From the Mountains to the Sea: Interdisciplinary Science and Applications Driven by the Flow of Water, Sediment, and Carbon

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Summary

Aligning human interests with environmental stewardship of fresh water and coastal oceans is a grand challenge, particularly in our rapidly changing world. The future of these resources is uncertain, and scientific knowledge of processes governing them remains limited. Space-based remote sensing provides a pathway to greater global understanding.

1. What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?

Rivers, lakes, estuaries, deltas, and coastal oceans are all components of an integrated system in which water, sediments, and carbon are transferred from the continental land surface to oceans. Earth's water bodies, fresh, brackish, and saline, therefore play key roles not only in the water cycle but also in geomorphic and biogeochemical cycles. Additionally, these water bodies host many of the most biologically productive and diverse ecosystems on Earth and are of critical importance to human economic and social structures. Approximately 50% of the Earth's population lives near coasts[1], and an overlapping ~50% lives within 10 km of a river[2]. Over the last two decades, science, applications, and operations community have made substantial progress in understanding and managing these systems using existing observation and modeling tools. However, despite their importance, our scientific understanding of the spatial and temporal dynamics of water, sediments, and carbon through this integrated network of rivers/lakes/wetlands/estuaries/coastal oceans often remains limited at scales ranging from local to global. As we seek to operationally manage human use of these environments, limited understanding of their dynamics can have direct impacts on decision-making processes. Moreover, we have limited knowledge of the processes by which changes to this system are driven by global warming, land use and land cover change, engineering modifications, and industrial/agricultural activities. This knowledge gap will only widen as human activities intensify and climate change accelerates. As such, a key question driving scientific research in this area is:

How is the transport of water, sediment, and carbon through the terrestrial surface water network and coastal oceans altered by natural and human forcings, and how are these associated changes affecting the human, ecological, and physical systems that coexist within these environments?

Addressing this question will require new links among diverse scientific communities. Terrestrial hydrologists, coastal oceanographers, geomorphologists, biogeochemists, ecologists, and social scientists must work together to understand the changing transport of water, sediment, and carbon. The following are three scientific grand challenges, with significant societal implications, that need to be addressed via further study of this integrated system:

- **Integrating the terrestrial and marine water cycles.** Historically, water cycle research has focused on either terrestrial process (e.g. atmospheric humidity, soil moisture) or oceanic processes (e.g. ocean circulation). This disciplinary paradigm needs to be changed. Investigating freshwater transport from continental interiors to coasts and within coastal ocean environments is not only compelling science but also is critical for protecting associated ecosystems, tracking freshwater availability for human use, and developing effective responses to global sea-level rise.
- **Describing global sediment sources, fluxes, and sinks** (*i.e.* erosion, transport, and deposition). These physical processes shape our lands and coasts on timescales from hours (e.g. during flood events) to millennia (e.g. via slow sediment accretion). Additionally, human exploration of subsurface resources (*e.g.* mining), alteration of the land surface (urban and agricultural), and modification of water conveyance (*e.g.* dams, canals, levees) have all impacted patterns of sedimentation and subsequently, waterbody morphology[3]. Understanding human influence on sedimentary and geomorphological processes and ensuing impacts on infrastructure is crucial for day-to-day management of coastal and upland environments and for disaster preparedness (*e.g.* landslides, floods, sea level rise). Deltas, important agricultural regions that host hundreds of millions of people globally, are threatened simultaneously by human infrastructure development, resource extraction, and the inexorable rise of the world's oceans[4]. Investments in developing innovative management strategies directly related to sediment erosion and deposition in deltas such as the Mississippi are already costing billions of dollars annually and are expected to further rise[5].
- **Characterizing the carbon cycle between terrestrial and coastal water bodies.** As sediments, carbon and other nutrients are transported through the hydrologic network from the land to the coast, they undergo biogeochemical transformations that culminate at the interface between marine and terrestrial ecosystems. Tidal wetlands are some of the most productive ecosystems on Earth with the highest

carbon sequestration rates of all ecosystems, and they provide key services to humans by protecting infrastructure from storm surge, incubating fish populations, and filtering pollutants[6]. Any changes in the hydrologic regime, and changes in upstream sediment and nutrient loading rates, can reduce their productivity and structure resulting in potentially irreversible damages to these valuable wetland and coastal ocean ecosystems. While it is clear these ecosystems regulate the water flow and mass (i.e. nutrient, carbon, salt) exchange at the coastal boundary, our understanding of their role and impact at regional scales remains limited by our current observational capabilities.

2. Why are these challenge/questions timely to address now especially with respect to readiness?

The challenges of aligning ever-increasing human population growth and a changing climate with sustainable environmental stewardship are particularly ubiquitous at the confluence of land and sea. Land loss in coastal areas is likely due to a combination of factors including sea-level rise, subsidence, and diminished sediment supplies, which are all being directly and indirectly accelerated by human activities (*e.g.* global climate change, river engineering, and local petroleum and water extraction). Deforestation has increased carbon fluxes into surface water bodies and outgassing from them[7,8]. Land use and land cover changes in urban areas have modified surface runoff dynamics and composition[9]. Intense fertilizer usage has created riverine and coastal algal blooms and their associated toxicity and hypoxic zones are detrimental to local ecosystems[10]. This situation thus creates an urgent scientific need to better understand the physical, biogeochemical, and human-mediated processes operating at the interfaces between terrestrial and coastal oceanic systems.

Existing physical and biogeochemical models are increasingly capable of simulating these complex environments, but initial efforts have either consisted of local case studies or global efforts incorporating major assumptions necessary due to the absence of synoptic observations[11]. Similarly, a lack of *integrated* approaches limits our understanding of how hydrologic, coastal, geomorphic, and biogeochemical processes are coupled. Moreover, the understanding of the biogeophysical processes must be coupled with the human dimension, *e.g.*, how can human constructs evolve toward a system with more desirable economic and ecological outcomes? The scientific communities focused on land/coastal/ocean systems must now work together to address these problems in a more integrated, holistic manner.

3. Why are space-based observations fundamental to addressing these challenges/questions?

Point-scale measurements of river discharge, sediment flux, and carbon content are strong assets, but they are sparsely available and are in global decline[12,13]. *In situ* gauges are of comparatively limited utility in complex two-dimensional flow environments including wetlands, floodplains, estuaries, and coastal oceans. There is thus a need for spatially distributed measurements of terrestrial water stores and fluxes, surface concentrations of sediment and carbon. Remote sensing technologies, combined with in-situ measurements and models, offer the best alternative to improve understanding of large-scale biogeophysical processes. The remote sensing science and engineering communities have recently begun to develop the types of hardware (*i.e.* instruments) and software (*i.e.* algorithms) needed to adequately address these pressing questions.

The Surface Water and Ocean Topography (SWOT) satellite mission, currently under development by NASA and CNES, with an expected launch of 2019, is expected to provide the first simultaneous, two dimensional measurements of water surface elevation and inundation extent in rivers, lakes, many wetlands, and oceans around the world[14]. Unlike legacy nadir altimeters such as the JASON series, it is designed to measure the submesoscale vertical and horizontal surface ocean structures required to understand the movement of water in coastal ocean environments. New methods have also been developed to estimate variations in river discharge (for rivers wider than 50-100 m) and surface-water storage variability directly from the expected SWOT measurements, with no requirement for *in situ* information. As such, technology developed for SWOT would improve our ability to monitor the movement of water on land and in the ocean.

In addition, the ongoing development of optical sensors, including multispectral and hyperspectral airborne instruments (*e.g.* AVIRIS-NG, PRISM) is providing new information on sediment concentrations and measures of organic material, such as colored dissolved organic matter (CDOM) and chlorophyll concentrations, that can be used to infer carbon transport and perhaps nutrient loading. A large number of studies dating back to at least the mid-1970s have demonstrated that SSC, CDOM, and chlorophyll in rivers, lakes, and coastal oceans can be robustly retrieved using optical instruments[15,16]. However, virtually all of these studies relied upon empirical relationships with spectral reflectance that are local or regional in nature[17]. Developing global relationships with reflectance remains challenging due, for example, to variations in sediment color, grain size, and other optical properties of the water column. In addition, separating out the influence of CDOM, chlorophyll, and sediment on reflectance, though possible, is not always simple[15]. Nonetheless, several recent studies have shown that these site-specific relationships are quite robust and could be transferred to other locales[15,17], suggesting that an appropriately designed optical remote sensing system could yield useful information on sediment and organic matter around the globe.

The rapid temporal variations in hydrologic and oceanic systems require truly simultaneous measurements of water flux and concentrations of sediment and carbon to reliably estimate the total fluxes of all three quantities. Such synoptic data must also be provided for response to floods, harmful algal blooms, and other events impacting human activities. The current array of *in situ*, airborne, and space-based sensors are providing important disparate datasets that provide invaluable technical heritage, but they cannot deliver simultaneous, high-resolution measurements. **The grand challenges outlined here will therefore not be addressed unless such synchronous, high-resolution observations of fluxes in water, sediment, and organic materials are gathered globally**. Additionally, despite the strengths of current and expected observing capabilities, technical barriers remain. The small spatial scales of river channels, especially in many deltaic environments, mandate higher spatial resolution than can be expected from SWOT. General multispectral instruments such as Landsat 8 and Sentinel 2 were not specifically designed to track water, sediment, and carbon in fluvial and oceanic environments. Synchronous, high-resolution, optimized remotely sensed data would provide instantaneous snapshots of transport processes that could be validated and combined with existing *in situ* measurements, assimilated into next-generation numerical models, and used to extend climate records begun by other sensors (*e.g.* SWOT). The integration of hydrology, geomorphology, and biogeochemistry will likely impact sustainable management from the mountains to the sea.

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