OBSERVATIONS OF WATER STORAGE VARIATIONS IN THE ARAL SEA FROM MULTI-SENSOR SATELLITE DATA

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Abstract

In this study we apply geometrical and gravimetrical observations from various Earth observation satellites in order to estimate the variability of the Aral Sea with respect to its geometrical extent and the water storage. 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. We present the change of the lake's surface extent based on optical remote sensing data from Landsat images that are analyzed for spring and autumn each year. Height variations of the lake surface are computed from multi-mission satellite altimetry. Both the surface extent and the water stage of the lake reached an absolute minimum in 2009 autumn. 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 the satellite gravimetry mission 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. It is shown that the different observations from all missions agree very well with each other with respect to their temporal behavior.

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 is available today, allowing to study the extent and dynamics of many continental water bodies over large scales 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 is ongoing due to undersupply of water as a result of the diversion of its tributaries for irrigation. In this paper we analyze geometrical changes of the lake and compare deduced variations of the lake volume changes with gravimetrical (i.e. mass-related) variations in the region. The latter have been observed by the dedicated satellite gravity field mission GRACE (Gravity Recovery And Climate Experiment) for more than one decade. It has been demonstrated in several studies that GRACE has the potential to observe hydrological storage variations in continental regions (Ramillien et al., 2008; Seitz et al., 2008). The time-fame of our study is 2002-2011.

Geometrical Changes in 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 (Singh et al., 2012). Volumetric variations can be deduced by intersecting these geometrical observations of water extent and level with a digital bathymetry model of the region.

Water extent

Changes in the Aral Sea surface area are derived from Landsat satellite images every year for spring and autumn between 2002 and 2011. Some additional months are also computed during periods of seasonal anomalies. Respective land/water masks are generated through image processing techniques using a maximum likelihood supervised classifier. Errors in images due to sensor problems are filled with data from the closest cycle.

Figure 1 shows a clear signal of desiccation between 2002 spring and 2009 autumn, when the East basin shrunk to less than 10% of its area observed in 2002. During this time the lake as a whole lost more than 60% of its area. 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 (see below). This was followed again by the dry year 2011 when the lake size suffered further decline. The North Aral Sea, in contrast, had 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.

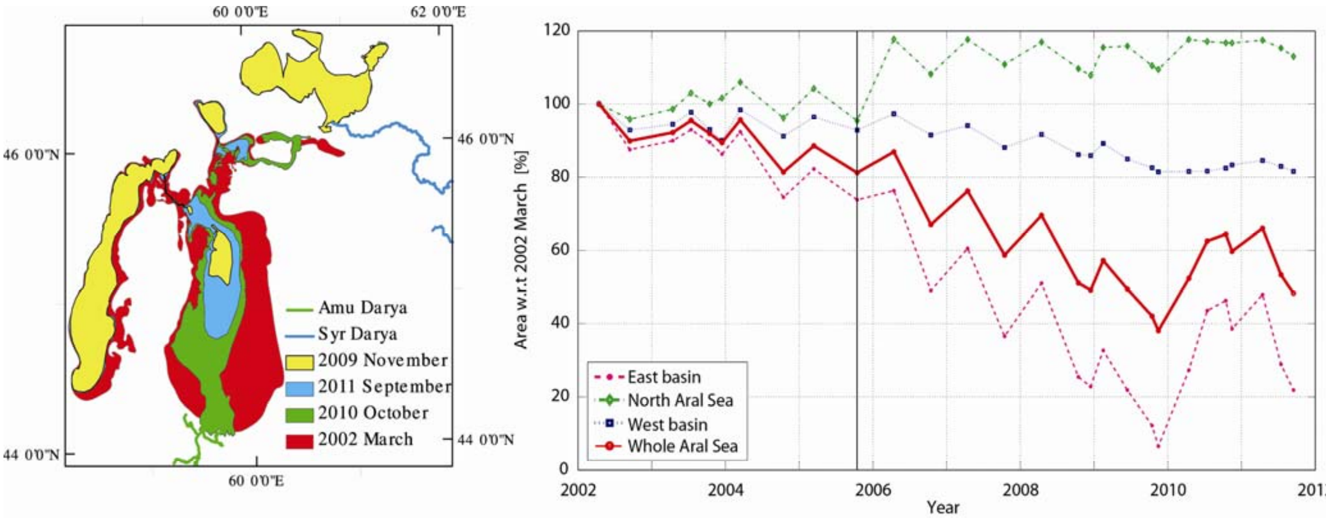

Figure 1: Left: Change of the Aral Sea surface area during the study period from Landsat images. Right: Percentage change of the surface area of the Aral Sea and its sub-basins with respect to March 2002. At this reference the whole Aral Sea covered 20,370 km^2, out of which the North Aral Sea covered 2,850 km^2, the West basin 4,660 km^2 and the East basin km^2 12,860 km2. The vertical black line indicates the construction of the Dike Kokaral dam.

Water level

During the last two decades satellite altimetry has been widely applied to monitor water levels of many continental water bodies (Calmant & Seyler, 2006; Crétaux et al., 2005; Becker, et al., 2010). In our study, water level time series were generated by combining observations from the missions Jason-1, Jason-1 extended mission (EM), Jason-2 and Envisat. The observations were corrected for atmospheric delay and geophysical effects i.e. for ionosphere, dry troposphere, wet troposphere, and solid Earth tides using calibration models. Heights refer to the geoid EGM2008. An additional cross calibration of 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 to avoid contamination of the measurements by land reflection. For this purpose the water masks generated from Landsat data were applied. As a consequence of the shrinking of the lake there is lack of observation of the East basin for almost half a year (November 2009 until June 2010) (Fig. 2).

The observations from each mission agree very well and are in concordance with in-situ data available from the INTAS-0511 REBASOWS project (www.cawater-info.net) and an expedition to the West basin (Zavialov 2010). A constant offset between the altimetry observations and in-situ data exists due to different height systems used as reference. Figure 2 shows a clear seasonal pattern and a drastic drop of the water level until the end of 2009 for the East basin. 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. Being 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 extended both vertically and horizontally due to exceptionally strong inflow from the Amu Darya (cf. Discussion). Similar to the trend observed from Landsat, 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 case of an extraordinary inflow from the Syr Darya.

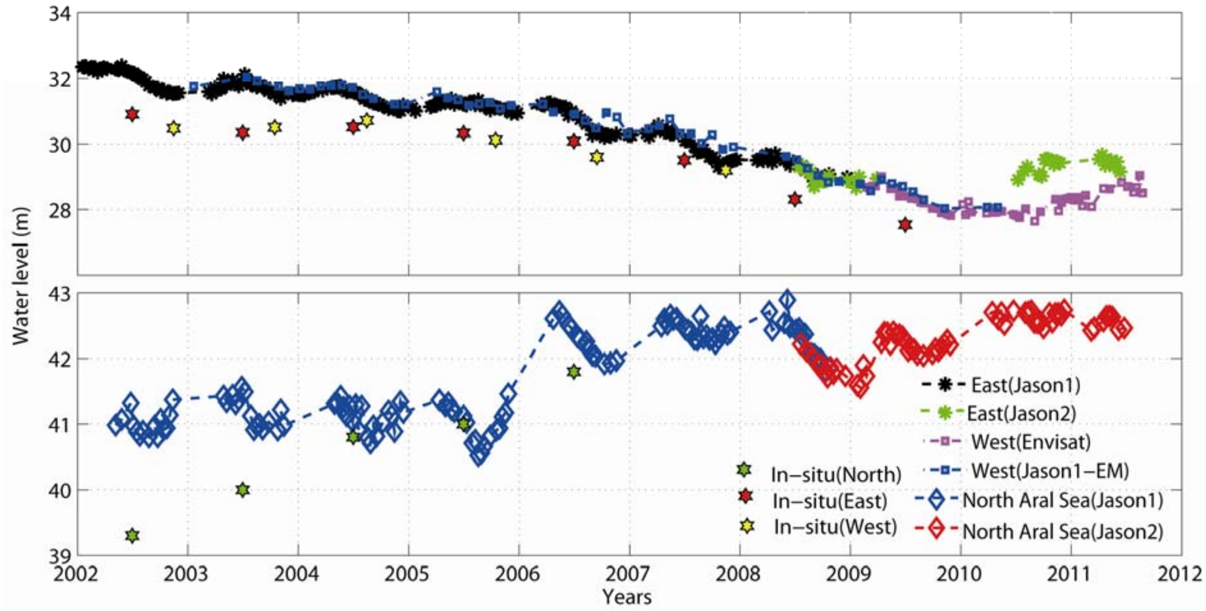

Figure 2: Water level changes in the East and West basin (upper panel) and North Aral Sea (lower panel) from multi-mission altimetry and in-situ observations.

Lake volume

Volumes of the basins are computed by intersecting a digital elevation model (DEM) of the Aral Sea floor with the water level computed from altimetry. Here we present first results of this procedure which are, however, preliminary since so far only one of the missions per basin has been applied at a time. We restrict ourselves to the consecutive altimetry missions Jason1 and Jason2 for the East basin and the North Aral Sea. For the West basin we computed the lake volume from Envisat and Jason1-EM. We transformed a 1° x 1° bathymetry model onto a 30 m grid using a nearest neighbourhood 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 needs to be subtracted from the model (see Crétaux et al., 2005, for details). From the interpolation we obtain the piecewise-constant interpolated DEM that is shown in Fig. 3. Water stages per 30m pixel are generated by subtracting the DEM from water levels observed by altimetry. For each basin, water volumes are computed by integrating corresponding water columns. The mean of the total volume of the Aral Sea for the whole study period is 101.76 km^3; this value is subtracted from the monthly observations in order to compute volumetric variations. The resultant variability is then compared with the mass signals derived from the GRACE gravity field mission in the Aral Sea region; see Fig. 5 (lower panel).

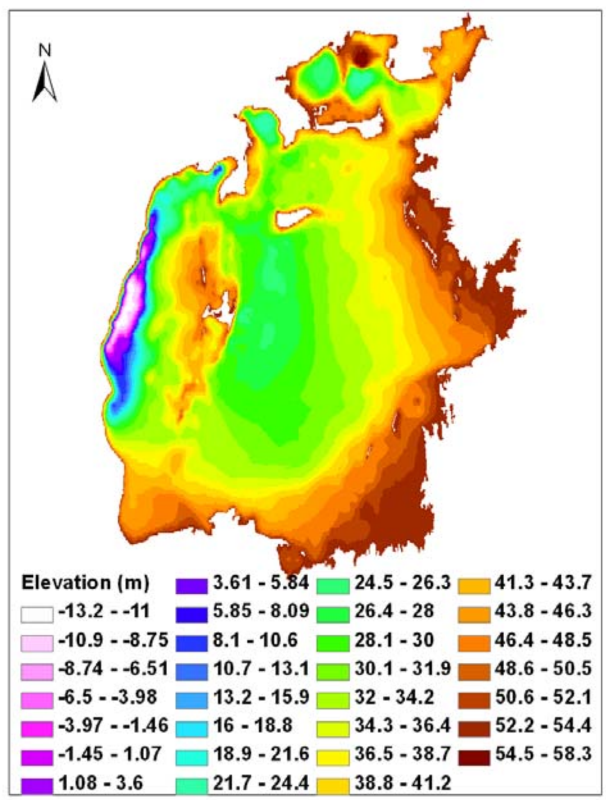

Figure 3: Digital elevation model of the Aral Sea.

Gravimetrical changes in the Aral Sea region

The satellite gravity field mission GRACE is sensitive to large-scale mass variations in the Earth system. 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. Here we chose a 4° x 4° quadrangle comprising all basins. This area is five times larger than the area of the lake in 2002. Consequently the observations of the GRACE are also significantly influenced by mass variations in other (predominantly hydrological) compartments in the surrounding of the lake (e.g. groundwater, soil moisture, water in artificial reservoirs, etc.).

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. Mass redistributions due to Earth and ocean tides, atmospheric pressure variations and ocean circulation are removed during pre-processing by respective background model (Flechtner, 2007). Therefore the remaining signals in our study area can be assumed to reflect mass redistribution 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 are computed via spherical harmonic synthesis (Wahr et al., 1998). To minimize aliasing effects, algorithms for smoothing and de-striping are applied (Swenson and Wahr, 2006). Contaminations due to leakage effects from the surroundings of our study area due to the spherical harmonic truncation at degree 60 are reduced on the basis of the WaterGAP Global Hydrology Model (WGHM; Döll et al., 2003), on which the same Gaussian filter is applied (see Singh et al., 2012 for details). Fig. 4 displays the results for mass variations from GRACE in the study area. In addition to our own computations a curve based on a GRACE analysis by Kusche et al. (2009) is shown (DDK1). The CSR solution shows slightly larger amplitudes, especially during the second half of the study period. A pronounced annual cycle and a clear long term mass loss (in particular between 2005 and 2008) followed by a significant increase can be seen in GRACE. This result is in concordance with the observations from the Landsat and altimetry missions.

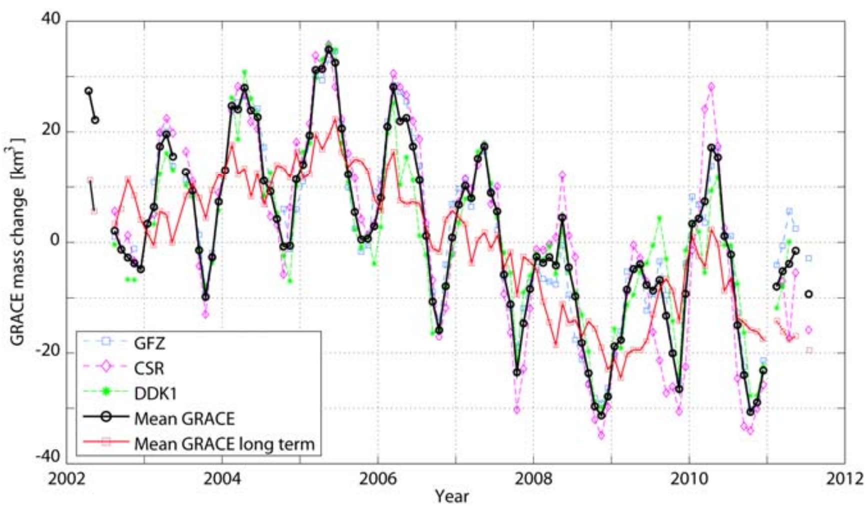

Figure 4: Variations of equivalent water mass in the Aral region from GRACE satellite gravimetry. Dashed curves: three different GRACE solutions; solid bold curve: mean of the three solutions; thin solid curve: mean long-term signal (solid bold curve reduced by seasonal variations).

Discussion

In Fig. 5 (lower panel) we compare the mean of three GRACE solutions (Fig. 4, solid curves) with water volume variations of the Aral Sea computed from altimetry and DEM. The long-term signals of the curves clearly resemble each other except for the years 2002/2003 and 2010 which were characterized by a strong inflow from Amu Darya (Fig. 5, upper panel). GRACE observations indicate that between mid-2005 and the end of 2008 approximately 60 km³ of water mass was lost in the area, while the lake itself lost only 30 km³. The total water loss of the lake between 2002 and 2009 was nearly 45 km³, followed by a gain of not more than 10 km³ in 2010. On the other hand GRACE observed 40 km³ of fluctuation in the year 2010. This comparison reveals that even though the lake produces a strong mass signal, GRACE observations are also highly influenced by other mass signals from the surrounding. GRACE contains contributions from other hydrological mass variations (e.g. in soil moisture, snow or groundwater) in the proximity of the lake whose magnitude and origin are widely unknown. Since our study area of GRACE is significantly larger than the lake itself, GRACE also observes the Priaralie delta region, compassing large parts of the two rivers Amu Darya and Syr Darya. A significant fraction of the incoming water gets diverted in this region (e.g. for irrigation purposes) and never reaches the lake. Therefore a perfect similarity of the mass signal of GRACE with the volume change of the lake cannot be expected.

The GRACE minimum in 2008 is related to a period of almost no water inflow from both rivers, and consequently there was also only little water in the surrounding area of the lake. GRACE observed a little mass gain in the year 2009, when the South Aral Sea was still shrinking, as some discharge from the Syr Darya already increased the water level of the North Aral Sea (Fig. 2).

In 2010 the GRACE followed exactly the same trend as observed by the water discharge from the Amu Darya. The integrated amount of water drained into the region by the Amu Darya and the Syr Darya was approximately 20 km³ and 10 km³ respectively. During this year GRACE observed a fluctuation of 40 km³. The difference can be accredited to corresponding changes in other hydrological compartments. During 2010 the Aral Sea also gained nearly 10 km³ 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 needed to reach the lake through the dried-out surroundings. During the summer, when GRACE 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 it's refilling throughout this period followed by an obvious decline in 2011 which is also well observed in GRACE.

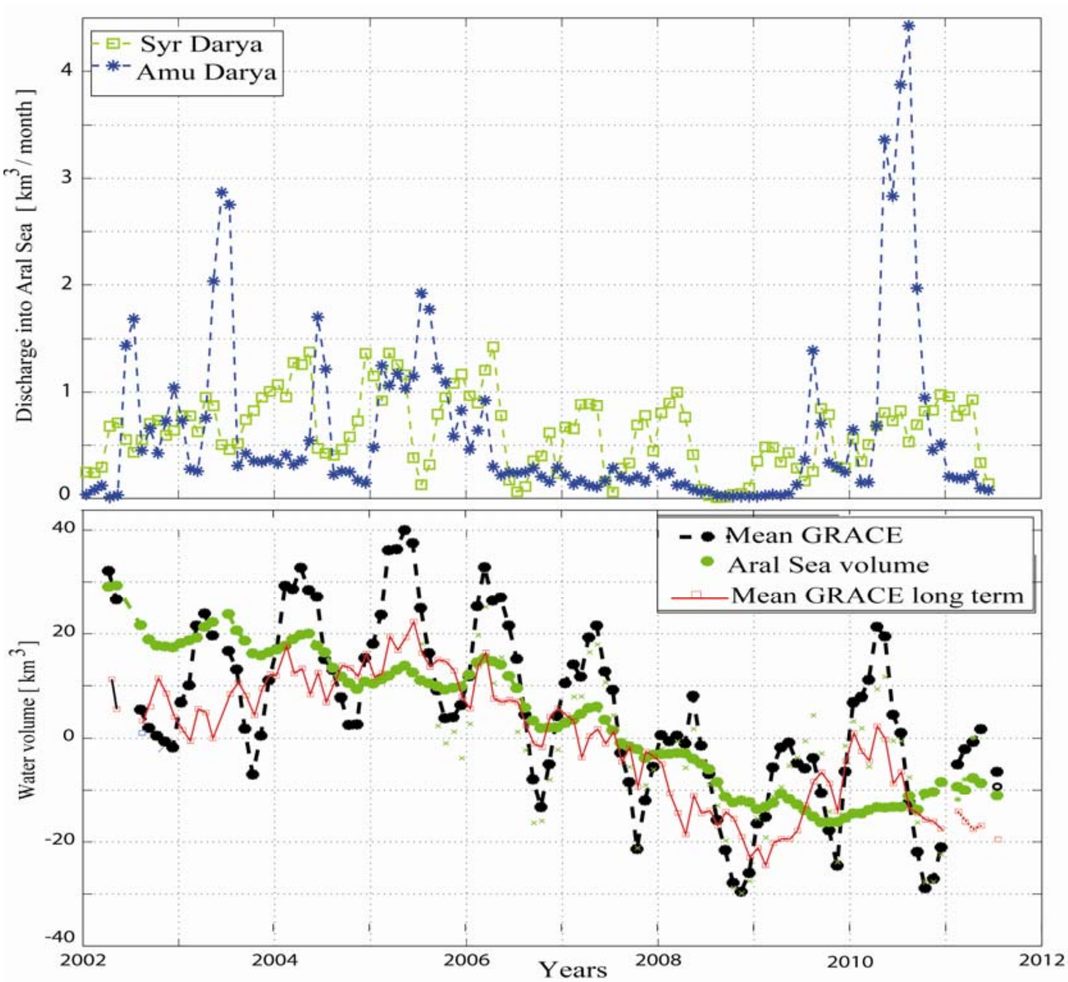

Figure 5: Lower panel: The mass change observed by GRACE and the total Aral Sea water volume change. Upper panel: Monthly discharge from Amu Darya and Syr Darya into the Aral Sea.

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 interannual signal, but the long-term characteristics 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 surrounding of 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 like ground water which is very difficult to measure globally. The combination of the multi-satellite data proved to be very effective in a comprehensive analysis of the hydrological condition of a region which otherwise is very poorly monitored by in-situ observations. As a next step the residual GRACE signal will be analysed with respect to its consistency with soil moisture, snow and ground-water changes from observations and hydrological models.

Acknowledgements

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