High-Resolution simulation in support of Sub-Mesoscale Ocean Dynamics Experiment (S-MODE)

Model description:
The California Current simulation is based on a hierarchical numerical set up, starting from a global ocean numerical simulation known as LLC4320, which is a collaborative effort between Massachusetts Institute of Technology (MIT), NASA's Jet Propulsion Laboratory (JPL) and Ames Research Center (ARC). The LLC4320 is a state-of-the-art high-resolution global simulation based on the Massachusetts Institute of Technology general circulation model (Marshall et al., 1997) machinery. The LLC4320 simulation solves the hydrostatic primitive equations for the velocity, potential temperature, and salinity with a seawater equation of state. The nominal resolution is $1/48_o$ (~ 2 km at midlatitudes) and 90 vertical levels with 1-m vertical grid spacing at the surface, gradually increasing to ~ 300 m near the 5000-m depth. LLC4320 is initialized from a data-constrained global ocean and sea ice solution provided by the Circulation and Climate of the Ocean, Phase II (ECCO2) project (Losch et al., 2010; Menemenlis et al., 2008). Despite LLC4320 is a free-run simulation compared to ECCO2, the former carries the full luni-solar tidal potential (Flexas et al., 2019), which provide the advantage to simulate sea surface height variance on a global scale (Savage et al., 2017) promoting the development of an internal gravity wave continuum (Arbic et al., 2018).

Although LLC4320's resolution (~ 2 km) is sufficient to resolve mesoscale features and sufficient to marginally resolve submesoscale features, it is insufficient to accurately simulate motions at horizontal scales equal or smaller than 10 km and smaller, where most of the submesoscale instabilities occurs (McWilliams 2016). So, in order to resolve such motions, a down-scaling approach was implemented: a one-way off-line regional nesting from LLC4320 simulation (parent grid) to finer scales was carried out in the northern-central part of the California Current, without feedback from the child grid onto the parent grid LLC4320. The nominal horizontal resolution of the children grid is 500 m. The vertical levels remain the same as LLC4320, 90 levels. The numerical settings of the children simulation are also the same as LLC4320: they include a flux-limited, seventh-order, monotonicity-preserving advection scheme (Daru and Tenaud, 2004) and the modified Leith scheme of Fox-Kemper and Menemenlis (2008) for horizontal viscosity. Vertical viscosity and diffusivity are parameterized according to the K-profile parameterization (Large et al., 1994). Bottom drag is quadratic (drag coefficient, C_d = 0.0021), and side drag is free slip. Parcel cells (Adcroft et al., 1997) are used to represent the slopping sea floor in our z-level vertical discretization. Bathymetry is from ETOPO-5. Since the tidal forcing is crucial for generating realistic internal gravity waves, the tidal forcing at the open boundary conditions were implemented from LLC4320 hourly-outputs. It is noteworthy that no sponge layer was used at the open boundaries to avoid the damping of the tidal energy fluxes into the child domain.

The children simulation is forced with 6-hourly near-surface atmospheric fields (10-m winds, air-temperature, humidity, downwelling long- and short-wave radiation, precipitation and atmospheric forcing) from the 0.14o ECMWF atmospheric reanalysis. The 6-hourly atmospheric fields were linearly interpolated in time. The Large and Pond (1982) bulk formulae for converting atmospheric conditions to ocean surface stress. The wind stress $\boldsymbol{\tau}$ accounts for the velocity of wind and ocean currents, as follows: $\boldsymbol{\tau} = \rho_{air} C_d |\boldsymbol{W} - \boldsymbol{U}|(\boldsymbol{W} - \boldsymbol{U})$, where ρ_{air} is the density of the air at sea level, C_d is the drag coefficient (Large and Pond, 2004), $\boldsymbol{W}$ is the wind field at 10 m, and $\boldsymbol{U}$ is the ocean surface velocities.

References:

Adcroft, A., Hill, C., & Marshall, J. A. (1997). Representation of topography by shaved cells in a height coordinate ocean model. *Monthly Weather Review*, *125*, 2293–2315.

Arbic, B. K., Alford, M. H., Ansong, J. K., Buijsman, M. C., Ciotti, R. B., Farrar, J. T., et al. (2018). A primer on global internal tide and internal gravity wave continuum modeling in HYCOM and MITgcm. In J. T. E. Chassignet, A. Pascual, & E. J. Verron (Eds.), *New frontiers in operational oceanography* pp. 307–392: GODAE OceanView. https://doi.org/10.17125/gov2018.ch13

Daru, V., and C. Tanaud (2004), High order one-step monotonicity-preserving schemes for unsteady compressible flow calculations. Journal of Computational Physics, 193, 563-594.

Large, W. G., McWilliams, J. C., & Doney, S. C. (1994). Oceanic vertical mixing: A review and a model with a nonlocal boundary layer parameterization. *Reviews of Geophysics*, *32*, 363–403

Large, W. G., & Pond, S. (1982). Sensible and latent heat flux measurements over the ocean. *Journal of Physical Oceanography*, *12*, 464–482.

Losch, M., D. Menemenlis, P. Heimbach, J–M. Campin, and C. Hill (2010), On the formulation of sea-ice models. Part 1: Effects of different solver implementations and parameterizations, *Ocean Modell*. 33, 129-144, doi:10.1016/j.ocemod.2009.12.008.

Fox-Kemper, B., & Menemenlis, D. (2008). Can large eddy simulation techniques improve mesoscale rich ocean models? In B. Fox-Kemper, & D. Menemenlis (Eds.), *Ocean modeling in an eddying regime* pp. 319–338). Washington, D. C.: Amer. Geophys. Union.

Marshall, J. A., A. Adcroft, C. Hill, L. Perelman, and C. Heissey (1997), A finite volume, incompressible Navier-Stokes model for studies of the ocean on parallel computers, *J. Geophys. Res.*, 102, 5753-5766.

Menemenlis, D., J.-M. Campin, P. Heimbach, C. Hill, T. Lee. A. Nguyen, M. Schodlok, and H. Zhang (2008), ECCO2: High resolution global ocean and sea ice data synthesis. *Mercator Ocean Quaterly Newsletter*, 31, 13-21.

McWilliams, J. C. (2016), Submesoscale currents in the ocean, *Philos. Trans. R. Soc. London, Ser. A*, 472, Doi: 10.1098/rspa.2016.0117.