The Southern Ocean Carbon Cycle in 2050: The Role of Ocean-Ice-Atmosphere Coupling on Air-Sea Exchange

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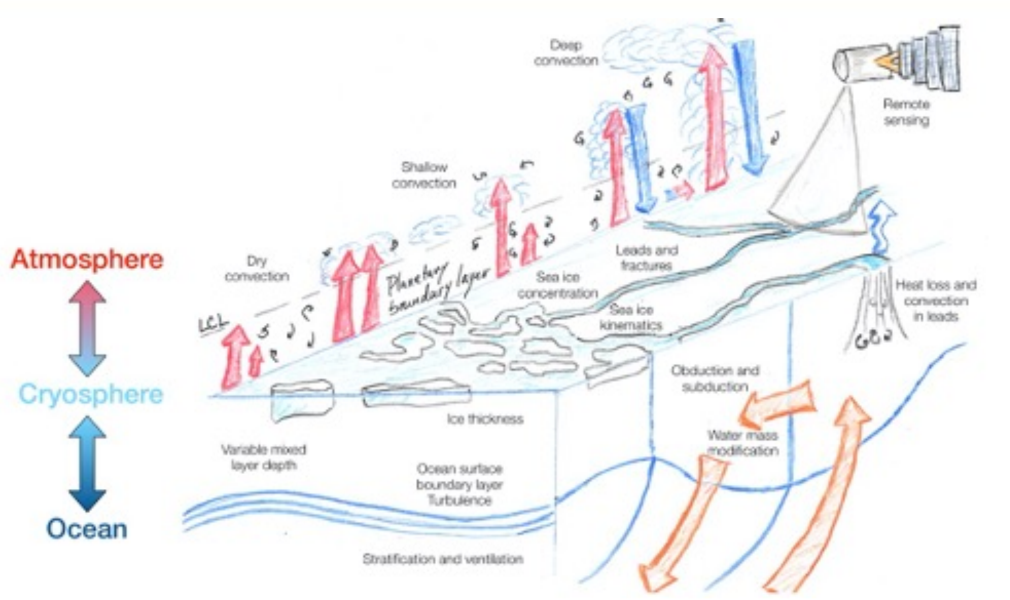
Objective: We aim to understand how coupled ocean-atmosphere-ice processes impact air-sea exchange in the Southern Ocean on decadal time scales, that is, attribute changes and uncertainty in Southern Ocean carbon uptake to variations in atmospheric wind patterns, ocean surface boundary layer characteristics, sea ice extent and concentration, and atmospheric boundary layer turbulence. The initiative includes observational, modeling, and uncertainty quantification components. The observational component is developing new, high-resolution ocean-ice products based on altimetry and SAR missions. These products include composite fields of sea surface height, ocean surface velocities in the Marginal Ice Zone, sea ice kinematics, and thickness [D]. The modeling component is developing and analyzing a suite of atmosphere-ocean-sea ice simulations based on the GEOS-MITgcm coupled model [F]. Model experiments are being used to evaluate the sensitivity of air-sea exchange to upper-ocean boundary layer properties, e.g., mixed layer depth, stratification at the base of the mixed layer, and sea-ice concentration. An improved representation of atmospheric boundary layer turbulence and its impact on Southern Ocean cloud distributions is also being assessed [G]. The uncertainty quantification component is developing new approaches and guidelines that are specifically designed for science modeling applications [E].

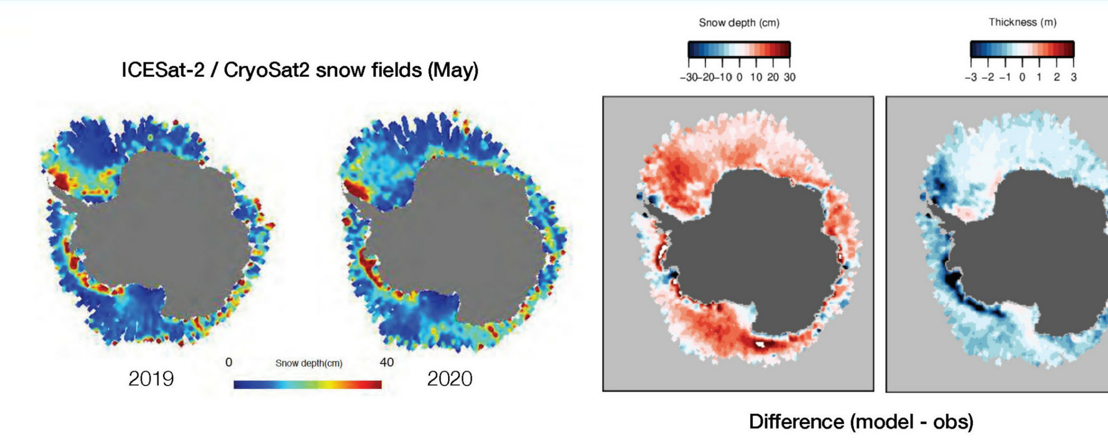
Background: We seek to improve predictions of the Southern Ocean's capacity to remain a sink of atmospheric carbon dioxide (CO_2) in response to changes in atmospheric forcing and sea ice conditions over the next 30 years. This multi-decadal time-scale is critical for the Southern Ocean as coupled ocean-atmosphere processes have been shown to cause the Southern Ocean's CO_2 uptake capacity to transition between a strong sink to a near-saturated state over time-scales as short as a decade. The Southern Ocean is the primary site where deep-ocean waters, the largest mobile reservoir in the climate system, interact directly with the atmosphere [C,H,I,J]. We have identified specific capabilities and areas of expertise, through which a combined campus and JPL effort can address unique components of the carbon cycle that have leading order impacts on Southern Ocean air-sea exchange. These are: the relatively unconstrained contribution of carbon exchange in the marginal ice zone and how it will change by 2050; the potential for change in upper-ocean stratification in response to changing patterns of atmospheric winds, precipitation, sea ice, and planetary boundary layer turbulence; and a quantitative assessment of how future combined remote sensing and in situ observing systems might reduce uncertainty in decadal predictions of Southern Ocean carbon uptake.

Approach and Result: The quantitative objectives of this initiative are: 1) 15-year gridded sea surface height product for the ice-covered Southern Ocean: The circulation of the Southern Ocean's polar gyres and the shelf seas is poorly observed. Yet, these regions ventilate deep water masses and are key CO_2 outgassing sites. During year 1 of this project, our team extended the first sea surface height (SSH) products in the Southern Ocean ice zone [A] to 15 years; this work is being refined for additional publication and analysis. In year 2, preliminary analysis of ICESat-2 data led to a successfully-funded project to create an Antarctic coastal altimetry product. 2) Sea-ice thickness and kinematics products for model evaluation over a seasonal cycle: Sea ice thickness is a particularly challenging feature to capture in the Southern Ocean due to high precipitation rates that lead to the formation of snow-ice that is not typically found in the Arctic Ocean. By combining sea ice freeboard from lidar (ICESat-2) and radar (CryoSat-2 and Sentinel3A/B) altimetry to resolve the location of the air-snow-ice interfaces, the first comprehensive sea-ice thickness maps have been generated. This work is now published [D] and the data product is being used to evaluate and adjust the model representation of the heat and mass balance of the Southern Ocean ice cover. 3) Include and adapt JPL's unified Eddy-Diffusivity/Mass-Flux (EDMF) planetary boundary layer (PBL) and cloud parameterization [G] in the coupled GEOS-MITgcm model: NASA's new unified cloud and PBL parameterization allows for stateof-the-art representation of atmospheric PBL dynamics but it has not previously been brought to bear on the unique features of the Southern Ocean (intense winds and large seasonal fluctuations in sea ice extent). The EDMF scheme has been successfully implemented in GEOS-MITgcm and is being used for comparison with observations to optimize EDMF parameters. 4) Assess the sensitivity of Southern Ocean air-sea-ice fluxes to different CO_2 forcing scenarios; provide attribution and uncertainty quantification: Coupled GEOS-MITgcm simulations will be carried out with adjustment of JPL's unified EDMF PBL and cloud parameterization [G]; the EDMF scheme has been successfully implemented in year 2. An analysis of non-local impacts of ice-shelf melt on atmospheric warming has been submitted to Science. Description of ECCO-Darwin is now published [B] and will be used to evaluate how sea-ice and stratification changes impact CO_2 uptake. 5) Develop and implement uncertainty quantification; assess uncertainty reduction due to new observations: Braverman, Owhadi, and Tavallali are developing techniques to assess uncertainty in sea-ice extent and air-sea fluxes. Owhadi's game theory approach [E] has been adopted and has been tested against a simple overturning circulation framework. The group is now focusing on sea-ice extent building on advances made by the Greenland 2050 team. Comprehensive UQ of ECCO-Darwin is being evaluated and prepared for publication and will help assess decadal-scale uncertainties in CO_2 flux estimates.

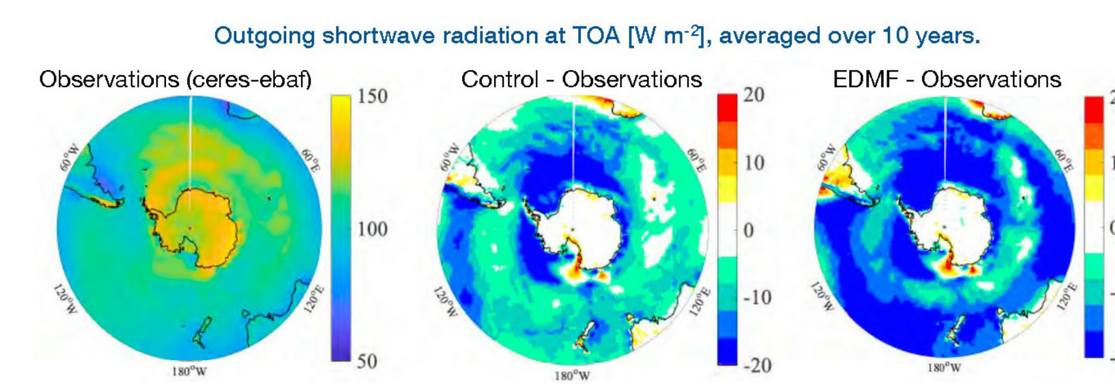
Significance/Benefits to JPL and NASA: We have started leveraging the the new capabilities arising from this R&TD research to preparation and submission of proposals to NASA ROSES and National Science Foundation (NSF) announcements of opportunity. A key missing observational component for Southern-Ocean studies is direct, frequent, and pervasive observations of air-sea fluxes of momentum, freshwater, heat, and carbon. We are working in collaboration with JPL engineers towards the formulation and development of missions that can be used to estimate these fluxes, including WaCM for momentum and FluxSat for heat and freshwater. Thompson is also working closely with the Climate Modeling Alliance (CliMA) project's effort to implement a new oceanic boundary layer parameterization in the MITgcm. Plans for implementing sea ice in the CliMA model are developing; results from the observational component of this project will be critical for future evaluation and adjustment of the CliMA model.



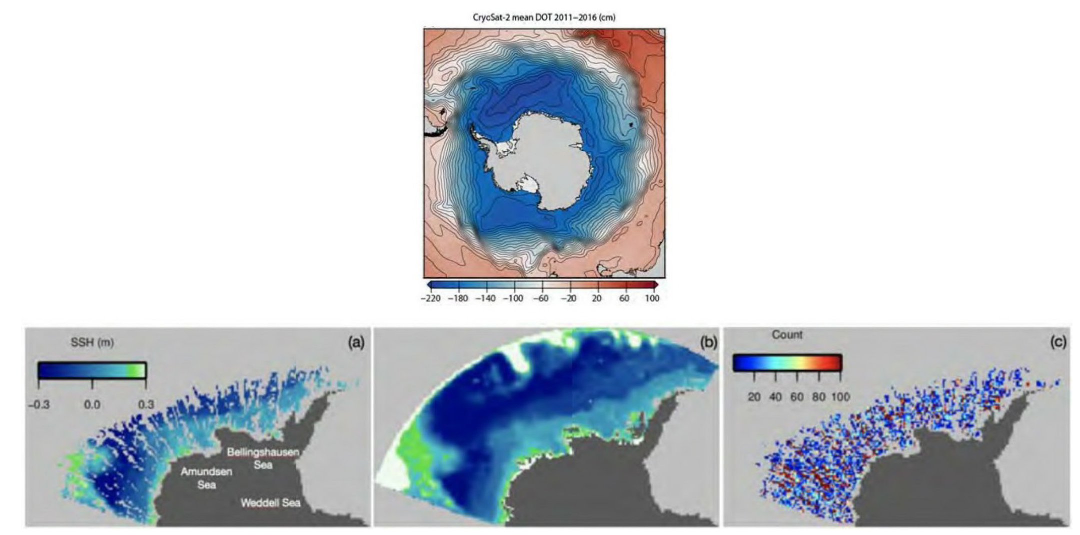
Schematic of key coupled processes explored by this initiative; emphasis is on the atmospheric planetary boundary layer, marginal ice zone, and ocean surface boundary layer.



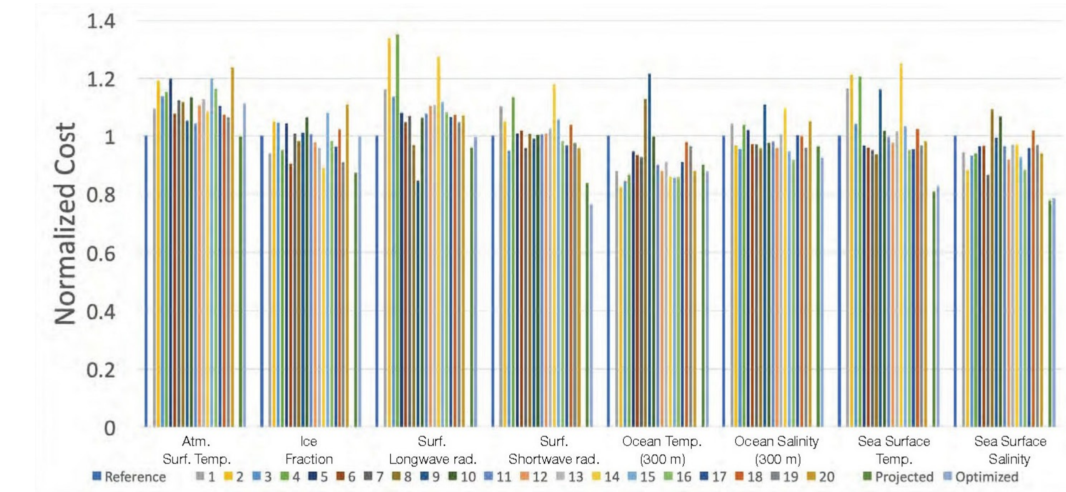
Estimates of sea ice thickness, snow depth of the Southern Ocean ice cover from ICESat-2 and CryoSat-2 for 2019 and 2020. Results summarized in [D].



Preliminary comparison of top of atmosphere outgoing shortwave radiation observations (left panel) with simulation without (middle panel) and with (right panel) the JPL EDMF parameterization [G].



The panels above are from a preliminary analysis on the feasibility of using ICESat-2 to derive a coastal altimetry product.



Adjustment of GEOS-MITgcm model with a Green's functions approach. Vertical bars represent cost (distance from observations) of baseline and 20 sensitivity experiments. Projected and optimized cost are also indicated.

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