Does Radiative Cooling of Stratocumulus Strengthen Summertime Subtropical Highs?

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1. Introduction

Some previous studies, including Liu et al. (2004), Wang et al. (2005), and Miyasaka and Nakamura (2005), have suggested that radiative cooling of stratocumulus (including stratus) might contribute to strengthening and/or localizing summertime subtropical highs. Our climate model MRI-ESM2 (Yukimoto et al. 2019), which is used in CMIP6 simulations, can represent low-level clouds such as subtropical stratocumulus relatively well and has a better score for radiative fluxes at the top of the atmosphere than any CMIP5 model (Kawai et al. 2019). In addition, stratocumulus off the west coast of continents can be completely removed in a physically consistent manner when the stratocumulus scheme is turned off in the model. Therefore, we can quantitatively examine the effect of radiative cooling of stratocumulus on subtropical highs by removing the clouds using a state-of-the-art global climate model that reproduces subtropical stratocumulus quite realistically.

2. Experiments

The model incorporates two stratocumulus schemes: the old one (Kawai and Inoue 2006) and the new one (Kawai et al. 2017, 2019). We ran the model with three settings: without a stratocumulus scheme, with the old scheme, and with the new scheme. We ran the model using two configurations: the atmospheric model (AMIP simulation) and the atmosphere–ocean coupled model (historical simulation). The models were run from 2000 to 2014, and data for the 10 years from 2005 to 2014 were used for analysis.

3. Results

3.1. Atmospheric model simulations

First, results from atmospheric model simulations for July are shown. As seen in Fig. 1, stratocumulus off the west coast of the continents, including off California, Peru, Mauritania, and Namibia, completely disappears when the stratocumulus scheme is turned off. When the old stratocumulus scheme is used, such clouds are represented more realistically. When the new stratocumulus scheme is used, all low-level clouds, including subtropical stratocumulus, are very similar to those observed. Although the negative bias in upward shortwave radiative flux at the top of the atmosphere due to the lack of reflection of solar radiation by stratocumulus is significantly large for the

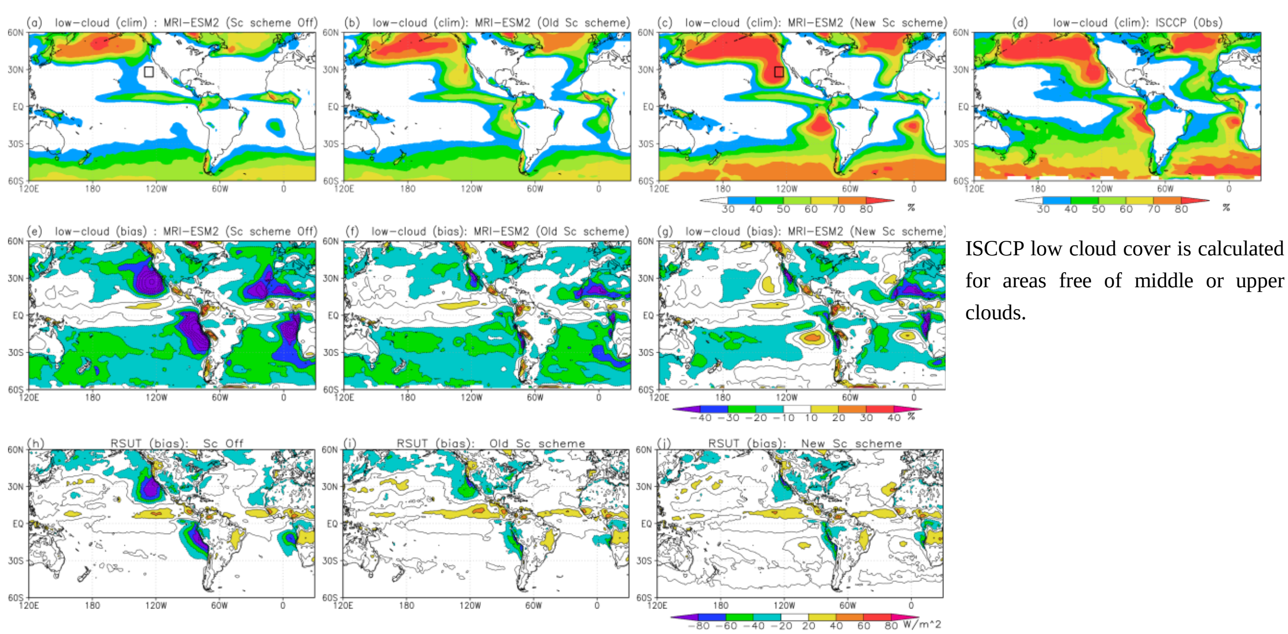

Fig. 1: From the top, climatologies of low cloud cover (%), biases of low cloud cover (%) with respect to ISCCP observations (shown in panel (d)), and biases of upward shortwave radiative flux (W/m^2) at the top of the atmosphere with respect to CERES-EBAF for July. From the left, results without stratocumulus schemes, with the old scheme, and with the new scheme. The climatologies cover the period 2005–2014 for model simulations and 1986–2005 for ISCCP data, and 2001–2010 for CERES-EBAF data.

simulation without a stratocumulus scheme, the bias is reduced for the simulation with the old stratocumulus scheme and is quite small for the new scheme simulation.

Figure 2 shows the impacts of the removal of stratocumulus on summertime subtropical highs as given by the difference between simulations with no stratocumulus scheme and with the old and new stratocumulus schemes. The figure shows that there is no change in the strength or locations of subtropical highs over the North Pacific and North Atlantic. Figure 3 shows the heating rate profiles of each physical process for the area off California shown by the box in Fig. 1a and 1c. It is clear that longwave cloud top cooling (about −14 K/day at the peak) is large when there are low clouds. However, most of the cooling is compensated by turbulent heating (5 K/day), heating by cloud condensation (6 K/day), and shortwave radiative heating (2 K/day). The response of the dynamics is relatively small. Therefore, cloud top cooling of stratocumulus cannot substantially change the strength of subtropical highs. This result is consistent with the fact that the strength of summertime subtropical highs was generally well represented in the JMA operational global model GSM even before 2004, although subtropical stratocumulus was not represented at all at the time (Kawai and Inoue 2006).

3.2. Coupled model simulations

The atmosphere–ocean coupled model simulations show results generally similar to those of the atmospheric model simulations. However, in the coupled model cases, subtropical highs can be altered through SST changes caused by the difference in solar insolation at the sea surface. Although SST is higher by 1–2 K in the simulation without a stratocumulus scheme owing to a lack of shielding of solar insolation, the decrease in pressure of the highs is only 1–2 hPa at the center of the highs (Figures not shown). A part of this decrease may even be attributed to the effect of SST increase over the global ocean, in addition to the effect of the local SST increase. Global SST increases over several years of model integration when the stratocumulus scheme is turned off, and it is known that subtropical highs are weaker for higher-SST conditions (e.g., Shaw and Voigt 2015, Kawai et al. 2018). The simulation results presented here lead us to conclude that no significant influence of radiative cooling of stratocumulus on summertime subtropical highs is identified in our simulations using a state-of-the-art climate model.

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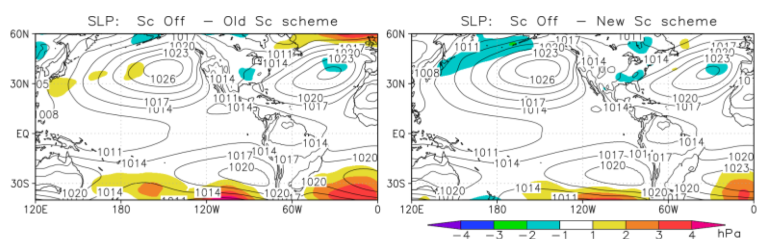

Fig. 2: Differences in climatologies of sea-level pressure for July for the period 2005–2014. Results without a stratocumulus scheme minus those (left) with the old scheme and (right) with the new scheme.

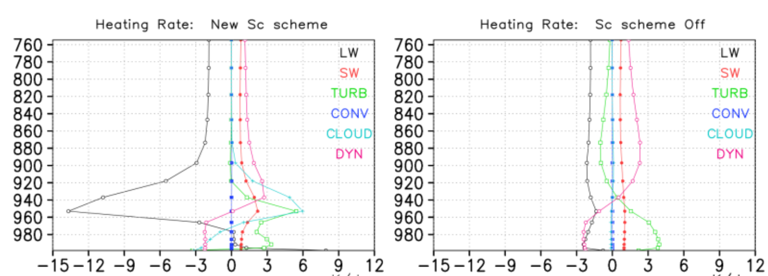

Fig. 3: Heating-rate profiles for each physical process for the area off California shown in Fig. 1a and 1c for July. Heating rate for longwave (black) and shortwave (red) radiation, turbulence (green), convection (blue), cloud (light blue), and dynamic (pink) processes with the new stratocumulus scheme (left) and without a scheme (right) for the period 2005–2014 are shown. The vertical axis shows pressure (hPa).