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Supporting Information for

High-frequency Submesoscale Motions Enhance the Upward Vertical Heat Transport in the Global Ocean

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Introduction

This document contains supporting information for describing the model and its setup, as well as describing the method of calculating the heat flux.

Text S1: Model description.

We analyze a set of global, full-depth ocean and sea ice numerical simulations carried out using the Massachusetts Institute of Technology general circulation model (MITgcm) on a Latitude-Longitude polar Cap (LLC) grid with primitive equations (Menemenlis et al. 2008). The computation is enabled by NASA Advanced Supercomputing. The model output is from the so-called LLC4320 simulation, which has a nominal horizontal grid spacing of 1/48° (0.75 km near Antarctica, 2.3 km at the Equator, and 1 km in the Arctic Ocean). Horizontal wavenumber spectra suggest that the effective resolution of LLC4320 is about 10 km. The 1/48° simulation spans 14 months from September 10, 2011 to November 15, 2012. The spin-up of this simulation is described in detail in Appendix D and Table D2 of Rocha et al. (2016). The spin up progresses from a 1/6° global ocean state estimate, generated by the Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2) project, to 1/12° and then 1/24° simulations. The 1/12°, 1/24° , and 1/48° simulations are forced with 6-hourly surface atmospheric fields (10-m wind velocity, 2-m air temperature and humidity, downwelling long and shortwave radiation, and atmospheric pressure load) from the 0.14° European Centre for Medium-Range Weather Forecasting (ECMWF) atmospheric operational model analysis, starting in 2011. These three simulations also include tidal forcing for the 16 most significant components, applied as additional atmospheric pressure forcing. Vertical mixing, including the effect of convection, is parameterized based on the critical value of Richardson number and is implemented using the K-Profile Parameterization (KPP) scheme (Large et al. 1994) that has been extensively used and evaluated in ocean modeling studies (Large et al. 1997).

This simulation's air–sea fluxes have similar magnitudes as climatological fluxes. This is because our model's global SST distributions are in a realistic range and the air–sea fluxes in our model depend on SST and the prescribed reanalysis of atmospheric state, such as near-surface air temperature, humidity, and wind speed according to the bulk formulae of Large et al. (2004).

The limitations of this simulation, as discussed in the main text, include the fact that this simulation does not have a full coupling between the atmosphere and ocean and it does not resolve motions at even smaller scales that may also significantly contribute to vertical flux. The current integration of this simulation is able to reach the equilibrium state for dynamics at scales $\lesssim 0.5^{\circ}$ because of their short timescales and they are triggered by an observationally-consistent stratification and mesoscale eddy field in the current simulation. But we acknowledge a longer integration is necessary to reach a new equilibrium state for the global ocean, but this is beyond the capacity of the most powerful computers at the current time.

Text S2: Definition and calculation of heat flux.

We calculate advective heat flux resolved in this simulation at a 0.1°-0.5° scale range in terms of longitude (~50km at mid-latitudes). This range is typically not resolved in current climate models. The physically-resolved length scale is usually estimated at 5 times the numerical resolution ($1/48^{\circ}$ in this simulation). Therefore, the flux discussed in this study is the resolved flux at the range 0.1° -0.5° (~10-50 km at mid-latitudes). Thus, the vertical velocity W at such scale range, denoted as W' , are the W anomalies from its $0.5^{\circ} \times 0.5^{\circ}$ spatial mean (averaged over a $0.5^{\circ} \times 0.5^{\circ}$ square box), representing W in the $1/48^{\circ}$ - 0.5°

scale range. Similarly, we can define temperature T' at such scale range. The vertical heat flux in this study is defined as $C_p\, \varrho \langle W'\, T' \rangle$ where C_p is the specific heat capacity, ϱ is the density, and $\langle * \rangle$ represents a time average. The spatial and temporal filters used in this study above have been similarly and widely used in other studies (Capet al. 2008a, 2008b; Su et al. 2018; Uchida et al. 2017). The mesoscale component of a quantity is defined as the temporal anomalies of a given quantity from the annual average and has a spatial scale larger than 0.5° (averaging over a $0.5^\circ \times 0.5^\circ$ square box) (Capet et al. 2008a).

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