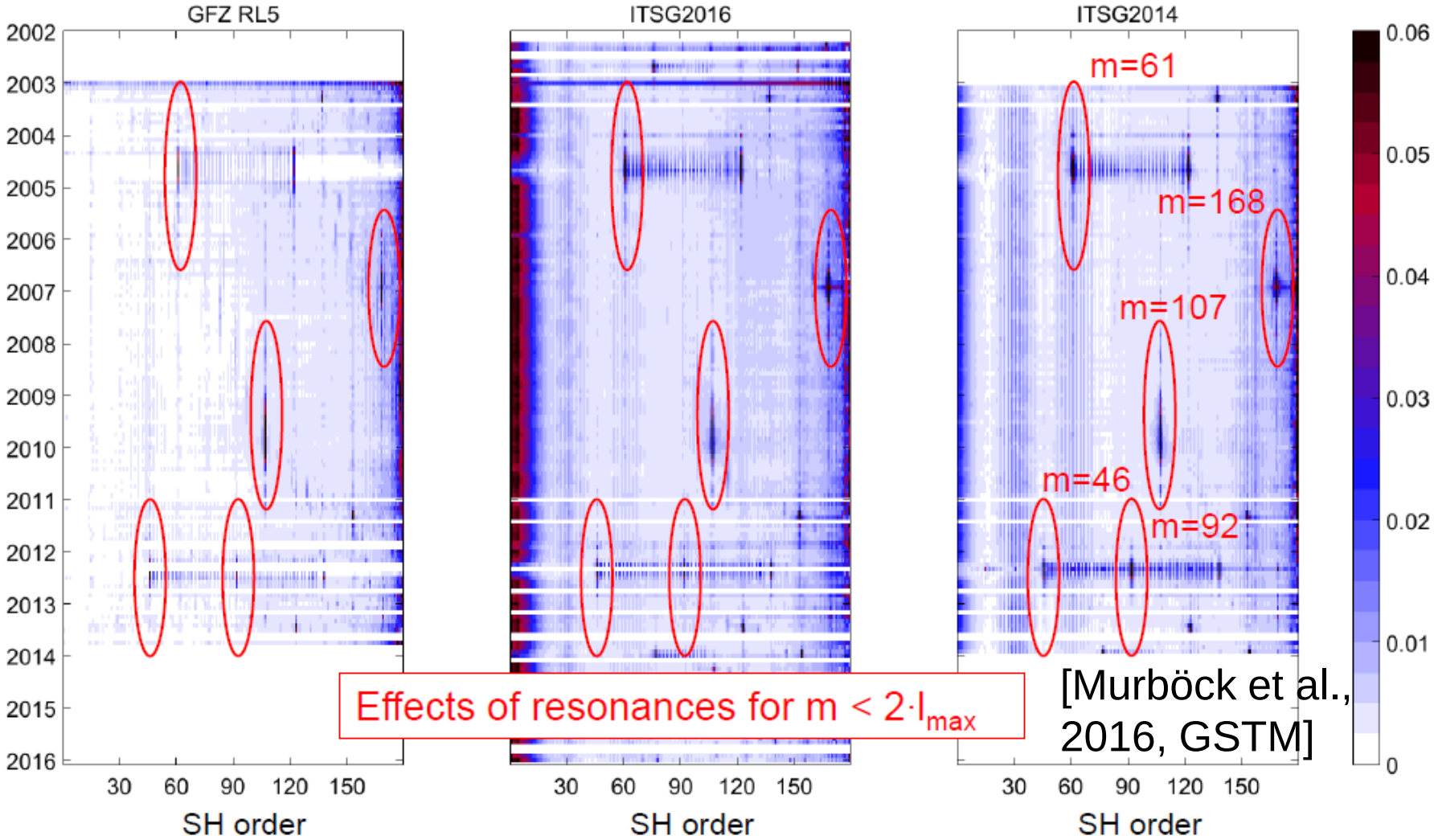
GRACE correlations, $m_i + m_j = \text{const.}$



Effects of resonances for $m < 2 \cdot l_{max}$

[Murböck et al., 2016, GSTM]