NASA Science Mission Directorate Research Opportunities in Space and Earth Sciences
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GRACE-FO Science Team

The Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) twin satellites launched on a SpaceX Falcon 9 rocket from Vandenberg Air Force Base, sharing their ride into space with five Iridium NEXT communications satellites. The mission is a partnership between NASA and the German Research Centre for Geosciences (GFZ). GRACE-FO is a successor to the original GRACE mission, which operated from 2002 to 2017. Like its predecessor, the two identical GRACE-FO satellites function as a single instrument. By tracking changes in their separation distance, the satellites are able to map regional gravity changes.

The main focus of this ROSES element is to engage the science community in developing methodologies that will enable the production of a continuous mass change measurement record among the GRACE and GRACE-FO observations. A high priority focus is data assimilation of GRACE and GRACE-FO data in a broad range of Earth System models and modeling systems. Projects for data assimilation work identify the expected advances and qualify the benefits of the improved models. Selected projects will advance the development of new methods, algorithms, and models for the exploitation of gravity field observations to be made by GRACE-FO, and future space based gravity field missions for the broad spectrum of Earth system science challenges. Finally some activities seek to develope techniques and algorithms capable of bridging gravity field observation across different gravity missions.

Overall funded research focuses on the identification and quantification of atmospheric, oceanographic, hydrospheric, cryospheric and solid Earth structure and dynamics manifested in the GRACE observations.

NASA received 38 proposals and selected 21 projects, including a project submitted by a foreign institution. The investigators associated with the selected proposals become members of the GRACE-FO science team for the term of their grants. The program will support 20 projects with a total funding of approximately $13.5 M for a period of 4-years.

Claudio Abbondanza/Jet Propulsion Laboratory
Assimilating GRACE-FO Observations into JPL TRF Determination
19-GRACEFO19-0003

As society faces the long-term consequences of an unrelentingly warming climate, one of the primary goals of Geodesy is to provide accurate Terrestrial Reference Frames (TRFs) through which the complex spatio-temporal patterns of the Earth system and global change signals can be meaningfully inves-tigated and interpreted. Quantifying sea level rise imposes stringent requirements on the accuracy (<1mm) and stability (<0.1 mm/yr) of global TRF products. With a stability of ~ 0.5 mm/yr, standard frame products such as International Terrestrial Reference Frame (ITRF) are characterized by errors whose magnitude roughly constitutes 15% of the global sea-level rise signal (~ 3 mm/yr). To allow for an unambiguous interpretation of global change signals, TRF accuracy needs to improve dramatically.

As an official International Earth Rotation and Reference System (IERS) TRF combination center, the Jet Propulsion Laboratory (JPL) combines Very Long Baseline Interferometry (VLBI), Satel-lite Laser Ranging (SLR), Global Navigation and Satellite Systems (GNSS) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) observations to determine its own frame products (JTRF). Unique to JPL is the ability of constructing, through a sequential estimation approach, sub-secular frames based on the adoption of stochastic models, like a random walk, to represent the non-secular and non-seasonal fluctuations of the solid Earth deformation.
In our predecessor ROSES2015-GRACE investigation "Improving the Terrestrial Reference Frame with GRACE", we examined the use of GRACE data to characterize the stochastic models adopted in our filter. GRACE data were used to infer the station-to-station correlations of the non-secular and non-seasonal component of solid Earth deformation and to augment the correlation matrix of the position process noise within our assimilation procedure. Complemented with GRACE-inferred correlations, JPL frame products are less affected by spatial and temporal gaps in the observations thus leading to an improved determination of geocenter motion.
In this follow-on investigation, we will expand the use of GRACE/GRACE-FO data into our sequentially estimated TRF. GRACE-FO represents an exceptional opportunity to extend the space gravimetry data record, thus providing new ways to elucidate the solid Earth deformation related to surface mass transport in the seasonal, inter-annual and even decadal frequency bands. We will use GRACE/GRACE-FO data to reconstruct loading-induced deformations that will be utilized as "input control" on the non-secular fluctuations of the frame inputs during the time update step of the sequential estimation. Rather than directly constrain the non-secular fluctuations to the values determined by space gravimetry, we will use GRACE/GRACE-FO data as models of solid Earth elastic displacements which will be corrected against closeness to observations (i.e. frame inputs) during the data update.
In our TRF assimilation study we will examine Level 2 GRACE/GRACE-FO data, as well as higher-resolution MASCON solutions. Also, taking advantage of the Bayesian framework offered by our sequential approach, we will compare GRACE/GRACE-FO data to publicly available geophysical models of loading elastic displacements and will determine in a rigorous statistical fashion the posterior probability associated with each data type.

Edward Beighley/Northeastern University
Global River Baseflows Derived from GRACE/GRACE-FO
19-GRACEFO19-0015

GRACE/GRACE-FO Total Water Storage Anomalies (TWSA) will be used to derived global river discharges (Q) based on new Q-TWSA relationships. Research OBJECTIVES are: (1) develop a global river network based on MERIT Hydro and integrate spatial-temporal datasets for relevant climate and watershed characteristics; (2) derived Q-TWSA relationships using in-situ streamflow; (3) generalize relationship coefficients from gauged sites to estimate coefficients for ungauged river reaches based on remotely sensed (via TRMM/GPM, MODIS, SMAP) quantities that capture relevant climate and watershed characteristics (precip., land surface temp., land cover, veg.

indices, soil moisture, topography); (4) produce a global river discharge product consisting of GRACE/GRACE-FO derived monthly discharges and associated uncertainties for individual river reaches for the period 2002-2022; (5) assess derived discharges using in-situ gauges and discharges derived from two models (VIC and CLM) within NASA’s NLDAS/GLDAS; and (6) assess the value of GRACE/GRACE-FO derived discharges in a hydrologic modeling application on the Mississippi River Basin.

We will evaluate research hypotheses and science questions related to: (A) understanding how the magnitude and rate of change in discharge is controlled by changes in total water storage; (B) understanding how climate and watershed characteristics and watershed drainage area influence the relationship between monthly river discharge and TWSA’s, (C) assessing GRACE/GRACE-FO derived discharges with in-situ and hydrologic model derived discharges, and (D) quantifying the value added (i.e., improved model performance) by using GRACE/GRACE-FO derived discharges in hydrologic modeling applications with limited in-situ streamflow.

The proposal addresses two GRACE-FO Science Team priority topics: (i) assimilation of GRACE and GRACE-FO data in a broad range of Earth System models and modeling systems, and (ii) use of GRACE and GRACE-FO data sets in multidisciplinary and multisensor studies. It also addresses NASA's Strategic Goal 2.1 to ""Advance Earth System Science to meet the challenges of climate and environmental change"" by developing and providing: (1) global monthly river discharges based on GRACE/GRACE-FO TWSA’s that are independent of a hydrologic model, providing discharges that can be used for understanding the hydrologic cycle in regions with limited in-situ data, parameterizing hydrologic models, assessing Earth System Model or remote sensing-based discharges, or as input to discharge algorithms being developed for future missions (e.g., Surface Water and Ocean Topography, SWOT); (2) new insights on the value of GRACE and GRACE-FO TWSA’s in hydrologic modeling applications; and (3) online user tools to explore GRACE and GRACE-FO TWSA’s, derived river discharges, and a suite of multisenor (TRMM/GPM, MODIS, SMAP) derived climate and watershed characteristics spatially averaged throughout the global river network.

While discharges will be produced globally with assessments at available stream gauge locations, detailed assessments will be performed throughout the Mackenzie, Mississippi, Susquehanna, Amazon, Congo, and Mekong River Basins using both in-situ and model derived discharges. Two model derived discharge series will be developed based on VIC and CLM surface and subsurface runoff from NASA’s GLDAS coupled with lateral/channel routing from the Hillslope River Routing (HRR) model. For the Mississippi and Susquehanna Rivers, VIC and CLM runoff from NLDAS will also be used. The selected study basins provide gradients in climate and watershed characteristics and the degree of water storage regulation; and build on prior PI research efforts. These gradients provide an experimental framework for assessing GRACE/GRACE-FO’s ability to capture discharges-storage behavior across a range of hydrologic systems and scales.

Don Chambers/University Of South Florida, Tampa
Determining Decadal Variability in Deep Ocean Currents from GRACE and GRACE Follow-On
19-GRACEFO19-0006

The long record of ocean bottom pressure provided by GRACE (March 2002- June 2017) and the continuing GRACE Follow-on (GRACE-FO) mission (March 2018 – present) provides unique insight into important aspects of ocean circulation. Gradients of ocean bottom pressure reflect changes in the strength of deep ocean currents that have major impacts on the Earth's climate. In particular, North Atlantic Deep Water (NADW) flowing south on the east coast of North America comprises the majority of the lower limb of the Atlantic Meridional Overturning Circulation (AMOC). Antarctic Bottom Water (AABW) flows north along ridges east of the Drake Passage at depths greater than 4000 m before it spreads throughout the world's oceans. The fronts and jets that are colloquially called the Antarctic Circumpolar Current (ACC) flow eastward through the Southern Ocean all the way to the seafloor, separating warmer waters in sub-tropical gyres from Antarctica. Little is known about the interannual to decadal variability of these bottom currents and how they are changing in a warming climate, primarily because they are so difficult to measure directly with in situ measurements.

In previous work, we have shown that GRACE is capable of measuring interannual variability in the integrated ACC transport, as well as interannual and decadal trends in NADW currents that are consistent with the AMOC upper limb transport. However, there are still remaining issues in the GRACE data that we can correct in order to improve the estimates. The primary issues are: 1) increasingly large non-oceanographic signals related to gravity, rotation and deformation (GRD) (also known as self-attraction and loading) from changes in mass on land and icesheets, and 2) leaked land hydrology signals and distortions in the North and South Atlantic due to opposite pressure signals on the western continental shelf and slope due to the anticorrelated signals in the upper and lower limbs of AMOC. In this work, we propose to create a new ocean-specific set of GRACE and GRACE-FO mascons that are corrected for both GRD signals and global mean ocean mass, and also utilize known oceanographic correlations to better constrain mascons along the North and South American continental shelves and slopes, as well as around large seamounts in the Southern Ocean. These improved mascons should allow a better determination of ACC and NADW currents, especially during the latter GRACE record when only one set of accelerometers was operating.

Additionally, we will test a new theory that relates form drag (proportional to horizontal gradients in bottom pressure across seamounts) at the Kerguelen Plateau and Drake Passage with a combination of signals from ACC and AABW currents. Using GRACE and GRACE-FO bottom pressure, ocean state estimates, and atmospheric wind stress products, we will derive a linear relationship between ACC and AABW current variability, form drag across the Kerguelen Plateau and the Drake Passage, and zonally-integrated wind stress in order to measure for the first time variability in AABW east of the Drake Passage. The sign of this transport (increasing or decreasing) over 20-year

record of GRACE + GRACE-FO will have important implications on the rate of heat sequestration in the deep ocean.

Jianli Chen/University of Texas, Austin
Multi-Scale Validations of GRACE/GRACE-FO Time-Variable Gravity Solutions
19-GRACEFO19-0012

One of the major challenges to GRACE and its FO mission is how to validate GRACE-derived time-variable gravity solutions, due to the lack of independent measurements of mass (or gravity) changes that are comparable to GRACE spatial resolution on a global basis. We propose to validate GRACE and its FO (hereafter noted as GRACE) time-variable gravity solutions at both global and regional scales using independent satellite altimeter measurements, Argo ocean temperature and salinity observations, and climate model predictions. GRACE satellite gravimetry has offered the means to quantify global mean ocean mass (GMOM) change from a completely new perspective. Satellite altimetry has been a well-established technique for accurately measuring global sea level change since 1992. The global mean sea level (GMSL) change is driven by two major forces, GMOM change due to water mass redistribution between the oceans and land (including polar ice sheets), and ocean volume or density change (the so-called steric sea level change) due to temperature and salinity variations. The difference between satellite altimeter and Argo derived GMSL change represents GMOM change.

We propose to quantify GMOM change from both GRACE and altimeter measurements minus Argo steric changes (Altimeter-Argo) over the period from 2005 (when the Argo array's global coverage became relatively complete and homogeneous) to the present (i.e., the FO time period). The Altimeter-Argo GMOM estimates provide independent validation of GRACE measurements at a global scale. This is particularly important considering that the low-degree spherical harmonic (SH) coefficients from both GRACE and its FO mission are subject to relatively large uncertainty (the FO low degree terms, e.g., degrees 2 & 3 zonal terms show substantially large uncertainty due to an accelerometer issue). The Altimeter-Argo GMOM estimates also offer a means to validate long-term variability of GRACE degree-2 and order-1 terms, which are related to the reference mean pole in the pole tide model used in GRACE data processing. Accurate GRACE GMOM estimates also rely on independent determination of geocenter motion (SH degree-1 terms), absent in GRACE solutions. The Altimeter-Argo GMOM estimates can help discern the accuracy of geocenter motion values used in GRACE estimates.

We propose to validate GRACE regional-scale mass changes through the study of Caspian Sea level (CSL) change using independent satellite altimeter measurements and other data. The Caspian Sea is the largest enclosed inland body of water on Earth, with a surface area of ~ 371,000 km^2. CSL has undergone substantial fluctuations during the past several hundred years. Over the GRACE (GRACE+FO) period, CSL change show large long-term variability (up to -9 cm/yr) and seasonal oscillations with peak-to-peak variations up to 40 cm. CSL change is dominated by water mass change, and steric effects probably play only a minor role. Without adequate direct temperature and salinity observations of the Caspian Sea available, we propose to use Argo measurements over the open ocean (in similar latitude zone and climate region) to estimate the steric contribution. The particularly large magnitudes and spatial scales of CSL change and the

well-defined geographical location of this water body within an arid continental region offer a unique means for validating GRACE observations at regional scales.

The proposed research activities at global and regional scales can help validate not only GRACE measurements and solutions themselves (e.g., different spherical harmonic and mascon solutions), but also different post-processing techniques that have been developed to estimate mass change from GRACE gravity or mascon solutions, including different spatial smoothing (and decorrelation filtering) and leakage correction methods.

Minkang Cheng/University of Texas, Austin
Understanding Decadal Variations of the Earth System from SLR, GRACE and EOP Data
19-GRACEFO19-0007

During the 15 years of its mission, the GRACE mission has successfully achieved its goal of dramatically improving our knowledge of the Earth's mean gravity field and measuring the mass flux and water transport between atmosphere, ocean, and land and the mass balance of ice sheets. GRACE Follow-on has now been orbiting since May 2018 to continue the measurements of the global mass flux for Earth system science. The geodetic satellite laser ranging (SLR) tracking data spanning over 45 years have recorded the global nature of the large-scale long-wavelength changes in the Earth's gravity field. In addition, SLR-based estimates of C20 have been essential because of the significant spurious variations apparent in the GRACE estimates. Analysis of SLR data for providing estimates of the C20 coefficient and geocenter motion (equivalent to degree 1) is therefore important for the various GRACE science applications. This research effort has been supported by NASA grant NNX08AE99E, NNH10ZDA001N and NNX16AF20G, as science team member, which will end on February 2020. The satellite laser ranging (SLR) data has also, over the past four decades, provided long-term, stable determinations of the Terrestrial Reference Frame (TRF) with accurate ties to the Earth's center of mass. In the past, we have found a significant deceleration and decadal variations in the Earth's oblateness and the equatorial ellipticity. Earth's equator is flattening with a linear rate of 0.014 mm/yr and a significant westward/eastward drift of the orientation of the principal axis of the least moment of inertia is observed and estimated to be 0.27 arc sec/yr. Part of the observed decadal variations could be attributed to the response of the solid mantle to the dynamic processes in the outer core. The objective of this proposal is to analyze the long-term SLR data for determining the lowest degree portion of the time-varying gravity field. In particular, (1) continue to provide a consistent time series of C20 and geocenter motion to support the GRACE and GRACE-FO science application, and (2) study the decadal variations in the Earth's dynamical oblateness, the Earth's figure axis, the equatorial ellipticity and the drift of the principal axis of the least moment of inertia. The objective is to improve our understanding of the large-scale long-wavelength mass exchange within the Earth system as part of the global water and energy cycles based on improved long-term time series of the degree 2 geopotential coefficients from SLR, GRACE and EOP (Earth orientation parameters) data, and the non-hydrostatic pressure data at the core-mantle boundary (CMB) derived from geomagnetic data assimilation. The results from this proposed research could potentially provide additional constraints on mantle rheology, the core dynamical state and core-mantle interactions.

Barton Forman/University of Maryland, College Park
Bridging Spatial and Temporal Gaps in Terrestrial Freshwater Understanding using GRACE/GRACE-FO

19-GRACEFO19-0027

The central objective of this proposal is to optimally merge gravimetric retrievals collected by GRACE and GRACE-FO in conjunction with satellite-based leaf area index (LAI) retrievals and ground-based global positioning system (GPS) observations of land surface deformation. An ensemble-based data assimilation framework within the NASA Land Information System (LIS) will be used to condition an advanced land surface model on the available observations. In addition, an explicit representation of groundwater pumping (and its subsequent application at the land surface for agricultural irrigation) will be integrated into the land surface model in order to better predict and characterize terrestrial water storage across regional and continental scales. The overarching goal of this proposed research is to provide a conditioned model estimate of terrestrial water storage (and its constituent components) that is superior to either the model or observations alone.

Terrestrial water storage (TWS) retrievals derived from GRACE and GRACE-FO will be used to better characterize vertically-integrated hydrologic stores of snow, surface water, near-surface soil moisture, root-zone soil moisture, and shallow groundwater. The proposed univariate and multivariate (joint) assimilation experiments will effectively yield estimates of TWS at finer spatial and temporal scales than what currently exists. In addition, the cohesive framework within LIS enables the utilization of the observations where available (in space and time) in order to provide a physically-consistent, global estimate of TWS while providing a means of bridging the gap between the GRACE and GRACE-FO missions.
Science questions addressed as part of this proposal include, but are not limited to:

1. Can the joint assimilation of ground-based GPS observations, LAI retrievals, and TWS retrievals within a data assimilation framework lead to enhanced model estimates of TWS (and its constituent components)?
2. Can the proposed assimilation framework effectively add vertical and/or temporal resolution to the gravimetric retrievals that currently does not exist?
3. Can the joint assimilation of GRACE+GPS+LAI help inform (and potentially correct) land surface model limitations related to anthropogenic activities (e.g., groundwater pumping; surface water abstractions)? Does the explicit inclusion of groundwater pumping further inform (and correct) these land surface model limitations?

NASA Land Information System (LIS) output across the globe – with and without assimilation – will be evaluated via comparison to: 1) Global Runoff Data Centre (GRDC) database observations of river runoff, 2) observations of snow water equivalent (e.g., SNOTEL) and snow depth (e.g., GSOD), 3) observations of near-surface and root-zone soil moisture from the International Soil Moisture Network (ISMN), and 4) observations of groundwater depth (e.g., USGS, Indian Ministry of Water) as well as against a number of satellite-based retrievals of soil moisture and snow water equivalent where such ground-based observations do not exist.

This project is relevant to a number of current and planned NASA research interests. Namely, the investigation is designed to examine the role of land surface hydrologic processes in the Earth system and offers promise toward improving their representation in global models. Further, this project will leverage a suite of existing NASA data products, and therefore, add value to previously incurred costs associated with measurement collection. Finally, the proposed research will reduce uncertainties in NASA LIS, and therefore, reduce uncertainties in the model-based products generated by NASA.

Benjamin Hamlington/Jet Propulsion Laboratory
Extension of Satellite-Measured Terrestrial Water Storage Using a Multivariate Approach
19-GRACEFO19-0004

Since 2002, the Gravity Recovery and Climate Experiment (GRACE) mission has provided accurate measurements of variations in Earth's gravity field, leading to new insights on a wide range of topics. Particular advancement has been made in our understanding of how water moves through the Earth System, with implications for understanding climate and human impacts. Despite the unquestionable value of the measurements it has collected, the GRACE mission ended in mid-2017, leaving the data record at only 15-years in length. To continue the record started by GRACE, the GRACE Follow-On (GRACE-FO) mission launched in 2018 with new data soon to be publicly released. However, the relatively short record from the two missions coupled with the gap between them still present challenges in examining long time-scale climate processes. One of the most significant is the difficulty in quantifying and extracting natural variability in TWS, which can vary on timescales ranging from subseasonal to decadal and longer. A long and continuous record is necessary to do this, something the current satellite record of TWS falls short of.

Here, we propose to apply a novel multivariate data analysis technique to meet the following objectives: 1) Extend the monthly data record of satellite-measured TWS back to 1979 to produce a dataset appropriate for studying lower-frequency natural variability. 2) Fill gaps in the GRACE record to provide a continuous dataset of TWS from 2002 to 2017 that is consistent with GRACE measurements. 3) Produce maps of TWS with monthly updates that that can be used to compare to GRACE-FO observations, potentially assisting in ongoing verification and validation efforts.

The technique we will apply is based on a multivariate cyclostationary empirical orthogonal function (CSEOF) reconstruction technique, originally developed to improve the understanding of 20th century sea level by leveraging other available observations. In this study, by establishing statistical and physical relationships between GRACE measurements of TWS and measurements of other climate variables, it is possible to reconstruct the TWS record into the past, fill gaps in the current record, and extend the record up to present day. In particular, we will use observations from satellite altimeters from 1993 to present, precipitation data from the Global Precipitation Climatology Project (GPCP) from 1979 to present, and surface temperature data from the GISS

Surface Temperature (GISTEMP) analysis from 1979 to present (to match the length of the GPCP dataset) to reconstruct TWS. By finding spatial patterns in those datasets that have a similar temporal evolution to patterns from GRACE, it is possible to extend the GRACE record to cover the same time period as the leveraged datasets. This technique has been demonstrated with sea level reconstructions and a methodology for estimating uncertainty on the resulting dataset has been developed.

The work proposed here has a number of potential benefits. One of the timeliest is the ability to provide a comparison dataset for the ongoing GRACE-FO observations. Given the lack of overlap between GRACE and GRACE-FO, validating the new observations is a challenge without the ability to make comparisons with other data.Scientifically, a longer record of TWS allows for the study of longer-term natural variability that could impact the way we interpret the current GRACE record, and allowing for sea level budget studies that yield new insights into global mean sea level change.

Shin-Chan Han/The University of Newcastle
Analysis and Modelling of Solid Earth Deformation Caused by Earthquakes Using GRACE-FO L1B (Microwave and Laser) and L2 Data
19-GRACEFO19-0010

The GRACE era (2002–2016) has been a rare opportunity from which we can study the Earth's response to great earthquakes across diverse tectonic settings at time scales from days to decades. The team has been analysing GRACE L1B and L2 data for gravity change after ~20 great (Mw ≥ 8.0) earthquakes, and reported regional-scale coseismic and postseismic gravity changes after 2004 Sumatra-Andaman, 2004 Macquarie, 2005 Nias, 2006/2007 Kuril, 2007 Bengkulu, 2009 Samoa-Tonga, 2010 Maule, 2011 Tohoku-Oki, 2012 Indian Ocean, and 2013 Okhotsk earthquakes. These events include shallow megathrust, strike-slip, normal faults ruptures, as well as one deep source (~600 km) source earthquake. We constrained the seismic source and long-wavelength slip distribution, elastic lithosphere thickness, sea water redistribution, and the Earth's rheological structure, to predict gravity changes and deformation from these earthquakes. The postseismic gravity changes are prolonged for many years and expected to continue during the GRACE Follow-On period (from 2018). In most cases, the cumulative postseismic gravity changes already exceeded the magnitude of coseismic changes.

In this follow-up study, we will finalize the earthquake models and the regional rheology models using a self-consistent approach and the entire GRACE datasets. We aim to validate new time series of GRACE Follow-On gravity solutions at early stage using our earthquake gravity change models and provide the earthquake correction models to the GRACE Follow-On project, in order to make GRACE and GRACE Follow-On data available free of earthquake signals to the scientific community. Our comprehensive products can be used to improve quantification of secular trends in the ocean and the cryosphere, and of hydrological mass transport, from GRACE and GRACE Follow-On measurements. We will examine additional great earthquakes which occurred in 2014-2018 (e.g., Chile (2), Mexico, deep Fiji), in addition to any future events that will

mandate investigating GRACE and GRACE Follow-On data for postseismic gravity changes observed systematically from the previous events.

During the present investigation, we found significant changes in KBR inter-satellite ranging caused potentially by the Earth's free oscillations for a few days after the 2004 earthquake and by transient density perturbation along with seismic wave propagation. We also found unambiguous signature of gravitational perturbation associated with tsunamis triggered by the 2004, 2010, and 2011 earthquakes. Seismologists demonstrated that transient gravity signals promptly excited by earthquakes should be useful for determining the size of fault ruptures faster and better than the present methods relying exclusively on seismic data; this new approach is potentially helpful for earthquake early warning. However, ground-based seismometers and gravimeters are paradoxically less sensitive to gravity changes due to significant cancellation by inertial (ground) acceleration. In principle, there is no such cancellation with a space-borne gravity sensor, and such transient phenomena can be better analysed with L1B data. We will develop innovative techniques of exploiting the GRACE and GRACE Follow-On L1B data to retrieve physical processes causing transient gravitational perturbations. We will evaluate the new capability of GRACE and GRACE Follow-On microwave and laser tracking data for studying transient gravity changes after earthquakes and tsunamis.

The continuous multi-decadal observations of GRACE and GRACE Follow-On gravity change will provide indispensable observations to reveal how the solid Earth responds to earthquakes at seismic (seconds to hours) and decadal time scales and to advance our understanding of earthquakes, thus helping mitigate earthquake hazards. Therefore, our investigation will deliver significant achievements towards NASA's solid Earth program and on-going and proposed missions.

Erik Ivins/Jet Propulsion Laboratory
Glacial Isostasy and Space Gravimetry
19-GRACEFO19-0001

The Gravity Recovery and Climate Experiment (GRACE), and the follow-on mission GRACE-FO, measure the change in the Earth's gravitational potential field. This mission has been seen by the Earth sciences community as providing a revolution in our understanding of global, large scale, mass transport. This transport largely involves the water masses of the hydrosphere, polar ice sheets and changes in ocean mass. Space gravimetry has provided a key element: a decadal scale time window for measuring several of the most important elements of climate change: the melting of continental ice, secular changes in the hydrological cycle, and the increase of water mass in the oceans. One part of the secular change in mass detected by GRACE and GRACE-FO owes to glacial isostatic adjustment (GIA). This phenomenon is caused by the slow relaxation of the solid Earth in response to the gravitational disequilibrium experienced by the Earth after great ice sheets expanded over North America and Eurasia, and Greenland and Antarctic ice sheets expanded and then melted away in about ten thousand years. This expansion caused sea-level to drop by 125-135 meters during an extended period some

30 - 21 thousand years ago. The gravitational change signal caused by this ongoing solid Earth relaxation process is substantial: causing the geoid to change by as much as 2 mm/yr over continental scales, with vertical land motions reaching 20 mm/yr. While this signal is exponentially decaying over hundreds to thousands of years, it appears as a secular, linearly varying, field in GRACE monthly time series. This change in the Earth's potential field caused by GIA can also dominate the sea-level changes measured either by ocean altimeters or coastal tide gauges. Modeling GIA requires assembling global records of paleosealevel, proximal glacio-geological records of the formerly expanded ice sheets, and geodetic measurements, including terrestrial gravity and crustal uplift data.

Since the emergence of global space geodesy in the 1980's and 90's, GIA models have relied on assembling these data sets, and forward modeling gravitational-viscoelastic deformation and coupled sea-level, and then determining which sets of parameters best fit the constraining data sets. In this process, little attention has been paid to rigorously quantifying uncertainty. In this proposal we shall construct GIA models that are specifically constructed with the purpose of quantifying the uncertainties associated with global GIA. In doing so, we will be providing the 1 and 2 sigma uncertainties, along with covariances, that may be used by members of the GRACE-FO Team that are interested in determining secular changes in the mass associated with the hydrosphere, sea-level and cryosphere. We will be especially interested in quantifying the effects of lateral heterogeneity in mantle viscosity, as this is now recognized in the GIA community as a most pervasive source of uncertainty in the models. We will also be implementing new models that rely on more complex viscoelastic formulations, as the recent suite of geodetic observations of solid Earth relaxation following great earthquakes (MW > 8.2) demonstrate that the deformation cannot be sufficiently modeled with the simple Maxwell rheology assumed in GIA models.

Bryant Loomis/Goddard Space Flight Center
Bridging the Gap and Advancing Time-Variable Gravity Recovery with Enhanced Mascon Techniques, Satellite Laser Ranging, and Tidal Inversions
19-GRACEFO19-0025

The GRACE and GRACE-FO missions have revolutionized the ability to monitor mass variability in the hydrosphere, cryosphere, ocean, and solid Earth at global scales. Despite the large improvements in the maturity and accuracy of the time-variable gravity (TVG) products since GRACE's launch in 2002, a number of notable limitations remain at both high and low spatiotemporal frequencies. At large spatial scales, a key issue is the ongoing need to replace the GRACE/GRACE-FO C20 values in post-processing with those obtained from Satellite Laser Ranging (SLR), along with strong evidence of problematic C30 values when either mission is operated in single-accelerometer mode. At smaller spatial scales, the innovative Level-1B (L1B) regression mascon approach recently developed by our group at NASA GSFC is highly effective at enhancing the spatial resolution of the recovered gravity signals by stacking multiple years of GRACE data to estimate temporal functions globally (e.g. trends and annual). Further algorithm

advancements could yield even greater science returns at small spatial scales. At high temporal frequencies, the uncertainties in the ocean tide and atmosphere and ocean dealiasing (AOD) models remain a leading error source in the GRACE/GRACE-FO gravity products. Lastly, in the context of NASA's stated goals to observe and understand long-term changes in the Earth climate system, the most fundamental limitation of the GRACE and GRACE-FO missions is their relatively limited time span and the data gap between them.

We propose to advance the science application of GRACE/GRACE-FO data by addressing the current limitations described above with the following new and innovative approaches and products:
1) Improved monthly and L1B regression mascons via combined GRACE/GRACE-FO/SLR solutions, resolving the issues with GRACE/GRACE-FO at low degrees, especially C20 and C30;
2) Ultra-high resolution/continuous mascons for the improved representation of coastlines and constraint regions, and optimization of the L1B regression technique;
3) New L1B regression mascon products that employ this innovative technique for estimating additional temporal functions such as accelerations, climatologies, climate indices, and coseismic/postseismic signals;
4) New SLR low-degree TVG products that leverage the advanced regularized mascon and regression approaches to extract continental-scale mass changes of the land, ice, and ocean for the years prior to GRACE and for bridging the gap between missions;
5) Continued assessment and improvement of tide models through GRACE/GRACE-FO range-acceleration residual analysis, tidal inversions, and tide model assimilation; and
6) Rigorous quantification of AOD-related TVG errors determined by processing the GRACE/GRACE-FO L1B data with both the project AOD1B and the new TUGO-m.

The proposed advancements to enhance mascon solutions at low and high spatial frequencies, and to assess and improve ocean tide models, directly apply to the solicitation request to "advance the development of new methods, algorithms, and models for the exploitation of gravity field observations made by GRACE, GRACE-FO, and future space-based gravity field missions," while the enhanced L1B regression products address the call to improve the recovery of secular variations. Additionally, the innovative methods proposed for producing new SLR TVG solutions meet the solicitation request to "[develop] techniques and algorithms capable of bridging gravity field observations across different gravity missions." We note that the advanced SLR TVG products directly address the priority of TVG continuity identified in the 2017 Decadal Survey and Science Goals contained within NASA's Strategic Goal 1.1, which aim to improve our understanding of "how the global water cycle evolves in response to climate change," and "the roles and interactions of the oceans, atmosphere, land, and ice in the climate system."

Cecilia Peralta-Ferriz/University of Washington, Seattle

North Pole Ocean Bottom Pressure Recorder: A Critical Tool for Ground-Truth Validation of GRACE-FO and for Accurately Bridging GRACE and GRACE-FO Observations to Track Ongoing Changes in Arctic Ocean Circulation
19-GRACEFO19-0005

The Gravity Recovery and Climate Experiment Follow-on (GRACE-FO) mission was launched in May 2018 – about a year after the last monthly solution available from its predecessor GRACE. Here we propose to 1) provide a ground-truth validation of GRACE-FO in the central Arctic Ocean; 2) bridge the gaps of ocean bottom pressure (OBP) observations from GRACE with those from GRACE-FO in the basin-wide Arctic Ocean; and 3) quantify changes in Arctic-wide OBP and their associated changes in ocean circulation from 2002-2022. This proposal directly addresses NASA's interest in the "development of techniques and algorithms capable of bridging gravity field observations across different gravity missions". Our focus is in the Arctic Ocean, but we build upon the techniques being applied during our ongoing efforts of creating a proxy representation of OBP, to merge GRACE and GRACE-FO OBP globally, as part of our NASA grant NNX16AF18G. These techniques are largely based on the atmosphere-ocean interactions revealed by the available 15 years of GRACE OBP data, combined with wind and sea level pressure data from reanalysis products (e.g., Peralta-Ferriz et al., 2014; Peralta-Ferriz et al., 2016), and include empirical orthogonal functions, maximum co-variance analysis, and conventional linear regression models.

The first stage of this proposal consists of building a customized, high-precision Arctic Bottom Pressure Recorder (ABPR) and installing it at the North Pole in 2021. The ABPR will remain on the ocean floor measuring OBP anomalies continuously for 5 years, and data will be collected acoustically from the surface of the ocean in a yearly basis. This OBP record will provide ground-truth validation of GRACE-FO OBP data, and will help assess the differences between, and help improve, the various GRACE-FO OBP products. Combined with the readily available in situ OBP records from the Beaufort Sea in the western Arctic Ocean, as well as with available atmospheric reanalysis products, the existing and proposed North Pole OBP records will also allow us to accurately merge the GRACE and GRACE-FO OBP in the Arctic, following the techniques implemented and validated in Peralta-Ferriz et al. (2016). The second stage of this proposal consists of using the merged GRACE and GRACE-FO Arctic OBP to track inter-annual and long-term changes in Arctic OBP variability, which combined with the Dynamic Ocean Topography (DOT) data from ICESat and ICESat-2, will allow us to quantify and monitor patterns in ocean circulation, freshwater content variability and their associated atmospheric forcings from 2002 through 2022. This goal supports this NRA's interest on "identification and quantification of atmospheric, oceanographic, hydrospheric, cryospheric and solid Earth structure and dynamics manifested in the GRACE-FO observations".

PI Peralta-Ferriz, an early-career, Latina investigator, will lead the fieldwork, data analyses and dissemination of results. Co-I Morison will advise in both fieldwork and data analyses. Co-I Guthrie, also an early-career investigator, will co-lead the fieldwork efforts. Unfunded collaborators Dr. Jennifer Bonin (USF), Dr. Ron Kwok (JPL), Dr.

Jinlun Zhang (APL-UW) and Dr. Frank Nilsen (UNIS) will provide, respectively, updated GRACE-FO OBP products, ICESat and ICESat2 DOT products, output from a state-of-the-art Arctic sea ice-ocean model, and logistics support during fieldwork years. All team members will participate in the interpretation, discussion and dissemination of results. This proposal will benefit: the GRACE and GRACE-FO science community by providing ground-truth validation for improvement of GRACE-FO OBP products; the climate research community through the insights revealed in Arctic-wide ocean circulation variability; future generations seeking a career in the Earth Sciences by providing partial support for and guidance to two undergraduate interns; and general audiences through public lectures and outreach events.

Rui Ponte/Atmospheric & Environmental Research, Inc.
Studies of Ocean Circulation, Sea Level and Climate Using Space Gravity Measurements
19-GRACEFO19-0028

Measurements of the Earth's changing gravity field from space are a key component of the climate observing system. The GRACE-Follow On mission will continue to gather data for improving estimates of variability of ocean bottom pressure (OBP), and changes in water and ice over land. In this proposal, we plan to use data from GRACE and GRACE-FO, together with many other data sets, ocean modeling tools, and advanced methods of data assimilation and state estimation, to study the ocean circulation, sea level and climate. The investigation will probe the characteristics of OBP variability over the global ocean and how that information can be combined with new and forthcoming data sets such as deep Argo floats to learn about sea level dynamics and budgets, changes in ocean currents and property transports, and the nature of freshwater exchanges among ocean, atmosphere and land. Leveraging available ocean state estimates and associated forward and adjoint modeling tools, proposed efforts will explore the usefulness of GRACE and GRACE-FO data to constrain the ocean circulation. These tools will also be used to inform the nature of OBP variability in relation to different forcing and dynamics, as a function of region and timescale. The ocean state estimates will be exploited as tools to bridge the gap between GRACE and GRACE-FO, extrapolate to periods prior to GRACE, as well as map the large-scale information in space gravity measurements to resolve finer scale ocean dynamics. In doing so, the proposal addresses several main themes of the GRACE-FO Science Team solicitation and will contribute to "advance Earth system science and meet the challenges of climate and environmental change" one of NASA's strategic goals.

John Reager/Jet Propulsion Laboratory
Advancing Groundwater Science Using MCM

19-GRACEFO19-0034

The freshwater resources of the Earth are primarily stored in snow, soils, surface water systems and groundwater. By far the bulk of the water potentially available for human use, roughly 96%, is not at the surface but instead stored below the land surface as deep soil moisture or groundwater – largely out of sight for human eyes and observing systems. For hydrology and water resource monitoring, NASA's GRACE mission has been revolutionary in its ability to "see" water beneath the land surface by measuring changes in gravity. However, the data may not yet have reached their full potential for characterizing freshwater availability, global groundwater depletion, and the human impact on the water cycle. Also, gravity-based groundwater has not yet been fully embraced by the hydrology community for reasons such as coarseness of resolution, a column-integrated convolution with overlying soil moisture and snow variability, and ta lack of process understanding in terms of coupling with other components of the Earth System.

He we propose a set of discrete targeted activities to help advance the ability of GRACE-like missions (mass change missions, 'MCM') to monitor and understand global groundwater changes. The goals of the proposed work are to: (1) offer improvements in methodology to provide clarity in interpretation, (2) link MCM groundwater estimates with other remote sensing observations to enhance resolution and understand the impact of groundwater changes on regional climate and land-atmosphere interactions and long-term storage capacity and (3) offer improved process insights for the study of groundwater.

To achieve those goals, we will tackle the major scientific and technical limitations of MCM groundwater in three basic categories. The expected research products of these tasks will be a set of publications to offer guidance and insight to the hydrology community and improve the utility of MCM for groundwater applications:

(1) Identification of error sources is gravity-based groundwater estimation and best-practices to reduce the potential for misinterpretation; This will include a detailed analysis of the state of global groundwater trends, including the world's major aquifers, using an enhanced approach to identifying soil moisture and snow modeling errors in groundwater trend timeseries.

(2) Improvement of resolution in MCM groundwater and opportunities for spatially-enhanced monitoring; This will include information on subsidence from Interferometric SAR and high-resolution groundwater models to enhance resolution and determine storage capacity losses for key regions.

(3) Combination with ancillary data sets on land-atmosphere coupling to offer more comprehensive process understanding; This will include a global assessment of human impacts on soil moisture and atmospheric interactions using AIRS and Cloudsat observations.

The proposal team was designed to make progress on each of these individual tasks, and includes expertise in Bayesian methods in data analysis, in the application of InSAR observations for groundwater subsidence mapping, and in the study of land-atmosphere

coupling and interactions. While the suite of proposed activities is broad, the overarching goal is to demonstrate the range opportunities available for future exploitation of MCM observations to advance the field of groundwater hydrology.

Matthew Rodell/Goddard Space Flight Center
Terrestrial Hydrology from GRACE and GRACE-FO: Refining the Interpretation of Water Storage Variations During All Phases of the Mass Change Data Record
19-GRACEFO19-0024

GRACE provided unprecedented observations of terrestrial water storage (TWS) anomalies that revolutionized our understanding of the global water cycle and how people and climate change are affecting it. GRACE-FO was launched in 2018 to ensure mass change observation continuity. However, the consistency of the 2002-present TWS data record is imperfect due to GRACE observational gaps beginning in 2011, malfunctioning of the GRACE-B accelerometer beginning in November, 2016, the nearly 1 year interim between GRACE and GRACE-FO, and malfunctioning of the GRACE-D accelerometer. Hence, one major goal of the proposed project will be to assess the consistency of GRACE and GRACE-FO based TWS seasonality and trends through these changes, making use of independent global observations (e.g., precipitation, surface water levels and extent, soil moisture) and data integrating models. The latter will also be evaluated as a gap filler. A second major goal will be to refine previous analyses of GRACE based TWS trends and seasonality using a newly developed approach that significantly improves signal recovery and enhances the spatial resolution to ~15,000 km2 at mid-latitudes. While GRACE-based mass trends have routinely been determined by linearly regressing the monthly time-variable gravity products, which have a spatial resolution of ~150,000 km2 at mid-latitudes, the new approach stacks multiple years of Level-1B normal equations in order to estimate full-period or multi-year “trends” or mean seasonal cycles directly, with enhanced spatial or temporal resolution, depending on the objective. The results localize and more accurately quantify previously smoothed and attenuated secular mass trends, enabling improved attribution of their origins. We will also apply the approach to the analysis of seasonal variations in TWS, which will enrich our understanding of regional water balance and related fluxes. Where sufficient river discharge are available we will provide new estimates of the seasonal cycle of evapotranspiration, computed as a water budget residual. The GRACE-FO data will be used to further refine GRACE-based TWS trend analyses and to evaluate previous predictions of which apparent trends are caused by climate change and/or direct human impacts, and thus likely to persist. Finally, we will perform a rigorous and innovative error analysis and use it to determine how uncertainty in the TWS data record changes in response to instrument malfunctions and other issues. All products of the proposed research will be made publicly available, and we will disseminate our findings to the GRACE-FO science team, in conference presentations, and in refereed journal publications. We will also work directly with the science team to resolve any inconsistencies that we discover in the satellite gravimetry data record.

Y. Tony Song/Jet Propulsion Laboratory
Bottom Pressure Validation and Kuroshio Transport Estimation from GRACE and GRACE-FO
19-GRACEFO19-0008

Ocean gravity signals are one of the weak time-varying signals contained in the GRACE or GRACE-FO data. Earlier GRACE studies suffered from the short term record and focused more on seasonal signals, although interannual variability is evident in all of these. In-situ bottom pressure recorder (BPR) measurements from the Deep-ocean Assessment and Reporting of Tsunamis (DART) buoys and the Kuroshio Extension System Study array are discontinuous with various gaps within every 2 years due to their battery lifespan. With the continuation of gravity missions, validating the GRACE and GRACE-FO data continuously for understanding of the interannual variability of the ocean circulation becomes of fundamental interest to oceanography. In addition, recent advances of gravity algorithms, such as the mascon solutions, have pushed the gravity solution closer to land boundaries. This project focuses on validating the long-term continuation of GRACE and GRACE-FO data and their applications to ocean mass transports of the Kuroshio in the Pacific and the Gulf Stream in the Atlantic, respectively.

Approaches and Objectives: We propose to collaborate with Japanese scientists of NEID to analyze the submarine cable-based BPR data from the Dense Ocean-floor Network System for Earthquakes and Tsunamis (DONET), which provides the longest continuous measurements since 2010 and has never been used for gravimetry study before. Recently, we have also developed an automated real-time analyzing, de-drifting, and de-tiding DART data by fitting into an established ocean general circulation model (OGCM). With the continuous long-term DONET data, we will be able to create a combined DONET-OGCM-DART data product for validating GRACE and GRACE-FO data. These continuous in-situ, satellite, and model datasets provide a unique opportunity to estimate the deep ocean transport. This effort has four research objectives:

1. Validate the GRACE and GRACE-FO data with the long-term DONET measurements and combine DART BPRs with OGCM for the interannual oceanic signals;
2. Develop a methodology for estimating the Kuroshio and Gulf Stream transports using the BPR measurements, gravimetry ocean-bottom-pressure (OBP) and altimetry sea-surface-height (SSH) data;
3. Diagnose the dynamical balance of time-changes between the wind torque and the ocean bottom torque imparted on the topographic slope in the western boundary currents; and
4. Calibrate the dynamic consistencies of the estimated transports by in-situ measurements and data-assimilated ECCO products.

Expected Results: The project will provide a methodology for “the development of a continuous mass change measurement record among the GRACE and GRACE-FO observations”, and the science applications to ocean circulation and mass transport are strongly aligned with the primary goal of the GRACE and GRACE-FO missions: “The

observed variability in the gravity field, satellite altimeter data, and other in situ data are used in geophysical models to advance our knowledge concerning changes in ocean heating, sea level, and oceanic currents."

Mohamed Sultan/Western Michigan University, Kalamazoo
Monitoring Deep Aquifer Response to Climatic Variability Using GRACE Data
19-GRACEFO19-0018

Our recent analysis of GRACE solutions over the largest aquifer system in Africa (the Nubian Sandstone Aquifer System: NSAS) revealed that while the response of deep aquifers to climatic variations remains a relatively slow process that takes thousands to tens of thousands of years, there is a much faster response in aquifers that are characterized by dense networks of faults, fractures and karst as is the case with the NSAS. This rapid groundwater flow, when it occurs, is detected as an increase in GRACE-TWS over areas downgradient and distant (hundreds of km) from the source areas over which increased precipitation occurred in wet periods. The increase in GRACE-TWS over these distant areas cannot be accounted for by an increase in precipitation, soil moisture, or surface water flow given the hyperarid conditions even during periods of increased precipitation over the source areas. In this proposal we will accomplish the following using the Saharan fossil aquifer systems in North Africa (North Western Saharan Aquifer System [NWSA], area: 1.2 x 106 km2; Lake Chad Basin Aquifer [LCBA], area: 2.3 x 106 km2) and in the Arabian Peninsula (Mega Aquifer System: area: 2 x 106 km2) as test sites: (1) investigate whether the rapid response observed over the NSAS could be common to many of the aquifers worldwide, (2) identify the conditions under which such rapid flow occurs, and (3) apply groundwater flow models in fractured rocks and use the models to develop sustainable and/or optimum scenarios for groundwater management in areas showing evidence of rapid groundwater flow. These three tasks will be accomplished by conducting the following for each of the investigated aquifer systems: (1) use satellite-based precipitation mission data to identify temporal (short-term climate variability: wet and dry periods) and spatial variations of precipitation over areas of interest (source versus discharge areas), (2) identify the spatial and temporal response of GRACE-TWS to short climate variability over the areas of interest, (3) generate GRACE-TWS phase, difference, and amplitude images to investigate the direction and extent of GRACE-TWS variations that are indicative of mass movement in dry and wet periods and seasons; (4) delineate potential preferred pathways for groundwater flow by mapping fault traces from shaded relief maps, radar backscatter images, and geologic maps and their postulated extension in the subsurface from tilt derivative (TDR) product of a selected Gravity Field and Steady-State Ocean Circulation Explorer (GOCE)-based global geopotential model (GGM). Finally GRACE-based inferences will be validated using: (1) field data (temporal head data, isotopic and geochemical composition for groundwater samples) along the identified structures and satellite-based (SMOS, SMAP) soil moisture content to test whether the identified structures represent preferred pathways for groundwater flow, and (2) groundwater flow models that simulate the rapid groundwater flow from the source areas towards discharge areas along preferred pathways and a much slower flow in the surrounding media. The

models will be calibrated against the temporal (annual and secular) and spatial variations in GRACE-TWS data and will serve as a numeric test bed for exploring aquifer management strategies and optimizing water extraction in a sustainable manner

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Alexander Sun/University of Texas, Austin
GRACE Flooding
19-GRACEFO19-0026

Climate extremes, including floods and droughts, have devastating impacts on society and are projected to increase in intensity with climate change. GRACE and GRACE Follow-On (GRACE-FO) missions provide unique information on the wetness state of a river basin with regard to its flood generation potential. So far, the long latency (up to 60 days) of GRACE products has limited the application of GRACE products in flood early warning. The primary objective of this proposed study is thus to develop a new 5-day GRACE product that can be used to calculate GRACE wetness indicators for flood forecasting and monitoring. Additional objectives include using novel physics-based data analytics to bridge the data gap between GRACE and GRACE-FO. The reliability of the 5-day product, along with other temporal GRACE solutions (1, 21, and 30 d), will be evaluated through hindcasting of floods from selected river basins globally, with emphasis on basins in the U.S. We will use data analytics to combine information from multiple satellite products (e.g., precipitation, vegetation, and synthetic aperture radar) along with GRACE to improve flood monitoring and forecasting. The ultimate deliverable will be a data-driven, probabilistic GRACE flood forecasting and monitoring tool that will be disseminated to emergency management and water resources management groups to be used to manage these extreme events.

Unique aspects of this proposed study include the development of a 5-day GRACE total water storage product based on GRACE data alone and not relying on land surface or hydrologic models. This approach complements studies being conducted in the European Gravity Service for Improved Emergency Management program (EGSIEM) that integrates GRACE and geophysical models using Kalman filtering. The emphasis on physics-based data analytics to bridge the gap between GRACE and GRACE-FO should improve the reliability of these data by combining multiple data sources (GRACE, precipitation, vegetation, and soil moisture) and ground-based monitoring, including streamflow, soil moisture, and groundwater levels, to constrain uncertainties. Additionally, data analytics will be used to integrate data from multiple sources to map the areal extent of floods and disaggregate the volume among surface water, soil moisture, and groundwater based on monitoring and modeling data. An assessment of the value of the information to end users will be investigated in parallel by our partners at EGSIEM and NASA programs. We will characterize different types of floods to assess their predictability using GRACE and potential lead times. We will test different temporal GRACE solutions to assess flood forecasting ability. We plan to complement existing forecasting studies being conducted at NASA and in Europe and will share our GRACE solutions to test against other options. We will work with water managers to

determine optimal approaches to managing flood water, including potentially modifying surface reservoir management and using managed aquifer recharge of depleted aquifers.

Our team, consisting of experts in both GRACE product development, data analyses, and hydrology, is in a unique position to carry out this proposed research. With our close connections to the domestic and global hydrological modeling communities, and our past success in delivering high quality GRACE-enabled research, we believe our new GRACE flood forecast products resulting from this project will be quickly adopted by and highly valuable to end users.

This proposed investigation is expected to expand the benefits of GRACE for near real-time flood forecasting and monitoring, which has strong socioeconomic significance and implications. This proposed research responds directly to NASA's Strategic Goal 2.1, Advance Earth System Science to meet the challenges of climate and environmental change.

Paul Tregoning/Australian National University
Mass Transport Estimates from GRACE and GRACE FO Data Using the Inter-Satellite Range Acceleration Observations
19-GRACEFO19-0020

The GRACE mission provided unprecedented capability to quantify mass transport on Earth, caused by geophysical processes related to mass balance change of glaciated regions, ocean circulation, hydrological processes and glacial isostatic adjustment. The GRACE FO mission continues the legacy of GRACE, while offering the potential of improved resolution through the inclusion of laser ranging interferometry (LRI).

At the Australian National University, we have developed our own software to process the Level-1B data of the GRACE and GRACE FO missions in order to estimate the temporal gravity field. Through a number of innovative approaches, we have developed a unique capability which offers the possibility of higher spatial and temporal resolution gravity field estimates. There are two significant new components to our approach:

- We use the inter-satellite range acceleration observable along with the range rate. While the Level-1B range acceleration observations contain very high levels of high-frequency noise, we have developed a method of reducing this noise without attenuating the gravity field signals themselves. Additionally, our filtering approach will be applicable for the analysis of the LRI observations because it introduces numerical artefacts well below the precision of the LRI observations.
- We parameterize the temporal gravity field using customisable, irregularly shaped mascons. This provides considerable benefits to the analysis including, for example reducing the leakage of signal from continents to oceans (and vice versa) and enabling different-sized mascons to be used in different regions (e.g. smaller mascons in regions with denser groundtrack coverage).

GRACE FO accelerometer data
The accelerometers on the GRACE FO satellites are not performing as well as was hoped. We have developed methods for mitigating long-wavelength, temperature-induced signals present in some GRACE accelerometer observations and we intend to investigate various options for mitigating the noise and spurious signals in the GRACE FO accelerometer data. We are unable to provide exact details at present, since GRACE FO Level-1 data have not yet been released publicly. The process of producing temporal gravity field estimates from GRACE FO data depends upon mitigating the noise in the accelerometer observations; therefore, we will invest resources into resolving this problem.

Use of the LRI data
The initial data of the GRACE FO mission shows that the LRI data is of excellent quality, offering the possibility of detecting smaller geophysical signals as well as characterizing possible errors arising from the performance of other instruments (e.g. star cameras). We will generate estimates of the temporal gravity field using data from only the MWI, only the LRI and from a combination of both inter-satellite observation datasets. We anticipate that there will be a need to revise our approach to regularizing the mascon inversion upon use of the new LRI observations. We will conduct the necessary tests to identify appropriate settings.

Additionally, our simulations show that errors introduced into mass change estimates by placing mascons on the reference ellipsoid rather than on the actual topographic surface of the Earth induces range rate/range acceleration signals which are too small to detect accurately using the MWI instrument but the signals should be clearly evident in the LRI range rate/range acceleration observations. We will investigate this using GRACE FO data and assess the impact of this effect on mass balance estimates in high-altitude regions.

In summary, we will investigate ways of mitigating the noise in the accelerometer observations on both GRACE FO satellites, investigate the advantages of incorporating LRI observations into the analysis using both range rate and range acceleration observables, and develop time series of temporal gravity fields for both GRACE and GRACE FO using our ANU GRACE software.

Susanna Werth/Arizona State University
Improved Resolution and Sampling of Total Water Storage Changes Through Data Fusion
19-GRACEFO19-0035

This 4-year project focuses on the Southwest (SW) US and aims at improving the spatial resolution, and temporal sampling of Total Water Storage Changes (TWSC) obtained from GRACE/GRACE-FO. GRACE observations are a powerful tool to monitor the evolution of hydrological systems and their responses to climate extremes or unsustainable water consumption. However, their low spatial resolution limits their

applicability for regional water management; and, at this point, there remains a major 1-year data gap in the time series. To counter that, we perform a fusion of the GRACE-based TWSC estimates with that obtained from a combination of all available ground-based observations and model-based estimates of hydrological components.
First, we generate large scale maps of vertical land motion (VLM) at 250-m resolution over the SW as a combination of all available SAR and GPS observations for the period 2003 - 2023. Next, we use VLM observations (excluding those above and near fast compacting aquifers) and perform time-dependent elastic load modeling to calculate the TWSC and its variance-covariance matrix. This estimate likely lakes most of the contribution from groundwater storage change. We also use various hydrological models and ground-based observations to calculate the aggregated volume change due to variations in soil moisture, surface water, and snow. This exercise will yield two independent estimates of TWSC minus groundwater storage change.
Next, we focus on major aquifers and combine VLM and groundwater level data to calculate the distribution of storage coefficients and associated errors for SW aquifer systems. In combination with observations from groundwater wells, we obtain a rough estimate of the groundwater volume change and uncertainties. We will also perform a 1D poroelastic model using VLM observations to solve for groundwater volume change and standard deviations independently. These two groundwater estimates are not entirely independent; however, the different approaches used will likely result in slightly different estimates. Combining two independent estimates of TWSC with both estimates of groundwater storage change will result in four estimates of TWSC with spatially and temporally variable resolution and uncertainties, which are independent of GRACE measurements.

To fuse these four estimates with the GRACE-based TWSC observations, we borrow from the “control theory,” assuming TWSC depicts a linear dynamic system, whose state is perturbed by random noise and data gaps. The goal is to update the dynamic system by using four other estimates of TWSC that act as measurement linearly related to the system but perturbed by their associated random noises. A data gap period in GRACE observations, in the context of control theory, means that the current status of the dynamic system is unknown while its variance-covariance is available. Availability of independent measurements of the dynamic system status enables estimating the missing data points. To this end, we will use the concept of linear Kalman Filtering, which is not sensitive to data gaps, variable sampling rate, and uncertainties, and it can be performed recursively.

The results from this project will provide essential insights into the complex interaction between terrestrial water cycle, aquifer dynamics, gravity changes, and surface deformation. It will also secure the continuity of TWSC, in between both GRACE missions. The method will be further beneficial in the case of additional gaps potentially occurring in the future. An accurate water budget closure and a spatiotemporal characterization of its components will be beneficial for understanding the impact of climate variability, climate extremes, and human water consumption on water resources. The datasets are of high importance for water managers in arid regions, like the SW,

which are susceptible to overdraft of water resources on and below the surface by growing population and economies.

David Wiese/Jet Propulsion Laboratory
Geodetic Data Combination for Increased Spatial Resolution in Earth System Mass Flux
19-GRACEFO19-0009

GRACE and GRACE-FO have demonstrated the ability to measure mass flux within the Earth system at spatial scales of approximately 90,000 square kilometers. While these measurements have been revolutionary for many Earth science domains, users are advocating for data products at higher spatial resolution than what can be provided by the current (GRACE-FO) and past (GRACE) satellite gravimetry mission architectures. Here, we propose to increase the spatial resolution of Earth system mass flux signals by rigorously integrating GRACE and GRACE-FO intersatellite range-rate measurements, satellite altimetry measurements of surface elevation changes over the ice sheets, and GNSS observations of vertical displacements of solid Earth's surface. Integrating the satellite altimetry and GNSS data improve GRACE's spatial resolution from its native 300 km to 100 km in locations with sufficient data strength. A global integrated 1° mascon solution will be determined and made publicly available. While our primary focus is on the development and validation of a new data product, we will perform initial scientific interpretation on the combination solution prior to releasing it to the wider scientific community. Validation and interpretation will be done largely by comparing the combination solution to global land surface models, higher-resolution groundwater models and models of ice sheet surface mass balance processes. We will additionally use ancillary observations (well observations, streamflow data, precipitation, evapotranspiration, solid ice discharge), to close the terrestrial water/ice budget in smaller regions, and help validate any improvement in spatial resolution obtained. When released to the broader scientific community, we anticipate this new geodetic data combination solution will allow for advancement in multiple Earth science domains, including 1) quantifying water storage changes in medium to small river and ice sheet drainage basins, allowing for the terrestrial water balance budget to be closed at ~100 km spatial scales in select regions, 2) improving signal separation (vertical and horizontal) of total water storage components, allowing for improved validation/calibration of global land surface hydrology models and regional surface mass balance models over Greenland and Antarctica, and 3) improving the predictive skills of models through data assimilation, allowing for enhanced ability to simulate changes in regional water/ice storage and better predict the future state of the hydrosphere. We explicitly note that successful local data combinations (GRACE+GNSS; GRACE+altimetry) have already been demonstrated through past efforts, including our previous GRACE Science Team investigation. This proposal leverages these previous investments and builds upon them, with a vision to ultimately form one coherent picture of Earth system mass change that is superior to what could be achieved using any single sensor platform.

Xiaoping Wu/Jet Propulsion Laboratory

Surface Mass Transport from Global Inverse and Data Combination
19-GRACEFO19-0002

The GRACE and GRACE-FO missions provide unprecedented opportunities to monitor global surface mass transport. However, significant spatiotemporal coverage gaps exist in the data stream. These include the missing degree-1 surface mass variation coefficients or the equivalent geocenter motion information in the data system as well as data gaps in and between the missions. Another major challenge in monitoring Present-Day surface Mass Trend (PDMT) using gravity data is the dual solid Earth signal of Glacial Isostatic Adjustment (GIA) and the mostly unknown and possibly large uncertainties in GIA models. We seek to use multiple space geodetic and geophysical data sets in the framework of global inverse to bridge these gaps by providing continuous data based geocenter motion and other coefficient time series. We will also use data combination to further separate PDMT and GIA signatures for comprehensive mass transport monitoring and for a global inverse appraisal of ice history and Earth rheology.

For geocenter motion, we will significantly improve the robustness and latency of our data based geocenter motion determination to support the GRACE-FO mission and the reprocessing of GRACE data. For non-linear motions, this will be done through a new unified inversion of geocentric displacements and GRACE+FO gravity data with their full covariance matrices. For linear trend in geocenter motion, absolute geocentric velocities and other data will be used in a kinematic and unified inversion for both PDMT and GIA. The unified approach uses both translational and deformational signatures of degree-1 surface mass transport in the displacement data, and has much stronger signal strength than the degree-1 deformation or ocean model approaches. The addition of GRACE+FO's near global coverage significantly reduces inherent biases in translational-alone approaches and spectral aliasing errors in the inversion.

Inverted non-linear surface mass transport from reprocessed GNSS deformation data and JPL's ECCO bottom pressure model has been reconciled globally with that from the GRACE data. With a burgeoning station distribution, the GNSS+ECCO results have growing and spatially variable resolutions better than degree and order 10. This capability will be used in conjunction with an Empirical Orthogonal Function (EOF) analysis of the GRACE data to fill temporal data gaps and calibrate the early GRACE-FO data.

To separate PDMT and GIA, we will complete the development of our simultaneous dynamic inversion platform, and use it to incorporate both modern geodetic data of multiple types and historical relative sea level (RSL) records. GIA models are mostly constructed by forward fitting the RSL data. Without reliable a priori uncertainty information for the models, kinematic inversions and other incremental GIA model improvements have largely discarded the very valuable global RSL information. The dynamic global inversion will be able to combine these data sets statistically, further strengthen the separation of PDMT and GIA, estimate ice history and Earth rheology, and provide an objective and quantitative assessment of uncertainties so that the estimates can be used in future improvements.