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# GRACE time-variable gravity and its application to geoscience: Quantitative analysis of relevant literature

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**Key Points:**

- Quantitative analysis of GRACE time-varying gravity in the earth sciences using literature analysis methods.
- Applications of GRACE time-varying gravimetry in the geosciences are classified and the main applications are discussed.
- The further application of GRACE time-varying gravity in earth sciences is prospected.

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**Abstract:** The Gravity Recovery and Climate Experiment (GRACE) is the most important gravity satellite to date in human history. Since its launch in 2002, GRACE time-varying gravity has had an unprecedented impact on earth science and has generated revolutionary changes. Because of natural phenomena such as climate warming, glacial melting, sea level rise, and earthquakes, earth science research has become an increasingly popular discipline in recent years. This article summarizes the importance of GRACE time-varying gravity, its application to geoscience, and its development. We analyzed the historical development and current status of GRACE time-varying gravity as well as research hotspots by searching the literature in the core collection databases of the China National Knowledge Infrastructure and the Web of Science over the past 20 years. The CiteSpace and VOSviewer software packages were applied with reference to the principle of literature metrology. Our investigation and analysis of characteristic indexes, such as the numbers of publications, co-occurrence of keywords, and co-citation of documents, uncovered the wide application and promotion of gravity satellites, especially GRACE time-varying gravity, in earth science. The results showed that the number of publications addressing GRACE data and time-varying gravity theory is increasing annually and that the USA, China, and Germany are the main producers. The Chinese Academy of Sciences, the National Aeronautics and Space Administration of the United States, and the Helmholtz Association of German Research Centres rank among the top three institutions in the world in terms of producing the most publications on this topic. We found that GRACE time-varying gravity plays unique roles in measuring changes in terrestrial water storage changes, ice and snow melting and sea level changes, and (co)seismic gravity changes, as well as in promoting other disciplines.

**Keywords:** Gravity Recovery and Climate Experiment (GRACE); Gravity Recovery and Climate Experiment Follow-On (GRACE-FO); time-varying gravity; bibliometry; mass change; CiteSpace; VOSviewer

## 1. Introduction

Geodesy is an ancient and modern basic discipline that has played an extremely important role in the progress of earth science. Through the continuous development and advancement of observational technologies, geodesy has also changed from classical geodesy to modern geodesy. One important difference between classical and modern geodetic surveys is reflected in the characteristics of static and dynamic measurements. Classical geodetic surveys previously focused on the position of the ground point, the shape of the earth, and its gravitational field (Chen JY, 2003) because of scientific and technological limitations and the observational technology of the times. The measurement results mainly described static characteristics of the earth, whereas less consideration was directed toward the characteristics of geodetic elements over time (Ning JS, 1997). However, the Earth is not a simple static system, as it is affected by external celestial and interaction forces within its own systems (Ning JS, 1997). The ground point position, the shape of the Earth and its gravitational field, and other elements change over time. Modern geodesy can detect and observe various physical quantities that change over time at different various spatiotemporal scales. Thus, scientists have completely shifted toward observing and studying earth science problems with a dynamic mindset. This shift has greatly promoted the further development and progress of Earth science.

The main feature of modern geodesy is spatial remote sensing and surveying, and it is referred to as the space era of geodesy. The continuous development of lasers, satellites, computers, artificial intelligence, and other technologies since the 1950s has led to a new era of geodesy represented by the Global Navigation Satellite System (GNSS), Satellite Laser Ranging (SLR), satellite altimetry, and satellite gravity. These developments have generated new branches in addition to geometric and physical geodetic surveys.

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Satellite or space geodetic surveys have largely influenced the study of positioning, the shape of the Earth, and changes in its gravitational field over time (Ning JS, 2003). The time-varying gravitational field of the Earth provided by gravity satellites can reflect mass migration of the Earth's surface and tectonic movement within its interior. This has revealed the nature of Earth dynamics and has become an important research topic in modern geodesy (Sun WK, 2002; Tapley et al., 2004).

The launch of gravity satellites during the 21st century has resulted in breakthroughs in observations and research into global gravitational fields, especially satellite time-varying gravity, that have promoted revolutionary progress in earth science (Xu HZ, 2001). The following gravity satellite missions have been launched: the Challenging Mini-Satellite Payload for Geophysical Research and Application (CHAMP) in 2000, the Gravity Recovery and Climate Experiment (GRACE) in 2002, Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) in 2009, and the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) in 2018. Launched in 2002 in collaboration with the U.S. National Aeronautics and Space Administration (NASA) and the German Aerospace Center (Deutsche Zentrum für Luft- und Raumfahrt, or DLR), GRACE primarily provides the time-varying gravity field of the Earth and has important application potential and value (Tapley et al., 2004). GRACE time-varying gravity has played a key role in the study of a series of changes in surface water storage, melting ice and snow, sea level changes, seismic deformations, geodesy, and geophysics (Ning JS et al., 2016; Cao Y et al., 2017; Peng C et al., 2017; Tu MZ et al., 2020; Fang TT and Fu GY, 2021).

GRACE time-varying gravity is widely applied. For example, Wahr et al. (2004) obtained the first results of time-varying gravity for the initial 11 months of GRACE and confirmed that they could be used to restore monthly changes in water storage on land and oceans with an accuracy of 1.0–1.5 cm; Han SC et al. (2006) used GRACE level-1 data to identify a gravitational change of ±15 μGal caused by the 2004 Sumatra earthquake. Chen JL et al. (2007) reported that the GRACE level-2 data used to investigate the 2004 Sumatra earthquake yielded results that agreed with those of Han SC et al. (2006) and Velicogna and Wahr (2006). Chen JL et al. (2009) used GRACE data to show that ice sheet melting in the Antarctic region is accelerating at a rate of about 190 ± 77 Gt/yr. Rodell et al. (2009) combined GRACE data and hydrological data sets, which revealed that the average rate of groundwater depletion in northwest India is 4.0 ± 1.0 cm/yr. Wang QY et al. (2016) and Ran JJ et al. (2019) applied GRACE time-varying gravity to study changes in water levels in plateau lakes and reservoirs. Sun and Okubo (2004), Heki and Matsuo (2010), Tanaka and Heki (2014), Panet et al. (2018), Zhou X et al. (2018), and others have studied seismic deformation, whereas Liu JH and Cui JM (2016) and Chang et al. (2019) have studied sediment mass accumulation in coastal oceans. Jacob et al. (2012), Gardner et al. (2013), Yi S and Sun WK (2014), and Wang QY et al. (2017) have investigated alpine snow and ice melting. Feng W et al. (2013) used GRACE satellite data and ground observation data from 2003 to 2010 to determine a groundwater loss rate of 2.2 ± 0.3 cm/yr in the North China Plain. Ciracì et al. (2020) estimated glacier losses of 29 ± 12 Gt/yr in high mountainous regions of Asia by using GRACE/GRACE-FO data. King et al. (2012), Yi S et al. (2015), Reager et al. (2016), and Chang and Sun (2021) found that rising global sea levels have recently accelerated. Wang QY et al. (2021) identified a continuous change in glacier mass of 28 ± 6 Gt/yr between 2003 and 2019 in the high mountains of Asia by using GRACE/GRACE-FO and Ice, Cloud, and land Elevation Satellite-1,2 (ICEsat-1,2) data. Feng GP et al. (2018) identified global sea level changes of 2.09 ± 0.54 mm/yr between 2003 and 2014 that were derived from changes in global terrestrial water and glacier mass determined by using the GRACE RL05 product. Duan et al. (2022) used Gravity Recovery and Climate Experiment (GRACE) data to invert the vertical crustal deformation velocity (VCDV) of the Tibetan Plateau.

In short, GRACE time-varying gravity has played an extremely important role in hydrology, seismology, geodesy, and geophysics. The number of reports describing the research application of time-varying gravity has remarkably increased. New development trends and research hotspots have been produced that have brought revolutionary changes to and had a profound impact on Earth science research. However, the comprehensive and quantitative sorting of these research hotspots and development trends is a challenge that requires reasonable and effective research tools and methods.

Therefore, we aimed to fully understand research hotspots, the status, potential, and development trends in the application of GRACE and time-varying gravity, and their roles and impact on Earth science. We used the literature visualization analysis software CiteSpace and VOSviewer to sort and summarize Chinese and international research results and to construct and visualize bibliometric networks. We also generated keyword co-occurrence, literature co-cited, and cluster maps, and we used other means to understand the status, potential, and development trends of the application of GRACE and time-varying gravity. Our results provide a reliable scientific reference for investigators of GRACE time-varying gravity.

## 2. Data Sources and Research Methods

### 2.1 Data Sources

In this study, we conducted research on the themes of GRACE and gravity, and we divided the literature data used into two parts: Chinese and international. The Chinese literature was obtained from the China National Knowledge Infrastructure (CNKI), using the search terms "GRACE" and "gravity." Because the GRACE gravity satellite was launched in 2002, we searched the Chinese literature between 2002 and 2022 and retrieved 588 results. We then manually screened and excluded conferences, newspapers, and dissertations that were unsuitable for analysis and obtained 346 Chinese articles.

We searched international literature in the Web of Science core collection database, using the search terms "GRACE" and "gravity," between January 1, 2002, and August 31, 2022. We identified 3,529 articles and analyzed the status of publications, keywords, and citations in the Chinese and international literature (Chen Y et al., 2015).

### 2.2 Research Methods

A scientific knowledge or knowledge graph is a bibliometric method that was introduced in China in 2005 (Chen Y et al., 2005); it developed rapidly and swept the country. The scientific knowledge graph can reveal development trends and research hotspots of a discipline or knowledge in a specific period and allow a better grasp of development trends (Chen CM, 2006). CiteSpace and VOSviewer are popular software packages that can create scientific knowledge graphs, and both are open-source and freely available. CiteSpace is bibliometric analysis software developed by Chaomei Chen based on the Java platform (Liao SJ and Xiao XT, 2009), and VOSviewer is bibliometric software jointly developed by Nees Jan van Eck and Ludo Waltman at Leiden University in the Netherlands (Feng TX et al., 2021). Both packages can analyze and visualize literature data and draw scientific knowledge maps, from which research hotspots and development trends can be determined. We used these two packages to map and analyze "GRACE" and "gravity."

## 3. GRACE and Time-Varying Gravity Literature Atlas Results and Analysis

### 3.1 Analysis of the History and Current Status of Articles

We explored the publication trends of literature related to the study of GRACE gravity satellites. The 346 Chinese and 3,529 international articles were drawn into a double vertical coordinate polyline chart according to the year of publication (Figure 1). The double vertical axes are convenient for comparing Chinese and international articles.

Figure 1 shows overall increasing trends in the publication of Chinese and international articles based on GRACE data and time-varying gravity, with small fluctuations. The volume of publications peaked in 2012, 2016, and 2021 and is associated with the climatic environment or natural disasters that occurred during this time frame. The overall trend indicated that the number of Chinese and international articles reached the highest point to date by the end of 2022.

Table 1 lists the 20 countries that have published the most

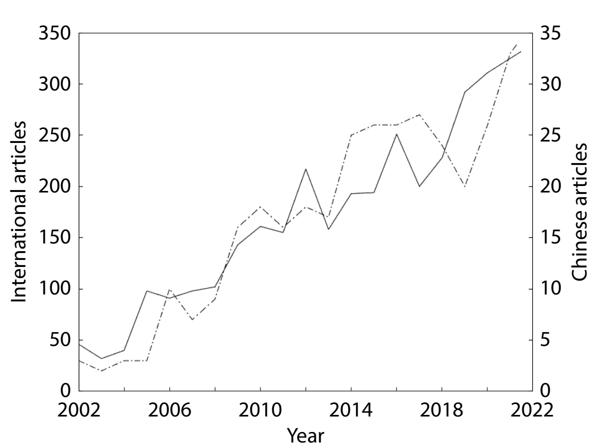


**Figure 1**. Numbers and trends of articles about GRACE and time-varying gravity published between 2002 and 2022. The horizontal line represents the trend in the number of literature studies in English, and the dotted line represents the trend in the number of literature studies in Chinese.

**Table 1.** Countries with the most published articles describing the research use of GRACE (January 1, 2002–August 31, 2022).

| Country/ region | Publications | Country/ region | Publications |
|---|---|---|---|
| The United States of America | 1,161 | Japan | 107 |
| The People's Republic of China | 976 | Switzerland | 73 |
| Germany | 695 | China Taiwan | 69 |
| France | 287 | Denmark | 68 |
| Netherlands | 257 | South Korea | 68 |
| Australia | 215 | Poland | 65 |
| England | 190 | Iran | 64 |
| Canada | 161 | Austria | 61 |
| Italy | 148 | Sweden | 57 |
| India | 108 | Czech Republic | 53 |

research articles associated with GRACE time-varying gravity. The USA, China, and Germany are the top three in terms of using GRACE gravity satellite data to study various topics. The GRACE gravity satellite was a joint launch by the National Aeronautics and Space Administration (NASA) of the United States and the German Aerospace Center (DLR), where research associated with GRACE began very early (Fang TT and Fu GY, 2021). The recent emphasis on and increased investment of China in scientific research has led to China exceeding Germany in terms of the number of relevant published articles. Table 1 also shows that many articles are generated mainly by the USA, Germany, France, the Netherlands, Australia, and other scientifically and technologically developed Western countries.

Table 2 further shows the top 20 publishers in terms of the number of articles associated with GRACE in the Web of Science. Table 2 shows that the Chinese Academy of Sciences (CAS), NASA, and the Helmholtz Association of German Research Centres ranked in the top three, with 482, 428, and 301 articles, respectively. In terms of published articles, 9 of the top 20 institutions are in the USA, and the top 4 among 20 institutions in China are CAS, Wuhan University, the University of CAS, and the Institute of Geodesy and Geophysics, CAS (presently renamed the Innovation Academy for Precision Measurement Science and Technology of the CAS).

Table 3 lists the major Chinese publishers. The results showed that CAS and its affiliated research institutes and universities are the main forces in China that conduct research on GRACE and time-varying gravity, followed by Wuhan University, which is famous for spatial information such as surveying, mapping, and remote sensing.

### 3.2 Keyword Co-occurrence Analysis

The keywords of articles are refined summaries of articles that express the theme and research focus of the articles (Liu JH and Cui JM, 2016). Counting the frequency of keywords in articles

**Table 2.** Main publishing organizations and publications in the Web of Science (January 1, 2002–August 31, 2022).

| Institute | Publications | Institute | Publications |
|---|---|---|---|
| Chinese Academy of Sciences (CAS) | 482 | University of CAS | 207 |
| National Aeronautics and Space Administration (NASA) | 428 | Centre national de la recherche scientifique (CNRS) | 194 |
| Helmholtz Association of German Research Centres | 301 | Delft University of Technology | 182 |
| California Institute of Technology | 249 | Institute of Geodesy and Geophysics, CAS | 173 |
| NASA Jet Propulsion Laboratory (JPL) | 246 | University of California System | 145 |
| University of Texas System | 242 | Udice French Research Universities | 133 |
| University of Texas at Austin | 234 | University of Bonn | 123 |
| Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences | 226 | Technical University of Munich | 121 |
| NASA Goddard Space Flight Center | 216 | University of Colorado Boulder | 107 |
| Wuhan University | 212 | University of Colorado System | 107 |

**Table 3.** Major publishing institutions in the China National Knowledge Infrastructure (January 1, 2002–August 31, 2022).[a]

| Institute | Publications |
|---|---|
| Institute of Geodesy and Geophysics, CAS | 77 |
| University of CAS | 59 |
| Wuhan University | 44 |
| Institute of Earthquake Forecasting, CEA | 22 |
| Institute of Seismology, CEA | 22 |
| Chang'an University | 20 |
| Others | 208 |

[a]CAS, Chinese Academy of Sciences; CEA, China Earthquake Administration.

leads to identifying research hotspots and development frontiers associated with GRACE research. A keyword co-occurrence map can be created by statistically calculating the frequency of keywords in an article, and research hotspots in the field can be studied by using the map. We selected the node type "Keywords" in CiteSpace and analyzed the literature exported by CNKI and the Web of Science. The 3,529 international-language articles exported from the Web of Science were directly analyzed, and those exported by CNKI required conversion into Web of Science format in CiteSpace for analysis. The other settings were as follows: study interval, 20 years (2002–2022); time slice, one year; algorithms, minimum pruning tree and pruning slice network (for English literature). Figure 2 shows the map of keyword co-occurrence.

Figure 2 shows nodes in ring style, and the node size indicates the frequency of keyword occurrence. Connections between nodes indicate the co-occurrence of keywords. In the knowledge graph network, mediation centrality represents the media capability of a node in the network corresponding to the annual ring of purple outside the annual ring node of CiteSpace. Thicker purple rings indicate nodes with higher centrality (Wang ZQ and Peng R, 2018).

The results of the literature analysis derived from CNKI (Figure 2) were roughly divided into five parts according to the frequency of occurrence of keywords. The keyword "satellite gravity" with the highest frequency of occurrence connects and communicates the entire keyword network, followed by "satellite altimetry," "gravity satellite," and "satellite observation," which represents observation technology and means, namely water storage, climate change, earthquakes, and crustal movement, as representatives of popular research content. Finally, the "Tibetan Plateau," North China, comprises a series of high-frequency research areas represented by the Yangtze River Basin and the Haihe River Basin. The keywords with the highest frequency in international literature were "GRACE," "gravity field," "time-variable gravity," "gravity recovery," and "groundwater depletion." The intermediary centrality of these words was >0.1. The international journal literature is focused more on water storage, climate, and sea level changes. Judging from the keywords of Chinese and international literature, the research hotspots of GRACE gravity satellites are mainly in the gravity field of the Earth, the time-varying gravity field, gravity field models, and using time-varying gravity information to detect changes in groundwater storage, sea levels, glaciers and the glacial isostatic adjustment (GIA), earthquake-associated issues, and crustal deformation. The hot spots of research are concentrated in the north and south poles, Tibetan Plateau, Amazon Basin, Yangtze River Basin, northern India, and China's North China Plain.

Figure 3 shows the keywords created by using VOSviewer plotted according to the co-occurrence map of time. The results show whether it is Chinese or international literature, as well as early research associated with GRACE that mainly focused on processing methods, product accuracy, spatial resolution, and gravitational field models. The results also show that recent investigations associated with GRACE have focused on changes in terrestrial water storage (Rodell and Famiglietti, 1999; Zhu GB et al., 2008), groundwater storage (Rodell et al., 2007; Strassberg et al., 2009; Famiglietti et al., 2011), and glaciers (Wang QY et al., 2021). Some of these studies used GRACE data to study worldwide seismic deformation

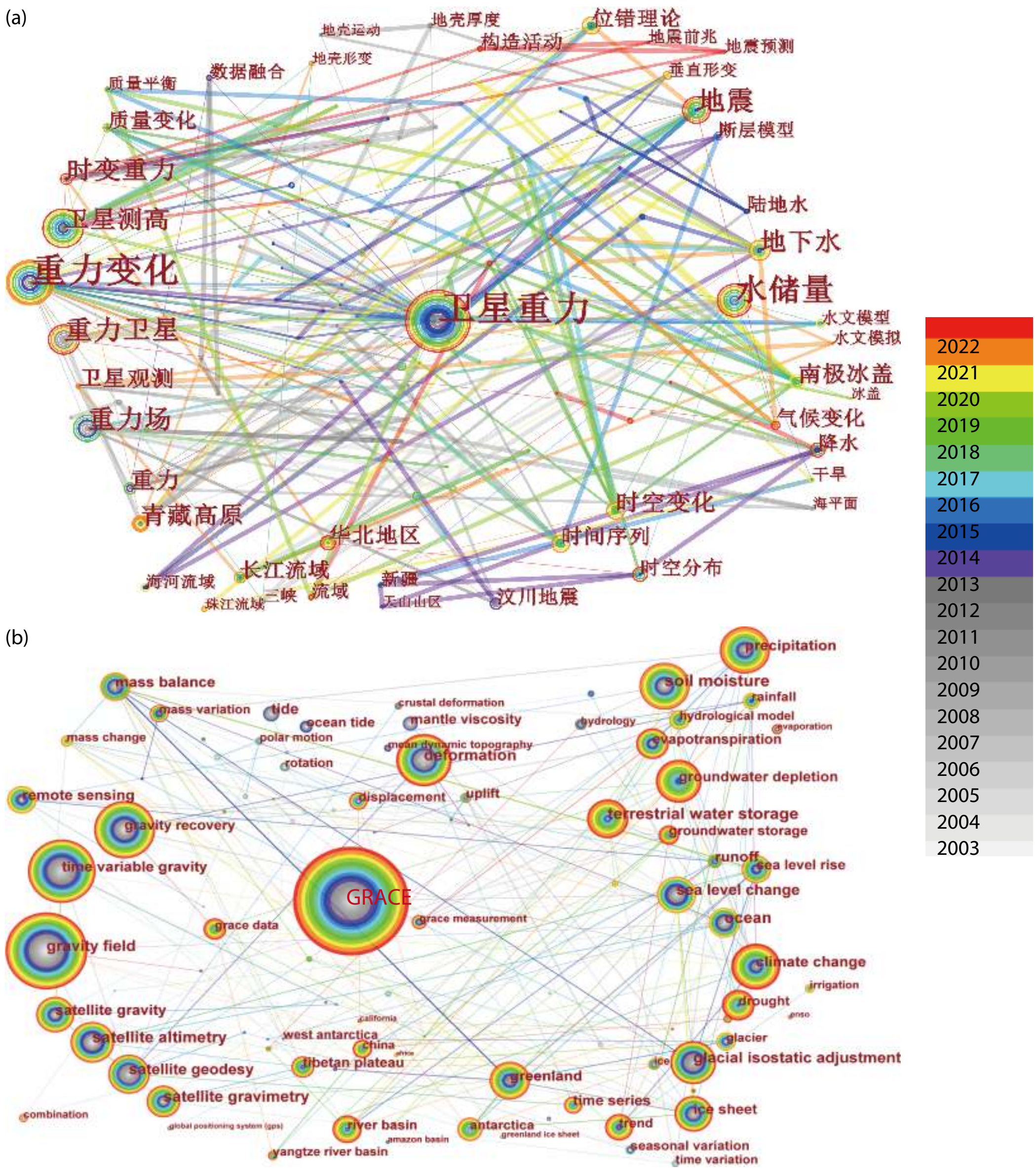


**Figure 2**. Co-occurrence map of keywords in Chinese (a) and English (b) literature. The node size represents the number of nodes associated with the keywords. Larger nodes indicate a higher frequency of corresponding keywords and connections.

and co- or postseismic gravitational changes. China is a vast country with various types of geological environments that are vulnerable to floods and droughts, earthquakes, and other natural disasters. All the situations mentioned can be studied by using GRACE observation data. The general laws of changes can be derived to reduce the adverse impacts of floods and droughts, earthquakes, and other natural disasters on society and the economy.

### 3.3 Analysis of Article Citations

Because the literature data exported from CNKI does not contain citation data, it cannot be analyzed for co-citation (citation analysis). Therefore, we analyzed only the English data. Co-citations with high mediation centrality in the citation analysis network that connect to at least two other citations are in the core position and have mediation centrality >0.1. All co-citations have a turning point and a central point effect (Lin DM and Liu ZY, 2009). We analyzed the co-citation intensity of the literature and identified the 20 articles with the highest co-citation intensity (Table 4). The average total citation intensity of these 20 articles was 147.1. Among all the nodes in the literature citation network, two had intermediary centrality >0.1. The intermediary centrality of the top 20 articles with the highest citation frequency was closest to 0.1 for article 19. Of the 20 articles, 9 were associated with changes in terrestrial and groundwater storage, as well as glacial or ice sheet mass. Four articles describe GRACE mass concentration (mascon) data, 2 each report climate changes and the shape of the earth, and 6 were other types of studies. The theme distribution shows that the launch and application of GRACE had the greatest impact on studies of global hydrological changes. This research further improved the hydrological monitoring network (Cao YP and Nan ZT, 2011), changed the profiles of hydrological application research, and created a new era. These features fully reflected the original intent and scientific goals of launching the GRACE gravity satellite (Wahr et al., 1998).

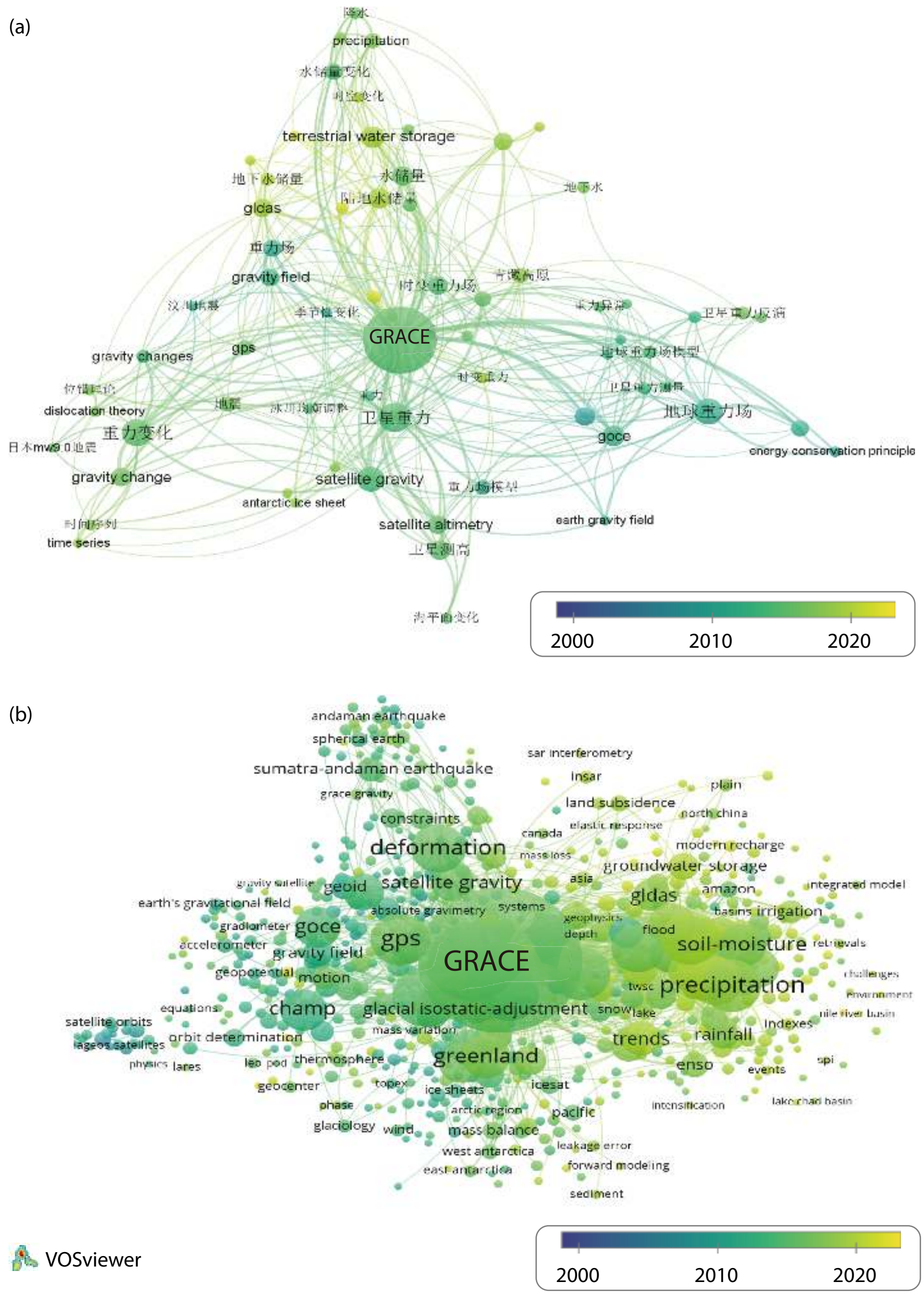


**Figure 3**. Co-occurrence heat map of keywords in the Chinese (a) and English (b) literature. Keyword popularity is indicated by the color scale. Colors closer to yellow represent recent keyword popularity.

To further understand the research topics and popular areas of GRACE time-varying gravity, we analyzed clusters of all citations in the selected literature and created an atlas of 20 clusters of citations (Figure 4). Table 5 shows the key words and information about each cluster. The clustering diagram in Figure 4 shows that GRACE research is roughly applied in the following directions: inverting the GRACE data, static gravity, constructing time-varying gravity fields (Rummel et al., 2011); determining the geoid (Cheng PF et al., 2019); using GRACE satellite data to implement mass changes in the Greenland and Antarctic ice sheet (Ramillien et al., 2006; Chen JL et al., 2006); changes in terrestrial and marine water storages, and other studies related to water storage (Tapley et al., 2004; Velicogna and Wahr, 2006); and using GRACE data to study co-seismic deformation (Heki and Matsuo, 2010; Zhou X et al., 2012) and gravitational changes (Wahr et al., 2004; Tanaka and Heki, 2014). Figure 5 shows a timeline graph of the co-cited literature analysis created based on the co-citation analysis of the literature shown in Figure 4.

Figures 4 and 5, and Table 5 show that cluster 0 terrestrial water storage is the largest, with 188 nodes, followed by clusters 1 GRACE-FO and 2 groundwater. The number of nodes was 157 and 155, respectively; the number of nodes in these three clusters exceeded 150. Almost all clusters had profile values >0.8, with the largest profile value being cluster 19 (profile value, 0.999). The average distribution of each cluster is basically between 2004 and 2016, which is the most dynamic period of development since the launch of GRACE. The popular application of rapidly updated

**Table 4.** Top 20 cited articles describing GRACE studies and their intermediary centrality (January 1, 2002–August 31, 2022).

| No. | First author | Cited literature | Co-citation intensity | Year of publication | Centrality |
|---|---|---|---|---|---|
| 1 | Save H | High-resolution CSR GRACE RL05 mascons | 264 | 2016 | 0.01 |
| 2 | Watkins MM | Improved methods for observing earth's time variable mass distribution with GRACE using spherical cap mascons | 214 | 2015 | 0.02 |
| 3 | Landerer FW | Accuracy of scaled GRACE terrestrial water storage estimates | 193 | 2012 | 0 |
| 4 | Tapley BD | The gravity recovery and climate experiment: Mission overview and early results | 186 | 2004 | 0.01 |
| 5 | Tapley BD | Contributions of GRACE to understanding climate change | 184 | 2019 | 0.01 |
| 6 | Tapley BD | GRACE measurements of mass variability in the Earth system | 169 | 2004 | 0 |
| 7 | Wiese DN | Quantifying and reducing leakage errors in the JPL RL05M GRACE mascon solution | 163 | 2016 | 0.01 |
| 8 | Swenson S | Post-processing removal of correlated errors in GRACE data | 161 | 2006 | 0.02 |
| 9 | Rodell M | Emerging trends in global freshwater availability | 154 | 2018 | 0.01 |
| 10 | Scanlon BR | Global evaluation of new GRACE mascon products for hydrologic applications | 152 | 2016 | 0.01 |
| 11 | Scanlon BR | Global models underestimate large decadal declining and rising water storage trends relative to GRACE satellite data | 149 | 2018 | 0.02 |
| 12 | Geruo A | Computations of the viscoelastic response of a 3-D compressible Earth to surface loading: An application to Glacial Isostatic Adjustment in Antarctica and Canada | 131 | 2013 | 0.01 |
| 13 | Wahr J | Time-variable gravity from GRACE: First results | 127 | 2004 | 0.01 |
| 14 | Cheng MK | Deceleration in the Earth's oblateness | 105 | 2013 | 0.01 |
| 15 | Jacob T | Recent contributions of glaciers and ice caps to sea level rise | 103 | 2012 | 0.01 |
| 16 | Rodell M | Satellite-based estimates of groundwater depletion in India | 102 | 2009 | 0.01 |
| 17 | Feng W | Evaluation of groundwater depletion in North China using the Gravity Recovery and Climate Experiment (GRACE) data and ground-based measurements | 101 | 2013 | 0.04 |
| 18 | Landerer EW | Extending the global mass change data record: GRACE Follow-On instrument and science data performance | 98 | 2020 | 0 |
| 19 | Tapley BD | GGM02—An improved Earth gravity field model from GRACE | 93 | 2005 | 0.07 |
| 20 | Velicogna I | Measurements of time-variable gravity show mass loss in Antarctica | 93 | 2006 | 0.03 |

GRACE data products during this time frame led to a golden period in the development of GRACE. After the official end of the life of the GRACE satellite, which was in service overtime, GRACE Follow-On was launched in 2018, which will surely bring various studies using GRACE and GRACE-FO data to a climax. However, the spatial resolution of GRACE data products can reach only ~350 km, which is somewhat low for studying some small space-scale physical problems, and uncertainties in satellite observations can be uncertain. Overcoming these challenges and problems requires urgent further investigation (Tu MZ et al., 2020).

Figure 6 shows a highlighted diagram of the first 20 citations obtained in the citation analysis. The academic community has a phased approach to research using GRACE data, indicating many innovative ways to use GRACE data for research (Yang XH and Sun XB, 2021) and several areas to which GRACE gravity satellite data can be applied.

## 4. GRACE Time-Varying Gravity Hotspot Applications

The results of the study in Section 3 showed that GRACE time-varying gravity is mainly applied to terrestrial water storage and changes in glacier mass, co-seismic gravity change, and long-term postseismic gravity change. Important progress has been made in these areas, which have become representative hot research topics and development directions. In this section, we discuss these areas.

### 4.1 GRACE Time-Varying Gravity Applied to Study Hydrological Variation

Changes in surface water systems are the most important component of Earth mass migration and are issues of great concern. However, because oceans cover ~70% of the Earth's surface, changes in terrestrial water storage are extremely complex. Observing changes in global or regional surface water storage is extremely difficult, and efficient techniques for global remote sensing are urgently needed. The GRACE gravity satellite can take uninterrupted, precise global measurements with coverage that provides opportunities for the comprehensive study of global changes in water systems at different spatiotemporal scales.

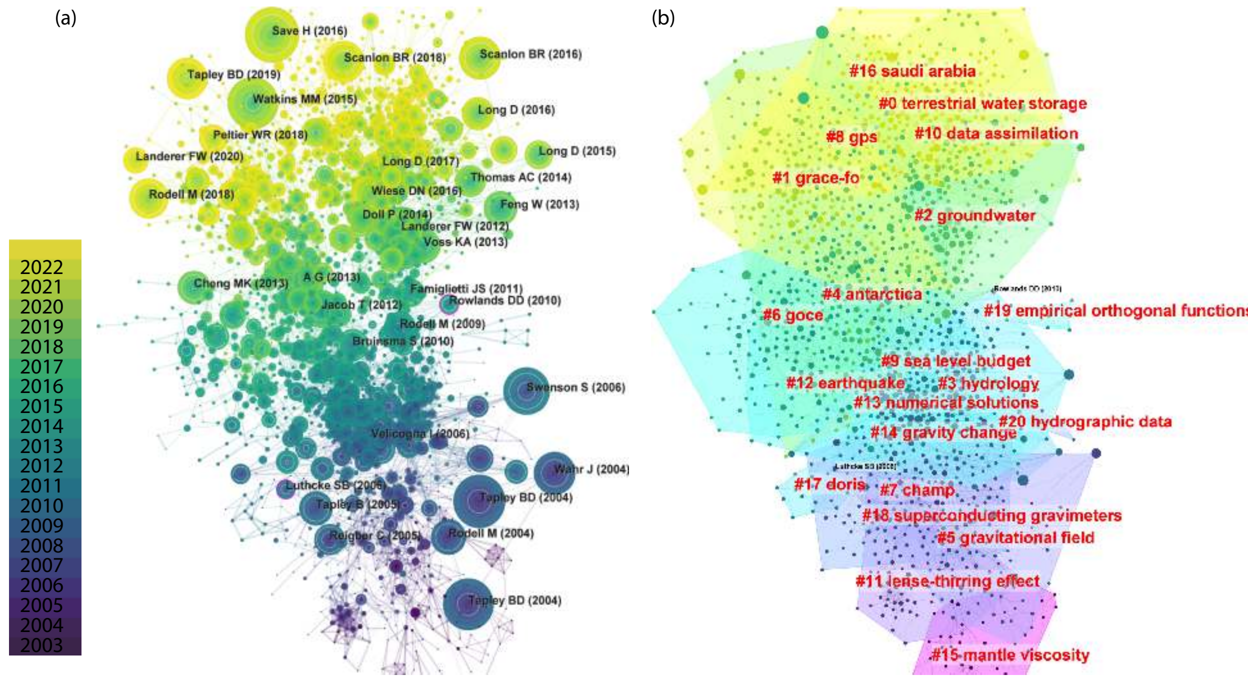


**Figure 4**. Citation co-occurrence and research clustering determined by using GRACE and time-varying gravity. Citation co-occurrence (a) and clustering (b). Text after numbers is the cluster label. The node size represents how often articles have been cited, and lines between nodes represent co-citations.

**Table 5.** Citation clustering to determine types of research that use GRACE and time-varying gravity (January 1, 2002–August 31, 2022).[a]

| Cluster ID | Clustering theme words | Nodes | CP values | Mean years |
|---|---|---|---|---|
| 0 | Terrestrial Water Storage | 188 | 0.830 | 2017 |
| 1 | GRACE-FO | 157 | 0.853 | 2016 |
| 2 | Groundwater | 155 | 0.836 | 2013 |
| 3 | Hydrology | 126 | 0.833 | 2007 |
| 4 | Antarctica | 124 | 0.768 | 2011 |
| 5 | Gravitational Field | 101 | 0.878 | 2001 |
| 6 | GOCE | 99 | 0.896 | 2001 |
| 7 | CHAMP | 90 | 0.894 | 2004 |
| 8 | GPS | 81 | 0.920 | 2015 |
| 9 | Sea Level Budget | 70 | 0.876 | 2007 |
| 10 | Data Assimilation | 58 | 0.960 | 2016 |
| 11 | Lense–Thirring Effect | 54 | 0.938 | 2002 |
| 12 | Earthquake | 50 | 0.925 | 2009 |
| 13 | Numerical Solutions | 47 | 0.918 | 2008 |
| 14 | Gravity Change | 46 | 0.916 | 2005 |
| 15 | Mantle Viscosity | 45 | 0.973 | 1998 |
| 16 | Saudi Arabia | 24 | 0.983 | 2019 |
| 17 | DORIS | 17 | 0.964 | 2007 |
| 18 | Superconducting Gravimeters | 14 | 0.995 | 2002 |
| 19 | Empirical Orthogonal Functions (EOF) | 7 | 0.999 | 2008 |
| 20 | Hydrographic Data | 6 | 0.989 | 2004 |

[a]CP, cluster profile; GOCE, Gravity Field and Steady-State Ocean Circulation Explorer; CHAMP, Challenging Mini-Satellite Payload for Geophysical Research and Application; GPS, Global Positioning System; DORIS, Doppler Orbitography and Radiopositioning Integrated by Satellite.

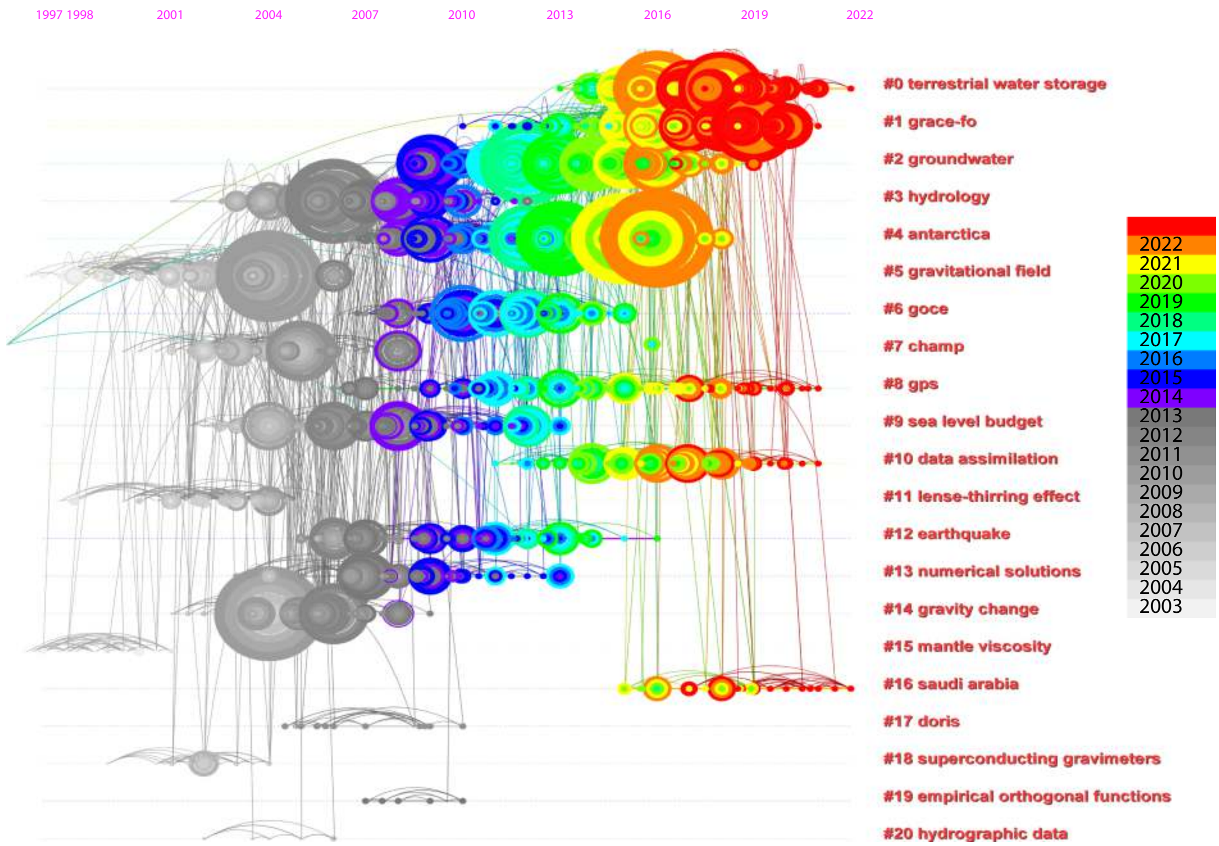


**Figure 5**. Timeline of research citation clusters based on GRACE and time-varying gravity. Cluster labels are on the right. Numbers above indicate the end of each time slice.

**Top 20 References with the strongest citation bursts**

| References | Year | Strength | Begin | End | 2002–2022 |
|---|---|---|---|---|---|
| Tapley BD, 2004, GEOPHYS RES LETT, V31, P0, DOI 10.1029/2004GL019920, DOI | 2004 | 98.47 | 2004 | 2009 | |
| Tapley BD, 2004, SCIENCE, V305, P503, DOI 10.1126/science.1099192, DOI | 2004 | 89.37 | 2004 | 2009 | |
| Wahr J, 2004, GEOPHYS RES LETT, V31, P0, DOI 10.1029/2004GL019779, DOI | 2004 | 66.98 | 2004 | 2009 | |
| Rodell M, 2004, B AM METEOROL SOC, V85, P381, DOI 10.1175/BAMS-85-3-381, DOI | 2004 | 48.41 | 2004 | 2009 | |
| Tapley B, 2005, J GEODESY, V79, P467, DOI 10.1007/s00190-005-0480-z, DOI | 2005 | 47.45 | 2006 | 2010 | |
| Velicogna I, 2006, SCIENCE, V311, P1754, DOI 10.1126/science.1123785, DOI | 2006 | 43.34 | 2006 | 2011 | |
| Swenson S, 2006, GEOPHYS RES LETT, V33, P0, DOI 10.1029/2005GL025285, DOI | 2006 | 77 | 2007 | 2011 | |
| Rodell M, 2009, NATURE, V460, P999, DOI 10.1038/nature08238, DOI | 2009 | 47.81 | 2011 | 2014 | |
| Landerer FW, 2012, WATER RESOUR RES, V48, P0, DOI 10.1029/2011WR011453, DOI | 2012 | 83.19 | 2013 | 2017 | |
| Jacob T, 2012, NATURE, V482, P514, DOI 10.1038/nature10847, DOI | 2012 | 40.66 | 2013 | 2017 | |
| Cheng MK, 2013, J GEOPHYS RES-SOL EA, V118, P740, DOI 10.1002/jgrb.50058, DOI | 2013 | 42.1 | 2014 | 2018 | |
| A G, 2013, GEOPHYS J INT, V192, P557, DOI 10.1093/gji/ggs030, DOI | 2013 | 50 | 2015 | 2018 | |
| Feng W, 2013, WATER RESOUR RES, V49, P2110, DOI 10.1002/wrcr.20192, DOI | 2013 | 43.22 | 2015 | 2018 | |
| Watkins MM, 2015, J GEOPHYS RES-SOL EA, V120, P2648, DOI 10.1002/2014JB011547, DOI | 2015 | 73.33 | 2017 | 2020 | |
| Save H, 2016, J GEOPHYS RES-SOL EA, V121, P7547, DOI 10.1002/2016JB013007, DOI | 2016 | 86.31 | 2018 | 2022 | |
| Wiese DN, 2016, WATER RESOUR RES, V52, P7490, DOI 10.1002/2016WR019344, DOI | 2016 | 50.37 | 2018 | 2022 | |
| Scanlon BR, 2016, WATER RESOUR RES, V52, P9412, DOI 10.1002/2016WR019494, DOI | 2016 | 45.87 | 2018 | 2022 | |
| Rodell M, 2018, NATURE, V557, P650, DOI 10.1038/s41586-018-0123-1, DOI | 2018 | 54.08 | 2019 | 2022 | |
| Scanlon BR, 2018, P NATL ACAD SCI USA, V115, P0, DOI 10.1073/pnas.1704665115, DOI | 2018 | 48.11 | 2019 | 2022 | |
| Tapley BD, 2019, NAT CLIM CHANGE, V9, P358, DOI 10.1038/s41558-019-0456-2, DOI | 2019 | 73.29 | 2020 | 2022 | |

**Figure 6**. Emergence of co-cited documents using GRACE and time-varying gravity for research.

Therefore, GRACE time-varying gravity has been widely applied to investigate global hydrological changes, and significant progress has been made.

Traditional methods of terrestrial water storage research include ground observation, hydrological modeling, and image remote sensing satellite inversion (Houser et al., 1998; Schmugge et al., 2002; Cao Y et al., 2017). However, ground-based observations require considerable amounts of human and material resources, and temporal and spatial resolution cannot be guaranteed. Hydrological modeling has low accuracy in terms of recognizing changes in water storage because of model uncertainty, and image remote sensing satellite inversion can observe only shallow surface hydrological changes. Therefore, traditional monitoring methods have severely hampered studies of changes in global or regional hydrological systems.

The application of GRACE time-varying gravity to global hydrological changes is mainly manifested in the study of terrestrial and marine hydrological changes. Using satellite time-varying gravity to study changes in terrestrial water storage avoids the drawbacks of traditional methods, such as manpower and material resources, while providing unprecedented possibilities for observing changes in hydrological mass in large areas and watersheds, including locations in no-man's-land. For example, Andersen and Hinderer (2005) used the GRACE gravity field for 15 months to show that GRACE can detect equivalent water height variations of 0.09 m at 1,300 km. GRACE time-varying gravity is used to invert changes in terrestrial water storage at global, regional, and watershed scales (Chen JL et al., 2005; Syed et al., 2005; Schmidt et al., 2006). Su XL et al. (2011) found that the rate of groundwater loss in the North China Plain between 2002 and 2010 was 11 mm/yr. Syed et al. (2008) and Feng W et al. (2012) identified significant changes in water storage in the Amazon Basin. Yi S et al. (2016a, b) used GRACE time-varying gravity to study changes in hydrological basin reserves in Chinese terrestrial and neighboring areas. They distinguished changes in water storage caused by human and natural factors and found reduced water storage in all but four of these hydrological basins, where it was increased. Li J et al. (2020) used the GRACE time-varying gravity model to assess mitigation effects of the North–South Water Diversion Project on water storage loss in the North China Plain. Chang L and Sun WK (2020) used GRACE time-varying gravity and other remote sensing data to determine that the Greening Project achieved an increase in green plants in Southern China. Rao WL and Sun WK (2022) combined GRACE time-varying gravity and hydrological models to determine total runoff variation problems in the Yangtze River Basin. They found that increasing runoff in the Yangtze River Basin was accompanied by a significant loss of terrestrial water. In summary, GRACE time-varying gravity has substantially promoted studies of changes in terrestrial water storage and groundwater storage in medium- and large-scale river basins, added new means of studying terrestrial hydrological changes, and created new approaches.

GRACE time-varying gravity on marine hydrological changes has mainly influenced monitoring seawater mass and changes in sea levels (Woodworth and Gregory, 2003; Cazenave and Chen JL, 2010; Chen JL et al., 2013). Tide stations are the most primitive method of monitoring sea level changes, and they are limited to coastal measurements. Thus, the status of changes at the global sea level cannot be determined. The emergence of satellite measurement technology has greatly changed the study of marine hydrological changes, and satellite altimetry technology has provided people with a more comprehensive and profound understanding of changes in sea levels (Fu LL and Cazenave, 2000). GRACE gravity satellites can assess global changes in sea levels from the perspective of mass changes. Woodworth and Gregory (2003) found that the GRACE gravity satellite confers a major advantage for studies of changes in sea levels and seawater mass. It can monitor mass changes in seawater and when combined with satellite altimetry technology, GRACE can determine corresponding geometric changes and the physical (mass) significance of sea levels. Yi S et al. (2015) and Chang and Sun (2021) supplemented GRACE time-varying gravity with measurements derived from the Array for Real-time Geostrophic Oceanography (ARGO) and found that the average global sea level increased at a rate of 3.4 ± 0.4 mm/yr between 1993 and 2019. The height of the dynamic sea surface can be detected by comparing the average elevation of the ocean surface with the geoid observed by gravity satellites. This provides important observations and references for marine physics.

In short, GRACE time-varying gravity data have played important roles in studies of changes in terrestrial water storage and sea levels and have achieved unprecedented scientific progress. The results have helped countries understand climate, drought, and other hydrological data in areas under their jurisdiction and have provided a scientific basis for social economic development and ecological environmental protection strategies.

### 4.2 Application of GRACE Time-Varying Gravity in the Study of Glacier Mass Change

In the context of global warming, the melting rates of remaining polar and mountainous glaciers on the surface of the Earth are accelerating. This has led to land ice water flowing into the ocean, then rapidly rising sea levels seriously affecting global and regional flora and fauna and causing changes in oceans and climates. According to the fifth report of the United Nations Intergovernmental Panel on Climate Change (IPCC), the global sea level increased from 0.52 to 0.98 m during the late 20th century (Church et al., 2013). However, this level remains uncertain owing to limitations of the observational technology. An important factor is that measurements of the melt rates of polar and alpine ice and snow are inaccurate. Melting rates of ice and snow closely correlate with increasing sea levels. Accurate measurements of changes in sea levels can provide constraints for melting ice and snow on land, as well as important conditions for changes in sea levels. Melting ice on land is more difficult to measure and estimate than changes in sea levels. The launch of gravity satellites, especially data products such as GRACE time-varying gravity, provides important observational techniques and inversion methods for melting land ice and snow.

As well as the GRACE time-varying gravity signal, crustal deformation, surface erosion, load effects, and groundwater changes are all influencing factors. These influences need to be isolated and removed to generate accurate information about melting ice and snow. Therefore, when using GRACE time-varying gravity, other auxiliary observation data are also required, such as GNSS measurements, weather station observations, satellite altimetry, image remote sensing measurements, and water models.

Only 2 years after the GRACE satellite was launched, Wahr et al. (2004) published the first study on the application of GRACE time-varying gravity and confirming its potential applications. Subsequently, Chen JL et al. (2006) used GRACE time-varying gravity data to determine a Greenland glacier melting rate of 239 ± 23 $km^2$/yr between 2002 and 2005. Khan et al. (2016) used the global positioning system (GPS) directly to measure the GIA of the Greenland Ice Sheet, and new estimates of glacier ablation history and GIA rise suggest that studies using the GRACE satellite missions to infer present-day changes in the Greenland Ice Sheet may have incorrectly corrected the GIA and underestimated the mass loss by ~20 Gt/yr. Ran J et al. (2018) proposed an improved mascon method to transform the GRACE spherical harmonic coefficients and thus estimate Greenland mass anomalies, showing a 24%–47% reduction in the difference between GRACE-based surface mass balance estimates and modeled surface mass balance when statistically optimal data weights are used in GRACE data processing. Velicogna and Wahr (2006) studied ice and snow melting in the Antarctic Western Ice Sheet between 2002 and 2005 and confirmed a reduction rate of 152 ± 80 $km^3$/yr.

GRACE time-varying gravity has also significantly advanced studies of melting ice and snow in the high mountains of Asia. Jacob et al. (2012) were the first to investigate the contribution of melting ice and snow from global glaciers and ice sheets in the alpine regions of Asia to increasing sea levels. Matsuo and Heki (2010) used GRACE data to determine that the average glacial ablation rate in the alpine region of Asia between 2003 and 2009 was 47 ± 12 Gt/yr. Yi S and Sun WK (2014) used the spatial domain method to measure melting ice and snow in the high mountainous areas of Asia. They identified a mixture of three types of signal sources that required careful separation. Their results showed annual glacier melts and groundwater loss in India of 35.0 ± 5.8 Gt/yr (corresponding to an increase of 0.09 mm/yr in the sea level) and 30.6 ± 5.0 Gt/yr, respectively, and a significant positive signal of +30 Gt/yr in the interior of the Tibetan Plateau. They also found that Pamir and Karakoram fluctuated in 5-year cycles, which could be explained by the effects of Arctic and El Niño-Southern oscillations. Yi S et al. (2016b) used GRACE time-varying gravity and multisource geodetic data to study melting ice and snow in the Tianshan Mountains and found accelerated melting with a stable trend. Zhang L et al. (2019) used GRACE mascon products to evaluate melting ice and snow in the Tianshan Mountains and discussed the applicability of the mascon products.

In summary, GRACE time-varying gravity products provide the means to monitor not only changes in high mountainous and polar glaciers, but also global melting snow and ice. GRACE time-varying gravity combined with satellite advanced remote sensing technology and hydrological models can precisely measure global and regional ice and snow melting rates. These data provide important references for studying global changes in sea levels, monitoring global mass migration, and gathering basic data for building global hydrological dynamic models.

### 4.3 Application of GRACE Time-Varying Gravity to Studies of Seismic Deformation

Seismic deformation is an important concern, as it is related to a series of problems, such as source mechanisms, the effects of high-magnitude earthquakes on pregnancy, and earthquake disasters. Observations of seismic deformation have traditionally relied mainly on seismology and measurements of surface deformation and gravity. Gravity measurement data play important roles in constrained fault inversion, especially for measuring large-scale mass migrations generated by earthquakes, and can more effectively constrain seismic moments. However, surface gravity measurements are influenced by low efficiency, and the surface environment interferes with generated observation data covering an area of seismic deformation. Quantitative satellite gravity data are generated using the most efficient observation techniques.

Before GRACE was launched, Sun and Okubo (2004) and Sun WK et al. (2006) found, based on dislocation theory studies, that the GRACE gravity satellite could detect seismic deformation of a shear earthquake with magnitude 9 or magnitude 7.5 tension. This finding was confirmed by data from the 2004 Sumatra earthquake, when GRACE observation level-1 data were applied for the first time to detect co-seismic gravity changes generated by an earthquake (Han SC et al., 2006). This established a precedent for studies of seismic deformation using GRACE time-varying gravity. Since then, more GRACE satellite secondary data have been used to analyze the co- or post-earthquake spatial and temporal evolution of the 2004 Sumatra, 2010 Chile, and 2011 Tohoku Japan earthquakes. (Heki and Matsuo, 2010; Matsuo and Heki, 2011; Zhou X et al., 2011, 2012). Han et al. (2014) found that postseismic gravitational changes at the epicenter remained at 6 μGal 3 years after the Great Tohoku Earthquake in Japan. Zhang GQ et al. (2015) revealed a gravity change in subduction under the Sumatra earthquake of 4.6 μGal. Heki and Matsuo (2010) confirmed this result, and their findings were consistent with the conclusions of Sun and Okubo (2004). Van Camp et al. (2017) argued that earthquakes of magnitude ≥8.0 can be observed by GRACE.

GRACE products are usually in the form of spherical harmonic coefficients. However, the conversion of spherical harmonic coefficients into corresponding physical values in practical applications requires a series of data processing and signal inversion processes that are challenging. Therefore, several international institutions have launched mascon-type products for GRACE data in the later stages (Watkins et al., 2015; Save et al., 2016). These have facilitated applied research for general users. Mascon products are similar to or better than spherical harmonic coefficient products at the basin scale (Scanlon et al., 2018).

Jing et al. (2019) compared trends in terrestrial water storage anomalies among various GRACE products on the Tibetan Plateau, and the results showed large differences. Zhang et al. (2019) studied the performance of Center for Space Research (CSR)-mascon products at small spatial scales and local mass sources and concluded that CSR-mascon products can recover gravity changes in terrestrial water storage anomalies greater than 3° × 3°. However, their performance was worse than that of spherical coefficient products in areas less than 3° × 3°. Zhang et al. (2020) further investigated the application of isoseismic gravity signals to the deformation of large earthquakes of mascon product after magnitude 9.0 on three levels (e.g., 2004 Sumatra earthquake, 2010 Chile earthquake, and 2011 Tohoku earthquake in Japan) and three smaller earthquakes. They mainly compared gravity signals, spherical harmonic coefficient products, and dislocation theory solutions among mascon products. Their findings showed that mascon products contained almost the same information as spherical harmonic coefficient products. Mascon products enhanced the co-seismic gravity change signal at ~2-fold the strength of spherical harmonic coefficient products. However, mascon products cannot fully recover complete seismic deformation information because they still have a finite spatial spectral domain that limits their use. This conclusion serves as a reminder for other scholars to use mascon products with caution.

In short, GRACE satellites have unique advantages for detecting major earthquakes, especially subduction zones or seismic deformations in seas. They provide observation capabilities with global coverage of seismic deformation. Appropriate data processing can identify co- and postseismic gravity changes caused by large earthquakes and lay a foundation for studying long-term changes in gravity after earthquakes. However, care is required when using GRACE mascon products to study seismic deformation.

In summary, since its launch, GRACE time-varying gravity has conferred unprecedented technological advantages and application potential on studies of global changes at different spatiotemporal scales, and many fields have progressed rapidly. GRACE time-varying gravity has been widely applied to studies of global changes that have led to breakthroughs in knowledge of hydrological mass, melting ice and snow, and seismic deformation. With the optimization of satellite orbits and improved observation accuracy, the measurement accuracy and spatial resolution of the next generation of gravity satellites will further improve. The ability to detect global mass migration will be strengthened, and knowledge of seismic deformation, land water storages, and changes in sea levels and glacier mass will reach new peaks through studies using GRACE time-varying gravity.

## 5. Summary and Conclusions

We statistically analyzed the scientific literature regarding GRACE time-varying gravity published in CNKI and the Web of Science Core Collection Database and summarized the development, current status, and characteristics of time-varying gravity research using GRACE. Analyses of characteristic indexes, such as numbers of published articles, the co-appearance of keywords, and literature co-citation revealed the wide application to Earth sciences and the promotion of gravity satellites, especially GRACE time-varying gravity.

We found that trends in the numbers of articles published in Chinese and international literature have increased rapidly since the GRACE satellite was launched in 2002. Predictions indicate that the total number of articles published in 2022 will reach a peak at the end of the calendar year. The USA, China, and Germany published the most articles. The Chinese Academy of Sciences, NASA, and the Helmholtz Association of German Research Centres ranked among the top three in terms of article volume. From the perspective of clustering keyword evolution, current research hotspots using GRACE are focused on changes in water storages, glacier and ice sheet mass, seismic and co-seismic gravity, post-earthquake mass migration, and sea levels. The frontier and hotspot of research is GRACE time-varying gravity combined with positive and inverse means to obtain time-varying gravity information about the Earth that can then be applied to water storage changes. Gravity satellites have improved the accuracy of global static gravity field models (Tapley et al., 2005).

GRACE time-varying gravity is uniquely useful to studies of changes in terrestrial water storage, melting snow and ice, sea level changes, and co-seismic gravity and has played important roles in the application and promotion of various other fields. We discussed the three most prevalent problems investigated by using GRACE time-varying gravity compared with traditional methods, the roles of GRACE time-varying gravity in these investigations, and the revolutionary impact and changes it has brought. Further development of gravity satellite observation technology will lead to more in-depth investigations into these physical problems. Such investigations will deepen understanding and improve global awareness of these issues.

It should be pointed out that, except for the three hotpots mentioned, many other hotspots of satellite gravity research have been carried out in the last years, and further research will be performed in the future. That is, the raw data processing and time-varying gravity field recovery of GRACE and GRACE-FO is also an important area of satellite gravity data research. In addition, GRACE, like any gravity satellite, is affected by the inaccuracy of the Atmosphere and Ocean De-aliasing model, which limits further improvement of the accuracy of the time-varying gravity field model. In addition, simulation research on the gravity satellite payload design, raw data processing, time-varying gravity field recovery, and next-generation gravity satellites are hotspots in satellite gravity research.

Because the orbital height of gravity satellites is limited, a signal attenuation phenomenon in the gravity field in the orbit prevents satellites from sensing higher degree components in the field. Therefore, current gravitational satellites such as GRACE can observe only low-degree and medium-degree gravity fields, and the corresponding surface space resolution, such as that of GRACE time-varying gravity, is relatively low, at ~350 km. This is a key weakness of satellite gravity measurements, as it limits application to physical problems at the surface at small spatial scales. The solution to these issues will depend on innovations in the next generation of gravity satellites, such as technologies for lower and multi-orbit, multi-satellite joint measurements and solutions.

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