Why Does Global Warming Weaken the Gulf Stream but Intensify the Kuroshio?

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ABSTRACT

The Kuroshio and Gulf Stream, the subtropical western boundary currents of the North Pacific and North Atlantic, play important roles in meridional heat transport and ocean–atmosphere interaction processes. Using a multimodel ensemble of future projections, we show that a warmer climate intensifies the upper-layer Kuroshio, in contrast to the previously documented slowdown of the Gulf Stream. Our ocean general circulation model experiments show that the sea surface warming, not the wind change, is the dominant forcing that causes the upper-layer Kuroshio to intensify in a warming climate. Forced by the sea surface warming, ocean subduction and advection processes result in a stronger warming to the east of the Kuroshio than to the west, which increases the isopycnal slope across the Kuroshio, and hence intensifies the Kuroshio. In the North Atlantic, the Gulf Stream slows down as part of the Atlantic meridional overturning circulation (AMOC) response to surface salinity decrease in the high latitudes under global warming. The distinct responses of the Gulf Stream and Kuroshio to climate warming are accompanied by different regional patterns of sea level rise. While the sea level rise accelerates along the northeastern U.S. coast as the AMOC weakens, it remains close to the global mean rate along the East Asian coast as the intensifying Kuroshio is associated with the enhanced sea level rise offshore in the North Pacific subtropical gyre.

1. Introduction

The Gulf Stream in the North Atlantic (Fig. 1a) and the Kuroshio in the North Pacific (Fig. 1b) are strong wind-driven subtropical western boundary currents in the Northern Hemisphere (Stommel 1948). They transport substantial amounts of water, heat, and salt from low to midlatitudes (Nitani 1972; Qiu and Lukas 1996; Imawaki et al. 2013), with broad impacts on the weather, climate, and ecosystems (Guo et al. 2012; Hu et al. 2015; Palter 2015). For example, the Kuroshio plays important roles in modulating atmospheric precipitation, winds, storm tracks, and tropical cyclone intensities (Xie et al. 2002; Wu et al. 2008; Xu et al. 2011; Nakamura et al. 2012; Sasaki et al. 2012; Liu et al. 2013). Because of their importance in the climate system, it is crucial to know how and why the Kuroshio and Gulf Stream will change in the face of future anthropogenic warming. Climate models project a weakening of the Gulf Stream in the twenty-first century in response to global warming (Yang et al. 2016). This weakening can be clearly seen in the robust pattern of sea level change in the North Atlantic with a larger sea level rise north than south of the Gulf Stream (Levermann et al. 2005; Yin...
et al. 2009; Bouttes and Gregory 2014; Chen et al. 2019). In contrast, the upper-layer Kuroshio is projected to intensify as a result of the spinup of the recirculation under global warming (Sakamoto et al. 2005; Cheon et al. 2012).

The change in the strength of the Gulf Stream is related to the changes in the Atlantic meridional overturning circulation (AMOC). Although there is an ongoing debate on whether the AMOC has declined in historical observations (Rahmstorf et al. 2015; Caesar et al. 2018; Smeed et al. 2018), the projected weakening of the AMOC expected under warmer climatic conditions is consistent across climate models (Srokosz et al. 2012; Collins et al. 2013; Liu et al. 2017). As part of the upper branch of the AMOC, the Gulf Stream will likely weaken as the AMOC slows in the twenty-first century (Yang et al. 2016).

With respect to the projected intensification of the upper-layer Kuroshio, many studies have considered the effect of wind changes. For example, a high-resolution climate modeling study showed that the projected intensification of the near-surface Kuroshio is due to wind stress changes over the North Pacific that spin up the Kuroshio recirculation gyre (Sakamoto et al. 2005). An intensification and/or poleward shift of surface wind forcing strengthen the surface Kuroshio and other Southern Hemisphere western boundary currents over the past century, as indicated by locally enhanced sea surface temperature (SST) warming over these currents (Wu et al. 2012; Yang et al. 2016). Stratification is another factor regulating the inertial recirculation. Using a two-layer quasigeostrophic ocean circulation model simulations, Sun et al. (2013) showed that the surface recirculation strengthens with increased ocean stratification. The projected change of the Kuroshio due to global warming could also depend on model resolution. Cheon et al. (2012) reported that the projected barotropic volume transport of Kuroshio is significantly intensified in the high-resolution coupled model, but slightly weakened in the low-resolution models.
Although the projected global warming weakens the Gulf Stream and the underlying dynamics have been well documented (Levermann et al. 2005; Yin et al. 2009; Yang et al. 2016), the changes of the Kuroshio remain to be characterized and the underlying dynamic mechanisms are not well understood. The present study compares the projected changes in the Kuroshio and Gulf Stream and investigates the differences in the mechanism. Using the projections from phase 5 of the Coupled Model Intercomparison Project (CMIP5), we show that the upper-layer Kuroshio intensifies as climate warms. In particular, the acceleration of the Kuroshio occurs coherently along its path from its origin to the extension, which is different from the previous results that the Kuroshio only accelerated as a result of the spinup of the recirculation (Sakamoto et al. 2005; Cheon et al. 2012). This projected strengthening of the Kuroshio contrasts markedly with the weakening of the Gulf Stream. To uncover the reasons behind these differences in the response of the two currents, an ocean general circulation model (OGCM) is used to investigate the effects of wind stress, SST, and sea surface salinity (SSS) changes. The OGCM experiments reveal that while decreasing SSS at high latitudes causes the weakening of the AMOC and Gulf Stream, the Kuroshio intensifies as a result of the sea surface warming.

The rest of the paper is organized as follows. Section 2 describes the data and the methods. Section 3 examines the responses of the Kuroshio and Gulf Stream to climate change in CMIP5 models. Sections 4 and 5 investigate the forcing and dynamic mechanisms driving the Kuroshio and Gulf Stream changes, respectively.
using the OGCM experiments. Section 6 is a summary with discussions.

2. Model and data

a. CMIP5 output

We use both historical and representative concentration pathway 4.5 (RCP4.5) simulations (Taylor et al. 2012) from 32 available CMIP5 models (Table 1). All these simulations were based on coarse-resolution (≈1°) OGCMs except MPI-ESM-MR, which possesses an eddy-permitting resolution (≈0.4°). Only one member run (r1i1p1) is used from each model to ensure equal weighting in the intermodel analysis. For each model, variables are interpolated onto a common 1° × 1° latitude–longitude grid with 50 levels in vertical. For each variable, the change due to climate warming is calculated by subtracting the 25-yr mean of 1976–2000 in the historical simulation from the 2076–2100 mean in the RCP4.5 runs.

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**TABLE 2. Design of the NEMO-OPA experiments.** The overbar denotes the monthly climatology from CMIP5 historical experiments (1976–2000), and the prime denotes the change from the year 1976 to 2100.

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<td>EXP.SSS2</td>
<td>$W$</td>
<td>$T$, $S + S'$ (Atlantic 40°S – 40°N)</td>
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![Fig. 2. As in Fig. 1, but for the eddy-permitting model MPI-ESM-MR only, whose ocean component possesses the finest horizontal resolution of all CMIP5 models.](image-url)
**b. OGCM and experiments**

The OGCM is the Océan Parallélisé (OPA) in Nucleus for European Modelling of the Ocean (NEMO; Madec 2008). This model is configured on a tripolar horizontal mesh of approximately $1^\circ$ horizontal resolution with 46 layers in the vertical (ORCA1; Barnier et al. 2007). A partial step scheme is applied to the bottom grid cell to give a better representation of the topography. The vertical viscosity and diffusion coefficients are parameterized using a turbulent kinetic energy scheme (Blanke and Delecluse 1993). Although the ocean model is not eddy resolved, it employs a spatially and temporally varying coefficient in Gent–McWilliams eddy parameterization (Gent and McWilliams 1990). For tracers such as temperature and salinity, the horizontal diffusion follows the Redi isoneutral diffusion operator (Redi 1982). The eddy-induced velocity coefficient is calculated by the model based on the baroclinicity of the ocean at each time step and varies in time and in horizontal space. A harmonic viscosity scheme is used with a spatially varying coefficient ranging from $1 \times 10^3$ m$^2$ s$^{-1}$ in the tropics to $1 \times 10^4$ m$^2$ s$^{-1}$ poleward of $20^\circ$N and $20^\circ$S.

To reach a quasi-equilibrium state, the model is first integrated for 100 years, forced by the climatological monthly Coordinated Ocean–Ice Reference Experiments, version 2 (CORE2), data (Large and Yeager 2009). Subsequently, the SST, SSS, and wind stress fields from CMIP5 are used to drive the ocean model for an additional 125 years to simulate the period from 1976 to 2100. The SST and SSS are strongly restored toward the prescribed CMIP5 output by using restoring conditions for both surface heat flux $Q_{ns}$ and freshwater flux (emp):

$$Q_{ns}^0 + \frac{dQ}{dT}(SST_{\text{model}} - SST_{\text{CMIP5}}),$$

$$\text{emp} = \text{emp}_0 + \gamma_s \frac{(SSS_{\text{model}} - SSS_{\text{CMIP5}})}{SSS_{\text{model}}},$$

where $SST_{\text{model}}$ and $SSS_{\text{model}}$ are the model surface layer temperature and salinity, $SST_{\text{CMIP5}}$ and $SSS_{\text{CMIP5}}$ are the SST and SSS fields from the CMIP5 ensemble mean, $Q_{ns}^0$ and $\text{emp}_0$ are climatological net heat flux and freshwater flux, and $dQ/dT$ is a negative feedback coefficient taken equal to $-120$ W m$^{-2}$ K$^{-1}$. For a 50-m mixed layer depth, this value corresponds to a relaxation time scale of 20 days. The negative feedback coefficient $\gamma_s$ is set to $-166$ mm day$^{-1}$. With these parameters of strong restoring, model SST and SSS are close to the prescribed CMIP5 SST and SSS. As a test, we doubled the relaxation time scale, and found that the results obtained were qualitatively similar to the results obtained under strong relaxation.

A suite of experiments (Table 2) are designed to probe the effects of wind stress, SST, and SSS changes on the response of the Kuroshio and Gulf Stream to global warming. For example, to target the climate response to SST changes only, we run an experiment (EXP.SST) forced with CMIP5 present-day monthly climatological wind stress ($\overline{W}$) and SSS ($\overline{S}$), but with an SST field constructed by adding the time-varying RCP4.5 SST
anomaly to the present-day climatology \((T + T')\). For experiments 1–7 (Table 2), the average of the last 25 years (2076–2100) of each experiment are used in the analysis presented here. It is worth noting that the EXP.wind experiment may also introduce buoyancy forcing arising from the feedback of the SST and SSS relaxation, but this feedback-induced part is very minor compared with the effect of wind stress.

To examine the physical processes by which the SST warming may induce changes in the Kuroshio, we carry out an experiment (EXP.uSST) in which a spatially uniform 1°C warming is introduced to the present-day climatological SST \((T + 1°C)\) to suppress the effects of spatial variations in SST change. This experiment is integrated for 20 years.

3. Gulf Stream and Kuroshio change from CMIP5 simulations

We first examine CMIP5 ensemble-mean changes in the Gulf Stream and Kuroshio under the RCP4.5 scenario. Figure 1 shows the climatology and changes of the currents at 100-m depth. In warmer climate, upper-layer
velocities of the Gulf Stream decrease from low to middle latitudes relative to the present (Fig. 1c). For the Kuroshio, the upper-layer velocities increase (Fig. 1d). The acceleration of the current speed occurs coherently from the east of Luzon all the way to the east of Japan, especially in the area in the East China Sea and south of Japan. This change of the Kuroshio is also obvious in the eddy-permitting model MPI-ESM-MR (Fig. 2), whose ocean component has the finest horizontal resolution of all CMIP5 models (Table 1). This coherent intensification along the entire path is different from the previous results that the Kuroshio only accelerated as a result of the spinup of the recirculation (Sakamoto et al. 2005; Cheon et al. 2012). The projected strengthening of the Kuroshio as climate warms contrasts quite markedly with the projected weakening of the Gulf Stream (Figs. 1c,d).
To test the robustness of these changes to the Kuroshio and Gulf Stream, we investigate the change in volume transport across sections near 28°N for each layer in 32 CMIP5 models (the locations of these sections are indicated in Figs. 1a and 1b). Although there is a considerable intermodel spreads in the magnitudes, most CMIP5 models show similar changes (Fig. 3). For example, at 100 m, 29 of 32 models project that the Kuroshio intensifies and 28 models project that the Gulf Stream weakens, suggesting that these changes are robust. Statistical analysis based on a binomial distribution shows that these results are significant at the 99.9% level. Integrating the velocity in the upper layer (0–300 m) shows that the volume transport of the Gulf Stream is projected to decrease by about 13.6%, while that of the Kuroshio is projected to increase by about 4.6%. When integrated from the surface to 1200 m, the Kuroshio transport shows a slight decrease of about 1.0%, which is consistent with the barotropic weakening of the Kuroshio due to the change of the wind stress curl (Cheon et al. 2012; Hu et al. 2015).
While the transport in the upper-layer Kuroshio is projected to intensify under global warming, the Kuroshio transport in the lower layer (350–1200 m) is projected to weaken, indicating that unlike the Gulf Stream, the Kuroshio change due to global warming has a significant baroclinic component (Fig. 3b). The weakening of the lower-layer Kuroshio may be related to the weakening of the subtropical gyre in the lower thermocline (Zhang et al. 2014; Wang et al. 2015), resulting from the strengthened ocean stratification, downward heat mixing (Wang et al. 2015), and/or cyclonic wind stress change in the interior of the subtropical gyre (Cheon et al. 2012; Zhang et al. 2014). A similar deceleration in lower-layer velocity is also found in Kuroshio Extension region (Terada and Minobe 2018). In this study, we focus on the surface change of the western boundary currents.

4. Effects of wind stress, SST, and SSS in OGCM

We use the NEMO-OPA OGCM to investigate what forces the Gulf Stream to weaken and the Kuroshio to intensify. Three forcing fields are considered: wind stress, SST, and SSS (Fig. 4). We begin by considering the combined changes in wind stress, SST, and SSS (EXP.full experiment). The response displays the weakened Gulf Stream and strengthened Kuroshio at 100-m depth (Figs. 5a and 6a), resembling the CMIP5 ensemble-mean change (Figs. 1c,d) despite some minor differences in magnitude (Fig. 7), which likely arise from the different model performances. The similarity between the EXP.full experiment and CMIP5 results justifies the usage of an OGCM to further explore the effect of each forcing: wind stress (EXP.wind), SST (EXP.SST), and SSS (EXP.SSS). It is worth noting that the difference in the ocean currents between the EXP.full experiment and the sum of the three single forcing experiments is small (Figs. 5e and 6e), meaning that the OGCM simulated response to surface fluxes is generally linear.

We start with the effect of the surface wind stress. Under global warming, both the Hadley cell and the midlatitude westerly winds are projected to shift poleward (Lu et al. 2007; Seidel et al. 2008; Amaya et al. 2018), including a poleward shift in the subtropical wind systems over the North Pacific (Fig. 4c). The change in the negative wind stress curl on the northern edge of the subtropical gyre intensifies the recirculation there (Fig. 6b). Compared with our result, the acceleration of the northern part of the Kuroshio and Kuroshio Extension north of 35°N due to the spinup of the recirculation gyre are much more obvious in high-resolution eddy-resolving coupled models (Sakamoto et al. 2005). Wind stress curl shows a weakly positive change in the central subtropical oceans (Fig. 4c; Terada and Minobe 2018), which weakens both the upper layer (Fig. 7b) and depth-integrated (Cheon et al. 2012) Kuroshio transport between 10° and 35°N. Thus, the wind stress change can partly explain the acceleration of the northern part of the Kuroshio and Kuroshio Extension (Sakamoto et al. 2005), but cannot explain the acceleration of the upper-layer Kuroshio from the east of Luzon to the south of Japan (Fig. 6a). The change in wind stress over the subtropical North
Atlantic is similar to that in the North Pacific (Fig. 4c). The weak deceleration of the Gulf Stream (Fig. 5b) indicates that the wind stress change is not the dominant forcing driving the total change of the Gulf Stream (Fig. 5a).

We then investigate the SSS effect. The magnitude of the SSS change in the North Pacific is weak (Fig. 4b) and so is the change in the Kuroshio in EXP.SSS (Fig. 6c). In contrast to the North Pacific, the SSS change in the North Atlantic is large (Fig. 4b). As a result, the Gulf Stream weakens markedly in this experiment (Figs. 5c and 7a). The reduction in the surface Gulf Stream is even larger than in EXP.full, the full forcing experiment, indicating the dominant role of SSS change in the Gulf Stream change.

Finally, we explore the role of SST forcing. In response to the SST increase (Fig. 4a), the upper-layer Kuroshio intensifies significantly over the same Luzon to Japan region described above (Fig. 6d). Accompanied with the upper layer strengthening, the Kuroshio weakens in the lower layer (Fig. 7b). Both the spatial pattern and magnitude of the SST effect are quite similar to the Kuroshio change seen in EXP.full. The comparison with the uniform SST warming experiment shows that the response of the Kuroshio is insensitive to the spatial pattern of surface warming. The upper-layer Gulf Stream also shows an intensification in EXP.SST (Fig. 5d), but the response is much smaller than that of the Kuroshio.

To summarize, the striking resemblance between Figs. 5a and 5c demonstrates that the weakening of the Gulf Stream is mostly driven by the SSS change, while the resemblance between Figs. 6a and 6d indicates that the Kuroshio intensification is driven by the SST change. Next, we examine the physical mechanisms behind these results by conducting additional OGCM experiments.

5. Mechanisms for the Gulf Stream and Kuroshio changes

Previous studies have shown that the weakening of the Gulf Stream is induced by the slowdown of the AMOC (Yang et al. 2016). Most of the AMOC slowdown can be attributed to the response to the SSS change (Fig. 8a). The SSS change in the North Atlantic exhibits a distinct pattern: decreasing north of 40°N and increasing to the south (Fig. 4b). We separate the effects of these two parts of the SSS forcing by conducting two additional OGCM experiments (EXP.SSS1 and EXP.SSS2). The first experiment (EXP.SSS1) is similar in spirit to the “freshwater hosing” experiments in other studies (Levermann et al. 2005; Yin et al. 2009; Bouttes and Gregory 2014; Liu and Liu 2013, 2014; Liu et al. 2014), wherein freshwater is added to the high-latitude North Atlantic. The results show that the surface salinity decrease north of 40°N is responsible for the AMOC slowdown (Fig. 8). Therefore, we conclude that the Gulf Stream, as part of the AMOC, slows down in response to sea surface freshening in the high-latitude North Atlantic that arises from global warming.

The SST change in the CMIP5 ensemble mean is characterized by a robust warming over the global ocean (Fig. 4a). How does the SST warming, regardless of its spatial pattern, cause the Kuroshio to intensify? Figure 9 shows the distribution of the change in the ocean temperature as a function of time and depth in the uniform SST change experiment (EXP.uSST). Forced by an abrupt SST increase of 1°C, the ocean temperature in the North Pacific undergoes a gradual warming over the upper 500 m. The surface layer warms up quickly and evenly (Fig. 9), but the warming in the subsurface layer is highly uneven in space. The warming is first found in the
subduction region to the east of Japan between 30° and 40°N [Figs. 9 and 10a(1)], where the winter mixed layer is thick (Oka et al. 2011). This result is consistent with the findings of Terada and Minobe (2018), who showed that the large heat uptake causes the warming of subtropical mode water. The warming is then advected to the southeast along the thermocline [Figs. 9 and 10a(1)–a(3)] riding on the subtropical gyre (Hanawa and Talley 2001; Luo et al. 2009; Xie et al. 2011; Hakkinen et al. 2016). The warming (e.g., the 0.3°C contour) can penetrate down to 500 m in the central subtropical gyre, but reaches less than 200 m in the low and high latitudes over the 20 years of model integration [Fig. 10a(3)]. This enhanced warming pattern in the subtropics was reported by Marshall et al. (2015) based on an OGCM forced by a globally uniform downward heat flux of 4 W m⁻². Marshall et al. (2015) showed that the background ocean circulation plays a dominant role in setting these distributions of ocean heat uptake and storage, although the banded structure of temperature in the southern subtropical gyre (Fig. 9) is due to the reduced formation of mode water and the weakening of the subtropical countercurrent (Xu et al. 2012). In the zonal sections [Figs. 10b(1)–b(3)], the warming subducted from the poleward edge of the subtropical gyre also advects eastward through the subsurface ocean pathway (Liu and Hu 2007) and upwells along isopycnals before it encounters the western boundary. Consequently, the subsurface (e.g., 100–500 m) warming is more prominent to the east of the Kuroshio than that to the west [Figs. 10b(2),b(3)], which increases the isopycnal slope and thereby intensifies the Kuroshio. The variations of upper-ocean temperature and isopycnal slopes across the Kuroshio, moreover, can be revealed from sea level change (Fig. 11).

In summary, our OGCM experiments show that the weakening of the AMOC caused by the global warming–induced surface freshening of the high-latitude North Atlantic is the dominant mechanism driving the slowdown of the Gulf Stream. Our experiments also revealed that the sea surface warming associated with a warming climate is the main cause intensifying the upper-layer Kuroshio through the ocean subduction and advection processes.

6. Conclusions and discussion

In contrast to the previously documented slowdown of the Gulf Stream, our study shows that climate warming...
will lead to a robust intensification of the upper-layer Kuroshio along its entire path from Luzon to Japan. This result differs from previous results in which the Kuroshio only accelerates as a result of the spinup of the recirculation (Sakamoto et al. 2005; Cheon et al. 2012). Our OGCM experiments demonstrate that the surface freshening of the high-latitude North Atlantic causes the slowdown of the AMOC and Gulf Stream. Although internal variability of the Kuroshio is driven by wind forcing (Xie et al. 2000; Tanaka et al. 2004; Qiu and Chen 2005; Wunsch 2011), our study shows that the long-term trend of the upper-layer Kuroshio transport under global warming is forced by the sea surface warming. Accordingly, the Kuroshio displays robust baroclinic change in its vertical structure: intensifying in the upper layer and weakening in the lower layer. This surface warming-driven upper-layer acceleration is much larger than the deceleration caused by changes in the wind stress, leading the Kuroshio to intensify as the climate warms. The possible physical mechanisms driving this change are that ocean subduction and advection processes result in a nonuniform warming pattern of subsurface ocean temperature change: stronger warming to the east of the Kuroshio than to the west increases the isopycnal slope across the Kuroshio, which leads to an intensification of the Kuroshio.

The Gulf Stream and Kuroshio maintain a strong cross-stream sea surface height gradient associated with geostrophic balance, with the coastal sea level lower by \(-1\)–\(-1.5\) m than on the seaward edge of the currents.
Changes in the western boundary currents are related to changes in sea surface height difference across the currents (Ezer et al. 2013; Sasaki et al. 2014). A slowdown in Gulf Stream corresponds to a reduced cross-current sea level difference, which leads to a higher sea level rise along the northeastern coast of North America and a smaller sea level rise in the central subtropical gyre (Yin et al. 2009; also see Fig. 12a). In contrast, an intensification of the Kuroshio is associated with an enhanced cross-current difference, which gives rise to a smaller sea level rise on the coast of East Asia than offshore (Fig. 12b). The faster sea level rise on the northeastern U.S. coast is due to an abnormally high sea level rise that propagates southward from the Labrador Sea (Minobe et al. 2017).

Although the Kuroshio and Gulf Stream changes are robust among CMIP5 models and in our OGCM, the magnitude of the current change in the MPI-ESM-MR (Fig. 2) is much larger than that in the CMIP5 ensemble mean (Fig. 1). This might be because the MPI-ESM-MR has a finer horizontal resolution permitting eddies. Previous studies indicated that in eddy-resolving models, the change in recirculation due to the nonlinear effects is important in the change of the Kuroshio (Sakamoto et al. 2005; Cheon et al. 2012). Our OGCM and most CMIP5 models are of coarse resolution (1°) for the ocean (Table 1), but it is important for future studies to explore eddy effects on the changes in the Kuroshio and Gulf Stream using high-resolution models.

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