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1     **Inter-annual Water Storage Changes in the Aral Sea from Multi-mission Satellite**  
2                   **Altimetry, Optical Remote Sensing, and GRACE Satellite Gravimetry**

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7

8     **Abstract**

9     The estimation of water storage variations in lakes is essential for water resource management activities  
10    in a region. In areas of ungauged or poorly gauged water bodies, satellite altimetry acts as a powerful  
11    tool to measure changes in surface water level. Remote sensing provides images of temporal coastline  
12    variations, and a combination of both measurement techniques can indicate a change in water volume.  
13    In this study variations of the water level of the Aral Sea were computed for the period 2002-2011 from  
14    the combination of radar and laser satellite altimetry data sets over the lake. The estimated water levels  
15    were analyzed in combination with coastline changes from Landsat images in order to obtain a  
16    comprehensive picture of the lake water changes. In addition to these geometrical observations  
17    temporal changes of water storage in the lake and its surrounding were computed from GRACE satellite  
18    gravimetry. With respect to its temporal evolution the GRACE results agree very well with the  
19    geometrical changes determined from altimetry and Landsat. The advancing desiccation until the  
20    beginning of 2009 and a subsequent abrupt gain of water in 2009-2010 due to exceptional discharge  
21    from Amu Darya can clearly be identified in all data sets.

22  
23    **Key words:** Aral Sea, satellite altimetry, optical remote sensing, satellite gravimetry, GRACE, water  
24    mass variation.

25    **Running Title:** Water Storage Changes in the Aral Sea.

26 **1. Introduction**

27 Water stored in surface reservoirs (i.e. lakes and rivers) is the best accessible form for human  
28 consumption. But at the same time terrestrial surface water is one of the most uncertain components of  
29 continental hydrology with respect to its spatial and temporal distribution (Solomon et al., 2007). In this  
30 study we address the Aral Sea, a saline lake located in an arid zone of central Asia at 45° north and 60°  
31 east. Until 1960, it was the fourth largest lake worldwide after the Caspian Sea, Lake Superior and Lake  
32 Victoria (Zavialov, 2005). From then onwards it experienced a devastating decline, mainly due to  
33 diversion of water from its two primary inlet rivers the Amu Darya and the Syr Darya for agricultural  
34 purposes (Micklin, 1988; Bortnik, 1999; Crétaux et al., 2005).

35  
36 Temporal variations of the level and the surface extent of the water body are linked to the changes in  
37 water storage and can be traced in observations of satellite altimetry and in optical or radar remote  
38 sensing images. Unfortunately for several years, availability of continuous in-situ water level  
39 observations has been limited in this region. A few gauge stations are located upstream, but due to  
40 evaporation and infiltration from canals, which were built on sand without sufficient sealing, an  
41 unknown fraction of water runoff may be lost in-between the observation point and the lake (Froebrich  
42 & Kayumov, 2004). Satellite altimetry was designed to measure oceanic surface water height but has  
43 demonstrated its potential for estimating changes in the level of terrestrial water bodies as well (Morris  
44 & Grill, 1994; Birkett, 1995; Cazenave et al., 1997; Prigent et al., 2007; Getirana et al., 2009) and has  
45 already been used on the Aral Sea (Crétaux et al., 2005; Crétaux et al., 2008; Kouraev et al., 2008;  
46 Calmant et al., 2009). MODIS Terra images (250 meter spatial resolution) were used by Kravtsova  
47 (2005) to observe seasonal variations in the Aral Sea surface in spring and autumn for the period 2000-  
48 2004. Since the spatial extent of the affected region is large related changes of water mass can be

49 identified in observations of temporal variations of the Earth's gravity field from space. The dedicated  
50 satellite mission GRACE has been continuously monitoring gravity field variations since almost a  
51 decade at a spatial resolution of about 300 km and a temporal resolution of better than one month.  
52 GRACE satellite gravity data was used in many studies to estimate terrestrial water storage changes  
53 (Ramillien et al., 2005; Güntner, 2008; Seitz et al., 2008; Werth et al., 2009). Large parts of the gravity  
54 signal (tides, atmosphere, and oceans) are already removed during pre-processing; consequently the  
55 remaining signals mainly reflect changes in water storage in the region.

56

57 In our study we compare the results of geometrical and gravimetric space and in-situ observation  
58 techniques for the time frame between 2002 and 2011. The usefulness of the combination of  
59 heterogeneous data sets has previously been demonstrated for other surface water bodies, e.g. for the  
60 East African lakes (Becker et al., 2010), the Amazon (Frappart et al., 2008) or the Ganges (Papa et al.,  
61 2008). In Section 2 variations of the water level in the Aral Sea and its sub basins from satellite  
62 altimetry will be presented and discussed. Section 3 outlines the geometrical variations of the lake  
63 surface from optical remote sensing images from Landsat. In Section 4 we present time series of water  
64 storage changes from GRACE satellite gravimetry. The temporal evolution of the mass changes with  
65 respect to the development of the lake geometry is discussed in Section 5, and conclusions from the  
66 work are provided in Section 6.

67

## 68 **2. Changes in water level**

69 The present appearance of the Aral Sea is not unique in its entire history. The paleo-variability of the  
70 Aral Sea was characterized by similar fluctuations in the past forced by natural climate changes. But in  
71 contrast, the continuous severe decline of the lake level that started in the 1960s is primarily caused by

72 strong anthropogenic consumption (Boroffka et al., 2005; Zavialov 2005). Figure 1 shows a time series  
73 of the mean lake level in yearly intervals since 1780. Data between 1780 and 1960 (pre-desiccation  
74 time) has been collected by Rogov (1957), data between 1911 and 2006 has been published in the frame  
75 of the INTAS-0511 REBASOWS project (Nachtnebel et al., 2006).

76

77 **Fig. 1 here**

78

79 The curve shows a decline of a few meters twice in the 19<sup>th</sup> century. During the first half of the 20<sup>th</sup>  
80 century the lake surface remained on a stable height. But since the beginning of the 1960s an immense  
81 decrease of the lake level due to the expansion of an irrigation project that drained out its two major  
82 tributaries can be observed (Micklin, 1988). In 1986 the lake was split into two parts: the smaller North  
83 Aral Sea and the larger South Aral Sea. The South Aral Sea continued its shallowing while the level of  
84 the North Aral Sea fluctuated with the construction, demolition and re-construction of a dam between  
85 the two parts of the Aral Sea. In the 180 years between 1780 and 1960 the lake had experienced only  
86 fluctuations of smaller than 5 meters. On the contrary it faced a decline of more than 25m over the past  
87 50 years.

88

89 In this study we focus on the quantitative changes of the Aral Sea from spring 2002 until autumn 2011.  
90 Water level changes were determined from radar altimetry measurements from Jason-1, Jason-1  
91 extended mission (EM), Jason-2, Envisat, Envisat extended mission (EM) and GFO, complemented by  
92 laser altimetry measurements from Icesat (for details see Table 1). The radar altimeter satellites provide  
93 a significantly higher temporal resolution (10-35 days) than Icesat (91 days). On the other hand the  
94 laser altimeter Icesat provides more precise observations because of its smaller footprint (70-90m) and  
95 higher frequency. Data were obtained from the Open Altimetry Data Base (OpenADB) of the German  
96 Geodetic Research Institute (DGFI) at <http://openadb.dgfi.badw.de/>.

97 **Tab. 1:** Altimetry data used in this study.

Satellite	Agency	R.r.a (*) Diameter	Revisit	Pass Numbers	From	Until	Source
<b>JASON-1</b>	CNES, NASA	16 cm	10 days	142, 107, 218	January 2004	January 2009	<a href="http://sealevel.jpl.nasa.gov/missions/jason1/">http://sealevel.jpl.nasa.gov/missions/jason1/</a>
<b>JASON-2</b>	CNES, NASA	16 cm	10 days	142, 107, 218	July 2008	August 2011	<a href="http://sealevel.jpl.nasa.gov/missions/ostm-jason2/">http://sealevel.jpl.nasa.gov/missions/ostm-jason2/</a>
<b>JASON-1 extended mission</b>	CNES, NASA	16 cm	10 days	107	February 2009	August 2011	<a href="http://sealevel.jpl.nasa.gov/newsroom/spotlights/index.cfm?FuseAction=ShowNews&amp;NewsID=338">http://sealevel.jpl.nasa.gov/newsroom/spotlights/index.cfm?FuseAction=ShowNews&amp;NewsID=338</a>
<b>Envisat, RA2</b>	ESA	20 cm	35 days	0126, 0797, 0711, 0670, 0584, 0211, 0253, 0167, 0625,	January 2004	July 2010	<a href="http://envisat.esa.int/earth/www/object/index.cfm?fobjectid=3774">http://envisat.esa.int/earth/www/object/index.cfm?fobjectid=3774</a>
<b>Envisat extended mission</b>	ESA	20 cm	30 days	0139, 455, 0730, 0771, 0369, 0685,	October 2010	July 2011	<a href="http://www.esa.int/esaCP/SEM08O1OWUF_index_0.html">http://www.esa.int/esaCP/SEM08O1OWUF_index_0.html</a>
<b>GFO</b>	US Navy	16 cm	17 days	253, 156, 339, 425	January 2004	September 2008	<a href="http://ibis.grdl.noaa.gov/SAT/gfo/bmpcoe/default.htm/">http://ibis.grdl.noaa.gov/SAT/gfo/bmpcoe/default.htm/</a>
<b>IceSAT</b>	NASA	18 cm	91 days	2660, 0561, 0293, 0055, 0190, 0799, 0458, 0696, 0531,	January 2004	October 2009	<a href="http://icesat.gsfc.nasa.gov/icesat/">http://icesat.gsfc.nasa.gov/icesat/</a>

98 (\*) R.r.a = Retro reflector array

99

100 Heights are provided with respect to the geoid EGM2008 (Palvis et al., 2008). All observations were  
 101 corrected for atmospheric delay and geophysical effects using calibration models and/or onboard  
 102 measurements for ionosphere, dry troposphere, wet troposphere, and solid Earth tides (see Fu &  
 103 Cazenave, 2001 for details). Model based ionospheric corrections were applied since corrections based  
 104 on onboard radiometer data are not applicable over inland water bodies. All above mentioned missions  
 105 except GFO are equipped with a dual frequency system (Ku and C band) from which respective  
 106 corrections can be modeled. GFO observations were corrected by data from Global Ionosphere Maps  
 107 (GIM; Schaer et al., 1996). Wet tropospheric corrections are based on ECMWF (European Centre for  
 108 Medium-Range Weather Forecasts) data except for Jason 1 which was corrected by data from the JMR  
 109 (Jason-1 Microwave Radiometer) following Brown (2010). An ultra stable oscillator range correction  
 110 was applied to Envisat observations. Altimetry observations between December and March could be

111 affected by errors due to ice cover, since the reflection of the signal on ice differs significantly from  
112 reflections on open water (Kouraev et al., 2008). To prevent a contamination of the measurements by  
113 reflections from land, only observation points with a distance of more than 5 km from the coast were  
114 considered. For this purpose twice a year in spring and autumn water masks generated from Landsat  
115 data were applied in order to account for the continuous changes of the coastline. As a consequence less  
116 reliable altimetry observations are available (Fig. 2) during periods when the horizontal extent of the  
117 lake is small.

118

119 The east basin of the Aral Sea, for example, was observed in October 2009 by Icesat for the last time  
120 before the mission was retired in the same month. For almost half a year (November 2009 – June 2010)  
121 no observations from the east basin are available, while it has been observed very well in earlier years  
122 by Envisat, GFO, Icesat and Jason1 (Figs. 2 and 3). After October 2010 Envisat-EM was capable of  
123 providing some measurements over that part of lake (Fig. 2, right), however due to problems of Envisat  
124 over ice-covered regions only few of these observations are reliable. The west basin is inadequately  
125 observed especially in its northern part mainly because fewer passes are available in this region  
126 (Envisat/Envisat EM and few Icesat observations) and furthermore the lake is so narrow that most of  
127 the data points are rejected due to the 5 km criteria. The southern part of the west basin was well  
128 observed by GFO, Envisat and Icesat until 2010, but afterwards only observations from Jason1-EM and  
129 very few reliable data points from Envisat-EM are available. In general all basins have been sparsely  
130 observed by altimetry for the last three years, firstly because fewer missions are available (i.e. only  
131 Jason2, Jason1-EM and few Envisat-EM observations) and secondly because of the smaller extent of  
132 the lake.

133

134 **Fig. 2 here**

135

136 With these limitations, a multi-mission altimetry data combination provides maximum information on  
137 the development of the lake level. A best possible harmonization was reached between the different  
138 missions by selecting similar calibration models as far as feasible. An additional cross calibration of the  
139 range bias was applied by estimating a constant offset of each mission relative to the orbit of  
140 Topex/Posidon (Bosch & Savcenko, 2007). Inter and intra mission crossover analysis was done over the  
141 east and north basin where the passes of GFO, Icesat, Envisat and Jason1 are close enough to compare  
142 the calibrated data with respect to each other. A nominal ground track on geographically fixed segments  
143 was maintained by aggregating all observations within a 10 km radius to a mean value per cycle.

144

145 **Fig. 3 here**

146

147 Figure 3, shows the results of our multi-mission altimetry analysis for the different basins of the Aral  
148 Sea. Here we approximate the lake level of each basin as a flat surface, i.e. we do not distinguish  
149 between the various locations of the footprints within an individual basin. The observations show the  
150 picture of one of the worst environmental catastrophes by illustrating the drastic drop of the water level  
151 in the west and east basins. The observations of all missions agree very well to each other. Besides the  
152 trends all curves feature clear seasonal signals. Data from altimetry agree quite closely to annual in-situ  
153 observations from the previously mentioned INTAS-0511 REBASOWS project (Nachtnebel et al.,  
154 2006) and from observations collected during expeditions on the west basin (Zavialov 2010). In-situ  
155 observations are available until 2006 (North Aral Sea), 2007 (west basin) and 2009 (east basin) with  
156 one data point per year. Although an offset of about 50-70 cm exists between the altimetry missions and



157 in-situ observations, they follow the same trend. The reason for the offset could be a difference in the  
158 reference systems since all altimetry measurements refer to EGM2008 while the in-situ observations  
159 refer to the mean seal level of the Baltic Sea. Furthermore, the in-situ water levels are given as one data  
160 point per year with (except for the west basin) no information about the time of acquisition.

161

162 The most drastic changes in water level were observed in the South Aral Sea, i.e. the east and west  
163 basin. The east basin suffered nearly 3.5 m decline in eight years (2002-2009) while the level of the  
164 west basin fell by about 4 m. The curve of the North Aral is significantly different due to the  
165 construction of the Dike Kokaral dam in October 2005. After its completion the water level increased  
166 by about two meters within only half a year. The inflow from the Syr Darya revived the North Aral and  
167 led to a rather stable water level since 2006 with fluctuations of less than 1 m. On the other hand the  
168 construction of the dam accelerated the desiccation in the other two basins from 2006 as the dam cut off  
169 the South Aral Sea from the tributary Syr Darya. Only in the case of overflow of the North Aral Sea  
170 water from this river is diverted into the southern basins. The east basin reached the stage of drying up  
171 of most of its area in 2009 (which led to the previously mentioned non-availability of reasonable  
172 altimetry data until the lake level started to rise again in 2010). Jason-2 observations indicate that the  
173 lake had regained more than 0.5 m by the last seven months of 2010 as a consequence of exceptionally  
174 strong inflow from the Amu Darya (see Section 5). This increase of the lake level was followed by the  
175 normal seasonal decline in summer 2011. A clear seasonal variability of the lake level due to season-  
176 dependent inflow and evaporation is obvious for all basins.

177

178 **3. Changes in the lake surface area**

179 Changes in the coastline of the Aral Sea and therewith of the horizontal lake extent were derived from  
180 Landsat multi-spectral remote sensing data (30 m spatial resolution) for a month in spring and autumn  
181 every year from 2002 to 2011. Due to the high computational effort of the data analysis we restricted  
182 ourselves to two snapshots per year. However, during periods of special interest (see Fig. 5 and Section  
183 5) the coastline was also computed for some additional months in order to get a better insight into the  
184 temporal development of the lake extent. Precision and terrain corrected Landsat images were obtained  
185 from USGS Earth Explorer website (<http://earthexplorer.usgs.gov>). Three Landsat images were  
186 combined in order to cover the entire area of the Aral Sea. Due to the presence of clouds and data  
187 problems in the course of the image acquisition it was not always possible to obtain an image  
188 combination with all images acquired within one month. In such cases images of two subsequent  
189 months were taken into account (e.g. for the spring season images from April and March, or for the  
190 autumn season images from October and September) in order to produce a complete picture of the  
191 horizontal lake geometry.

192

193 Water absorption bands, i.e. short wave infra-red (SWIR), near infra-red (NIR) and middle infra-red  
194 (MIR) bands of Landsat images were stacked. The three Landsat images per date were mosaicked to a  
195 complete map of the Aral area. The mosaicked images were then classified with a maximum likelihood  
196 supervised classifier (MLC) to generate a water mask. The MLC was trained by the a priori knowledge  
197 of the spectral signature of water and non water classes. In the course of this training step the  
198 variance/covariance matrix of the training site classes is calculated. Based on Bayesian statistics the  
199 probability of a pixel belonging to the class is estimated. A pixel is assigned to the class which has the  
200 highest probability. Accuracy assessments of the classified images were done by a confusion/error

201 matrix formed by reference data in columns and classified data in rows. In this study an original image  
202 was used in place of reference data, and pixels from stratified random sampling were verified visually.  
203 The producer accuracy for all classified images was found to be between 85 to 90%. This value  
204 indicates how well a certain area is classified. It is computed by dividing the number of pixels of the  
205 reference class that were correctly classified with the total number of pixels of that reference class. The  
206 classified image was then transformed into a boolean image in order to obtain the water mask.

207

208 A few Landsat images feature striping errors due to a failure of the scan line corrector (SLC) that led to  
209 a permanent data loss ([http://landsat.usgs.gov/products\\_slc\\_off\\_data\\_information.php](http://landsat.usgs.gov/products_slc_off_data_information.php)). In the used  
210 spectral bands (bands 3, 5 and 7) a SLC gap has a maximum width of 14 pixels. In order to avoid  
211 negative effects on the extracted water boundary by applying a destriping algorithm (e.g., a low pass  
212 convolution filter) we preferred to fill the scan gaps with data for the same location from the closest  
213 cycle. In most of the cases this substitution of data decreased the scan line gap to 2-3 pixels, which can  
214 be filled by simple low pass filter without a strong effect on the boundary lines. In few severe cases,  
215 when a close cycle was not available (e.g. due to clouds), the classified images have been digitized and  
216 edited manually to generate a polygon vector layer. The area under water was subsequently calculated  
217 from each of the generated seasonal masks. Figure 4 shows the drastic changes in the extent of the Aral  
218 Sea during the analyzed period. Between spring 2002 and autumn 2009 a clear signal of desiccation is  
219 visible. This decline is followed by a significant increase of the lake extent reaching its maximum  
220 revived stage between autumn 2010 and spring 2011. This period is followed by substantial decline  
221 until the end of our data set.

222

223 **Fig 4 here**

224

225 During spring the area under water is generally larger due to substantial inflow of melt water from the  
226 tributaries of the lake (Kravtsova, 2005) and relatively low evaporation during the winter months. On  
227 the contrary, strong evaporation during the summer months and a cooling of the lake towards autumn  
228 lead to lower water levels in the second half of the year. Figure 5 shows the temporal evolution of the  
229 lake surface area with respect to spring 2002 for the entire lake and separately for its sub-basins. The  
230 seasonal changes of the lake surface area are obvious in all curves.

231

232 **Fig 5 here**

233

234 In 2002 the Aral Sea consisted of two completely separated sub-basins, the North Aral Sea and the  
235 larger South Aral Sea. The latter was later divided into two parts (west and east basin), connected by a  
236 narrow channel. The shrinking rate of the Aral Sea is largest in the east basin, while a negative trend  
237 can also be seen for the west basin. The curve for the surface area of the North Aral Sea shows a stable  
238 geometry with normal seasonal variations after an increase due to the construction of the dam in  
239 2005/2006. Thus it matches the characteristics of the corresponding curve of the lake level (Fig. 3). The  
240 west basin suffered comparatively little loss in area over the first eight years of our analysis (2002-  
241 2009), but it also does not show any significant increase in size in 2010 where the signal of re-flooding  
242 can clearly be observed in the east basin. This relative stability of the area of the west basin can be  
243 explained by its steeper coastline (Zavialov, 2005). Some inflow from ground water (Jarsjo, 2004) also  
244 compensates the water loss by evaporation to a certain extent. Overall, the east basin, being quite  
245 shallow (Roget et al., 2009), experienced the largest changes of coastline and surface area over the  
246 analyzed period. After the erection of the Dike Kokaral dam it was cut-off from its former tributary Syr

247 Darya (see above). An especially rapid decrease of the surface area of the east basin was observed in  
248 2006. This strong reduction of the lake size can be attributed to increased evaporation due to high  
249 temperature anomalies between 1-3°C and very dry conditions in the region during this year (Arguez,  
250 2007) in combination with almost no water inflow from the Amu Darya in 2006 (see Fig.8).

251

252 The Aral Sea as a whole suffered 62% area loss within eight years (spring 2002 - autumn 2009), out of  
253 which the east basin contributes the largest fraction: With respect to its extent in spring 2002 only 6%  
254 were left in autumn 2009. With the shrinking of the lake salt crusts of up to 2-10 km width formed  
255 along the coast (Kravtsova & Tarasenko, 2010). The boundary of this moist salty surface changes its  
256 shape frequently, especially in the shallow east basin. Once the crust dries up it is eroded by strong  
257 winds that are prevalent in the region. As a consequence the topography of the land that has fallen dry  
258 changes quickly due to the salty dust storms. This explains why during the refilling in April 2010 the  
259 lake did not regain a similar same shape as it had before although it nearly reached the same surface  
260 area (52% of the area of spring 2002) as it had in autumn 2008 (Fig. 5).

261

#### 262 **4. Mass changes in the region of the Aral Sea observed from by GRACE**

263

264 Ongoing changes of sea surface area and height are associated with strong variations of water mass  
265 being stored in the individual basins. These storage changes map into satellite-based observations of  
266 temporal variations of the Earth's gravity field as they are provided from the dedicated satellite gravity  
267 field mission GRACE (Gravity Recovery And Climate Experiment) (Tapey et al., 2004; Wahr et al.,  
268 2004). Several previous studies have shown the potential of GRACE observations for the estimation of  
269 hydrological storage variations in continental regions (e.g., Ramillien et al., 2008; Schmidt et al., 2008;  
270 Seitz et al., 2008). Due to the characteristics and height of the GRACE orbit, meaningful results are  
271 restricted to regions not smaller than 200.000 km<sup>2</sup> (Swenson and Wahr, 2007). At this scale the  
272 maximum temporal resolution amounts to approximately one month. The coarse resolution of GRACE  
273 prevents the assessment of water storage for each individual sub basin of the Aral Sea from satellite  
274 gravimetry. Instead we provide quasi-monthly estimates of water mass variability within the region  
275 confined by the minimum and maximum latitudes of 43.5 °N and 47.5 °N and by the minimum and  
276 maximum longitudes of 58 °E and 62 °E respectively. This quadrangle comprises the area of the Aral  
277 Sea in its historic dimensions and thus the entire region affected by desiccation over the past decades.  
278 Its surface area amounts to 220.000 km<sup>2</sup>. Even though this study region is much larger than the present  
279 surface of the Aral Sea it can be assumed that the prominent part of mass variations on long (i.e. inter-  
280 annual) time scales originates from the long-term storage change of water in the Aral Sea. Other sources  
281 of water storage variations in its surrounding area (e.g. variations in groundwater, soil moisture or snow  
282 cover) are expected to predominantly result in seasonal variations. Therefore we interpret the GRACE  
283 signal reduced by seasonal components as an approximation of the long-term water storage in the Aral  
284 Sea.

285

286 Our GRACE analyses are based on quasi-monthly sets of spherical harmonic coefficients of the Earth's  
287 gravity field (GRACE Level-2 data) as provided by the GFZ German Research Centre for Geosciences  
288 and the Center for Space Research (CSR), USA, in its well-established latest releases RL04 (Flechtner  
289 et al., 2010; Bettadpur, 2007). Mass redistributions on sub-monthly time scales (e.g. due to Earth and  
290 ocean tides, atmospheric pressure variations and ocean circulation) would lead to alias effects of the  
291 gravity estimates from GRACE in the course of the inversion of the GRACE monthly gravity field  
292 solutions. Therefore, those effects are reduced from the GRACE observations already during pre-  
293 processing using respective background models; see Flechtner (2007) for details. For continental non-  
294 polar regions the largest part of the remaining gravity field changes provided in the monthly Level-2  
295 GRACE products is assumed to reflect mass redistributions within the continental hydrology.

296

297 We analyze monthly GRACE gravity field solutions covering the time span from April 2002  
298 (CSR)/August 2002 (GFZ) until July 2011. Due to orbit maneuvers and data problems, few individual  
299 months are unavailable. Variations of the gravity field are computed with respect to a long-term mean,  
300 i.e. the mean GRACE gravity field over the entire time span. In a spherical harmonic synthesis the  
301 coefficients of the residual monthly solutions complete up to degree and order 60 are converted into  
302 geographical grids of so-called equivalent water height (EWH) variations (Wahr et al., 1998). EWHs  
303 mean an idealized representation of surface mass densities in terms of a thin water layer that needs to be  
304 added to (or removed from) the Earth's surface. By expressing GRACE-derived gravity field changes in  
305 changes of the thickness of a water layer, it is implicitly assumed that the total observed gravity signal  
306 is caused by variations of water storage. The accuracy of the EWH estimates from GRACE is assumed  
307 to be 1-2 cm, depending on region and size of the study area (Swenson et al., 2003; Wahr et al., 2006).

308

309 Mission-specific errors in the GRACE Level-2 data that show up as meridional stripes in maps of  
310 gravity field variations have to be treated in the course of the conversion of the gravity field coefficients  
311 into EWH variations. Those errors emerge from satellite orbit characteristics and measurement  
312 limitations which result in an in-ability to separate spherical coefficients at all degrees and orders, in  
313 particular near orders of resonant coefficients. In addition un-modelled mass fluctuations on sub-  
314 monthly timescales (see above) cause high-frequency aliasing. In order to minimize the effects of these  
315 errors on the solutions of monthly EWH variations algorithms for smoothing and destriping are applied.  
316 In our study we follow the widely used procedures described by Swenson and Wahr (2006) and Wahr et  
317 al. (1998), in which correlated errors in the gravity field coefficients are reduced by a least squares  
318 polynomial filter and noisy short wavelength components are smoothed using an isotropic Gaussian  
319 filter with a half-width of 300 km. As a consequence of Gaussian smoothing, leakage effects from  
320 strong mass signals outside of our region of interest emerge (Baur et al., 2009; Swenson and Wahr,  
321 2007). In order to eliminate this contamination of the mass signal within the Aral region, leakage effects  
322 from the surrounding area are forward modelled using the WaterGAP Global Hydrology Model  
323 (WGHM; Döll et al., 2003) on which the same Gaussian filter is applied. The resulting leakage signal is  
324 subsequently reduced from the GRACE signal in the study area. A final correction step accounts for the  
325 attenuation of the mass signal as a consequence the spherical harmonic truncation at degree and order  
326 60 and the Gaussian smoothing. In order to derive meaningful values, the GRACE signal amplitude  
327 needs to be rescaled. Following the procedure outlined by Swenson and Wahr (2007) a simulated water  
328 layer of 1 cm within the study region was developed into spherical harmonic coefficients up to degree  
329 and order 60. Taking into account the filter procedure described above, these coefficients were applied  
330 in a spherical harmonic synthesis in order to reconstruct the water height in the study region. The



331 relation of the simulated and the mean of the reconstructed water height (i.e. 1 cm vs. 0.38 cm) let us  
332 conclude that the GRACE signal is attenuated by a factor of 2.6. Therefore each value of the grid is  
333 multiplied by this factor. We compare the result of our own GRACE Level-2 data analysis from GFZ  
334 and CSR with a result based on publicly available spherical harmonic coefficients based on GFZ RL04  
335 data that have been de-correlated using the filter DDK1 after Kusche et al. (2009). These coefficients  
336 are provided by the International Centre for Global Earth Models (ICGEM) at [http://icgem.gfz-](http://icgem.gfz-potsdam.de/ICGEM)  
337 [potsdam.de/ICGEM](http://icgem.gfz-potsdam.de/ICGEM).

338

339 **Fig 6 here**

340

341 Figure 6 displays the rescaled results of the GRACE analysis in the study area. Water mass variations  
342 (provided in units of km<sup>3</sup>) are derived by multiplying the surface area of the region with monthly  
343 averages of the gridded EWH residuals. The dashed curves show the complete GRACE signal in quasi-  
344 monthly time steps from the GFZ, CSR and DDK1 solutions respectively. The bold solid curve  
345 represents the mean of the three solutions and the thin solid curve is the long-term component of this  
346 mean curve, i.e. a composite seasonal cycle is removed. The results of the two approaches based on the  
347 GFZ data agree very well whereas the curve computed from CSR data shows larger discrepancies  
348 especially during the second half of the study period. This lets us conclude that the spread of the results  
349 is dominated by the different processing strategies at GFZ and CSR rather than on the different  
350 approaches for the conversion of the Level-2 data into EWH variations.

351

352 Besides a pronounced annual cycle the GRACE signal indicates a clear long-term mass loss between  
353 2005 and 2008. The effect of the previously mentioned anomalous warm and dry conditions of the year

354 2006 (cf. Section 3) can also be identified in the observations of GRACE that indicate a strong decrease  
355 of water storage during summer 2006. From the end of 2009 until mid-2010 the GRACE observations  
356 indicate a strong increase of mass in the Aral region which is followed by a rapid decline to the  
357 previous level.

358

359 Between mid-2005 and the end of 2008 approximately 60 km<sup>3</sup> of water mass were lost in the study  
360 area. In a rough calculation we relate this mass loss to a change of the water level given the mean  
361 surface areas of the lake in 2005 (around 18.000 km<sup>2</sup>) and in 2009 (about 10.000 km<sup>2</sup>) (cf. Fig. 5). For  
362 simplicity we take 14.000 km<sup>2</sup> as a mean value of the lake's surface area during this period. For this  
363 horizontal extent the observed mass loss of 60 km<sup>3</sup> of water corresponds to a sea level change of about  
364 4.3 m which coincides well with the observations from satellite altimetry (Figs. 5 and 6). Since the  
365 actual lake geometry is much more complex this estimate can of course only be viewed as a rough  
366 plausibility check. Due to its integrative nature the GRACE signal also contains contributions from  
367 other mass changes (e.g. due to surface or groundwater variations) in the proximity of the lake whose  
368 magnitude and origin are widely unknown. Especially during periods, when the spatial extent of the  
369 lake is small (i.e. when the largest part of our GRACE study area is not covered by water), the relative  
370 contribution of mass changes from other sources is increased. Due to the limited spatial resolution of  
371 GRACE this problem cannot be solved by a stepwise adaptation of the size of the study area to the  
372 respective extent of the lake. For a more precise estimation of the contribution of the lake water change  
373 to the GRACE signal volume variations of the lake can be computed considering its actual bathymetry  
374 (Crétaux et al, 2005). But since the bathymetry of the lake has been shown to be subject to considerable  
375 changes resulting from the previously mentioned dust storms such computations are a challenging task  
376 for future research (see Section 6) and beyond the scope of the present paper.

377

378 **5. Discussion:**

379 Figure 7 shows the mean curve of the GRACE solutions with the temporal change of the surface area of  
380 the entire Aral Sea (bold solid line from Fig. 5). In this figure only values for those GRACE months are  
381 displayed for which the surface area has been computed. Both curves clearly resemble each other in  
382 terms of inter-annual and seasonal variations and the correlation coefficient between the curves  
383 amounts to 0.74. The characteristics of both curves match well between 2004 and 2008, but the  
384 agreement is less good during the first two and the last two years of our analysis. While the minima of  
385 the GRACE curve in the autumn of 2008, 2009 and 2010 reach very similar values, the curve of the  
386 surface area as well as the time series of the water level (see Fig.3) feature a clear minimum in autumn  
387 2009. However it has to be kept in mind that GRACE is sensitive not only for variations of water mass  
388 within the lake but also for the integral effect of all mass changes in the surrounding of the Aral Sea.

389

390 In the Priaralie region, i.e. the region compassing the mouths of the two rivers Amu Darya and Syr  
391 Darya, a significant fraction of the incoming water is diverted before it reaches the lake. This holds  
392 especially for the region of the very large Amu Darya delta. A part of the diverted water subsequently  
393 evaporates or is accumulated as groundwater around the Aral Sea (Nezlin et al., 2004). In either case its  
394 positive or negative mass effect affects the GRACE signal in our study region but it is not reflected in  
395 the observations of the lake geometry.

396

397 **Fig 7 here**

398

399 In order to study the effect of the surrounding area, data on the water delivery from both rivers into the

400 Aral Sea and its delta were analyzed that is provided by the INTAS-0511 REBASOWS project  
401 (Nachtnebel et al., 2006) on the website <http://www.cawater-info.net>. In Fig. 8 variations of the lake  
402 surface area and the mass changes from GRACE are compared with in-situ water discharge  
403 observations from Amu Darya and Syr Darya. Discrepancies between the curves of the surface area and  
404 the mass signal occur mainly during periods of strong inflow from the Amu Darya into the Aral Sea.

405

406 **Fig 8 here**

407

408 GRACE shows a minimum of water mass by the end of 2008. During this time almost no discharge was  
409 observed at both rivers. Some discharge of Syr Darya in the beginning of 2009 increased the water level  
410 of the North Aral Sea that had reached its minimum stage by the end of 2008 (Fig. 3). In summer 2010  
411 an abnormally increased discharge into the Aral Sea was observed at Amu Darya. This flood led to the  
412 strongest increase of the lake level and extent during our study period. A time lag of few months is  
413 obvious between the GRACE curve and the lake water extent. Again this can be explained by the  
414 sensitivity of GRACE for signals from the adjoining region. The usual strong intra-annual shrinking of  
415 the lake (i.e. lower water levels in autumn than in spring) cannot be observed in 2010 because of the  
416 exceptional water inflow from Amu Darya during summer 2010. The lake has experienced a similar  
417 anomaly of the annual cycle in 2003 where relatively strong inflow (the second largest amount in our  
418 study period) also attenuated the usual minimum in autumn. Also here a comparable phase difference  
419 between GRACE and the lake extent is visible.

420

421 In general there is a very good agreement between the curve of the discharge measured at the Syr Darya  
422 gauge station and the GRACE signal. Since the GRACE study area covers a large part of the region east

423 of the Aral Sea through which the Syr Darya is passing, GRACE is sensitive to the water transport of  
424 the river and hydrological processes (evaporation, infiltration, water management) in this region. In  
425 particular during the first seven years the inter-annual signal component of both time series (i.e. the  
426 increase from 2002 to 2005 and the decrease between 2005 and 2008) matches in both curves. For the  
427 last years of our analysis the GRACE time series has mainly been influenced by the exceptional water  
428 transport from Amu Darya.

429 In 2010 GRACE observed a decrease in mass between April and September. On the other side a  
430 significant refilling of lake was ongoing during this period due to the strongest inflow from the Amu  
431 Darya during the whole study period. Between August and November 2010 the discharge curve  
432 dropped back to its previous low level. The GRACE curve precedes the discharge curve of Amu Darya  
433 by two to three months. This can also be seen in other years with strong discharge from Amu Darya  
434 (e.g. 2003). Since the Amu Darya is passing through the Kara-Kum desert a large amount of surface  
435 water is lost due to seepage which is accompanied by the accumulation of groundwater along the river  
436 bed and around the Aral Sea (Nezlin et al., 2004). It is assumed that in the case of strong runoff from  
437 Amu Darya aquifers around the Aral Sea are filled before the water reaches the lake and thus influence  
438 the observations of GRACE.

439

440 **Fig 9 here**

441 Figure 9 relates the lake area to mass changes from GRACE. Data points are taken from Fig. 7. The line  
442 shows a best fit estimate that has been computed in a least squares adjustment procedure. A statistically  
443 significant linear relationship indicates the link between the GRACE mass estimates and the Aral Sea  
444 water surface at the inter-annual scale.

445

446

447 **6. Conclusions**

448

449 The combination of multi-satellite data of the Aral region allows for a comprehensive study of the  
450 hydrological conditions in this area. Satellite altimetry, remote sensing, and satellite gravimetry provide  
451 information on various aspects of the ongoing storage changes in the Aral Sea and its basins that are  
452 largely related to anthropogenic activities. While satellite altimetry and remote sensing data allow for  
453 an accurate assessment of a three dimensional geometrical change of the lake surface, satellite  
454 gravimetry is capable of observing the related variations of water mass. Even though the spatial  
455 resolution of geometrical and gravimetric observations is very different, both types of observations  
456 provide valuable and unique information on different aspects of the hydrological situation.

457 The observations revealed that the impact of desiccation on the lake geometry is most severe in the  
458 comparatively shallow east basin. The completion of the Dike Kokaral dam resulted in a splitting of the  
459 smaller North Aral Sea from the larger South Aral Sea. While the dam led to a stabilization of the water  
460 level of the north basin, the south basin suffered an increased desiccation since it was cut off from the  
461 tributary Syr Darya, and the water discharge from the Amu Darya was too low (especially during 2006-  
462 2009; see Fig. 8) to compensate for the high rate of evaporation due to its very large size. Since the  
463 deeper west basin is characterized by a steeper coastline, the horizontal shrinkage of the west basin is  
464 comparatively low while the water level varies significantly. The patterns of desiccation and subsequent  
465 refilling observed by the geometrical observation techniques are also clearly visible in the GRACE  
466 satellite gravimetry data. However due to the small size of the lake a direct comparison of observed  
467 mass variations and the lake geometry is very difficult since the GRACE signal is strongly affected by  
468 the variability of the water mass in the adjoining area.

469 Therefore we aim at an independent computation of mass variations from water volume changes in a

470 next step of our project. In a geometrical approach time-variable masks of water surface extent from  
471 Landsat shall be intersected with a high-resolution DEM, using satellite altimetry as vertical constraint.  
472 This way volume changes from geometrical observation techniques and mass change from gravity field  
473 observations can be compared qualitatively which will also allow for an improved assessment of the  
474 influence of hydrological mass variations in the proximity of the lake. The study has shown that all  
475 applied data sets correspond well with respect to their temporal development. Therefore multi-satellite  
476 approaches can be seen as a very promising method for the analysis of hydrological processes also in  
477 regions that are poorly monitored by in-situ observations.

478

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484

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609 **Figure captions**

610 **Fig. 1:** Water level changes in the Aral Sea (1780-2006).

611 **Fig. 2:** Passes of different satellite altimetry missions over the Aral Sea in (A) March 2002, (B) November 2009  
612 and (C) September 2011.

613 **Fig. 3:** Water level changes in the (A) east basin, (B) west basin and (C) North Aral Sea from multi-mission  
614 altimetry and in-situ observations.

615 **Fig. 4:** Change of the Aral Sea surface area during the study period from Landsat images.

616 **Fig. 5:** Percentage change of the surface area of the Aral Sea and its basins with respect to March 2002. At this  
617 reference, the respective absolute values of the surface extent amounted to 20,370 km<sup>2</sup> (whole Aral Sea), 2,850  
618 km<sup>2</sup> (North Aral Sea), 4,660 km<sup>2</sup> (west basin), and 12,860 km<sup>2</sup> (east basin). The vertical black line indicates the  
619 construction of the Dike Kokaral dam.

620 **Fig. 6:** Variations of equivalent water mass in the Aral region from GRACE satellite gravimetry. Dashed curves:  
621 three different GRACE solutions; solid bold curve: mean of the three solutions; thin solid curve: mean long-term  
622 signal (solid bold curve reduced by seasonal variations).

623 **Fig. 7:** Mass change in the Aral region from GRACE (solid; left axis) in comparison with the total Aral Sea  
624 surface area from Landsat (dashed; right axis) for corresponding epochs.

625 **Fig. 8:** Monthly discharge from Amu Darya and Syr Darya into the Aral Sea (lower panel) in comparison with  
626 the mass change observed by GRACE (upper panel; left axis) and the total Aral Sea surface area (upper panel;  
627 right axis).

628 **Fig. 9:** Quantitative comparison between the total Aral Sea surface area and GRACE mass change (data taken  
629 from Fig. 7).

630

631

Figure 1

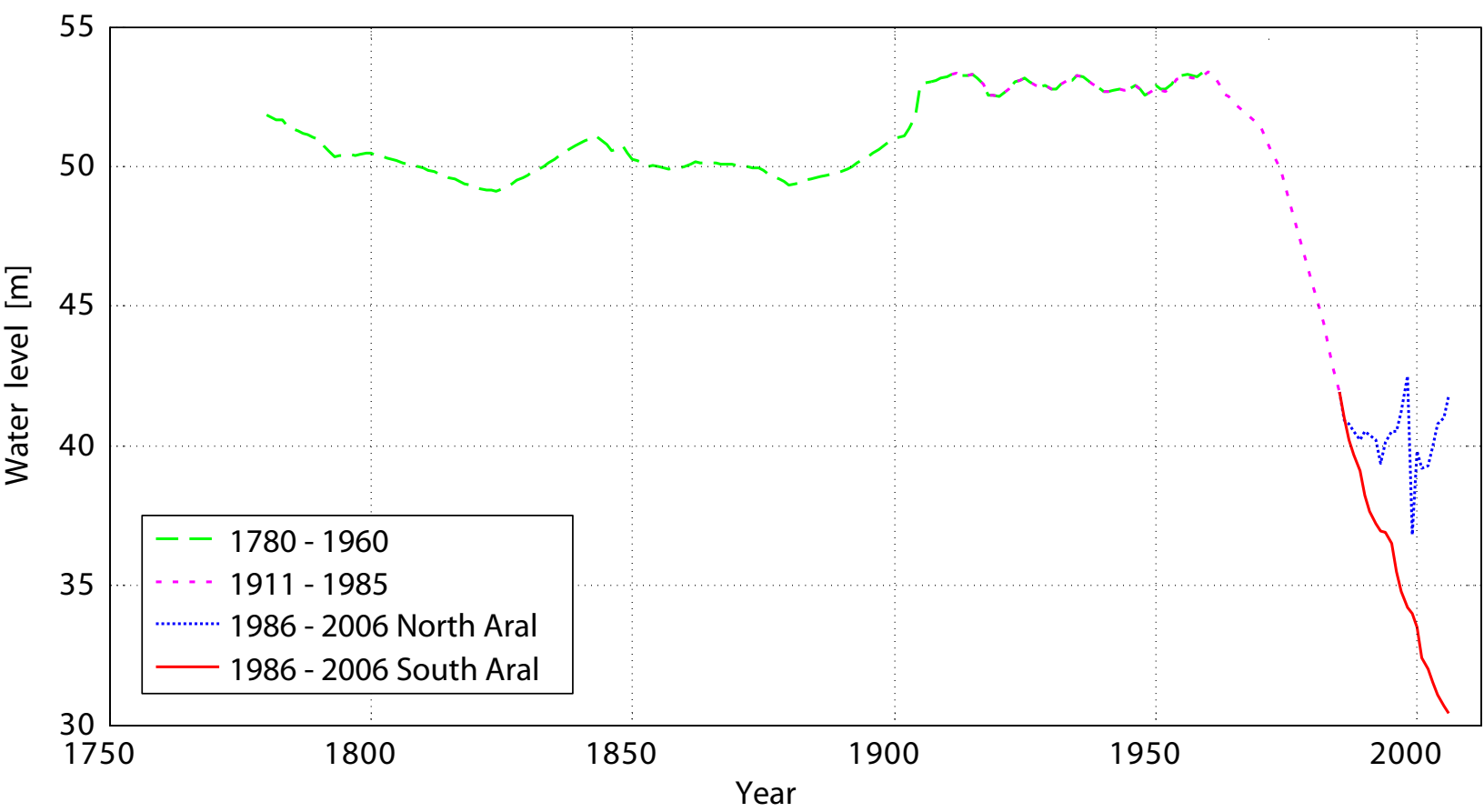


Figure 2

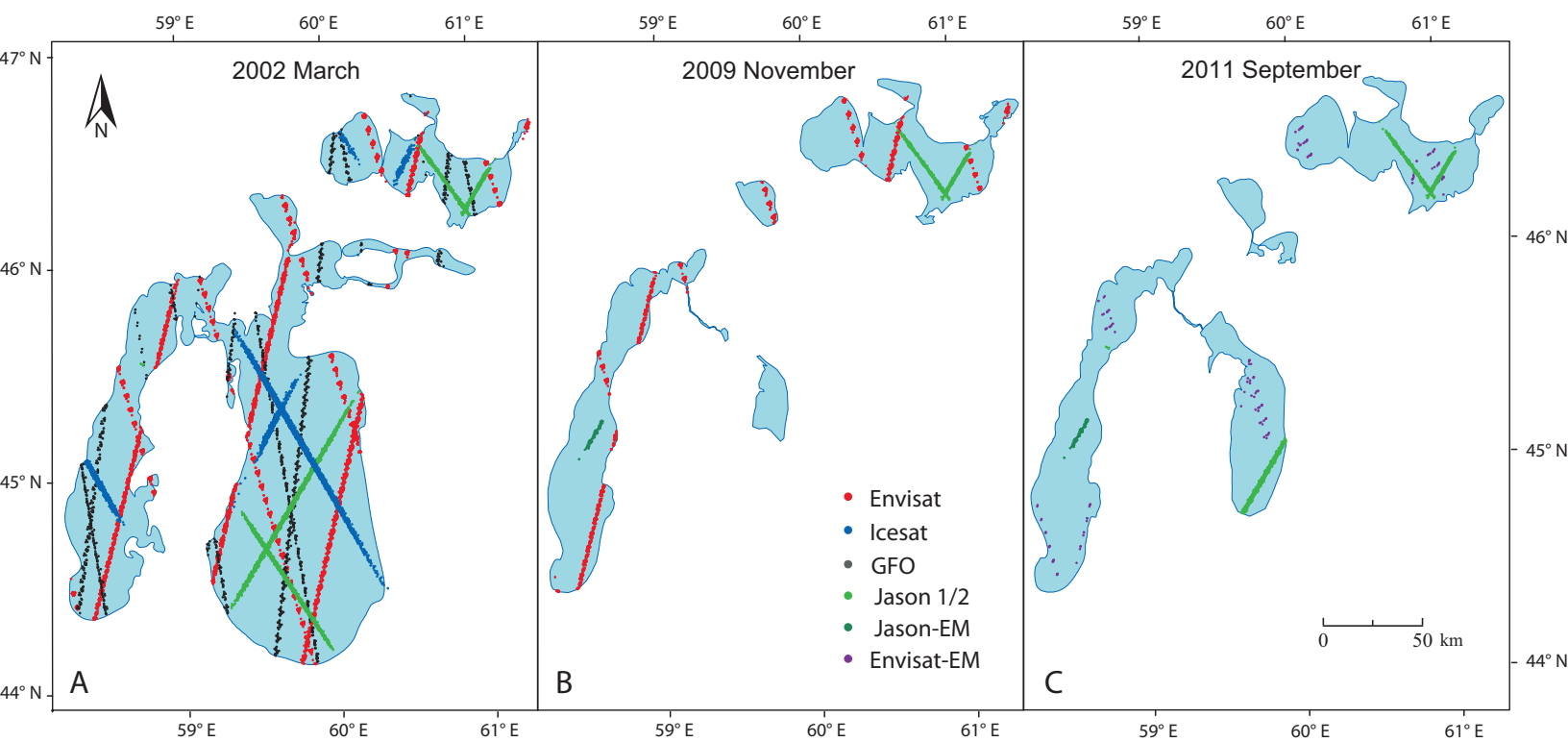


Figure 3

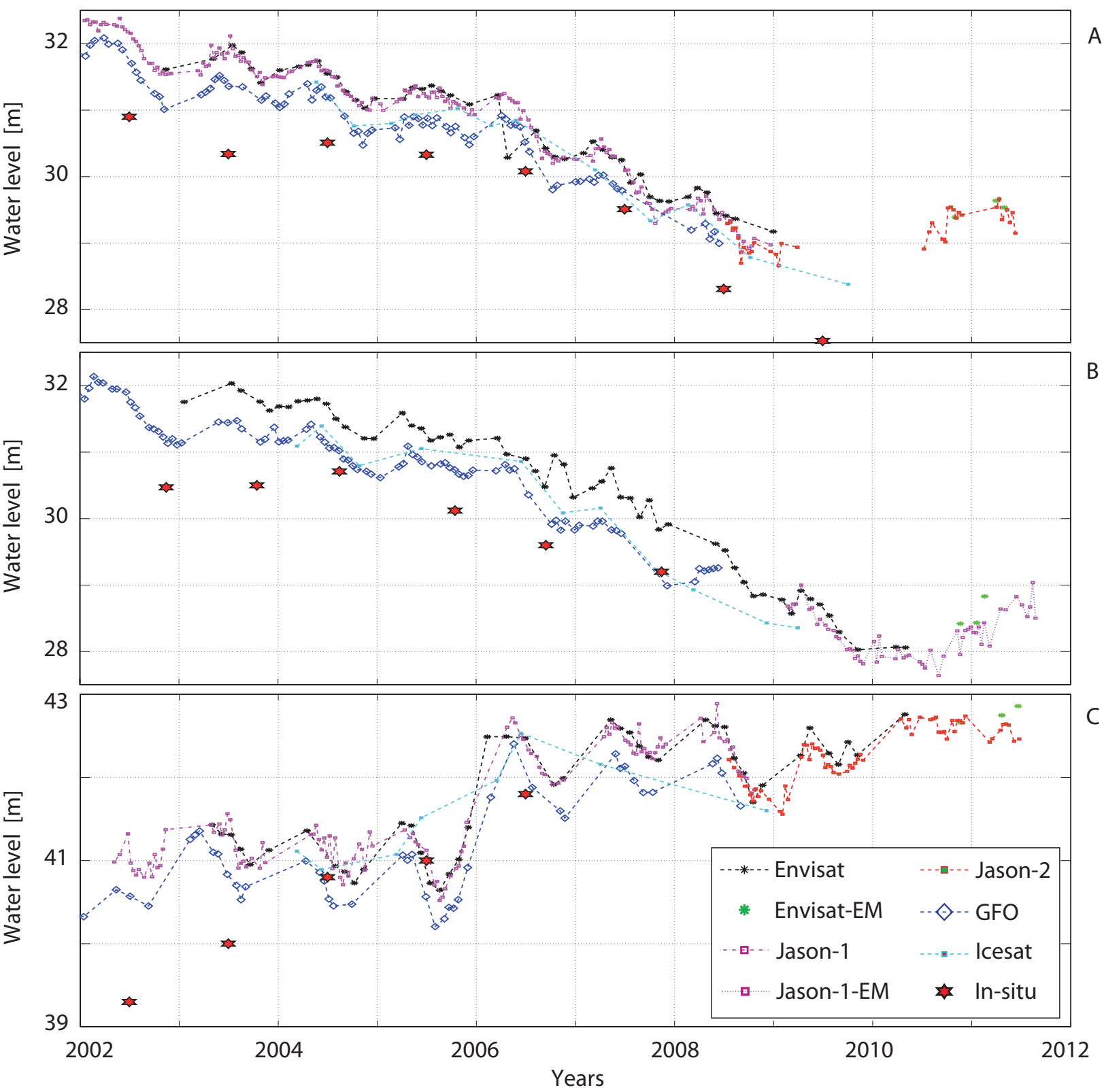


Figure 4

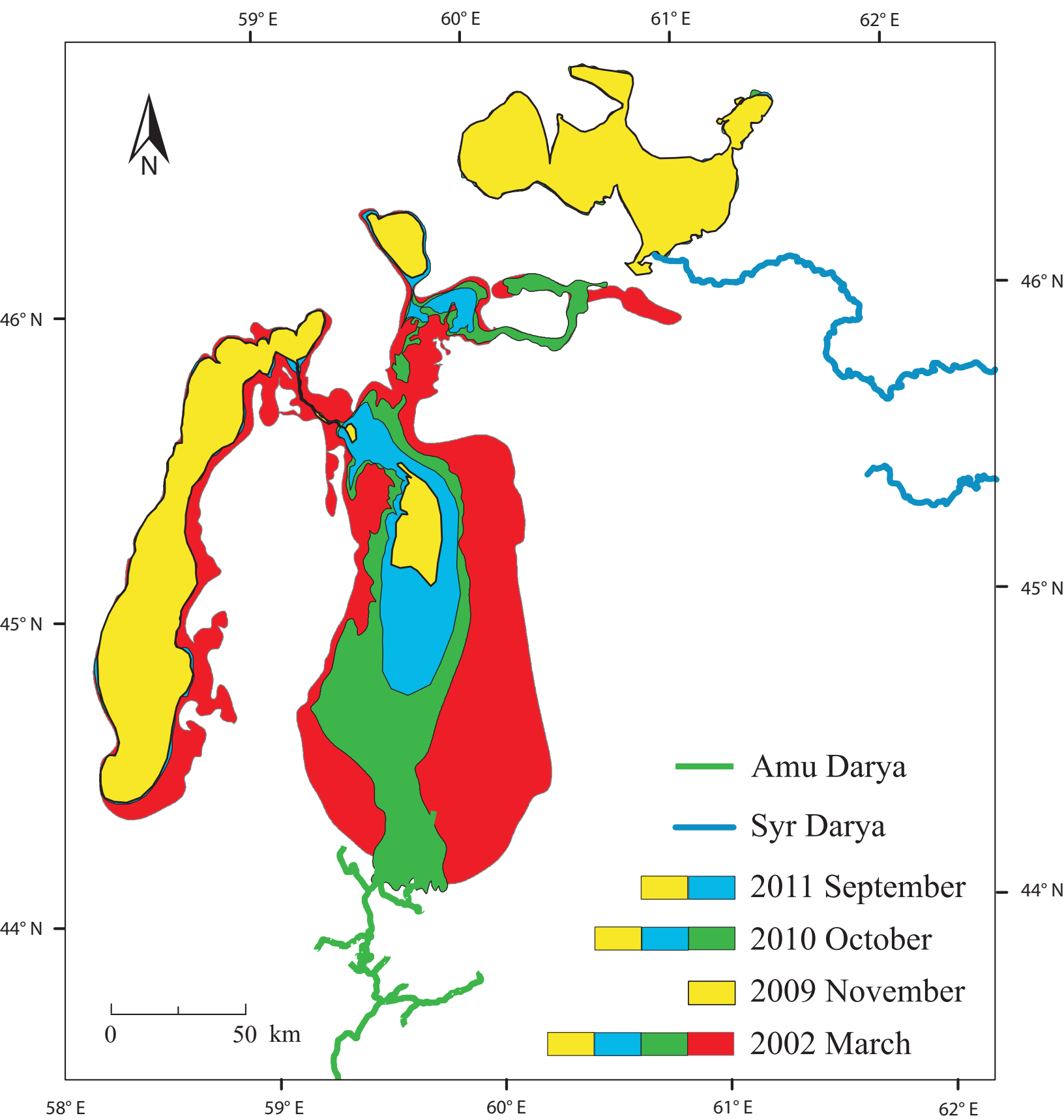




Figure 5

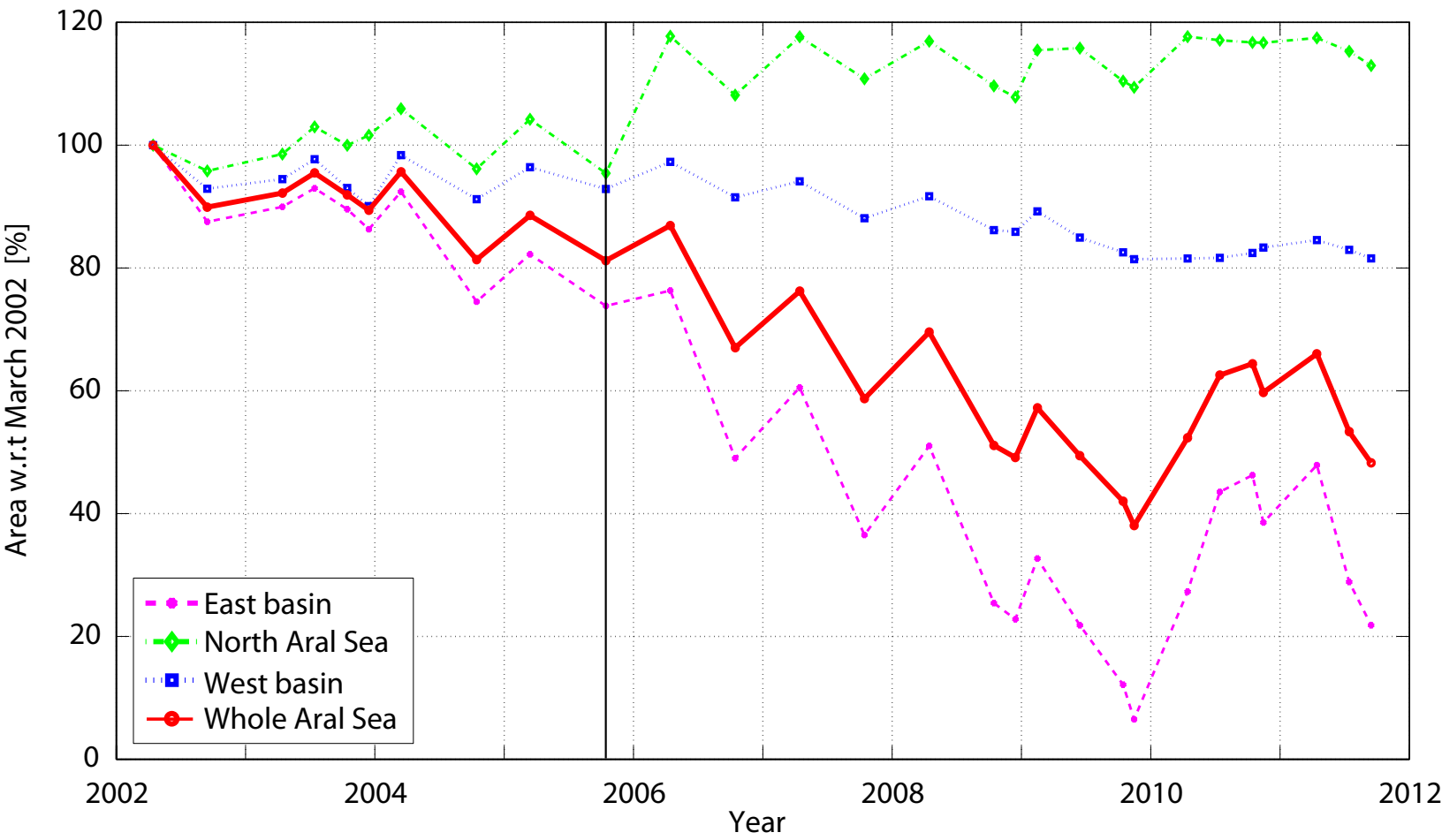


Figure 6

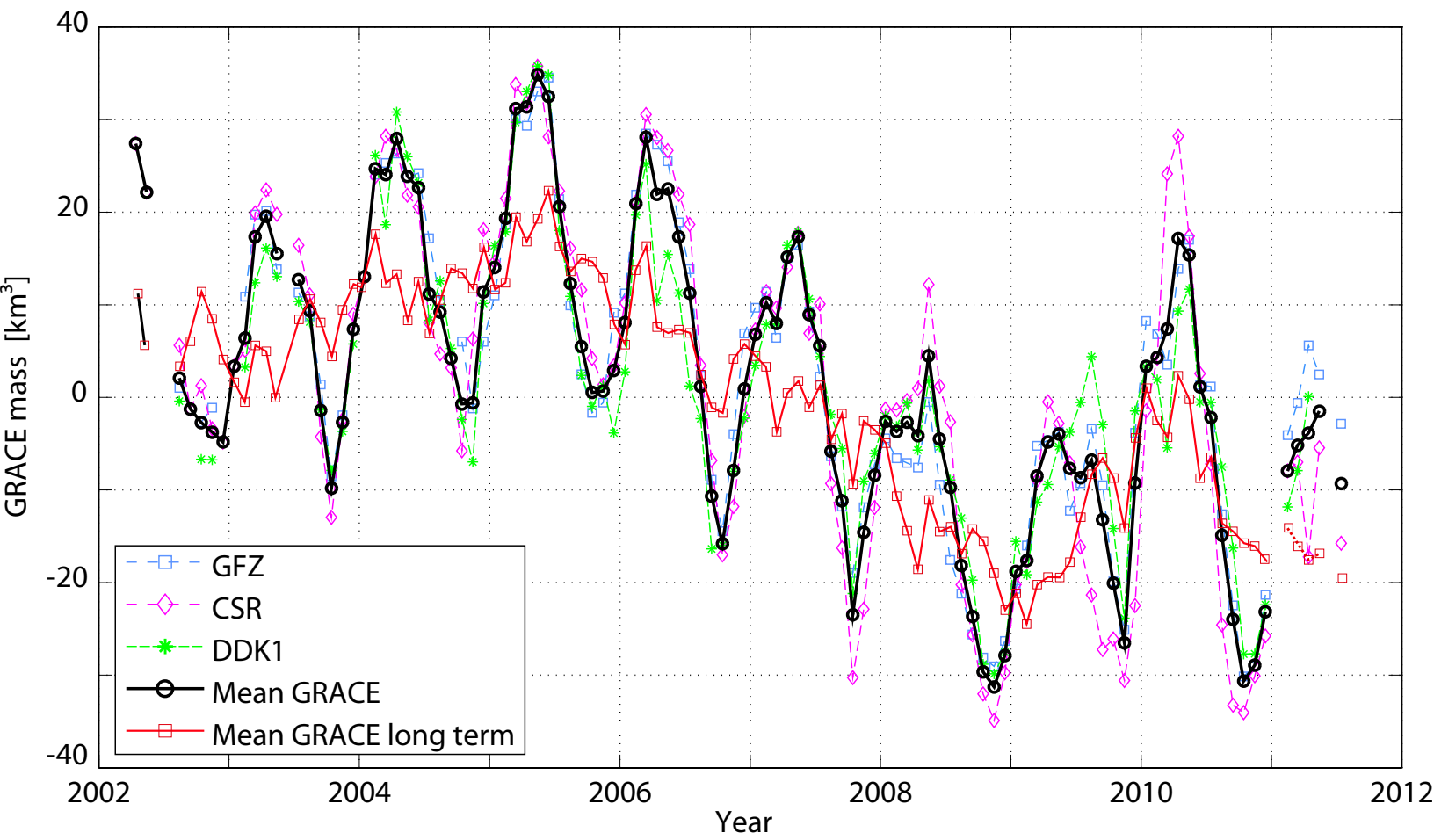


Figure7

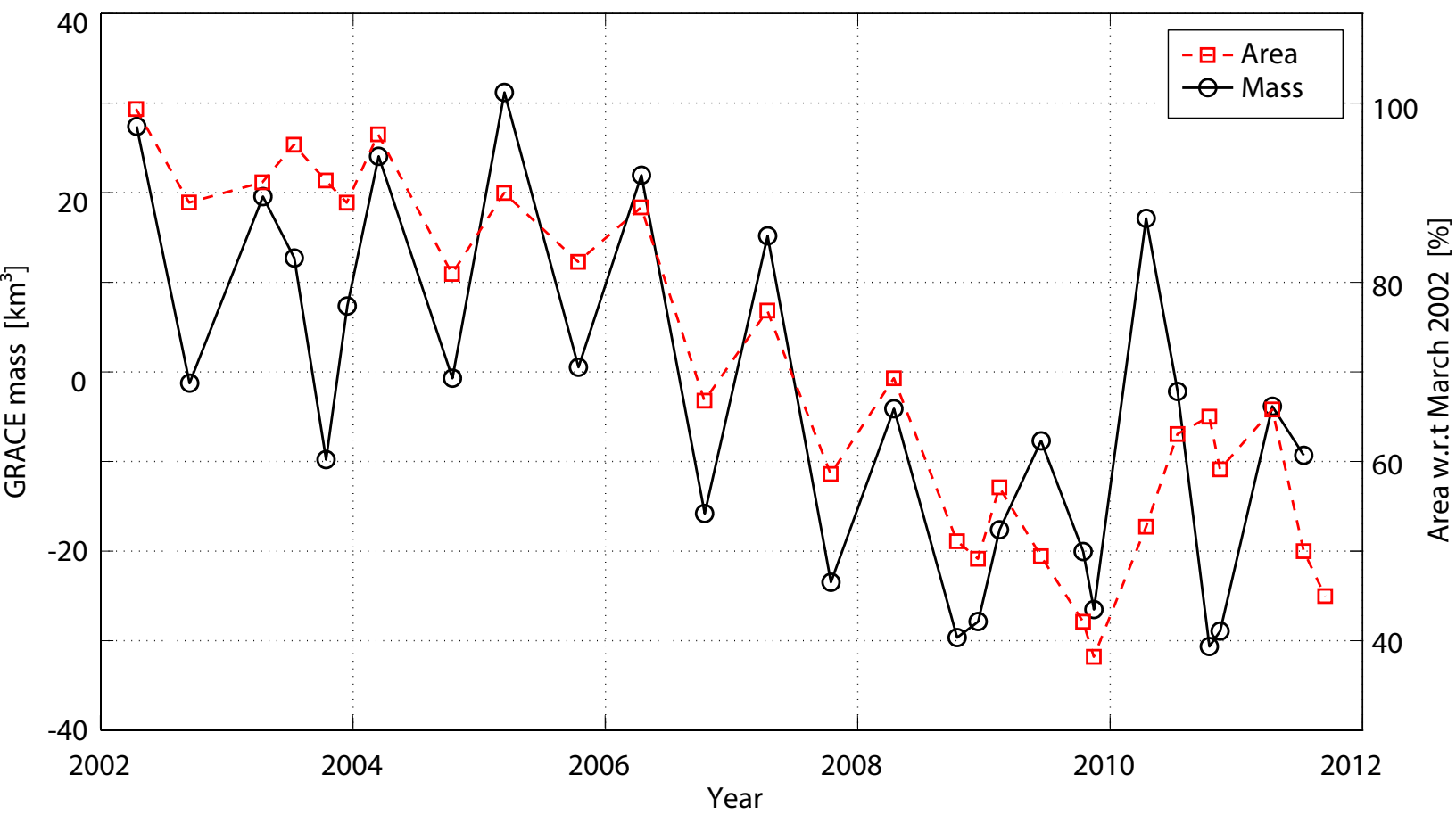


Figure 8

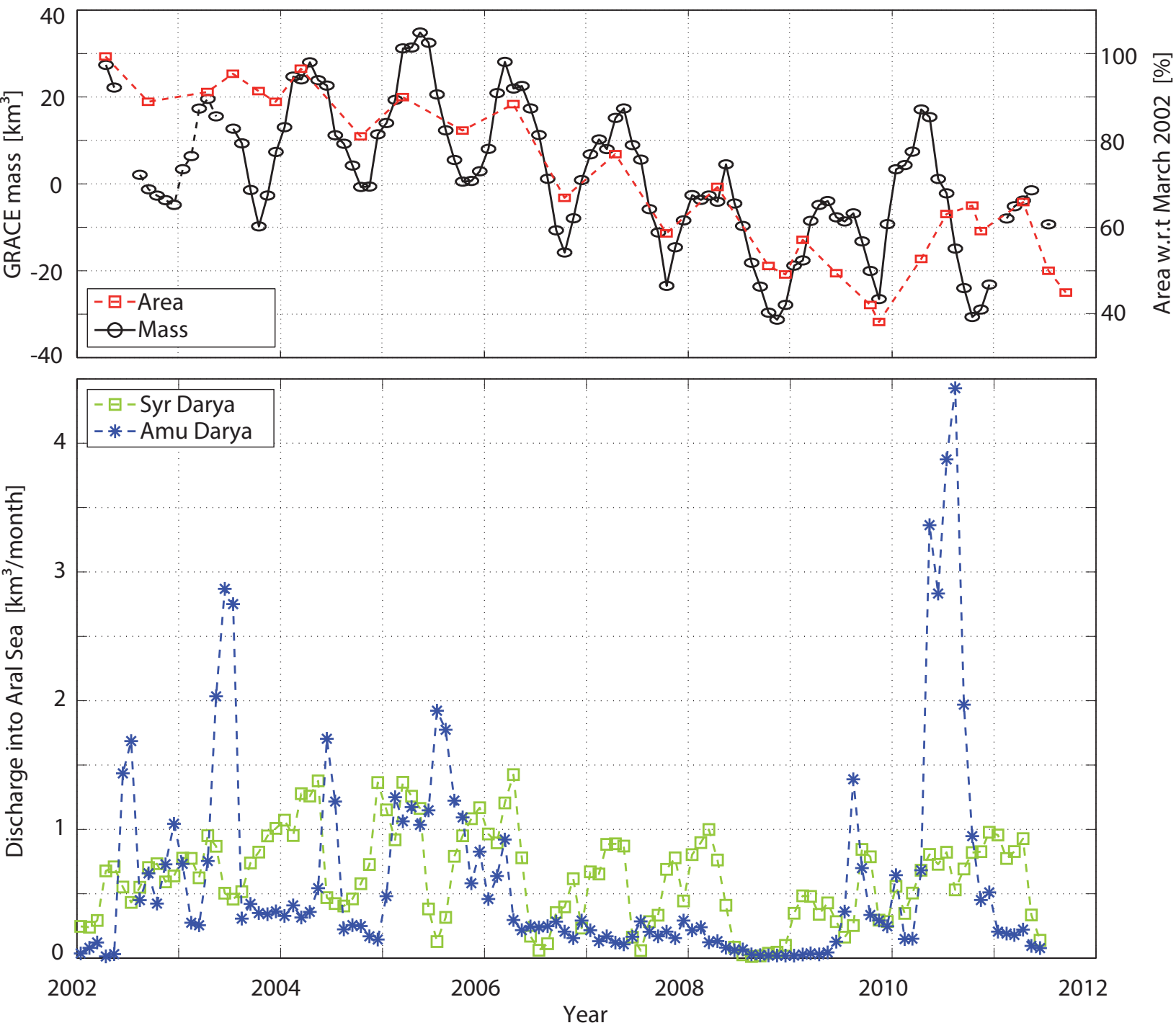


Figure 9

