The development of the new GEOS-MITgcm atmosphere-ocean model for coupled data assimilation system

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Overview

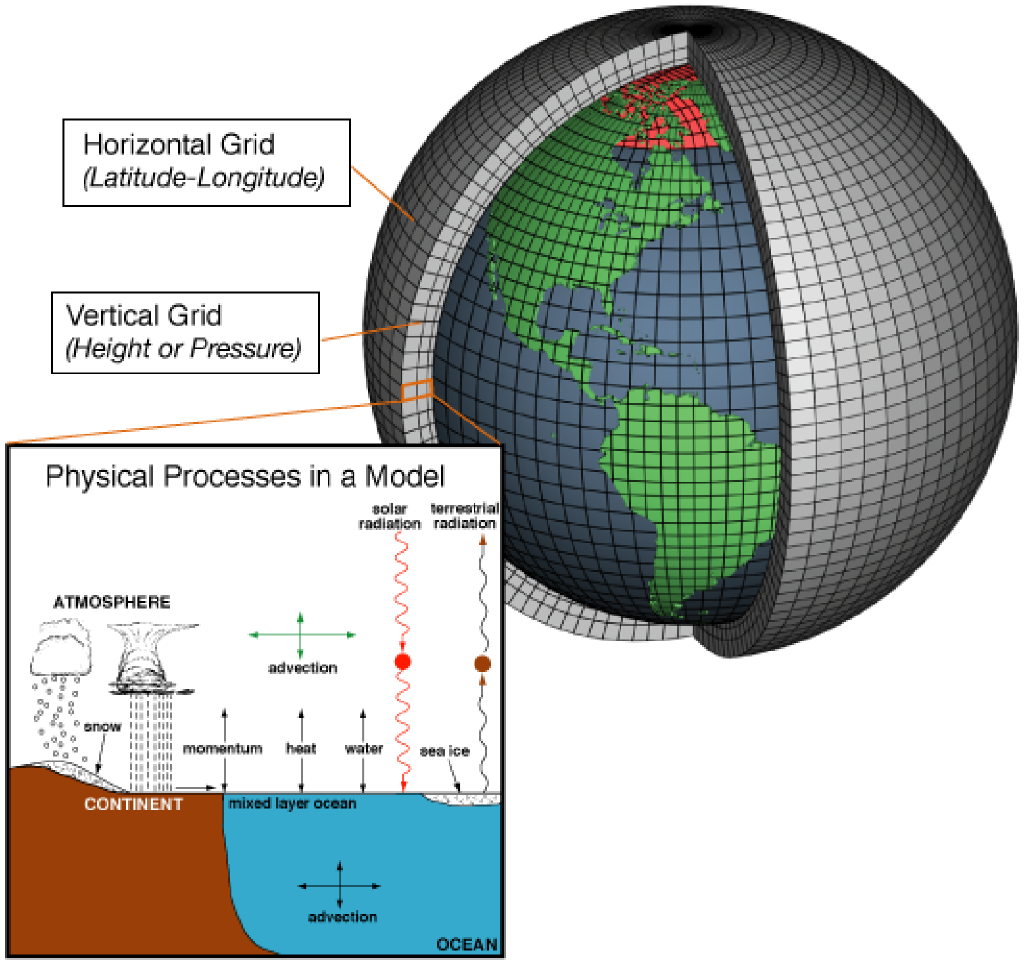
- Part I: Earth System models and data assimilation
- Part II: Towards a closed budget planetary assimilation system GEOS-MIT model
- Part III: Air sea interactions in the high resolution GEOS-MIT

Part I:
Earth System models and data assimilation.

Earth System Models

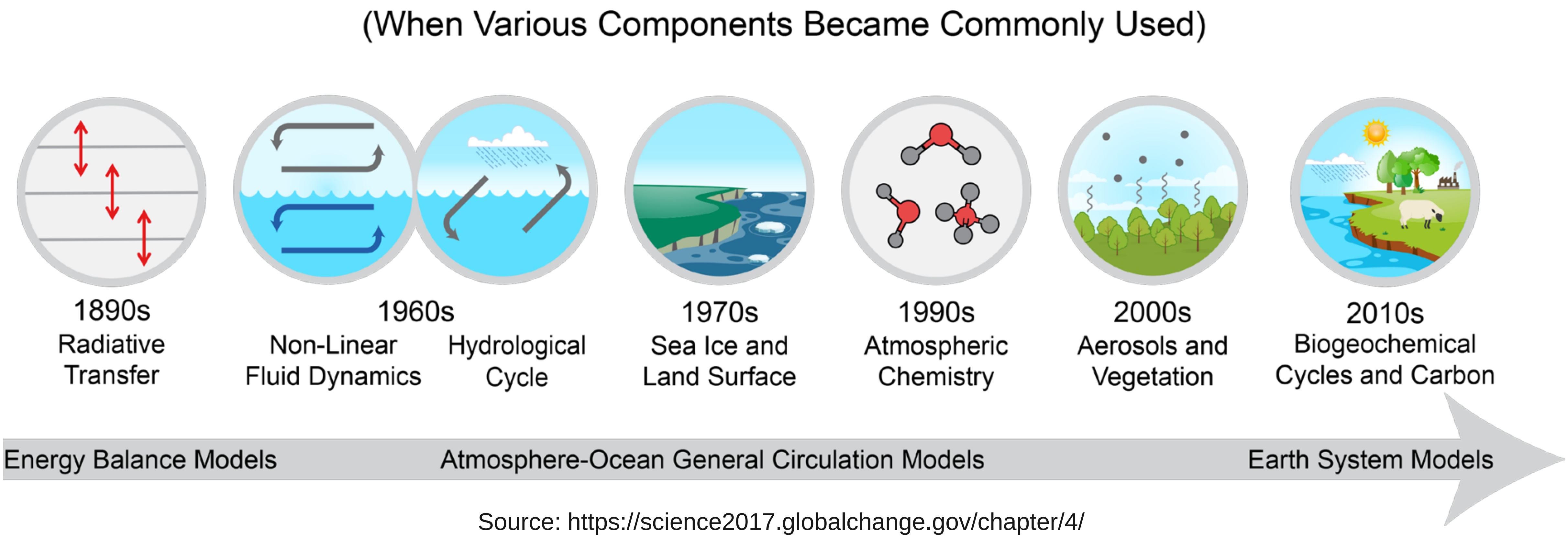
- Numerical models representing physical processes in the atmosphere, ocean, cryosphere and land surface.

  - The planet is divided into a 3-dimensional grid.
  - A set of differential equations describing the circulation is defined.
  - Variables such as temperature, wind and pressure are predicted for each of the grid cells at different times.



Source: https://en.wikipedia.org/wiki/General_circulation_model

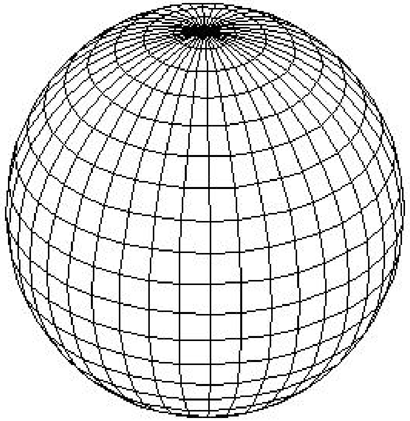
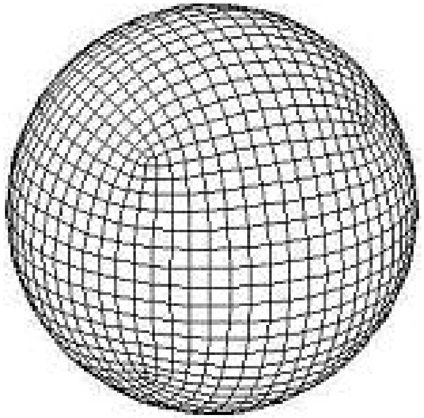
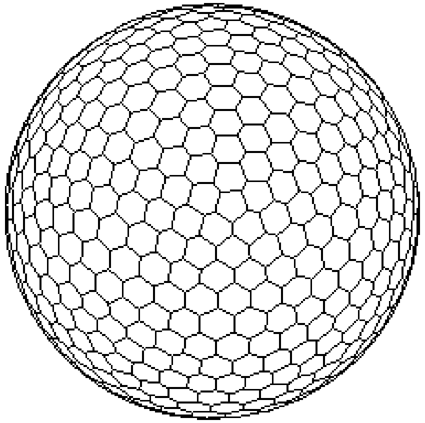
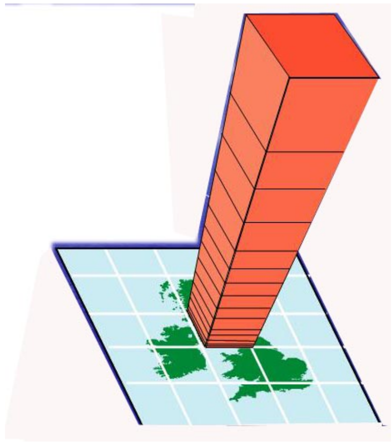
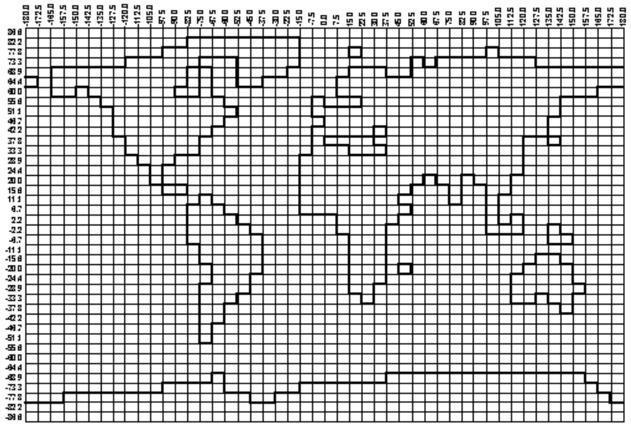
Modeling Timeline



Source: https://science2017.globalchange.gov/chapter/4/

Earth System Models

- Domain – the location where predictions are made.
- Dynamical core - equations describing the thermodynamics and fluid dynamics of the model.
- Parameterizations (physics) - approximations for processes that can not be represented directly in a model because they are either too small scale, too complicated or not well understood.

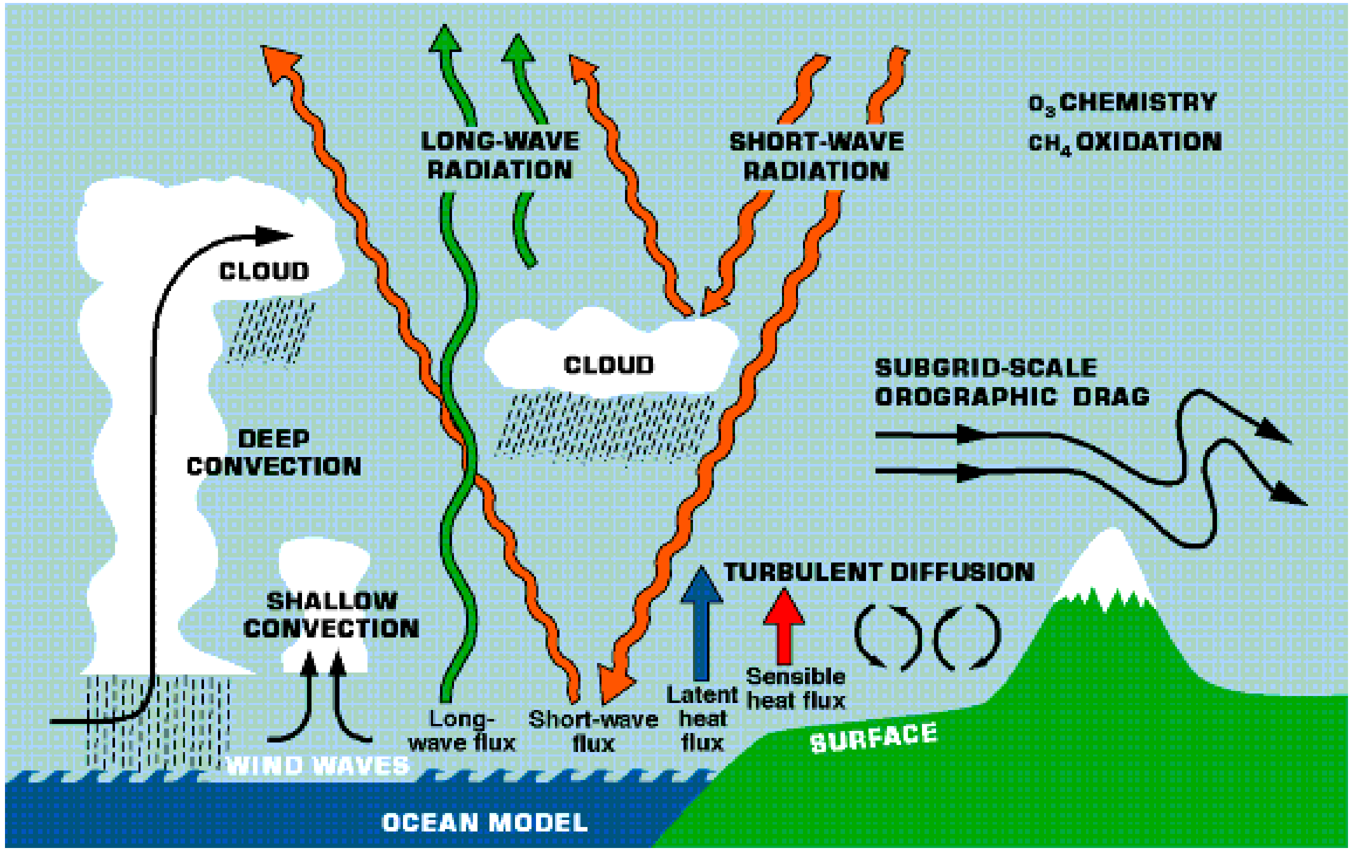
Atmospheric General Circulation Models (AGCM)

Dynamical core:

- Newton's Second Law of Motion
- First Law of Thermodynamics
- Conservation of Mass
- Equation of State

Physics:

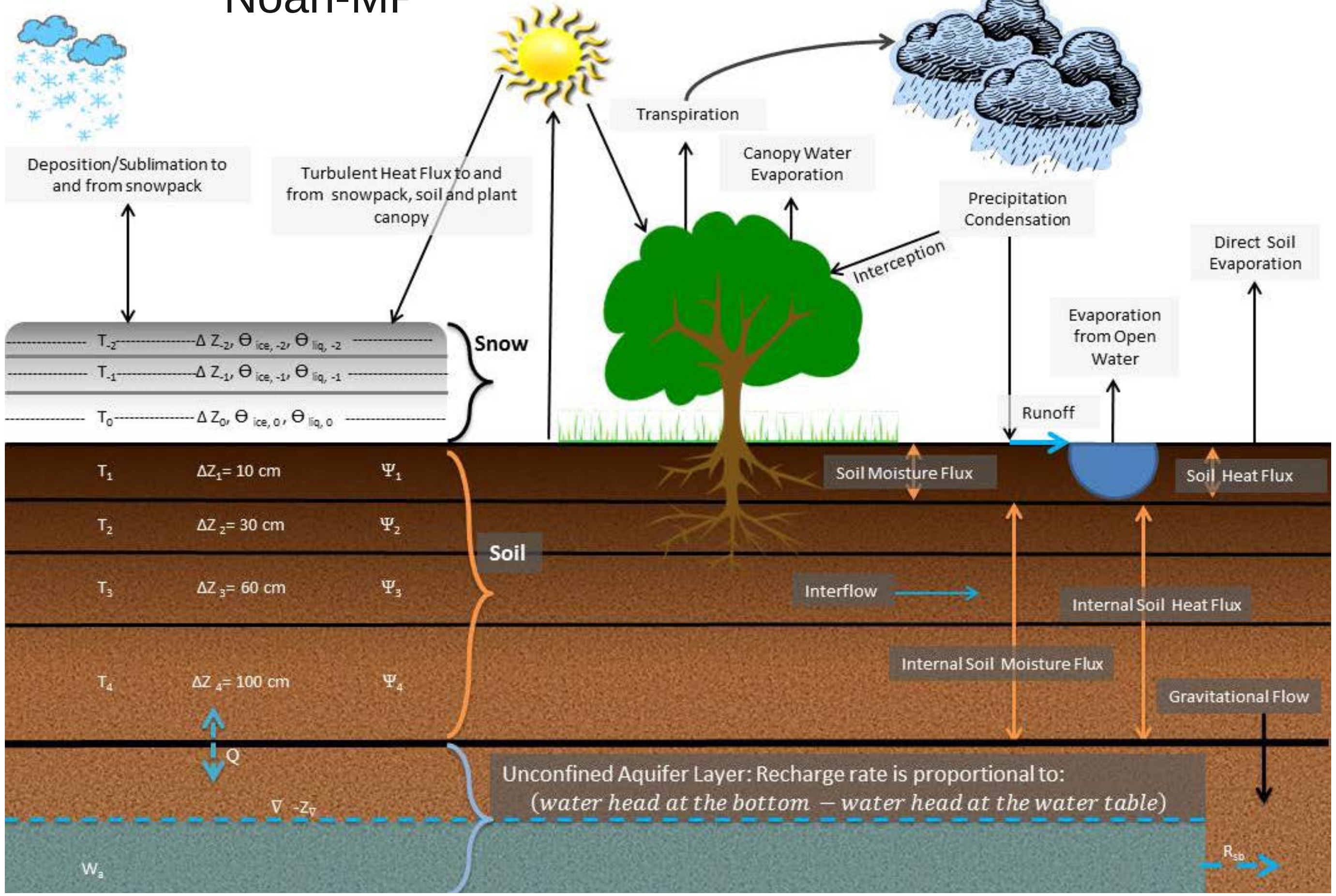
- Radiation
- Clouds and convection
- Turbulence
- Planetary Boundary Layer (PBL)
- Surface layer
- …



Land Surface Models (LSMs)

Simulate the exchange of surface water and energy (temperature) fluxes at the soil–atmosphere interface.

Noah-MP



From: https://www.jsg.utexas.edu/noah-mp

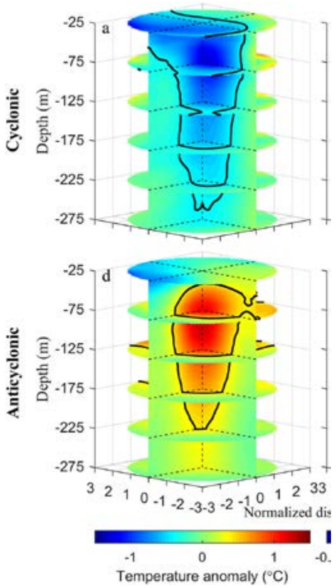
Oceanic General Circulation Models (OGCM)

Dynamical core:

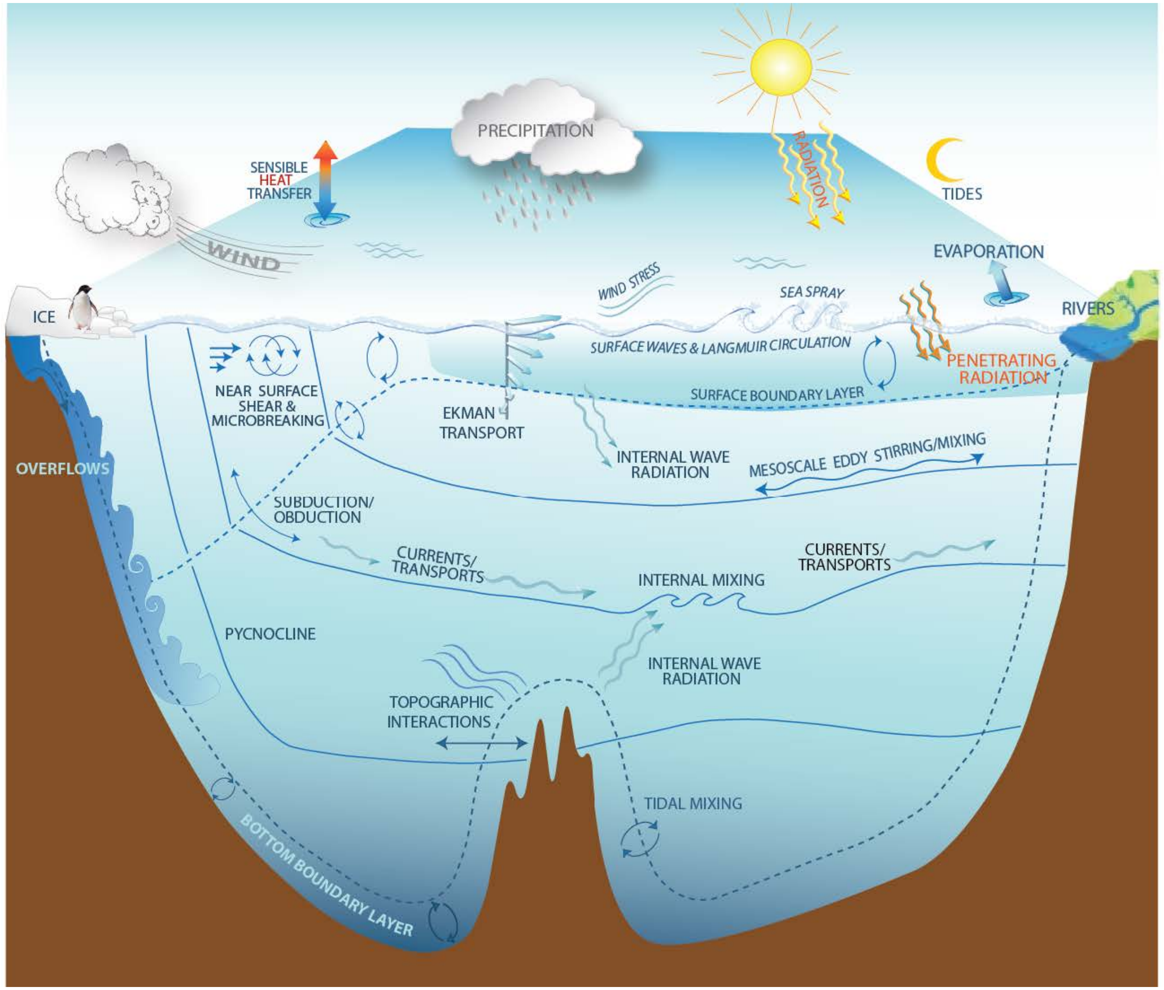
- Newton's Second Law of Motion
- First Law of Thermodynamics
- Conservation of Mass
- Equation of State

Physics:

- Mixed layer
- Sub Grid Scale ocean eddies



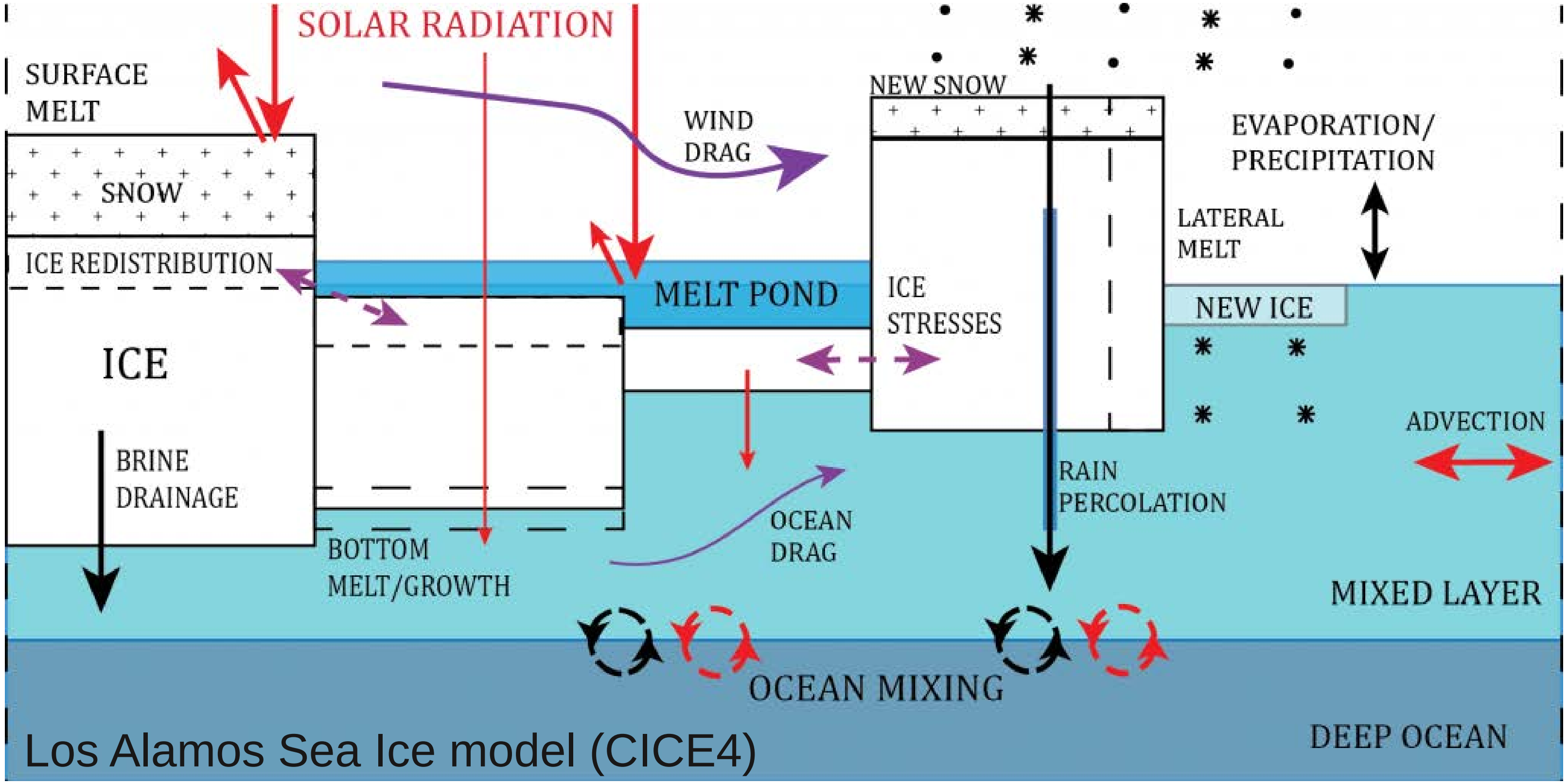
He *et al* (2018)



Source: Griffies and Treguier (2013)

Sea-ice Models

- Multiple ice thickness categories.
- Multiple thermodynamic layers within the sea ice.
- Sea ice rheology - how the ice moves/deforms under stress.
- Ridging - Ice being pushed around into piles.
- Snow accumulation.



Source: Climate Lab Book

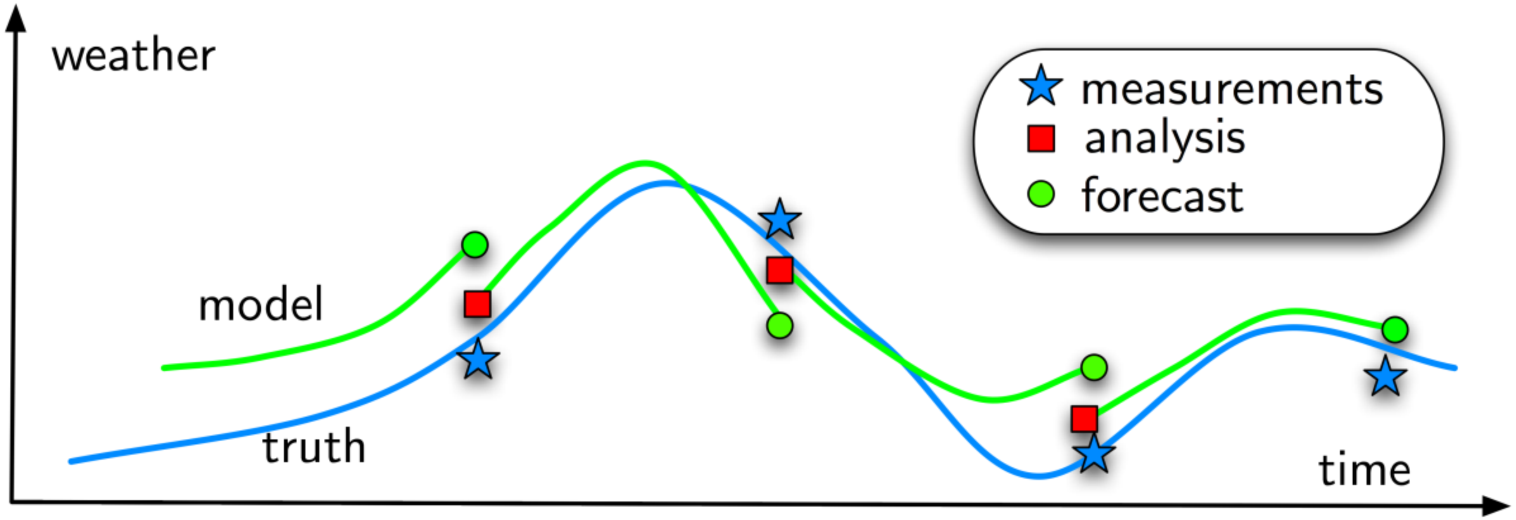
Other Sub-models

- Biosphere - Equations to Predict evolution of vegetation.
- Cryosphere - Growth/Ablation of Glaciers and ice sheets.
- Chemistry (Atmosphere & Ocean) - Reactions between gases to predict concentrations.
- Biology (Ocean) - Growth of algae, biota which are relevant for carbon cycle.

Data Assimilation

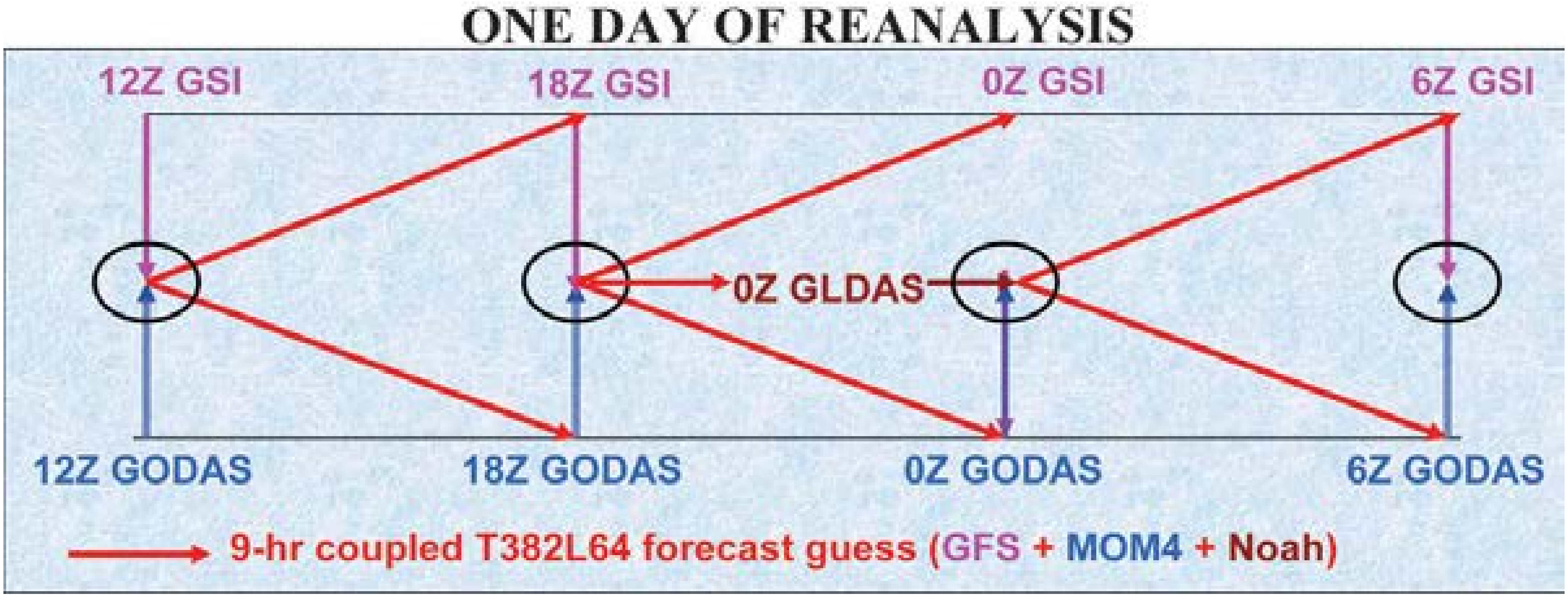
- Mathematical discipline that seeks to optimally combine theory (usually in the form of a numerical model) with observation. (Wikipedia)

- Data Assimilation Systems components:
  - Observation system
  - Model
  - Data assimilation algorithm
- Uses:
  - Initialization of GCMs.
  - Investigate past patterns of variability (Reanlysis).

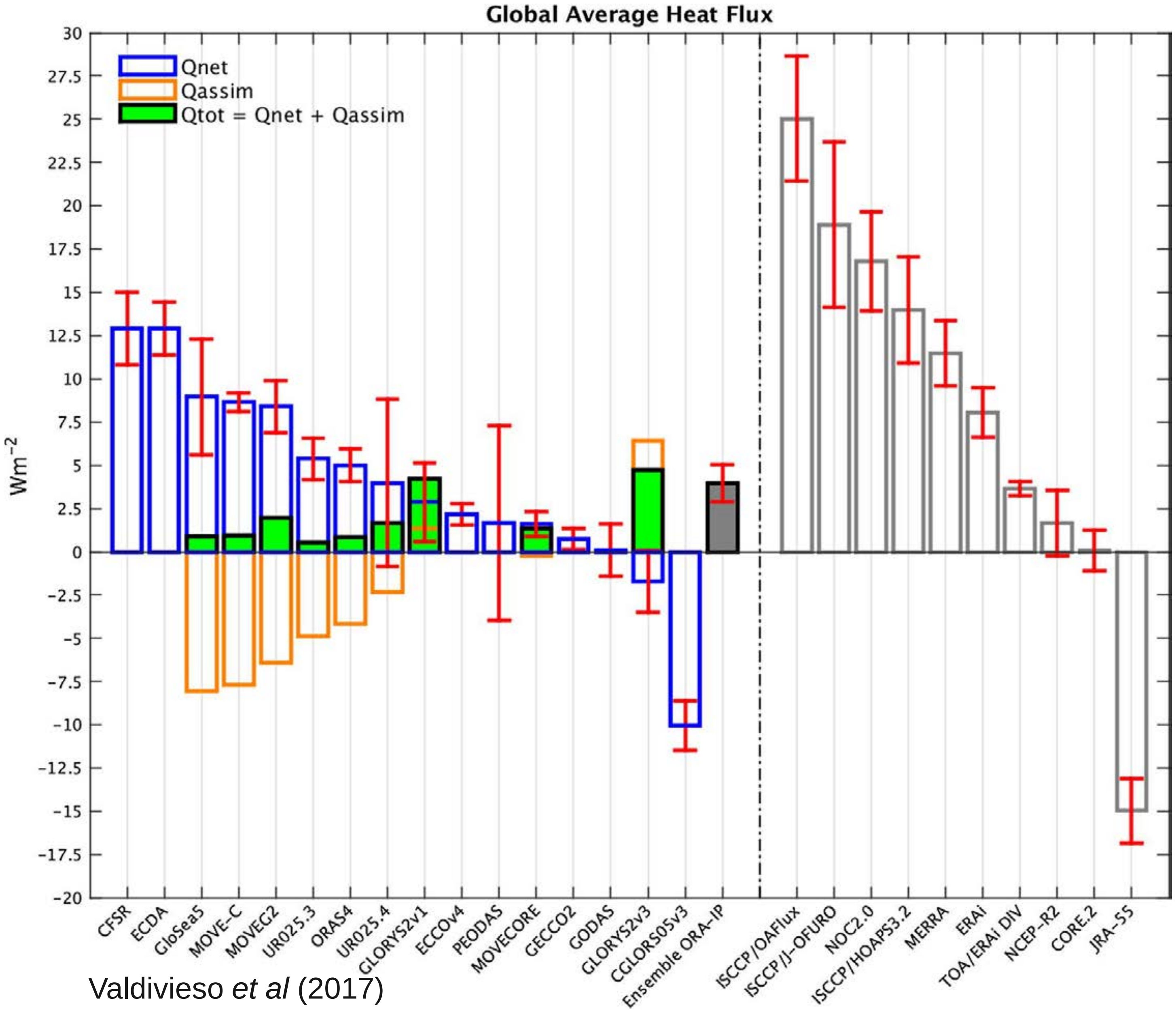


Source: https://blogs.surrey.ac.uk/mathsresearch/2017/03/27/epsrc-awards-grant-to-naratip-santitissadeekorn-for-data-assimilation/

Example – CFSR reanalysis



Net heat flux from various reanalysis datasets



Valdivieso *et al* (2017)

Overall motivation of the research program

- Couple the models underlying the MERRA-2 atmospheric reanalysis (GEOS) and the ECCO-v4 ocean state estimate (MITgcm).
- Develop a prototype ocean-ice-atmosphere coupled data assimilation system.
- Work toward closed budget global data assimilation system.

Applications

- Recent sea ice and ice sheet changes.
- Sub-seasonal to decadal climate predictions.
- Observation System Simulation Experiments (OSSEs).

Part II:
Towards a closed budget planetary assimilation system GEOS-MIT model

GEOS GCM main relevant features

- **Dynamical core:** finite-volume (Lin, 2004)
- **Physics:**
  - **Moist processes:** Based on the Relaxed Arakawa–Schubert (RAS) scheme (Moorthi and Suarez,1992).
  - **Turbulent mixing:** Non-local scheme (Lock et al., 2000).
  - **Surface layer:** Monin–Obukhov similarity theory (Helfand and Schubert,1995).
  - **Radiation:** long wave (Chou and Suarez, 1994), short wave (Chou and Suarez, 1999).
  - **Gravity wave drag:** Orographic (McFarlane, 1987) and non-orographic (Garcia and Boville, 1994).
  - **Land surface model:** Koster et al. (2000).
  - **Chemistry:** Goddard Chemistry, Aerosol, Radiation, and Transport (GOCART, Chin et al. 2002).
  - **Glacial thermodynamic:** Cullather et al. (2014).

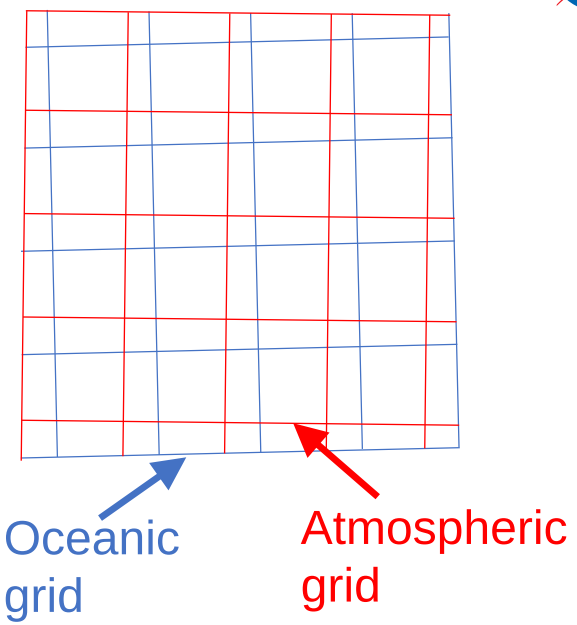
MITgcm main relevant features

- Dynamical core: finite-volume (Adcroft et al., 1997).
- Nonlinear free-surface & real freshwater flux.
- Physics:
  - Sub-grid scale eddy parameterization (Gent and Mcwilliams, 1990; Redi,1982).
  - Ocean vertical mixing:
    - KPP - The nonlocal K-profile parameterization scheme (Large et al., 1994).
    - GGL90 - TKE vertical mixing scheme (Gaspar et al., 1990).

GEOS-MIT air-sea coupling

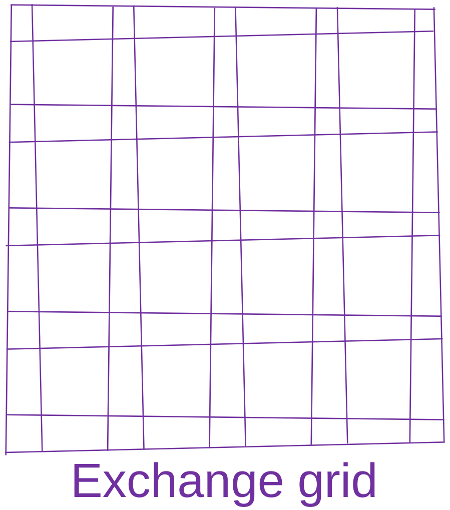
Exchange grid

- The exchange grid is a new grid composed of all cells enclosed by the two grids intersections.
- Exchange of properties between the ocean and the atmosphere is done on the exchange grid.
- Conservative exchange of water heat and momentum.



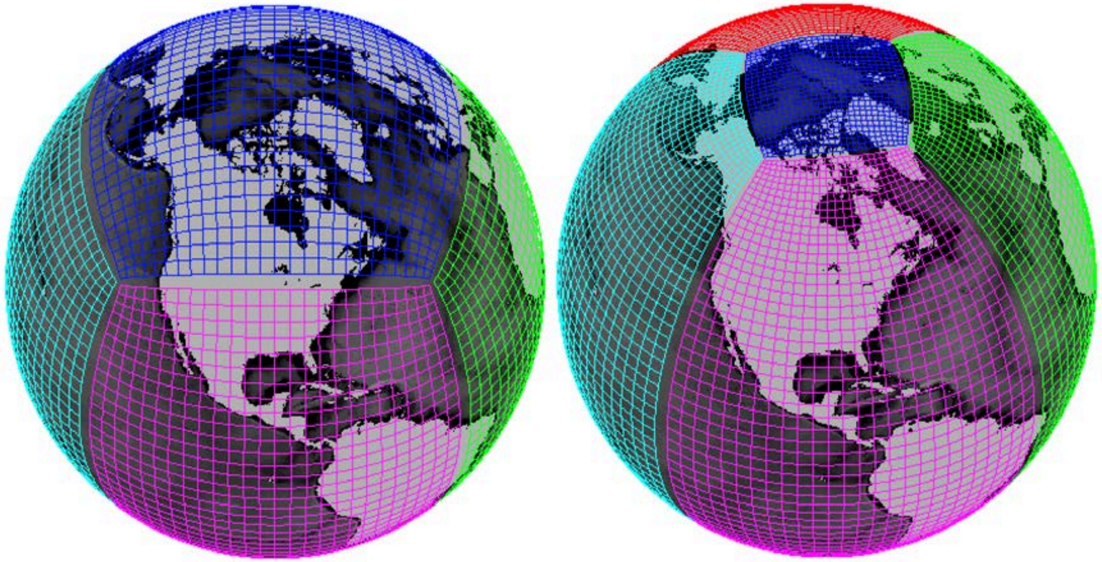
Sea-ice

- Thermodynamics – Los Alamos Sea Ice model (CICE4) (Hunke and Lipscomb 2010).
- Advection – viscous-plastic (VP) model (Hilber, 1979; Hilber, 1980; Losch et al. ,2010).



Experimental setup

- 8 year run (2000/04-2008/04)
- Atmosphere – GEOS:
  - Atmospheric initial conditions – MERRA-2
  - Horizontal grid type – Cubed sphere, $1^{\circ} X1^{\circ}$.
  - Vertical grid type – hybrid sigma-pressure, 72 levels
- Ocean – MITgcm
  - Oceanic initial conditions – ECCO-v4
  - Horizontal grid type – Lat-Lon-Cap, $1^{\circ} X1^{\circ}$
  - Vertical grid type – z^{*} rescaled height vertical coordinate, 50 levels

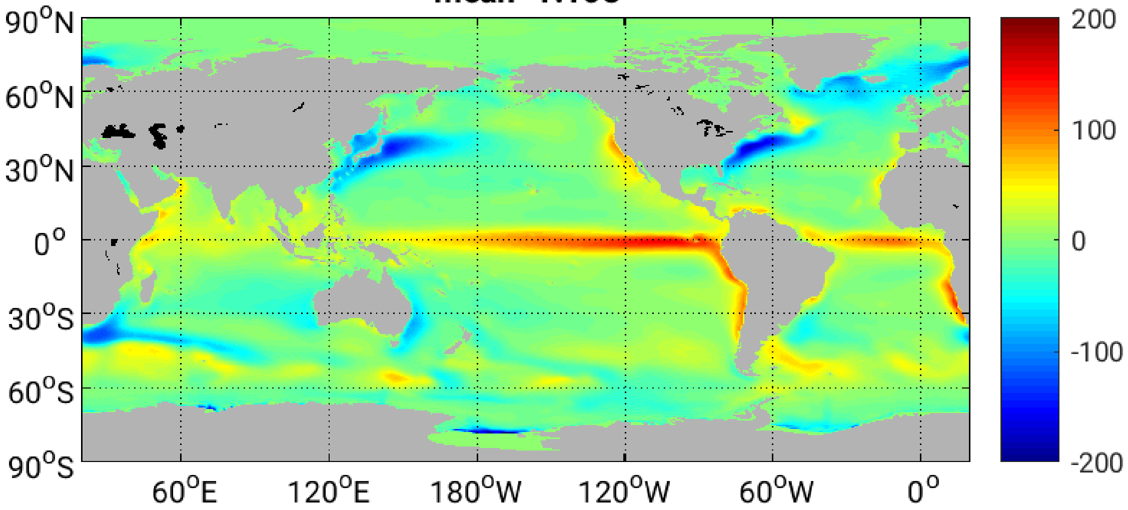


Cubed sphere grid (left) and Lat-Lon-Cap (right)

Net heat flux [W/m²]

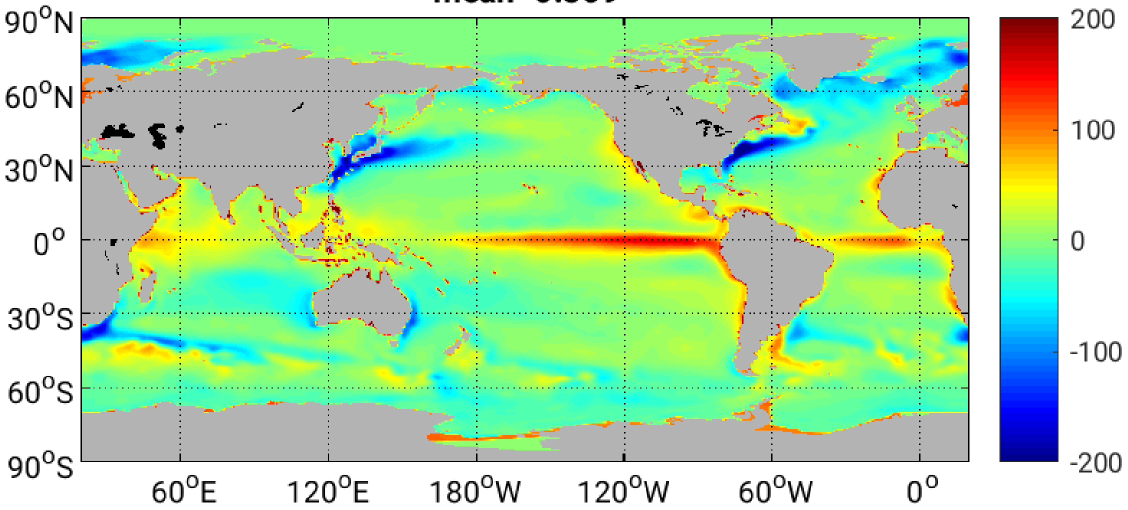
GEOS-MIT

mean=1.108



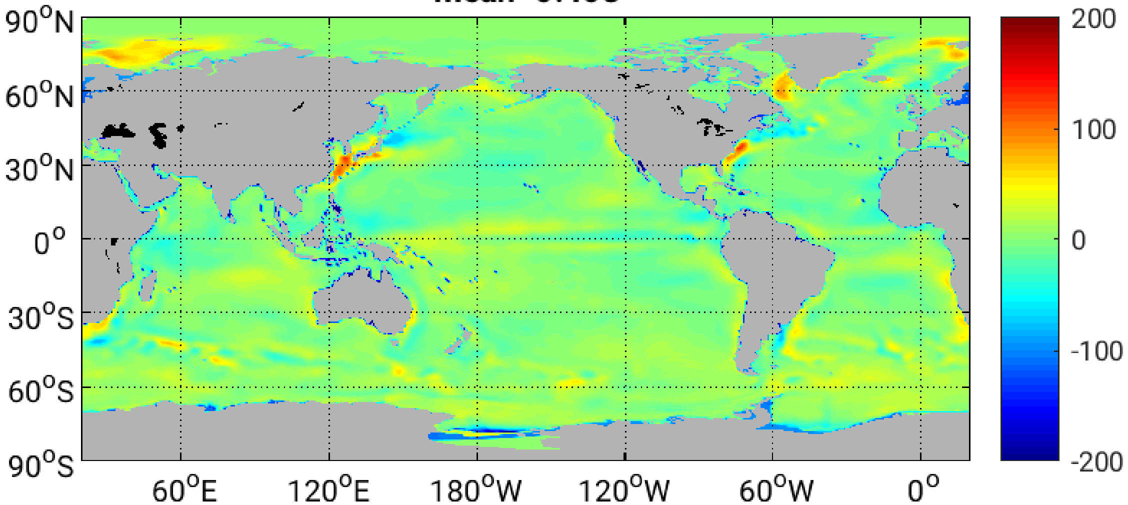
ECCO-v4

mean=0.369

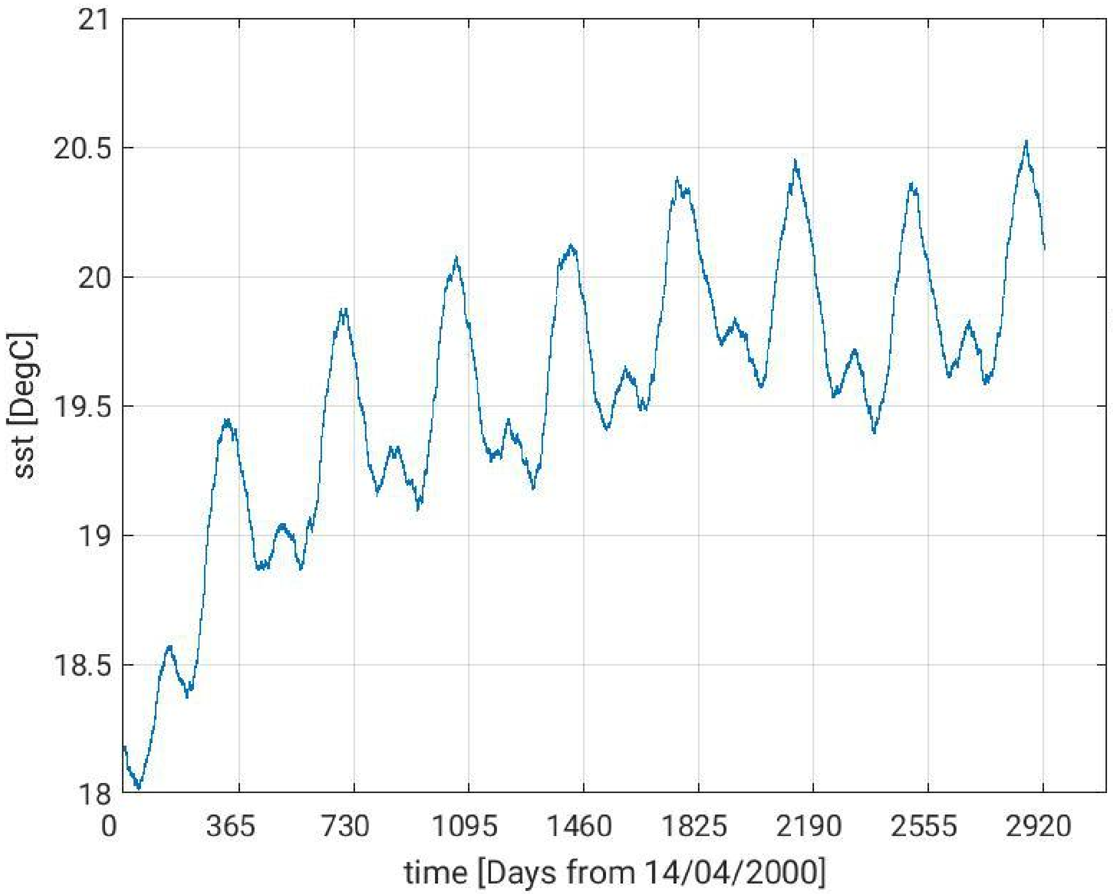


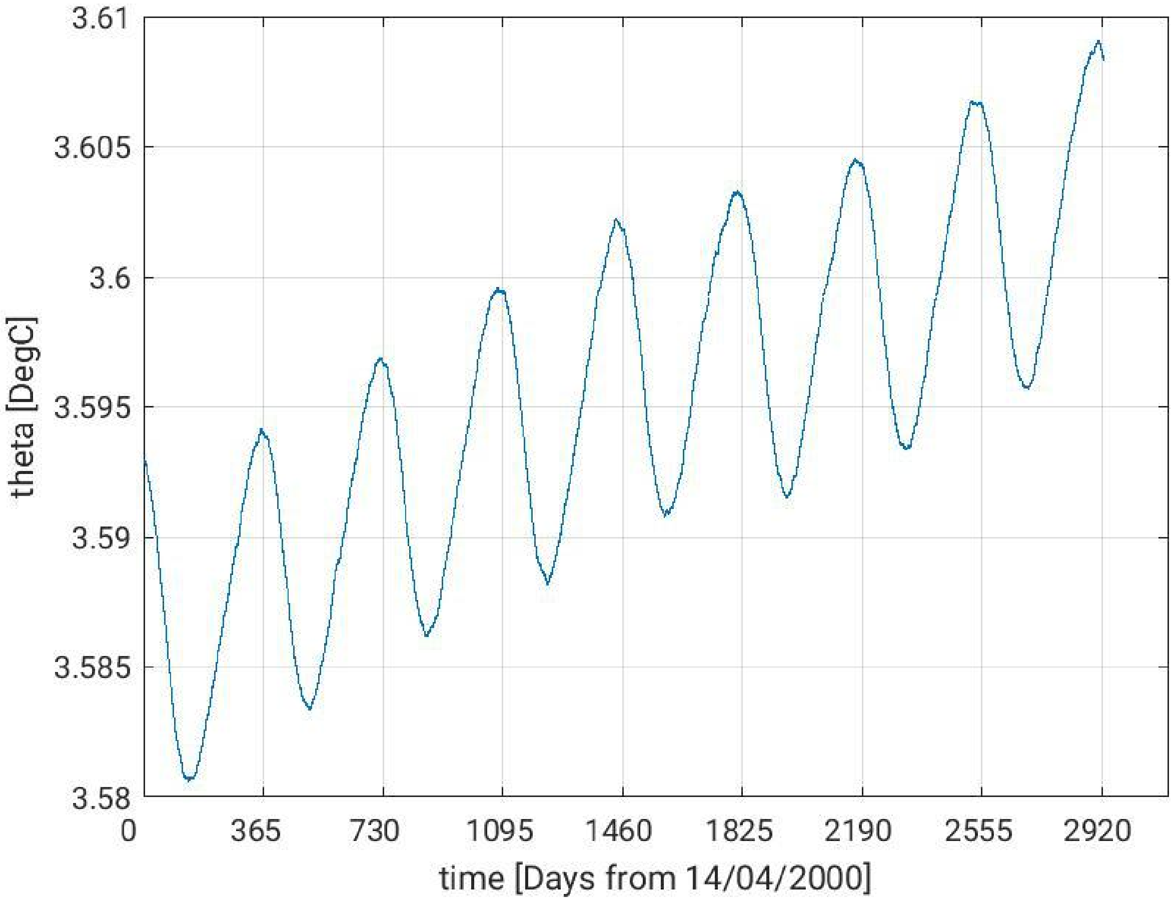
GEOS-MIT - ECCO-v4

mean=0.403



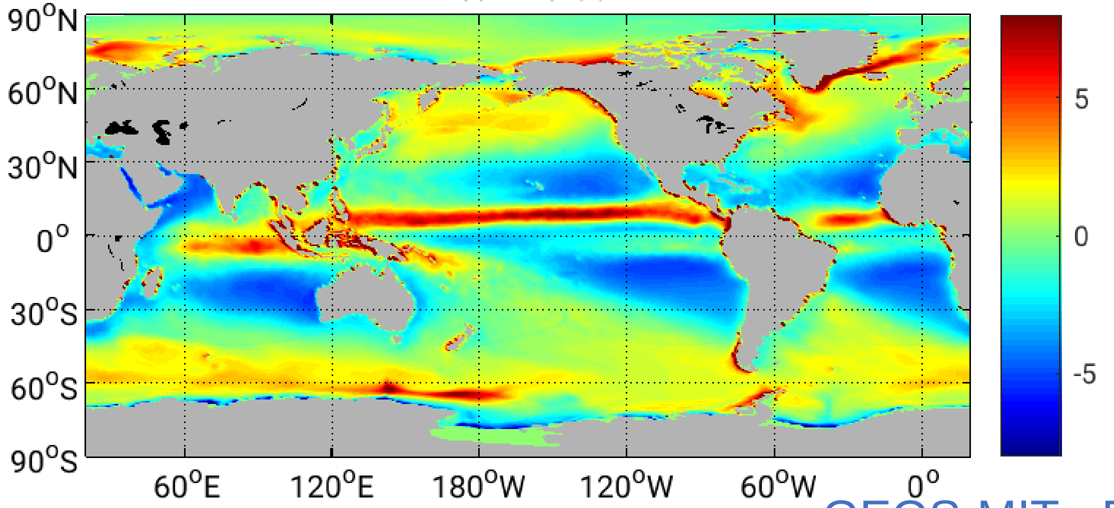
Global ocean temperature drift



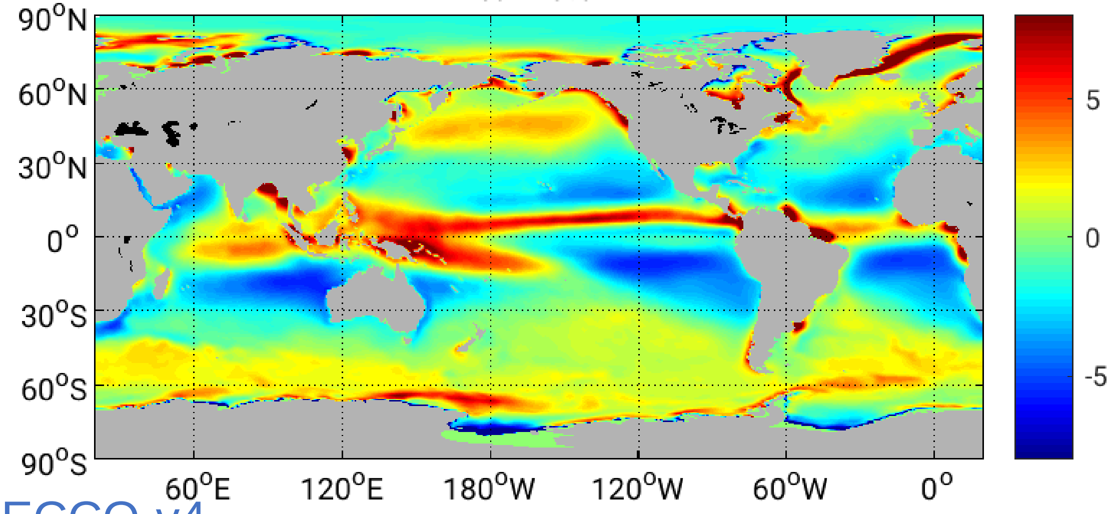


Net fresh water flux [mm/day]

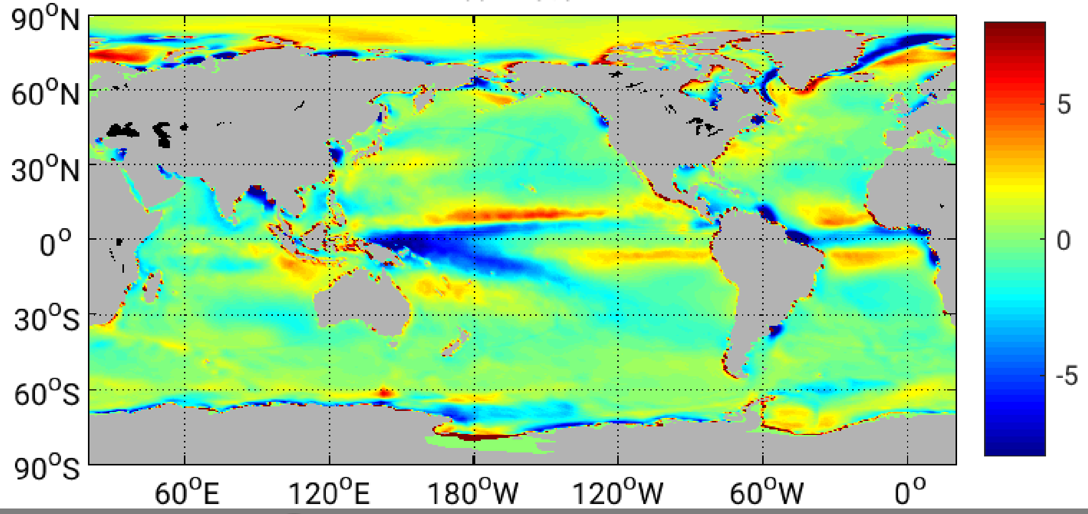
GEOS-MIT
mean=-0.001



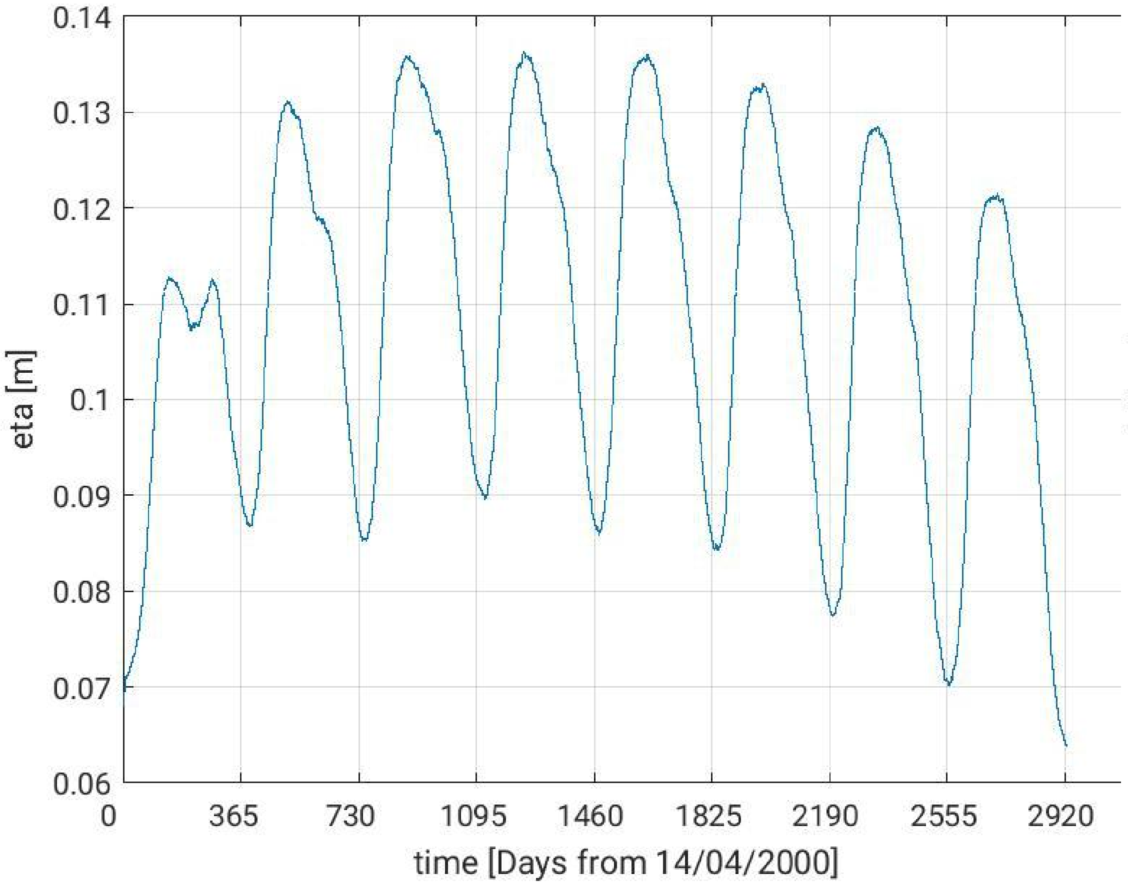
ECCO-v4
mean=0.011

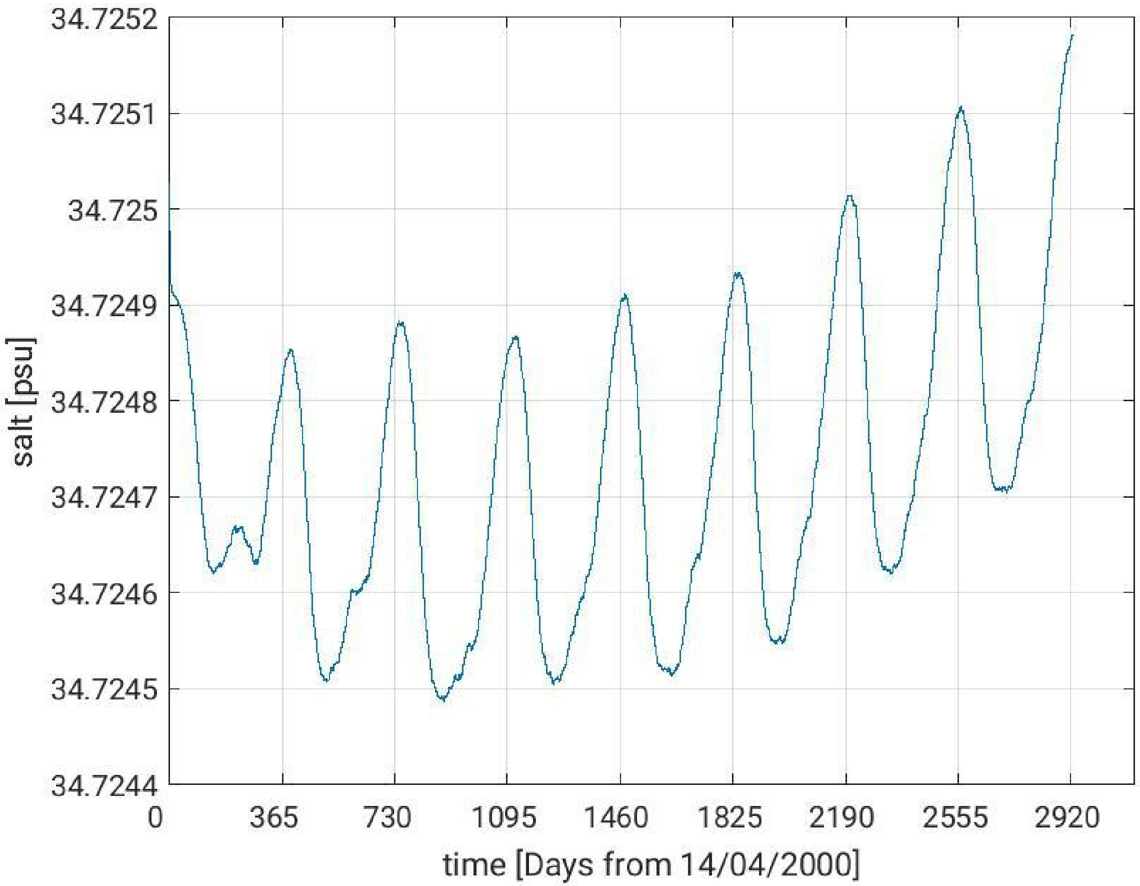


GEOS-MIT - ECCO-v4
mean=0.011



Global sea level and salt



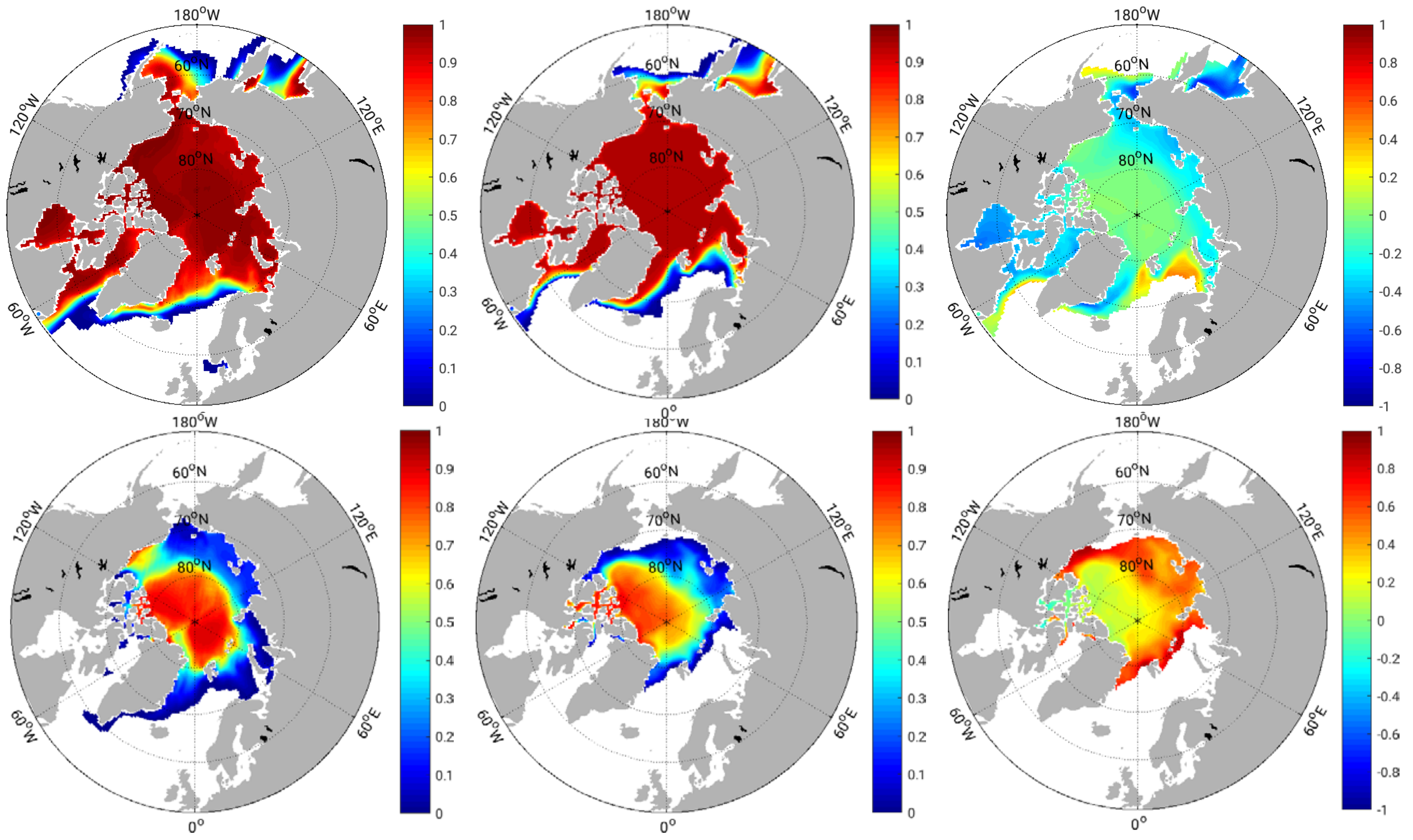


Sea-ice Area – North Pole (fraction of grid cell)

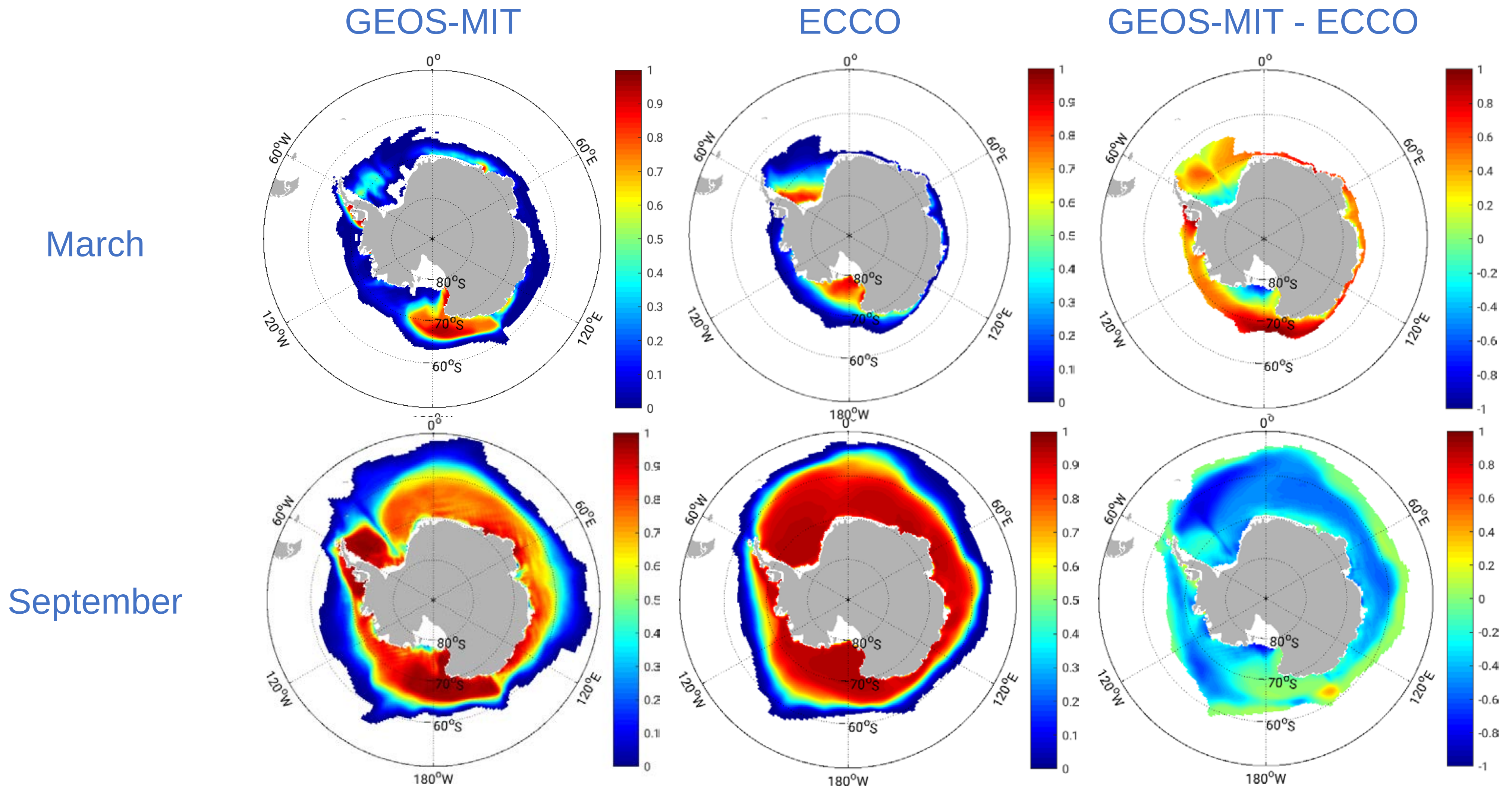
GEOS-MIT | ECCO | GEOS-MIT - ECCO

March

September



Sea-ice Area - South Pole (fraction of grid cell)



Conclusions (part II)

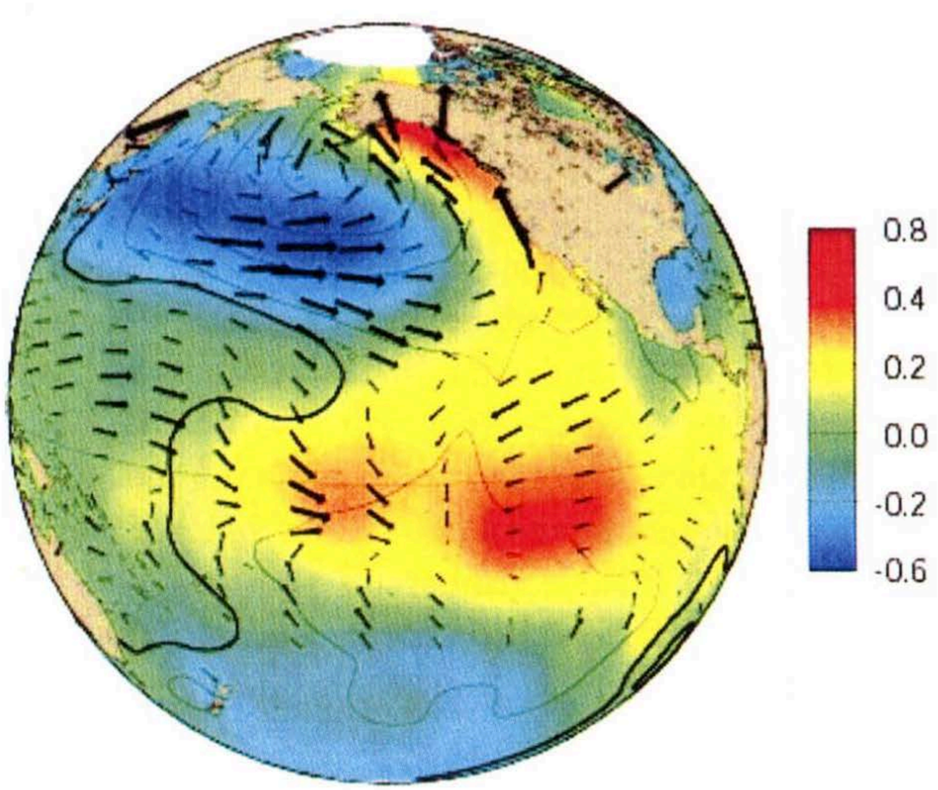
- GEOS-MIT model is now operational.
- Too much net heat flux to the ocean.
- “The double ITCZ (intertropical convergence zone) problem”
- Sea-ice area is too large in summer but overall realistic.
- Tuning is about to commence using Green’s function method (Menemenlis *et al*., 2005).

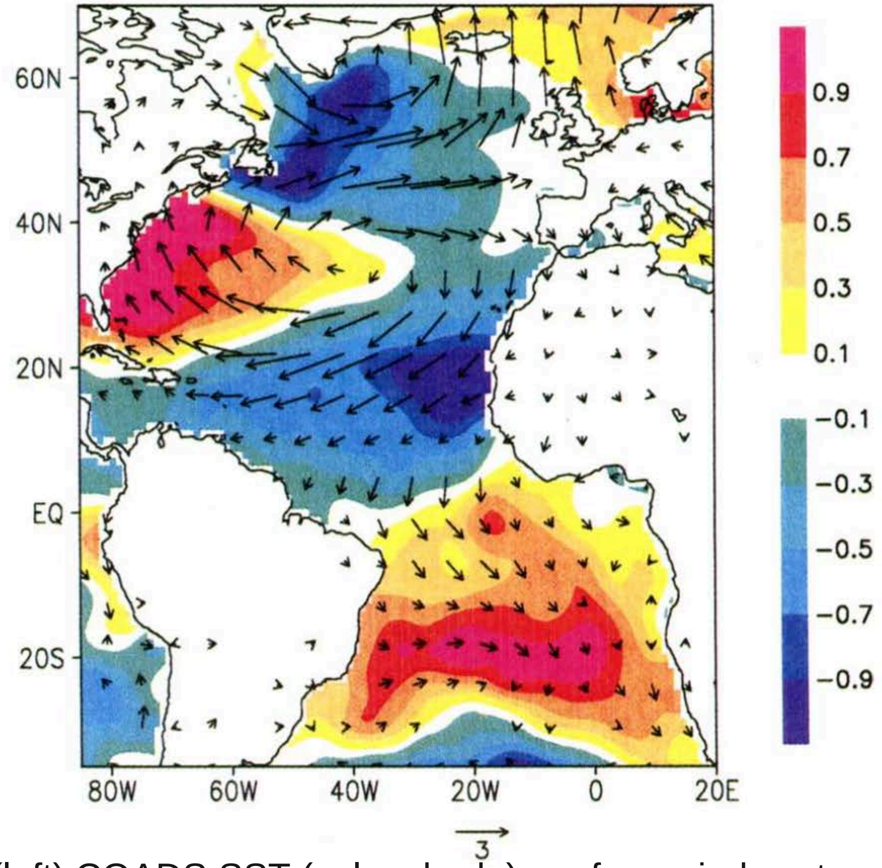
Part III:
Air sea interactions in the high resolution GEOS-MIT

Current objectives of this study

- Develop a high resolution coupled ocean-atmosphere run for studying air sea interactions and simulating an observation system.
- Investigate the ability of the coupled model to capture the strong observed positive correlations between SST and wind stress/speed.
- Compare near-surface diagnostics of the fully coupled ocean-atmosphere set-up to equivalent atmosphere-only simulations.

Background: observed SST/wind speed anomaly correlations





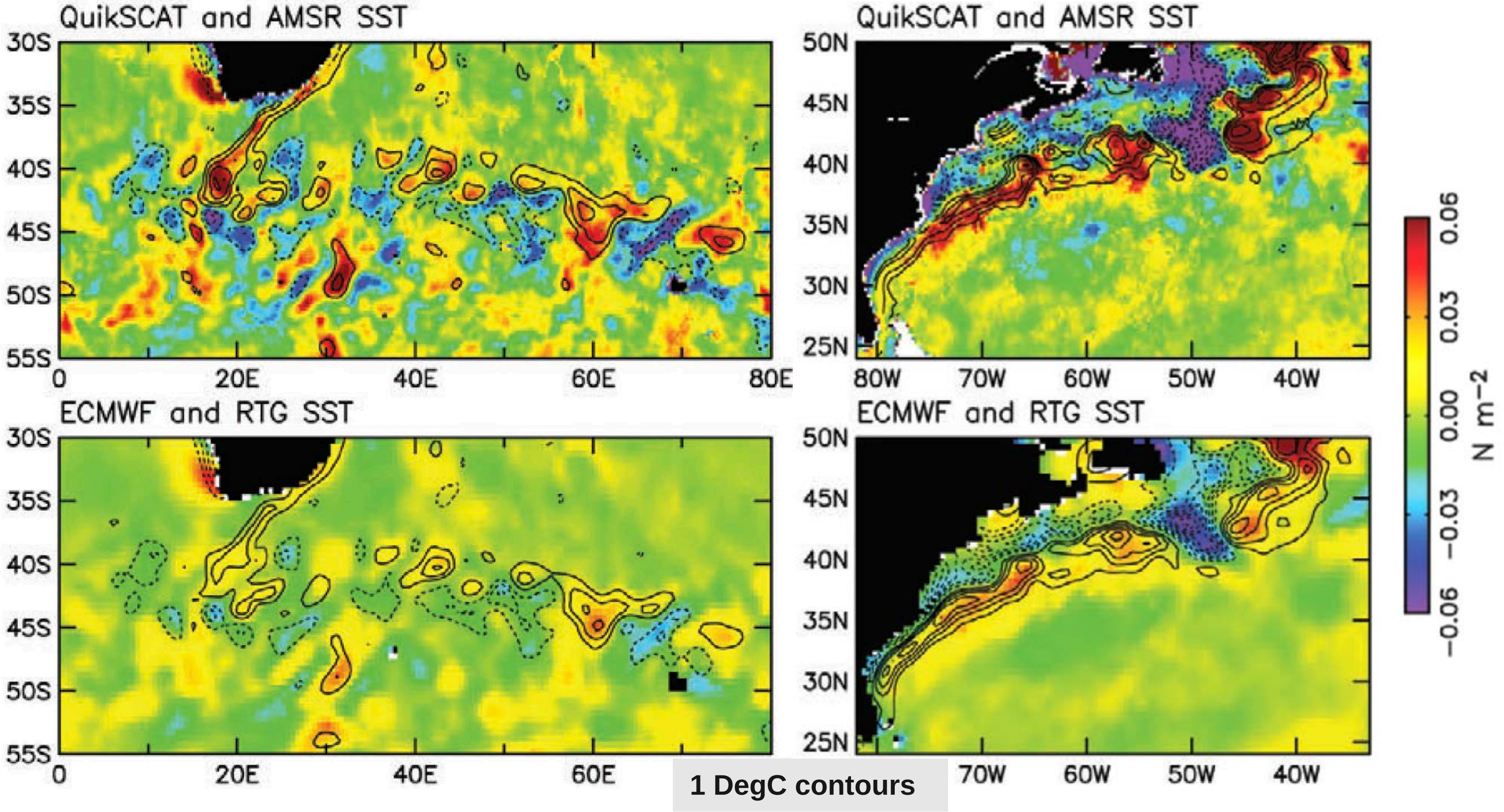
"Most often negative correlations between SST and surface wind speed variability are observed in the extra-tropics for seasonal means and on the basin scale"

Xie *et al* (2004)

SST-wind relation in the North Pacific and Atlantic Oceans, (left) COADS SST (color shade), surface wind vectors, and SLP regressed upon the Pacific decadal oscillation index (Mantua et al. 1997). (right) COADS SST (color in °C) and NCEP surface wind (m s^{-1}) composites in Jan-Mar based on a cross-equatorial SST gradient index (Okumura et al. 2001).

Background: observed SST/wind stress anomaly correlations

Agulhas Return Current | Gulf Stream

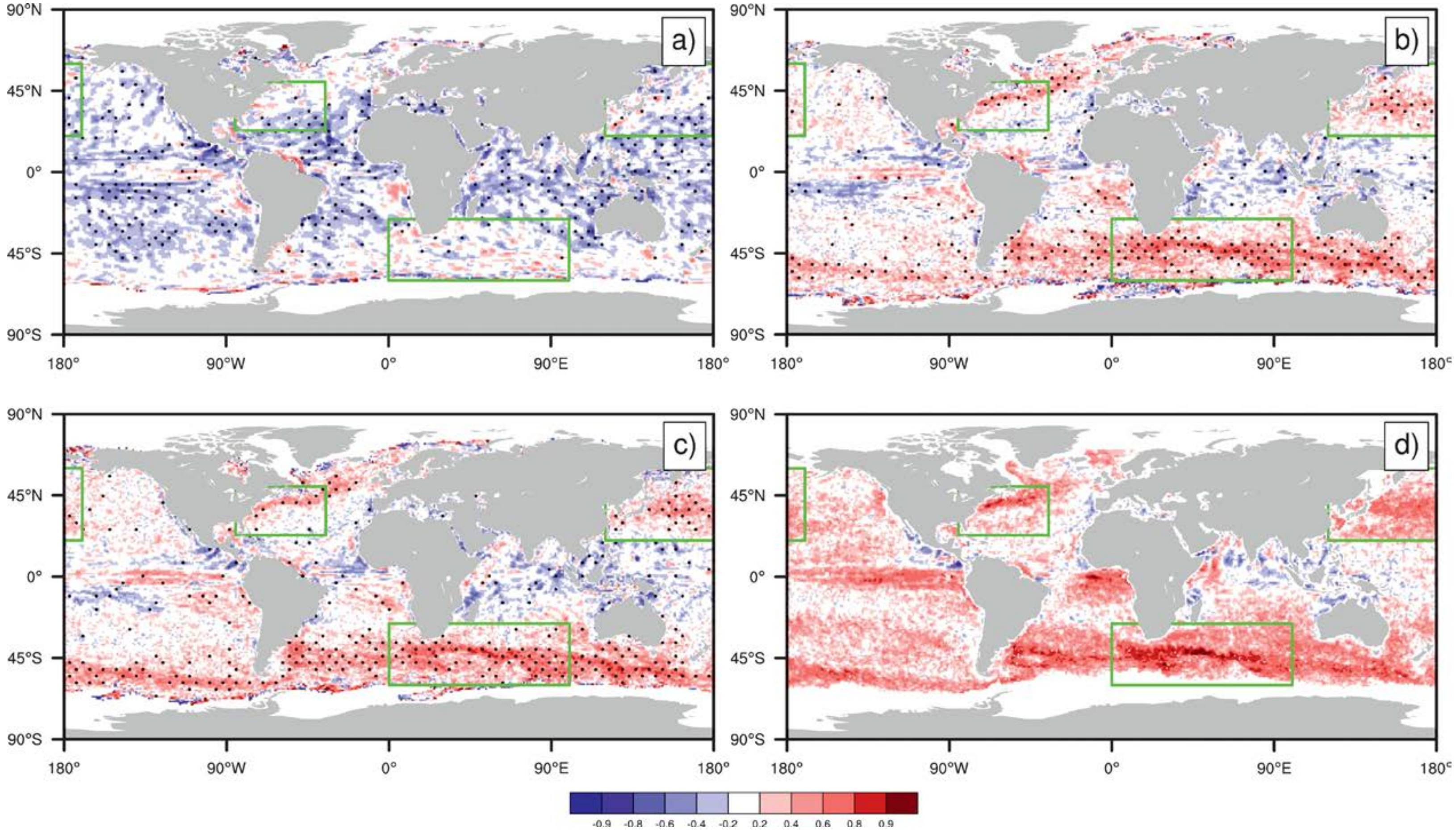


Two-month averages (January–February 2008) of **spatially high-pass-filtered sea surface temperature (SST)** overlaid as contours on **spatially high-pass-filtered wind stress.**

"Satellite observations have revealed a remarkably strong positive correlation between sea surface temperature (SST) and surface winds on oceanic mesoscales of 10–1000 km."

Chelton *et al., Oceanography (2010)*

Background: modeled SST/wind speed correlation



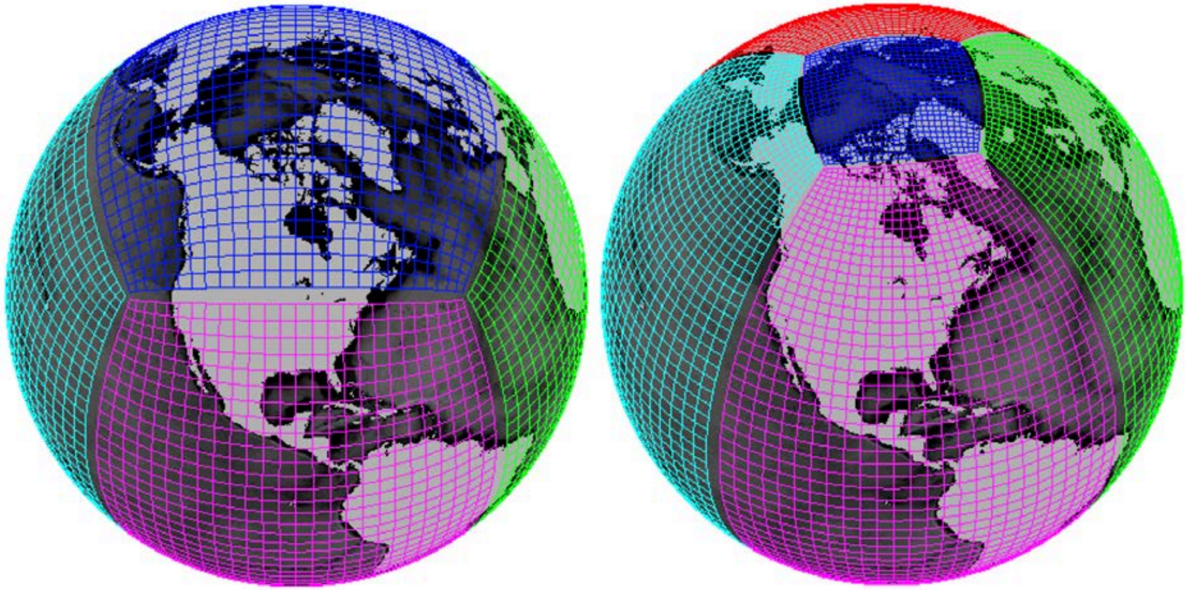
"… the output of a suite of Community Climate System Model (CCSM) experiments indicates that … correlation between SST and surface wind stress, is realistically captured only when the ocean component is eddy resolving."

Bryan *et al., J. Clim. (2010)*

Temporal correlation of **high-pass filtered surface wind speed with SST.** (a) 1.0° ocean and 0.5° atmosphere (b) 0.1° ocean and 0.5° atmosphere (c) 0.1° ocean and 0.25° atmosphere. (d) Satellite observations.

Methods - models

- Atmosphere – GEOS:
  - Horizontal grid type – Cubed sphere, 1/8° X1/8°
  - Vertical grid type – hybrid sigma-pressure, 72 levels
- Ocean – MITgcm
  - Horizontal grid type – Lat-Lon-Cap, 1/12° X1/12°
  - Vertical grid type – z^* rescaled height vertical coordinate, 90 levels



Cubed sphere grid (left) and Lat-Lon-Cap (right)

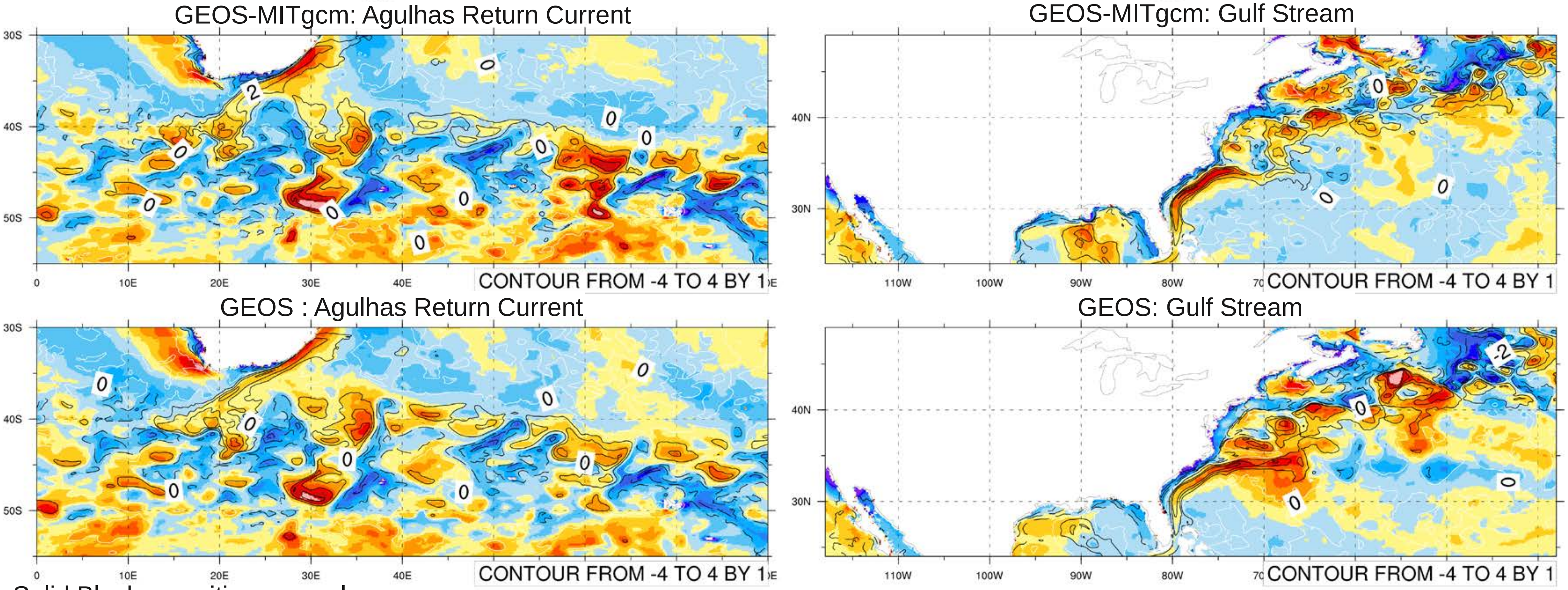
Methods - experimental setup

1) Ocean only – MITgcm (OGCM):
   - Jan, 1 – Jun 15, 2012
   - Forcing: 0.14°, 6 hourly ECMWF
2) Atmosphere Only – GEOS (AGCM)
   - Feb, 9 – Apr 9, 2012
   - Forcing: SST and ice fraction from run 1
   - Initial conditions: MERRA-2
3) Coupled – GEOS-MITgcm (AOGCM)
   - Feb, 9 – Apr 9, 2012
   - Ocean initial conditions: from run 1
   - Atmospheric initial conditions: MERRA-2 (same as the run 2)

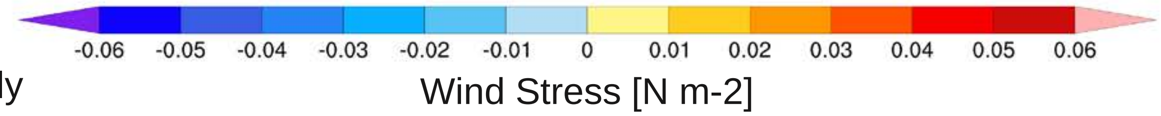
Ocean surface current

Precipitation

Wind stress (shading) and SST (contours)

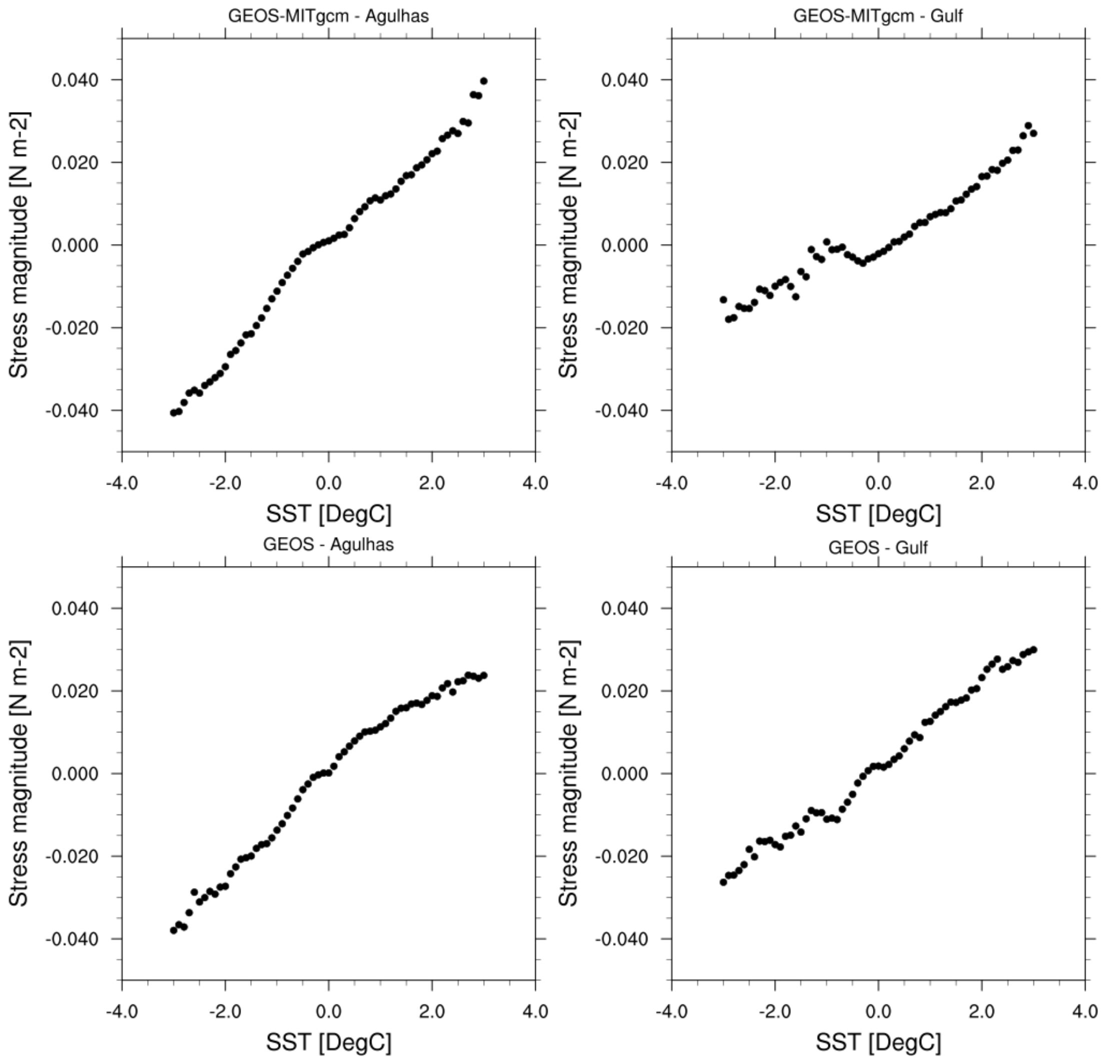


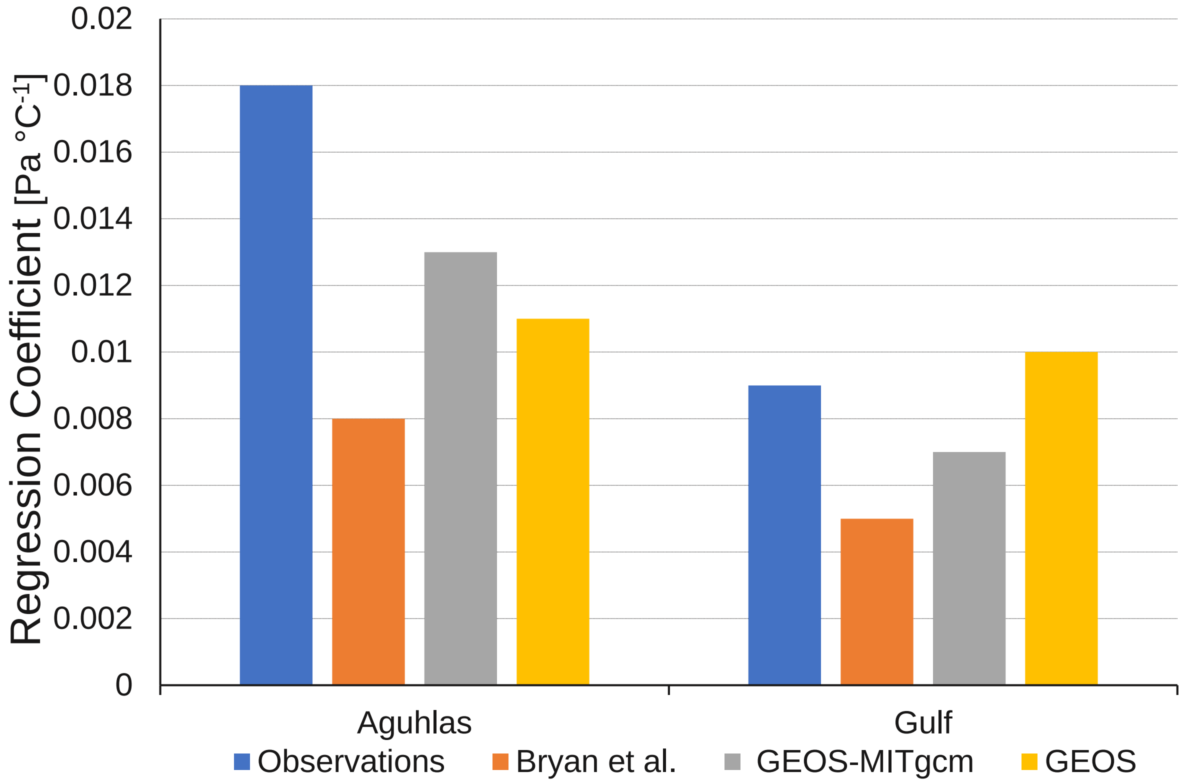
Solid Black – positive anomaly
White – zero
Dashed black – negative anomaly



Both GEOS and GEOS-MITgcm show positive correlation between wind stress and SST consistent with previous results

Linear relation between wind stress and SST

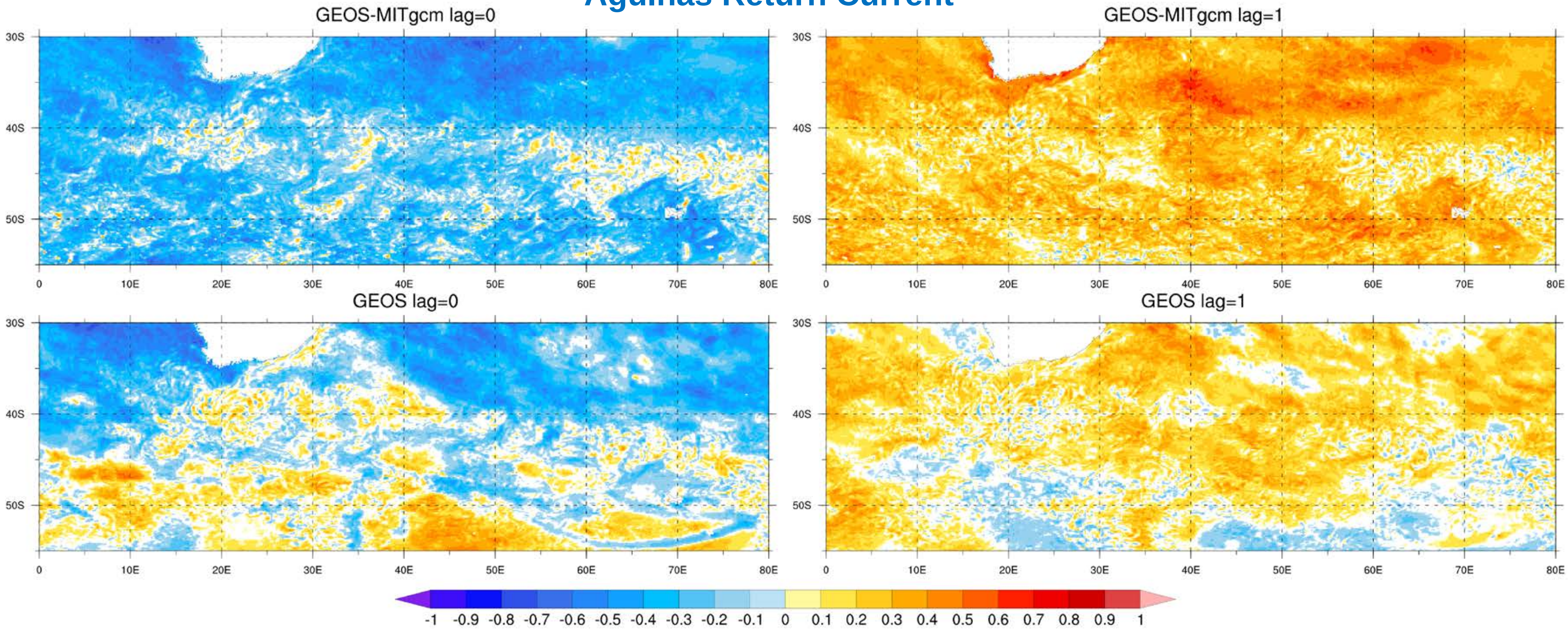




The linear relation between the stress and the SST in our coupled model is closer to the observed values compared to the previous modeling study.

Correlation between daily SST $\left(\frac{\Delta SST}{\Delta t}\right)$ and wind speed $\left(\frac{\Delta WS}{\Delta t}\right)$

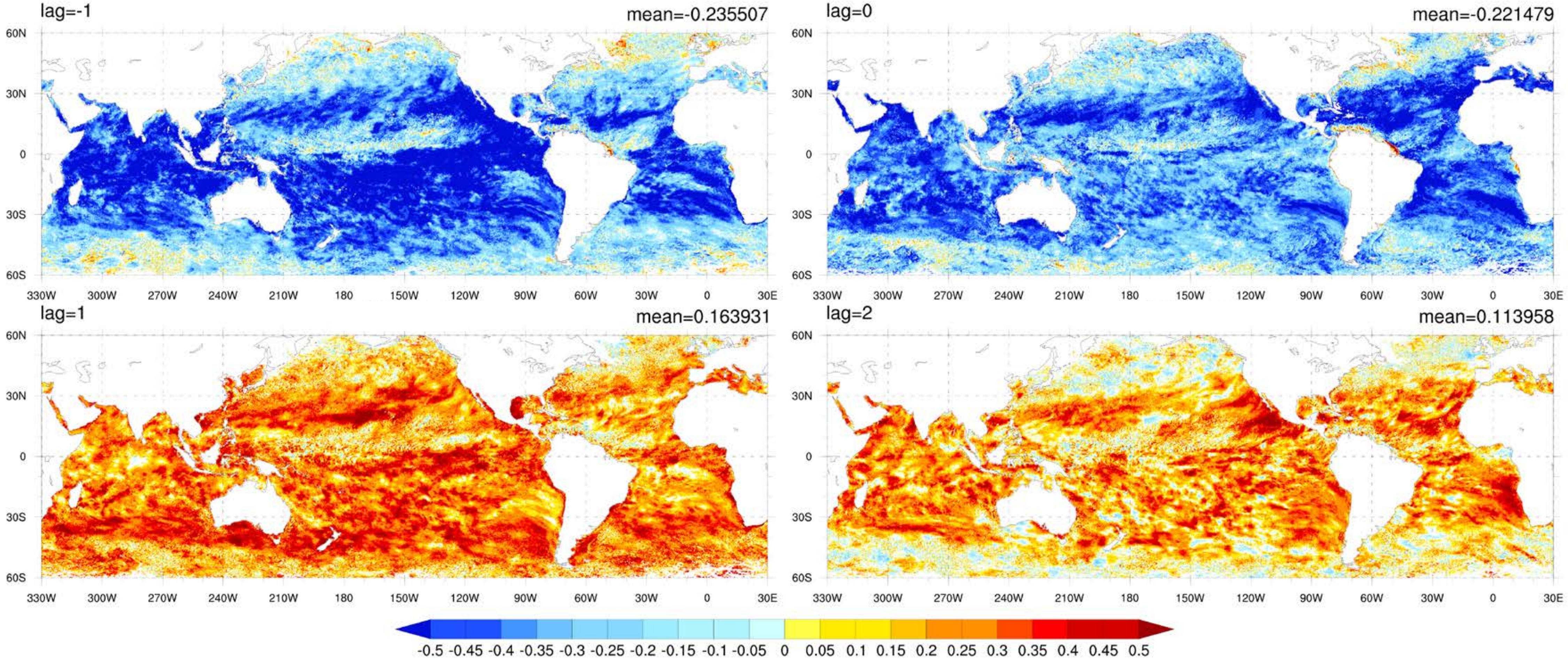
Agulhas Return Current



Wind speed is lagging the SST by ~1day

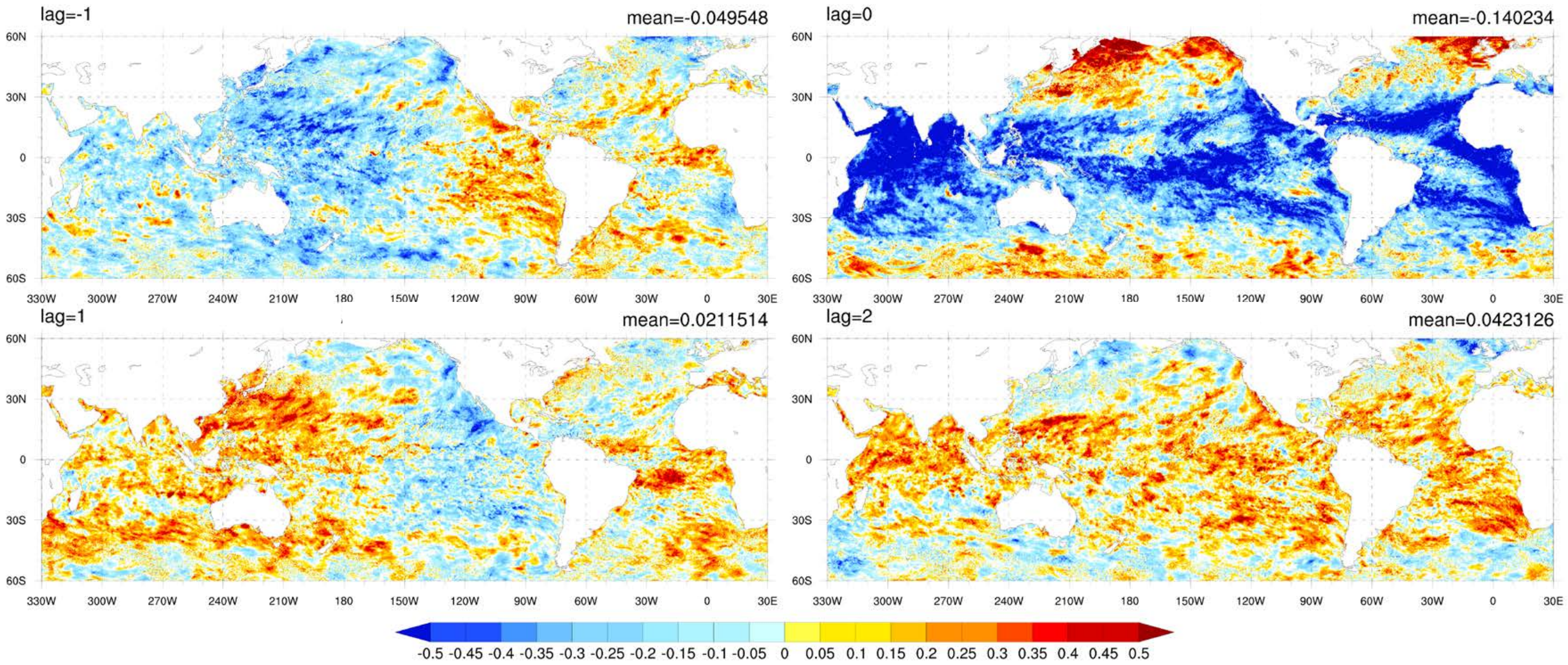
Correlation between daily SST $\left(\frac{\Delta SST}{\Delta t}\right)$ and wind speed $\left(\frac{\Delta WS}{\Delta t}\right)$

GEOS-MITgcm

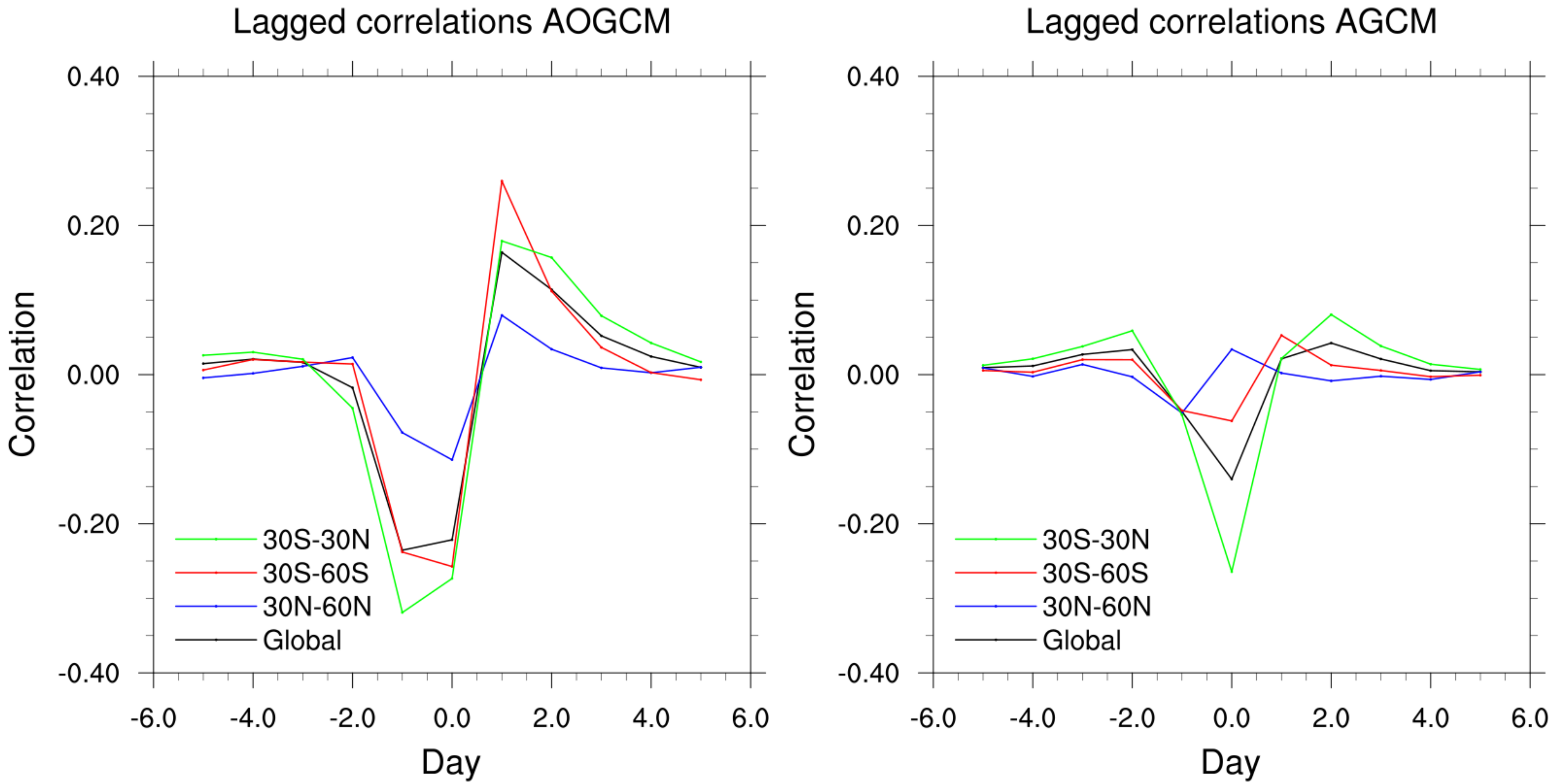


Correlation between daily SST $\left(\frac{\Delta SST}{\Delta t}\right)$ and wind speed $\left(\frac{\Delta WS}{\Delta t}\right)$

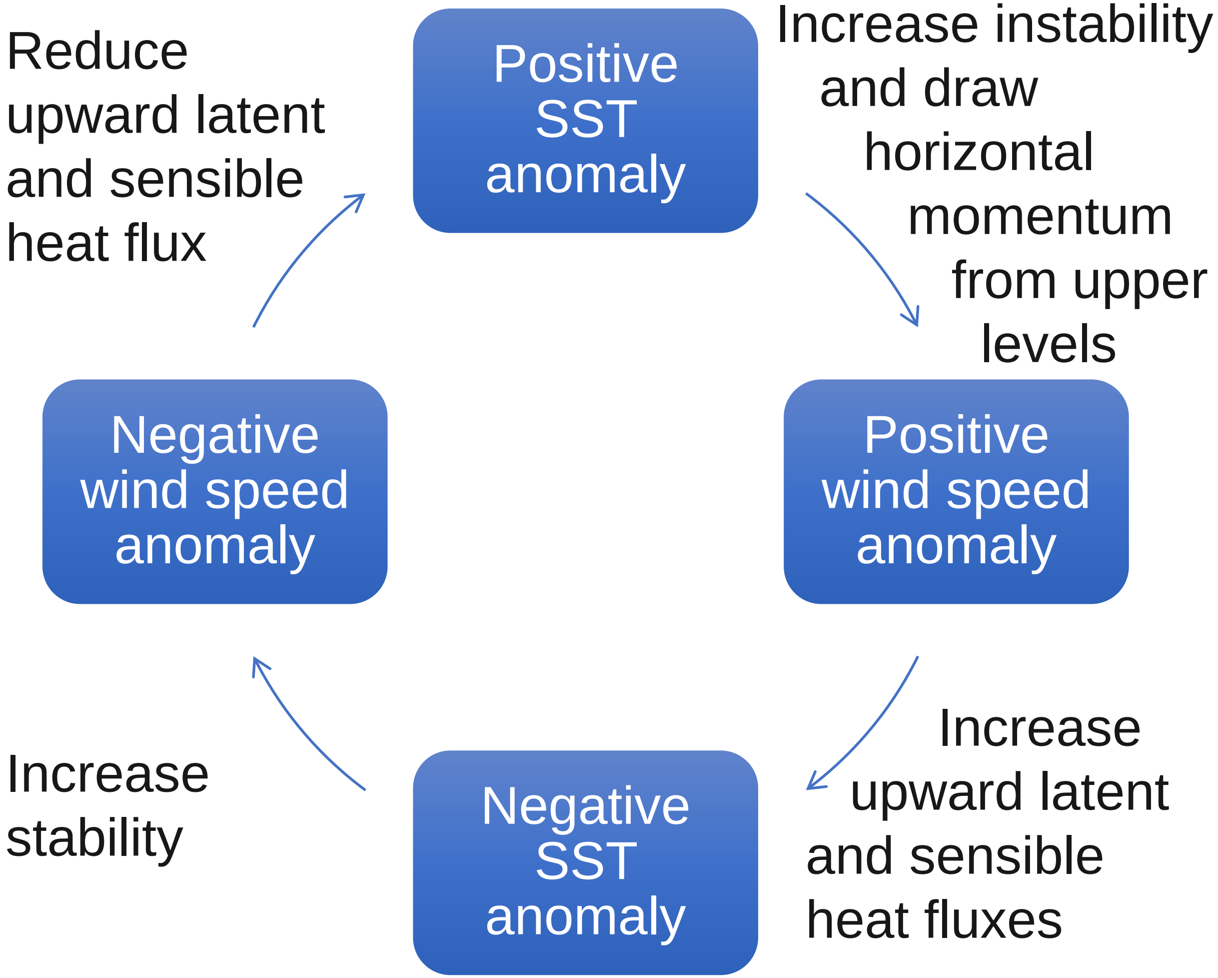
GEOS

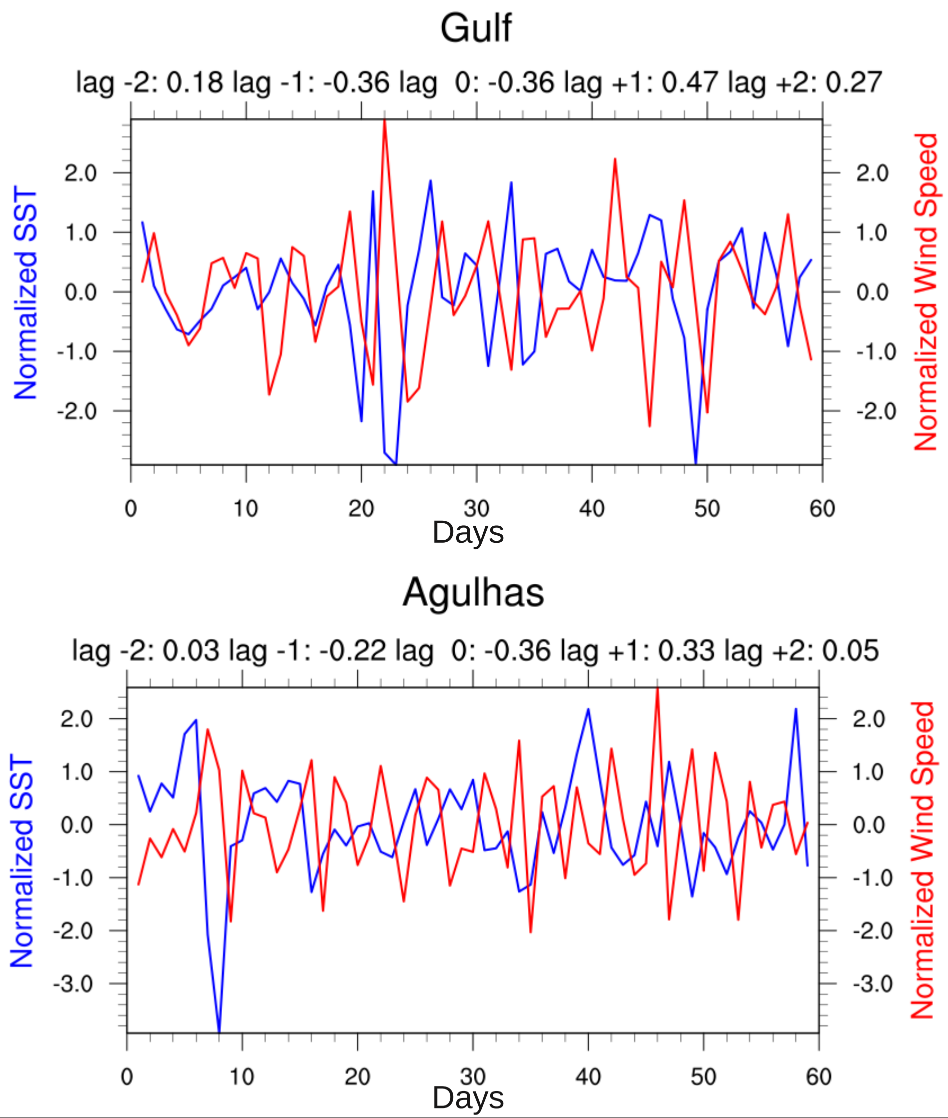


Correlation between daily SST $\left(\frac{\Delta SST}{\Delta t}\right)$ and wind speed $\left(\frac{\Delta WS}{\Delta t}\right)$



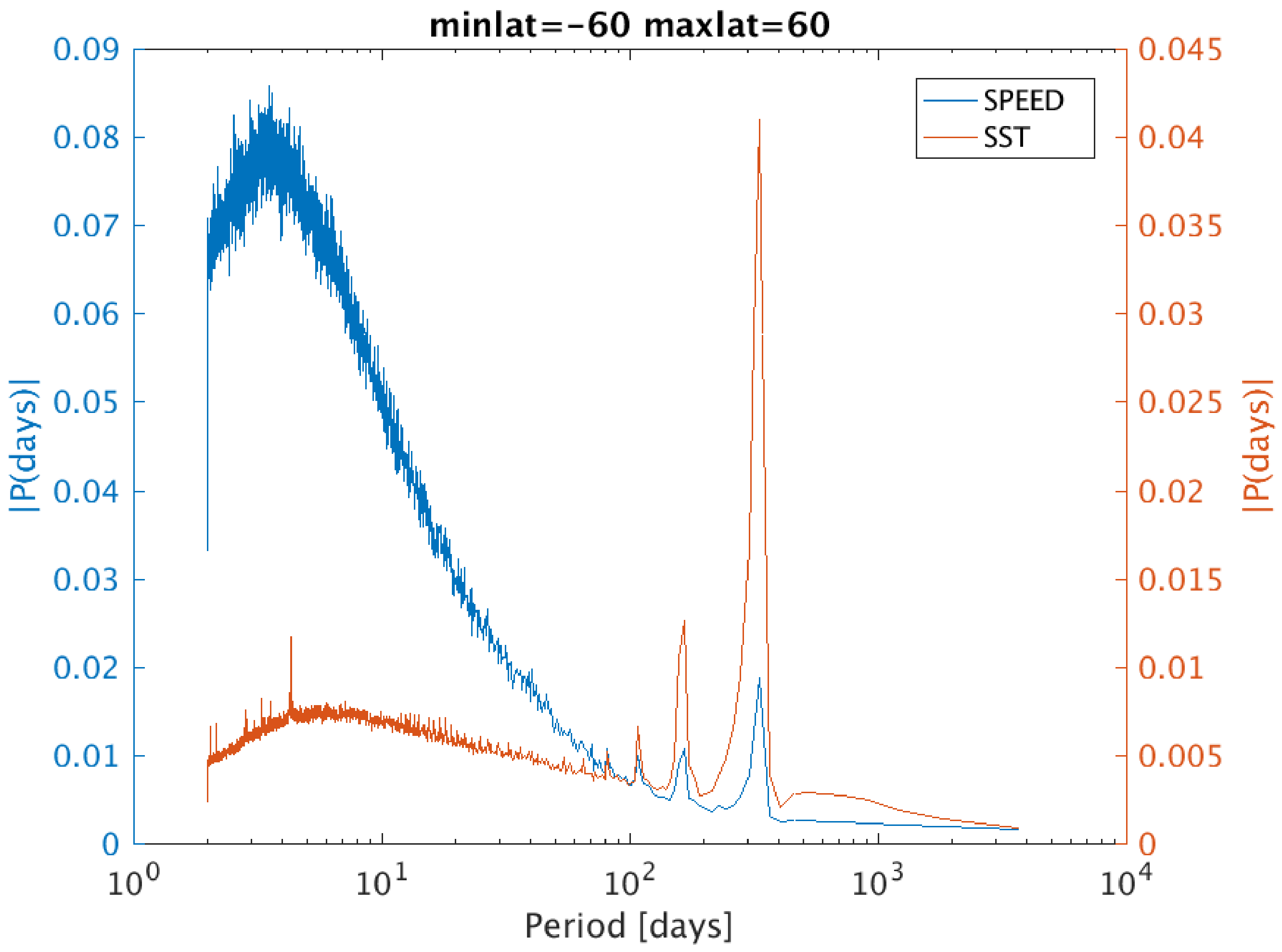
Possible mechanism





Spectral density of $\frac{\Delta SST}{\Delta t}$ and wind speed $\frac{\Delta WS}{\Delta t}$

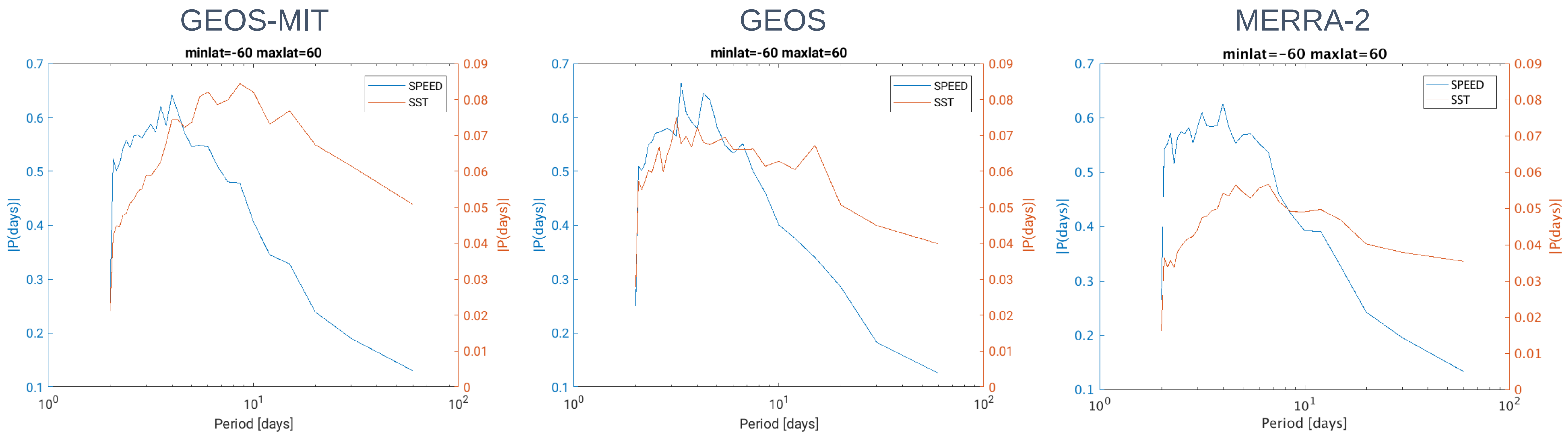
MERRA-2
(2006-2015)



An observational based product (MERRA-2) demonstrates cycles of several days both in surface wind and SST

Spectral density of $\frac{\Delta SST}{\Delta t}$ and wind speed $\frac{\Delta WS}{\Delta t}$

2 months



The GEOS-MIT model is able to reproduce the MERRA-2 spectral density but with higher SST amplitudes. May indicate strong air-sea interactions.

Conclusions (part III)

- First analysis of the ~10km coupled GEOS-MITgcm model reproduces realistic synoptic and mesoscale patterns.
- The coupled model shows positive correlations between SST and wind speed/stress, and the relation is slightly closer to observational estimates compared to previous simulations.
- The fact that the atmosphere-only experiment can reproduce the positive correlation suggests that the atmosphere responds to the ocean.
- Daily time series suggest a three-four-day cycle induced by air-sea feedbacks.

Next steps/future work

- Model tuning using green's function method.
- Increasing horizontal resolution (~1km).
- Initialized sub-seasonal to decadal prediction system.
- Observation System Simulation Experiments (OSSE).