# Toward seamless simulation, estimation, and prediction of weather and climate with the GEOS/ECCO model and data assimilation system

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Abdullah Al Fahad, Atanas Trayanov, Jean-Michel Campin, An Nguyen, Gael Forget,
Patrice Klein, Hector Torres, Brian Arbic, Hong Zhang,
Chris Henze, Bron Nelson, David Ellsworth, Nina McCurdy, and others

**ECCO Annual Meeting, January 25-26, 2023, Caltech, Pasadena**

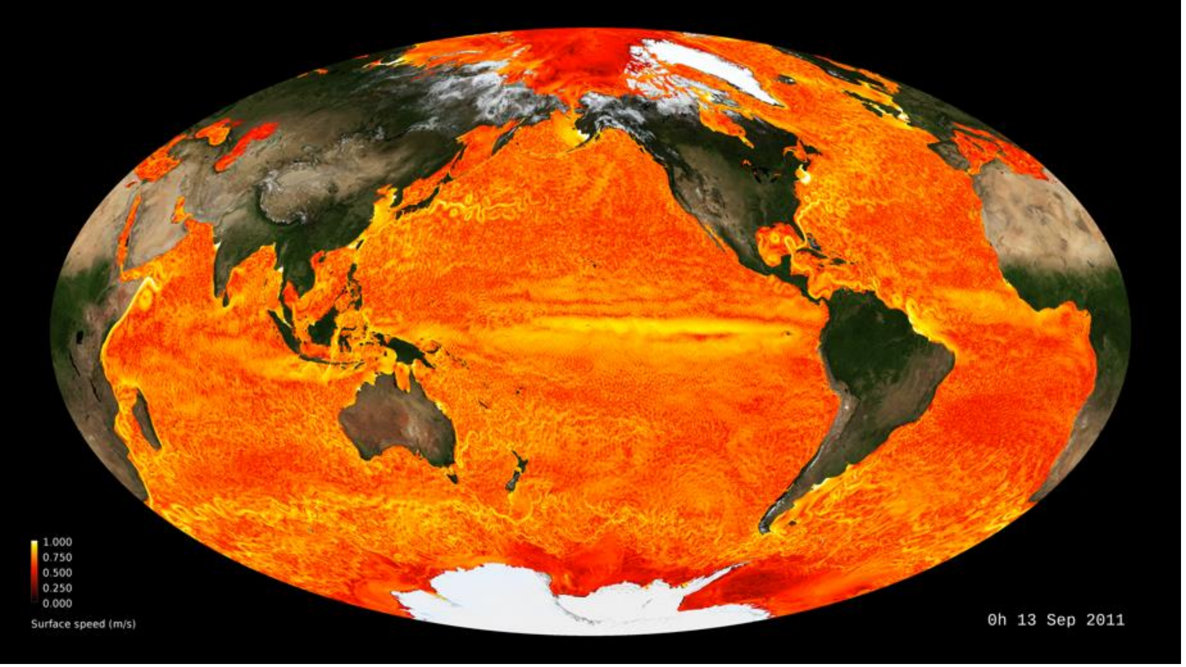
Jet Propulsion Laboratory
California Institute of Technology

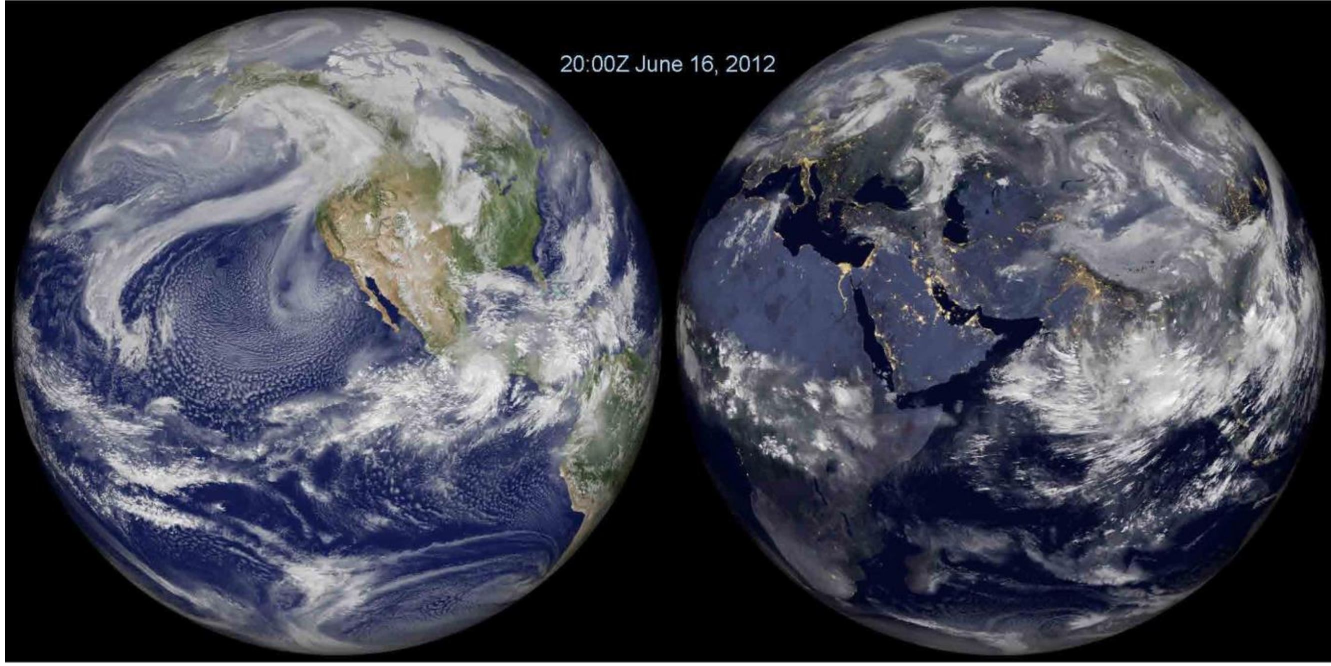
# Motivation for coupling GEOS and ECCO

Make incremental but significant advances in NASA's subseasonal-to-decadal simulation and prediction capability by combining expertise from two flagship NASA modeling and assimilation efforts.

Objective 1: Coupled ice-ocean-atmosphere simulation, where all three fluids are integrated globally with km-scale horizontal grid spacing.

Objective 2: Incorporation of ECCO data assimilation assets into GEOS toward improved subseasonal-to-decadal prediction.




Map of surface current speed from a 1/48° global-ocean and sea ice simulation carried out using the MITgcm.

Importantly this simulation includes both atmospheric and tidal forcing and it admits submesoscale eddies and internal waves.

Over 120 science publications make use of output from this simulation.

Extensively used for pre-SWOT, internal-wave, mesoscale, submesoscale, vertical heat flux, and many other oceanographic studies.

Global, cloud-resolving simulation with GEOS, carried out with horizontal grid spacing of 1.5-km. Up to 2020, this was the highest-resolution atmospheric simulation carried out with any US global model.

Explicit cloud-resolving simulations provide valuable insight on the 'grey-zone' of physics parameterizations, where sub-grid scale processes are partially resolved.

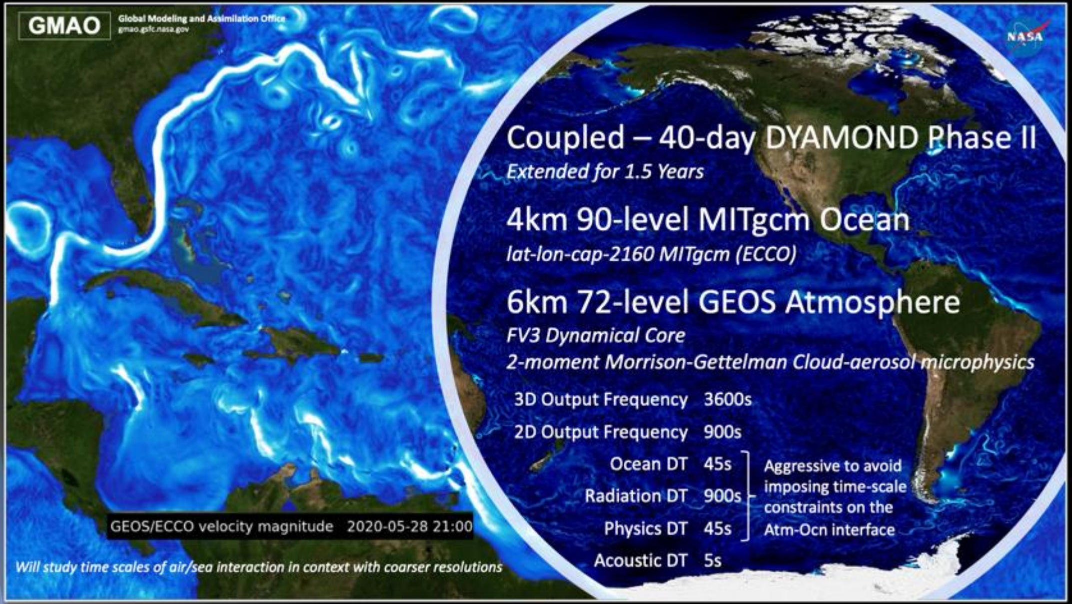
What is missing from both simulations is high-frequency and wavenumber, interactive air-sea boundary conditions for more realistic representation of planetary boundary layers.

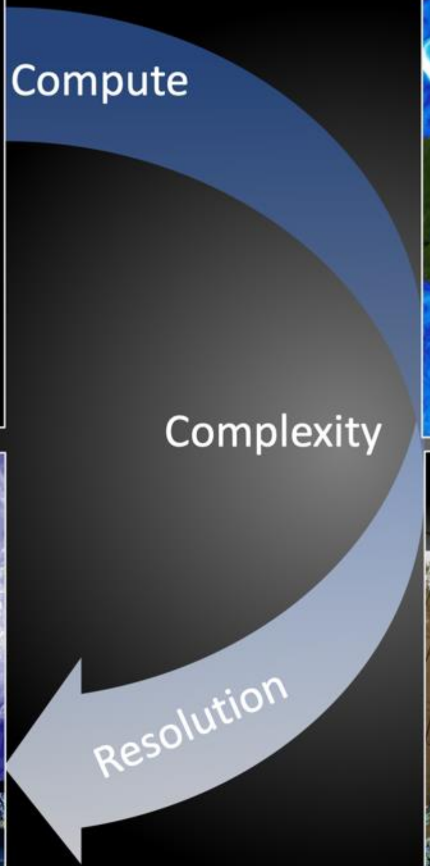
National Aeronautics and Space Administration

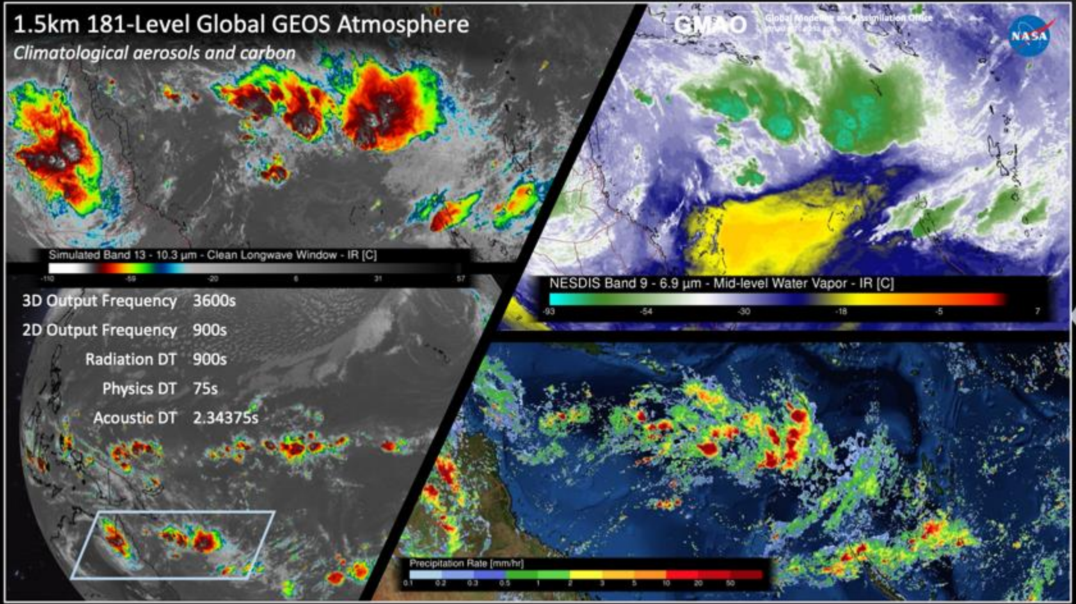
# An overview of the GEOS Non-Hydrostatic DYAMOND Phase-II Simulations

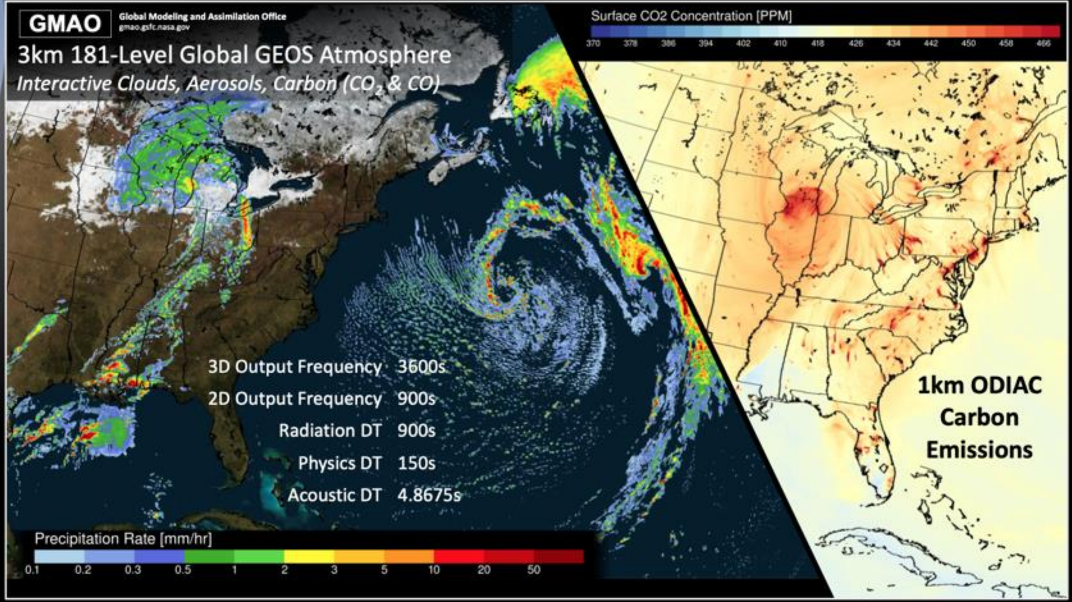
## GEOS DYAMOND Phase-II 40-day Simulations

| Configuration | Total Cores - "System" | Throughput | Data Volume |
|---|---|---|---|
| **Coupled Atm-Ocn**<br>6km 72-Level Atm<br>4km 90-Level Ocn | **8,160 Intel Xeon Haswell**<br>processor cores<br>"Pleiades" NASA-NAS | **3 Simulated Days /**<br>Wallclock Day | **0.3 Petabytes** |
| **Atmosphere+Carbon**<br>3km 181-Level Atm | **39,360 Intel Xeon Skylake**<br>processor cores<br>"Discover" NASA-NCCS | **7 Simulated Days /**<br>Wallclock Day | **2.0 Petabytes** |
| **Atmosphere**<br>1.5km 181-Level Atm | **39,440 Intel Xeon Skylake**<br>processor cores<br>"Discover" NASA-NCCS | **1.5 Simulated Days /**<br>Wallclock Day | **1.3 Petabytes** |

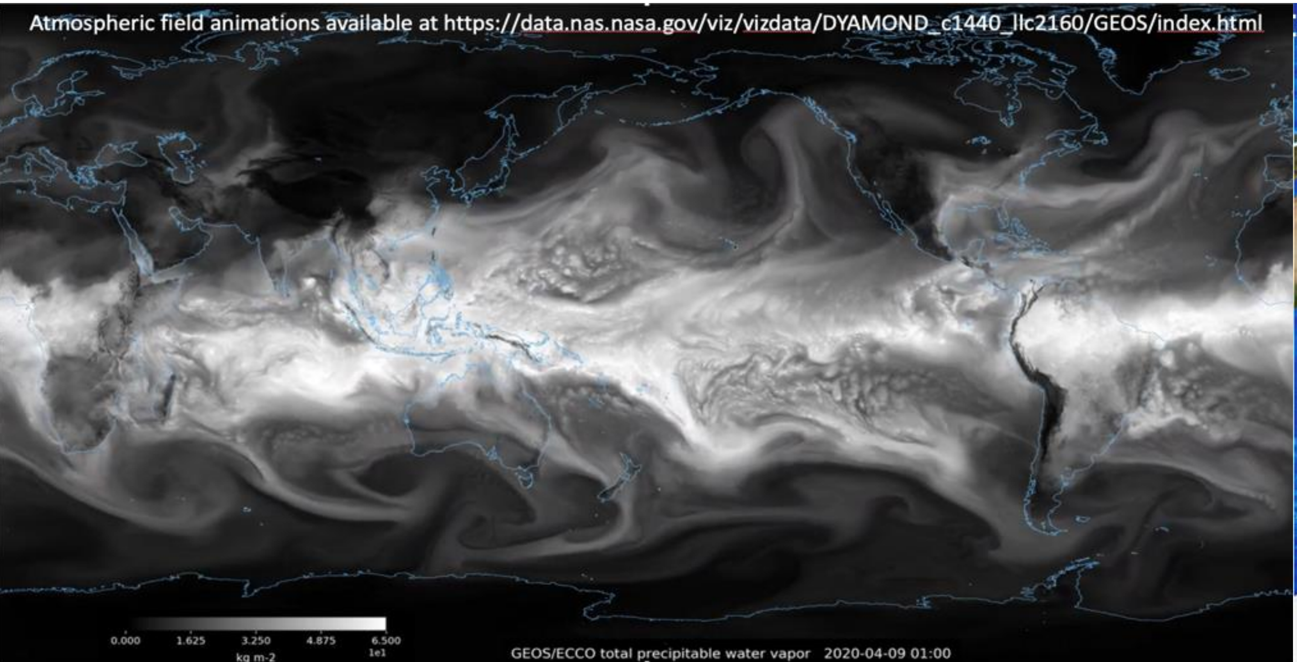


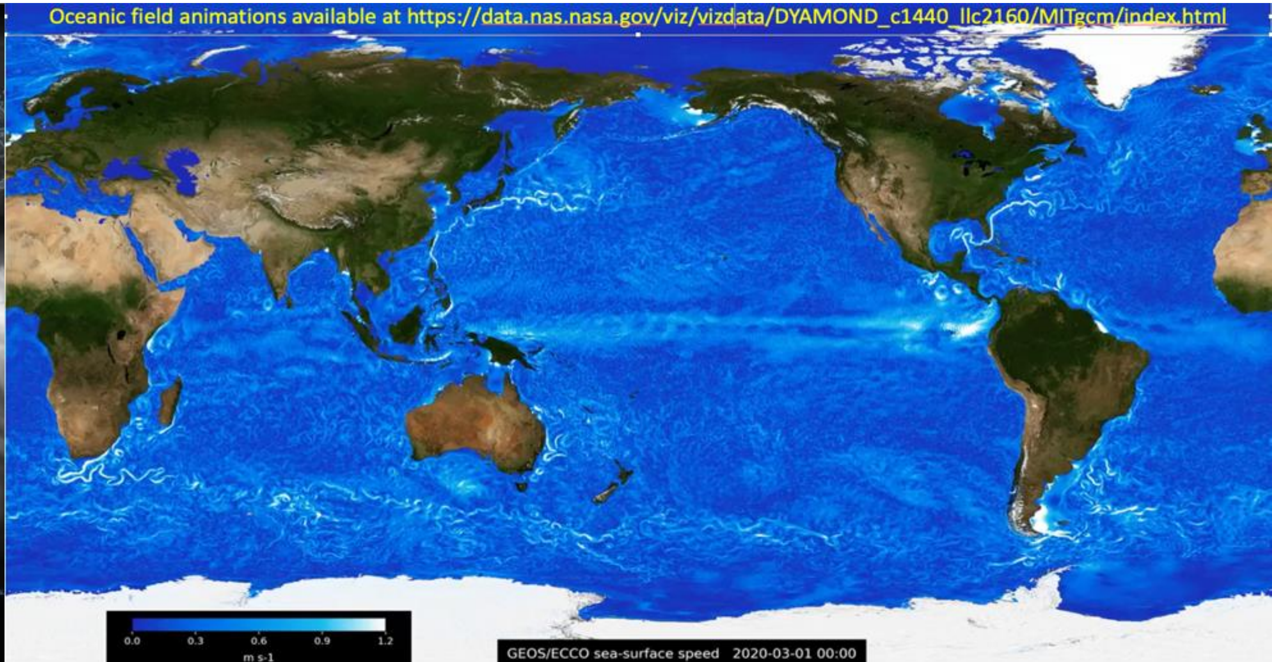
GMAO Global Modeling and Assimilation Office
gmao.gsfc.nasa.gov

**William Putman**
with contributions from the GMAO SI Team, Andrea Molod, Dimitris Menemenlis, Lesley Ott, Ehud Strobach, and the GMAO Modeling Team

# Studying air-sea interactions at mesoscale and submesoscale (< 50 km)

- New atmosphere-land-ocean coupled simulation developed in the context of DYAMOND (DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains)
- Makes use of the GEOS (atmosphere/land/ice) and MITgcm (ocean/ice) models.
- Nominal horizontal grid spacing is 1/16° for GEOS and 1/24° for MITgcm.
- Integrated for 14 months with hourly (and some sub-hourly) output of all prognostic and many diagnostic ocean-atmosphere variables.



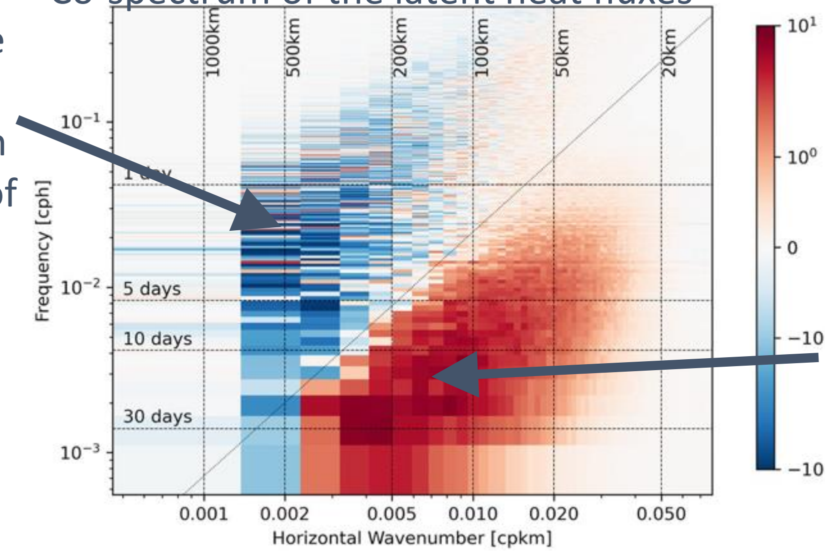



# Local air-sea interactions at ocean mesoscale and submesoscale in a Western Boundary Current (Strobach et al., 2022)

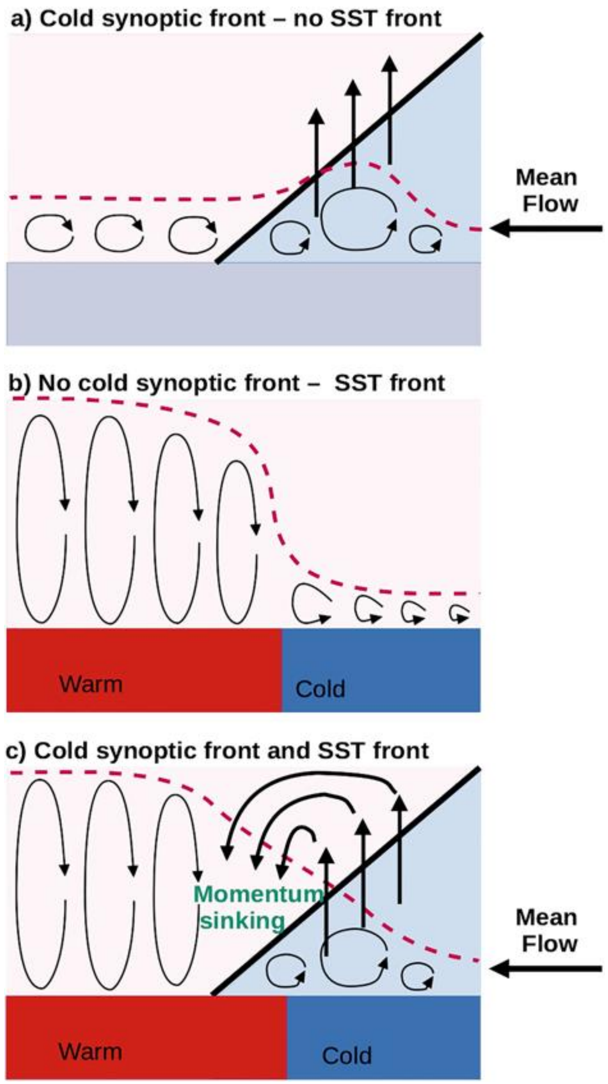
The study focuses on recurring intermittent wind events in the Gulf Stream region associated with SST anomalies with horizontal scales smaller than 500-km. These events are associated with a secondary circulation that acts to fuel the latent heat bursts by transferring dry air and momentum down to the surface.

Co-spectrum of the latent heat fluxes

Larger scale motions dominate in this region of spectrum




Secondary Circulations occur in this region of spectrum




Cold air blows from the right over an SST change from cold to warm. The red dotted line represents the atmospheric boundary layer height (PBL).

a) A cold synoptic front approaches a gradual Sea Surface Temperature (SST) gradient (from right to left), the warmer air at the surface is pushed upward. **No secondary circulation**

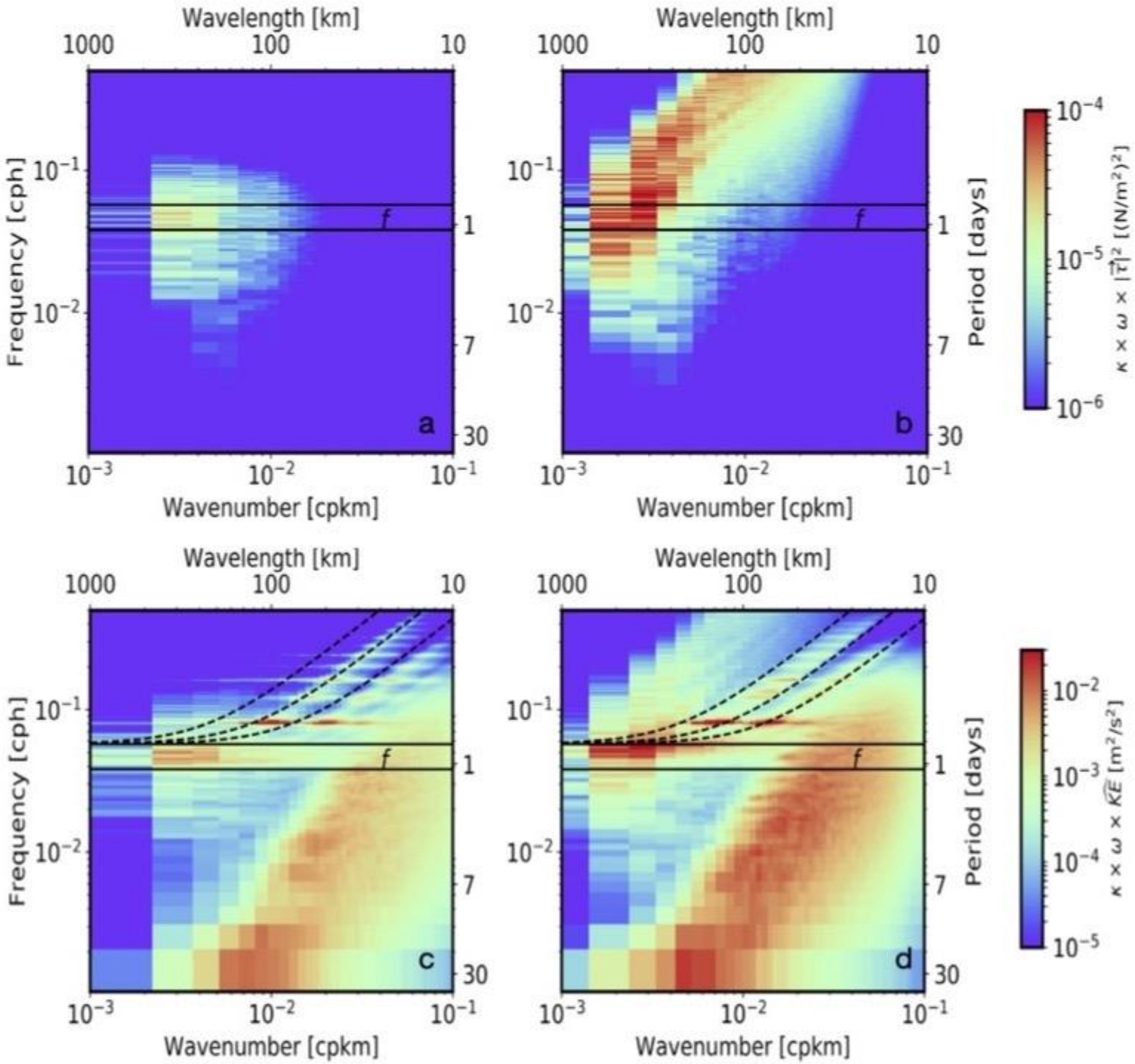
(b) Cold air blows over an SST front. Higher atmospheric PBL forms above warmer SST due to higher mixing at no front conditions. **No secondary circulation.**

(c) A cold synoptic front approaches an SST front and produces momentum sinking above the front due to mixing. **Secondary circulation enhances the turbulent fluxes and atmospheric gradients.**

**Wind convergence and divergence explained by submesoscale SST fronts** trigger **a secondary circulation** that transfers dry air and momentum down to surface. This secondary circulation intensifies **Latent Heat Flux by 30%.**

Uncoupled MITgcm simulation

Coupled GEOS/MITgcm simulation




Wind stress Frequency-Wavenumber Spectra

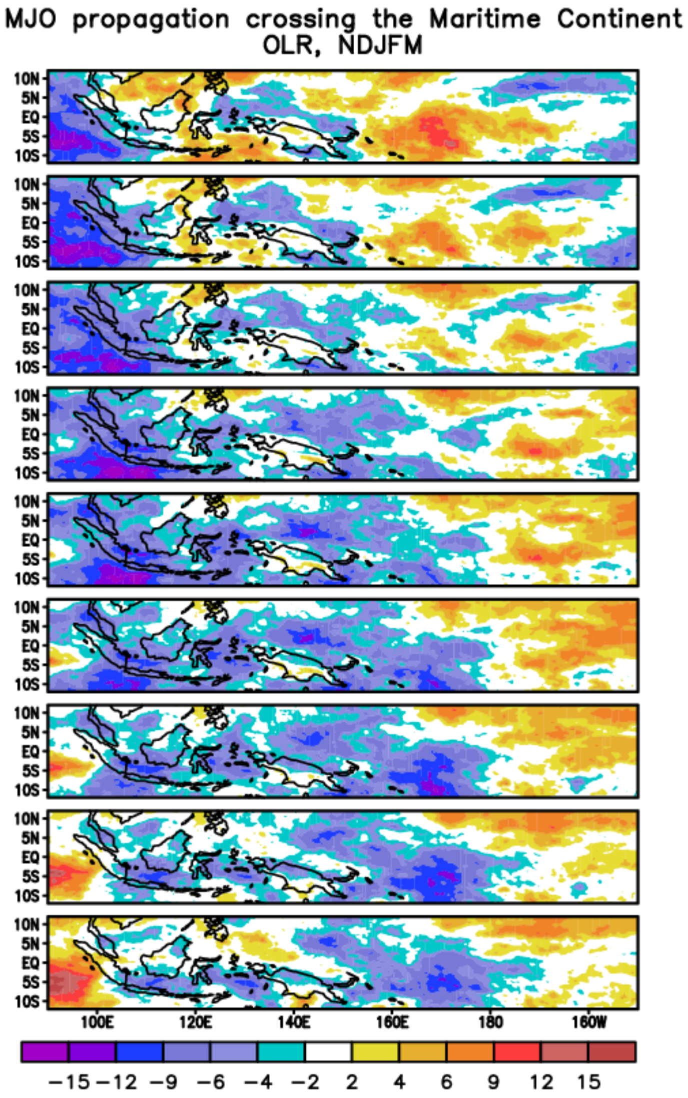
Surface current Frequency-Wavenumber Spectra

**Wind work at the air-sea interface: A Modeling Study in Anticipation of Future Space Missions** (Torres, et al., 2022)

The study examines the different components of wind work, the transfer of kinetic energy between the ocean and the atmosphere, defined as the scalar product of ocean wind stress and surface current.

The wind work spans a broad range of spatial and temporal scales, from 10 to 3000 km and one hour to at least 3 months, emphazing the need to high spatial and temporal scale information to study this multiscale phenomenon.

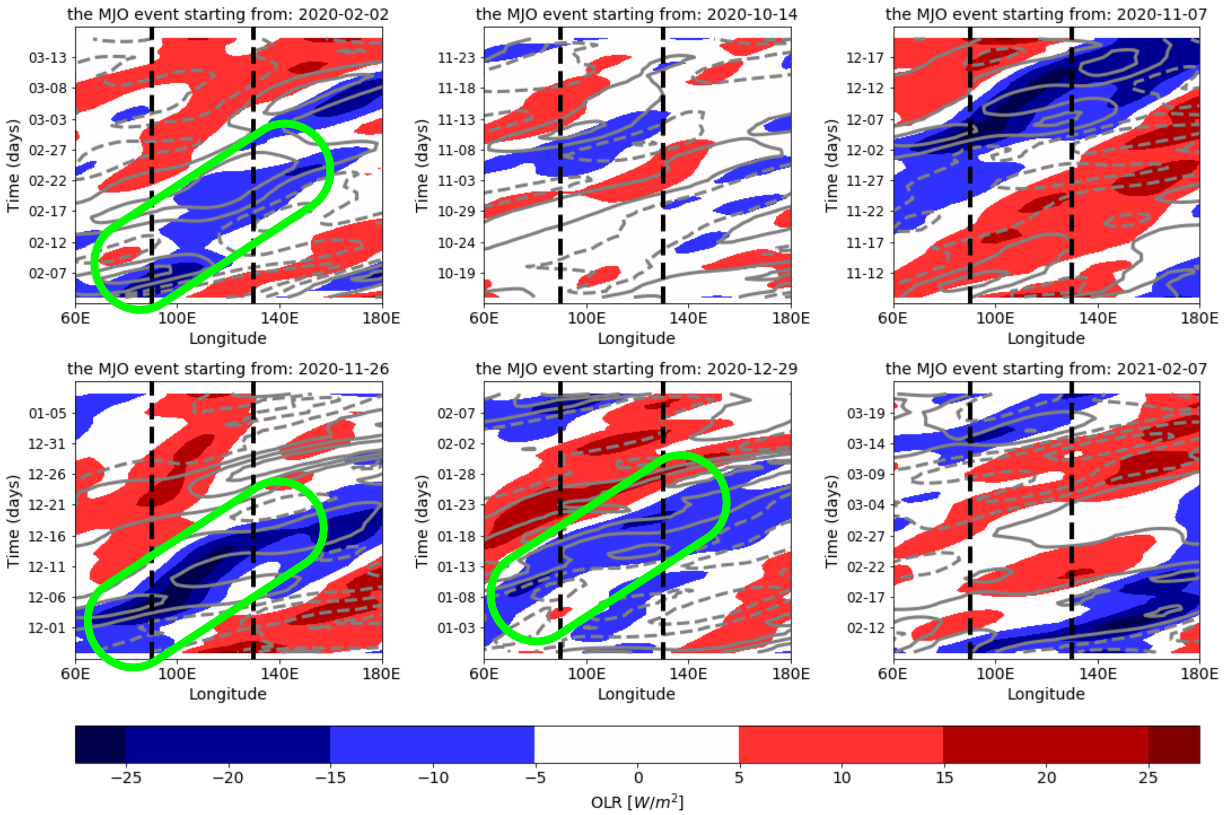
# GEOS/MITgcm Coupled Model – Selected Analysis




**Examination of the behavior of the Madden-Julian Oscillation – Propagation across the Maritime Continent - Young-Kwon Lim, Danni Du**

MJO as represented by OLR.

The simulation MJO composite indicates that it takes about 40~45 days to complete one round along the equator. (45 days => 5m/sec)



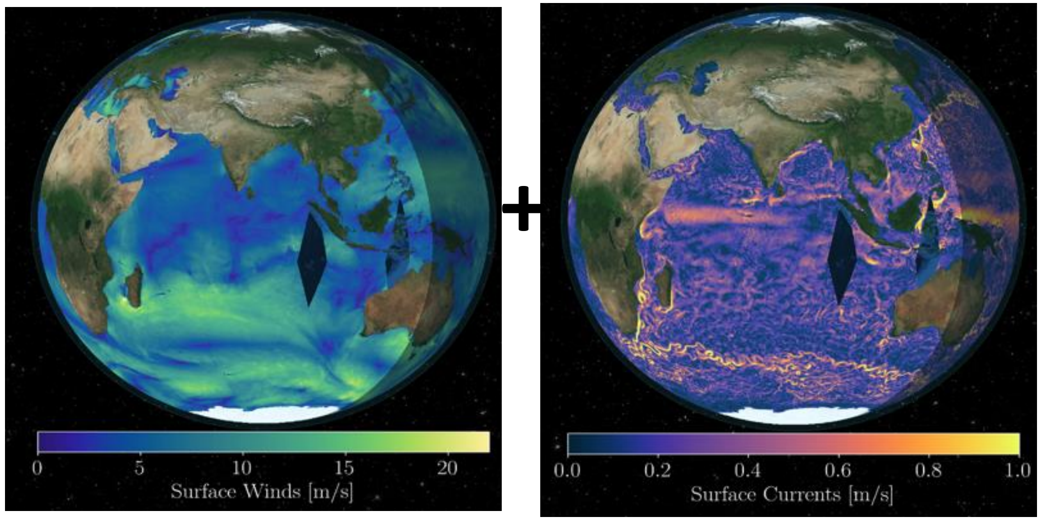

**During the model simulation period (~430days), there are 3 MJO events propagating across the Maritime Continent.**

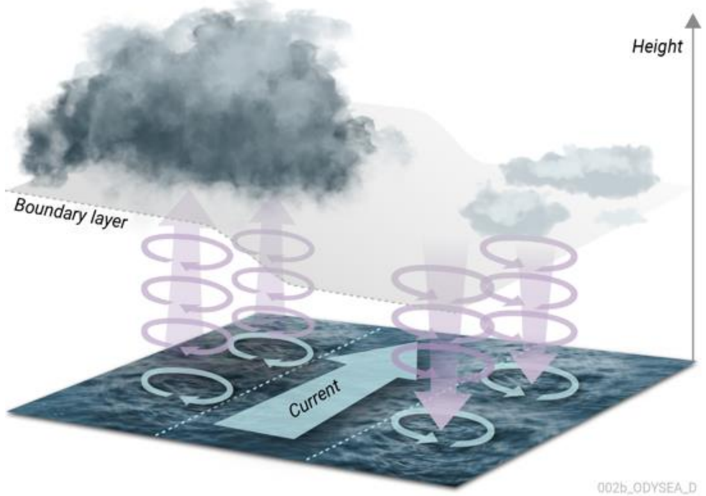
# **ODYSEA** (**O**cean **DY**namics and **S**urface **E**xchange with the **A**tmosphere)

- A mission concept for upcoming competition under the NASA Earth System Explorers (ESE) program.

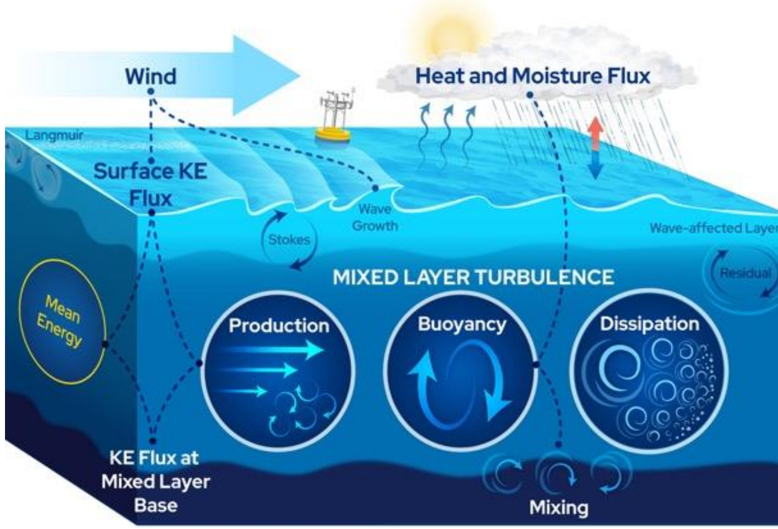
- ODYSEA fulfills a longstanding Earth Science community goal by providing the **first-ever measurements of total ocean surface current from space** and the **first global observations of ocean-surface current-wind interactions.**

- ODYSEA brings wind and current measurements up to speed to advance Earth system science and operational applications that save lives.



Small-scale wind-current interaction & effect on atmospheric BL



Parsing the kinetic energy budget of the ocean surface mixed layer *(Zippel et al, 2022)*

## Objective 2: Incorporation of ECCO data assimilation assets into GEOS toward improved subseasonal-to-decadal prediction.

From its inception two decades ago, and indeed in the choice of its very name, the ECCO project has implicitly assumed that an accurate estimate of the state of the ocean is a vast reservoir of climate predictive skill.

But simply prescribing ECCO initial conditions to a given coupled ocean-atmosphere model, regardless of how excellent these initial conditions might be, is not sufficient for optimally capturing the ocean's predictive information content.

Predictive skill also depends on the quality of the climate model that is used to evolve these initial conditions and on the degree to which these initial conditions are consistent with this coupled climate model.

## Objective 2: Incorporation of ECCO data assimilation assets into GEOS toward improved subseasonal-to-decadal prediction.

A first set of ECCO climate predictive skill is provided by the estimation of geographically (and potentially seasonally) varying background diapycnal and GM-Redi coefficients.

The requirement that ECCO solutions satisfy model equations exactly meant that early ECCO solutions did not fare well in ocean-reanalyses beauty contests.

Stammer (2005) demonstrated that it was possible to use ECCO adjoint estimation tools to adjust empirical sub-grid scale parameters, e.g., mixing coefficients.

In a first step towards improving the predictive skill of the GEOS-ECCO model, we are using the ECCO-V4 model configuration and optimized mixing coefficients.

# Objective 2: Incorporation of ECCO data assimilation assets into GEOS toward improved subseasonal-to-decadal prediction.

In a second step towards improving the predictive skill of the GEOS-ECCO model, we experimented with a Green's Functions-based (poor-person's adjoint) adjustment of empirical model parameters in the coupled system.

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## Earth system model parameter adjustment using a Green's functions approach

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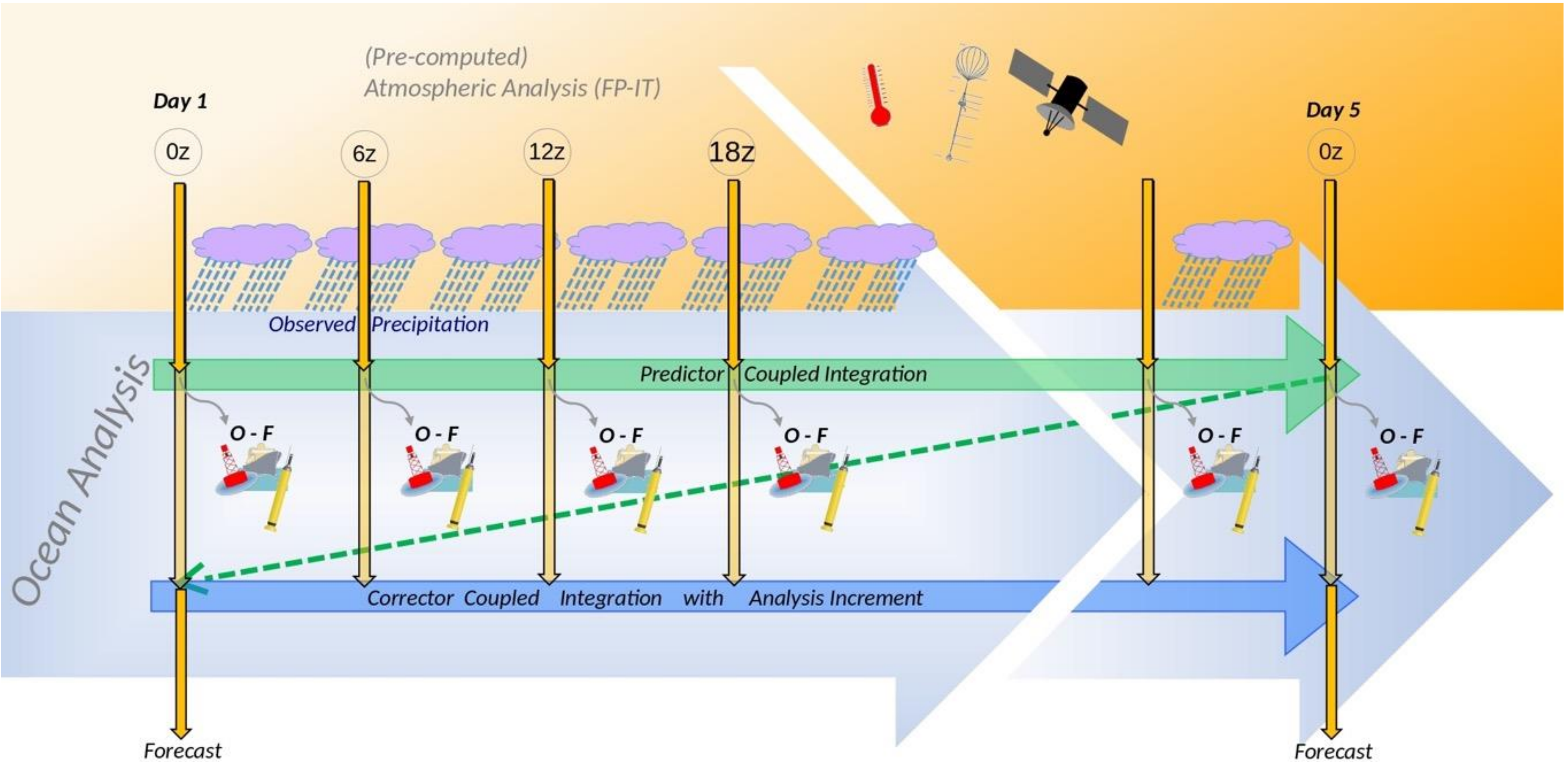
**Abstract.** We demonstrate the practicality and effectiveness of using a Green's functions estimation approach for adjusting uncertain parameters in an Earth system model (ESM). This estimation approach has previously been applied to an intermediate-complexity climate model and to individual ESM components, e.g., ocean, sea ice, or carbon cycle components. Here, the Green's functions approach is applied to a state-of-the-art ESM that comprises a global atmosphere/land configuration of the Goddard Earth Observing System (GEOS) coupled to an ocean and sea ice configuration of the Massachusetts Institute of Technology general circulation model (MITgcm). Horizontal grid spacing is

# Objective 2: Incorporation of ECCO data assimilation assets into GEOS toward improved subseasonal-to-decadal prediction.

In a third step towards improving the predictive skill of the GEOS-ECCO model, we plan to use ECCO adjoint-model tools to estimate oceanic initial conditions and air-sea exchange coefficients.



# GEOS/ECCO summary and ongoing work

- A GEOS/ECCO "Nature Run" simulation was conducted at ~6km atmosphere, ~2-4 km ocean grid spacing for 14 months (2/2020 to 4/2021) with hourly (or sub-hourly) output.
- Model fields are already being used to support SWOT and ODYSEA simulators and under consideration for coupled OSSEs by the SynObs OceanPredict project.
- Studies using the GEOS/ECCO model output for mesoscale air-sea interactions, wind work, MJO propagation, etc., are underway and starting to be published.
- Ongoing work aims to set-up a 1/32° atmosphere coupled to a 1/48° ocean simulation.

- ECCO-V4 model configuration and optimized mixing parameters are being used for coarse-resolution simulations and prediction experiments.
- A demonstration coupled ocean-atmosphere optimization using the Green's Functions estimation approach has been published.
- The coupled GEOS/MITgcm/ECCO model was recently updated to be part of GEOS-ESM on github and to use the latest GEOS code base (Jason).
- Work is underway to experiment with adjoint-method ocean initialization of subseasonal-to-decadal hindcasts.