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Supplement of

ISOM 1.0: a fully mesoscale-resolving idealized Southern Ocean model and the diversity of multiscale eddy interactions

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This document provides supplementary materials for two versions of the idealized southern ocean model. The current version refers to the model presented in the main text of the GMD manuscript submitted in August 2024. The early version refers to the model we initially submitted to GMD in April 2024. The current version has undergone significant optimizations based on feedback from reviewers and our accumulated simulation experience. These optimizations include the following:

(1) Expanding the computational domain from 14400 km x 2400 km to 18000 km x 3000 km.

(2) Increasing the bottom depth from 3000 m to 4000 m.

(3) Optimizing the design of iconic topography, including setting the shallowest depth in the Drake Passage to 2,500 m and optimizing its internal slopes, introducing asymmetry on the African continent, adding a mid-ocean ridge on the eastern side of the African continent, optimizing the settings of ridges, and Optimizing the relative position of the topographic features.

(4) Adding the KPP scheme to enhance the realism of simulated mixed layer.

Figs. S1 and S2 for the current ISOM. Figs. S3-S8 for the early design. Fig. S9 show the potential enstrophy conversion between the large-scale and eddy components of the flow in the current version of ISOM. Tables S1 and S2 for the configuration of the early design.

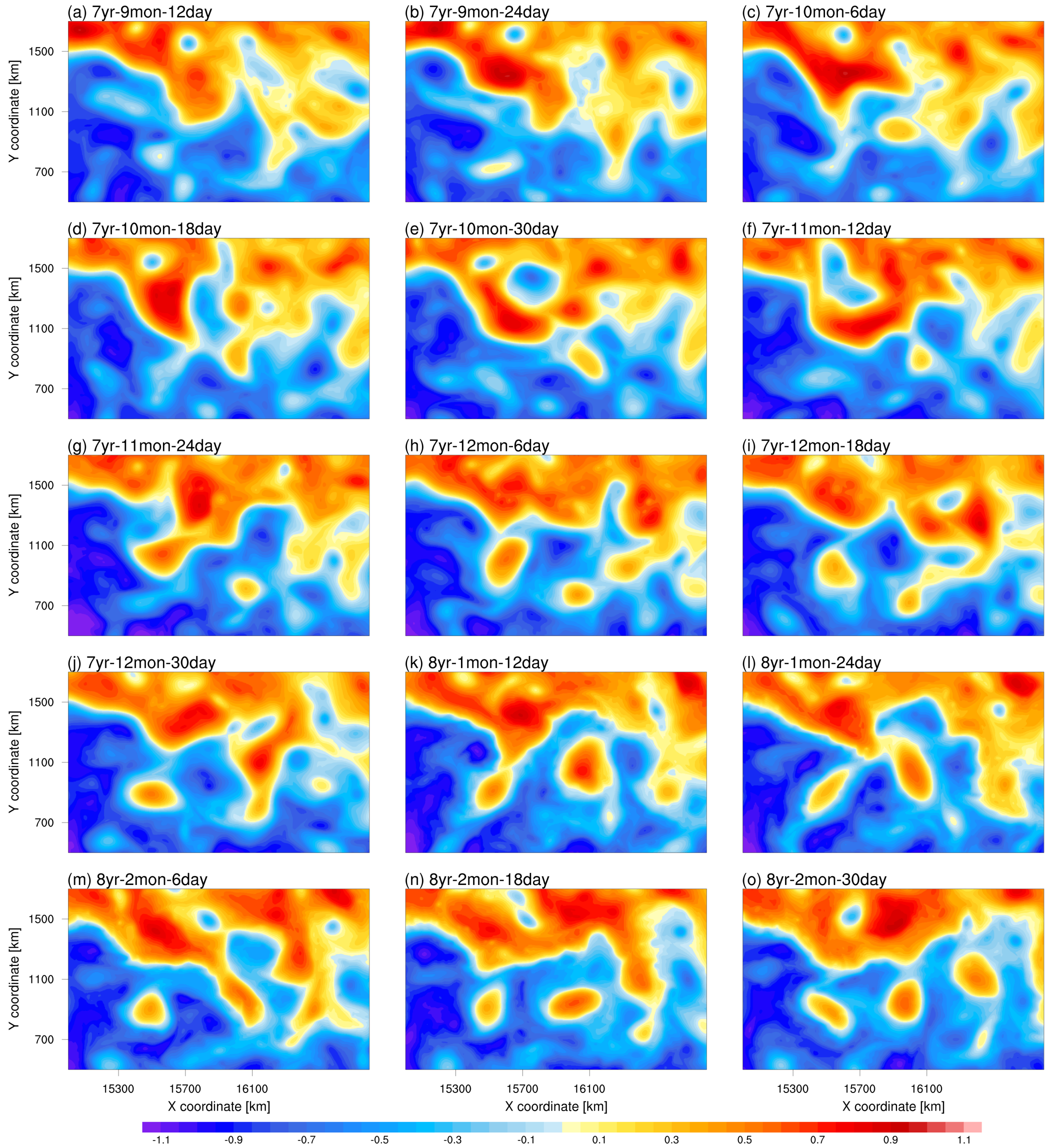

Figure S1. The evolution of sea surface height for six model months of the 2-km simulation. The stationary eddy can exist for more than three months. The jet may borrow the eddy circulation during the eddy's lifespan.

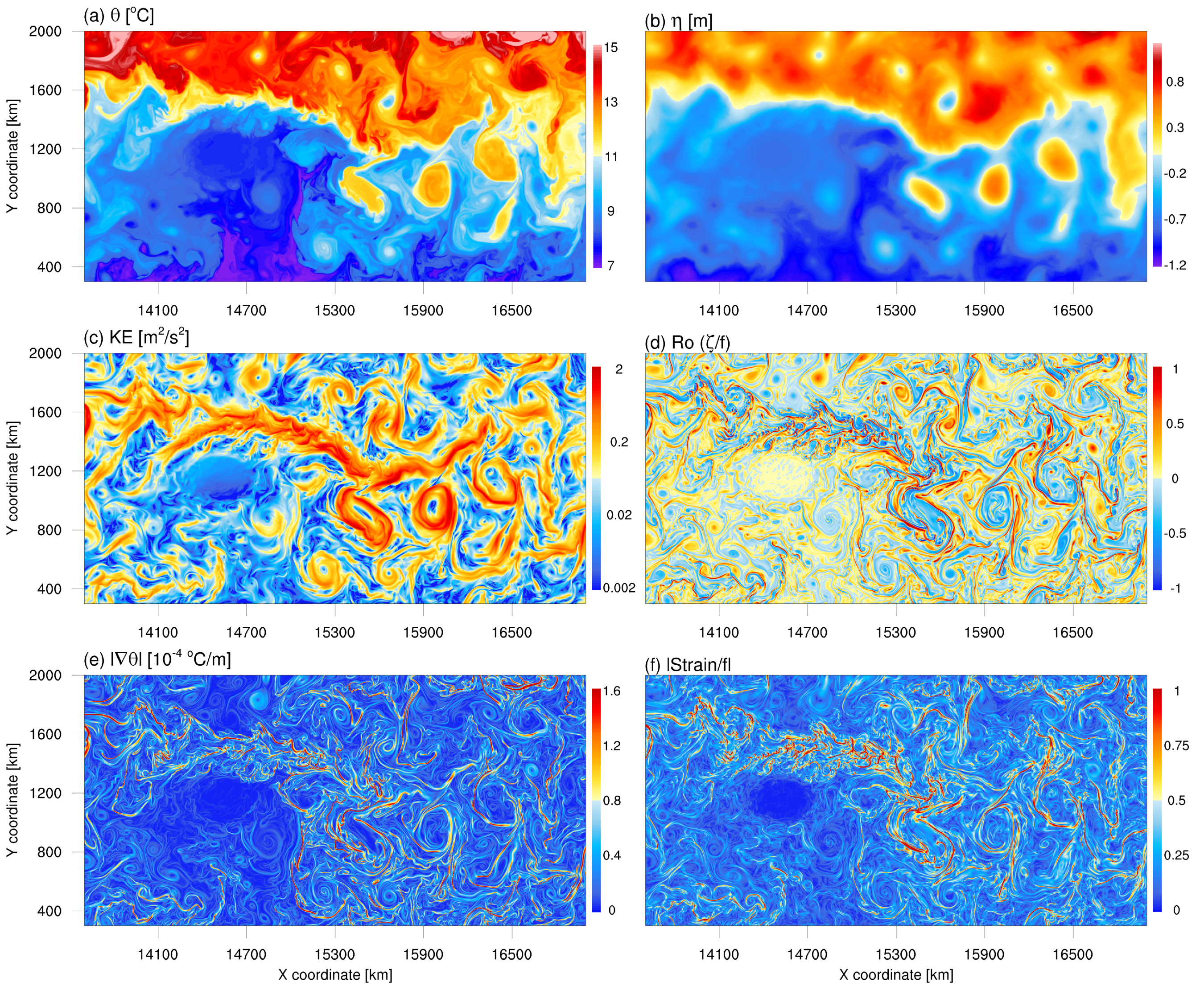

Figure S2. Same as Fig. 7 in the main text but for Surface snapshot of day 60 in the 8th model year of the 2-km simulation in the Gaussian plateau region. (a) Potential temperature, (b) sea surface height, (c) kinetic energy, (d) Rossby number (normalized relative vorticity), (e) the magnitude of the horizontal temperature gradient, and (f) normalized strain rate.

Table S1. Basic parameters of the early ISOM design.

Symbol	Value	Description
L_x, L_y	14400 km,2400 km	Domain size
H	3000 m	Domain depth
Δz	5 - 200 m	Vertical grid spacing
L_{sponge}	240 km	Sponge layer size
τ_{sponge}	7 days	Shortest Sponge layer relaxation timescale
λ	30 days	Surface temperature relaxation time scale (outside the sponge layer)
f_0	$-1 \times 10^{-4}\text{s}^{-1}$	Reference Coriolis parameter
β	$1 \times 10^{-11}\text{m}^{-1}\text{s}^{-1}$	Meridional gradient of Coriolis parameter
g	9.81 m s^{-2}	Gravitational acceleration
τ_0	0.2 N m^{-2}	Wind stress magnitude
C_d	1×10^{-2}	Quadratic bottom drag parameter
ρ_c	1035 kg m^{-3}	Reference density
α	$2 \times 10^{-4}\text{K}^{-1}$	Linear thermal expansion coefficient
κ_v	5×10^{-6} m s^{-2}	Vertical diffusivity
κ_h	0	Horizontal diffusivity
A_v	3×10^{-4} m s^{-2}	Vertical viscosity

Table S2. Parameters of the early ISOM simulations with different horizontal resolution at their statistical steady state. DST-33 is 3rd order DST (direct space-time) flux limiter. 7-order is 7th order monotonicity-preserving scheme.

Symbol	Value 1	Value 2	Value 3	Description
$\Delta x, \Delta y$	2 km	4 km	8 km	Horizontal grid spacing
A_h	2	4	50	Horizontal viscosity(m s^{-2})
A_4	1×10^8	5×10^9	1×10^{10}	Horizontal hyperviscosity(m^4 s^{-1})
	DST-33	DST-33	7-order	Advection scheme
	33	33	7	MITgcm scheme code

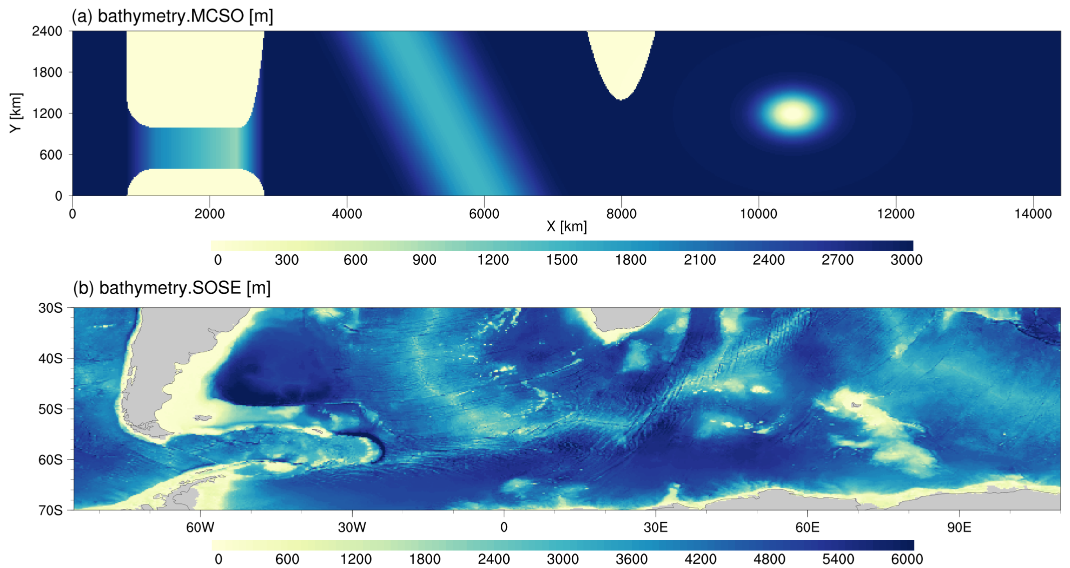

Figure S3. The bathymetry of (a) the early version ISOM and (b) Southern Ocean State Estimate (SOSE).

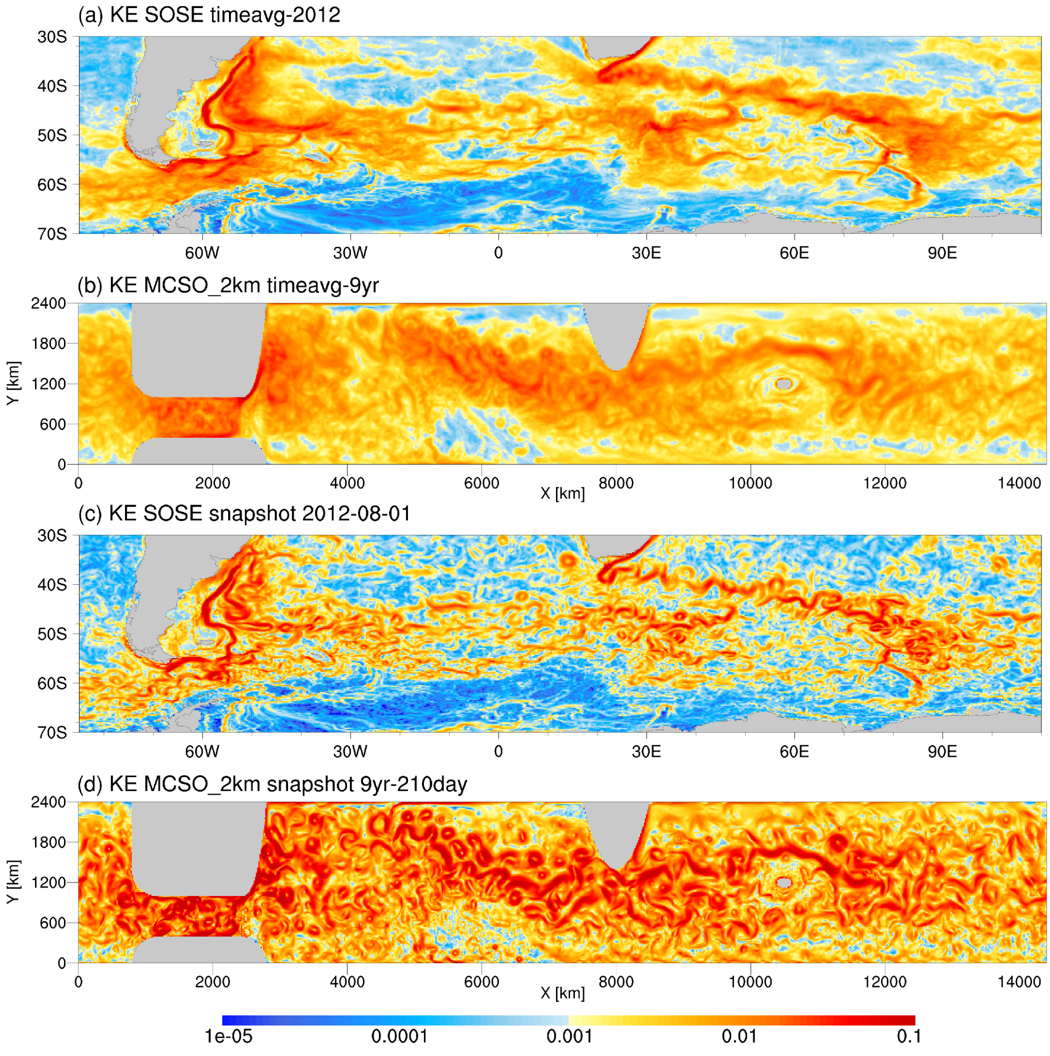

Figure S4. (a) The kinetic energy of time-averaged velocity in 2012 of SOSE, (b) the kinetic energy of time-averaged velocity in the 9th model year of the 2-km simulation using the early version of ISOM, and the snapshot of kinetic energy of (c) SOSE and (d) the 2-km simulation.

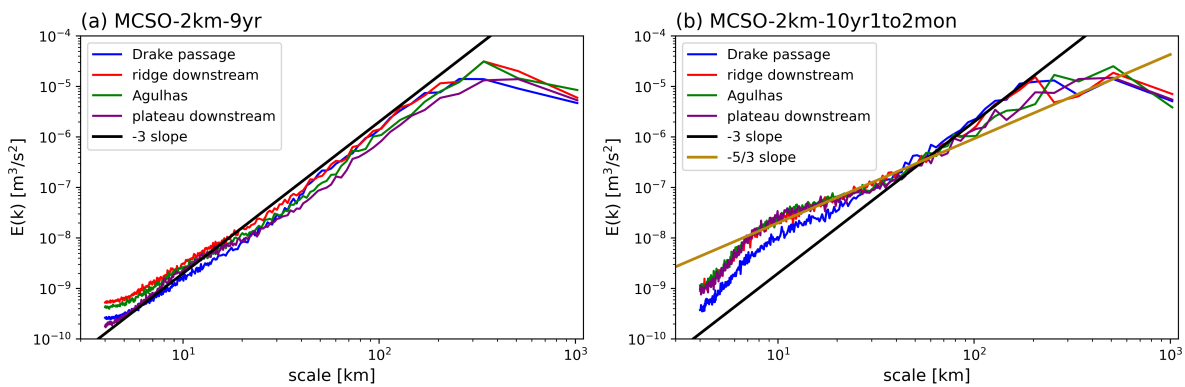

Figure S5. The averaged spectral density function of surface EKE of the 2-km simulation using the early version of ISOM. The early design only use the background vertical viscosity and diffusivity and did not use the KPP scheme. The flow in near-surface levels are overly intensified. Though the numerical stability issues did not appear, the intensification might lead to unrealistic submesoscale activities. (a) is from the 3-day-averaged output in the 9th model year, and (b) is from the snapshots in the first two months of the 10th model year. Lines with different colors represent different sampling positions. The eddy velocity is defined as subtracting the time and zonal average of a 1024km zonal segment of meridional velocity in each position.

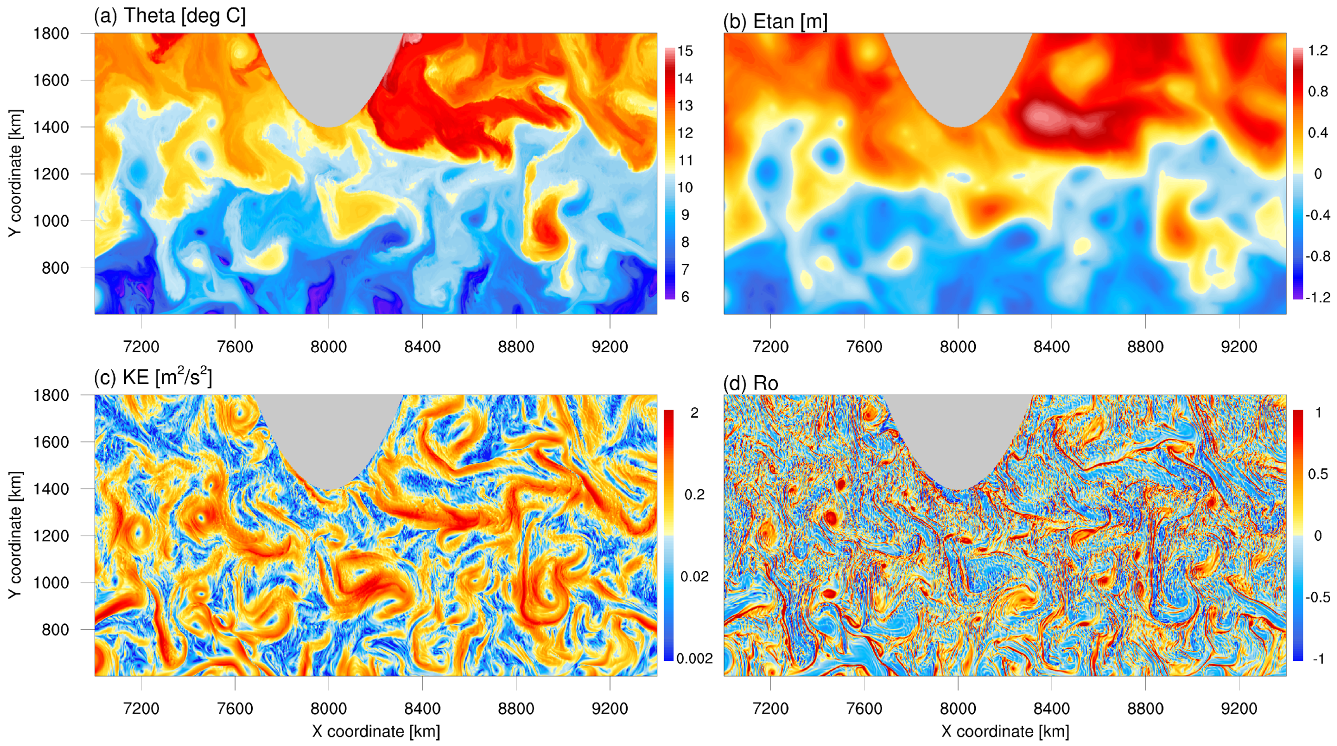

Figure S6. Surface snapshot of the 27th model day in the 10th model year of the 2-km simulation in Agulhas area using the early version of ISOM. (a) Potential temperature, (b) the linearized free surface height or sea surface height anomaly, (c) kinetic energy, and (d) Rossby number (defined as relative vorticity divided by local Coriolis parameter).

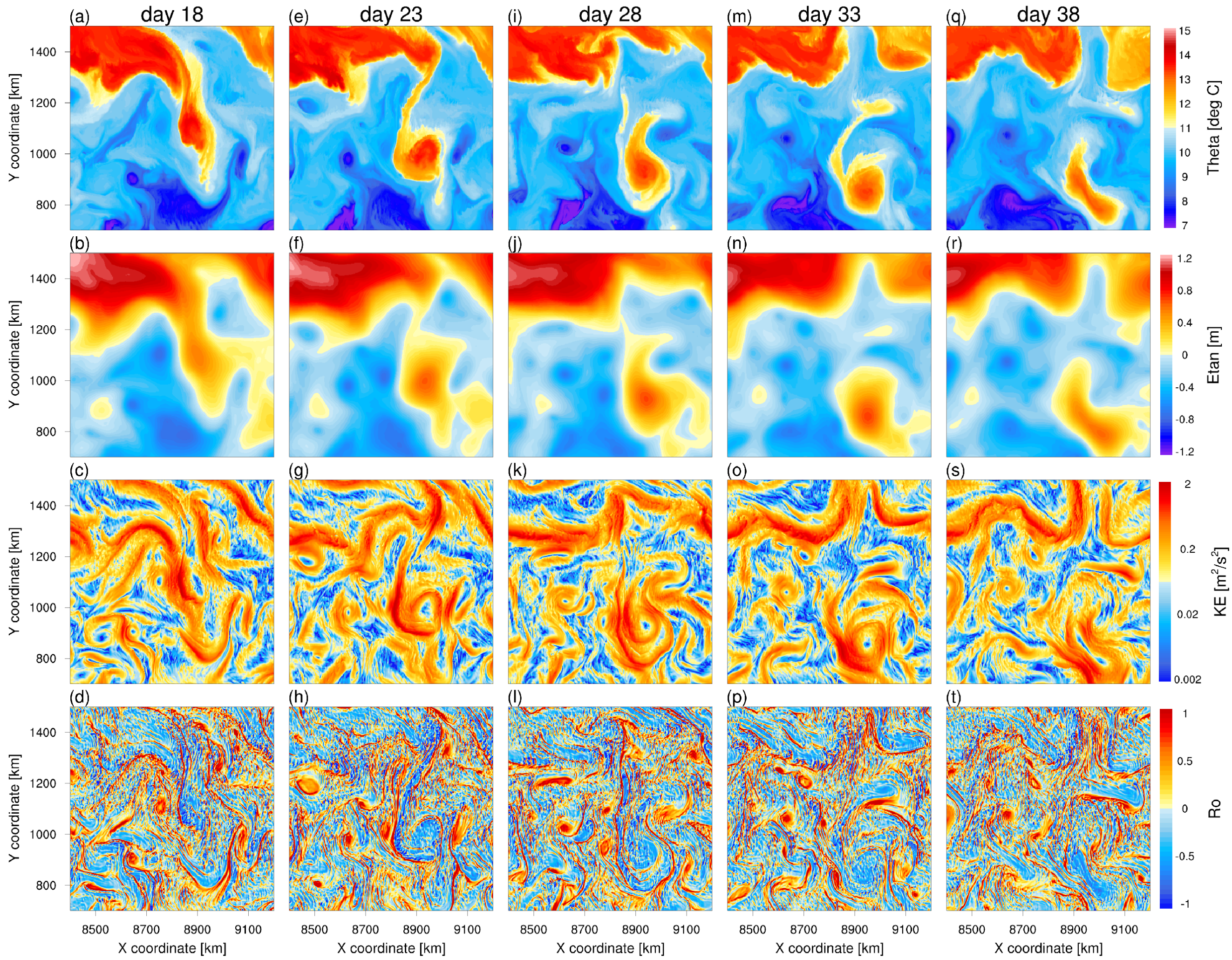

Figure S7. An example for warm eddy and meandering jet evolution using the early version of ISOM. From top to bottom are the potential temperature, the linearized free surface height, kinetic energy, and Rossby number.

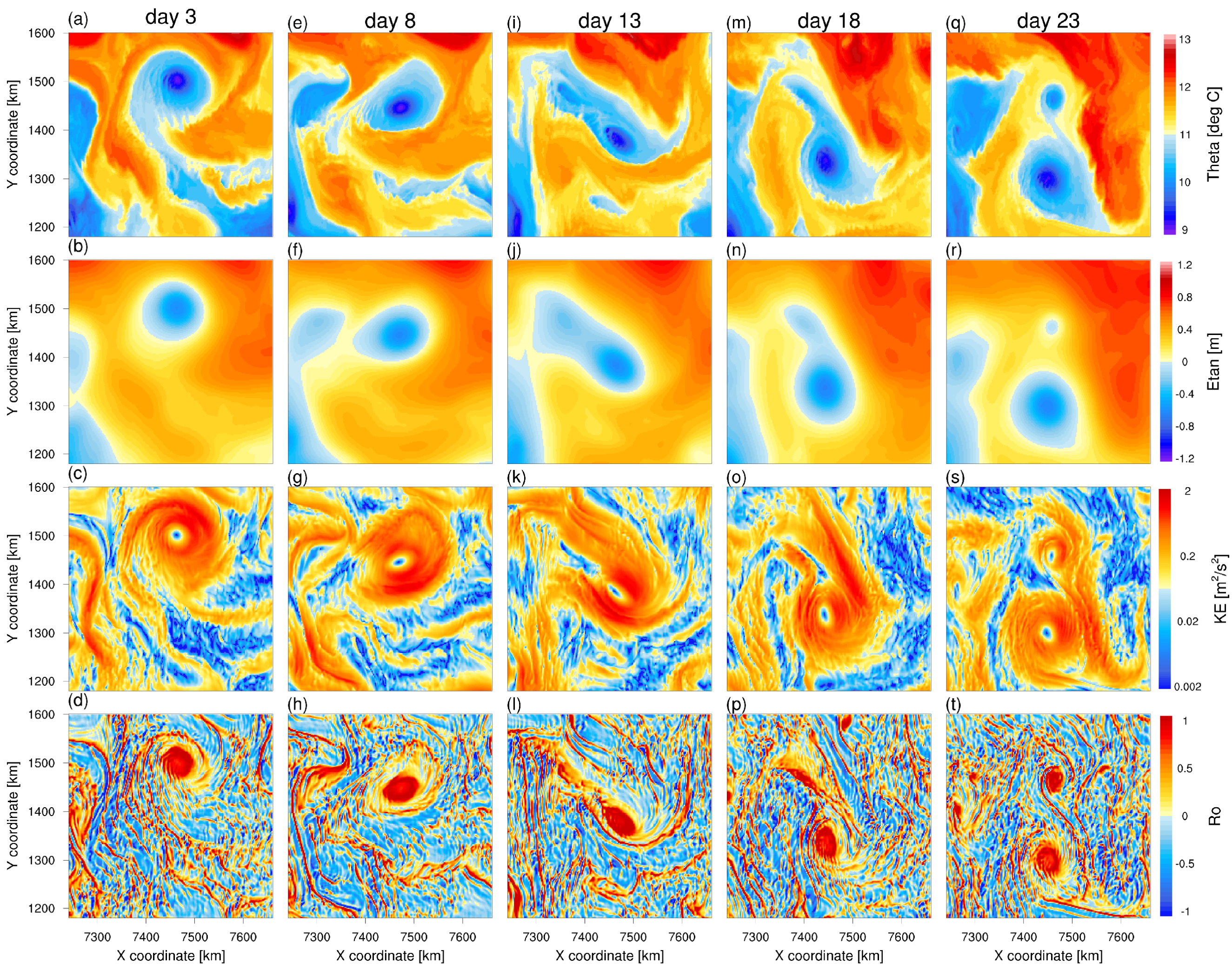

Figure S8. Same as Fig. S7 but an example for cold eddy evolution.

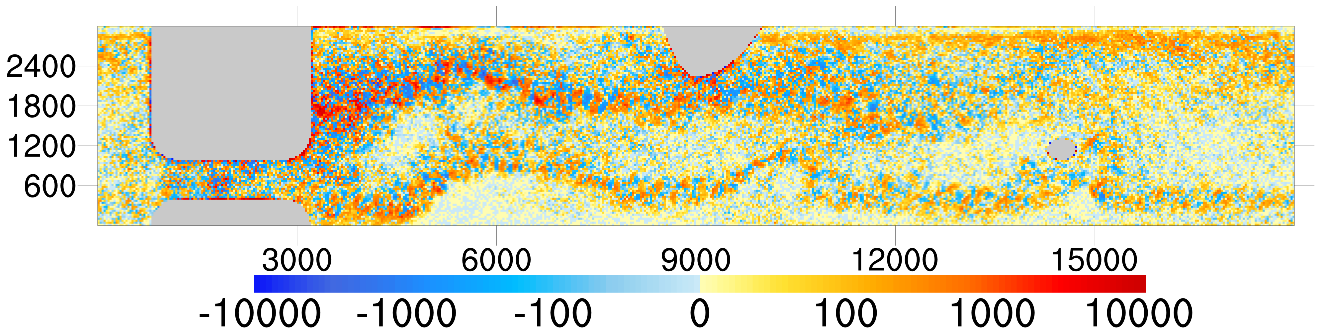

Figure S9. The potential enstrophy conversion between the large-scale and eddy components of the flow, $-\overline{\mathbf{u}'q'} \cdot \nabla \bar{q}$ (unit: $10^{-30} m^2 s^{-3}$). $\mathbf{u}$ is the velocity. The potential vorticity $q = \frac{f+\zeta}{\rho} \frac{\partial \rho}{\partial z}$ as Holland et al. (1984). Bar and prime represent the Reynolds' time average and fluctuation, respectively. When the term is positive, there is a conversion of potential enstrophy from the large-scale to the eddying field on average (relevant discussion in Wilson and Williams (2004) or Eaves et al. (2024)). Though the term has spatial variation, the intense forward potential enstrophy transfer towards small scales can happen in regions with active eddy activities. The domain average of the term is also positive, which indicates holistically a forward potential enstrophy cascade in the model. [1] Holland, W., Keffer, T., and Rhines, P. (1984). Dynamics of the oceanic general circulation: the potential vorticity field. Nature, 308(5961), 698-705. [2] Wilson and Williams (2004). Why are eddy fluxes of potential vorticity difficult to parameterize? Journal of physical oceanography, 34(1), 142-155. [3] Eaves et al. (2024). An energy and enstrophy constrained parameterization of barotropic eddy potential vorticity fluxes. Authorea Preprints.