National Aeronautics and Space Administration

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

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Background: The Southern Ocean is the primary site where deep-ocean waters, the largest mobile reservoir in the climate system, interact directly with the atmosphere. Coupled ocean-atmosphere processes **(Figure 1)** 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. *Will the Southern Ocean 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?*

APPROACH AND RESULTS:

Produce a 15-year gridded Sea Surface Height (SSH) product for the ice-covered Southern Ocean: The circulation of the Southern Ocean's polar gyres and shelf seas is poorly observed. Yet, these regions ventilate deep water masses and are key CO_2 outgassing sites. JPL has developed the first SSH products in the Southern Ocean ice zone **[A]**, which has proven critical for evaluating gyre circulations in ocean models **(Figure 2)**. Our team extended this SSH product to 15 years.

Sea-ice thickness and kinematics products for model evaluation over a seasonal cycle: By combining sea ice freeboard from lidar (ICESat-2) and radar (CryoSat-2 and Sentinel-3A/B) altimetry to resolve the location of the air-snow-ice interfaces, the first comprehensive sea-ice thickness maps have been generated. Specifically, we completed estimates of sea ice thickness and snow depth for the Southern Ocean using ICESat-2 and Cryosat-2 **[B,C]**, analyzed the variability of snow depth and ice thickness, and started comparisons with output from numerical simulations **(Figure 3)**. We also studied the impact of increased glacier runoff, propagated along coastal boundary currents throughout West Antarctica marginal seas, on basal melt rates **[D]**.

Include and adapt JPL's unified EDMF parameterization in the coupled Goddard Earth Observing System (GEOS)-ECCO model: The EDMF PBL parameterization allows for state-of- the-art representation of atmospheric PBL dynamics but had 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-ECCO, we have demonstrated a strategy for coupled model adjustment using Green's Functions **[E]**, and we have found evidence of coupling at oceanic meso- and submesoscales impacting atmospheric boundary layer and air-sea fluxes **[F,G,H]**.

Assess the sensitivity of Southern Ocean air-sea fluxes to different CO_2 forcing scenarios: We used the state-of-the-art ECCO-Darwin biogeochemistry model to resolve marine carbon cycle dynamics. A description of ECCO-Darwin is now published **[I]** and a manuscript was published on Dissolved Inorganic Carbon (DIC) budget analysis **[J]** **(Figure 4)**. Some preliminary analysis of impact of sea-ice extent on carbon uptake and export has been carried out.

Develop and implement new Uncertainty Quantification (UQ) tools: A campus/JPL effort to design new UQ approaches for climate model output, joint with the Greenland Earth 2050 initiative, took place. New techniques, e.g., a game- theory approach, were developed to assess uncertainty in sea-ice extent and air-sea fluxes **[K]**. A comprehensive UQ of ECCO-Darwin is being prepared for publication, which will help assess decadal-scale uncertainties in CO_2 flux estimates.

Significance/Benefits to JPL and NASA: This project (1) enhances the link between JPL and campus on sea ice dynamics and ocean boundary layer turbulence, (2) extends collaborations to include coupled ocean-atmosphere processes, e.g., changes in cloud and precipitation patterns that are poorly understood in the Southern Ocean, and (3) initiates new collaborations between JPL and campus to develop uncertainty quantification that is intended to guide future air-sea flux satellite missions.

Objectives: Use JPL and campus capabilities, e.g., analysis of high-resolution Synthetic Aperture Radar (SAR) data, the Eddy-Diffusivity/Mass-Flux (EDMF) Planetary Boundary Layer (PBL)/cloud parameterization, and the Estimating the Circulation and Climate of the Ocean (ECCO)-Darwin ocean biogeochemistry model, to study mechanisms that can lead to decadal changes in Southern Ocean carbon uptake, e.g., variations in atmospheric wind patterns, sea ice extent and concentration, ocean surface boundary layer characteristics, and atmospheric PBL turbulence.

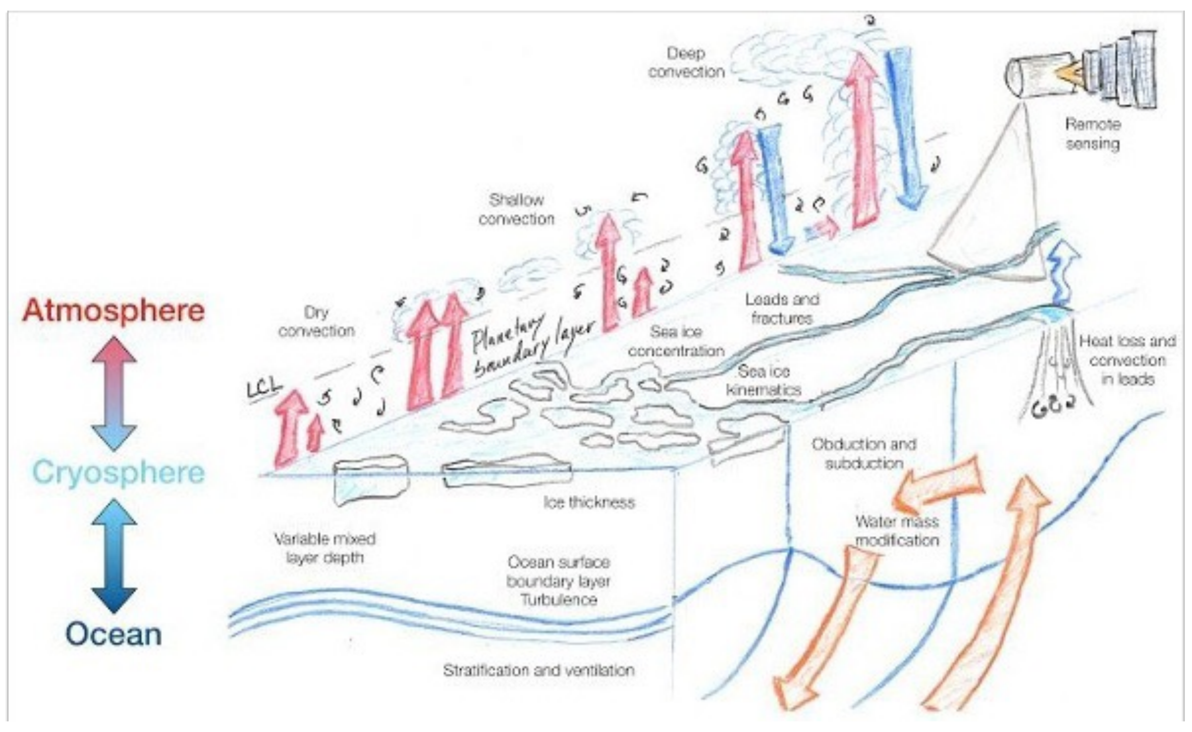

Figure 1. Schematic of key coupled processes explored by this initiative; emphasis is on the atmospheric Planetary Boundary Layer (PBL), Marginal Ice Zone (MIZ), and ocean surface boundary layer.

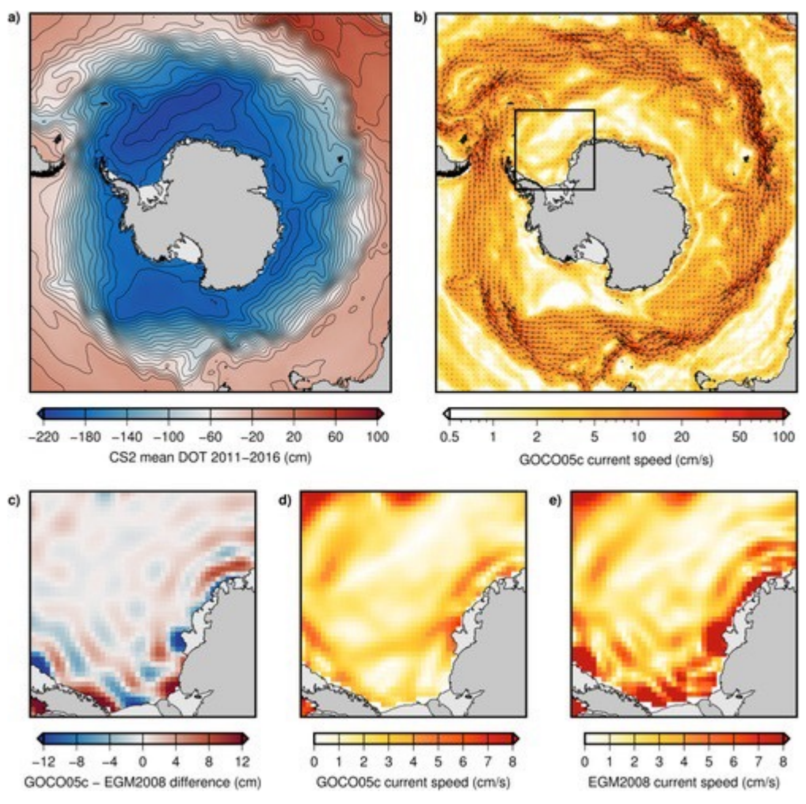

Figure 2. Example result from **[A]**: 2011–2016 mean dynamic topography estimated relative to the GOCO05c geoid (cm) with contours drawn every 10 cm; (b) the mean current speed (cm/s); (c) the difference between the GOCO05c and EGM2008 geoid models (cm) for the Weddell Sea region (the black box in b); (d) the GOCO05c and (e) the EGM2008 current speed (cm/s) in the Weddell Sea region.

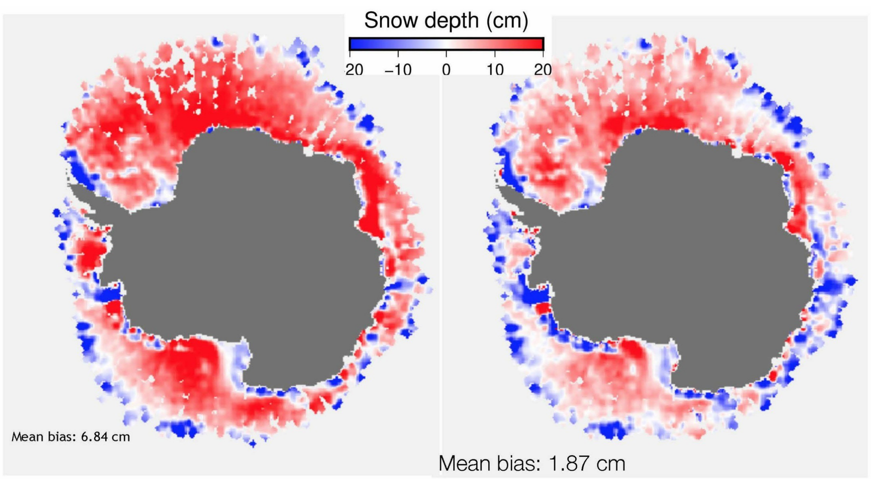

Figure 3. Observed snow depth obtained as described in **[B,C]** compared with simulated snow depth in one of the ECCO simulations. The model-data bias is being used to evaluate and improve the ECCO simulation.

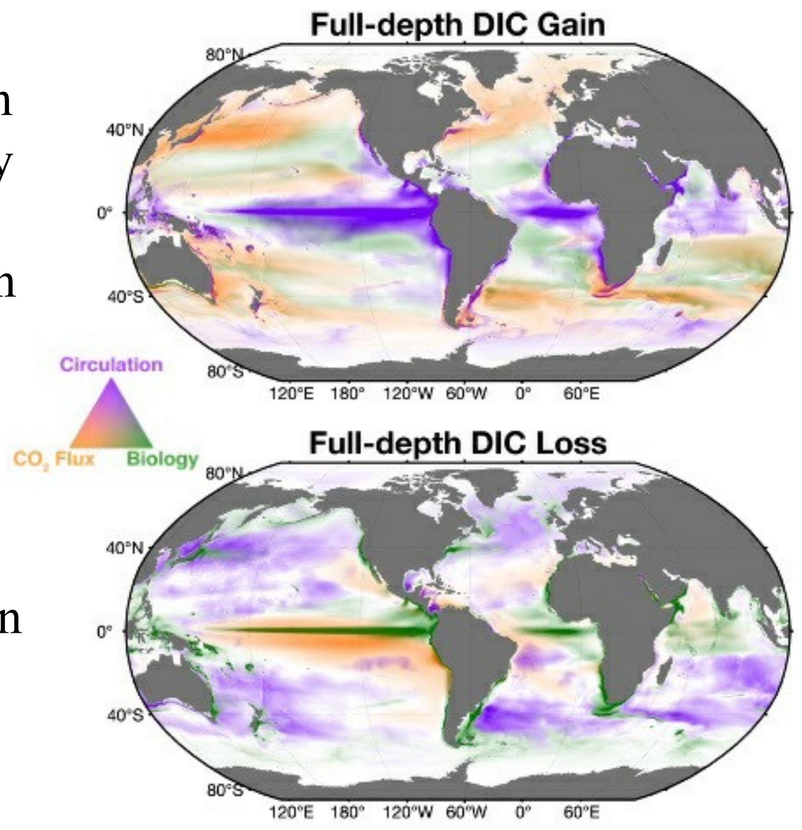

Figure 4. Example result from **[J]**: patterns of Dissolved Inorganic Carbon (DIC) gain (top) & loss (bottom) in full-depth-ocean. DIC gain from air-sea CO_2 flux (orange) occurs in boundary currents, subpolar regions, and the Southern Ocean, while losses occur along the Equator. Biology (green) provides a gain of DIC from deep remineralization, concentrated in subtropical gyres, and a loss at the equator from plankton blooms. DIC loss from circulation (purple) highlights the extratropical divergence (downwelling) required to balance equatorial convergence of DIC-rich waters (upwelling).

Publications:

[A] Armitage et al. (2018) https://doi.org/10.1002/2017JC013534
[B] Kacimi et al. (2020) https://doi.org/10.5194/tc-14-4453-2020
[C] Kwok et al. (2021) https://doi.org/10.5194/tc-15-821-2021
[D] Flexas et al. (2022) https://doi.org/10.1126/sciadv.abj9134
[E] Strobach et al. (2022) https://doi.org/10.5194/gmd-15-2309-2022
[F] Light et al. (2022) https://doi.org/10.1007/s00382-022-06257-6
[G] Strobach et al. (2022) https://doi.org/10.1029/2021GL097003
[H] Torres et al. (2022) https://doi.org/10.5194/egusphere-2022-294
[I] Carroll et al. (2020) https://doi.org/10.1029/2019MS001888
[J] Carroll et al. (2022) https://doi.org/10.1029/2021GB007162
[K] Bajgiran et al. (2022) https://doi.org/10.1016/j.jcp.2022.111608

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