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Shuang Yi

Application of Satellite Gravimetry to Mass Transports on a Global Scale and the Tibetan Plateau

Doctoral Thesis accepted by
the Chinese Academy of Sciences, Beijing, P.R. China

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Supervisor's Foreword

I am honored to be invited to write a preface for Dr. Shuang Yi's thesis. In 2010, when he graduated from Wuhan University, his university teacher (my friend) recommended him to apply for my postgraduate student, hoping to study for a degree under my guidance. At that time, I just returned home from University of Tokyo, hoping to have excellent students, which is what all teachers hope. Generally speaking, I believe that the students recommended by university teachers should be excellent, as evidenced by his entrance examination and five years of postgraduate life.

At that time, the gravity satellite GRACE had been continuously observed for nearly ten years, providing good global time-varying gravity field data. Dr. Shuang Yi had a better understanding and mastery of GRACE knowledge and basic data processing skills during his university years. We chose the use of GRACE observation data to study surface mass transports as his research direction. On the basis of learning and mastering the achievements of predecessors, he quickly entered the fast lane of scientific research after questioning, exploring and thinking for a certain period of time.

In the past five years, he has made important contributions to global sea level change, land water storage changes in Asia and China, glacier change in Asia and tectonic process in eastern Tibet, and has made great achievements in scientific research. The research results become the main content of this paper, including the new GRACE data processing method, the new discovery of the mass transfer problem at different spatial scales from global to local. Therefore, this book should be a good reference for those who want to use this method to recover and invert the mass changes of any spatial and temporal scales of the earth surface.

Dr. Shuang Yi has two characteristics that make him outstanding in peers. The first one is his enthusiasm and keen insight into science. The second is his technical expertise. Based on his performance on different research topics, he can quickly learn new skills or cooperate with relevant scholars. He is good at mathematics and has a strong background in geophysics and geodesy. Especially, he thinks positively and is good at new discoveries. His doctoral dissertation and published journal papers show that he was a very excellent Ph.D. graduate. When he graduated from the University of Chinese Academy of Sciences (2016), he won the title of outstanding postgraduate, the President Award of the Chinese Academy of Sciences, and the outstanding postgraduates in Beijing in 2016. His Ph.D. dissertation was one of 100 Excellent Ph.D. Dissertations of the Chinese Academy of Sciences in 2017. This is really a reward for his talent, his perseverance and unremitting efforts.

I spent five years with Shuang Yi to study the application of time-varying gravity field. This is an important period for us to grow up. When I look back, it is like yesterday. I would like to thank him for his patience, diligence and creativity while working with me. Dr. Shuang Yi has become a very qualified young professional scientist. I believe he will make great achievements in scientific research.

Thanks Springer for offering the opportunity to publish the book. I hope this is the new beginning of Dr. Shuang Yi's academic career. I wish him a bright future.

Beijing, P.R. China
January 2019

Prof. Wenke Sun

Abstract

Human activities, climate change and environmental change are three tight coupling elements, whose relationship and evolution will impact the sustainability of human society. Since the three elements involve a global scope of diversified influences, it is impossible to be estimated by traditional techniques. The three elements are always accompanied by mass transports in the water circulation system, e.g., water exchange between the land and the ocean and glacier melting, so satellite gravimetry provides an effective approach to systematically evaluate them. The Tibetan Plateau is one of the most tectonically active regions of the world, and studies concerning its dynamics will benefit the understanding of continental collision and plateau building. Here, we also adopt satellite gravimetry to investigate the mass transports caused by melting glaciers and tectonic process in the Tibetan Plateau. The topics of the dissertation include four parts:

1. Global Sea Level Change
   The global mean sea level (GMSL) dropped 5 mm due to the 2010/11 La Niña and has been rising rapidly ever since. A reconciled sea level budget, based on observations by Argo project, altimeter and gravity satellites, reveals that the true GMSL rise has been obscured by ENSO-related fluctuations and its rate has increased since 2010. After extracting the large fluctuation brought by the land water storage, it is shown that the GMSL has been rising at a rate of 4.4 ± 0.5 mm/yr for more than three years, due to acceleration in the rate of both land ice loss and steric change.
2. Terrestrial Water Storage Changes in Asia and China
   A study of the Asian region shows that its TWS decreased 1500 km^3 during the period of 2003–2009 but exhibited marked stability during 2010–2014, which was concurrent with an alternation between dry and wet years. This slowdown of water depletion can also be found in the water-depleting basins of Indus, Ganges, Tigris-Euphrates and Haihe. To correct for the climate-driven effect, we put forward a linear relationship between the variations of water storage and precipitation. We find that the anthropogenic water depletion in the Asia, Tigris-Euphrates and Ganges regions has been greatly over-estimated due to the

perturbation of precipitation. Our study on the water storage in China shows that tremendous mass accumulation has occurred from the Tibetan Plateau (12.1 ± 0.6 Gt/yr) to the Yangtze River (7.7 ± 1.3 Gt/yr) and southeastern coastal areas, which is suggested to involve an increase in the groundwater storage, lake and reservoir water volume and the flow of materials from tectonic processes. Additionally, the mass loss has occurred in the Huang–Huai–Hai-Liao River Basin (−10.2 ± 0.9 Gt/yr), the Brahmaputra–Nujiang–Lancang River Basin (−15.0 ± 1.1 Gt/yr) and Tianshan Mountains (−4.1 ± 0.3 Gt/yr), a result of groundwater pumping and glacier melting.

3. Glacier Change in the Asian High Mountains
   A new spatial inversion method and 10 years of satellite gravimetry data are used to evaluate the glacier melting rate in high mountain Asia (HMA). We find that in HMA area there are three different kinds of signal sources that should be treated together. The two generally accepted sources, glacier melting and Indian underground water depletion, are estimated to change at the rate of −35.0 ± 5.8 Gt/yr (0.09 mm/yr sea level rising) and −30.6 ± 5.0 Gt/yr, respectively. The third source is the remarkable positive signal (+30 Gt/yr) in the inner Tibet Plateau, which is challenging to explain. Further, we have found that there is a five-year undulation in Pamir and Karakoram, which can be explained by the influence of Arctic Oscillation and El Niño-Southern Oscillation. We carefully examine glaciers in Tianshan, which have been steadily decreasing with a value of −4.0 ± 0.7 Gt/yr during 2003–2014 by space gravimetry and −3.4 ± 0.8 Gt/yr during 2003–2009 by laser altimetry.
4. Tectonic Process in Eastern Tibet
   Various geophysical observations, including seismological and magnetotelluric imaging, have implied that the deep crust beneath eastern Tibet may be partially melted and flowing faster than the brittle upper crust. However, it is still unclear how much faster the deep crust is flowing. We use modern geodetic observations, satellite gravimetry and GPS, to give a constraint in the flow rates of the middle and lower crust (MLC). Therefore, two plausible models for the surface uplift are discussed under the geodetic constraints. In the deep crustal flow model, the crustal thickening requires the horizontal flow rate of the MLC to be 330–670% of the rate of motion of the upper crust. In the hybrid model of deep crustal flow and convective removal, the Moho is uprising and there is a weak or moderate (130–250%) deep crustal flow, which comes with a weak or moderate crustal thickening beneath eastern Tibet.

Keywords Satellite gravimetry · Mass transports · Tibetan Plateau · Sea level rise · Terrestrial water storage · Glacier melting

Published Work

Parts of this book have been published in:

1. **Yi, S.**; Sun, W. Evaluation of glacier changes in high-mountain Asia based on 10 year grace rl05 models. ***Journal of Geophysical Research: Solid Earth*** 2014, 119, 2504–2517.
2. **Yi, S.**; Sun, W.; Heki, K.; Qian, A. An increase in the rate of global mean sea level rise since 2010. ***Geophys. Res. Lett.*** 2015, 42, 3998–4006.
3. **Yi, S.**; Wang, Q.; Sun, W. GRACE captures basin mass dynamic changes in China based on a multi-basin inversion method, ***Journal of Geophysical Research: Solid Earth*** 2016, 121, 3782–3803.
4. **Yi, S.**; Sun, W.; Feng, W.; Chen, J. Anthropogenic and climate-driven water depletion in Asia, ***Geophys. Res. Lett.*** 2016, 43, 9061–9069.
5. **Yi, S.**; Wang, Q.; Chang, L.; Sun, W. Changes in mountain glaciers, lake levels and snow coverage in Tianshan monitored by GRACE, ICESat, altimetry and MODIS, ***Remote Sensing*** 2016, 8, 798.
6. **Yi, S.**; Freymueller, J.; Sun, W. How fast is the middle-lower crust flowing in eastern Tibet? A constraint by geodetic observations, ***Journal of Geophysical Research: Solid Earth*** 2016, 121, 6903–6915.

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Thanks to my bachelor supervisor, Prof. Shen Wenbin from Wuhan University, for helping me during my university studies and bachelor's thesis, so that I could quickly find a direction in my graduate research. After my graduation, I met Prof. Shen occasionally in many meetings, and he often cared about my research and life. It is because of his recommendation that I can have the honor to meet Prof. Sun.

I would like to thank other teachers who instructed and helped me, including Prof. Kosuke Heki from Hokkaido University (who is also the host professor of my first postdoc), Prof. Chen Jianli from the University of Texas and Prof. Jeff Freymuelley from the University of Alaska. The cooperation and communication with them inspired me to have a deeper understanding of my research. I am grateful to the University of Chinese Academy of Sciences for providing me with a comfortable research and living environment. I would also like to express my gratitude to my classmates for their frequent communications and discussions.

Thanks to my high school classmate, Dr. Cao Tao, who graduated from the Shanghai Institute of Organic Chemistry and is currently working at Riken, Japan. Thank you for supporting me in my most difficult time. He made me not alone on the road of scientific research.

Finally, I want to thank my family. Thanks to my parents, sister and brother-in-law for their understanding, support and encouragement in my research work. I would also like to thank my wife, Dr. Cai Yan. She and science complete my life.

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