**Response to Decadal Survey RFI:**

**Linkage of the Water Cycle, Ocean Circulation, and Climate**

Tong Lee (Jet Propulsion Laboratory, California Institute of Technology)

***US co-authors (in last-name alphabetical order):***

Eric Bayler (National Oceanic and Atmospheric Administration)

Fred Bingham (University of North Carolina Wilmington)

Frank Bryan (National Center for Atmospheric Research)

Subrahmanyam Bulusu (University of South Carolina)

Jim Carton (University of Maryland)

Kyla Drushka (University of Washington)

Paul Durack (Lawrence Livermore National Laboratory)

Rana Fine (University of Miami)

Arnold Gordon (Columbia University)

Seymon Grodsky (University of Maryland)

Eric Hackert (University of Maryland)

Gary Lagerloef (Earth and Space Research)

Tim Liu (Jet Propulsion Laboratory, California Institute of Technology)

Ricardo Matano (Oregon State University)

Thomas Meissener (Remote Sensing System, Inc.)

Julian Schanze (Earth and Space Research)

Ray Schmitt (Woods Hole Oceanographic Institution)

Tony Song (Jet Propulsion Laboratory, California Institute of Technology)

Graeme Stephens (Jet Propulsion Laboratory, California Institute of Technology)

Nadya Vinogradova (Atmospheric and Environmental Research)

Frank Wentz (Remote Sensing System, Inc.)

Pingping Xie (National Oceanic and Atmospheric Administration)

Lisan Yu (Woods Hole Oceanographic Institution)

Simon Yueh (Jet Propulsion Laboratory, California Institute of Technology)

***Non US co-authors (in last-name alphabetical order):***

Aida Alvera Azcarate (University of Liège, Belgium)

Chris Bank (National Oceanographic Centre, UK)

Jacqueline Boutin (University of Paris, France)

Christine Gommenginger (National Oceanographic Centre, UK)

Johhny Johannessen (Nensen Environmental and Remote Sensing Center, Norway)

Nicolas Kolodziejczyk (University of Brest, France)

Armind Köhl (University of Hamburg, Germany)

Christophe Maes (French Research Inst. for Exploitation of the Sea –IFREMER, France)

Nicolas Reul (French Research Inst. for Exploitation of the Sea –IFREMER, France)

Gilles Reverdin (University of Paris, France)

Monica Rhein (University of Bremen, German)

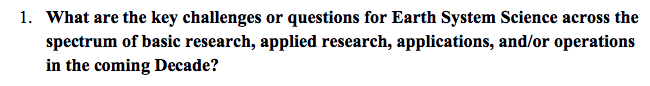
Roberto Sabia (European Space Agency ESRIN, Italy)

Meric Srokosz (National Oceanographic Centre, UK)

Detlef Stammer (University of Hamburg, Germany)

Antonio Turiel (Institute of Marine Sciences, Spain)

Susan Wijffels (Commonwealth Scientific & Industrial Research Organization, Australia)

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Water availability is critical to humanity and is one of WCRP’s Grand Challenges (http://www.wcrp-climate.org/grand-challenges/gc-water-availability). Climate change is expected to substantially alter the Earth’s water cycle1, impacting society and ecosystems globally2. The ocean component dominates the global water cycle, comprising nearly 97% of the Earth’s water and with over 75% (85%) of the annual global precipitation (evaporation) occurring over the ocean3-7. While the society critically depends on the terrestrial elements of the water cycle, those elements are fundamentally linked to the ocean through atmospheric moisture transport and continental runoff 8-10. A coordinated observational program of the global water cycle, centered on the dominant oceanic branch, is therefore necessary to address the following key challenges in Earth System Science that are relevant to a broad spectrum of basic and applied research as well as applications and operations:

***How is the water cycle changing?***

Changes in the global water cycle can be detected by monitoring the fluxes of water among the oceanic, terrestrial, and cryospheric components of the Earth system, as well as the water storage within each of them. There are substantial challenges associated with each of these measurements11-13. For example, while satellites can provide global measurements of precipitation, little direct measurements are available for oceanic evaporation. The latter must be estimated empirically from measurements of wind speed, air and sea surface temperature, and humidity and is subject to considerable uncertainty. The ocean-atmosphere net water flux, evaporation-precipitation (E-P), is the difference between two large uncertain quantities (E and P). Substantial discrepancies exist among E-P products12,14. Responding to E-P instead of E and P separately and by integrating over the intermittent E-P changes, salinity acts as a sentinel for basin to global E-P changes4,15. It also reflects the export (import) of water and latent heat energy from (into) a region. In particular, the subtropical highs and underlying salinity maximum regions serve as the sources of the global water cycle, exporting fresh water to high latitudes, the tropics and land16.

Deciphering climate change effects on terrestrial elements of the water cycle (e.g., total continental runoff) has been complicated by human activities (e.g., dams and agriculture). Land-based precipitation records, although spanning over a century, are spatially too heterogeneous to provide continental or global view, and are extremely sparse in the tropics and mid-latitudes over many continents11,13. Despite inconclusive evidence for trends in total continental runoff 17,18, ocean salinity measurements have shown significant trends15,19-26. In the past five decades, the large-scale salinity contrast has strengthened24 (“salty gets saltier and fresh gets fresher”). This is the strongest available evidence for an intensification of the global water cycle2 (“wet gets wetter and dry gets drier”). Climate models forced by increasing greenhouse gasses also project such enhancement of salinity contrast27-29 and the rate of salinity pattern intensification is linearly related to both the rate of the water cycle increase and the global surface warming rate28. Increasing evidence closely links flood and drought cycles and extremes to variations in the oceanic water cycle across various time scales13,30.

***How does the change in the ocean element of the water cycle influence ocean circulation and climate?***

Salinity and temperature determine seawater density and have been identified by WMO as essential climate variables (https://www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables). Together they influence ocean circulation and the ventilation of the ocean interior. Changes in global sea surface salinity (SSS) distributions, influenced by changes in the water cycle, enhance or inhibit the subduction of water masses and the sequestration of heat, anthropogenic carbon, and other gases to the subsurface ocean31. Ocean circulation mediates the forcing by E-P, river runoff, and ice-melt and redistributes freshwater geographically32. At high-latitudes, salinity changes associated with melting sea ice and ice sheet/shelf have significant implications to ocean thermohaline circulation and related heat transport33. In the tropics, salinity mediates air/sea coupling34,35 and influences ENSO dynamics and forecast skills36-39. Oceanic water cycle and salinity are also important to sea level changes40,41. Oceanic latent heat release due to evaporation affects the global energy balance42.

***How are marine ecosystems and the carbon cycle influenced by a changing water cycle?***

Marine ecosystem and ocean carbon cycle strongly depend on ocean circulation43, which is influenced by salinity and water cycle changes. In addition, oceanic total alkalinity, an important parameter for carbon cycle and ocean acidification studies, correlates strongly with salinity44,45. Hence, marine ecosystem and carbon cycle research and applications need a good knowledge of ocean salinity.

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Significant knowledge gaps exist regarding the above challenges. Given the increasing evidence for an intensification of the water cycle (references in section 1), it is imperative to fill these knowledge gaps in the next decade and beyond. In particular, it is vital to sustain and enhance ocean salinity measurements to detect continuing trends, to shed light on water cycle changes, to examine the relative contributions from climate change and natural decadal variability, to investigate the consequences for ocean circulation and the potential feedbacks to the climate system, and to assess the impacts on marine ecosystems and the carbon cycle.

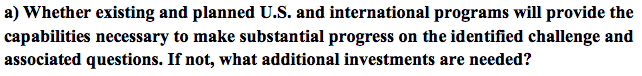
Major advances have been made in the past decade in observing salinity through in-situ and satellite technologies. There are currently over 3700 autonomous Argo profiling floats sampling the upper 2000 m of much of the open ocean. Recent satellite missions have demonstrated the capability to map global SSS with much finer and more uniform sampling. These include NASA’s Aquarius mission (August 2011-June 2015) and ESA’s Soil Moisture and Ocean Salinity (SMOS) mission (2009-present).

Significant advances in ocean state estimation have enabled synthesis of ocean observations with state-of-the-art ocean general circulation models46 to estimate E-P constrained by ocean observations and dynamics47,48. The fidelity of climate models has improved in parallel2. These models are useful for examining the sensitivity of the water cycle to climate change and the links between the oceanic and terrestrial elements of the water cycle. However, their further improvement in the next decade hinges on the continuity and enhancement of observations of the oceanic water cycle that are needed to adequately validate the models.

These complementary developments in satellite and in-situ ocean observing systems, ocean state estimation, and climate models have put researchers in a strong position to address the above challenges in the coming decade.

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Addressing the above challenges requires global SSS measurements with spatial and temporal resolutions that resolve the energetic mesoscale ocean variability (tens to hundreds of km, days to months). To avoid grounding, very few Argo floats were deployed in coastal oceans and marginal seas that are important links to regional or basin wide water cycle. Argo also has limited coverage in high-latitude oceans, where strong links to the cryosphere component of the water cycle (e.g., sea ice and ice shelf/sheet) exist. Moreover, Argo can capture variability larger than several hundred km and on monthly and longer time scales, but is insufficient to resolve mesoscale variations that are important to ocean dynamics, air-sea interaction, and marine biology49-51. Therefore, space-based SSS observations are fundamental for addressing the above challenges. Satellite SSS and other space-based observations are providing new insights in biogeochemistry52-56.

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NASA’s Aquarius mission dedicated to SSS measurements was lost in June 2015. ESA’s SMOS mission continues to provide SSS measurements. SSS retrievals from NASA’s Soil Moisture Active-Passive (SMAP) mission, which has a similar L-band active (radar)-passive (radiometer) design to Aquarius, are under development. SMAP’s radar would have provided measurements to correct surface roughness effect on SSS retrievals. Unfortunately, the radar stopped functioning in July 2015. The L-band radiometers of these missions have poor salinity sensitivity at low water temperatures (high-latitude oceans) and limited ability to detect the thickness of salinity-influencing sea ice. In high-latitude oceans, salinity is the dominant factor determining water density and has a major influence on thermohaline ocean circulation. Therefore, it is imperative for future satellite missions to improve the accuracy of SSS measurements at high-latitudes and the capability to monitor sea ice thickness.

ESA is coordinating exploratory studies to address the continuity of L-band SSS and soil moisture measurements. It is important for the US to invest and coordinate with the international community to continue space-borne SSS measurements, especially for enhancing the capability to capture mesoscale ocean variability and to monitor coastal regions, marginal seas, and high-latitude oceans.

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Synergistic use with other satellite measurements further enhances the value of satellite SSS measurements. Combining SSS, soil moisture, gravity, sea level, precipitation, and atmospheric water vapor measurements facilitates studying the links of oceanic, atmospheric, and terrestrial elements of the water cycle. SSS and cryospheric measurements (e.g., sea ice, ice shelf/sheet) can be used together to study ocean-cryosphere interaction, which is essential for understanding sea level rise.

For the ocean, SSS and surface temperature measurements together enable space-based determination of sea surface density for the study of water mass formation processes. SSS together with ocean surface current estimates derived altimetry and scatterometry and with in-situ Argo measurements allow the investigation of salinity and freshwater budgets in the ocean mixed layer. Ocean state estimation using these data as constraints makes possible the estimation of oceanic freshwater transport and E-P across the air-sea interface.

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Addressing the above challenges will improve the understanding of the changing global water cycle and the links among its elements. This has significant implications to water and food supply, health, and power supply. It will also improve the understanding of related feedbacks to the climate through ocean-atmosphere interaction. Change in latent heat release from the ocean due to evaporation affects global energy balance, which is important to climate change. Monitoring SSS changes related to the water cycle will benefit research and applications of marine ecosystems and carbon cycle. Enhanced understanding of the linkages of the water cycle with the ocean, climate, marine ecosystems, and carbon cycle will lead to better predictions and projections that benefit the human society through improved policies, decisions, mitigation, and adaptation regarding floods and droughts, agriculture, and fisheries.

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The challenges involve broad communities across various disciplines including oceanography, land hydrology, cryosphere, atmosphere, climate, and biogeochemistry.

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