# Global Warming Effect on Ocean Horizontal Stirring Characterized by Finite-Size Lyapunov Exponents

IBS Center for Climate Physics

**Gyuseok Lee** (gyuseok@pusan.ac.kr)[1,2], June-Yi Lee[1,2], Axel Timmermann[2,3], Karl Joseph Stein[2,3], Eun Young Kwon[2,3], Sun-Seon Lee[2,3], and Myeong-Hyeon Kim[1,2]

[1] Pusan National University, Department of Climate System, Busan, South Korea, [2] Center for Climate Physics, Institute for Basic Science, Busan, South Korea,
[3] Pusan National University, Busan, South Korea

## Ocean Horizontal Stirring

Stirring is a turbulent phenomenon that promotes mixing speed by deforming the fluid into an elongated shape. In the global surface ocean, where horizontal flow dominates over vertical flow, horizontal stirring is almost everywhere accompanied by other dynamical oceanic processes such as eddies, meandering, currents, and fronts. And it ultimately plays an important role in various phenomena like ocean heat transport, air-sea gas exchange, and marine pollution and ecosystems.

## Research Questions

- How will ocean horizontal stirring change in response to global warming?
- Where will robust changes in the horizontal stirring occur?
- What are dominant drivers for the changes?

## Methods

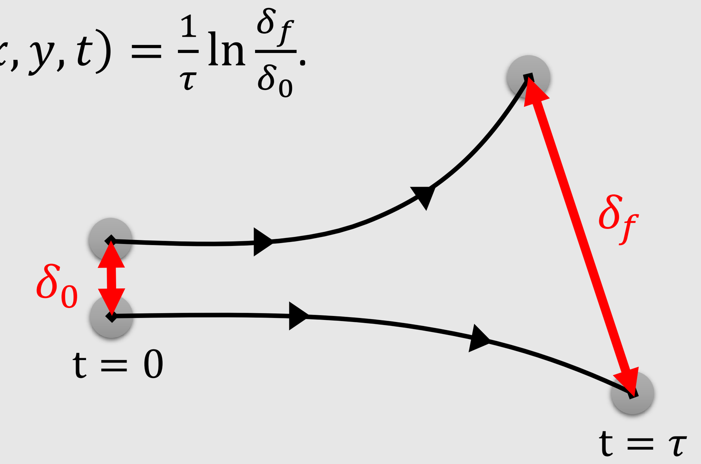
### Finite-Size Lyapunov Exponents

To characterize ocean horizontal stirring, we utilized the finite-size Lyapunov exponent (FSLE).

It is a Lagrangian metric that characterizes the dispersion rate of two infinitesimally separated particles as an exponential function in a chaotic system.

When a pair of particles are moving along each trajectory in a turbulent fluid, the increasing distance $\delta$ between the two particles can be expressed by $\delta(t) = \delta_0\, e^{\lambda t}$ at a time $t$. The $\lambda$ (FSLE) can be obtained by specifying an initial distance $\delta_0 = 0.1°$ (≈ 10 km) and a final distance $\delta_f = 1.0°$ (≈ 110 km) and integrating $u, v$ over the flow:

$$\lambda(x, y, t) = \frac{1}{\tau} \ln \frac{\delta_f}{\delta_0}.$$




(Here, $\tau$ means the time it takes for $\delta(t)$ to increase from $\delta_0$ to $\delta_f$.)

In this study, the FSLE was calculated by integrating the flow in the inverse time direction (backward-in-time FSLE).

## Data

### Global Warming Experiments

To explore the response of horizontal stirring to greenhouse warming, we used the results of the model experiments below.

- Model: the fully-coupled Community Earth System Model (CESM) version 1.2.2
- Horizontal resolution: 25 km (atmosphere) and 10 km (ocean)
- The experiments include a present-day control experiment (367 ppm) and two ideal experiments with 2×$CO_2$ (734 ppm) and 4×$CO_2$ (1,468 ppm) conditions.
- To quantify the horizontal stirring at the surface ocean, we use daily $u, v$ fields at the second layer of the ocean model component of the CESM, Parallel Ocean Program version 2 (POP2), corresponding to a 15 m depth.

## Results

### 1. Horizontal Stirring in Present-Day Simulation

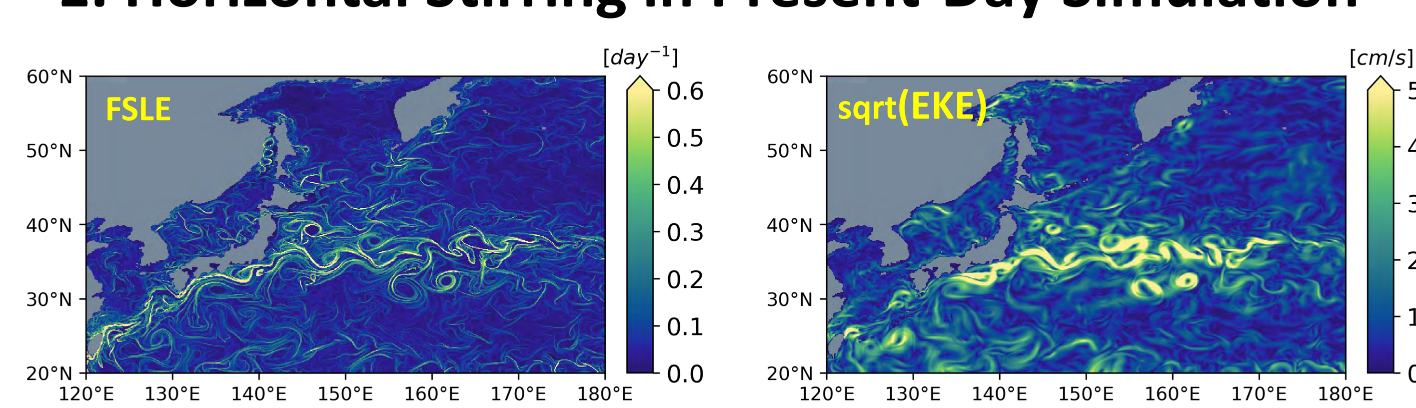



**Fig. 1 |** 1-day snapshot of FSLE and EKE for the same model date (Jan 1st, 130) in the present-day simulation. EKE $\left(= \frac{1}{2}\sqrt{u'^2 + v'^2}\right)$ was calculated using perturbations $u' = u - \bar{u}, v' = v - \bar{v}$ that removed the mean flow using a 10-year high pass filter.

- The daily backward-in-time FSLEs, calculated from the daily $u, v$ at a depth of 15 m, were used to characterize the horizontal stirring of the surface ocean (Fig. 1).
- The FSLEs shown in the 1-day snapshot have complicated filament-like structures and tend to be high values at the edges of fast-moving currents and vortices, which are related to large horizontal velocity shears or strong stretching.

**Reference**

- d'Ovidio, F., Fernández, V., Hernández-García, E. & López, C. Mixing structures in the Mediterranean Sea from finite-size Lyapunov exponents. *Geophys. Res. Lett.* **31**, 17203 (2004).
- Hernández-Carrasco, I., López, C., Hernández-García, E. & Turiel, A. Seasonal and regional characterization of horizontal stirring in the global ocean. *J. Geophys. Res. Oceans* **117**, (2012).
- Small, R. J. *et al.* A new synoptic scale resolving global climate simulation using the Community Earth System Model. *J. Adv. Model. Earth Syst.* **6**, 1065–1094 (2014).
- Chu, J.-E. *et al.* Reduced tropical cyclone densities and ocean effects due to anthropogenic greenhouse warming. *Sci. Adv.* **6**, (2020).

### 2. Future Changes in Horizontal Stirring

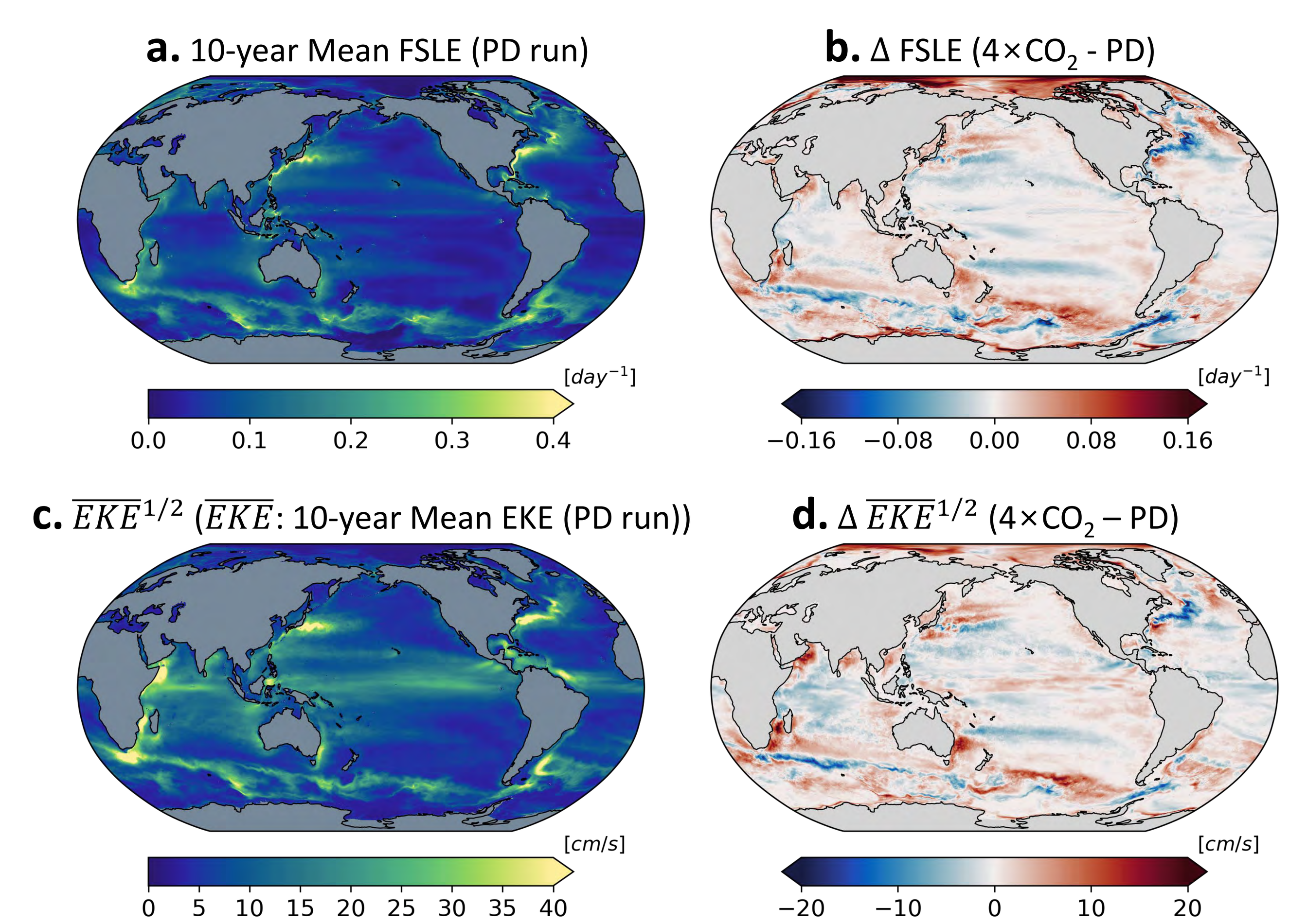



**Fig. 2 |** Future changes in FSLE and EKE.

- Fig. 2 represents the 10-year mean of FSLE (Fig. 2a) and EKE (Fig. 2c) in the present-day condition.
- By averaging the daily FSLEs over time, we can identify regions of strong and weak horizontal stirring in a climatological sense.
- The future changes of horizontal stirring were presented as the difference between the 10-year mean of FSLE under the 4×$CO_2$ condition and the present-day simulation (Fig. 2b).
- The most pronounced changes in FSLE are found in the Arctic and Southern Ocean (Fig. 3b). FSLE values increase in the higher $CO_2$ conditions over the entire Arctic Ocean and along the Antarctic continent periphery where the Antarctic Coastal Current (ACoC) is flowing westward.
- There are also changes in the Western Boundary Currents region, with the Kuroshio current region and the Gulf Stream region showing distinctly different patterns of change.

## Possible Mechanisms Driving FSLE Changes

### Arctic Ocean Case

Here we present possible mechanisms for FSLE changes in the Arctic Ocean, where the change is most pronounced due to sea ice decline (Fig. 3).

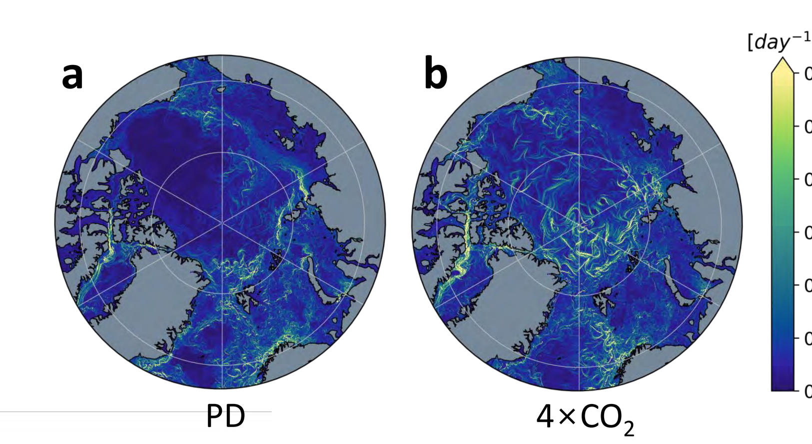



**Fig. 3 |** 1-day snapshots of FSLE over the Arctic Ocean in the (a) present-day (model date: Jan 1st, 130) and (b) 4×$CO_2$ (model date: Jan 1st, 160) simulations.

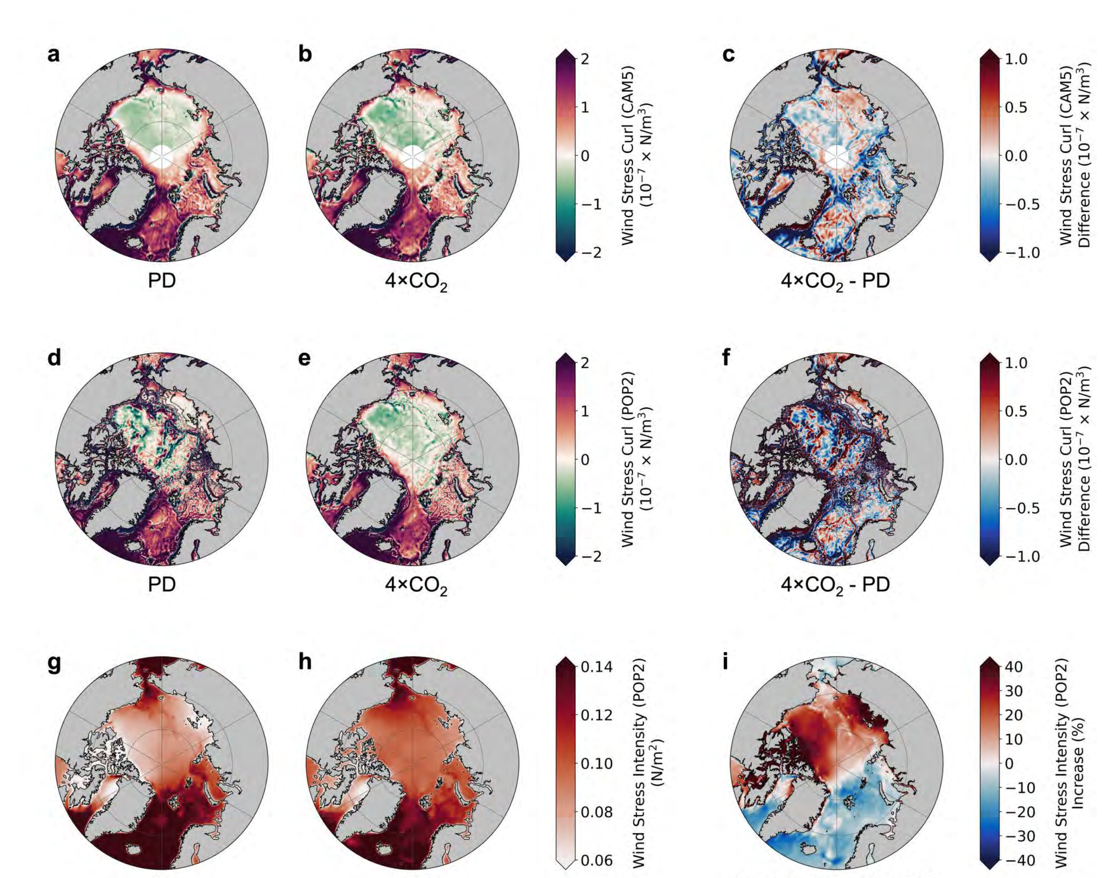



**Fig. 4 |** Future changes in wind stress curl and wind stress intensity. 10-year mean of wind stress from (a, b) the atmosphere model (CAM5) and (d, e) the ocean model (POP2) in the present-day (left) and 4×$CO_2$ (right) conditions. The difference between (a) and (b) and between (d) and (e) is shown in (c) and (f), respectively. The change in wind stress intensity is shown in (g, h) and the percentage increase is shown in (i).

- In the Arctic Ocean, an increase of FSLE is strongly associated with a strengthening of Beaufort Gyre and Transpolar Drift. Beaufort Gyre strengthens due to the elevated sea surface height at the center of gyre where anomalous negative wind stress curl results in filing up of low-density seawater.
- In the present-day simulation, the presence of sea ice impedes the direct transfer of momentum from surface wind stress suppressing wind-driven surface currents and it can be seen from the difference between the wind stress curl of the atmospheric model (CAM5) and the ocean model (POP2) in Fig. 4a and 4d.
- The surface wind stress changes can directly drive the upper ocean circulation changes (Fig. 4b and 4e).
- In addition to the increase in wind stress intensity itself (Fig. 4i), increasing geopotential height due to surface water freshening caused by sea-ice loss can also contribute to speeding up surface currents over the Arctic Ocean.