Application of Multi-Sensor Satellite Data to Observe Water Storage Variations

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***Abstract*—In this study we apply geometric and gravimetric observations from various Earth observation satellites in order to estimate the variability in a lake with respect to its geometrical extent and water storage. Our test case is the Aral Sea, located in the arid zone of central Asia. Due to the diversion of its primary inlet rivers for irrigation purposes the lake suffered a devastating decline until its south eastern part had almost dried out in 2009. The study is focused on the period of the satellite gravity field mission GRACE from 2002 onwards. We present the change of the lake's surface extent based on optical remote sensing data from Landsat images that were analyzed for spring and autumn each year. Height variations of the lake surface were computed from multi-mission satellite altimetry. Both the surface extent and the water stage of the lake reached an absolute minimum in autumn 2009. However in 2010 a clear reversal of the negative trend of the previous years is visible. A geometrical intersection of the water level with a digital elevation model allows for estimating water volume changes. The resulting volume changes are subsequently analyzed with respect to satellite-based estimates of mass variations observed by GRACE. The results reveal that water storage variations in the Aral Sea are indeed the principal contributor to the GRACE signal of mass variations in this region. The different observations from all missions agree very well with respect to their temporal behavior.**

***Index Terms*—GRACE, Landsat, satellite altimetry, volume changes.**

I. INTRODUCTION

WATER stored in surface water bodies plays a key role in the global hydrological cycle. A large number of recent satellite missions with different objectives are available today, allowing us to study the extent and dynamics of many continental water bodies on a wide scale and in remote areas.

Until the 1960s, the Aral Sea was the fourth largest lake in the world. From then onwards a catastrophic drying process has been ongoing due to undersupply of water as a result of the diversion of its tributaries for irrigation [1]. In this paper we analyze geometrical changes of the lake surface and compare deduced variations of the lake volume with gravimetric (i.e. mass-related) variations in the region. Volume changes are geometrically determined from water height variations observed by multi-sensor altimetry in combination with a digital elevation model of the lake floor. Gravity field changes have been observed by the dedicated satellite gravity field mission GRACE (Gravity Recovery and Climate Experiment) since 2002. It has been demonstrated in several studies that GRACE has the potential to observe hydrological storage variations in continental regions [2], [3]. The time-frame of our study is 2002–2011.

II. GEOMETRICAL CHANGES OF THE ARAL SEA

Temporal changes of the storage in a water body are related to changes of its level and surface extent. Such variations can be traced in observations from satellite altimetry and optical remote sensing images [4]. Volumetric variations can be deduced by intersecting these observations with a digital bathymetry model of the water body.

A. Water Extent

Changes in the Aral Sea surface area were derived from Landsat satellite images every year for spring and autumn between 2002 and 2011. Some additional months were also computed for periods of seasonal anomalies. Bulk download of the Landsat images was performed from http://earthexplorer.usgs.gov not only for the area under water, but also for adjoining regions to fill SLC-off (Scan Line Corrector) gaps in the Landsat7 (ETM+) datasets. From May 2003 Landsat7 suffered a failure in the SLC, which resulted in stripe-type data gaps. Six sets of images were mosaicked for each time frame to generate a complete picture of the lake at 30 m spatial resolution and to fill the gaps as good as possible. Remaining data gaps were filled by convolving first 5 × 5 followed by 3 × 3 mean focal filters. Because of frequent changes in the lake geometry in one of its sub-basins, preceding and subsequent images were not found to be suitable to fill the gaps as they sometimes create artifacts due to a too long time lag between usable images. Respective land/water masks were generated through image processing techniques using a maximum likelihood supervised classifier in IDL-ENVI through batch processing. Morphological operations were carried out on all masks to remove minor artefacts in the images through erode and dilation. For each of the three sub-basins of the Aral Sea (north, east and west) we obtained a time-series of the area covered by water.

Fig. 1 shows seasonal and long-term variations of the surface area for the three basins between 2002 and 2012 in twice-yearly

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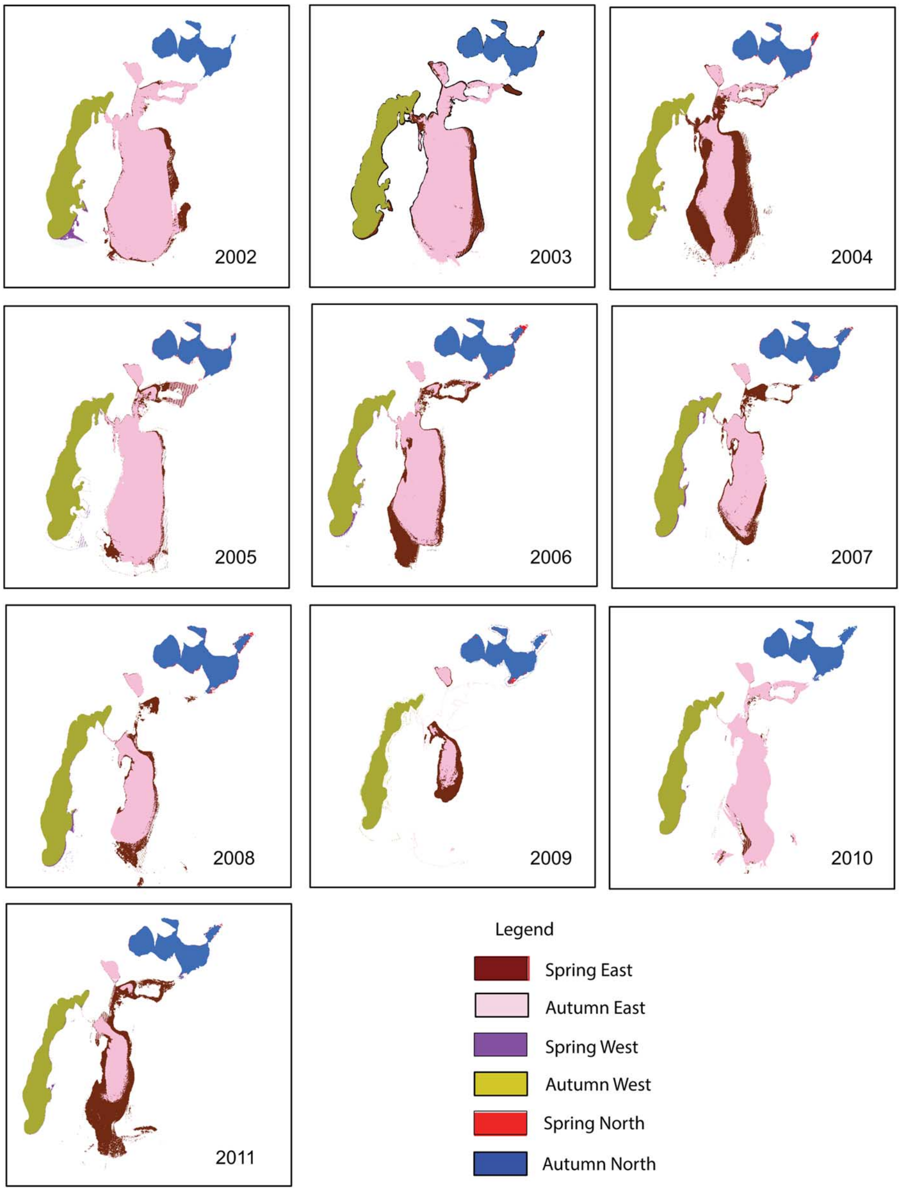

Fig. 1. Seasonal and long-term change of the Aral Sea surface area in spring and autumn during 2002–2011 observed from Landsat images.

snapshots (color coded). A clear process of desiccation is evident between 2002 and 2009. The year 2010 was observed as a reviving year for the lake due to a significant inflow from its primary inlets Amu Darya and Syr Darya [Fig. 7]. After 2010 desiccation continued. The largest changes are observed in the shallow east basin. Within only seven years it shrunk to less than 10% of its area observed in 2002 and lost nearly 10,000 km^2. The west basin suffered consistent changes but with far smaller amplitude [cf. Fig. 3, left]. The North Aral Sea, in contrast, features a different development, as it remained comparatively stable, except for the years 2005–2006, when its size increased by nearly 10%, due to the construction of the Dike Kokaral dam in 2005.

B. Water Level

During the last two decades satellite altimetry has been widely applied to monitor water levels of many continental water bodies [5]–[7]. In our study, water level time series were generated by combining observations from radar altimetry missions, i.e. Jason-1, Jason-2, Jason-1 extended mission (EM), and Envisat. The lake was very well observed by different altimetry missions in the first part of our study period, but unfortunately later not only the lake size shrank, but also several altimetry missions retired. As a result the lake was only observed by Jason-2 and Jason-1-EM by the end of our study period. All observations were corrected for atmospheric delay and geophysical effects, i.e. for ionosphere, dry troposphere, wet troposphere, and solid Earth tides using calibration models.

Altimetry data and correction models were downloaded from DGFI's open altimetry data base (OpenADB) at http://openadb.dgfi.badw.de. Heights refer to the geoid EGM2008. An additional cross calibration of the range bias was applied to harmonize the observations between different missions. Observation points at a distance less than 5 km from the coast were rejected

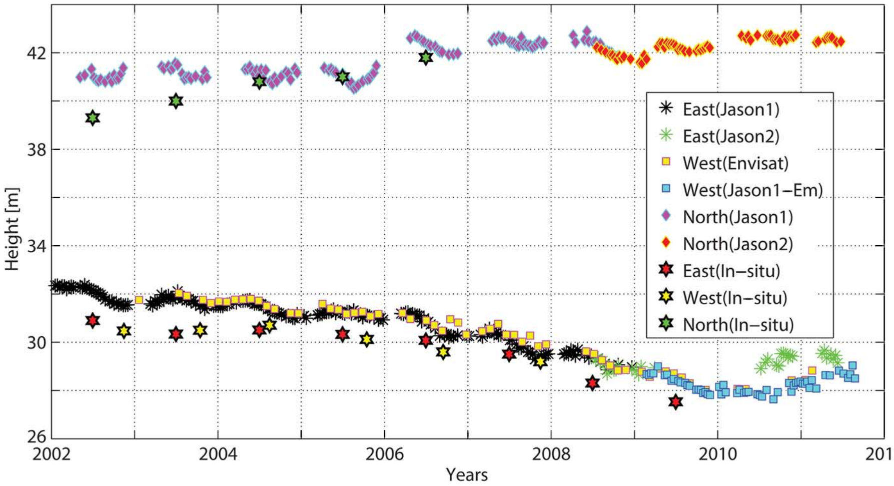

Fig. 2. Water level changes in the east and west basin (upper panel) and North Aral Sea (lower panel) from multi-mission altimetry and in-situ observations.

to avoid any contamination of the measurements by land reflection. For this purpose the water masks generated from Landsat data were applied. Water masks were re-projected from UTM to a geographic coordinate system, resampled from 30 m onto a 0.025° grid, and finally eroded by a 3 × 3 matrix to obtain the masks from which we deduced the 5 km range from the coast.

The altimetry observations from all missions agree very well within a range of few decimetres [Fig. 2]. The temporal development of the lake level as seen by altimetry is in concordance with in-situ data available from the INTAS-0511 REBASOWS project (www.cawater-info.net) [8] and an expedition to the west basin [9]. However, an almost constant offset between the altimetry observations and in-situ data exists due to different height systems used as reference. Fig. 2 upper panel shows a clear seasonal pattern and a drastic drop of the water level until the end of 2009 for the South Aral (east and west basin). As a consequence of the shrinking of the lake there is a lack of observations of the east basin for almost half a year (November 2009 until June 2010). By this time the small channel between the two basins of the South Aral Sea dried out completely, and the west basin was separated. It continued to recede until summer 2010. As it is deep and also fed by ground water, its decline was accompanied by a relatively small change of its volume. After spring 2010 both southern basins revived and expanded both vertically and horizontally [cf. Fig. 3, left] due to exceptionally strong inflow from the Amu Darya (see Discussion). The North Aral Sea remained almost stable with nearly 1 m of annual fluctuation and an additional gain of approximately 1 m in 2005/2006. This rise resulted from the construction of the dam by which the South Aral Sea was cut off from its former tributary Syr Darya. The dam which is usually closed is only released in the rare event of an extraordinary inflow from the Syr Darya. Fig. 3 compares time series of surface area and water height for all basins. Both quantities show a very similar development. In the shallow east basin their correlation is 0.98. The scatter plot between the two quantities shows a distinct linear relationship [Fig. 3, right]. West and north basin feature more pronounced variations in the water level than in the surface area due to larger depth and steeper shorelines. Correlation coefficients between water level and surface area amount to 0.94 (north) and 0.77 (west) respectively.

C. *Lake Volume*

Volumes of the basins were computed by intersecting a digital elevation model (DEM) of the Aral Sea floor (provided by Dr. P. Zavialov from the Physical Oceanography Division, Russian Academy of Science though personal communication) with the water levels computed from altimetry [10]. We used a mean water level from all altimetry missions for each basin to generate volumetric time-series. We transformed a 1° × 1° bathymetry model onto a 30 m grid using a bilinear algorithm. Depth values are provided w.r.t. the Kronstadt gauge. In order to obtain heights of the sea floor w.r.t. the geoid, a constant offset of 53 m had to be subtracted from the model [5] [Fig. 4, left]. Water stages per 30 m pixel were generated by subtracting the DEM from water levels observed by altimetry. For each basin, water volumes were computed by integrating corresponding water columns with negative values (positive values correspond to areas uncovered by water). The mean of the total volume of the Aral Sea [Fig. 4, right] over the entire study period is 101.76 km^3; this value was subtracted from the monthly observations in order to compute volumetric variations. These variations were later compared with the mass signals derived from the GRACE gravity field mission in the Aral Sea region; see below. As the bathymetry map was generated in the 1960s and the spatial resolution is rather poor, we expect an (unknown) error in the volumetric computation. This error can, however, be viewed as marginal for our comparison since the resolution of the GRACE data is limited to a spatial scale of a few hundred kilometers.

III. GRAVIMETRIC CHANGES IN THE ARAL SEA REGION

The Gravity Recovery and Climate Experiment (GRACE) twin satellite mission was launched in 2002 to measure the Earth's gravity field and monitor mass variations over space and time around the planet [17]. The twin spacecraft uses a microwave ranging system to accurately measure changes in the distance between two satellites that are caused by minute

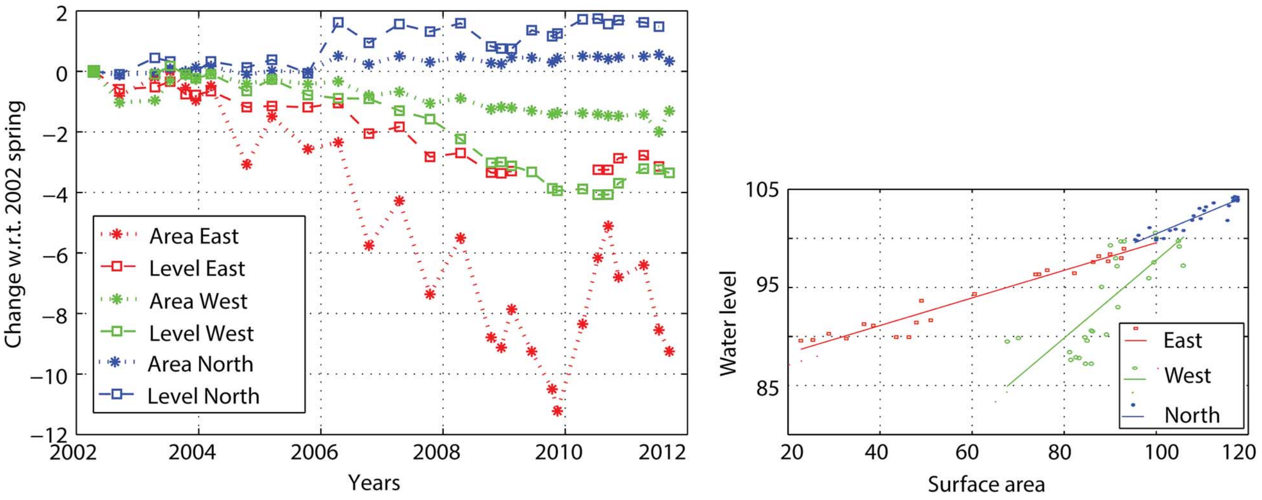

Fig. 3. Left: Changes in the Aral Sea water level in meters and surface area in 1000 km^2 for each basin with respect to its state in spring 2002 (East, West and North Aral had water levels of 32, 32 and 41 m and surface areas of 12.000, 5.200 and 2.800 km^2 respectively). Right: Least squares linear regression between the scatter plot of water level and surface area of each basin, both given in percent (100% corresponds to spring 2002).

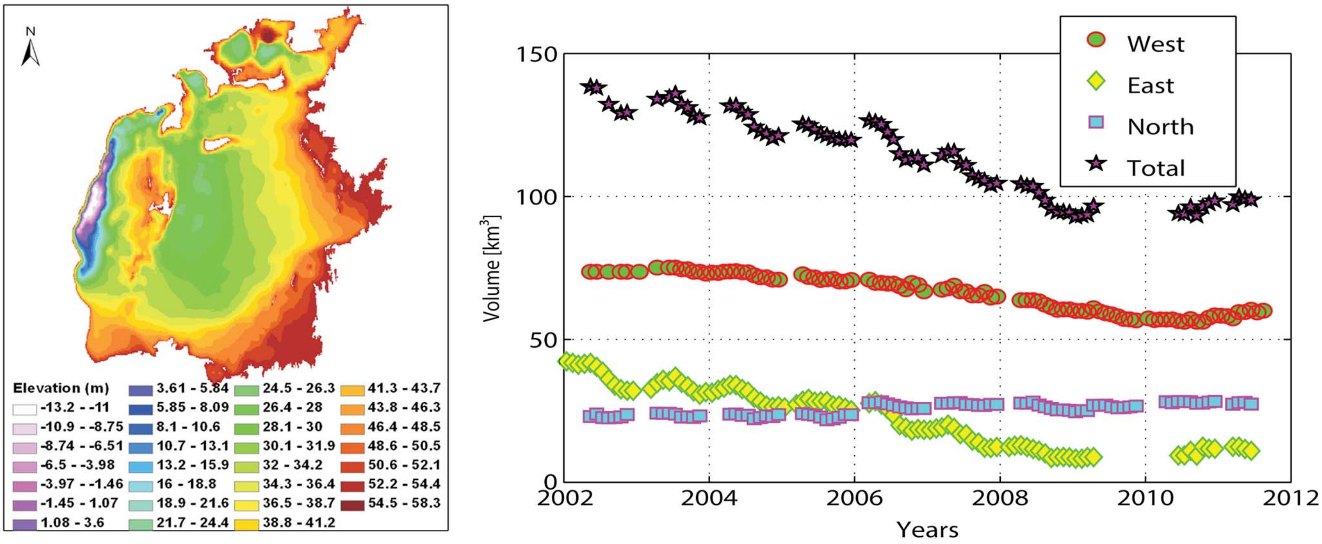

Fig. 4. Left: Digital elevation model of the Aral Sea floor; Right: water volumes computed for each basin and their sum.

variations in Earth's gravitational attraction. The mission is sensitive to large-scale mass variations in the Earth system and many studies in last decade have demonstrated its usability to monitor water storage changes [2], [3], [18]. On spatial scales larger than a few hundred km a temporal resolution of approximately one month can be achieved. Due to the mission's coarse resolution it is not possible to distinguish between individual contributions of water mass changes from the three sub-basins of the Aral Sea to the observed signal of mass variations in the region. For our GRACE analysis we chose a $4^\circ \times 4^\circ$ quadrangle comprising all basins. This area is five times larger than the area of the lake in 2002. Consequently the observations of GRACE are also significantly influenced by other (predominantly hydrological) mass variations in the surrounding area (e.g. groundwater, snow, soil moisture, water in rivers and floodplains, etc.) that are partly characterized by a distinct seasonal variability.

We used quasi-monthly sets of spherical harmonic coefficients of the Earth's gravity field (GRACE Level-2 data) provided by the German Research Centre for Geosciences (GFZ), Germany, and the Centre for Space Research (CSR), USA. Redistributions of mass due to Earth and ocean tides, atmospheric pressure variations and ocean circulation were removed already during pre-processing via respective background models [11]. Therefore the remaining signals in our study area can be assumed to reflect the redistribution of mass within the continental hydrology. Variations of the gravity field w.r.t. a mean field over the entire time span are expressed in so-called equivalent water height (EWH) variations that were computed via spherical harmonic synthesis [12]. In order to minimize aliasing effects, algorithms for smoothing and de-striping were applied [4], [13]. Contaminations by leakage effects from the surroundings of our study area due to the spherical harmonic truncation at degree/order 60 were reduced on the basis of the Water-GAP Global Hydrology Model (WGHM) [14], [15], on which the same Gaussian filter were applied. In Fig. 5 the results for mass variations from GRACE for the study area are displayed in units of km^3 (Equivalent Water Volume; derived from the multiplica-

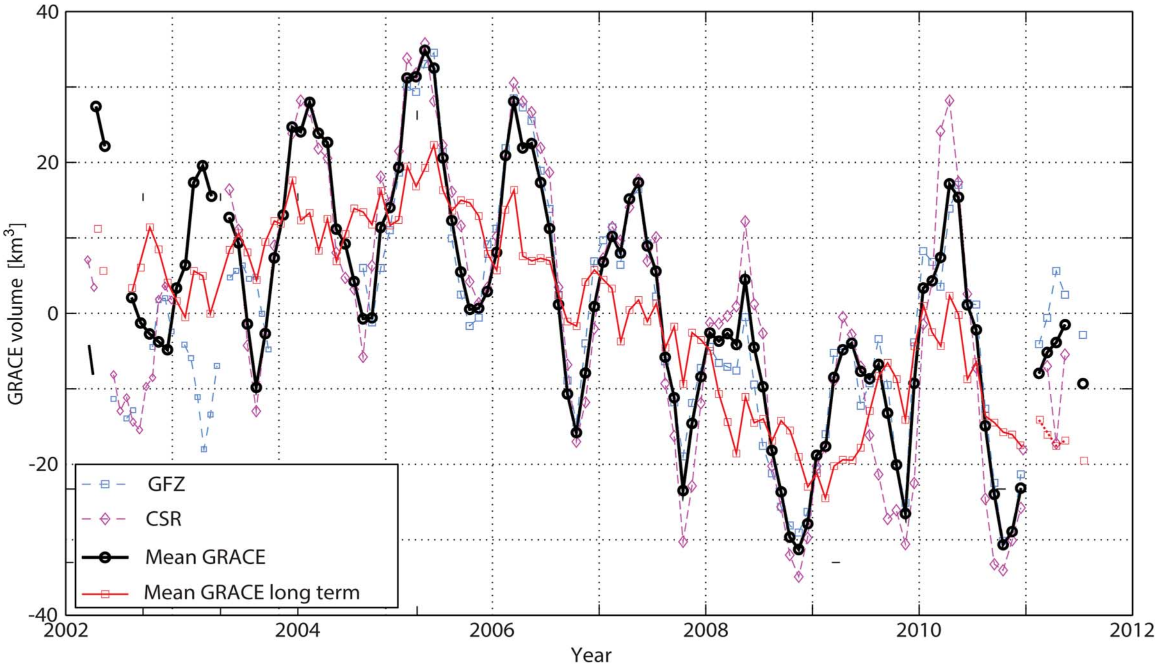

Fig. 5. Variations of equivalent water volume in the Aral region from GRACE satellite gravimetry. Values are anomalies w.r.t. a long term mean over the GRACE era. Dashed curves: two different GRACE solutions; solid bold curve: mean of the two solutions; thin solid curve: mean long-term signal (solid bold curve reduced by seasonal variations).

tion of EWH changes with the area). The CSR solution shows slightly larger amplitudes, especially during the second half of the study period.

Nevertheless, in general the two solutions from GFZ and CSR are very consistent. For further comparisons we use the mean of both solutions [Fig. 5]. A pronounced annual cycle and a clear long term mass loss (in particular between 2005 and 2008) followed by a significant increase is obvious. The temporal development of the signal agrees with the observations from Landsat and the altimetry missions.

IV. DISCUSSION

The comparison of GRACE-derived volume estimates with water volume variations computed from altimetry and the bathymetry model shows a good agreement of both curves in terms of trend and seasonal variability [Fig. 6]. The correlation coefficient between the volumes from GRACE and the geometrical approach is 0.74 over the entire study period. During the period of the strongest desiccation (2004–2009) the correlation amounts to 0.85. Composite seasonal cycles of the curves were computed from the mean values of each month over the entire time frame [Fig. 6, right]. Both cycles show a seasonal variation of volume with consistent phase. The trend observed by GRACE (4 $\mathrm{km}^3/\mathrm{year}$) is somewhat smaller than the trend computed from the geometrical approach (5 $\mathrm{km}^3/\mathrm{year}$) [Fig. 6, left]. GRACE observations indicate that between mid-2005 and the end of 2008 approximately 60 km^3 of water mass were lost, of which the lake contributed only 30 km^3. The total water volume loss of the lake between 2002 and 2009 was nearly 45 km^3, followed by a gain of not more than 10 km^3 in 2010. On the other hand GRACE observed 40 km^3 of fluctuation in the year 2010 [Fig. 5]. This comparison reveals that even though the lake produces a dominant mass signal, GRACE observations are also highly influenced by mass changes in the surrounding of the Aral Sea. As stated above, the integrative GRACE signal contains contributions from other hydrological signals originating in the proximity of the lake. Their magnitude and origin are largely unknown. But as stated above some of the hydrological compartments feature a distinct seasonal variability (e.g. snow, groundwater). Therefore the annual amplitudes of the mean GRACE curve can be expected to be larger than the annual amplitudes of the lake volume change.

Since our study area of GRACE is significantly larger than the lake itself, GRACE also observes the Priaralie delta region, encompassing large parts of the two rivers Amu Darya and Syr Darya delta. A significant fraction of the incoming water gets diverted in this region (e.g. for irrigation purposes) and never reaches the lake. Therefore it cannot be expected that the mass signal seen by GRACE and the volume change of the lake fully resemble each other.

The GRACE minimum in 2008 is related to a dry period with almost no water inflow from both rivers [Fig. 7]. In 2010 the GRACE curve follows the curve of the water discharge from the Amu Darya. The integrated amount of water reaching the lake by the Amu Darya and the Syr Darya was approximately 20 km^3 and 10 km^3 respectively. During this year GRACE observed a fluctuation of 40 km^3. The difference can be explained by corresponding changes in other hydrological compartments. During 2010 the Aral Sea also gained nearly 10 km^3 water volume but it did not suffer such a significant drop as observed from GRACE and the Amu Darya discharge. This can be partly explained by the travel time that the water needs to reach the lake through the dried-out surroundings. During the summer, when GRACE

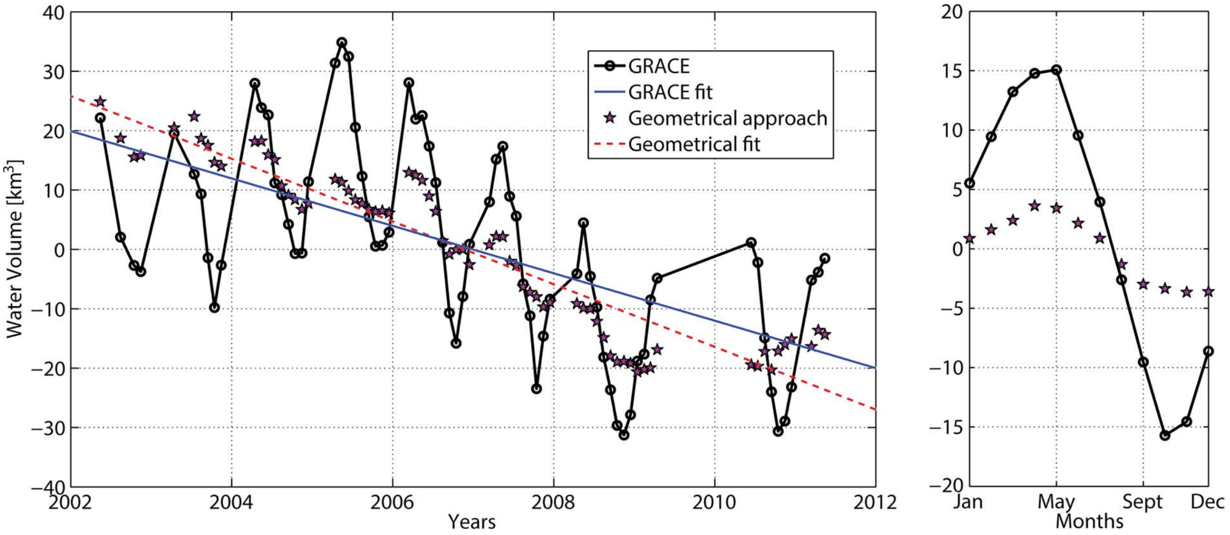

Fig. 6. Left: Volume change in $[\mathrm{km}^3/\mathrm{year}]$ of the Aral Sea resulting from GRACE and the geometrical approach; Right: Respective composite seasonal cycles of lake water storage.

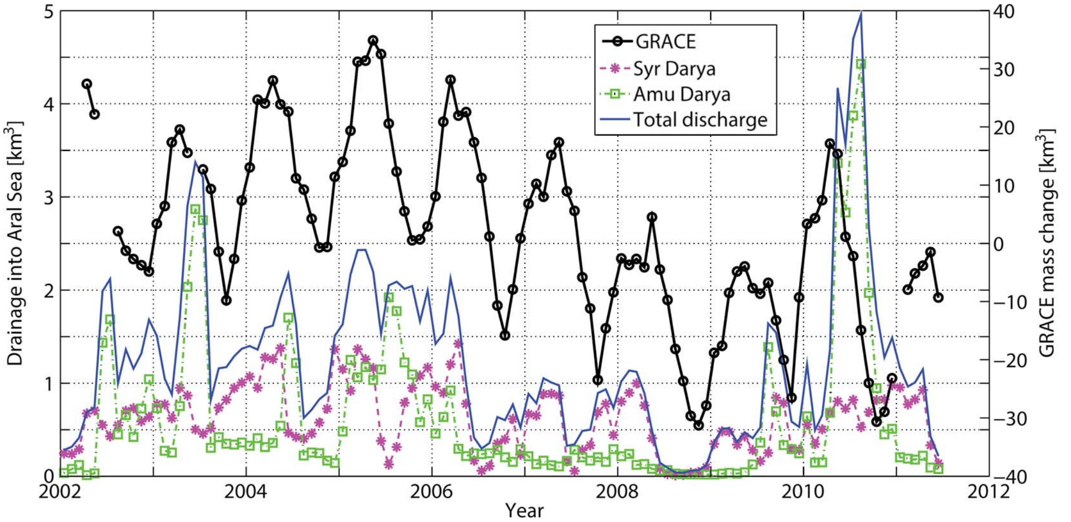

Fig. 7. Monthly discharge from Amu Darya, Syr Darya and their sum into the Aral Sea (axis on the left), compared with GRACE (axis on the right).

already observed a drastic mass loss, presumably due to strong evaporation from the large open surface area of the irrigated region in the surroundings, the lake continued refilling throughout this period followed by an obvious decline in 2011 which is also well observed in GRACE.

V. CONCLUSIONS

A generally good agreement between observed mass variations from GRACE and lake water volume variations has been found. GRACE features a much more pronounced inter-annual signal, but the long-term characteristics of gravimetrical and geometrical data are very similar. Hence, water storage in the Aral Sea turned out to be a strong contributor to the long-term mass change observed by GRACE. However there are also significant contributions from other mass signals in the area surrounding the lake. The comparison of geometrically based volume estimates with GRACE mass changes provides a promising means to analyse and separate the GRACE signals and—in turn—to estimate mass change signals in other hydrological compartments such as ground water. The combination of multi-satellite data proved to be effective in a comprehensive analysis of the hydrological condition of a region which otherwise is very poorly monitored by in-situ observations. Future work will comprise the analysis of the residual GRACE signal with respect to its consistency with soil moisture, snow and ground-water changes from observations and hydrological models.

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