A global, atmosphere-ocean simulation with km-scale horizontal grid spacing for air-sea exchange studies and climate-observing system design

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In support of air-sea exchange studies and climate observing system design, we have carried out a global, atmosphere-ocean simulation with km-scale horizontal grid spacing. The simulation comprises a C1440 configuration of the Goddard Earth Observing System (GEOS) atmospheric model with 7-km horizontal grid spacing and 72 vertical layers coupled to a LLC2160 configuration of the Massachusetts Institute of Technology general circulation model (MITgcm) with 2-4-km grid spacing and 90 vertical levels. The ocean model includes tidal forcing. The C1440-LLC2160 simulation has been integrated for 14 months starting from nominal January 20, 2020 initial conditions, the first 40 days of which has been submitted to the DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains (DYAMOND) intercomparison project. Hourly atmospheric and oceanic model output of all prognostic and some diagnostic variables has been saved and is being made available to the scientific community. This "nature" simulation provides a unique synthetic data set for atmospheric and oceanic boundary layer studies and for satellite and in-situ observing system design.

Jet Propulsion Laboratory
California Institute of Technology

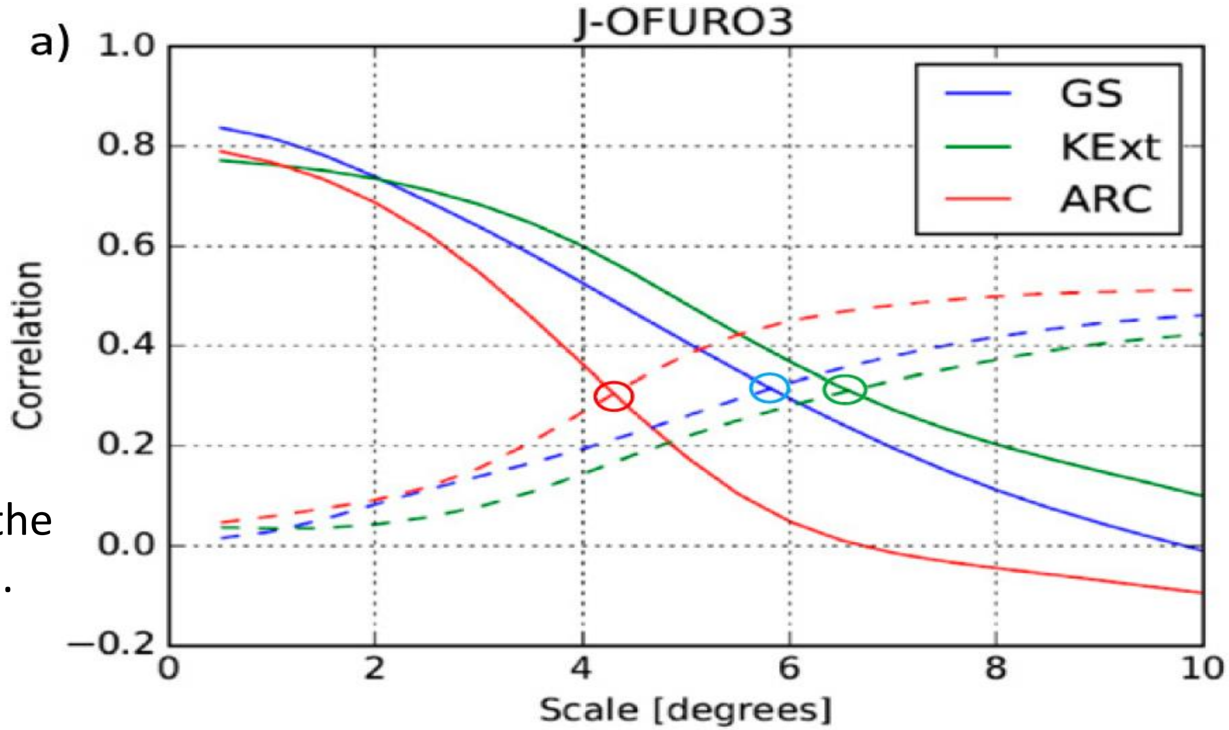
Background and Motivation

- Slides taken from a presentation given by Patrice Klein this past Friday (November 11, 2022) at the JPL Center for Climate Sciences (CCS).
- https://jpl.webex.com/recordingservice/sites/jpl/recording/a55933484410103bbfc700505681f366/playback

Correlation between Turbulent Heat Flux (THF) and Sea Surface Temperature (SST) as a function of scale

THF and SST: correlation >0 means the ocean forces the atmosphere (solid lines).

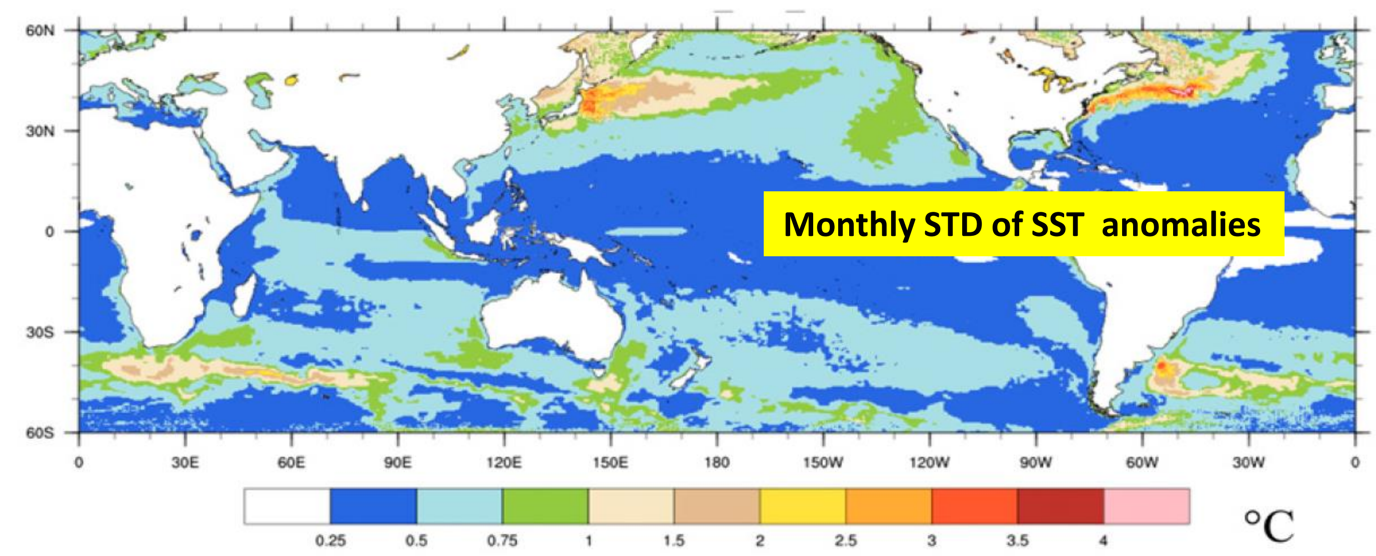
THF and $-\partial SST/\partial t$: correlation >0 means the atmosphere forces the ocean (dashed lines).



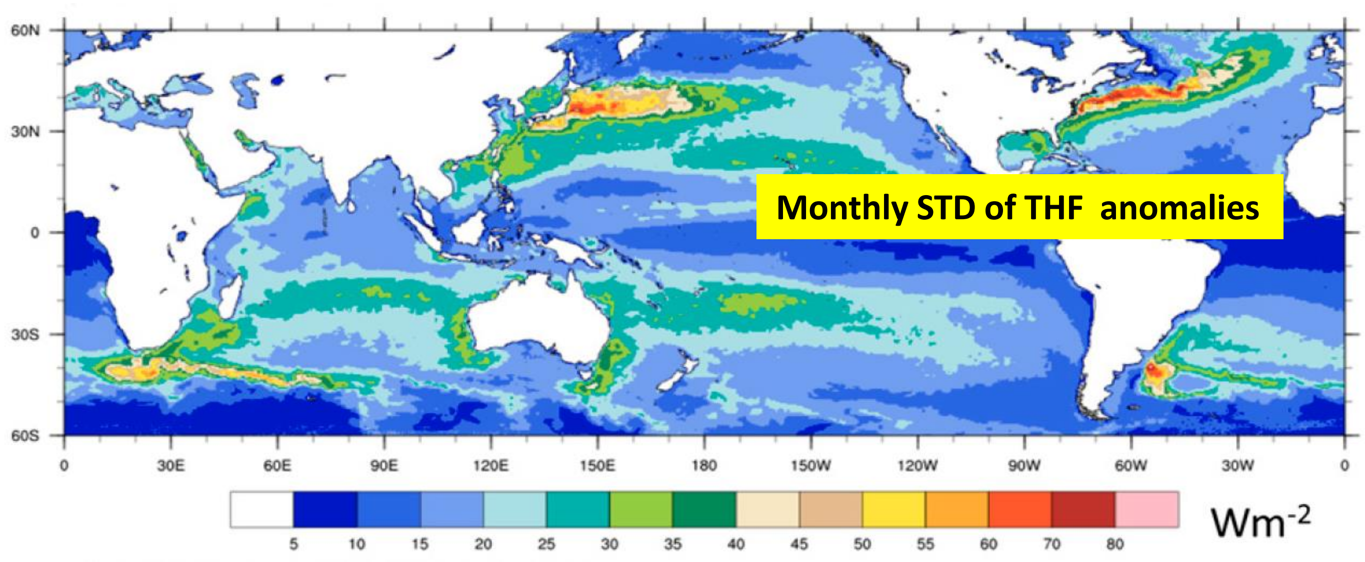
The ocean forces the atmosphere at mesoscales (< ~400 km)

Small et al. (JC 2019)

From Small et al. (JC 2019)



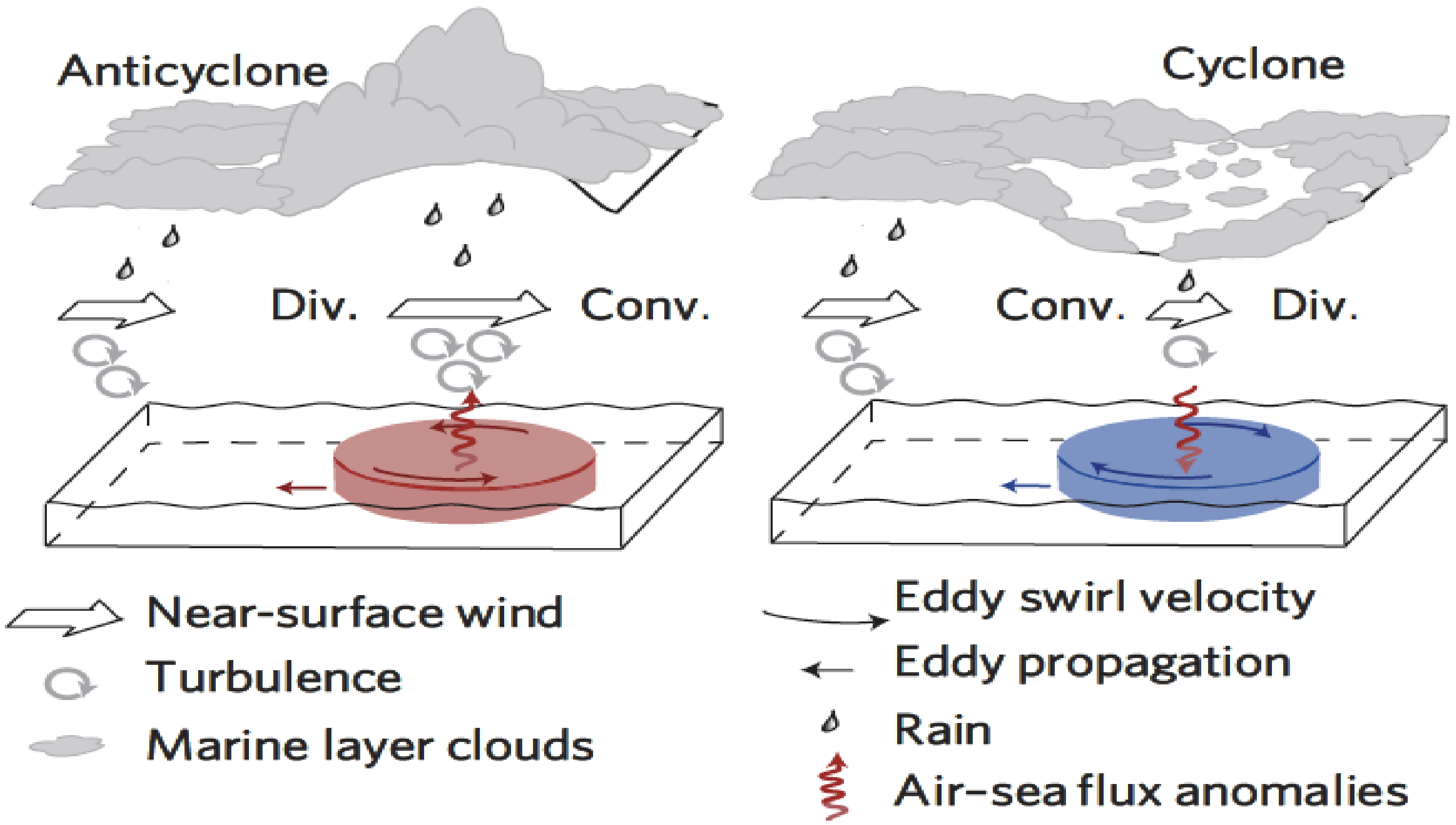
50% of Sea Surface Temperature (SST) anomalies **explained by mesoscale eddies**



> 50% of Turbulent Heat Flux (THF) anomalies **explained mesoscale eddies**

"Ocean mesoscale eddies moisten the atmosphere"

Mechanisms that explain the positive correlation between SST and LHF anomalies at mesoscale



Frenger et al. NG 2013

- Above warm eddies, **THF increases**.
- Wind divergence and convergence at the eddy edges trigger vertical velocities that can reach the tropopause
- The opposite occurs above cold eddies, BUT **the net effect of eddies is to significantly moisten the atmosphere and energize storms** (Ma et al. 2015, Foussard et al. 2019a,b, Hirata et al. 2019).

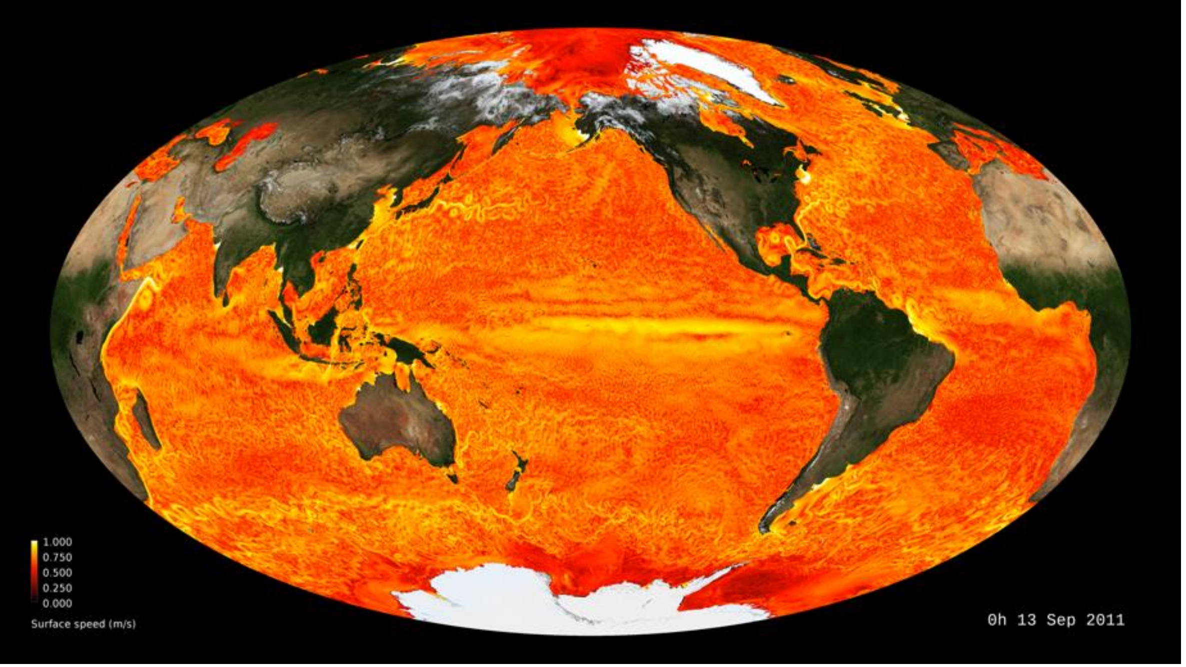
In summary:

The traditional view, that the ocean responds passively to atmospheric forcing, is challenged by new studies indicating that **ocean mesoscale eddies force the atmosphere.**

Presence of ocean eddies with their submesoscale SST fronts trigger strong wind stress divergence that intensifies latent heat fluxes. In that sense, **mesoscale eddies and submesoscales energize atmospheric storms and impact the atmospheric water vapor cycle.**

- We need to **further understand the impact of ocean submesoscales on the atmospheric weather.**
- We also need **collocated observations, with high resolution, of ocean currents, wind stress, and SST.**
- At last, we need **a stronger collaboration between ocean and atmospheric scientists**

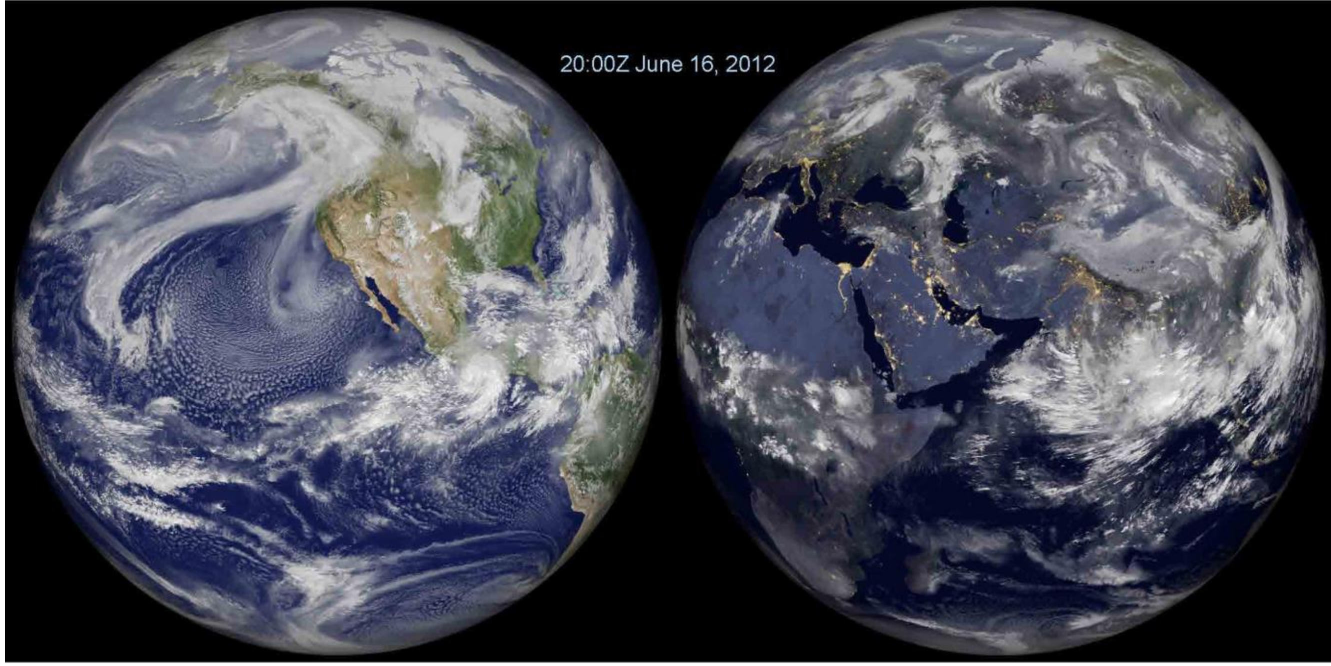
Modeling and Visualization Tools



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.

Preliminary work started in October 2012, with successful integration 1/48-deg simulation started in January 2014.

Over 100 science publications make use of output from this simulation.



Global, cloud-resolving simulation with GEOS, carried out with horizontal grid spacing of 1.5-km. Up to one year ago, 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.

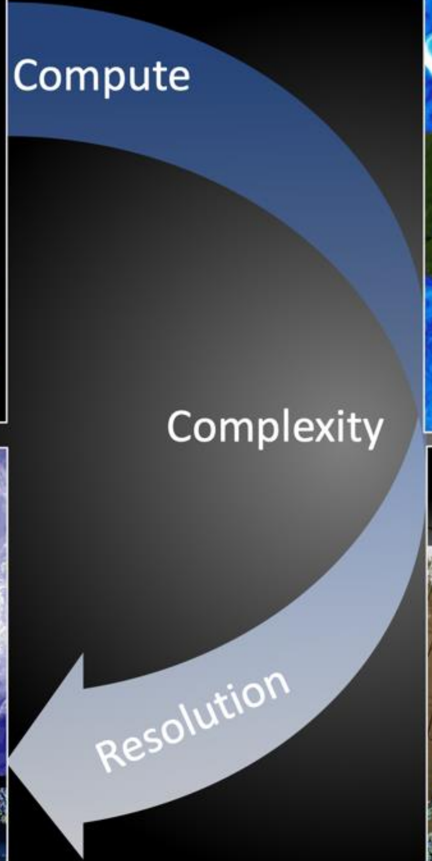
This engineering demonstration led to rapid development of the infrastructure of GEOS to support high-resolution global downscaling applications for climate and weather.

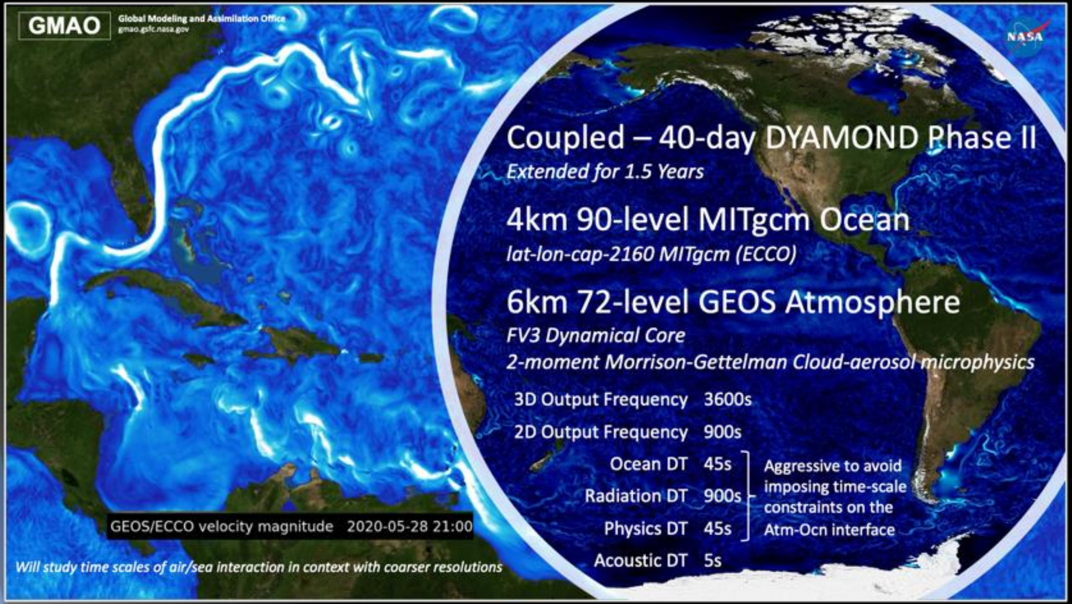
National Aeronautics and Space Administration

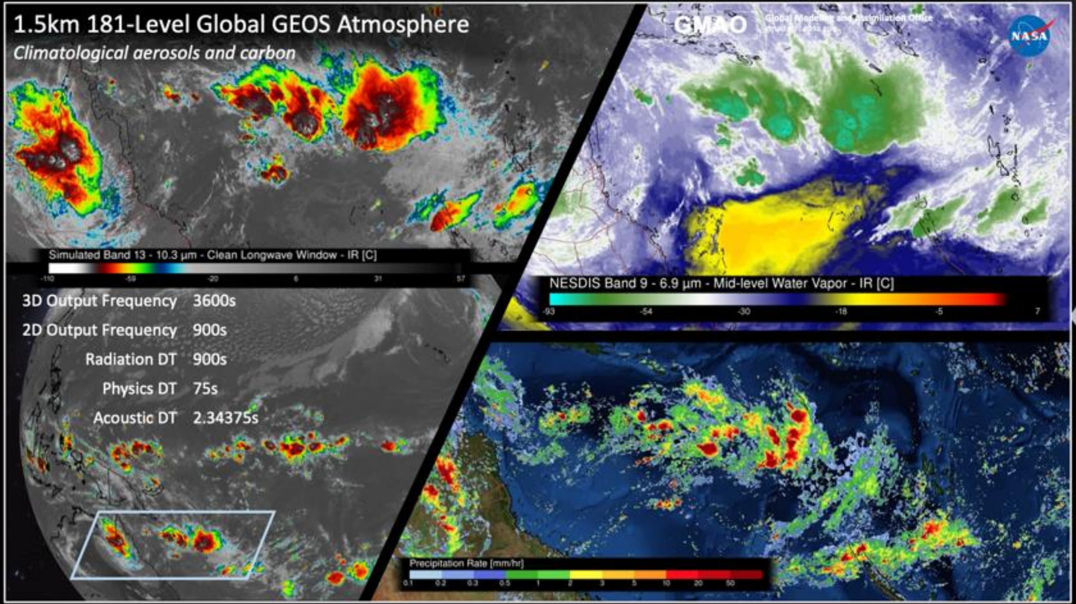
An overview of the GEOS Non-Hydrostatic DYAMOND Phase-II Simulations

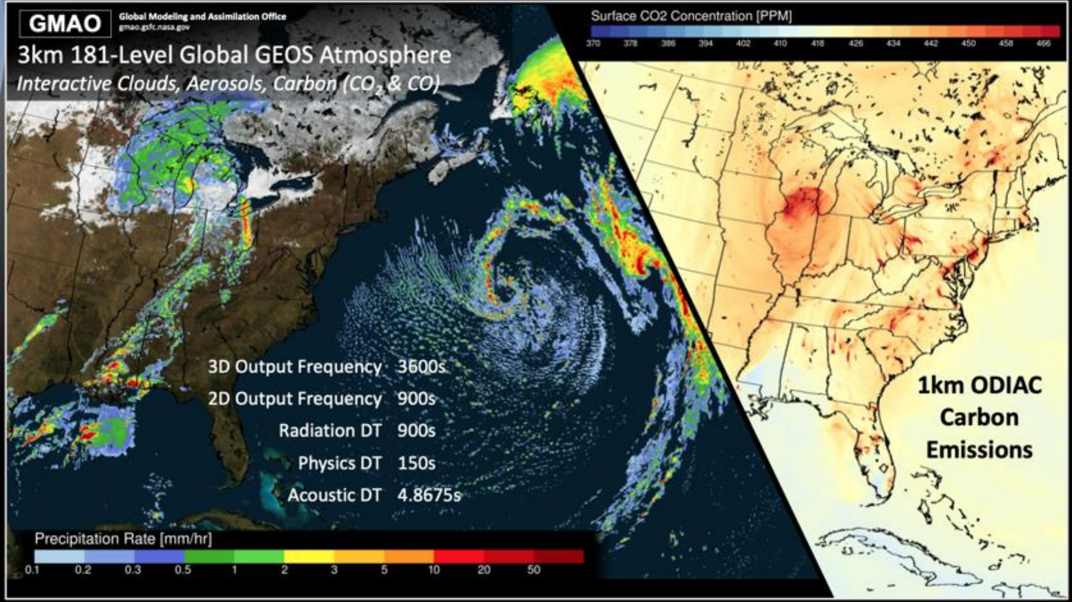
GEOS DYAMOND Phase-II 40-day Simulations

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

Towards a submesoscale, internal-gravity-wave, and cloud admitting simulation

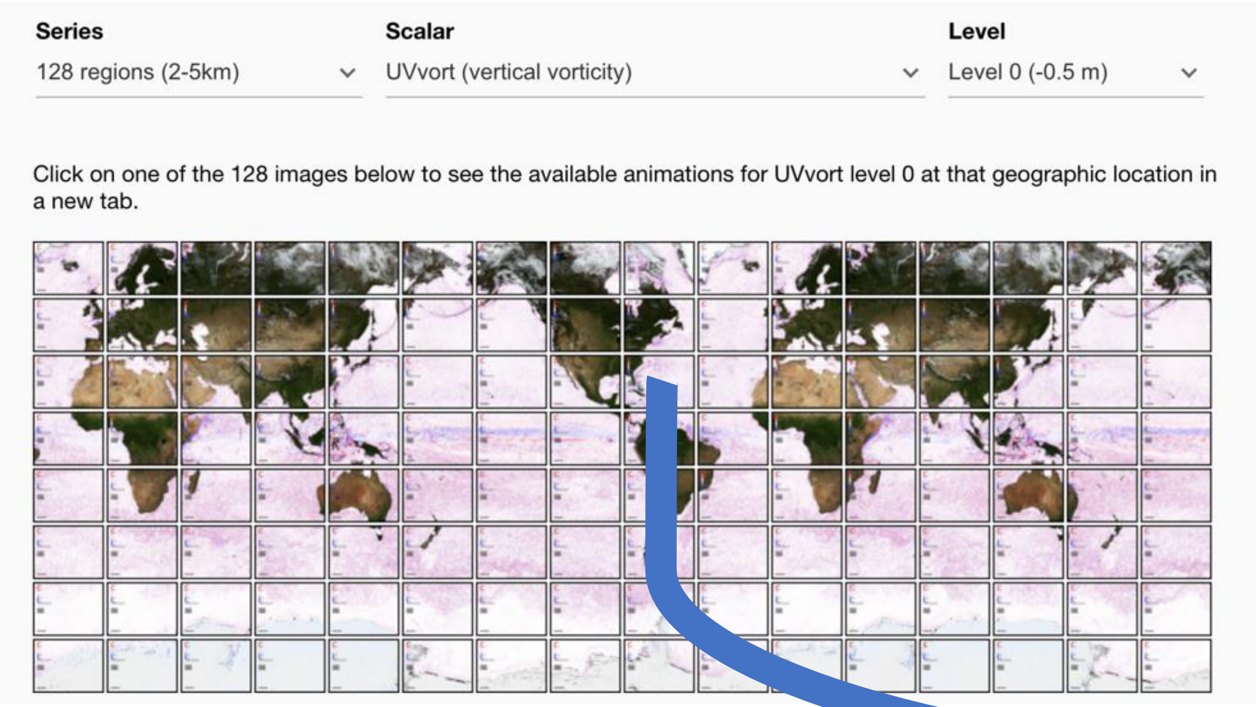
Simulation	Nominal grid spacing	Period
ECCO2 cs510 adjoint-method estimate	1/6 deg	January 2009 to December 2011
llc1080	1/12 deg	January 2010 to July 20, 2012
llc2160	1/24 deg	January 2011 to April 22, 2013
llc4320	1/48 deg	September 10, 2011 to November 15, 2012
cs1440-llc2160	1/16 deg over 1/24 deg	January 20, 2020 (2012) to March 25, 2021 (2013)
cs2880-llc4320	1/32 deg over 1/48 deg	TBD

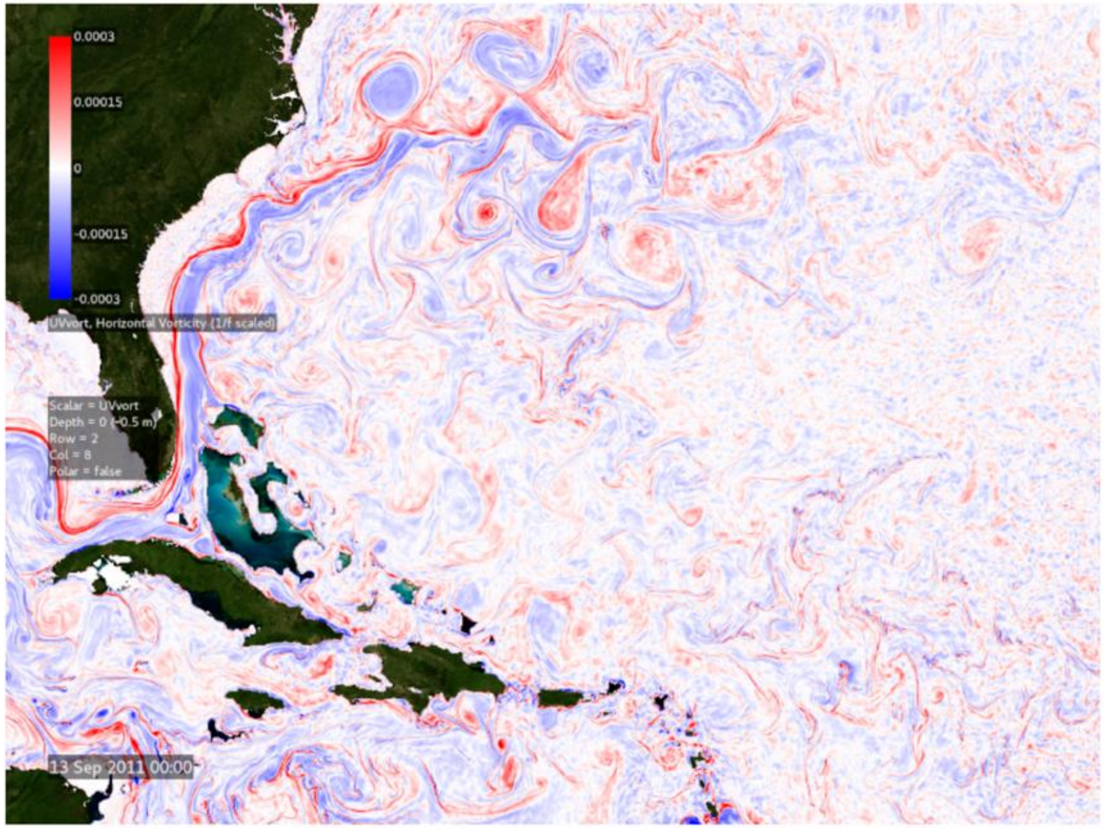
The c1440-llc2160 GEOS/ECCO simulation was integrated for an additional 12 months beyond the DYAMOND period with hourly output of all prognostic and many diagnostic atmospheric and oceanic variables.

The NASA Advanced Supercomputing (NAS) Hyperwall enables interactive visualization of multi-petabyte, time-varying, multivariate data.

Hyperwall at home

https://data.nas.nasa.gov/viz/vizdata/llc4320/index.html





Hyperwall at home capability allows visual exploration of the hi-res simulation from a remote workstation.

The buttons below will select a visualization of UVvort (horizontal vorticity) level 0 (depth -0.5 m) located at row 2 column 8 in the 128-region series of animations. The different buttons are for either a MP4 animation or a full size image. Animations are available for different resolutions and image sizes, and for a range of time steps. The sizes listed are for the MP4.

Timestep	Animation Pixel Resolution and File Size							
	5.4 km / 800x600				2.7 km / 1600x1200			
1 hour	172 MB	Play MP4	Download MP4	Image	788 MB	Play MP4	Download MP4	Image
3 hours	58 MB	Play MP4	Download MP4	Image	313 MB	Play MP4	Download MP4	Image
6 hours	39 MB	Play MP4	Download MP4	Image	199 MB	Play MP4	Download MP4	Image
12 hours	22 MB	Play MP4	Download MP4	Image	110 MB	Play MP4	Download MP4	Image
24 hours	14 MB	Play MP4	Download MP4	Image	65 MB	Play MP4	Download MP4	Image

Simulation Details and Available Output

GEOS/MITgcm Coupled Model (Simulation 2/2020-4/2021)

Atmosphere+Infrastucture (GEOS GCM)

- Recent GEOS AGCM, including interactive aerosol model + aerosol-cloud interaction
- Horizontal Grid: Cubed Sphere, C1440, approximately 6-7 km resolution
- Vertical Grid: Hybrid eta-pressure, 72 levels, approximately 8 levels inside boundary layer, 30 above tropopause
- MAPL (Modeling, Analysis and Prediction Layer) interface to ESMF infrastructure

Ocean (MITgcm)

- MITgcm, Hydrostatic primitive equations for velocity, potential temperature and salinity, with an implicit free surface
- Includes tidal forcing
- KPP vertical mixing of Large et al. (1994), non-local term disabled
- Horizontal Grid: Latitude-Longitude-polar-Cap 2160 (LLC2160), approximately 2-4 km resolution
- Vertical Grid: 90 levels, 1m resolution near surface, ~300m resolution at 5000m depth

Sea Ice

- Sea Ice Thermodynamics of CICE4.0;
- Sea Ice Advection (each ice thickness category separately) in MITgcm

Atmosphere-Ocean Interface

- “Skin layer” of Price, et al., 1978
- Implicit backward surface flux calculation assures absolute conservation of energy and water across the interface

GEOS/MITgcm Coupled Model Output - Atmosphere

Hourly “Instantaneous” 3D Prognostic/Diagnostic Fields on “native” horizontal and vertical grid:

U, V, W, H, DELP, P, T, QV, QL, QI RI, RL, FCLD, DTHDT, DTHDTCN, CO, CO2

15-minute “Instantaneous” Prognostic/Diagnostic Fields on “native” horizontal grid:

U10M, V10M, TS, QA, T2M, QS, Q2M, TQV, TQI, TQL, TQR, TQS, CWP, LWP, IWP, CAPE, INHB,
OMEGA, RH, ZLE at 800, 700, 500, 200 hPa

Hourly “Time Averaged” 3D Diagnostic Fields on “native” horizontal and vertical grid:

Convective Mass Fluxes, Turbulence Eddy Coefficients, “Tendency terms” from diabatic forcing

Hourly ”Time Averaged” 2D Diagnostic Fields on “native” horizontal grid:

TROPP_EPV, TROPP_THERMAL, TROPP_BLENDED, TROPT, TROPQ, TA, US, VS, SPEED, THAT, QHAT, PLS, PCU, CCWP, TAUTT, TAULO, TAUMD, TAUHI, CLDTT, CLDLO, CLDMD, CLDHI, RUNSURF, BASEFLOW, CT, CQ, CM, LAI, GRN, SNOMAS, ITY, WET1, WET2, WET3, TSOIL1, TSOIL2, FRACI, USTAR, Z0, Z0H, RHOS, U2M, V2M, T10M, Q10M, U50M, V50M, GUST, VENT, ASNOW, ALBVR, ALBVF, ALBNR, ALBNF

15-minute “Time Averaged” 2D Diagnostic Fields on “native” horizontal grid:

PRECANV, PRECCON, PRECLSC, PRECTOT, PRECSNO, ZPBL, RADSRF, FLNS, FLNSC, FLNSA, OLR, OLC, OLA, LWS, LCS, EMIS, LAS, SFCEM, CLDTMP, CLDPRS, OSR, OSRCLR, SWTNET, SWTNETC, SWTNETCNA, SWTNETNA, RADSWT, SWGDWN, SWGDWNC, SWGNET, SWGNETC, SWGNETNA, SWGNETCNA, ALBEDO, EFLUX, EVAP, HFLUX, TAUX, TAUY

GEOS/MITgcm Coupled Model Output - Ocean

<u>Hourly "Instantaneous" Prognostic/Diagnostic Fields on "native" horizontal and vertical grid:</u>

Eta	sea surface height (m)
KPPhbl	mixing layer depth (m)
PhiBot	bottom pressure (m^2/s^2)
SIarea	fractional ice-covered area for 5 categories [0 to 1]
SIheff	effective ice thickness for 5 categories (m)
SIhsnow	effective snow thickness for 5 categories (m)
SItice	ice surface temperature for 5 categories (deg K)
SIuice	zonal (relative to grid) ice velocity, >0 from West to East (m/s)
SIvice	merid. (relative to grid) ice velocity, >0 from South to North (m/s)
Salt	salinity (g/kg)
Theta	potential temperature (deg C)
U.	zonal (relative to grid) velocity, >0 from West to East (m/s)
V.	merid. (relative to grid) velocity, >0 from South to North (m/s)
W.	vertical velocity (m/s)
oceFWflx	net upward freshwater flux, >0 increases salinity (kg/m^2/s)
oceQnet	net upward surface heat flux (including shortwave), >0 decreases theta (W/m^2)
oceQsw	net upward shortwave radiation, >0 decreases theta (W/m^2)
oceSflux	net upward salt flux, >0 decreases salinity (g/m^2/s)
oceTAUX	zonal (relative to grid) surface wind stress, >0 increases uVel (N/m^2)
oceTAUY	meridional (relative to grid) surf. wind stress, >0 increases vVel (N/m^2)

Please note that U, V, oceTAUX, oceTAUY, SIuice, and SIvice are aligned relative to model grid, not geographical coordinates, and that they are specified at the SouthWest C-grid velocity points. All other scalar fields are specified at the tracer point, i.e., the center of each grid box.

GEOS/MITgcm Coupled Model Output - Visualizations

Field-by-field animations of GEOS Atmosphere-related output (interpolated to a lat/lon grid):
https://data.nas.nasa.gov/viz/vizdata/DYAMOND_c1440_llc2160/GEOS/index.html

(Example: https://data.nas.nasa.gov/viz/vizdata/DYAMOND_c1440_llc2160/GEOS/mp4/HD_latlon_EFLUX-15mn.mp4)

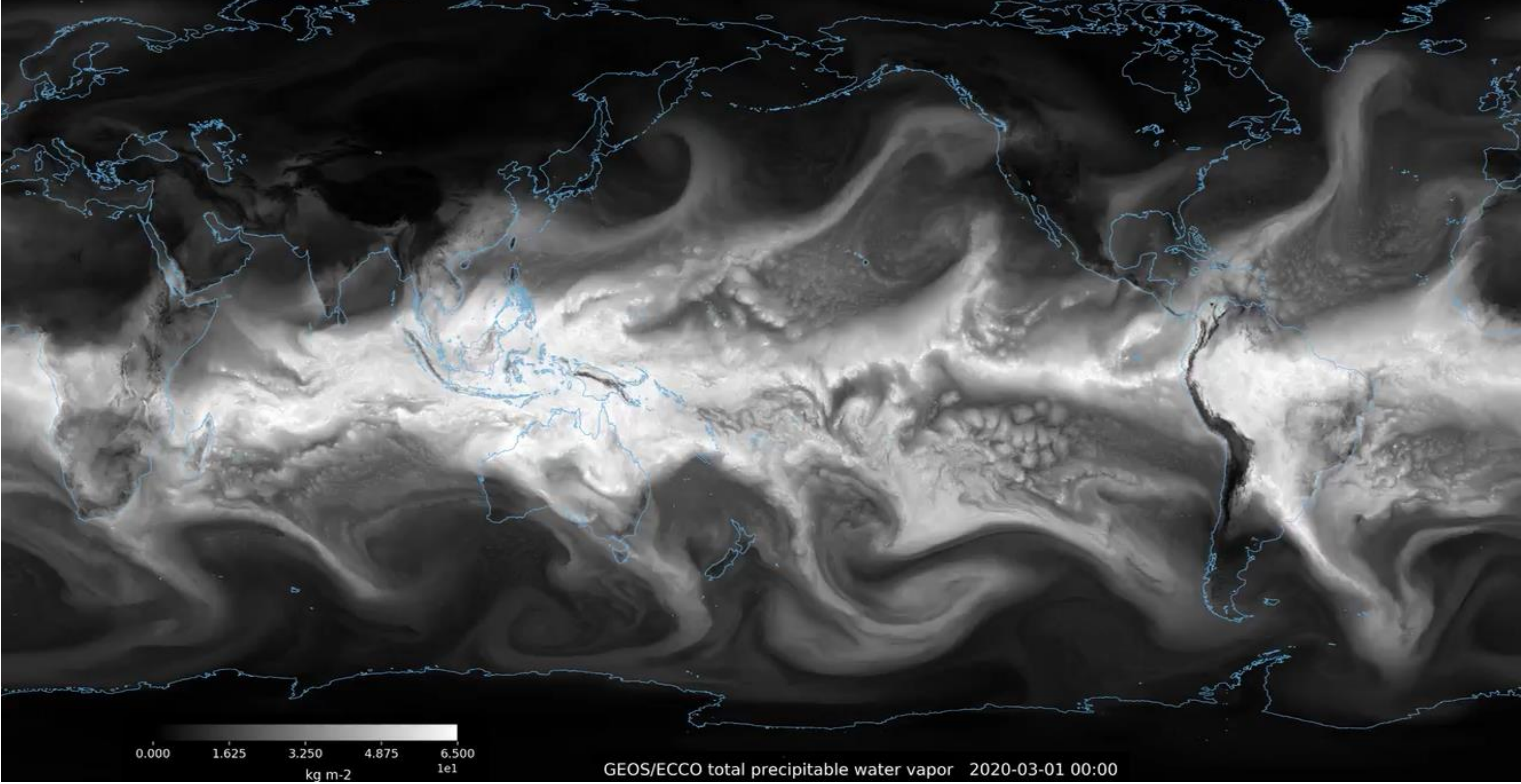
Field-by-field animations of MITgcm Ocean-related output (interpolated to a lat/lon grid):
https://data.nas.nasa.gov/viz/vizdata/DYAMOND_c1440_llc2160/MITgcm/index.html

(Example: https://data.nas.nasa.gov/viz/vizdata/DYAMOND_c1440_llc2160/MITgcm/mp4/HD_latlon_SSSPEED.mp4)

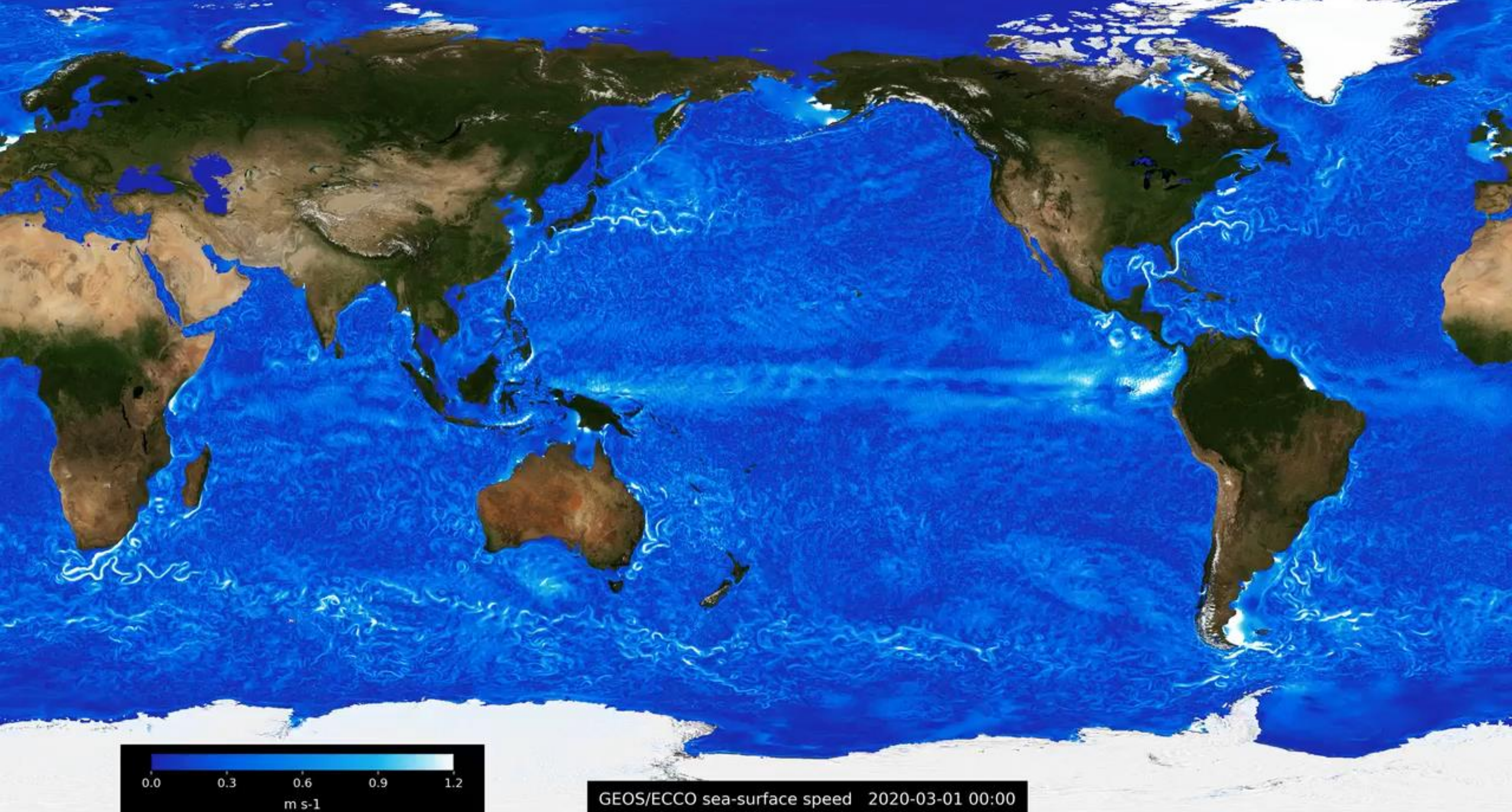
Additional selected fields with native grid visualizations:
https://data.nas.nasa.gov/viz/data.php?dir=/vizdata/nmccurdy/DYAMOND_c1440_llc2160/native_grid

Additional regionally-focused animations:
https://portal.nccs.nasa.gov/datashare/g6dev/WebGL/geos_dyamondv2.html

Atmospheric field animations available at https://data.nas.nasa.gov/viz/vizdata/DYAMOND_c1440_llc2160/GEOS/index.html

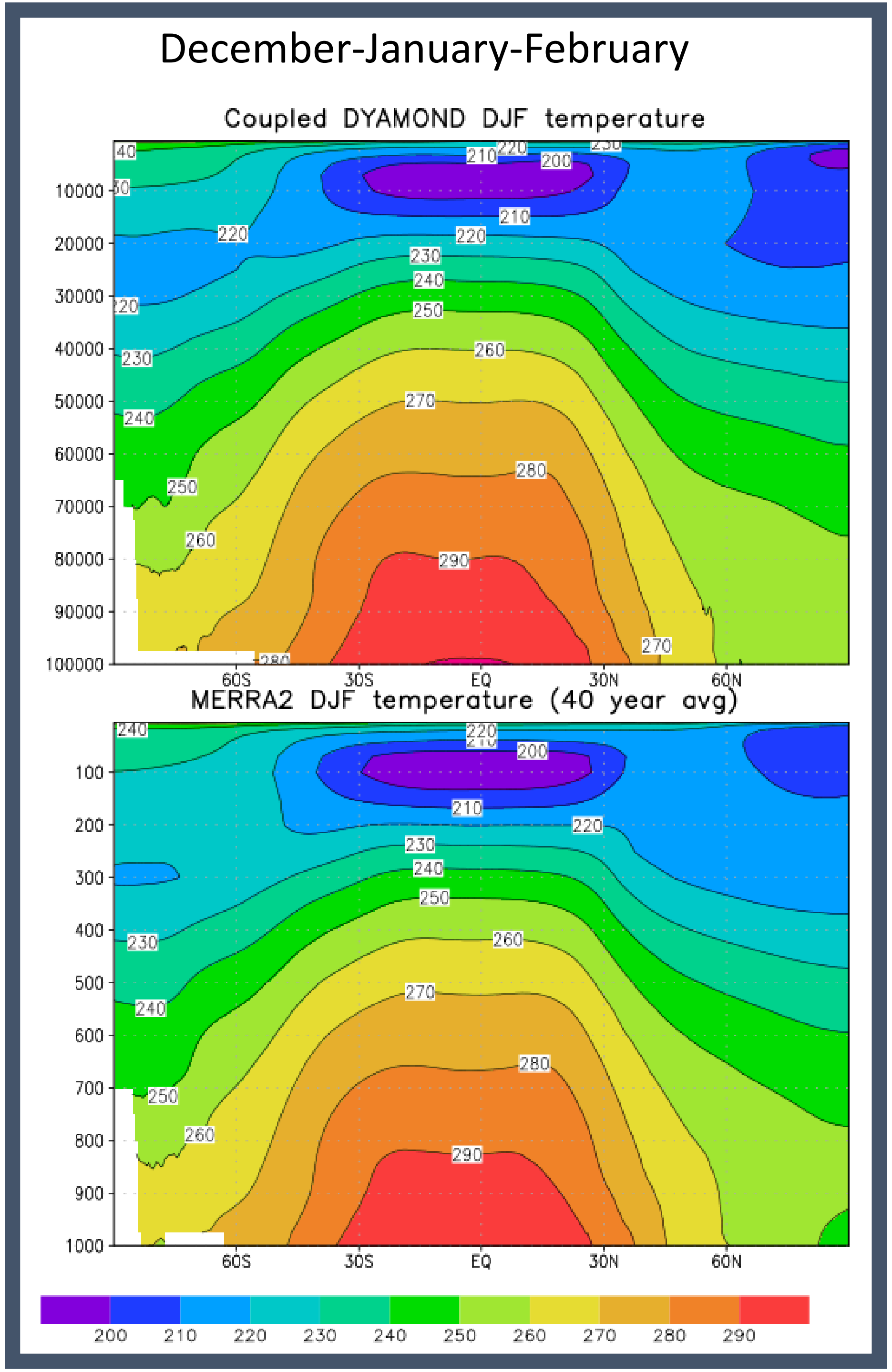


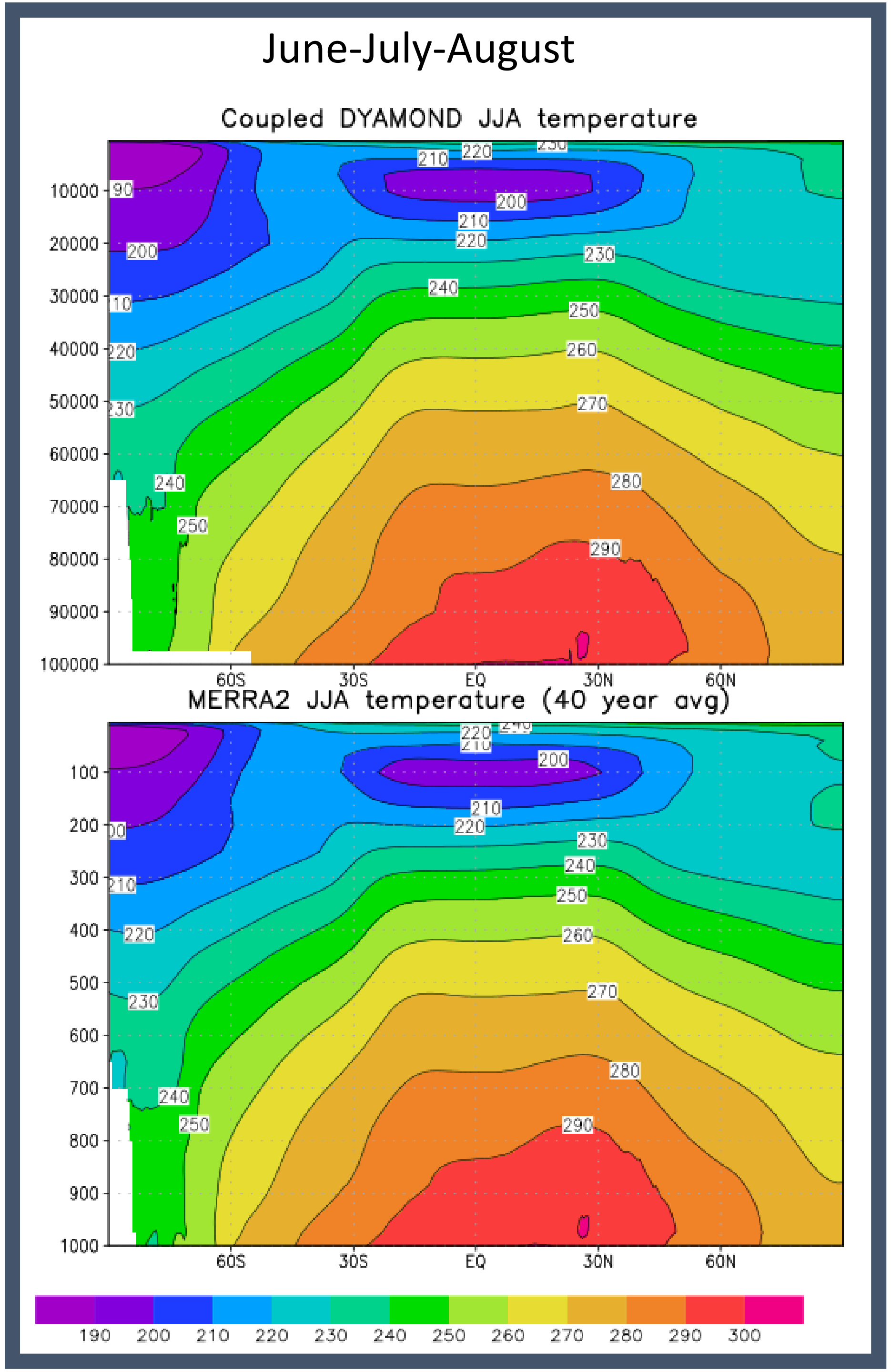
Oceanic field animations available at https://data.nas.nasa.gov/viz/vizdata/DYAMOND_c1440_llc2160/MITgcm/index.html



Some Preliminary Evaluation

Temperature

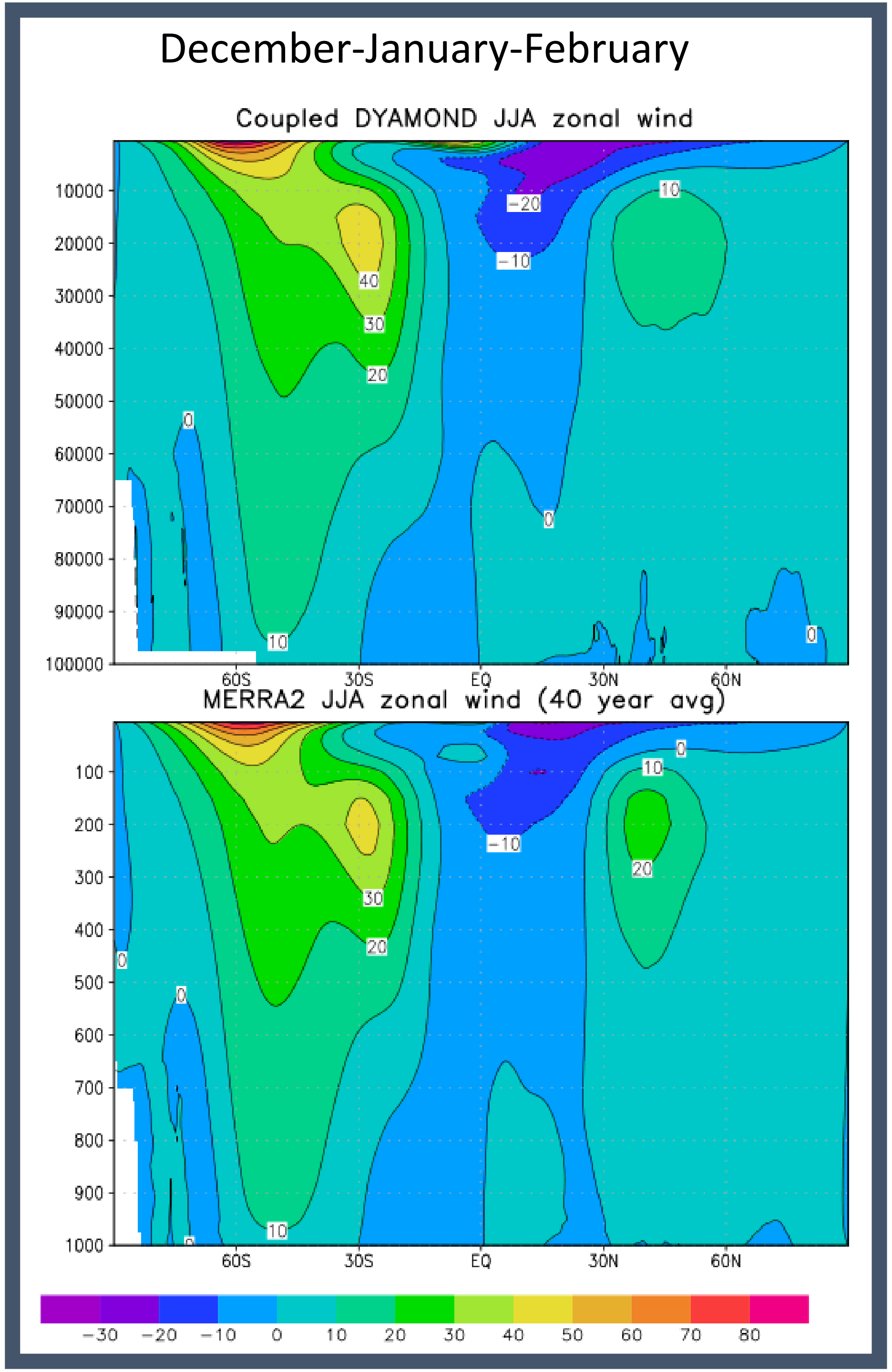


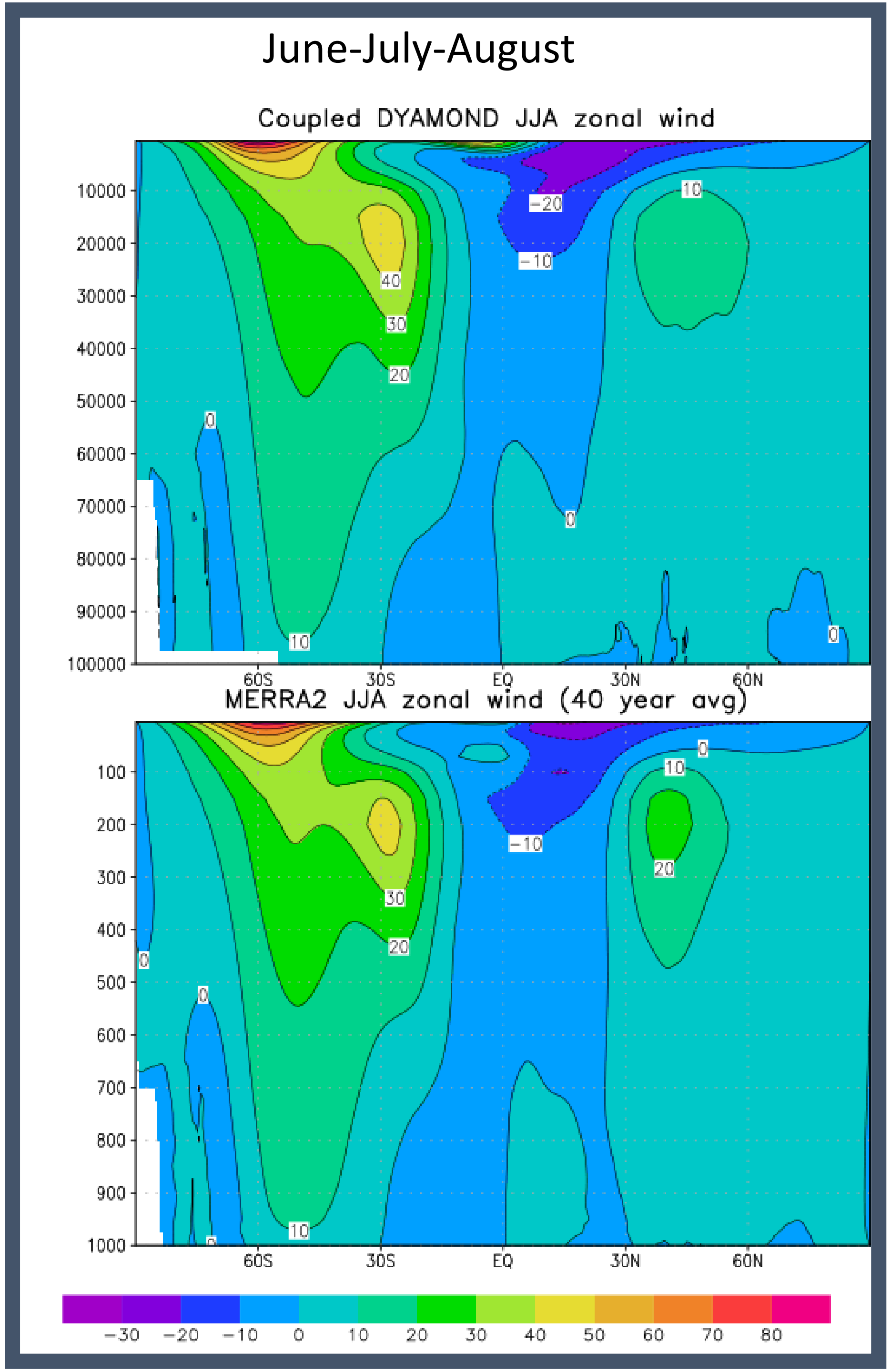


GEOS/MITgcm simulation

MERRA2 reanalysis

Zonal Wind

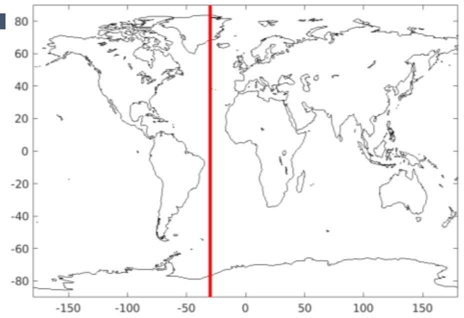




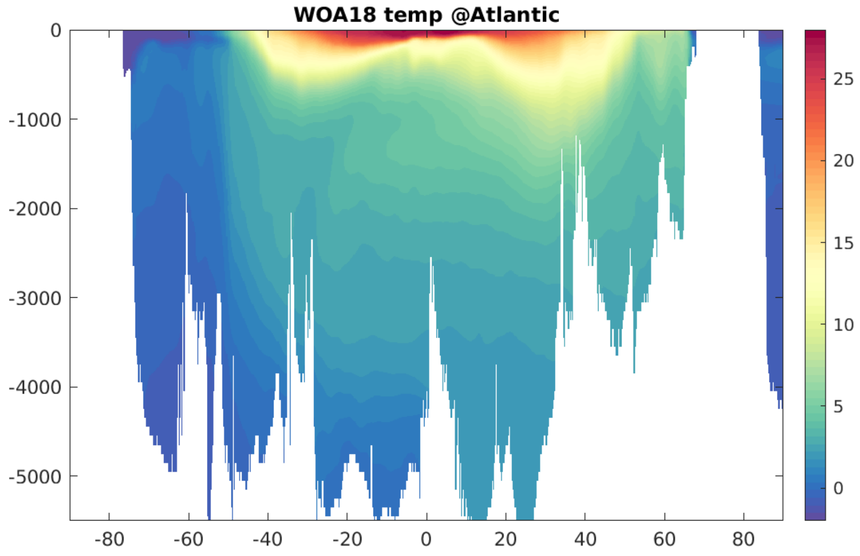
GEOS/MITgcm simulation

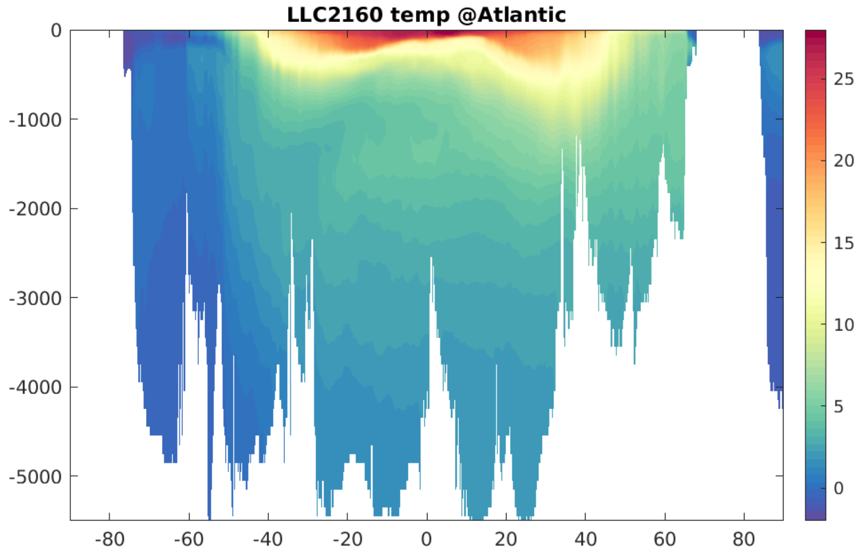
MERRA2 reanalysis

Atlantic Section

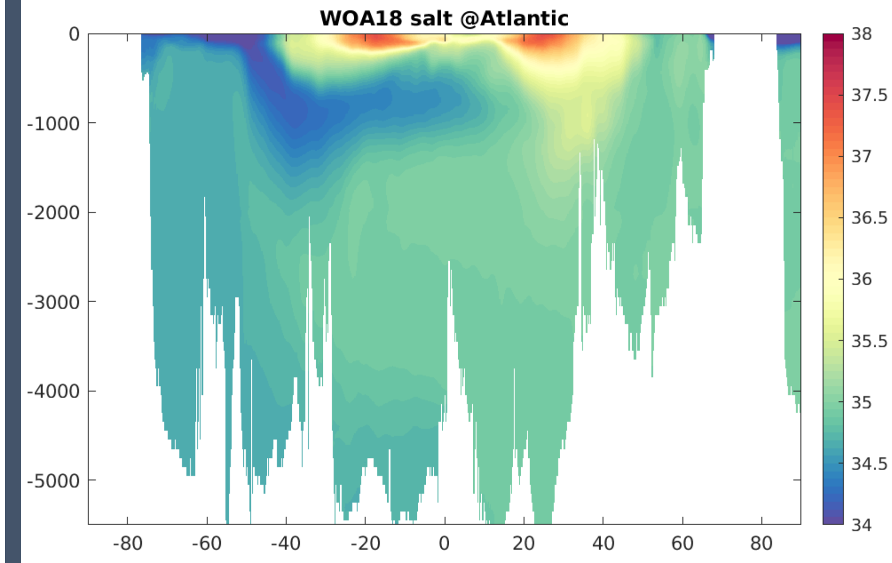


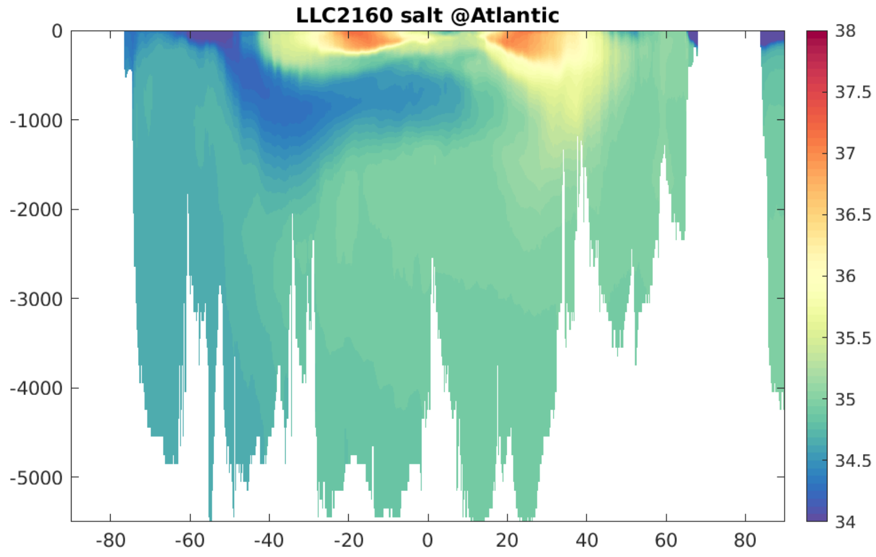
World Ocean Atlas Climatology | GEOS/MITgcm simulation mean





Temperature

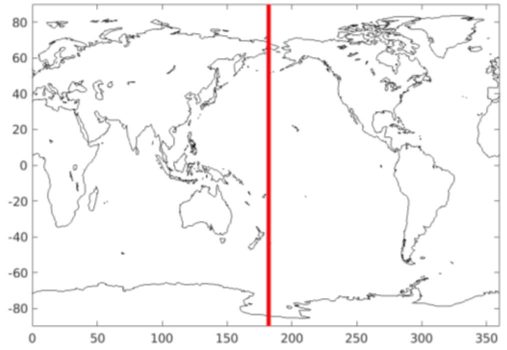


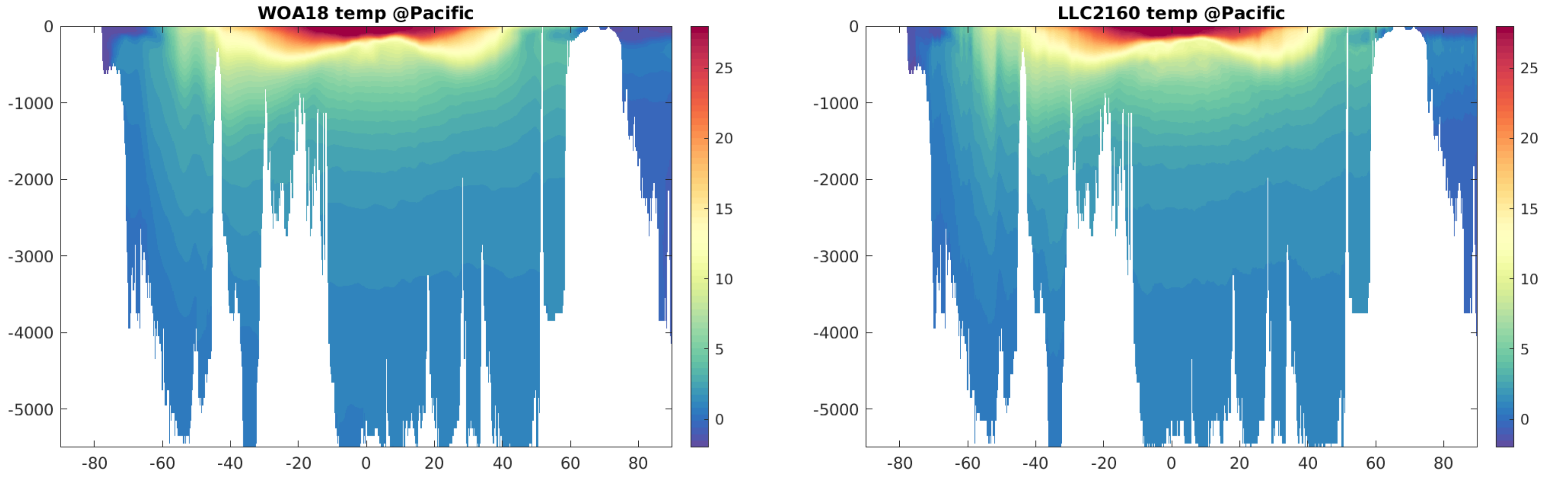


Salinity

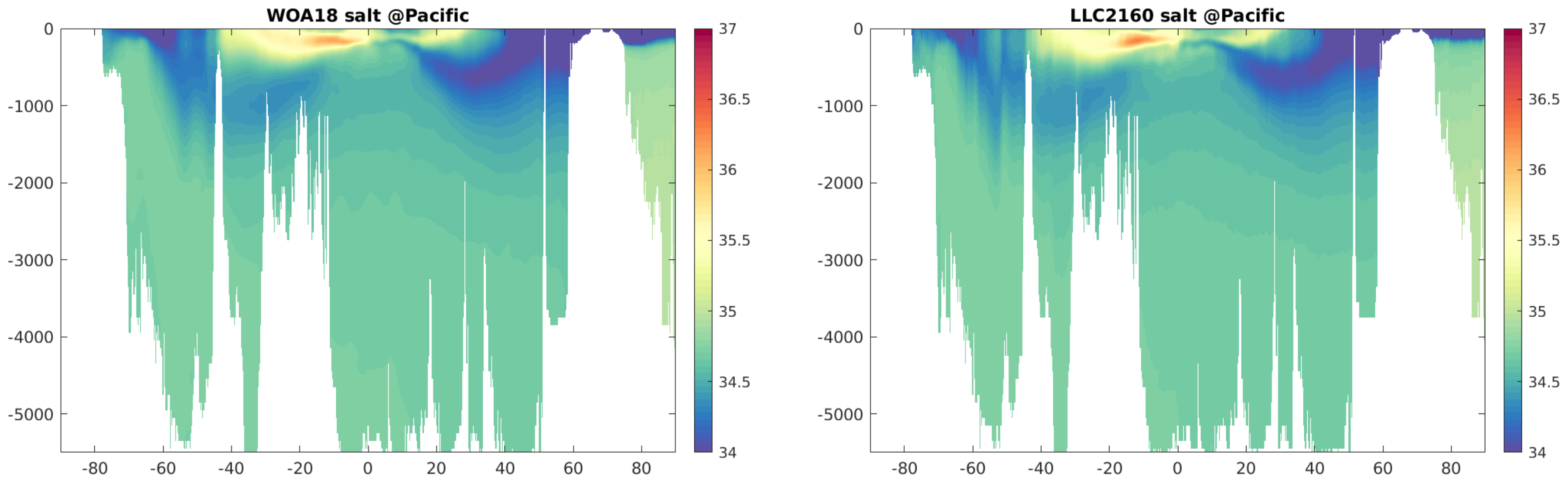
Pacific Section

World Ocean Atlas Climatology | GEOS/MITgcm simulation mean





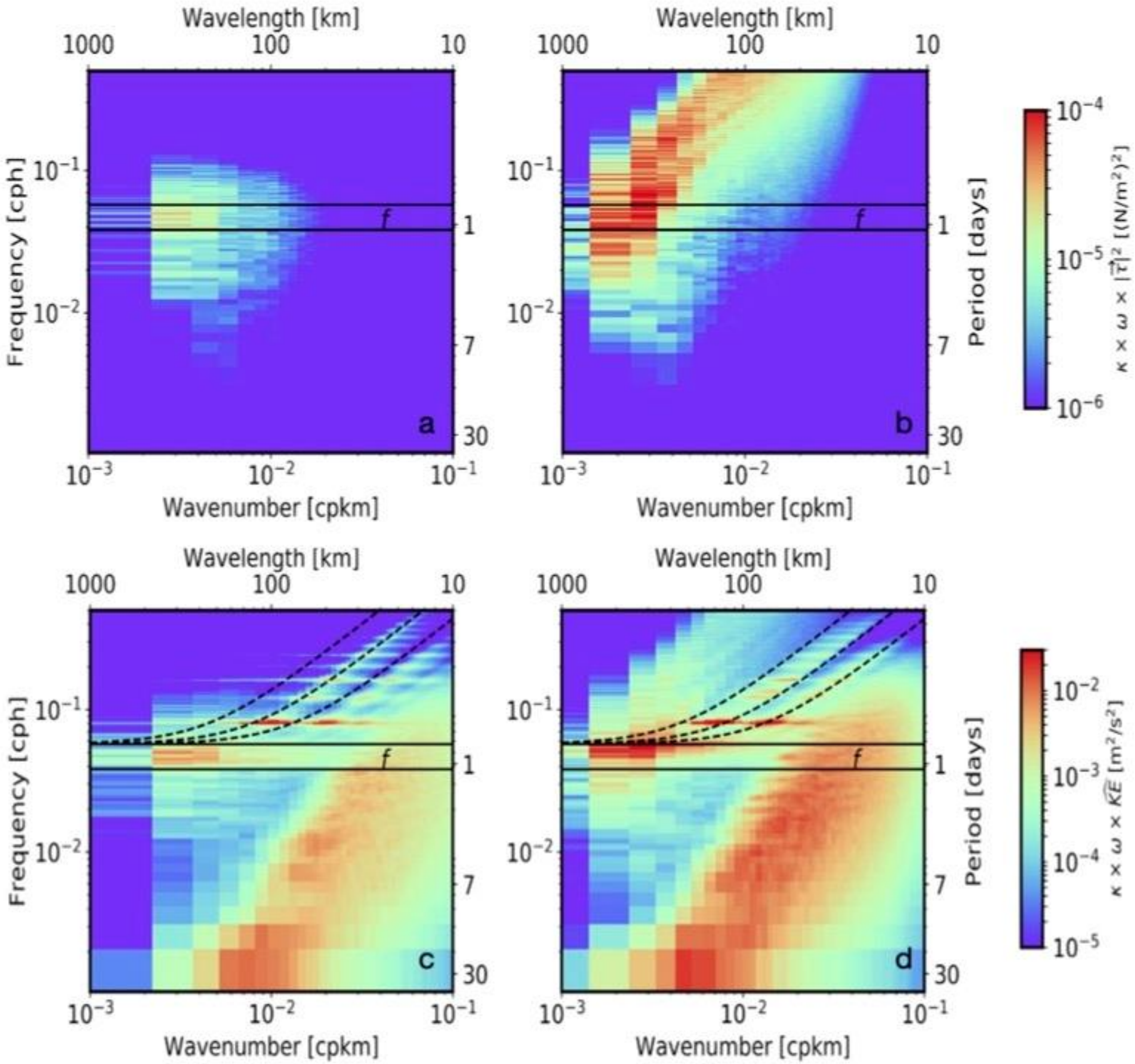
Temperature



Salinity

Some Early Science Results

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.

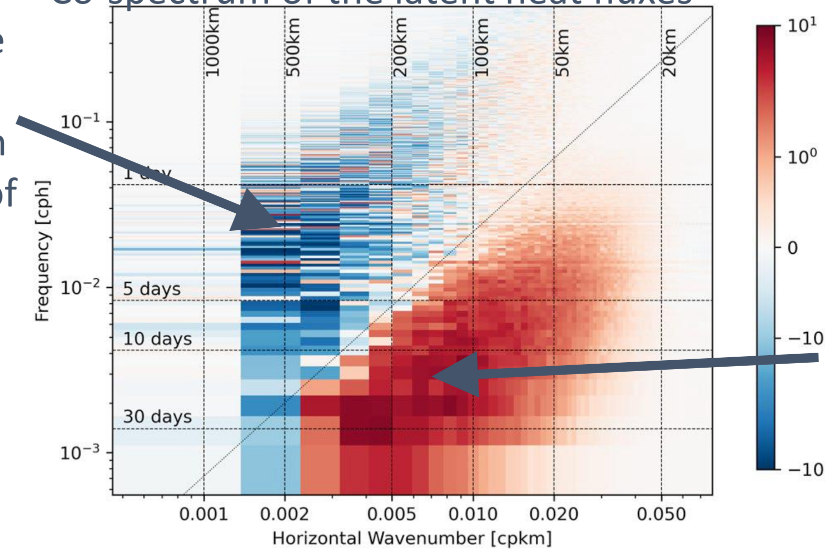
The wind work spans a broad range of spatial and temporal scales, from 10 to 3000 km and one hour to at least 3 months, emphazing the need to high spatial and temporal scale information to study this multiscale phenomenon.

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

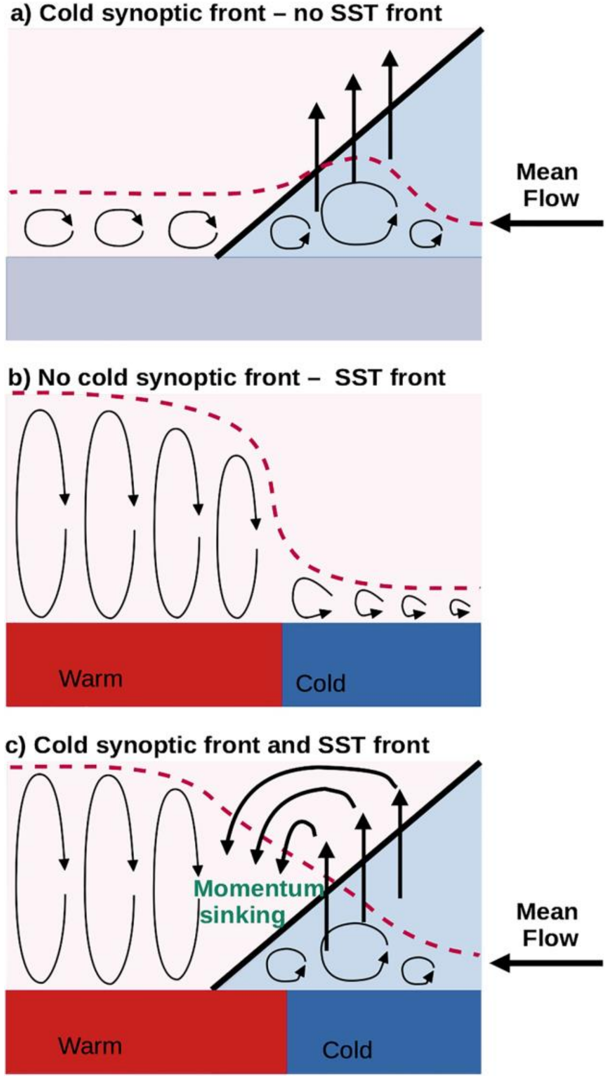
The study focuses on recurring intermittent wind events in the Gulf Stream region associated with SST anomalies with horizontal scales smaller than 500-km. These events are associated with a secondary circulation that acts to fuel the latent heat bursts by transferring dry air and momentum down to the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

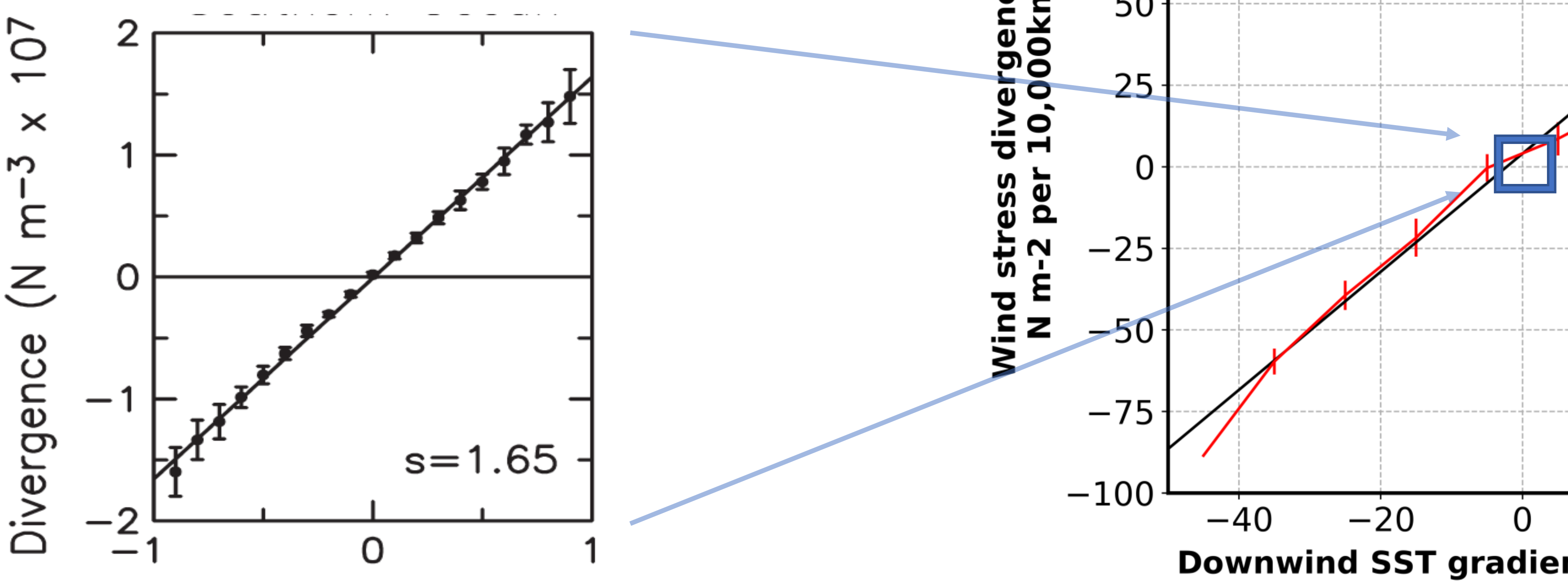
a) A cold synoptic front approaches a gradual Sea Surface Temperature (SST) gradient (from right to left), the warmer air at the surface is pushed upward. **No secondary circulation**

(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.**

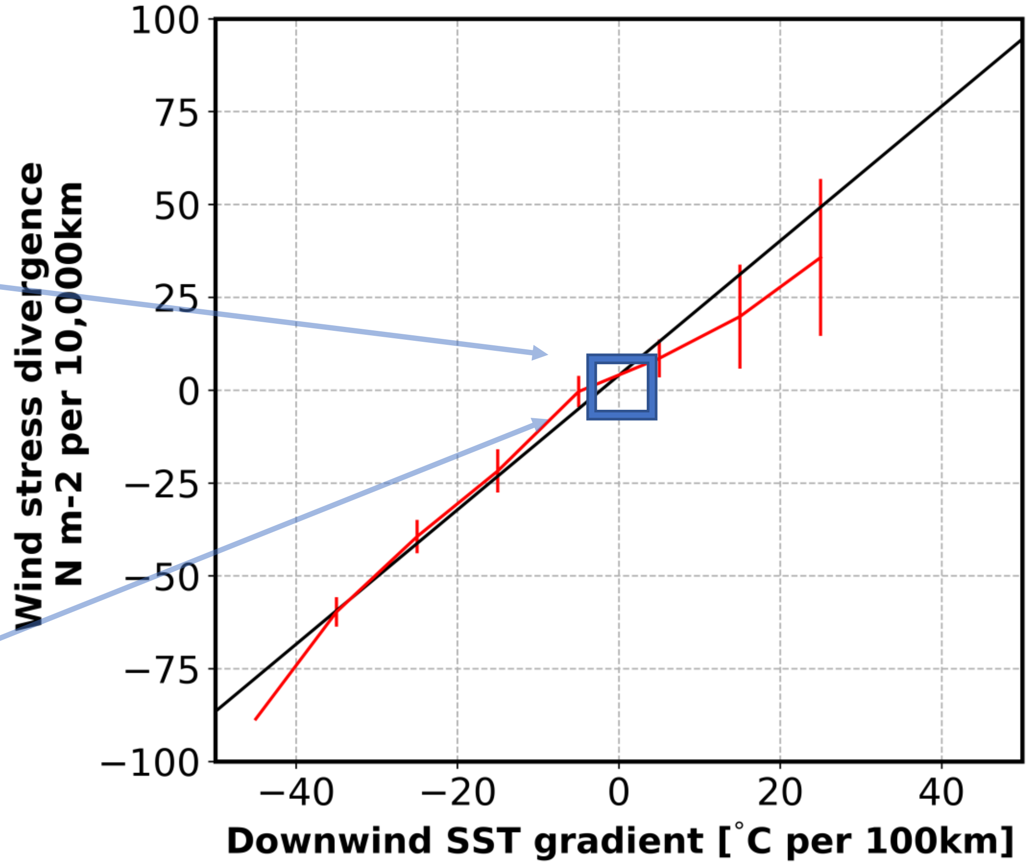
(c) A cold synoptic front approaches an SST front and produces momentum sinking above the front due to mixing. **Secondary circulation enhances the turbulent fluxes and atmospheric gradients.**

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%.**

Strong correlation between wind stress divergence and SST gradients: Impact of the resolution



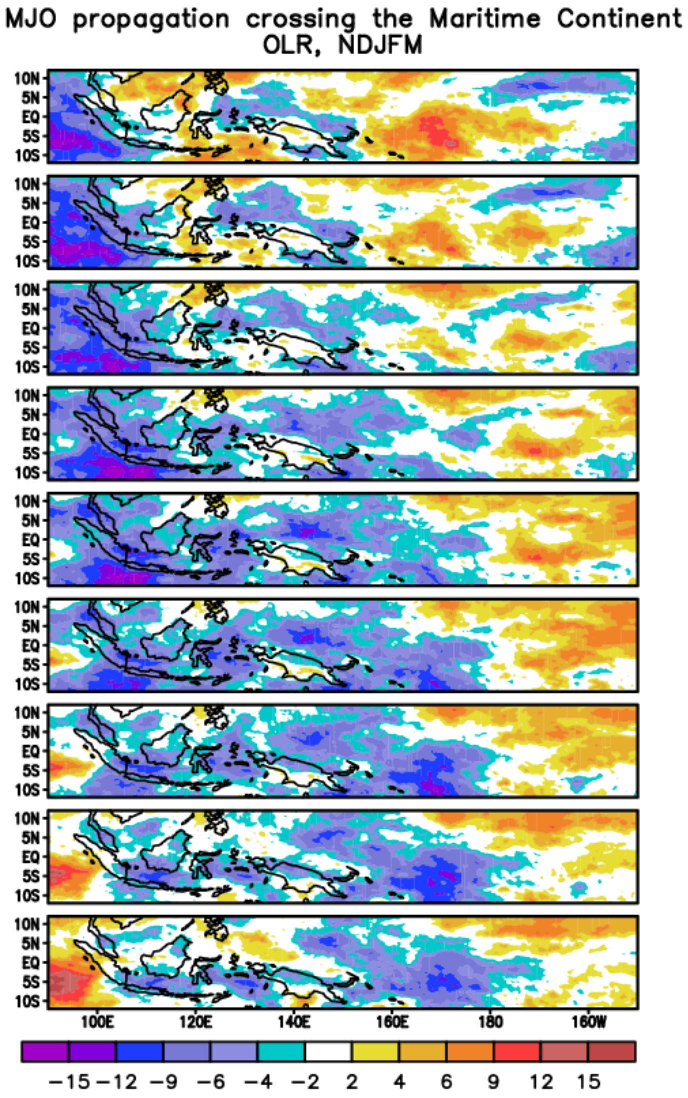
Chelton et al. Sci (2004)
See also T. Liu et al. JC (2007)



Blue square: Chelton et al.'04

From Torres et al. (in preparation)

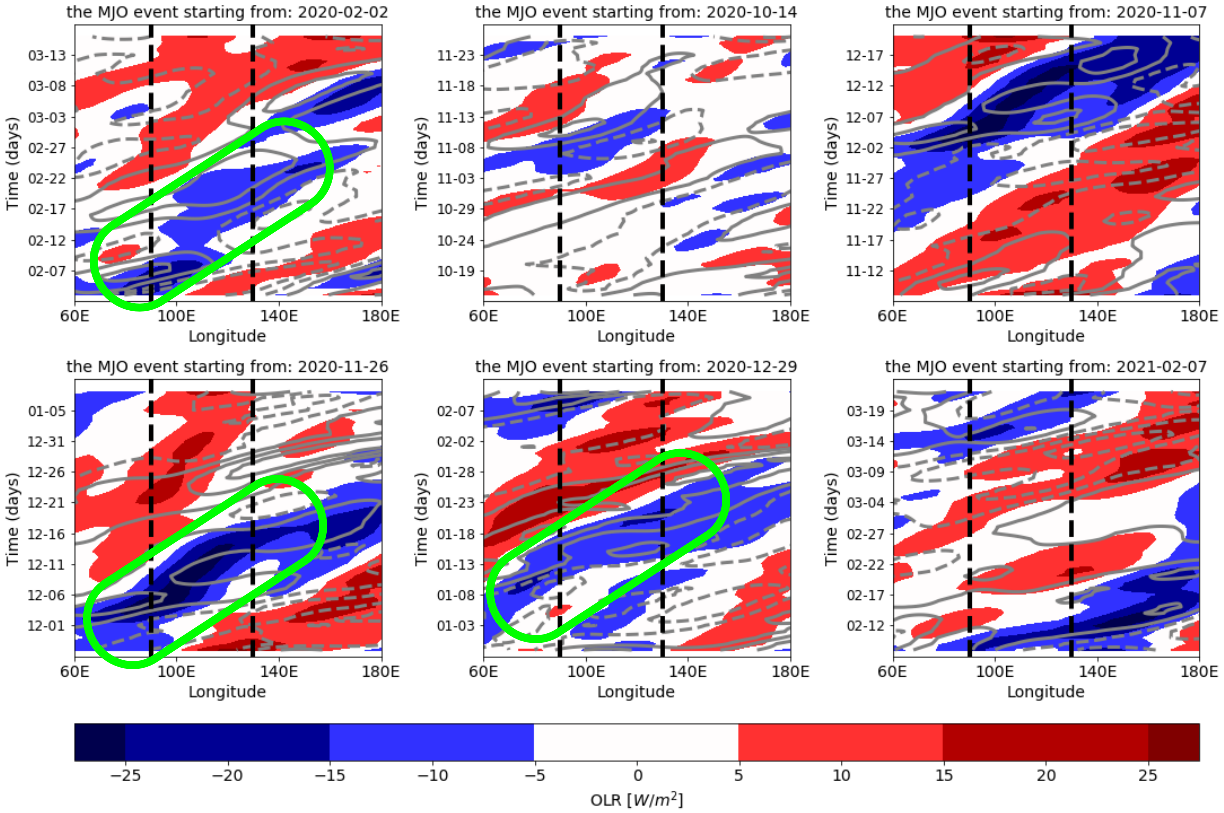
GEOS/MITgcm Coupled Model – Selected Analysis



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.

Summary and concluding remarks

- GEOS/MITgcm “Nature Run” simulation was conducted at ~6km atmosphere, ~2-4 km ocean grid spacing for 14 months (2/2020 to 4/2021).
- Hourly (or sub-hourly) output is available for the fields needed to conduct (coupled) OSSEs.
- Preliminary examination of output included broad-brush examination of visualizations
- Interpolation of monthly means to a lat/lon grid for comparison against observational estimates is under way.
- Studies using the output of mesoscale air-sea interactions, wind work, MJO propagation, etc., are underway.
- Work is underway to set-up a 1/32° atmosphere coupled to a 1/48° ocean simulation.