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Impact of Ocean Eddy Resolution on the Sensitivity of Precipitation to CO_2 Increase

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Key Points:
- The incorporation of ocean eddy resolution has substantial influences on regional precipitation changes
- The largest impact of ocean eddy resolution on precipitation projections is found in eddy-rich regions and the deep tropics
- Land regions are generally not very sensitive to ocean eddy resolution

Supporting Information:
- Supporting Information S1

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Abstract The past few years have seen a growing investment in the development of global eddy-resolving ocean models, but the impact of incorporating such high ocean resolution on precipitation responses to CO_2 forcing has yet to be investigated. This study analyzes precipitation changes from a suite of Geophysical Fluid Dynamics Laboratory models incorporating eddy-resolving (0.1°), eddy-permitting (0.25°), and eddy-parameterizing (1°) ocean models. The incorporation of eddy resolution does not challenge the large-scale structure of precipitation changes but results in substantial regional differences, particularly over ocean. These oceanic differences are primarily driven by the pattern of sea surface temperature (SST) changes with greater sensitivity in lower latitudes. The largest impact of ocean resolution on SST changes occurs in eddy-rich regions (e.g., boundary currents and the Southern Ocean), where impact on precipitation changes is also found to various degrees. In the Gulf Stream region where previous studies found considerable impact of eddy resolution on the simulation of climatological precipitation, we do not find such impact from the Geophysical Fluid Dynamics Laboratory models, but we do find substantial impact on precipitation changes. The eddy-parameterizing model projects a banded structure common to the Coupled Model Intercomparison Project (Phase 5) models, whereas the higher-resolution models project a poleward shift of precipitation maxima associated with an enhanced Gulf Stream warming. Over land, precipitation changes are generally not very sensitive to ocean resolution. In eastern North America adjacent to the Gulf Stream region, moderate differences are found between resolutions. We discuss the mechanisms of land differences, which arise through the simulation of both climatological SST and SST changes.

Plain Language Summary Global coupled atmosphere-ocean models have not included the explicit simulation of ocean mesoscale eddies (turbulent ocean flow with a horizontal scale of less than 100 km) until the recent few years. As a result, current estimates of precipitation responses to greenhouse gases increase have predominantly relied on models in which ocean eddies have to be parameterized. Given the importance of eddies on ocean heat transport and the strong dependence of precipitation on ocean surface temperature, the lack of ocean eddy resolution may have influenced the projection of precipitation changes. In this study, we compare precipitation changes from CO_2 forcing in models with and without explicit ocean eddy simulation. It is found that the incorporation of ocean eddy resolution can substantially influence the simulation of precipitation changes in eddy-rich regions and the deep tropics. Some land regions are also affected, albeit to a lesser degree compared to the oceanic regions.

1. Introduction

The ocean plays a critical role in the projection of anthropogenic precipitation changes. Oceanic processes modulate the rate of global mean surface warming, which determines changes in the overall strength of the hydrological cycle (Held & Soden, 2006) and, given the evidence for pattern scaling of the response of climate to CO_2, also sets the amplitude of regional climate change (Kent et al., 2015). In addition, the pattern of sea surface temperature (SST) changes is an important mechanism for the spatial structure of precipitation changes. Particularly in the tropical oceans, enhanced surface warming (e.g., at the equatorial Pacific) tends to drive a positive local precipitation change, which is frequently referred to as the *warmer-get-wetter* phenomena (Ma & Xie, 2013; Xie et al., 2010). Outside the tropical oceans, the impact of the pattern of SST changes is generally smaller (He et al., 2014) but can be important in certain ocean basins, such as the extratropical North Atlantic (Long & Xie, 2015).

The simulation of the ocean state requires a representation of processes across a wide range of spatial scales. Transient eddies at the mesoscale have been identified as a key component of ocean circulation and heat transport (Griffies et al., 2014; Morrison et al., 2013; Newsom et al., 2016) and can thus be crucial to the establishment of surface conditions for the simulation of precipitation. However, the majority of climate models used in current climate projections (e.g., Coupled Model Intercomparison Project, Phase 5, CMIP5) have resolutions too low to resolve mesoscale eddies and must rely on parameterization, which inevitably induces biases and uncertainty. In recent years, several high ocean resolution (0.1°) climate models have been developed to attempt the explicit simulation of mesoscale eddies (Bryan et al., 2013; Delworth et al., 2012; Kirtman et al., 2012). Some of these models simulate substantially different ocean surface climatology and changes at both global (Winton et al., 2014) and regional (Saba et al., 2016; Siqueira & Kirtman, 2016) scales compared to their lower-resolution counterparts. Because of the strong dependence of precipitation on ocean surface conditions, the emergence of the eddy-resolving climate models may challenge the current understanding of precipitation changes that are predominantly based on eddy-parameterizing models.

Previous studies of the eddy-resolving CCSM3.5 model found great improvement on the simulation of the present-day precipitation. Particularly in the North Atlantic region where mesoscale eddies are important for the simulation of the Gulf Stream, the position and amount of precipitation climatology are substantially improved (Feng et al., 2017). In addition, the high-resolution CCSM3.5 also simulates more intense air-sea coupling, resulting in larger precipitation-SST covariability (Kirtman et al., 2012, 2017). These improvements suggest that the new generation of eddy-resolving models may provide a better baseline for projecting future precipitation changes.

In this paper, we compare precipitation changes from a suite of Geophysical Fluid Dynamics Laboratory (GFDL) model simulations incorporating eddy-resolving (0.1°), eddy-permitting (0.25°), and eddy-parameterizing (1°) ocean models. Previous studies have compared the oceanic aspects of these simulations and found significant differences in the changes in the global ocean heat uptake, the Atlantic Meridional Overturning Circulation and North Atlantic and Southern Ocean SSTs (Griffies et al., 2014; Saba et al., 2016; Winton et al., 2014). To the best of our knowledge, this is the first study to investigate the impact of ocean eddy resolution on the precipitation response to CO_2 increase.

2. Models and Simulations

The GFDL models we use are CM2.6 (Winton et al., 2014), CM2.5 (Delworth et al., 2012), and FLOR-A06 (Vecchi et al., 2014) with 0.1°, 0.25°, and 1° ocean resolutions, respectively. FLOR stands for Forecast Low Ocean Resolution. As documented in Vecchi et al. (2014), there are two versions of FLOR: FLOR-A06 and FLOR-B01; FLOR-A06, which is used here, has more consistent parameterizations with CM2.5 and CM2.6 and therefore provides a cleaner comparison, whereas FLOR-B01 has several parameterization changes in addition to FLOR-A06. In previous studies of FLOR-CM2.6 comparison, Winton et al. (2014) used both FLOR-A06 and FLOR-B01, whereas Saba et al. (2016) used FLOR-B01. Both CM2.6 and FLOR-A06 are descendants of CM2.5 with only changes in the ocean model resolution and the required ocean eddy parameterizations. Specifically, FLOR-A06 uses the Gent-McWilliams eddy parameterization (Gent & Mcwilliams, 1990) for the effects of mesoscale eddies, but no such parameterization is applied in CM2.6 or CM2.5. The high ocean resolution allows CM2.6 to simulate realistic eddy activity, whereas in CM2.5 the eddy representation is less complete, particularly at high latitudes (Delworth et al., 2012; Griffies et al., 2014). All three models use the same 0.5 atmosphere model, AM2.5.

All models have a fully coupled 1860 control simulation (CPL_ctrl) initialized from present-day ocean conditions. After a 100-year spin-up (120 years for CM2.6), a fully coupled 1pctCO2 simulation (CPL_1pct) branches off the control simulation with CO_2 increasing by 1% per year and is run for 80 years. We calculate climate change from the coupled simulations as the difference between years 61 and 80 of CPL_1pct and the corresponding years of CPL_ctrl. We normalize the changes by dividing them by each model's global mean SST change and rescale them to their original units by multiplying them by the three-model average global mean SST change. The purpose of the normalization is to remove the impact from the difference in the models' climate sensitivity, which has been suggested as unimportant for causing intermodel disparity in regional precipitation projection (Kent et al., 2015) and also to facilitate the comparison of the atmosphere-only simulations, which we describe next. The global mean SST changes of CM2.6, CM2.5 and FLOR-A06 are

1.43, 1.26, and 1.28 °C; the faster warming of CM2.6 has been associated with its slower Atlantic Meridional Overturning Circulation decline (Winton et al., 2014).

Because of the shortness of the coupled simulations, precipitation changes obtained from these simulations must contain substantial internal variability (Deser et al., 2012), and extending these coupled simulations is difficult due to the costliness of the high-resolution ocean models. However, we found that the SST changes obtained from the 20-year averages at double CO_2 are relatively robust and are dominated by the anthropogenic forcing (supporting information Figure S1). This means that most of the internal precipitation variability is generated by atmosphere and land internal dynamics, consistent with previous studies (Deser et al., 2012; He et al., 2017; Zhang & Delworth, 2018a, 2018b). To reduce the influence of internal atmospheric variability and to decompose the mechanisms of precipitation changes, we perform three extended atmosphere-only simulations with AM2.5 for each of the coupled models: (1) a 200-year control simulation (Atmospheric Model Intercomparison Project, AMIP_ctrl) with preindustrial radiative forcing and a repeating seasonal cycle of climatological monthly SSTs taken from years 61 to 80 of CPL_ctrl, (2) a 200-year structured warming simulation (AMIP_structured) with double CO_2 and repeating climatological SSTs taken as the SSTs from years 61 to 80 of CPL_ctrl plus the normalized climatological seasonal cycle of SST changes from each coupled model, and (3) a 200-year uniform warming simulation (AMIP_uniform) with double CO_2 and repeating climatological SSTs taken as the SSTs from years 61 to 80 of CPL_ctrl plus a spatially uniform SST change set equal to the three-model average global mean SST change. Note that we do not include the changes in SST variability (beyond the mean seasonal cycle) in the atmosphere-only simulations, which may impact changes in the mean precipitation in regions of nonlinear SST-precipitation interactions (He et al., 2017). Nevertheless, these extended atmosphere-only simulations allow us to effectively eliminate the effects of sampling atmospheric internal variability on our results (supporting information Figure S2) while being able to retain the anthropogenic signal from the coupled simulations (He & Soden, 2015). For this reason, our analyses of precipitation changes will be solely based on the atmosphere-only simulations, whereas the fully coupled results are provided in supporting information Figure S3. However, these atmosphere-only simulations still contain SST internal variability, which remains a caveat and will be taken into account in the interpretation of our results.

Because all the AMIP_uniform simulations have the same SST changes, the differences in their precipitation responses result solely from the coupled models' climatological SSTs from their control simulations. By subtracting AMIP_uniform from AMIP_structured, we obtain the effect of the pattern of SST changes, which we refer to as AMIP_pattern. Although the AMIP_pattern simulations also contain different climatological SSTs, we assume that the differences in these simulations are dominated by differences in the models' pattern of SST changes (which will become obvious in the results).

Lastly, to assess the climatological biases, we use a 40-year 1990 control run from each model (with a 100-year spin-up), as documented in Delworth et al. (2012). Their climatologies are compared against the observed 1981–2010 precipitation (Xie & Arkin, 1997) and SST (Reynolds et al., 2007).

3. Results

3.1. Overview

As shown in the left panels of Figure 1, the large-scale structure of precipitation changes (AMIP_structured minus AMIP_ctrl) is fairly consistent between resolutions, with positive changes in most of the deep tropics and extratropics and negative changes in many of the subtropical regions. This is not surprising because the processes that drive these large-scale features, such as the moistening of the atmosphere (Held & Soden, 2006), the expansion of the Hadley cell (Scheff & Frierson, 2012a, 2012b), and the land-sea warming contrast (He & Soden, 2017), are generally considered robust climate responses independent of ocean resolution. Precipitation changes from the coupled simulations are provided in supporting information Figure S3, which shows similar large-scale features as the uncoupled results with less spatial coherency due to the large atmospheric internal variability.

At regional scales, noticeable differences exist between resolutions. Most of these differences, particularly over the ocean, can be found in AMIP_pattern (not shown) and are therefore dominated by the differences in the coupled models' pattern of SST changes. Although the changes in SST are more consistent between the high and low resolutions in the tropics (with a spatial correlation of 0.74) than the extratropics (with a

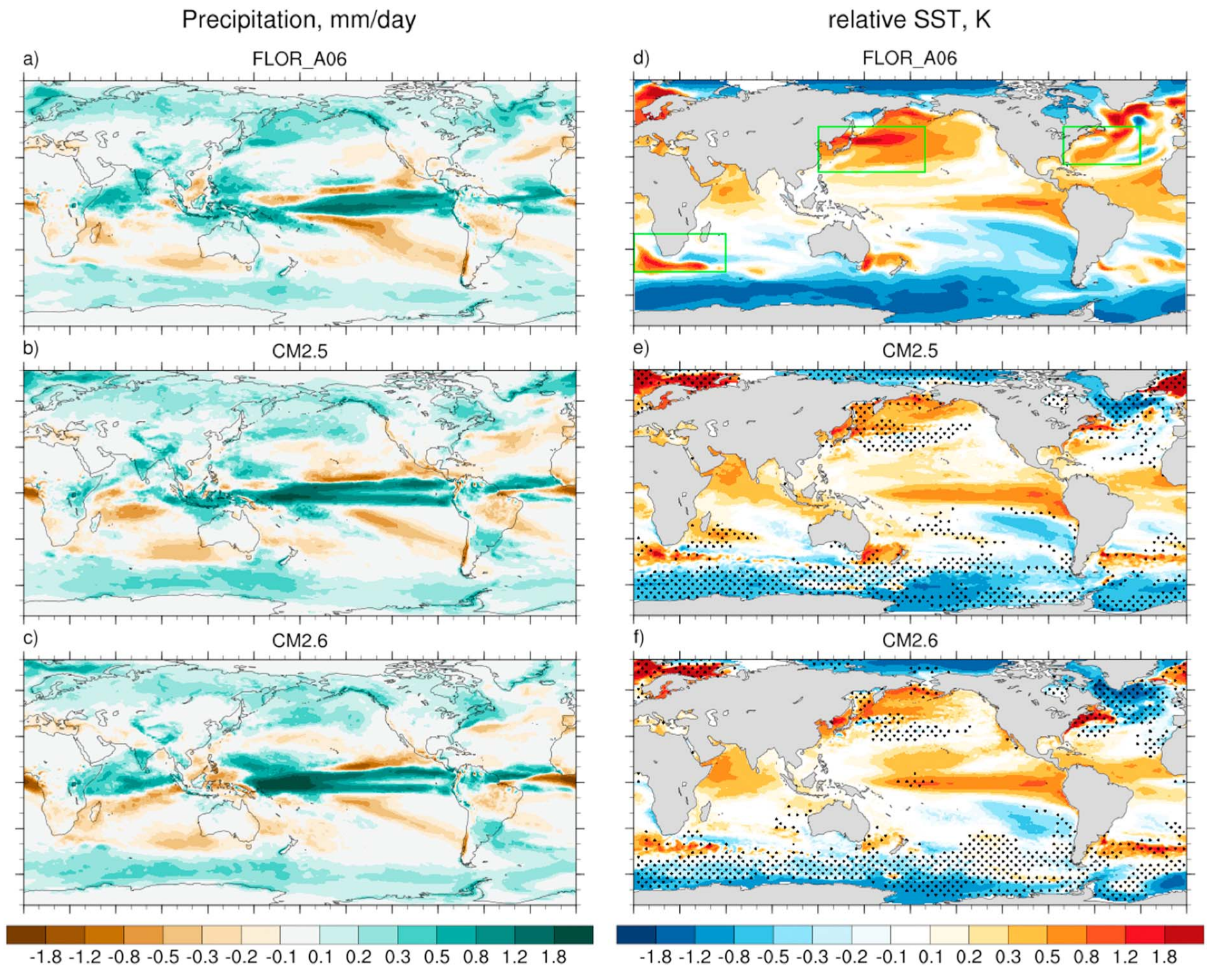

Figure 1. Annual mean precipitation (left column) and relative SST (right column) changes in FLOR-A06 (top row), CM2.5 (middle row), and CM2.6 (bottom row). The relative SST changes are calculated as the total SST changes minus the global average SST changes. Precipitation changes are calculated from the Atmospheric Model Intercomparison Project simulations and SST changes from the coupled simulations, as described in section 2. Stippling in (e) and (f) indicates that the SST changes are significantly different from those in FLOR-A06 at the 90% level based on the Student's *t* test (two-tailed). The Gulf Stream, Kuroshio, and Agulhas regions are highlighted by the green boxes in (d). SST = sea surface temperature; FLOR = Forecast Low Ocean Resolution.

spatial correlation of 0.49), the opposite is true for the precipitation changes (with a spatial correlation of 0.50 for the tropics and 0.68 for the extratropics; see supporting information Table S1). This reflects a greater sensitivity of precipitation changes to the pattern of SST changes in the tropics, which has also been identified in the low-resolution CMIP5 model projections (He et al., 2014). Over land, precipitation changes are less sensitive to ocean resolution (as indicated by the spatial correlations in supporting information Table S1), with a few noticeable exceptions in the tropics. For example, the increase in precipitation in South America is located in a band roughly between São Paolo and Buenos Aires in the two eddying models but is much reduced in the noneddying model. Differences in precipitation changes are also perceivable in the Northern Sahel and the Eastern Australia when these changes are viewed as percentage changes (i.e., normalized by the climatology, supporting information Figure S4). Unlike the ocean, the differences over land receive comparable contributions from the simulation of SST changes and the climatological SST, which will be discussed later.

As shown in the right column of Figure 1, the three models project very similar patterns of SST changes in the tropics, with only significant differences in the small area of the western equatorial Pacific and the eastern equatorial Atlantic in CM2.6 relative to FLOR-A06. Precipitation, however, responds dramatically to the relatively small SST differences. For example, the more westerly extended equatorial Pacific warming in CM2.6 causes the precipitation increase to concentrate in the western part of the equator (i.e., the ascending branch of the Walker cell), whereas a more easterly focused precipitation response is projected in FLOR-A06. In the tropical Indian Ocean, precipitation also differs substantially, with an east-west dipole in FLOR-A06, a banded structure in CM2.5, and a north-south dipole in CM2.6; the former is more common in most eddy-parameterizing projections (e.g., Xie et al., 2010). However, the differences in precipitation changes are not clearly reflected in the local SST changes as all three models project a relatively similar east-west dipole response in SST. Some of the difference in precipitation response is likely remotely driven (e.g., by the convection response in the equatorial Pacific through mechanisms analogous to the remote influence of the internally varying El Niño–Southern Oscillation; e.g., Klein et al., 1999), which will not be explored further here.

In the extratropics, the incorporation of eddy resolution results in significantly different SST changes in most of the eddy-rich regions, such as the western boundary currents and the Southern Ocean. Compared to the tropics, the extratropical precipitation changes are overall less sensitive to ocean resolution, but there are noticeable differences in some of the eddy-rich regions. The Gulf Stream region is the most sensitive to ocean resolutions compared to the other two major western boundary current regions (i.e., the Kuroshio and Agulhas), with virtually zero spatial correlation between the high and low resolutions (supporting information Table S1). In the next section, we will focus on the Gulf Stream region, which has also historically attracted much attention in studies of high-resolution modeling (e.g., Feng et al., 2017; Kirtman et al., 2012; Small et al., 2014).

3.2. The Gulf Stream Region

We first examine the climatological precipitation in the Gulf Stream region. In the observations, the precipitation climatology features a southwest-northeast band following the maximum Gulf Steam current off the North American coastline (red contours in Figure 2). All three models show similar precipitation biases, with overall positive biases north of the observed precipitation maxima and negative biases to the south (Figure 2, left column). The SST biases (black contours) are predominantly negative, particularly north of 40°N and are not aligned well with the general structure of precipitation biases. This indicates that much of the precipitation biases in these GFDL models are likely unrelated to local SST biases. One exception can be found off the coast of the Delmarva Peninsula, where the SST and precipitation biases are large and positive in FLOR-A06 (known as the *Gulf Stream separation problem* common to low-resolution climate models; Dengg et al., 1996) and are much reduced in CM2.6.

The overall insensitivity of precipitation climatology to ocean resolution contrasts with previous results from the CCSM3.5 models, which showed substantial improvements with the incorporation of ocean eddy resolution (Kirtman et al., 2012, their Figure 8; see also Feng et al., 2017). The smaller impact of ocean resolution in the GFDL models is largely due to the fact that the low-resolution GFDL model (i.e., FLOR-A06) already has well-represented SST and precipitation climatologies compared to the low-resolution CCSM3.5 model (supporting information Figure S5).

Despite their similar precipitation climatologies, the three models have very different changes in precipitation, particularly over oceanic regions (Figure 2, right column). Over the adjacent land of eastern North America, differences in precipitation changes are much smaller albeit noticeable. In the northeast Atlantic, FLOR-A06 projects a narrow banded structure oriented in the southwest-northeast direction, whereas CM2.5 and CM2.6 project a poleward shift of the climatological precipitation maxima with CM2.6 showing larger amplitude of change than CM2.5. In all three models, changes in precipitation have a similar structure to the corresponding patterns of SST changes (shown in contours), with a warmer-get-wetter relationship similar to that identified in the tropical oceanic regions (Xie et al., 2010). The banded structure in FLOR-A06 is also a common response in the low-resolution CMIP5 models and is associated with changes in the midlatitude mode waters (Long & Xie, 2015; Xie et al., 2010). The unique structure of precipitation changes in CM2.5 and CM2.6 is associated with a poleward shift and an enhanced warming of the Gulf Stream, which was documented thoroughly in Saba et al. (2016). The enhanced Gulf Stream warming results from the combination of a retreat of the cold Labrador Current and an intrusion of the warm Atlantic Temperate Slope Water into the Northeast Channel off the coast of Maine. These mechanisms cannot be simulated in the low-resolution model due to the lack of a realistic Labrador Current and the unresolved bathymetry at the Northwest Atlantic Shelf.

To further understand the differences in precipitation sensitivities, particularly those over land, we decompose the precipitation changes in two ways. (To keep the analyses succinct, we only present results for

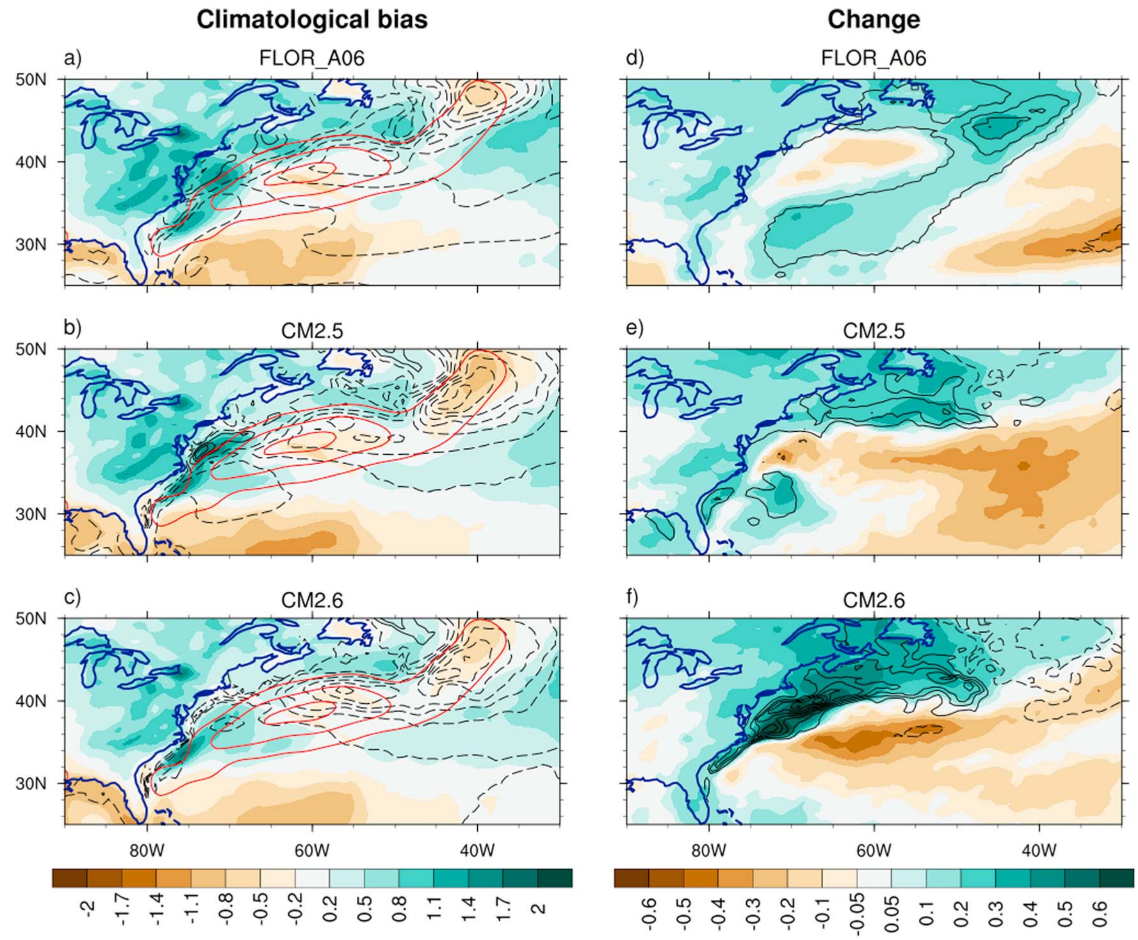

Figure 2. Annual mean climatological biases (left column) and changes (right column) in precipitation (shading, unit: mm/day) and SST (black contours) from the three Geophysical Fluid Dynamics Laboratory models. The climatological biases are calculated using a 40-year 1990 control run from each model (with a 100-year spin-up) against the observed 1981–2010 precipitation and SST (section 2). SST changes are shown as the relative SST changes (described in Figure 1). Precipitation changes are calculated from the Atmospheric Model Intercomparison Project simulations and SST changes from the coupled simulations, as described in section 2. Contour interval is 1 °C for the climatological SST biases and 0.5 °C for the SST changes. Dashed contours indicate negative values. Zero contours are omitted. The red contours show the observed precipitation, with a contour interval of 1 mm/day starting at 4 mm/day. SST = sea surface temperature; FLOR = Forecast Low Ocean Resolution.

FLOR-A06 and CM2.6 and neglect CM2.5.) As shown in Figures 3 and 4, we first analyze the AMIP_uniform and AMIP_pattern simulations separately. As discussed in section 2, the AMIP_uniform simulations only differ from each other by their climatological SSTs, whereas differences among the AMIP_pattern simulations are dominated by their patterns of SST changes. We then divide the precipitation changes in the AMIP simulations into convective changes and large-scale changes. The convective precipitation is simulated through parameterizations of subgrid-scale cumulus clouds, whereas the large-scale precipitation is simulated through the formation of grid-scale stratiform clouds. We note that the division between convective and large-scale precipitation depends on model parameterization; it may not truthfully represent that in nature and could vary between models. Here we present these analyses in the hope of offering some new perspectives on local versus large-scale precipitation responses and potentially an alternative approach for understanding the intermodel spread.

As shown in Figures 3a and 3b, the precipitation responses to uniform sea surface warming are similar between the high and low resolutions. Over ocean, the precipitation changes mimic the climatological pattern of precipitation minus evaporation ($P - E$, shown in contours in Figures 3a and 3b), with negative changes in the subtropics and positive changes in the extratropics. These changes were suggested to reflect an intensification of the existing hydrological cycle as a result of the increasing atmospheric moisture (Held & Soden, 2006), although more recent studies have challenged this mechanism in the subtropics (He & Soden,

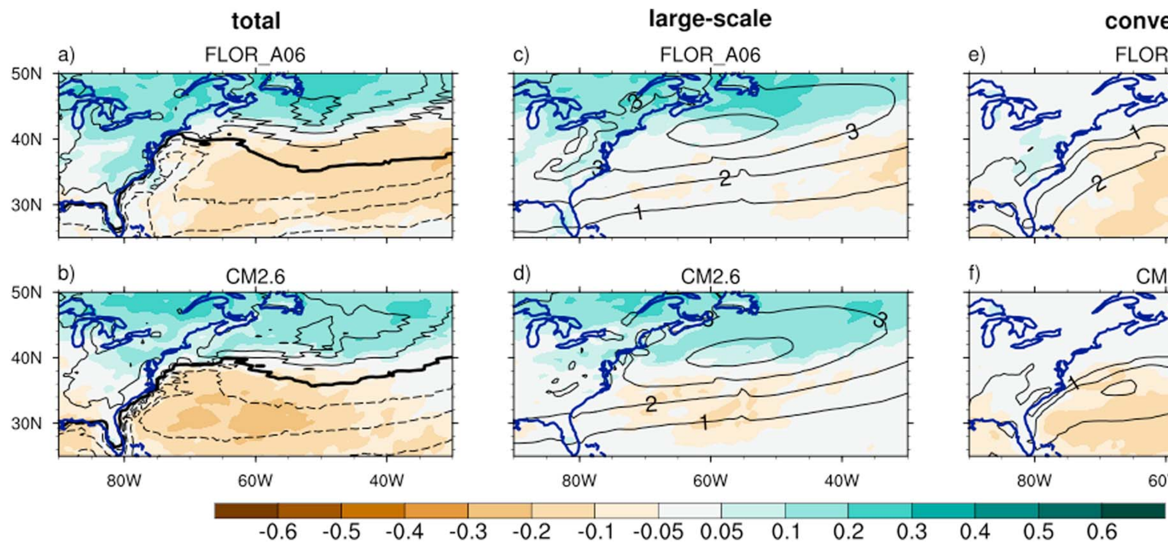

Figure 3. Precipitation responses (unit: mm/day) to uniform SST warming from FLOR-A06 (top row) and CM2.6 (bottom row). Shown from left to right are total, large-scale, and convective precipitation changes. Contours show the climatological $P - E$ in (a) and (b), climatological large-scale precipitation in (c) and (d), and climatological convective precipitation in (e) and (f). All climatological field are calculated from the AMIP_ctrl simulation. Contour interval is 0.5 mm/day. Dashed contours indicate negative values. Zero contours are thickened. SST = sea surface temperature; FLOR = Forecast Low Ocean Resolution.

2017; Scheff & Frierson, 2012a, 2012b). In Figures 3c–3f, we show that the precipitation changes are simulated through different schemes in the subtropics and extratropics. The subtropical decline is dominated by convective changes, indicating that these changes could be associated with localized heating of land and atmosphere as suggested by He and Soden (2017). Note that the climatological precipitation in the subtropical North Atlantic (equatorward of the zero $P - E$ contour) is overall equally partitioned into convective and large-scale schemes albeit with regional differences (contours in Figures 3c–3f). On the other hand, the extratropical increase is dominated by large-scale changes and is located poleward of the climatological large-scale precipitation maxima. In the adjacent land regions of eastern North America, there is a general moistening with the exception of drying in the south in CM2.6, which is not projected in FLOR-A06.

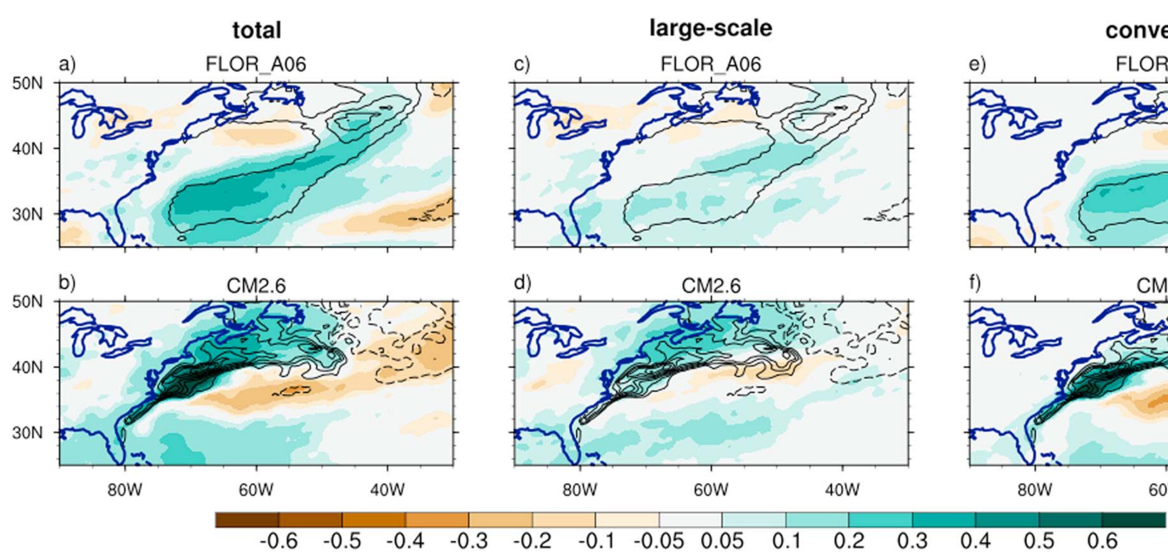

Figure 4. Precipitation responses (unit: mm/day) to the pattern of SST changes in FLOR-A06 (a, c, and e) and CM2.6 (b, d, and f). Shown from left to right are total, large-scale, and convective precipitation changes. Contours show the relative SST changes as defined in Figure 1. Contour interval is 0.5 °C. Dashed contours indicate negative values. Zero contours are omitted. SST = sea surface temperature; FLOR = Forecast Low Ocean Resolution.

Not surprisingly, the precipitation responses in AMIP_pattern are well aligned with the pattern of SST changes in both high- and low-resolution models (Figures 4a and 4b). In addition, it appears that the pattern of SST changes becomes less effective toward higher latitudes. For example, in FLOR-A06 (Figure 4a), the largest precipitation increase is located around 35°N, south of the largest SST increase. Over the land regions, there is a consistent coastal moistening associated with the enhanced Gulf Stream warming in CM2.6, which is not projected in FLOR-A06. By comparing the land differences between Figures 3a and 3b and those between Figures 4a and 4b, there appear to be comparable contributions from AMIP_uniform and AMIP_pattern. This indicates that both the climatological SSTs and the pattern of SST changes are important for the intermodel differences in land projections (He & Soden, 2016). Figures 4c–4f show that the precipitation responses to the pattern of SST changes are dominated by convective changes, which are concentrated at the SST signals and do not propagate toward land. The large-scale changes, on the other hand, are smaller in magnitude and more spread out but account for most of the land precipitation responses to the pattern of SST changes.

4. Summary and Discussion

In this paper, we investigate how ocean eddy resolution, which has recently been incorporated into some global climate models (Bryan et al., 2013; Delworth et al., 2012; Kirtman et al., 2012), impacts the sensitivity of precipitation to increasing CO_2. We compare a suite of GFDL model simulations containing eddy-resolving (0.1°), eddy-permitting (0.25°), and eddy-parameterizing (1°) ocean models. These resolutions simulate similar large-scale structures of precipitation changes but substantially different regional responses, particularly over ocean. The differences in oceanic precipitation changes are primarily associated with differences in the pattern of SST changes. In the extratropics, SST changes are significantly different between the low and high resolutions at the western boundary currents and the Southern Ocean. Compared to the extratropics, the tropics has much more consistent SST changes but overall less consistent precipitation changes, reflecting a greater effectiveness of the pattern of SST changes in regulating precipitation changes at lower latitudes (He et al., 2014). Although we cannot determine whether the SST changes and the associated precipitation changes are more accurate in the higher-resolution models, a higher ocean resolution for these GFDL models generally yields a better representation of the climatological SST and the dynamic processes that drive SST variability both in the tropics and extratropics (Delworth et al., 2012; Saba et al., 2016).

The Gulf Stream region is among the most sensitive regions to ocean resolution with virtually no similarity in the precipitation responses of the low- and high-resolution models. The eddy-parameterizing model projects a narrow banded structure of precipitation changes that is common to most low-resolution CMIP5 models (Long & Xie, 2015). But the eddy-resolving and eddy-permitting models project a poleward shift of the precipitation maxima, which is associated with the poleward shift and enhanced warming of the Gulf Stream (Saba et al., 2016). A poleward shift in the zonal mean precipitation maxima has been diagnosed in current climate projections and is often associated with the poleward shift of midlatitude baroclinicity (e.g., Yin, 2005) or the strengthening of humidity gradients (Seager et al., 2014). Here it is shown that the incorporation of eddy resolution can regionally intensify the poleward shift of precipitation maxima through enhanced local surface warming.

It is interesting that the increase in resolution in the GFDL models has a small impact on the Gulf Stream climatology but a great influence on the changes. This indicates that the climatology and changes can be sensitive to different things. The eddy parameterizations used in the low-resolution GFDL model are able to create a similar climatology to the high-resolution model but still fail to represent the key processes responsible for future SST changes (i.e., the Labrador Current and the flow's interaction with the coastal bathymetry; Saba et al., 2016). This creates a fundamental challenge in climate projection with low-resolution models. On the other hand, the sensitivity to resolution may depend on details of the parameterizations, which could lead to differing sensitivities between low-resolution models.

Over the land regions of eastern North America adjacent to the Gulf Stream, differences in precipitation responses arise from comparable contributions from the simulation of climatological SSTs and SST changes. Because the eddy-resolving model has overall the most realistic climatological SSTs (Delworth et al., 2012), it arguably provides a more reliable baseline for the projection of land precipitation changes. Alternatively, climate projections over land may be improved by using atmosphere-only simulations that are integrated using observed SSTs, which are much less computationally expensive than coupled eddy-resolving models (He & Soden, 2016). However, the use of atmosphere-only models does not account for the uncertainty in changes in SST, which we have shown could be influenced by changes in model resolution even in models that simulate a good climatology with low resolution.

By decomposing the precipitation responses into convective and large-scale changes, we are able to gain some interesting perspectives. For example, we show that the subtropical drying is largely reflected in convective precipitation changes, whereas the extratropical wetting is dominated by large-scale changes. We also show that the effect of the Gulf Stream SST changes on land precipitation is primarily achieved through large-scale precipitation, indicating that the simulation of large-scale precipitation changes might hold the key to understanding the remote impact of extratropical SST changes. On the other hand, the division of precipitation into convective and large-scale components depends on model parameterization and resolution and may yield inconsistent results among models. However, it provides an alternative approach to understanding precipitation projections and diagnosing intermodel spread in addition to the commonly used decomposition methods, such as the moisture decomposition (Chadwick et al., 2013; Seager et al., 2010) and the energetic decomposition (Muller & O'Gorman, 2011).

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