Assessment of Water Storage Changes Using GRACE and GLDAS

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Abstract

Water crisis is one of the main global risks that has different impacts on the society. This work uses available data and tools to track water storage changes in Iran, where lack of observations limits hydroclimatological studies and thus causes disasters. Data from Global Land Data Assimilation System (GLDAS) and Gravity Recovery and Climate Experiment (GRACE) are combined to analyze water storage changes (LWE) in Iran. GRACE signals indicate a large reduction of the water storage in North of Iran along the coast of the Caspian Sea (the largest global inland water body), where the water level has been oscillating significantly. In addition, results show the largest reduction of the water storage that occurred in the karstic and alluvial aquifers in Zagros, where groundwater is overused and many dams are constructed across the rivers. In addition to anthropogenic forcing, climate change has short- and long-term impact on the water storage. The highest correlation between LWE and climatological variables including temperature and precipitation is at 3- and 2-month lags, respectively. Natural and anthropogenic forcing caused the maximum rate of LWE reduction (maximum average reduction) in Kermanshah province, where a sequence of earthquakes occurred (in 2017, 2018, and 2019). Results highlight the main role of water storage monitoring in management plans and decision-making processes to conserve natural resources and reduce hazards.

Keywords Terrestrial water storage · Climate changes · Anthropogenic forcing · GRACE · GLDAS

1 Introduction

Many regions of the world are facing water scarcity. The water crisis as one of the severe challenges influences different sectors (e.g. environment, energy, food, health, and economy). The severity of impact of water shortages depends on different conditions such as topography

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of the domain, weather pattern over the region, and management plans, which are applied. In addition, different forcing such as human activities and climate change can add an extra pressure on water resources. For instance, an increase in temperature/evaporation and changes in precipitation distribution affect hydrological cycle and thus water resources including surface and groundwater (Moghim 2018; Liuzzo et al. 2015). Groundwater as one of the valuable resources has been decreasing significantly in many parts of the world particularly in developing countries. Use of groundwater in agriculture as the main water user has been increasing (Foster and Custodio 2019; Cai et al. 2014; Siebert and Döll 2010). Improper management and lack of correct control of resources cause sectors like agriculture overuse water resources (Salem et al. 2017). In some countries like Iran farmers dig even illegal wells to access more water for irrigation (Wright 2018; JICA 2014).

Many studies investigated water resources changes in different regions using satellites, models, and ancillary data. Rodell and Famiglietti (2001) showed the ability of the Gravity Recovery and Climate Experiment (GRACE) to estimate terrestrial water storage in Illinois. Their results indicated soil moisture and groundwater changes caused the largest water storage variations. Tiwari et al. (2011) used GRACE to evaluate water storage changes in southern India. They stated that hydrological changes have strong impact on gravity filed measured by the GRACE. They showed that the positive and negative trend of the land water storage follows the precipitation pattern. Sarachi et al. (2010) used GRACE data to evaluate groundwater changes in the Kura-Araks watershed, one of the main watersheds in southwest of Asia. Their results showed a decreasing trend of 2.5 cm per year mainly due to the overuse of groundwater. Moiwo et al. (2011) evaluated water storage variations in the Himalayas and Tibetan Plateau using GRACE and an empirical model. Their results confirmed that GRACE can detect storage changes with small random errors. Groundwater decline due to irrigation and snow cover reduction due to warmer climate are the main reasons of the downward trend in water storage of this region. Scanlon et al. (2012) used GRACE to study groundwater changes in Central Valley (an important irrigated region). They confirmed that GRACE is able to evaluate groundwater changes. Their results showed a decreasing trend in groundwater storage during drought from 2006 to 2010. Nie et al. (2018) used terrestrial water storage (TWS) from GRACE to provide global drought index (TSDI), which is correlated with other drought indicators. Their results showed TSDI can be used to monitor drought globally. Chinnasamy and Agoramoorthy (2015) used Global Land Data Assimilation System (GLDAS) and GRACE dataset to evaluate changes in groundwater that is mainly used for agriculture in Tamil Nadu (India). Their results showed a remarkable depletion rate that is larger than recharge rate. Syed et al. (2008) showed that TWS from GRACE is consistent with the corresponding simulations from GLDAS. In addition, their results revealed dominant effects of soil moisture and snowpack on TWS at low and high latitudes, respectively, while precipitation, evapotranspiration, and snowmelt showed the greatest impact on water storage variations at tropic, mid, and high latitudes, respectively. Nie et al. (2016) used 65 years of GLDAS and GRACE products to reconstruct TWS dataset in the Amazon Basin. This dataset can be used to analyze water resources changes and hazards like drought.

Iran as the second largest country in the Middle East has been experiencing water shortage that has affected ecosystem, agriculture, air pollution, health system, and society (Moghim and Garna 2019). Almost all lakes in Iran are drying including Lake Urmia (the second largest saline lake), which has shrunk by 90% (AghaKouchak et al. 2015). Water is mainly used (more than 92%) for agricultural purposes in Iran like many other countries (Shibuo et al. 2007; Hassanzadeh et al. 2012; Iran daily 2015). Lack of surface water caused people to overuse

groundwater. Overpumping of groundwater leads to land subsidence and water contamination due to saltwater intrusion. Lack of data and studies for water storage variation in Iran and many countries has led to delayed action and thus water stress. In addition, the depletion rate of water resources is accelerating due to population growth and economic development. The fast rate of water resources depletion relative to the replenishment rate affects water and food (quality and quantity), pollution (in water-air-soil), health system, and hazards. This study indicates the necessity of monitoring water resources changes using available tools (e.g. satellites and models) to prevent not only environmental degradation but also possible natural hazards (e.g. flood, drought, landslide, and earthquake).

2 Methods and Data Analysis

Water storage including surface and groundwater is the main component of the hydrological cycle (Eq. 1) that affects climate and environment.

$$P-Q-G-ET = \frac{dS}{dt} \tag{1}$$

where P, Q, G, ET, and $\frac{dS}{dt}$ refer to precipitation, runoff, groundwater, evapotranspiration, and storage changes, respectively. Lack of observations in many regions like Iran has led to underestimate the water shortage. This study uses model and satellite data to analyze water storage changes in Iran, where faces severe water scarcity.

2.1 Gravity Recovery and Climate Experiment (GRACE)

Track of water storage changes (spatially and temporally) is not feasible by field measurements in most regions due to the high cost or limited observations. Thus, satellite is one of the main tools that can be used for data collection almost in all regions. The widely used satellite that can evaluate global water storage changes is Gravity Recovery and Climate Experiment, GRACE (e.g. Wahr et al. 2004; Ramillien et al. 2004; Schmidt et al. 2006, among others). This satellite that is launched in March 2002, is a joint mission between US and German agencies (NASA and DLR).

GRACE includes two satellites that are following each other at about 220 km distance in a polar orbit of about 500 km altitude (Rodell and Famiglietti 2001). Changes in the Earth's gravity field affect the distance of the twin satellites, which is measured continuously by the microwave ranging system (Tapley et al. 2004a). These measurements can produce time-space variability of the Earth's gravity field, which can indicate the water mass variations over land (Wahr et al. 1998; Tapley et al. 2004b).

GRACE data include monthly anomalies from April 2002 to Jan 2017 that are computed relative to a time-mean baseline (2004–2009). The positive anomaly shows mass gain and the negative one indicates mass loss. Different processing centers provide three datasets including GFZ (GeoforschungsZentrum Potsdam), CSR (Center for Space Research at University of Texas, Austin), and JPL (Jet Propulsion Laboratory). This study uses average of all three datasets. Data are available at http://grace.jpl.nasa.gov and supported by the NASA MEaSUREs Program (Swenson 2012; Landerer and Swenson 2012). Missing data are filled using linear interpolation.

2.2 Global Land Data Assimilation System (GLDAS)

Global LDAS (GLDAS) is developed at the Hydrological Sciences Laboratory, NASA Goddard. It uses data assimilation to incorporate satellite and observation in advanced land surface models (LSMs) including Catchment, Noah, Community Land Model (CLM), and the Variable Infiltration Capacity (VIC) to provide land surface states and fluxes (Rodell et al. 2004). The GLDAS-2.0 uses the Princeton meteorological dataset for the forcing data (Sheffield et al. 2006), GTOPO30 for the elevation, Modified IGBP MODIS 20-category vegetation, and Hybrid STATSGO/FAO for the soil texture. The forcing of the GLDAS-2.1 are NOAA-GDAS atmospheric fields (Derber et al. 1991), GPCP (Global Precipitation Climatology Project) (Adler et al. 2003), and the AGRMET (AGRicultural METeorological modeling system) radiation fields. GLDAS provides a global dataset including radiation, heat fluxes, hydrological components, and meteorological variables at 3-hourly and monthly temporal resolution from 1948. This study uses monthly temperature, precipitation, and terrestrial water storage including soil moisture, snow water equivalent, and plant canopy surface water from April 2002 to Jan 2017. Data are publically available at https://hydro1.gesdisc.eosdis.nasa.gov/data/GLDAS. This consistent hydroclimatological dataset is widely used in water resources and climate studies particularly in the regions, where data are temporally and spatially limited (Wang et al. 2011; Mueller et al. 2011). Results of the GLDAS validation confirmed that this consistent product can be used for water resources and climate studies in Iran, where lack of observations inhibits advanced hydroclimatological studies and sustainable water resources managements (Moghim 2018).

3 Liquid Water Equivalent (LWE) by GRACE

GRACE can measure time dependent gravity field, which can represent surface mass changes and water storage variations. The measured temporal changes can yield the equivalent water thickness (LWE). The LWE, mass deviation from the baseline, can reflect water storage variation. Analysis of the data indicates that the maximum change of the water storage in Iran occurred recently in Jan 2017 (Fig. 1a).
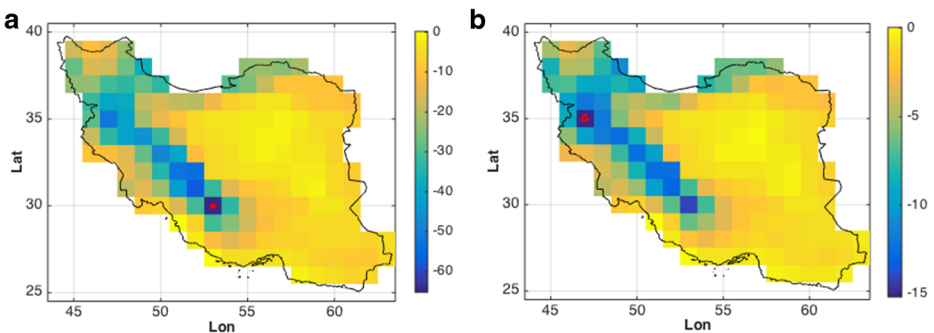

Fig. 1 (a) Water storage changes in 2017 and (b) average water storage changes. Red plus and triangle show the maximum reduction of the liquid water equivalent, LWE (cm)

Figure 1a shows the spatial water storage variation in Iran in Jan 2017. The larger negative values (blue and green color) show the areas with greater decrease in water mass. The west and north parts of Iran have experienced the most water storage reduction. The same area (red plus in Fig. 1a) in western Iran has experienced both the maximum mass gain and mass loss in different years (2005 and 2017, respectively). Indeed, the spatial pattern of water storage has completely reversed between 2005 and 2017. For instance, the western and northern Iran with the largest reduction of LWE in 2017 have experienced the largest increase of LWE in 2005. This storage variation can refer to changes in surface and groundwater, soil moisture, accumulated snow, and canopy water, which are discussed in the following sections. To monitor water storage changes in Iran, time series of the spatial average of the LWE is illustrated in Fig. 2.

The maximum increase of water storage is in March 2005. This increase can be caused by the irrigation development policy in country particularly during 2000–2005 (FAO 2008). The maximum decrease of the LWE has occurred recently (Jan 2017, the last time of the available data). Results show that the domain average of the LWE has significant downward trend (p value <0.01) with an annual reduction of about 1 cm. This decreasing trend is even more remarkable in some locations. For instance, the water storage has been decreasing about 4.5 cm per year in Kermanshah province, where the maximum average decrease of LWE occurred (see red triangle in Fig. 1b). Ashraf et al. (2017) also showed that the discharge of the Kermanshah aquifer is remarkably larger than aquifer recharge.

The annual cycle of the LWE revealed that the maximum increase of LWE in each year occurs in spring when remarkable precipitation and snow/ice melting occur. While the maximum decrease of LWE occurs in fall, when Iran has been experiencing remarkable decrease in precipitation (Moghim 2018). These positive and negative changes in LWE can reflect rainy and dry seasons. Indeed, the water storage varies in different months that can be captured from space by the signal of the Earth's gravity field changes (GRACE). To better illustrate the time-varying water storage, the domain average of the LWE is estimated for all months (Fig. 3).

Figure 3 indicates that although water storage has been decreasing in all months, the highest reduction rate occurred in Jan, Feb, and March (JFM). The positive values (increase) in LWE have changed to the negative values (decrease) almost in all months since year 2008, when one of the worst droughts (a long and intense drought) occurred in Iran and neighbors (Trigo et al. 2010; NASA 2008). This severe drought caused a significant reduction in Iran's agricultural yield in 2008 (Mesgaran and Azadi 2018; Pourbabae et al. 2014).

The spatial pattern of water storage changes is similar in all months (figures are not shown), with the maximum decrease mostly in western and northern Iran and the minimum decrease mostly in eastern Iran (see Fig. 1b).
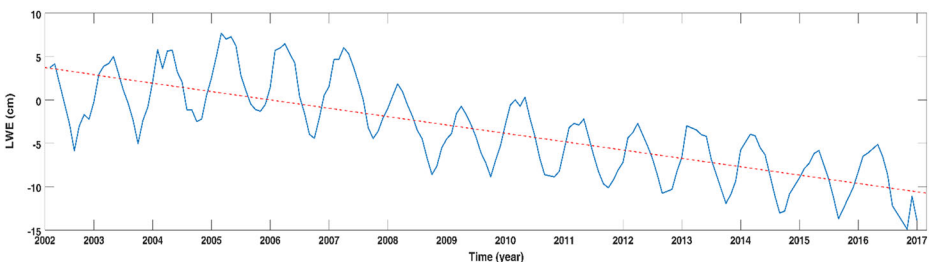

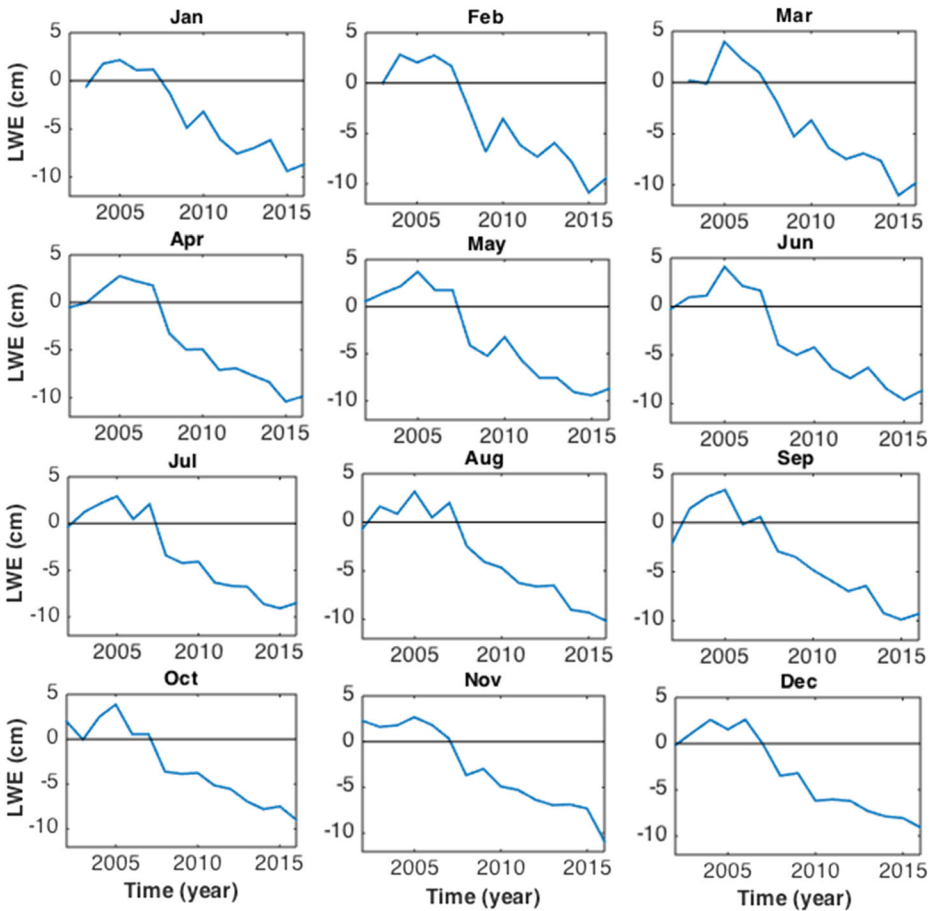Fig. 2 Time series of the domain average of the liquid water equivalent (LWE) in Iran

Fig. 3 Domain average of the liquid water equivalent (LWE) in different months

4 Terrestrial Water Storage (TWS) by GLDAS

The water storage variation can be examined by the terrestrial hydroclimatology from GLDAS. Although terrestrial water storage (TWS) includes all surface and subsurface water (e.g. surface and groundwater), GLDAS provides TWS data as

$$TWS = SM + SWE + CW \qquad (2)$$

where SM is soil moisture in all layers, SWE is accumulated snow, and CW is plant canopy surface water. To assess the trend of TWS, time series of the domain average TWS is illustrated in Fig. 4.

The domain average of TWS shows that soil moisture (SM), accumulate snow (SWE), and canopy water (CW) have been decreasing since 2002 (Fig. 4). Results illustrate that soil moisture tends to decrease about 15.5 mm per decade. The largest reduction in SM occurred in March, Jan, and Feb due to climate change. Indeed, climate change can affect soil moisture through temperature and precipitation changes. Higher temperature can increase evaporation
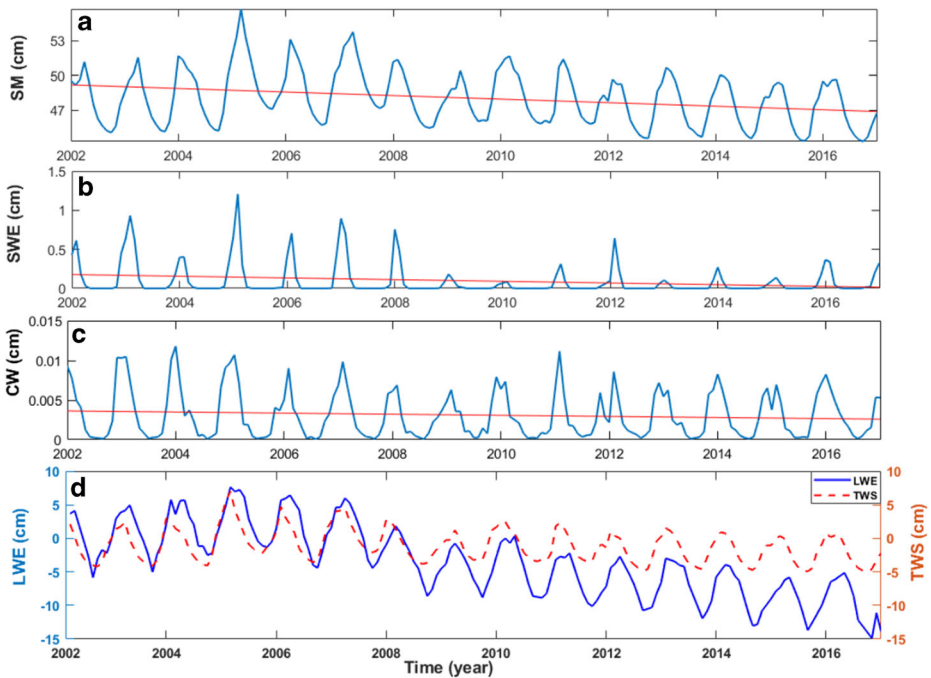
Fig. 4 Time series of the domain average TWS including (a) soil moisture SM, (b) accumulated snow SWE, and (c) plant canopy surface water CW, and (d) anomalies of the LWE (blue solid line) and TWS (red dashed line) from 2002 to 2017

and thus decreases soil moisture. In addition, climate change can affect not only frequency and magnitude of the precipitation but also types of precipitation. For instance, increased temperature can provide proper condensation conditions to form more raindrops than snowflakes, which is more noticeable in winter. The result is consistent with the downward trend of SWE, which is more remarkable in Jan, Feb, and March. Thus, terrestrial water storage including SM, SWE, and CW has the largest decline in Jan, Feb, and March.

To evaluate the relationship between water storage from GLDAS (TWS) and GRACE (LWE), monthly anomalies (Δ_{set}) of the GLDAS dataset is calculated as

$$\Delta_{set} = P_{mon} - P_{base} \tag{3}$$

where P_{mon} refers to the monthly GLDAS variables and P_{base} is the average value of the variables in the baseline period (2004–2009) that is used to derive LWE from GRACE. The domain average of the TWS and LWE anomalies from GLDAS and GRACE is illustrated in Fig. 4d. Results show that TWS and LWE are highly correlated ($\rho = 0.70$) with a decreasing trend, which has been dominant in LWE since 2008. This dominant trend can indicate that surface and groundwater that are not considered in TWS of the GLDAS data have been decreasing significantly since 2008. To further illustrate the spatial pattern of relationship between anomalies of the TWS (GLDAS) and LWE (GRACE), their cross correlation is calculated pixel by pixel (Fig. 5).

Figure 5 shows that although TWS and LWE anomalies are positively related in most pixels, there is a negative correlation in southeast, which can indicate TWS is inversely related to the water storage (LWE). To better illustrate this pattern, the cross correlation between LWE
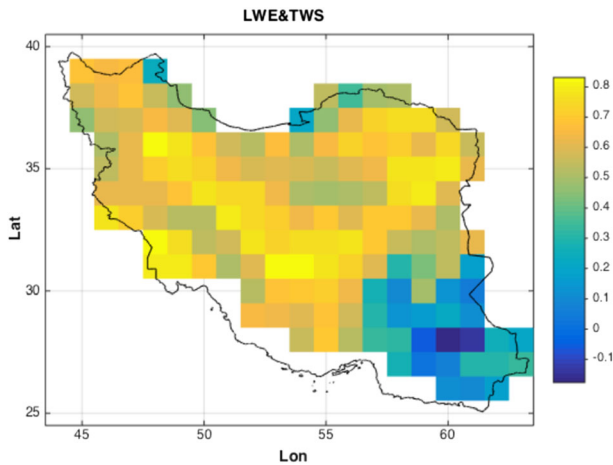
Fig. 5 Spatial pattern of correlation between LWE and TWS anomalies

and individual components of the TWS from GLDAS (Eq. 2) including SM, SWE, and CW is calculated. The highest (positive) correlation is between LWE and SM ($\rho = 0.71$). Indeed, the pattern of cross correlation between LWE and TWS closely follows that of LWE and SM. The downward trend of domain average of LWE during 2002–2008 closely follows the trend of SM, SWE, and CW, which represents the trend of the terrestrial water storage (TWS) in GLDAS. After 2008, the decreasing trend of LWE is more significant than that of TWS. This can reveal remarkable reduction of surface and groundwater since 2008, when the severe drought has occurred in Iran and neighbors. Results also confirmed that there is no mass gain (positive LWE) after 2008. The negative correlation between anomalies of the TWS and LWE in southeast area can indicate other components of the terrestrial water storage (e.g. surface and groundwater) have decreased, which resulted in LWE reduction.

5 Analysis of Changes in Water Storage

Results confirmed that water storage (surface and groundwater) has been decreasing in Iran due to natural and anthropogenic forcing. To assess impacts of climate change on this reduction, correlation between LWE and anomalies (Eq. 3) of the climatic variables (temperature and precipitation) is calculated (Fig. 6).

Figure 6a illustrates that rising temperature can reduce water storage in most regions from northwest to southeast (negative correlation). Indeed, the direct effect of climate change like increased temperature and evaporation can decrease water resources (Potter 2018). In addition to the short-term effect, climate change has long-term impact on water storage. For instance, low average precipitation (rain and snow) influences agriculture and irrigation (Moghim 2018). Lack of water storage causes farmers to overuse surface and groundwater. To further illustrate the linkage between climate change and LWE, different time-lagged cross correlations (ρ_l) between LWE and hydroclimate anomalies have been calculated as

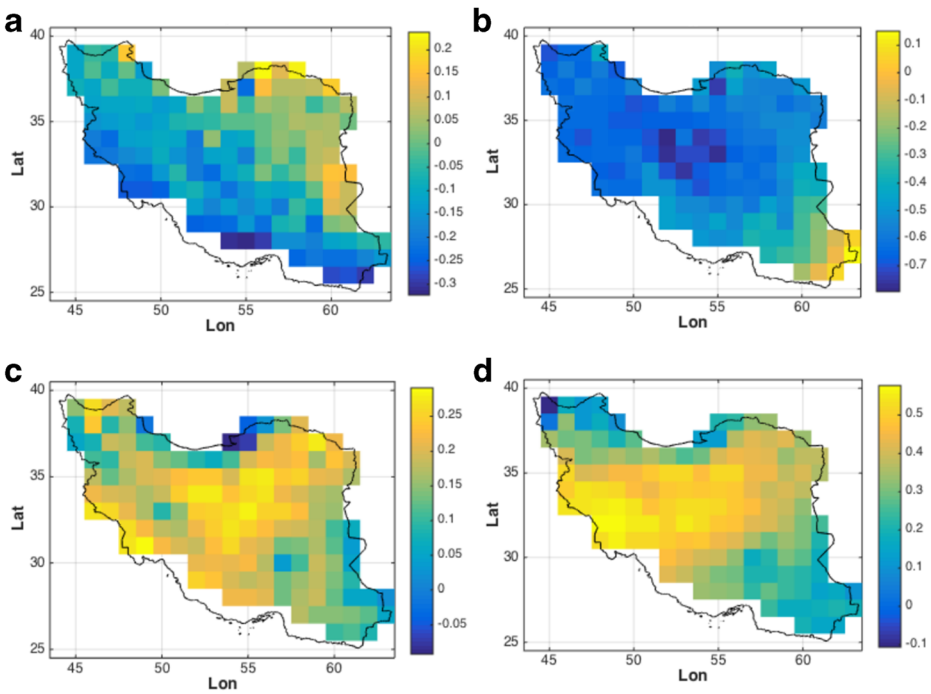$$\rho_l = \frac{cov(LWE_{t+l}, V_t)}{\sigma_{LWE}\sigma_V} \tag{4}$$

Fig. 6 Spatial pattern of correlation between LWE and (a) anomalies of temperature at 0 lag, (b) anomalies of temperature at 3-month lags, (c) anomalies of precipitation at 0 lag, and (d) anomalies of precipitation at 2-month lags

where V denotes variables (temperature or precipitation) and l refers to time lag ($l = 0{:}3$ month). The largest correlation between temperature anomalies and LWE occurred at 3-month lags ($\rho_3 = -0.62$). In other words, increased temperature shows the highest negative impact on water storage after 3 months almost in all pixels (Fig. 6b). For other climatic variable (precipitation) the largest average correlation occurred at 2-month lags ($\rho_2 = 0.50$). Results show that although the most pixels have positive correlation at lag zero and two (Fig. 6c,d), the ranges of the correlation in lag two is twice as large as lag zero (without lag). Correlation at lag zero can refer to the direct impact of climate change. For instance, precipitation increases water bodies and soil moisture instantly, while the response time of the system to increased precipitation can be longer (with lag). Indeed, required time for collection of runoff from different water sources (e.g. rain and meltwater) and running to a drainage basin varies in different locations. In addition, thin layers of snow should accumulate to be accounted for water storage. Smaller positive and negative correlation occurred in northwest, southeast, and a small domain in north of Iran, which can be due to the low precipitation and human impacts. For instance, increased precipitation in northwest and north of Iran can motivate farmers to extend agricultural production (unregulated agriculture growth) and thus use a large amount of water (surface and groundwater).

The largest decrease in LWE (blue color in Fig. 1) occurred in the karstic aquifers in Zagros, which contain base flow and groundwater (Stevanović et al. 2009; Raeisi 2008). Results confirmed that climate change (increase in temperature and decrease in precipitation/snowpack) influences water storage. For instance, precipitation can recharge

karstic aquifers and thus increase water storage, which can lead to the high positive relationship (yellowish color in Fig. 6d). In addition to climate change, human activities have significant impact on water storage. Population growth, urbanization, agriculture, dam construction, and improper management are the main factors that influence water storage. The maximum decrease of LWE during 2002–2017 occurred in Fars Province in 2017 (red plus in Fig. 1a). This reduction is consistent with the results obtained by Dashti et al. (2016). They showed negative water budget in the Kazerun Karstic Zones and Sasan springs in Fars. Water was mainly used for agriculture and irrigation (Raeisi and Stevanović 2010). In addition, dam construction across the mainstream of the rivers (e.g. Khersan Dam) affected this negative water balance. Dam influences not only the stream (e.g. regulation, fragmentation, and diversion of the rivers) but also tectonic layers of the rocks.

The increasing water demand and decreasing surface water add extra pressure on groundwater. Overpumping of groundwater affects ecosystem, water quality, and soil functionality. For instance, groundwater decline and depletion influences structure, porosity, and density of the soil. These changes are usually irreversible. For instance, recharge of aquifer cannot completely restore lost strength and flexibility of the soil. Furthermore, these changes can affect tectonic forces and thus active faults, which are able to release energy and cause earthquakes. Several strong earthquakes hit west of Iran recently. For instance, 7.3 magnitude earthquake struck off Kermanshah province in the border of Iran-Iraq in 2017 (NY Times 2017), where the maximum rate of decrease and the largest average reduction of LWE occurred (see red triangle in Fig. 1b). Earthquakes with the magnitudes of 6.4 and 5.9 hit Kermanshah again in 2018 and 2019, respectively (BBC 2018; MEHR NEWS 2019). These earthquakes caused serious injuries, mental problems, and damages, which have not recovered yet. Furthermore, the strong tectonic activity can change the structure of the aquifer zone and halt water flow (Milanovic and Aghili 1990). These serious effects can indicate that groundwater monitoring is essential for sustainable water managements to conserve natural resources.

Results showed that northern Iran has also experienced large reduction in water storage (see Fig. 1). This water storage variation can be caused by the significant oscillation in the Caspian Sea level in the north of Iran. The sea level has decreased 6.72 cm per year since 1995 (Chen et al. 2017). Furthermore, stressed aquifers due to groundwater withdrawal can result in LWE decline (Madani 2014; ECC Factbook 2018, IGRAC 2015).

Since temperature and average precipitation are projected to increase and decrease, respectively, sustainable management plans are required to mitigate damages and reduce human-induced changes in water resources and ecosystem.

6 Conclusions

People are facing water scarcity all over the world. Although the severity level varies in different countries, the consequences of water resources depletion and environmental degradation are of particular concern for almost all regions. The vulnerability to water risk that is closely linked to many sectors (e.g. energy, food, environment, health) is increased by human ignorance, population growth, natural and anthropogenic forcing, and improper management. Lack of valid and enough observations and studies in many countries particularly developing countries causes ignorance and improper managements.

This study indicates the main role of satellite and models for long-term water storage analysis particularly in the regions with limited observations. These regions usually underestimate the risks associated with water crisis.

GRACE provides liquid water equivalent (LWE) that is based on the mass difference (mainly refers to the water) from the baseline (2004–2009). LWE includes soil moisture (SM), snow water equivalent (SWE), plant canopy water (CW), surface and groundwater.

Analysis of the data from GRACE and GLDAS revealed that water storage has been decreasing in all domains particularly in west and north of Iran. The spatial pattern of the LWE reduction (from GRACE) closely follows the pattern of soil moisture (from GLDAS). In addition, the significant decrease of surface and particularly groundwater is reflected in GRACE signals.

Water storage is vulnerable to the pressures from climate change and human activities. Results indicated that climate change (e.g. increase in temperature and decrease in average precipitation) affects water storage directly (without time lag) and indirectly (with time lag). For instance, the effects of increased temperature and decreased precipitation are more remarkable after 3- and 2- month lags, respectively. The long-term effects of climate change are usually ignored and they are not well defined, which can lead to underestimate climate change consequences. Thus, nonlinear relationship and possible time lags between correlated signals need to be determined in order to reduce losses and damages.

The combined effect of climate change and anthropogenic forcing can cause water resources crisis, hazards, and disasters, which need to be defined. Limited observations in many regions highlight the role of the GRACE to clearly show changes in water storage including surface and groundwater. The large reduction of the water storage in north of Iran recorded by the GRACE can confirm significant fluctuation of the Caspian Sea level. The largest reduction of the LWE over west of Iran occurred in karstic aquifers in Zagros. Groundwater withdrawals (from aquifers and springs) mainly for irrigation resulted in significant water storage decline. Another reason of water storage reduction is dam construction that alters river's flow, riverbed, and groundwater level. These human activities can affect not only water storage and ecosystem but also tectonic plates and faults lines, which can trigger earthquake. For instance, Kermanshah province in west of Iran that has experienced the maximum rate of LWE reduction (maximum average reduction in LWE) was struck by the sequence of the earthquakes in 2017, 2018, and 2019. In addition, GRACE can be used to find other hazards such as flood and drought. For instance, a change of the positive signals of the LWE to the negative ones in all months from year 2008 can specify the intense and long drought in Iran at that time.

Results confirm that monitor of the water storage is essential not only for sustainable water management but also for alarming systems and detection of any possible disaster. Indeed, sustainable management plans should track changes in the water storage system to reduce high-impact risks and irreversible losses from water storage decline and depletion. It is important to use available data and tools to find critical regions and possible reasons of any change in the system and thus modify managements.

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