CSQ-3 Summary

Question	Knowledge Advancement Objectives	Observables	Measurement Requirement	Tools & Models	Policies / Benefits
How has the ocean carbon cycle responded to anthropogenic CO2 and climate change?	A) Can space-based measurements track changes in ocean uptake and removal of CO_2 associated with changes in atmospheric CO_2 concentration, sea surface temperature, ocean transport and biological productivity at 1°x1° resolution over the globe.	• Precise/accurate estimates of near-surface atmospheric CO_2 and its spatial and temporal gradients • Sea surface temperature (SST) and salinity • Surface vector winds • Ocean colour	• Precise/accurate (0.1 ppm) CO_2 and O_2 from high-spectral-resolution spectroscopy and LiDAR • Ocean colour • SST, salinity and wind speed at 1°x1°	• Atmospheric GHG retrieval algorithms • Atmospheric flux inverse models • Global ocean biogeochemical models (GOBMs) • Enhanced Cal/val	CC mitigation and adaptation policy
	B) How is the Southern Ocean CO_2 sink responding to climate perturbations and long-term climate change.	• Precise/accurate estimates of near-surface atmospheric CO_2 and its spatial changes throughout the seasonal cycle • SST • Surface vector winds	• Precise/accurate (0.5 ppm) CO_2 and O_2 from high-spectral-resolution spectroscopy and LiDAR • SST, salinity & wind at 1°x1°	• Atmospheric GHG retrieval algorithms • Atmospheric assimilation systems • GOBMs • Coordination with surface in situ data	
	C) What is the impact of human activities and climate change on coastal processes that regulate the carbon sink, including river runoff, upwelling and biological productivity?	• XCO_2 and its spatial and temporal gradients near coastlines • SST and salinity • Surface vector winds • Ocean colour	• Precise/accurate (< 0.1 ppm) imaging spectroscopy of XCO_2 at < 1km resolution • High spatial resolution SST, salinity and ocean colour	In situ reference systems Enhanced techniques for integrating data sources	

CSQ-3 Narrative

The ocean carbon cycle is driven by interactions with CO_2 in the atmosphere, ocean dynamics and ocean biology. At the surface, CO_2 absorption is governed by Henry's Law (i.e., the amount of dissolved gas in a liquid is proportional to its partial pressure above the liquid, pCO_2). However, ocean dynamics continually transports anthropogenic carbon away from the surface into the interior and refreshes the surface with lower pCO_2 water. Some of the carbon transported to depth is remineralized and precipitates out of solution into a long-term sink. Biological processes within the ocean act to increase natural carbon with depth. All of these processes are now being affected by rapidly-increasing atmosphere CO_2 concentrations and the resulting changes in climate.

Over the industrial age, the amount of CO_2 absorbed by the ocean has increased in proportion to the increasing atmospheric CO_2 partial pressure, such that the ocean sink has continued to absorb about 25% of all anthropogenic emissions. While this has substantially reduced the atmospheric CO_2 growth rate and resulting climate change, this carbon absorption has contributed directly to ocean acidification. Other impacts are more difficult to assess because the spatial sampling of the ocean carbon measurement system is very sparce. Existing ship-based *in situ* measurements are accurate, but cover less than 1% of the 1°x1° grid boxes across the ocean on decadal time scales, providing far too little resolution or coverage to track transient events or the effects of climate change. These ship-based measurements are now being augmented by *in situ* carbon measurements collected by autonomous platforms, but these data have much lower accuracy than the ship-based measurements.

Ocean carbon observations with much greater coverage, resolution and repeat frequency are needed to monitor changes in the ocean sink expected in response to human activities and climate change. The ocean sink is expected to respond quickly to reductions in anthropogenic emission intensity. The Southern Ocean, a major component of the ocean carbon sink, is currently poorly constrained by observations and is expected to evolve in response to climate change. If not carefully monitored and understood, the changes in the ocean sink could partially mask the effectiveness of the emissions reductions efforts and potentially undermining their continuity and expansion.

In principal, global, space-based measurements of atmospheric CO_2 could dramatically improve the spatial resolution and coverage provided by the *in situ* data. Unfortunately, existing space-based measurements do not have the precision and accuracy needed to resolve the subtle (< 0.1 ppm) CO_2 concentration gradients associated with the weak, spatially-extensive ocean sources and sinks.

Observations needed to track changes in the ocean carbon sink

Improved and sustained, global, space-based observations and models of the ocean carbon cycle are critically needed to enhance the scientific utility of these data and to support carbon management strategies. Space-based estimates of XCO_2 could provide the data needed to upscale carbon fluxes inferred from the sparse *in situ* measurements collected by surface ships and autonomous platforms, but substantial (factor of 5) improvements in their precision and accuracy are needed for this application.

Fortunately, to monitor these processes over the open ocean, these observations do not need high spatial resolution. Space-based measurements could revolutionize our understanding of the ocean CO_2 sink if they could yield precisions and accuracies of 0.1 to 0.2 ppm on spatial scales of 1°x1° at monthly time scales. The largest challenge will be to deliver observations with this resolution and coverage over the polar oceans during the winter, when there is little sunlight and the regions are persistently cloudy. Active CO_2/O_2 lidars might be needed to address this need. These advances are achievable, but are not currently being targeted by any space agency.

Monitoring changes in the ocean sink associated with coastal processes (e.g., river runoff, upwelling, biological productivity) poses different challenges. Here, much higher high spatial and temporal resolution are needed to resolve the underlying biogeochemical and transport processes associated with the coastline. However, somewhat less precision and accuracy may be needed to resolve the atmospheric CO_2 signals associated with the coastal processes. Space-based CO_2 monitoring systems currently being developed to monitor anthropogenic and land biospheric processes may therefore provide the precision, accuracy, resolution and coverage needed for this application.

Sustained and improved space-based observations of weather and climate variables (ocean surface winds, ocean topography, and sea surface temperatures, salinity, ocean color and ice cover) are also needed to better constrain the relative roles of surface winds and ocean dynamics on CO_2 fluxes as these critical ocean processes continue to evolve in response to anthropogenic emissions and climate change.

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